2

Nuclear Power Development

2.1 Present Status of Nuclear Power

Nuclear reactors are now being used in 31 countries for the generation of electricity. Overall, they supply about one-sixth of the world's electricity [1]. As of November 2003, there were 440 operating nuclear power reactors in the world, with a combined net generating capacity of 360 gigawatts-electric (GWe) [2].[1] Summary data on these reactors are presented in Table 2.1, which lists for each country the total nuclear generation and nuclear power's fraction of the total electricity generation.

The United States is the leader in total generation and France, among the larger countries, is the leader in the fraction of electricity obtained from nuclear power. By and large, use of nuclear power is concentrated in the industrialized countries of the Organization for Economic Co-operation and Development (OECD) and of Eastern Europe. However, some countries in the OECD have no nuclear power (for example, Italy) and some Asian countries that are not OECD members are increasing their nuclear programs (e.g., China and India).

The listing in Table 2.1 includes only reactors used for electricity generation. In addition, there are a large number of reactors throughout the world used for research and the production of radioisotopes for medical and industrial applications. Beyond these civilian reactors, an undisclosed number of

[1] We here use data compiled by the International Atomic Energy Agency (IAEA) and posted, with periodic updating, on its website [2, 3].

Table 2.1. World nuclear status: Operating power reactors (November 2003), net generation (2002), nuclear share of electricity generation (2002).

	Status 11/17/03		Generation, 2002		Percent
Country	Number of Units	Capacity (Net GWe)	Net TWh	Net GWyr	Nuclear 2002
United States	104	98.2	780	89.1	20
France	59	63.1	416	47.4	78
Japan	54	44.3	314	35.8	34
Germany	19	21.3	162	18.5	30
Russia	30	20.8	130	14.8	16
South Korea	18	14.9	113	12.9	39
United Kingdom	27	12.1	81	9.3	22
Ukraine	13	11.2	73	8.4	46
Canada	16	11.3	71	8.1	12
Sweden	11	9.4	66	7.5	46
Spain	9	7.6	60	6.9	26
Belgium	7	5.8	45	5.1	57
Taiwan	6	4.9	34	3.9	21
Switzerland	5	3.2	26	2.9	40
China	8	6.0	23	2.7	1.4
Finland	4	2.7	21	2.4	30
Bulgaria	4	2.7	20	2.3	47
Czech Republic	6	3.5	19	2.1	25
Slovakia	6	2.4	18	2.0	55
India	14	2.5	18	2.0	4
Brazil	2	1.9	14	1.6	4
Lithuania	2	2.4	13	1.5	80
Hungary	4	1.8	13	1.5	36
South Africa	2	1.8	12	1.4	6
Mexico	2	1.4	9.4	1.1	4
Argentina	2	0.9	5.4	0.6	7
Slovenia	1	0.7	5.3	0.6	41
Romania	1	0.7	5.1	0.6	10
Netherlands	1	0.5	3.7	0.4	4
Armenia	1	0.4	2.1	0.2	40
Pakistan	2	0.4	1.8	0.2	2.5
WORLD TOTAL	440	360	2574	294	

Note: IAEA data are used for this table. Other compilations differ somewhat, due to differences in defining the status of some reactors and in dates (e.g., *Nuclear News* lists 444 reactors worldwide at the end of 2002, with a capacity of 364 GWe [4]).
Source: Data from Refs. [2] and [3].

reactors have been used for the production of plutonium and the propulsion of ships.

2.2 Early History of Nuclear Energy

2.2.1 Speculations Before the Discovery of Fission

Atomic energy, now usually called nuclear energy,[2] became a gleam in the eye of scientists in the early part of the 20th century. The possibility that the atom held a vast reservoir of energy was suggested by the large kinetic energy of the particles emitted in radioactive decay and the resultant large production of heat. In 1911, 15 years after the discovery of radioactivity, the British nuclear pioneer Ernest Rutherford called attention to the heat produced in the decay of radium, writing:

> This evolution of heat is enormous, compared with that emitted in any known chemical reaction. . . . The atoms of matter must consequently be regarded as containing enormous stores of energy which are only released by the disintegration of the atom. [5]

At this time, however, Rutherford had no concrete idea as to the source of this energy. The magnitudes of the energies involved were gradually put on a more quantitative basis as information accumulated on the masses of atoms, but until the discovery of fission in 1938, there could be no real understanding of how this energy might be extracted. In the interim, however, important progress was made in understanding the basic structure of nuclei. Major steps included the discovery by Rutherford in 1911 that an atom has a nucleus, the discovery in 1932 of the neutron as a constituent of the nucleus, and a series of experiments undertaken in the 1930s by Enrico Fermi and his group in Rome on the interactions between neutrons and nuclei, which eventually led to the discovery of fission.[3]

As these developments unfolded, there was general speculation about atomic energy. One of the earliest scientists to have thought seriously about the possibilities was Leo Szilard, who was later active in efforts to initiate the U.S. atomic bomb program and then to limit it. He attributed his first interest in the extraction of atomic energy to reading in 1932 a book by the British novelist H. G. Wells. Writing in 1913, Wells had predicted that artificially

[2] Although the two terms mean the same thing, there has been some shift in usage with time. Originally, "atomic energy" was the more common designation, but it has been largely replaced by "nuclear energy." For example, the U.S. *Atomic* Energy Commission was established in 1946 and the U.S. *Nuclear* Regulatory Commission in 1975.

[3] Historically oriented accounts of these developments and the discovery of fission are given in Refs. [6]–[8]. A discussion of basic nuclear physics concepts and terminology is presented in Appendix A.

induced radioactivity would be discovered in 1933 (he guessed the actual year of discovery correctly!) and also predicted the production of atomic energy for both industrial and military purposes. In Szilard's account, he at first "didn't regard it as anything but fiction." A year later, however, two things caused him to turn to this possibility more seriously: (1) He learned that Rutherford had warned that hopes of power from atomic transmutations were "moonshine"[4] and (2) the French physicist Frederic Joliot discovered artificial radioactivity as predicted by H. G. Wells[5] [9, pp. 16–17].

Szilard then hit upon a "practical" scheme of obtaining nuclear energy. At the time, it was thought that the beryllium-9 (^{9}Be) nucleus was unstable and could decay into two alpha particles and a neutron. This was a misconception, based on an incorrect value of the mass of the alpha particle. Actually, ^{9}Be is stable if only by a relatively small margin. In any event, Szilard thought that it might be possible to "tickle" the breakup of ^{9}Be with a neutron and then use the extra neutron released in the breakup to initiate another ^{9}Be reaction. In each stage, there is one neutron in and two neutrons out. This is the basic idea of a chain reaction. This particular chain reaction cannot work, as was soon realized, because too high a neutron energy is required to cause the breakup of ^{9}Be, and even then, there is a net loss of energy in the process, not a gain.

