WESTINGHOUSE PWR: THE RISE AND FALL OF A DOMINANT DESIGN IN THE ELECTRIC POWER INDUSTRY

by

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Master in Nuclear Engineering
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Submitted to the Engineering Systems Division
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ABSTRACT

In the early 1950s the electric power industry was shaken by the introduction of a new type of energy source that pledged to be the most cost-efficient way of producing electricity. Counting on the promise of huge profits –attributed to large economies of scale- governments and utilities rushed to develop and construct nuclear power plants. From 1952 to 1985, four hundred units were built all across the industrialized world, from the United States to the Soviet Union and from Sweden to Taiwan. Nuclear power accounted for the most impressive capacity build-up in 100 years of electricity history.

As was the case with most of the strategic technologies developed in the 20th century, the first nuclear prototypes were developed in the United States, with the sponsorship of the federal government. The funding ended up mainly in R&D expenditures administered by the Atomic Energy Commission (AEC). As a result of such a strong commitment to nuclear, the United States quickly became the technological leader in the world. Such leadership meant not only building most of the nuclear power plants in its territory –125 out of 480- but establishing industry standards in many areas: from design, licensing and construction to commercial operation, and decommissioning.

This research explores one of the most substantial legacies of the U.S. nuclear power undertaking: the PWR reactor developed by Westinghouse. The research examines the story of the PWR from its origins in the drawing rooms of the Bettis Laboratories in the 1950s to its rapid adoption in the 1960s as the dominant design in the industry. The main goal of the research is describing the dynamics of the process, building at the same time a workable framework of analysis.

The first part of the research digs down into plants' data. Using a large database of reactors' records, the dominant design hypothesis is tested thoroughly. The analysis confirms that the early design proposed by Westinghouse quickly became the standard of the industry. Nearly two-thirds of all reactors built in the world have their roots in the early Westinghouse design.

The reasons for the emergence of such a dominant design are numerous: (a) the influence of military nuclear programs, such as the nuclear submarine; (b) the monopoly of the AEC regarding nuclear secrecy, technology transfer and industry partnership; (c) the role of the cold war as a driving force in nuclear and space policy; and (d) the obscure alliance between Westinghouse and GE regarding competition on electrical components, notably the large steam-turbines used in nuclear power plants.

The emergence and consolidation of a dominant design in any industry has many consequences. In nuclear power, some of the relevant issues are standardization, learning effects, economies of scale, and regulation. All these issues are important to study not only in the United States context. The international consequences are vast on nuclear power programs and policies of countries such as Japan and France.

Since most dominant designs have a rise and a fall, the research includes an analysis of why in the mid-1980s the Westinghouse PWR collapsed, along with the entire nuclear power industry. The thesis is that incumbent firms that have successful dominant designs in the market, very often fail to be aware of subtle –but disrupting- shifts in customer needs. Westinghouse was busy building large and complex units in order to increase efficiency and profits, while customer needs were moving in a radically different direction, towards less investment risk.

Thesis Supervisor: John S. Carroll
Title: Professor of Behavioral and Policy Sciences

In gratitude

When I graduated with the degree of nuclear engineer, I thought that in order to understand my profession I needed to gain mastery in the intricacies of complex subjects such as nuclear physics, reactor theory, fluid mechanics, thermal transfer, etc. After some years I realized that in order to fulfill my goal of understanding nuclear engineering more profoundly I needed to move in other direction. I needed to understand nuclear technology in its human dimension, as the outcome of the effort of a particular group of people, who directed an enormous amount of work and capital pursuing an elusive and controversial objective.

My quest for insight inspired me to visit Hiroshima, Japan in 1997 and more recently Los Alamos, New Mexico. But more importantly, it motivated me to write this thesis which is, above all, a tenacious attempt to understand the complex issues surrounding the birth and growth of nuclear power in the United States and abroad. It also fulfills the requirement for the Degree of Master of Science in Technology and Policy but, to be honest, that has been only a secondary objective.

I am particularly indebted to Professor John S. Carroll, who took the risk of supervising a young man's way into MIT; to Sydney Miller for her support, encouragement and patience during a process that became especially difficult in the last mile; to Dean Isaac Colbert and Sarah Gallop for their willingness to help. In addition to these mentors, Professors Neil Todreas, Richard Lester, Ernest Moniz and Andrew Kadak helped throughout the research with valuable comments and feedback. MIT has been for me the fountain of knowledge and human generosity.

I am similarly indebted to Rotary Foundation for sponsoring my studies and for providing me the opportunity to develop a lasting friendship with many Rotarians of the Boston area. Rotary's ambassadorial scholarship has increased the value of my studies enormously and has helped me to go through the turbulent waters of graduate school. In particular I want to mention Karen and EJ Swaim-Babin, Chris and Dianne Fraser, and Alberto and Zareen Araoz. I also want to thank Yu-Ling Hsu for helping me with the typing of several long and tortuous fragments of the text. Her support and her unhesitating faith on my ability to finish the thesis have been an inspiration to me.

I owe the most to my family in Argentina –my parents Carlos and Martha- for my absence from home during very difficult times. I dedicate my thesis to them.

Carlos J. Barrientos

Cambridge, May 24th 2002

Introduction

THE DAWN OF NUCLEAR ENERGY

Nuclear energy emerged after the strikes over Japan at the end of World War II. At 8:15 am of August 6th, 1945, a bomb was dropped over Hiroshima from an aircraft flying at 31,600 feet. Fifty seconds later a flash was seen by the pilot and immediately a shock wave hit the plane. Five minutes later, a dark gray cloud some three miles in diameter hung over the center of Hiroshima. Because of this dense smoke cloud, which ultimately rose to a height of 35,000 feet, it took several hours to have a clear view of the devastated city. Two-thirds of the total urban area was completely destroyed and, according to Japanese official estimates, 71,000 people died and 68,000 were injured. Two days later, a second bomb was dropped over Nagasaki from an altitude of 29,000 feet. This nuclear device seemed to be less lethal as only 44% of the urban area was destroyed, and the fatal casualties, according to an US survey, amounted to 35,000 people dead or missing (Del Sesto, 1979).

One can hardly imagine a more sensational and dramatic way to mark the dawn of a new technology. It was by any account the most amazing display of energy ever unfolded by human civilization. As for the planet harboring that civilization, it was one of the largest explosions registered in modern history, rivaled only by the impact of a large meteorite in Siberia at the beginning of the 20th century.

Notwithstanding its spectacular and devastating introduction as a weapon, nuclear technology has made its way in modern civilization primarily by means of peaceful applications. As many other post-war branches of knowledge, nuclear technology evolved during the second half of the 20th century from full military monopoly to extensive civilian control. This technology has found a thorough utilization in fields as diverse as medicine, materials science research, forensic analysis, archaeology, oil exploration, and electricity production.

All across the world, scores of professionals use nuclear equipment in their routine activities. Physicians use Cobalt irradiators for cancer therapy. Courts base their findings on forensic studies that involve the use of sophisticated techniques such as neutron activation analysis. Archaeologists determine the chronological date of items using the powerful Carbon-14 methodology.

Even though the above-mentioned applications have been very important, no other civilian use of nuclear technology has had a more profound impact in our society than the use of nuclear energy for producing electricity. No other source of energy has evolved so rapidly over the last five decades and –without any doubt- no other source of energy has inspired so much public controversy about its benefits and risks.

PURPOSE OF THE STUDY

This study is centered on the spectacular growth of nuclear power between the 1950s and the late 1980s. Its main purpose is to determine the role of the PWR -a design developed in the U.S. by Westinghouse- which quickly became the industry standard. In the same way that Douglas shaped the commercial aircraft industry with the introduction of the DC-3 in the early 1930s, Westinghouse profoundly molded the nuclear power industry with the inception of its PWR design.

The purpose of the study is thus twofold. On the one hand it has a historical focus on describing the PWR's chronological progress in the two crucial dimensions of product development: technology and market. On the other hand the study has a policy goal which is to identify the public and private policies that both favored the emergence of the PWR as an industry standard, and eventually caused its demise a few decades later.

Studying the development of nuclear power plants is an interesting exercise for many reasons. First, nuclear power is a very complex technology that has an enormous economic impact nowadays. That by itself makes it an important subject of study. But the analysis of nuclear power reveals that the industry has followed an observable technology cycle characterized by a rapid penetration of the market and in a like manner, a rapid phase out. Analogously to Kuhn's pioneering work on the structure of scientific revolutions, nuclear technology has described the characteristic pace of technological progress. It advanced slowly at first, then accelerated, and then inevitably declined (Kuhn, 1962).

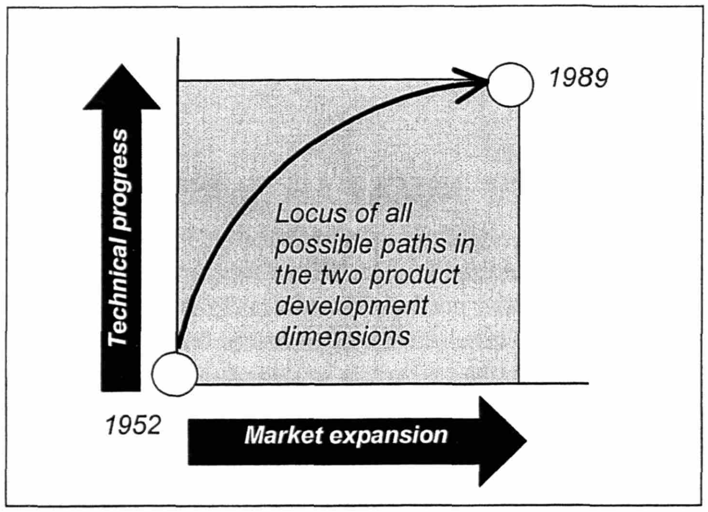


Figure I.1.Nuclear power development from 1952 to 1989

In the particular case of nuclear power, the processes of acceleration and decline were embedded in the designs that populated the marketplace. The thesis of this study is that those processes were shaped by the fact that an industry standard –or dominant design- emerged at some point in the story (Utterback, 1994).

MAIN RESEARCH QUESTIONS

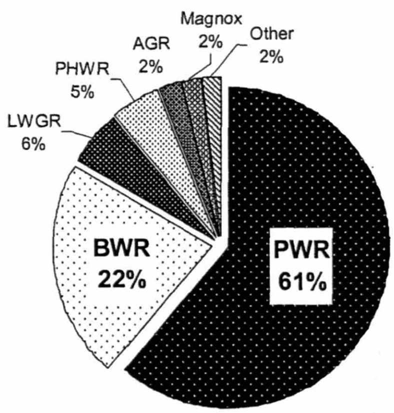
If the data presented in the study show sufficient indications to believe that the PWR achieved the status of a dominant design, then a number of interesting questions arise:

1. Identifying and understanding the **reasons** that motivated the overwhelming adoption of this particular design. In particular: (a) public policies that favored the PWR, (b) inherent competitive advantages of this technology over other designs, (c) Westinghouse's value proposition to eventual buyers, (d) the role of other participants of the value chain, including suppliers, and (e) the impact of technology transfer policies to foreign countries.
2. Identifying and understanding the **consequences** of the emergence of a dominant design in the nuclear power industry. In particular: (a) effects on the survival of firms, (b) impact on the performance of the industry, (c) role in the industry's technology cycle, particularly in promoting –or inhibiting- innovation, and (d) accountability for the ultimate collapse of the nuclear power industry.
3. Identifying and understanding the **lessons** of the Westinghouse PWR case for other rapid-growing industries. In particular: (a) dominant designs and its role on technology cycles, (b) public policies that both promote and regulate an industry, (c) early warnings regarding firms' destructive competition, and (d) policies to stimulate innovation and industrial performance.

SCOPE OF THE STUDY

The scope of this study includes all the commercial nuclear power plants that were built in the world before 1989. This large ensemble accounts for 481 units in more than 25 countries (Figure I.2) and consists of 100% of the market.

Even though the scope of the study is over 481 units, the study has a particular focus on the 282 PWR and BWR reactors, for reasons that will become clear in later chapters. The rest of the nuclear power plants – 199 units- were units of other designs: AGR, PHWR, LWGR, etc. In addition, there is an unintentional focus on U.S. plants for two reasons: it is the nation where the PWR concept was originally developed and where more PWR units were built.



USA	136
FRANCE	60
USSR	59
UK	42
JAPAN	38
GERMANY	30
CANADA	21
SWEDEN	13
SPAIN	10
CZECH REP.	9
KOREA	9
BELGIUM	8
INDIA	7

SWITZERLAND	6
TAIWAN	6
BULGARIA	5
FINLAND	4
HUNGARY	4
ITALY	4
ARGENTINA	2
HOLLAND	2
MEXICO	2
S. AFRICA	2
PAKISTAN	1
YUGOSLAVIA	1
TOTAL	**481**

Figure I.2. NPPs that started operation before 1989, divided by country and design.

In order to draw valid conclusions, a specific database was built with data assembled from different sources, especially from industry handbooks of the late 1980s (Cruickshank, 1989). This database was developed in SPSS format and is composed of 481 cases and 51 variables. SPSS is a standard statistics software that expedites the management of data and allows multiple operations.

It is important to note that the research scope is commercial nuclear power plants that started operation before 1989, both units that are still functioning and those that have been shutdown. The following reactors are excluded from the study:

1. Nuclear power plants that started operation after 1989, including units that are currently under construction and those with works temporarily halted or cancelled.
2. Nuclear reactors that are not intended for electricity generation, namely (a) research reactors, (b) radioisotope production reactors, and (c) plutonium production reactors.
3. Nuclear reactors developed for propulsion. In particular, (a) reactors for space propulsion, and (b) reactors for naval propulsion such as the ones installed in submarines and aircraft carriers. As will be shown in subsequent chapters, these reactors had a significant role in the emergence of the PWR as a dominant design and that connection will be explored in detail. However these reactors are not the primary focus of the research.

SYNOPSIS

Since the main thesis of this study is that a dominant design in the nuclear power industry emerged in the 1960s, the first part of the study is devoted to a historical recount of the PWR's origins and a thorough analysis of its progress in the technology and market dimensions. After establishing with reasonable confidence that a dominant design effectively emerged in this industry, the final part of the study is aimed to develop a feasible explanation of the PWR progress: from early development and market acceptance, to its final demise. The goal is to develop a workable framework that serves to explain both the reasons and the consequences of the emergence of a dominant design. In order to achieve these objectives systematically, the material is distributed in the following chapters:

1. The early origins of the PWR Design

The chapter starts explaining the foundation in 1946 of a civilian nuclear power program managed by the AEC. Then it introduces the complex relationship between military and civilian objectives in the dawn of the nuclear age, which was shaped by the advent of the cold war. The chapter also explains the early years of the partnership between AEC and the industry for building nuclear reactors. In particular, the chapter discerns the role of Westinghouse as main contractor of key military projects and AEC's decision of selecting it for supplying the power system for the 1st nuclear submarine. The chapter includes a thorough analysis of the environment at the time, namely: (a) the rush to finish the projects ahead of schedule and (b) the conflicting interests of stakeholders such as Congress, AEC, the military, and Westinghouse.

2. The rise of the PWR in the marketplace

Following the successful development of a nuclear submarine in 1954, Westinghouse started the construction of the first PWR nuclear power plant at Shippingport using a design based on the submarine reactor. This reactor and project manager -Admiral Hyman Rickover- shaped the nature of the Westinghouse PWR and ultimately of the US nuclear power program. The chapter analyzes the PWR's subsequent progress on the technology and market dimensions. It shows how the design quickly became the most sold nuclear power plant in the world, capturing almost two-thirds of the market. The objective of the chapter is to show that if a dominant design emerged in the industry that dominant design was the Westinghouse PWR.

3. The dominant design

This chapter first describes the Westinghouse PWR design in detail, focusing on its distinctiveness from other designs. A large amount of data is provided, with the proposition that all the main design parameters of the reactor, such as pressures, temperatures, and mass flows, converged to the same numbers. The dominant design quickly emerged as the industry standard not only in the U.S. but also in France, Japan, Belgium and the rest of the western countries.

4. The BWR and the hidden link with the PWR

This chapter focuses on the development of the BWR design, i.e. the GE approach to the civilian nuclear power plant and the main competitor to the Westinghouse PWR. The chapter starts with a thorough description of the design and the differences and similarities with the PWR. The BWR also stabilized in certain values and this will be shown following the same criteria explained in the previous chapter. Using appropriate data, this chapter also shows that the main connection between the designs proposed by GE and Westinghouse was through the use of similar suppliers and components. In particular both designs have essentially the same steam turbine. This finding is used to argue that one of the main reasons why the Westinghouse PWR design stabilized so quickly was because of the standardization of one of the main component of nuclear power plants: the steam-electric turbine.

5. The relationship between Westinghouse and General Electric

This chapter is basically about antitrust. It starts with a summary of several cases of price fixing where Westinghouse and GE were involved. The emphasis is on the notorious case in the early 1960s involving large turbines, which led to the imprisonment of several corporate executives. Since the subject of the thesis is not primarily antitrust, the stress is purely historical and within the context of nuclear power plants. The question that the chapter raises is whether price-fixing strategies employed by Westinghouse and GE in large electric components molded the rise of the PWR as a dominant design in the market.

6. The manufacturers game

Given the relevance of collusion and price fixing in the power industry, this chapter has an analysis of manufacturers and their involvement in the design and construction of nuclear power plants. The analysis starts with a model of the order/construction process, which describes the role of utilities, architect-engineers, civil constructors, reactor vendors and secondary suppliers. The way these firms interacted had a profound significance on the consolidation of the Westinghouse PWR design. In addition, the chapter focuses on the performance of the PWR design internationally. The data on France, Japan, Belgium, Germany, Sweden, Spain, Taiwan and Korea seem to show that these countries overwhelmingly accepted the Westinghouse and GE designs as the industry standards.

7. The demise of the dominant design

An analysis of the PWR's collapse in the mid-1980s suggests that incumbent firms that have successful dominant designs in the market, such as Westinghouse and its PWR design, very often fail to be aware of subtle -but disrupting- shifts on the demand side. While Westinghouse was busy building large and complex units in order to increase efficiency and profits the customer needs were moving in a radically different direction, towards power units that had less inherent risk (as large capital investments). The chapter shows that there was a fundamental change of mindset among industry participants and consumers from the late 1950s to the early 1980s.

8. The 1990s and beyond: lessons from the Westinghouse PWR case

A rapid fast-forward through the 1990s explores the achievement of the long-awaited positive externalities of a dominant design. It shows how the performance of nuclear power plants has increased notably, through a combination of industry consolidation, specialization, cumulative learning effects, and economies of scale. The chapter finishes with a summary of the Westinghouse PWR case and a framework for understanding the issues from the point of view of public policy and management of technology. Some of the issues discussed are: (a) dominant designs and their role on innovation and industrial performance; (b) pros and cons of standardization; (c) factors that promote the emergence of dominant designs; (d) dominant designs triggered by suppliers; and (e) dominant designs vs. customer needs.

Chapter 1

THE EARLY ORIGINS OF THE PWR DESIGN

The chapter starts with the foundation in 1946 of a civilian nuclear power program managed by the AEC and the complex relationship between military and civilian objectives in the dawn of the nuclear age. Then it explains the early years of the partnership between AEC and the industry for building nuclear reactors. In particular, the chapter discerns the role of Westinghouse as main contractor of key military projects and AEC's decision of selecting it for supplying the power system for the 1st nuclear submarine. The chapter includes a thorough analysis of the environment at the time, namely: (a) the rush to finish the projects ahead of schedule and (b) the conflicting interests of stakeholders such as Congress, AEC, the military, and Westinghouse

FROM 1934 TO 1946

Nuclear energy was one of the key technologies developed in the last century and one of the most spectacular examples of rapid scientific advance. A giant technological leap occurred between the 1930s, when the fission process was discovered, and the late 1950s, when commercial nuclear power broke into the world's electricity market.

In 1934, Italian physicist Enrico Fermi conducted experiments that showed neutrons could split certain atoms. Four years later in 1938, German scientists Otto Hahn and Fritz Strassman fired neutrons into uranium. They were surprised to find lighter elements, such as barium, in the leftover materials. In the next few months, they concluded that the barium and other light elements found during the experiment resulted from the splitting of uranium. The fission process had been discovered.

During the war and under the auspices of the Manhattan Project a group of scientists led by Fermi were recruited to put their theories into practice. By 1942, the team gathered at the University of Chicago was ready to begin the construction of the world's first nuclear reactor, which was erected on the floor of a squash court beneath the University's athletic stadium. On December 2, 1942, they obtained a self-sustained nuclear reaction. Fermi and his group had successfully transformed scientific theory into reality and the world had entered the nuclear age.

A number of other technical breakthroughs achieved under the scope of the Manhattan project lead to the development of the first atomic bomb. By July 1945, the first prototype was tested in Alamogordo, New Mexico and in August 1945, two full-scale bombs were dropped on Hiroshima and Nagasaki.

THE QUEST FOR GOVERNMENT CONTROL

The two atomic bombs dropped three days apart devastated two Japanese cities, killing some 106,000 people and injuring 136,000 others. In the aftermath of the explosions, U.S. policy makers promptly realized that the new energy needed a strong national and international control. Within Congress, there was consensus on the necessity of legislation ruling atomic energy. However, the complexities of the technology and the difficult post-war challenges made the enacting of such legislation an extremely difficult task.

The stakes were high for the United States. On the one hand there were a number of national security issues that needed to be addressed properly. Among them: (a) the need to set up a sufficiently credible nuclear deterrent, (b) the need to avoid the proliferation of nuclear technology abroad, and (c) the need to create an organizational structure capable of managing nuclear weapons.

On the other hand, there were non-military goals that concerned to average citizens. Among them the need to (a) enhance scientific progress and disseminate it within the community, (b) benefit from the peaceful applications of nuclear technology, and (c) capture the value created by the new technology.

Both types of objectives –military and civilian- were equally legitimate. The United States was emerging from a long war and national security had a prime place in the domestic agenda, but it was also important to reap the benefits of the new technology. The immense investment in the Manhattan project had unveiled a new source of energy and it was a legitimate claim to capture the economic benefits of the innovation. It is important to note, however, that military and civilian objectives were generally at odds. National security objectives would demand a tight control of the technology, while economic growth objectives would demand opening the technology to free enterprise (Sweet, 1998).

THE COLD WAR AND ITS FRAMES OF THOUGHT

At the end of World War II, the American society was extremely favorable to nuclear technology. There was strong confidence in the ability of institutions to handle such a complex technology, which was seen as the paragon of scientific progress (Duffy, 1997). This overconfidence contrasts with today's public perception of nuclear energy –especially after Three Mile Island and Chernobyl.

By 1949, the Cold War had started, and the Soviet Union's rise was perceived as a threat to the United States. On August 29, 1949 the Soviets exploded they first atomic bomb. The blast came as a total surprise since experts believed that they would not possess that capability until 1952. This early success was followed by the explosion of a hydrogen bomb in 1953.

The ideological struggle of the Cold War had swiftly moved to the issue of technological superiority not only regarding nuclear but also in space technology. To make it worse, the technical contest was exacerbated by effective Soviet propaganda. The latter was dramatically shown in October 3, 1957, when the Soviet Union placed a satellite –the Sputnik- in orbit at 900 km above the earth. At the same time the announcement of the breakthrough went public, Moscow radio provided the frequencies to track the spacecraft using a radio receiver. The wave of hysteria that this announcement generated in the United States was monumental. Similar broadcasts proclaiming the existence of a Soviet Intercontinental Ballistic Missile (ICBM) had a profound impact on the political environment within the United States (McDougall, 1997).

The point is that in the mind of policy makers it was clear that the United States could not afford to fall behind in space and nuclear technology. They had to do whatever was necessary in order to maintain U.S. technological leadership in these strategic areas.

Besides the struggle to match Soviet technology achievements, there was an additional reason to speed up the development of U.S. domestic nuclear industry: the potentially steep competition from the UK, France and Canada. These nations had initiated their own nuclear power programs and threatened to reap the profits of the new industry. That was something that the United States could not allow, as it was the innovator that opened the market. In the mindset of policy makers, the nation that "created" the value had to be the nation that "captured" that value.

MAIN STAKEHOLDERS

Figure 1.1 summarizes the main stakeholders involved in the development of nuclear technology. The U.S. Congress was a fundamental stakeholder with the main objective of enacting sensible legislation to both regulate and promote nuclear energy. In addition Congress had the intent to be a watchdog of the

Federal Government on nuclear issues, as it was perceived that the new technology had unprecedented importance for the nation.

For the White House, nuclear technology was seen as an important tool for enhancing the myth of presidential leadership and probably the single most important weapon of influence on foreign policy issues. In addition, and especially during the Eisenhower administration, nuclear was seen as a burden to the resolute intent of the President to slash public spending (McDougall, 1997).

The military –represented by the Departments of War and Navy and later by the Department of Defense (DoD)- were stakeholders viewing the nuclear era in terms of military applications. There was a compelling interest in building a credible nuclear deterrent. This was indeed an urgent objective as the U.S. nuclear arsenal was literally emptied by the war (Dawson, 1976). Therefore there was a will – promoted by the military- to build dual-purpose reactors that would produce weapons grade Plutonium and generate electricity at the same time. Additionally, there was desire to have tight control of the technology in order to guarantee a high level of secrecy that would avoid eventual nuclear proliferation abroad.

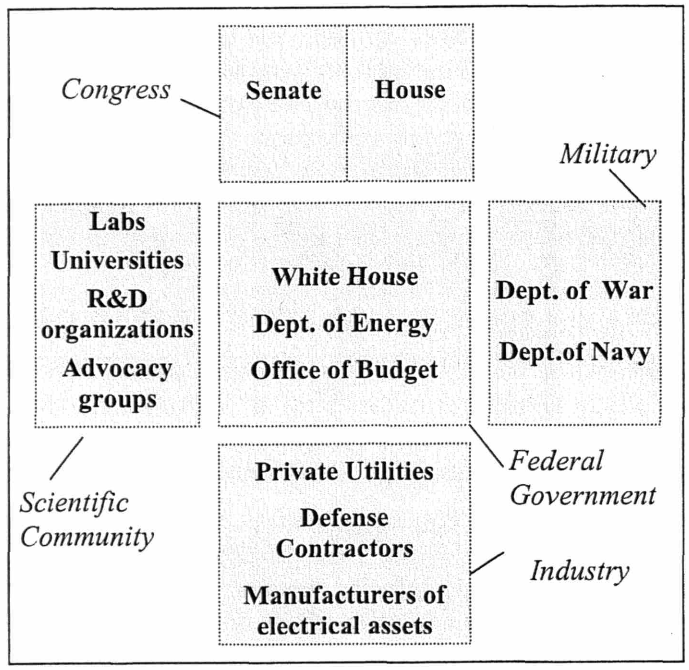


Figure 1.1. Stakeholders in nuclear technology

The issue of the control of the technology was therefore in the top place of the nuclear agenda. Whether to hand full monopoly to the military or whether to create an autonomous civilian agency, were important considerations in the legislators' minds.

The issue of secrecy was at odds with other important stakeholders: the scientific community. On one side of the equation there was the principle of free dissemination of the new technology to promote scientific progress and to maintain the traditional openness regarding scientific and technical literature. On the other side, there were national security interests that needed to be protected. In the words of the prestigious von Neumann, "It is now that physical science has become important in that painful and dangerous sense which causes the state to intervene. The legislation on atomic energy represents the first attempt in history to regulate science in this sense" (Del Sesto, 1979).

The private industry completed the club of main nuclear stakeholders. Electrical utilities viewed the government-sponsored nuclear power program both as a threat and as an opportunity. In like manner, former Manhattan contractors and a number of other potential entrants wanted to take a portion of the future nuclear business.

Both the U.S. Congress and the Federal Government understood that the nuclear industry would take off only via the participation of private industry, as had been the case with other technology-intensive industries. But how to involve the private industry became a particularly difficult issue. Secrecy, product liability, patents, and R&D costs, became formidable obstacles for the development of the technology.

CREATION OF THE AEC

Two different proposed laws had been under discussion in the Congress at the end of 1945, where the major point of disagreement concerned the role of the military: the May-Johnson Bill, which placed heavy emphasis on the military control of the atom, and the McMahon Bill, which proposed the creation of a civilian-controlled bureau. After a laborious eight-month debate on both legislative bodies, the McMahon Bill prevailed, and was signed in August 1946 as the Atomic Energy Act.

In the declaration of the Atomic Energy Act, Congress acknowledges the significance of the atomic bomb for military purposes but stresses the need to promote and regulate the civilian applications of nuclear energy. The Atomic Energy Act asserts that "the development and utilization of atomic energy shall be directed toward improving the public welfare, increasing the standard of living, strengthening free competition among private enterprise so far as practicable, and cementing world peace" (Duffy, 1997). It was a clear commitment to strengthen the exploitation of nuclear technology for peaceful –and civilian- purposes and an invitation for the involvement of private enterprise.

The Atomic Energy Commission (AEC), the agency that emerged from the 1946 Atomic Act, was a five-man commission that had the mandate to both regulate and promote nuclear energy. The AEC was given full control in the atomic energy development, both regarding military as well as civilian activities. In what became an exceptional feature, the military aspects of the new technology were incorporated into the civilian programs, without divesting the AEC of civilian control. There were dissimilar projects under the same umbrella, such as (a) military and national security programs, (b) civilian power, (c) production of fissionable materials, and (d) physical research programs.

The AEC was given a total monopoly on nuclear assets, including all fissionable materials, plants, laboratories, facilities, and equipment. Even the technical information and related sources –patents, drawings, experiment data, documents- became exclusive property of the new agency. This issue was subjected to especially heavy attack during the debates, with opponents claiming that the compulsory monopoly on nuclear patents and the restriction on the free dissemination of technical information would transform the U.S. free-enterprise system into a socialist regime. Most lawmakers seemed to support the idea of the freedom of scientific information but they were not in favor of removing all security provisions. Thus the substance of the McMahon Bill finally prevailed untouched (Del Sesto,1979).

AEC's OPERATIVE ARMS

From an organizational point of view a five-man commission was considered necessary given the complexity of nuclear issues. However, as several programs were already in progress –including activities related with nuclear weapons- there was a need for a managerial approach. For this reason, the position of General Manager was established who held enormous power and was directly appointed by the President of the United States.

The Act also provided for the necessary links of the AEC with the main stakeholders in the nuclear field. First, a Joint Committee on Atomic Energy (JCAE) was created in order to provide Congress with an effective authority over the AEC. Congress' intent in this regard was not to leave regulatory power solely in the hands of the AEC. Secondly, recognizing the complexities and extent of the military programs, a Military Liaison Committee (MLC) was created. This was an advisory body to help the AEC deal with its military duties. Finally, the General Advisory Committee (GAC) was created to provide the AEC with scientific advice.

Figure 1.2 is a sketch that summarizes the linkages between AEC and the nuclear stakeholders. The main point is that instead of creating an AEC that would be an island within the Federal Government, the 1946 Atomic Act transferred the control of the new technology to a rather larger subsystem that included other participants, such as lawmakers, military experts, scientists, and industry leaders.

JCAE was comprised of eighteen members, representing the two bodies of the U.S. Congress. Nine were from the House and nine from the Senate and no more than five members from either body were allowed to belong to the same political party. JCAE's duties were: (a) involvement on all bills, resolutions and reports produced by Congress, (b) effective watchdog power over the AEC on nuclear energy and nuclear weapons, and (c) authority on identifying, reviewing and analyzing nuclear policy issues.

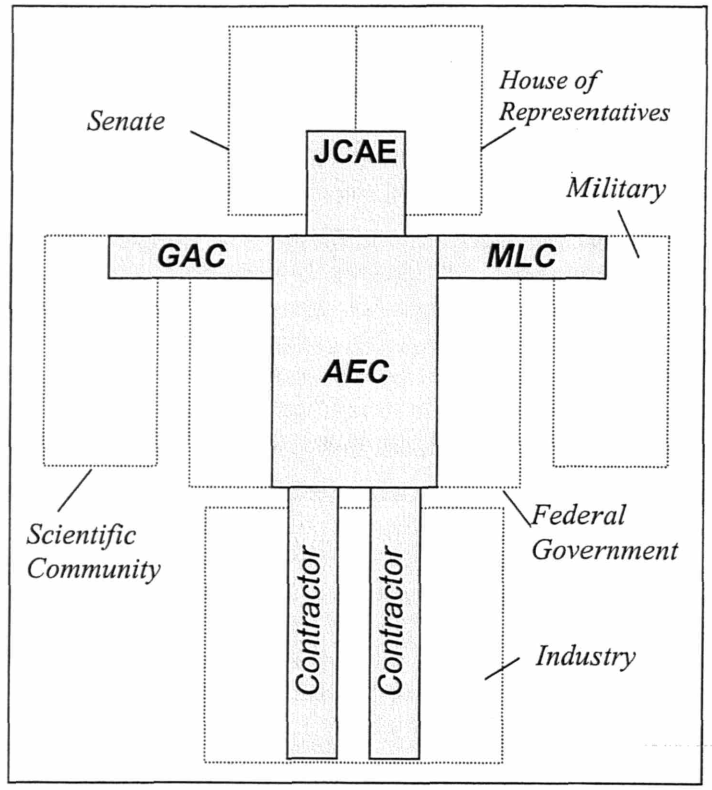


Figure 1.2. The AEC and its linkage with stakeholders

MLC was an advisory arm on issues related to military programs. It was comprised of representatives of the Departments of War and Navy (later Dept. of Defense). Finally, GAC was an advisory committee on technical and scientific issues, comprised of nine members of relevant prestige appointed by the President. Top-notch scientists held positions here, among them Fermi, Oppenheimer and Seaborg.

THE NUCLEAR SUBGOVERNMENT

Many political scientists have made the point that the organization invented by the Atomic Energy Act, was the archetype of a sub-government, namely "a small, cohesive, and stable group of actors that exercised considerable autonomy in policymaking". (Duffy, 1997). Most of the participants involved in nuclear policy in the postwar had either an economic, political, or organizational stake. But unlike the familiar example of subsystems –where government actors are lobbied by industry incumbents- in the nuclear case there was no nuclear industry at the outset. Indeed, the creation of a nuclear power industry was one of the objectives of the 1946 Act and, interestingly enough, the authority to conceive, develop, and monitor these policies was within the AEC.

The emergence of a de-facto sub-government on nuclear issues was favored by a number of factors. First, nuclear was perceived as an extremely complex technology and therefore only few people would be able to understand policy issues. Because the United States was the only nation with the "atomic secret", secrecy was considered to be an essential part of the effort to retain the atomic monopoly. In addition, the onset of the Cold War with its prospects of a long-term conflict with the Soviet Union gave rise to strong personal commitments toward the effective development of U.S. nuclear capabilities. People who were involved in the nuclear effort during this time –lawmakers, military, scientists and industry leaders- had little doubt on the need and importance of what they were doing. More importantly, the planning and executing teams worked together through consecutive projects and objectives, with a very low attrition rate and a high degree of stability and collective learning.

PROS AND CONS OF THE 1946 ACT

The 1946 Atomic Energy Act set up the grounds for the development of nuclear power in the United States. Its positive elements were: (a) it set up the grounds for the participation of private enterprise in the effort, and (b) it established an organization with high autonomy and the explicit mandate to invest heavily in the development of commercial nuclear power plants.

The shortcomings were: (a) secrecy and monopoly of patents were restraints on entrepreneurial creativity, (b) the taboo of product liability was an obstacle for industry involvement –particularly utilities, (c) the opposing functions of promotion and regulation created conflict of interests, and (d) the de-facto sub-government caused insufficient external scrutiny.

The shortcomings became evident and eventually forced the introduction of modifications to the organization envisaged in 1946. In 1954 the Atomic Energy Act was amended to address the issues of private patent rights and limited product liability. In 1974 the AEC was split into a regulatory body, the National Regulatory Commission (NRC), leaving the promotion side in the hands of the Department of Energy (U.S. Congress, HR 8631).

As Figure 1.3 points out, each of these changes can be seen as the transition from an organization with a tight control of the technology towards an organization with a higher degree of entrepreneurial freedom.

