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Life assessment of the U.S. nuclear electric generating stock

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University of Pennsylvania, 1994

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LIFE ASSESSMENT OF THE U.S. NUCLEAR ELECTRIC GENERATING STOCK

Ivan Alfredo Vera

A DISSERTATION
in
Energy Management and Policy

Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

1994

John D Keenan
Supervisor of Dissertation

William G Grigsby
Graduate Group Chairperson

DEDICATION

TO MY MOTHER DORA OFELIA AYESTARAN DE VERA AND TO MY FATHER JUSTO ALIPIO VERA CARDENAS, WHO THROUGHOUT MY LIFE TAUGHT ME THE IMPORTANCE OF EDUCATION AND THE VALUE OF PERSEVERANCE.

ESTE TRABAJO ES DEDICADO CON GRAN AMOR Y PROFUNDO RESPETO A MIS PADRES DORA OFELIA AYESTARAN DE VERA Y JUSTO ALIPIO VERA CARDENAS QUIENES A TRAVES DE TODA MI VIDA ME ENSEÑARON LA IMPORTANCIA DE UNA BUENA EDUCACION Y EL VALOR DE LA PERSEVERANCIA.

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ABSTRACT

LIFE ASSESSMENT OF THE U.S. NUCLEAR ELECTRIC GENERATING STOCK

IVAN ALFREDO VERA

JOHN KEENAN

Although nuclear electricity represents about twenty percent of the net electricity generated in the United States, there are no technical design specifications that determine the life expectancy of the 109 nuclear reactors operating in the nation. As the U.S. nuclear stock continues aging, deterioration of critical engineering equipment and increasing operating costs have forced the permanent retirement of nuclear reactors expected to operate beyond the end of this century. These retirements are creating uncertainty with respect to the future of nuclear power and bring into question the commonly accepted assumption that nuclear reactors will operate for the 40 years for which they are licensed to operate.

This dissertation provides an analytical tool that incorporates specific engineering and economic data into an integrated modeling system designed to estimate nuclear life expectancy. The modeling system allows the forecasting of engineering performance through time and then equates nuclear generating costs to this performance. The final life estimates are determined based on the evaluation of replacement costs and the incorporation of nuclear engineering constraints. The implementation of this tool in the U.S. nuclear generating stock allows the identification of early nuclear retirements, thus facilitating forecasts of potential electricity capacity shortages and more accurate electricity supply planning.

Two sets of results have been generated from the analysis of two scenarios that consider different engineering performance forecast approaches. Although the scenarios produce very different results, both scenarios indicate that a considerable number of reactors will retire before they reach their expected licensed life of 40 years. The results also show a wide dispersion of life expectancies among nuclear reactors. The regions identified with potential electricity supply problems are South Atlantic, Midwest, New York/New Jersey, and especially New England. Forecasts for the year 2000 imply that New England will have insufficient baseload capacity and capacity margins to ensure adequate electricity supplies, the New York/New Jersey region will not have enough baseload capacity to replace retiring nuclear reactors, and the South Atlantic and Midwest regions will lack adequate capacity margins.

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CHAPTER I

INTRODUCTION

It has been commonly assumed that the useful operating life of nuclear reactors in the United States equals at least the 40 years for which they have been licensed to operate. Utilities, energy research organizations, and planning and forecasting institutes in the United States have based their studies, projections and decisions on the premise that all nuclear operating units will in fact operate for at least 40 years. This assumption is reflected in all the data and publications available that relate to the subject. For instance, the data forms submitted to the Department of Energy by utilities operating nuclear reactors show an expected operating life of 40 years for all operable reactors. All the base-case forecasts of electricity generation (developed by public and private institutions) for short-, mid-, and long- term periods indicate a nuclear share in electricity generation based on the assumption of a 40-year life. Other important planning activities and decisions, such as the addition of new electric generating capacity, the recovery of capital investments, the availability of decommissioning funds, the volume of nuclear spent fuel discharges, the size and availability of the national nuclear waste repository site, and the expected uranium needs, are all based on the assumption of an useful operating life for reactors of at least 40 years.

This assumption about life expectancy is clearly no longer valid. None of the nuclear reactors already permanently retired has reached a 40-year life. A total of 21 nuclear electric generating units previously licensed to operate have been permanently shutdown in the U.S. The average life of all the commercial reactors included in this group has been only 15 years. For the five reactors permanently retired after 1980 (i.e., excluding all reactors shutdown during the 1960s and 1970s when nuclear technology was considered to be still evolving), the average life is 20 years, just half of what has been assumed.

The original decision to issue licenses for a 40-year period was not based on proven technical capabilities for these plants to operate for at least that period. The Atomic Energy Act of 1954, which provided the original set of regulations regarding commercial nuclear power plant licensing, included a statutory limit of 40 years for the duration of licenses issued to electric utilities that operate commercial nuclear plants.[1] As described in Chapter II, the first nuclear reactor connected to the electrical network started operation in 1957, three years after the statutory limit was defined. Thus, the selection of a 40-year license could not have been based on proven technical capabilities since the decision was made even before the first plant was in service. In fact, the license limit decision was based on financial and licensing considerations.[2] Utilities interested in building nuclear reactors were asking for a 60-year license to ensure the recovery of the large capital cost involved in the construction of nuclear reactors. Other utilities, not quite ready to commit themselves to nuclear power, were demanding a shorter license because of concerns about their competitors having a 60-year monopoly in electricity generation. A compromise was reached for a 40-year license limit after taking into consideration additional safety concerns expressed by some regulators.[3]

In the last few years the nuclear electric generating industry has seen the final retirement of some nuclear reactors that had been expected to operate beyond the end of this century. Reactors of all sizes, including Yankee Rowe, Rancho Seco, San Onofre 1, and Trojan have been forced to shutdown for several different reasons, including deterioration of critical equipment, consistently poor performance, and high generating costs. Although some people argue that public attitude is a contributing reason for these retirements, in most cases the problems are the result of an unanticipated rate of deterioration affecting, in particular, equipment exposed to nuclear radiation. The recent nuclear reactor retirements and the implications of an aging stock have captured public attention, raising awareness of the importance of the life expectancy issue.[4]

The U.S. nuclear electric generating stock is responsible for twenty percent of the net electricity generated in the nation. The 109 nuclear reactors operating in the U.S. generate over 600 billion kilowatthours per year and have a net summer capability of 100 gigawatts.[5] Of the 33 states with nuclear reactors, seven rely on nuclear power for more than 50 percent of their electricity. Eleven additional states rely on nuclear power for 25 to 50 percent of their electricity. Thus, for several states and regions the life expectancy of nuclear reactors should be of great concern.

Although nuclear generation has tripled in the last 18 year, a declining trend in nuclear electricity generation is expected in the intermediate and long terms. No successful order for the construction of a nuclear reactor has been placed since 1973, and there are only two more nuclear units under construction expected to be completed.[6] New orders are not expected in the future unless changes occur in major prevailing conditions affecting the nuclear industry. Thus, even assuming that all reactors will operate for a 40-year license period, the U.S. nuclear generating stock will start to decrease by the year 2000 and will be completely lost by the year 2030. However, if enough nuclear reactors are forced to shutdown before their 40-year licensed life is reached, there is a potential for electricity capacity shortages. These shortages could be critical in areas that depend heavily on electricity generated by nuclear reactors.

The estimation of the life expectancy of nuclear reactors is necessary not only to identify potential electricity shortages but to assess the impact on other related issues including capacity additions, decommissioning funds, electricity rates, reactors' depreciation schedules, nuclear waste disposal, and uranium supplies.

The major objective of this study is the development of an analytical tool for predicting the life expectancy of nuclear reactors. The method incorporates nuclear engineering and economic data into a modeling system designed to generate forecasts of life expectancy on a reactor-by-reactor basis. The approach considers plant-specific engineering data related to structures, equipment, and components that are critical in nuclear reactors. A second objective of the study is the implementation of this tool to predict the lives of U.S. nuclear generating reactors. Life expectancy scenarios allow the prediction of whether early nuclear reactor retirements will pose serious electricity supply problems at regional levels.

Research Method

Although experts have recognized that the life of nuclear reactors depends on several factors which are interrelated, only a few attempts have been made to formulate an analytical tool that could be used for the assessment of the life of nuclear reactors. In fact, the only attempts found in the literature focus primarily on operating cost factors.[7] Other related studies include methods to assess the potential for nuclear plant life extension.[8] The method proposed in this study consists of an integrated modeling system that incorporates and relates relevant factors into an evaluating tool capable of estimating the useful operating lives of nuclear reactors.

The forecasting system consists of an engineering module and an economic module. The output of these two major components are interrelated to produce the final result of a nuclear life assessment on a reactor-by-reactor basis. The engineering module includes a nuclear performance submodule and a nuclear technological constraint submodule. The performance submodule projects performance of nuclear reactors in terms of efficiency parameters and based on reactor-specific characteristics such as age, size, initial performance, equipment type and designs. The performance function is solved following two approaches that allow the generation of two life expectancy scenarios. The first approach uses a non-linear function solved by multiple regression analysis. The second approach uses a similar non-linear function that is solved according to mathematical principles and based on curve parameters that fully describe this function. The forecasts are translated from point values into probabilistic ranges by a probabilistic analysis based on normal distribution assumptions. The technological constraint submodule considers constraints related to the progressive deterioration of materials and equipment due to aging and in particular due to problems associated with radiation. Critical technical constraints include vessel embrittlement, ductile fracture resistance, and piping deterioration in the steam generators. The technological constraint submodule affects the life expectancy estimates by imposing limitations on the expected life derived from the performance functions.

The economic module consists of a nuclear cost submodule and a replacement cost submodule. The nuclear cost submodule relates nuclear power production costs to performance levels. Cost-performance functions are used to measure the escalation of production costs as a reactor's performance deteriorates through time. The replacement cost submodule incorporates power replacement costs, derived from power pool shutdown probability simulations, with the cost-performance functions. The comparison of the two costs allows the determination of the minimum efficiency level beyond which it becomes more expensive to operate the reactor than to replace the power.

The study is fundamentally different from previous approaches because it assesses the life of nuclear reactors by explicitly considering specific critical factors identified in engineering and economic areas. These factors are considered in an integrated manner implying that their interdependence is indispensable for the assessment of the nuclear reactors' lives. The study represents the first attempt in the formulation of such an integrated and comprehensive approach.

Outline of Dissertation

This dissertation begins with a historical overview of the development and commercialization of nuclear power presented in Chapter II. In addition, this chapter contains a review of the present status of the nuclear electricity generating stock in the United States and a summary of the factors affecting the nuclear power industry.

Chapter III assesses the problem of retiring nuclear capacity and describes the factors affecting nuclear power plant life. The chapter includes the characterization of critical engineering equipment, case studies of reactors permanently shutdown, and a summary of the general analytical approach followed in this study for the estimation of the life expectancy of the U.S. nuclear electric generating stock.

Chapter IV reviews existing literature on the general issue of nuclear life expectancy and background information on particular issues pertinent to the development of this study. Different approaches used in the past for the evaluation of nuclear engineering performance, engineering constraints, and nuclear cost trends are summarized. In addition, methods used in the evaluation of the potential for nuclear life extension are outlined.

Chapter V presents a detailed description of the research method followed in this study. The description includes details of the engineering module and its components, the engineering performance submodule, and technical constraints submodule. Two approaches are presented for the generation of nuclear reactor performance forecasts. The economic module is also described incorporating details about the nuclear cost submodule and the replacement cost submodule.

Chapter VI is a detailed description of the data used in this study. The chapter includes a discussion on data availability, quality, limitations, requirements, and sources. Also, the database design and general data characteristics of the U.S. nuclear generating stock are described.

Chapter VII presents and analyzes the results of this study. Results from two case scenarios are described in detail. The analysis of the results includes the age assessment of all the nuclear reactors, their expected year for retirement, the location of the reactors expected to shutdown prematurely, and implications of early nuclear retirement with respect to electricity supplies. In addition, discussions are included on evaluation of results and policy implications.

Chapter VIII presents general and specific conclusions derived from the results of this research activity. Also, this chapter includes a summary of this study including a brief discussion of the research objective, problem statement, and research method.

The study includes two appendices. Appendix A presents tables listing selected input data values and the results obtained for the two scenarios considered in the study. Appendix B describes potential replacement options for areas with reactors expected to retire prematurely.

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5. This dissertation uses data from 113 U.S. nuclear reactors. This sample includes 108 operating nuclear reactors and 5 permanently retired nuclear reactors. The sample excludes data on Comanche Peak 2. This is a nuclear reactor which entered operation in 1993 and therefore has not accumulated any operating data.

6. Several orders placed between 1974 and 1978 were all subsequently canceled. There are 5 additional nuclear units in the construction pipeline but their construction has been indefinitely deferred (see Chapter II).

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CHAPTER II

NUCLEAR POWER INDUSTRY

This chapter provides a historical overview of the development and commercialization of nuclear power, a review of the present status of the nuclear electricity generating stock in the United States, and a summary of the factors affecting the nuclear power industry.

NUCLEAR POWER DEVELOPMENT AND COMMERCIALIZATION

Nuclear fission was discovered in Germany shortly before World War II by Otto Hahn and Fritz Strassmann in 1938. The discovery of nuclear fission is considered one of the most significant events in human history. The applications of nuclear fission as both a military weapon and a source of electricity make this energy source one of the most controversial and relevant technological advances shaping world affairs during the 20th century.

L. Szilard, a scientist involved in early fission research, feared potential military uses by the Germans and persuaded Albert Einstein to write his famous letter to President Franklin Roosevelt in August 2, 1939. In this letter Einstein explained the energy and weapons potential of uranium fission. President Roosevelt immediately committed the country to nuclear research by creating the Advisory Committee on Uranium. In November 1, 1939, the Committee reported: "If it could be achieved and controlled... it might supply power for submarines. If the reaction should be explosive, it would provide a possible source of bombs with a destructiveness vastly greater than anything now known."[1]

The potential for nuclear fission applications in submarine propulsion was promptly given to the Navy while the Army became responsible for the development of an atomic bomb. Other government committees and organizations were also created to promote the development of the fission process for weapons purposes.

The first successfully sustained-fission reaction was achieved by Enrico Fermi and other scientists working for the Manhattan Project on December 2, 1942. This experience is considered the event that marked the birth of nuclear power. The first reactor with a power output of one thermal megawatt went into operation at Oak Ridge, Tennessee in November 1943. The first large plutonium production reactor began operation at Hanford, Washington, in September 1944. The destructive potential of nuclear power was demonstrated in Hiroshima and Nagasaki in August 1945. The United States brought World War II to an end by using atomic bombs for the first time in history.

All the early nuclear fission research was conducted under absolute secrecy due to its sole military purpose. However, plans were initiated after World War II for the establishment of a program that would allow nuclear power applications for peacetime purposes while retaining the exclusive U.S. government role of military weapons technology. As a result of this initiative, the Congress passed the Atomic Energy Act in 1946 giving the responsibility for nuclear development to the Atomic Energy Commission (AEC). This five-member commission was granted extensive powers for the control and use of nuclear energy.

The AEC inherited the control of the nuclear weapons research and development programs that started with the Manhattan Project. In addition, the AEC had control over existing industrial organizations that produced nuclear materials and components for all military branches. The AEC maintained this exclusive control over the nuclear industry for 8 years until the passage of the Atomic Energy Act of 1954. The AEC recognized the potential applicability of nuclear power to a wide range of fields, necessitating the development of diverse reactor types suitable for each purpose, including naval propulsion, large-scale industrial and commercial uses, as well as small-scale experimental and testing purposes. The strategy was to encourage the development of multiple reactor designs and technological approaches. "There is little question that the policy of multiple development must be seen as one of the major elements in the Commission's success in bringing commercial reactors on-line in such a period of time."[2]

The Atomic Energy Act of 1946 also created the Congressional Joint Committee on Atomic Energy (JCAE). The primary function of the JCAE was to oversee the AEC and to coordinate and recommend nuclear-related legislation in Congress. A few years after its creation, the JCAE assumed a broader role in industrial development of nuclear power for non-weapons purposes. In particular, the JCAE became involved in the formulation of legislation that would allow the transfer of nuclear technology to private industry for purposes of electricity generation. This marks the beginning of a great effort by the federal government to promote nuclear-powered electricity.[3] The JCAE is considered one of the most important entities which provided leadership and influenced the direction of nuclear energy programs in the United States through the sixties and up to its dissolution in 1977.

Under the sponsorship of the AEC, small experimental reactors designed for the specific purpose of electricity generation were built during the late forties and early fifties. A small amount of electricity was first produced by the Experimental Breeder Reactor 1 (EBR-1) in 1951 at the National Reactor Testing Station in Idaho. The first considerable amounts of useful power were produced by the Submarine Thermal Reactor 1 (STR-1) which was developed under the Naval Reactors Program and began operation in 1953. It has been recognized that the nuclear submarine propulsion program of the late forties and early fifties is one of the successful military applications that exerted a crucial influence on the later selection of reactor types for electricity production.[4]

Although the JCAE and the AEC were actively encouraging private interest in nuclear electricity reactor's development, industry could not participate since the 1946 Atomic Energy Act restricted ownership of reactors and fuels exclusively to the government. Nevertheless, from 1951 to 1953 numerous joint industry-government groups were established by the AEC to examine power reactor concepts. In 1954 a new Atomic Energy Act was in force. The Energy Act of 1954 eliminated the federal monopoly over non-military uses of atomic energy and allowed the beginning of several reactor demonstration and development programs. The 1954 Act authorized the AEC to license private and public groups to construct, own, and operate power reactors taking into consideration health and security regulations. The AEC retained ownership of nuclear fuel and other fissionable materials, but could lease them for private use.

Private industry participation was encouraged by the creation of a "Five-Year Power Reactor Development Program" that included the construction of five separate reactor technologies at a cost of $199 million. The reactors built under this program are listed in Table II.1. As a result of this program, the Shippingport nuclear reactor in Shippingport, Pennsylvania, became the first nuclear reactor to be connected to the electrical network. Shippingport was a pressurized water reactor (PWR) with a 60 megawatt-electric (MWe) capacity that started operation in 1957. The success of Shippingport played a major role in proving the technical concept of central nuclear stations for application by electric utilities.

Another program sponsored by the AEC was the Power Demonstration Reactor Program (PDRP) announced in 1955 and designed to prove the economic competitiveness of nuclear power. The program was intended "to bring private industry into the engineering of nuclear reactors and to advance the time when nuclear power would become economically competitive."[5] This program was a government-industry effort implemented in three phases that resulted in the construction of 14 reactors listed in Table II.2. The program was considered a success and it led to an industry-wide commitment to two types of light-water reactor designs. These are the Boiling Water Reactors (BWR) and the Pressurized Water Reactors (PWR).

A final impediment to full private industry participation was the issue of who would be liable for possible damages in the event of an accident. At this time, utilities were concerned about the possibility of a catastrophic accident and their liability was

Table II.1: Five-Year Power Reactor Development Program (AEC)

NAME	TYPE	MWe	LOCATION	OWNER	STARTUP DATE	SHUTDOWN DATE
Shippingport	PWR	60.0	Shippingport, PA	AEC	1957	1972
EBWR	Experimental BWR	4.0	Argonne National Lab, IL	AEC	1956	1967
SRE	Sodium Graphite	5.7	Santa Susana, CA	AEC	1957	1964
EBR-2	Experimental Breeder Reactor	20.0	National Reactor Testing Station, ID	AEC	1963	N/A
HRE-2	Homogeneous Reactor Experiment	.30	Oak Ridge, TN	AEC	1952	1954

Source: Dawson, Frank G., *Nuclear Power, Development and Management of a Technology*, University of Washington Press, Seattle, Washington, 1976, p.93.

Table II.2: Power Demonstration Reactor Cooperative Program

NAME	TYPE	MWe	LOCATION	OWNER	STARTUP DATE	SHUTDOWN DATE
Phase One Yankee Rowe	PWR	175.0	Rowe, MA	Yankee Atomic Electric Co.	1960	1991
Hallam	Sodium graphite	75.0	Hallam, NB	AEC/Consumers Public Power District	1962	1964
Fermi 1	Sodium-cooled	60.9	Lagoona Beach, MI	Power Reactor	1962	1964
Phase Two Elk River	BWR	22.0	Elk River, MN	AEC/Elk River Rural Coop Power Association	1962	1968
Piqua	Organic Cooled	11.4	Piqua, OH	AEC/City of Piqua	1963	1966
LaCrosse (Genoa)	BWR	50.0	LaCrosse, WI	Dairyland Power Coop	1967	1987
BONUS	Boiling Water, Super-heat	16.5	Punta Higuera, PR	AEC and Puerto Rico Water Resources Authority	1964	1968

Source: Dawson, Frank G., *Nuclear Power, Development and Management of a Technology*, University of Washington Press, Seattle, Washington, 1976, p.93.

Table II.2: Power Demonstration Reactor Cooperative Program (continued)

NAME	TYPE	MWe	LOCATION	OWNER	STARTUP DATE	SHUTDOWN DATE
<u>Phase Three</u>[3] Big Rock Point	BWR	72.0	Big Rock Point, MI	Consumers Power Co.	1962	Operating
San Onofre 1	PWR	436.0	San Clemente, CA	So. Cal Edison/San Diego G&E	1967	1992
Connecticut Yankee	PWR	575.0	Haddam Neck, CT	Conn. Yankee Atomic Power Co.	1967	Operating
Carolinas-Virginia Tube Reactor	Pressurized-Tube, Heavy Water	17.0	Parr, SC	Carolinas-Virginia Nuclear Associates	1963	1967
Pathfinder	Boiling Water, Superheat	58.5	Sioux Falls, SD	Northern States Power Co.	1964	1967
Peach Bottom 1	HTGR	40	Peach Bottom, PA	Philadelphia Electric Co.	1966	1974
Fort St. Vrain	HTGR	330	Plattville, CO	Public Service Co. of Colorado	1974	1989

Source: Dawson, Frank G., *Nuclear Power, Development and Management of a Technology*, University of Washington Press, Seattle, Washington, 1976, p.93.

perceived to be many times greater than insurance coverage available to other industries. Operators and suppliers agreed on the need for the government to provide a suitable program to limit their potential liability.

To address the liability problem, the Price-Anderson Act was passed by the Congress in 1957 with two basic provisions: (1) to guarantee compensation to the public in case of a nuclear accident and (2) to limit industry's liability in such an accident to a level that would allay fears of bankruptcy. The Act limited the total liabilities for losses in an accident to not exceed $560 million. The original Act stipulated that part of the liability be covered from private insurance purchased by utilities from an insurance pool, which in 1957 was limited to $60 million. The remaining $500 million would be underwritten by the Federal government. The Act was due to expire after 10 years, but it has since been extended three times in 1965,1975 and 1988, with its latest extension in force until 1998. The 1975 amendment provided for a reduced government role commensurate with the growth and safety record of the nuclear industry.

By the early sixties a number of demonstration reactors were operating and the attention centered on the technical results and economics of all different reactor types. The results showed advantages for both the BWR and PWR light-water reactors. Economic analysis at this time indicated that the busbar generating cost for nuclear reactors would have to be in the range of 4 to 7 mills per kilowatt-hour (KWh) to be competitive with fossil fuel reactors.[6] The costs at Shippingport were estimated at 50 mills per KWh but early operating data on the few larger units indicated costs of about 10 mills per KWh. Soon the economies of scale became obvious to vendors and preliminary estimates by both the AEC and manufacturers indicated that indeed large nuclear units would hold a competitive advantage over comparably-sized coal reactors.

The first large nuclear reactor in which the Federal government had no financial involvement was the Oyster Creek nuclear plant purchased by the Jersey Central Power and Light Company in late 1963. The plant was a 650-MWe BWR purchased from General Electric at a fixed price, adjusted only for inflation. The Oyster Creek contract represented the first clear effort by private manufacturers to encourage utilities to order large nuclear units. In addition to General Electric, Westinghouse, Babcock and Wilcox, and Combustion Engineering offered "turnkey" contracts to utilities in which the manufacturers were responsible for the entire project at a fixed cost to the utility allowing only for inflation. Utilities placed several orders for the construction of large nuclear reactors and this marked the beginning of the commercialization of nuclear power and the minimization of government dependence.[7]

Private ownership of nuclear fuels was finally allowed by legislation in 1964. The legislation stipulated the need for the government to provide toll enrichment services for privately owned uranium. The AEC would regulate the use of nuclear materials by issuing licenses and regulations to protect public health and safety. In addition, the AEC had the responsibility to prevent unlawful possession or use of nuclear materials. At this time, the Government retained direct control only over toll enrichment services and nuclear waste disposal.

The confidence in nuclear generation was such that by the end of 1965 utilities had ordered 66 units for an overall capacity of 57,000 MWe, even though prior to these orders the total capacity of all units in commercial operation was less than 1,000 MWe. In addition, the orders were placed for larger units with an average size of 850 MWe. The largest operating unit at that time was a 265 MWe unit in New York (Indian Point 1). Manufacturers without any practical knowledge at the time committed to the construction of larger nuclear units based on what has been called "design by extrapolation" method.[8] Thus, nuclear units reached the same size as fossil-fuel plants in less than a decade since their introduction.[9] In fact, of the 66 units ordered by 1965, 22 were larger than 1000 MWe.[10]

From 1953 through 1978, the industry ordered a total of 251 nuclear electrical generation units. Table II.3 lists the number of orders and respective capacities. The nuclear capacity ordered annually is presented in Figure II.1. The total number of orders represented a net capacity of 248,269 MWe. As more technical and economic data became available, the BWR and PWR light-water reactor types dominated the market. The manufacturers' market was then controlled by 4 companies. General Electric built all the BWR units while PWR units were built by Westinghouse, Babcock and Wilcox, and Combustion Engineering. The Atomic Energy Commission predicted in 1973 that there would be more than 1000 large nuclear power plants in the U.S. by the year 2000.

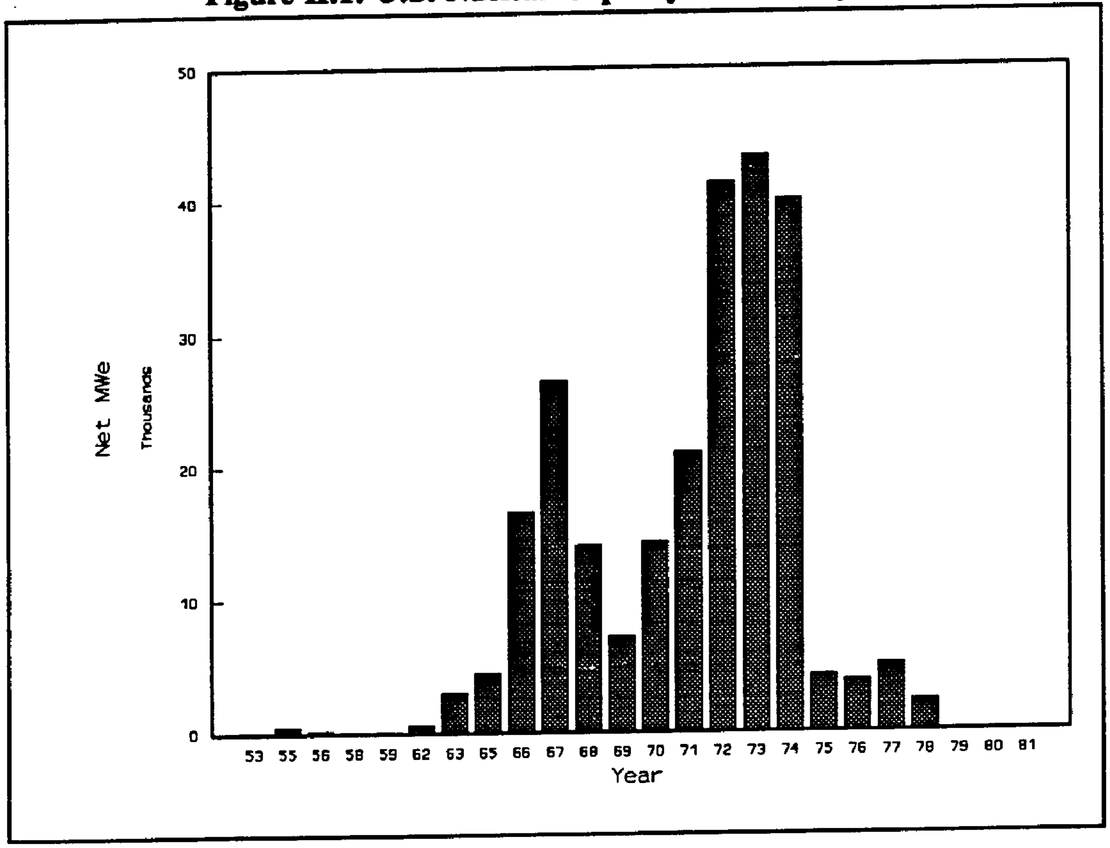
Several reasons influenced the large number of reactor orders during the period from 1963 to 1973. Utilities were observing a nationwide annual growth rate in electricity demand of about 7 to 8 percent. The perception was that nuclear power was the most economical choice to satisfy the demand of baseload capacity. Estimates of

Table II.3: U.S. Nuclear Reactor Orders

YEAR	NUMBER OF UNITS	CAPACITY (Net MWe)
1953	1	60
1955	2	465
1956	1	175
1958	1	65
1959	1	72
1962	2	630
1963	5	3,018
1965	7	4,475
1966	20	16,526
1967	31	26,462
1968	15	14,018
1969	7	7,203
1970	14	14,264
1971	21	20,957
1972	38	41,313
1973	38	43,319
1974	34	40,015
1975	4	4,148
1976	3	3,804
1977	4	5,040
1978	2	2,240

Source: DOE, EIA, *U.S. Commercial Nuclear Power*, DOE/EIA-0315, March 1982.

Figure II.1: U.S. Nuclear Capacity Ordered by Year



busbar generating costs showed an advantage for large nuclear units over fossil-fuel units.[11]

In the long term, it was expected that the high capital costs associated with nuclear units would be offset by low fuel costs. Finally, the late sixties and early seventies period was characterized by a continuous increase in oil-fuel prices and unstable political situations in oil producing countries. Thus, nuclear energy was perceived as an alternative that could reduce the U.S. dependence on foreign oil.

The AEC was dissolved in 1974 and its activities were separated and became functions of two organizations. The Nuclear Regulatory Commission (NRC) was created to ensure the regulation of the nuclear industry while the Energy Research and

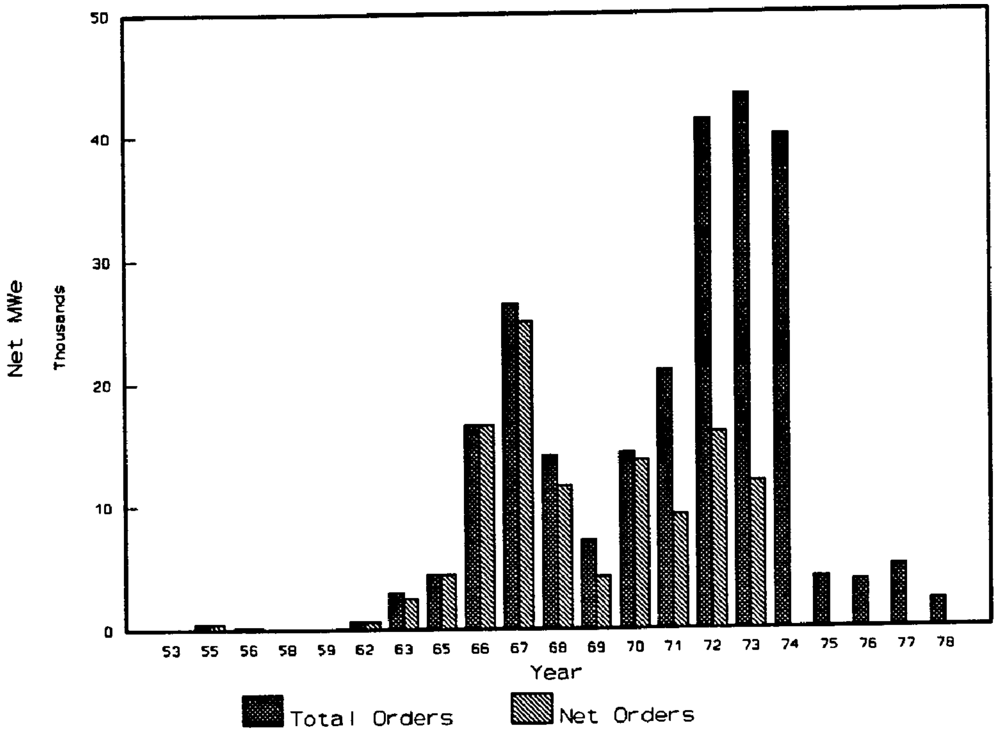
Development Administration (ERDA) absorbed the research and development activities of the AEC. The NRC is still the regulator of the nuclear industry and the ERDA became part of the U.S. Department of Energy in 1977.

The extraordinary growth and rapid penetration of the nuclear technology as expected by the 251 nuclear reactor orders placed by 1978, however, was not fully realized. Beginning in 1972 a new trend characterized by a large number of nuclear reactor cancellations prevailed, bringing the growth in nuclear electrical generation to an end. Table II.4 lists the number of cancellations by year of order and by year of cancellation and the corresponding capacities. A comparison of total and net number of orders in terms of generating capacity is shown in Figure II.2. As it became evident that the projections of electricity demand were not going to be realized and nuclear construction expenses grew to unexpectedly high levels, utilities had no alternative but to cancel several nuclear construction orders. Associated delays in project schedules, stricter regulations and the 1979 accident at the Three Mile Island nuclear plant further affected the decision to cancel more units. By 1981, 84 orders were canceled totalling almost 90,000 MWe.[12] By 1992 the total number of canceled orders was 120 (48%) corresponding to about 131,700 MWe of capacity. No new orders have been placed since 1978 and the last non-canceled orders were placed in 1973.

Table II.4: Nuclear Reactor Orders Subsequently Canceled

	By Year of Order		By Year of Cancellation	
Year	Number of Units	Net MWe	Number of Units	Net MWe
1963	1	462	0	0
1967	2	1,482	0	0
1968	3	2,425	0	0
1969	3	2,947	0	0
1970	1	583	0	0
1971	12	11,686	0	0
1972	24	25,431	6	5,002
1973	28	31,418	0	0
1974	34	40,015	9	9,516
1975	4	4,148	10	11,729
1976	3	3,840	5	5,090
1977	4	5,040	10	10,814
1978	2	2,240	11	11,287
1979	0	0	13	15,252
1980	0	0	14	15,501
1981	0	0	6	5,781
1982	0	0	18	21,937
1983	0	0	6	6,049
1984	0	0	6	6,724
1985	0	0	2	2,260
1986	0	0	1	1,310
1987	0	0	0	0
1988	0	0	3	3,438

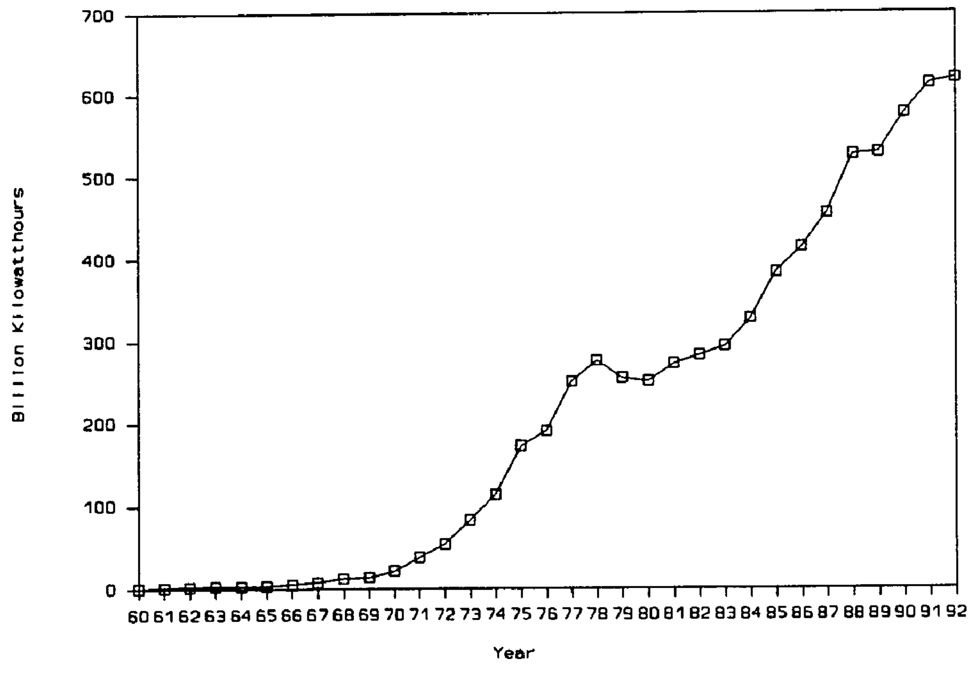
Figure II.2: Total and Net Orders of Nuclear Reactors



STATUS OF NUCLEAR GENERATING STOCK

The 109 nuclear reactors operating in the United States generate over 600 billion kilowatthours per year of electricity for a net summer capability of about 100 gigawatts.[13] The nuclear generation corresponds to twenty percent of the total net electricity generated in the United States and about 22 percent of total electricity generated by electric utilities.[14] Figure II.3 shows the net generation of nuclear electricity in billions of kilowatthours for the period from 1960 through 1992.

Figure II.3: U.S. Nuclear Electric Generation by Year



Since 1975, nuclear electric generation has tripled, coal-fired generation has

Since 1975, nuclear electric generation has tripled, coal-fired generation has almost doubled, while electricity generated by all other major sources (i.e. hydroelectric, natural gas, and petroleum) has decreased by 26 percent.[15] Figure II.4 shows the net electric generation by nuclear, coal, and other major sources for the period from 1975 through 1991.

Nuclear reactors are located in nine of the ten United States Federal Regions. Table II.5 lists the Federal Regions, their corresponding states, and the number of operating nuclear units per region. The Federal Regions are presented as defined by the U.S. Department of Energy.[16] Six Federal Regions depend on nuclear

Figure II.4: U.S. Net Electric Generation by Source

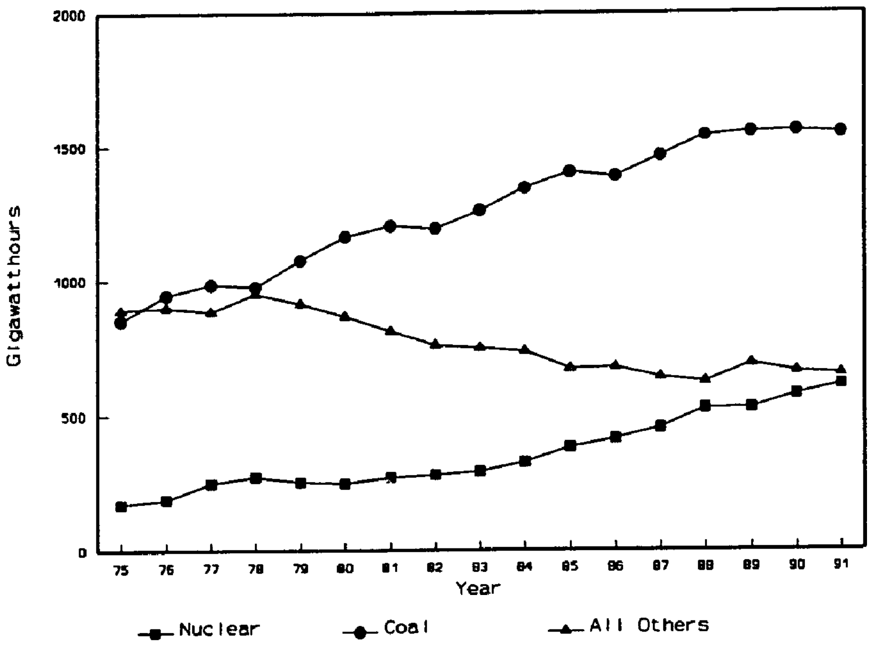
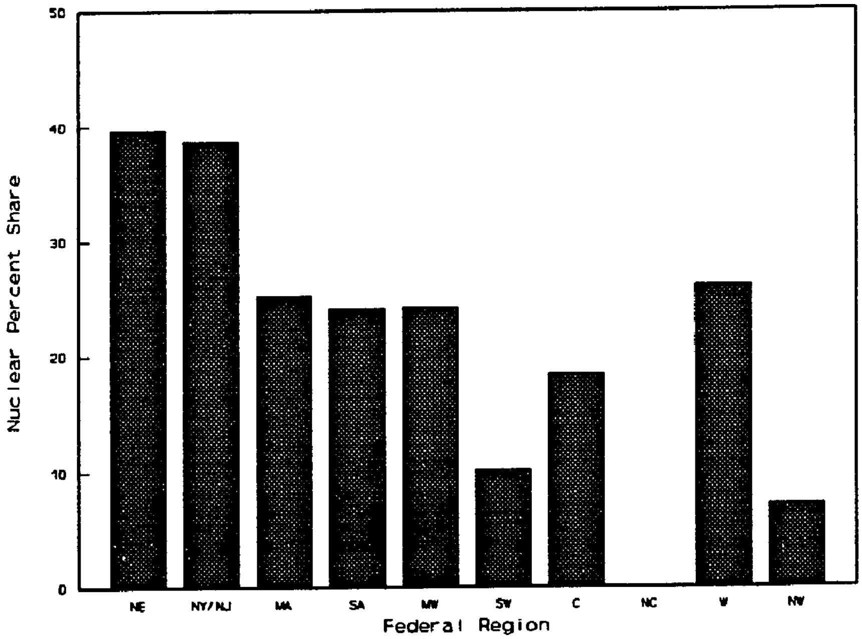


Table II. 5: Federal Regions, States, and Number of Operating Nuclear Units

Federal Region	States	Number of Nuclear Units
I. New England	Maine, Vermont, New Hampshire, Massachusetts, Rhode Island, Connecticut	8
II. New York/ New Jersey	New York, New Jersey	10
III. Middle Atlantic	Pennsylvania, Delaware, D.C., Maryland, Virginia, West Virginia	15
IV. South Atlantic	Kentucky, Tennessee, North Carolina, South Carolina, Mississippi, Alabama, Georgia, Florida	29
V. Midwest	Minnesota, Wisconsin, Michigan, Illinois, Indiana, Ohio	26
VI. Southwest	New Mexico, Oklahoma, Arkansas, Texas, Louisiana	8
VII. Central	Nebraska, Iowa, Kansas, Missouri	5
VIII. North Central	Montana, North Dakota, South Dakota, Wyoming, Utah, Colorado	0
IX. West	California, Nevada, Arizona, Hawaii	7
X. Northwest	Washington, Oregon, Idaho, Alaska	1

power for the generation of more than 25 percent of their electricity demand.[17] The New England region has the largest percent of nuclear generated electricity, at about 40 percent. Figure II.5 presents the nuclear generation percent shares by Federal Region. Nuclear generating units located in 33 states produce about one-fifth of the nation's electricity. Seven states rely on nuclear power for more than 50 percent of their electricity. Eleven additional states rely on nuclear power for 25 to 50 percent of their electricity. Table II.6 lists the states with the corresponding nuclear percent shares of electricity generation and capacity. In most of the states, the nuclear generation percent share is larger than the nuclear capacity percent share. The larger generation percent share is due to the fact that nuclear power plants are part of the baseload capacity and therefore they are kept in service at all times possible and at their maximum capacity.

Figure II.5: Nuclear Electricity Percent Shares by Federal Region



In addition to the 109 operable nuclear reactors there are two units under construction expected to start operation before 1996. Five other units are partially built but construction has been indefinitely deferred.

Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) are the two types of operable nuclear reactors in the U.S. About 65 percent of all the operable reactors are PWR and about 35 percent are BWR. There are a total of 80 different nuclear reactor designs, and units are located in 71 different sites. The nuclear industry consists of 4 manufacturers (General Electric, Westinghouse, Babcocx & Wilcox, and Combustion Engineering) and 48 utilities holding nuclear licenses.

By 1993, 21 nuclear reactors had permanently shutdown. None of these reactors had operated for the expected 40-year licensed life. Table II.7 lists these reactors and their corresponding shutdown dates. This table does not include some of the original experimental government-funded nuclear reactors which have been permanently shutdown.

The 109 reactors currently licensed to operate have accumulated 1,523 reactor-years of experience. Reactors permanently shutdown accumulated 193 additional reactor-years of experience.

Table II.6: 1991 Nuclear Percent Share of Electric Capacity and Electricity Generation in Each State

	Percent Net Nuclear	
State	Capacity	Generation
Alabama	24%	19%
Arizona	26%	38%
Arkansas	18%	33%
California	11%	30%
Connecticut	46%	52%
Florida	12%	16%
Georgia	18%	28%
Illinois	39%	56%
Iowa	6%	13%
Kansas	12%	18%
Louisiana	12%	24%
Maine	36$	66%
Maryland	15$	24%
Massachusetts	9%	12%
Michigan	18$	29%
Minnesota	17%	30%
Mississippi	16%	39%
Missouri	7%	16%
Nebraska	23%	35%
New Hampshire	44%	53%
New Jersey	28%	67%
New York	16%	23%
North Carolina	23%	36%
Ohio	7%	11%
Oregon	10%	3%
Pennsylvania	26%	35%
South Carolina	40%	63%
Tennessee	14%	23%
Texas	6%	8%
Vermont	46%	78%
Virginia	25%	49%
Washington	5%	4%
Wisconsin	14%	23%
Others	0	0

Table II.7: U.S. Commercial Nuclear Power Reactors Formerly Licensed to Operate

Unit	Con Type	OL Issued	Decommissioning Alternative Selected
Location	MWt	Shut Down	Current Status
Bonus*	BWR	04/02/64	ENTOMB
Punta Higuera, PR	50	06/01/68	ENTOMB
CVTR**	PTHW	11/27/62	SAFSTOR
Parr, SC	65	01/01/67	SAFSTOR
Dresden 1	BWR	09/28/59	SAFSTOR
Morris, IL	700	10/31/78	NRC Review
Elk River*	BWR	11/06/62	DECON
Elk River, MN	58	02/01/68	DECON Completed
Fermi 1	SCF	05/10/63	SAFSTOR
Lagoon Beach, MI	200	09/22/72	SAFSTOR
Fort St. Vrain	HTG	12/21/73	DECON
Platteville, CO	842	08/18/89	DECON in Progress
GE VBWR	BWR	08/31/57	SAFSTOR
Pleasanton, CA	50	12/09/63	SAFSTOR
Hallam*	SCGM	01/02/62	ENTOMB
Hallam, NE	256	09/01/64	ENTOMB
Humboldt Bay 3	BWR	08/28/62	SAFSTOR
Eureka, CA	200	07/02/76	SAFSTOR
Indiana Point 1	PWR	03/26/62	SAFSTOR
Buchanan, NY	615	10/31/74	NRC Review
La Crosse	BWR	07/03/67	SAFSTOR
Genoa, WI	165	04/30/87	SAFSTOR
Pathfinder	BWR	03/12/64	SAFSTOR
Sioux Falls, SD	190	09/16/67	DECON in Progress
Peach Bottom 1	HTG	01/24/66	SAFSTOR
Peach Bottom, PA	115	10/31/74	SAFSTOR
Piqua*	OCM	08/23/62	ENTOMB
Piqua, OH	46	01/01/66	ENTOMB

Rancho Seco Herald, CA	PWR 2772	08/16/74 06/07/89	SAFSTOR NRC Review
San Onofre 1 San Clemente, CA	PWR 1347	03/27/67 11/30/92	SAFSTOR (1)
Shippingport* Shippingport, PA	PWR 236	1957 1982	DECON DECON Completed
Shoreham Wading River, NY	BWR 2436	04/21/89 06/28/89	DECON DECON in progress
Three Mile Isl. 2 Londonderry Township, PA	PWR 2770	02/08/78 03/28/79	(2)
Trojan Portland, OR	PWR 3411	11/21/75 11/09/92	(3)
Yankee-Rowe Franklin Co., MA	PWR 0600	12/24/63 10/01/91	(4)

* AEC/DOE owned; not regulated by NRC.

** Holds byproducts license from State of South Carolina.

(1) San Onofre 1 is scheduled to submit their decommissioning plan to the NRC in 1994.

(2) Three Mile Island 2 is undergoing decontamination in selected areas. On completion of these activities, the plant will be placed in a monitored storage mode for an indefinite period.

(3) Trojan submitted a request for a possession only license on 01/27/93. As of 03/01/93, a decommissioning alternative had not been selected.

(4) Yankee-Rowe received a possession only license on 08/05/92. As of 03/10/93, a decommissioning alternative had not been selected.

Source: DOE Integrated Data Base for 1990; U.S. Spent Fuel and Radioactive Waste, Inventories, Projections, and Characteristics (DOE/RW-0006, Rev. 6), and Nuclear Regulatory Commission.

Notes:

ENTOMB is defined as the alternative in which radioactive contaminants are encased in a structurally long-lived material, such as concrete. The entombment structure is appropriately maintained, and continued surveillance is carried out until the radioactivity decays to a level permitting unrestricted release of the property.

SAFSTOR is defined as the alternative in which the nuclear facility is placed and maintained in such condition that the nuclear facility can be safely stored and subsequently decontaminated (deferred decontamination) to levels that permit release for unrestricted use.

DECON is defined as the alternative in which the equipment, structures, and portions of a facility and site containing radioactive contaminants are removed or decontaminated to a level that permits the property to be released for unrestricted use shortly after cessation of operations.

FACTORS AFFECTING THE NUCLEAR POWER INDUSTRY

There are several critical factors and prevailing conditions in technical, legislative, regulatory, economic, and political areas affecting the present status and future of nuclear power in the U.S. Most of the factors affecting the nuclear industry in the United States are negative. As explained in the previous section, although nuclear power penetrated the electricity market at an accelerated pace, prevailing conditions have affected the industry so negatively that no successful order for a nuclear reactor has been placed in 20 years. In fact, the nuclear industry recognized in November 1992 that "without major technical and regulatory reforms, no utility in the United States is likely to order a nuclear plant, no state regulators would approve it, and no Wall Street investment house would issue the bonds to finance it."[18]

The most important factors and prevailing conditions include:

1) High generating costs,

2) High construction costs and long construction times,

3) Early unexpected retirement of some nuclear reactors,

4) Uncertainty about the decommissioning process,

5) Lack of standardized design,

6) Multiple-step nature of the regulatory licensing process,

7) Slow growth of electricity demand,

8) Industry inability to ensure itself against potential risks,

9) Lack of permanent repository site to dispose of nuclear radioactive material,

10) Strong public opposition to nuclear power, and

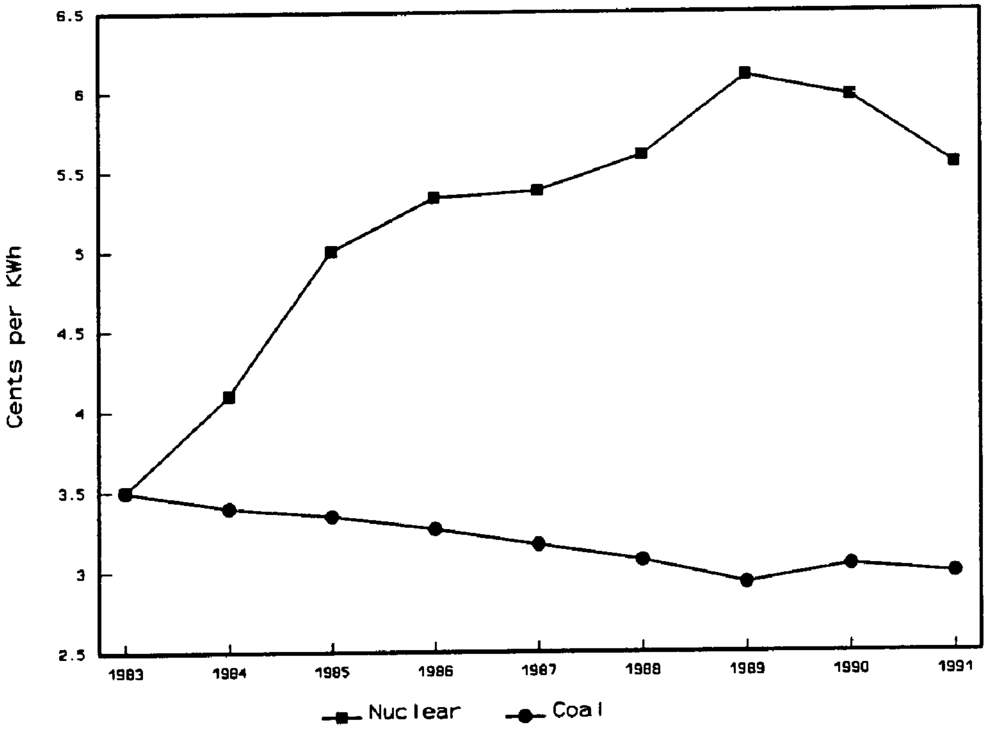
11) Increasing environmental concerns with respect to fossil-fuel emissions.

Although these factors are greatly interrelated and should be considered in an integrated manner, an attempt is made in the following sections to provide a short description of each of their effects in the nuclear industry.