Szilard tried to find other ways to obtain a chain reaction, but his efforts failed. Nonetheless, in the interim, he went so far as to have a patent on neutron-induced chain reactions entrusted to the British Admiralty for secret safekeeping, the military potential of nuclear energy being important in his thinking [8, p. 225]. However, the key to a realizable chain reaction—fission of heavy elements—eluded Szilard as well as all others.

In these early speculations, there was an awareness of the potential of atomic energy for both military and peaceful applications, and the latter loomed large in the thinking of some scientists. For example, in a document dated July 1934, Szilard explained planned experiments that, if successful, would lead to

> power production. . .on such a large scale and probably with so little cost that a sort of industrial revolution could be expected; it appears doubtful for instance whether coal mining or oil production could survive after a couple of years. [9, p. 39]

[4] It is not clear from the Szilard reference whether the word "moonshine" was Rutherford's own or whether it was a paraphrase appearing in *Nature* in a summary of Rutherford's talk.

[5] Joliot, later Joliot-Curie, shared with his wife, Irene Joliot-Curie, the 1935 Nobel Prize in Chemistry for their discovery in 1933 of artificial radioactivity. They were the son-in-law and daughter of Marie and Pierre Curie, recipients (with Becquerel) in 1903 of the Nobel Prize in Physics, awarded for the discovery of radioactivity.

Along the same lines, Joliot prophesied in his 1935 Nobel Prize acceptance speech:

> scientists, disintegrating or constructing atoms at will, will succeed in obtaining explosive nuclear chain reactions. If such transmutations could propagate in matter, one can conceive of the enormous useful energy that will be liberated. [10, p. 46]

2.2.2 Fission and the First Reactors

Fission of uranium was discovered—or, more precisely, recognized for what it was—in 1938.[6] Scientists quickly recognized that large amounts of energy are released in fission and that there was now, in principle, a path to a chain reaction. By early 1939, it was verified that neutrons are emitted in fission, and it soon became apparent that enough neutrons were emitted to sustain a chain reaction in a properly arranged "pile" of uranium and graphite.[7] It took several more years to demonstrate the practicality of achieving a chain reaction. This work was led by Fermi, who had left Italy for the United States, and it culminated in the development and demonstration of the first operating nuclear reactor on December 2, 1942 at an improvised facility in Chicago.

The discovery and preliminary understanding of fission came at a time when the prospect of war was much on people's minds. The start of World War II in Europe in August 1939 ensured that military, rather than civilian, applications of atomic energy would take primacy, and the early work was heavily focused on the military side, in both thinking and accomplishments. A major goal of the nuclear program was the production of plutonium-239 (^{239}Pu), which was recognized to be an effective material for a fission bomb. The ^{239}Pu was to be produced in a reactor, by neutron capture on uranium-238 (^{238}U) and subsequent radioactive decays.

The first reactor in Chicago was very small, running with a total power output of 200 W. However, even before the successful demonstration of a chain reaction in this reactor, plans had started for the construction of the much larger reactors required to produce the desired amounts of plutonium. A pilot plant, designed to produce 1 MW, was completed and put into operation at Oak Ridge, Tennessee in November 1943 [11, p. 392]. A full-size 200-MW reactor began operating at the Hanford Reservation in Washington state in September 1944—a millionfold increase in power output in less than 2 years.[8]

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[6] See Sections 6.1 and 6.2 for a brief description of fission and its discovery.

[7] The uranium was the fuel. The graphite served as a "moderator," to slow the neutrons down to energies where they were most effective in producing fission in uranium. See Section 7.2 for a discussion of moderators.

[8] Power is commonly measured in watts (W), kilowatts (kW), megawatts (MW), and gigawatts (GW), where 1 kW = 10^3 W, 1 MW = 10^6 W, and 1 GW = 10^9 W. The basic energy output of a reactor is in the form of heat and often this is explicitly recognized by specifying the power in *megawatts-thermal* (MWt).

The laboratories at Oak Ridge and Hanford were new wartime installations. The Hanford site was not selected until early 1943, and construction of the first reactor began in June 1943. Workers completed the reactor within about 15 months, despite the absence of any directly relevant prior experience.[9] The speed with which the program was pursued is breathtaking by present standards, but it can be understood in the context of the exigencies of World War II.

The pressures of wartime bomb development pushed work on peaceful applications largely into the background, but there was still considerable thinking about future civilian uses. An official report on the development of the atomic bomb was prepared by Henry Smyth, a Princeton physicist. It was published in 1945, shortly after the end of the war, to inform the public about the bomb project. In a closing section, entitled "Prognostication," Smyth pointed out:

> The possible uses of nuclear energy are not all destructive, and the second direction in which technical development can be expected is along the paths of peace. In the fall of 1944 General [Leslie] Groves appointed a committee to look into these possibilities as well as those of military significance. This committee. . .received a multitude of suggestions from men on the various projects, principally along the lines of the use of nuclear energy for power and the use of radioactive by-products for scientific, medical, and industrial purposes. [12, pp. 224–225]

With or without such a committee, it was inevitable that imaginative scientists would consider ways of using nuclear energy for electricity generation. The possibility, for example, of power production from a reactor that used water at high pressure for both cooling the reactor and moderating the neutron energies was suggested as early as September 1944, in a memorandum written by Alvin Weinberg who was then working closely with Eugene Wigner on reactor designs [13, p. 43]. This is the basic principle of the dominant reactor in the world today, the *pressurized light water reactor* (PWR).[10]

For reactors designed to produce electricity, the more interesting quantity is the output in *megawatts-electric* (MWe). (For a reactor operating at an efficiency of 33%, the output in MWt is three times the output in MWe.) The maximum electrical power of a nuclear reactor is its *capacity*. When the specification is not explicit, the term "megawatt" usually means MWe for reactors used to produce electricity and MWt for reactors used for other purposes, including the early WWII reactors.

[9] An early summary of this chronology is given in Ref. [11], Chapter XIV.

[10] *Light water reactor* (LWR) refers to a reactor cooled and moderated with ordinary water, the word "light" being used to differentiate these reactors from those cooled or moderated with heavy water [i.e., water in which the hydrogen is primarily in the form of deuterium (^2H)]. The PWR is one version of the LWR. Characteristics of LWRs are discussed at length in later chapters.

2.3 Development of Nuclear Power in the United States

2.3.1 Immediate Postwar Developments

Interest in Commercial Nuclear Power

In the years immediately following World War II, the main activities of the American nuclear authorities continued to be directed toward further military developments, but increased attention was turned to electricity generation. A somewhat guarded assessment of the future was presented in the Smyth report:

> While there was general agreement that a great industry might eventually arise. . .there was disagreement as to how rapidly such an industry would grow; the consensus was that the growth would be slow over a period of many years. At least there is no immediate prospect of running cars with nuclear power or lighting houses with radioactive lamps although there is a good probability that nuclear power for special purposes could be developed within ten years. [12, p. 225]

This turned out to be rather close to the mark, although the words "slow" and "immediate" may have had different connotations in 1945—in the wake of the rapid pace of wartime development—than they do today.