Figure 1.3 shows that there was a trade-off between exerting tight control of the technology and favoring entrepreneurial freedom. Clearly, it was impossible to manage a technology having at the same time a tight control of the nuclear secrets– for national security reasons- and a full "free-enterprise" legislation to promote innovation, entrepreneurship and free dissemination of knowledge. Surely Congress understood the trade-off but tilted the early legislation toward the side of tight control, secrecy and national security objectives. As the time passed the direction was corrected in 1954 and 1974. The question is how late these changes were introduced and which were the consequences of this delay on the outcome of the nuclear power industry.

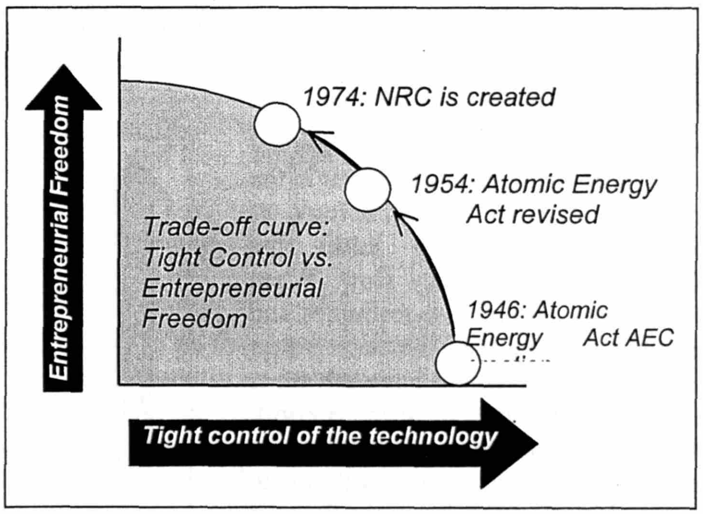


Figure 1.3. AEC's beginnings as an organization with tight control of the technology but little free-enterprise

THE ROAD AHEAD

After the Atomic Energy Act set up in 1946 the grounds for a civilian nuclear program directed by the AEC, a promising future for nuclear power came into sight. The conditions necessary for a rapid development of the technology were reasonably outlined by the new legislation, namely: people, resources, and goals. However, the strategy to meet these goals efficiently and in a timely manner was not obvious.

The coexistence of two different nuclear programs –military and civilian- under the same umbrella introduced a number of challenges, opportunities and difficulties. Given those boundary conditions, one can picture the development goals of the first AEC's management team in two broad categories:

- **Military projects:** (a) Nuclear weapons, with the goal of creating a sufficiently credible nuclear deterrent in terms of number of nuclear weapons and long distance strike capability. (b) Nuclear naval propulsion, with the goal of developing operative nuclear-powered naval units with high fuel autonomy and long-distance nuclear strike capability.
- **Civilian projects:** (a) Research reactors, with the goal of benefiting from nuclear applications, (b) Nuclear power plants, with the goal of affordable and large scale commercial production of electricity.

In summary, the four key product lines necessary to accomplish the goals pledged by the AEC were: (a) nuclear weapons, (b) research reactors, (c) nuclear submarines and (d) nuclear power plants.

It does not mean that these were the only product-lines in AEC's plans but these four were the critical trails. In addition, there were some key enabling technologies in the sense that without them it would not be possible to carry out the projects. These enabling technologies were: (a) uranium enrichment, or industrial-scale production of U235 for supplying power plants and weapons, (b) reprocessing, aimed at producing weapons-grade Pu239, (c) front end technologies, such as uranium mining and manufacturing of nuclear fuel, and finally (d) back en technologies such as the management of spent nuclear fuel and radioactive materials.

Figure 1.4 summarizes AEC's four critical product lines in a sketch consisting of an S-curve. The latter is a typical way to graph the relationship between effort put into developing a technology and the results one gets back for the investment. For most products and processes, when the results are plotted, what usually appears is a curve with an S-shape.

The reasoning behind this empirical result can be explained as follows. In the very early stage of the technology, as funds are poured into R&D, the technical progress is very slow. When the necessary cumulative resources and learning are put in place the curve enters in a second stage where huge advances are obtained with relatively small effort. Finally, in the last stage of the curve, it becomes more and more difficult to make technical progress regardless of how much money is spent in R&D. In other words, there is always a limit on the development of a product or process using a technology (Foster, 1986).

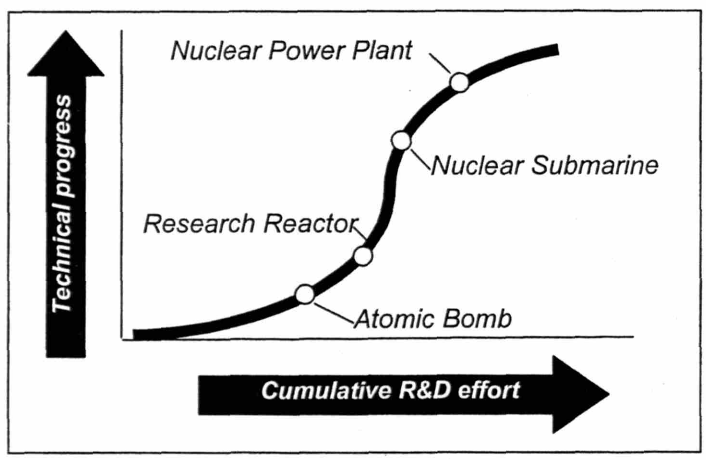


Figure 1.4. Development roadmap in terms of products and cumulative R&D effort needed to develop them

S-curves are generally outlined for a single product or process. But in the particular case of early nuclear technology one can extend the reasoning and think of a single and "broad" S-curve. This simplification is possible because all the projects: (a) were managed under the same organizational umbrella, (b) using the same people, and (c) building up collective learning from a pool of common shared innovations.

Unlike most of the conventional R&D effort nowadays, the key innovations in nuclear technology under AEC sponsorship made extensive use of the state-of-the-art technology developed in prior phases of the program. For instance, the theory of reactor physics was developed during the Manhattan project and was useful when designing the first research reactors. The know-how obtained in fuel manufacturing and the operation of research reactors was then used in designing the first naval reactors. Such swift technology transfer has few comparable cases in modern technology.

The resultant intricate path of civilian and military products and their multiple interrelations is shown schematically in Figure 1.5. As it is shown, civilian and military product lines coexisted within the same umbrella and no single product could have been developed without the cumulative know-how, R&D investment, and learning effects due to previous products.

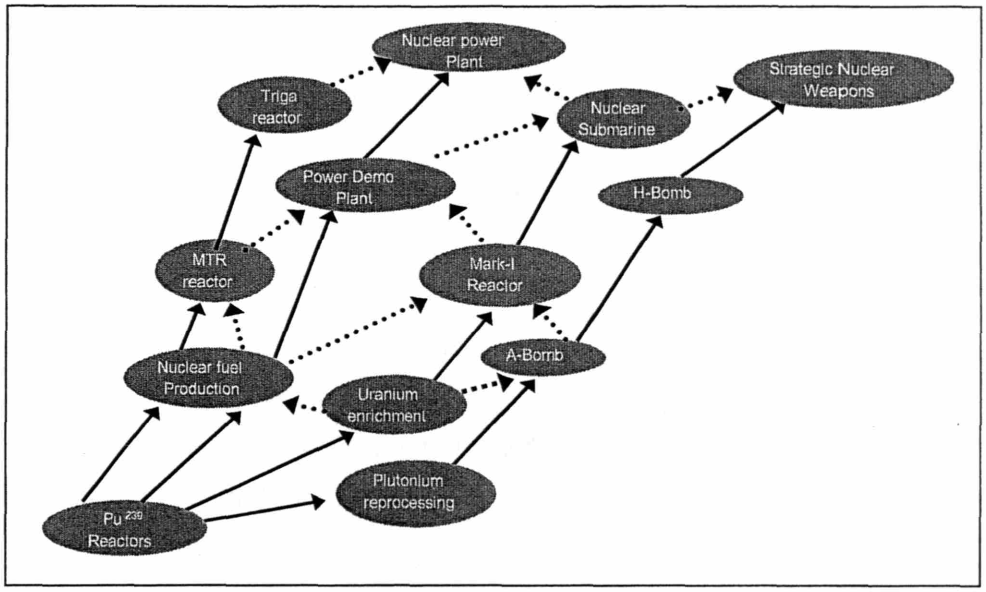


Figure 1.5. Conceptual roadmap of military and civilian nuclear projects pursued by the AEC, and their complex interrelations

MILITARY PROJECTS UNDER AEC

Figure 1.6 summarizes the military product lines that were on the drawing boards of the AEC in the late 1940s: nuclear weapons and nuclear submarines. The cornerstone of nuclear deterrence was having a large inventory of nuclear warheads, but at the end of World War II, the United States possessed not a single nuclear weapon. It is not surprising then that AEC's first major drive was towards developing an extensive industrial capacity for producing enriched uranium and plutonium, which are the prime inputs in nuclear weapons.

Fissile U235 uranium can be produced enriching natural uranium by gaseous diffusion, centrifugation or electrostatic separation. Weapons-grade Pu239 plutonium can be produced only in reactors. Increasing the energy of each device was an important objective and consequently, the H-bomb was developed. In November 1st, 1952 a prototype of the H-bomb nicknamed Mike was exploded in the Marshall Islands. Mike released an energy of 10,000 kilotons, roughly one thousand times the energy released by the A-bomb dropped over Hiroshima in 1945. The mushroom-shaped cloud created by the explosion had a radius of 8 miles and reached a height of 27 miles.

AEC's interest in developing the technologies for manufacturing nuclear fuel and building plutonium-producing reactors was explicit. The construction of dual-purpose reactors that would produce weapons-grade plutonium and electricity was pursued by the AEC from the outset. Considering that the US was able to build a nuclear arsenal of nearly 20,000 warheads, one can have an idea of how many reactors were needed in order to meet those needs. It is important to note that like the United States other countries were also interested mainly in dual-purpose reactors. For instance, early British efforts focused on developing dual-purpose reactors to meet the needs of the UK Atomic Energy Agency. In 1953, the UK-AEA announced the future construction of a 60Mwe gas-cooled dual-purpose reactor in Calder Hall (Patterson, 1985).

The point is that the first civilian projects of the AEC, namely constructing nuclear reactors, enrichment facilities and nuclear fuel factories, had indeed a military objective: producing fissile materials for nuclear warheads.

Having enough warheads was a necessary but not sufficient condition in order to have effective deterrence capacity. There was also a need for having long distance strike capability. This was initially achieved by long still-air range aircraft such as the B-52 but the ultimate devices in this segment were: (a) intercontinental ballistic missiles –ICBM- and (b) nuclear-powered submarines equipped with short-range missiles. Hence the interest of the AEC in cooperating actively with the development of the ICBM and funding the nuclear submarine project (Suid, 1990).

Although some minor work had taken place previously, it was the detonation of the Soviet A-bomb in August 1949 which precipitated the genesis of the submarine project. As a first step, a contract was awarded to Westinghouse for constructing a prototype reactor, the Mark I, which became the laboratory for testing the design concepts used in the submarine. It is interesting to point out that Westinghouse was selected as a contractor in this crucial project not because of a competitive bid but because its main competitors –GE, Allis-Chalmers, Gulf- were already involved in other projects. In particular GE was working on a breeder reactor and a military reactor in Hanford, Washington (Beaver, 1990).

In summary, as it is shown in Figure 1.6, the development of military products had the ultimate goal of attaining a credible long-range nuclear strike capability. Under this objective, the nuclear submarine project was a crucial step. Not only it condensed the state-of-the-art in nuclear reactor utilization, it also set up the basis for future nuclear power plants. Westinghouse was awarded this important project because its competitors had their hands full with other AEC contracts. As it will be shown afterwards, this turned out to be a fortunate outcome for Westinghouse.

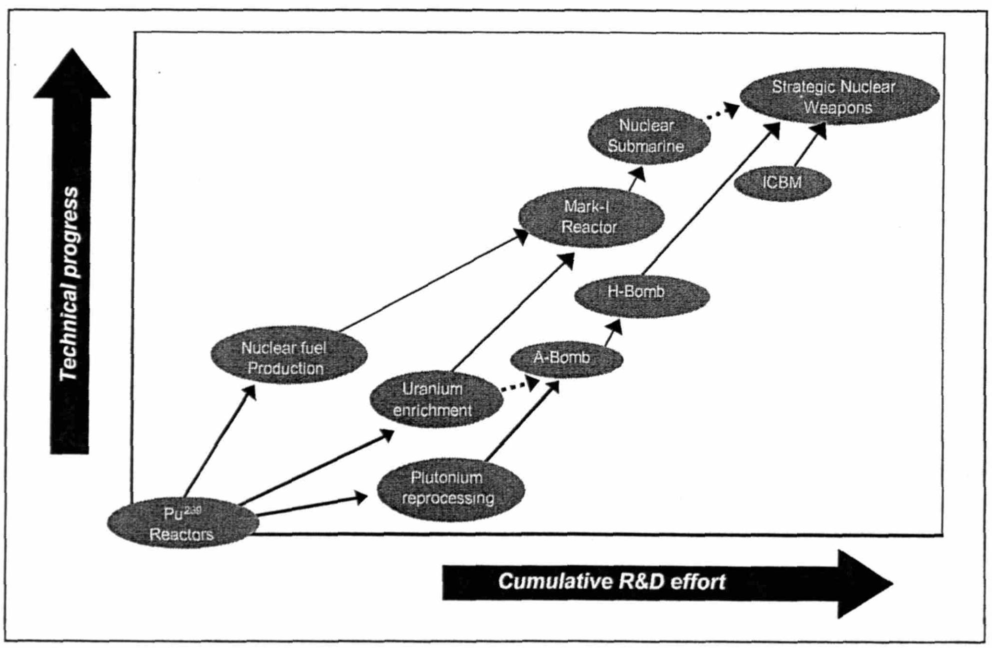


Figure 1.6. Military nuclear products and processes and the cumulative R&D effort needed to develop these products

CIVILIAN PROJECTS UNDER AEC

Figure 1.7 shows that the development of civilian projects under AEC auspices had the principal goal of building a commercial nuclear power plant. The scheme also shows that the necessary technical expertise to build such a plant was extracted from two predecessor projects: (a) the nuclear submarine project with its prototype Mark I reactor, and (b) research reactors such as the Triga and the MTR.

Research reactors were built by smaller vendors like General Atomics and were marketed to Labs and Universities for research, training and radioisotope production. Figure 1.7 also shows the fundamental role of enabling technologies whose dominion was key for the development of reactors most notably (a) the process of enriching uranium, and (b) the manufacturing of nuclear fuel.

Similarly, the role of the nuclear submarine in the development of a commercial nuclear power plant was fundamental. As it will be shown in next chapter, the first power plant –a PWR reactor- was literally a ground-based extension of the submarine reactor.

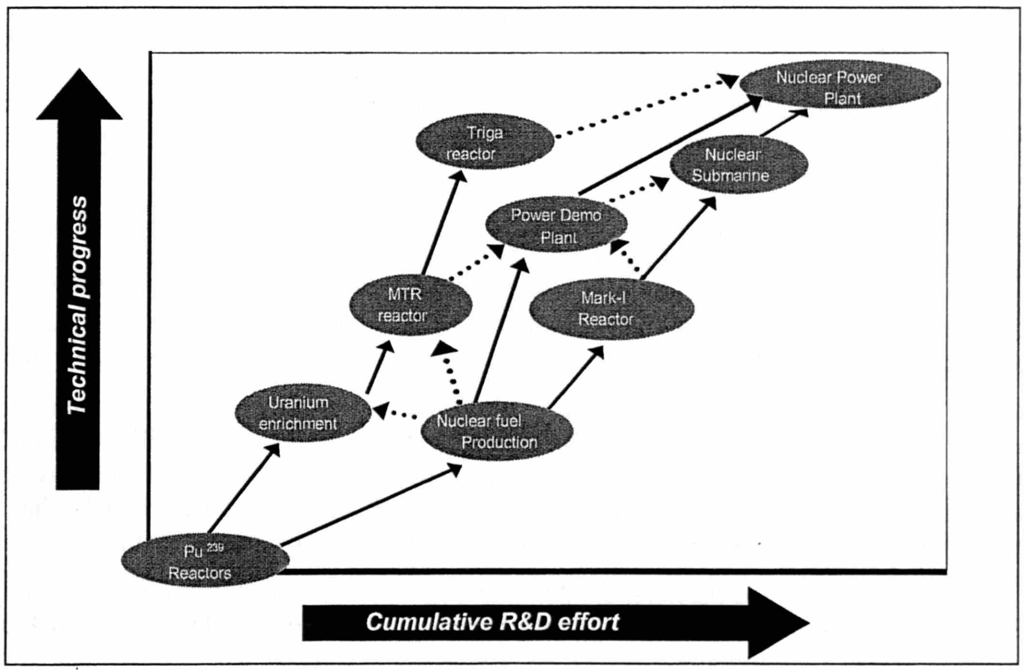


Figure 1.7. Civilian nuclear products and processes and the cumulative R&D effort needed to develop these products

THE AEC-INDUSTRY PARTNERSHIP

It is clear that in order to achieve its goals the AEC needed to develop a number of reactors, from research reactors, to plutonium-producing units, to a workable prototype of a submarine power unit. In order to carry out the development of such a variety of projects, the AEC established programs aimed to provide incentive to private industry for participating in nuclear development. These programs were (a) the Reactor Development Program announced in 1948, and (b) the Power Reactor Demonstration Program announced in 1955. Both programs had the intention to execute the different reactors planned by the AEC and –as an expected externality- to develop a capacity for building nuclear power plants within the private sector.

Although in the long run the private nuclear industry indeed emerged in the United States, in the early years 1945-1960, the so called AEC-industry partnership was basically a process to assign contracts to a selected club of contractors. Moreover, since the technology was in a fluid phase and it was not clear which reactor design would be the best, the AEC managed a portfolio of projects at the same time and assigned arbitrarily these projects to different contractors.

AEC had a policy of maintaining product diversity. Some contractors would bid for a certain project that looked interesting from a strategic point of view, but given the huge technical uncertainty of most of these projects, one can argue that the process of assigning contracts was essentially a random process.

The nuclear submarine project illustrates the point for two top contractors: General Electric and Westinghouse. General Electric had been awarded the project to develop a sodium-cooled reactor whereas Westinghouse had been awarded the project for developing a water-cooled reactor. Both firms developed land-based prototype reactors that started operation in the early 1950s. In the case of Westinghouse the prototype reactor Mark I started operation in 1950 at the Idaho Testing Station. Four years later, in 1954, a modified version of this reactor was installed in the Navy's first nuclear submarine, the Nautilus, which was a highly successful vessel (Del Sesto, 1979).

General Electric on the other hand, developed a land-based prototype reactor, which started operation in 1955 at the Idaho site. Later, General Electric modified the design to fit the Navy's second nuclear submarine, the Seawolf, which put to sea in 1957. But because of the danger of leaks and the violent reaction of sodium with water, the Seawolf was removed from service the following year (Del Sesto, 1979).

With the Nautilus, Westinghouse not only developed the basic design concept that became the standard of all nuclear submarines of the US Navy in the next four decades, it also set up the basis for the design that would eventually become the first nuclear power plant. On the other hand, the Seawolf not only was a faulty design concept for a submarine but also resulted in an inferior technological bid for future nuclear power plants. Sodium-cooled reactors were abandoned a few decades later everywhere else in the world.

It is important to note that in 1949, when both prototypes were on the drawing boards, neither looked to be superior and therefore the decision of which model was better was not really obvious. Indeed Westinghouse was selected as a contractor in this particular project because General Electric was working on a breeder reactor and a military reactor in Hanford, WA and AEC authorities thought that the firm would not be capable to manage the development of yet another reactor (Beaver, 1990).

In addition to the above-mentioned reactors, the AEC developed a number of different projects under the scope of the Reactor Development Program of 1948 and the Power Reactor Demonstration Program of 1955. For instance:

- Experimental breeder reactor developed by Argonne Laboratory. This reactor produced the world's first electric power generated from a nuclear reaction in December 20, 1951.
- Material Testing Reactor (MTR) developed in 1950 Argonne and Oak Ridge Laboratories.
- Experimental Boiling Water Reactor (EBWR), developed at Argonne, and completed in 1957.
- Sodium Reactor Experiment (SRE) developed in Santa Susana, Santa California in 1957.
- Homogeneus Reactor Experiment (HRE 2) developed by the Oak Ridge National Laboratory, which was abandoned in 1957.

Chapter 2.

THE RISE OF THE PWR IN THE MARKETPLACE

Following the successful development of a nuclear submarine, Westinghouse started the construction of the first PWR nuclear power plant at Shippingport using a design based on the submarine reactor. This reactor and project manager -Admiral Hyman Rickover- shaped the nature of the Westinghouse PWR and ultimately of the US nuclear power program. The chapter continues with a recounting of the PWR's subsequent progress on the technology and market dimensions. It shows how the design quickly became the most sold nuclear power plant in the world, capturing almost two-thirds of the market. The objective of the chapter is to show that if a dominant design effectively emerged in the industry the dominant design was the Westinghouse PWR.

RICKOVER AND THE NUCLEAR SUBMARINE PROJECT

A nuclear-powered submarine had the potential to revolutionize naval warfare. First, its ability to remain submerged for long periods made it the best vehicle for transporting nuclear devices to distant war scene. Secondly, even without nuclear devices on-board, a nuclear submarine was fundamentally superior in performance versus other comparable submerged vessels.

Westinghouse was granted the contract to build the nuclear submarine. But the effective control of the project was in the hands of the Navy. The leadership of the nuclear submarine project was given to then captain Hyman Rickover, largely because of his successful tenure as head of the Navy's electrical section during World War II, and because he was one of the few individuals with knowledge of both naval and nuclear issues.

By 1949, Rickover became chief of the AEC's Naval Reactors Branch. This was a dual agency serving both the Navy and the AEC. Westinghouse was linked to Naval Reactors by the operation of Bettis laboratories in Pittsburgh, PA. This was a laboratory built by Westinghouse under government contract and with the exclusive objective of carrying out projects assigned to Westinghouse by the AEC and Naval Reactors. Thus Rickover had to lead a three-hat organization made up by the AEC, the Navy and Westinghouse. In retrospective, working with three organizations under the same umbrella seems an impossible task. But Rickover was no ordinary man. Rickover would become one of the most intriguing figures in nuclear history. He was described as a genius, a man of vision and a master politician. Without any doubt he was a man of strong leadership, able to motivate R&D engineers, naval officers and politicians towards his vision of achieving high goals.

MARK-I AND NAUTILUS

The first achievement of Rickover and his staff was the design and construction of the Mark I, a prototype reactor that would become the cornerstone of the PWR concept.

Despite the fact that many of the reactor's components had to be invented from scratch, the design evolved swiftly. Many of the fundamental ideas that would eventually be used in the nuclear submarine and in the PWR reactors were developed at Bettis during the design of the Mark I prototype. They developed a special fuel (UO2) to avoid damage during sailing conditions, and used zirconium alloy to protect the highly enriched uranium from corrosion effects of water at 320 C.

In retrospective, the Mark I design is certainly the best design for a nuclear submarine. If today a committee of nuclear engineers had to select a reactor design for a submarine, they would agree that a pressurized light water reactor is the best alternative. It can't be a boiling water reactor because the latter requires taller pressure vessels, spreads water contamination all across the submarine and it is noisy because of boiling phenomena. Obviously it can't be a reactor using other coolant such as gas, sodium or heavy water. Ordinary water is the best choice. Hence, in addition to his leadership skills, Rickover had the ability to make complex technologies work and to make the right technical choice at the right time.

Mark I went critical on March 1953. Subsequent test runs revealed that the reactor not only worked but it worked very well. This reactor not only provided a basis for commercial PWR reactors in the United States, it linked the name of Rickover and Bettis Labs as a synonymous of efficiency and unquestioned nuclear expertise.

A modified version of the Mark I was installed on the first nuclear-powered submarine. By 1954, the "Nautilus" was launched from the Electric Boat Yard in Croton, Connecticut. The Nautilus operated successfully for over two years before having its reactor core removed for refueling for the first time. It remained in the U.S. fleet for several years. Indeed, nearly one hundred nuclear submarines were built in the U.S. afterwards, basing their design on the early Nautilus PWR type nuclear reactor.

SHIPPINGPORT

After the successful experience of Mark I and Nautilus, the AEC made the decision of extend the PWR design to a commercial nuclear power plant. For a while the Eisenhower administration doubted building government-sponsored nuclear civilian reactors. But two external events prompted the decision to move ahead with the project. One was the start of a soviet demonstration nuclear plant at Obninsk in 1954. The other was the advanced design status of a gas-cooled reactor in the UK -Calder Hall- which eventually went critical in 1956.

The decision to support the PWR project demonstrated the urgent need to enhance American prestige and counter Soviet and British advances in nuclear power. However, the AEC wanted to include an industrial partner in order to avoid criticism from conservative foes. Luckily for AEC, Duquesne Light of Pittsburgh agreed to participate in the project, Duquesne agreed to invest money building the electric generating section of the plant, while the AEC funded the R&D and the capital costs of the reactor itself (Beaver, 1999).

The selection of a PWR design and Westinghouse as prime contractor of the power plant had two strategic benefits. First, the AEC wanted to have a plant operating as soon as possible and Westinghouse and its Bettis Laboratory already had a workable prototype (Mark I) and a successful submarine (Nautilus) based on the PWR concept. Second, the team that had worked under Rickover's direction had a record of achievements. Therefore it was a sound decision to hand a complex project over to one of the best nuclear engineering teams available in the U.S.

The construction of the first nuclear power plant in the United States began in April 1955 in Shippingport, PA. Since the AEC wanted the plant in operation by 1957, the construction process was virtually a "mission in a hurry". The rush to complete the plant does reinforce the fact that Shippingport was more a political project than a commercial endeavor (Beaver 1999).

Plant construction began under the rigid direction of Rickover and Naval Reactors. Westinghouse was the prime contractor, while Stone and Webster acted as architect-engineer. Dravo was the construction company. The turbine generator was provided by Westinghouse even though a number of technical difficulties arose during the design, Rickover and his "three-hat" organization were able to finish the project in three years which is a remarkable achievement. The plant was officially inaugurated in May 1958. It worked properly for 25 years.

THE QUEST FOR TECHNOLOGY AND MARKET

AEC set up the grounds for a rapid development of nuclear power in the United States, particularly of designs that received heavy government-sponsored R&D up front such as the PWR design. A giant technological and commercial leap occurred between 1952, when the construction of the Mark-I prototype started, and 1989 when nearly four hundred reactors were operative worldwide (half of them PWRs).

As it is shown in Figure 2.1, nuclear power plants evolved in the two classical dimensions of product development, namely, technology and market. In the technology dimension the advance was remarkable given the complexity of this technology. Generating electricity from the atom is one of the highest scientific and technological achievements of the 20th century, involving the mastery and integration of different disciplines such as nuclear physics, material sciences, thermal-hydraulics, control systems, radiation protection, etc.

Most of these technologies had dual applications for the development of nuclear military devices as well as civilian commercial products. In fact, most of the contractors involved in the design of nuclear power plants -including GE and Westinghouse- were also involved as defense contractors in projects ranging from the development of a plutonium producing facility to the design of a nuclear submarine. The resulting economies of scope were significant.

The second dimension of rapid product development has been the market dimension. Nuclear power has an enormous economic impact nowadays. The commercial nuclear power plants currently operating in the world are the 3rd largest electricity supplier, behind only gas and coal, and ahead of hydro and other renewable sources.

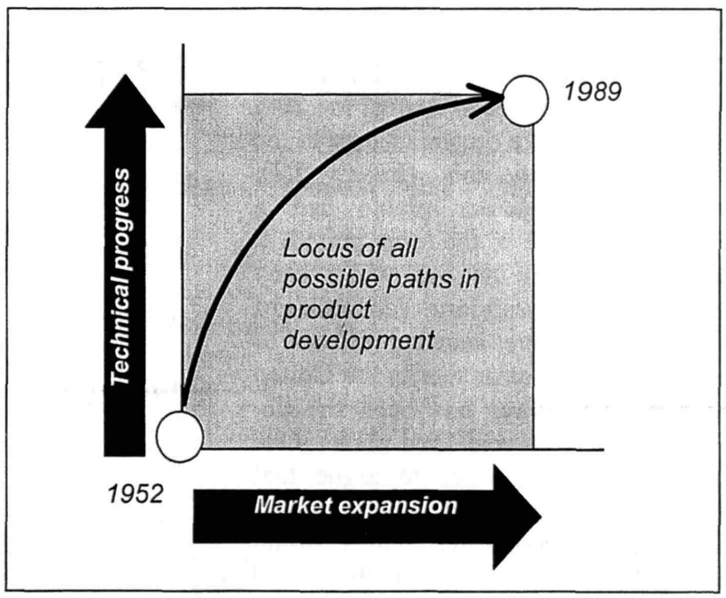


Figure 2.1. Nuclear power development from 1952 to 1989

In the United States nuclear occupies second place with a strong 23% of the total domestic electricity generation (2000). With 103 operating reactors, the country also hosts the largest fleet in the world, accounting for one-fourth of the world's 410 operating plants. In year 2000 U.S. nuclear plants produced 730 billion kilowatts hour (Figure 2.2). At about 6.7 cents per kilowatt-hour –the price an average utility charged to consumers in year 2000- the nuclear power industry creates a value of about $50 billion per year.

In some countries –like France, Belgium and Japan- nuclear is the first source of electricity with an involvement of between 40% to 75% of national generation. For these countries the importance of nuclear power is given not only in terms of economic scale but also in view of other strategic issues such as energy self-reliance, economic independence and sovereignty.

THE RAPID EXPANSION OF NUCLEAR POWER

Nuclear power is an interesting topic of study because of the speed at which this technology was developed and introduced in the marketplace. In the U.S. the first commercial nuclear power plant started its construction in 1954 in Shippingport, PA with strong support of the government. It reached full power in 1957 and it was the first of a vast group of reactors subsequently identified as Pressurized Water Reactors or PWRs. Two years later, in 1959, the first U.S. nuclear plant built entirely without government support achieved a self-sustaining nuclear reaction.

After a strong government-supported introduction, the U.S. nuclear power industry grew rapidly by its own wings. Private firms became more and more involved in developing reactors either as prime contractors, architects-engineers, civil constructors, or components' suppliers. These firms fueled the already strong market push driven by the government. They offered turnkey plants at very competitive prices and rapidly secured early contracts. As a result, by the end of the 1960s, twenty plants were in full operation in the United States.

Utilities saw this new form of electricity production as an opportunity to achieve economies of scale and hence higher profits and rapidly jumped into the bandwagon. Consequently the decade of the 1970s registered the largest increase in reactor orders. By 1973 -in the midst of a severe imported oil shortage- U.S. utilities ordered the exceptional number of forty-one new units, widening the fleet to one hundred units ordered in less than two decades. By 1986, the Perry power plant in Ohio became the 100th U.S. nuclear power plant under operation.

Such a rapid expansion of nuclear power in the U.S. in the second half of the 20th century introduced a drastic change in the domestic electricity mix (Figure 2.2). Only coal-fired power plants had a comparable growth in the same period. It is important to note that coal was already a mature industry with large economies of scale and extensive learning effects to benefit from. It is clear that in the United States nuclear power has been the de-facto alternative to coal-fired plants. One can go one step further to argue that without the emergence of nuclear power, the increase of coal-fired plants would have been 1.6 times larger in the period between from 1950 to 2000. This is an important environmental consideration given the well-known connection between carbon-dioxide emissions released by coal-fired plants and global warming phenomena.

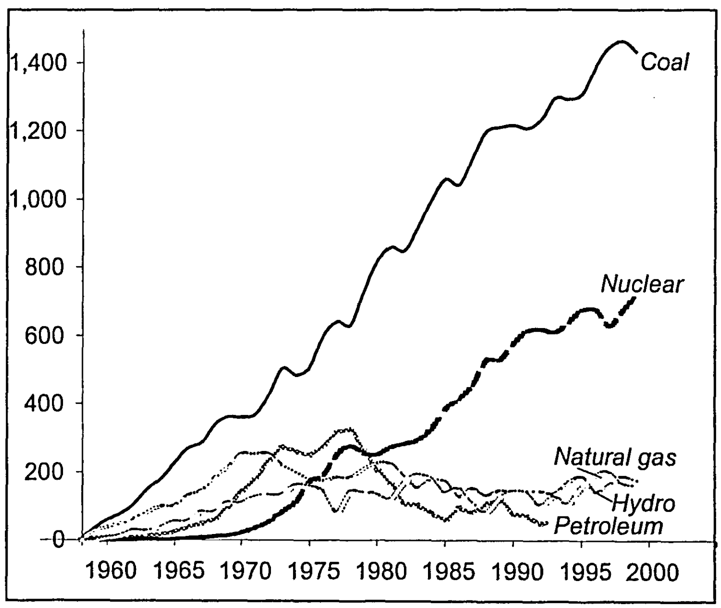


Figure 2.2. Electricity Net Generation Addition at U.S. Electric Utilities, 1958-1999 (Billion Kilowatt-hours). Source DOE Energy Outlook '01

DOMESTIC AND INTERNATIONAL COMPETITION

After 1945, a number of reactor proposals quickly came out from different design teams working around-the-clock in the United States, Soviet Union, United Kingdom and Canada.

As Figure 2.3 shows, these early designs lead to ten basic types of nuclear power plants that were eventually constructed later. Obviously there were hundreds of other designs, but these ten were the only ones that made it into the marketplace. Surprisingly these basic designs correspond to just three key decisions. The first is the fuel itself, which can be an oxide compound of natural or enriched uranium (in which the concentration of the fissile U235 isotope is increased from its natural 0.7% to about 3%). The second component is the moderator, whose function is to slow down the neutrons from the fission process so that they are suitable to sustain the chain reaction. In practice the options are graphite, ordinary water and heavy water. The third major component is the coolant, where the options are helium, carbon dioxide, and ordinary/heavy water.

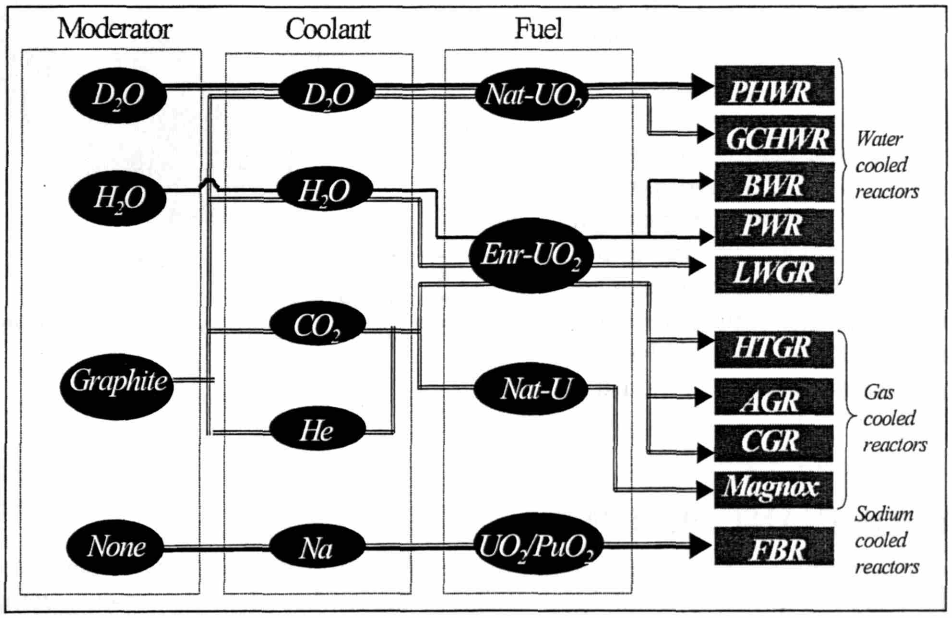


Figure 2.3. Diagram of the designs that made into the market (1958-1989)

One can argue that given the state of the art prevailing in the 1950s, any of these basic designs could have become the commanding design. There were -a priori- no technical reasons why any of these designs could be a more judicious choice. Indeed, nations committed their prestige and public resources to different designs. For instance, the UK committed to the Magnox and the AGR, Canada supported the PHWR, while the US ended up building PWRs and BWRs. Figure 2.4 shows the outcome of the above-presented designs by 1989, in terms of number of units that started commercial operation worldwide. It is clear that the PWR design was the winner as it was able to capture 244 out of 481 power plants that were put into operation by 1989. Its success was matched only by the BWR –another U.S. design- that was able to secure 101 units built worldwide.