High generating costs

This is one of the most critical factors affecting the nuclear industry. The main benefit expected from the use of nuclear power in the electricity generation process was low operating costs as compared to other competing technologies. During the 1960s when nuclear started to penetrate the market, it was perceived that nuclear power plants would benefit from the use of plentiful uranium resources and stable uranium markets as compared to the volatile fossil fuel markets and fossil fuel prices observed at that time. This expectation, however, was not realized. Increasing regulatory constraints, operating and maintenance requirements, and unexpected engineering problems have forced the cost of nuclear generated electricity to levels above the cost of other competing technologies. By 1991 the average total generation expenses of nuclear power plants was about 5.54 cents per KWh or an increase of about 68% over the generation expenses in 1984 (3.30 cents per KWh). As compared to coal generation expenses, nuclear generated electricity in 1991 was about 85% more expensive than electricity generated by coal plants (2.99 cents per KWh).[19] The total generation expenses include operating and maintenance, fuel, and capital addition expenses. The difference between nuclear and coal generation costs for the period from 1983 through 1991 is illustrated in Figure II.6. During 1992 and 1993 the generation costs for both nuclear and coal have remained about the same levels observed in 1991.

Figure II.6: Average electricity Generating Expenses



Source: DOE/EIA,*Electric Plant Cost and Power Production Expenses 1991*, DOE/EIA-0455(91), May 1993.

Thus, for the last 10 years electric utilities (on average) have spent a lot more money generating electricity from nuclear plants than from coal plants. The last year in which average generating costs for nuclear and coal were about the same was 1983. In this year the average cost for generating one KWh was 3.5 cents using either coal or nuclear plants.[20]

Taking into consideration only non-fuel operating and maintenance costs and measuring these costs in terms of real dollars ($1982) per KW of capacity, the nuclear O&M costs have increased from $17/KW in 1974 to $67/KW in 1989. This represents an annual rate increase of about 9 percent.[21]

The case of the Rochester Gas & Electric Company's Ginna station serves to illustrate the trend of increasing operating costs observed in the nuclear industry. Since 1970, its first full year of operation, the annual O & M cost has increased from $3.2 million to almost $60 million, while operating staff has risen from 59 people to nearly 600. Invested capital in the Ginna plant today totals $400 million, more than four times the original capital cost of $88 million, although the plant size has remained the same 470-MW.[22]

The increase in real nuclear plant operating costs has important implications related to the life expectancy of nuclear reactors and the competitive advantage of nuclear over baseload technologies including coal. High operating costs have been associated with the decision to permanently retire some nuclear reactors. The increase in generating costs observed in nuclear plants in the last several years can be attributed in part to a decreasing trend in the efficiency of older nuclear reactors. The reasons for this cost escalation include engineering, regulatory, and economic factors. Engineering problems are related to aging and unanticipated effects of radioactivity in materials and equipment. Some of these factors will be analyzed in detailed in Chapter III.

High construction costs and long construction times

Great uncertainty characterizes the costs and times related to the construction of nuclear reactors in the United States. The average construction cost (in 1988 dollars) for a kilowatt of generating capacity increased dramatically within a 15 year period, escalating from $817 (for 13 plants going into operation between 1971 and 1974) to $3100 (for 10 plants that went into operation during 1987 and 1988). These costs do not take into account inflation and interest payments on loans but are based on what the plants would cost if constructed overnight.[23] In addition to uncertainties raised by increased costs from one decade to the next, nuclear plants of the same generation and the same size ranged widely in construction costs.

The industry's cumulative cost overruns are significant, totaling close to $100 billion. A DOE study found that 75 nuclear reactors cost three times as much as originally projected. At least 35 plants cost six to eight times as much, and this is without taking into consideration decommissioning costs.[24] It is estimated that a new nuclear reactor in the U.S. would cost between $4 and $7 billion.[25] Recently completed plants have been among the most expensive to build in the industry's history: $4.6 billion for Hope Creek in New Jersey, $7.2 billion and $4.1 billion for Comanche Peak 1 and 2 in Texas.

The cost of $6.6 billion for New Hampshire's Seabrook drove its primary owner, Public Service of New Hampshire, to seek bankruptcy protection, the first private utility to do so since the Depression.

During the period from 1970 through 1979, the average construction time for 63 nuclear power plants was 6.3 years. From 1988 through 1989, the average construction time went up to 11 years for 47 plants. It seems that in the nuclear industry, a planner could not predict construction cost and time for a given plant design. Apparently the assumption at the time these plants were ordered was that nuclear was a mature technology while in fact it was still evolving. Second generations of nuclear reactors embodied 50% to 85% more design work, more hours of craft labor, and more materials than the first generations of nuclear plants.[26] Longer construction times got translated into higher costs especially due to interest costs.

Utilities often tried to cover these unexpected construction costs by passing them on to the consumer. In some areas, this meant a possible 25-percent increase in the rates that could be charged. The public reacted angrily over the rate shock, prompting state utility commissions to question the cost of nuclear plant construction. Established by the commissions to evaluate such requests for rate-hikes, prudency reviews allow the commissions to accept, after a plant has been completed, which of the final construction costs may be recovered from ratepayers. After reviewing 88 nuclear power plants during the 1980s, state commissions prevented investor-owned utilities from raising rates to a level that would have let them recover $14.4 billion in plant costs.[27] In some states, public utility commissions have mandated that construction expenses incurred due to mistakes or poor management must be absorbed by the public utility. According to the Edison Electric Institute, more than $16 billion in nuclear-power-plant construction costs have been disallowed by state commissions in utility-rate hearings around the country.

Early Unexpected Retirements

The uncertainty relative to the life of nuclear reactors is another factor affecting the nuclear industry. Twenty-one U.S. reactors have already been permanently retired (see Table II.7), among which only Yankee Rowe operated longer than 25 years. In the past 5 years alone, these 5 reactors have been permanently shutdown sooner than originally expected: Yankee Rowe in Massachusetts, 25-year-old San Onofre 1 and 15-year-old Rancho Seco in California, Oregon's 17-year-old Trojan, and Colorado's 16-year-old Fort St. Vrain. In addition, the Shoreham plant in New York closed before ever operating at full power not because of premature aging but because the utility could not devise sufficient safeguards to protect the surrounding population in the event of a serious accident. In 1979, only after one year of operation, Three Mile Island 2 also was shutdown prematurely, bringing to seven the number of large reactors that have been prematurely retired. Other nuclear reactors permanently retired include: California's Humboldt Bay, Illinois' Dresden, Pennsylvania's Shippingport, New York's Indian Point 1, and Nebraska's Hallam.

Not only does early retirement enhance the perceived risk associated with nuclear reactors, it also makes it difficult for utilities, regulators and planners to assess issues such as decommissioning funds and schedules, capacity additions plans, depreciation of equipment and waste disposal site availability. Early retirement will be analyzed in detail in Chapter III.

Uncertainty About Decommissioning Costs

Since no big nuclear reactor has ever been dismantled, techniques and tools remain to be developed and the decommissioning costs and process are uncertain. In 1988 the NRC put the costs of decommissioning at $105 million to $135 million for large plants, depending on their type.[28] The General Accounting Office (GAO) and others criticized those numbers as far too low, a conclusion eventually accepted by the industry itself. Decommissioning for the comparatively small 175-megawatts Yankee Rowe plant has been projected at $247 million, compared to $333 million for dismantling the 330-MW Fort St. Vrain reactor. Larger reactors may require five times what the NRC estimated in 1988; for instance, the 1100-MW Trojan may cost $541 million to dismantle, while Indiana Michigan Power may have to pay as much as $550 million to decommission each of its two 1000-MW Cook reactors. The California state utility commission has ordered Southern California Edison Company and San Diego Gas and Electric Company to collect $2.2 billion in future dollars to pay for the decommissioning of the three San Onofre nuclear reactors.[29] The first San Onofre reactor has already been permanently retired.

Contributing factors to the increase of decommissioning costs include high radioactive levels in materials, complex dismantling techniques required to prevent radiation exposure, and the huge amounts of waste involved. Another factor contributing to the decommissioning cost uncertainty is the fact that no permanent repository site is available for the final disposal of high level nuclear waste. The timing for the availability of this site is also highly uncertain.

Lack of a standardized design

There are 80 different nuclear reactor designs in the U.S. Standardization of the nuclear reactor designs could be translated into faster procurement, improvement in the quality of equipment and materials, and better operating principles and procedures. All of these advantages could be shared throughout the whole nuclear industry.[30] Standardization could result ultimately in nuclear reactors which are less expensive to build and to operate. The Energy Policy Act of 1992 (EPACT) includes a provision for certification of standardized nuclear reactors designs. However, the details for the implementation of this provision are not finalized. Since 1990, DOE has been sponsoring a cooperative program with private industry to certify four standardized Advanced Light Water Reactor (ALWR) designs. The program will lead to NRC certification of two large size designs (1250 MWe) and two mid-size designs (600 MWe). Most of these ALWR designs are expected to become commercially available in the next decade.

Multiple step nature of the regulatory licensing process

The nuclear licensing process as implemented by NRC includes two separate steps: the issuance of a construction permit and the issuance of an operating licensing. The system is perceived to be of great financial risk for the utilities since after investing billions of dollars in construction, an operating license can be denied. The Energy Policy Act of 1992 has a provision for a combined construction and operating license. However, there are still several legal problems involved with the one-step licensing process.

Slow growth of electricity demand

The slow growth in the demand of electricity observed during the 1980s and 1990s has affected the growth of the nuclear industry and its perception as a necessary technology. In 1974 electricity demand was expected to grow at an average annual rate of 7.6 percent for the following decade. The growth rate during this period was only about 2.9 percent.[31]

The new trends that characterize electric consumption are allowing enough conservation to keep the electricity demand at a level at which large new generating plants and especially new nuclear reactors are not required in most areas, at least for the short term. Some of the new conservation measurements include Demand Side Management (DSM) programs, increasing efficiency standards for electric appliances, and increased shell efficiencies in residential, commercial, and industrial facilities.

Some energy analysts agree that conservation, through aggressive energy efficiency programs, and alternative technologies such as wind power, solar, and cogeneration can provide much of the increased need for electricity more cost-efficiently than nuclear energy, if they are given the opportunity.[32] The 1992 Energy Policy Act took a step in that direction by allowing other actors to have the same access, as major utilities have, to transmission of electric power across their grids. This and other advances should make independent power producers and alternative technologies more competitive in the future. Thus, nuclear energy could even become less competitive compared to other sources of electricity.

Inability to ensure against potential risks

The potential risk of an accident in a nuclear power plant could result in the sudden loss of multibillion-dollar investments, and several legal and financial problems for the utility owning the plant. The utility industry is protected against such a risk through the Price-Anderson Act passed by the Congress in 1957. The Act's latest extension is in force until 1998. Clearly, without this type of protection from the government it is difficult to believe that any utility would be willing to operate a nuclear reactor much less order a new one. Furthermore, without Price-Anderson the cost of commercial insurance to nuclear utilities would substantially raise the cost of nuclear energy. There is even a question of whether there are insurance companies willing to ensure a nuclear plant.

Alternative forms of energy do not have those high perceived risks. In a real free-market a premium would be placed on nuclear plants in order to avoid these types of risks, which would make nuclear power more difficult to compete.

As most recently amended, the Price-Anderson Act requires nuclear utilities to jointly hold only $200 million worth of insurance to cover public liability for a nuclear accident; for claims over that amount, there is a cap of $63 million per reactor for which each nuclear utility can be held liable.[33] The amount the nuclear utilities would have to pay in case of an accident falls far short of the potential costs to human health and property. These costs could vary, from $15 billion under average weather conditions, according to a 1987 General Accounting Office (GAO) estimate, to a worst-case scenario in which financial losses range from $56 to $314 billion, according to a 1982 analysis by Sandia National Laboratory for the Nuclear Regulatory Commission (NRC).

The Nuclear Regulatory Commission has estimated that the chance of a major "core melt" nuclear accident within the next 20 years is about 45 percent. Thus, many people believe that in case of a serious accident the taxpayers would be the ones paying the bill. The Price-Anderson Act is due for extension in 1998. If opposition is strong and the extension of this Act is not passed, the future of the nuclear generating stock is perceived as very uncertain. Some analysts believe that "without Price-Anderson the nuclear industry would have gotten nowhere." [34]

Lack of permanent repository site to dispose nuclear radioactive material

A permanent repository site for nuclear spent fuel discharges is necessary to ensure the proper long-term disposal of the highly radioactive waste produced in nuclear power plants. By the end of 1992 more than 24,000 metric tons of commercial spent fuel were in storage, primarily at about 70 reactor sites and in more than 30 states; 2000 additional tons are produced every year. Acceptable sites and technologies for the permanent isolation of spent fuel and high-level waste have yet to be demonstrated by any nation.[35] Public support for nuclear power is particularly sensitive to the nuclear waste disposal issue and public opposition is expected in several states until the issue is successfully resolved. In fact, in the US. some states have declared a moratorium on the construction of new nuclear plants because of this problem.

Because some nuclear reactors are running out of space to store spent fuel, the DOE has been under pressure to find a suitable interim site while a permanent site is being developed. DOE has been offering a multimillion-dollar annual payment to a locality or Native American tribe that would allow its land to be used for such an interim national storage facility. Construction of a monitored retrievable storage (MRS) facility has been authorized. It is estimated that an MRS facility could begin to accept spent fuel on a limited basis for temporary storage as early as 1998.[36]

To address the need for a definitive solution to the nuclear waste disposal problem, the Nuclear Waste Policy Act of 1982, as amended, directs the Department of Energy to site, design, construct, and operate the nation's first geologic repository for the permanent disposal of spent nuclear fuel and high-level radioactive waste. The primary candidate for the permanent repository site is Yucca Mountain, Nevada. The most optimistic scenario assumes this site to be ready by the year 2010.[37] The Department of Energy is conducting studies to determine whether Yucca Mountain can isolate radioactive materials by using natural and engineered barriers. This site investigation is not expected to be completed until the year 2001 or later, at least 5 to 13 years longer than planned, further delaying the opening and increasing the project's total cost. The licensing and approval process would start only after these studies are completed. The Department of Energy estimates total construction costs for the Yucca Mountain facility at $26 billion, of which $6 billion is just to determine whether the site is suitable.

Strong public opposition to nuclear power

Strong public opposition affects the nuclear industry in the United States. Many of the people in favor of nuclear power claim that unjustified public opposition is the major reason for the ending of the expansion process of the commercial nuclear energy industry in this country. However, a close look at public attitudes toward nuclear reflect a genuine concern about several factors that characterize the nuclear industry. Some studies have concluded that important concerns have adversely affected the general acceptance of nuclear power.[38] Some of these factors have been described in the previous sections. The most important factors can be listed as follows:

- concerns about the acceptable resolution of the nuclear waste disposal problem,
- concerns about the safe operation of nuclear reactors and the inability of the industry to ensure itself against its own risk,
- concerns about a highly expensive technology that cannot compete with other generating alternatives,
- concerns about increasing proliferation of nuclear weapons.

Although recent opinion polls suggest that the public believes nuclear power in general is important, few want to see a nuclear power plant build near their own homes.[39] According to a 1992 opinion poll, 65% of the public opposes building any more nuclear reactors.[40] A Washington Post/ABC News poll performed in May 1992 showed that 65% of Americans would prefer enhanced energy efficiency and conservation over increased output of any form of manufactured energy including nuclear.[41] The environmental lobby is opposed to the expansion of nuclear power mainly because the waste problem is unresolved and also because increasing energy efficiency might significantly reduce the need for new electricity.

One of the reasons for public opposition is the doubt that any nuclear plant could be made acceptably safe. The accidents at Three Mile Island and Chernobyl are examples of how unsafe nuclear plants are and people believe that even improved technology would be susceptible to unforseen problems.[42]

Consequences of nuclear proliferation is another reason for public opposition to nuclear power. Reports of weapons programs conducted at "research" nuclear facilities in North Korea, Iraq, and South Africa have created new concerns in the international community about the desirability of civilian nuclear-power programs. The perception exists that commercial nuclear programs are the excuses for some countries to equip themselves with the technology and fuel needed to pursue nuclear weapon development programs.

Increasing environmental concerns with respect to fossil-fuel emissions

The only important factor affecting the nuclear industry positively is the increased concern about emissions from fossil-fueled generating plants which affect the air quality and the global climate. The concerns have become more important due to the 1990 Clean Air Act Amendments (CAAA) and the 1992 Energy Policy Act (EPACT).

Nuclear power is being perceived by many as the only long-term alternative to fossil fuels. Nuclear power produces no greenhouse gases, or sulfur dioxide, and almost no particle emissions, carbon monoxide, volatile compounds, or methane. Other alternatives to fossil fuel include conservation, renewables, hydropower, and biofuels. All of these other alternatives are considered limited and unable to play a role in electricity baseload generation.[43]

Although nuclear power is perceived as an alternative for the reduction of greenhouse gases, the role that nuclear power can play to mitigate global warming has been questioned. Some analysts agree that an increase in nuclear generation would have only a marginal impact on CO_2 emissions in the next two or three decades.[44]

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CHAPTER III

RETIRING NUCLEAR CAPACITY

As explained in Chapter II, one of the major factors affecting the nuclear electric generating industry in the U.S. is the early retirement of nuclear reactors expected to operate for several more years into the future. In this chapter issues related to early retirement and nuclear life assessment are analyzed in detail. The chapter begins with the assessment of the problem and a summary of different expectations with respect to the life of nuclear reactors. This assessment is followed by a description of the factors affecting the reactors' life and a characterization of critical engineering equipment that potentially could be affected by aging. Case studies of six permanently retired reactors (Rancho Seco, Yankee Rowe, Trojan, San Onofre 1, Fort St. Vrain, and Shoreham) are presented to illustrate the problem. The chapter ends with a general description of the analytical approach selected in this study to estimate the life expectancy of nuclear reactors.

PROBLEM ASSESSMENT

The major problem addressed in this dissertation is the need to estimate the life expectancy of nuclear reactors currently operating in the U.S. In the historical overview section of Chapter II, it was described how manufacturers of nuclear reactors in the 1960s rushed into the construction of large generating units without having any practical knowledge about this new technology and about the impact of nuclear radiation on critical equipment. The result of such accelerated construction was the lack of data and design specifications that could be used as the basis to define the useful life of nuclear reactors. Today, the only guidance available to assume a life is the period for which nuclear reactors are licensed to operate. This license period in the U.S. is 40 years.

The Atomic Energy Act of 1954[1] provided the original set of regulations regarding commercial nuclear power plant licensing, which included setting a statutory limit of 40 years for the duration of licenses issued to electric utilities that operate commercial nuclear plants. The selection of a 40-year limit was not based on the anticipated useful life of the nuclear plants but rather on financial and licensing considerations.[2] The 40-year license decision was essentially arbitrary, based on the economics related to the depreciation of equipment rather than technical experience.[3] In addition, the final decision of 40-year life was an apparent compromise between those who wanted a short operating license because of concerns about unknown factors of the new nuclear technology and those who wanted the same 60-year operating licenses as hydroelectric plants.[4] Thus, contrary to expectations, the 40-year life associated with nuclear reactors only represents a "licensed life" and does not necessarily coincide with the real useful life of nuclear reactors. In fact, major components in nuclear reactors have warranties for less than 15 years. In some cases, critical components such as steam generator tubes in some plants have warranties for only one or two years.[5]

The lack of technical data supporting a specific reactor life provides grounds for the formulation of different scenarios about the remaining life of U.S. nuclear electric generating stock. The scenarios that are most frequently assumed include:

(1) Nuclear reactors will operate for their 40-year licensed life;

(2) Life extension (license renewal) will allow operation over the 40-year licensed life;

(3) New orders will allow nuclear power to continue playing an important role in electricity generation;

(4) Nuclear reactors will operate for less than 40-years.

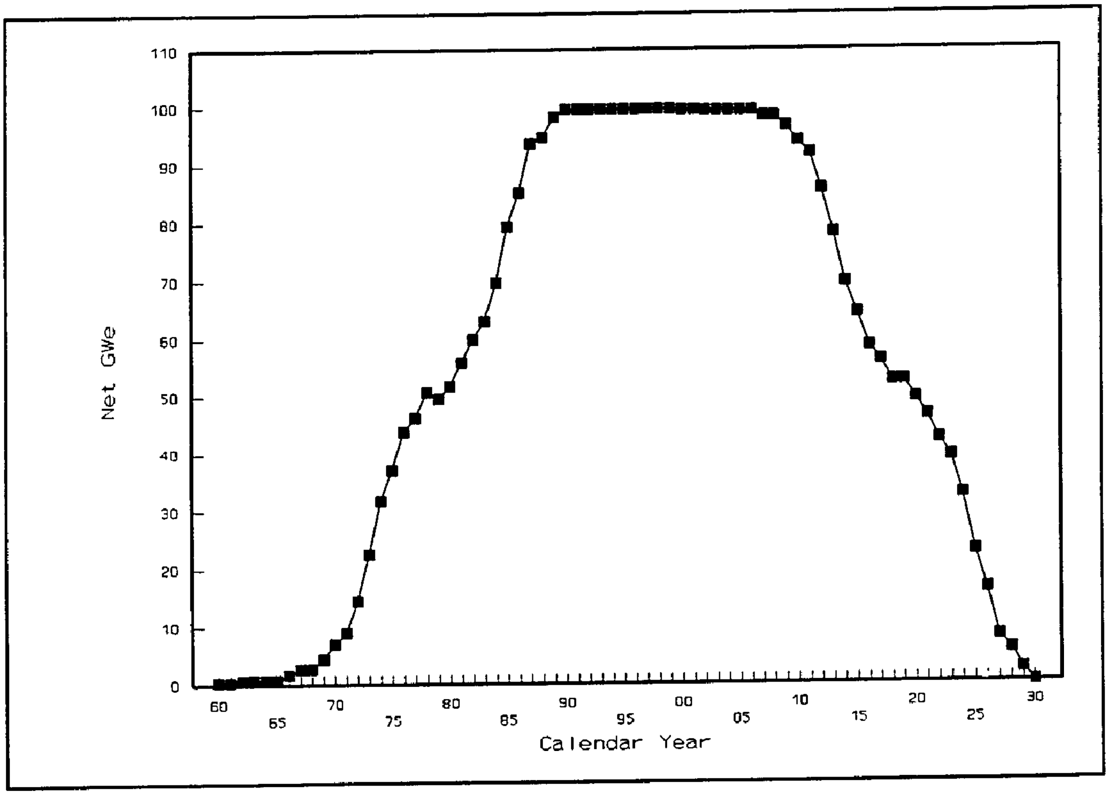
(1) Life expectancy assumed equal to 40-year licensed life

This scenario is based on the assumption that reactors will operate for the 40-years for which they are licensed. None of the reactors which have been permanently shutdown has reached the expected 40-year life. Assuming a 40-year reactor life expectancy with no new orders, and no life extension, the amount of electricity generated by nuclear reactors can only follow a decreasing trend in the intermediate- and long-terms. With only two reactors in the pipeline which are expected to start operation before 1996 and no new orders that have not been subsequently canceled since 1973 (20 years), the U.S. nuclear capacity is expected to start decreasing in the year 2000 and to be almost fully lost by the year 2030.

Figure III.1 illustrates the U.S. nuclear generating capacity assuming a 40-year life in all nuclear reactors. This is the scenario that is most commonly assumed by regulators, planners, decision makers, and energy forecasting institutions.[6] In fact, several issues related to nuclear power, such as depreciation of equipment, volumes of spent fuel discharges, decommissioning funds, and electricity supply forecasts, are defined using as the basis this 40-year life scenario.

According to this scenario only a few reactors will be shutdown by the year 2010 (11 reactors). Most of the rest of the nuclear reactors will be shutdown during the period starting in 2010 and going through 2025 (79 reactors). Thus, if reactors indeed operate for 40 years, the potential problems related to the replacement of this capacity will not become critical until around the beginning of the second decade of the next century or around 17 years from now.

Figure III.1: U.S. Nuclear Generating Capacity Assuming A 40-Year Life



(2) Nuclear plant life extension

This scenario is based on the assumption that nuclear equipment can be refurbished to extend the life of nuclear reactors for as much as 20 years beyond their 40-year licensed life. No nuclear plant has gone through a life extension procedure. Some sensitivity scenarios about the future of the nuclear generating stock have been defined assuming nuclear power plant life extension or license renewal.[7] The regulatory process for license renewal is being developed by the Nuclear Regulatory Commission.[8] However, the leading pressurized water reactor (Yankee Rowe) which was attempting to demonstrate the feasibility of the process was forced to shutdown in 1992 because of vessel embrittlement problems discovered in 1991.[9] The other leading plant in the license renewal program was Monticello, a boiling water reactor. Because of economic and regulatory costs involved, the Monticello plans for life extension were canceled in 1993, leaving the program without any firm candidate.[10]

(3) New nuclear reactor orders

Positive nuclear scenarios would imply the resumption of nuclear power plant orders which is considered indispensable for nuclear technology to maintain and expand its role in the production of electric power. There are several critical factors and prevailing conditions affecting the possibility of future nuclear plant orders in the U.S.

Critical factors and prevailing conditions have been identified by several research organizations.[11] Most of these factors were described in Chapter II. Changes in these factors and conditions are necessary for any type of positive nuclear scenario to take place.

Positive nuclear forecasting scenarios are developed annually by the Department of Energy.[12] However, all the scenarios assume the partial or full resolution of all the following issues:

- Nuclear power is shown to be economically advantageous over alternative baseload generating technologies in at least some regions of the country.
- A form of turnkey pricing (vendor acceptance of fixed-price contracting) or risk-sharing will be available to utilities.
- Regulators will ensure utilities an adequate return on their investment in nuclear plants.
- The nuclear waste disposal problem is successfully resolved.
- One-step licensing, for both construction and operation of nuclear reactors, is established.
- Reactor designs become standardized.
- Financial protection of the industry becomes available through extension of The Price-Anderson Amendments Act of 1988, or by a similar type of liability coverage.

(4) Life Expectancy shorter than 40-year licensed life

Another scenario that is increasingly being considered is the possibility that the operating nuclear reactors will not last the 40 years for which they have been licensed to operate. This assumption is supported by the unexpected early retirement of some nuclear reactors in the U.S.

There are 21 nuclear reactors which have been permanently shutdown. Excluding experimental reactors and considering only commercial nuclear reactors permanently shutdown since 1970, the average life has been only 15 years. Five nuclear reactors that were shutdown in the last five years averaged only a 20-year life. Because nuclear units continued shutting down prematurely through the eighties and nineties, the aging of nuclear plants is becoming a more evident and controversial issue.[13] By 1993, some nuclear reactors that had been expected to operate well beyond the beginning of the next century were already shutdown. They include large operating reactors such as Trojan in Oregon (1104 MWe) and Rancho Seco (873 MWe) in California, medium size reactors such as San Onofre 1 (436 MWe) in California, and small reactors such as Yankee Rowe (167 MWe) in Massachusetts and Fort Saint Vrain (217 MWe) in Colorado.

Figure III.2 presents four scenarios developed for the U.S. nuclear generating stock based on different nuclear reactor life expectancy assumptions. The scenarios include nuclear reactor life expectancies of 20, 25, 30 and 40 years.

The figure illustrates the potential for the issue to become critical in a very short period of time if reactors do not last their expected licensed life of 40 years. The number of reactors shutting down according to each scenario and the corresponding percent of the nuclear generating stock are listed in Table III.1. For example, if a 25-year life is assumed, 49 nuclear reactors will be shutdown by the year 2000 (7 years from 1993), corresponding to about 35% of the total nuclear generating stock. This compares to only one reactor shutdown by the year 2000 if a 40-year life is assumed. If a 20-year life is assumed, 65 reactors will shutdown by the year 2000 and this corresponds to 50% of the total nuclear generating stock.

Figure III.2: U.S. Nuclear Generating Capacity

Different Life Expectancies

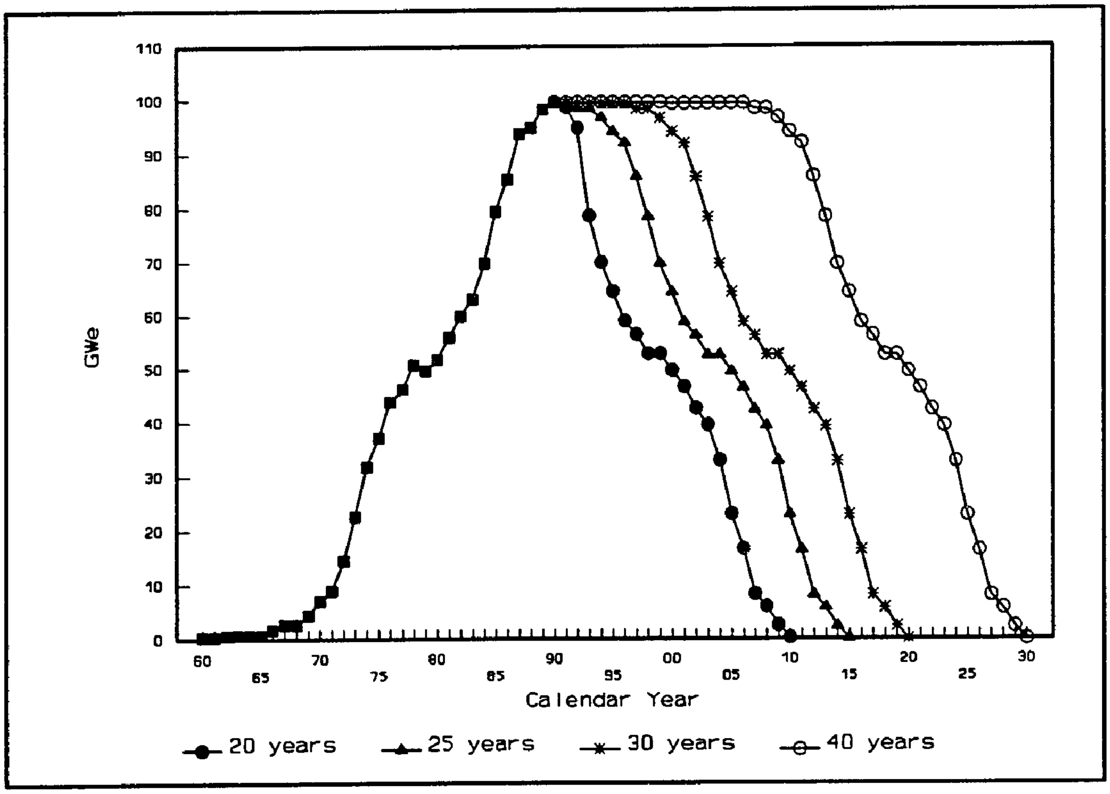


Table III.1: Number of Reactors Shutting Down Based on Different Life Expectancies

Calendar Year	Life = 20 Years	Life = 25 Years	Life = 30 Years	Life = 40 Years
2000	65 (50%)	49 (35%)	11 (6%)	1 (0.1%)
2005	90 (77%)	65 (50%)	49 (35%)	2 (0.3%)
2010	111 (All)	90 (77%)	65 (50%)	11 (6%)
2015		111 (All)	90 (77%)	49 (35%)
2020			111 (All)	65 (50%)
2025				90 (77%)
2030				111 (All)

The potential for electricity shortages is greater in those areas that depend heavily on electricity generated by nuclear reactors and areas with a nuclear stock containing several reactors which already have reached maturity. Two federal regions that potentially could be affected are the New England region and the New York/New Jersey region. New England, with almost 40% of its net electricity generated by nuclear reactors, could face a shortage if its reactors are prematurely shutdown. Six of the eight nuclear reactors in New England are over 18 years old. If a 25-year life were to be assumed, these six reactors would be shutdown by the year 2000. The New York/New Jersey region, with 8 of its 10 reactors already over 17 years old and with a 33% nuclear share, could also be seriously affected if some of these reactors were shutdown prematurely.

Because of the lack of technical design data supporting a particular life expectancy scenario, the formulation of an analytical tool that explicitly considers and relates in a quantitative manner factors affecting the life of nuclear reactors is necessary. This is the main research objective of this dissertation work. The design of such an analytical tool requires the understanding of the factors affecting nuclear reactor life, the analysis of critical equipment that could be potentially affected by aging, and the study of cases of permanently retired nuclear reactors.

FACTORS AFFECTING NUCLEAR REACTORS' LIFE

Several factors have been identified as critical in the assessment of nuclear reactor life.[14] All relevant factors are interrelated and should be considered in an integrated manner. These factors can be classified as follows:

1. Engineering Factors

These are technical factors affecting the reactor's physical ability to operate efficiently and safely. Indications of this ability can be found in the analysis of the aging process of critical equipment, in the overall plant performance, and in the results of engineering tests performed routinely to assess the status of materials and equipment and to identify future potential problems. The physical ability is a function of the reactor vintage, reactor age, reactor type, reactor manufacturer, reactor size, and even the type of utility managing the reactor.

2. Economic Factors

The economics of operating and maintaining a nuclear reactor play an important role in the estimation of its life. The economics are determined by several factors including: (a) the actual power production costs including O&M costs and capital additions, (b) the comparison of these costs versus purchasing replacement power costs in the particular region or pool where the reactor is located, (c) the comparison of these costs with respect to competing technologies, (d) the costs of nuclear power plant life extension, and (e) the decommissioning costs.

3. Environmental Factors

The environmental constraints include nuclear environmental constraints and fossil fuel environmental constraints. The nuclear constraints refer to the availability of a permanent repository site for the disposal of nuclear waste, and the spent fuel storage capabilities on-site. The nuclear waste issue is also related to the problem of decommissioning. If the nuclear plant is being considered for retirement and the replacement alternative is the construction of a coal plant, then the fossil fuel emission constraints as defined by the 1990 Clean Air Act Amendments (CAAA) for the particular region as well as potential carbon dioxide emission constraints need to be considered.

4. Public Opinion Factors

The acceptance of nuclear power generation by the community where the unit operates is another important factor affecting the reactor's life. The acceptance of nuclear power generation has been related in the past to the perception of the risk of a nuclear accident and the availability of storage capabilities for nuclear waste. The acceptance category includes public acceptance, utility status and acceptance, and the acceptance by the State Public Utility Commission. The acceptance criteria can be quantified at a regional level based on the review of the historical events such as public referenda, political events and public polls on nuclear power plants. The acceptance criteria are particularly important when the life extension of nuclear reactors is being considered. In addition, acceptance is important when construction of a new nuclear reactor is being evaluated.

5. Electricity Demand Factors

Projected electricity requirements affect the potential for the construction of new nuclear plants and could also affect the life of currently operating reactors. The electricity demand factor is only relevant if there are reasons to believe that the demand for the baseload electricity being satisfied by the operating nuclear reactor will not exist at any time in the future. However, the expected increasing electricity demand in the U.S. implies that there at least would be a demand for the baseload electricity supply already in place.

CRITICAL ENGINEERING COMPONENTS

Although there are economic, environmental, and political factors determining the life of nuclear reactors, the deterioration of critical engineering components is what eventually starts to affect the efficiency and safety of nuclear reactors and could be the leading cause of premature shutdown. The status of critical components is particularly important in the life assessment of the U.S. nuclear generating stock because of the aging condition that characterizes this stock. The U.S. has the oldest nuclear generating stock in the world with 32 reactors being 20 years old or older.

Aging is one of the most important factors affecting the long-term life of nuclear reactors. Aging needs to be considered in the systematic evaluation of all systems and components and especially in the evaluation of those components exposed to nuclear radiation. Determining the aging effect in such components is considered a critical challenge. Evaluating requirements and methods currently applied to radiated exposed materials are derived primarily from either design-basis accidents as specified by regulations, or appropriate design/construction codes. Because of the lack of long-term experience in radiation exposure, there is no guarantee that these criteria are defining the life of the nuclear reactor components accurately. A particular concern is that multiple failures of age-degraded components could occur during transients or accidents and result in core damage and release of radiation. In the past, failure of components have occurred because of age related degradation processes. These include corrosion, radiation, and thermally induced embrittlement of electric insulation, surface erosion, metal fatigue, oxidation, creep, binding and wear.

The Nuclear Plant Aging Research (NPAR) program of the Nuclear Regulatory Commission (NRC) is responsible for the research necessary to understand the effects of aging on electrical and mechanical components of commercial nuclear plants. Research under this program has been directed at critical components and the determination of their residual lives. However, most of the research is in a developing phase and more time is needed to establish definite results. Another program at NRC, the Heavy Section Steel Technology program, has been designed to research reactor vessel materials. The program has developed a method using fracture-mechanisms techniques to quantify the effects of any potential flaw indications. This forms the key basis for use of fracture mechanisms technology for thick-plate reactor vessels and other pressure-boundary materials. These methods can be used to monitor the health of critical equipment and could help to predict the life expectancy of some components.

Engineering components that need to be evaluated for the estimation of a reactor's life include both active and passive elements. The active elements include components expected to deteriorate by aging even before the operating license limit is reached. Passive elements include pressure boundaries and structural components which are infrequently replaced or refurbished. The primary concern is with passive elements since the extent to which these components must be refurbished is critical in the life assessment.

The most critical engineering components in a nuclear reactor include:

(1) Pressure vessel,

(2) Steam generators,

(3) Containment structure,

(4) Pressurizer unit,

(5) Steam-turbine,

(6) Steam condenser and cooling water systems,

(7) Feedwater heater, and

(8) Major piping systems.

(1) Pressure Vessel

The reactor pressure vessel is considered the most critical component in the life of a nuclear reactor. The pressure vessel contains the reactor core, the structures that support the core fuel assemblies, the control assemblies, and the coolant circulation channels. This is a large, heavy, and deeply embedded element of a nuclear plant. The cost to replace a pressure vessel has been estimated at about 15% of the cost of a new reactor.[15] Assuming that a new nuclear reactor would cost between $4 to $7 billion, then the replacement cost would be between $600 million and $1 billion. The life of a pressure vessel depends on several factors including:

1) chemical and physical properties of materials used in its construction,

2) the effects of radiation on these materials,

3) flaw indications and their growth, and

4) neutron flux.

Three major mechanisms have been identified that contribute to the deterioration of a pressure vessel. These are neutron embrittlement, ductile fracture, and thermal fatigue.

Neutron Embrittlement and the Pressurized Thermal Shock Test (PTS)

Long-term neutron bombardment makes the vessel of nuclear reactors brittle. The portion of the vessel most affected is the area where neutron flux is greatest. This area is the area immediately adjacent to the core. Embrittlement may be a problem for plants operating at neutron fluence levels close to design parameters. The ability of the reactor pressure vessel to endure a long life has been questioned on the basis that the high levels of radiation experienced at the belt-line could embrittle the metal to the point where thermal transients could fracture it.[16]

Although technically possible, a reactor pressure vessel has never been replaced. A replacement procedure would imply modifications to the containment structure and some other difficult, related changes. A second alternative would be to anneal the vessel to restore toughness. Annealing procedures have never been attempted in the U.S. If attempted it is expected to add only 18 months to two years to the life of a nuclear reactor. This option is considered very limited for the U.S nuclear reactor designs because of a lack of space between the vessel and the containment needed for the transferring of equipment.[17]

The pressurized thermal shock (PTS) test refers to a test designed by the NRC to assess a reactor vessel integrity with respect to its potential for embrittlement. The PTS test applies only to pressurized water reactors (PWR). The test and screening criteria as applied to each of the operating PWR were defined by NRC in 1989.[18]

Prolonged exposure to nuclear bombardment can originate changes in the characteristics of steel and weldments in the vessel of a PWR. A parameter that can be affected is the nil reference temperature for nil ductility transition (RT_{NDT}). This temperature is determined from a set of fracture tests that are conducted at successively higher temperatures to find the onset of the transition from brittle to ductile behavior. Vessels can withstand greater pressure at high temperatures than at low temperatures. In case of an emergency, the sudden injection of cold emergency coolant might drop the vessel below the reference temperature RT_{NDT} for a period long enough for the vessel to suffer damage from pressure. This is what is defined as a pressurized thermal shock. Operating records for nuclear reactors in the 1970s contained several PTS events in which a rapid cooldown from operating temperature was followed immediately by repressurization. The combined thermal and pressure stresses could have been high enough to induce fracture in a reactor vessel that contained a pre-existing flaw, if the event had occurred later in life when the vessel was significantly embrittled by neutron radiation.[19]

The screening criterion as defined by NRC is given in terms of RT_{NDT} calculated as a function of the copper and nickel content of the material and neutron fluence. This parameter is referred to as the RT_{PTS} to distinguish it from other procedures for calculating RT_{NDT}.[20]

The PTS test allows the determination of the estimated year in which the PTS screening criterion limit would be reached. For some nuclear reactors this screening criterion is expected to be reached before the end of their licensed lives.[21] In the case of Yankee Rowe this screening criterion was reached 10 years before the end of its 40-year licensed life. Yankee Rowe was forced into premature retirement in 1991 as a result of PTS tests indicating a large potential for vessel embrittlement. Other reactors with PTS screening criteria expected to be reached before or close to the end of their licensed lives include:

1) Palisades
2) Fort Calhoun
3) Calvert Cliffs 1
4) Kewaunee
5) Point Beach 1
6) Point Beach 2
7) Diablo Canyon 1
8) Indian Point 3
9) Zion 1

Ductile Fracture and the Upper Shelf Energy Test

Another important mechanism that could affect the pressure vessel integrity is the possibility of ductile fracture or brittle-to-ductile fractures in some areas of the vessel. This mechanism could affect both PWR and BWR reactor types. The NRC has been developing and defining analysis methods and evaluation criteria for reactor pressure vessels fabricated with welds that could be susceptible to low-energy ductile fracture.

The fracture resistance of reactor vessel materials decreases with increased fluence. Changes are manifested by an increase in the brittle-to-ductile transition temperature and a reduction in the upper shelf energy. These variations in fracture resistance need to be carefully monitored and periodically assessed through reactor vessel surveillance programs to ensure that specified margins of safety are satisfied for reactor vessels.

The NRC has developed mathematical models capable of predicting the fracture toughness of pressure vessel steels and weldments, with particular consideration to the low upper-shelf welds. The NRC regulations require that the ductile fracture resistance in this type of welds remain above a specific limit, as measured by the material's "Charpy V-notch upper-shelf energy."[22] The criterion in the regulation specifies a 50 ft-lbs upper shelf energy as the minimum limit. If the upper-shelf energy is less than the 50 ft-lbs regulatory limit, the reactor does not satisfy the criterion. In this case a detailed analysis is required to demonstrate that an adequate margin against fracture exists, or the vessel may need to be replaced or thermally annealed.

There are some vessels currently in service with welds in which the Charpy V-notch upper-shelf energy is already below the existing regulatory limit or is expected to be below the limit before the end of the reactors' licensed life. In 1993, using the generic criteria, the NRC identified fifteen (15) plants that have calculated reactor vessel material upper shelf energies of less than 50 ft-lbs.[23] These reactors are:

1) Nine Mile Point 1

2) Oyster Creek 1

3) Arkansas Nuclear 1

4) Crystal River 3

5) Ginna

6) Oconee 1

7) Oconee 2

8) Point Beach 1

9) Point Beach 2

10) Robinson 2

11) Three Mile Island 1

12) Turkey Point 3

13) Turkey Point 4

14) Zion 1

15) Zion 2

NRC also found three additional reactor vessels with upper shelf energies of less than the 50 ft-lbs limit before the end of their operating licenses. These plants are:

1) Oconee 3

2) Millstone 2

3) Watts Bar 1

Thermal Fatigue

Thermal cycling fatigue also contributes significantly to pressure-vessel deterioration. Its effect is more evident after long-term operations and it is usually greater during startup and shutdown routines. Areas subject to the greatest thermal fatigue are those located at the stress concentrations of the pressure boundary. Some of these areas include nozzles and supports. If the zones are adjacent to the core, then thermal fatigue could compound the embrittlement problem and cause especially high deterioration in certain areas.

The effect of thermal fatigue on a vessel can be determined by comparing the vessel design transients with the actual transients experienced after operation. Based on historical trends, the maximum cumulative fatigue usage factor can be calculated and a life for the vessel can be estimated.

(2) Steam Generators

Apart from the reactor pressure vessel, the steam generators of a PWR may represent the most costly and mechanically difficult refurbishing component in a nuclear plant. Steam generators have proved to be a major contributor to the relatively low availability and capacity factors in some PWRs. Thus, overall nuclear reactors' efficiency has been limited in part because of problems in the steam generators. About

20% of all the performance limitations experienced by PWR reactors during the period from 1968 through 1988 were due to steam generator problems. Virginia Power replaced the lower assemblies of the steam generator of the Surry plant. The operation took nine months during the 1979-1980 period. The direct cost was estimated at $81 million. If replacement power costs are added to the direct cost of replacing a steam generator the overall cost could reach three times the direct cost.

Steam generators are extremely expensive to repair, and potentially dangerous. As of mid-1992, unanticipated aging and leakage had forced utilities to replace 12 steam generators. Over the next 17 years, 50 to 60 more replacements may be required, at a cost of hundreds of millions of dollars.[24]

Metallic corrosion has affected several steam generators. Secondary-side corrosion is another key process that adversely affects steam-generator life. Corrosion-related problems in the tube bundle have been solved by sleeving. Mechanical concerns are mechanisms such as tube wear, which can be detected using eddy-current testing, and fatigue-induced cracking of the feedwater nozzle.

One of the nuclear plants affected with steam generator problems is Millstone 2 located in Connecticut. The steam generators of this plant were replaced in 1992. Millstone 2 experienced tube degradation in the steam generators since beginning operation in 1975. It has been determined that caustic stress corrosion was the main contributor to the tube-cracking in this plant. By 1990, of the total 17,038 tubes in both steam generators, 3,851 had been sleeved and more than 3,300 had been plugged limiting the reactors' performance drastically.

The steam generators of Palisades, a nuclear reactor located in Michigan, were replaced in 1990. The use of phosphate chemistry control, coupled with carbon steel tube sheets, and drilled tube supports, led to severe tube denting and corrosion, forcing the replacement of the steam generators. The direct cost for this operation was estimated at $75 million with $200 million additional cost for power replacement.

Trojan, a 1095 MWe PWR reactor located in Oregon, was permanently retired in 1992 because of the continuing degradation of its steam generator. The utility owning the reactor decided to shut it down instead of proceeding with a very expensive replacement plan. Other nuclear plants with steam generator tube failures include: Byron 1, Connecticut Yankee, Zion 1, Indian Point 3, Cook 1, and Mc Guire 1.

(3) Containment Structure

The containment structure is another critical component determining the life of a nuclear reactor. Mechanical and chemical degradation can affect the containment structure. The potential degradation processes occur over a long period of time. Corrosion of the steel rebar is important because it could cause extreme and damaging changes in the steel's properties. These changes would also disrupt the concrete. Mechanically, only freeze/thaw damage is of great concern.

The concrete itself is particularly subject to chemical attack. Acids, sulfates, and leaching of lime water can deteriorate concrete. Sulfates can produce expansive forces and disintegrate the concrete. Aggregate reactions, particularly those involving silica and carbonate, can be damaging to concrete. Alkali/silica and alkali/carbonate reactions cause the concrete to expand and crack. The cracks then expose more concrete to the external sources of deterioration. The containment liner, anchored to the concrete with studs, is another area of concern. Failure of these studs could cause failure of the entire liner.

No containment has ever been replaced in a nuclear plant. Replacement would certainly imply extremely high costs and in such a case the plant would most likely be permanently retired.

(4) Pressurizer Unit

The pressurizer in PWRs is a critical component that should operate properly at all times to ensure plant safety. Replacement of the pressurizer would mean a high direct cost and an extended outage. Fatigue primarily affects spray and surge nozzles and the shell barrel in the steam space near the top of the pressurizer. The spray activation and the inflow and outflow from the pressurizer caused by plant power changes subject this equipment to relatively large thermal transients. Initial comparison of design transients to actual estimated transients indicates that these components at the most would last for the 40-year licensed life.

Stress corrosion cracking often occurs on the inside and outside surfaces of the stainless steel safe ends on the surge and spray nozzles near the pressurizer. Other equipment in the pressurizers such as immersion heaters are degraded by mechanical wear. This occurs when thermal growth causes a rubbing action at the interface of the heaters and the heater support plate, thinning the heater sheath.

Problems in pressurizers have been experienced in some nuclear reactors. In 1989 Calvert Cliff 2 experienced leaks in the pressurizer heater sleeve welds. The problem forced a lengthy outage and expensive repairs.

(5) Steam-Turbine

Steam-turbine problems have been observed in both BWR and PWR. The problem has occurred more often in turbines manufactured by Westinghouse. Blade failures are often the cause of steam-turbine unreliability. Most of these failures are caused by solid-particle erosion and high-cycle fatigue damage to high-pressure blades, and stress-corrosion cracking and moisture erosion damage to the last rows of low-pressure blades. All blades, however, are susceptible to a variety of erosion, corrosion, and stress fatigue-damage mechanisms. Large losses in capacity factors at nuclear reactors have been the result of vibration induced failures of low pressure turbine blading. Many problems are the outcome of a combination of poor steam/water chemistry, excess vibration, certain blade-design factors that vary among turbine manufacturers, and system operating parameters.

Some sections of the blade are particularly susceptible to damage mechanisms. Blade roots are another source of frequently occurring damage. Fatigue is a common failure mode for blade roots, and it is often assisted by a generic type of fault in design or manufacture. Root-fillet radii are subjected to high stress concentrations, and can crack relatively easily.

Low pressure turbines have been replaced in some nuclear plants including Brunswick 2, Dresden 3, and Oyster Creek. Other reactors such as Yankee Rowe, North Anna 1, Salem 2, and Connecticut Yankee have experienced lengthy outages to repair faulty turbines. In addition, low pressure turbine rotors have been replaced in many plants including Zion 1, Maine Yankee, Mc Guire 2, and Byron 1.

(6) Steam Condenser and Cooling Water Systems

Several steam condenser and cooling water system problems have been observed in both BWR and PWR reactors. However, the problem occurs more often in the BWR reactors. About 33% of the capacity factor losses in BWRs are the result of problems with the reactor cooling system. For PWRs, 20% of the losses are due to this problem.[25] Most of the problems in the steam condenser are associated primarily with deterioration of the condenser tubes. The problem is translated into high labor costs for plugging the tubes, replacement power costs while tubes are being plugged, and steady-state heat rate increase caused by deteriorating condenser performance. The major causes of tube failures are erosion and corrosion.

Aging degradation has contributed to over 70% of the cooling water system failures in the past. The most common aging mechanism in these systems is "wear." Of all the failures it has been determined that 50% resulted in degraded performance of the system and in consequence of the nuclear plant.[26]

The intergranular stress corrosion cracking of stainless steel has been the major problem in BWR reactors. This type of corrosion is the product of weld sensitization, high tensile stresses, and an aggressive environment related to high levels of oxygen and chemical contaminants. Condenser tubes have been replaced in Nine Mile Point 1, Pilgrim 1, Hatch 1, Monticello, Cooper, and Dresden 3.

Many of the steam condenser problems in PWR reactors are related to thermal sleeves that are part of the reactor cooling system. Thermal sleeves have been replaced in Davis Besse 1, Salem 1, and Salem 2.

(7) Feedwater Heater

Several feed-water heater tubes have experienced corrosion and erosion-corrosion type failures. The end of useful life of a feedwater-heater has been defined as the time when an increasing number of tube leaks cause frequent outages and plugging accumulates to more than 15% to 20% of the tubes. The problems could be related to the feedwater purity. Heaters that are shutdown more than two or three times between outages represent a problem and should be monitored closely. Tube vibration, impingement-plate, subcooling-zone entrance, and shroud problems are among the most common faults. The need for retubing or complete replacement of the heater is indicated by frequent tube failures or by the total number of tubes already plugged on heaters 15 or more years old (10 years for carbon steel). Complete replacement becomes economic when a heater goes out of service every three or four months and/or the total number of plugged tubes exceeds about 15%.

Many PWR reactors have replaced some or all of their copper alloy feedwater heater tubes with stainless steel tubes. A report by EPRI on feedwater heaters concluded that "if an older plant is going to be in service for another 15 years, there is a strong probability that its feedwater heaters will need to be replaced, even if performance has been satisfactory to date."[27]

Reactors which have replaced feedwater heaters include: Arkansas 1, Point Beach 1 and 2, Maine Yankee, Surry 1 and 2, Pilgrim, and Ginna.

(8) Major Piping Systems

Deterioration of some of the major piping systems is another problem becoming more evident as the result of aging. The major piping systems are both difficult and costly to replace, especially in BWRs. Erosion/corrosion is the primary degradation mechanism for above-ground piping, mainly where moisture, sharp bends, and two-phase flow exist. Corrosion is the main degradation process for underground piping.

A type of stainless steel identified as cast duplex austenitic-ferritic stainless steel is used extensively in the nuclear industry in several components and in primary coolant piping in PWR reactors. It has been determined that embrittlement of the ferrite phase in this type of steel could occur after 10 to 20 years at reactor operating temperatures. This problem could affect the structural integrity of pressure boundary components during special events.[28]

In 1986, Surry 2 experienced a catastrophic failure of the main feedwater pipe. Since that event NRC, in conjunction with the industry, has taken steps to develop monitoring programs to anticipate and prevent the rupture of high-energy piping because of single-phase erosion/corrosion. Wall thinning has been discovered in both safety related and non-safety related portions of major piping systems.