There were, however, impediments to quick progress. For one, fossil fuels were plentiful in the 1950s, so no immediate urgency was felt. Nuclear facilities and technical knowledge were under the tight control of the AEC, with many aspects kept secret because of the military connections. Further, there was indecision as to the relative roles to be played by the government and private utilities in the development of nuclear power. Finally, it was not clear which type or types of reactor should be built.

The U.S. Navy made a decision first and, under the leadership of Hyman Rickover, built and began tests of pressurized light water reactors by the first part of 1953 [14, p. 188]. These reactors became the foundation of the U.S. nuclear submarine fleet. After some hesitation and consideration of alternative designs for a reactor for the generation of commercial electric power, the AEC announced in autumn 1953 that it would build a 60-MWe power plant [14, p. 194]. Participation by utilities was sought. The general reactor configuration was to be the same as that used by the navy, namely a pressurized light water reactor. A Pennsylvania utility won the competition to participate in this project, contributing the land and buildings and undertaking to run the facility when completed. The reactor was built at Shippingport, Pennsylvania and was put into operation at the end of 1957 [14, pp. 419–423].

Early Enthusiasm: "Too Cheap to Meter"?

Despite the considerable caution in initiating the U.S. nuclear power program, many euphoric statements about the future of nuclear power were made in the 1940s and 1950s. Such statements even go back as far as H. G. Wells in 1913. Nuclear power was to be abundant, clean, and inexpensive. Of course, thoughtful observers modulated and qualified even their optimistic prophecies, but some of the optimism was quite unbridled. For example, an article in *Business Week* in 1947 stated, "Commercial production of electric power from atomic engines is only about five years away.... There are highly respected scientists who predict privately that within 20 years substantially all central power will be drawn from atomic sources" [15].

However, among all the enthusiastic quotations from that era, one in particular has come to haunt nuclear advocates. In the 1980s, as nuclear power became more expensive than electricity from coal, an earlier phrase, "too cheap to meter," was thrown back in the faces of proponents of nuclear power as illustrating a history of false promises and overweening and foolish optimism.

The phrase originated with Lewis L. Strauss, the chairman of the Atomic Energy Commission (AEC) in the 1950s. Speaking at a science writers meeting, he stated: "It is not too much to expect that our children will enjoy electrical energy in their homes too cheap to meter." The phrase was used in a *New York Times* headline on September 17, 1954, the day after the speech.[11] A fuller version of Strauss' remarks, as they appeared in his prepared text, indicated a broadly euphoric technological optimism about nuclear energy and its applications [16, p. 2].

It is doubtful that many professionals shared this euphoria at the time. A more official version of the AEC position, expressed in Congressional testimony in June 1954, held out the hope that

> ...[nuclear power] costs can be brought down—in an established nuclear power industry—until the cost of electricity from nuclear fuel is about the same as the cost of electricity from conventional fuels, and this within a decade or two. [16, p. 4].

Overall, the history appears to have been one of hesitation and examination, followed by a conviction developing in the 1960s that nuclear power would indeed be less expensive than the fossil fuel alternatives. For a period, in the 1970s, this expectation was fulfilled in the United States, and it is still partially fulfilled in some countries. The failure of this expectation in later

[11] An account of the history of the remark is given in a brief report prepared by the Atomic Industrial Forum (AIF), a nuclear advocacy organization [16]. There is a good chance that Strauss was thinking of fusion power, not fission power, although he could not be explicit because the practicalities of fusion were secret in 1954, with the development of the hydrogen bomb only recently started. The AIF report quotes Lewis H. Strauss, the son of Lewis L. Strauss and himself a physicist: "I would say my father was referring to fusion energy. I know this because I became my father's eyes and ears as I travelled around the country for him."

years in the United States was a surprise and disappointment to nuclear proponents as well as to many neutral analysts. There was a serious misjudgment, but not as egregious a folly as connoted by the "too cheap to meter" phrase.

2.3.2 History of U.S. Reactor Orders and Construction

The First Commercial Reactors

The Shippingport reactor was a unique case. Although used to supply commercial electricity, it was largely financed by the federal government and built under navy leadership. Following the order of the Shippingport reactor in 1953, there was a fitful pattern of occasional orders by utilities during the next 10 years. This early period of reactor development was characterized by extensive exploration, with a wide variety of reactors being developed for military and research applications and for electricity generation. For the latter, a total of 14 reactors were ordered in the period from 1953 through 1960 [17]. They included nine light water reactors (LWRs), not identical by any means, plus five other reactors with a wide variety of coolants and moderators.[12] With three exceptions, these reactors all had capacities under 100 MWe.

The three reactors ordered in this period that had capacities above 100 MWe were the 265-MWe Indian Point 1 (New York), the 207-MWe Dresden 1 (Illinois), and the 175-MWe Yankee Rowe (Massachusetts) reactors, which were ordered in 1955 and 1956 [17].[13] These were all LWRs. The first to go into operation was Dresden 1, in 1960.

Growth Until the Mid-1970s

The exploratory period ended quickly. There was a brief lull in reactor orders after 1960, with only five more orders until 1965, and then a period of rapid increase from 1965 through 1974. The dominance of LWRs in U.S. reactor orders was complete after 1960, the only exception being the gas-cooled Fort St. Vrain reactor, ordered in 1965.

None of the reactors ordered before 1962 had a capacity as large as 300 MWe. After that, there was a substantial escalation in reactor size, in an effort to gain from expected economies of scale. Some critics believe that the growth in size was too fast to permit adequate learning from experience. The mean size of reactors ordered in 1965 was about 660 MWe, but by 1970, the mean size exceeded 1000 MWe, with some above 1200 MWe. The largest reactors completed and licensed to date in the United States have a (net) capacity of 1250 MWe.

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[12] These were a fast breeder reactor, a sodium graphite reactor, a high-temperature gas-cooled reactor, an organic moderator reactor, and a heavy water reactor. The variety of reactor types is discussed in Chapter 8.

[13] These reactors have all been shut down, most recently Yankee Rowe in 1991.