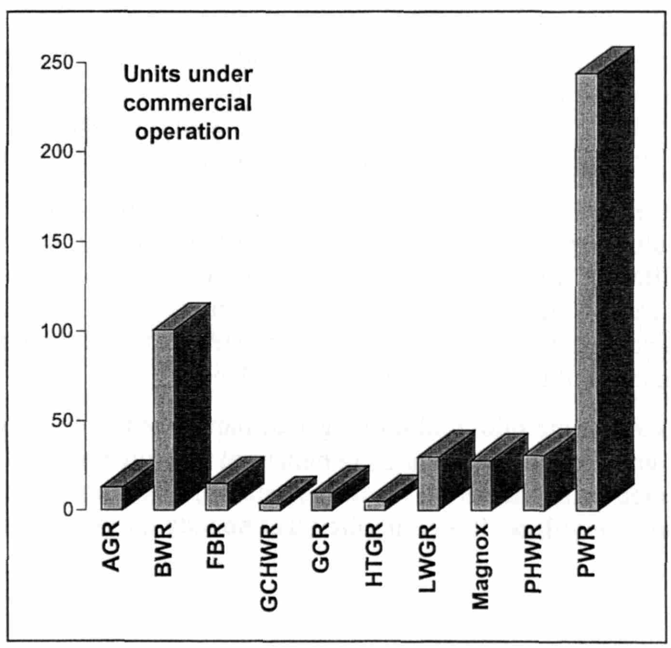


Figure 2.4. Summary of total number of NPPs that started commercial operation before 1989 (World).

In terms of market share, the right dimension is the installed electricity capacity, which means the total MWe that each design managed to connect to a commercial grid. Again the PWR emerges as the industry leader, with a strong 61% (corresponding to 2x105 MWe of installed capacity). It is interesting to note that there is a direct correlation between Figure 2.5 and Figure 2.4, due to the fact that most designs had similar electric power per unit. Therefore the leadership in number of units sold gives rise to a similar leadership in installed capacity.

It is also important to note that the summaries presented in Figures 2.4 and 2.5 correspond to worldwide data. Therefore, the dominance of the PWR means the supremacy in various countries and with products manufactured by different sets of contractors. This is a strong indication that the PWR was indeed a dominant design in the nuclear power industry.

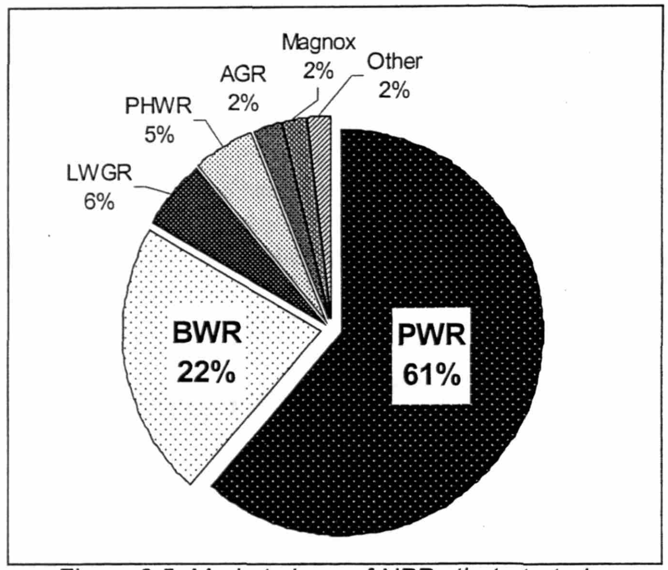


Figure 2.5. Market share of NPPs that started commercial operation before 1989 in terms of installed electricity capacity (World).

WHAT IS A DOMINANT DESIGN?

Perhaps the best way to define a dominant design is to provide examples of dominant designs available in the marketplace. The IBM PC format is a dominant design in the market of small personal computers. In the early 1980s it came to define the concept of the personal computer for at least 80 percent of the market. The Palm III is probably also a dominant design in the handheld Personal Digital Assistants (PDAs) market –now challenged by the pocket PC, both seems to capture most of the features that users expect from a PDA. A Corona typewriting machine with a QWERTY keyboard, visible type, tab and shift keys, and carriage cylinder is also an example of a more aged dominant design. Finally, the classic example of a DC-3 aircraft with two wings containing the fuel inventory, two engines positioned in each wing, a retractile landing gear, single tail, and movable flaps. The DC-3 is an illustration of a dominant design that emerged in the 1930s but still influences modern aircraft designs such as the Boeing B767-200 or the Airbus A320.

In other words, a dominant design is the product that wins the enthusiasm of the marketplace. It is the design that all competitors and new entrants must adhere to if they hope to command significant market share. Thus, the IBM PC format is still manufactured nowadays not only by IBM but by other firms such as Compaq, HP and Dell. Since most of the users are interested in performance of the product, one can affirm that the dominant design is the one that summarizes all the explicit performance requirements of the users and makes them implicit to the design (Utterback, 1996).

Thus an airline pilot will no longer demand a retractile landing gear on a plane; he/she will take for granted that any "reasonable" large commercial aircraft will include such a feature. The dominant design that emerged with the DC-3 made the retractile landing gear an implicit performance requirement of a large commercial plane. It is so implicit that nobody questions it anymore.

WAS THE PWR A DOMINANT DESIGN?

This is the fundamental question of this research and will be answered in three steps. First, the previous data shows the long run leadership of the PWR design and its adoption by a large percentage of the market, which is a strong indication. Second, this section will show its market share progression over time. One might expect that a dominant design would gain the market progressively over time, since by hypothesis a dominant design is the product that wins the enthusiasm of the marketplace. Finally, in the next chapter it will be shown how the architecture of the PWR design achieved a stable status.

Table 2.1 summarizes the number of nuclear power plants sold as a function of time, as well as the resulting new electricity capacity resulting from these new units. The data show what happened with the PWR design in the period between 1955 and 1989. The market reception to the PWR increased rapidly both in terms of units sold and in terms of market share, which supports the notion of dominant design.

From the data of Table 2.1, the share in sales can be calculated and plotted in a user-friendly way. The latter is an incremental value, defined as the share of all new operating nuclear electricity capacity that is added to the marketplace within a given period. If a design has increasing sales share over the time, one can conclude that the buyers are increasingly enthusiastic with the product. This supports the thesis that the PWR was indeed the dominant design in the market of nuclear power plants.

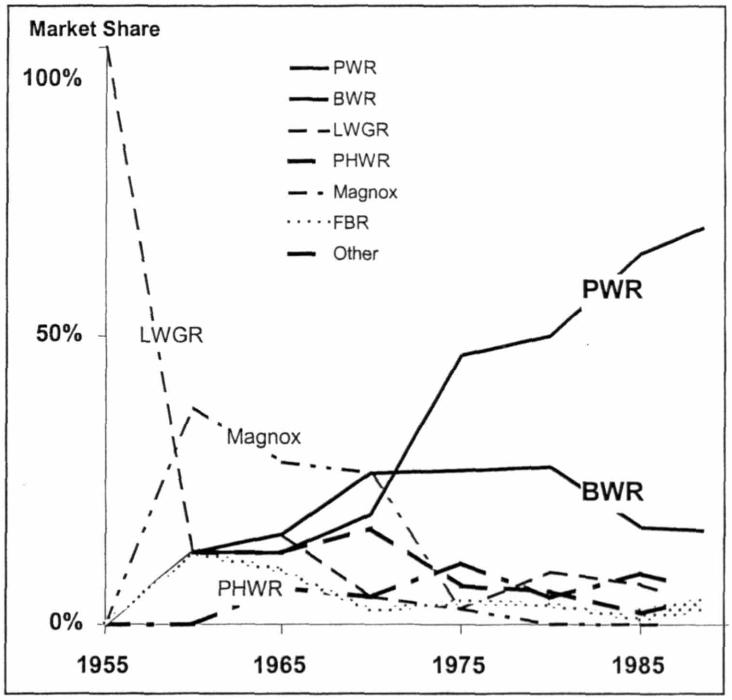


Figure 2.6. Progress of PWR's sales' share -in terms of new nuclear electricity capacity. Data corresponds to units starting operation in the world in the same period.

Figure 2.6 is a plot of sales share data –in percentage points corresponding to the portion of new nuclear electricity generated using this technology- as a function of time. It shows the progress of PWR sales share over time, versus comparable designs. It is very clear from the data presented in Figure 2.6 that the PWR increased its sales acceptance over time. While in 1965 only 19% of all new NPPs were a PWR, by the end of the 1980s the sales share had increased to 68%. The latter is a strong indicator that the PWR emerged as a dominant design in the industry.

Figure 2.6 also shows that comparable designs did not have the same fortune in the same period, as PWR grew at the expense of the other designs. The BWR for instance could not emerge consistently and after a peak of 27% in 1970, its sales share decreased to 17% in 1990. The PHWR remained marginal at less than 10% of the market. The most dramatic changes occurred with two graphite-moderated reactors: the LWGR and the Magnox. Before 1965, these designs were the most successful in the marketplace but later their sales plunged to zero. The LWGR is a graphite-cooled light-water reactor primarily constructed by the Soviet Union, and its most notorious example is Chernobyl Unit II. The Magnox on the other hand is a reactor developed in the UK. See Figure 2.7 for schemes of some of these reactors.

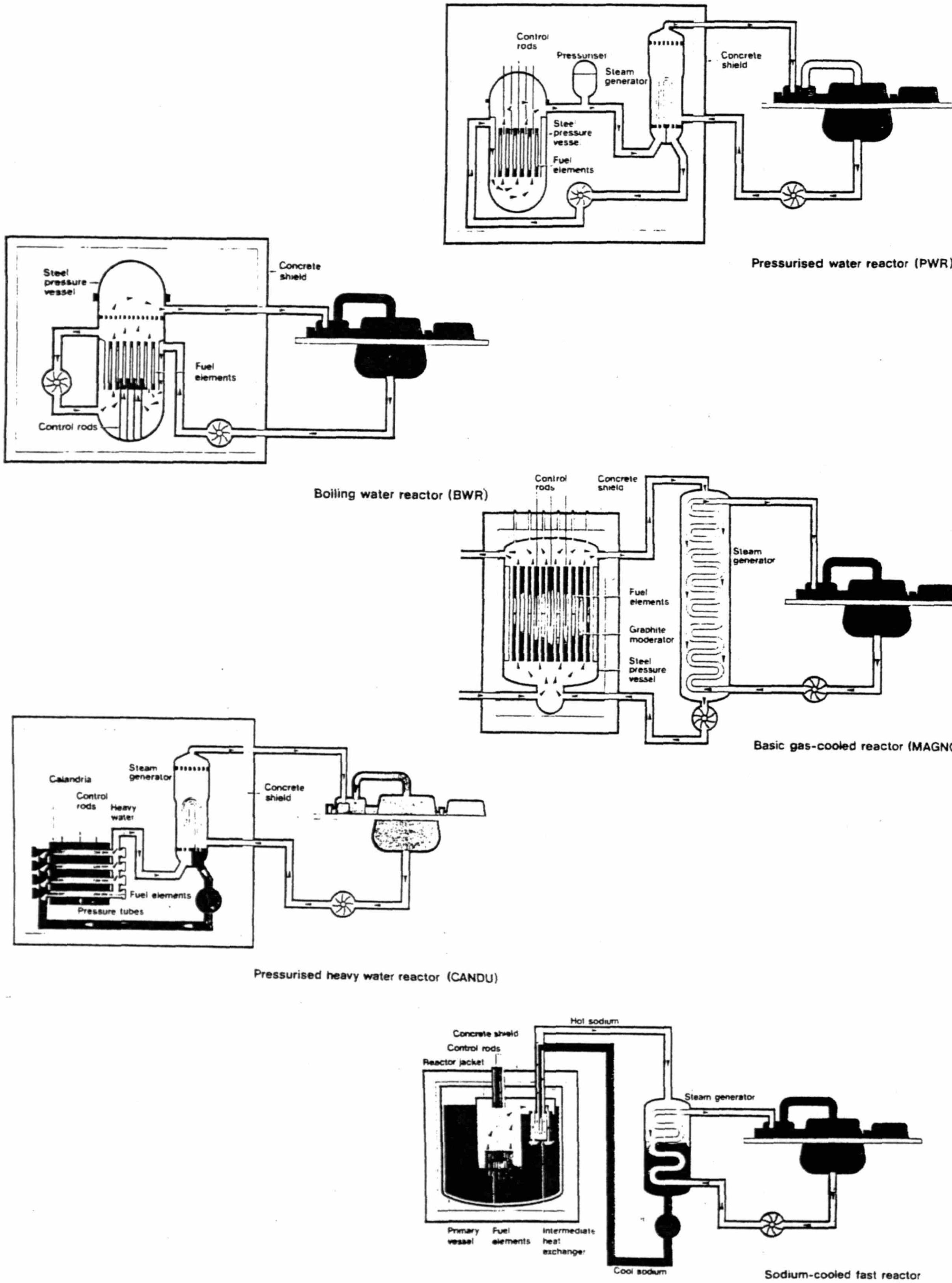


Figure 2.7. Schemes of some of the most common world nuclear reactors

Table 2.1. Progress of NPPs that started commercial operation between 1950 and 1989 in number of units and additional total electricity output (in MWe). Worldwide data.

	Year of Start of Commercial Operation							
	1950/54	1955/59	1960/64	1965/69	1970/74	1975/79	1980/84	1985/89
AGR			1			4	2	6
BWR		2	5	11	20	24	17	22
FBR		2	3	1	3	3	1	2
GCHWR				2	2			
GCR		2	2	3	3			
HTGR			1	2		1		1
LWGR	1	2	5	2	2	8	7	3
Magnox		6	9	11	2			
PHWR			2	2	8	4	9	6
PWR		2	4	8	35	44	65	86
Group Total	1	16	32	42	75	88	101	126

		Year of Start of Commercial Operation							
		1950/54	1955/59	1960/64	1965/69	1970/74	1975/79	1980/84	1985/89
		Total	Total	Total	Total	Total	Total	Total	Total
AGR	(MWe)	.	.	36	.	.	2640	1320	3960
BWR	(MWe)	.	10	513	1902	13256	18625	16660	22264
FBR	(MWe)	.	23	115	65	412	390	600	1255
GCHWR	(MWe)	.	.	.	84	249	.	.	.
GCR	(MWe)	.	44	125	990	1516	.	.	.
HTGR	(MWe)	.	.	1	57	.	342	.	308
LWGR	(MWe)	5	200	508	1054	1012	5036	7500	3500
Magnox	(MWe)	.	364	1298	3156	1310	.	.	.
PHWR	(MWe)	.	.	37	276	3148	3280	5117	4010
PWR		.	64	461	2876	22370	35128	54168	88571
Group Total		5	5	705	3094	10460	43273	65441	85365

Chapter 3.

THE DOMINANT DESIGN

This chapter first describes the Westinghouse PWR design in detail, focusing on its distinctiveness from other designs. A large amount of data is provided, with the proposition that all the main design parameters of the reactor, such as pressures, temperatures, and mass flows, converged to the same numbers. The dominant design quickly emerged as the industry standard not only in the U.S. but also in France, Japan, Belgium and the rest of the western countries.

THE PWR AS A SUBGROUP OF POWER PLANTS

A nuclear power plant is just an electricity-generating machine with a nuclear heat source to produce heat and a conventional turbine/generator group to transform heat into work and into electricity. The unique characteristic of a nuclear plant is the heat source. While coal, oil, or gas is burned in conventional plants, in a nuclear reactor the heat is obtained from nuclear fission.

In a nuclear power plant the heat source is referred as the nuclear heat supply system while the rest of the plant is often known as the conventional system.

As Figure 3.1 shows, a fluid -steam or gas – flows between these two systems and transports the energy from one system to the other. It captures the heat produced by the nuclear reaction and through a complex energy conversion process it converts heat into work and into electricity.

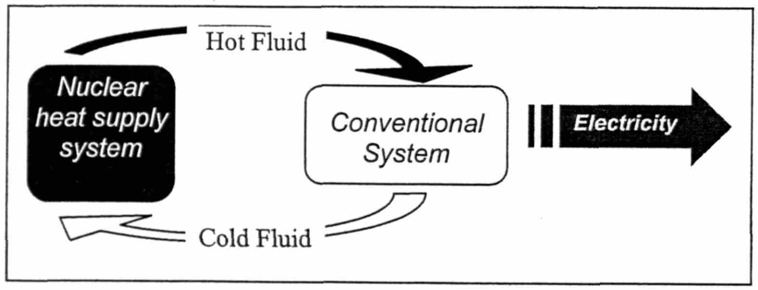


Figure 3.1 Conceptual division between nuclear and conventional systems in a nuclear power plant

The main component of the conventional system of a nuclear power plant is a turbine/generator, but there are other minor conventional equipment such as feed pumps, heat exchangers, and condensers.

Since the steam or gas flowing into the conventional system is not significantly contaminated with radiation, nuclear power plants use commercial off-the-shelf parts manufactured by standard vendors. These vendors market their products to both nuclear and fossil fueled power plants.

Table 3.1. Characteristics of the PWR and other designs

	Fuel	Coolant	Moderator
PWR	*UO_2 in zircaloy clad, enriched at 3.0% U_{235}*	*Light water H_2O at 160 bar (boiling not allowed)*	*Light water H_2O*
BWR	*UO_2 in zircaloy clad, enriched at 3.0% U_{235}*	*Light water H_2O at 75 bar (boiling is allowed)*	*Light water H_2O*
PHWR	*UO_2 in zircaloy clad, not enriched (0.7% U_{235})*	*Heavy water D_2O at 90 bar (boiling not allowed)*	*Heavy water D_2O*
Magnox	*U metal in a magnesium alloy clad, not enriched (0.7% U_{235})*	*Carbon Dioxide CO_2 at 20 bar*	*Graphite*
AGR	*UO_2 in stainless steel clad, enriched at 2.5% U_{235}*	*Carbon Dioxide CO_2 at 40 bar*	*Graphite*

Unlike the conventional system, the nuclear heat supply system is unique to each type of reactor design. The main differences arise on the selection of the materials used to produce the nuclear fission reaction inside the reactor. As Table 3.1 shows, there are three major reactor components where the choice of a material has to be made. The first is the fuel itself, which can be an oxide compound of natural or enriched uranium (in which the concentration of the fissile U235 isotope is increased from its natural 0.7% to about 3%). The second component is the moderator, whose function is to slow down the neutrons from the fission process so that they are suitable to sustain the chain reaction. In practice the options are graphite, ordinary water and heavy water. The third major component is the coolant, where the options are helium, carbon dioxide, and ordinary/heavy water.

As Table 3.1 shows, it is the permutation of the available options that gives rise to the variety of nuclear designs that populate the nuclear power fleets of countries like the US, France, Japan, Canada and the UK. The PWR uses a unique selection of these materials.

BRIEF DESCRIPTION OF THE PWR DESIGN

Westinghouse and its engineering team at Bettis Laboratories originally developed this design for submarine propulsion. In addition to this firm, Babcock & Wilcox and Combustion Engineering have built this type of reactor in the United States while Mitsubishi, Framatome, and Siemens/KWU have done it in the rest of the western world. As it is shown in Figure 3.2, the PWR reactor has a single pressure vessel –where the reactor core is located- and two separate cooling subsystems.

The primary cooling subsystem is the only subsystem that passes through the reactor core. The fission process heats up the water that passes upward past the reactor core, from a temperature of about 290°C to a temperature of about 320°C. Outside the reactor pressure vessel, the primary system is divided in two to four cooling "loops" connected to a central pressurizer. The latter maintains the primary pressure constant at 160 bar. At this pressure water remains always liquid since its saturation temperature is well above 320°C and therefore no boiling can occur. Each loop contains a primary pump and a steam generator. The water coming from the reactor is pumped to the primary side of the steam generators where it transfers heat to the secondary coolant subsystem.

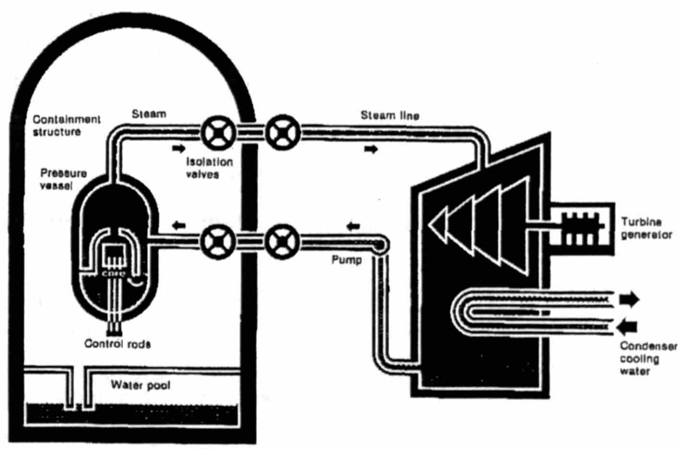


Figure 3.2. Simplified scheme of a PWR nuclear power plant

The secondary cooling subsystem consists of cold water, which passes on the secondary side of the steam generator, is heated and converted to steam. The later is possible because the water in the secondary subsystem is at a pressure of about 70 bar and its saturation temperature is 280°C. Therefore boiling can occur, taking into account the high temperature of the primary subsystem. The steam then passes to the turbine and turn shafts that are mechanically connected to the electricity generator. The redundant steam from the turbine condenses the water, which is then pumped again to the steam generators. The condenser is the ultimate heat sink of the reactor. Here the heat that was not converted into work is cooled by cold water pumped through the condenser. As a cold sink the condenser uses water extracted from the sea, river, or a water reservoir. Another choice of cold source is the atmosphere and on that occasion the device for heat rejection is a cooling tower.

One can go one step further, defining the PWR architecture in terms of system, subsystem, components and main design variables. Following the systemic approach traditional in engineering settings, the following definitions are adopted: (a) system is an independent part that can be treated as a whole, (b) subsystem is an element of a system, which performs a particular function, (c) key components are the most important parts that comprise a subsystem, and (d) main variables are the critical physical properties of a given subsystem and/or component.

For example, one can define the conventional system as the part of the nuclear power plant whose function is to take steam coming from the nuclear heat supply system in order to extract electricity. The steam subsystem can be defined as the part of the conventional system that has the function of processing the steam coming from the reactor and converting part of its energy into work. In this case the key components are the turbine, the condenser and the secondary pumps, while the main subsystem variables are the steam pressure and the coolant mass flow.

Table 3.2 and Figure 3.3 summarize the PWR architecture taking these considerations into account. The selection of key components and main variables is not arbitrary. It is based on the premise that the selected items and variables are the crucial elements of the design concept. Less important components –valves, tanks, process subsystems- are not taken into account, as they are irrelevant for the analysis. The same holds for physical variables which are intrinsically dependent on others (e.g. the saturation temperature is an intrinsic function of fluid pressure).

It is important to note that a particular subsystem can be exposed to either architectural or component changes. An architectural modification would be, for instance, if instead of using only one turbine the designer decides to use four smaller turbines. On the other hand, the changes can be at the component level if, for example, instead of using traditional rotating pumps the designer introduces piston-type pumps. Finally any subsystem as a whole can undergo incremental innovations without changing the basic architecture or the core components leading to the enhancement of a certain performance variable, for instance higher thermal cycle efficiency.

Table 3.2. System description of the PWR architecture

System	Subsystem	Key Components	Design variables
Nuclear Heat Supply System	Primary cooling subsystem	Primary Pumps Steam generators Pressurizer	Primary Pressure (Kg/cm^2) Primary mass flow (ton/hr) Inlet Temperature (°C) Outlet Temperature (°C)
	Heat source	Reactor Vessel Reactor Internals Reactor Core	Thermal Power (MWth) Vessel diameter (m) Vessel height (m)
Conventional system	Secondary cooling subsystem	Turbine Secondary pumps Condenser	Steam Pressure (Kg/cm^2) Secondary Mass flow (tn/hr)
	Electricity subsystem	Generator	Gross Power (Mwe)

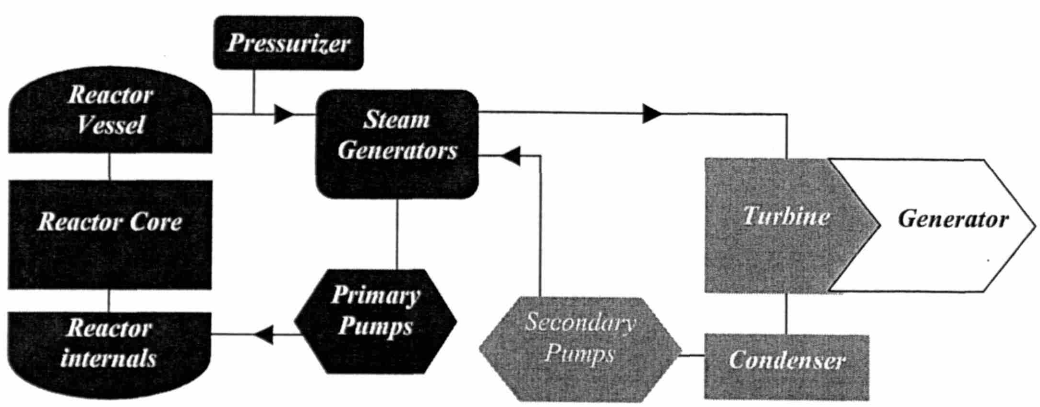


Figure 3.3. Conceptual scheme of the main components of a PWR design

CORE DESIGN CONCEPT

In the previous section, the PWR design concept was described as it was originally conceived in the mid-1950s. However, there are several architectures which can meet this rather basic design concept and, in principle, a variety of different components and materials that can be utilized. As a matter of fact, the PWR design concept as it was introduced can be considered as vague and undefined as it can be an SUV concept in a newspaper's automobile section.

What transforms a set of engineering choices into a design concept are not only the components and concepts that are utilized. It is the use of an architecture that links the components and core concepts in a certain manner that not only is consistent but also stable over time. In the SUV example above, it is the constant use of an architecture defined by a high power gasoline engine, above 4.5 liters, a 4-wheel drive automatic transmission, and a light external structure with a sport appearance mounted on a frame rather than on the axles. Furthermore, it is the way these components are linked in order to make the driver feeling like driving a 2002 Saab car rather than a 1965 Chevy truck.

In the particular case of the PWR, the core concepts, components and linkages between them can be summarized as follows:

1. The reactor core is contained by a cylindrical pressure vessel made of stainless steel (it could have been prestressed concrete as in the Magnox).
2. The fuel is uranium dioxide enriched at 3% with a can-shaped zircaloy clad (it could have been a lower enrichment and a clad of stainless steel as in the AGR).
3. The primary coolant is ordinary water maintained at a fixed pressure of about 160 bar by a single pressurizer connected to the primary cooling subsystem and whose job is to avoid bulk boiling within the primary (the coolant could have been allowed to boil as in the BWR).
4. The heat is transferred from the primary coolant to the secondary system through tube/shell steam generators (this intermediate process could have been avoided as in the BWR).
5. The mass flow rate is provided by rotating pumps, which are located outside the reactor (it could have been piston-driven pumps or natural convection).
6. The reactor control drive mechanisms are on top of the pressure vessel (they could have been located in the bottom of the pressure vessel as in the BWR).
7. The containment of the nuclear heat supply system is a "dry" spherical stainless steel structure designed to withstand up to 5 bar of internal overpressure (it could have been a "wet" pressure-suppression containment with a cylindrical shape as in most BWR reactors).

TESTING THE DOMINANT DESIGN HYPOTHESIS

Up to this point, the main proposition has been that a complex system like a nuclear power plant can be accurately described in terms of a handful of systems, subsystems, components and variables; which will account for the most important physical processes involved in the system. Namely, that a PWR system can been reduced to the simplicity of Figure 3.3.

The next step in the analysis is proposing a definition as to when a design concept fulfills the conditions necessary to become a dominant design. A reasonable criterion is that the emergence of a dominant design should be manifested at least by the following features: First, two consecutive products must maintain exactly the same architecture in terms of systems and subsystems, and must have exactly the same number and type of key components. Second, at some time the main physical variables of the system should attain a convergence or consensus value.

For example, if the secondary cooling subsystem consists of a single turbine, a single condenser and two feed water pumps, then the number and type of these components must be maintained constant in two consecutive products. Moreover, variables like the gross power of the turbine or the steam pressure must also stay invariable.

It is important to note that architectural stability is a necessary but not a sufficient reason for a particular product to become a dominant design because it does not take into account the market, which may or may not adopt the product. It is just a strong indication of the emergence of a dominant design. A firm will freeze the design and focus its energy in achieving economies of scale, only when the firm senses that it has a product sufficiently attractive in the marketplace. Otherwise it will continue to experiment with alternative concepts.

EVOLUTION OF THE PWR DESIGN

Figures 3.4 to 3.10 contain a graphic representation of the main information concerning the PWR design evolution.

After an initial turmoil, which occurred in the 1950s and early 1960s, a consensus design clearly emerged.

The design was refined and improved in the following decades but basically the PWR architecture remained unchanged. The type and number of components in all the subsystems were maintained between two consecutive products and, similarly, the most significant variables attained a consensus value.

For example, one can explore the history of the most critical thermal variables in the plant, that affect the process of extracting heat from the reactor and converting it into work. These variables are pressures, temperatures and heat rates.

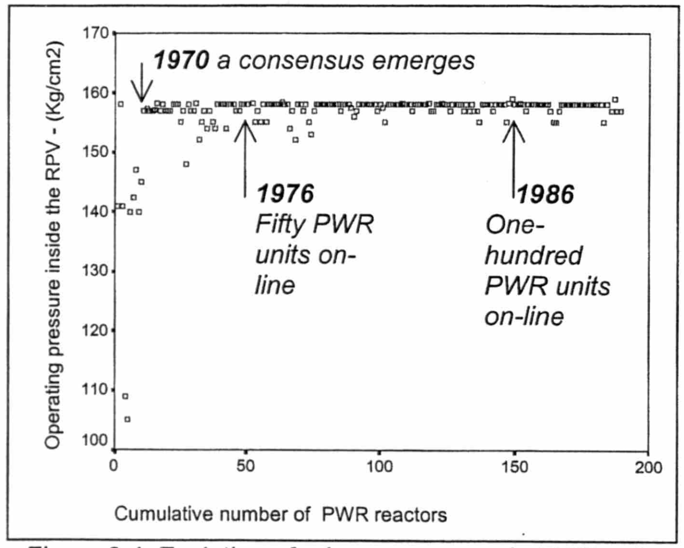


Figure 3.4. Evolution of primary pressure in PWR units that started commercial operation in the western world

Since the first PWR started commercial operation in 1957, the primary pressure varied significantly in the early designs, until it attained a convergence pressure of around 158 Kg/cm². The latter is arguably the most critical design parameter in the PWR design and achieved a remarkable consensus as can be seen in Figure 3.4. The major PWR vendors converged on a figure that has been maintained in PWR reactors even today.

It is important to note that the data presented in Figure 3.4 correspond to worldwide data – except the Soviet Union. Therefore it can be concluded that 158 kg/cm2 was the gold standard of all PWR reactors built either in the United States or abroad.

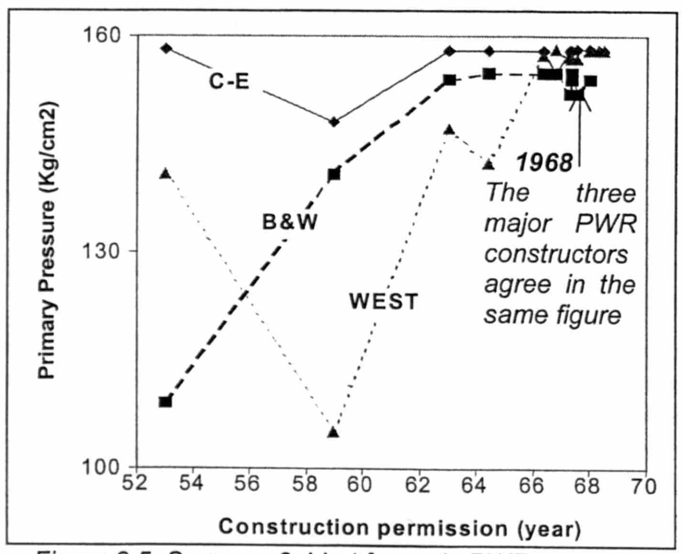


Figure 3.5. Same as 3.4 but for early PWR units as a function of the year construction permit was issued

Figure 3.5 provides a closer look at the same data but as a function of the year that the construction permit was issued. In the late

1960s there was a delay of about five years between construction permit issuance and commercial operation. As shown, the major PWR vendors in the United States – Westinghouse, Combustion Engineering and Babcock & Wilcox- seemed to agree on a consensus figure.

Given the fact that the three main PWR manufacturers were independent firms competing for market share, their agreement is a strong indication that a dominant design effectively emerged in the 1960s. The data also show that these three firms competed evenly in the beginning of nuclear power in the United States, building similar numbers of units. Later, this equal market penetration finished in a strong leadership of Westinghouse. However, the three firms provided essentially the same design and utilized the same supplier base. For instance, Babcock & Wilcox and Combustion Engineering did not manufacture turbine generators and therefore were forced to buy these key components from either Westinghouse or General Electric.

As a result of the convergence in the primary pressure, the core outlet temperature, or the temperature at which the coolant exits the reactor vessel, also followed a convergence trend. The final consensus temperature was about 320°C. The same holds for the core inlet temperature, which stabilized at 290°C.

The convergence of the two core temperatures to their consensus values is shown in Figure 3.6, which summarizes worldwide data –excepting the Soviet Union. As it is shown, the convergence evidence is overwhelming.

Figure 3.7 provides a closer look at the same data presented in the previous figure but as a function of the year that the construction permit was issued. Note that there were five years between construction permit issuance and commercial operation.

Again, as shown in Figure 3.7, the major PWR vendors in the United States –Westinghouse, Combustion Engineering and Babcock & Wilcox- seemed to agree on a consensus figure.

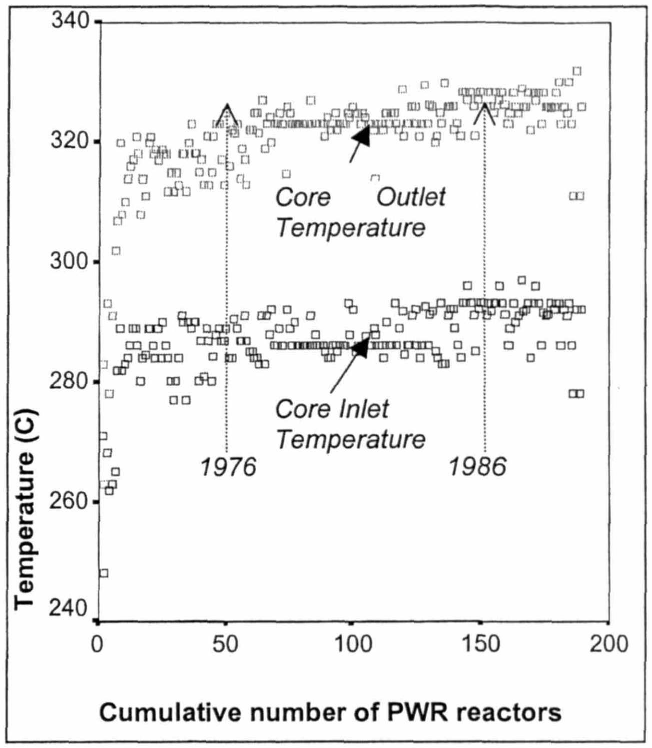


Figure 3.6 *Evolution of primary* temperatures *in PWR units that started operation in the western world*

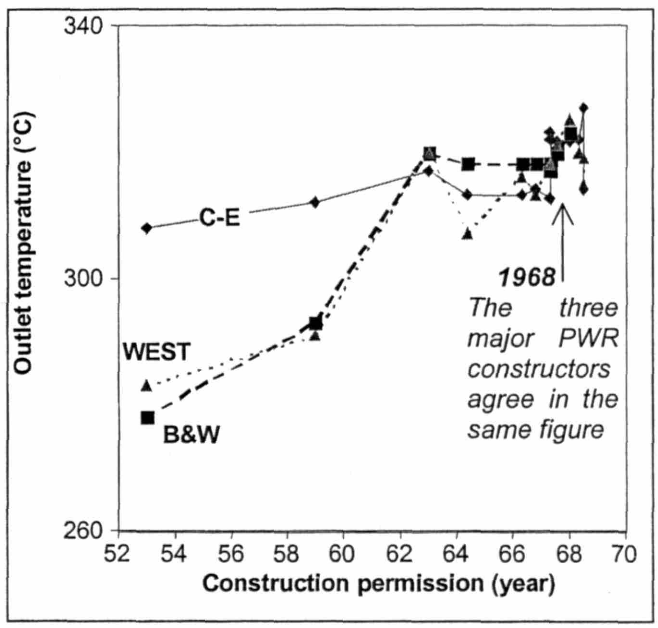


Figure 3.7. *Same as 3.6 but for early PWR units, as a function of the year construction permit was issued*

A very interesting feature in the PWR design evolution appears when comparing the number of primary loops and pumps as a function of time. Initially PWR reactors started with one or two loops and one or two primary pumps. When the power was increased the number of loops was also increased. At a final stage of the evolution, the PWR dominant design consisted of four loops and four pumps. Figure 3.8 is a scheme of this process.