PERMANENTLY RETIRED NUCLEAR REACTORS: CASE STUDIES

Nuclear reactors permanently retired are listed in Table II.7 of Chapter II. Six of the twenty-one nuclear reactors in this list were retired in the last five years. These reactors are Fort St. Vrain, Yankee Rowe, Rancho Seco, Shoreham, San Onofre 1, and Trojan. The analysis in this section is limited to these reactors, since most of the other prematurely retired reactors are either not representative of the currently operating stock or were originally designed as experimental reactors.

Table III.2 lists these reactors, their age, retirement year, and major retirement causes. As explained in previous sections, several factors may affect the life of nuclear reactors and in most cases it is a combination of these factors, rather than just a single factor, that motivates the decision for premature shutdown. Thus, other factors and circumstances (not included in Table III.2) surrounding each reactor case should be considered when assessing the retirement decision. In addition, reaching specific conclusions from the analysis of this sample is not recommended since the sample size is not large enough to perform any kind of statistical analysis.

Table III.2: Reactors Permanently Retired

Name	Retirement Year	Age	Major Retirement Cause
Rancho Seco	1989	15	Poor Performance/ Steam Turbine and Other Equipment Failures
Yankee Rowe	1991	30	Critical Equipment Constraint/ Pressure Vessel Embrittlement
Trojan	1992	17	Critical Equipment Constraint/ Steam Generator Tubes Failure
San Onofre 1	1992	25	Critical Equipment Constraint and Poor Performance/ Steam Generator Tubes Failure
Fort St. Vrain	1989	16	Poor Performance/Cooling System and Other Equipment Failures
Shoreham	1989	0	Public Opposition/ Environmental Limitations

The average life of the nuclear reactors in Table III.2 is only 17 years. If Shoreham is not included, the average age is 20.6. Yankee Rowe and San Onofre 1 are the only ones with lives beyond 20 years.

The main causes for permanent retirement are diverse. In the case of Rancho Seco and Fort St. Vrain, poor performance throughout their lives eventually forced their owners to closed them. Critical equipment constraints forced the retirement of Yankee Rowe and Trojan. Both reactors had good performance records but continuing operation implied the replacement of critical equipment at an unacceptable cost-- in the case of Yankee Rowe, replacement or annealing of the pressure vessel; for Trojan, performance deteriorated drastically in the last two years and then replacement of the steam generators became evident. Again their owners opted for their shutdown. San Onofre 1 is a combination of critical equipment constraints and poor performance. Shoreham is a very special case, in which public opposition forced its retirement before entering commercial operation. Shoreham is the only case in which engineering problems cannot be identified as causes for retirement.

Other important characteristics of this sample of retired reactors are listed in Table III.3. Four of the six reactors are located in federal regions west of the Mississippi river. Their capacities vary from 167 MWe (Yankee Rowe) to 1095 MWe (Trojan). With the exception of Fort St. Vrain, all are pressurized water reactors. Westinghouse provided three of the nuclear steam systems and three were engineered and built by Bechtel. Their lifetime capacity factors vary considerably from a low of 17.9% in Fort St. Vrain to a high of 70.6% in Yankee Rowe. However, with the exception of Yankee Rowe, the capacity factors are all below the industry average (about 66% in 1991). In general, all these reactors were very expensive to operate.

Table III.3: Characteristics of Permanently Retired Reactors

Name	Region	Capacity MWe	Type	Steam System Supplier	Architect Engineer	Life Cap. Factor
Rancho Seco	West	873	PWR	Babcock & Wilcox	Bechtel	31.5
Yankee Rowe	New England	167	PWR	Westinghouse	Stone & Webster	70.6
Trojan	North West	1095	PWR	Westinghouse	Bechtel	51.6
San Onofre 1	West	436	PWR	Westinghouse	Bechtel	51.3
Fort St. Vrain	North Central	330	High Temp Gas Cool	General Atomic Corp.	General Atomic Corp.	17.9
Shoreham	New York/ New Jersey	809	PWR	General Electric	Stone & Webster	Not oper.

Rancho Seco

Rancho Seco is a pressurized water reactor with a net design capacity of 873 MWe. The reactor is located 25 miles southeast of Sacramento, California. The owner of Rancho Seco is the Sacramento Municipal Utility District (SMUD), a publicly-owned utility. The architect-engineer and constructor was Bechtel and the nuclear steam system was supplied by Babcock & Wilcox. The plant operated from 1974 through 1989 (15 years). Total construction cost was $350 million.

Although some people assert that Rancho Seco was closed because of public opposition, a review of its operating history reveals poor performance and reliability as the major causes for retirement. The performance of the plant throughout its 15-year life is illustrated by its lifetime capacity factor of only 31.50%. This is one of the poorest performances in the nuclear electric generating industry. The capacity factor reached values above 50% in only 4 of the 15 years of operating life. The plant experienced several forced outages and was out of service in 1986 and 1987.

Rancho Seco experienced serious problems in some critical engineering components including: steam turbine, cooling water system, steam generator, and feedwater equipment.[29] More than $400 million were spent in plant modifications. These direct costs plus replacement power costs due to lengthy plant shutdowns forced SMUD to increase its rate to customers by 90% in 1986. Nevertheless, SMUD was unable to reverse the plant's poor operating record.

During the 27-month shutdown beginning in 1986, two local citizen groups placed a proposition on the local ballot that would prevent plant restart unless voters' approval was given. SMUD also added its own alternative proposition on the ballot. The SMUD proposition called for an operational trial period during which Rancho Seco must meet a 50% minimum capacity factor for four consecutive months to avoid closure. The January 1988 referendum resulted in a victory for the SMUD proposition. However, Rancho Seco was permanently shutdown in 1989 after failure to meet the minimum capacity factor specified on the ballot.[30]

The Rancho Seco case exemplifies the typical nuclear retirement case in which several interrelated factors determined the final retirement time. People could argue as major causes public opinion, economics or engineering factors.

Yankee Rowe

Yankee Rowe is a small pressurized water reactor with a net capacity of 167 MWe. Yankee Rowe was the oldest operating commercial nuclear plant in the U.S. until 1991 when it was forced to shutdown. The reactor located in Rowe, Massachusetts is owned by Yankee Atomic Electric Co., a consortium of 10 northeastern utilities. The architect-engineer and constructor was Stone & Webster and the nuclear steam system was supplied by Westinghouse. The plant, built at a cost of $48 million, operated for 30 years from 1961 to 1991.

Yankee Rowe was permanently retired in 1991 because of potential embrittlement problems in its pressure vessel. Concerns about Yankee Rowe's vessel integrity began in 1990 when the NRC performed Pressurized Thermal Shock (PTS) tests in Yankee Rowe indicated that the reactor was not in compliance with the screening criterion specified in the PTS regulation. The embrittlement potential is associated with the weld chemistry of the reactor vessel and the effects of coarse grain plate material on reference temperatures. In 1991, NRC repeated the tests finding a considerably higher probability for the reactor's pressure vessel to fail under certain accident conditions. NRC recommended immediate shutdown because of safety concerns. The utility was required to perform a series of actions before attempting a restart of the plant.[31]

After considering vessel replacement and annealing procedures the utility opted for permanent retirement. The owners declared that the reasons for closing the plant were the high cost of required testing and refurbishment of the reactor vessel, the lack of certainty of regulatory approval, and lower demand for electricity in the region.[32]

Yankee Rowe was the PWR leading plant in the license renewal procedure and was expecting to extend its operating license for 20 more years. Its retirement brought the nuclear power plant life extension program to a virtual halt in 1991.

Trojan

Trojan is a pressurized water reactor with a net design capacity of 1,095 MWe. The reactor is located in Rainier, Oregon. The owner of Trojan is Portland General Electric Company. The architect-engineer and constructor was Bechtel and the nuclear steam system was supplied by Westinghouse. The plant operated from 1975 through 1992 (17 years). Total construction cost was $741 million.

The deterioration of the steam generators was the major cause for the permanent retirement of Trojan. Replacement of the steam generators was estimated at about $200 million. Extensive age-related cracking in the steam generator pipes was limiting performance to the point at which replacement was necessary. The utility opted to retire the plant rather than to invest in the replacement since there was uncertainty about whether the utility could recover the investment through rate increases. The Portland General Electric Company had already incurred $350 million of unrecovered investment in this nuclear plant.

Trojan is the largest nuclear reactor permanently retired. Steam generator problems similar to the ones experienced in this reactor are expected in other reactors. About 50 reactors have the same type of Westinghouse steam generator tubes found in Trojan. According to Steve Trich from Westinghouse, steam generator tubes like the ones in Trojan were warranted for only one to two years.[33]

San Onofre 1

San Onofre 1 is a pressurized water reactor with a net design capacity of 436 MWe. The reactor is located near San Clemente, California. The owners of San Onofre 1 are Southern California Edison and San Diego Gas and Electric. The architect-engineer and constructor was Bechtel and the nuclear steam system was supplied by Westinghouse. The plant operated from 1967 through 1992 (25 years). Total construction cost was $90 million.

San Onofre 1 closed because costs continued to escalate and safety remained an issue. The owners invested $660 million in upgrades over the operating years. Problems are mainly related to the steam generator and the cooling system. Tube sleeving has caused lengthy outages and poor performance. It was estimated that the utility would have spent around $125 million in capital improvements over two years to keep the reactor operating without guarantee of improving efficiency.[34]

Fort St. Vrain

Fort St. Vrain is a high-temperature, gas-cooled design type reactor that utilizes helium gas to produce steam. This is the only reactor of this type in the U.S. The reactor is owned by Public Service Company of Colorado, and is located near Platteville, Colorado. Fort St. Vrain has a net capacity of 330 meggawatts and it was designed and built by General Atomic Corporation of San Diego, California. The plant operated from 1973 through 1989 (16 years). The total construction cost for Fort St. Vrain was $224 million.[35]

Fort St. Vrain was shutdown in 1989 as a result of consistently poor performance and high operating and maintenance costs. Throughout its whole operating life, the reactor experienced failures in several critical components including control rod drives (core injection), electrical systems, steam generator, and cooling water system. The lifetime capacity factor of the plant was only 14% after 16 years in operation. In 1986 the plant's owner recorded losses of $93.7 million because of unrecoverable costs associated with plant operations.

Fort St. Vrain represents a special case since it is the only reactor of this type in the U.S. Nevertheless, the failure of similar critical components in other reactors have been experienced.

Shoreham

Shoreham is a pressurized water reactor located near Brookhaven, New York. The plant has a net capacity of 809 MWe and is owned by the Long Island Lighting Company (Lilco) . Stone & Webster served as the architect-engineer and constructor. The General Electric Company provided the containment and nuclear steam system.

Lilco announced plans to build Shoreham in April 1966, in order to reduce Long Island's dependence on imported oil for electricity generation and allow a number of aging oil-fired units to be retired. Shoreham was originally designed as a 540 MWe plant. It had an expected construction cost of about $70 million, and was to enter commercial operation by 1973. However, in March 1969, Lilco's Board of Directors approved a plan to upgrade the unit to 820 MWe to improve operating economics. The new construction cost estimate was $269 million, and the construction completion date was extended to 1975. In November 1983, Shoreham construction was completed at a total cost of $4.2 billion.[36]

Shoreham was retired before it entered commercial service. The plant received NRC approval for full power operation in April 1989. However, the plant was permanently retired in June of the same year after Lilco shareholders approved the settlement with New York State officials to sell the plant to the Long Island Power Authority.[37]

Strong opposition by New York state authorities and the New York State Public Service Commission was the most important factor in the retirement of the plant. The opposition was based on several factors including perception of high risk, high construction costs, and low electricity demand in the region. Environmental concerns based on the inadequacy of the emergency procedures in Shoreham were major factors responsible for the retirement. Opposition was also based on the extraordinary final capital cost of the plant at $5.5 billion, or $6,800 per kilowatt. The Shoreham final settlement agreement was accelerated by the weakened financial condition of Lilco-- the result of a $1.4 billion disallowance and rate increase denial.

DISSERTATION APPROACH TO NUCLEAR REACTOR LIFE ASSESSMENT

The basis for the formulation of the approach selected in this study is the result of the extensive analysis of the retiring nuclear capacity problem and the factors affecting the nuclear industry in the U.S. In particular, the review of critical engineering equipment and causes and circumstances surrounding the permanent retirement of nuclear reactors (described in previous sections) allowed the definition of the major components of this approach.

The major objective of this study is the formulation of an analytical approach based on specific nuclear engineering and economic data that can be used to estimate the life of nuclear reactors. A second objective of this study is the definition of nuclear retirement scenarios through the implementation of this tool on the U.S. nuclear generating stock. By accomplishing these objectives, more accurate electricity supply planning can be prepared and early nuclear shutdowns may be identified allowing the forecast of potential electricity capacity shortages at regional levels. In addition, such a forecasting system could help in the assessment of other important related issues including replacing electrical capacity options, decommissioning schedules, equipment depreciation, etc.

There are at least five different types of lives that can be used to define the useful life of a piece of equipment and in this case of a nuclear reactor. These life types are: a licensed life, an accounting life, a regulatory life, an economic life, and a technological life.

A licensed life corresponds to the period for which the equipment is legally allowed to operate. Nuclear reactors are allowed to operate for 40 years from the issuance of the operating license. This licensed life was established by the Atomic Energy Act of 1954.[38] All the activities related to the retirement of nuclear reactors in the United States (such as decommissioning funds, replacement alternatives, spent fuel discharges volumes, etc.) are indeed based on the expectation that nuclear reactors will shutdown when they reach their licensed life of 40 years.

The accounting life represents the period over which capital costs are recovered. The accounting life for nuclear reactors is typically 30 years as defined for rate-making purposes and 10 years as defined for tax purposes.[39]

The regulatory life is the life defined by the regulatory process with respect to environmental and safety issues. The regulatory life may differ from the licensed life if there are changes in regulations and these changes force a nuclear reactor to stop operating because of its inability to comply with the new regulations.[40]

The economic life of a power plant is defined by the time at which the benefits of continuing operation are less than its operating costs. As described in previous chapters, the economic life has been defined in terms of a capital budgeting approach. Based on this approach the life of the plant is determined by looking at the net present value of all future operating costs versus other investment alternatives such as a new coal plant.[41]

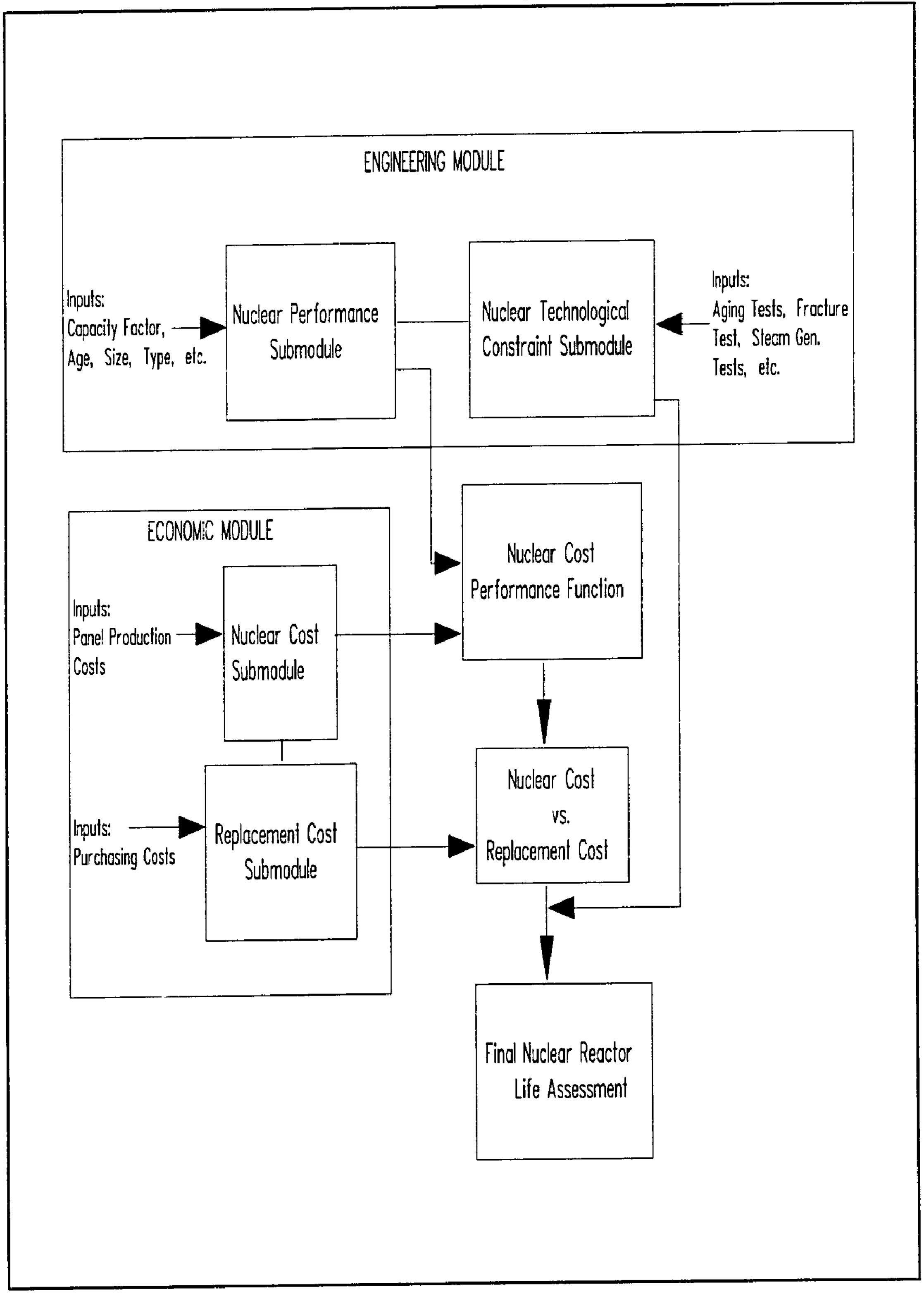
The technological life is defined by the physical ability of the unit to operate. Indications of this ability can be found in the analysis of its aging process, in its past performance, and in the results of engineering tests performed routinely to assess the status of materials and equipment and to identify future potential problems.

The approach followed in this study is based on the evaluation of both the technological life as well as the economic life of the nuclear reactors. The approach recognizes that these are the most important life types determining the useful life of nuclear reactors and that these lives are greatly interrelated and need to be taken into consideration in an integrated manner. Furthermore, the approach allows the consideration of the aging process and its effect on equipment performance.

The method proposed in this study consists of an integrated modeling system that incorporates and relates relevant engineering and economic factors allowing the estimation of nuclear plant lives. The integrated approach is indispensable because the useful life of nuclear reactors is limited by technological and economic factors which are interdependent. Technological factors include engineering performance and engineering constraints. Economic factors include nuclear power production costs and replacement costs. The approach is based on the following assumptions: (1) nuclear reactors have useful lives that do not necessarily coincide with their expected 40-year licensed life, (2) the useful life of nuclear reactors is defined by relevant interrelated factors that include nuclear engineering and economic factors, and (3) these factors can be integrated in a dynamic modeling system to determine on a plant-by-plant basis the time at which the reactors will be shutdown.

Figure III.3 is a schematic of the proposed nuclear life assessment modeling system. This analytical approach is divided into two major modules: an engineering module and an economic module. These modules are interconnected to produce the final objective of the nuclear life assessment on a reactor-by-reactor basis. The engineering module includes a nuclear performance submodule and a nuclear technological constraint submodule. The nuclear reactor performance submodule describes the performance of nuclear reactors through time according to efficiency parameters and based on general and technical characteristics such as age, size, and type. The nuclear technological constraint submodule considers constraints related to the progressive deterioration of materials and/or equipment due to the aging process and in particular due to problems associated with nuclear radiation. Critical technical constraints include potential vessel embrittlement and ductile fracture, and piping deterioration in the steam generators. The nuclear technological constraint submodule affects the nuclear performance submodule by imposing limitations on the expected performance of the reactors.

FIGURE III.3: Schematic of the Nuclear Life Assessment Forecasting System



The economic module includes a nuclear cost submodule and a replacement cost submodule. The nuclear cost submodule defines the cost of producing nuclear electricity as a function of efficiency parameters such as nuclear capacity factors. This submodule is then related to the replacement cost submodule on a reactor-by-reactor basis to determine the minimum efficiency level beyond which it becomes more expensive to operate the reactor than to replace the power.

The study is independent of previous work because it incorporates and relates specific relevant nuclear engineering and economic data into an analytical tool that allows the estimation of the useful nuclear life on a reactor-by-reactor basis. This is considered the first attempt in which such an integrated and comprehensive approach, that explicitly considers engineering parameters, is used in the assessment of the lives of nuclear reactors. In the next chapter it will be explained that all previous nuclear life assessment approaches have been based exclusively on the comparison of nuclear operating costs with costs of alternate generating technologies, primarily coal.

In summary, the approach followed in this study is considered unique because:

(1) it attempts to assess the nuclear reactors' lives by explicitly considering specific critical factors identified in engineering and economic areas;

(2) the factors are considered in an integrated manner implying that their interdependence is fundamental for the assessment of the nuclear reactors' lives,

(3) the approach focuses, in general, on nuclear engineering characteristics, and in particular, on the deterioration of the performance of nuclear reactors due to their aging process.

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CHAPTER IV

LITERATURE REVIEW

This chapter summarizes previous work related to the issue of nuclear reactor life expectancy. The chapter begins with the review of methods specifically developed to estimate the useful life of nuclear reactors. This section is followed by a description of attempts to forecast life extension of nuclear reactors in the U.S. The last section of the chapter includes summaries of previous work identified in the literature on areas relevant to the approach followed in this study. These areas include: nuclear reactors' performance through time, nuclear engineering constraints, nuclear electricity production costs, and nuclear replacement costs.

PREVIOUS WORK ON NUCLEAR REACTOR LIFE ASSESSMENT

As described in previous chapters, the life expectancy of the U.S. nuclear generating stock is a very important issue with critical implications in electricity supply requirements and forecasts, decommissioning plans, and other financial matters. In Chapter III, it was described that there is no technical basis supporting any life expectancy scenario and that in particular the scenario assuming a 40-year life cannot be supported by either the experience of retired nuclear reactors or by critical equipment designed to operate for less than 15 years. Regardless of the importance and lack of understanding of the issue, only a few attempts have been made to formulate an analytical tool that could be used for the assessment of the nuclear reactors' life. Furthermore, the only studies found in the literature fail to consider plant-specific engineering data indispensable for such an assessment. Analyses of the status of critical engineering components and of the effect of aging in the long-term operation of equipment are absent in all previous work related to the issue.

Three studies were found in the literature that directly address the life expectancy issue in nuclear reactors. These studies were developed by Hewlett, Kokkelenberg, and by Kee.[1] All of them are economic assessments and they focus purely on operating cost factors.

Hewlett

Hewlett's research has centered on the examination of the effects of the escalation in non-fuel operating costs on the lives of the U.S. nuclear power plants. Hewlett has performed extensive research in the area of nuclear plant operating costs.[2] His method is based on the premise that a reactor will be retired when the costs of its continued operation exceed its benefits. The present value of the cost savings derived from deferring the construction and operation of new replacement capacity is the major benefit of continuing to operate a nuclear power plant. His approach assumes that the economics of the retirement decision is a "straight forward capital budgeting problem." Therefore, a nuclear plant will be retired if the discounted operating costs are greater than the

the discounted cost of the replacement capacity.

Hewlett evaluated two alternatives: (1) retiring a nuclear unit "now" and replacing it with a series of new coal fired power plants and (2) operating a nuclear unit for a given number of years (20 years, for example) and then replacing it with the same series of new coal fired power plants. The discounted costs of each alternative were computed over an 80-year period. The difference between the two alternatives, as measured in terms of discounted costs, were used as the basis to assess the reactor lives. Hewlett simply compared the cost of retiring a nuclear plant "now" and replacing it with a coal plant versus the cost (including O&M and capital additions costs) of operating the plant for an additional 20 years and then replacing it with the same coal plant. In his analysis he divided a reactor sample of the U.S. nuclear generating stock into five groups according to their levelized operating costs in terms of mills (0.1 cents) per KWh. The five groups were based on the operating cost distribution using the 10th, 25th, 50th, 75th, and 90th percentiles. The reactor sample consisted of all nuclear units operating before 1981 with capacities larger than 300 MWe.

The method was developed according to four major assumptions: (1) a capacity factor of 60 percent for both the nuclear unit and the coal reactors, (2) current environmental standards are met by a conventional coal plant so that environmental costs are included in the overall cost of the coal plants, (3) to build new capacity is considered the only alternative for the replacement of the nuclear capacity, thus power purchasing and other replacement alternatives to coal are considered more expensive, and (4) there is no effect of decommissioning in the decision to either continue operating or retiring the nuclear plant.

Hewlett considered two scenarios. The first one assumes operating costs remaining at the 1989 level. Thus, this scenario implies no future escalation in the real O&M and capital additions costs. The second scenario assumes that operating costs will increase following the same trend observed in the period pre-1989. The forecast of operating costs is based on a multiple regression analysis considering factors influencing changes in O&M and capital addition costs. According to this approach the operating costs increase about 50% by the year 2000.

Hewlett's results, assuming operating costs at the 1989 level, show that about 5 GW of the nuclear capacity will be retired before the end of their 40-year licensed lives. This premature retiring capacity corresponds to the most expensive plants and is about 10% of the plants which entered operation before 1981. In particular, Hewlett concluded that the levelized cost of operating a nuclear reactor in the 90th percentile for 20 additional years, and then replacing it with a coal plant is greater than the cost of retiring the nuclear plant now. This scenario also found that about 10 GW capacity could be life extended. This corresponds to the 10% of the plants with the lowest operating costs.

Results from the scenario based on operating costs increasing from $100 per KWe in 1989 to $150 per KWe by the year 2000 imply that it would be more economical to retire about 50% of the plants considered in the sample.

Although Hewlett does not explicitly consider aging factors, one of his general conclusions from his research is that if the Nuclear Regulatory Commission increases its regulatory requirements with respect to aging, resulting in costs of about $300 to $500 per KWe, it may be economic to retire the average plant before its 40th year. This conclusion is based on the assumption that aging-related problems will increase as the nuclear stock continues aging.

Hewlett's work is the most relevant and complete found in the literature on the issue of nuclear plant life. However, the analysis is purely economic and does not consider engineering factors or any other plant-specific factors except operating costs. The results of this type of analysis are very sensitive to the assumptions made. For instance, the cost of building and operating a new coal plant 20 years from now is very uncertain. In addition, the assumptions of either constant nuclear operating costs through the future or extrapolation of the past trends are simplistic and may not be accurate. Another major arguable assumption in his study is that capacity factors for nuclear reactors and coal plants will remain constant throughout the life of the plants. This assumption implies that performance does not deteriorate with age. The experience with nuclear and coal reactors from the last decades clearly indicates the contrary. Finally, replacement options other than coal, such as purchasing power, conservation or other fuel-fired plants were not considered. Utilities could defer the construction of new replacement capacity if the least cost alternative is purchasing power, or by implementing conservation programs.

In addition to the work described above, Hewlett has performed extensive analysis on the effects and implications of decommissioning on the decision for either early retirement or life extension of nuclear reactors.[3] Again Hewlett's approach is based on the expectations of future operating costs and their effect on the economic life of nuclear reactors. From this work Hewlett concluded that decommissioning is not necessarily one of the most important factors affecting the nuclear life decision.

Kokkelenberg

Kokkelenberg evaluated different alternatives to assess the economic life of existing nuclear power capacity. Kokkelenberg centered his research on looking at the nuclear stock as a capital good and in determining the economic value and economic life of this capital stock.

Methods considered include: an inventory method that takes into account depreciation and obsolescence, a capital budgeting approach based on discount cash flows, an econometric simulation that produces an optimal nuclear capital stock, and an inferring value approach based on prices of input, output and plant. As did Hewlett, Kokkelenberg selected a capital budgeting approach to determine the economic life of nuclear reactors.

Kokkelenberg approach consisted of the use of capital budgeting techniques to determine net present values of future streams of cash flows to select among investment alternatives. The discounted cash flow analysis was viewed in two different ways. The first method assumed that the firm wished to minimize the net present value of all future costs. The second method assumed that the regulatory body would force the firm to minimize the net present value of its revenue requirements. Kokkelenberg assessed that different investment plans would result from these two different views.

Kokkelenberg's approach included two scenarios: (1) to continue operating a 750 MWe nuclear plant for 30 years and then replace it with 3 gas turbines of 250 MWe capacity each, and (2) decommissioning the nuclear plant after 10 years of operation and replacing it with a coal plant of 1000 MWe capacity that will last for 50 years.

Although Kokkelenberg's report describes several implications related to his approach, it does not present any results. His method is very similar to the one used by Hewlett. However, Kokkelenberg includes additional financial factors such as income taxes, depreciation, and rate base issues from the utility point of view. Again the approach is purely economic and does not consider any technical or engineering factors.

Kee

Kee's analysis is also based on the level of operating costs as the essential factor that affects the decision of whether to retire or extend the operating life of nuclear reactors. His approach suggests that those plants with low operating costs are the best candidates for life extension while plants with high operating costs are best candidates for early retirement.

Kee compared two options: (1) retire the nuclear plant immediately; or (2) retire the plant at the end of its current operating license and replace it with a coal plant. To continue operation until the end of the licensed life is viewed as a valid alternative since the major capital expenditure for replacement capacity is accelerated by early retirement.

Kee asserts that there is a significant benefit from postponing the replacement expenditure as long as there is a positive real interest rate during the remainder of the plant licensed life. A positive real interest refers to the portion of financial return that, over a given time period, remains above the rising cost of what an organization might choose to spend investable funds on.

Kee identifies five major factors associated with the decision of early retirement: (1) the operating cost of the nuclear plant during the remainder of its normal life, (2) the cost of future repairs under normal operation of the nuclear reactor, (3) the level and timing of decommissioning expenses, (4) the cost of the replacement capacity, and (5) the cost and duration of the purchase of temporary replacement power.

Kee's paper on nuclear reactor life assessment does not provide results with respect to the U.S. nuclear generating stock. As explained with the approaches followed by Hewlett and Kokkelenberg, this approach is based on purely economic factors and fails to consider engineering or any other factor types.

PREVIOUS WORK ON NUCLEAR PLANT LIFE EXTENSION

Other methodologies found in the literature focus on assessing the potential for nuclear power plant life extension. Methodologies to assess nuclear life extension have been developed by SANDIA National Laboratories for the U.S. Department of Energy and by Decision Analysis Corporation of Virginia for the Energy Information

Administration (EIA).[4]

SANDIA National Laboratories

SANDIA developed a cost/benefit analysis of nuclear power plant life extension for the Department of Energy in 1988. The study compares the nuclear plant life extension alternative in the U.S. with other competing power sources in the early 21st century.

The study included two approaches. First, national and regional analyses were conducted based on the Electricity Sector Model developed by Data Resources Incorporated (DRI). Secondly, a national assessment was developed using levelized cost calculations to compare the nuclear life extension alternative with new coal plants.

The analysis included a general assessment for the overall U.S. based on widely varying economic assumptions and a more specific estimate for individual U.S. nuclear units under most likely (baseline) assumptions. The studies assess the benefits and costs of life extension relative to the anticipated competing sources of electricity supply in the first three decades of the next century. The studies associate net benefits with electricity cost savings.

SANDIA's analysis of nuclear life extension uses electricity demand forecasts up to the year 2030 produced by the DRI Electricity Sector Model. This is a long-run type electricity demand model based on economic growth and real electricity prices. This electricity model includes six submodels: electricity demand, capacity, generation, fuel demand, cost of service, and pricing.

The national and regional economic analysis of nuclear life extension is based on a comparison of expected costs for extending the life of nuclear reactors by 20 years versus expected costs associated with replacement alternatives. A new coal plant was considered the most likely alternative to nuclear life extension. Uncertainty surrounding the capital cost needed for nuclear life extension implied the formulation of a wide range of case scenarios. Capital costs were assumed from a minimum of about $300 per KWe to a maximum reaching close to $2500 per KWe in 1986 dollars.

The study found positive benefits from life extension for all of the existing nuclear units in the U.S. The benefits vary according to plant type and location. The large forecasts of electricity demand projected for the first decades of the next century benefit the life extension alternative. The benefits derived from life extension were found to be greatest in the east coast and California. In the most optimistic case, over $900 billion savings are expected from extending the lives of all the reactors in the U.S. nuclear generating stock. The basecase scenario implies savings of about $360 billion and the most pessimistic case expects to breakeven with a case scenario based on new nuclear units.

Although the study is important because it provides estimations of nuclear life extension capital costs, the effort is considered biased in favor of nuclear power. The great uncertainty surrounding capital costs for both nuclear life extension and new coal plants in the next century allowed for a highly optimistic nuclear scenario. As explained before these types of economic assessments produce results that are highly dependent on cost assumptions. The research was funded directly by the Department of Energy during the Reagan/Bush era. During this time period, a study like this one was needed to justify more funding for nuclear power in the country. A more objective approach would have found life extension as the winning alternative in some cases rather than all cases. The authors did not take into consideration the actual capability for some nuclear plants to even operate for their 40-year licensed life. In addition, the study does not consider other important factors such as operating costs and status of critical equipment on a reactor-by-reactor basis.

Decision Analysis Corporation of Virginia / Energy Information Administration

Decision Analysis Corporation of Virginia developed a nuclear life extension ranking approach for the Energy Information Administration (EIA) in 1990. This approach allows the ranking of all the U.S. nuclear electric generating plants according to their likelihood for life extension. The system has been updated for EIA in 1991 and 1993.

The factors considered in this approach are grouped into five major criteria including economics, engineering performance, acceptance, environmental, and electricity demand forecasts. All factors are specified on a plant-by-plant basis and they are all transformed from physical units into uniform indices for comparison reasons.

Economics factors include operating costs, capital costs for life extension, decommissioning costs, replacement cost, and indices developed to measure nuclear competitiveness at a regional level. Engineering performance factors include lifetime capacity factors, forced outage rate, and cumulative NRC penalties. In addition, results from tests measuring the status of critical equipment are included. These are the Pressurized Thermal Test and the Upper Shelf Energy Test. Environmental factors include nuclear spent fuel storage capabilities and fossil-fuel and greenhouse gas emissions from competing technologies at a regional level. The acceptance criteria include indices developed to measure public acceptance, utility acceptance and State Public Utility Commission acceptance. Electricity demand forecasts refer to cumulative unplanned capacity additions.

The nuclear ranking system allows the generation of different nuclear life extension assessments based on seven basic scenarios and two combinations of scenarios. In addition to a basecase scenario, assessments are produced for scenarios with emphasis in Clean Air Act Amendments, higher oil prices, and higher and lower nuclear power acceptance.

This is the only approach found in the literature that directly incorporates, in addition to economic factors, other factors which are considered relevant in the assessment of the life of nuclear reactors. However, the approach does not produce an assessment of the useful life or possible life extension of the nuclear reactors. Instead, the approach produces a simple ranking of all the reactors by comparing characteristics among them and according to relative scores and weights determined subjectively by the analyst. All the factors are quantified and normalized to provide an overall ranking for each of the reactors according to their potential for life extension. The approach has been used by EIA in the last few years in the development of future scenarios of nuclear generating capacity in which life extension is assumed.[5]

PREVIOUS WORK ON AREAS RELATED TO THIS DISSERTATION'S APPROACH

Reviews of previous work in areas related to the methodology submodules are presented in the sections that follow. These areas include: nuclear engineering performance, nuclear engineering constraints, nuclear electricity production costs, and nuclear replacement costs.

Nuclear Engineering Performance

Because the life assessment of nuclear reactors is a function of engineering performance, it is important to review previous work related to the analysis of nuclear performance. Five studies have been identified in the literature that attempt to explain nuclear engineering performance. Three of these studies have been performed by consulting groups including the Washington Consulting Group, SAIC and Komanoff Energy Associates.[6] The other two studies were performed by Geoffrey Rothwell of Stanford University and by Krautmann and Solow.[7] Three additional studies compared the performance of nuclear reactors with the performance of fossil-fuel electricity generating reactors. These studies were performed by Komanoff, Roberts *et al.*, and Lester and McCabe. [8]

The study by Grace Hu of the Washington Consulting Group (WCG) is based on a linear regression analysis that examines the factors affecting capacity factors. The approach uses pooled time-series and cross-section of plants generating electricity from nuclear power. Since the average age of the plants considered in this study was about 6 years, the study results are based on relatively short time period data. The study identified the age, age squared, size, multiunit status, and O&M costs as relevant factors affecting the performance of nuclear reactors as measured by capacity factors. Similar factors were identified by Komanoff and Krautmann and Solow in their studies. The WGC study found a positive effect of age in the first few years followed by a negative effect in the long term. In addition, it was found that the age when the plants reached their maximum capacity factor was 10 years.

All the other studies with the exception of the one by Rothwell found a negative relation between nuclear reactor performance and age when data over long periods of time are used.

All the studies comparing nuclear performance with fossil fuel performance found a similar negative trend in the long-term as both nuclear and fossil-fuel reactors age through time. In particular, the study by Roberts *et al.* found similar aging profiles for availability factors of nuclear and fossil plants based on forced outages.

Nuclear Engineering Constraints

Nuclear engineering constraints refer to critical equipment or material that could limit the life of nuclear reactors. The progressive deterioration of these critical parts are the product of an aging process especially associated with nuclear radiation. Critical technical components in nuclear reactors include the nuclear reactor vessel and its integrity as it is tested for embrittlement or ductile fracture, the steam generators and specific coolant and plant safety systems. Information on the status of critical components and the results from tests to measure the criticality of a component is only available from the Nuclear Regulatory Commission (NRC).[9] The analysis of the aging of critical components in nuclear reactors is coordinated by NRC through the Nuclear Plant Aging Research Program (NPAR).[10] No study has been found that incorporates these constraints in the assessment of nuclear reactors' lives.

Nuclear Electricity Production Costs

Nuclear electricity production costs are available from the Energy Information Administration (EIA) of the U.S. Department of Energy.[11] In this annual report, EIA lists electric plant cost and O&M production expenses for all types of electric generating reactors. In particular, the publication includes a comparison between nuclear and coal generating expenses and a procedure to estimate generating expenses including capital carrying charges.

Analysis of nuclear power plant operating costs excluding fuel costs have been published twice by EIA.[12] The reports considered important factors affecting operating costs such as plant aging, performance, regulatory and enforcement activities and replacement costs.

Nuclear Replacement Costs

Nuclear replacement costs based on purchasing power are analyzed and forecast by NRC on a plant-by-plant basis. The last nuclear replacement cost report by NRC includes forecasts to 1996.[13] In addition to the NRC replacement cost publication, EIA publishes two reports that include purchasing costs to utilities.[14]

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CHAPTER V

RESEARCH METHOD

This chapter presents a detailed description of the research method followed in this study. The specific analytical approach is presented in six sections corresponding to the most important components of the nuclear life assessment forecasting system. These sections are:

(1) Nuclear performance,

(2) Nuclear production costs and cost-performance functions,

(3) Replacement costs,

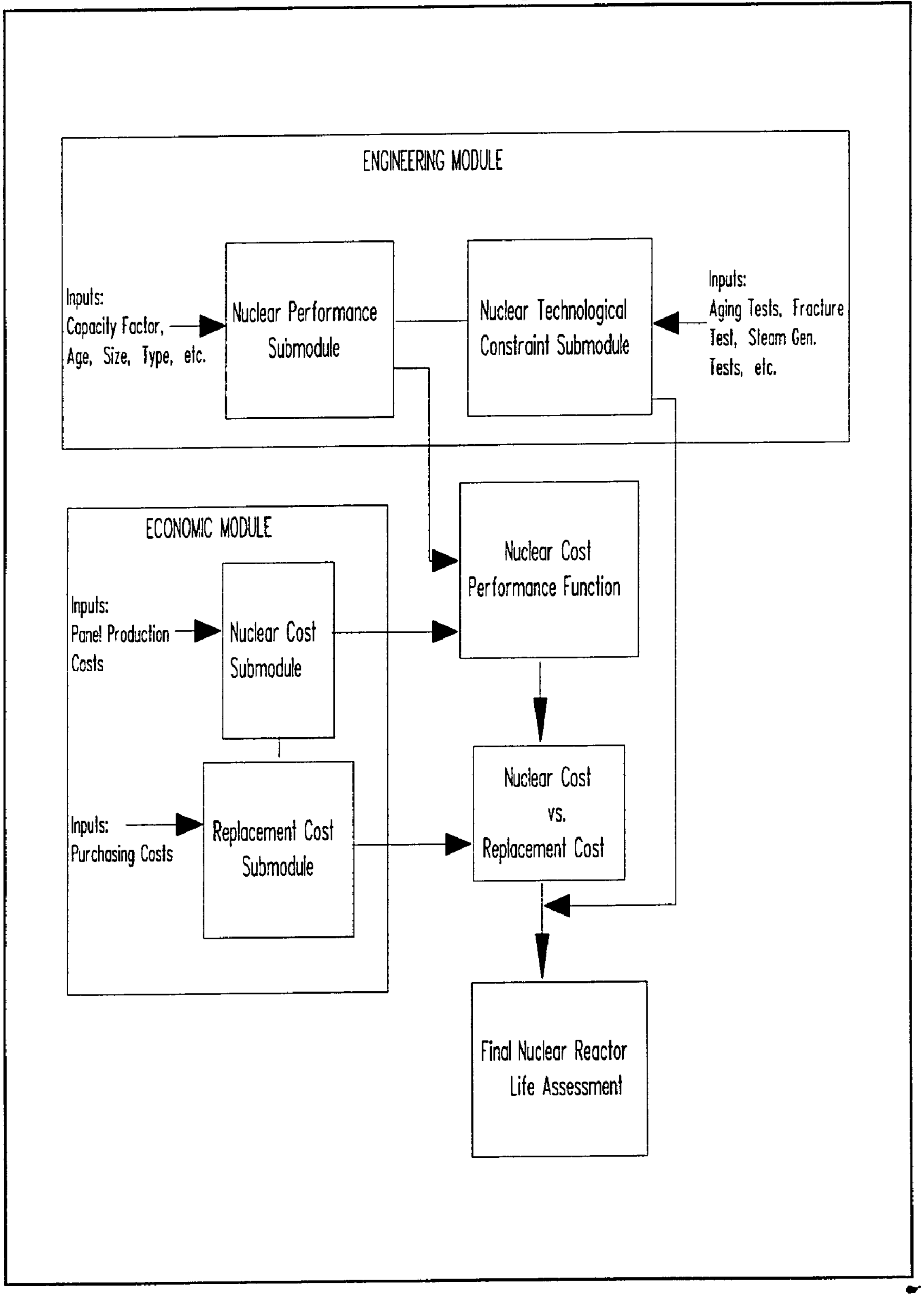
(4) Nuclear costs vs replacement costs,

(5) Nuclear technological constraints, and

(6) Final nuclear reactor life assessment.

The research method consists of an integrated modeling system (Figure V.1) that incorporates relevant engineering and economic factors into an estimation of nuclear plant life. A general description of the research method was presented in the last section of Chapter III. In summary, the modeling system allows the forecasting of engineering performance through time and then equates this performance to nuclear electrical generating costs. The final life estimates are determined based on an evaluation of replacement costs and consideration of nuclear engineering constraints.

FIGURE V.1: Schematic of the Nuclear Life Assessment Forecasting System



The analytical approach is divided into two major modules: an engineering module and an economic module. These modules are interconnected to produce the final estimate of the life of reactors on a reactor-by-reactor basis. The engineering module includes a nuclear performance submodule and a nuclear technological constraint submodule. The nuclear reactor performance submodule describes the performance of nuclear reactors through time according to efficiency parameters and to general and technical characteristics such as age, size, and type. The nuclear technological constraint submodule considers reactor operating limitations related to the deterioration of critical components due to the aging process and in particular due to problems associated with nuclear radiation. Critical technical constraints include potential vessel embrittlement and ductile fracture, and piping deterioration in the steam generators.

The economic module includes a nuclear cost submodule and a replacement cost submodule. The nuclear cost submodule defines the cost of producing nuclear electricity as a function of efficiency parameters such as nuclear capacity factors. This submodule is then related to the replacement cost submodule on a reactor-by-reactor basis to determine the minimum efficiency level beyond which it becomes more expensive to operate the reactor than to replace the power.

As explained in previous chapters, the nuclear industry is being affected by the early retirement of reactors that had been expected to operate beyond the end of this century. A review of the causes and circumstances surrounding the decision to permanently retire these reactors reveals that there have been engineering problems in critical components that have either limited their performance or have forced their final retirement. The review of the previous efforts relative to nuclear life assessments, presented in Chapter IV, indicated that none of these efforts has directly considered engineering factors or the deterioration of critical equipment.

The approach followed in this study is fundamentally different because it is based on the premise that life expectancy is a consequence of the status and expected deterioration of nuclear engineering components rather than being dependent purely on the comparison of nuclear operating costs to alternative generating costs. Indeed, the operating costs, assumed in previous efforts as the basic factors affecting life expectancy, should be considered the results of engineering problems, as is life expectancy. Therefore, operating costs and life expectancy are both being causally affected by engineering factors.

Thus, the approach formulated in this dissertation is based on this fundamental assumption. It is recognized that engineering factors can affect nuclear reactors by either reducing the efficiency of their performance or by imposing critical constraints that limit their operating lives. Once performance is assessed through time and expected engineering constraints are defined, then their operating costs (as a function of performance) and replacement costs can be used to estimate the final life expectancy. This is considered the first attempt in which such an integrated and comprehensive approach, that explicitly considers engineering parameters, is used in the assessment of the lives of nuclear reactors.

(1) NUCLEAR PERFORMANCE

The nuclear performance submodule evaluates the levels of efficiency shown by nuclear reactors throughout their lives. Based on this evaluation, a functional form is defined that allows the forecasting of performance for the remaining life of the reactors. The performance of nuclear reactors can be measured in terms of the following variables: availability factor, capacity factor, equivalent availability factor, equivalent forced outage rate, availability factor loss, and capacity factor loss.[1] The most important of these variables are the availability factor and the capacity factor. Both are described below, though only the latter is used in this study.

A plant availability factor provides a measure of the percentage of the time the unit has been operating or is capable of operating. The availability factor can be defined as the number of hours the plant was on-line plus the reserve shutdown hours (the hours the unit was available but not operating) divided by the total number of hours in the time period.

The capacity factor is a measure of the amount of energy that has been produced by a unit, compared with a calculated maximum amount of energy the unit theoretically could have produced had it operated for the entire time period at full power. The capacity factor can be defined as the net actual generation divided by the electric rating (net electric output for the generator corresponding with the unit's licensed thermal power under the best normal experienced seasonal conditions) multiplied by the total period of hours or clock time. This can be expressed as follows,

$$CapacityFactor = \frac{NAG}{NER * PH} \tag{V.1}$$

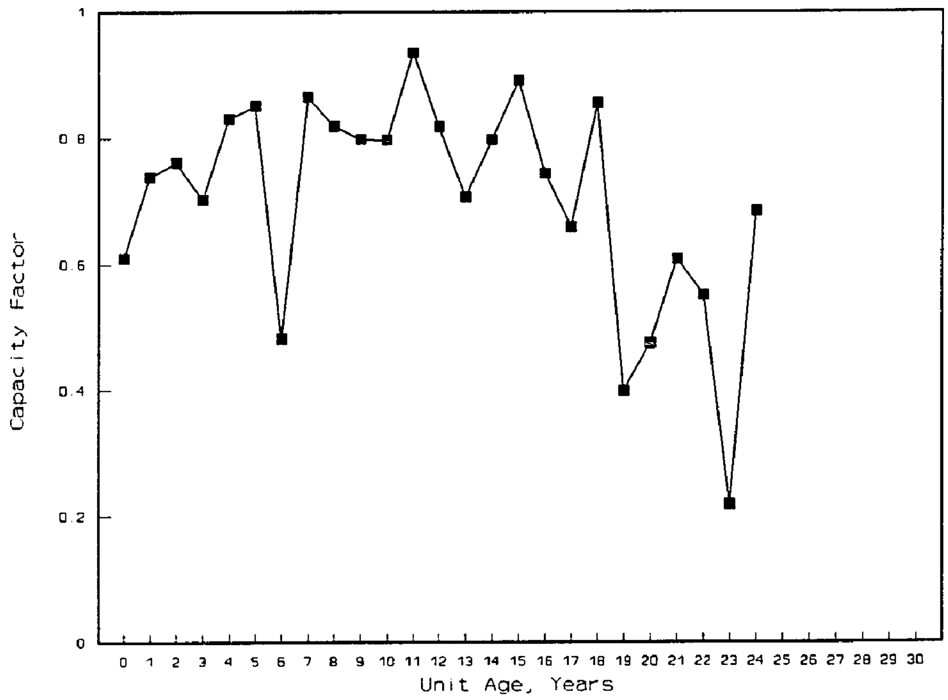
where:

NAG = Net Actual Generation
NER = Net Electric Rating (Capacity)
PH = Period Hours

The availability of data on capacity factors and the fact that nuclear reactors are normally used as baseload generating units (i.e. they are expected to operate 24 hours a day and at their maximum possible capacity) are important reasons for the selection of this parameter over the availability factor.

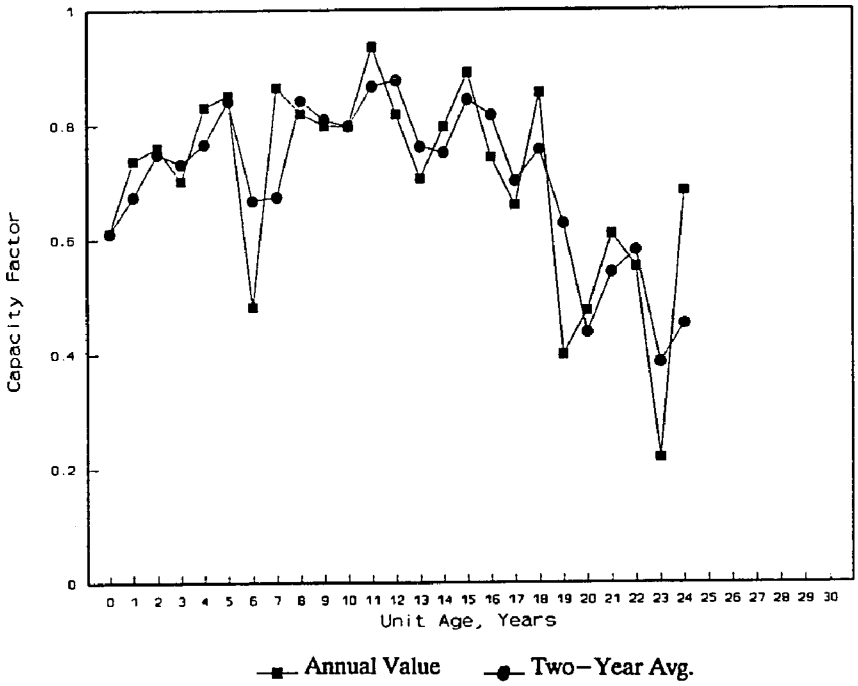
An example of the capacity factor variation as a function of age is presented in Figure V.2. The capacity factor values are for the Connecticut Yankee nuclear reactor through its 24 years of operation. A review of historical data on capacity factors from several nuclear generating plants reveals a common characteristic also observed in the Connecticut Yankee capacity factor data. This characteristic is the large bi-annual variation in the capacity factor values. This great dispersion is attributed to the fact that on average nuclear reactors are forced to shutdown after approximately 18 months for refueling reasons.

FIGURE V.2: NUCLEAR CAPACITY FACTOR
Connecticut Yankee



Instead of annual capacity factors, two-year average capacity factors were selected for use in this study as the basis for the forecast. This approach provides smoother performance curves and it is justified because the two-year capacity factor better represents the trend in performance through time. Figure V.3 presents the annual capacity factors and two-year average capacity factors for Connecticut Yankee.

FIGURE V.3: TWO-YEAR AVERAGE NUCLEAR CAPACITY FACTOR
Connecticut Yankee



The next step in the formulation of a functional form capable of describing the nuclear reactors' performance trends is the identification of the factors affecting performance. These factors are:

1) Condition of critical components, equipment, and structures,

2) Specific characteristics of the equipment and reactors,

3) Increasing operating knowledge, corrections in equipment installation, and construction improvements, and

4) Integration process or successful construction of the reactor.

1) Condition of critical components, equipment, and structures

As described in Chapter III, there are degradation mechanisms that affect the efficient operation of critical components and these problems eventually start to affect the overall performance of nuclear reactors. Some of the degradation processes include corrosion, nuclear radiation, surface erosion, metal fatigue, stress fracture, oxidation, creep, binding, and tube wear. The degradation mechanisms are specific to each component and environment. Thus, the measurements of the condition of equipment include engineering techniques such as level of oxidation of materials, variations in wall thickness due to corrosion and erosion, amount of neutron flux in components exposed to radiation, pressure and temperature resistance, etc.