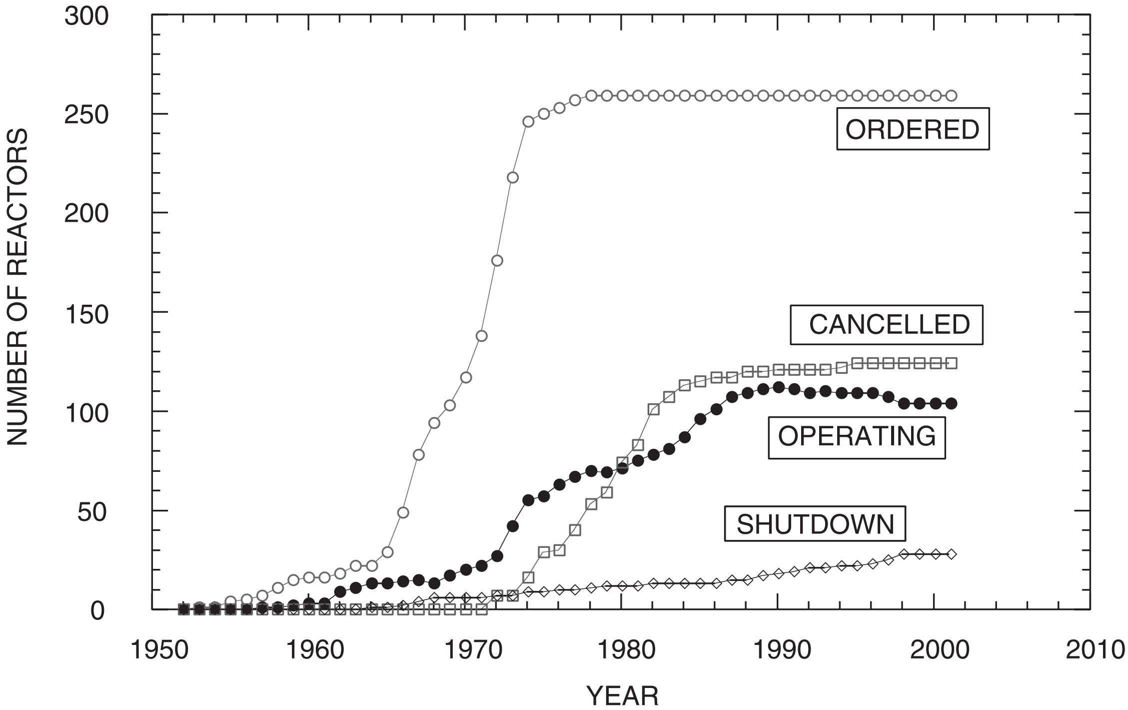

Fig. 2.1. Cumulative history of nuclear reactor orders in the United States, 1953–2001, including cancellations and shutdowns. (Data from Ref. [18], p. 253.)

The history of nuclear reactor deployment from 1953 through 2001 is summarized in Figure 2.1, which shows the cumulative pace of reactor orders as well as the number of reactors that were in operation, that have been canceled, or that have been shut down. There was a period of rapid growth in the number of orders from 1965 to 1975. At first, reactors were completed within about 6 years, and by the early 1970s nuclear power had begun to assume significant proportions. At the end of 1974, there were about 55 reactors in operation, with a total capacity of almost 32 GWe, providing 6% of U.S. electricity [18, p. 255].

Reactor Deployment Since the Mid-1970s

The picture changed abruptly in the mid-1970s. In contrast with the 4-year period from 1971 to 1974, when 129 reactors had been ordered, only 13 reactors were ordered during 1975–1978. After 1978, new orders ceased entirely and all reactors ordered after 1973 have been canceled. The de facto moratorium on commercial reactor orders has continued in subsequent years, and at the time of this writing (early 2004), no new orders are in clear prospect.

A major factor in this change was a sharp drop in the growth in electricity demand, as reflected in Figure 1.1. The growth in electricity consumption averaged over 7% per year from 1953 to 1973—a doubling time of under 10 years. This growth ended in 1974, with an actual drop of 0.4% that year, precipitated by the economic shock of OPEC's oil embargo in late 1973. After 1974, with a reduced rate of economic growth and a new emphasis on conservation, electricity sales grew at a much slower rate than in preceding decades, averaging about 2.7% per year during 1975–2000. Utilities that had previously placed orders for generating facilities found themselves facing a surplus of planned capacity. A first response was to stop plans for expansion.

Nuclear power was particularly impacted by the lessening demand for electricity, because it was additionally confronted by growing opposition and by increasing costs of reactor construction. These factors all worked to slow nuclear deployment after 1974, although reactors continued to go on line until the Three Mile Island accident in March 1979. The accident led to a 1-year hiatus, followed by a gradual resumption of deployment of reactors that were already in the pipeline. Overall, 51 new reactors have been put into commercial operation since 1979. The last of these was in 1996—the Watts Bar I reactor operated by the Tennessee Valley Authority (TVA).

At the end of 2003, there were 104 operating reactors in the United States with a net capacity of 98 GWe.[14] All are light water reactors. Total net generation in 2002 was 772 billion kilowatt-hours, or, in alternative units, 88 gigawatt-years (GWyr) where 1 gigawatt-year = 8.76×10^9 kWh [20]. The fraction of electricity provided by nuclear power has risen to about 20% in recent years. Until 1990, the driving force in the increased nuclear output was the addition of new reactors. Since 1990, there has been little change in nuclear capacity, with 7 new reactors having gone into operation and 11 reactors (in general smaller) shut down. Nonetheless, there was an increase of 34% in total nuclear generation due to improved operation of existing reactors (see Section 2.4.2).

Three additional reactors, with capacities of roughly 1200 MWe each, are in something of a state of limbo [4]. They are each listed as more than 50% completed, but construction has been halted for many years, and as of mid-2003, there were no announced plans to resume construction.[15] They all belong to the TVA, which has six licensed reactors, including Browns Ferry 1.

No further nuclear reactors are on the immediate horizon in the United States, and for the time being, nuclear power in the United States is at a plateau. However, the federal government in recent years has looked with more favor on nuclear power. The U.S. Department of Energy in 1998, acting upon the recommendation of the President's Committee of Advisors on Science and Technology (PCAST), launched a Nuclear Energy Research Initiative (NERI) designed to stimulate innovative thinking on topics such as:

[14] One of these reactors, the 1065-MWe Browns Ferry 1 reactor, operated by the TVA, was shut down in 1985 along with four other TVA reactors that have since gone back into service. The TVA Board voted in May 2002 to restart Browns Ferry 1 [19]. Major changes are to be made in the reactor building and contents, and the restart will not occur for several years. (During the shutdown period, Browns Ferry 1 has been included in most U.S. government compilations as an "operating reactor" because it has an operating license.)