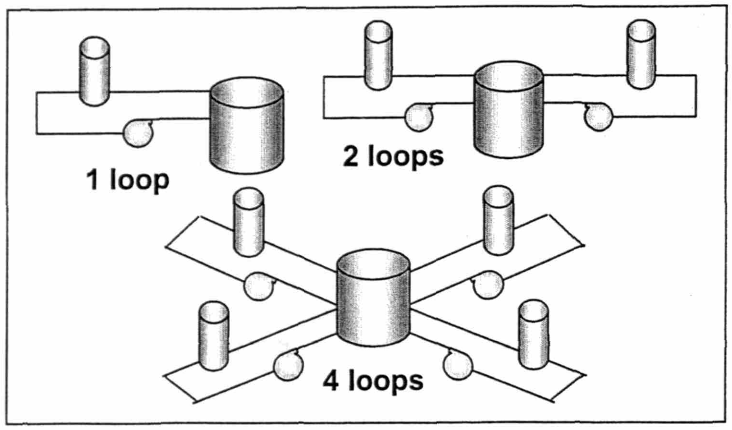


Figure 3.8 Scale up in the PWR design: how higher ratings were achieved using more cooling loops

Notwithstanding the fact that the number of pumps changed, the fundamental parameter associated with the PWR design –which is the mass flow rate- was maintained constant. As can be seen in Figure 3.9, the mass flow rate per pump attained a consistent convergent trend. By the mid-1960s all the PWR designers were using pumps rated at about 19,000 ton/hr.

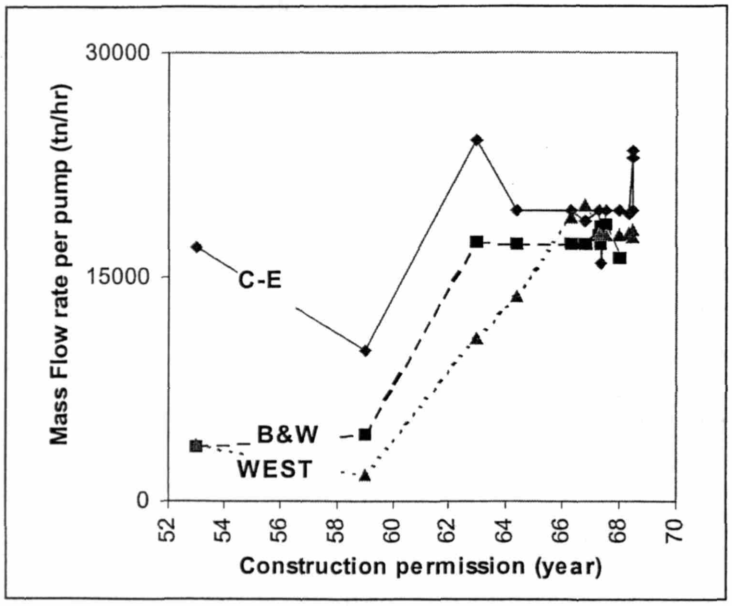


Figure 3.9 Mass flow rate per pump as a function of the date the construction permit was issued

The convergence in mass flow rate suggests that all the designers were using the same type of pumps, perhaps provided by the same manufacturer. However this hypothesis could not be verified. It should be pointed out that the primary pumps are large components subjected to stringent requirements both in terms of temperature and pressure.

The mass flow rate was maintained constant –at a consensus value- even though there was a drive to increase the power ratings of nuclear power plants in order to achieve economies of scale. The scale up process –which lead to 1,300 MWe units- was achieved without changing the core concepts of the design. The scale up process occurred just by adding cooling loops. This was a way to reduce the need for further R&D costs.

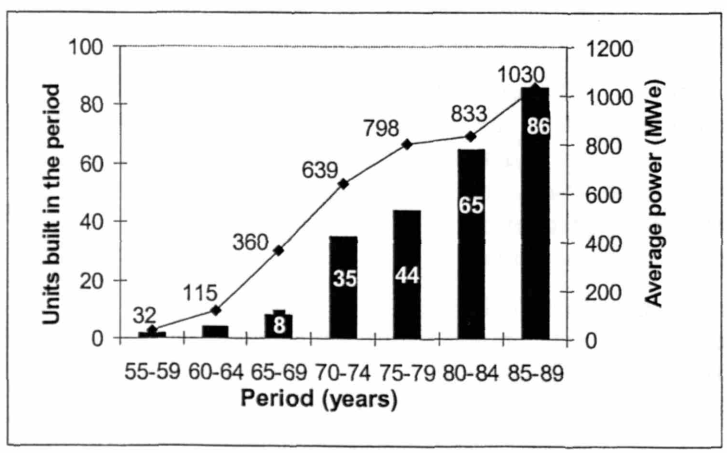


Figure 3.10 Average electric power rating (MWe) of PWR plants (worldwide) that went on line prior to 1989

In summary, it can be affirmed that a dominant PWR design appeared in the late 1960s. It had four primary pumps rated at 19,000 ton/hr, operated at a pressure of 158 kg/cm², with coolant temperatures of 320°C and 290°C.

Regarding power rate –thermal power and electricity output- the units advanced constantly to a target rating that changed over time. As it is shown in Figure 3.10, in the late 1980s, the average PWR had an electrical rating of 1,000 MWe, although some units attained 1,300 MWe.

Consequently, one can argue that the designers were able to maintain a stable dominant design even though there was an extensive scale-up operation going on. This is also an important indication of the robust architecture of the PWR. It allowed power increases without a significant change in the design concept itself. Other designs, such as the Magnox, faced significant difficulties when designers tried to scale up (Patterson, 1985).

To strengthen the point, it is interesting to note that notwithstanding the increase in power, large components of the primary system, such as the reactor pressure vessel, did not change significantly. As an illustration, Figure 3.11 summarizes the evolution of the two main dimensions of the pressure vessel, showing that it did not change at all.

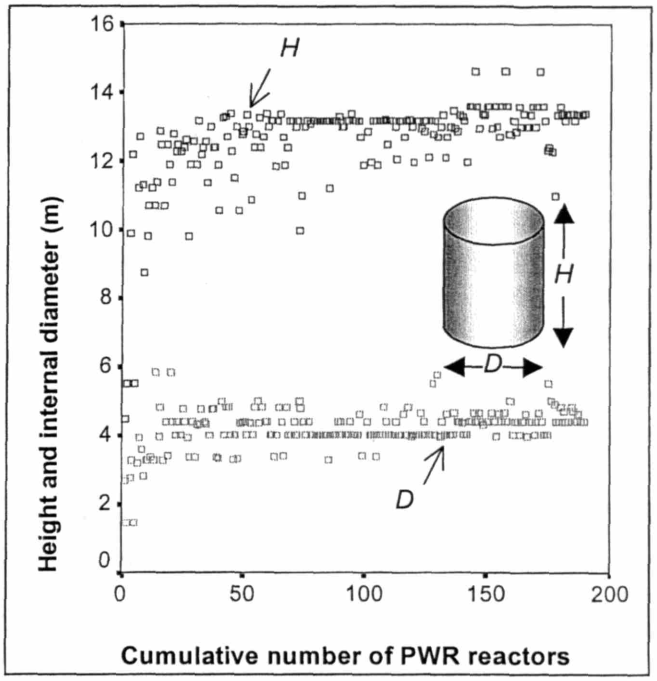


Figure 3.11 Evolution of PWR pressure vessels

A PATTERN OF INCREMENTAL INNOVATION

The previous sections defined a "general" description of a PWR design. Some units had features slightly different and some minor innovations at the component level. What is important to note however is that all the PWR units developed in the US or abroad had the same design from an architectural point of view. Namely, the way the core concepts and components were integrated and linked together has not fundamentally changed even though there were minor innovations at the component level. The above-described pattern is consistent with the incremental innovation pattern defined in the framework of incremental, architectural, modular and radical innovation (Henderson and Clark, 1990).

Henderson and Clark's framework classifies innovations along two dimensions: (a) the innovation's impact in components and (b) the innovation's impact in the linkages between different components that compose the system. This idea is summarized in the matrix presented in Figure 3.12.

Based on the data of all the PWR units constructed before 1989, one can argue that the PWR design had only incremental changes after the concept was introduced in 1957. Its core design concepts were reinforced and the linkages between its components remained unchanged.

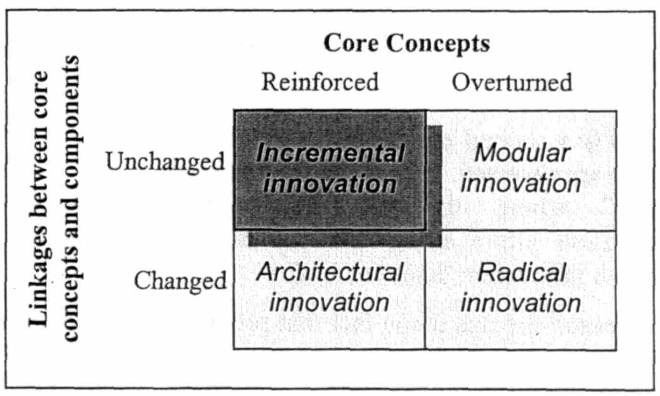


Figure 3.12 Henderson and Clark framework for defining innovation

A comparative example of a product that reached an era of pure incremental innovation is the diesel engine. Even though diesel engines still improve continuously, there are no big innovations that shake the core concepts or the way these concepts and the components are linked. Engineers do not reevaluate the decision to use a particular core concept of the diesel engine every time they develop a new product.

Architectural stability is a necessary condition for a particular set of engineering choices to become a dominant design. Once a dominant design is established, progress takes the shape of improvements in the components within the boundaries of a stable architecture. The core engineering choices of a dominant design are not revisited every time a new product comes out from the factory because firms cannot waste valuable resources in re-inventing the wheel. In fact the dominant design often emerges in response to the opportunity given by stable architectures to obtain economies of scale and/or to take advantages from externalities (Abernathy, 1978).

The same holds for the PWR. From 1957 to 1989 the core concepts of the design have not changed and the design engineers focused on improving the performance of stable architectures. The parameters that summarize the balance of the plant, such as pressures, temperatures, mass flows, all attained a consensus value. Some innovations have occurred in the component side, for instance, design improvements in pumps, control rods, nuclear instrumentation and steam generators. However the basic PWR architecture and its core concepts did not change, which is a finding that strongly supports the dominant design hypothesis.

FROM PRODUCT INNOVATION TO PROCESS INNOVATION

The previous sections described the evolution of the PWR as a product. The design concept evolved from an initial stage of high variety and uncertainty to a dominant design, where there was only incremental innovation on a largely standardized product. The industry itself changed from an era where it was fragmented, unstable, and where many products were making their way to the marketplace to a more mature era in the late 1980s with standardized products.

The above-presented pattern is consistent with the framework of product and process innovation developed by Abernathy and Utterback. The framework hypothesizes that the rate of major innovation for both products and processes follows a general pattern over time and that product and process innovations are related as shown in Figure 3.13 (Abernathy, 1978).

The rate of product innovation is highest during the initial formative "fluid" phase. This is a period where product experimentation occurs both in terms of testing different options and gaining experience. During this fluid period of high product innovation, much less attention is given to the processes by which products are made so the rate of process innovation is less rapid.

There is a second period, however, where things are reversed. This is the 'transitional phase" where the rate of product innovation slows down and the rate of process innovation takes the lead.

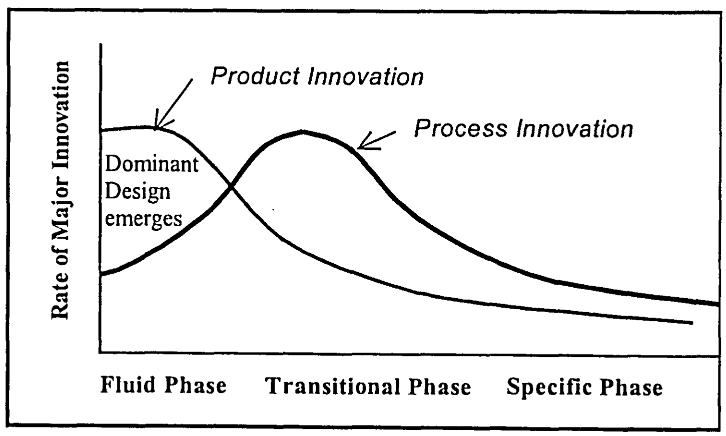


Figure 3.13 The dynamics of innovation (Utterback, 1994)

The reason for this is the fact that product variety gives way to standard designs that have proved to be well accepted in the marketplace. At this point, a dominant design emerges which is in general the product that best satisfies the buyers' needs (Utterback, 1994). Finally, there is a third period, where the rate of both product and process innovation declines. Here is where the industry becomes more focused on cost, volume and capacity.

Based on the data available, one can argue that the PWR design emerged as a dominant design in the late 1960s, after a flurry of product innovations such as the Magnox, the FBR, the AGR, etc. Since then process innovation became the preferred way to introduce changes and these changes were incremental innovations on the dominant PWR design. The manufacturing progressed from heavy reliance on R&D to more systematic and repetitive engineering tasks. The organizations in charge of building reactors changed from small, cohesive and creative groups- such as Bettis Labs – toward a more hierarchical organization with defined tasks and procedures. Engineers became more focused on improving the performance of the design or at least what was considered performance of a nuclear power plant at that time, namely: (a) increasing the efficiency of the thermal cycle, (b) building larger units and (c) increasing the number of redundant safety features.

A relevant point is whether the change from product innovation to process innovation was made at the right time. In other words, could a better design have emerged if the industry spent more time in a fluid phase? But as was explained in chapter 1, there was a government-sponsored "rush" to move forward in the learning curve and attain a truly "operational" U.S. nuclear power capacity.

Abernathy and Utterback's framework also predicts substantial changes in the industry arising from the emergence of a dominant design, but these changes are discussed in Chapter 6. Some of these issues are: (a) competition from new entrants building PWR reactors, (b) organizational control through project and task groups, and (c) vulnerability of industry leaders.

Chapter 4.

THE BWR AND THE HIDDEN LINK WITH THE PWR

This chapter focuses on the development of the BWR design, i.e. the GE approach to the civilian nuclear power plant and the main competitor to the Westinghouse PWR. The chapter starts with a thorough description of the design and the differences and similarities with the PWR. The BWR also stabilized in certain values and this will be shown following the same criteria explained in the previous chapter. Using appropriate data, this chapter also shows that the main connection between the designs proposed by GE and Westinghouse was through the use of similar suppliers and components. In particular both designs have essentially the same steam turbine. This finding is used to argue that one of the main reasons why the Westinghouse PWR design stabilized so quickly was because of the standardization of one of the main component of nuclear power plants: the steam-electric turbine.

THE BWR AS A SUBGROUP OF POWER PLANTS

Allis-Chalmers and General Electric had introduced commercially the BWR design in the United States in the early 1950s. Although Allis-Chalmers abandoned the business in 1962, GE remained in the market and was able to sell nearly fifty units within the U.S and abroad. In addition to U.S. vendors, Hitachi, Toshiba, Asea and Siemens/KWU built BWR plants abroad generally as licencees of GE. As a result, one hundred nuclear power plants were built worldwide before 1989, making the BWR the second best sold design in the world. To illustrate this point, Figure 4.1 compares the market evolution of the BWR with respect to the PWR.

The first BWR was built at Argonne National Laboratory partially with involvement of Allis-Chalmers. It received the name of Experimental Boiling Water Reactor (EBWR) because it was originally conceived as a pilot plant to test the concept of a reactor where boiling was allowed to occur. In addition to its nominal thermal rating of 20MWth it was expected to produce 5MWe of electricity using a turbine generator manufactured by Allis-Chalmers. The facility went into operation in late 1956 and was operative until mid-1959 when it was shut down in order to be modified for a number of experiments, including an upgrade to produce 100MWth, five times the original heat power rating. Thereafter, EBWR operated till 1967.

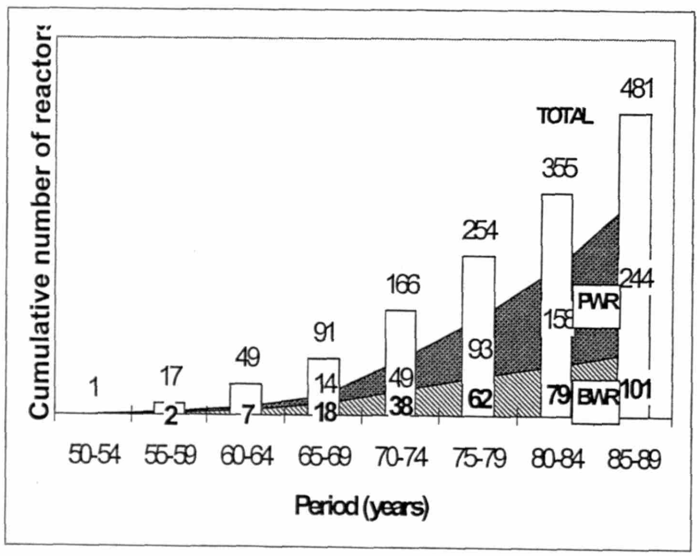


Figure 4.1. Comparison of PWR & BWR units that started operation before 1989 (worldwide data)

After EBWR, the participation of Allis-Chalmers as designer and constructor of BWRs had increased throttle in 1957, when the firm was granted a contract to build the Pathfinder reactor in Sioux Falls, SD. This was a 59 MWe unit operated by Northern States Power from July 1966 until late 1967.

The BWR made a commercial leap when it became the first reactor sold on a purely competitive basis and without government support. This reactor, Dresden-1, achieved a self-sustaining nuclear reaction at Morris, IL, in October 1959. Under the ownership of Commonwealth Edison, Dresden 1 operated commercially at a rating of 200MWe until its programmed shutdown in 1978. The reactor heat supply was designed and constructed by General Electric as well as its turbine generator. Bechtel was the other participant in the project in the double role of constructor and architect-engineer.

44 out of 47 BWR nuclear plants built in the United States before 1989 followed the same formula of the Dresden 1 reactor. Namely, GE as manufacturer of the reactor heat supply system and the turbine generator and a major engineering firm, such as Bechtel, Stone & Webster, or Sargent & Lundy, taking the central role of architect-engineer and constructor.

Table 4.1. Main characteristics of the PWR and BWR

	Fuel	Coolant	Moderator
PWR	*UO_2 in zircaloy clad, enriched at 3.0% U_{235}*	*Light water H_2O at 160 bar (boiling not allowed)*	*Light water H_2O*
BWR	*UO_2 in zircaloy clad, enriched at 3.0% U_{235}*	*Light water H_2O at 75 bar (boiling is allowed)*	*Light water H_2O*

BRIEF DESCRIPTION OF THE BWR DESIGN

In the same way as a PWR, the heat source of BWR reactor is referred as the nuclear heat supply system while the rest of the plant is often known as the conventional system. As Table 4.1 shows, both designs make use of essentially the same fuel –with minor differences- and the same coolant. The main difference is that boiling is allowed to occur in the BWR and the steam produced in the reactor pressure vessel directly drives the turbine generator with no intermediate steam generators in the pathway.

Since the steam flowing into the conventional system comes directly from the reactor in a once-through cycle, the BWR turbine generator is slightly more complex in order to avoid contamination with radiation. Excluding these minor differences, turbine generators of BWR and PWR reactors are fundamentally the same. Both operate at a pressure of about 70-75 bar.

Unlike the PWR design, the BWR reactor has only one cooling subsystem (see Figure 4.2 for comparison). First, in the reactor section of the cooling subsystem, water circulates through the reactor core removing heat as the water moves past the fuel assemblies. The water eventually is

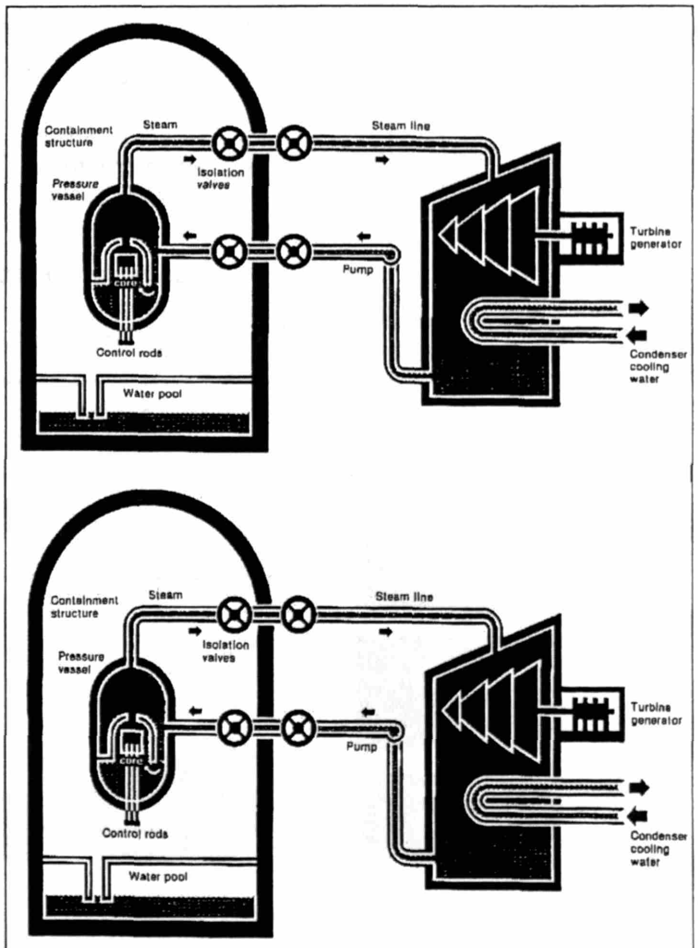


Figure 4.2. Schemes of the PWR and BWR designs

heated enough to convert to steam. The later is possible because the water inside the reactor is at a pressure of about 70-75 bar, its saturation temperature is 280°C and therefore boiling can occur.

Steam separators in the upper part of the reactor remove water from the steam. The steam then passes directly to the turbine and turns shafts that are mechanically connected to the electricity generator. The redundant steam from the turbine condenses into water, which is then pumped again into the reactor.

The condenser is the ultimate heat sink. Here the heat that was not converted into work is cooled by heat exchange with cold water pumped through the condenser. As a cold sink the condenser uses water extracted from the sea, river, or a water reservoir. Another choice is the atmosphere and the device for heat rejection is a cooling tower.

One can go one step further, defining the BWR architecture in terms of system, subsystem, components and main design variables. Using the following definitions: (a) system is an independent part that can be treated as a whole, (b) subsystem is an element of a system, which performs a particular function, (c) key components are the most important parts that comprise a subsystem, and (d) main variables are the critical physical properties of a given subsystem.

Table 4.2 summarizes the BWR architecture taking these considerations into account. The selection of key components and main variables is based on the idea that the selected components and variables are the crucial elements of the design concept.

Table 4.2. System description of the BWR architecture

System	Subsystem	Key Components	Design variables
Nuclear Heat Supply System	Heat source	Reactor Vessel Reactor Internals Reactor Core	Thermal Power (MWth) Vessel diameter (m) Vessel height (m)
Conventional system	Cooling subsystem	Feedwater pumps Turbine Condenser	Inlet Temperature (°C) Outlet Temperature (°C) Steam Pressure (Kg/cm²) Coolant Mass flow (tn/hr)
	Electricity subsystem	Generator	Gross Power (Mwe)

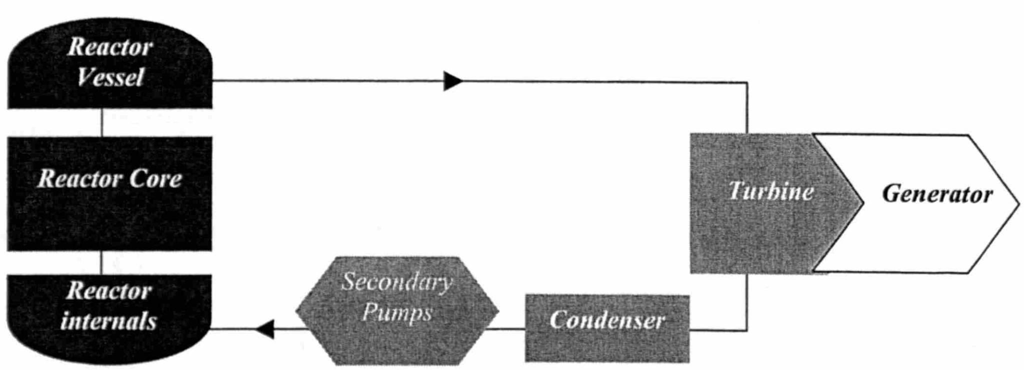


Figure 4.3. Conceptual scheme of the main components of a BWR design

It is important to note that only key components and subsystems are taken into account. Less important components are not taken into account, as they are irrelevant for the analysis. For instance primary circulation pumps and the subsystem for water purification are less significant items and do not determine the boundaries of the BWR design. The same holds for physical variables which are intrinsically dependent on others.

CORE DESIGN CONCEPT

In the particular case of the BWR, the core concepts, components and linkages between them can be summarized as follows:

1. The reactor core is contained by a cylindrical pressure vessel made of stainless steel (the same as the PWR but taller in order to allow natural convection to occur).
2. The fuel is uranium dioxide enriched at 3% with a can-shaped zircaloy clad (same as the PWR except that rods are slightly thicker).
3. The primary coolant is ordinary water but unlike the PWR, bulk boiling is allowed to occur within the primary, at a saturation pressure of 70 bar.
4. The heat is directly transported by steam from the primary coolant to the turbine secondary system (there are no intermediate tube/shell steam generators as in the PWR design).
5. The mass flow rate is part natural convection and part forced convection provided by jet pumps (in the PWR design there are circulating pumps and natural convection effects are negligible).
6. The reactor control drive mechanisms are located on the lowest part of the pressure vessel whereas in the PWR control rods are on the highest part of the pressure vessel.
7. The containment of the nuclear heat supply system is a "wet" containment, namely a cylindrical stainless steel structure designed to withstand up to 5 bar of internal pressure. Unlike the PWR "dry" containment, the BWR utilizes steam condensation as main mechanism of heat rejection.

EVOLUTION OF THE BWR DESIGN

Figures 4.4 to 4.10 summarize the main information concerning the BWR reactor. The evolution of this design follows essentially the same pattern as in the PWR case.

After an initial turmoil in the early 1950s, a stable BWR architecture emerged in the 1960s. Since then, the BWR design was refined and improved but basically its architecture remained unchanged. Similarly to what happened with the PWR, the number of components in all the subsystems were maintained between two consecutive products and the most significant variables attained a consensus value. For instance, the key thermal variables in the plant that affect the process of extracting heat from the reactor and converting it into work.

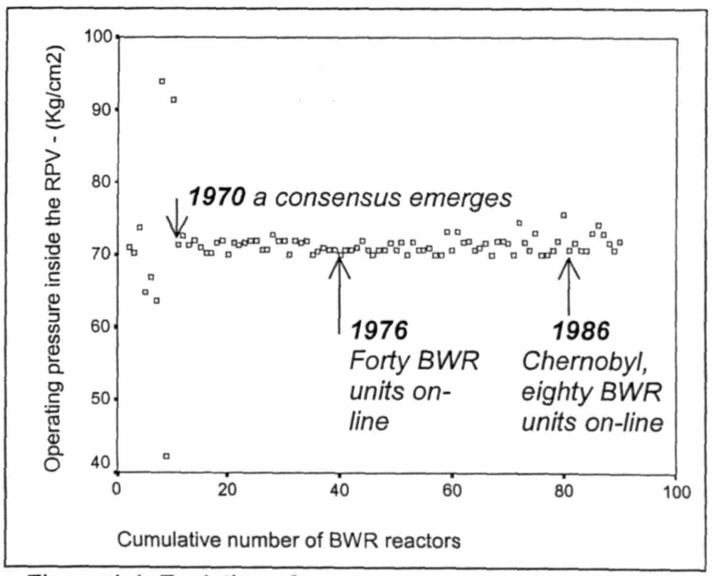


Figure 4.4. Evolution of reactor pressure in BWR reactors that started commercial operation in the western world

As it is shown in Figure 4.4, in the years when the first BWR reactors were ordered, the primary pressure varied significantly. But afterwards the pressure attained a consensus value of about 72 Kg/cm². The data correspond to all reactors that started operation worldwide. The 72 kg/cm2 was therefore the gold standard of all BWR reactors built either in the United States or abroad (the Soviet Union did not develop the BWR concept to an operational level)

Figure 4.5 provides a closer look at the same data but as a function of the year the construction permit was issued. In the late 1960s there was a delay of about five years between construction permit issuance and commercial operation. As it is shown, the major BWR vendor in the United States –General Electric- set up the consensus, because the other BWR builder –Allis Chalmers- abandoned the business after building only three BWR reactors. Some years later, other international manufacturers –notably Toshiba, Hitachi and Asea - initiated the production of BWRs and eventually built as many reactors as GE did. But these firms did not change GE's standards. One reason is that there was appreciable operating experience accumulated by General Electric to discourage changes. The other was that GE secured license agreements with the Japanese manufacturers to build BWRs and market them in Japan. In fact some of the early units built there were jointly built by GE and one of the two Japanese builders.

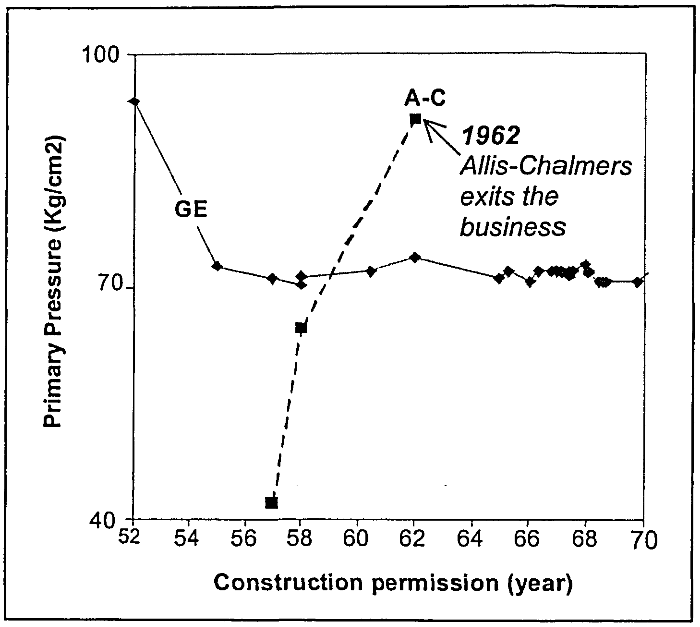


Figure 4.5. Same as 4.4 but for early BWR reactors as a function of the year construction permit was issued

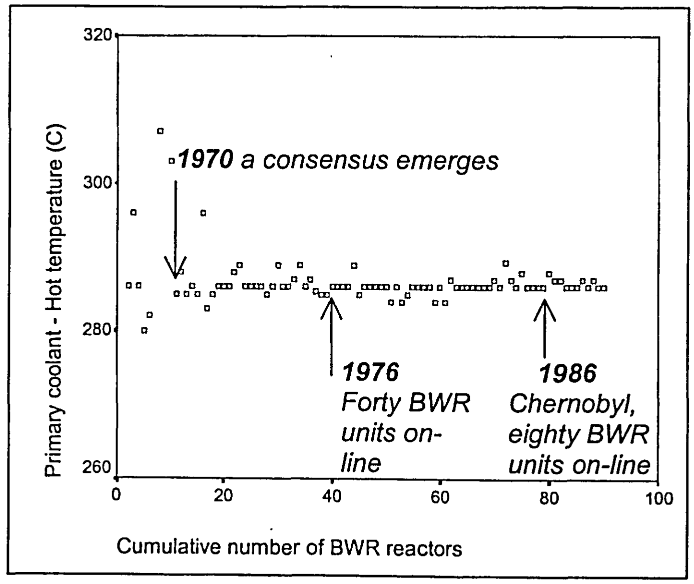


Figure 4.6 Evolution of primary temperatures in BWR reactors that started operation in the western world before

As a result of the convergence in the primary pressure, the core outlet temperature also followed a convergence trend. As it is shown in Figure 4.6, the final temperature was about 285°C. The latter is an obvious result since the BWR is a boiling reactor and hence there is a relationship between pressure and saturation temperature.

The same trend prevailed in the rest of the main variables associated to the BWR design; such as dimensions and geometry of the reactor vessel, reactor internals, core inlet temperature, etc.

As an illustration, Figure 4.7 summarizes the evolution of the two main dimensions of the pressure vessel, showing that they did not change at all. As shown,t the BWR vessel is taller and wider than the PWR vessel, in order to allow coolant circulation and –to some extent- natural convection

It is important to note that although the BWR attained a "stable" architecture it did not become the dominant design in the sense that it did not become the preferred product in the marketplace.

The dominant design was the PWR. One can argue that GE decided to pursue standardization or architectural stability in order to achieve economies of scale and learning effects. Namely the same reasons that Westinghouse had when it decided to freeze the PWR concept.

General Electric expected its strategy would eventually match the competencies developed by Westinghouse with its PWR. But Westinghouse had an early lead in nuclear power with the design of the nuclear submarine "Nautilus" and the Shippingport PWR plant. General electric was a market follower.

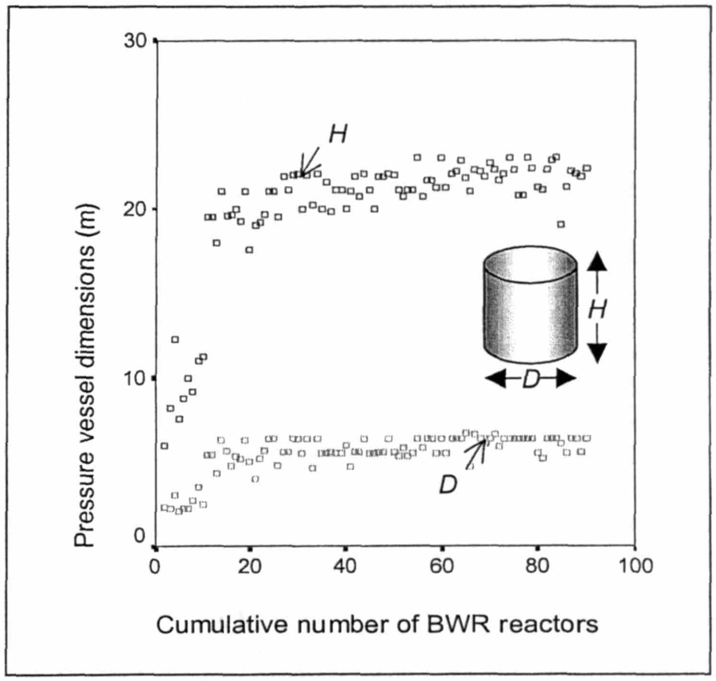


Figure 4.7 Evolution of BWR pressure vessels in reactors that started operation before 1989

THE LINK BETWEEN PWR & BWR DESIGNS

An unexpected feature that arises from the survey conducted over the BWR reactors and the PWR reactors is that although these designs are different in architecture, they surprisingly share some common features.