The impact of plant component problems on the performance of nuclear reactors in the U.S is summarized in Table V.1. This table lists the percent of capacity factor losses due to functional systems for the period from 1968 through 1988. The percents are disaggregated by nuclear reactor type.

In Boiling Water Reactors (BWRs) the losses are primarily the result of failures in the cooling and safety systems. In general, BWRs have more components and equipment exposed to nuclear radiation than PWRs, and on average, they have lower lifetime capacity factors than PWRs. About 33% of the efficiency losses

TABLE V.1: IMPACT OF PLANT COMPONENTS ON PERFORMANCE

Percent of Capacity Factor Losses due to functional systems (1968-1988)		
BWR		
1.	Reactor Cooling System (Main Cooling Pumps & Piping)	33%
2.	Safety Systems (Containment, Core Injection, Auxiliary feedwater systems)	27%
3.	Fuel (Fuel Assemblies, Tube Failures)	12%
4.	Turbine (Blades, Rotors, Supports)	7%
5.	Condensate and Feedwater (Condenser, Feedwater, Heater drain equipment)	6%
PWR		
1.	Steam Generator (Shell, Internal, and Tubes)	20%
2.	Safety System	20%
3.	Reactor Cooling System	20%
4.	Turbine	10%
5.	Condensate and Feedwater	7%

Source: EPRI, *Nuclear Unit Operating Experience: 1987-1988*, EPRI NP-7191, February 1991.
Note: Data exclude capacity factor losses due to refueling and planned maintenance.

in BWRs are the result of problems with the cooling system. Most of the problems are located in the steam condensers and in particular they are associated with the deterioration of condenser tubes. The failure of condenser tubes is due to aging degradation mechanisms manifested in the form of erosion and corrosion. The major aging degradation problem in cooling systems of BWRs has been identified as intergranular stress corrosion cracking of stainless steel in condenser tubes. This type of corrosion is the product of weld sensitization, high tensile stresses, and the continuous exposure to an aggressive environment related to high levels of oxygen and chemical contaminants. The progressive wearing out of the cooling water system is translated into the gradual deterioration of nuclear plant performance.

Additional aging degradation problems in BWRs include failures in safety systems, which have occurred in components such as containment, core injection, auxiliary feedwater systems, and piping systems. Wall thinning of safety related major piping systems has affected performance in BWRs. Single phase erosion/corrosion is the main aging degradation mechanism in piping systems. Mechanical and chemical degradation have affected containment structures after years of operation. Corrosion of the steel rebar and chemical attack on concrete are examples of mechanical and chemical degradation affecting containment structures.

In PWRs the major source of efficiency losses is failures in the steam generators. If data for the period 1989-1993 are included in Table V.1, the percent of capacity factor losses due to steam generator failures in PWRs will increase considerably as compared to other causes.[2] Steam generator problems affect performance in several PWRs and have been the major cause for the permanent retirement of Trojan and San Onofre 1. Aging degradation processes in steam generator tubes include metallic and caustic stress corrosion, wear, denting, and fatigue-induced cracking.

Other major sources of efficiency losses in PWRs are the product of failures in the safety and cooling systems. Problems in safety system (core injection) and cooling systems affected performance in Fort St. Vrain. Turbine failures reduced efficiency in Rancho Seco. Most of the turbine failures are caused by age degradation mechanisms identified as solid particle erosion and high cycle fatigue damage in high-pressure blades, and stress-corrosion cracking and moisture erosion damage in low-pressure blades.

A proxy to all these component conditions is age. The time for which components have been operating or the time that they have been exposed to the particular environments serves as an indicator of the condition of components and ultimately of the expected level of efficiency of the reactor in question. The use of specific engineering measurements of component conditions would be very complex as there are many different measurements and components that would need to be evaluated. Therefore, age can be used as a proxy for the condition of critical components.

2) Specific characteristics of the equipment and reactors

Nuclear reactors in the U.S. generating stock have been built following different designs and sizes, using different materials, and according to different types. There are a variety of steam generator systems, containment types, turbines, cooling systems, etc. The performance of these components differ according to their specific characteristics and designs. These characteristics affect the overall performance of the reactors. The major characteristics of nuclear reactor components should be incorporated into the functional form designed to describe performance.

The review of historical data reveals different levels of performance for different types of nuclear reactors. Some of the differences are summarized as follows:

- A large number of Boiling Water Reactors have experienced low lifetime performance as compared to Pressurized Water Reactors
- Of the two major manufacturers, Westinghouse nuclear reactors have a better

performance record over the last three decades

- Nuclear reactors with high efficiency performance records in the first few years of operation tend to perform better than other reactors over their overall lives
- Many of the nuclear reactors engineered or designed by Bechtel and TVA have experienced lower lifetime capacity factors as compared to reactors engineered by other firms
- Nuclear reactors with "Dry, Ambient Pressure" containment types have superior lifetime performance as compared to nuclear reactors with other containment types
- Nuclear reactors with steam systems of the "Westinghouse Two-Loop" type have performance records above reactors with other steam system designs
- Many nuclear reactors using "sea water" instead of fresh water for their cooling system have experienced more losses in their efficiency due to problems in the cooling system.

These observations can be used as the basis for the selection of specific characteristics to include in the performance functional form. In particular the design types of critical equipment such as steam generators, containments, and cooling systems can be potential explanatory variables in the definition of performance.

3) Increasing operating knowledge, corrections in equipment installation, and construction improvements

These are factors that have a positive effect on performance. The effects from increasing operating knowledge and equipment installation corrections are most likely manifested in the first few years of operation of the nuclear reactors. Thus, age can be used as a proxy to describe these effects. Construction improvements can also be reflected by age because younger reactors should have benefitted from improvements derived from experience in older reactors. Another factor that can be used to describe these improvements is operating and maintenance (O&M) costs. However, O&M cost data are not available on a reactor-by-reactor basis and they incorporate not only the costs for correcting identified problems or deficiencies but also the routine costs of operating and maintaining the plants. A final factor that can be used is whether the reactor is built as part of a multiunit nuclear facility or as a single unit. Reactors built in a multiunit complex should benefit from the experience acquired from units previously built in the same location and usually based on similar designs.

4) Integration process or successful construction of the reactor

The performance of a multiple component machine is the result not only of the characteristics of its components but of the successful integration or building process. Although this factor is very difficult to measure, proxies include the particular firms involved in the construction process (such as architects, engineers, and builders) and the utility managing the project. Another indicator is the initial performance of the reactor. In general, nuclear operating data indicate that reactors with good initial performance tend to perform well throughout their lives. The average capacity factor of the first two years can be used as a proxy to represent this factor.

Based on the framework specified above, the search for a functional form that could describe performance of nuclear reactors was initiated. It was desirable to incorporate in this form, as explanatory variables, the following parameters:

1) Age as a proxy for equipment condition, increasing operating knowledge, and construction improvements.

2) Characteristics of components including designs and types of critical equipment such as containments, steam generators, turbines, and cooling systems.

3) Firms involved in the construction and design of the reactors as proxies to adequacy of integration process.

4) Initial capacity factor as proxy of adequacy in the integration process, construction improvements, corrections and equipment replacement.

Multiple regression analyses were attempted in which several parameters expected to affect capacity factors were included as explanatory variables. The regressions were resolved using the Ordinary Least Square (OLS) method. Data included real historical observations in the form of time series and cross sectional data for the 113 nuclear reactors considered in this study. Data availability, sources, accuracy, and limitations are described in Chapter VI. Four different functional forms were attempted. They are:

1) Linear,
2) Log-Linear,
3) Asymptotic (Logistic), and
4) Quadratic

Linear Form

First a linear form, which is the simplest functional form, was attempted. The use of this form implies that the trend in capacity factors will follow a straight line. This form can be represented as

$$Y = a + bX_1 + cX_2 + dX_3 + eX_4 + fX_5 \qquad \text{(V.2)}$$

The linear form was originally tested including as explanatory variables the following 10 parameters:

Age
Size
Containment Type
Steam System Type
Cooling Water System Type
Turbine Type
Cooling Water Type
Architect/Engineer
Initial Capacity Factor
Multi/Single Unit Status

The statistical analysis for this function (Table V.2) reveals that four of these explanatory variables (multiunit, cooling system type, cooling water type, and turbine type) have coefficients that are not significant at the 95% confidence interval. This is reflected by T values for these coefficients below the critical T value of 1.96. Based on these results, these 4 variables were excluded from the function and the regression was performed again. The new results (Table V.3) indicate that all the selected parameters have coefficients that are significant at the 95% confidence interval. The F value of 33.69 allows the rejection of the null hypothesis that there is no relationship between the capacity factors and the explanatory variables selected for this form. This F value is above the critical F value of 5.65 at the 99% confidence interval. The R^2 value of only 19% indicates that the function has a low explanatory potential for the variation of the capacity factors. Based on these statistical results more advanced functional forms were attempted.

TABLE V.2: STATISTICAL PARAMETERS FROM LINEAR FUNCTIONAL FORM

Constant	0.3465
Std Err of Y Est	0.1559
R Squared	0.1935
No. of Observations	1415
Degrees of Freedom	1404
No. of Nuclear Reactors	113
F value	33.69

Independent Variable	Coefficient	Standard Error	t Statistics
Age	-0.00256	0.000824	-3.10
Size	-0.000073	0.000024	-3.11
Containment	0.046942	0.009644	4.87
Steam Syst. Type	0.070213	0.019507	3.60
Architect/Eng.	0.054355	0.009245	5.88
Initial CF	0.467852	0.033756	13.86
Multiunit	0.01037	0.009787	1.06
Cooling Syst.	-0.01039	0.01073	-0.97
Turbine Type	-0.00792	0.00981	-0.81
Water Type	0.016136	0.011348	1.42

TABLE V.3: STATISTICAL PARAMETERS FROM LINEAR FUNCTIONAL FORM

Constant	0.3541
Std Err of Y Est	0.1560
R Squared	0.1904
No. of Observations	1415
Degrees of Freedom	1404
No. of Nuclear Reactors	113
F value	55.18

Independent Variable	Coefficient	Standard Error	t Statistics
Age	-0.0027	0.000811	-3.32
Size	-0.000063	0.000022	-2.83
Containment	0.037911	0.008749	4.33
Steam Syst. Type	0.078	0.0177	4.39
Architect/Eng.	0.05072	0.008632	5.88
Initial CF	0.467496	0.033404	13.99

Log-Linear Form

The second functional form attempted was the Log-Linear form. This form assumes an exponential type of trend in the capacity factors. The general log-linear form can be represented by the following equation

$$Ln\ Y = a + bX_1 + cX_2 + dX_3 + eX_4 + fX_5 \qquad (V.3)$$

The Log-linear form was originally tested including several explanatory variables. The statistical analysis for this test (Table V.4) reveals that four of these explanatory variables (multiunit, cooling water type, turbine type, and steam system type) have coefficients that are not significant at the 95% confidence interval. This is reflected by T values for these coefficients below the critical T value. Based on these results, these 4 variables were excluded from the function and the regression was performed again. The new results (Table V.5) indicate that all the selected parameters have coefficients that are significant at the 95% confidence interval. The F value of 26.13 allows the rejection of the null hypothesis that there is no relationship between the capacity factors and the explanatory variables selected in this form. This F value is above the critical F value of 5.65 at the 99% confidence interval. The R^2 value of only 15% indicates an even lower explanatory power than the linear form. Thus, it was decided to reject this function and to test other functions.

TABLE V.4: STATISTICAL PARAMETERS FROM LOG-LINEAR FUNCTIONAL FORM

Constant	-1.079
Std Err of Y Est	0.6433
R Squared	0.1574
No. of Observations	1415
Degrees of Freedom	1404
No. of Nuclear Reactors	113

F Value	26.23

Independent Variable	Coefficient	Standard Error	t Statistics
Age	-0.02256	0.003401	-6.63
Size	-0.00039	0.000097	-4.01
Containment	0.153247	0.039808	3.85
Architect/Eng	0.20377	0.038161	5.34
Initial CF	1.146307	0.139333	8.23
Multiunit	-0.01441	0.040398	-0.36
Turbine Type	-0.00323	0.040493	-0.08
Cooling Water	0.044489	0.046838	0.95
Steam System	0.026929	0.080516	0.33
Water Syst.	0.126169	0.04429	2.85

TABLE V.5: STATISTICAL PARAMETERS FROM LOG-LINEAR FUNCTIONAL FORM

Constant	-1.0369
Std Err of Y Est	0.6427
R Squared	0.1566
No. of Observations	1415
Degrees of Freedom	1404
No. of Nuclear Reactors	113
F Value	26.13

Independent Variable	Coefficient	Standard Error	t Statistics
Age	-0.02235	0.003386	-6.60
Size	-0.00042	0.000084	-4.97
Containment	0.150324	0.035502	4.23
Architect/Eng	0.2108	0.0371	5.68
Initial CF	1.16886	0.136063	8.59
Water Syst.	0.101686	0.038621	2.63

Asymptotic or Logistic Form

The asymptotic or logistic function assumes that the dependent variable follows an increasing trend that eventually slows down and reaches an asymptotic limit. This function can be represented by the following equation

$$Y = a + b \frac{1}{\exp^{X_1}} + c\, X_2 + d\, X_3 + e\, X_4 \qquad \text{(V.4)}$$

The asymptotic functional form was originally tested with several explanatory variables including the age parameter in a reciprocal exponential form that would allow the definition of the asymptotic function. The statistical analysis for this function (Table V.6) reveals that five of these explanatory variables (reciprocal of age exponential, multiunit, cooling water type, turbine type, and water system type) have coefficients that are not significant at the 95% confidence interval. This is reflected by T values for these coefficients below the critical T value. Based on these results, four of these five variables were excluded from the function and the regression was performed again. The reciprocal of the age parameter was not excluded from the function because such exclusion would transform the function into a linear form which had already been tested. The new results (Table V.7) indicate that all the selected parameters with the exception of the reciprocal of the age have coefficients that are significant at the 95% confidence interval. The F value of 39.52 allows the rejection of the null hypothesis that there is no relationship between the capacity factors and the explanatory variables selected in this form. This F value is above the critical F value of 5.65 at the 99% confidence interval. The R^2 value is about 23.6%, which is an improvement over the previous forms tested. However, since the coefficient of the explanatory variable that makes this function asymptotic was not significant, it was concluded that this is not a good representation of the capacity factor variations and it was decided to test another function.

TABLE V.6: STATISTICAL PARAMETERS FROM LOGISTIC (ASYMPTOTIC) FUNCTIONAL FORM

Constant	0.305728
Std Err of Y Est	0.156273
R Squared	0.2378
No. of Observations	1415
Degrees of Freedom	1404
No. of Nuclear Reactors	113
F Value	39.83

Independent Variable	Coefficient	Standard Error	t Statistics
Recip.Exp.Age	-0.06114	0.0426	-1.44
Size	-0.000048	0.000023	-2.09
Containment	0.047166	0.00967	4.88
Steam System	0.073626	0.019542	3.77
Archit/Engin.	0.056037	0.009265	6.05
Initial CF	0.480027	0.033766	14.22
Water System	0.009782	0.009815	0.996
Multiunit	-0.01766	0.010631	-1.66
Turbine Type	-0.00839	0.009837	-0.85
Water Type	0.012756	0.011347	1.12

TABLE V.7: STATISTICAL PARAMETERS FROM LOGISTIC (ASYMPTOTIC) FUNCTIONAL FORM

Constant	0.314924
Std Err of Y Est	0.156287
R Squared	0.2360
No. of Observations	1415
Degrees of Freedom	1404
No. of Nuclear Reactors	113
F Value	39.52

Independent Variable	Coefficient	Standard Error	t Statistics
Recip.Exp.Age	-0.06317	0.042575	-1.48
Size	-0.000041	0.000021	-1.90
Containment	0.040823	0.00885	4.61
Steam System	0.0773	0.0178	4.34
Archit/Eng.	0.056454	0.009021	6.26
Initial CF	0.485547	0.033584	14.46
Water System	-0.02254	0.009324	-2.42

Quadratic Form

The quadratic form assumes that the function includes a parameter that is quadratic. Depending on whether the coefficient of the quadratic term is positive or negative, the function implies an increasing or decreasing quadratic trend in the long-run. The general quadratic function is represented by

$$Y = a + b\,X_1 + c\,X_1^2\,d\,X_2 + e\,X_3 + f\,X_4 \qquad \text{(V.5)}$$

The quadratic functional form was originally tested including the several explanatory variables identified previously as relevant. The statistical analysis for this function (Table V.8) reveals that four of these explanatory variables (multiunit, cooling water type, turbine type, and cooling water system type) have coefficients that are not significant at the 95% confidence interval. This is reflected by T values for these coefficients below the critical T value. Based on these results, these four variables were excluded from the function and the regression was performed again. The new results (Table V.9) indicate that all the selected parameters have coefficients that are significant at the 95% confidence interval. The F value of 64.52 allows the rejection of the null hypothesis that there is no relationship between the capacity factors and the explanatory variables selected in this form. This F value is above the critical F value of 5.65 at the 99% confidence interval. The R^2 value is about 24.30%, which is an improvement over all the previous forms tested. Although the R^2 is low, this is the functional form and combination of explanatory variables that best describes the historical variation of capacity factors in nuclear reactors.

TABLE V.8: STATISTICAL PARAMETERS FROM QUADRATIC FUNCTIONAL FORM

Constant	0.318108
Std Err of Y Est	0.155385
R Squared	0.2470
No. of Observations	1415
Degrees of Freedom	1403
No. of Nuclear Reactors	113
F Value	41.84

Independent Variable	Coefficient	Standard Error	t Statistics
Age	0.005762	0.002822	2.04
Age Squared	-0.00043	0.000139	-3.08
Size	-0.000075	0.000023	-3.22
Containment	0.047116	0.009615	4.90
Steam System	0.069492	0.019449	3.57
Archit/Eng.	0.054962	0.009219	5.96
Initial CF	0.473859	0.033713	14.06
Multiunit	0.009042	0.009767	0.93
Water System	-0.01065	0.010698	-0.99
Turbine Type	-0.00795	0.009781	-0.81
Water Type	0.01656	0.011314	1.46

TABLE V.9 STATISTICAL PARAMETERS FROM QUADRATIC FUNCTIONAL FORM

Constant	0.3261
Std Err of Y Est	0.1556
R Squared	0.2430
No. of Observations	1415
Degrees of Freedom	1407
No. of Nuclear Reactors	113
F Value	64.52

Independent Variable	Coefficient	Standard Error	t Statistics
Age	0.005535	0.002816	1.97
Age Squared	-0.00042	0.000139	-3.05
Size	-6.6E-05	0.000022	-2.98
Containment Type	0.0381	0.0087	4.36
Design Type	0.077191	0.017699	4.36
Architect	0.051268	0.008608	5.96
1st Cap. Factor	0.47328	0.03336	14.19

As a final test, regressions were performed using the quadratic functional form but reducing the data used to implement the test to only the first 10, 15 and 20 years of operation. Although the major concern is in the characterization of the nuclear reactor performance in the last stage of their lives, the test was attempted to try to obtain a better fit (better R^2) of the function. However, none of these attempts resulted in an improvement of the fit. Table V.10 presents the statistics for the regression in which data for only the 15 first years of operation were utilized. In this case the R^2 was reduced to 19%.

TABLE V.10 STATISTICAL PARAMETERS FROM QUADRATIC FUNCTIONAL FORM (DATA FROM FIRST 15 YEARS OF OPERATION)

Constant	0.3672
Std Err of Y Est	0.1582
R Squared	0.1903
No. of Observations	1236
Degrees of Freedom	1227
No. of Nuclear Reactors	113
F Value	41.20

Independent Variable	Coefficient	Standard Error	t Statistics
Age	0.016793	0.004384	3.83
Age Squared	-0.00126	0.000275	-4.58
Size	-6.9E-05	0.000025	-2.80
Containment Type	0.0476	0.0095	4.99
Design Type	0.075062	0.020236	3.71
Architect	0.04815	0.009317	5.17
1st Cap. Factor	0.35191	0.038103	9.24

In summary, the quadratic function developed using available data for all years provides the best representation of the capacity factors of nuclear reactors. The function includes as explanatory variables the following factors:

Age
Size (Capacity)
Initial Capacity Factor (First year)
Reactor Containment Type
Steam System Design Type
Architect/Engineer

The selected function is represented as follows:

$$CF_t = a + b\,Ag + c\,Ag^2 + d\,Siz + e\,CF_1 + f\,Cont + g\,Des + h\,Ar \qquad (V.6)$$

where:

Ag = Age in number of years
Siz = Capacity in MW
CF_1 = Capacity Factor in year 1
Cont = Reactor Containment Type
Des = Steam System Design Type
Ar = Architect/Engineer

The coefficient of the quadratic term (Ag^2) in Equation V.6 is negative (Table V.9). This indicates that the function is inverse reflecting an improving trend in the short-term followed by a decreasing trend in the long-run.

The proportion of total variation on capacity factors that is explained by this function is limited as reflected by the low R^2 obtained from the statistical analysis. The low explanatory power may be the result of large variations (on a year-by-year basis) in the range of capacity factors observed among all the U.S. nuclear reactors throughout their operating lives. In addition, the approach requires the use of proxies to represent complex factors affecting reactor performance such as physical conditions of equipment, increasing operating knowledge, and others. However, the inverse quadratic function corroborates the trend observed in the performance of several nuclear reactors when they are considered on a reactor-by-reactor basis rather than as a group. This trend is characterized by an improvement in performance observed during the first years of operation followed by a decreasing trend as the reactor ages. The improving trend in the first years of operation can be attributed to improvements in human performance and to the correction of some installation, design and operational problems. As the generating plant accumulates years of operating experience, errors are identified and corrections implemented securing improvements in performance. The decreasing trend in the long-term can be attributed to the deterioration of the condition of critical components, systems or structures in the nuclear reactors. This deteriorating condition limits the nuclear reactor performance in the long-term and is the product of normal anticipated and unanticipated degradation or aging effects. The normal anticipated degradation refers to the expected deterioration of equipment through time due to normal degradation of materials. The unanticipated degradation is the result of inadequate designs and/or evaluating criteria. It is important to note that the same decreasing performance trend expected in the long-term operation of nuclear plants has been observed in fossil-fuel plants.[3] However, the nuclear operating experiences reveal a faster deterioration rate as compared to the fossil-fuel plants. This can be attributed in particular to the exposure of critical components to nuclear radiation.

Based on the previous analysis two scenarios were developed for the forecast of nuclear performance. These two scenarios allowed the formulation of two estimates of life expectancy for the U.S. nuclear generating stock.

Scenario 1

This scenario consists of performance forecasts based on the best functional form and combination of explanatory variables resulting from the multiple regression analysis previously described. The performance is based on the implementation of Equation V.6 over all the US nuclear stock. The analysis was implemented using data from 113 nuclear reactors. This reactor sample corresponds to 108 operating nuclear plants and the 5 nuclear reactors permanently retired in the last 5 years. This sample does not include two nuclear reactors-- Comanche Peak 2 and Shoreham. Comanche Peak 2 entered operation in 1993 and therefore has not accumulated any operating data. Shoreham does not have any data because it was never put into operation.

Scenario 2:

After Scenario 1 was completely defined, a second scenario was created for the purpose of comparison. The knowledge acquired during the formulation of Scenario 1 as well as previous research on capacity factors of both nuclear and coal powered plants provided the basis for the formulation of this different approach. The previous research indicated that the performance of nuclear reactors in the long-run is best described by an inverse quadratic function. In Scenario 2 this performance function is solved using a mathematical approach. Regardless of what the function is representing, mathematically such a function is fully described by four factors:

1) The explanatory variable X_t (Age of the reactor),

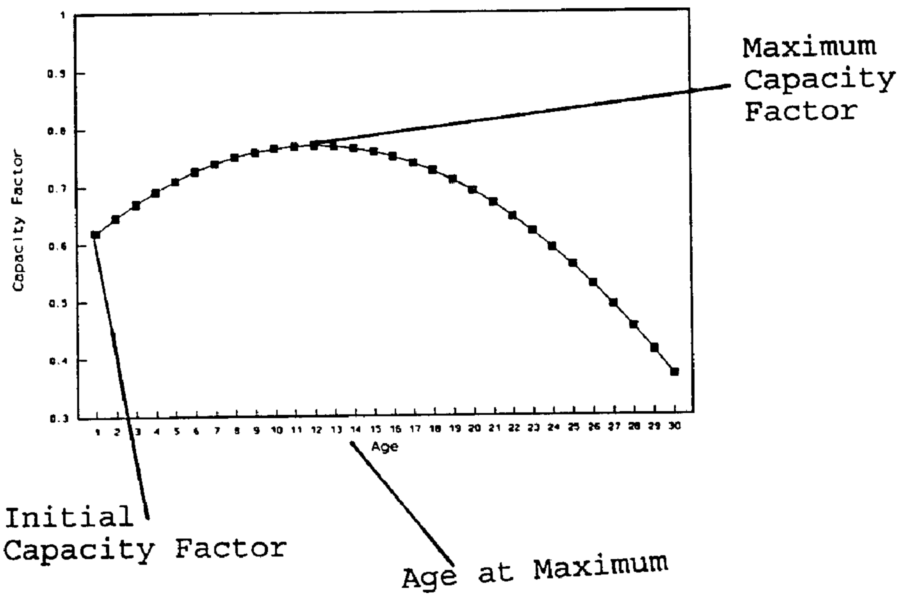
2) The initial value of the dependent variable Y_1 (Initial capacity factor),

3) The maximum attainable value for the dependent variable Y_M (Maximum capacity factor), and

4) The value of the explanatory variable at which the dependent variable is maximum X_M (age at which capacity factor is maximum).

Graphically, these factors can be illustrated as in Figure V.4.

Figure V.4: Factors affecting performance in Scenario 2



Intrinsically, this mathematical approach implies that there is a maximum value for the dependent variable, and that this maximum is reached for a particular value of the explanatory variable. In the real case that is being represented, this mathematical approach implies that there is a particular age for a nuclear reactor at which its capacity factor will reach a maximum. This assumption is unique to this approach and differs from the econometric method followed in Scenario 1. In Scenario 1 there is no assumption about a maximum performance value or about a time at which the performance factor becomes maximum.

Mathematically, this inverse quadratic function can be represented as follows:

$$CF_t = \alpha - \beta\,(age - \gamma)^2 \qquad \text{(V.7)}$$

Where:

α is the highest attainable capacity factor
γ is the time at which the maximum capacity factor is attained
β is a function of the initial capacity factor (CF_1) , α and γ; and it is defined by:

$$\beta = \frac{\alpha - CF_1}{(1 - \gamma)^2} \qquad \text{(V.8)}$$

The approach followed in Scenario 2 further assumes that the maximum attainable capacity factor and the time at which this maximum is reached are functions of other engineering characteristics already found to be relevant and that are distinctive to each reactor. Functional forms were created to determine these factors. In particular, regression analyses were performed to identify the best combination of explanatory variables that could be used to define these two factors. The statistics for the functions found that best fit the data are listed in Tables V.11 and V.12.

The equation that best describes the highest capacity factor (α) is represented as,

$$\alpha = a + b\ Siz + c\ Des + d\ Cont \qquad \text{(V.9)}$$

where:

Siz = Capacity in MW
Des = Steam System Design Type
Cont = Reactor Containment Type

And, the equation that best describes the time (γ) at which the capacity factor is maximum is represented as,

$$\gamma = e + f\ Siz + g\ Ar \qquad \text{(V.10)}$$

where:

Siz = Capacity in MW
Ar = Architect/Engineer

Once the α and γ values are estimated for each reactor, they are used in Equations V.7 and V.8 in combination with the age to determine the capacity factors through time.

TABLE V.11 STATISTICAL PARAMETERS FOR MAXIMUM CAPACITY FACTOR EQUATION

Constant	0.8875
Std Err of Y Est	0.0552
R Squared	0.4149
No. of Observations	1094
Degrees of Freedom	1090
No. of Nuclear Reactors	61
F Value	257.65

Independent Variable	Coefficient	Standard Error	t Statistics
Size	-0.00016	9.3E-061	-16.9888
Steam System	0.0266	0.003532	7.5349
Containment T	0.0514	0.006332	8.1193

TABLE V.12 STATISTICAL PARAMETERS FOR TIME AT MAXIMUM CAPACITY FACTOR EQUATION

Constant	11.8937
Std Err of Y Est	3.7726
R Squared	0.27753
No. of Observations	1094
Degrees of Freedom	1090
No. of Nuclear Reactors	61
F Value	209.54

Independent Variable	Coefficient	Standard Error	t Statistics
Size	-0.00508	0.000568	-8.95189
Steam System	4.260339	0.239006	17.82528

In summary, the assumptions followed in Scenario 2 include:

1) Reactor performance is a function of four parameters: age, maximum attainable capacity factor, time at which this maximum is reached, and initial capacity factor.

2) The maximum attainable capacity factor and the time at which this maximum is reached are functions of all other engineering characteristics already identified as relevant.

3) The maximum attainable capacity factor is assumed to be reached within the first 15 years of operation.

The third assumption of a maximum capacity factor attained by age 15 was supported by the fact that all reactors 20 years old and older have reached this maximum on average at around their 12th operating year. Nevertheless, the assumption of reaching a maximum by age 15 may not hold for younger vintages of nuclear reactors which should have benefitted from improvements in the technology.

The manner in which this function was defined implied the knowledge of the maximum attainable capacity factor and the time at which this maximum is reached. These requirements implied the use of only data from the subsample of reactors 15 years old and older in the determination of the function. Reactors younger than 15 years old were excluded because at their age their maximum may not have been reached yet. Therefore the original dataset needed to define this function was reduced from 113 to only 61 reactors. Although the number of observations used in the function is considerably reduced, the newly built reactors that are excluded could not add much information on the long-term effects of aging on nuclear performance. The disadvantage of using this subsample of older reactors is that the results may be biased toward early retirement because they do not reflect any benefits in the newer units resulting from operating experiences and construction improvements.

The differences between the approaches followed in Scenario 1 and Scenario 2 can be summarized as follows:

1) Scenario 1 uses a typical econometric approach in which a functional form and a set of explanatory variables are identified through multiple regression analysis to describe reactors' performance. Scenario 2 uses a mathematical formulation based on previous knowledge and solved according to mathematical principles.

2) Scenario 2 is based on the premise that capacity factors can be described in terms of the age, the initial capacity factor, the maximum attainable capacity factor, and the time at which this maximum performance is reached. Subsequently, the maximum capacity factor and the time at which this maximum is reached are considered functions of other relevant engineering characteristics.

3) Scenario 2 is developed using data from the subsample of 61 reactors 15 years old and older. Scenario 1 uses data from the overall sample of 113 reactors.

4) Scenario 2 assumes that the maximum attainable capacity factor in a nuclear reactor is achieved within the first 15 years of operation. Scenario 1 is not based on any specific assumptions about maximum performance.

The approach followed in Scenario 2 is original work that has not been attempted before or suggested in any of the publications available in this subject. Scenario 2 produces performance forecasts that are different from the ones generated in Scenario 1. In general, the analysis of most of the nuclear reactors in Scenario 2 indicate a faster deterioration of plant efficiency through time.

The results from these two analyses are the basis for the two nuclear life expectancy scenarios developed in this study. The final results from these scenarios are described in detail in Chapter VII.

Probabilistic Performance Forecast Analysis

The method described in the previous sections allows the generation of deterministic capacity forecasts for each year in the forecasting period. As described before, there is great uncertainty related to nuclear reactor performance especially because of the exposure of critical equipment to nuclear radiation and unexpected aging mechanisms. The uncertainty was reflected in the low explanatory power observed in all the different functions attempted to describe lifetime capacity factors. Therefore, the procedure was expanded to convert these deterministic forecasts to probabilistic forecasts allowing the capture of some of the uncertainty.

The single capacity factor forecasts generated for each year were converted into a probabilistic range by computing a probability distribution. Since the values of capacity factors are true estimates (derived from historical data) and the sample size is large enough (over 100 observations per year), the probability distribution is assumed to be normal and fully described in terms of the mean (or best estimate) and the standard deviation (SD) or variance of the estimate.[4] The probability ranges in terms of capacity factor forecasts resulting from this analysis at different confidence intervals are:

At the 80% (1.28*SD) Confidence Interval: Capacity Factor Forecast ± 2.8%

At the 95% (1.96*SD) Confidence Interval: Capacity Factor Forecast ± 5.1%

At the 99% (2.57*SD) Confidence Interval: Capacity Factor Forecast ± 7.1%

Due to the great dispersion of the capacity factors through time, the low and high capacity factor values at the 80% confidence interval were selected for this study. As an example, if the quadratic function estimates that the most likely capacity factor for a specific reactor and at a specific year in the future is 55%, then there is an 80% probability that the actual capacity factor in that future year will be a value within the 52.2% and 57.8% range.

This capacity factor range can be translated into an average year range by computing the equivalent year range at which a capacity factor forecast can be expected. These ranges vary from reactor to reactor according to the particular forecasts generated with the corresponding quadratic functions. Results show on average that the ranges in terms of years at the different confidence intervals are:

At the 80% Confidence Interval: Life Expectancy Forecast ± 1.5 years

At the 95% Confidence Interval: Life Expectancy Forecast ± 2.3 years

At the 99% Confidence Interval: Life Expectancy Forecast ± 3.0 years

As an example, if a capacity factor forecast of 55% is estimated for a specific year such as the year 2005, then there is an 80% probability that the reactor will experience this capacity factor during the period beginning in mid 2003 and ending in mid 2007.

The reduction of uncertainty by this probabilistic performance forecast analysis is limited due to the selection of the 80% confidence interval over the 95% or 99%. However, the resulting range allows a more precise definition of the time period at which a capacity factor forecast should be expected.

(2) NUCLEAR PRODUCTION COSTS AND COST-PERFORMANCE FUNCTIONS

The next step in the nuclear life expectancy forecast system is the definition of functions that relate nuclear power production costs to performance. These functions allow the estimation of the escalation of production costs as a reactor's performance deteriorates through time.

Production costs are used in this study in terms of mills (0.1 cent) per KWh and include operating, maintenance, materials, supplies, and fuel costs. These costs do not include capital costs or any other investment costs. Nuclear power production cost curves are developed as a function of capacity factors using cost and performance data for all the 113 nuclear reactors. The historical data correspond to the period 1982-1991. Data are available from the Energy Information Administration.[5] Annual nuclear power production costs for selected plants are listed in Table A6 of Appendix A of this study.

Historical data on production costs, in terms of mills per KWh, show a great variation among all nuclear reactors operating in the U.S. For the period from 1982 through 1991, the cost of producing a KWh by nuclear reactors varied from a low of 9 mills (0.9 cents) to a high of over 300 mills (over 30 cents). Because of this great variation in costs, the overall stock of nuclear reactors was divided into four groups based on their computed average production cost per KWh. These four groups correspond to the production cost quartiles. Then, four different nuclear cost curves were developed representing each of the quartiles.

The curves for each of the quartiles are defined by regressing the corresponding cost data using capacity factor as the independent variable. After attempting different functional forms, a reciprocal function with respect to capacity factor was found to be the best functional form for the description of the nuclear cost data. This form can be represented as follows,

$$NuclearCost_{cf} = a + b\left(\frac{1}{CF}\right) \quad (V.11)$$

where:

CF = Capacity factor

The resulting cost curves for each of the quartiles are presented in Figure V.5. The corresponding nuclear power production cost values at different levels of capacity factors are listed in Table V.13. The large difference in nuclear power production costs among nuclear reactors is evident from the great differences observed in the cost values for the different quartiles at various capacity factor levels. The statistical parameters from this analysis for the four curves are listed in Table V.14. The fitting of the selected functional form seems to improve when implemented on the groups of reactors with higher production costs. This is reflected by R^2 increasing from 42% for the 1st

Quartile to 81% for the 4th Quartile. The T statistics indicate that the coefficients are all significant at the 95% confidence interval.

The approach followed in the formulation of cost-performance functions is well founded and represents a reliable way to describe nuclear production costs as a function of performance. As described previously the curves are generated based on historical operating data of the overall sample of nuclear reactors. Furthermore, the effort is made to disaggregate these reactors into four cost groups allowing the definition of more customized functions. The statistical analysis suggests that the cost-performance functions better represent the cost data of the reactors in the higher cost groups.

FIGURE V.5: NUCLEAR POWER PRODUCTION COSTS

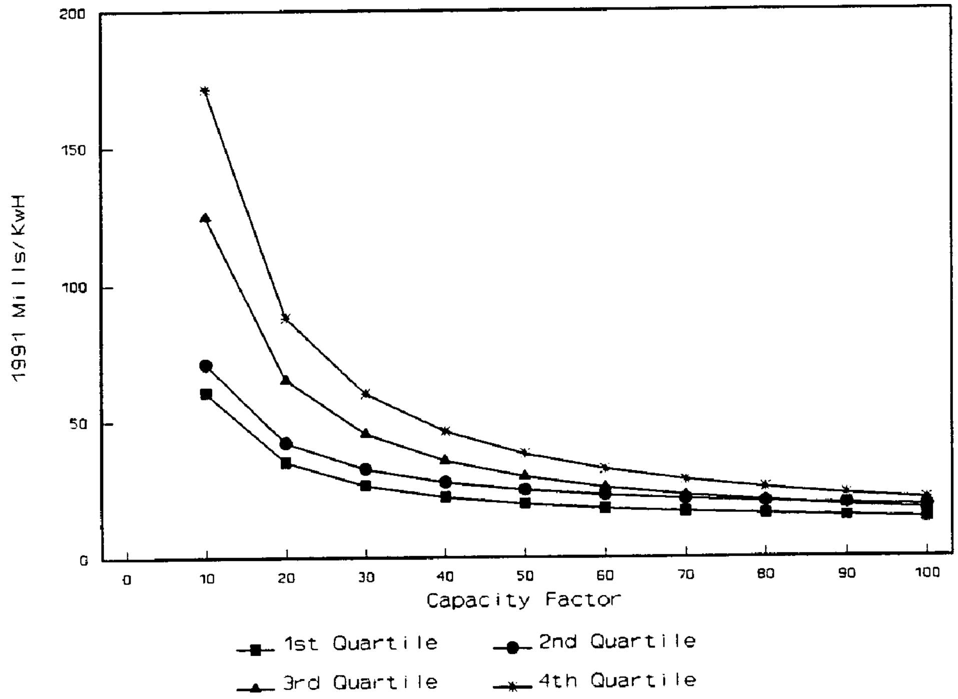


TABLE V.13: NUCLEAR POWER PRODUCTION COSTS AS A FUNCTION OF CAPACITY FACTOR (Mills per KWh)

Capacity Factor	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
10	60.74	71.17	124.71	171.23
20	35.00	42.11	65.21	87.91
30	26.42	32.43	45.38	60.14
40	22.13	27.59	35.46	46.26
50	19.55	24.68	29.51	37.93
60	17.84	22.74	25.55	32.37
70	16.61	21.36	22.71	28.41
80	15.69	20.32	20.59	25.43
90	14.97	19.52	18.93	23.12
100	14.40	18.87	17.61	21.26

Note: Mills refer to 0.1 cents of a 1991 dollar.

TABLE V.14: STATISTICAL PARAMETERS FROM REGRESSIONS OF NUCLEAR POWER PRODUCTION COSTS BY QUARTILES

	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
Constant	9.25	13.06	5.71	4.60
Std Err of Y Est	2.93	3.77	8.84	25.11
R Squared	0.42	0.55	0.78	0.81
No. of Observations	150	137	147	150
Degrees of Freedom	148	135	145	148
X Coefficient(s)	514.9082	581.0631	1189.993	1666.265
Std Eff of Coef.	50.18258	45.05175	52.86953	66.89984
t Statistics	10.2607	12.89768	22.50811	24.90686

(3) REPLACEMENT COST FORECASTS

The nuclear power production costs are compared to the replacement purchasing costs to determine the capacity factor level at which purchasing electricity from the power pool becomes less expensive than producing nuclear electricity. The replacement purchasing costs are defined on a reactor-by-reactor basis based on a probability assessment of the shutdown of the particular nuclear reactor in the particular generation pool where it is located.

The nuclear replacement purchasing costs are from a study by the Nuclear Regulatory Commission.[6] The NRC report includes forecasts of replacement costs for each nuclear reactor. The replacement costs represent the change in generating-system production cost that results from the shutting down of the nuclear reactor in question. The change in production cost is determined by the difference between the total variable costs when the reactor is available for generation and when the reactor is shutdown. The total variable costs include variable fuel costs, variable operation and maintenance costs, and purchased energy costs.

The modeling tools used by the NRC to forecast nuclear replacement costs include the Investigation of Costs and Reliability Utility Systems (ICARUS) model from Argonne National Laboratory and an extensive data base of electric utility systems identified as Automated Data Assembly Package (ADAP).[7] The replacement costs are derived from probabilistic production-cost simulations of pooled utility-system operations performed at a pool level. These simulations incorporate several related economic and technological factors affecting electricity generation. Factors affecting replacement energy costs, such as random unit failures, maintenance and refueling requirements, heat rates, costs, and load variations, are treated in the NRC analysis. Therefore, the replacement costs reflect the real cost the utility will have to bear under very realistic simulated conditions. The resulting costs reflect scenarios that consider the possibility of multiple plant shutdowns within the same power pool.

Although the NRC nuclear replacement costs report provides the most accurate and comprehensive approach for the estimation of the cost of nuclear power replacement, the forecasts are limited to 1996. The forecasts of these costs further into the future would require the use of complex and data intense models such as ICARUS. Because such a model is not available, it was decided to extrapolate replacement cost trends on a reactor-by-reactor basis. The extrapolation analysis was based on the trend observed in purchasing costs and in the expected trend through 1996 as defined by the NRC study.

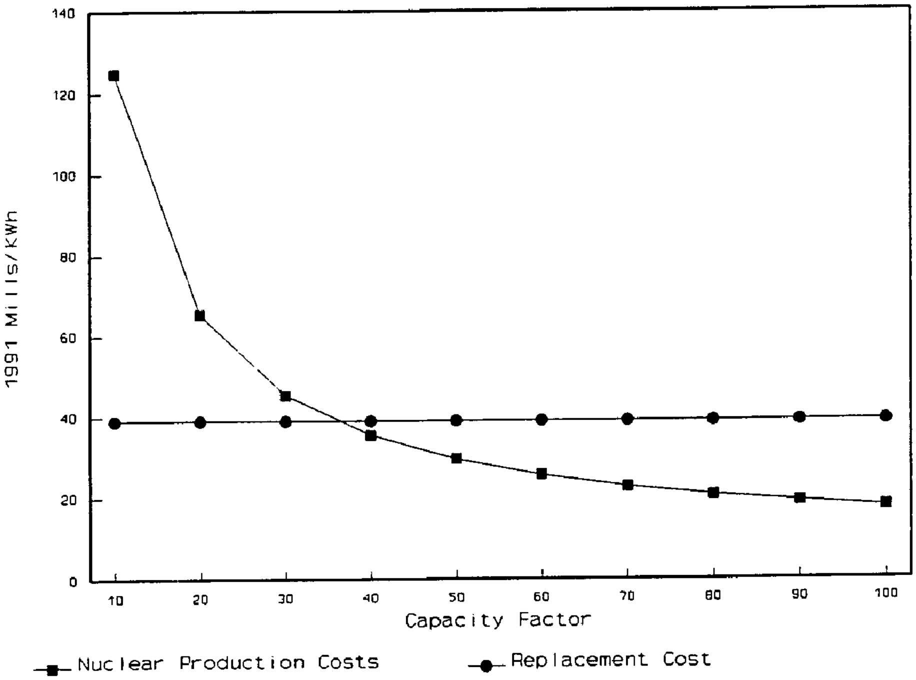
Although the basic replacement cost forecasts from the NRC study are very well founded, the use of an extrapolation trend for replacement costs after 1996 limits the accuracy of the approach and represents a source of uncertainty in the overall estimation of nuclear reactors' life expectancy. In addition, even though the NRC forecasts include the probability of multiple shutdowns, such forecasts do not represent critical electricity supply situations that could be derived from the simultaneous shutdown of several nuclear reactors operating in a single region.

(4) NUCLEAR COSTS VS REPLACEMENT COSTS

The nuclear cost-performance functions are compared to the replacement power costs to determine the minimum efficiency level beyond which it becomes more expensive to produce a KWh by operating a nuclear reactor than it is to purchase the KWh. As an example, Figure V.6 presents the case of Vogtle 1, a nuclear plant located in Waynesboro, Georgia. This plant is included in the 3rd operating cost quartile. The nuclear power production cost curve of Vogtle 1 is compared to the replacement purchasing costs in the year 2000. The replacement cost for Vogtle 1 is expected to be about 39 (1991)Mills/KWh. If by 2000 the reactor experiences a deterioration of performance to a level below a 35% capacity factor, then it is most likely that the utility will choose to purchase the power instead of continuing to operate the reactor. In the absence of any critical engineering constraints before 2000, this reactor will be retired at that time due to production costs that are higher than expected replacement costs.

The accuracy in the determination of the minimum efficiency level for the operation of nuclear reactors is limited mainly by the procedures for estimating both the nuclear performance functions and the replacement cost forecasts. As explained previously, the functional form that best describes the capacity factors has a low explanatory power indicating that there are still other factors affecting performance that have not been fully accounted for. The replacement costs, although based on reliable probabilistic forecasts for the period ending in 1996, are uncertain in the long-run. On the other hand, the cost-performance functions seem to accurately represent the variation of nuclear production costs as a function of performance.

FIGURE V.6: NUCLEAR POWER PRODUCTION COSTS AND REPLACEMENT COSTS (VOGTLE 1)



(5) NUCLEAR TECHNOLOGICAL CONSTRAINTS

The next step in the life assessment of nuclear reactors is the consideration of critical engineering constraints. Engineering constraints refer to equipment, structures or systems that have been identified as having critical progressive deterioration due to the aging process and in particular due to problems associated with nuclear radiation.

Critical engineering constraints are overimposed on the performance and cost analysis to determine if the constraint will limit the reactor's life before it reaches the critical capacity factor at which replacement purchasing costs are lower than operating costs. This study considers three major critical engineering constraints: vessel embrittlement, vessel ductile fracture, and steam generator piping deterioration. These constraints were described in detail in Chapter III.

Vessel Embrittlement

The potential for vessel embrittlement is measured by the Pressurized Thermal Shock (PTS) test and it is highly dependent on the vessel-specific operating and building characteristics. The problem refers to the potential fracture of the pressure vessel due to embrittlement during accidents or occurrences in which there is a sudden drop in temperature followed by an immediate pressurization. This is defined as a pressurized thermal shock and affects the pressurized water reactor types. The PTS test allows the identification of the number of years that the plant can operate before it reaches a critical point at which the risk for embrittlement is so high that the reactor is forced to shutdown. Other unlikely alternatives are the replacement of the vessel or its refurbishing by annealing processes. None of these two alternatives has ever been attempted.

Table V.15 lists the nuclear reactors with expected life limitations due to vessel embrittlement. The table also lists the year at which these reactors' licenses expire and the years at which the PTS screening criteria will be reached. The table includes Yankee Rowe, a nuclear reactor permanently retired in 1991 due to this problem.

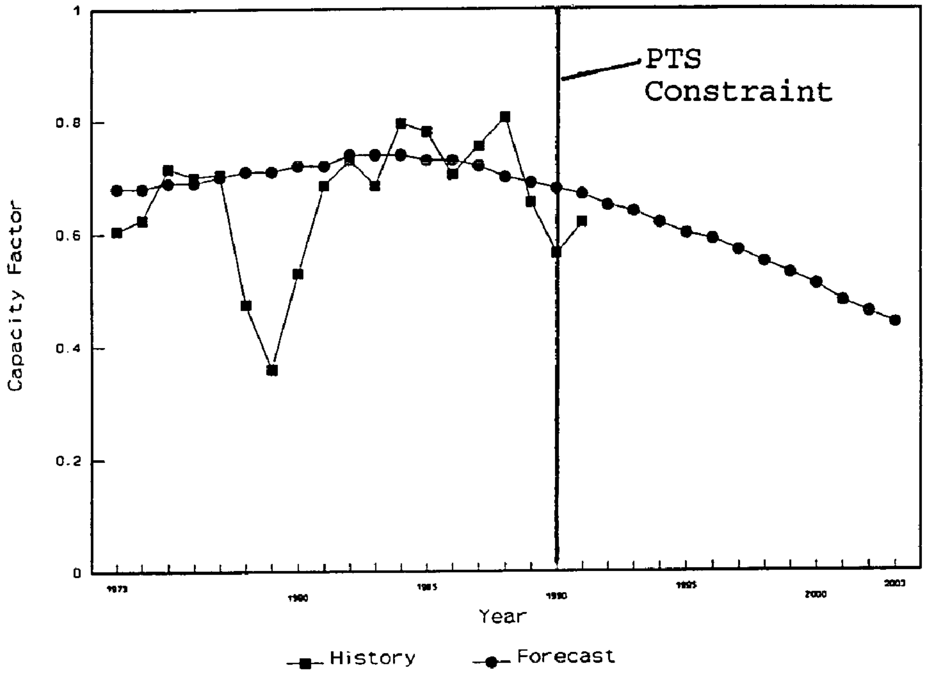
Figure V.7 presents the performance forecasts developed for Yankee Rowe using the procedure specified in the previous section. In addition, a vertical straight line placed in 1990 indicates that the reactor has an engineering constraint limiting its life to up to that time. In the case of Yankee Rowe, this constraint is the embrittlement potential and it corresponds to the time when the reactor became 30 years old. Regardless of the level of performance and of the comparison of production costs versus replacement costs, the reactor was forced to shutdown in 1991 because of this constraint. The reactor was permanently retired even though it was performing efficiently from a capacity factor standpoint.

TABLE V.15: NUCLEAR REACTORS WITH EXPECTED LIFE LIMITATIONS DUE TO VESSEL EMBRITTLEMENT (PRESSURIZED THERMAL SHOCK TEST)

PLANT NAME	END OF LICENSED LIFE	ESTIMATED YEAR SCREENING CRITERION WILL BE REACHED
Yankee Rowe	2000	1990
Palisades Plant	2011	1992
Fort Calhoun	2008	1998
Calvert Cliffs Nuclear Power Plant Unit No. 1	2015	1997
Kewaunee Nuclear Power Plant	2014	2006
Point Beach Nuclear Plant Unit 2	2012	2008
Diablo Canyon Unit No. 1	2024	2008
Indian Point Unit 3	2016	2010
Point Beach Nuclear Plant Unit 1	2010	2011
Zion Station Unit 1	2013	2011

Source: NRC, Regulatory Analysis for PTS, Enclosure 3, 10CFR50PT61 Reg Analysis, 1988.

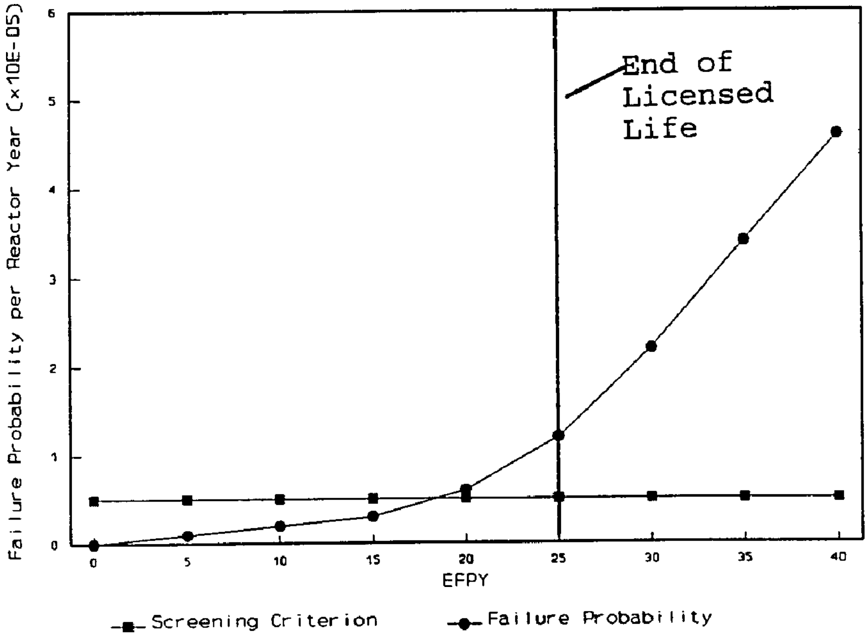
FIGURE V.7: NUCLEAR CAPACITY FACTOR PROJECTIONS AND TECHNOLOGICAL CONSTRAINT (PTS LIMIT)
(Yankee Rowe)



Although the mathematical approach to estimate potential embrittlement is probabilistic, the retirement of the reactors due to this problem is deterministic. The mathematical approach is probabilistic because the potential for embrittlement due to neutron bombardment is measured by the probability of vessel failure. This probability changes through time as the vessel accumulates more years of radiation exposure. The probability of vessel failure is defined based on the reactor's pressurized thermal shock reference temperature (RT_{pts}) and the effective full power year (EFPY). Figure V.8 is an illustration of the probabilistic calculation using as an example the nuclear reactor Fort Calhoun, located in Fort Calhoun, Nebraska.[8] RT_{pts} was described in Chapter III.