[15] The three reactors are Bellefonte 1 & 2 and Watts Bar 2.

proliferation-resistant reactors or fuel cycles; new reactor designs with higher efficiency, lower cost, and improved safety to compete in the global market; low-power units for use in developing countries; and new techniques for on-site and surface storage and for permanent disposal of nuclear waste. [21, p. 5–13]

The DOE in 1998 also established the Nuclear Energy Research Advisory Committee (NERAC) to advise on nuclear technology programs. The work of NERI has led to a number of imaginative proposals for new reactors, and NERAC has developed plans to encourage the deployment of new reactors by 2010 as well as the development of advanced designs for later deployment. These initiatives are discussed further in Chapter 16.

2.3.3 Reactor Cancellations

Quantitative detail on the history of orders and cancellations is given in Figure 2.2, which indicates the numbers of reactors ordered in each year and the number of these orders that were not canceled. Overall, almost all reactors now in operation were ordered in the period from 1965 through 1973. This is a very compressed interval, and one that did not allow much opportunity for the manufacturers and utilities to learn from experience.

A striking feature of the data shown in Figure 2.2 is the large number of cancellations of reactors after they had been ordered. In fact, the number of canceled reactors exceeds the number of reactors that are still in operation. The wave of orders in the 1965–1974 period was followed by a wave of cancellations in 1974–1984. The overall record is summarized in Table 2.2, which gives the total nuclear reactor orders from the 1950s to the end of 2002 and a summary of the disposition of the orders.

As seen in Table 2.2, almost one-half of the reactors that were ordered since 1953 have had their orders canceled. In many cases, although not most, cancellation came after construction had started. The other half of the ordered reactors were completed and put into operation, but some of these have since been permanently shut down. The large number of cancellations reflects the same forces that led to the cessation of new orders: the decline in the electricity growth rate, public or political opposition to nuclear power, and increased costs.

2.4 Trends in U.S. Reactor Utilization

2.4.1 Permanent Reactor Closures

One of the threats to the nuclear industry has been the prospect of the permanent shutdown of reactors before the expiration of their operating licenses (commonly issued for 40 years). This has happened to 28 reactors out of 132

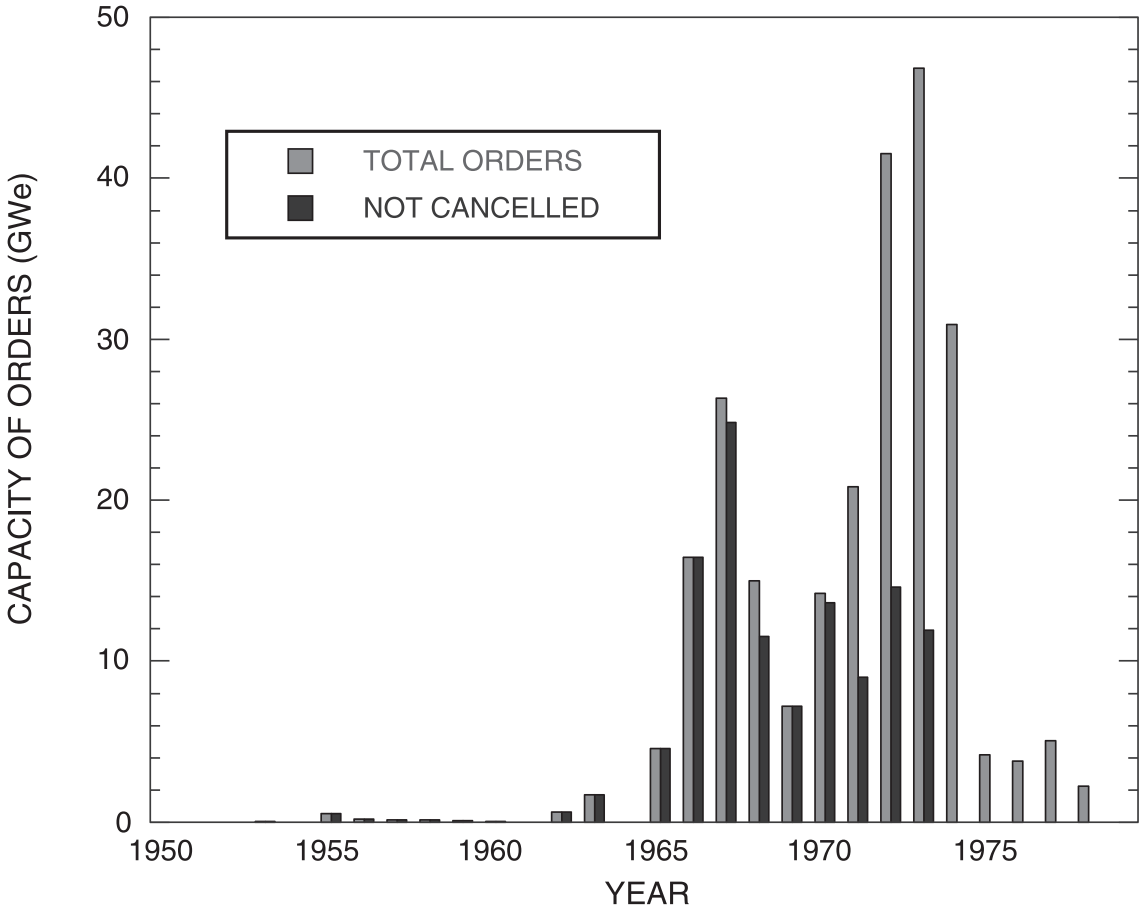

Fig. 2.2. Reactor orders in the United States, 1953–1978 (in GWe of total capacity). Annual figures are given for all orders and for those that were not subsequently canceled. The "not canceled" category includes operating reactors, reactors that have been shut down, and three partially completed reactors. (Data from Ref. [17]; the plot does not reflect several additional cancellations since 1994.)

Table 2.2. Cumulative record of nuclear power in the United States, 1953–2003.

Status	Number of Reactors
Orders for power reactors	259
Construction permit issued	177
Order canceled before reactor operated	124
Construction halted, but not canceled	3
Put into operation	132
Operable as of 12/31/03	104
Permanently shut down, before 12/31/03	28

Source: Ref. [18], p. 253, for period through 12/31/01; there were no changes during 2002 or 2003.

that have gone into operation.[16] However, the large majority of the closed reactors began operating in the 1960s, including 12 with capacities under 80 MWe that were shut down before 1970. Some of the larger of the 1960s reactors remained in operation considerably longer, with several lasting until the 1990s. The largest of the 1960s reactors was the Hanford N reactor (860 MWe), which was built in part for plutonium production and was operated by the U.S. Department of Energy, not by an electric utility. It was shut down in 1988.