First, in both types of reactors, the total power rating attained a similar value. This agreement is quite interesting because there were two different reactor architectures, involving two sets of competitors supposedly not interrelated. In theory both designs should have followed different paths. But as Figure 4.8 shows, this was not the case. Both design concepts agreed on similar values for reactor power ratings. It is important to note that the reactor power ratings increased as a function of time, as nuclear power plants increased size in order to achieve economies of scale. But at any given time, the BWR units and the PWR units that started commercial operation had similar ratings. Particularly in the 1970s, the consensus

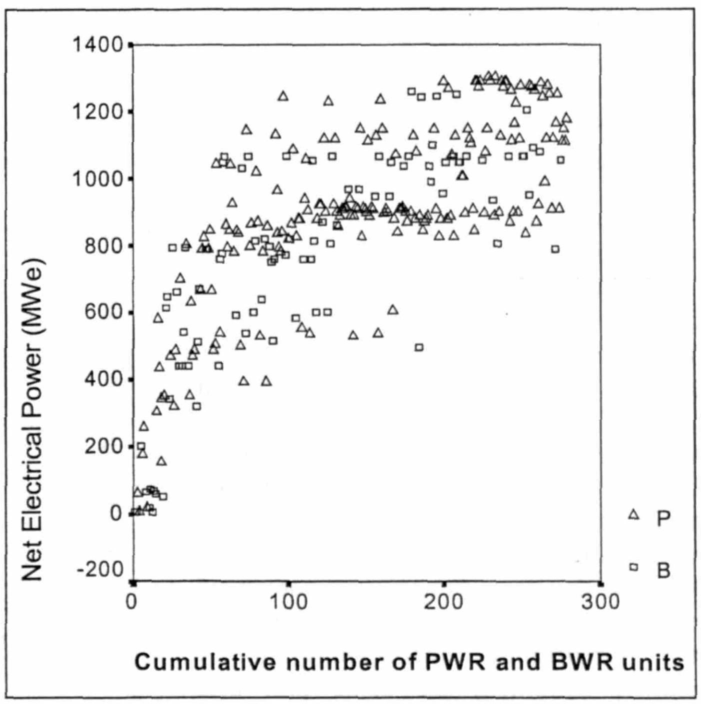


Figure 4.8 Power ratings of PWR (P) and BWR (B) reactor units that started commercial operation before 1989 in the western world.

was 900 MWe, but this consensus shifted to 1300 MWe in the 1980s as shown in Figure 4.8. This change was pursued basically by Japanese and French vendors: Mitsubishi and Framatome.

The second unexpected agreement appears when plotting the gross power of turbine generators as a function of the cumulating number of reactors in operation at a given time. As it is shown in Figure 4.9, the turbine gross power rapidly attained a consensus value. It is important to note that the turbine gross power is defined as the maximum power that the turbine/generator can provide to the electrical grid. This is different from the net electrical power actually produced by the plant because turbine/generators most of the time work below full power capability. It is common, for example, that a 1200 MWe turbine will be operating at 1150 MWe. The data show that most of the BWR and PWR reactors used essentially the same type of turbine/generator, with the turbine manufactured by GE in the lead.

Taking this agreement into account, it is not unreasonable to conclude that the key factor in limiting the power of the nuclear power plants was the fact that, at that time, the standard large-scale turbine/generator in the United States market was 1200 MWe. All the players in nuclear system design agreed to use this particular type of unit. Either (a) larger units were not available at the time or (b) the cost of developing and optimizing a larger unit was far beyond the expectations to obtain profit from economies of scale. This conclusion is also supported by the fact that not only the turbine gross power achieved a convergence value. Results presented in Exhibit 4.10 show that, in addition, the main variables involved in the process followed a similar pattern. For instance, the figure shows that the steam temperature converged to a nominal value of about 280°C. Since the steam temperature corresponds to a saturation condition, the same plot also illustrates the fact that the operating pressure inside the turbine was kept constant: around 60 Kg/cm².

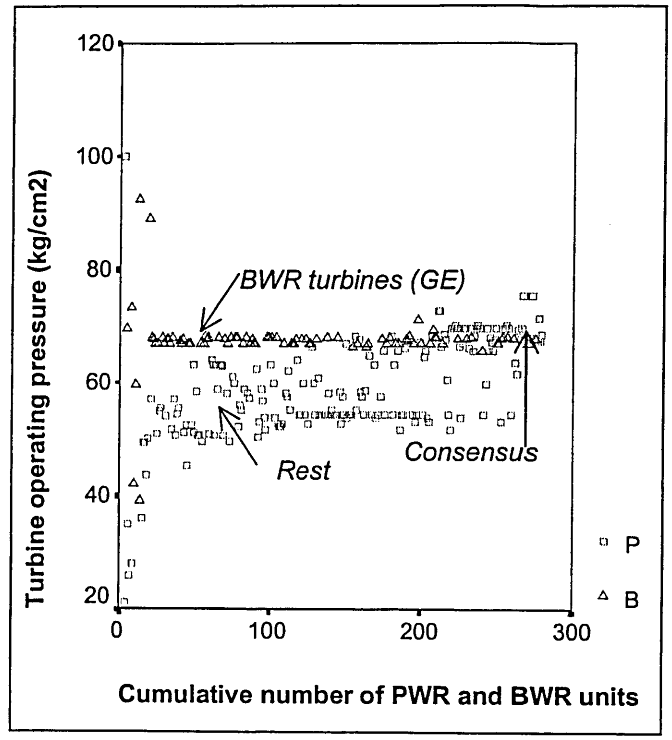


Figure 4.9 Gross power generated by turbine of all PWR (P) and BWR (B) units that started commercial operation before 1989

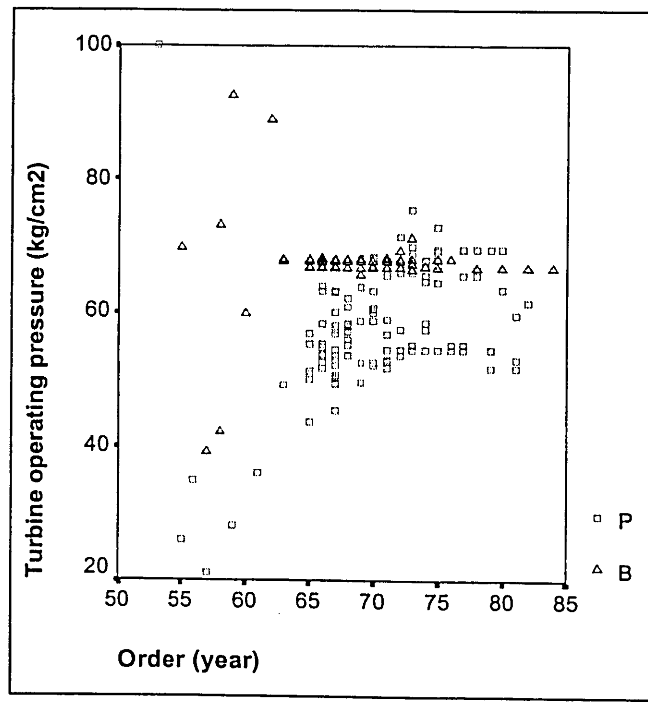


Figure 4.10. Pressure of turbines of reactors PWR(P) and BWR(B) in the world as a function of the year of initial commercial operation

CONSEQUENCES FOR THE PWR DESIGN

Turbine/generators utilized in the nuclear industry were not specifically developed for this purpose. In fact, these products were a standard component of other power plants. By 1950, both General Electric and Westinghouse were the leaders in the manufacturing and design of turbine/generators used in coal and gas electric-generating stations. This helps us understand why both companies offered the same standard product with a gross power of nearly 1200 MWe. A feasible explanation is that since they were both involved in the larger market of conventional electric-generation plants, their strategy was to provide a standard product. In this way, they increased the chances to compete against outsiders.

As mentioned previously, the driving force in the development of nuclear reactors was the desire of obtaining economies of scale by means of increasing power. The criterion of "high power output implies more efficiency" was consistently pursued by reactor vendors. However, in order to meet the strict goal of efficiency, designers were faced with the dilemma of increasing power but at the same time utilizing standard components. As was accurately pointed out by a nuclear researcher who worked in the industry during those days:

> *The pressure of the marketplace and the desire to make a profit in this business-after many years of losing money-was the main motivation to limit the size of nuclear reactors and standardize the designs. (Lahey, 2000)*

In the early sixties the designers were confronted with the fact that they were not able to increase the power of nuclear plants indefinitely. The "ceiling" in the size of plants was defined by the availability of large-scale-unit turbine/generators. And this ceiling became visible at 1200 MWe.

In simple words, it was like trying to design "the biggest four-wheel-drive car utilizing a 3 liter engine". Under such severe constraints there were not too many design alternatives and obviously a dominant design will appear rapidly.

It is notable that the same firms that monopolized the turbine market were also involved in the reactor design. However, it is important to note that these were different divisions of the same corporation and, to the extent of this investigation, they should be understood as different business units. For that reasons, there are no grounds to speculate that the nuclear designers had any influence in reshaping the design of the turbine generators. Designers were simply compelled to use the state-of-the-art standard product provided by their corporation.

Chapter 5

THE RELATIONSHIP BETWEEN WESTINGHOUSE AND GENERAL ELECTRIC

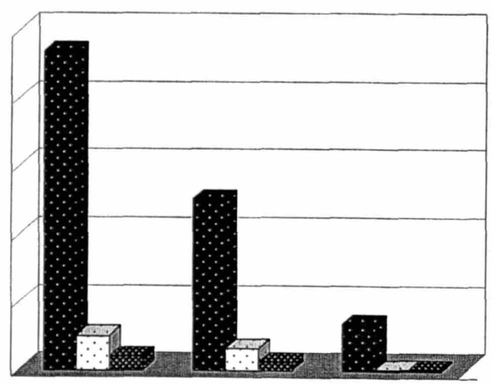
This chapter is basically about antitrust. It starts with a summary of several cases of price fixing where Westinghouse and GE were involved. The emphasis is on the notorious case in the early 1960s involving large turbines, which led to the imprisonment of several corporate executives. Since the subject of the thesis is not primarily antitrust, the stress is purely historical and within the context of nuclear power plants. The question that the chapter raises is whether price-fixing strategies employed by Westinghouse and GE in large electric components molded the rise of the PWR as a dominant design in the market.

THE MARKET FOR LARGE TURBINE GENERATORS

Historically, the market of large turbine generators has been dominated by only a handful of players. The reason for such concentration of market power within a small number of manufacturers is the existence of high barriers to entry. These barriers to entry are due -basically- to the following factors: (a) to manufacture the product a heavy capital investment is required up front, (b) R&D costs are huge, and (c) there are strong learning effects arising from cumulative output. All these issues constitute an effective deterrent against newcomers

When nuclear power emerged in the United States in the mid 1950s, only three firms - General Electric, Westinghouse and Allis-Chalmers - were in condition to build the large steam turbine generators required by nuclear power plants. Given the fact that turbine generators produced over 80% of the U.S. power supply, it is clear that firms competed over the dominance of a big market.

In the late 1950s, General Electric was probably as diversified as it is nowadays. The manufacturing of large turbine generators was part of its key division of heavy-capital goods, which accounted for nearly one-fourth of the corporation's total sales. As Figure 5.1 shows, General Electric was the clear leader in the market for large turbine generators, both in terms of accumulated experience and total sales.



	General Electric	Westinghouse	Allis-Chambers
■ Total Sales ($MM)	2340	1260	340
□ Total R&D ($MM)	254	163	8
▩ Shipments (GW)	102.7	53.1	11.3

Figure 5.1. U.S. manufacturers, aggregated financial results from turbine generators from 1948 to 1962

Nearly 60% of all the new capacity installed in the United States in the period between 1948 and 1962 was captured by General Electric. Its sales almost doubled the sales of its immediate competitor, Westinghouse. Thanks to its favorable position in the market, General Electric had also been the price leader, with its two main competitors usually matching GE's book prices.

General Electric was also the leading R&D investor in the segment, reinvesting nearly 15% of its revenues on developing product and process innovations. As a result, General Electric had not only been the market leader in terms of sales but also in terms of technology. It had historically been the pioneer in the introduction of innovations that led to the remarkable increase of energy conversion efficiencies of large turbine generators.

Westinghouse was also a diversified manufacturer of capital goods -among them large turbine generators- and was a corporation as big and as profitable as General Electric. By the late 1950s, Westinghouse held a solid second place in sales with an average market share of 30%. But in the particular market of large turbine generators Westinghouse was widely perceived as a market follower, with most of its marketing and technology strategies designed to match GE's leadership. The main focus of Westinghouse was in standardizing units, in order to benefit from economies of scale, reduce costs and -in the long run- being able to challenge the price leadership of General Electric.

Allis-Chalmers was the third competitor on large turbine generators in the United States, although its market share was quite small. It could not match the prices of the two incumbents and had not been able to sell enough units to benefit from economies of scale as its competitors did. In addition, Allis-Chalmers had not invested enough in R&D and therefore its products were becoming obsolete. Unable to differentiate itself in terms of quality or price, the firm finally decided to exit this market in 1962 after decades of marginal results.

Finally, two European firms, Brown Boveri and Parsons, had attempted to break into the U.S. market but were quickly neutralized by sharp price cuts from both GE and Westinghouse. In addition, they lobbied in Washington for tariffs, arguing that the entry of these firms in the domestic market was considered a threat to energy independence. The two incumbents effectively barred potential foreign competition by raising entry barriers, using pricing and lobbying strategies.

CHARACTERISTICS OF THE PRODUCT

As it is shown in Figure 5.2, a large turbine generator is rather complex and expensive equipment whose main function is to convert heat rate into work rate and ultimately into electricity.

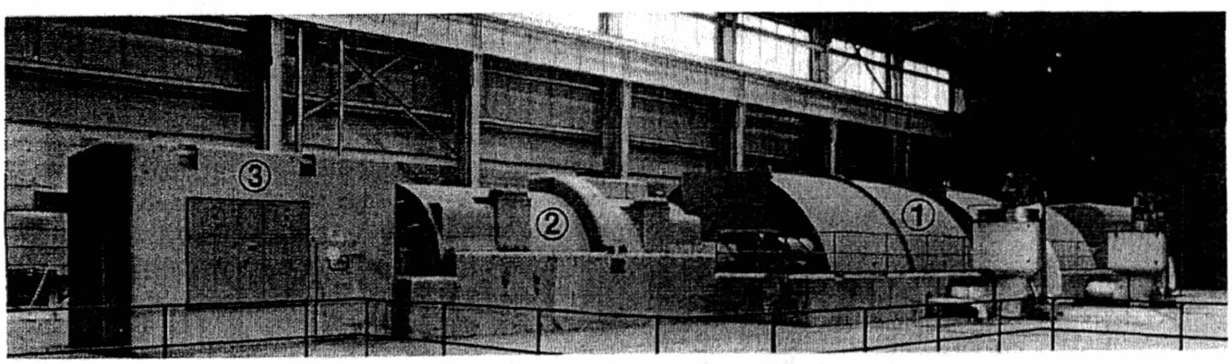


Figure 5.2. A large turbine generator (1,000 MWe unit). (1) the turbine converts heat into mechanical work, (2) the generator converts work into electricity, and (3) the generator alterix maintains the electric field.

Although manufacturers have made a strong effort to standardize the product, most of the times engineers need to customize each unit to a particular specification. As a result, the engineering and marketing costs to adapt a product to the buyer are relevant (on the order of 10% of the total cost of an order).

As a heavy capital-intensive good, most of the costs are direct costs due to parts and labor. The overhead costs are small compared to other manufactured capital goods, accounting for less than 25% of total cost (USGPO, 1981).

The main performance parameter of a large turbine generator is the thermal efficiency. The latter is defined as the ratio of electricity output to total energy input. In the 1930s the standard thermal efficiency of turbine generators was around 20%, but a number of innovations introduced in the 1940s boosted this parameter to 35%.

However, improving the efficiency had a technological limit –which turned out to be 35%- and by the turn of the decade manufacturers had to pursue another way to increase value to their customers and to differentiate themselves from competition. This was by offering larger and more complex units, which reduced operating costs and also decreased the investment cost (in dollars per installed electric kilowatt).

Utilities grasped the opportunity for increasing profits and began to buy larger and larger units. In the early 1950s the largest turbine generator available was 200 MWe while in the early 1960s units had been introduced with ratings well above 500 MWe. By the end of the 1960s, the standard large turbine generator offered to utilities was around 1000 MWe, a trend that was magnified by the massive introduction of nuclear power plants. The latter is a case of strong economies of scale. As Figure 5.3 shows, when economies of scale are manifested, larger, more complex designs exhibit a different price-size curve from smaller, simpler designs (Shy, 1998).

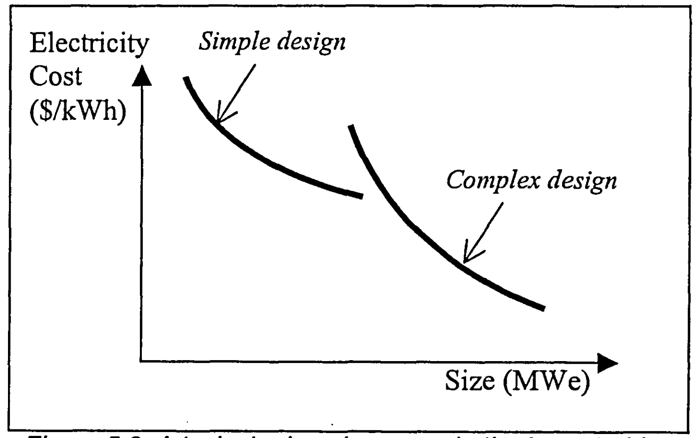


Figure 5.3. A typical price-size curve in the large turbine generator market

Turbine generators' buyers –generally large private-owned utilities- benefited from economies of scale because, by buying and operating a large turbine generator, the total cost per unit of output was reduced, even though the product became more complex. This makes sense for any large utility, as smaller and simpler units are competitive only in the niche market of small grids (e.g. remote isolated areas).

In addition to economies of scale –which allow the buyers to obtain more profits- a large turbine generator is a product with intrinsic learning effects. This means that as the manufacturer produces more of a product, the unit cost of production reduces at a decreasing rate. This phenomenon is frequently described with a learning curve –as shown in Figure 5.4- namely a plot of the cost of producing a unit versus the organizational experience. The price per unit drops by virtue of increasing the cumulative number of units produced.

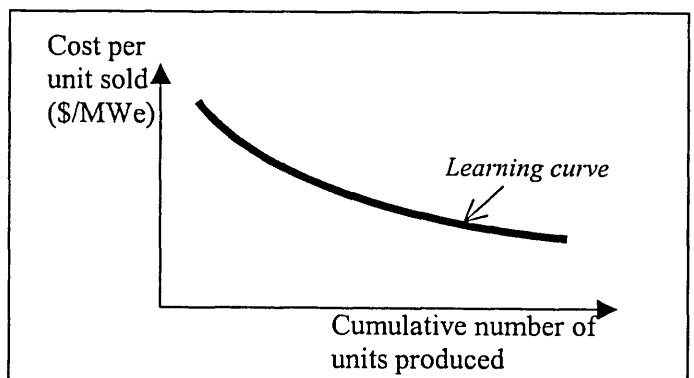


Figure 5.4. A typical learning curve in the large turbine generator market

Learning curves have been documented in a number of organizations in both the manufacturing and service sectors, and the yardstick for comparison has been the progress ratio. According to its definition, each doubling of cumulative output leads to a reduction in unit cost to a percentage of its former value. This percentage is the progress ratio. Thus, an 80% progress ratio means that each doubling of cumulative output leads to a 20% reduction in unit cost (Argote, 1990).

According to the literature, the learning curve of large turbine generators exhibited a progress ratio of 90% (Porter, 1986). The latter means that each doubling of cumulative output led to a 10% reduction in unit cost. The result is comparable to learning curves in other manufacturing sectors of large capital goods, for instance, commercial aircraft and merchant ships (Ghemawat, 1985).

In summary, the buyers- utilities- had an incentive to buy large complex turbine generators instead of small units, and the manufacturers had a strong incentive to increase sales volume in order to benefit from learning effects.

THE BUYING PROCESS

In 1962, the U.S. market for large turbine generators was segmented in three categories: (a) 143 private-owned utilities such as Duke Power or Edison Electric, (b) 62 Federal Government utilities such as the Tennessee Valley Authority, and (c) over 1,500 Municipal utilities. Figure 5.6 summarizes the market share of the three segments.

In the 1960s, the sale of a large turbine generator was a process that took around two and a half years. The long delivery times were due first to a six-month negotiation time. Then it was the engineering and construction time of a year to eighteen months. The rest of the delivery time reflected the manufacturer's order backlog. With these long delays, the turbine generator was the bottleneck in constructing a new power plant and accordingly utilities' managers spent a lot of effort in trying to speed up the entire buying process. The buying process itself differed according to the market segment.

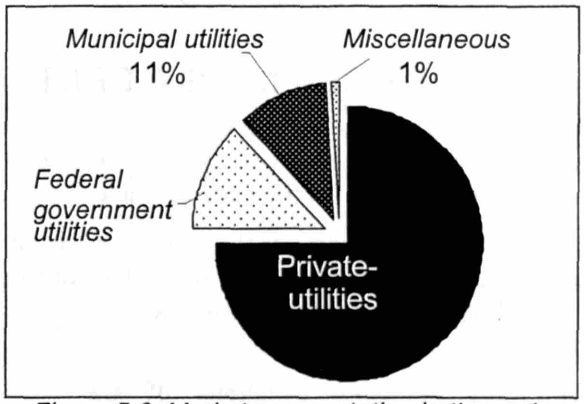


Figure 5.6. Market segmentation in the early 1960s

For Government-owned utilities as well as Municipal authorities, the process generally took the form of a standard public procurement process, namely: specifications, sealed bids, and purchase decisions based on a competitive basis. Private-owned utilities had a rather more complicated and dubious process. Whenever a utility had an interest in buying a new asset, it would ask the manufacturers to submit price quotes. Then a long negotiation process followed which generally took place under incomplete information on both sides. Manufacturers did not know each other bids, and utilities did not know the real manufacturer's costs. Even after an order was placed, the mystery about the final price was not revealed. Given the high price tags of large turbine generators, final negotiations were generally conducted by top-executives and involved a long process of proposals and counterproposals where the main negotiation point was price. Degrees of quality, post-sale service, and delivery times were similar among competitors and played a minor role in the negotiations. The clear differentiating factor was price (Gilbert, 1996).

THE PRICE-FIXING SCANDAL

Between 1961 and 1965 there were a number of judiciary prosecutions involving executives of both General Electric and Westinghouse. Prosecutors had initiated investigations after a complaint from the government-owned Tennessee Valley Authority concerning identical bids they were getting from manufacturers of large turbine generators even though the bids were submitted in sealed envelopes (Geis, 1996).

The investigation lead to one of the most notable antitrust cases in the United States. Prosecutors argued that Westinghouse, General Electric and other minor electrical equipment manufacturers were engaged in price-fixing practices. They claimed that top executives were engaged in a willful price-fixing conspiracy, which is a crime contrary to the spirit of the Sherman Antitrust Act of 1890, which forbade price-fixing arrangements as a horizontal restraint upon free trade.

As a result of the investigation, four grand juries were ultimately convened and subpoenaed a large number of persons, some of whom cooperated with the prosecutors revealing the modus operandi of the association. As a result, 20 indictments were issued involving at least 45 executives. Given the weight of the evidence against these individuals, most of them pled guilty, avoiding in this way the social cost of a public trial.

Millions of dollars in fines and treble damages were charged against the individuals and corporations involved in the scandal but, most importantly, several executives were sentenced to brief jail terms. Seven executives from General Electric and Westinghouse, four of them vice-presidents of these two companies, ended the day "handcuffed in pairs" and conducted to the Montgomery County Jail in Norristown, Pennsylvania. As an illustration of the magnitude of the scandal surrounding the case, during their term in prison, none of the seven men "had visitors during the Wednesday and Saturday periods reserved for visiting; all indicated a desire not to be seen by their families or friends" (Geis, 1996)

WHEN IS PRICE-FIXING A CRIME?

The antitrust statutory body is given by the following acts: (a) the Sherman Act of 1890, (b) the Clayton Act of 1914 later amended in 1936 by the Robinson-Patman Act and in 1950 by the Celler-Kefauver Anti-merger Act, and (c) the Federal Trade Commission Act of 1914.

The Sherman Act remains as the cornerstone in antitrust statutes, prohibiting contracts, combinations, and conspiracies that restrain free trade. The infringement of this law triggers criminal penalties when enforced by the government. Violation can also result in fines and, for individual transgressors, prison terms (Kaye, 1990).

The most common violations of the Sherman Act, and the most harshly treated, are the so-called horizontal restraints of trade. These are concerted actions among firms in actual or potential competition with one another. The reason for the zero tolerance to these kinds of practices is that antitrust laws postulate a competitive marketplace where rival firms compete in terms of price, product and services. Any arrangement reducing the competitive environment is against the essence of antitrust laws (Kaye, 1990)

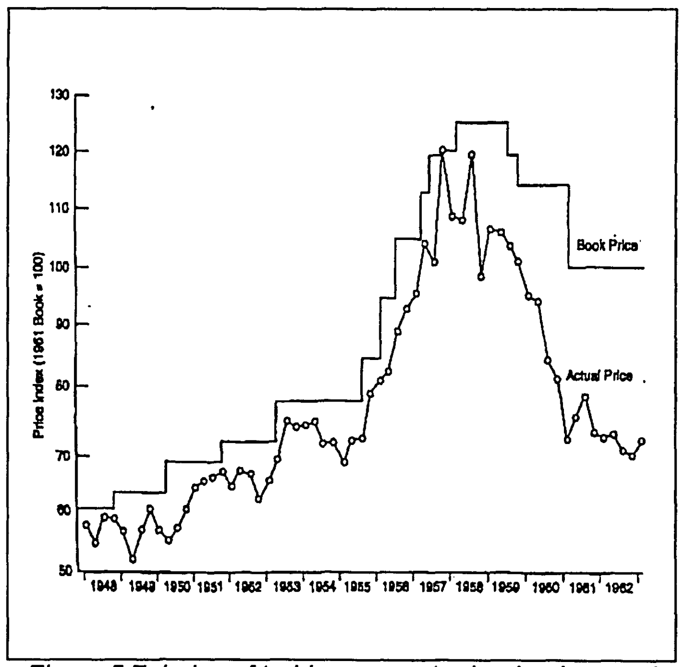


Figure 5.7. Index of turbine generator book prices and actual order prices (Civil Action, Ohio Elec. vs. GE 1965)

Price-fixing is the capital crime in horizontal restraint of trade. Any agreement among competitors with respect to prices is illegal regardless of who is involved and what the surrounding circumstances are. First, competitors can not agree on the actual prices they will charge or pay for a product or service. Secondly, competitors can not agree on a price-range within which they will compete, or on a common list or book price. Thirdly, competitors can not divide markets by territory or by customers.

Prosecutors found that Westinghouse and General Electric had effectively set a book price for large turbine generators. Figure 5.7 shows the time behavior of book prices and actual order prices for large turbine generators (Civil Action, Ohio Elec. vs. GE 1965). Salesmen from both firms would visit utility executives and offer prices according to a jointly accorded price. Whenever it was necessary, both firms would modify the book price to cooperatively drive prices up or down.

Having a book-price however is not the only condition to trigger antitrust penalties. There are three necessary conditions that need to be put in place: agreement, monitoring and enforcement. The agreement was largely demonstrated in court by the existence of a price-book, and was not the main issue.

The main issue in court was whether there were monitoring and enforcement provisions in order to make the price-fixing scheme work. The latter was the core of the conspiracy charges. In other words, the question was if there was an established organization, which made price-fixing arrangements, monitored these arrangements and enforced penalties to cheaters.

The outcome of the process, with executives pleading guilty and serving terms in jail and corporations paying million-dollar settlements, overwhelmingly demonstrates that indeed there was a conspiracy.

WHITE-COLLAR CRIME

When most of General Electric and Westinghouse executives were sentenced to jail, a newspaper reporter described them with a certain degree of sarcasm as "middle-class men in Ivy League suits- typical business men in appearance, men who would never be taken for lawbreakers" (Geis, 1996).

On the same line of thought, Edwin H. Sutherland coined the phrase "white collar crime" for defining a crime committed by a person of respectability and high social status in the course of his occupation. Consequently the definition excludes many crimes of the upper class –murders, abuse cases- that are not committed in the workplace, and also excludes wealthy members of the underworld, since they are not persons of respectability and high social status. Hence, the sophisticated offenses that white collar crime encompasses are things like restraint of trade, deceptive advertising, and patent infringement. (Sutherland, 1996).

Sutherland points out two important characteristics of white-collar crime. First, most of the offenders are not really aware of the seriousness of their acts. For most of them, the borderline between duty and crime is blurred by a corporate culture where incentives are tilted towards productivity, sales performance, and profit margins. In the case of large turbine generators, a high-ranking executive categorically denied the illegality of his behavior. "We did not fix prices" he said, "all we did was recover costs" (Geis, 1996).

The second characteristic of white-collar crime is the recurrence of crimes. In the period between 1930 and 1955, General Electric and Westinghouse had prompted a number of decisions in courts regarding restraint of trade -13 decisions for GE and 10 for Westinghouse. Despite this record of indictments both firms continued to practice price-fixing, and have probably continued to do so after 1965 (Sutherland, 1996 and Fuller, 1962). Westinghouse in particular had a similar experience regarding the uranium business (Joskow, 1976).

REASONS FOR COOPERATIVE ARRANGEMENTS

The price conspiracy that unfolded in the late 1950s and early 1960s involved large turbine generators and other heavy electrical equipment. The reasons why a cooperative –though illegal- arrangement between GE and Westinghouse emerged are numerous and difficult to confirm. The following are some of the most likely reasons:

1. **Response to destructive competition.** Very often cooperative arrangements arise after a prolonged destructive competition between firms on the grounds of price. This generally occur with homogeneous products such as oil (OPEC), copper (CIPEC) or diamonds (DeBeers). In the case of turbine generators the product is not homogeneous but the buyers –utilities- were remarkably engaged in price bargaining. Product performance, post-sale service and delivery times were similar across all competitors.
2. **Inelastic demand.** Price-fixing schemes can only be applied in markets with inelastic demand, namely, where the product demand is not significantly reduced by price increases. Since large turbine generators were key components of power plants and utilities had to necessarily buy these assets, they ended up paying the asked price.
3. **High entry barriers.** Price-fixing arrangements work perfectly when there are barriers to entry. As it has been shown in previous sections, the large turbine generator market had huge barriers to entry. These were due to the heavy capital investment that is required up front in order to being able to manufacture any unit, along with the R&D costs necessary to be technologically competitive. In addition, there are strong learning effects arising from cumulative output that favor the incumbents versus the newcomers.
4. **Weak legal impediments.** Historically antitrust laws have been difficult to enforce because (a) conspiracies are difficult to prove and (b) the all-embracing statutory language of the laws is not applied. For instance, in 1911 by the Supreme Court introduced the "rule of reason" ruling that despite the all-embracing statutory language, the Sherman Act reached only those trade restraints which are unreasonable. In other words, courts weigh the anti-competitive consequences of a challenged practice against the business justification, leaving most offenders unaccountable.

CONSEQUENCES FOR THE INDUSTRY

In the particular area of large turbine generators, the consequences of the price-fixing arrangement between General Electric and Westinghouse were enormous. First this might have been the main reason for the exit of Allis-Chalmers from the business, and also the main entry deterrent to other competitors – like Parsons from the UK and Brown Boveri from Switzerland. Using these practices, the two incumbents, General Electric and Westinghouse, were able to seize a larger portion of the turbine generator market and reap more profits per unit sold. In addition they benefited from the externalities arising from larger cumulative manufacturing experience in such a critical area.

In the utility sector, the increasing costs –depicted in Figure 5.7- were directly charged to end users, because this was the common practice during those years. Large overnight capital costs meant higher electricity prices to end-users. Since the electricity demand is inelastic –at least in the short run- the electricity demand was not noticeably affected by this practice (Lean, 1982).

CONSEQUENCES FOR THE PWR DESIGN

The story of price-fixing in large turbine generators became public when the first nuclear power plants were beginning to operate. In 1957 the first nuclear power plant in Shippingport went on line. In October 1959, Dresden-1, the first U.S. nuclear plant built entirely without government funding, achieved a self-sustaining nuclear reaction. In August 1960, the third U.S. Nuclear Power Plant, Yankee Rowe Nuclear Power Station, achieved a self-sustaining nuclear reaction. All these plants utilized large turbine generators. All in all, although their operation started a few years later, sixteen nuclear powered units were ordered in the period between 1952 and 1963.

BWR units:

1955	*Dresden 1, IL*	*200 MWe*	*Commonwealth Edison*	*Oper.*	*Jul-60*
1957	*Pathfinder, SD*	*59 MWe*	*Northern States Power*	*Oper.*	*Jul-66*
1958	*Humboldt Bay 3, CA*	*63 MWe*	*Pacific Gas and Electric*	*Oper.*	*Aug-63*
1958	*Elk River, MN*	*18 MWe*	*River Coop. Power*	*Oper.*	*Jul-64*
1959	*Big Rock Point, MI*	*69 MWe*	*Consumers Power Co.*	*Oper.*	*Nov-65*
1960	*Puerto Rico Bonus*	*72 MWe*	*P.Rico Water Authority*	*Oper.*	*Aug-64*
1962	*La Crosse, WI*	*51 MWe*	*Dairyland Power*	*Oper.*	*Nov-69*
1963	*Nine Mile Point 1,NY*	*615 MWe*	*Niagara Mohawk Power*	*Oper.*	*Dec-69*
1963	*Oyster Creek,NJ*	*650 MWe*	*General Public Utilities*	*Oper.*	*Dec-69*

PWR units:

1953	*Shippingport, PA*	*60 MWe*	*Duquesne*	*Oper.*	*Dec-57*
1955	*Indian Point 1, NY*	*257 MWe*	*Consolidated Edison*	*Oper.*	*Jan-63*
1956	*Yankee-Rowe, MA*	*175 MWe*	*Yanquee Atomic Co.*	*Oper.*	*Jul-61*
1957	*Saxton, PA*	*4 MWe*	*Saxton Nuclear Exp.*	*Oper.*	*Jul-59*
1959	*Carolinas, SC*	*17 MWe*	*Carolinas Nucl. Power*	*Oper.*	*Dec-63*
1963	*Haddam Neck, CT*	*582 MWe*	*Connect. Yankee Power*	*Oper.*	*Jan-68*
1963	*San Onofre1,CA*	*436 MWe*	*Southern Cal. Edison*	*Oper.*	*Jan-68*

All these plants were acquired by privately-owned utilities with some support from the AEC. Most were turnkey projects where the reactor system and the turbine generator were offered together as a bundle. To show the manufacturers that were involved, Table 5.1 provides data on vendors of turbine generators versus vendors of the reactor systems, in these 16 power plants.

Table 5.1. PWR (∍) and BWR (#) units ordered from 1952 to 1963
Turbine generator manufacturers versus reactor manufacturers

		Turbine/generator manufacturer			
		A-C	**GE**	**WEST**	**Total**
Reactor	**A-C**	# # #			*3*
System	**B&W**			∍ ∍	*2*
Design and	**GE**		# # # # # #		*6*
Manufact.	**WEST**			∍ ∍ ∍ ∍ ∍	*5*
Total		*3*	*6*	*7*	*16*

As Table 5.1 shows, GE and Westinghouse benefited evenly in terms of sales during this period, with Allis-Chalmers falling behind. Allis-Chalmers not only built turbine generators; it also built three of the first nuclear reactor systems in the United States. The self-evident question is therefore whether the duopoly exerted by GE and Westinghouse indirectly prompted the exit of a potentially harmful competitor like Allis-Chalmers.