EFPY refers to the theoretical total number of years of plant operation at full capacity. This is calculated as the product of the operating calendar years and the lifetime capacity factor. The probability of vessel failure through time is represented by the increasing probability curve and is defined for Fort Calhoun at RT_{pts} equals to 302^0 F. The probability associated with the screening criterion is the horizontal straight line and it corresponds to 270^0 F. This probability is about $0.5x10^{-5}$. The figure illustrates that the probability of vessel failure for Fort Calhoun reaches the screening criterion probability when EFPY equals 19. This is 6 EFPYs before the end of its licensed life which is reached at 25 EFPYs. This corresponds to 10 calendar years short of its 40-year licensed life assuming a 63% capacity factor. Thus, the retirement of the unit is defined in a deterministic manner by the specific probability associated with the screening criterion.

FIGURE V.8: VESSEL FAILURE PROBABILITY AND PTS CRITERION



Vessel Ductile Fracture

Vessel ductile fracture potential is another critical constraint identified in nuclear reactors. As explained in Chapter III, the fracture resistance in reactor vessels decreases with the increase in neutron fluences. The weakness of the vessel is manifested by the reduction of the energy of the upper shelf section of the vessel. NRC regulations specify that the upper shelf energy must be no less than 50 ft-lbs. Reactors that do not satisfy this requirement must demonstrate that an adequate margin against fracture exists, or the utility may need to replace the vessel or thermally anneal it. Otherwise the reactor needs to be shutdown.

In 1992 NRC performed a review of all nuclear reactors to see whether they satisfy the 50 ft-lbs minimum requirement. The NRC found that, based on the generic criteria, 15 plants have calculated vessel material upper shelf energies below the minimum limit. In addition, 3 other plants would have upper shelf energies below the minimum by the time they reach the end of the operating licenses. The 18 reactors identified by NRC are listed in Table V.16.[9] After the generic criteria analyses were performed, the NRC requested reactor specific margin analysis from the utilities. Table V.16 includes the reactor type, lifetime capacity factor, and indications of other engineering problems such as low performance and embrittlement problems. All the reactors with the exception of Watts Bar 1 are over 15 years old. Although most of them are PWRs, the list includes two BWRs. Three reactors have vessel embrittlement problems in addition to the potential ductile fracture problem. Three other reactors have lifetime capacity factors below 55% which can be cataloged as low performers.

The upper shelf energy test is a probabilistic type of test similar to the PTS test. Nevertheless, the estimation of the retirements due to this critical factor is deterministic since it is based on the specific 50 ft-lbs limit.

Steam Generator Tube Failures

Steam generator failure is another major factor affecting nuclear reactor performance and retirement. Trojan, a nuclear reactor located in Oregon, is the typical example of an early retirement due to deterioration of tubes in the steam generator system. In this case the problem acted as a technological constraint.

Steam generator failures are a consequence of the particular design and materials used in the nuclear steam generator system. As indicated by historical data, most of the reactors experiencing tube problems are the ones supplied by Westinghouse. The particular Westinghouse system designs are the 3-Loop and 4-Loop steam designs. Forty-six of the 109 operating nuclear reactors in the U.S. have these nuclear steam systems. Thirteen are of the 3-Loop type and 33 are 4-Loop designs.

It is difficult to assess whether steam generator problems will affect performance or will act as technological constraints forcing early retirement. Although the early retirement of Trojan and San Onofre 1 can be attributed to steam generator failures, some nuclear units in the U.S. have opted for partial equipment replacement.

TABLE V.16: NUCLEAR REACTORS WITH UPPER SHELF ENERGY PROBLEMS (BELOW 50 FT-LB)

NAME	Type	Lifetime Capacity Factor	Other Engineering Problems
Oyster Creek	BWR	53.7%	Low Performance
TMI 1	PWR	49.5%	Low Performance
Nine Mile Pt. 1	BWR	54.1%	Low Performance
Ark. Nuclear 1	PWR	59.7%	
Crystal River 3	PWR	57.5%	
Ginna	PWR	75.0%	
Oconee 1	PWR	68.2%	
Oconee 2	PWR	69.2%	
Point Beach 1	PWR	73.9%	PTS
Point Beach 2	PWR	80.4%	PTS
Robinson 2	PWR	61.0%	
Turkey Point 3	PWR	57.1%	
Turkey Point 4	PWR	57.4%	
Zion 1	PWR	56.3%	PTS
Zion 2	PWR	60.7%	
Oconee 3	PWR	69.0%	
Millstone 2	PWR	63.1%	
Watts Bar 1	PWR	N/A	

Nevertheless, the replacement procedures for steam generator tubes are risky, cumbersome, costly and time consuming. A review of the data indicates that most of the replacements have occurred in reactors with steam generators of the Westinghouse 3-Loop design. Steam generator tubes have been replaced in Surry 1, Surry 2, Robinson 2, Turkey Point 3, and Turkey Point 4. Also, the replacement alternative has been pursued more often when the cost estimates are below $100 million. On the other hand, Trojan has a 4-Loop system and its replacement cost was estimated to be over $200 million. In this case the utility opted for permanent retirement. Table V.17 lists reactors with the same steam system design type as Trojan (Westinghouse, 4-Loop) which have already shown tube degradation. Another important factor is the warranty period or expected life specified by the steam generator tubes manufacturers. The literature on the subject indicates that tubes similar to the ones in the Trojan steam system have warranties for only 15 years.[10]

The performance forecast approach followed in this study considers the type of steam system design as one of the explanatory variables describing performance. The performance function captures the effect of steam generator tube deterioration in the capacity factor projections for all nuclear reactors. Although it is clear that steam generator tube failure represents an important nuclear life limitation, there are no specific criteria that can be followed to determine whether this problem will only affect performance or indeed will limit the reactor's life. Therefore, this study does not consider this factor directly as a technological constraint.

The limitations in the technological constraint approach followed in this study are mainly due to the fact that research is still being developed for the assessment of the deterioration of critical components.. Future research could allow the identification of other technological constraints limiting the nuclear reactors lives and that are not included in this study. In addition, limiting life factors such as steam generator tube failures have been clearly identified but can not be used in the approach until specific criteria are specified.

TABLE V.17: NUCLEAR REACTORS WITH 4-LOOP WESTINGHOUSE STEAM SYSTEM DESIGNS

NAME	AGE
Byron 1	8
Byron 2	6
Cook 1	19
Cook 2	15
Indian Point 3	17
Connecticut Yankee	25
Zion 1	20
Zion 2	20
Sequoyah 1	13
Sequoyah 2	12
Mc Guire 1	10

(6) FINAL NUCLEAR REACTOR LIFE ASSESSMENT

The final estimates of nuclear life assessment are obtained by comparing the life limitations determined by the nuclear performance-cost functions to the life limitations imposed by the technological constraints. The ultimate life of a nuclear reactor is defined by the limitation that is reached first. Therefore, nuclear life expectancy is determined according to two situations:

1) The efficiency of the nuclear plant deteriorates to a point at which the cost of producing the power is more expensive than the cost of replacing it. This point is reached before technological constraints become relevant.

2) The nuclear reactor reaches an age at which the condition of a critical component is such that the reactor must be retired. This situation is reached before the performance deteriorates to an uneconomical level.

Two different sets of results are generated as the nuclear performance-cost functions are defined for two scenarios. A detailed description of the results is presented in Chapter VII.

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7. VanKuiken, J., *An Efficient Simulation Approach for Evaluating the Effects of Potential Nuclear Power Plant Shutdowns on Electrical Utility Systems*, NRC Report NUREG/CR-3553, Argonne National Laboratory Report ANL/EES-TM-233, June 1983.

8. Figure V.6 is an illustration derived from data taken from NRC, "Regulatory Analysis" Enclosure 3, 10CFR50PT61 REG Analysis, 1988. Fort Calhoun is used as an example to illustrate the process. The specific data used in the figure are not exact.

9. NRC, "Status of Reactor Pressure Vessel Issues Including Compliance with 10 CFR Part 50, Appendices G and H,"(wits 9100165), SECY-93-048.

10. *The Philadelphia Inquirer*, "Nuclear Reactors Dying Young," January 1993. p.1.

CHAPTER VI

DATA REQUIREMENTS

This chapter provides an insight into the availability, quality, limitations, and sources for data relevant to nuclear life expectancy. Data requirements for the implementation of the proposed method are specified in detail. Also, the database design and general data characteristics for the U.S. nuclear generating stock are described.

DATA AVAILABILITY

One of the advantages derived from doing research in the field of nuclear generation is that a great amount of the data accumulated from about 33 years of experience in the United States is available to the public. The safety concerns and controversies that have surrounded the nuclear energy industry have forced regulatory agencies and utilities to allow public access to engineering and economic data collected from currently operable nuclear units, as well as units already permanently shutdown.

Since this dissertation work is focused on the assessment of the life of nuclear reactors and this assessment is based on the analysis and integration of engineering and economic data, then most of the data needed are real historical data that characterize the types of reactors already built and the nuclear technology as it has evolved through the last three decades. Since the scope of the research does not include the analysis of new technologies or advanced nuclear reactor designs for which enough data have not been accumulated, there is no need for developing data estimates for the characterization of these future developments.

DATA LIMITATIONS

Almost all data used in this study are historical data collected and published by official organizations such as the Nuclear Regulatory Commission, the Energy Information Administration, and the Department of Energy. Although no primary data were used (i.e. no mail questionnaires or surveys were used), some of the information relevant to assess engineering and economic problems in nuclear reactors were obtained from telephone interviews with people related to the issue.

Data estimates (rather than historical data), as published by the NRC, were used for the determination of replacement cost forecasts and critical engineering constraints. Replacement cost forecasts are based on probabilistic estimates and they are published up to 1996.

Not all data required for the implementation of the research method were fully available. Probabilistic estimates could not be performed in critical engineering constraints because some of the required technical data are confidential and could not be released by organizations such as the NRC. In some cases related to regulatory constraints, the procedures that define the data (e.g tests and criteria) have yet to be fully developed.

Most of the data available are limited to the period from 1968 through 1991. This corresponds to the period covered by most of the nuclear publications. In particular, the nuclear production cost data used in the study were limited to the 1982-1991 period.

DATA QUALITY

Historical operating data used throughout the implementation of the approach are considered accurate, reliable and unbiased. The utilities are required to provide accurate data on the operation and economics of their nuclear reactors to the data collecting organizations under the law. The data are often subject to verification procedures performed to ensure their authenticity.

Estimated data such as replacement power cost forecasts and critical constraint time limits are the result of probabilistic analyses that carry a certain degree of uncertainty. These estimates are generated by NRC and there are no reasons to believe that they are biased in any way.

Replacement power cost data (in terms of $/KWh) from the NRC were preferred to equivalent data from the Department of Energy. Although attempts were made to use the DOE data, errors were found in files containing overall electricity purchases (annual purchases of KWh) and total annual electricity cost. In addition, the DOE data are available only by utility and not by plant.

There were some cases in which operating data were available from both EIA and the Electric Power Research Institute (EPRI). In these cases, the EIA data were selected over the EPRI data assuming less chance for bias.

DATA SOURCES

The major sources for engineering and economic data on operable and retired U.S. nuclear reactor stocks are the Nuclear Regulatory Commission (NRC), the Electric Power Research Institute (EPRI), and the Energy Information Administration (EIA), an independent agency within the U.S. Department of Energy. The major data sources are listed in Table VI.1. Other sources of data include the Nuclear Assurance Corporation (NAC), Nucleonics Week, and the Utility Data Institute (UDI).

The NRC is the most important source of nuclear reactors data on an individual basis. The NRC maintains a national Public Document Room in Washington D.C. that provides public access to all its publications and documents pertaining to the licensing and regulation of all the nuclear generating units in the U.S.[1] In addition, the NRC maintains local public rooms near the site of each commercial nuclear reactor. The NRC Public Document Room in Washington includes individual reactor dockets with information related to events affecting the status of reactors through all their lives.

In addition to individual data documents for each of the nuclear reactors, NRC publishes annual reports that contain summary data and comparisons among all licensed operating reactors. Three of the annual reports published by NRC are particularly relevant to this dissertation. The *Licensed Operating Reactors: Status Summary Report* contains information based on operating data submitted by the utilities (licensees) to NRC on a monthly basis.[2] This report, commonly referred as the "Gray Book," was published monthly until 1990. The new annual publication contains data summaries for the nation and individual power generation data on a year and lifetime cumulative basis.

TABLE VI.1: MAJOR DATA SOURCES

NUCLEAR REGULATORY COMMISSION

1. Information Digest, NUREG-1350, Vol. 4
2. Licensed Operating Reactors, NUREG-0020, Vol. 17
3. Annual Report, NUREG-1145, Vol. 7
4. Replacement Energy Costs for Nuclear Electricity Generating Units in the U.S., NUREG/CR-4012, ANL-AA-30, Vol. 2

ENERGY INFORMATION ADMINISTRATION/U.S. DEPARTMENT OF ENERGY

1. Electric Plant Costs and Power Production Expenses, DOE/EIA-0455
2. An Analysis of Nuclear Power Plant Operating Costs, DOE/EIA-0511
3. Electric Trade in the United States, DOE/EIA-0531
4. World Nuclear Capacity and Fuel Cycle Requirements, DOE/EIA-0436
5. Commercial Nuclear Power, DOE/EIA-0438

ELECTRIC POWER RESEARCH INSTITUTE

1. Nuclear Unit Operating Experience, NP-7191
2. Nuclear Unit Operating Experience, NP-1191
3. Nuclear Unit Operating Experience, NP-2092
4. Nuclear Unit Operating Experience, NP-3480
5. Nuclear Unit Operating Experience, NP-5544

The operating data are mainly in the area of engineering performance. Parameters listed include: gross and net electric generation, capacity and availability factors, forced outage rates and hours of generator on-line, critical and shutdown. In addition, the report lists the number of shutdowns during the period and the causes and corrective actions.

The NRC *Information Digest* is a summary of the status of nuclear power generation in the U.S. and of the relevant activities and accomplishments of NRC.[3] The publication is a reference to major facts in the nuclear industry and it provides listings of all the nuclear reactors in the U.S. and their status as operable, permanently shutdown, canceled, under construction and deferred. The listings include all the relevant dates such as start of construction, operation, license issue, and license expiration. Information on reactor types, manufacturers, nuclear steam system supplier and design, architect-engineer, and owners is also provided in this publication. There are also performance data listed such as automatic scrams while critical, safety system actuations, significant events, safety system failures, forced outage rate and equipment-forced outages per 1000 critical hours.

The NRC *Annual Report* is an important source for summaries of programs being conducted for the evaluation of engineering components and overall reactor performance.[4] In particular, this report reviews the status of programs related to reactor vessel and piping integrity, aging and probabilistic risk assessment. Special problems, accidents and licensing and regulatory developments observed during the annual period are summarized and described. A listing of the penalties and orders issued by NRC is also provided in this publication.

Another important data source from NRC is a report on nuclear replacement costs which has been published three times. The *Replacement Energy Costs for the Nuclear Electricity-Generating Units in the United States* report has been published in 1984, 1987 and 1992.[5] This report contains replacement cost estimates derived from probabilistic production-cost simulations of pooled utility-system operations. The cost estimates are derived for five-year periods and they represent additional costs expected from the purchase of power from nearby power stations for periods in which the nuclear reactors could be shutdown. The information is provided on a reactor-by-reactor basis and by power pool. Replacement costs are specified by season and a per day and per KWh basis.

The EIA is a major source for economic data, status and outlook on nuclear generating reactors. The EIA report entitled *Electric Plant Cost and Power Production Expenses* presents electric utility statistics on power production expenses and construction costs of electric generating plants including annual fixed charges.[6] A comparison of generation expenses for both nuclear and coal plants is provided. Information on nuclear reactors include: general operating characteristics, historical plant cost, power production expenses, fuel used, and plant characteristics. The source is particularly useful because of the listing of the annual nuclear power production expenses in terms of mills per KWh.

In 1988 and 1991, EIA published a report called *An Analysis of Nuclear Power Plant Operating Costs*.[7] This report analyzes nonfuel operating costs for nuclear reactors in the U.S. The costs include operating and maintenance costs, and capital additions costs. Listings of these costs on a reactor-by-reactor basis are included. The report contains very valuable information related to the factors affecting the operating costs such as aging, size, replacement power, etc.

Two other reports by EIA include information related to the cost of purchasing power by utilities with nuclear reactors. The *Electric Trade in the United States* report lists the cost in dollars related to the purchase of power and the amount of electricity bought per year by utilities in terms of KWh.[8] The report provides data on electric trade at the national, regional, and electric utility level. The EIA *Financial Statistics of Selected Electric Utilities* also provides the same type of purchasing information but disaggregated by private and publicly owned utilities. This report includes current and historical financial accounting data for selected electric utilities.

Another annual publication by EIA reports current status and projections of nuclear capacity, generation, and fuel cycle requirements for the U.S. and the world. The *World Nuclear Capacity and Fuel Cycle Requirements*, formerly called *Commercial Nuclear Power*, presents the status of the nuclear generating reactors and the factors affecting their future.[9] In addition, future scenarios are developed based on assumptions modeled in mid-term and long-term scenarios. The report lists the operable, under construction, and canceled nuclear reactors including general characteristics.

Since 1980, EPRI has published five reports with nuclear data identified as *Nuclear Unit Operating Experiences.*[10] This series of reports contains nuclear unit performance data on a unit-by-unit basis, as a function of calendar year and age or years in operation. Data are listed for the period from 1968 through 1988 for all nuclear reactors with a capacity larger than 400 MWe. Performance indices include: capacity factors, availability factors, equivalent availability factors, capacity factor loss, scram rates, and equivalent forced outage rates. In addition, the report series includes data on units-year experience aggregated by unit, unit design and pedigree, calendar and commercial year performance aggregated by reactor supplier and type, and indices quantifying the impact of systems and components on unit performance. These reports are particularly relevant to the work in this dissertation because they include some analysis of the impact of plant systems on unit performance, and specific component problems.

DATA REQUIREMENTS

The approach followed in this dissertation requires historical and current engineering, economic, and general data for reactors in operation and for reactors already permanently shutdown. All the information has been obtained or derived from the data sources specified in the previous section. One hundred thirteen nuclear generating units are analyzed. These reactors are listed in Table VI.2. The list includes 108 operable reactors and 5 reactors permanently shutdown. The 108 operable nuclear units correspond to the sample of reactors operating by the end of 1991. This sample does not include Shoreham or Comanche Peak 2 since no operating data exist from these reactors. The five retired nuclear units are: Fort Saint Vrain, Rancho Seco, Yankee Rowe, San Onofre 1, and Trojan.

The data requirements can be classified as general data needed for the overall characterization of the nuclear reactors, and specific data needed for the implementation of all the modules and submodules that conform to the analytical approach selected for this research. Samples of general and specific engineering reactor data are presented in Tables A.1, A.2, and A.3 of Appendix A. Economic data are presented in Table A.4.

TABLE VI.2: NUCLEAR REACTORS IN THE U.S., 1992

1	Ark. Nuc. 1	28	Diablo Canyon 2
2	Ark. Nuc. 2	29	Dresden 2
3	Beaver Valley 1	30	Dresden 3
4	Beaver Valley 2	31	Duane Arnold
5	Big Rock Point	32	Farley 1
6	Braidwood 1	33	Farley 2
7	Braidwood 2	34	Fermi 2
8	Browns Ferry 1	35	Fitzpatrick
9	Browns Ferry 2	36	Fort Calhoun 1
10	Browns Ferry 3	37	Fort St. Vrain
11	Brunswick 1	38	Ginna
12	Brunswick 2	39	Grand Gulf 1
13	Byron 1	40	Haddam Neck (C.Y.)
14	Byron 2	41	Harris 1
15	Callaway 1	42	Hatch 1
16	Calvert Cliffs 1	43	Hatch 2
17	Calvert Cliffs 2	44	Hope Creek 1
18	Catawba 1	45	Indian Point 2
19	Catawba 2	46	Indian Point 3
20	Clinton 1	47	Kewaunee
21	Comanche Peak 1	48	LaSalle 1
22	Cook 1	49	LaSalle 2
23	Cook 2	50	Limmerick 1
24	Cooper	51	Limmerick 2
25	Crystal River 3	52	Maine Yankee
26	Davis-Besse 1	53	Mc Guire 1
27	Diablo Canyon 1	54	Mc Guire 2

TABLE VI.2: NUCLEAR REACTORS IN THE U.S.
(continued)

55	Millstone 1	81	Rancho Seco
56	Millstone 2	82	River Bend 1
57	Millstone 3	83	Robinson 2
58	Monticello	84	Salem 1
59	Nine Mile Point 1	85	Salem 2
60	Nine Mile Point 2	86	San Onofre 1
61	North Anna 1	87	San Onofre 2
62	North Anna 2	88	San Onofre 3
63	Oconee 1	89	Seabrook 1
64	Oconee 2	90	Sequoyah 1
65	Oconee 3	91	Sequoyah 2
66	Oyster Creek 1	92	South Texas 1
67	Palisades	93	South Texas 2
68	Palo Verde 1	94	St. Lucie 1
69	Palo Verde 2	95	St. Lucie 2
70	Palo Verde 3	96	Summer 1
71	Peach Bottom 2	97	Surry 1
72	Peach Bottom 3	98	Surry 2
73	Perry 1	99	Susquehanna 1
74	Pilgrim 1	100	Susquehanna 2
75	Point Beach 1	101	Three Mile Island 1
76	Point Beach 2	102	Trojan
77	Prairie Island 1	103	Turkey Point 3
78	Prairie Island 2	104	Turkey Point 4
79	Quad-Cities 1	105	Vermont Yankee
80	Quad-Cities 2	106	Vogtle 1

TABLE VI.2: NUCLEAR REACTORS IN THE U.S.
(continued)

107	Vogtle 2	111	Yankee Rowe 1
108	Wash. NP 2	112	Zion 1
109	Waterford 3	113	Zion 2
110	Wolf Creek		

The characterization of all the nuclear reactors according to specific parameters such as age, performance, and critical engineering constraints implies the need for data in the following areas: general reactor characteristics, specific engineering characteristics, performance parameters, engineering constraints, economic indicators, and environmental limitations. The data required for a general characterization are listed in Table VI.3.

The general reactor characteristics which are needed include information about the reactor location, vintage and type. In addition, information is necessary about organizations involved in the design, construction and operation of the reactors. The location data include state, federal region, National Electric Reliability Council (NERC) region, and the power pool. The vintage information includes data on age, years under construction, start date of operation, and start date of construction. The reactor type data relate to the general nuclear reactor type, the nuclear steam design type, the containment type, and the capacity size. Data on organizations include the names of the nuclear steam system supplier, architect/engineer, constructor and operator (utility).

Specific engineering characteristics that are needed for the analysis include data on major nuclear reactor components such as main cooling pumps, steam generators, fuel assemblies, turbine, feedwater pumps, auxiliary feedwater pumps, and condenser.

TABLE VI.3: DATA REQUIRED FOR GENERAL CHARACTERIZATION OF NUCLEAR REACTORS

Location:
- State
- Federal Region
- NERC Region
- NERC Power Pool Number

Vintage:
- Start Date of Construction (Vintage)
- Start Date Operation
- Years under Construction
- Age

Reactor Type:
- Capacity (size)
- Reactor Type
- Containment Type
- Nuclear Steam System Design Type

Organizations:
- Architect/Engineer
- Constructor
- Owner (Utility)
- Nuclear Steam System Supplier

Engineering Performance:
- Capacity Factor
- Availability Factor
- Forced Outage Rate
- Forced Outage Hours

Engineering Constraints:
- Vessel Integrity (Embrittlement) PTS Problem
- Vessel Integrity (Ductile Fracture) Upper Shelf Energy
- Steam Generator Piping Integrity (Piping replacement rate)

TABLE VI.3: DATA REQUIRED FOR GENERAL CHARACTERIZATION OF NUCLEAR REACTORS
(Continued)

OTHER ENGINEERING CHARACTERISTICS

Main Cooling Pumps:
- Manufacturer
- Number of Pumps

Steam Generators:
- Model
- Number
- Type of Cooling Water (Fresh or Salt)
- Demineralization
- Loop Isolation Valve
- Feedwater Chemical Treatment Type

Fuel Assemblies:
- Number of Fuel Assemblies in Core
- Fuel Rodlet Array
- Type of Cooling Water
- Control Cell Core (Yes or No)

Turbine:
- Number of High Pressure
- Number of Low Pressure
- Manufacturer
- Size of Last Stage Low Pressure Blades

Feedwater Pumps:
- Number
- Manufacturer
- Type

Auxiliary Feedwater Pumps:
- Number of Steam Turbine Driven
- Number of Motor Driven

Condenser:
- Tube Material
- Cooling Water System Type
- Heat Sink Type

TABLE VI.3: DATA REQUIRED FOR GENERAL CHARACTERIZATION OF NUCLEAR REACTORS

(Continued)

Economic Data:
- Average Annual O&M Costs per KW of Capacity
- Average Annual Capital Additions per KW of Capacity
- Power Production Expenses per KWh of Generation
- Purchase Power Costs per KWh
- Life Extension (NUPLEX) Costs

Environmental Data:
- Decommissioning Costs
- Spent Fuel Storage Capabilities (Number of Years)

Engineering performance data include lifetime parameters such as capacity factors, availability factors, forced outage rates, and forced outage hours. Major engineering constraints include data on vessel integrity and steam generator integrity. The vessel integrity data are mainly in the areas of embrittlement and ductile fracture potentials. Steam piping integrity refers to the rate of piping replacement due to deterioration through time. Specific probability data on vessel ductile fracture and piping integrity are not available to the public and therefore could not be used to perform specific probability analyses.

The economic data include: average annual operating and maintenance costs per KW of capacity, average annual capital addition costs per KW of capacity, annual power production expenses per KWh of generation, replacement power costs per KWh of generation and purchase power cost per KWh of generation.

The specific data required for the execution of the method proposed in this study are listed in Table VI.4. The analytical approach followed in this dissertation consists of two modules: an engineering module and an economic module. These modules are interconnected to produce the final objective of the nuclear life assessment on a reactor-by-reactor basis. The engineering module includes a nuclear performance submodule and a nuclear technological constraint submodule. The nuclear performance submodule contains historical data on annual capacity factors. These data are needed to perform a multiple regression analysis that allows the forecasting of this performance factor. The data needed on independent variables used to define the capacity factor function include: reactor age, size or generating capacity, architect/engineer, reactor containment type, and steam system design type. The nuclear technological constraint submodule considers constraints related to the progressive deterioration of materials and/or equipment due to the aging process and in particular due to problems associated with nuclear radiation. This nuclear constraint submodule requires data on the time expectation for the critical deterioration of important components. In particular, time expectation data on embrittlement and ductile fracture of the nuclear vessel are necessary. In addition, time expectation data are required for the critical deterioration of the steam generator piping system.

TABLE VI.4: SPECIFIC DATA REQUIRED FOR EXECUTION OF APPROACH

ENGINEERING MODULE

1. Annual Capacity Factors
2. Two-Year Average Capacity Factors
3. Size (Generating Capacity)
4. Architect/Engineering
5. Age
6. Reactor Containment Type
7. Steam System Design Type
8. Time Expectation for Critical Embrittlement
9. Time Expectation for Critical Ductile Fracture
10. Time Expectation for Critical Deterioration of Steam Generator Piping System

ECONOMIC MODULE

1. Annual Nuclear Power Production Costs
2. Ten-Year Average Nuclear Power Production Costs
3. Replacement Purchasing Cost Forecasts
4. Annual Purchasing Costs

The economic module includes a nuclear cost submodule and a replacement cost submodule. The nuclear cost submodule defines the cost of producing nuclear electricity as a function of nuclear capacity factors. This submodule requires data on annual nuclear power production costs, including operating and maintenance costs, capital addition costs, and fuel costs. Ten-year average nuclear production costs are needed to classify the nuclear reactors according to the level of operating costs. The replacement cost submodule uses data on replacement cost forecasts on a reactor-by-reactor basis and in terms of dollars per KWh. In addition, historical purchasing costs are necessary in this submodule.

DATABASE DESIGN

A database has been developed for the implementation of this research. The database includes files in spreadsheet form with all relevant data needed for the assessment of the life of the nuclear reactors. Table VI.5 lists the major data included in the database. The database consists of the following nine data files:

1) Major Reactor Data File

This file includes all the general characteristics and some specific parameters of the 113 nuclear units considered in this research. Lifetime performance factors and economic factors are included. The file allows the characterization of all nuclear reactors according to specific parameters. The characterization analysis of the U.S. nuclear reactor stock as a whole is accomplished by the manipulation of this data file. Any other samples selected within the stock according to specific parameters such as age, performance, engineering constraints, and costs can be analyzed with this file.

TABLE VI.5: DATABASE FILES

1. MAJOR REACTOR DATA FILES

- Location
- Age
- Lifetime Capacity Factor
- Reactor Types
- Engineering Constraints
- Lifetime Production Costs

2. HISTORICAL CAPACITY FACTORS, DETERMINANTS, AND REGRESSIONS

- Annual Capacity Factors
- Size
- Architect/Engineer
- Containment Type
- Steam Systems Design Type

3. NUCLEAR CAPACITY FACTORS FORECAST

- Capacity Factors Forecast
- Capacity Factor Forecast Ranges

4. ANNUAL POWER PRODUCTION EXPENSES

5. NUCLEAR COST CURVES AS FUNCTIONS OF CAPACITY FACTORS

6. REPLACEMENT COST FORECASTS

7. HISTORICAL PURCHASING COSTS

8. ENGINEERING CONSTRAINT FILES

9. INDIVIDUAL REACTOR RESULT FILES

2) Historical Capacity Factors, Determinants, and Regressions

This file includes historical annual capacity factors, factors identified as important determinants of this performance parameter, and the results of the regressions performed using these factors. Historical capacity factors for a selected group of nuclear reactors are presented in Table A.5.

3) Nuclear Capacity Factors Forecasts

This file includes forecasts of nuclear capacity through time for all the 113 nuclear units. The forecasts are developed based on the regression results obtained in the previous file and they are listed according to the age of the nuclear units. Capacity factors range forecasts are included in this file. These ranges are developed based on normal distribution assumptions.

4) Annual Power Production Expenses and Ten-Year Averages

This file contains historical data with the annual power production expenses and ten-year averages. The averages are needed for the classification of the 113 reactors into quartiles according to their ten-year average. Annual production costs are included in Table A.6.

5) Nuclear Cost Curves as Functions of Capacity Factors

This file contains regressions performed to develop four nuclear cost curves as functions of capacity factors. The curves are based on data from the last ten years on nuclear power production expenses and capacity factors.

6) Replacement Cost Forecasts

This file includes the replacement forecasts from the NRC and extensions of these forecasts based on trends. The replacements costs are specified on a reactor-by-reactor basis. A minimum and a maximum are listed to provide a range at which replacement costs become competitive with production costs.

7) Historical Purchasing Costs

This file contains historical purchasing costs for utilities with nuclear reactors. The data are for a five-year period and they provide the basis for the forecast of replacement costs.

8) Engineering Constraint File

This file includes the time expectation data for the critical deterioration of major components and systems. Data on three major constraints are included. The constraints are: vessel embrittlement, vessel potential for ductile fracture, and piping integrity in the steam generators.

9) Individual Reactor Result Files

These are a series of files generated on a reactor-by-reactor basis in which data from all the submodules are combined. The files identify a year or year range at which the reactor will be expected to shutdown. The files include general characteristics of the reactors as well as specific information related to location, corresponding nuclear cost quartile curve and expected replacement costs.

U.S. NUCLEAR GENERATING STOCK CHARACTERIZATION

This study considers a total of 113 nuclear generating units. Only 108 of these units are operable nuclear reactors. The other five units are units which have been permanently shutdown. The data in the major reactor data file of the database described in the previous section allow the characterization of the U.S. nuclear reactor stock. Table VI.6 summarizes this characterization. There are several other parameters included in the major reactor data file that can be used to characterize the nuclear stock but that are not included in this summary table. For example, the average number of years under construction is 7.7; the average nonfuel annual operating costs in 1982 dollars is 63.9 per KW of capacity; and about 54 percent of all the reactors are PWR reactors with a "Dry-Ambient Pressure" containment type.

TABLE VI.6: CHARACTERISTICS OF THE U.S. NUCLEAR GENERATING STOCK

	ALL REACTORS SAMPLE
AV. CAPACITY MW	890
AV. VINTAGE (Construction Start)	1971
AV. AGE	15
PERCENT NUMBER OF BWR	35%
PERCENT NUMBER OF PWR	65%
PERCENT SUPPLIED BY B&W	6%
PERCENT SUPPLIED BY CE	14%
PERCENT SUPPLIED BY GE	33%
PERCENT SUPPLIED BY WESTINGHOUSE	47%
LOCATED IN NEW ENGLAND	7%
LOCATED IN NY/NJ	9%
LOCATED IN MID AT	14%
LOCATED IN SOUTH AT	27%
LOCATED IN MW	24%
LOCATED IN SOUTHW	6%
LOCATED IN CENT	5%
LOCATED IN NORTHC	1%
LOCATED IN WEST	7%
LOCATED IN NORTHWEST	2%
AV. CAPACITY FACTOR	63.4%

A sample of reactors with at least 20 years of life is presented in Table VI.7. This sample includes a total of 34 nuclear reactors which represent the oldest nuclear reactors in the country. A summary of the characteristics of these units is presented in Table VI.8. The units are characterized, as compared to the overall stock, by having a smaller capacity (672 versus 890 for the stock), and their locations with larger percents in the Midwest, New England and New York/New Jersey federal regions. Their lifetime average capacity factor of 62.2 % is just below the average for the overall stock (63.4 percent). This sample includes only two of the five reactors permanently shutdown. The average age of the sample is about 22 years old while the average age for the overall nuclear stock is about 15 years. This reactor sample is affected mainly by deterioration of critical components due to aging processes. Critical equipment and aging in nuclear reactors were described in detailed in Chapters III and V.

TABLE VI.7: NUCLEAR REACTORS 20 YEARS OLD AND OLDER

#	UNIT NAME	FEDERAL REGION	CAPACITY FACTOR	AGE
1	Yankee Rowe 1	I (NE)	70.60	32
2	Big Rock Point	V (MW)	56.80	30
3	San Onofre 1	IX (West)	51.30	25
4	Haddam Neck (CY)	I (NE)	71.00	25
5	Nine Mile Pnt 1	II (NY/NJ)	54.10	24
6	Oyster Creek 1	II (NY/NJ)	53.70	24
7	Dresden 2	V (MW)	56.60	23
8	Robinson 2	IV (SA)	61.00	23
9	Point Beach 1	V (MW)	73.90	23
10	Ginna	II (NY/NJ)	75.00	23
11	Dresden 3	V (MW)	54.70	22
12	Monticello	V (MW)	72.20	22
13	Palisades	V (MW)	42.50	22
14	Millstone 1	I (NE)	69.00	22
15	Pilgrim 1	I (NE)	50.20	21
16	Point Beach 2	V (MW)	80.40	21
17	Quad Cities 1	V (MW)	63.40	21
18	Vermont Yankee	I (NE)	72.80	21
19	Quad Cities 2	V (MW)	62.70	21
20	Surry 1	III (MA)	59.00	21
21	Turkey Point 3	IV (SA)	57.10	21
22	Prairie Island 1	V (MW)	77.30	20
23	Surry 2	III (MA)	59.50	20
24	Turkey Point 4	IV (SA)	57.40	20
25	Browns Ferry 1	IV (SA)	31.10	20

TABLE VI.7: NUCLEAR REACTORS 20 YEARS OLD AND OLDER
(Continued)

26	Oconee 1	IV (SA)	68.20	20
27	Fort Calhoun 1	VII Central	66.70	20
28	Oconee 2	IV (SA)	69.20	20
29	Kewaunee	V (MW)	79.00	20
30	Peach Bottom 2	III (MA)	51.10	20
31	Zion 1	V (MW)	56.30	20
32	Indian Point 2	II (NY/NJ)	61.10	20
33	Zion 2	V (MW)	60.70	20
34	Maine Yankee	I (NE)	70.30	20

TABLE VI.8: CHARACTERISTICS OF NUCLEAR REACTORS 20 YEARS OLD OR OLDER

	REACTORS 20 YEARS OLD AND OLDER	ALL REACTORS SAMPLE
AV. CAPACITY MW	672	890
AV. VINTAGE	1967	1971
AV. AGE	22	15
PERCENT NUMBER OF BWR	38%	35%
PERCENT NUMBER OF PWR	62%	65%
PERCENT SUPPLIED BY B&W	6%	6%
PERCENT SUPPLIED BY CE	9%	14%
PERCENT SUPPLIED BY GE	38%	33%
PERCENT SUPPLIED BY WESTINGHOUSE	47%	47%
LOCATED IN NEW ENGLAND	18%	7%
LOCATED IN NY/NJ	12%	9%
LOCATED IN MID AT	9%	14%
LOCATED IN SOUTH AT	18%	27%
LOCATED IN MW	38%	24%
LOCATED IN SOUTHW	0%	6%
LOCATED IN CENT	3%	5%
LOCATED IN NORTHC	0%	1%
LOCATED IN WEST	3%	7%
LOCATED IN NORTHWEST	0%	2%
AV. CAPACITY FACTOR	62.2%	63.4%

A sample of reactors with a low lifetime performance is presented in Table VI.9. The performance is based on lifetime capacity factors. The low performance sample is defined based on a lifetime capacity factor below 55 percent. The characteristics of these reactors as they compare to the characteristics of the overall stock are presented in Table VI.10. The sample has an average lifetime capacity factor of only 46.2 percent. This compares to a 63.4 percent lifetime capacity factors for the overall stock. The low performance sample is characterized by a larger percent of BWR reactor types. The percent of these reactors supplied by General Electric and Babcock and Wilcok are also higher. Larger percents of the low performance reactors are located in the New York/New Jersey and the West regions. The average age is about 3 years older than the corresponding average for the overall stock. Problems in critical components resulting in low performance were described in detail in Chapters III and V.

TABLE VI.9: NUCLEAR REACTORS WITH LOW LIFETIME PERFORMANCE

#	UNIT NAME	REGION	REACTOR SIZE	AGE	CAPACITY FACTOR
1	Fort St. Vrain	VIII (NCen.)	200	17	17.90
2	Browns Ferry 3	IV (SA)	1065	17	28.40
3	Browns Ferry 1	IV (SA)	1065	20	31.10
4	Ranch Seco	IX (West)	873	19	31.50
5	Browns Ferry 2	IV (SA)	1065	19	36.70
6	Palisades	V (MW)	730	22	42.50
7	Brunswick 2	IV (SA)	754	18	46.20
8	Sequoyah 1	IV (SA)	1122	13	49.20
9	Davis-Besse 1	V (MW)	874	16	49.30
10	Three Mile Isl. 1	III (MA)	808	19	49.50
11	Nine Mile Point 2	II (NY/NJ)	1097	6	50.20
12	Pilgrim 1	I (NE)	670	21	50.20
13	Brunswick 1	IV (SA)	767	17	50.80
14	Peach Bottom 2	III (MA)	1055	20	51.10
15	San Onofre 1	IX (West)	436	25	51.30
16	Trojan	X (NW)	1095	18	51.60
17	Peach Bottom 3	III (MA)	1035	19	52.10
18	Sequoyah 2	IV (SA)	1122	12	52.80
19	Palo Verde 1	IX (West)	1221	8	53.10
20	Oyster Creek 1	II (NY/NJ)	610	24	53.70
21	Nine Mile Point 1	II (NY/NJ)	615	24	54.10
22	Indian Point 3	II (NY/NJ)	965	17	54.40
23	Dresden 3	V (MW)	773	22	54.70

TABLE VI.10: CHARACTERISTICS OF LOW PERFORMANCE NUCLEAR REACTORS & OF THE OVERALL NUCLEAR STOCK

	LOW PERFORMANCE SAMPLE	ALL REACTORS SAMPLE
AV. CAPACITY MW	70	890
AV. VINTAGE	1969	1971
AV. AGE	18	15
PERCENT NUMBER OF BWR	55%	35%
PERCENT NUMBER OF PWR	45%	65%
PERCENT SUPPLIED BY B&W	14%	6%
PERCENT SUPPLIED BY CE	10%	14%
PERCENT SUPPLIED BY GE	55%	33%
PERCENT SUPPLIED BY WESTINGHOUSE	18%	47%
LOCATED IN NEW ENGLAND	4%	7%
LOCATED IN NY/NJ	17%	9%
LOCATED IN MID AT	13%	14%
LOCATED IN SOUTH AT	30%	27%
LOCATED IN MW	13%	24%
LOCATED IN SOUTHW	0%	6%
LOCATED IN CENT	0%	5%
LOCATED IN NORTHC	4%	1%
LOCATED IN WEST	13%	7%
LOCATED IN NORTHWEST	4%	2%
AV. CAPACITY FACTOR	46.2%	63.4%

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CHAPTER VII

MODEL RESULTS

This chapter presents the results derived from the implementation of the analytical approach to estimate life expectancy of the U.S. nuclear generating stock. Results are presented for two scenarios that are derived from different procedures used in the forecast of engineering performance. The analysis of the results includes the age assessment of all the nuclear reactors, their expected year for retirement, the location of the reactors expected to shutdown prematurely, and the implications of early nuclear retirement with respect to electricity supplies. In addition, evaluation of results and policy implications are discussed.

The research method developed in this study and described in Chapter V includes two different approaches for the generation of nuclear reactor performance forecasts. The implementation of these approaches resulted in the formulation of two nuclear life expectancy case scenarios. Tables A7 and A8 of Appendix A list the results on a reactor-by-reactor basis for Scenarios 1 and 2 respectively. These tables include the estimated life expectancy, the expected retirement year, the cause for retirement, and the expected retirement range as defined by the earliest and latest expected retirement years. The ranges vary among reactors, but on average they are about plus or minus 1.5 years, using a probability range of 80%, as explained in Chapter V. In cases where reactors are expected to have their lives limited by engineering constraints, the probability of retirement at the most likely year approaches 100%.

The results in Scenario 1 indicate that 19 reactors out of 108 will retire due to technological constraints. Eight of these reactors will have lives limited due to embrittlement problems, while eleven are expected to retire because of potential ductile fracture problems. All other reactors' lives are limited due to poor performance. In Scenario 2, only 5 reactors are expected to retire due to technological constraints, four of these reactors because of embrittlement problems and one due to potential ductile fracture problems.

The results for each scenario are described in detail in the following sections. Although the results are generated in terms of a range, in this chapter they are analyzed in terms of the most likely projected year for retirement. As described in Chapter V all the steps in the nuclear life assessment forecasting system developed in this study include limitations that need to be taken into consideration while evaluating results and formulating conclusions.

SCENARIO 1

Scenario 1 is derived from performance forecasts based on the best functional form and combination of explanatory variables resulting from a multiple regression analysis. The approach considers all relevant factors equally in the definition of the performance functional form. The approach implies that all factors have the same importance in the determination of capacity factors through time.

In this scenario all nuclear reactors, regardless of their age and years of experience, are included within the sample from which the coefficients affecting capacity factor forecasts are developed. The inclusion of all the reactors was considered necessary in order to incorporate, in the functional form, technological improvements in the newer designs and human performance improvements gained from operational experience from early years. The reactor sample includes a total of 113 nuclear reactors, of which 108 are operating and 5 are already permanently retired. One operating nuclear reactor (Comanche Peak 2) was excluded because it just started operation (1993) and therefore has not accumulated any data.

The results from Scenario 1 indicate that the majority of the 108 operating nuclear reactors (62%) will have operating lives that range between 30 and 40 years (Table VII.1). Only 10 will have operating lives of less than 26 years, and only 8 will last beyond 40 years. The median life expectancy according to this scenario is 34 years.

According to Scenario 1, 13 reactors will be shutdown by the year 2000, 20 by the year 2005, and 47 by the year 2010 (Table VII.2). By 2015 the U.S. nuclear stock would be reduced by over 60%. By comparison, assuming a 40-year life, only 1 reactor would shutdown by the year 2005, and just 9 by the year 2010. Even though most reactors will not reach their licensed life of 40 years, most will exceed their expected financial life, for accounting purposes, of 30 years.

The regions of the country with the highest number of reactors shutting down by the year 2005 are the South Atlantic, Midwest,and Middle Atlantic regions (Table VII.3).

TABLE VII.1: LIFE EXPECTANCY OF NUCLEAR REACTORS FROM SCENARIO 1

Years	Number of Reactors
Less than 20 years	2
20 to 25	8
26 to 30	20
31 to 35	24
36 to 40	46
over 40	8
MEDIAN	34

These regions are the same regions with the largest number of operating nuclear reactors. The New England region, Central region, and the New York/New Jersey region are the regions losing the highest proportion of nuclear generating stock by 2005, according to Scenario 1. The New England region will lose 25%, the Central region will lose about 40%, and the New York/New Jersey region about 30 percent of its nuclear stock. By that year, the Central and New York/New Jersey regions would have lost 60% of their nuclear stock, while New England will see its nuclear stock reduced by 75%.

TABLE VII.2: EXPECTED NUMBER OF REACTORS SHUTTING DOWN (1990-2030) SCENARIO 1

Year	Number of Reactors	40-Year Scenario Number of Reactors
by 2000	13	0
2001-2005	7	1
2006-2010	27	8
2011-2015	23	35
2016-2020	13	16
2021-2025	21	25
2026-2030	2	21
after 2030	2	2

TABLE VII.3: LOCATION AND NUMBER OF UNITS SHUTTING DOWN ACCORDING TO SCENARIO 1 BY 2000, 2005, 2010, and 2015

REGION		BY 2000	BY 2005	BY 2010	BY 2015
I.	New England	1	2	6	6
II.	New York/New Jersey	0	3	6	8
III.	Mid Atlantic	3	4	6	8
IV.	South Atlantic	3	5	13	17
V.	Midwest	4	4	9	19
VI.	Southwest	0	0	1	3
VII.	Central	2	2	3	0
VIII.	North Central	0	0	0	0
IX.	West	0	0	3	6
X.	Northwest	0	0	0	0
TOTAL		13	20	47	67

SCENARIO 2

Scenario 2 uses performance forecasts obtained from a non-linear function that is solved assuming that the performance of nuclear reactors throughout their lives follows an inverse quadratic trend. The procedure is implemented in a sequential way which implies that capacity factors are directly dependent on age and indirectly dependent on other explanatory engineering variables. This function is assumed to be completely defined by four parameters: the maximum attainable capacity factor, the time at which this maximum capacity factor is reached, the initial performance, and the age of the reactor. The approach assumes that the maximum attainable capacity factor is reached within the first 15 years of operation.

The coefficients for the performance function in this scenario are derived from a subsample of older nuclear reactors. Because of the assumptions relating to a maximum attainable capacity factor, this sample is limited to the 61 nuclear reactors which were fifteen years old and older by the end of 1991.

The results from Scenario 2 indicate that the majority of the nuclear reactors (67%) will have operating lives of less than 30 years (Table VII.4). The median life expectancy according to this scenario is only 28 years.

TABLE VII.4: LIFE EXPECTANCY OF NUCLEAR REACTORS FROM SCENARIO 2

Year	Number of Reactors
Less than 20 years	20
20 to 25	22
26 to 30	30
31 to 35	16
36 to 40	5
over 40	15
MEDIAN	28

According to Scenario 2, 37 reactors will be shutdown by 2000 and 64 by the year 2005 (Table VII.5). Assuming a 40-year life, only 1 reactor would shutdown by the year 2005.

The regions of the country with the highest number of reactors shutting down by the year 2005 are the South Atlantic, Midwest,and Middle Atlantic regions (Table VII.6) These regions are the same regions with the largest number of operating nuclear reactors. Based on Scenario 2, the New England region will lose the largest percent of nuclear generating stock. The 6 reactors which will shutdown in the New England region by the year 2005 according to this scenario represent about 75 percent of the region's nuclear stock. Since 40 percent of the 1991 net electricity generated in New England comes from nuclear reactors, the shutting down of 6 reactors would represent a shortfall of about 30 percent of net electricity supply for the area, assuming that the electricity generation requirements remained at the 1991 level. According to Scenario 2, the situation in all of the federal regions depending on nuclear energy will be of serious concern, with over 50 percent of the nuclear generating capacity gone by the year 2005. By 2010 only about 25% of the national nuclear stock will still be operating. This compares to 100 reactors (92%) expected to be operating by 2010 based on the 40-year life assumption.

TABLE VII.5: EXPECTED NUMBER OF REACTORS SHUTTING DOWN, 1990-2030
SCENARIO 2

Year	Number of Reactors	40-Year Scenario Number of Reactors
by 2000	37	0
2001-2005	27	1
2006-2010	17	8
2011-2015	7	35
2016-2020	4	16
2021-2025	6	25
2026-2030	4	21
after 2030	6	2

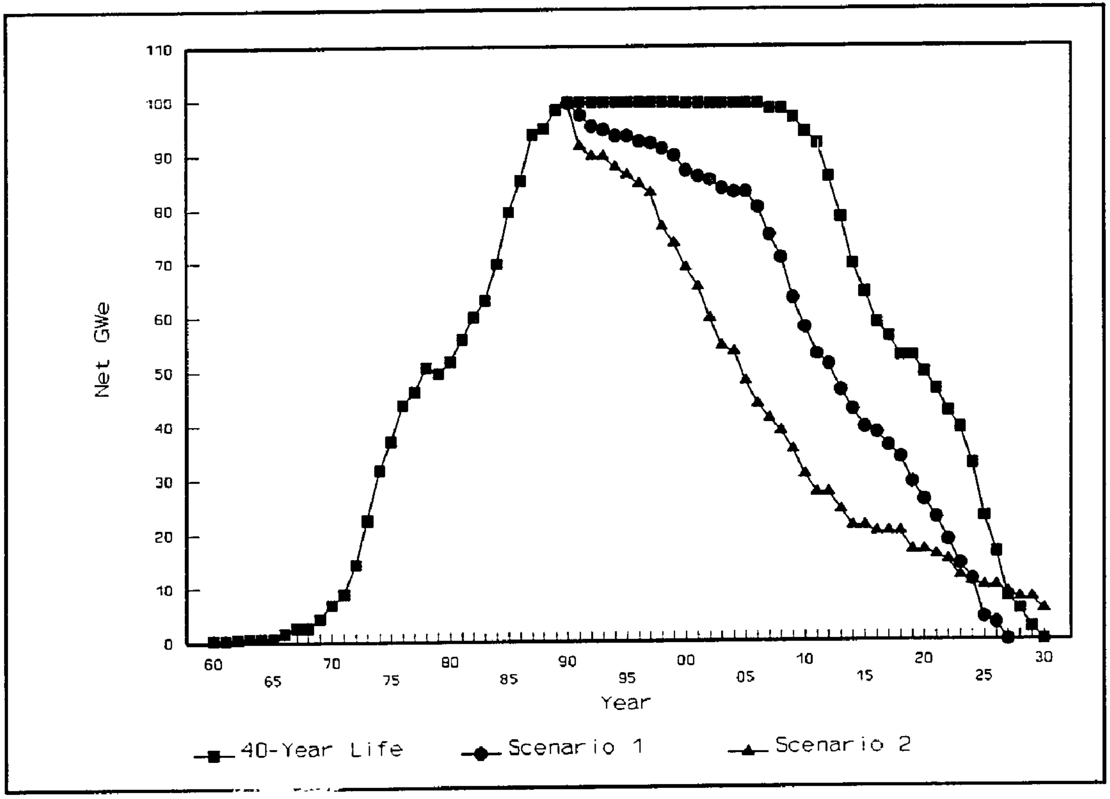
TABLE VII.6: LOCATION AND NUMBER OF UNITS SHUTTING DOWN ACCORDING TO SCENARIO 2 BY 2000, 2005, 2010, AND 2015

REGION		BY 2000	BY 2005	BY 2010	BY 2015
I.	New England	3	6	7	7
II.	New York/New Jersey	3	5	9	9
III.	Mid Atlantic	6	9	11	12
IV.	South Atlantic	10	18	20	22
V.	Mid West	7	14	19	21
VI.	Southwest	3	5	5	5
VII.	Central	1	3	4	5
VIII.	North Central	0	0	0	0
IX.	West	4	4	6	6
X.	Northwest	0	0	0	1
TOTAL		37	64	81	88

SCENARIO ANALYSIS

The results of the two scenarios developed in this study indicate that the commonly accepted assumption of a 40-year life for nuclear reactors is optimistic. The projected longevity estimates are illustrated in Figure VII.1. The figure presents the nuclear generating capacity for the period from 1960 through 2030. The nuclear capacity up to 1990 is the observed historical nuclear capacity. The three curves beginning in 1990 and going through 2030 represent the life assessments derived from Scenarios 1 and 2 and the expected life assessment based on the assumption of a 40-year life. The scenarios represent the 113 nuclear reactors considered in this study. None of the scenarios assume that new nuclear plants will be built during the 1990-2030 period being considered. Thus, two nuclear units (Watts Bar 1 and Watts Bar 2) expected to start operation in 1994 and one unit (Comanche Peak 2) that just started operation in 1993 are not included.