In addition to the closing of these older reactors, nine reactors that went into operation after 1970 have been shut down. These are listed in Table 2.3. Their total capacity was 7.5 GWe. They fall into several categories:

- Three Mile Island 2, which went into operation in 1978. It was severely damaged in 1979 in one of the world's two major reactor accidents (the other being the much worse accident at Chernobyl). The damage to the reactor and resulting contamination to the building made it impossible to put the reactor back into operation.
- Shoreham in Long Island, New York, which operated briefly at very low power after issuance of a low-power license in 1985. Local and state opposition prevented the issuance of a license to operate at full power and,

Table 2.3. U.S. reactors that went into operation after 1970 and that have been shut down.[a]

Reactor	Capacity (MWe)	Year of Shutdown	Year of Initial Operation
Millstone 1	660	1998	1971
Zion 1	1040	1998	1973
Zion 2	1040	1998	1974
Maine Yankee	860	1997	1972
Trojan	1095	1992	1976
Shoreham[b]	809	1989	—
Fort St. Vrain	330	1989	1979
Rancho Seco	913	1989	1975
Three Mile Island 2	792	1979	1978

[a]Status as of December 31, 2003.
[b]The Shoreham reactor received a low-power license but was never put into full-scale operation.
Source: Ref. [4].

[16] The precise numbers of reactors in these categories is a matter of definition. The DOE tabulation of Ref. [18] indicates that 28 reactors have been shut down. A tabulation in *Nuclear News* names 24 closed reactors [4], and an IAEA listing names 22 closed reactors [3]. The latter list includes three reactors, none larger than 22 MWe, that were shut down in the 1960s that are not in the *Nuclear News* list. The discrepancies in the listings all involve special cases, where the question of whether the reactor was ever in "commercial operation" is blurred.

after lengthy negotiations, the reactor was closed, with neither its status as having been in operation nor its date of "shutdown" crisply defined.

- Three reactors that were shut down by 1992 that had a history of poor performance and low capacity factors, which weakened their economic and political viability (Rancho Seco, Fort St. Vrain, and Trojan). Considerable public controversy surrounded the decisions as to their fates.
- Four reactors that were shut down in 1997 and 1998, in financial decisions by the utilities that operated them. From the utility standpoint, it was less costly to shut down the reactor than to continue to operate it, and these actions elicited little controversy.

Each of these categories carries a cautionary note. In the case of Three Mile Island it is obvious: A serious accident must be avoided. The case of the Shoreham reactor has probably been the most worrisome to utilities, because in this instance a reactor was completed, but public hostility prevented its use. The weak performers in the third group are a reminder that a reactor is vulnerable, for both economic and political reasons, if its performance is poor. The fourth group provides additional warning on the need to be economically competitive.

The reactor closures of the 1990s were interpreted by some as the forerunner of a cascade of further closures, but, in fact, they stopped after 1998. Instead, as discussed in Section 2.4.5, there has been a switch in the opposite direction, with a wave of applications for operating license renewals.[17]

2.4.2 Capacity Factors

The cessation of reactor orders, the absence of any new orders on the horizon, and a spate of closures have represented discouraging trends for U.S. nuclear power. A bright spot, however, has been the recent improvement in operating performance. We discuss a number of specific indicators of improved performance in Section 14.4. An overall, more immediate measure of how well a reactor is performing is given by its *capacity factor*. The capacity factor for a reactor in any period is the ratio of its total electrical output during that period to the output if it had run continuously at full power. Capacity factors are usually expressed in percent, the ideal being 100%.

Although a capacity factor above 90% for an individual reactor in a given year was not uncommon before the late 1990s,[18] the capacity factors were usually well below 90% over a more extended period due to scheduled and

[17] This does not mean that no reactors will be shut down before their 40 years of operation are completed. For example, there is pressure from some local environmental groups and political bodies to shut down the Indian Point nuclear plant located north of New York City. They argue that terrorist attacks could lead to large releases of radioactive material from the plant and that emergency plans to evacuate people within a 10-mile radius are inadequate. The plant has two PWRs, each rated at about 1000 MWe.

[18] For example, the 90% level was exceeded by 29 U.S. reactors in 1994 [23].

unscheduled maintenance and variations in demand. For many years, a capacity factor greater than 80% was considered to be very good. However, in a development that probably even took most nuclear enthusiasts by surprise, the average capacity factor for U.S. reactors has been above 85% since 1999.

The average capacity factor for U.S. reactors since 1973 is plotted in Figure 2.3. After hovering around 50%, it gradually rose to over 60% in 1977 and 1978, but dropped following the Three Mile Island accident in 1979, which precipitated a period of precautionary repairs and modifications. Some of these entailed long periods during which a reactor was out of operation. With the completion of most of these modifications, there has been a significant increase in the annual average capacity factor beginning in 1988. The capacity factor reached 66% in 1990 and then rose to 77% in 1995 and to 90% in 2002 [20, Table 8.1].

The improvement in capacity factors has been attributed by the nuclear industry to concerted efforts at improvement, including modifications in equipment and operator training, as well as better communications within the nuclear industry to facilitate learning from experience. These efforts resulted in fewer unintended shutdowns and a shortened period for planned shutdowns, such as those for refueling the reactor. Some of the capacity factor increase may also be due to the abandonment of reactors that had been below average in performance.