The evidence is just circumstantial. There is evidence that GE and Westinghouse were involved in price-fixing in the large turbine generator sector in general, but there is no direct evidence that these practices were used in the particular case of nuclear power plants –regarding reactor systems, turbines or a bundle of both products. Chances are however that many of these deals were indeed non-competitive.

The modality of turnkey projects that prevailed during these early contracts offered an excellent opportunity for tying together the reactor system and the turbine. The same manufacturer would build both the reactor system and the turbine generator. As Table 5.1 shows, this was the favored option for Westinghouse (5 cases) and General Electric (6 cases). The danger of this practice is when incumbents use horizontal and vertical restraints of trade to keep a competitor out of the game. Although the evidence is not conclusive, this looks to be the case with regards to Allis-Chalmers.

The cooperative arrangement between GE and Westinghouse seemed to be a win-win deal. Both were able to exploit their technical competencies in manufacturing large turbine reactors and at the same time gaining cumulative experience in building reactor systems. Economies of scale, economies of scope and learning effects all seemed to be in favor of the two incumbents.

It is true that both firms had different designs, General Electric developed BWR reactors while Westinghouse developed PWR reactors. But as it was shown in previous chapters, both designs are light water reactors and their designs are very similar and complementary. It is clear then that any non-competitive practice that existed in the sector helped both the BWR and the PWR designs, at least in the short run –obviously to the detriment of other designs such as gas cooled reactors. In the long run one of the two "rewarded" designs would eventually prevail as the favorite of the buyers. It turned out to be the PWR but it could have been the BWR. The market made its choice in this matter, although with only two options on the table.

The question is why the buyers preferred the PWR over the BWR if both products had similar performance and similar economic benefits? The most probable answers come from two areas. First, operators were not comfortable by the fact that in the BWR design water contamination spreads all over the plant, including the turbine generator. For them the PWR had the advantage of clearly separating the plant in two different systems –conventional and nuclear. The second reason is related with the supplier base. The PWR design had a broader suppliers base in the U.S. market –Westinghouse, Babcock & Wilcox, Combustion Engineering- while the BWR was manufactured -with high vertical integration- by General Electric only. In the minds of the operator managers, a broader supplier base meant less investment risk (Kadak, 2002).

Chapter 6

THE MANUFACTURERS GAME

Given the relevance of collusion and price fixing in the power industry, this chapter has an analysis of manufacturers and their involvement in the design and construction of nuclear power plants. The analysis starts with a model of the order/construction process, which describes the role of utilities, architect-engineers, civil constructors, reactor vendors and secondary suppliers. The way these firms interacted had a profound significance on the consolidation of the Westinghouse PWR design. In addition, the chapter focuses on the performance of the PWR design internationally. The data on France, Japan, Belgium, Germany, Sweden, Spain, Taiwan and Korea seem to show that these countries overwhelmingly accepted the Westinghouse and GE designs as the industry standards.

THE PRODUCT

Nuclear Power Plants are complex electricity-generating assets that bring together a nuclear heat source - the reactor- with a conventional system -turbine generator- that converts heat into work and into electricity.

The main component of a nuclear power plant is the reactor itself. This is a very complex machine and its design requires the competence of a number of sophisticated technologies such as neutron physics, thermal-hydraulics, radiation shielding, reactor dynamics, radioprotection, etc. Most of these technologies were still under development in the late 1950s and therefore only a handful of firms with extensive R&D capabilities could handle the development of nuclear reactors.

The conventional system, on the other hand, is just an extension of an existing product line, the large steam-driven turbine generators. This electricity equipment was part of most of the fossil-fueled power plants in the United States (about 80% of the U.S. power supply in the early 1960s). Thus, there were \huge economies of scope and scale, which the incumbent vendors of large turbine generators could benefit from. For a manufacturer of large turbine generators, nuclear power plants were only a new market segment with similar needs. There was little need for additional R&D effort as adapting the turbine generator utilized in a coal-fired plant to a nuclear power plant was relatively straightforward.

In summary, in the early 1960s nuclear power plants were simple product substitutes addressing an existing market for electricity-generating assets. The new product was half based on a revolutionary innovation -the nuclear reactor- and half was a conventional machine that enabled the conversion of thermal energy to electricity.

Nuclear power plants broke into the electricity-generating market when electricity operators were looking for units of larger power ratings. Unable to boost profit margins by means of increasing efficiencies of the steam thermal cycle, as they had done in the 1940s and 1950s, electricity operators envisioned a future where power plant ratings would be in the thousands of megawatts rather than in the hundreds. The vision of higher profits by means of economies of scale was shared by U.S. utilities and by other electricity operators in the rest of the world, like Electricite de France or Tokyo Electric Power. Rapidly, reactor vendors focused on enhancing the power output of nuclear power plants.

As it is shown in Figure 6.1 the average size of a nuclear power plant shifted from 200 MWe in the early 1970s to 900 MWe in 1980s. Nuclear power plants surfaced as a commercial product just at the perfect time. The new technology could provide the means of building large power plants with very low fuel cost.

Starting in the late 1960s a number of environmentalist groups pushed for increasing levels of safety in nuclear power plants and advocated for the application of tougher environmental standards. For instance, there was concern over the thermal pollution of nuclear power plants, i.e. the fact that water from the condenser would be discharged directly into the sea, lakes, and rivers; increasing ambient temperatures.

In 1966 the dispute had emerged publicly during a disagreement over an application for a construction permit for the Millstone Nuclear Power Station in Connecticut. Shortly later, Vermont Yankee Power had a similar problem during the licensing of a nuclear power plant, and rapidly the furor over thermal pollution extended to the licensing of any new power unit in the United States.

The thermal pollution controversy finally died down in 1970 after the introduction of the Water Quality Improvement Act, which requested that federal agencies, including the AEC, would consider thermal pollution issues in the course of their licensing reviews. This legislation prompted the mandatory installation of cooling towers, which cool the water from the condenser -via natural convection - through the atmosphere (Duffy, 1997).

The change of safety culture is

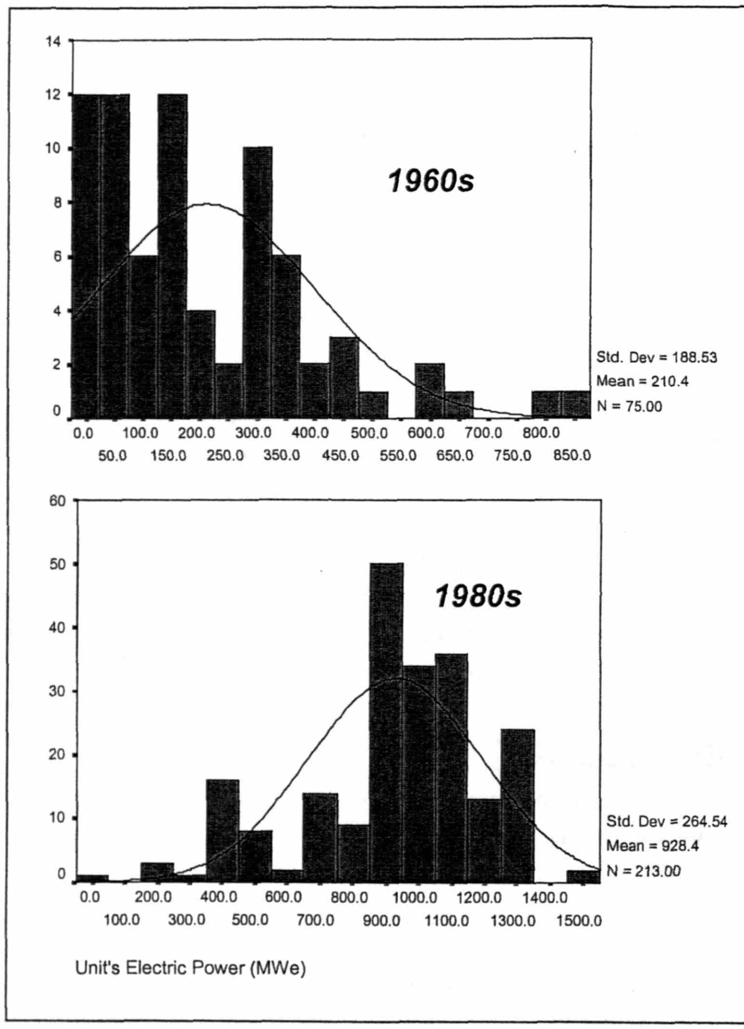


Figure 6.1. Histogram of power ratings (in MWe) of PWR and BWR reactors in the decades 1960-69 and 1980-89

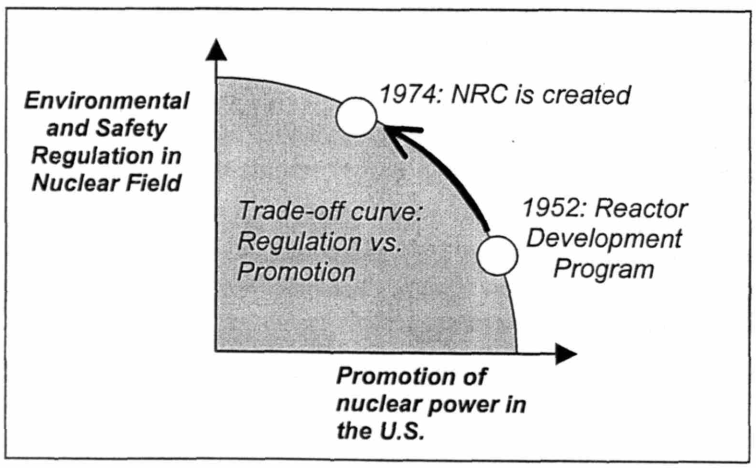


Figure 6.2. Sketch of the AEC evolution from tight control of the technology and little free-enterprise to openness

schematically shown in Figure 6.2 as a trade-off between almost exclusive promotion in 1952, to almost exclusive nuclear regulation in 1974. There is a trade-off because it is obviously impossible to have high regulation and high promotion at the same time and under the same government agency. In part due to public concerns, the AEC, which had the double role of promoting and regulating the nuclear industry, tilted towards the side of safety. This change of policy was accentuated in 1974 when Congress dissolved the AEC and created the Nuclear Regulatory Commission (NRC) with the sole responsibility of enforcing safety standards.

Similar safety and environmental controversies prompted the introduction of changes to existing safety systems. For instance, in the early 1970s, there was a huge controversy over the emergency core cooling system (ECCS) that ended up in tougher regulatory standards.

One of the peculiarities of power plants is that reactors were built with an unusual degree of variability and diversity regarding civil works and piping. From a "macro" point of view units of the same design concept were equal. But at a more detailed level they were very different. Essentially every reactor was custom-designed and custom-built. The degree of standardization was minimal (USGPO, 1981).

The required safety level of a nuclear plant is orders of magnitude higher than the safety required in conventional power plant designs. This fact caused a significant increase in the complexity of the licensing process. For instance, after Three Mile Island, nuclear power plants were the only electricity-generating assets that required a probabilistic safety analysis (PSA) in order to be granted a construction permit. The PSA is a sophisticated methodology that allows the identification of all possible initiating events and the calculation of the consequences of these events in terms of collective dose.

Although it is a nice standard, a PSA demands an extremely time-consuming process that involves thousands of engineering hours in order to be performed adequately. The fact that almost every reactor was one-of-a-kind caused difficulties in identifying initiating events and verifying the safety of individual plants.

The complexity of safety systems and the environmental concern experienced in the late 1960s and 1970s led to longer licensing process times. The AEC (and later the NRC) ended up allocating more human resources per reactor application. It is important to note that this is an abnormal feature because normally the licensing process becomes more efficient relative to the cumulative number of operating units.

To make it more difficult, the early 1970s were the years when the orders of new power

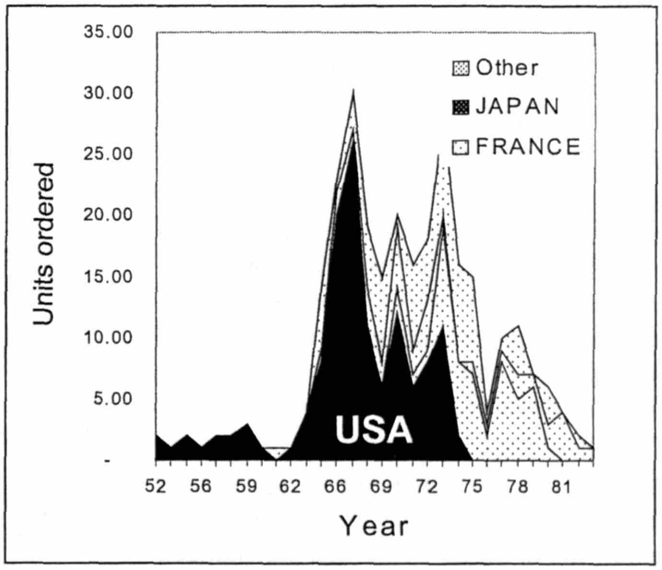


Figure 6.3. Reactors orders in the U.S. France, Japan and Rest of the World (except Soviet Union)

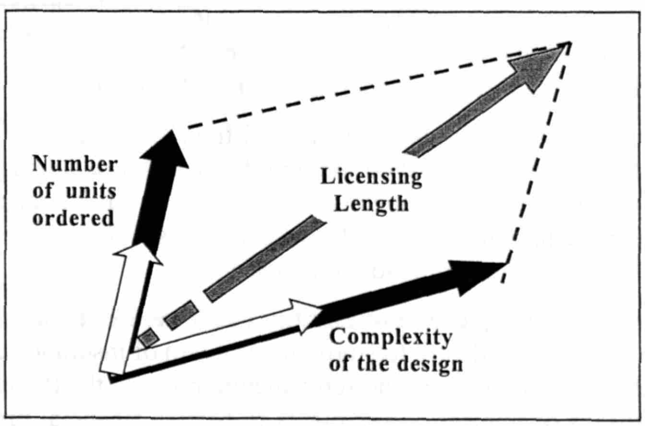


Figure 6.4.Effect of compounding on licensing delays

plants peaked. As shown in Figure 6.3, in 1973, thirty-five units were in operation in the United States and utilities ordered the exceptional number of 41 new nuclear power plants.

Figure 6.4 illustrates schematically the compounded processes of (a) increasing the complexity of safety features and licensing applications and (b) the number of applications per year. The result is obviously an increase in the average length of the licensing process.

BUYING PROCESS

The natural buyers for nuclear power plants were private and government owned electricity operators.

As Figure 5.6 shows, in the United States 75% of the electricity capacity was owned by private utilities, 13% by the federal government and 11% by municipal authorities. In addition to the above-mentioned natural buyers, there were new entrants willing to participate in the nuclear undertaking. An example was Yankee Atomic Power, which was an organization created explicitly for the construction and operation of a nuclear power plant built in 1960 in Rowe, MA. Yankee Power was owned by a consortium of New England utilities.

Figure 6.5 has a geographic distribution of nuclear power sites. As can be seen, there was little consolidation in the industry and several utilities -all across the country - embarked on nuclear power projects. Some of them were not aware of the difficulties and complexities inherent in building and operating a nuclear power plant.

As a former chief executive of Yankee Atomic Power recalls, "lured by the prospect of higher profits, operators underestimated the complexity of undertaking a project with a myriad of participants and managing a highly complex plant" (Kadak, 2002).

In the first years of the AEC, from 1946 to 1954, it was very difficult to get private utilities committed to participate in nuclear power. Some of the issues that discouraged these firms were (a) the compulsory government ownership of any nuclear reactor, (b) the risk of unlimited product liability in the event of a reactor accident, (c) the mandatory government ownership of the fuel elements utilized by any reactor, and (d) the uncertainty inherent to a new technology.

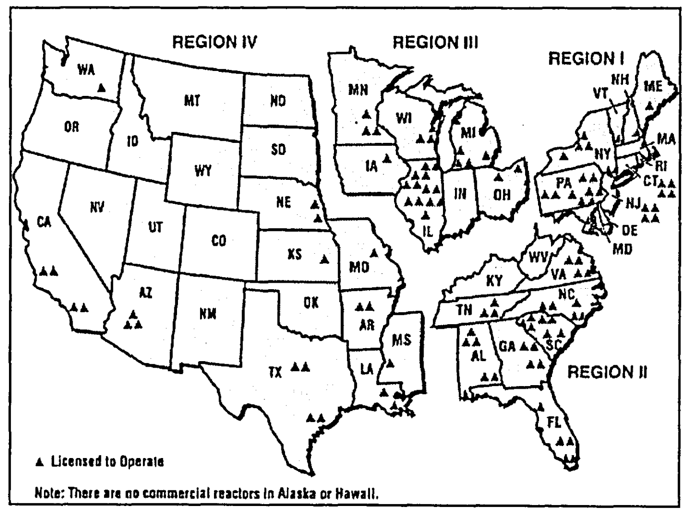


Figure 6.5. Nuclear power sites in the U.S. by 1989

Most of these barriers were lifted in the period between 1954 and 1963. The Amendment of the Atomic Act passed in 1954 paved the way for a new relationship between the AEC and the industry. It allowed private ownership of nuclear reactors under AEC licensing and provided for near-normal patent rights. The government maintained ownership of special nuclear materials -such as Plutonium- but was allowed to lease these materials to the industry.

Regarding the question of liability in the case of an accident, in 1955 the AEC established a group from the insurance industry to study the problem of insurance coverage for peaceful uses of atomic power. This and other studies were the fundamental roots of the Price-Anderson Act passed in 1957. The Act required licensees of nuclear power plants to furnish financial protection to cover public liability claims up to an amount specified by the AEC, and provided government indemnity in the amount of $500 million for each nuclear incident over and above the amount of financial protection required. The Act further specified that the maximum coverage available from private sources was $60 million (Dawson, 1976).

In addition to removing all barriers for commercial participation, the AEC developed a program of subsidies for nuclear power plants. The program designed to foster industry participation in nuclear power as named as Reactor Development Program (RDP). The pioneer deal in this respect was Shippingport, the first PWR developed in the United States and which started commercial operation in late 1957. The participant utility -Duquesne Light- offered to furnish the site in Pennsylvania, build and maintain the electrical generating section of the plant, contribute $5 million to the construction of the reactor and purchase the steam produced by the reactor for the equivalent of 8 mills per kilowatt hour. For its part, the AEC agreed to finance 90 percent of the reactor costs, build the reactor plant, and assume legal liability for the plant. The AEC would own the reactor and the nuclear fuel while Duquesne owned the conventional part of the plant.

A contract like the one signed by Duquesne, was really a sweet deal. The Shippingport plant ended up costing $55 million and produced electricity for 25 years until its programmed shutdown in 1982. Duquesne invested only $5 million in the nuclear heat source and about $10 million in the conventional electricity-generating unit. In the case of Yankee Atomic Power, the contract signed in 1956 included a commitment from the AEC to fund up to $5 million in R&D in support of the project. The AEC also agreed to waive its normal charge for use of special nuclear materials to fuel the reactor, a figure approximately $3 million. The total cost of the plant was $34 million (Dawson 1976).

Similar cases of AEC subsidies paved the way for private participation of the industry. With time these subsidies vanished and by early 1970s, the full capital cost of nuclear power plants was absorbed by private utilities. But by this time the industry had sufficient R&D investment and collective learning to fly by itself.

It is important to note that the subsidies provided by the AEC were the "carrot" to attract private utilities into the nuclear power business. There was a "stick" that would be present in the minds of utility managers which was the concern about government-owned-and-operated nuclear power plants. Much of the concern stemmed from the Atomic Act of 1946, which allowed only the government to own nuclear materials. Given the fact that the government-owned Tennessee Valley Authority had nearly 13% of the power supply in the United States in the late 1950s, it is clearly that the US government could become a formidable competitor if utilities did not rush to build nuclear plants themselves.

CONSTRUCTION PROCESS

The process of designing and constructing a nuclear power plant was not performed by only one firm. Generally the process involved the participation of a number of different companies. As it is shown conceptually in Figure 6.6, each of the major participants in the process of designing and constructing a nuclear power had a particular role within the project organization:

1. The nuclear heat supply system vendor designed and built the NHSS.
2. The architect-engineer firm was in charge of the balance of plant.
3. A main construction company was in charge of civil works.
4. A supplier of the turbine generator.
5. A supplier of large nuclear components (reactor pressure vessel and reactor internals)

The total number of companies involved may well have been in the hundreds, but the above-mentioned effectively controlled the major decisions during the project.

Whenever an electric utility decided to build a nuclear power plant, the first step was hiring an architect-engineer to help estimate costs, select the other industry participants and execute the actual management of the project.

As a prime contractor, the architect-engineer's main function was to design the balance of the plant.

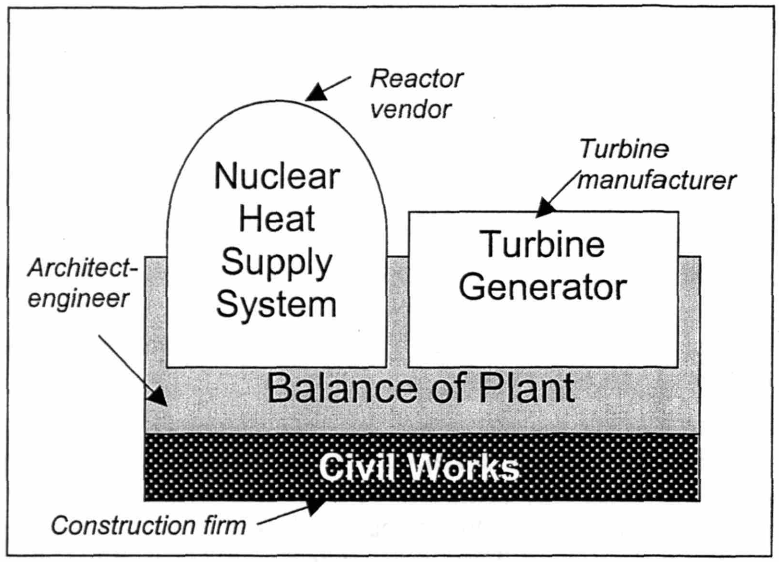


Figure 6.6. Components of the design & construction process

The balance of the plant consisted of all the equipment, in addition to the nuclear heat supply system and turbine generator, which is necessary to produce electricity from a nuclear power plant. In other words, the Architect-Engineer had the responsibility to match the requirements of the NHSS with the requirements of the turbine generator and assure that the nuclear power plant would work as an integrated system rather than a mere collection of disconnected pieces.

The architect-engineer had the most critical role in the design and construction of a nuclear power plant for two reasons. First it was economically relevant as almost 80 percent of the budget of the plant corresponded to the balance of plant. The second reason was a safety-related preeminence, as 90 percent of the necessary paperwork required by the NRC to license the plant was the responsibility of the architect-engineer. Given the complexity of the licensing process it is clear that a smooth passage through NRC scrutiny depended overwhelmingly on the technical competency of the architect-engineer.

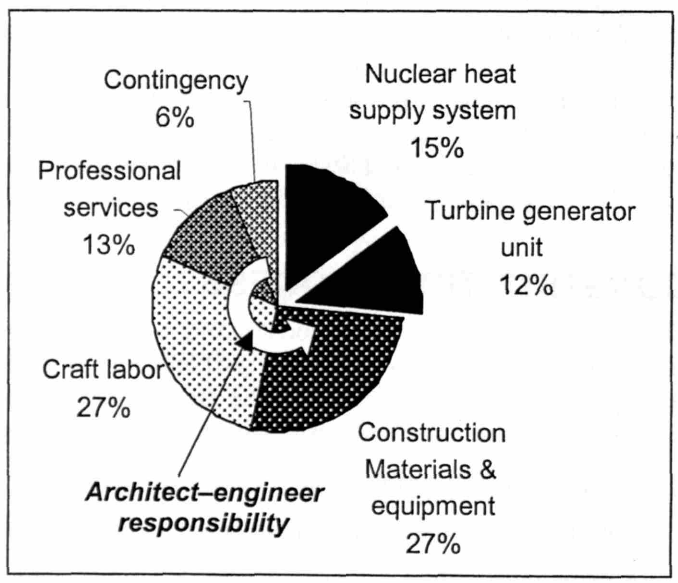


Figure 6.7. 1,000 MWe overnight construction cost breakup (not including financial costs, escalation charges, inflation and tax deductions)

One of the top functions of an architect-engineer was to recruit the suppliers of the two key components of the plant: the NHSS and the turbine/generator. In general there were only a handful of options in this respect, as it will be explained in subsequent sections. Very often it occurred that the electric utility had already an agreement with some of the suppliers. This weakened the position of the Architect-Engineer firm as chief project contractor.

In particular, in the United States the incumbent suppliers of the NHSS and the turbine/generator were the same companies -General Electric and Westinghouse- and became the controlling part of the project. The construction company was generally hired by the Architect-Engineer and its function was relatively minor regarding the control of the project. In summary, the firms with higher power within the project - additionally to the electric utilities- were the architect-engineer and the suppliers of the NHSS and the turbine generator. Their relative share in the total costs of a typical project is summarized in Figure 6.7.

As it is shown in figure 6.7, the relative economic weight of the nuclear system vendor was small compared with the magnitude of responsibility on the side of the architect-engineer.

ARCHITECT-ENGINEERS AND CONSTRUCTORS

In the United States, 22 firms participated as architect-engineers and 25 as civil construction companies. With only a few exceptions, the companies that build nuclear power plants were the same architect-engineer firms that designed them. The role of the construction firm is to build the plant according to the specifications given by the architect-engineer and the reactor system manufacturer.

It is important to note that nearly 80% of the design of the plant is in the hands of the architect-engineer. The most relevant architect-engineers in the U.S. power industry have been Bechtel (41 units built), Stone &Webster (17 units), and Sargent &Lundy (15 units)

	Civil Constructor								
Architect-engineer	BECH	CWE	DUKE	Dravo	EBSO	S&L	S&W	TVA	UE&C
BECH	34				2				
DBDB			3						
DUKE			4						
EBSO					6				
PUBS									2
S&L		8				1			4
S&W				2			13		
TVA								6	
Total	37	8	7	2	8	1	14	6	8

Figure 6.8 Cross tabulation of civil constructors and architect-engineers

REACTOR SYSTEM AND TURBINE VENDORS

Five firms participated in the business of supplying nuclear systems in the United States: General Electric, Westinghouse, Combustion Engineering, Combustion Engineering and Allis-Chalmers. Regarding turbine generators only three participated: General Electric, Westinghouse and Allis-Chalmers.

Firms participating in the design and construction of nuclear power plants selected different strategies for capturing value in the business. These strategies were based on several tradeoffs, which can be summarized in the following categories: (a) economies of scope, (b) diversification, (c) market power, (d) vertical integration, and (e) cumulative learning.

REACTOR SYSTEM VENDORS	PRESSURE VESSEL MANUFACTURERS						
	A-C	B&W	C-E	CB&I	GE	RDM	WEST
A-C	2						
B&W		11					
C-E			15				1
GE		7	11	16	8	2	
WEST		9	32	3		4	18
Total	2	27	58	19	8	6	19

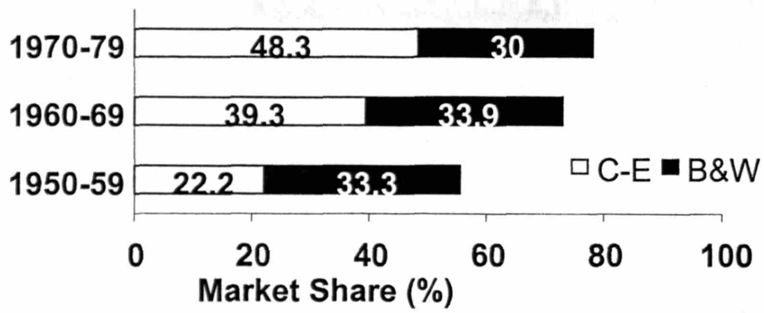


Figure 6.9 shows how C-E and B&W dominated the market of reactor pressure vessels in terms of (a) units sold and (b) market share increase

The first dimension, economies of scope, refers to benefits arising from cumulative output in parallel industries. For example, when Honda introduced its first car in the early 1970s, the company benefited from the economies of scope arising from the previous cumulative output of motorcycles. Although cars and motorcycles are different products, there have similar manufacturing and development processes.

The ability to expand horizontally to create new products leads to an increasing diversification of the firm. Sometimes the diversification of product portfolios goes too far and the organization becomes unmanageable, the brand unrecognizable and the profits shrink. Therefore there is an optimum balance between these two competing forces. Honda seems to be doing fine with motorcycles, cars, and SUVs and does not look very eager to jump into the market for large trucks.

Babcock & Wilcox and Combustion Engineering benefited from economies of scope because these two firms were the incumbent producers of large equipment for applications in fossil-fueled power plants, such as heat exchangers, pressure vessels and high temperature circuits. It is not a surprise, therefore, that these two firms became the incumbent manufacturers of reactor pressure vessels, steam generators, and reactor internals. They used the experience accumulated in conventional power plants to enhance its performance in the nuclear market.

Figure 6.9 shows that the market share of these two firms in producing these items increased over time. Although successful in using economies of scope to build key reactor components, B&W and C-E had limited experience in designing complete nuclear power plants. Consequently and after an early successful introduction, these companies were unable to erode Westinghouse's dominance as PWR vendors. Previously, in the market of turbine generators, these two firms had tried to compete with GE and Westinghouse. But it was clear -even before the 1950s- that it was an attempt doomed to failure.

REACTOR VENDORS	TURBINE GENERATORS MANUFACTURERS							
	A-C	BBC	GE	Hitachi	KWU	MHI	S-Laval	WEST
A-C	2							
B&W			5					6
C-E			9					7
GE			40	1	1			6
WEST	2	2	17			2	3	49
Total	4	2	71	1	1	2	3	68

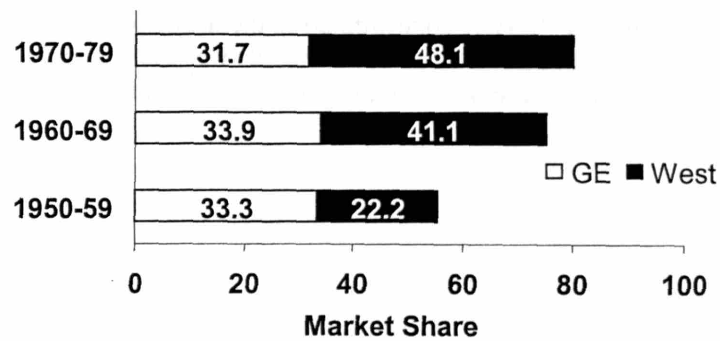


Figure 6.10 shows how GE and Westinghouse dominated the market of reactor systems and reactor turbines in terms

In summary, B&W and C-E entered into the nuclear business benefiting from economies of scale, but this effect was insufficient to make them solid NHSS vendors. As large diversified firms General Electric and Westinghouse also benefited from economies of scale when they became NHSS manufacturers. Both had already marketed a huge production of large turbine generators and had developed entire conventional power plants. Their experience in R&D of complex power assets was already significant. Hence, both firms were able to manage the process of building nuclear power plants. As a result, their market share in the segment of nuclear systems increased over time as it is shown in Figure 6.10, as the same time as they increased their predominance in turbine-generators.

The third dimension, market power, refers to the total market share that a firm can have in a given market or segment of the market. For instance Microsoft has enormous market power in operating systems, while Intel excels in computing processors.

Both of these firms have high market power due to their large market shares. They can obtain higher profits by commanding output and price in the segment. However, Microsoft and Intel have been able to obtain high market power, in part because they are focused firms and address a market of little vertical integration. Neither of them tried to approach the computer business with high vertical integration as Digital did in the 1980s.

When firms compete for market power, the tradeoffs are (a) whether to concentrate efforts in a particular segment in order to gain market share or to diversify, and (b) whether to attack a particular segment of the industry or try to be an integrator. In the nuclear power business, GE approached the nuclear power business with high degree if vertical integration. In a given project GE developed the reactor system, the turbine generator, the pressure vessel, etc. Whereas Westinghouse focused its efforts only in the critical areas of reactor systems and turbine generators. Regarding pressure vessels, for instance, it gave up the market to Combustion Engineering and Babcock and Wilcox.

To summarize, the following are the market share ratios in the different segments of reactor construction:

	Reactor System	*Pressure Vessel*	*Reactor Internals*	*Turbine Generator*
# Firms in the business	*5*	*10*	*9*	*6*
Main two players	*GE, WEST*	*C-E, B&W*	*GE, WEST*	*GE, WEST*
2-firm market share	*76%*	*64%*	*71%*	*95%*

The market power in this industry was heavily concentrated in the hands of two players, General Electric and Westinghouse. Only in the small segment of pressure vessels was their predominance overshadowed by other participants. The most severe case of concentration was in the turbine generator segment. With such concentration,

6. *The manufacturers game*

Chapter 7

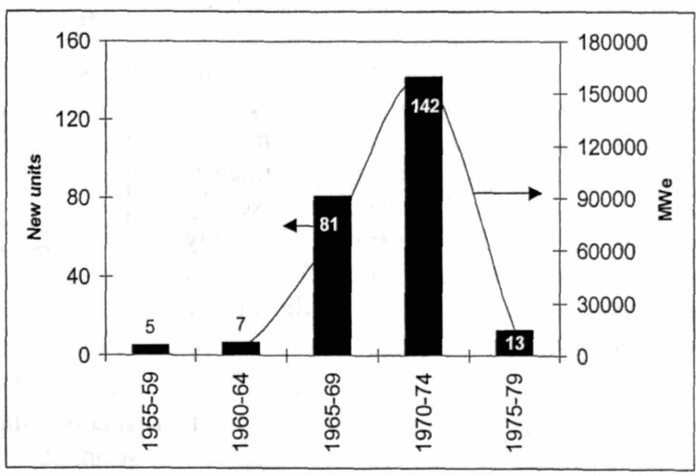
THE DEMISE OF THE DOMINANT DESIGN

This chapter explores the reasons why the Westinghouse PWR collapsed in the mid-1980s. Data suggests that incumbent firms that have successful dominant designs in the market, such as Westinghouse and its PWR design, very often fail to be aware of subtle -but disrupting- shifts on the demand side. While Westinghouse was busy building large and complex units in order to increase efficiency and profits the customer needs were moving in a radically different direction, towards power units that had less inherent risk (as large capital investments). The chapter shows that there was a fundamental change of mindset among industry participants and consumers from the late 1950s to the early 1980s.

THE DEMAND CRASH

After a remarkable surge in orders between 1965 and 1974, the U.S. demand for nuclear power plants unexpectedly collapsed and since 1980 there have been no new orders. Moreover, in the 1980s a number of reactors under construction were cancelled or temporarily shutdown. Elsewhere in the world, reactors continued to be built but inevitably the demand was reduced even in countries that strongly supported nuclear energy such as France and Japan. Current worldwide demand is less than one-tenth of the U.S. demand typical of the late 1960s. Such impressive decline is unusual in the energy sector, which is characterized by long product cycles and stable technologies. The demise of a well-accepted product such as the PWR is therefore a extraordinary episode in nuclear history. Several reasons have been considered in order to account for such a decline. The most commonly mentioned are the following:

Three Mile Island and Chernobyl: The huge negative impact of these accidents on public opinion is probably the single most mentioned reason for the demise of nuclear power. Namely, that electrical utilities could not afford to buy new nuclear power plants after the wide public opposition against the construction of these kinds of electricity-generating assets because of underlying safety concerns. A referendum in Sweden banning nuclear power additions and similar government-lead efforts in Holland, Germany and Spain are often mentioned as examples of a global anti nuclear endeavor that gained momentum after Three Mile Island (1979) and Chernobyl (1986).



Notwithstanding the importance of these accidents in nuclear power demand, Figure 7.1 provides a contradictory view regarding this point. It shows that the demand of nuclear power collapsed even before the accident of Three Mile Island in 1979. Actually, in the five years between 1975-79 demand was for just 13 new reactors while in the previous five years demand had been for more than 140 new reactors. Following a simple cause and effect reasoning, it looks like the major nuclear accidents had a secondary role in the collapse of nuclear power. Presumably they made things worse, making a demand recovery less likely to occur. But it cannot be said that the demand slump was caused by the 1979 and 1986 events.