FIGURE VII.1: U.S. NUCLEAR GENERATING CAPACITY BASED ON DIFFERENT LIFE SCENARIOS



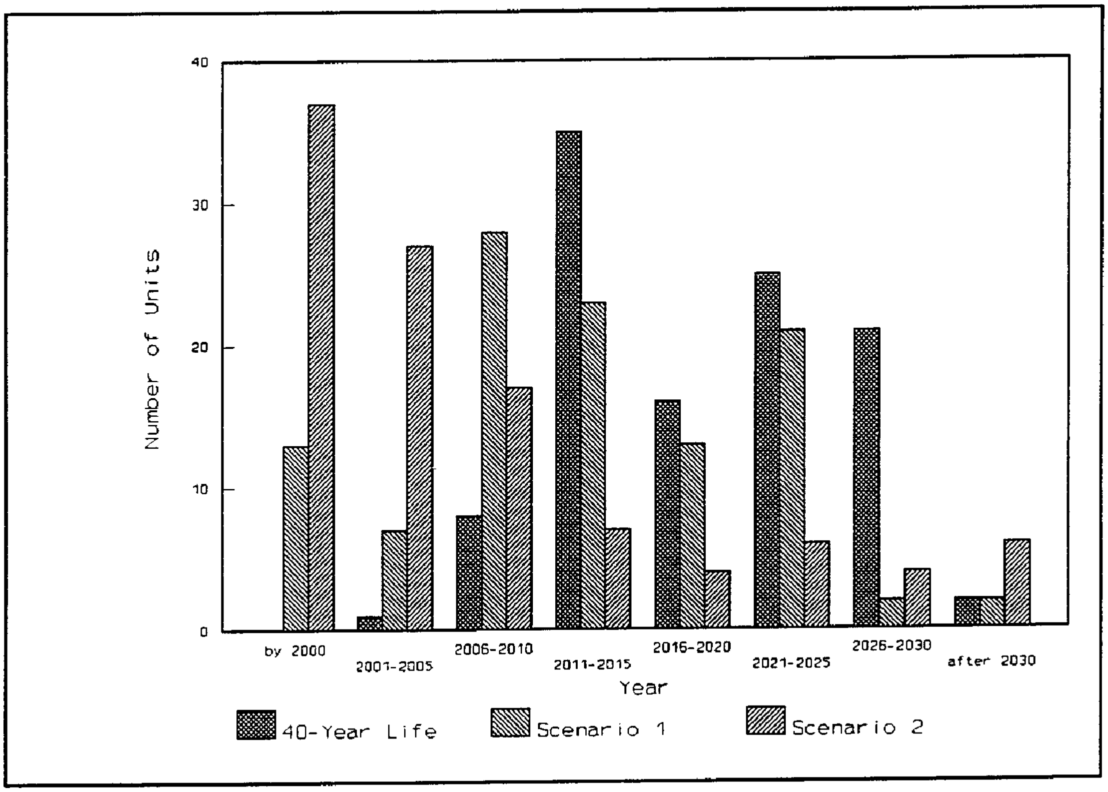
The two scenarios developed in this research indicate a considerable amount of reactors retiring before they reach their expected licensed life of 40 years. The decrease in the remaining nuclear capacity stock is most dramatic in Scenario 2. Scenario 1 is an intermediate forecast, in between Scenario 2 and the 40-year life case scenario (Table VII.7 and Figure VII.2).

The situation for the period between 1994 and 2005 (the next 12 years) is particularly interesting since the process of siting, planning, and building any type of power replacement facility has been estimated to take eight to twelve years.[1] Using the assumption of a 40-year life, only one reactor would be shutdown between 1990 and 2005. Three reactors have already shutdown since 1990 (Yankee Rowe, San Onofre 1, and Trojan). Under Scenario 1, 20 reactors (or about 18% of the stock) would shutdown during the same period. Scenario 2 forecasts 64 reactors, representing over half of the nuclear stock, shutting down in the same period. The situations predicted with both Scenarios 1 and 2 point to the potential for electricity shortages in some areas depending on the location of the reactors shutting down. In particular, Scenario 2 implies a very tight electricity supply situation for the U.S. during this period.

TABLE VII.7: EXPECTED NUMBER OF REACTORS SHUTTING DOWN, 1990-2030

Year	40-Year Scenario Number of Reactors	Scenario 1 Number of Reactors	Scenario 2 Number of Reactors
by 2000	0	13	37
2001-2005	1	7	27
2006-2010	8	27	17
2011-2015	35	23	7
2016-2020	16	13	4
2021-2025	25	21	6
2026-2030	21	2	4
after 2030	2	2	6

FIGURE VII.2: NUMBER OF UNITS SHUTTING DOWN 1990-2030

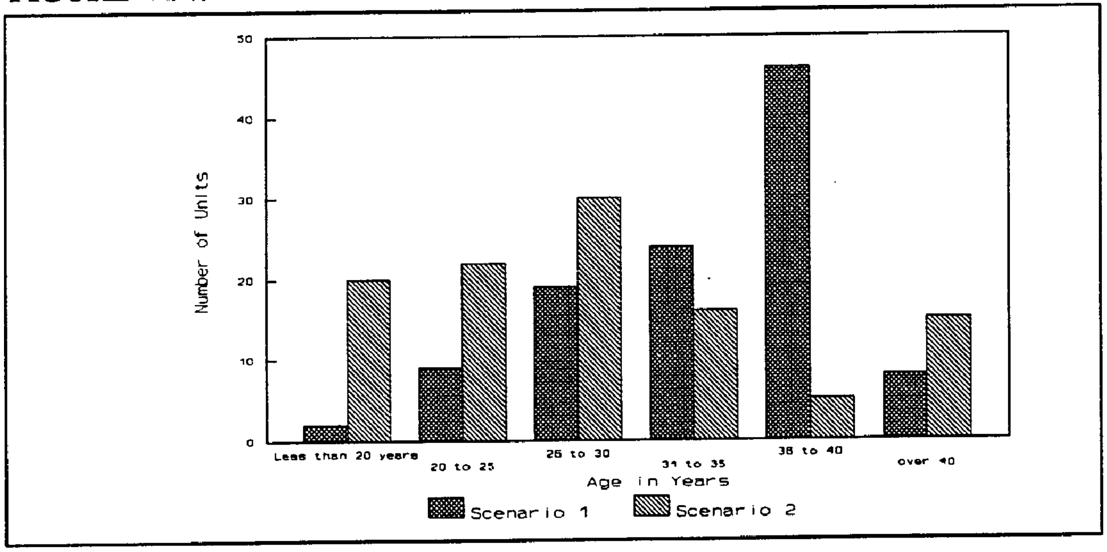


The two scenarios developed in this study produce median life expectancies of less than 40 years (Table VII.8). The age expectancy difference between these two scenarios is further illustrated in Figure VII.3. Scenario 1 identifies 10 reactors with life expectancies of no more than 25 years. Scenario 2 has a total of 42 reactors with expected life of no more than 25 years with 20 of them expected to last no more than 20 years. Scenario 1 with a higher median life expectancy projects only 8 reactors going life extension beyond 40 years. Conversely, Scenario 2 that produces less optimistic forecasts for most of the nuclear plants, identifies 15 reactors lasting over 40 years. A combination of high performance experienced in these reactors in their initial operating years and the particular approach followed in Scenario 2 in which initial capacity factors play a more important role in performance are the reasons for this unexpected result.

TABLE VII.8: LIFE EXPECTANCY OF NUCLEAR REACTORS

	Scenario 1 Number of Reactors	Scenario 2 Number of Reactors
Less than 20 years	2	20
20 to 25	9	22
26 to 30	19	30
31 to 35	24	16
36 to 40	46	5
over 40	8	15
MEDIAN	34	28

FIGURE VII.3: NUMBER OF NUCLEAR UNITS BY LIFE EXPECTANCY



In both scenarios, the reactors expected to shutdown by 2005 are not concentrated in one specific area. On the contrary, they are broadly distributed among the different regions. Table VII.9 shows the number of nuclear reactors shutting down by the year 2005 according to their location. The regions with the highest number of reactors shutting down in both scenarios are the South Atlantic, Midwest and Mid Atlantic. These are the regions with the largest number of operating nuclear reactors. The determination of potential electricity shortages depends greatly on the location of these reactors not only by region, but by state, power pool location, and North American Electric Reliability Council (NERC) location.[2]

TABLE VII.9: LOCATION AND NUMBER OF UNITS SHUTTING DOWN BY THE YEAR 2005

		Scenario 1	Scenario 2
I.	New England	2	6
II.	New York/New Jersey	3	5
III.	Mid Atlantic	4	9
IV.	South Atlantic	5	18
V.	Midwest	4	14
VI.	Southwest	0	5
VII.	Central	2	3
VIII.	North Central	0	0
IX.	West	0	4
X.	Northwest	0	0
TOTAL		20	64

A large percent of the nuclear generating stock will be lost by 2005 (Table VII.10). According to Scenario 1 four regions will lose over 25 percent of their nuclear reactors while two other regions will lose over 15 percent of their reactors. According to Scenario 2 nine of the 10 regions will lose over fifty percent of their nuclear reactors by 2005.

Table VII.10: Percent of Nuclear Plants Retiring by 2005

Region	% of nuclear plants Scenario 1	% of nuclear plants Scenario 2
I. New England	25%	75%
II. New York/New Jersey	30%	50%
III. Middle Atlantic	27%	60%
IV. South Atlantic	17%	62%
V. Midwest	15%	54%
VI. Southwest	0	71%
VII. Central	40%	60%
VIII. North Central	0	0
IX. West	0	57%
X. Northwest	0	0

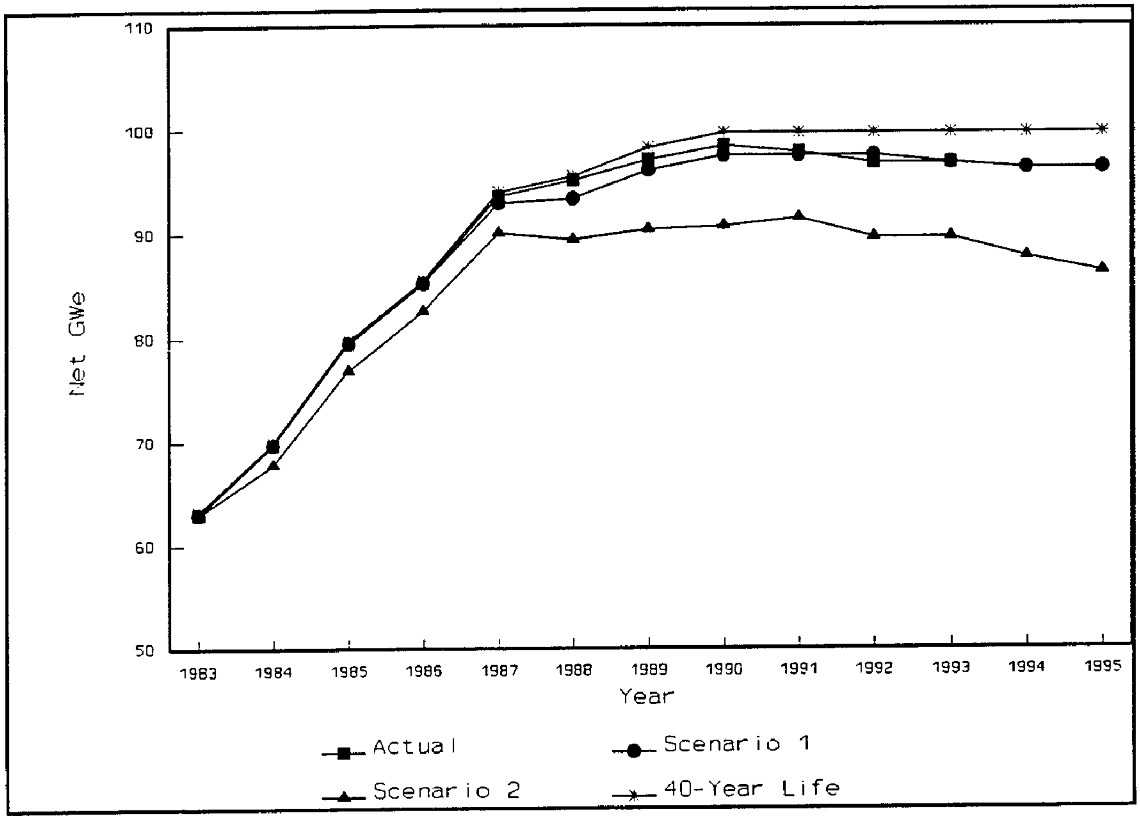
EVALUATION OF RESULTS

The evaluation of the results derived from Scenarios 1 and 2 is limited due to the small sample of nuclear reactors which have been permanently retired and to the lack of similar research studies.

A close look at how each scenario "predicted" nuclear retirements for the period 1983-1993 indicates that Scenario 1 is a better representation of historical nuclear retirements than is Scenario 2. The overall comparison of actual and predicted life expectancies is summarized in Figure VII.4. The figure presents historical data and different forecast scenarios for the total U.S. nuclear generating capacity. The figure is similar to Figure VII.1 but it is limited to the 13 year period from 1983 to 1995, and it includes the actual evolution of the U.S. capacity during this period. The curves include the 113 nuclear reactors considered in this study. This sample consists of 108 operating reactors and 5 permanently retired reactors. In order to be able to evaluate the results it was necessary to exclude the three nuclear reactors (Comanche Peak 2, Watts Bar 1 and Watts Bar 2) entering operation after 1990.

Scenario 1 provides the closest representation to what has happened historically. Scenario 2 underestimates the life of the nuclear generating stock, indicating that the approach projects more nuclear retirements than what has occurred during the period. The 40-year life case scenario overestimated the nuclear capacity for the period. It is important to note that the historical data sample is not large enough to permit any kind of statistical analysis. Nevertheless, the limited comparison implies that Scenario 1 provides the best results.

FIGURE VII.4: U.S. NUCLEAR GENERATING CAPACITY, 1983-1995



The results from Scenario 1 differ from those from Scenario 2 because their functional forms are different. In Scenario 1 all factors are considered equally and the coefficients are derived from the total sample of 113 reactors. The factors include: age, initial capacity factor, steam generator type, containment type, capacity, and architect/engineer. In Scenario 2 the emphasis is on four factors: age, initial performance, maximum attainable capacity factor, and the time at which this maximum is reached. Also, the coefficients in Scenario 2 are derived from the sample of older reactors (15 years old and older). In particular, the assumption used in Scenario 2, that a maximum attainable capacity factor is reached by the age of 15 years, results in many of the younger reactors (less than 15 years old) having shorter lives in Scenario 2 than in Scenario 1. This difference can be explained by the fact that many of these reactors may attain their maximum performance after the age of 15 years rather than before. This possibility is supported by the fact that many of these younger reactors have benefitted from advances in the technology and increasing operating knowledge.

The Initial Performance variable as represented by the first two-years capacity factor is another important variable causing the results to differ. Although this is considered an explanatory variable in both methods, in Scenario 2 its effect in the results is more obvious. In general, it can be asserted that nuclear reactors with good initial performance tend to perform well throughout their lives. This observation parallels similar experiences with other integrated technologies such as automobiles. The final performance of a multiple component machine is the result of a series of factors that characterize its parts and the way its integration process is carried out. In Scenario 2, the performance function is formulated in a mathematical way that gives this factor a more important role in the estimation of the reactors' lives.

There are 13 nuclear reactors which are predicted to be decommissioned at about the same time under both scenarios. Seven of these reactors are over 15 years old, and in fact 5 of them are over 20 years old. These reactors have similar life predictions because they are from the older reactors' vintage for which the assumption of maximum performance by 15 years of age is valid. Also, these reactors could have not benefitted from increasing knowledge and experience as reflected by the performance trend described by the functional form in Scenario 1. The similar predictions for the other 6 younger reactors is probably due to the fact that even though they could have benefitted from increasing knowledge and experience, the particular designs and equipment types that characterize them do not allow these benefits to make a considerable difference in the overall lifetime performance.

There are 12 reactors for which Scenario 2 predicts longer lives than Scenario 1. All of these reactors have very long lives under both scenarios and with only one exception they are all expected to operate beyond the 40-year licensed life under Scenario 2. They are reactors with very good performance in both scenarios. The most common characteristic of this group of reactors is a very good initial performance as reflected by extremely high capacity factors in their first year of operation. Their average initial capacity factor is 78% as compared to 57% for the overall sample. The initial performance variable plays a more relevant role in the life prediction process in Scenario 2 as compared to Scenario 1. In this group of reactors the initial capacity factor is so high that it overcomes the negative effect from other factors that normally would reduce the life predictions obtained from Scenario 1. Therefore, the very high initial capacity factors create results that may be biased toward longer lives than would otherwise be expected.

In summary, Scenario 1 should be selected over Scenario 2 for four reasons:

1. The performance function of Scenario 1 was derived from data on the total sample of 113 nuclear reactors. This sample includes all the reactors in the U.S. from old and young vintages. In particular, the sample includes the subsample of the youngest 52 reactors (15 years old and younger about 46% of the overall sample), which have benefitted from construction improvements, increasing operating knowledge, and better human performance derived from years of experience in early reactors' vintages. The performance function in Scenario 2 was developed based on a subsample that excludes these younger reactors and therefore the results cannot incorporate these benefits.
2. The performance function in Scenario 1 is solved without having to make any assumptions about the time at which the maximum performance is reached. Scenario 2 assumes that the maximum attainable capacity factor will be reached within the first 15 years of operation. Although this assumption is valid for the older generation of reactors, it may not hold for the younger subsample. Therefore, when the Scenario 2 performance function is applied to the younger group of reactors, the function may indicate a faster deterioration on plant efficiency than is reasonable.
3. When implemented over the last 10-year period (1983-1993), Scenario 1 provides a closer representation to what has happened historically. Scenario 2, on the other hand, underestimates the nuclear generating stock, indicating that the approach projects more nuclear retirements than

what has been observed during the period.

4. The results from Scenario 1 indicate that 82% of the stock will retire due to poor performance. The other 18% of the stock is retiring due to technological constraints. By contrast the results of Scenario 2 indicate that up to 95% of the nuclear reactors will retire due to poor performance. Since technological constraints provide more specific time limits for reactors' lives, Scenario 1 provides results that should be more accurate.

Assuming that Scenario 1 well represents the life expectancy of nuclear reactors in the U.S., then most of the problems associated with early retirement are important and should be addressed promptly, but they should not become as critical as implied in Scenario 2.

As explained in Chapter IV, the only study found in the literature that presents retirement estimates is the one by Hewlett. This study expects that 5 GWe of nuclear capacity will be retired by the year 2000. According to Scenario 1, 13 plants having about 11 GWe of electricity capacity will retire by the year 2000. Hewlett's results differ from those of this study because the methods used in the estimation of life expectancies are different. Hewlett simply looked at the costs of operating a nuclear reactor versus the cost of replacing it with a coal plant. His results indicated that for the 13 plants with more expensive operating costs it is more economic to replace the nuclear reactors with new coal plants. The approach followed in this study considers specific engineering and economic data not treated in Hewlett's approach.

Although the implementation of this forecasting system allows the definition of nuclear life expectancy scenarios, it is important to keep in mind that there are limitations associated with the particular approach. Some of the most important limitations include: low explanatory power in performance functions, limited reduction of uncertainty by the probabilistic performance forecast analysis, and uncertainty in the estimation of power replacement costs in the long-run.

Other limitations might make the life expectancy estimates less accurate. For instance, the discovery of new technological constraints might make some reactors retire sooner than predicted. As the nuclear generating stock continues aging, the deterioration of equipment and the long-term effects of nuclear radiation will become more evident. Some of the deterioration problems already identified or even not yet identified may eventually be classified as critical, forcing reactors to shutdown. On the other hand, technological improvements might make some reactors retire later than predicted. However, the impact of technological advancements in the nuclear stock already in operation is very limited. Nuclear experts might identify materials with higher resistance to radiation that can be used to build reactors components that last longer and at a lower cost. The problem is that the replacement procedures for critical components in nuclear operating reactors are risky, cumbersome, and costly. Many times the replacement procedures imply dangerous tasks in which personnel need to be exposed to radiation and contaminated tools and materials need to be disposed under strict regulated procedures. All these activities could increase the cost to a point at which the utility may opt to continue operating with the old components rather than replace them. The alternative to extend the useful life of certain reactor components is to change the operating conditions of the reactor (such as temperature, pressure, etc) so that the intensity of the components' exposure through time is reduced. These changes usually limit the reactor's efficiency and/or the ability to operate 24 hours as needed for baseload reactors. By contrast, technological improvements should be of great benefit in the design and economics of <u>new</u> nuclear reactors.

The accuracy of the estimates could also be reduced by drastic variations in electricity prices in the long-run. Electricity prices could affect the predictions in either direction. If the electricity prices drop considerably due to lower oil, coal, and gas prices, some reactors may shutdown sooner than expected. If electricity prices increase considerably, some reactors may operate longer than predicted. The subject is usually considered in electric capacity expansion planning studies. A model could be built to describe and quantify these effects.

The approach followed in this dissertation uses projections of electricity replacement costs at a power pool level. The replacement costs are derived from probabilistic simulations performed with a production-cost model that attempts to model the most likely scenarios expected in power pools. The cost for replacing the electricity already takes into consideration the fact that the particular nuclear reactor in question has been shutdown and the probability of other (nuclear and no-nuclear plants) shutdowns occurring at the same time in the same power pool. Thus, the replacement cost estimates attempt to emulate realistic scenarios that are commonly observed at the power pool level. If one considers the more unique situation, in which only the particular nuclear reactor in question is shutdown and all the other reactors in the pool remain in service, then the replacement costs may be lower than what is expected from this study. This situation implies more pessimistic results as more nuclear reactors will reach their uneconomical point at an earlier time. However, it is important to realize that the replacement costs are highly dependent on the characteristics of the particular power pool where the nuclear reactor operates. For power pools with low reserve capacity margins and high dependence on expensive fuels such as oil and gas, replacement energy costs for multiple shutdown cases may differ relative to single nuclear shutdown cases. On the other hand, power pools characterized by a large number of inexpensive power plants with sufficient capacity margins should experience about the same level of replacement costs whether a typical multiple or single nuclear shutdown scenario is considered.

Finally, it is important to note that the replacement costs considered in this study do not reflect critical scenarios of widespread multiple nuclear reactor shutdowns that may affect not only the replacement costs within a power pool but among different pools located in the same region. The simulation of this situation would require a data-intense recursive or equilibrium model capable of iterative procedures that would allow the convergence of electricity prices and plant shutdowns accordingly. The development of such a model goes beyond the scope of this study.

IMPACT OF EARLY RETIREMENTS

The impact of early nuclear plant retirements in electricity supplies need to be addressed at regional levels. The analysis in this section focuses on retirement estimates from Scenario 1 since this scenario has been selected over Scenario 2.

The consequences of early nuclear retirements in electricity supplies can be described with respect to expected total demand for electricity generation and electric capacity. In addition, since nuclear power is utilized as baseload capacity, it is important to assess the losses in overall baseload capacity due to early nuclear retirements. Ultimately, the criticality of electricity supplies at regional levels can be established by looking at forecasts of capacity margins and baseload capacity.

The Energy Information Administration (EIA) publishes electricity generation and capacity projections through 2010 at a regional level (Tables VII.11 and Table VII.12). Using these projections, the expected generating and capacity losses due to early nuclear plant retirements can be estimated. Unfortunately, EIA's forecasts are not available for the period post-2010. Thus, the analysis is limited to the period ending in 2010.

Table VII.11: EIA's Projections of Electricity Generation in Billion KWh

Region	2000	2005	2010
I. New England	115.3	129.4	143.3
II. New York/New Jersey	239.5	269.9	302.3
III. Middle Atlantic	409.4	443.5	486.3
IV. South Atlantic	723.0	789.3	864.2
V. Midwest	677.0	752.1	837.8
VI. Southwest	465.4	503.0	545.2
VII. Central	186.3	203.6	222.3
VIII. North Central	188.6	200.5	212.7
IX. West	340.7	384.1	429.9
X. Northwest	179.3	199.8	220.7
TOTAL	3524.5	3875.2	4264.7

Table VII.12: EIA's Projections of Electric Capacity in GW

Region	2000	2005	2010
I. New England	25.8	28.5	31.3
II. New York/New Jersey	52.8	59.7	66.1
III. Middle Atlantic	83.1	90.7	100.1
IV. South Atlantic	153.5	161.5	177.0
V. Midwest	138.1	153.3	170.7
VI. Southwest	109.9	111.7	121.3
VII. Central	46.2	50.6	55.3
VIII. North Central	31.7	33.8	36.1
IX. West	76.8	86.5	96.7
X. Northwest	41.6	45.4	49.3
TOTAL	759.5	821.7	903.9

Source: EIA, *Annual Outlook for U.S. Electric Power 1990: Projections through 2010*, DOE/EIA-0474(90).

The projected losses in electricity generation due to early retirement of nuclear reactors according to Scenario 1 (Table VII.13) are related to the EIA's projections to determine the percent losses in total electric generation (Table VII.14). The losses in terms of billion KWh are greatest in the South Atlantic region with over 60 billion KWh losses by 2010. This region is followed by the Middle Atlantic, Midwest and New York/New Jersey regions with over 10 billion KWh losses by 2005 and over 20 billion KWh by 2010. If the losses are analyzed in terms of percent of total electric generation, the New England region will incur the highest percent losses at 12.5% by 2010. Other regions with losses over 6% by 2010 include South Atlantic, New York/New Jersey and Middle Atlantic.

The projected losses in electric capacity due to early nuclear retirements in Scenario 1 (Table VII.15) are related to EIA's capacity projections to determine the percent losses in total electric capacity (Table VII.16). The capacity losses in terms of GW are greatest in the South Atlantic region with over 10 GW losses by 2010. This region is followed by the Middle Atlantic, Midwest and New York/New Jersey regions. If the losses are analyzed in terms of percent of total electric capacity, again the New England region will experience the highest percent losses at 9.3% by 2010. Other regions with losses over 5% by 2010 include South Atlantic, Middle Atlantic, and New York/New Jersey.

Table VII.13: Projected Losses in Electric Generation due to Early Nuclear Retirements, Scenario 1 (Billion KWh)

Region	2000	2005	2010
I. New England	4.1	7.5	17.9
II. New York/New Jersey	0	12.3	21.4
III. Middle Atlantic	17.9	22.9	32.6
IV. South Atlantic	19.6	28.3	69.4
V. Midwest	13.5	13.5	28.1
VI. Southwest	0	0	5.1
VII. Central	6.1	6.1	10.8
VIII. North Central	0	0	0
IX. West	0	0	20.7
X. Northwest	0	0	0
TOTAL	61.2	90.6	205.9

Table VII.14. Percent of Total Electric Generation Losses due to Early Nuclear Retirements, Scenario 1

Region	2000	2005	2010
I. New England	3.5%	5.8%	12.5%
II. New York/New Jersey	0%	4.6%	7.1%
III. Middle Atlantic	4.4%	5.2%	6.7%
IV. South Atlantic	2.7%	3.6%	8.0%
V. Midwest	2.0%	1.8%	3.4%
VI. Southwest	0%	0%	0.9%
VII. Central	3.3%	3.0%	4.9%
VIII. North Central	0%	0%	0%
IX. West	0%	0%	4.8%
X. Northwest	0%	0%	0%
TOTAL	1.74%	2.34%	4.83%

Table VII.15. Projected Losses in Electric Capacity due to Early Nuclear Retirements, Scenario 1 (GW)

Region	2000	2005	2010
I. New England	0.67	1.23	2.91
II. New York/New Jersey	0	2.01	3.48
III. Middle Atlantic	2.92	3.73	5.31
IV. South Atlantic	3.2	4.62	11.32
V. Midwest	2.21	2.21	4.59
VI. Southwest	0	0	0.84
VII. Central	0.99	0.99	1.76
VIII. North Central	0	0	0
IX. West	0	0	2.97
X. Northwest	0	0	0
TOTAL	9.98	14.78	33.18

Table VII.16. Percent of Total Electric Capacity Losses due to Early Nuclear Retirements, Scenario 1

Region	2000	2005	2010
I. New England	2.60%	4.32%	9.30%
II. New York/New Jersey	0%	3.37%	5.26%
III. Middle Atlantic	3.51%	4.11%	5.30%
IV. South Atlantic	2.08%	2.86%	6.40%
V. Midwest	1.60%	1.44%	2.69%
VI. Southwest	0%	0%	0.69%
VII. Central	2.15%	1.96%	3.18%
VIII. North Central	0%	0%	0%
IX. West	0%	0%	3.07%
X. Northwest	0%	0%	0%
TOTAL	1.32%	1.80%	3.67%

In summary, the analysis of the results with respect to future forecasts of electric generation and electric capacity indicate that the regions with largest potential for electric supply shortages due to early nuclear retirements are New England, South Atlantic, Middle Atlantic, and New York/New Jersey. New England in particular will experience the largest percent losses. Presently, New England is the region with the highest dependency on nuclear power in the country.

The criticality of electricity supplies is evaluated by looking at forecasts of baseload capacity and electric capacity margins. Baseload capacity refers to the generating capacity that is used to satisfy the basic demand of electricity that is required continuously. This demand is satisfied using power generating plants that are kept in service at all times possible and at their maximum capacity. In general the baseload capacity includes coal, nuclear and hydroelectric power plants. Although the requirements of baseload capacity vary from region to region, it is desirable to maintain as baseload 40% to 60% of the overall capacity available. The projections of baseload capacity through 2010 indicate that the New England and the New York/New Jersey regions will count on baseload capacities close to the desired minimum by 2005 and 2010(Table VII.17). If the percent of total electric capacity losses due to early nuclear retirements (in Table VII.16) are subtracted from the forecasts of baseload capacity for these two regions, their baseload capacities will drop below the minimum of 40% by 2005. The New England region will have a baseload capacity of only 35.4% by 2010 while the New York/New Jersey region of only 39.2%. The analysis on baseload capacity indicates potential electricity supply problems in these two regions.

Another parameter that can be used to determine the electricity supply adequacy in regions with early nuclear retirements is the capacity margins. Capacity margins refer to the amount of generating capacity available to provide for scheduled maintenance, emergency outages, system operating requirements, and unforeseen electricity demand.[3] The capacity margins ensure adequate electricity supplies above expected peak demands providing flexibility for emergencies, equipment deratings due to various causes, and other uncertainties. Although capacity margins requirements vary from region to region, it is considered adequate to keep capacity margins above 15% of the total electricity capacity to ensure reliability.[4]

Table VII.17. Baseload Capacity as a percent of Total Capacity Forecasts

Region	2000	2005	2010
I. New England	40.0%	41.4%	44.7%
II. New York/New Jersey	34.3%	42.2%	44.5%
III. Middle Atlantic	71.7%	72.8%	74.2%
IV. South Atlantic	72.2%	74.0%	75.5%
V. Midwest	73.3%	74.8%	76.0%
VI. Southwest	46.4%	48.8%	52.8%
VII. Central	66.7%	65.4%	66.2%
VIII. North Central	83.3%	77.8%	72.3%
IX. West	48.4%	51.8%	54.5%
X. Northwest	87.7%	80.4%	74.0%

Source: Baseload capacity derived using data from EIA, *Annual Outlook for U.S. Electric Power 1990: Projections through 2010*, DOE/EIA-0474(90).

Forecasts of capacity margins are developed at the power pool level by the North American Electric Reliability Council (NERC). The latest forecasts of capacity margins available are for the year 2002. When the forecasts are adapted to the 10 federal regions used in this study, all the regions with the exception of the New England region are expected to have margins above the 15% desired minimum by 2002 (Table VII.18). The capacity margins in the New England region are expected to drop from 22.5% in 1995 to 3.4% in 2002. Other regions with capacity margins below 20% include South Atlantic, Midwest, Southwest, and West. Since there are no forecasts of capacity

Table VII.18. Capacity Margin Forecasts as a Percent of Total Planned Capacity

Region	1995	2000	2002
I. New England	22.5%	13.2%	3.4%
II. New York/New Jersey	30.1%	27.5%	26.2%
III. Middle Atlantic	19.0%	20.6%	20.0%
IV. South Atlantic	16.8%	16.7%	15.6%
V. Midwest	17.2%	16.2%	16.2%
VI. Southwest	19.2%	17.0%	16.5%
VII. Central	24.9%	22.6%	21.4%
VIII. North Central	24.9%	22.6%	21.4%
IX. West	22.7%	18.7%	17.3%
X. Northwest	29.9%	30.1%	29.8%

Source:Regional values derived from power pool forecasts published in NERC, *Electricity Supply and Demand 1993-2002*, June 1993.

margins for the period ending in 2010, the impact of nuclear retirements by 2010 cannot be assessed. However, if the percent of total electric capacity losses due to early nuclear retirements (Table VII.16) for the years 2000 or 2005 are subtracted from the capacity margins for either 2000 or 2002, the regions with inadequate capacity margins will be New England, South Atlantic, and the Midwest. Therefore, if early nuclear retirements occur in these regions as predicted in Scenario 1, there will not be enough additional capacity in the form of capacity margins that can be used to replace this power.

The analysis on the criticality of electricity supplies indicate that the region that will be most badly affected by early nuclear retirements is New England. Forecasts of both baseload capacity and capacity margins for this region imply insufficient electricity supplies as early as the year 2000. Other regions with potential supply problems are New York/New Jersey, South Atlantic, and Midwest. The New York/New Jersey region is not expected to have sufficient baseload capacity available to replace generation from nuclear reactors even though it will have adequate capacity margins . Although the South Atlantic and Midwest regions will have sufficient baseload capacity, they will lack capacity margins above the desired minimum.

POLICY IMPLICATIONS

The implications related to early retirement are very important and diverse. In addition to potential problems related to electricity supplies and replacement capacity, there will be negative effects on rate payers, utility shareholders, and state and federal taxpayers. Forecasting and planning activities related to nuclear waste disposal, replacement capacity, uranium supplies, and capital investments would have to be modified. Some of the most uncertain implications are in the area of finance. There would be important questions related to who should pay for the large losses in capital investment if the reactors are retired before they are fully depreciated. Who would pay for the rest of the funds needed for decommissioning activities? Should all these expenses be paid by the ratepayers who benefitted from using the nuclear reactors in the past? Or should the future ratepayer be charged for all these costs? Or should all these costs be born by the utility shareholders who were responsible for building and operating these plants?

Policies can be suggested in the following areas: planning and reporting activities, electricity supply, nuclear waste disposal, decommissioning funds, and capital investment depreciation. Each of these is discussed below.

In the area of planning and reporting activities, utilities with nuclear reactors should be asked to report objectively the time at which they are expecting their reactors to be permanently retired. By looking at the poor engineering status and the increasing operating cost of some nuclear reactors, it seems obvious that the owners of these reactors are not expecting lives of 40 years. However, utilities are not willing to accept this in public nor are they willing to report a life of less than 40-years in the required annual survey forms. The objective life estimate reports from the utilities can be used in the development of more accurate electricity supply forecasts, replacement scenarios, and related activities.

In the area of electricity supplies, the Department of Energy, State Public Utility

Commissions, and utilities should develop electricity supply scenarios that should consider cases in which nuclear reactors do not operate for their 40-year licensed lives. These forecasts should incorporate replacement options accordingly. The replacement alternatives to the nuclear generating stock depend on the particular location and the timing at which the replacement would be needed. An overview of potential replacement options is presented in Appendix B.

In the area of nuclear waste disposal, the Federal government and the states should accelerate the development of the permanent repository site for high level nuclear waste as well as state sites for low-level nuclear waste. If several nuclear reactors are forced to retire earlier than expected, final decommissioning of these reactors cannot take place because there will not be facilities available for the safe disposal of high level nuclear radiated materials, equipment and tools. If several years are needed before decommissioning is performed, then there will be high costs related to the temporary storage of nuclear waste in provisional facilities built on-site. In addition, since the reactors might not be taken apart immediately after permanent retirement, additional personnel may be needed to ensure proper maintenance and security of mothballed reactors. Thus, the collection of funds by DOE for the building of a national nuclear permanent repository site should be accelerated and should be increased if necessary.

Decommissioning activities related to the safe disassembly and disposal of nuclear reactors and components will also be affected by early nuclear retirements. The U.S. decommissioning rule establishes that owners of nuclear reactors have to provide a reasonable assurance of adequate funds for the safe and complete decommissioning of facilities by the time the reactors are permanently retired.[5] Each utility is required to develop and maintain a funding plan specifying cost and time tables. The Nuclear Regulatory Commission performs certification and periodic reviews of each plan. These plans are based on a 40-year life assumption. The current method of choice to ensure adequate funds for decommissioning activities is an external sinking fund reserve. This type of fund ensures the availability of segregated reserves dedicated exclusively to the payment of nuclear decommissioning costs. The rule attempts to protect the decommissioning assets from the claim of creditors in case of bankruptcy proceedings. There is already controversy about the rate of collection of funds since decommissioning is a very uncertain process characterized by complex dismantling techniques. Early nuclear retirements imply the unavailability of adequate funds for decommissioning activities. Therefore, the collection of these funds should be accelerated for those nuclear reactors expected to retire prematurely.

In the area of capital depreciation, utilities should recalculate their depreciation time frames to account for a life expectancy shorter than the 40-year licensed life. In general all financial planning activities should be reassessed based on the objective estimate of nuclear reactor lives.

References

1. *Nuclear Engineering International*, "Supporting License Renewal in the U.S.," a Plant Life Extension article, February 1990, pp.54-55. Ferguson, Jack, "Counting the Cost of Delay," *Nuclear Engineering International*, November 1988, pp.49-50.

2. Power pools refer to associations of two or more interconnected electric systems formed to provide better system reliability and efficiencies. The North American Electric Reliability Council regions refer to nine regional reliability councils that encompass all power systems in the contiguous U.S.

3. NERC, *Electricity Supply and Demand 1993 - 2002*, June 1993.

4. OTA, *Electric Power Wheeling and Dealing: Technological Considerations for Increasing Competition*, 1989.

5. NRC, "General Requirements for Decommissioning Nuclear Facilities," *Federal Register*, 54(123): 24108-24056, 1988.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

This chapter presents a summary of this study, including a brief discussion of the research objective, problem statement, and research method. The second section of the chapter summarizes general and specific conclusions derived from this research activity.

SUMMARY

The major objective of this research is to develop a replicable method for estimating the life expectancy of nuclear reactors. The analytical approach is formulated based on assumptions derived from relevant engineering and economic data specific to nuclear reactors. A second objective is the implementation of this forecasting tool in the estimation of the life expectancy of the U.S. nuclear generating stock. By reaching these objectives, this study allows the identification of early nuclear retirements, thus facilitating forecasts of potential electricity capacity shortages and more accurate electricity supply planning. In addition, the evaluation of nuclear reactor life expectancy provides information necessary for the analysis and assertion of several related issues such as nuclear waste disposal, decommissioning, capital investment recovery, and other planning, financial, and regulatory activities.

Although nuclear electricity represents about twenty percent of the net electricity generated in the United States, there are no technical design specifications that determine the life expectancy of the 109 nuclear reactors operating in the nation. The lack of design data is the result of the accelerated construction of large nuclear generating units by manufacturers without having enough knowledge about the nuclear technology and about the impact of nuclear radiation on critical equipment. As the U.S. nuclear stock continues aging, deterioration of critical engineering equipment and increasing operating costs have forced the permanent retirement of nuclear reactors expected to operate beyond the end of this century. These retirements are creating a sense of uncertainty with respect to the future of nuclear power and bring into question the commonly accepted assumption that nuclear reactors will operate for the 40 years for which they are licensed to operate. This research study provides an analytical tool that considers specific engineering and economic data for the estimation of nuclear life expectancy.

The approach followed in this study is based on the evaluation of both the economic life and the technological life of the nuclear reactors. The approach recognizes that these are the most important determinants of the useful life of nuclear reactors and that they need to be taken into consideration in an integrated manner.

The research method consists of an integrated modeling system that incorporates and relates relevant factors allowing the assessment of nuclear plant lives (Figure V.1). The forecasting system includes an engineering module and an economic module. The engineering module components are: a nuclear performance submodule and a nuclear technological constraint submodule. The nuclear reactor performance submodule describes the performance of nuclear reactors through time according to efficiency parameters based on general and technical characteristics such as age, size, and equipment designs and types. The nuclear technological constraint submodule considers constraints related to the progressive deterioration of materials and equipment due to the aging process and in particular due to problems associated with nuclear radiation. The nuclear technological constraint submodule imposes limitations on the final life of nuclear reactors regardless of the level of performance defined by the performance submodule. The economic module consists of a nuclear cost submodule and a replacement cost submodule. The nuclear cost submodule defines the cost of producing nuclear electricity as a function of capacity factors. This submodule is then related to the replacement cost submodule on a reactor-by-reactor basis to determine the minimum efficiency level beyond which it becomes more expensive to operate the reactor than to replace the power.

Two sets of results have been generated from the analysis of two scenarios that consider different engineering performance forecast approaches. Although the scenarios produce very different results, both scenarios indicate that a considerable number of reactors will retire before they reach their expected licensed life of 40 years.

This research effort is different from previous works because it is based on the premise that nuclear life expectancy is a direct consequence of the status and future deterioration of nuclear engineering components. All previous efforts have been based purely on operating costs, and they have not considered critical engineering data. This study also considers operating costs but in an integrated manner and as a function of plant performance, implying that their escalation through time is the result of engineering constraints.

CONCLUSIONS

A general conclusion is that a method has been developed capable of estimating the life expectancy of nuclear reactors. The approach incorporates and relates relevant engineering and economic data into a modeling system that differs from all previous work in the field. The method is replicable and as more data on nuclear reactors accumulate more accurate life predictions can be made. This analytical tool has been implemented on the U.S. nuclear generating stock allowing the formulation of two life expectancy scenarios. The approach is applicable to other countries' nuclear stocks subject to availability of technical data specific to the designs and types of reactors operating in those countries.

There are limitations related to the approached followed in this study. The limitations are associated with the particular method used and with data availability. The method presents limitations in its performance, technological constraint, and cost components. Performance functions, developed to forecast the level of efficiency of the reactors through time, have low explanatory potential for the description of the variation of capacity factors. This deficiency may be the result of the use of proxy parameters such as age and initial performance to describe complex mechanisms affecting the condition of critical equipment and ultimately the reactor's performance. In addition, the low explanatory power is the result of large variations (on a year-by-year basis) in the range of capacity factors observed among nuclear reactors throughout their operating lives. Also, the lack of operating data for the latter half of the life of nuclear reactors (after the age of 15 to 20 years) limits the fitting process of functional forms needed to represent the performance variations expected in the long-run. Technological constraint limitations are mainly due to the fact that research is still being conducted for the assessment of the deterioration of critical components exposed to nuclear radiation. Future research could allow the identification of other technological constraints limiting the life of nuclear reactors and not considered in this study. In addition, limiting life factors such as steam generator tube failures have been clearly identified but cannot be used in the approach until specific criteria are specified. Finally, there are limitations in the cost component which are mainly related to the replacement cost estimates. Although the replacement costs are based on reliable probabilistic forecasts, the estimations are uncertain in the long-run.

Although it is important to understand that there are limitations related to the analytical tool developed in this study, it is clear that many of these limitations will diminish as more relevant data become available. For instance, performance functions that better fit capacity factor variations can be identified as reactors accumulate more operating data especially for the second half of their lives. Also, it is expected that more technological constraints will be identified and more complete evaluating criteria will be specified allowing a better assessment of nuclear retirements due to critical constraints.

The implementation of the method on the U.S. nuclear generating stock indicates that the commonly-used 40-year life assumption for nuclear reactors is optimistic. As explained throughout this document, utilities and other institutions involved in planning, forecasting, and regulatory processes for the nuclear and electric generating industry are assuming that nuclear plants have useful lives equivalent to at least the 40 years for which they are licensed to operate. This research study predicts that several nuclear reactors will retire before the end of their licensed life.

The life expectancy results from the scenarios developed in this study show a wide dispersion of life expectancies among nuclear reactors (Table VII.1 and Table VII.4). Scenario 1 estimates the median life of the still-active U.S. nuclear generating stock to be 34 years. Scenario 2 indicates a median life of 28 years. Median forecasts from both scenarios seem optimistic as compared to the sample of 21 permanently retired nuclear reactors. The average life for this sample of retired reactors is only 15 years. However, many of these retired reactors do not represent the current operating stock of nuclear reactors in the U.S. because of technological advances in the newer plants.

Scenario 1 indicates that the majority of the nuclear reactors, about 62 percent, will have operating lives that range between 30 and 40 years. According to this scenario, 13 reactors will be retired by the year 2000 and a total of 20 reactors will shutdown by 2005. Although the South Atlantic, Midwest and Middle Atlantic regions will have the largest number of reactors shutting down by 2005, the New England, Central, and the New York/New Jersey regions are the ones expected to lose the highest proportion of nuclear generating stock.

Scenario 2 indicates that the majority of the nuclear reactors, about 67 percent, will have operating lives of less than 30 years. According to this scenario, 37 reactors will be retired by the year 2000 and a total of 64 reactors will shutdown by 2005. This represents almost 60 percent of the nuclear generating stock. Although the South Atlantic, Midwest and Middle Atlantic regions will have the largest number of reactors shutting down by 2005, the New England region is expected to lose the highest proportion of nuclear generating stock (about 75%).

The evaluation of the nuclear life expectancy results from this research study is limited due to insufficient data on either historical observations or similar research activities. Nevertheless, Scenario 1 seems to provide the best assessment of the problem and should be accepted as the most likely life expectancy scenario for the U.S. nuclear generating stock. Scenario 1 was developed using a sample of nuclear reactors that better represents the current stock. The approach followed in this scenario also better considers changes in construction quality and operating knowledge over time. In addition, Scenario 1 generates the closest representation to what has happened historically when implemented over the 1983-1993 period. Conversely, Scenario 2 was developed based on assumptions of maximum attainable capacity factors that may not hold for the subsample of younger reactors expected to have benefitted from technological and operating improvements. Therefore, the results from Scenario 2 may indicate a faster deterioration of plant efficiency than is warranted.

The impact of early nuclear plant retirements on electricity supplies are addressed at regional levels based on results from Scenario 1 since this scenario has been selected over Scenario 2. The consequences of early nuclear retirements are measured using forecasts of total electricity generation and electric capacity for the period ending in 2010. This analysis indicates that the regions with the largest potential for electric supply shortages due to early nuclear retirements are New England, South Atlantic, Middle Atlantic, and New York/New Jersey. New England in particular will experience the largest percent losses (12.5% losses in generation and 9.3% losses in total capacity).

The criticality of electricity supplies at regional levels is established by looking at forecasts of baseload capacity and capacity margins. Based on this analysis, the regions identified with potential electricity supply problems are New England, South Atlantic, Midwest, and New York/New Jersey. The region that will be most badly affected by early nuclear retirements is New England. Forecasts of both baseload capacity and capacity margins for this region imply insufficient electricity supplies as early as the year 2000. The South Atlantic and Midwest regions will lack capacity margins above the desired minimum also by 2000. However, these regions are expected to have enough baseload capacity. Finally, the New York/New Jersey region is expected to have sufficient capacity margins but not enough baseload capacity to replace retiring nuclear reactors.

The options for the replacement of retiring nuclear capacity vary from region to region. A summary of replacement options per region is presented in Appendix B. Coal seems to be the obvious option to replace baseload capacity in many regions. However, environmental constraints imposed by the 1990 Clean Air Act Amendments could make coal a very expensive option. Natural gas will play an important role in replacing nuclear reactors in many regions. Nevertheless, there will be supply limitations and expected increases in natural gas prices may make this option less competitive. Regions such as New England and the Northwest may be able to satisfy demand by purchasing power in the form of imports from Canada. Purchases from non-utility producers is another option for the New England and West regions. New nuclear power will be a possibility only for certain regions such as the South Atlantic. Conservation is a major alternative if federal, state, and local governments implement policies that create incentives for Demand Side Management and other conservation programs. Renewables will only be able to play a limited role due to efficiency constraints and the level of technological development. The West is the only region expected to replace a considerable part of its retiring nuclear capacity with renewables.

The implications related to early retirement are very diverse and far reaching. In addition to concerns about electricity supplies and replacement capacity, negative consequences are expected for ratepayers, utility shareholders, and state and federal tax payers. Modifications will be necessary in planning, forecasting and financing activities in areas related to nuclear waste disposal, capital investments, and fuel supplies. Important legal and regulatory issues will arise because of the need to determine who will pay for non-fully depreciated but permanently retired nuclear plants and who will provide additional funds needed for decommissioning. Utilities with nuclear reactors should be required to provide objective reports supporting the life expectancy estimates of their nuclear reactors and their plans for capacity replacement. The Department of Energy, the State Public Utility Commissions, and utilities should develop electricity supply scenarios that consider early nuclear retirements and respective replacement alternatives. The Federal government should accelerate the construction and collection of funds for the development of the national permanent repository site for nuclear waste disposal. Also, the collection of funds for decommissioning should be accelerated. Finally, utilities should reassess all financial planning activities including depreciation schedules.