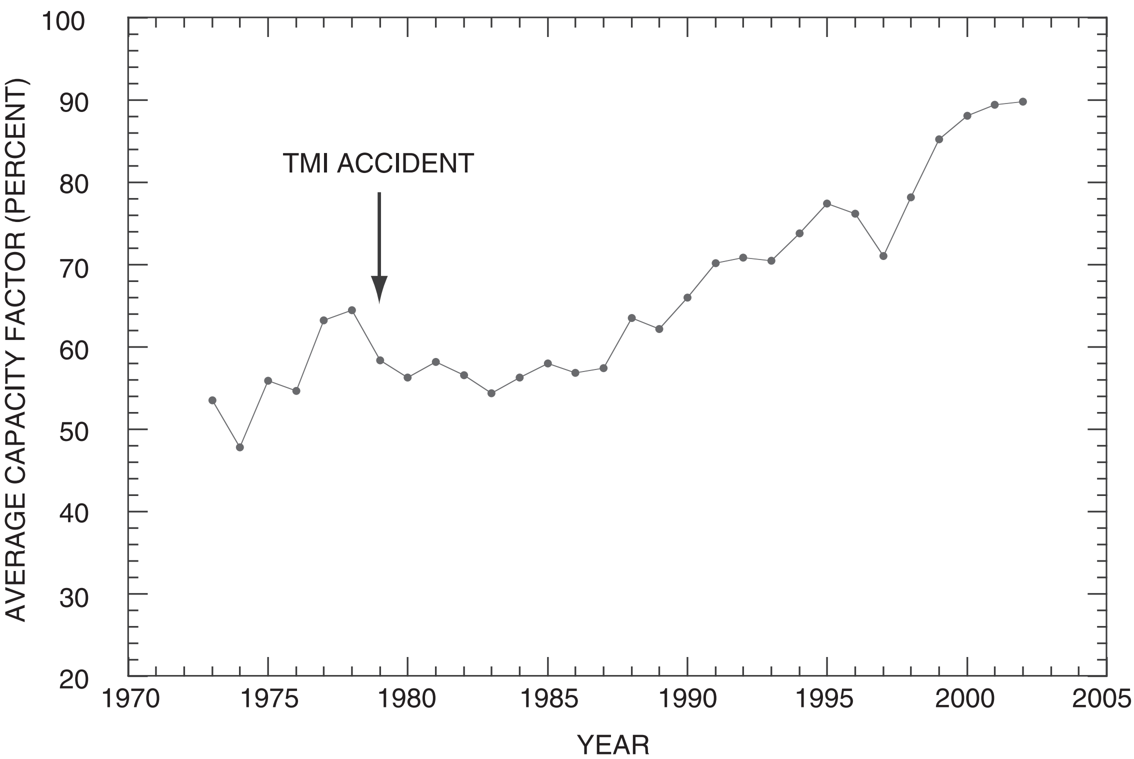

Fig. 2.3. Average capacity factor of U.S. reactors in a given year, 1973–2002. (Data from Ref. [22].)

The improvement in capacity factors has important implications for the economic position of nuclear power. An increase from, say, 60% to 90% corresponds to an increase in output of 50%—equivalent to the addition of roughly 50 reactors—and leads to a large reduction in the cost of electricity. The expenses of a nuclear utility do not change greatly as its electricity output rises or falls, because the capital costs are fixed and the operating costs are insensitive to changes in output. The cost of electricity from a given reactor is therefore reduced by almost one-third if its capacity factor increases from 60% to 90%. A higher capacity factor also reflects a lesser need for repairs or modifications in the reactor, making further savings likely.

2.4.3 Consolidation in the U.S. Nuclear Industry

One of the trends in the U.S. nuclear industry in recent years has been a consolidation of companies that operated nuclear reactors. In early 1998, there were 105 reactors in the United States being operated by 44 separate entities [24]. By the beginning of 2003, the number of operating entities had been reduced to 31, with 104 reactors [4]. The largest of the operators was Exelon Generating, with eight reactors formerly run by Commonwealth Edison and four reactors formerly run by Philadelphia Electric Company. At least in principle, this sort of consolidation allows for greater efficiencies and more concentrated expertise.

Even with the consolidation to date, the U.S. nuclear industry is very fragmented compared to other countries. France is at the other extreme. All but one of its 59 reactors is operated by Electricité de France. The one exception is the Phenix fast breeder reactor, operated by the French atomic energy commissariat.

2.4.4 Renewal of Reactor Operating Licenses

Reactors in the United States operate under Nuclear Regulatory Commission licenses that are issued for a period of 40 years. This period was specified by Congress, according to the Nuclear Energy Institute, because it "was a typical amortization period for an electric power plant," not because of "safety, technical or environmental factors" [25]. Experience with reactors to date indicates no compelling reason to shut them down at the end of 40 years, although, in some cases, retrofits and replacement of components may be necessary.

If a reactor continues to run safely, without the need for a major overhaul, the incentive to extend its operating life is obvious. The capital costs of the reactor have been paid off and the remaining costs of operating the plant are relatively low. Extending the license means relatively inexpensive power for the continued life of the plant. The requirements for obtaining a license renewal are set forth by the Nuclear Regulatory Commission (NRC) and include a study of the effects of aging on reactor safety [26, Part 54]. If granted, a license renewal is specifically limited to 20 years.

The first applications for license renewals were received by the NRC in 1998. By October 2003, the NRC had approved 18 applications and was reviewing 12 more [27]. Looking ahead, the NRC indicated that it expected to receive applications for more than 25 additional reactors by 2006. In view of the financial benefits of continued operation, applications for renewal may eventually be made for most presently operating reactors.

An application for license renewal indicates an intent but not an irrevocable commitment. Just as some reactors have been shut down before the expiration of their original 40-year licenses, it is possible that some renewal applications will be withdrawn, denied by the NRC, or not implemented by the utility. Nonetheless, the rather sudden increase in activity in this area indicates a revived optimism in the U.S. nuclear industry.

2.5 Worldwide Development of Nuclear Power

2.5.1 Early History of Nuclear Programs

The above discussion has emphasized the U.S. nuclear program. However, the United States was not alone in having an early interest in nuclear energy. Other countries had similar interests, although their development lagged because they lacked the head start provided by the U.S. World War II atomic bomb program and they had smaller technological and industrial bases.

For the countries that wanted nuclear weapons, the priority was the same as that of the United States. The bomb came first and peaceful nuclear energy later. Thus, the construction and testing of nuclear weapons was achieved by the USSR in 1949, Britain in 1952, France in 1960, and China in 1964. Commercial nuclear electricity followed: The USSR started with several 100-MWe reactors in 1958[19], Britain with a 50-MWe reactor at Calder Hall in 1956 (preceding the U.S. reactor at Shippingport), France with a 70-MWe prototype reactor at Chinon in 1964, and China with three reactors that went into commercial operation in 1994 [4].

Additional countries had no intention of building nuclear weapons and went directly to nuclear reactors for electric power. These included other countries of Western Europe, beyond France and Britain, as well as Japan. As in the United States, the reactors put into operation in the late 1950s for electricity generation were relatively small in size and few in number, and exploitation of nuclear power remained on a relatively modest scale until the 1970s.

[19] A 5-MWe electric plant was put into operation in Obinsk in June 1954, which has been cited by some Soviet authors as being the "first nuclear power plant in the world" (see Ref. [28]).

2.5.2 Nuclear Power Since 1973

Trends in Nuclear Growth

Worldwide nuclear power generation grew rapidly from the 1970s through the 1980s and then slowed. Details on the growth from 1973 to 2000 are shown in Table 2.4 for the world, Western Europe, and the Far East, as well as for the three countries with the greatest individual outputs of nuclear energy.

Looked at broadly, one sees a rapid expansion in the 1970s and 1980s followed by a marked slowdown in the pace of growth in the 1990s. World generation [excluding the former Soviet Union (FSU) and Eastern Europe] increased by more than a factor of 9 between 1973 and 1990—an average increase of 14% per year. Even in the latter part of this period, from 1980 to 1990, the rate was 11% per year. However, it dropped to 2.5% for these countries for 1990 to 2000. For the world as a whole (including all countries), the average annual growth was 2.4% in the period from 1992 to 2001.[20]

The growth rate has become even slower in the most recent years. Six new reactors, with a total capacity of 5.0 GWe, are listed by the IAEA as having been connected to the local electrical grids in 2002 [3]. This represents a 1.4% increase in the world's total nuclear capacity. Five of these additions were in Asia, continuing the recent trend of Asian leadership seen in Table 2.4.[21]

Table 2.4. World growth of nuclear power, 1973 to 2000.