Regulatory complexity. Many people argue that the increasing intricacy of the regulatory process, particularly in the United States, discouraged electrical utilities from ordering new nuclear plants. The licensing process had become so cumbersome that most private firms had decided to dodge these difficulties by relying completely on other electricity-generating assets, such as coal-fired plants and gas combined cycles, which have a very good economic performance and less regulatory paperwork. It is important to note, however, that after the collapse of demand in the 1980s, the NRC made a substantial effort to speed up the regulatory process and conducted a profound turnover of its licensing standards. One can argue that nowadays there would be few regulatory obstacles to the licensing of a new nuclear power plant but nevertheless there is no demand upsurge. This might be showing that regulatory complexity is not by itself the sole reason for nuclear power decline.

Competition from other energy sources. It might be that nuclear power was abandoned because it could not compete with other fossil-fueled electricity sources such as coal and gas. Although competition seems to have been a compelling reason for the nuclear power demise, there are a number of facts that show that this by itself was not the only reason. First, although it is true that nuclear power has not been competitive during some periods of time, its competitiveness has been highly dependent on the prevailing prices of fossil fuels, which have been highly unstable over time. According to DOE releases, the 2001 nuclear power bus-bar costs were lower than the costs of average gas-fueled plants, but this by itself has not prompted a bandwagon of orders from the electrical utility sector. The truth is that the decision to buy large electricity-generating assets obeys an elaborate tradeoff that is more profound than simple short-term energy prices. This tradeoff involves: (a) volatility of energy costs in the long run, (b) reliance on imported energy sources, and (c) the underlying financial risk of electricity-generating assets.

It is true that real overnight costs of nuclear power plants increased notably in the period when demand soared -between 1965 and 1975- as is shown in Figure 8.2. An overnight cost is the cost that manufacturers ask to an electrical utility for delivering the generating-asset. It is called "overnight" cost because it is settled as if the manufacturers could deliver the product overnight –not in five years. As shown, the unit cost of nuclear installed capacity in the United States increased from about $600/kWe in 1966 to $3,000/kWe in 1980. A prevailing higher overnight cost had definitely an impact in U.S. nuclear power competitiveness but its role seems to be coupled with other factors. For instance, it could be the case that the increase on the overnight price tag of nuclear power assets was simply a demand vs. supply response to market pressure. The only conclusion at hand from Figure 7.2 is that there were diseconomies of scale in the construction cost.

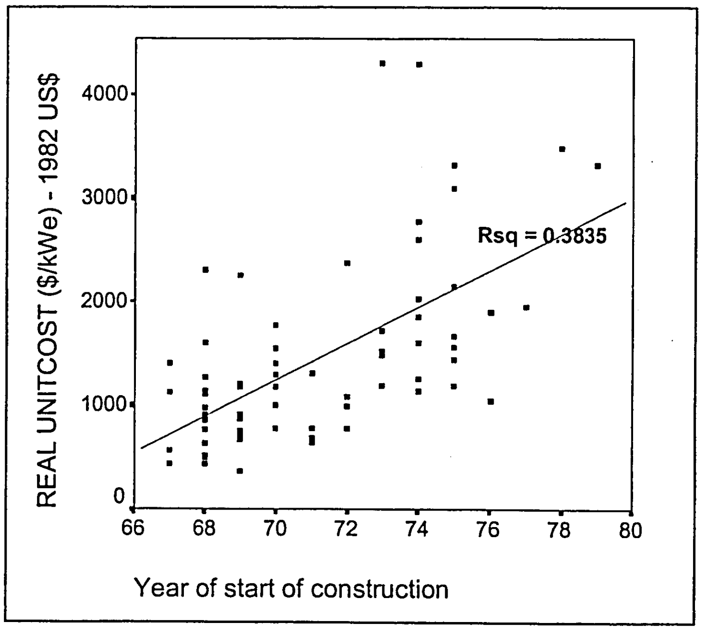


Figure 7.2 Real overnight costs of nuclear power plants built in the United States (1982 U.S. dollars).

In summary, there is empirical evidence that the profound decline of reactor orders was somehow influenced by safety concerns, adverse public opinion, regulatory intricacy, and lower costs of alternative energy sources. But none of these reasons is sufficiently strong to explain thoroughly the demise of nuclear power. It seems that these issues are small parts of a broader picture that has not yet been fully understood. The next sections are an attempt to do so.

THE UNFULFILLED EXPECTATIONS THESIS

The fundamental proposal is that the demise of nuclear power was caused essentially by unfulfilled expectations on the part of buyers –the electrical utilities- and an incorrect reading of user needs on the part of the manufacturers of reactor systems.

In the early 1960s, the main expectation from electrical utilities was to benefit from economies of scale by buying large nuclear power plants. It was thought that the unit cost of producing electricity –in dollars per KWh- was going to be lower for larger nuclear units, even if the design of these units was much more complex than the design of simpler, smaller plants. An illustration of this reasoning is provided in figure 7.3. It shows that scale economies would provide for large profits if there were sufficiently large units in the market. The estimated breakeven size of price-competitive units was around 1,000 MWe.

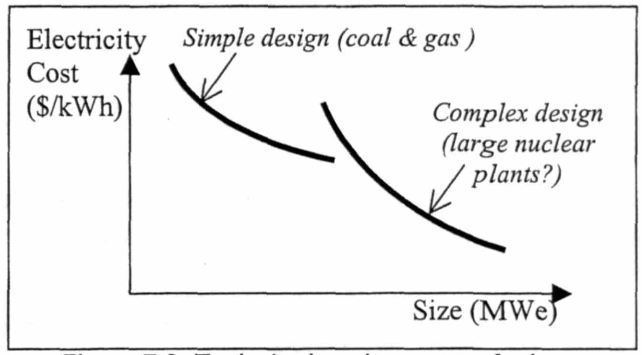


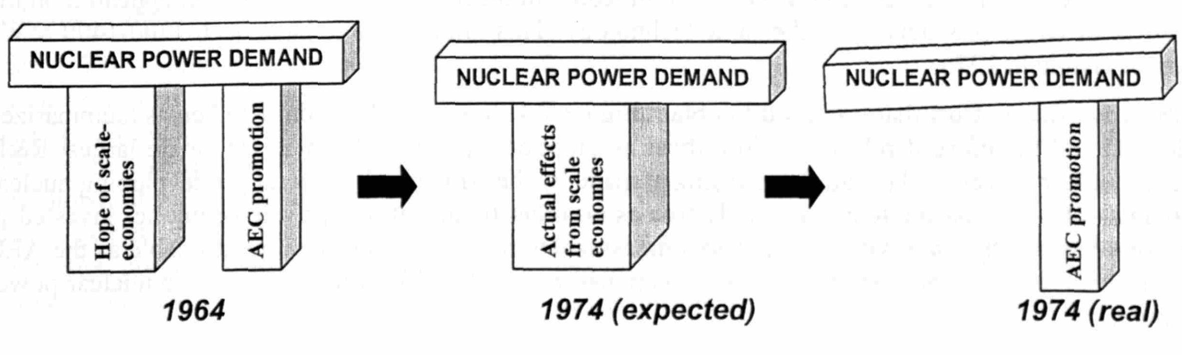
Figure 7.3. Typical price-size curves for large electricity-generation assets

Reactor system vendors and electrical utilities both adopted the same postulate. Reactor system vendors developed standard designs that could easily scale up. For instance, the PWR can be seen as an effort from Westinghouse to provide a product platform that could easily work for power ratings between100 MWe and 1,000 MWe, with no fundamental changes of the design concept. In fact, the PWR was a reactor concept derived from a nuclear submarine power unit (~10MW) and therefore it started and evolved through successive adaptations.

As for electrical utilities, the hope of economies of scale triggered a different course of actions. First, they were inclined to buy the reactor design that was more suitable for achieving scale economies, namely, a design that could easily adapt to larger power ratings. The market data seem to indicate that the PWR was the preferred concept for utility managers because it is arguably easier to scale up than its main competitor, the BWR. To illustrate the point, the introduction of jet pumps in the BWR design was a major change of the original concept prompted by the need to achieve higher power ratings (early BWRs relied only on natural convection). The PWR did not have this problem.

Under these assumptions, it seems that the inexorable leadership of the PWR in the marketplace was a self-fulfilling prophecy. It was a design concept suitable for producing higher power ratings without significant design changes and it addressed a market where a premium was paid to firms that could come up with such a design.

At the outset of the bandwagon of reactor orders –circa 1964- an electrical utility would base its buying decision on two key issues: (a) the hope of attaining economies of scale, and (b) the promotional benefits stemming from AEC's policies. Ten years later the expectation of actual economies of scale simply vanished, and without such promise the demand collapsed:



LISTENING TO THE WRONG SIGNAL

Christensen cites a number of cases where well-managed firms fail in the long run because of listening excessively to their mainstream customers. These firms invest aggressively in product improvements that would provide their customers the kind of benefits that they want. After a meticulous analysis of customer needs, they allocate resources towards the goal of satisfying the needs explicitly stated by the buyers, but paradoxically, many of these firms fail in the long run and lose their leadership positions (Christensen, 1997).

The point is that many times mainstream buyers demand the wrong performance dimension and induce the vendors to excel in this dimension while the real "unexpressed" needs are moving towards a radically different dimension.

In the particular case of nuclear power plants, the single most important performance parameter for electrical utilities was scale. The larger the unit the better, as it was assumed that larger sizes implied lower electricity costs (in dollars per kilowatt-hour).

Reactor vendors worked hard to achieve the goal of higher power ratings and were quite successful in the effort. To illustrate this point, Figure 7.4 summarizes the achievement of higher ratings as a function of cumulative R&D effort. The latter is a typical way to graph the relationship between effort put into developing a technology and the results one gets back for the investment. For most products and processes, when the results are plotted, what usually appears is a curve with an S-shape (Foster, 1986). In the particular case of nuclear power plants, the picture is also an "S" shaped curve.

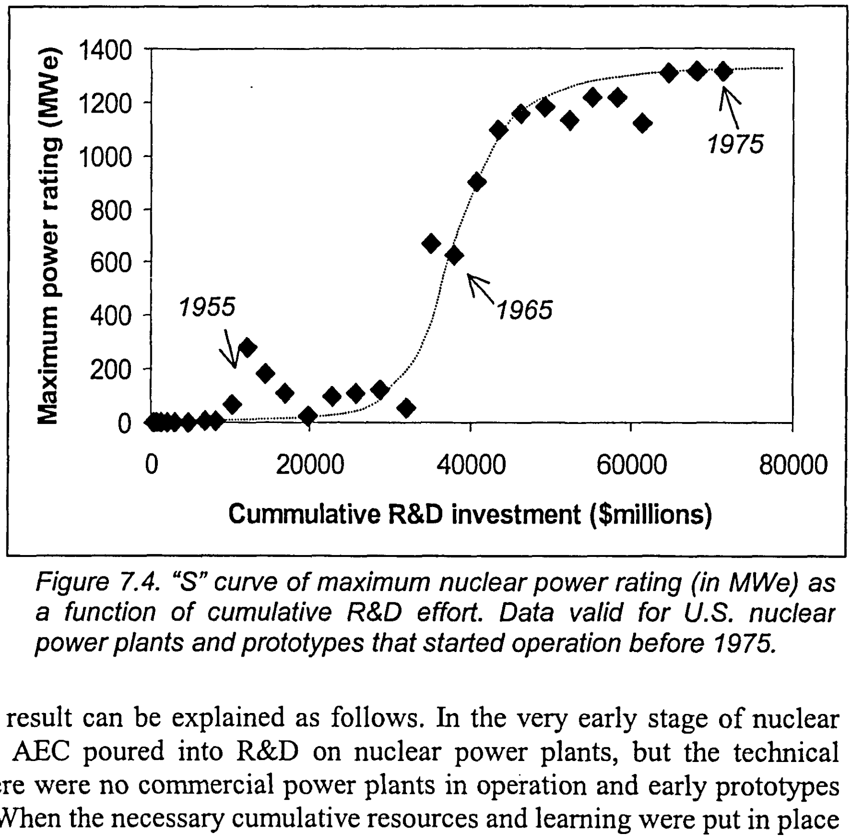


Figure 7.4. "S" curve of maximum nuclear power rating (in MWe) as a function of cumulative R&D effort. Data valid for U.S. nuclear power plants and prototypes that started operation before 1975.

The reasoning behind this empirical result can be explained as follows. In the very early stage of nuclear technology, funds coming from the AEC poured into R&D on nuclear power plants, but the technical progress was very slow. By 1955 there were no commercial power plants in operation and early prototypes had ratings no higher than 50 MWe. When the necessary cumulative resources and learning were put in place the curve entered a second stage where huge advances were obtained with relatively small additional R&D effort (circa 1965). Finally, in the last stage of the curve, it became more and more difficult to make technical progress regardless of how much money was spent in R&D. In other words, a physical limit appeared on the development of larger products using the same technology. This limit seems to have been 1300-1400 MWe and became visible in 1975.

The cumulative R&D effort that was used to obtain Figure 7.4. was extracted from AEC costs (summarized in Table 7.1) and therefore it relies on two critical assumptions: (a) the AEC was the single largest R&D investor in nuclear power, and (b) all the investment made by the AEC was beneficial for developing nuclear power plants. The first assumption is certainly true as no other organization –private or public- invested in nuclear power as much as the AEC did. The second assumption is a little bit more questionable as the AEC invested in other product lines –such as nuclear weapons- that are less likely to have a role in nuclear power development.

Given the expectations regarding the benefits of economies of scale inherent in large power generating assets, one can imagine that in 1974 most directors at Westinghouse and the AEC would have been very pleased looking at Figures 7.1 and Figure 7.4. What these two figures were telling was that the demand of new power plants was robust –especially PWRs- and that the prevailing power ratings of units was exactly what electrical utilities were expecting. In other words, there was a greedy market for PWRs and Westinghouse had achieved the long awaited goal of power plants in the 1,300 MWe range. Westinghouse was clearly listening to its customers and had a strong product to address their needs.

However, listening to market demand and customer needs was exactly the wrong thing to do in 1974. The right signals to listen were the increasingly long times required to construct plants. Originally in the early 1960s, when utilities jumped into the nuclear bandwagon, they expected construction times in the order of 5 years with slight increases due to increasing complexity. In other words, using the same x-axis of Figure 7.4, namely cumulative R&D effort, a flat curve was expected. But as Figure 7.5 clearly shows this was not the case. Construction times actually increased and peaked in 1975 at around 12 years.

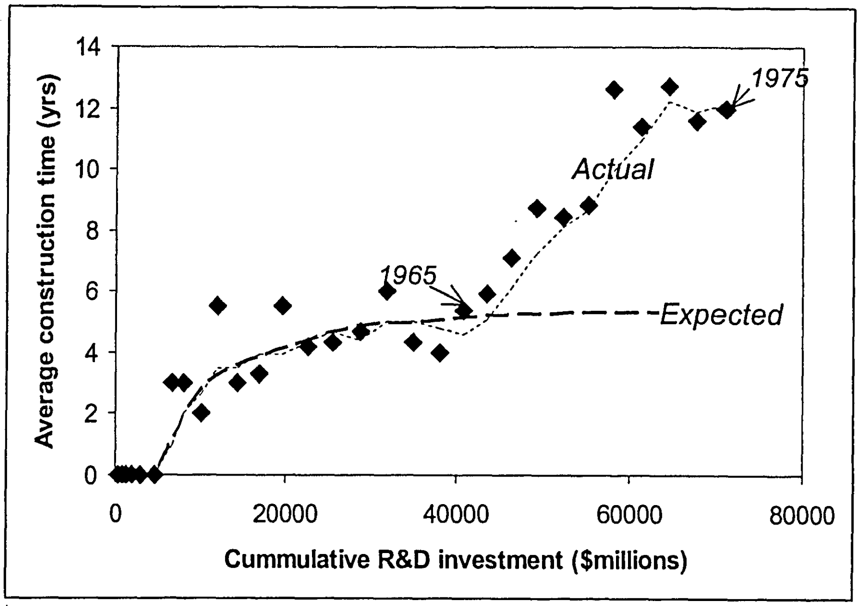


Figure 7.5. Curve of average construction times as a function of cumulative R&D effort (same as Fig 7.4). Data valid for U.S. nuclear power plants and prototypes that started operation before 1975.

The first nuclear power plant in the United States, Shippingport, was built in three years, and in days to come it was predicted that normal construction times of larger units would take on average five years. But this prediction totally underestimated the complexity of nuclear plant construction in the United States. Just to provide an example, it took 17 years to build the Diablo Canyon nuclear power plant in California (1968-85).

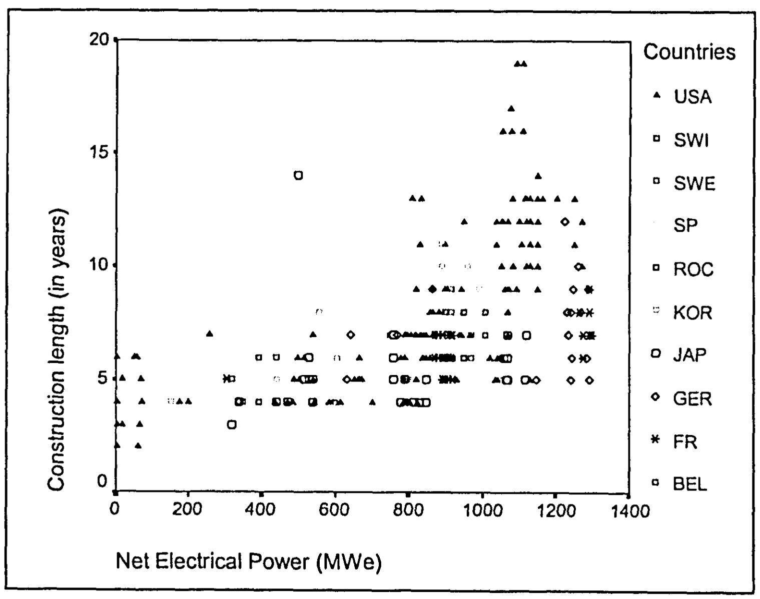


Figure 7.6. Scatter plot of construction time versus net electrical power for all nuclear power plants built in the world (except Soviet Union) between 1955 and 1989.

Figure 7.6 contains a plot of construction time versus net electrical power for all nuclear power plants built in the western world, between 1955-89. As is shown, it seems that the larger the nuclear power plant, the larger the construction process. One has to be very cautious however regarding this seemingly logical statement. First, the same graph shows that there are many countries -like Germany and France- that were able to build complex plants of 1,300 MWe in five years. Second, beneath the role of higher power ratings there are other issues that are highly correlated, like year of construction. Whereas all small plants were built in the early 1960s, most of the large complex units were constructed in the 1980s when the regulatory and industrial environment was different. Hence it is difficult to separate the effects of size from other issues.

In summary, whereas the manufacturers of nuclear reactor systems were gratified by the fact that they had a seemingly strong market demand and value proposition for buyers, construction times were skyrocketing and that was very dangerous for the future of the industry.

WHY CONSTRUCTION TIMES ARE IMPORTANT

The longer the time required to construct a nuclear power plant, the more expensive is the capital cost of the project and consequently the lifetime-levelized busbar cost of electrical energy. To understand the previous statement it is necessary to note that the cost of any power plant is made up by three terms: (a) capital-related costs, (b) operation & maintenance costs, and (c) fuel costs.

Each of the three components of electricity cost depend on financial charges such as the annual rate of inflation, the cost of capital, mortgage rates, tax charges, etc. But the capital cost is the most sensitive component because of the long times required to construct power plants. A large lump sum is required up front as an investment and the revenue stream is unleashed only when the plant starts commercial operation. To understand the tradeoffs involved in nuclear electricity economics, a simple model of the lifetime-levelized busbar cost of electricity e_b is provided below:

For plants fueled by coal and natural gas:

$$e_b = \underbrace{\frac{100\Phi I_o}{8760C_F}\left[1+\frac{x+y}{2}\right]^B}_{CapitalCost} + \underbrace{\frac{100M_1}{8760C_F}\left[1+\frac{y(L-1)}{2}\right]}_{FixedO\&M\ costs} + \underbrace{10^{-6}H_R F_1\left[1+\frac{y(L-1)}{2}\right]}_{Fuel\ cost-fossil}$$

For a nuclear power plant (only the fuel term changes):

$$e_b = \underbrace{\frac{100\Phi I_o}{8760C_F}\left[1+\frac{x+y}{2}\right]^B}_{CapitalCost} + \underbrace{\frac{100M_1}{8760C_F}\left[1+\frac{y(L-1)}{2}\right]}_{FixedO\&M\ costs} + \underbrace{\frac{100F_2}{24\eta B_U}\left[1+\frac{y(L-1)}{2}\right]}_{Fuel\ cost-fossil}$$

The description of the various input parameters and their typical values are given as following:

	Natural Gas	*Coal*	*Nuclear*
Overnight cost of the plant I_o (\$/kW)	1,000	2,000	2,500
Capacity factor during operation C_F	0.92	0.90	0.90
After tax cost of capital x (%/yr)	9	9	9
Inflation/escalation rate y (%/yr)	4	4	4
Plant construction time B (yrs)	3	4	6
Plant operation lifetime L (yrs)	30	30	30
O&M cost in 1st year of operation M_1 (\$/kW)	30	60	120
Plant thermodynamic efficiency η			0.33
Plant heat rate H_R (BTU/kWh)	7,000	9,800	
Fossil fuel cost F_1 (cents/million BTU)	600	150	
Nuclear fuel cost of 1st core F_2 (\$/kgU)			1,800
Nuclear fuel burnup B_U (kWd/kgU)			40,000

Substituting the input data in the above-presented formulas one can obtain the total cost of electricity (in cents/kWh) of the three alternatives, and one can compare with a lifetime-levelized busbar cost. This is the cost that any electrical utility would need to pay over the entire lifetime of the plant in order to break even.

Numerical results are presented in Figure 7.7. They show that the main cost component of electricity generated by nuclear means is the capital cost, which accounts for 70% of the total cost. Point number one is therefore that the capital cost is the fundamental parameter in the competitiveness of nuclear power plants. Point number two is the relative importance of the construction time B in the cost of capital. In other words, the cost of capital changes significantly from B=6 yrs and B=12 yrs. To test this dependence, one can readily use the model presented above changing the parameter B while maintaining the rest of the variables constant. The results are shown in Figure 7.8. By duplicating the construction time from 6 to 12 years the total cost increases 33%.

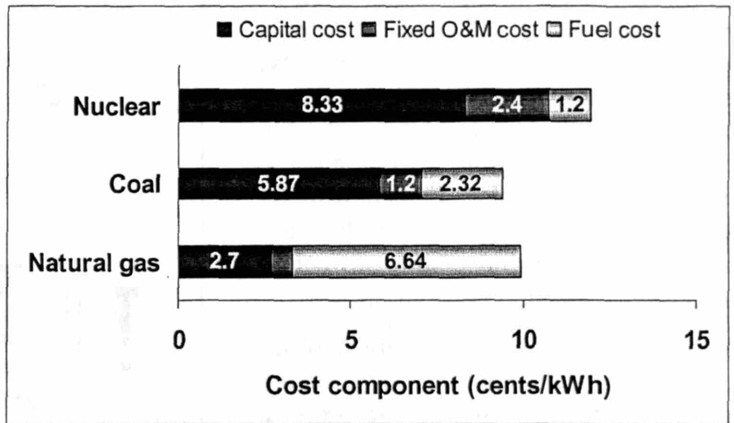


Figure 7.7 Cost components of power plants

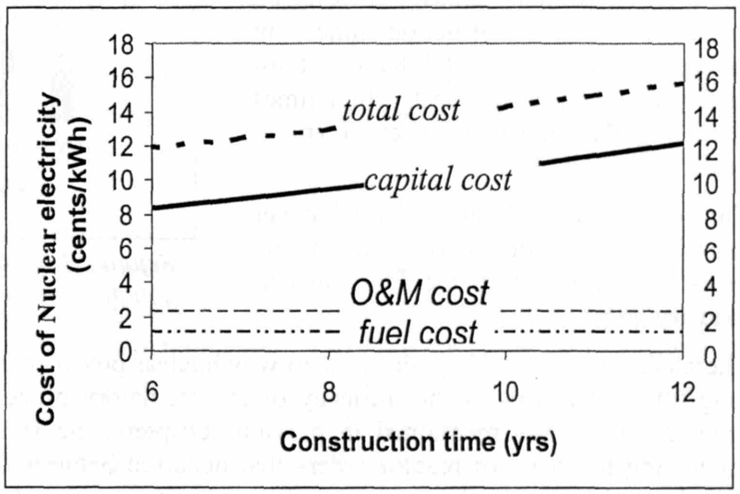


Figure 7.8 Cost increase due to longer construction times in a nuclear power plant

In summary, from 1965 to 1975, construction times of nuclear power plants increased abnormally, from an average of 6 years to an average of 12 years. This rise in construction times increased the capital costs of nuclear power plants by nearly one-third of the original "overnight" capital cost. Since 70% of the cost of electricity generated by a nuclear power plant is due to the up front capital cost, these delays increased the underlying cost of these assets by at least 30%. Such an abrupt increase in cost simply could not be afforded by electrical utilities.

The original promise of economies of scale could not be fulfilled. Instead of having lower unit costs (in $/kWh) the electricity producers were having higher unit costs. Utilities virtually had to manage large complex and challenging generating assets to have input costs that were above market value. It was not a sound investment at all, i.e. economies of scale affected O&M and fuel costs which were the smaller portion of total costs.

WHAT WENT WRONG?

Certainly the participants did not want or encourage long construction times. It was most likely an unexpected outcome of the construction process. The question is what caused this sharp increase in construction times.

In order to answer this question it is useful first to see whether this was a general pattern of the nuclear industry or it was a manifestation of the U.S. industry only. Figure 7.9 summarizes average construction times of nuclear power plants in the United States, Germany, France, Japan and Sweden. These countries account for 60% of the worldwide production of nuclear electricity. In particular, France with 60 reactors and Japan with 45 reactors are two of the strongest advocates of nuclear energy in the world.

As Figure 7.9 shows, the average times required for construction skyrocketed only in the United States, for projects starting around 1965. The rest of the countries had minor increases or managed to reduce their construction times. In Japan, reactors built in 1980-83 were built in 5 years. In France construction times were slightly higher, between 6 and 7 years.

The conclusion is therefore that whatever caused the slowdown of construction times was inherent to the U.S. nuclear industry only.

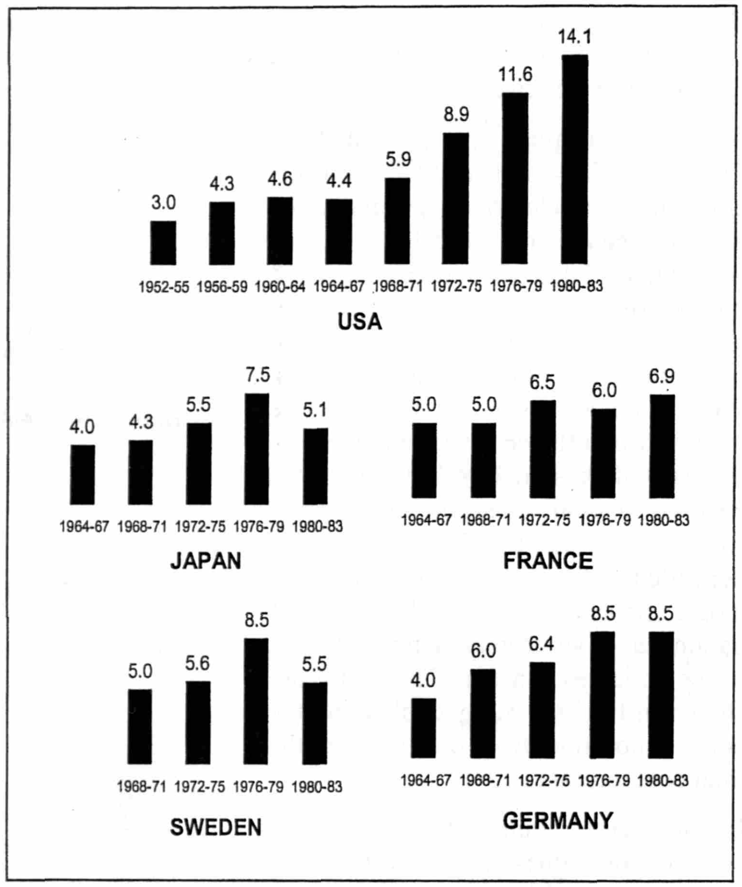


Figure 7.9 Average construction times in selected countries versus the year when the project was half-done

There are a number of hypothesis as to why nuclear power plant construction in the United States took such long times. The first is the intricacy of the regulatory process, which introduced innumerable delays to projects. As it was mentioned in previous chapters, the U.S. nuclear regulatory body had a hard time processing the burst of reactor orders that occurred between 1965 and 1974 (see Figure 7.1). The second hypothesis is that the long construction times were caused by the large number of participants in the construction process and their relative inexperience in building power plants. As it was mentioned in chapter 6, the main participants on the design & construction process were: (a) the electrical utility, (b) the architect-engineer, (c) the reactor system vendor, (d) the turbine generator manufacturer and (e) the construction company.

In the United States, there were 60 utilities operating 115 nuclear power plants, 15 architect- engineers and a similar number of construction firms, 4 reactor system vendors and 2 turbine generator manufacturers. The possible permutations of that many players are utterly immense. It is similarly huge the complexity of the construction process and the organizational challenge of undertaking an extremely technically difficult project, such as a nuclear power plant, with so many participants on board. Notice that the process is progressive since as more reactors are built, more participants are attracted, there are more firms involved and ultimately construction times increase. That would explain why in the beginning (before 1965) reactors were built in the United States in less than 5 years. At that time there were few firms involved.

Compare this situation with France, which has only 1 utility operating 60 reactors, Electricite de France, which is also the architect-engineer of plants. There is 1 reactor vendor, Framatome, and 1 turbine generator manufacturer, Alshom. Obviously the degree of organizational complexity is much lower in France than it is in the United States.

It is important to note that the first hypothesis is somehow included in the second hypothesis. Namely, if the construction process in the U.S. was chaotic because of the large number of participants then one can expect that the whole licensing process would be difficult and long. After all it would be in the NRC's best interest to detect potential sources of problems arising from messy organizational structures. However, the first hypothesis is really difficult to prove. It is not easy to show that reactors with longer construction times faced more regulatory difficulties than reactors that were built faster. For these reasons, we shall focus only on testing the second hypothesis, i.e. firm diversity.

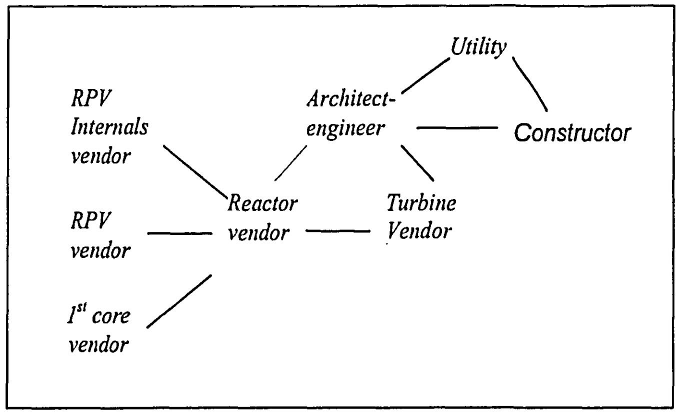


Figure 7.10 Critical interactions during the design and construction of a nuclear power plant

To test the influence of the number of firms on total construction times, using a statistical analysis tool (SPSS), some "diversity" parameters have to be defined. These parameters evaluate diversity by pairs, and refer to the most critical interactions that are expected to occur during the design & construction process. These interactions are summarized in Figure 7.10.

AExCIV:	*Architect-engineer and civil constructor*	*(=0 if are the same, =2 otherwise)*
RSxTUR:	*Reactor system vendor and turbine vendor*	*(=0 if are the same, =2 otherwise)*
UTIxAE:	*Utility and architect-engineer*	*(=0 if are the same, =2 otherwise)*
UTIxCIV:	*Utility and civil constructor*	*(=0 if are the same, =2 otherwise)*
RSxRPV:	*Reactor system vendor and RPV vendor*	*(=0 if are the same, =2 otherwise)*
TURxSTR:	*Turbine vendor and steam riser vendor*	*(=0 if are the same, =2 otherwise)*
TURxAE:	*Turbine vendor and architect engineer*	*(=0 if are the same, =2 otherwise)*
RSxAE:	*Reactor system vendor and architect-engineer*	*(=0 if are the same, =2 otherwise)*
RSxCORE:	*Reactor system vendor and 1st core vendor*	*(=0 if are the same, =2 otherwise)*
RSxINTER:	*Reactor system vendor and RPV internals*	*(=0 if are the same, =2 otherwise)*
DIVERSE:	*Average of all previous variables*	*(=0 lowest diversity, =2 highest)*

The correlation matrix between these parameters is shown in Table 7.2 for worldwide data corresponding to 279 reactors built before 1989 (189 of them PWRs). For clarity, the main results involving the **correlation between diversity parameters and construction length** are summarized below, organized by country:

	AEXCIV	RSXTUR	UTIXAE	UTIXCIV	RSXRPV	TURXSTR	TURXAE	RSXAE	RSXCORE	RSXINTER	DIVERSE
USA	.081	.029	**-.295***	**-.229***	.080	.131	.052	.a	-.077	**-.154***	**-.031***
JAPAN	**-.548***	**-.165***	.a	a	.128	**-.206***	**-.242***	**-.223***	-.056	**-.205***	**-.337***
SWEDEN	-.123	-.070	-.031	**-.186***	.119	.026	.093	.078	**-.258***	**-.163***	**-.666***
BELGIUM	-.117	-.083	-.038	**-.170***	.093	.011	.087	.072	**-.248***	**-.155***	**-.842***
ALL	-.119	-.086	-.040	**-.171***	.098	.007	.085	.071	**-.236***	**-.147***	**-.163***

**Correlation is significant at the 0.05 level (1-tailed).* *a cannot compute a result because one of the two parameters is constant*

First, let us focus on the United States. The results show that there is no statistically significant correlation between DIVERSE (which accounts for overall diversity) and the construction length of the projects. This might be indicating that the number of firms by itself does not make a project messy. It is the way the participants orchestrate themselves that makes a project a big success or a failure. One can argue that Japan had a very organized and well-managed system for delivering nuclear power plants on schedule, while the United States had a less efficient system; not because there were many players on board but because they were badly organized.

However, the results show some parameters that are statistically significant and are negatively correlated with construction times. The first, UTIXCIV, accounts for the relationship between the construction firm and the electrical utility. Projects where the constructor was the utility had substantially shorter construction times. This finding might be indicating that one of the bottlenecks of the construction process was in the construction firm and how it interacted with its two immediate partners: the architect-engineer and the electrical utility. The other parameters that are negatively correlated are RSXCORE and RSXINTER. These parameters account for the relation between the reactor system vendor and two of its main suppliers: the 1st core supplier and the core internals manufacturer. Since the correlation is negative with construction length it means that projects where the reactor vendor was also the supplier had substantially shorter construction times. This finding might be showing that in the U.S. most delays in the construction process were introduced by late deliveries of these components, which are in the critical path of the construction of the reactor. For instance, without a timely delivery of the reactor internals, a number of extremely time-consuming tasks can not be done on time.

Let us focus now Japan, Sweden and Belgium. Note that, as it was mentioned before, these nations managed to have lower construction costs and –arguably- a more organized construction and delivery process. The matrix correlation shows a statistically significant correlation between construction time and most of the diversity variables –including DIVERSE. Again, since the correlation is negative with construction length it means that projects where there were many participants involved had substantially longer construction times.

In the particular case of Japan, for instance, there is a strongly negative correlation between construction length and AEXCIV, which means that projects where the architect-engineer and the civil constructor were the same company, had shorter construction times. The same conclusion holds for RSXTUR, TURXAE and TURXSTR, namely, when the turbine generator manufacturer was also the reactor vendor, the architect-engineer and the steam-rising supplier, then the project was more likely to finish on time.