APPENDIX A

TABLE A1: REACTOR GENERAL CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	REGION	STATE	NERC POOL	NERC REGION	REACTOR TYPE	CONTAINT TYPE	MDC CAPAC. REACTOR SIZE	AGE	VINTAGE FIRST YEAR Constr.	YEARS UNDER CONSTR.	VINTAGE FIRST YEAR Operat.
Ark. Nuc. 1	VI (SW)	Arkansas	20	SPP	PWR	DRYAMB	836	19	1969	5	1974
Ark. Nuc. 2	VI (SW)	Arkansas	20	SPP	PWR	DRYAMB	858	15	1973	5	1978
Beaver Valley 1	III (MA)	Pennsylvania	2	ECAR	PWR	DRYSUB	810	17	1970	6	1976
Beaver Valley 2	III (MA)	Pennsylvania	2	ECAR	PWR	DRYSUB	820	6	1974	13	1987
Big Rock Point	V (MW)	Michigan	4	ECAR	BWR	DRYAMB	67	30	1960	3	1963
Braidwood 1	V (MW)	Illinois	8	MAIN	PWR	DRYAMB	1120	6	1976	11	1987
Braidwood 2	V (MW)	Illinois	8	MAIN	PWR	DRYAMB	1120	5	1976	12	1988
Browns Ferry 1	IV (SA)	Alabama	18	SERC	BWR	MARK1	1065	20	1967	6	1973
Browns Ferry 2	IV (SA)	Alabama	18	SERC	BWR	MARK1	1065	19	1967	7	1974
Browns Ferry 3	IV (SA)	Alabama	18	SERC	BWR	MARK1	1065	17	1968	8	1976
Brunswick 1	IV (SA)	North Carolina	19	SERC	BWR	MARK1	767	17	1970	6	1976
Brunswick 2	IV (SA)	North Carolina	19	SERC	BWR	MARK1	754	18	1970	5	1975
Byron 1	V (MW)	Illinois	8	MAIN	PWR	DRYAMB	1105	8	1976	9	1985
Byron 2	V (MW)	Illinois	8	MAIN	PWR	DRYAMB	1105	6	1976	11	1987
Callaway 1	VII Central	Missouri	9	MAIN (10)	PWR	DRYAMB	1125	9	1976	8	1984
Calvert Cliffs 1	III (MA)	Maryland	7	MAAC	PWR	DRYAMB	825	19	1969	5	1974
Calvert Cliffs 2	III (MA)	Maryland	7	MAAC	PWR	DRYAMB	825	17	1969	7	1976
Catawba 1	IV (SA)	South Carolina	19	SERC	PWR	ICECND	1129	8	1975	10	1985
Catawba 2	IV (SA)	South Carolina	19	SERC	PWR	ICECND	1129	7	1975	11	1986
Clinton 1	V (MW)	Illinois	9	MAIN (10)	BWR	MARK3	930	6	1976	11	1987
Comanche Peak 1	VI (S.West)	Texas	5	ERCOT6	PWR	DRYAMB	1150	3	1975	15	1990
Cook 1	V (MW)	Michigan	1	ECAR	PWR	ICECND	1020	19	1969	5	1974
Cook 2	V (MW)	Michigan	1	ECAR	PWR	ICECND	1090	15	1969	9	1978
Cooper	VII Central	Nebraska	12	MAPP	BWR	MARK1	764	19	1968	6	1974
Crystal River 3	IV (SA)	Florida	16	SERC	PWR	DRYAMB	821	16	1968	9	1977
Davis–Besse 1	V (MW)	Ohio	2	ECAR	PWR	DRYAMB	874	16	1971	6	1977
Diablo Canyon 1	IX (West)	California	27	WSCC	PWR	DRYAMB	1073	9	1968	16	1984
Diablo Canyon 2	IX (West)	California	27	WSCC	PWR	DRYAMB	1087	8	1971	14	1985
Dresden 2	V (MW)	Illinois	8	MAIN	BWR	MARK1	772	23	1966	4	1970
Dresden 3	V (MW)	Illinois	8	MAIN	BWR	MARK1	773	22	1966	5	1971
Duane Arnold	VII Central	Iowa	12	MAPP	BWR	MARK1	515	19	1970	4	1974

TABLE A1: REACTOR GENERAL CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	REGION	STATE	NERC POOL	NERC REGION	REACTOR TYPE	CONTAINT TYPE	MDC CAPAC. REACTOR SIZE	AGE	VINTAGE FIRST YEAR Constr.	YEARS UNDER CONSTR.	VINTAGE FIRST YEAR Operat.
Farley 1	IV (SA)	Alabama	17	SERC	PWR	DRYAMB	814	16	1972	5	1977
Farley 2	IV (SA)	Alabama	17	SERC	PWR	DRYAMB	824	12	1972	9	1981
Fermi 2	V (MW)	Michigan	4	ECAR	BWR	MARK1	1060	8	1972	13	1985
Fitzpatrick	II (NY/NJ)	New York	15	NPCC	BWR	MARK1	780	19	1970	4	1974
Fort Calhoun 1	VII Central	Nebraska	12	MAPP	PWR	DRYAMB	478	20	1968	5	1973
Fort St. Vrain	VIII(NCen.)	Colorado	28	WSCC	HTGR		200	17	1968	8	1976
Ginna	II (NY/NJ)	New York	15	NPCC	PWR	DRYAMB	470	23	1966	4	1970
Grand Gulf 1	IV (SA)	Mississippi	20	SPP17	BWR	MARK3	1143	9	1974	10	1984
Haddam Neck (C.Y)	I (NE)	Connecticut	14	NPCC	PWR	DRYAMB	560	25	1964	4	1968
Harris 1	IV (SA)	North Carolina	17	SERC	PWR	DRYAMB	860	6	1978	9	1987
Hatch 1	IV (SA)	Georgia	17	SERC	BWR	MARK1	741	19	1969	5	1974
Hatch 2	IV (SA)	Georgia	17	SERC	BWR	MARK1	761	15	1973	5	1978
Hope Creek 1	II (NY/NJ)	New Jersey	7	MAAC	BWR	MARK1	1067	7	1974	12	1986
Indian Point 2	II (NY/NJ)	New York	15	NPCC	PWR	DRYAMB	939	20	1966	7	1973
Indian Point 3	II (NY/NJ)	New York	15	NPCC	PWR	DRYAMB	965	17	1969	7	1976
Kewaunee	V (MW)	Wisconsin	11	MAIN	PWR	DRYAMB	511	20	1968	5	1973
LaSalle 1	V (MW)	Illinois	8	MAIN	BWR	MARK2	1036	11	1973	9	1982
LaSalle 2	V (MW)	Illinois	8	MAIN	BWR	MARK2	1036	9	1973	11	1984
Limmerick 1	III (MA)	Pennsylvania	7	MAAC	BWR	MARK2	1055	8	1974	11	1985
Limmerick 2	III (MA)	Pennsylvania	7	MAAC	BWR	MARK2	1055	4	1974	15	1989
Maine Yankee	I (NE)	Maine	14	NPCC	PWR	DRYAMB	860	20	1968	5	1973
Mc Guire 1	IV (SA)	North Carolina	19	SERC	PWR	ICECND	1129	12	1973	8	1981
Mc Guire 2	IV (SA)	North Carolina	19	SERC	PWR	ICECND	1129	10	1973	10	1983
Millstone 1	I (NE)	Connecticut	14	NPCC	BWR	MARK1	654	22	1966	5	1971
Millstone 2	I (NE)	Connecticut	14	NPCC	PWR	DRYAMB	863	18	1971	4	1975
Millstone 3	I (NE)	Connecticut	14	NPCC	PWR	DRYSUB	1137	7	1974	12	1986
Monticello	V (MW)	Minnesota	12	MAPP	BWR	MARK1	536	22	1967	4	1971
Nine Mile Pnt 1	II (NY/NJ)	New York	15	NPCC	BWR	MARK1	615	24	1965	4	1969
Nine Mile Pnt 2	II (NY/NJ)	New York	15	NPCC	BWR	MARK2	1097	6	1974	13	1987
North Anna 1	III (MA)	Virginia	19	SERC	PWR	DRYSUB	911	15	1971	7	1978
North Anna 2	III (MA)	Virginia	19	SERC	PWR	DRYSUB	909	13	1971	9	1980

TABLE A1: REACTOR GENERAL CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	REGION	STATE	NERC POOL	NERC REGION	REACTOR TYPE	CONTAINT TYPE	MDC CAPAC. REACTOR SIZE	AGE	VINTAGE FIRST YEAR Constr.	YEARS UNDER CONSTR.	VINTAGE FIRST YEAR Operat.
Oconee 1	IV (SA)	South Carolina	19	SERC	PWR	DRYAMB	846	20	1967	6	1973
Oconee 2	IV (SA)	South Carolina	19	SERC	PWR	DRYAMB	846	20	1967	6	1973
Oconee 3	IV (SA)	South Carolina	19	SERC	PWR	DRYAMB	846	19	1967	7	1974
Oyster Creek 1	II (NY/NJ)	New Jersey	7	MAAC	BWR	MARK1	610	24	1965	4	1969
Palisades	V (MW)	Michigan	4	ECAR	PWR	DRYAMB	730	22	1967	4	1971
Palo Verde 1	IX (West)	Arizona	26	WSCC	PWR	DRYAMB	1221	8	1976	9	1985
Palo Verde 2	IX (West)	Arizona	26	WSCC27	PWR	DRYAMB	1221	7	1976	10	1986
Palo Verde 3	IX (West)	Arizona	26	WSCC27	PWR	DRYAMB	1221	6	1976	11	1987
Peach Bottom 2	III (MA)	Pennsylvania	7	MAAC	BWR	MARK1	1055	20	1968	5	1973
Peach Bottom 3	III (MA)	Pennsylvania	7	MAAC	BWR	MARK1	1035	19	1968	6	1974
Perry 1	V (MW)	Ohio	2	ECAR	BWR	MARK3	1166	7	1977	9	1986
Pilgrim 1	I (NE)	Massachusetts	14	NPCC	BWR	MARK1	670	21	1968	4	1972
Point Beach 1	V (MW)	Wisconsin	11	MAIN	PWR	DRYAMB	485	23	1967	3	1970
Point Beach 2	V (MW)	Wisconsin	11	MAIN	PWR	DRYAMB	485	21	1968	4	1972
Praire Isl. 1	V (MW)	Minnesota	12	MAPP	PWR	DRYAMB	503	20	1968	5	1973
Praire Isl. 2	V (MW)	Minnesota	12	MAPP	PWR	DRYAMB	500	19	1968	6	1974
Quad–Cities 1	V (MW)	Illinois	8	MAIN12	BWR	MARK1	769	21	1967	5	1972
Quad–Cities 2	V (MW)	Illinois	8	MAIN12	BWR	MARK1	769	21	1967	5	1972
Rancho Seco	IX (West)	California	27	WSCC	PWR		873	19	1968	6	1974
River Bend 1	VI (SW)	Louisiana	20	SPP	BWR	MARK3	936	8	1977	8	1985
Robinson 2	IV (SA)	South Carolina	19	SERC	PWR	DRYAMB	683	23	1967	3	1970
Salem 1	II (NY/NJ)	New Jersey	7	MAAC	PWR	DRYAMB	1106	17	1968	8	1976
Salem 2	II (NY/NJ)	New Jersey	7	MAAC	PWR	DRYAMB	1106	12	1968	13	1981
San Onofre 1	IX (West)	California	27	WSCC	PWR	DRYAMB	436	25	1964	4	1968
San Onofre 2	IX (West)	California	27	WSCC	PWR	DRYAMB	1070	11	1973	9	1982
San Onofre 3	IX (West)	California	27	WSCC	PWR	DRYAMB	1080	10	1973	10	1983
Seabrook 1	I (NE)	New Hampshire	14	NPCC	PWR	DRYAMB	1150	3	1976	14	1990

TABLE A1: REACTOR GENERAL CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	REGION	STATE	NERC POOL	NERC REGION	REACTOR TYPE	CONTAIN TYPE	MDC CAPAC. REACTOR SIZE	AGE	VINTAGE FIRST YEAR Constr.	YEARS UNDER CONSTR.	VINTAGE FIRST YEAR Operat.
Sequoyah 1	IV (SA)	Tennessee	18	SERC	PWR	ICECND	1122	13	1970	10	1980
Sequoyah 2	IV (SA)	Tennessee	18	SERC	PWR	ICECND	1122	12	1970	11	1981
South Texas 1	VI (SW)	Texas	5	ERCOT6	PWR	DRYAMB	1251	5	1976	12	1988
South Texas 2	VI (SW)	Texas	5	ERCOT6	PWR	DRYAMB	1251	4	1976	13	1989
St. Lucie 1	IV (SA)	Florida	16	SERC	PWR	DRYAMB	839	17	1970	6	1976
St. Lucie 2	IV (SA)	Florida	16	SERC	PWR	DRYAMB	839	10	1977	6	1983
Summer 1	IV (SA)	South Carolina	19	SERC	PWR	DRYAMB	885	11	1973	9	1982
Surry 1	III (MA)	Virginia	19	SERC	PWR	DRYSUB	781	21	1968	4	1972
Surry 2	III (MA)	Virginia	19	SERC	PWR	DRYSUB	781	20	1968	5	1973
Susquehanna 1	III (MA)	Pennsylvania	7	MAAC	BWR	MARK2	1040	11	1973	9	1982
Susquehanna 2	III (MA)	Pennsylvania	7	MAAC	BWR	MARK2	1044	9	1973	11	1984
Three Mile Isl.1	III (MA)	Pennsylvania	7	MAAC	PWR	DRYAMB	808	19	1968	6	1974
Trojan	X (NW)	Oregon	25	WSCC	PWR	DRYAMB	1095	18	1971	4	1975
Turkey Point 3	IV (SA)	Florida	16	SERC	PWR	DRYAMB	666	21	1967	5	1972
Turkey Point 4	IV (SA)	Florida	16	SERC	PWR	DRYAMB	666	20	1967	6	1973
Vermont Yankee	I (NE)	Vermont	14	NPCC	BWR	MARK1	504	21	1968	4	1972
Vogtle 1	IV (SA)	Georgia	17	SERC	PWR	DRYAMB	1100	6	1974	13	1987
Vogtle 2	IV (SA)	Georgia	17	SERC	PWR	DRYAMB	1097	4	1974	15	1989
Wash. NP 2	X (NW)	Washington	25	WSCC	BWR	MARK2	1085	9	1973	11	1984
Waterford 3	VI (SW)	Louisiana	20	SPP	PWR	DRYAMB	1075	8	1974	11	1985
Wolf Creek	VII Central	Kansas	22	SPP	PWR	DRYAMB	1135	8	1977	8	1985
Yankee Rowe 1	I (NE)	Massachusetts	14	PPCC	PWR	DRYAMB	167	32	1957	4	1961
Zion 1	V (MW)	Illinois	8	MAIN	PWR	DRYAMB	1040	20	1969	4	1973
Zion 2	V (MW)	Illinois	8	MAIN	PWR	DRYAMB	1040	20	1969	4	1973

TABLE A2: GENERAL AND ENGINEERING CHARACTERISTICS

UNIT NAME	REACTOR SUPPLIER	DESIGN TYPE	ARCHIT. ENGIN.	CONST RUCTOR	UTILIT.	DER NET LIFETIME CAPACITY FACTOR	LIFETIME AVAILABLE FACTOR	UNIT FORCED OUTAGE RATE	FORCED OUTAGE HOURS	PTS PROBLEM DEFICIT YEARS
Ark. Nuc. 1	B&W	LLP	BECH	BECH	EOI	59.70	70.60	11.8	14822	41
Ark. Nuc. 2	COMB	CE	BECH	BECH	EOI	66.70	73.80	12.2	11500	38
Beaver Valley 1	WEST	3LP	S&W	S&W	DUQLC	56.60	64.80	15.9	16797	38
Beaver Valley 2	WEST	3LP	S&W	S&W	DUQLC	75.80	85.10	3.2	1276	100
Big Rock Point	GE	1	BECH	BECH	CPC	56.80	71.00	11.9	15992	100
Braidwood 1	WEST	4LP	S&L	CWE	CEC	65.50	74.70	10.0	3236	100
Braidwood 2	WEST	4LP	S&L	CWE	CEC	72.90	83.80	3.7	1197	100
Browns Ferry 1	GE	4	TVA	TVA	TVA	31.10	36.10	59.2	84548	100
Browns Ferry 2	GE	4	TVA	TVA	TVA	36.70	42.80	50.2	67473	100
Browns Ferry 3	GE	4	TVA	TVA	TVA	28.40	31.80	63.8	77940	100
Brunswick 1	GE	4	UE&C	BRRT	CPLC	50.80	60.80	16.0	16088	100
Brunswick 2	GE	4	UE&C	BRRT	CPLC	46.20	57.90	13.5	13563	100
Byron 1	WEST	4LP	S&L	CWE	CEC	71.50	82.90	2.6	1403	26
Byron 2	WEST	4LP	S&L	CWE	CEC	68.60	84.60	3.0	1244	100
Callaway 1	WEST	4LP	BECH	DANI	UEC	79.10	85.30	2.9	1776	26
Calvert Cliffs 1	COMB	CE	BECH	BECH	BGEC	64.60	68.50	9.3	10824	−17
Calvert Cliffs 2	COMB	CE	BECH	BECH	BGEC	67.90	71.40	5.9	6235	34
Catawba 1	WEST	4LP	DUKE	DUKE	DUKEPC	67.60	72.50	11.1	5932	26
Catawba 2	WEST	4LP	DUKE	DUKE	DUKEPC	69.00	74.90	11.1	5217	26
Clinton 1	GE	6	S&L	S&L	IPC	57.50	65.80	12.6	4252	100
Comanche Peak 1	WEST	4LP	G&H	BALD	TUEC	61.70	72.50	7.9	1297	100
Cook 1	WEST	4LP	AEP	AEP	IMPC	64.30	73.70	6.4	7801	28
Cook 2	WEST	4LP	AEP	AEP	IMPC	57.30	64.50	16.4	16060	41
Cooper	GE	4	B&R	B&R	NPPD	62.70	76.00	4.3	5537	100
Crystal River 3	B&W	LLP	GIL	JONES	FPC	57.50	64.10	18.4	20079	31
Davis−Besse 1	B&W	LLP	BECH	BECH	TEC	49.30	58.90	22.9	21593	39
Diablo Canyon 1	WEST	4LP	PG&E	PG&E	PGEC	75.20	81.50	3.5	1964	0
Diablo Canyon 2	WEST	4LP	PG&E	PG&E	PGEC	77.30	83.80	4.3	2252	40
Dresden 2	GE	3	S&L	UE&C	CEC	56.60	72.30	12.1	19748	100
Dresden 3	GE	3	S&L	UE&C	CEC	54.70	69.30	11.3	16548	100
Duane Arnold	GE	4	BECH	BECH	IELPC	58.60	72.00	12.5	16087	100
Farley 1	WEST	3LP	SSI	DANI	SNOC	72.10	76.70	6.7	7245	38
Farley 2	WEST	3LP	SSI	BECH	SNOC	81.10	84.80	4.0	3579	38
Fermi 2	GE	4	S&L	DANI	DEC	63.20	71.70	7.8	2613	100
Fitzpatrick	GE	4	S&W	S&W	PASNY	58.80	66.60	12.9	15071	100
Fort Calhoun 1	COMB	CE	GHDR	GHDR	OPPD	66.70	76.40	4.3	5833	−15
Fort St. Vrain	HTGR					17.90				100
Ginna	WEST	2LP	GIL	BECH	RGEC	75.00	78.20	5.8	9757	20
Grand Gulf 1	GE	6	BECH	BECH	EOI	68.80	79.30	6.2	3748	100

TABLE A2: GENERAL AND ENGINEERING CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	REACTOR SUPPLIER	DESIGN TYPE	ARCHIT. ENGIN.	CONSTRUCTOR	UTILIT.	DER NET LIFETIME CAPACITY FACTOR	LIFETIME AVAILABLE FACTOR	UNIT FORCED OUTAGE RATE	FORCED OUTAGE HOURS	PTS PROBLEM DEFICIT YEARS
Haddam Neck (C.Y)	WEST	4LP	S&W	S&W	CTYAPC	71.00	77.00	5.7	10079	46
Harris 1	WEST	3LP	EBSO	DANI	CPLC	71.50	78.60	4.1	1660	100
Hatch 1	GE	4	BECH	GPC	GPC	62.30	71.10	12.3	14886	100
Hatch 2	GE	4	BECH	GPC	GPC	63.90	72.40	7.0	6402	100
Hope Creek 1	GE	4	BECH	BECH	PSEGC	77.40	82.20	5.0	2287	100
Indian Point 2	WEST	4LP	UE&C	WDCO	CONEC	61.10	67.80	7.1	8404	34
Indian Point 3	WEST	4LP	UE&C	WDCO	PASNY	54.40	61.60	15.3	15922	1
Kewaunee	WEST	2LP	PSE	PSE	WPSC	79.00	84.60	2.3	3232	−7
LaSalle 1	GE	5	S&L	CWE	CEC	58.40	67.00	6.9	3911	100
LaSalle 2	GE	5	S&L	CWE	CEC	61.80	69.60	12.6	7202	100
Limmerick 1	GE	4	BECH	BECH	PEC	68.90	76.80	5.3	2613	100
Limmerick 2	GE	4	BECH	BECH	PEC	82.90	86.70	4.6	1101	100
Maine Yankee	COMB	CE	S&W	S&W	MYAPC	70.30	77.90	7.5	11431	42
Mc Guire 1	WEST	4LP	DUKE	DUKE	DUKEPC	60.10	70.10	13.5	10677	25
Mc Guire 2	WEST	4LP	DUKE	DUKE	DUKEPC	70.20	75.50	7.6	4822	37
Millstone 1	GE	3	EBSO	EBSO	NNEC	69.00	75.30	12.5	20896	100
Millstone 2	COMB	CE	BECH	BECH	NNEC	63.10	67.60	15.5	18348	40
Millstone 3	WEST	4LP	S&W	S&W	NNEC	66.40	71.80	18.8	9732	100
Monticello	GE	3	BECH	BECH	NSPC	72.20	79.20	3.7	5748	100
Nine Mile Pnt 1	GE	2	NIAG	S&W	NMPC	54.10	62.20	26.0	44690	100
Nine Mile Pnt 2	GE	5	S&W	S&W	NMPC	50.20	57.70	22.3	6896	100
North Anna 1	WEST	3LP	S&W	S&W	VEPC	64.70	71.50	11.4	11721	39
North Anna 2	WEST	3LP	S&W	S&W	VEPC	76.00	81.40	5.8	5310	39
Oconee 1	B&W	LLP	DBDB	DUKE	DUKEPC	68.20	75.10	10.9	15609	27
Oconee 2	B&W	LLP	DBDB	DUKE	DUKEPC	69.20	77.70	9.2	12719	6
Oconee 3	B&W	LLP	DBDB	DUKE	DUKEPC	69.00	75.10	11.0	14677	43
Oyster Creek 1	GE	2	B&R	B&R	GPUNUC	53.70	64.30	11.0	15957	100
Palisades	COMB	CE	BECH	BECH	CPC	42.50	53.80	30.4	43371	−15
Palo Verde 1	COMB	CE80	BECH	BECH	APSC	53.10	56.50	18.1	7587	28
Palo Verde 2	COMB	CE80	BECH	BECH	APSC	67.20	70.90	6.5	2695	100
Palo Verde 3	COMB	CE80	BECH	BECH	APSC	66.50	69.90	8.0	2645	100
Peach Bottom 2	GE	4	BECH	BECH	PEC	51.10	58.40	14.5	16041	100
Peach Bottom 3	GE	4	BECH	BECH	PEC	52.10	59.90	12.6	13707	100
Perry 1	GE	6	GIL	KAIS	CEIC	67.60	71.90	8.0	2792	100
Pilgrim 1	GE	3	BECH	BECH	BEC	50.20	57.90	12.3	14281	100
Point Beach 1	WEST	2LP	BECH	BECH	WISEPC	73.90	81.70	1.7	2653	1
Point Beach 2	WEST	2LP	BECH	BECH	WISEPC	80.40	86.20	1.1	1651	−5
Praire Isl. 1	WEST	2LP	FLUR	NSP	NSPC	77.30	84.00	5.4	7945	42

TABLE A2: GENERAL AND ENGINEERING CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	REACTOR SUPPLIER	DESIGN TYPE	ARCHIT. ENGIN.	CONST RUCTOR	UTILIT.	DER NET LIFETIME CAPACITY FACTOR	LIFETIME AVAILABLE FACTOR	UNIT FORCED OUTAGE RATE	FORCED OUTAGE HOURS	PTS PROBLEM DEFICIT YEARS
Praire Isl. 2	WEST	2LP	FLUR	NSP	NSPC	80.00	87.10	2.8	3990	42
Quad-Citles 1	GE	3	S&L	UE&C	CEC	63.40	76.70	5.8	8547	100
Quad-Citles 2	GE	3	S&L	UE&C	CE	62.70	75.70	7.8	11444	100
Rancho Seco	B&W		BECH	BECH	SAC	31.50				100
River Bend 1	GE	6	S&W	S&W	GULFSUC	63.60	69.20	10.5	4650	100
Robinson 2	WEST	3LP	EBSO	EBSO	CPLC	61.00	68.60	14.8	22853	43
Salem 1	WEST	4LP	PUBS	UE&C	PSEGC	56.80	63.40	21.5	23616	12
Salem 2	WEST	4LP	PUBS	UE&C	PSEGC	56.20	62.60	22.9	18237	42
San Onofre 1	WEST	3LP	BECH	BECH	SCE/SDG	51.30				46
San Onofre 2	COMB	CE	BECH	BECH	SCE/SDG	71.20	72.60	6.9	4403	37
San Onofre 3	COMB	CE	BECH	BECH	SCE/SDG	71.40	75.10	6.9	4285	37
Seabrook 1	WEST	4LP	UE&C	UE&C	PSCNH	74.40	78.10	5.5	1315	100
Sequoyah 1	WEST	4LP	TVA	TVA	TVA	49.20	53.20	38.5	33617	40
Sequoyah 2	WEST	4LP	TVA	TVA	TVA	52.80	59.30	33.2	27319	40
South Texas 1	WEST	4LP	BECH	EBSO	HLPC	62.00	66.20	14.4	4233	100
South Texas 2	WEST	4LP	BECH	EBSO	HLPC	69.70	74.30	12.0	3135	100
St. Lucie 1	COMB	CE	EBSO	EBSO	FPLC	75.40	76.70	4.1	4569	40
St. Lucie 2	COMB	CE	EBSO	EBSO	FPLC	84.20	84.00	5.4	3969	27
Summer 1	WEST	3LP	GIL	DANI	SCEGC	71.90	78.60	5.9	3901	37
Surry 1	WEST	3LP	S&W	S&W	VEPC	59.00	66.70	18.4	25580	7
Surry 2	WEST	3LP	S&W	S&W	VEPC	59.50	64.90	14.4	18762	37
Susquehanna 1	GE	4	BECH	BECH	PPLC	71.90	76.70	7.6	5258	100
Susquehanna 2	GE	4	BECH	BECH	PPLC	77.40	81.20	5.4	3219	100
Three Mile Isl.1	B&W	LLP	GIL	UE&C	GPUNUC	49.60	52.50	41.8	60690	3
Trojan	WEST	4LP	BECH	BECH	PGEC	51.60	61.50	13.7	13287	39
Turkey Point 3	WEST	3LP	BECH	BECH	FPLC	57.10	63.20	12.5	15867	13
Turkey Point 4	WEST	3LP	BECH	BECH	FPLC	57.40	62.80	12.0	14457	13
Vermont Yankee	GE	4	EBSO	EBSO	VTYNPC	72.80	79.50	5.2	8165	100
Vogtle 1	WEST	4LP	SBEC	GPC	GPC	80.90	84.30	6.3	2769	100
Vogtle 2	WEST	4LP	SBEC	GPC	GPC	83.20	87.60	1.9	528	100
Wash. NP 2	GE	5	B&R	BECH	WPPSS	56.60	67.60	13.3	7273	100
Waterford 3	COMB	CE	EBSO	EBSO	EOI	77.00	80.90	3.9	2111	26
Wolf Creek	WEST	4LP	BECH	DANI	WCNOC	73.10	78.80	5.2	2806	25
Yankee Rowe 1	WEST	4LP	S&W	S&W	YAEC	70.60				-10
Zion 1	WEST	4LP	S&L	CWE	CEC	56.30	65.40	16.7	21885	3
Zion 2	WEST	4LP	S&L	CWE	CEC	60.70	69.60	15.4	20370	15

TABLE A3: ENGINEERING CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	MAIN COOL PUMP NUMBER	MAIN COOL PUMP MANUF.	STEAM GENERATOR COOL WATER TYPE	STEAM GENERATOR STEAM GENER DEMI	STEAM GENER CHEM TREAT	TURBINE TURBINE MANUF	CONDENSER CONDEN TUBE MATERI	CONDENSER TYPE COOL WATER SYSTEM	CONDENSER CONDEN HEAT SINK TYPE
Ark. Nuc. 1	4	BJ	FRESH	YES	A	WEST	ADMIR	OPEN	RESERVOIF
Ark. Nuc. 2	4	BJ	FRESH	NO	A	GE	CUNI	CLOSED	NDCT
Beaver Valley 1	3	WEST	FRESH	NO	A	WEST	TITAN	CLOSED	NDCT
Beaver Valley 2	3.00	WEST	FRESH	YES	A	WEST	TITAN	CLOSED	NDCT
Big Rock Point			FRESH	YES					
Braidwood 1	4.00	WEST	FRESH	YES	A	WEST	STAINLESS		RIVER
Braidwood 2	4.00	WEST	FRESH	YES	A	WEST	STAINLESS		
Browns Ferry 1	2.00	BJ	FRESH	YES		GE	ADMIR	CC	RIV & MCT
Browns Ferry 2	2.00	BJ	FRESH	YES		GE	ADMIR	CC	RIV & MCT
Browns Ferry 3	2.00	BJ	FRESH	YES		GE	ADMIR	CC	RIV & MCT
Brunswick 1	2.00	BI	SALT	YES		GE	TITAN	OPEN	ESTUARY
Brunswick 2	2.00	BI	SALT	YES		GE	TITAN	OPEN	ESTUARY
Byron 1	4.00	WEST	FRESH	YES	A	WEST	STAINLESS	CLOSED	MCT & RIV
Byron 2	4.00	WEST	FRESH	YES	A	WEST	STAINLESS	CLOSED	MCT & RIV
Callaway 1	4.00	WEST	FRESH	YES	A	GE	CUNI/SS		MCT & RIV
Calvert Cliffs 1	4.00	BJ	SALT	YES	A	GE	STAINLESS	OPEN	SEA
Calvert Cliffs 2	4.00	BJ	SALT	YES	A	WEST	TITAN	OPEN	SEA
Catawba 1	4.00	WEST	FRESH	YES	A	GE	STAINLESS		MCT&LAKE
Catawba 2	4.00	WEST	FRESH	YES	A	GE	STAINLESS		MCT&LAKE
Clinton 1	2.00	BI	FRESH	YES		GE	STAINLESS	CLOSED	LAKE
Comanche Peak 1			FRESH	YES					
Cook 1	4.00	WEST	FRESH	NO	A	GE	ASCU	OPEN	LAKE
Cook 2	4.00	WEST	FRESH	NO	A	BB	TITAN	OPEN	LAKE
Cooper	2.00	BJ	FRESH	YES		WEST	STAINLESS	OPEN	RIVER
Crystal River 3	4.00	BJ	SALT	YES	A	WEST	CUNI	OPEN	SEA
Davis–Besse 1	4.00	BJ	FRESH	YES	A	GE	304 SS	CLOSED	NDCT
Diablo Canyon 1	4.00	WEST	SALT	YES	A	WEST	TITAN	OPEN	SEA
Diablo Canyon 2	4.00	WEST	SALT	YES	A	WEST	TITAN	OPEN	SEA
Dresden 2	2.00	BJ	FRESH	YES		GE	STAINLESS	OPEN	SPRAY RES
Dresden 3	2.00	BJ	FRESH	YES		GE	STAINLESS	OPEN	SPRAY RES
Duane Arnold	2.00	BJ	FRESH	YES		GE	STAINLESS	CC	RIV & MCT
Farley 1	3.00	WEST	FRESH	NO	A	WEST	TITAN	CC	MCT & RIV
Farley 2	3.00	WEST	FRESH	NO	A	WEST	TITAN	CC	MCT & RIV
Fermi 2	2.00	BJ	FRESH	YES		GE	CUNI		LAKE+CT
Fitzpatrick	2.00	BJ	FRESH	YES		GE	ADMIR	OPEN	LAKE
Fort Calhoun 1	4.00	BJ	FRESH	YES	A	GE	304 SS	OPEN	RIVER
Fort St. Vrain			FRESH	YES					
Ginna	2.00	WEST	FRESH	YES	P&A	WEST	ADMIR/SS	OPEN	LAKE
Grand Gulf 1	2.00	BJ	FRESH	YES		AC	STAINLESS	CLOSED	NDCT

TABLE A3: ENGINEERING CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

			STEAM GENERATOR			TURBINE	CONDENSER		
UNIT NAME	MAIN COOL PUMP NUMBER	MAIN COOL PUMP MANUF.	COOL WATER TYPE	STEAM GENER DEMI	STEAM GENER CHEM TREAT	TURBINE MANUF	CONDEN TUBE MATERI	TYPE COOL WATER SYSTEM	CONDEN HEAT SINK TYPE
Haddam Neck (C.Y)	4.00	WEST	FRESH	NO	P&A	WEST	ADMIR	OPEN	RIVER
Harris 1		WEST	FRESH	YES	A				
Hatch 1	2.00	BJ	FRESH	YES		GE	ADMIR	CC	RIV & MCT
Hatch 2	2.00	BJ	FRESH	YES		GE	ADMIR	CC	RIV & MCT
Hope Creek 1	2.00	BJ	SALT	YES		GE			RIVER
Indian Point 2	4.00	WEST	SALT	NO	P&A	WEST	ADMIR	OPEN	ESTUARY
Indian Point 3	4.00	WEST	SALT	NO	A	WEST	ADMIR	OPEN	ESTUARY
Kewaunee	2.00	WEST	FRESH	NO	P&A	WEST	ADMIR	OPEN	LAKE
LaSalle 1	2.00	BI	FRESH	YES		GE	STAINLESS	CLOSED	RESERVOIF
LaSalle 2	2.00	BI	FRESH	YES		GE	STAINLESS	CLOSED	RESERVOIF
Limmerick 1	2.00	BJ	FRESH	YES		GE	SS/ADMIR	CLOSED	NDCT
Limmerick 2	2.00	BJ	FRESH	YES					
Maine Yankee	3.00	BJ	SALT	NO	A	WEST	SS	OPEN	SEA
Mc Guire 1	4.00	WEST	FRESH	NO	A	WEST	304 SS	OPEN	LAKE
Mc Guire 2	4.00	WEST	FRESH	NO	A	WEST	SS	OPEN	LAKE
Millstone 1	2.00	BJ	FRESH	YES		GE	CUNI	OPEN	SEA
Millstone 2	4.00	BJ	SALT	NO	A	GE	CUNI	OPEN	SEA
Millstone 3	4.00	WEST	SALT	YES	A	GE	TITAN	OPEN	SEA
Monticello	2.00	BI	FRESH	YES		GE	TITAN	CC	RIV & MCT
Nine Mile Pnt 1	5.00	BJ	FRESH	YES		GE	ADMIR	OPEN	LAKE
Nine Mile Pnt 2	2.00	BI	FRESH	YES		GE	CUNI/ADMIR		
North Anna 1	3.00	WEST	FRESH	YES	A	WEST	304 SS	OPEN	RESERVOIF
North Anna 2	3.00	WEST	FRESH	YES	A	WEST	304 SS	OPEN	RESERVOIF
Oconee 1	4.00	WEST	FRESH	YES	A	GE	304 SS	OPEN	RESERVOIF
Oconee 2	4.00	BI	FRESH	YES	A	GE	304 SS	OPEN	RESERVOIF
Oconee 3	4.00	BI	FRESH	YES	A	GE	304 SS	OPEN	RESERVOIF
Oyster Creek 1	4.00	BI	SALT	YES		GE	TITAN	OPEN	SEA
Palisades	4.00	BJ	FRESH	NO	P&A	WEST	CUNI	CC	LAKE&MCT
Palo Verde 1	4.00	KS	FRESH	YES		GE	TITAN	CLOSED	CT+SEWAG
Palo Verde 2	4.00	KS	FRESH	YES	A	GE	TITAN	CLOSED	CT+SEWAG
Palo Verde 3	4.00	KS	FRESH	YES	A	GE	TITAN	CLOSED	CT+SEWAG
Peach Bottom 2	2.00	BJ	FRESH	YES		GE	ADMIR	OPEN	MCT & RIV
Peach Bottom 3	2.00	BJ	FRESH	YES		GE	ADMIR	OPEN	MCT & RIV
Perry 1	2.00	BJ	FRESH	YES		GE	STAINLESS		
Pilgrim 1	2.00	BJ	SALT	YES		GE	ASAL-BRAS	OPEN	SEA
Point Beach 1	2.00	WEST	FRESH	NO	A	WEST	ADMIR	OPEN	LAKE
Point Beach 2	2.00	WEST	FRESH	NO	P&A	WEST	ADMIR	OPEN	LAKE
Praire Isl. 1	2.00	WEST	FRESH	YES	P&A	WEST	STAINLESS	CC	RIV+MCT

TABLE A3: ENGINEERING CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	MAIN COOL PUMP NUMBER	MAIN COOL PUMP MANUF.	STEAM GENERATOR COOL WATER TYPE	STEAM GENER DEMI	STEAM GENER CHEM TREAT	TURBINE MANUF	CONDENSER CONDEN TUBE MATERI	TYPE COOL WATER SYSTEM	CONDEN HEAT SINK TYPE
Praire Isl. 2	2.00	WEST	FRESH	YES	A	WEST	STAINLESS	CC	RIV+MCT
Quad-Cities 1	2.00	BJ	FRESH	YES		GE	STAINLESS	OPEN	SPR CANAL
Quad-Cities 2	2.00	BJ	FRESH	YES		GE	STAINLESS	OPEN	SPR CANAL
Rancho Seco	4.00	BI	FRESH	YES	A	WEST	STAINLESS	CLOSED	NDCT
River Bend 1	2.00	BI	FRESH	YES		GE	ADMIR	CLOSED	RIV&NDCT
Robinson 2	3.00	WEST	FRESH	NO	A	WEST	ADMIR	OPEN	LAKE
Salem 1	4.00	WEST	SALT	YES	A	WEST	AL-6X	OPEN	ESTUARY
Salem 2	4.00	WEST	SALT	YES	A	WEST	CUNI	OPEN	ESTUARY
San Onofre 1	3.00	WEST	SALT	NO	P	WEST	TITAN	OPEN	SEA
San Onofre 2	4.00	BJ	SALT	NO	A	GE	TITAN	OPEN	SEA
San Onofre 3	4.00	BJ	SALT	NO	A	GE	TITAN	OPEN	SEA
Seabrook 1			FRESH	YES					
Sequoyah 1	4.00	WEST	FRESH	NO	A	WEST	CUNI	CC	LAKE+CT
Sequoyah 2	4.00	WEST	FRESH	NO	A	WEST	CUNI	CC	LAKE+CT
South Texas 1	4.00	WEST	FRESH	YES	A	WEST	TITAN		RIVER
South Texas 2			FRESH	YES					
St. Lucie 1	4.00	BJ	SALT	NO	A	WEST	TITAN	OPEN	SEA
St. Lucie 2	4.00	BJ	SALT	NO	A	WEST	TITAN	OPEN	SEA
Summer 1	3.00	WEST	FRESH	NO	A	GE	STAINLESS	OPEN	RESERVOIR
Surry 1	3.00	WEST	SALT	YES	A	WEST	TITAN	OPEN	ESTUARY
Surry 2	3.00	WEST	SALT	YES	A	WEST	TITAN	OPEN	ESTUARY
Susquehanna 1	2.00	BJ	FRESH	YES		GE	STAINLESS	CC	NDCT
Susquehanna 2	2.00	BJ	FRESH	YES		GE	STAINLESS	CLOSED	NDCT
Three Mile Isl.1	4.00	WEST	FRESH	YES	A	GE	STAINLESS	CLOSED	NDCT&MCT
Trojan	4.00	WEST	FRESH	YES	A	GE	ADMIR	CLOSED	NDCT
Turkey Point 3	3.00	WEST	SALT	YES	A	WEST	TITAN	OPEN	SEA
Turkey Point 4	3.00	WEST	SALT	YES	A	WEST	TITAN	OPEN	SEA
Vermont Yankee	2.00	BJ	FRESH	YES		GE	STAINLESS	CC	RIV & MCT
Vogtle 1	4.00	WEST	FRESH	YES	A	GE	TITAN		RIV + CT
Vogtle 2			FRESH	YES					
Wash. NP 2	2.00	BI	FRESH	YES		WEST	CUNI	CLOSED	MCT
Waterford 3	4.00	BJ	FRESH	YES	A	WEST	STAINLESS	OPEN	RIVER
Wolf Creek	4.00	WEST	FRESH	YES	A	GE	CUNI/SS	OPEN	LAKE
Yankee Rowe 1			FRESH	YES					
Zion 1	4.00	WEST	FRESH	NO	P&A	WEST	STAINLESS	OPEN	LAKE
Zion 2	4.00	WEST	FRESH	NO	P&A	WEST	STAINLESS	OPEN	LAKE

TABLE A4: ECONOMIC CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	AVER. ANNUAL NON-FUEL OPER COSTS 82$/KW	CAPITAL ADDITION 82$/KW	O&M COSTS 82$/KW	power prod. expen. 1990 cost mil/kwh	1989 level cost mil/kwh	1996 PURCH. POWER mills/kwh
Ark. Nuc. 1	50.31	17.36	32.95	22.28	23.87	15.30
Ark. Nuc. 2						15.30
Beaver Valley 1	102.59	49.25	53.34	35.86	36.92	14.10
Beaver Valley 2	102.59	49.25	53.34	35.86	36.92	14.10
Big Rock Point				47.33	49.33	23.70
Braidwood 1				14.10	17.69	28.20
Braidwood 2				14.10	17.69	28.20
Browns Ferry 1	40.60	13.40	27.20			7.60
Browns Ferry 2	40.60	13.40	27.20			7.60
Browns Ferry 3	40.60	13.40	27.20			7.60
Brunswick 1	81.63	27.98	53.65	20.15	21.34	22.70
Brunswick 2	81.63	27.98	53.65	20.15	21.34	22.70
Byron 1				16.95	13.57	28.50
Byron 2				16.95	13.57	28.50
Callaway 1				18.83	17.25	13.20
Calvert Cliffs 1	42.33	12.17	30.16	139.64	49.10	23.70
Calvert Cliffs 2	42.33	12.17	30.16	139.64	49.10	23.70
Catawba 1				16.80	16.00	22.20
Catawba 2				16.80	16.00	22.20
Clinton 1				44.98	44.68	9.30
Comanche Peak 1				18.67		19.60
Cook 1	39.29	12.70	26.59	21.85	17.19	12.30
Cook 2	39.29	12.70	26.59	21.85	17.19	12.30
Cooper				20.22	18.59	11.90
Crystal River 3	79.98	15.58	64.40	30.20	40.50	29.90
Davis-Besse 1	131.49	60.86	70.63	41.12	30.38	13.50
Diablo Canyon 1				16.68	19.78	33.20
Diablo Canyon 2				16.68	19.78	33.20
Dresden 2	43.42	12.80	30.62	19.71	18.42	28.30
Dresden 3	43.42	12.80	30.62	19.71	18.42	29.00
Duane Arnold	82.17	33.26	48.91	29.23	19.40	10.80
Farley 1	58.84	18.34	40.50	16.96	17.74	20.80
Farley 2	58.84	18.34	40.50	16.96	17.74	20.90
Fermi 2				27.65	40.69	18.60
Fitzpatrick	78.97	20.43	58.54	28.76	19.20	29.90
Fort Calhoun 1	65.65	15.76	49.89	41.00	40.76	9.70
Fort St. Vrain					92.41	
Ginna	75.93	31.13	44.80	23.46	26.15	30.90
Grand Gulf 1				26.38	25.68	12.20

TABLE A4: ECONOMIC CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	AVER. ANNUAL NON-FUEL OPER COSTS 82$/KW	CAPITAL ADDITION 82$/KW	O&M COSTS 82$/KW	power prod. expen. 1990 cost mil/kwh	1989 level cost mil/kwh	1996 PURCH. POWER mills/kwh
Haddam Neck (C.Y)	84.19	22.36	61.83	72.81	38.70	21.90
Harris 1				14.08	16.76	23.00
Hatch 1	84.30	30.64	53.66	22.90	22.93	18.40
Hatch 2	84.06	30.40	53.66	22.90	22.93	18.40
Hope Creek 1				16.77	19.74	23.70
Indian Point 2	74.21	17.01	57.20	25.57	32.61	30.00
Indian Point 3	92.50	35.29	57.21	27.55	24.57	31.40
Kewaunee	55.26	10.74	44.52	20.51	18.35	24.10
LaSalle 1	39.97	5.86	34.11	14.65	15.48	27.90
LaSalle 2	39.97	5.86	34.11	14.65	15.48	28.00
Limmerick 1				22.69	45.79	22.70
Limmerick 2				22.69	45.79	22.70
Maine Yankee	34.86	9.77	25.09	18.98	10.90	26.60
Mc Guire 1	46.36	3.92	42.44	22.34	15.25	21.60
Mc Guire 2	46.36	3.92	42.44	22.34	15.25	21.70
Millstone 1	81.27	35.91	45.36	20.75	22.68	23.00
Millstone 2	63.68	24.27	39.41	20.75	22.68	23.20
Millstone 3				20.75	22.68	23.40
Monticello	75.18	34.60	40.58	14.88	23.91	12.40
Nine Mile Pnt 1	64.79	38.94	25.85	54.63	61.61	27.70
Nine Mile Pnt 2	64.79	38.94	25.85	54.63	61.61	28.30
North Anna 1	44.53	16.85	27.68	12.90	15.68	23.80
North Anna 2	44.53	16.85	27.68	12.90	15.68	23.80
Oconee 1	37.06	9.31	27.75	13.19	14.24	22.90
Oconee 2	37.06	9.31	27.75	13.19	14.24	22.90
Oconee 3	37.06	9.31	27.75	13.19	14.24	22.90
Oyster Creek 1	158.08	62.42	95.66	31.10	53.35	22.40
Palisades	68.92	23.88	45.04	30.79	26.93	23.80
Palo Verde 1				37.41	89.47	19.80
Palo Verde 2				37.41	89.47	19.80
Palo Verde 3				37.41	89.47	19.80
Peach Bottom 2	62.79	18.85	43.94	25.02	75.21	21.10
Peach Bottom 3	62.79	18.85	43.94	25.02	75.21	21.10
Perry 1				45.16	54.63	11.90
Pilgrim 1	126.76	61.79	64.97	26.70	67.65	25.40
Point Beach 1	32.44	7.89	24.55	12.08	12.31	24.60
Point Beach 2	32.44	7.89	24.55	12.08	12.31	24.60
Prairo Isl. 1	40.17	14.13	26.04	15.03	10.40	12.60

TABLE A4: ECONOMIC CHARACTERISTICS

SOURCES: EIA, DOE, EPRI, NRC

UNIT NAME	AVER. ANNUAL NON-FUEL OPER COSTS 82$/KW	CAPITAL ADDITION 82$/KW	O&M COSTS 82$/KW	power prod. expen. 1990 cost mil/kwh	1989 level cost mil/kwh	1996 PURCH. POWER mills/kwh
Praire Isl. 2	40.17	14.13	26.04	15.03	10.40	12.60
Quad-Cities 1	39.30	12.20	27.10	20.23	17.76	25.20
Quad-Cities 2	39.30	12.20	27.10	20.23	17.76	25.40
Rancho Seco	82.04	28.10	53.94		48.30	
River Bend 1				31.47	39.01	11.70
Robinson 2	63.93	25.33	38.60	28.96	24.39	22.70
Salem 1	82.53	23.44	59.09	22.01	17.07	23.50
Salem 2	82.53	23.44	59.09	22.01	17.07	23.50
San Onofre 1	103.52	59.31	44.21	25.75	27.44	28.80
San Onofre 2	103.52	59.31	44.21	25.75	27.44	29.00
San Onofre 3	103.52	59.31	44.21	25.75	27.44	29.00
Seabrook 1				27.23		24.80
Sequoyah 1	67.45	22.28	45.17	16.50	20.88	7.70
Sequoyah 2	67.45	22.28	45.17	16.50	20.88	7.70
South Texas 1				19.96	18.16	20.60
South Texas 2				19.96	18.16	20.60
St. Lucie 1	51.66	21.32	30.34	22.27	13.80	30.20
St. Lucie 2	51.66	21.32	30.34	22.27	13.80	30.20
Summer 1				18.97	20.23	22.00
Surry 1	51.46	25.01	26.45	15.71	27.87	22.40
Surry 2	51.46	25.01	26.45	15.71	27.87	22.40
Susquehanna 1	72.55	19.83	52.72	18.41	20.47	22.40
Susquehanna 2	72.55	19.83	52.72	18.41	20.47	22.40
Three Mile Isl.1	69.14	19.57	49.57	21.66	17.06	23.50
Trojan	51.31	17.75	33.56	21.91	23.42	19.00
Turkey Point 3	69.44	35.01	34.43	32.47	35.49	30.10
Turkey Point 4	69.44	35.01	34.43	32.47	35.49	30.10
Vermont Yankee	69.25	19.67	49.58	25.53	21.60	26.20
Vogtle 1				21.07	17.36	17.70
Vogtle 2				21.07	17.36	17.70
Wash. NP 2				19.27	19.12	18.50
Waterford 3				18.12	20.86	15.40
Wolf Creek				12.85	9.32	18.10
Yankee Rowe 1				60.05	34.05	
Zion 1	30.25	7.66	22.59	26.44	14.76	28.20
Zion 2	30.25	7.66	22.59	26.44	14.76	28.20

Table A5: Annual Capacity factors by Age (Historical values for first 15 years)

Source: EPRI, Operating Experiences, 1984-1987

Age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Arkansas1	0.66	0.52	0.69	0.71	0.45	0.51	0.66	0.50	0.43	0.62	0.70	0.48	0.64	0.53	0.43
Browns Ferry1	0.44	0.00	0.59	0.54	0.64	0.61	0.65	0.71	0.58	0.47	0.54	0.00	0.00	0.00	0.00
Browns Ferry2	0.06	0.31	0.65	0.62	0.75	0.64	0.79	0.34	0.80	0.32	0.00	0.00	0.00	0.00	0.00
Browns Ferry3	0.77	0.61	0.54	0.71	0.59	0.63	0.48	0.17	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Brunswick1	0.48	0.58	0.62	0.50	0.37	0.24	0.40	0.66	0.33	0.71	0.63	0.62	0.56	0.43	0.58
Brunswick2	0.37	0.36	0.59	0.52	0.30	0.42	0.27	0.61	0.17	0.73	0.33	0.82	0.52	0.95	0.56
Calvert Cliff1	0.79	0.62	0.66	0.70	0.58	0.66	0.74	0.79	0.66	0.74	0.71	0.56	0.75	0.71	0.18
Calvert Cliff2	0.84	0.65	0.72	0.68	0.84	0.62	0.86	0.70	0.72	0.86	0.60	0.94	0.19	0.00	0.46
Connetlcut Yan	0.74	0.76	0.70	0.83	0.85	0.48	0.86	0.82	0.80	0.80	0.94	0.82	0.71	0.80	0.89
Cook1	0.68	0.58	0.59	0.64	0.66	0.75	0.65	0.71	0.61	0.47	0.49	0.64	0.75	0.73	0.56
Cook2	0.67	0.67	0.58	0.80	0.71	0.51	0.82	0.25	0.61	0.49	0.00	0.66	0.48	0.81	
Cooper	0.60	0.51	0.60	0.60	0.75	0.60	0.63	0.64	0.73	0.55	0.16	0.55	0.56	0.59	0.93
Crystal River3	0.71	0.36	0.52	0.46	0.56	0.66	0.50	0.86	0.38	0.35	0.48	0.77	0.39	0.54	0.72
Davis-Besse	0.28	0.39	0.26	0.55	0.41	0.62	0.54	0.25	0.00	0.64	0.15	0.90	0.51	0.72	
Duane	0.53	0.55	0.64	0.20	0.69	0.63	0.48	0.50	0.51	0.61	0.41	0.65	0.55	0.64	0.65
Farley1	0.80	0.24	0.71	0.37	0.64	0.72	0.75	0.80	0.80	0.91	0.78	0.99	0.79	0.90	0.71
Fitzpatrick	0.49	0.64	0.67	0.29	0.52	0.83	0.51	0.69	0.77	0.43	0.84	0.60	0.83	0.23	0.81
Fort Calhon	0.51	0.69	0.68	0.71	0.76	0.52	0.72	0.71	0.53	0.63	0.89	0.63	0.69	0.98	0.35
Hatch1	0.60	0.54	0.62	0.49	0.70	0.40	0.42	0.58	0.52	0.69	0.53	0.74	0.60	0.91	0.57
Indian Point2	0.64	0.52	0.43	0.54	0.80	0.53	0.30	0.76	0.53	0.72	0.59	0.49	0.86	0.61	0.80
Kewanee	0.66	0.62	0.75	0.64	0.84	0.68	0.79	0.82	0.78	0.81	0.80	0.81	0.86	0.84	0.95
St Lucie1	0.76	0.71	0.70	0.74	0.70	0.92	0.15	0.57	0.79	0.95	0.77	0.84	0.91	0.59	0.76
Maine Yankee	0.48	0.52	0.65	0.85	0.74	0.75	0.63	0.61	0.72	0.63	0.79	0.71	0.74	0.86	0.56
Millstone2	0.62	0.60	0.62	0.59	0.64	0.80	0.66	0.33	0.87	0.46	0.66	0.90	0.75	0.62	0.88
Monticello	0.58	0.71	0.65	0.75	0.67	0.86	0.74	0.82	0.74	0.84	0.67	0.58	0.41	0.49	0.72
Oconee1	0.57	0.48	0.63	0.62	0.59	0.65	0.51	0.73	0.29	0.76	0.90	0.78	0.66	0.77	0.73
Oconee2	0.57	0.58	0.58	0.64	0.66	0.51	0.74	0.32	0.83	0.76	0.65	0.81	0.78	0.67	0.94

Table A5: Annual Capacity factors by Age (Historical values for first 15 years)