France is not included in the correlation matrix because most of the parameters were constant. In other words, all the French reactors were built using exactly the same formula –as was pointed out- and therefore it is impossible to make a correlation. However it is important to note that France has a good record of timely construction as it is shown below:

	Number of BWRs built	Average Construction time (yrs)	Number of PWRs built	Average Construction time (yrs)
JAPAN	19	5.9	16	4.7
SWITZ.	2	7.0	3	4.7
FRANCE		.	48	6.5
GERMANY	7	8.1	13	6.5
BELGIUM		.	7	6.7
KOREA		.	8	6.9
SWEDEN	9	5.4	3	7.3
SPAIN	2	7.5	7	8.6
USA	**47**	**7.7**	**82**	**8.7**

It is important to note that there is no significant difference between the PWR and other competitive designs regarding construction delays. The problems associated with mismanagement of nuclear power projects in the United States affected both BWR and PWR projects.

Table 7.1. Summary of AEC's Research and Development costs from 1948 to 1974

Table 7.2 Correlation matrix between diversity parameters. Data valid for 279 reactors, 189 of them PWR, built worldwide before 1989

Correlations

	AEXCIV	RSXTUR	UTIXAE	UTIXCIV	RSXRPV	TURXSTR	TURXAE	RSXAE	RSXCORE	RSXINTER	DIVERSEI	Construction length (in years)
AEXCIV	1.000	.137*	-.143*	.144*	.005	.056	-.183*	-.123*	.399*	.274*	.374*	-.119*
RSXTUR	.137*	1.000	-.361*	-.004	-.382*	.778*	.259*	.289*	.209*	.227*	.648*	-.086
UTIXAE	-.143*	-.361*	1.000	.251*	.469*	-.343*	-.186*	-.180*	-.444*	-.491*	.143*	-.040
UTIXCIV	.144*	-.004	.251*	1.000	-.093	.006	-.103*	-.099*	.175*	.190*	.268*	-.171*
RSXRPV	.005	-.382*	.469*	-.093	1.000	-.278*	-.324*	-.243*	-.247*	-.132*	.131*	.098
TURXSTR	.056	.778*	-.343*	.006	-.278*	1.000	.115*	.070	.195*	.312*	.573*	.007
TURXAE	-.183*	.259*	-.186*	-.103*	-.324*	.115*	1.000	.855*	-.331*	-.198*	.346*	.085
RSXAE	-.123*	.289*	-.180*	-.099*	-.243*	.070	.855*	1.000	-.312*	-.194*	.398*	.071
RSXCORE	.399*	.209*	-.444*	.175*	-.247*	.195*	-.331*	-.312*	1.000	.653*	-.058	-.236*
RSXINTER	.274*	.227*	-.491*	.190*	-.132*	.312*	-.198*	-.194*	.653*	1.000	.049	-.147*
DIVERSEI	.374*	.648*	.143*	.268*	.131*	.573*	.346*	.398*	-.058	.049	1.000	-.049
Construction length (in years)	-.119*	-.086	-.040	-.171*	.098	.007	.085	.071	-.236*	-.147*	-.049	1.000

*. Correlation is significant at the 0.05 level (1-tailed).

**. Correlation is significant at the 0.01 level (1-tailed).

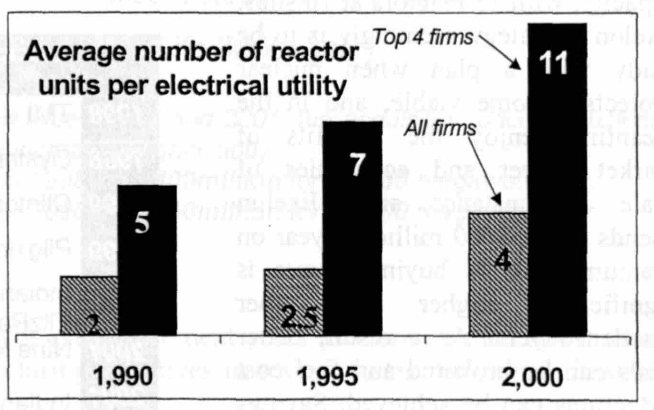
THE 1990S AND BEYOND: LESSONS FROM THE PWR CASE

This chapter is a rapid fast-forward through the 1990s. It explores the achievement of the long-awaited positive externalities of a dominant design. It shows how the performance of nuclear power plants has increased notably, through a combination of industry consolidation, specialization, cumulative learning effects, and economies of scale. The chapter finishes with a summary of the Westinghouse PWR case and a framework for understanding the issues from the point of view of public policy and management of technology.

CONSOLIDATION OF NUCLEAR OPERATORS

In 1990 there were 112 nuclear power plants under commercial operation in the United States, which were operated by 54 electrical utilities. This means that a typical electrical utility owning nuclear electricity-generating assets would on average own only two nuclear reactor units. The extreme fragmentation among nuclear power operators before 1990, was a consequence of the overconfidence that prevailed among utility managers at the time when most plants were constructed. For them, a nuclear power plant was just a large electricity-generating asset not very different than standard plants fueled by coal and natural gas. For the most part, the unique organizational and technical skills required to operate nuclear plants efficiently were greatly underestimated at that time (Kadak, 2002).

During the 1990s, things started to change. Under a new environment marked by deregulation and competition, electrical utilities reevaluated the value of nuclear assets. Some firms decided to get rid of nuclear power plants while others actively pursued the acquisition of these power units. As a result, the structure of nuclear power operators changed significantly.



As it is shown in Figure 8.1, the number of firms was reduced from 54 in 1990 to 24 in the year 2000. The average ownership raised from 2 reactors per nuclear operator to 4 reactors. In 2000, the top four firms owned on average 11 reactors, with some owning as many as 17 units.

The process of consolidation within the nuclear power industry occurred primarily through two parallel processes: (a) mergers and acquisitions between electrical utilities, and (b) purchases of nuclear power plants. The first process –mergers and acquisitions between different firms- increased momentum between 1998 and 2001 and the outcome is summarized below (including Figure 8.2):

Alliant Energy (1), Northern States (3), Wisconsin Electric (3) } NUMCO (7)
Virginia Power (4), Northeast Utilities (2) } Dominion (6)
Duquesne (2), First Energy (2) } First Energy (4)
Florida P&L (5), Entergy (6), New York Power (2) } Entergy/FPL (6)
GPU (2), CommEd-Unicom (11), PECO (4) } Exelon (17)

Note: Number of reactors between parenthesis

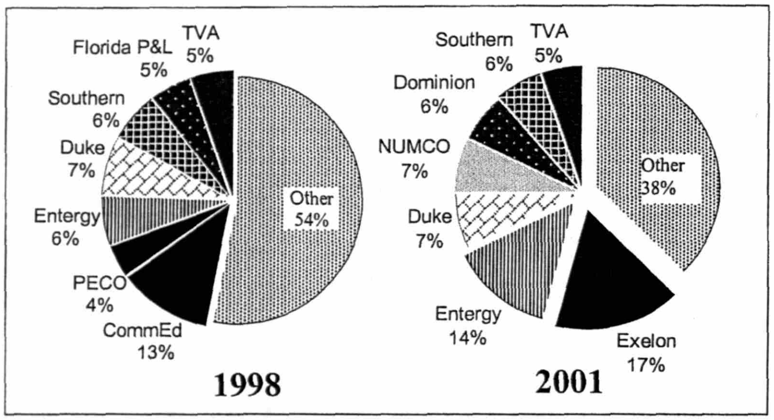


Figure 8.2. Consolidation of U.S. electrical utilities owning nuclear power plants between 1998 and 2001.

- *In 1998, 4-Firm ratio was **30 %***
- *In 2001, 4-Firm ratio was **45 %***

The process of mergers and acquisitions between nuclear power operators is not an isolated story. It has occurred at the same time energy markets in general have been restructured. Vertically integrated utilities have been broken up. A new-generation industry has sprung up with new players and business dynamics. In the nuclear arena, mergers and acquisitions led to multiple plants among fewer owners. Most companies that own nuclear plants have nuclear as their core business. The emerging nuclear operating companies are focused on the management and oversight of their operating plants with increased economies of scales and resource sharing among a larger plant base. In brief, nuclear consolidation seems to occur in conjunction with specialization.

In particular, Exelon Corporation is building a case for nuclear power. Exelon currently represents nearly one-fifth of the U.S. nuclear power capacity, with 17 reactors at 10 sites. Exelon's strategy seemingly is to be ready with a plan when nuclear projects become viable, and in the meantime enjoy the benefits of market power and economies of scale. For instance, since Exelon spends about $600 million a year on uranium fuel its buying power is significantly higher than other smaller buyers. As a result, better deals can be brokered and fuel cost reductions can be achieved. Savings are also realized by spreading O&M and overhead costs across the company, and using the same contractors during refueling outages

Table 8.1. Between 1998 and 2001, fifteen U.S. nuclear power plants were acquired by other electrical utilities.

- *In 1998-99, **4** reactors sold for **$404** million.*
- *In 2000/01, **9** reactors sold for **$3.7**.billion*

	Reactor Unit	Useful Life (year x MW)	Acquisition Price
1998	TMI - 1	13x819	$100m
1998	Oyster Creek	8x650	$10m
1999	Clinton 1	26x933	$182m
1999	Pilgrim 1	11x655	$112m
2000	Indian Point 3 FitzPatrick	15x965 14x816	$967m
2001	Nine Mile Point 1, 2	8x613; 27x1143	$824m
2001	Indian Point 1, 2	10x986; 12x986	$602m
2001	Millstone 1,2,3	14x870; 25x1154	$1305m

and maintenance activities. Thus while the industry average down time for refueling is about 32 days, Exelon units were down an average of 22 during 2000. The same year, Exelon's nuclear plants had a capacity factor of 93.8 percent compared to an industry average of 89.6.

Regarding the second process leading to nuclear power consolidation, i.e. the purchasing of electricity-generating assets, it is important to note that a few years ago nuclear power plants were seen as expensive liabilities. But today their perceived value has increased. As shown in Table 8.1, facilities designed for shutdown have been recently sold to the highest bidder. Three Mile Island 1, the sister unit to Three Mile Island 2, the reactor that had an accident in 1979, started the path when it was sold in 1998 for $100 million. The sale of Clinton 1 followed course when the reactor was purchased form Illinois Power Co. for $182 million. The latter cost Illinois Power $4.2 billion to build.

The early purchases of nuclear plants –between 1998 and 1999- were cheap compared to more recent prices of nuclear electricity-generating assets. The reason why these early sales were less expensive is because some companies were looking to lean their assets in order to be competitive –in a deregulated environment- and nuclear power was not their core business. Companies that were actively looking to be in the nuclear business benefited from this situation and bought assets at bargain prices, i.e. Exelon, Entergy, NumCo. Once market forces started to act, competition increased and assets began to be sold for higher prices. Hence, when in 2000 Entergy bought Indian Point 3 and Fitz-Patrick nuclear plants from New York Power Authority, it had to pay $967 million. Again, the surge of sales in the northeast reflects the relatively pace of deregulation in states like New York, Massachusetts, Connecticut and Pennsylvania.

To illustrate the point of increasing bidding prices, Figure 8.3 provides a summary of purchases versus the underlying value of the electricity-generating asset. The later is plotted in the x-axis and accounts for the product of useful life times the electricity generating capacity. This in theory is the maximum amount of energy (in kilowatt-hour) that a nuclear operator can extract from an asset. One can consider this number as something "in theory" because the NRC is granting operational extensions that can extend the useful life 10 years and even 20 years in some particular cases. However these extensions are analyzed on a case-by-case basis and cannot be taken for granted.

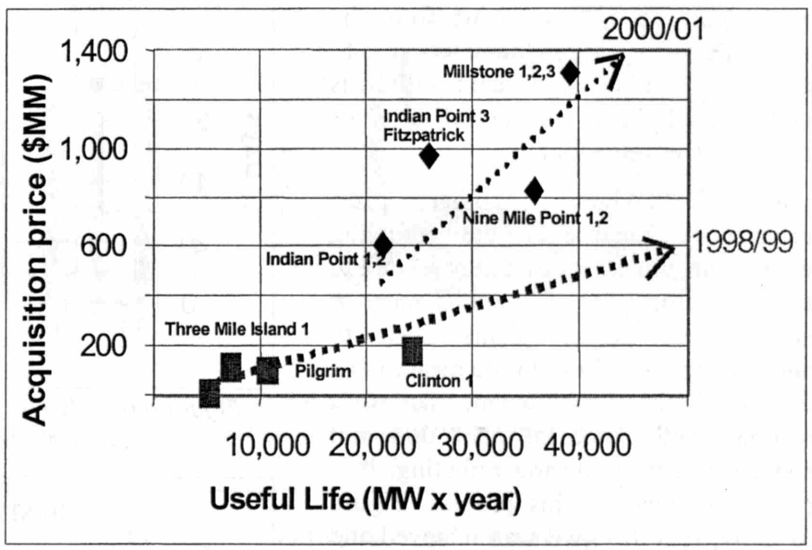


Figure 8.3. Between 1998 and 2001, the acquisition price of nuclear power plants increased significantly.

- *In 1998/99, **$400million** for **10,000** megawatt-year.*
- *In 2000/01, **$150million** for **10,000** megawatt-year.*

Additional nuclear plants are expected to be up for sale in the next years as more utilities divest their electricity-generating assets in response to restructuring initiatives in several states that remain heavily regulated.

IMPROVED OPERATING PERFORMANCE

There are a number of ways to measure the operating performance of a nuclear power plant. In what follows, some of the most common performance factors are presented, in order to show that the 1990s were indeed years of uninterrupted improvements.

Figure 8.5 shows an increase of the capacity factor of nuclear power plants from around 60% in the early 1980s to 90% in the late 1990s. Capacity factor is defined as the yearly ratio of electricity that a nuclear power plant actually supplies to the electrical grid over installed capacity. Note that according to this definition a plant with a capacity factor of 100% is operating at full power for 365 days a year. Most of the increase in capacity factors is certainly due to simple learning effects arising from the more experienced operating crews at U.S. power plants, but a significant portion is due to consolidation and specialization of nuclear power operators

Figure 8.6 shows another plant performance parameter, the refueling outage time, which is intimately related to capacity factor. Every 18 months, more or less, nuclear power plants need to shutdown for refueling. In the meantime a number of critical maintenance activities are conducted. Since the plant does not produce electricity during refueling, it is critical to speed up this process. Figure 8.6 shows that this goal was achieved and there has been a significant reduction during the 1990s.

The achievement of higher operative performance within U.S. nuclear power plants was not constrained to parameters that are intimately related with higher profits. Figure 8.7 shows that the industrial safety accident rate also decreased substantially during the last two decades. This indicates better management and more experienced crews.

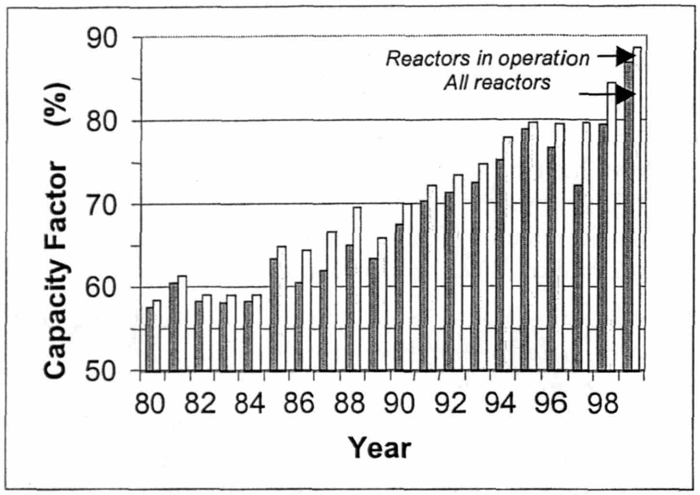


Figure 8.5. Between 1980 and 2000 there has been a dramatic increase of the capacity factor among U.S. nuclear power plants

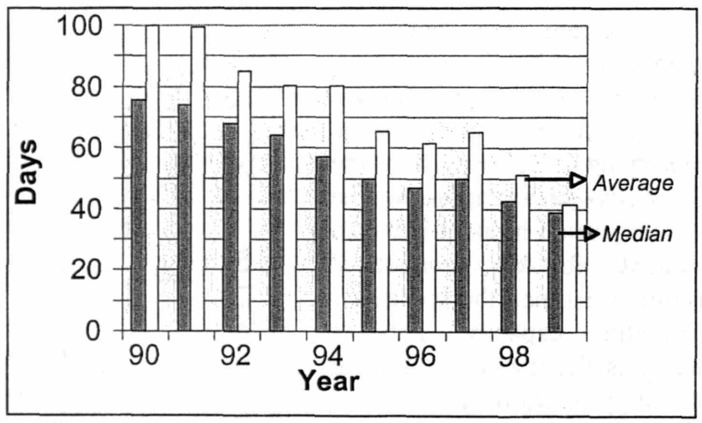


Figure 8.6. Between 1990 and 2000 there has been a reduction of refueling outage times

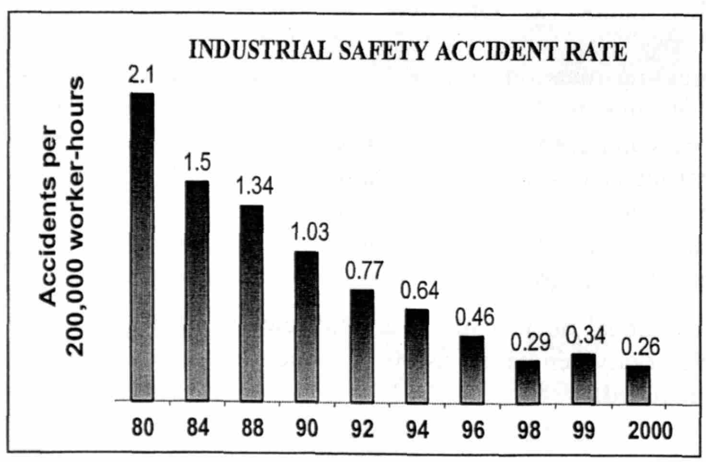


Figure 8.7. Reduction of the rate of accidents due to industrial reasons (not necessarily nuclear-related incidents)

SUMMARY OF THE 1990s

The dramatic improvements in performance in the 1990s can be explained in the following terms. First, consolidation of nuclear operators and increasing specialization necessarily lead to higher efficiency and profits. This statement is schematically illustrated in Figure 8.4. Consolidation and specialization lead to higher efficiency for a number of reasons:

1. Economies of scale stemming from the shared use of infrastructure and O&M resources among a larger base of nuclear power plants.
2. More efficient use of human resources, including having an in-house critical mass in technical areas and a management team more specialized in managing nuclear power plants.
3. Learning effects arising from cumulative experience operating a broader base of reactors.
4. More buying power regarding suppliers such as uranium producers, service organizations, etc.
5. More lobbying power over critical agencies in the nuclear energy sector such as NRC, DOE and EPA.

Figure 8.4 shows a loop that is positively reinforced. Once higher efficiency is achieved, profits also increase and the management becomes more committed to pursue even more specialization and consolidation. Empirical data shows that in the 1990s the reinforcing loop has been functioning very well.

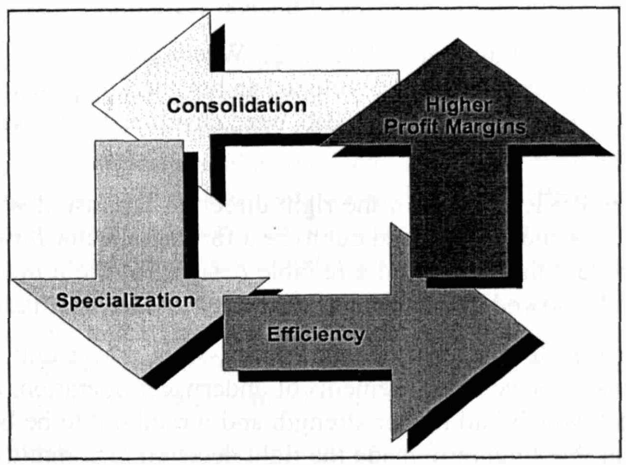


Figure 8.4. Schematic representation of the effect of consolidation among nuclear operators and their increasing nuclear specialization

It is important to note that the reinforced loop explained above did not appear in the 1970s and 1980s. Indeed, some scholars found no evidence that a learning process was going on in nuclear power plants. The question is therefore what changed in the 1990s that led to substantial learning and scale effects. One can argue that the answer is embedded in the process of consolidation and specialization of nuclear operators. The fact that nuclear operators became more focused on managing several nuclear plants with more specialized management and operation teams, certainly had a role on the overall performance of the industry.

In summary, The 1990s finally brought the promises of economies of scale and large profit margins that the industry analysts had foreseen forty years before. As it is shown in Figure 8.8, nuclear power actually increased in the 1990s by 30% while the number of nuclear power plants was reduced from 112 to 103 reactors. Had the efficiency of existing plants not increased, almost 30 new reactors would have been needed to produce the same amount of electricity. The question is why the nuclear industry did not achieve the same results in the mid-1970s when the demand of power plants was in its peak? Why did Westinghouse, who had the successful PWR in the marketplace, lose the grip on the technology and the market? These questions are answered in the following section.

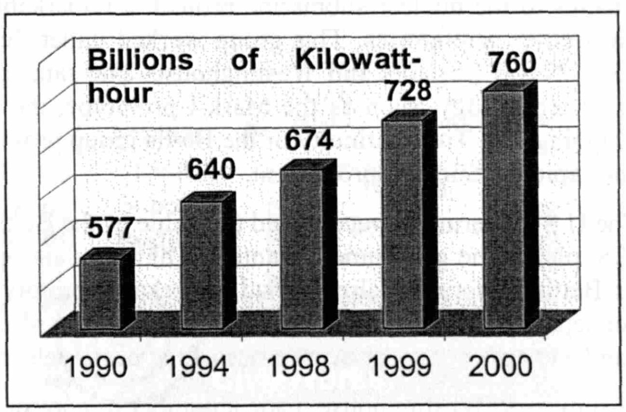


Figure 8.8. In the 1990s electricity produced by U.S. nuclear power plants increased roughly 30%

LESSONS FROM THE WESTINGHOUSE PWR CASE

There are two possible ways to analyze the PWR case. One is from the point of view of public policy, addressing the issue of the use of law and public funds to promote the nuclear power industry in general and the PWR in particular. The other is the point of view of private policy, addressing the issue of how Westinghouse, benefited from a particular regulatory and competitive environment to develop and market a product. The conclusions stated subsequently address the latter case, namely, the analysis of strategies that Westinghouse carried out to sell its successful PWR product in the marketplace.

In order to address the issue in order, the PWR story is divided in two phases. The first phase is the process of value creation and goes from 1945 to 1960, when Westinghouse was able to develop a promising product from scratch. The second phase is the process of value capture and goes from 1960 to 1975, when Westinghouse was able to sell a large number of units in the United States.

First phase

In the late 1940s the U.S. government wanted to develop nuclear power plants as soon as possible. As it was explained in Chapter 1, the main reasons for the rush for building power plants were the externalities associated with military programs, such as the massive production of weapons grade plutonium, and the need to capture the value created by this innovation ahead of other nations. In addition, getting ahead of the Soviet Union in terms of nuclear technology was a national objective.

As was shown in Chapter 2, Westinghouse benefited from the business opportunity and –using government funding- developed an outstanding product, the PWR. A number of other products –Magnox, PHWR, BWR, LWGR, FBR- were developed at the same time but none of them became more successful than the PWR.

The PWR evolved in the right direction because it was intended for the propulsion system of a nuclear submarine. This turned out to be a fortunate factor for three reasons: (a) the nuclear sub was a challenging product that requested a reliable design, (b) the project had the highest government priority, and (c) the rush allowed Westinghouse engineers to have a rapid learning process.

The nuclear submarine was a small-scale power unit with all the complexities of a nuclear power plant plus the severe requirements of underwater operation. For instance, engineers had to design a new type of fuel, which had higher strength and turned out to be better than fuels designed previously. On can argue that Westinghouse made the right decision in committing to this project because the project turned out to have a higher potential than other projects sponsored by the AEC. The difficulties of designing a challenging reactor created an environment favorable for product innovation.

Thanks to the nuclear submarine project, a remarkable group of engineers and scientists was formed at the Bettis Laboratories. This group worked under the leadership of Rickover and the joint umbrella of AEC, Naval Reactors and Westinghouse. The same people worked on a platform of products using the same technology, such as the Mark-I prototype, the Nautilus and the eventually the first PWR plant - Shippingport. The continuity of the Bettis group provided an excellent opportunity for collective learning and rapid technical improvement.

The U.S. government recognized the value of the Bettis group and selected the PWR design to be the first U.S. plant. The government wanted to have a plant operating as soon as possible and Westinghouse and its Bettis Laboratory already had a workable prototype and a successful submarine based on the PWR concept. Additionally, the Bettis team had a record of achievements and it seemed a sound decision to hand a complex project over to one of the best nuclear engineering teams available in the U.S.

In summary, Westinghouse made a number of correct decisions during the first phase of the development of nuclear power plants, when product innovation rate was much higher than process innovation. This early phase is summarized in Figure 8.9, using the framework of innovation patterns introduced in Chapter 3 (Utterback, 1994).

The rate of product innovation is highest during the "fluid" first phase, which for nuclear plants occurred approximately between 1945 and 1960. This is a period where product experimentation occurs both in terms of testing different options and gaining experience. Westinghouse took the most challenging product –the nuclear submarine- and invested time and effort to create a first class engineering staff –the Bettis group. By 1960 Westinghouse was in a great competitive position: it had created a dominant design that served for submarines and power plants, and it had gathered substantial construction experience.

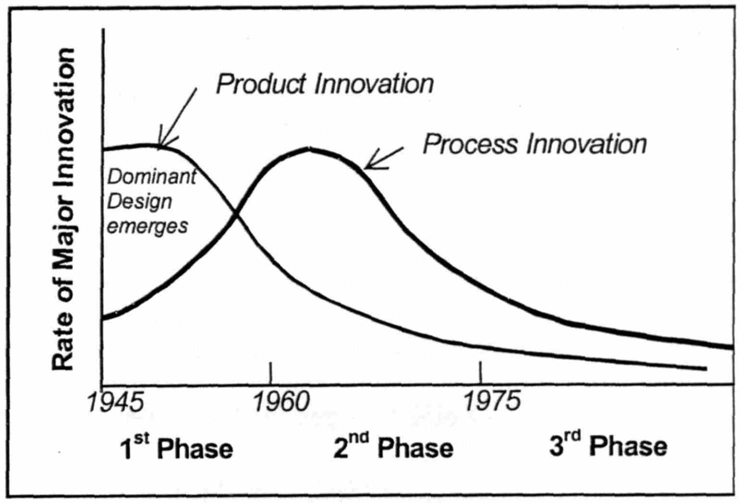


Figure 8.9 The dynamics of innovation (Utterback, 1994)

Second phase

As shown in Figure 8.9, during the first "fluid" period of high product innovation, little attention is given to the processes by which products are made so the rate of process innovation is less rapid. There is a second period, however, where things are reversed. This is the "transitional" second phase where the rate of product innovation slows down and the rate of process innovation takes the lead. That occurred with the PWR design after 1960. Westinghouse became more focused on cost, volume and capacity. Process innovation became the preferred way to introduce changes and these were just incremental innovations on the dominant PWR design. The manufacturing progressed from heavy reliance on R&D to more systematic and repetitive engineering tasks. The organizations in charge of building reactors changed from the small, cohesive and creative group at Bettis Lab toward a more hierarchical organization with defined tasks and procedures. Engineers became more focused on improving the performance of the design or at least what was considered performance of a nuclear power plant at that time.

After securing the first deals in the first half of the 1960s –by means of turnkey projects and the use of government subsidies- Westinghouse was ready for a second phase where the main goal was to capture value from the innovation. In other words, to make profits out of the PWR product.

As shown in the scheme of Figure 8.10, Westinghouse chose to focus on its role of supplier of two of the main components of a nuclear power plant: the nuclear system and the turbine generator. Westinghouse did not seek a high level of vertical integration by entering in the areas of balance of plant and civil construction. On the one hand these areas were not part of Westinghouse's core competencies. On the other, most managers seemed to act as if the demand for reactor systems and turbines was infinite and left the rest of the project in the hands of utilities, architect-engineers and

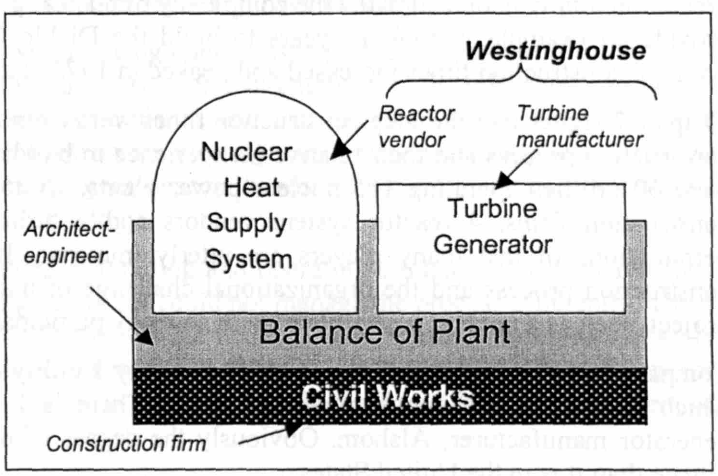


Figure 8.10. Components of the design & construction

construction firms. Westinghouse adopted this strategy probably because it was the familiar way. As was shown in Chapter 5, Westinghouse had a history of selling large turbine generators for conventional power plants. In this segment of the market Westinghouse had been a pure player, with no involvement in other areas of the plant. Therefore, when the first nuclear power plants started to be built, the extension of this role of pure supplier was natural. However, to dodge the complexities of the construction process and to act as if the demand was infinite had a downside: long construction times that jeopardized the competitiveness of nuclear power plants.

The PWR is probably one of the few dominant designs that emerged because of the role of suppliers, in this case the supplier of the reactor system –Westinghouse- and the supplier of the turbine generator –also Westinghouse. As it was shown in Chapter 5, tying these two components together is probably on the borderline of antitrust infringement. Indeed there was an antitrust case against GE and Westinghouse regarding large turbine generators. One can argue that this non-competitive strategy was a win-win deal for both firms that hurt other designs, such as gas-cooled reactors, but by itself it does not explain the early success of the PWR.

General Electric took the same strategic approach as Westinghouse but it was less successful probably for three reasons: (a) utility managers did not like to have water coming from the reactor inside the turbine generator and therefore preferred the PWR over the BWR, (b) the supplier base that Westinghouse was able to assemble was broader, and (c) from the outset Westinghouse issued licenses to firms developing the PWR, thus there were a number of manufacturers of PWR technology such as Framatome, Mitsubishi, Babcock&Wilcox and Combustion-Engineering.

Westinghouse also made the mistake of listening excessively to its customers, the electrical utilities, which were asking for larger power plants. As it was shown in Chapter 7, in the 1960s and 1970s the single most important performance parameter for electrical utilities was scale. The larger the unit the better, as it was assumed that larger sizes implied lower electricity costs (in dollars per kilowatt-hour).

Reactor vendors worked hard to achieve the goal of higher power ratings and were quite successful in the effort, building power plants with power ratings on the order of 1,300 MWe. However, listening to market demand and customer needs was exactly the wrong thing to do. The right signals to listen were the increasingly long times required to construct plants.

Originally in the early 1960s, when utilities jumped into the nuclear bandwagon, they expected construction times in the order of 5 years with slight increases due to increasing complexity. The first nuclear power plant in the United States, Shippingport, was built in three years, and in days to come it was predicted that normal construction times of larger units would take on average five years. But this prediction totally underestimated the complexity of nuclear plant construction in the United States. Just to provide an example, it took 17 years to build the Diablo Canyon nuclear power plant in California. Average construction times increased and peaked in 1975 at around 12 years.

Chapter 7 argues that the long construction times were caused by the large number of participants in the construction process and their relative inexperience in building power plants. In the United States, there were 60 utilities operating 115 nuclear power plants, 15 architect- engineers and a similar number of construction firms, 4 reactor system vendors and 2 turbine generator manufacturers. The possible permutations of that many players are utterly immense. It is similarly huge the complexity of the construction process and the organizational challenge of undertaking an extremely technically difficult project, such as a nuclear power plant, with so many participants on board.

Compare this situation with France, which has only 1 utility operating 60 reactors, Electricite de France, which is also the architect-engineer of plants. There is 1 reactor vendor, Framatome, and 1 turbine generator manufacturer, Alshom. Obviously the degree of organizational complexity is much lower in France than it is in the United States.

The rise in construction times increased the capital costs of nuclear power plants by nearly one-third of the original "overnight" capital cost. Since 70% of the cost of electricity generated by a nuclear power plant is due to the up front capital cost, these delays increased the underlying cost of these assets by at least 30%. Such an abrupt increase in cost simply could not be afforded by electrical utilities. Hence, the original promise of economies of scale could not be fulfilled. Instead of having lower unit costs (in \$/kWh) the electricity producers were having higher unit costs. Utilities virtually had to manage large complex and challenging generating assets to have input costs that were above market value. It was not a sound investment at all, i.e. economies of scale affected O&M and fuel costs which were the smaller portion of total costs (see Figure 8.11).

The fact of the matter is the first priority of an electrical utility is to have a low degree of financial risk and that goal was not achieved. Nuclear power plants had a huge financial risk because many plants were not completed on time and more than one was cancelled prior to the opening. Had Westinghouse put investment security as first priority then its strategy would have been different, probably with more control over the management of projects. Instead of focusing on the role of supplier Westinghouse should had a more proactive role in project management.

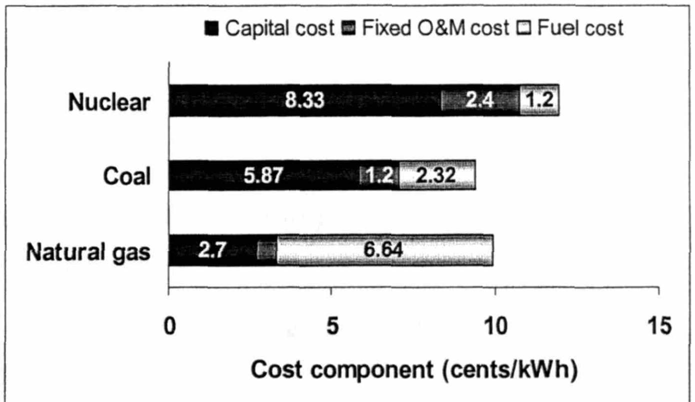


Figure 8.11 Cost components of power plants

Westinghouse made the decision to standardize the PWR in order to speed up the delivery of products and benefit from learning effects. Arguably, that was the right decision at the right time. However, the rest of the plants were largely not standardized, and were built on a one-of-a-kind basis. This lack of overall plant standardization jeopardized the PWR because units could not be delivered on time. Construction times skyrocketed and licensing applications became a mess.

The roles of architect-engineers and construction firms are fundamental in the timely delivery of a nuclear power plant. Also important is how these firms interact with the utility that will operate the plant. Nonetheless, the careful analysis and of these interactions were absolutely overlooked by the AEC and reactor system vendors. In the rush for building power plants, these critical participants did not think about what turned out to be the Achilles' heel of the U.S. nuclear power industry.

Westinghouse should have been more proactive in having control over project management since it was the number one stakeholder in the PWR technology. An architect-engineer such as Bechtel can be the prime contractor of coal-fired plants, combined cycle plants, etc; and therefore not be committed to a particular design such as the PWR reactor. As a lesson for Westinghouse, sometimes suppliers of critical components need to look for more control of the project, especially when there are many participants and none of them is particularly engaged with the technology.

Electrical utilities underestimated the difficulties of building and operating a nuclear power plant. They rushed to buy these fancy electricity-generating assets but could not manage the process efficiently. Three decades later, a large consolidated operator like Exelon has learned to benefit from the economies of scale possible in large nuclear power plants. Regulated electricity markets did not provide the opportunity for the emergence of a nuclear operator such as Exelon in the 1960s. Only the deregulation environment of the 1990s allowed this to occur.

Policymakers were naïve regarding the partnership of electrical utilities with the AEC to build nuclear power plants. Given the heavily regulated environment, the creation of large government-owned and largely nuclear-specialized utility would have been the best choice. The example of EdF in France is worthwhile to mention here. EdF managed to build 60 nuclear power plants with construction times on the order of 6 years (half the time most U.S. utilities spent building plants back in the 1970s).

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