Source: EPRI, Operating Experiences, 1984-1987

Age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Oconee3	0.65	0.61	0.68	0.78	0.42	0.67	0.73	0.27	0.91	0.69	0.63	0.78	0.66	0.77	0.79
North Anna	0.74	0.49	0.61	0.69	0.26	0.67	0.68	0.67	0.66	0.52	0.92	0.52	0.67	0.68	
Oyster Creek	0.77	0.78	0.76	0.63	0.65	0.55	0.68	0.57	0.64	0.80	0.34	0.46	0.35	0.04	0.05
Palisades	0.30	0.41	0.01	0.42	0.49	0.84	0.41	0.53	0.37	0.53	0.52	0.58	0.13	0.82	0.13
Peach Bottom2	0.69	0.46	0.53	0.68	0.78	0.53	0.70	0.52	0.76	0.33	0.02	0.68	0.47	0.00	0.00
Peach Bottom3	0.57	0.65	0.51	0.75	0.66	0.77	0.34	0.92	0.26	0.80	0.36	0.52	0.16	0.00	0.03
Pilgrim	0.70	0.34	0.44	0.41	0.45	0.75	0.83	0.52	0.59	0.56	0.61	0.00	0.85	0.18	0.00
Point Beach1	0.75	0.67	0.63	0.72	0.67	0.78	0.85	0.87	0.70	0.67	0.60	0.62	0.55	0.71	0.77
Point Beach2	0.89	0.72	0.79	0.82	0.89	0.91	0.81	0.89	0.85	0.78	0.79	0.61	0.82	0.78	0.83
Praire Isl1	0.31	0.80	0.70	0.80	0.82	0.63	0.67	0.83	0.84	0.84	0.89	0.79	0.82	0.77	0.82
Praire Isl2	0.68	0.57	0.84	0.85	0.90	0.75	0.67	0.83	0.80	0.84	0.78	0.83	0.95	0.84	0.80
Quad Cities1	0.70	0.41	0.59	0.61	0.52	0.57	0.82	0.49	0.84	0.48	0.84	0.48	0.74	0.79	0.64
Quad Cities2	0.74	0.46	0.56	0.58	0.55	0.77	0.38	0.74	0.44	0.81	0.36	0.80	0.70	0.63	0.77
Salem1	0.39	0.52	0.43	0.43	0.55	0.37	0.59	0.59	0.76	0.85	0.60	0.94	0.62	0.58	0.66
Surry1	0.50	0.48	0.57	0.64	0.73	0.68	0.33	0.36	0.34	0.80	0.61	0.48	0.81	0.65	0.67
Surry2	0.69	0.41	0.69	0.41	0.75	0.61	0.00	0.61	0.71	0.83	0.53	0.74	0.69	0.45	0.89
TMI1	0.79	0.77	0.60	0.81	0.60	0.68	0.79	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.70
Turkey Point3	0.55	0.60	0.72	0.71	0.74	0.74	0.48	0.72	0.15	0.62	0.71	0.79	0.56	0.74	0.15
Turkey Point4	0.65	0.63	0.72	0.54	0.67	0.58	0.75	0.73	0.72	0.31	0.58	0.78	0.30	0.55	0.64
Zion1	0.38	0.54	0.52	0.55	0.74	0.61	0.72	0.68	0.52	0.44	0.62	0.53	0.54	0.66	0.68
Zion2	0.46	0.54	0.60	0.72	0.72	0.43	0.74	0.43	0.61	0.65	0.81	0.56	0.57	0.92	0.09
Dresden2	0.58	0.72	0.49	0.43	0.63	0.51	0.82	0.71	0.66	0.49	0.74	0.49	0.64	0.45	0.67
Dresden3	0.71	0.53	0.46	0.32	0.58	0.75	0.55	0.50	0.63	0.74	0.56	0.60	0.31	0.63	0.22
Ginna	0.65	0.82	0.56	0.60	0.67	0.57	0.65	0.67	0.69	0.81	0.73	0.61	0.71	0.66	0.73
Inlan Point3	0.76	0.47	0.84	0.30	0.36	0.26	0.01	0.52	0.56	0.54	0.57	0.87	0.65	0.55	0.56
Millstone1	0.70	0.41	0.47	0.64	0.66	0.69	0.77	0.83	0.72	0.41	0.66	0.71	0.95	0.75	0.79
Nine MileP1	0.42	0.60	0.61	0.65	0.61	0.57	0.77	0.55	0.84	0.56	0.85	0.61	0.21	0.52	0.68
Rancho Seco	0.23	0.50	0.63	0.70	0.45	0.61	0.43	0.33	0.45	0.44	0.08	0.00	0.01	0.51	0.17
Robinson	0.57	0.66	0.73	0.79	0.68	0.76	0.56	0.81	0.60	0.62	0.46	0.41	0.38	0.12	0.76
San Onofre1	0.34	0.69	0.81	0.88	0.75	0.60	0.84	0.66	0.66	0.62	0.71	0.89	0.22	0.21	0.14
Trojan	0.40	0.59	0.29	0.45	0.67	0.57	0.35	0.65	0.48	0.66	0.70	0.47	0.65	0.57	0.62
Vermont Yankee	0.39	0.57	0.74	0.72	0.79	0.72	0.76	0.74	0.74	0.90	0.64	0.74	0.75	0.37	0.79
Yankee Rowe	0.65	0.57	0.75	0.78	0.64	0.75	0.77	0.18	0.56	0.56	0.64	0.64	0.75	0.87	0.71
Beaver Valley1	0.50	0.30	0.15	0.12	0.55	0.50	0.62	0.61	0.83	0.65	0.60	0.80	0.49	0.81	0.48

TABLE A6: ANNUAL POWER PRODUCTION COSTS

UNITS: 1991 MILLS/KWH

SOURCE: EIA, ELECTRIC PLANT COST AND POWER PRODUCTION EXPENSES, DOE/EIA-0455

Reactor Name	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	Average
Cooper	11.9	18	13.71	44.47	18.38	15.58	19.24	18.59	20.22	18.46	19.86
Fort Calhoun	12.61	13.03	16.73	17.13	17.24	21.61	34.94	40.76	41	30.68	24.57
Seabrook									27.23	26.78	27.01
Oyster Creek	21.07	363.1	311.57	32.35	100.37	44.85	34.52	53.35	31.1	44.91	103.72
Hope Creek						18.84	19.12	19.74	16.77	19.63	18.82
Salem	12.17	36.51	46.28	20.2	22.19	21.01	20.16	17.07	22.01	19.46	23.71
Indian Point	24.62	15.16	35.47	16.43	30.09	27.93	18.01	32.61	25.57	46.16	27.21
Nime Mile Point1	19.68	14.37	13.25	9.75	12.98	9.08	43.7	61.61	54.63	25.13	26.42
Indian Point 3	23.93	15.23	17.49	25.29	17.67	19.04	13.07	24.57	27.55	17.96	20.18
Fitzpatrick	10.12	800.61	17.69	21.99	15.8	25.34	25.55	19.2	28.76	38.25	100.33
Ginna	13.97	15.16	15.91	13.78	15.58	15.55	17.29	26.15	23.46	23.69	18.05
Brunswick	23	25.01	26	26.43	19.64	17.8	20.69	21.34	20.15	23.32	22.34
Harris						19	18.88	16.76	14.08	16.45	17.03
McGuire	14.2	17.47	12.28	14.93	18.6	16.78	16.82	15.25	22.34	15.46	16.41
Perry						21.52	37.1	54.63	45.16	31.79	38.04
Davis	24.53	16.76	20.63	53.74		34.07	151.93	30.38	41.12	27.42	44.51
Trojan	13.12	14.33	15.72	12.55	12.91	23.04	17.63	23.42	21.91	110.58	26.52
BeaverV	19.08	23.22	23.65	19.65	24.16	22.02	35.59	36.92	35.86	43.51	28.37
TMI1				112.75	18.67	32.55	19.04	17.06	21.66	21.62	34.76
Susquehana		18.83	19.3	18.05	19.39	16.7	18.65	20.47	18.41	18.9	18.74
Limmerick					16.6	33.49	23.92	45.79	22.69	18.62	26.85
Peach Bottom	14.15	26.12	20.57	39.12	21.59	81.84		75.21	25.02	33.17	37.42
Robinson	21.14	15.97	387.26	14.65	17.1	17.7	25.1	24.39	28.96	19.68	57.20
Catawa				23.2	21.28	16.92	16.98	16	16.8	17.52	18.39
Oconee	14.2	10.32	11.28	13.92	14.45	16.04	14.59	14.24	13.19	14.4	13.66
Summer			22.22	20.93	14.88	18.13	18.9	20.23	18.97	20.65	19.36
Sequoyah	9.28	11.16	12.97	15.7			92.21	20.88	16.5	15.47	24.27
South Texas							12.02	18.16	19.96	17.51	16.91
Comanche Peak									18.67	26.33	22.50
Vermont Yankee	15.69	22.63	19.38	22.4	32.79	21.51	17.88	21.6	25.53	18.18	21.76
North Anna	12.3	8.45	12.89	9.56	10.83	16.43	8.05	15.68	12.9	13.75	12.08
Surry	9.44	12.88	13.22	12.61	16.1	14.92	25.73	27.87	15.71	17.55	16.60
Washington NP1							17.4	19.12	19.27	21.65	19.36
Point Beach	12.68	16.46	14.59	12.23	11.68	11.92	12.25	12.31	12.08	13.87	13.01
Kewaune	16.6	14.73	12.97	14.9	13.77	14.81	17.42	18.35	20.51	24.51	16.86
Rancho Seco	17.49	23.71	22.18	57.29			52.27	48.3			36.87
St Vrain	36	31.43	576.08			145	182.44	92.43			177.23

TABLE A6: ANNUAL POWER PRODUCTION COSTS

UNITS: 1991 MILLS/KWH

SOURCE: EIA, ELECTRIC PLANT COST AND POWER PRODUCTION EXPENSES, DOE/EIA−0455

Reactor Name	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	Average
Farley	10.9	10.49	14.33	16.4	16.65	18.17	16.02	17.74	16.96	17.67	15.53
Browns Ferry	9.07	12	16.97	27.25						87.52	30.56
Palo Verde					22.6	34.8	28.24	89.47	37.41	27.66	40.03
Arkansas1	14.75	16.91	15.52	16.23	18.3	18.94	23.94	23.87	22.28	21.33	19.21
Diablo Canyon				13.71	19.8	19.34	25.49	19.78	16.68	21.03	19.40
San Onofre	118.93	106.38	44.87	12.46	35.62	25.93	25.05	27.44	25.75	27.01	44.94
Connecticut Yan	15.42	21.89	25.67	18.65	48.53	45.62	29.44	38.7	78.81	31.61	35.43
Millstone	13.2	20.68	18.18	24.72	18.66	21.4	18.68	22.68	20.75	40.52	21.95
Crystal River	16.46	27.54	19.32	30.94	33.58	28.42	20.83	40.5	30.2	25.14	27.29
St. Lucie	12.05	17.65	14.97	14.03	12.9	16.11	13.54	13.8	22.27	17.95	15.53
Turkey Point	6.71	9.67	12.41	14.41	28.49	42.32	41.29	35.49	32.47	110.19	33.35
Hatch	15.02	19.59	32.07	21.61	35.3	21.03	20.93	22.93	22.9	22.4	23.38
Vogtle						28.76	27.86	17.36	21.07	19.28	22.87
Brainwod							19.57	17.69	14.1	18.83	17.55
Byron				23.2	16.14	15.87	15	13.57	16.95	14.09	16.40
Dresden	10.14	12.09	15.77	15.55	20.16	19.08	20.56	18.42	19.71	31.47	18.30
LaSalle	22.26	33.89	14.59	16.39	17.45	18.13	18.6	15.48	14.65	14.45	18.59
Quad Cities	11.25	10.79	14.49	12.43	13.93	14.88	16.7	17.76	20.23	22.01	15.45
Zion	10.86	10.49	10.35	13.32	11.94	13.58	15.66	14.76	26.44	20.56	14.80
Clinton						49.03	24.28	44.68	44.98	24.48	37.49
Duane	18.84	27.28	21.33	39.26	19.99	28.19	24.44	19.4	29.23	16.89	24.49
Wolf				14.33	16.38	16	16.4	9.32	12.85	18.5	14.83
River					34.6	37.53	26.06	39.01	31.47	32.33	33.50
Waterf				14.98	22	20	22.44	20.86	18.12	20.06	19.78
Maine Yankee	12.77	10.54	13.16	13.34	9.7	18.4	16.1	10.9	18.98	12.24	13.61
Calvert Cliff	11.24	10.28	11.6	13.61	11.71	12.96	12.53	49.1	139.64	24.29	29.70
Pilgrim	17.8	15.02		18.93	80.64			67.65	26.7	31.49	36.89
Yankee Rowe	35.75	24.29	37.1	37.14	24.45	38.8	41.31	34.05	60.05	51.17	38.41
BigRock	48.7	53.39	38.73	46.24	33.5	46.6	45.5	49.33	47.33	45.67	45.50
Palisades	19.7	23.47	82.37	19.95	91.13	32.5	29.8	26.93	30.79	22.73	37.94
Fermi							48.26	40.69	27.65	30.36	36.74
Cook	9.46	10.72	13.27	21.73	17.52	20.05	19.58	17.19	21.85	14.67	16.60
Monticello	17.4	10.94	164.45	11.77	15.35	16.7	13.76	23.91	14.88	23.52	31.27
Praire Island	8.6	9.38	9.94	12.54	12.14	12.22	13.8	10.4	15.03	13.23	11.73
Grand Gulf				37.82	39.14	22.32	23.48	25.68	26.38	18.59	27.63
Callaway				7.85	12.08	19.3	15.76	17.25	18.83	14.23	15.04

TABLE A7: RESULTS FROM SCENARIO 1

Reactor Number	Expected Retirement Year	Expected Life (Years)	Range Earliest Expected Retire Year	Latest Expected Retire Year	Retirement Cause
# 1	1988	13	1987	1990	Poor Performance
# 2	1991	15	1990	1993	Poor Performance
# 3	1994	20	1992	1996	Poor Performance
# 4	1992	21	1992	1992	Embrittlement Const.
# 5	1999	22	1997	2000	Poor Performance
# 6	2008	23	2006	2010	Poor Performance
# 7	2000	23	1999	2002	Poor Performance
# 8	1997	23	1997	1997	Embrittlement Const.
# 9	2009	23	2008	2010	Poor Performance
# 10	2008	23	2008	2008	Embrittlement Const.
# 11	2008	25	2006	2010	Poor Performance
# 12	1998	25	1998	1998	Embrittlement Const.
# 13	1999	26	1997	2001	Poor Performance
# 14	2013	26	2012	2015	Poor Performance
# 15	1998	26	1996	1999	Poor Performance
# 16	2000	26	1999	2001	Poor Performance
# 17	1999	26	1996	2000	Poor Performance
# 18	2011	26	2010	2012	Poor Performance
# 19	1999	26	1997	2001	Poor Performance
# 20	2002	26	2001	2003	Poor Performance
# 21	2011	26	2010	2012	Poor Performance
# 22	2000	26	1997	2001	Poor Performance
# 23	2013	26	2012	2014	Poor Performance
# 24	2007	27	2005	2010	Poor Performance
# 25	2001	27	1999	2003	Poor Performance
# 26	1994	27	1991	1995	Poor Performance
# 27	2013	28	2012	2015	Poor Performance
# 28	2006	28	2004	2008	Poor Performance
# 29	2010	29	2009	2011	Poor Performance
# 30	2000	29	1999	2001	Poor Performance
# 31	2006	29	2006	2006	Ductile Const.
# 32	1990	29	1990	1990	Embrittlement Const.
# 33	2011	30	2010	2013	Poor Performance
# 34	2017	30	2016	2019	Poor Performance
# 35	2004	30	2003	2006	Poor Performance
# 36	2006	31	2006	2006	Ductile Const.
# 37	2006	31	2004	2007	Poor Performance
# 38	2001	31	2001	2001	Ductile Const.
# 39	2021	31	2020	2024	Poor Performance
# 40	2013	31	2009	2014	Poor Performance
# 41	2006	32	2006	2006	Ductile Const.
# 42	2001	32	2001	2001	Ductile Const.
# 43	2001	32	2001	2001	Ductile Const.
# 44	2019	32	2017	2021	Poor Performance
# 45	1996	33	1994	1997	Poor Performance
# 46	2007	33	2006	2008	Poor Performance
# 47	2006	33	2006	2006	Embrittlement Const.
# 48	2009	33	2007	2011	Poor Performance
# 49	2023	34	2022	2024	Poor Performance
# 50	2020	34	2018	2021	Poor Performance
# 51	2019	34	2018	2021	Poor Performance
# 52	2010	34	2010	2010	Embrittlement Const.
# 53	2006	34	2006	2006	Ductile Const.
# 54	2010	34	2009	2011	Poor Performance
# 55	2009	35	2008	2011	Poor Performance
# 56	2021	35	2019	2023	Poor Performance

TABLE A7: RESULTS FROM SCENARIO 1

Reactor Number	Expected Retirement Year	Expected Life (Years)	Range Earliest Expected Retire Year	Latest Expected Retire Year	Retirement Cause
# 57	2019	35	2018	2021	Poor Performance
# 58	2025	35	2024	2026	Poor Performance
# 59	2003	35	2002	2004	Poor Performance
# 60	2018	36	2016	2020	Poor Performance
# 61	2020	36	2019	2021	Poor Performance
# 62	2008	36	2008	2008	Embrittlement Const.
# 63	2025	36	2023	2026	Poor Performance
# 64	2019	36	2018	2022	Poor Performance
# 65	2009	36	2009	2009	Ductile Const.
# 66	2014	36	2013	2015	Poor Performance
# 67	2009	36	2008	2011	Poor Performance
# 68	2009	36	2009	2009	Ductile Const.
# 69	2009	36	2007	2010	Poor Performance
# 70	2021	37	2019	2022	Poor Performance
# 71	2024	37	2022	2026	Poor Performance
# 72	2013	37	2012	2015	Poor Performance
# 73	2022	37	2020	2023	Poor Performance
# 74	2021	37	2020	2022	Poor Performance
# 75	2025	37	2023	2026	Poor Performance
# 76	2026	37	2024	2028	Poor Performance
# 77	2009	37	2008	2010	Poor Performance
# 78	2019	37	2017	2020	Poor Performance
# 79	2009	37	2008	2010	Poor Performance
# 80	2011	37	2009	2012	Poor Performance
# 81	2015	37	2014	2017	Poor Performance
# 82	2017	37	2016	2019	Poor Performance
# 83	2011	37	2011	2011	Ductile Const.
# 84	2023	37	2022	2024	Poor Performance
# 85	2011	38	2009	2012	Poor Performance
# 86	2011	38	2010	2012	Poor Performance
# 87	2009	38	2008	2011	Poor Performance
# 88	2024	38	2023	2025	Poor Performance
# 89	2011	38	2011	2011	Ductile Const.
# 90	2023	38	2022	2026	Poor Performance
# 91	2009	38	2008	2010	Poor Performance
# 92	2025	38	2023	2027	Poor Performance
# 93	2016	38	2014	2018	Poor Performance
# 94	2023	39	2022	2025	Poor Performance
# 95	2021	39	2019	2022	Poor Performance
# 96	2022	39	2021	2023	Poor Performance
# 97	2016	39	2014	2017	Poor Performance
# 98	2012	39	2011	2014	Poor Performance
# 99	2011	39	2010	2012	Poor Performance
# 100	2011	39	2010	2012	Poor Performance
# 101	2025	40	2024	2027	Poor Performance
# 102	2013	40	2011	2014	Poor Performance
# 103	2014	40	2013	2016	Poor Performance
# 104	2025	40	2022	2026	Poor Performance
# 105	2027	40	2026	2029	Poor Performance
# 106	2011	41	2007	2012	Poor Performance
# 107	2022	41	2021	2023	Poor Performance
# 108	2022	41	2021	2024	Poor Performance
# 109	2011	41	2011	2011	Embrittlement Const.
# 110	2012	42	2010	2013	Poor Performance
# 111	2018	42	2016	2019	Poor Performance
# 112	2031	43	2028	2032	Poor Performance
# 113	2031	44	2027	2032	Poor Performance

TABLE A8: RESULTS FROM SCENARIO 2

Reactor Number	Expected Retirement Year	Expected Life (Years)	Range Earliest Expected Retire Year	Range Latest Expected Retire Year	Retirement Cause
# 1	1988	13	1987	1989	Poor Performance
# 2	1989	13	1988	1990	Poor Performance
# 3	1994	20	1993	1995	Poor Performance
# 4	1985	14	1983	1988	Poor Performance
# 5	1991	14	1990	1992	Poor Performance
# 6	1997	12	1996	1998	Poor Performance
# 7	2006	29	2004	2008	Poor Performance
# 8	1997	23	1997	1997	Embrittlement Const.
# 9	2008	22	2006	2010	Poor Performance
# 10	2008	23	2008	2008	Embrittlement Const.
# 11	1996	13	1995	1997	Poor Performance
# 12	1999	26	1999	1999	Embrittlement Const.
# 13	2001	28	2000	2004	Poor Performance
# 14	2028	41	2025	2029	Poor Performance
# 15	1989	17	1988	1991	Poor Performance
# 16	1990	16	1988	1991	Poor Performance
# 17	1984	11	1983	1985	Poor Performance
# 18	2016	31	2013	2018	Poor Performance
# 19	1987	14	1986	1988	Poor Performance
# 20	1997	21	1996	1999	Poor Performance
# 21	1998	13	1997	1999	Poor Performance
# 22	1984	10	1983	1985	Poor Performance
# 23	1999	12	1998	2000	Poor Performance
# 24	1995	15	1994	1996	Poor Performance
# 25	1994	20	1993	1996	Poor Performance
# 26	1988	21	1985	1990	Poor Performance
# 27	2008	23	2007	2009	Poor Performance
# 28	2004	26	2002	2006	Poor Performance
# 29	1999	18	1998	2000	Poor Performance
# 30	1993	22	1992	1994	Poor Performance
# 31	2003	26	2002	2004	Poor Performance
# 32	1990	29	1990	1990	Embrittlement Const.
# 33	2002	21	2001	2004	Poor Performance
# 34	2008	21	2007	2010	Poor Performance
# 35	2002	28	2001	2004	Poor Performance
# 36	1995	20	1994	1998	Poor Performance
# 37	1998	23	1997	1999	Poor Performance
# 38	2000	30	1998	2002	Poor Performance
# 39	2010	20	2009	2013	Poor Performance
# 40	1997	15	1996	1998	Poor Performance
# 41	1995	21	1994	1996	Poor Performance
# 42	1997	28	1996	1999	Poor Performance
# 43	2001	32	2001	2001	Ductile Const.
# 44	2018	31	2016	2019	Poor Performance
# 45	1989	26	1988	1992	Poor Performance
# 46	2001	27	2000	2003	Poor Performance
# 47	2006	33	2006	2006	Embrittlement Const.
# 48	1999	23	1998	2000	Poor Performance
# 49	2004	15	2003	2005	Poor Performance
# 50	2012	26	2011	2014	Poor Performance
# 51	2009	24	2008	2010	Poor Performance
# 52	2007	31	2006	2008	Poor Performance
# 53	1993	21	1992	1994	Poor Performance
# 54	2004	28	2003	2006	Poor Performance
# 55	2022	48	2021	2023	Poor Performance
# 56	2029	43	2027	2031	Poor Performance
# 57	2007	23	2006	2008	Poor Performance
# 58	2001	11	2000	2002	Poor Performance
# 59	2005	37	2004	2006	Poor Performance

TABLE A8: RESULTS FROM SCENARIO 2

Reactor Number	Expected Retirement Year	Expected Life (Years)	Range Earliest Expected Retire Year	Range Latest Expected Retire Year	Retirement Cause
# 60	1999	17	1998	2000	Poor Performance
# 61	2027	43	2025	2029	Poor Performance
# 62	2009	37	2006	2011	Poor Performance
# 63	2000	11	1999	2001	Poor Performance
# 64	2024	41	2023	2025	Poor Performance
# 65	1999	26	1998	2001	Poor Performance
# 66	2012	34	2011	2013	Poor Performance
# 67	1999	26	1998	2002	Poor Performance
# 68	1999	26	1998	2001	Poor Performance
# 69	1995	22	1994	1997	Poor Performance
# 70	2010	26	2009	2012	Poor Performance
# 71	2035	48	2032	2038	Poor Performance
# 72	2004	28	2002	2006	Poor Performance
# 73	2032	47	2030	2033	Poor Performance
# 74	2011	27	2009	2012	Poor Performance
# 75	2005	17	2003	2006	Poor Performance
# 76	2018	29	2016	2020	Poor Performance
# 77	2001	29	2000	2003	Poor Performance
# 78	2013	31	2011	2014	Poor Performance
# 79	2001	29	2000	2003	Poor Performance
# 80	2005	31	2003	2006	Poor Performance
# 81	1998	20	1997	2001	Poor Performance
# 82	2023	43	2022	2025	Poor Performance
# 83	2006	32	2004	2009	Poor Performance
# 84	2017	31	2014	2020	Poor Performance
# 85	2000	27	1999	2002	Poor Performance
# 86	2002	29	2000	2005	Poor Performance
# 87	2004	33	2001	2005	Poor Performance
# 88	2031	45	2028	2032	Poor Performance
# 89	2002	29	2001	2004	Poor Performance
# 90	2013	28	2011	2016	Poor Performance
# 91	2001	30	1999	2003	Poor Performance
# 92	2023	36	2021	2024	Poor Performance
# 93	2009	31	2007	2010	Poor Performance
# 94	2012	28	2009	2014	Poor Performance
# 95	2012	30	2010	2014	Poor Performance
# 96	2026	43	2023	2027	Poor Performance
# 97	2004	27	2003	2005	Poor Performance
# 98	2004	31	2002	2005	Poor Performance
# 99	2004	32	2002	2005	Poor Performance
# 100	2003	31	2001	2004	Poor Performance
# 101	2009	24	2007	2010	Poor Performance
# 102	2009	36	2008	2010	Poor Performance
# 103	2005	31	2003	2006	Poor Performance
# 104	2022	37	2020	2024	Poor Performance
# 105	2034	47	2032	2036	Poor Performance
# 106	2007	37	2004	2008	Poor Performance
# 107	2001	20	2000	2004	Poor Performance
# 108	2033	52	2032	2034	Poor Performance
# 109	1996	26	1995	1997	Poor Performance
# 110	2010	41	2007	2011	Poor Performance
# 111	2021	45	2019	2022	Poor Performance
# 112	2031	43	2030	2032	Poor Performance
# 113	2005	18	2004	2008	Poor Performance

APPENDIX B

APPENDIX B

REPLACEMENT OPTIONS

As seen in Chapter VII, this study predicts that nuclear capacity in the U.S. will continue to shutdown sooner than originally anticipated. In 1991, the Energy Information Administration (EIA) projected that only 3 gigawatts (GWe) of nuclear capacity will be retired by 2010.[1] To the contrary, this study has shown that either 18 Gwe (Scenario 1) or 58 GWe (Scenario 2) actually will be lost by that year. This loss is 6 to 19 times greater than is currently being predicted. Utilities will have to include replacement for this lost capacity in their plans for increasing capacity in the coming years.

In general, current plans to increase capacity in the 1990s are focused on peak and intermediate load production, as baseload production is seen as being overly represented in the production mix. This situation is the result of conservation efforts in the 1970s which were in reaction to the oil crisis. Reduced growth in electricity demand did not meet the levels anticipated when construction of new powerplants in the 1960s and early 1970s was begun. While electric demand is now catching up with this excess capacity, baseload production still is being seen as sufficient to satisfy demand up through the end of this century. Baseload production will decline, however, as nuclear power production decreases. This will create a need for additional increased capacity beyond what is already being planned.

In this section, the options to replace retiring nuclear capacity are presented, along with a short description of energy supply projections, and a more specific look at what each region can reasonably depend upon in both the short term and the long term. The replacement options that are discussed in this section are the following: coal, new nuclear, natural gas, oil, renewables (including hydropower, geothermal, wind, solar, biomass/municipal solid waste), purchases (from other utilities and from nonutilities), and conservation/demand side management programs.

REPLACEMENT OPTIONS

Coal

Coal currently is considered the leading source of fuel to run electric power plants. It is in plentiful supply in the United States and is relatively inexpensive compared to other fuels. Thus, it has been the main source for baseload generation and is expected to account for 40% of new capacity, aimed at baseload production, between 2000 and 2010.

The drawbacks with coal are mainly environmental, as the economic and supply reliability factors are in its favor. Coal, especially "dirty" coal, is high in polluting emissions, such as sulfur dioxide, which contributes to acid rain, and CO_2, a leading compound within "greenhouse gases." The effects of the 1990 Clean Air Act Amendments (CAAA) are expected to shift the type of coal used (from high sulfur to low sulfur) rather than to restrict coal's share in electricity generation.[2] It is expected to remain dominant, providing roughly 52% of electricity generated through 2010.

Future technologies may make coal a more environmentally acceptable alternative.

Conventional coal technologies can meet CAAA standards when scrubbers are added to smokestacks for flue-gas desulfurization. Clean coal technologies are being developed that will further reduce the amount of sulfur dioxide and CO_2 emitted into the air. These include coal gasification, atmospheric fluidized bed systems, pressurized fluidized bed systems, and injecting pulverized limestone into the coal-fired furnace. Integrated gasification combined cycle (IGCC) is another alternative. These methods could work well as parts of retrofitting old coal-fired plants or in new small plants as well as in new large plants, allowing for more flexibility in the use of coal.

New Nuclear

Replacing retiring nuclear plants with new nuclear plants should not be discounted as an option. According to some proponents, Advanced Light Water Reactors (ALWRs) theoretically are ten times more safe than those of the previous generation. Even newer designs, such as the AP600 (advanced passive 600MW--developed by Westinghouse and partner companies), are considered inherently safe and as such should be 1000 times safer.[3] These estimates are controversial, however, because there are no operating data to prove or disprove safety claims. Two examples of the newer designs are the modular high-temperature gas-cooled reactor (MHTGR) and the Power Reactor Inherently Safe Module (PRISM). The MHTGR is cooled with helium instead of water and therefore supposedly can operate at a higher temperature and lower pressure than ALWRs. The PRISM is a liquid-metal reactor, using liquid sodium as a coolant.

These new designs also could be used for smaller plants, since it has been found that the higher cost of maintenance in the larger plants can outweigh the advantages of economies of scale, using more smaller plants may be more practical. Smaller plants also are more easy to make inherently safe, by using gravity for circulation and reducing the need for pumping. With respect to cost, these new nuclear plants might be competitive with coal for baseload requirements. If standardized designs are approved in advance, regulatory constraints should not impede construction of the new nuclear plants. Some new generation designs, such as the AP600 and the SBWR (simpler/smaller/safer Boiling Water Reactor--developed by GE, Bechtel, and Massachusetts Institute of Technology), are expected to pass licensing requirements and be ready for commercial orders by 1995. The PRISM and MHTGR design might not be ready for orders until 2000.[4] Construction time and costs, obstacles in the past, should be lower. Estimations range from 4-5 years to 7 years for a plant to be constructed and placed into commercial operation.[5]

The main drawback may be public opinion. Several recent polls, however, have shown that public opinion on this issue is ambiguous. A majority thinks that nuclear power should be used in the future in the United States, yet a minority thinks that new plants should be built.[6] They also do not want powerplants in their own communities. A study developed for EIA quantified nationwide public acceptance on a state-by-state basis by analyzing various public opinion polls and historical referenda.[7] This study shows that public acceptance of nuclear power varies greatly from region to region, from a factor of 0 (the lowest) in California, Missouri, Maine, and Washington to a factor of 8 (out of a possible 10) in Alabama, North Carolina, South Carolina, and Wisconsin.

Two of the major issues that make nuclear power unattractive to the public (possibility of accidents, and waste disposal) could be addressed by the new reactor designs and by progress on the Yucca Mountain site for nuclear waste disposal.

Natural Gas

Historically, natural gas has been a relatively clean yet nonabundant and expensive fuel. In fact, the Fuel Use Act of 1978 had blocked the use of natural gas to generate electric power as it was believed that it should be reserved for other uses, such as residential heating. New laws, however, are allowing natural gas to surge in importance in the electric power industry. The Energy Policy Act of 1992 provides for expanded markets for natural gas, especially for electric power generation. Also, open access transportation, as initiated by the Federal Energy Regulatory Commission (FERC) in 1984, allows for more direct negotiations between end user and supplier, increasing competition and lowering prices. After an 8-year decline in wellhead prices for natural gas ended which in 1992, prices to electric utilities are substantially lower than they were in the 1970s, when natural gas was considered too expensive.

Power plants using natural gas also have become more efficient. Advanced natural gas combined cycle generation has increased productivity and is replacing older technologies. Steam-injected Gas turbines (STIG) and Intercooled Steam-Injected Gas turbines (ISTIG) show even greater promise. These last two were developed based on aircraft engine technology by the aircraft division of General Electric (GE). STIG and ISTIG systems are expected to raise efficiency levels to close to 50%. These systems could provide baseload capacity on a competitive level with coal and nuclear plants.

The increased interest in natural gas for electricity generation coincides with planned expansion of the natural gas supply pipeline network. For example, the planned Iroquois system will bring natural gas from Canada to New England and New York. (Imports were estimated to equal 8% of total US consumption of natural gas in 1991.) Pipeline construction, however, includes both incoming and outgoing capacity, as some regions either export natural gas to other regions or act as conduits between regions. The anticipated net flow, entrance or exit, of natural gas per region, in 1991 and projected for 1995 indicate that 5 of the U.S. federal regions will experience a net increase in the availability of natural gas (Table B.1). The expected increase of supply of natural gas for end-use in these regions imply that there is a potential for expansion of natural gas-fired electricity generation.

TABLE B.1: NET ENTRANCE [NET EXIT] OF NATURAL GAS FOR SIX REGIONS, 1991 and 1995 (million cubic feet per day)

Region	1991	1995	% Change
Northeast	8,692	10,132	+17%
Southeast	5,110	7,364	+44%
Midwest	14,972	14,990	+0.1%
Southwest	[31,812]	[35,638]	[+12%]
Central	1,606	1,259	-22%
West	7,111	10,719	+51%

Source: Derived from data presented in EIA *Natural Gas 1992: Issues and Trends*, 1993.

EIA expects that natural gas will be the key source fueling new capacity in the 1990s and will retain an important role in the next century, possibly accounting for 33% of new capacity.[8]

Oil

Although oil in the past had been a key source of fuel for the electric power industry, since the oil crisis of the 1970s it has been seen as not only expensive but vulnerable to supply disruptions. In addition, it is environmentally opposed because of CO_2 emissions. Therefore, oil has had a decreasing role in electric power production and is not expected to be a major source to replace retiring nuclear powerplants. In some regions, however, it may maintain an important role for peak and/or intermediate load production.

Renewables

Independent Power Producers (IPPs) and cogenerators rely more on renewables than do utilities. Renewables include hydropower, biomass/municipal solid waste, solar, wind, and geothermal.[9] Some of these resources offer limited potential, while others could be bountiful given the right economic and policy mix to encourage their adoption and development.

Hydropower. Hydropower (which represents 10% of all electric power generation), is a mature industry, with most of the available sites having been developed already. Developing new sites may be difficult due to environmental constraints.

Although there is predicted to be some growth in generation from hydropower plants, it is small.

Biomass/Municipal Solid Waste. Biomass often is based on wood and pulp, particularly from the forestry products and paper industries which are common in the eastern states, in the northwest, and the west. Energy crops to grow biomass for power production is more common in the central states. Municipal solid waste, which is burned in waste incinerators, can supply energy in urban areas. These resources, although renewable, could be reduced by other projects that benefit the environment, such as recycling.

Geothermal. Current geothermal capacity, totaling 2.7 GWe in 1991, is concentrated in the western states, particularly California, Utah, and Nevada. The largest capacity plant, with 1.3 GWe, is located in The Geysers in California. This field is the largest producer of geothermal electric power, accounting for 69% of all geothermal installed capacity. It is one of the few sources of vapor-dominated geothermal power. Most other sites utilize liquid-dominated (hydrothermal) power and have much smaller capacities. Table B.2 shows projected hydrothermal capacity in the Western States by 1995 and 2010.

Geothermal, though normally small, is used for baseload capacity and thus, if developed enough, could complement coal and nuclear. In its favor, geothermal is a clean source of energy and geothermal plants can be constructed and put into operation in only 2 years. It is estimated that geothermal resources of the type currently exploited in the western states could equal 23 GWe capacity for a lifetime of 30 years. Possible additions of undiscovered sources could raise this figure to 72-127 GWe of capacity. Bonneville Power Administration estimated 185 GWe capacity residing in the Cascade Range. Geothermal power is expected to provide the greatest amount of growth among renewable energy sources.

The expense of geothermal is a detriment. Costs for a hypothetical 50 MW plant would be on the order of 6.4 cents per kwh, relatively high compared to the possible purchase price of 2 cents per kwh for some Canadian power.[10] Another disadvantage is that, to date, all developed geothermal resources are located in western states, not in the east where demand might be higher. In addition, developable sites may be far from demand and therefore might not be economical enough to develop.

TABLE B.2: PROJECTED HYDROTHERMAL CAPACITY IN GWe, for EIA's BASE AND ALTERNATE SCENARIOS, 1995 AND 2010

State	1995	2010 Base	2010 Alternate*
Arizona	0	.190	.380
California	2.700	7.866	10.645
Colorado	0	.770	1.0
Hawaii	.003	.150	.300
Idaho	.005	.665	1.670
New Mexico	0	.370	.490
Nevada	.096	.400	.650
Oregon	.002	.825	2.200
Utah	.040	.400	.550
Washington	0	.025	.050
Total	2.843	11.661	17.935

*Alternate scenario assumes improved technology and accelerated exploration[11]
Source: EIA, *Renewable Resources in the U.S. Electricity Supply*. Washington, D.C, 1993.

A new technology that might be able to start supplying geothermal power in 2000 is hot dry rock, which has demonstration facilities in New Mexico and in the U.K. This type of geothermal power might be more evenly distributed around the country because it does not depend on the geological condition of heat and water in the same location but injects water down to where the heat (hot dry rock) is.

Solar. Solar energy that is currently used on a commercial basis to generate electricity is obtained from solar panel collectors, which concentrate solar energy in order to heat a working medium, such as water, to produce steam and generate electricity. This is an emission-free process, yet the costs involved, the limitation of feasible sites, and the inability to use it during night or cloudy days limits its potential as a major source for baseload electricity, although it can play a role in a mix of fuels in the western states.

Photovoltaics, used on small-scale items such as solar-powered calculators, hold much potential. In this technology, solar energy excites positively and negatively charges atoms within the photovoltaic cell which generates a charge. To use this source on a commercial level requires much more research and development, however, it shows potential in long-term energy supply scenarios.

Wind. Wind power, like solar power, is environmentally kind yet expensive. Winds of sufficient speed to economically generate electricity are not located nationwide. Also, winds are variable, and therefore wind technology is not a good candidate to supply baseload capacity.

Purchases

The trend of utilities' purchasing electric power from other sources will continue. Such sources include other utilities, other countries, and nonutility generators or independent power producers. While some regions will be losing needed capacity, some regions will still have excess capacity and will continue to be able to sell bulk power over the national transmission grid. New links with Canada, such as between New England Electric and HydroQuebec, will increase the availability of Canadian hydropower to energy-poor regions. Other suppliers will be nonutility generators, such as independent power producers.

The 1978 Public Utility Regulatory Policies Act (PURPA) encouraged the growth of the independent power industry by guaranteeing that Qualified Facilities (QFs) would have a market for their power production. QFs, as defined by PURPA, are either cogenerators or nonutility power producers that use natural gas or renewable energy sources. Nonutilities are increasing capacity at a rate comparable to utilities in the 1990s and by 2010, when utilities may increase their rate of capacity additions, nonutilities still might account for 20%-25% of new capacity. This share could allow the independent power industry to provide 10% of utilities' generation needs. Imports from Canada and Mexico also are going to play a larger role on the U.S. scene.

Cogeneration, especially strong in Texas and California, is increasingly relying on natural gas. Cogeneration plants tend to be smaller, on the order of 50MW or so. New arrangements with cogenerators and other independent power producers may make it possible for the latter to provide an increasing share of utilities' total generation needs.

Conservation/demand-side management programs

This is a potentially important source of "negawatts." The concept of meeting demand by lowering it rather than by increasing electric output is catching on. Yet until regulations are changed, can not spread as fast in other states as it did in California where utilities are allowed to charge more while supplying less and thereby retain their profit margins. Such an approach would take many small contributions, from encouraging residential consumers to use energy-efficient light bulbs and appliances, to going "inside the fence" to run cogeneration plants for industrial users on-site. Conservation and demand-side management programs will most likely move slowly unless government policy provides incentives beyond market considerations for utilities to pursue such programs.

ENERGY SUPPLY PROJECTIONS

There have been some studies that estimate the roles each fuel type will play in future electric power generation. One done by the Office of Technology Assessment compared 1989 figures with 6 scenarios forecasting energy use in 2015.[12] Those scenarios are Base, High Growth, Moderate Efficiency, High Efficiency, High Renewables, and High Nuclear (Table B.3). EIA has made similar projections for 2000 and 2010, forecasting scenarios for High Oil Price, Reference, and High Economic Growth (Table B.4).[13] These projections summary the expectations with respect of fuel composition for future electricity generation in the U.S. None of the scenarios developed by OTA or EIA consider the possibility of early nuclear retirements s the scenarios developed in this dissertation show.

TABLE B.3: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE BASED ON OTA PROJECTIONS FOR 2015

Source	BASE	HIGH GROWTH	MOD EFFI	HIGH EFFI	HIGH RENEW	HIGH NUCLEAR
Coal	63%	55%	52%	23%	38%	32%
Nuclear	8%	16%	19%	30%	14%	32%
Natural Gas	14%	14%	12%	23%	9%	13%
Oil	3%	3%	4%	1%	4%	3%
Renewables	12%	11%	13%	23%	36%	20%

Source:OTA, *Energy Technology Choices: Shaping Our Future*, OTA-E-493, Washington, D.C., 1991.

TABLE B.4: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE BASED ON EIA PROJECTIONS FOR 2000 AND 2010

Source	BASE 2000	HIGH OIL 2000	HIGH GROWTH 2000	BASE 2010	HIGH OIL 2010	HIGH GROWTH 2010
Coal	53%	54%	51%	57%	55%	56%
Nuclear	18%	19%	17%	16%	17%	16%
Natural Gas	13%	12%	15%	15%	14%	14%
Oil	6%	5%	7%	4%	5%	6%
Renew	10%	10%	9%	9%	9%	8%

Source: EIA, *Annual Outlook for U.S. Electric Power 1991: Projections Through 2010*, Washington, D.C, 1991.

REGIONAL ASSESSMENT

As seen in Chapter VII, Scenario 1 predicts the closure of 20 reactors in 6 regions by 2005, while Scenario 2 predicts 64 to close in 8 regions by 2005. The following sections assess what each region that faces premature retiring of nuclear capacity can do to meet the gap. Comparisons are made to regional projections generated by EIA. Comparisons to OTA projections are not possible because OTA does not produce forecasts at regional levels.

New England

By 2005, New England will lose the output from either 2 reactors (Scenario 1) or 6 reactors (Scenario 2). This represents an estimated loss of 1.2 to 4.1 GWe of capacity. Table B.5 shows projections derived from EIA forecasts for electrical generation by fuel share in New England, not taking into consideration the closure of nuclear capacity.[14] Because EIA's forecasts did not anticipate the closure of either 2 or 6 reactors in the region, the nuclear share of electrical generation will be lower than the 39% and 31% shown for 2000 and 2010, respectively. The table also shows nonutility generation as a percent of total (utility + nonutility) generation as a measure of potential availability of electric power for purchase.

As seen in Table B.5, coal and oil are expected to remain the leading sources of fuel for electricity generation (given that nuclear will be declining) despite the 1990 CAAA. Most likely this assumes that clean coal technologies and pollution abatement equipment will be installed in any new coal powerplants. It is unlikely, however, that oil will fuel any new plants built to replace lost nuclear capacity.

Natural gas is seen to be increasingly used but should not be considered the final option unless pipeline capacity is increased more than is currently planned. As shown in Table B.1, pipeline capacity for natural gas entering the region is being expanded only 17%. This might not be enough of an increase to provide sufficient natural gas to replace the losses from retiring nuclear capacity. On the other hand, additional supplies from the Iroquois system might increase the amount currently projected to enter the region.

Expansion in nonutility generation is even greater than that predicted for natural gas. Purchases from independent power producers (which often rely on natural gas or wood biomass in cogeneration projects) and imports from Canada are likely to increase. Increases in transmission lines, especially interconnections with HydroQuebec and other sources in Canada, indicate that the region already is planning to go in this direction. Conservation and demand-side management projects will most likely be important as well. Renewables, other than limited hydropower and wood biomass, are lacking in New England and are not foreseen to provide a large role in power production.

According to a GE study, a mix of combustion turbines and combined cycle plants would be the best source of new capacity, but when externalities are considered (such as costs in terms of air pollution) then new nuclear is favored.[15] The average public acceptance factor for nuclear power in the region, however, is low, indicating that nuclear may not be an option.

TABLE B.5: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE, NEW ENGLAND

Source	1989	2000 Reference	2010 Reference
Coal	18%	16%	23%
Nuclear	34%	39%	31%
Natural Gas	5%	7%	12%
Oil	38%	33%	30%
Renewables	5%	5%	4%
Nonutility generation	11%	17%	23%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010*, DOE/EIA-0474, 1991.

New York/New Jersey

By 2005, Region II will lose either 2.6 GWe (3 units--Scenario 1) or 4.3 GWe (5 units--Scenario 2) of nuclear capacity. Table B.6 shows projected electrical generation by fuel share in New York/New Jersey, not taking into consideration the closure of nuclear capacity. Because the EIA forecasts did not take into consideration the early shutdown of either 3 plants or 5 nuclear plants, the nuclear share of electrical generation will be lower than the 24% and 17% shown in the table for 2000 and 2010, respectively. The table also shows nonutility generation as a percent of total (utility + nonutility) generation as a measure of potential availability of electric power for purchase. The table shows that, as nuclear and oil decline in importance to the region, use of coal and natural gas increase. Renewables have a stronger position compared to New England, yet are not expected to have much growth within the region. The role for nonutilities also is expanding. Many cogeneration projects have applied for licenses to import natural gas from Canada. Given a further decline in nuclear, it is most likely that natural gas (and natural-gas fired cogeneration) and coal will increase even more. Purchases from Canada also are likely to increase, as the New York power pool is reinforcing its connections between Canada and central and southeast New York state.[16]

TABLE B.6: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE, NEW YORK/NEW JERSEY

Source	1989	2000 Reference	2010 Reference
Coal	20%	14%	31%
Nuclear	27%	24%	17%
Natural Gas	13%	19%	20%
Oil	27%	27%	19%
Renewables	14%	15%	12%
Nonutility Generation	4%	9%	14%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010,* DOE/EIA-0474, 1991.

Middle Atlantic

Region III will lose between 3.7 GWe from 4 reactors (Scenario 1) and 8.3 GWe from 9 reactors (Scenario 2) by 2005. Table B.7 shows projected electrical generation by fuel share in the Middle Atlantic region, not taking into consideration the closure of nuclear capacity. The table shows a higher nuclear share (19% for both 2000 and 2010) than will be expected based on this study. The table also shows nonutility generation as a percent of total (utility + nonutility) generation as a measure of potential availability of electric power for purchase.

Coal is overwhelmingly the fuel of choice in this region, and will continue to be so in the future. With oil declining, the other sources to replace nuclear would be a slight increase in natural gas and additional purchases from cogenerators and other independent power producers. The region also purchases power from coal-fired utilities in the Midwest region.

TABLE B.7: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE, MID ATLANTIC REGION

Source	1989	2000 Reference	2010 Reference
Coal	74%	68%	70%
Nuclear	17%	19%	19%
Natural Gas	<1%	2%	6%
Oil	7%	8%	4%
Renewables	1%	<1%	<1%
Nonutility Generation	5%	11%	13%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010,* DOE/EIA-0474, 1991.

South Atlantic

The South Atlantic region will lose the most from early retirement, facing a decline in either 4.6 GWe of capacity (5 units) or 16.6 GWe (18 units) by 2005, according to Scenarios 1 and 2, respectively. Table B.8 shows projected electrical generation by fuel share in the South Atlantic region, not taking into consideration the closure of nuclear capacity. This study will predict lower nuclear shares than the 23%

and 21% for 2000 and 2010, respectively, that were forecast by EIA.

The South Atlantic region also has a strong reliance on coal. Here, however, acceptance of nuclear is the strongest of all regions so that new nuclear would have a good chance to replace old nuclear. Expansion of natural gas coming into the region could allow for a greater role than is suggested in Table B.8. Other sources would be minor players in this region. The utilities in the region do not expect to rely on cogeneration, other independent power, or demand-side management programs to any great extent.[17] Because of flat terrain and sunny climate, however, solar power could be a possibility that has not been developed yet.

TABLE B.8: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE, SOUTH ATLANTIC REGION

Source	1989	2000 Reference	2010 Reference
Coal	60%	57%	63%
Nuclear	24%	23%	21%
Natural Gas	4%	8%	7%
Oil	5%	7%	5%
Renewables	7%	5%	4%
Nonutility Generation	4%	6%	8%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010,* DOE/EIA-0474, 1991.

Midwest

By 2005, the Midwest Region will lose between 3.3 GWe from 4 reactors (Scenario 1) or 11.7 GWe from 14 reactors (Scenario 2). Table B.9 shows projected electrical generation by fuel share in the Midwest Region, not taking into consideration the closure of nuclear capacity. The EIA forecasts from which these data are derived predict higher share for nuclear power (20% and 17% for 2000 and 2010, respectively) than would be expected based on this study.

TABLE B.9: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE, MIDWEST REGION

Source	1989	2000 Reference	2010 Reference
Coal	73%	72%	69%
Nuclear	25%	20%	17%
Natural Gas	<1%	6%	13%
Oil	<1%	<1%	<1%
Renewables	<1%	1%	<1%
Nonutility Generation	3%	6%	6%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010,* DOE/EIA-0474, 1991.

With the decline of nuclear power, use of natural gas could increase at a faster pace than shown in the table. The Midwest has the highest fossil fuel emissions in the nation, so although coal is a dominant fuel source at present time, it might not be relied upon as heavily for alternatives to nuclear capacity. Public acceptance of nuclear is average, so that new nuclear could be an option. The region is not expected to look to cogeneration or independent power producers, although conservation and demand-side management programs could prove to be important. As a net exporter of electricity to New England, the Midwest region could also rely on some excess capacity to fill any gap made by losses from nuclear shutdowns, reducing exports if needed.

Southwest

The Southwest region will lose nuclear capacity only according to Scenario 2, with a loss of 5.2 GWe from 5 units by 2005. Table B.10 shows data derived from EIA projections for electrical generation by fuel share in the Southwest region.[18] Because the EIA forecasts do not take into consideration the closure of nuclear capacity, actual nuclear shares in 2000 and 2010 will most likely be lower than the 11% and 9%, respectively, shown in the table.

TABLE B.10: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE, SOUTHWEST REGION

Source	1989	2000 Reference	2010 Reference
Coal	52%	50%	49%
Nuclear	8%	11%	9%
Natural Gas	37%	37%	40%
Oil	<1%	<1%	<1%
Renewables	2%	2%	2%
Nonutility Generation	12%	12%	13%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010,* DOE/EIA-0474, 1991.

As a net exporter and producer of natural gas, most likely any loss in nuclear capacity would be replaced with natural gas rather than with other sources. Cogeneration and independent power are very strong in the region, especially in the Houston area, and could potentially provide enough for the short-term. Nuclear is not especially accepted by the public, and renewables are not cost-effective compared with natural gas.

Central

Region VII, the Central region, will lose 2 units (2.1 GWe) under Scenario 1 and 3 units (2.4 GWe) under Scenario 2 by 2005. Table B.11 shows projected electrical generation by fuel share in the Central region, not taking into consideration the closure of nuclear capacity. These data are derived from forecasts made by EIA and show a higher nuclear share 13% for 2000 and 12% for 2010 than would be predicted by this study. Table B.11 also shows nonutility generation as a percent of total (utility + nonutility) generation as a measure of potential availability of electric power for purchase.

TABLE B.11: PROJECTED ELECTRIC GENERATION BY FUEL SHARE, CENTRAL REGION

Source	1989	2000 Reference	2010 Reference
Coal	76%	73%	77%
Nuclear	20%	13%	12%
Natural Gas	1%	12%	9%
Oil	<1%	<1%	<1%
Renewables	2%	2%	2%
Nonutility Generation	1%	6%	7%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010*, DOE/EIA-0474, 1991.

The Central region also relies very heavily on coal and would most likely replace nuclear capacity with it. Natural gas could provide some additional capacity than is now planned. New nuclear is not likely to be an option, given low public acceptance and the strength of coal. Renewables will not likely play any significant role. Independent power, on the other hand, is expected to grow and could play some role in a mix relying more heavily on coal and natural gas.

West

The West will lose 4 units, or roughly 4.5 GWe, by 2005 according to Scenario 2. Table B.12 shows projected electrical generation by fuel share in the West Region, using data derived from EIA forecasts. Because these data do not take into consideration the closure of nuclear capacity, actual nuclear share in 2000 and 2010 should be lower than the 18% and 15%, respectively, shown in the table. Table B.12 also shows nonutility generation as a percent of total (utility + nonutility) generation as a measure of potential availability of electric power for purchase.

Because of environmental regulations and public attitudes in California, it would be difficult to replace retiring nuclear capacity with new nuclear or oil. Although there is some growth expected in use of coal, the region most likely will attempt to develop natural gas, renewables and independent power producers as much as possible. The expansion of natural gas pipeline capacity entering the region, as shown in Table B.1, will allow for greater use of natural gas, a major source for cogeneration in the region.

Indeed, independent power producers in California have contracted for 15 GWe of capacity, which may lead to an overcapacity problem.[19] Conservation programs also have been the strongest in this region than in any other, although strides in demand-side management probably could not by itself replace losses in nuclear capacity.

TABLE B.12: PROJECTED ELECTRICAL GENERATION BY FUEL SHARE, WEST REGION

Source	1989	2000 Reference	2010 Reference
Coal	22%	24%	38%
Nuclear	19%	18%	15%
Natural Gas	28%	27%	20%
Oil	8%	6%	4%
Renewables	23%	25%	23%
Nonutility Generation	17%	20%	23%

Source: EIA, *Annual Outlook for the U.S. Electric Power 1991: Projections through 2010,* DOE/EIA-0474, 1991.

In summary, the discussion in this appendix has shown that there are several alternatives to replace retiring nuclear capacity so that regions need not be caught with power shortages if they begin to plan now to offset those losses. Table B.13 provides a summary of the mix of replacement options that best fits each region. Although there are ten federal regions, the North Central region is not included in this table because it currently has no nuclear capacity.

TABLE B.13: BEST REPLACEMENT OPTIONS BY REGION

Region	Mix of Replacement Options
Northeast	Natural gas, conservation, purchases from imports and nonutilities
New York/New Jersey	Natural gas, coal, purchases from nonutilities and imports
Middle Atlantic	Coal, purchases
South Atlantic	New nuclear, natural gas, renewables
Midwest	Natural gas, new nuclear, conservation
Southwest	Natural gas
Central	Coal, natural gas
Northwest	Imports from Canada
West	Conservation, renewables, natural gas

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