	World (inc.)[a]	West Europe	Asia	United States	France	Japan
Gross generation (GWyr)						
1973	22	8.4	1.4	10	1.7	1.1
1980	71	24	11	30	7.0	9.5
1990	202	84	32	69	36	22
2000	260	102	57	89	47	37
Average increase (% per year)						
1973–1980	18	16	34	17	23	36
1980–1990	11	13	11	8.6	18	8.8
1990–2000	2.5	1.9	5.7	2.6	2.8	5.2

[a]The world figures are incomplete; they exclude Eastern Europe and the former Soviet Union. Nuclear generation for these countries was 32 GWyr in 2000, raising the world total to 292 GWyr.
Source: Ref. [20]; data not included for Eastern Europe and the former Soviet Union (FSU) prior to 1992.

[20] These data are from the U.S. DOE publication *Monthly Energy Review*, which does not include data for the FSU and Eastern Europe for the years prior to 1992 [20].

[21] The five reactors in Asia included four in China (Qinshan 2-1 and 3-1 and Lingao 1 and 2), and one in South Korea (Yonggwang 6). The other reactor was in the

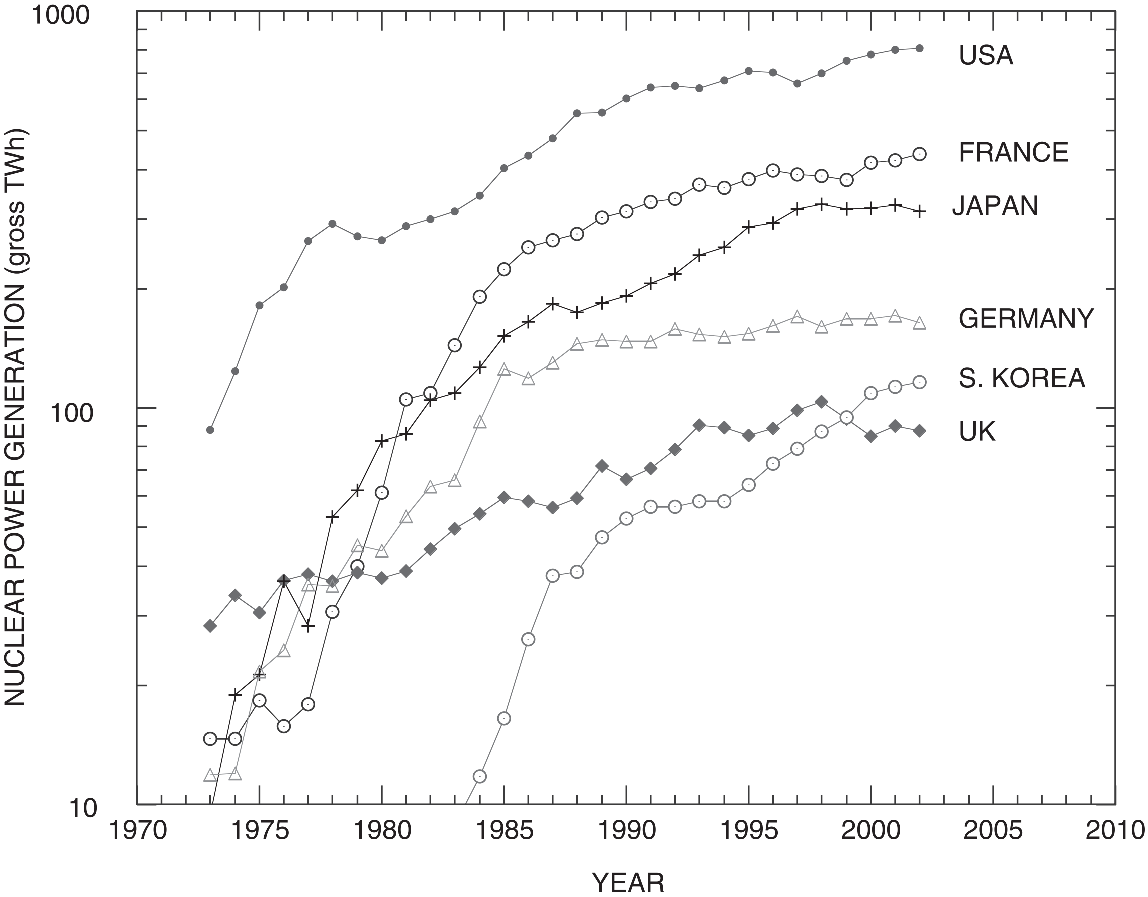

Fig. 2.4. Growth of annual nuclear power generation in selected countries, 1973–2002. (Data from Ref. [20].)

The history of nuclear generation from 1973 to 2002 is shown in Figure 2.4 for several countries with relatively large nuclear programs. France, Japan, and Germany began large-scale use of nuclear power after the United States, but then had larger fractional growth rates, especially in the 1975–1985 period. South Korea, the latest major entry, has had rapid growth in the past 15 years, but its overall program is still relatively small. The United Kingdom, one of the original leaders in nuclear power, later lagged substantially.

Recent Developments in Individual Countries

Despite the overall negative recent history for nuclear power, there were favorable developments in some countries:

- France added 10 new reactors from 1990 through 2002. These were large reactors, each 1300 MWe or more. In most of this period, nuclear power

Czech Republic (Temelin-2). Construction had started in 1996 or later on the Asian reactors and in 1987 on the Czech reactor.

accounted for more than 75% of France's electricity generation, and France was an exporter of electricity to its neighbors. However, no further reactors are presently in the pipeline.

- Japan added 16 new reactors in the same period, most with capacities above 1000 MWe.
- South Korea added nine new reactors in this period, more than doubling its nuclear generation.
- The average capacity factor of U.S. reactors grew from 66% in 1990 to 90% in 2002, giving a large increase in total output, despite a slight decrease in total capacity.
- In Switzerland, voters rejected proposals to phase out nuclear power, in referenda held in May 2003.

On the other side of the ledger, there has been a turning away from nuclear power among some countries that used it. The first to take this step was Italy, which by 1990 had completely shut down its small reactor program, consisting of four reactors with a combined capacity of 1.4 GWe [3]. Since then, decisions to phase out nuclear power has been taken by the governments of Sweden, Germany, and Belgium, each of which obtain a large fraction of its electricity from nuclear power (see Table 2.1). The phasing out is planned to be gradual. By the end of 2003 these decisions had led to two closures, that of the 615-MWe Barsebaeck-1 reactor in Sweden at the end of 1999 and the 640-MWe Stade reactor in Germany in late 2003. The policy was adopted for generalized political or environmental reasons, rather than specific problems with the existing reactors, and could be modified or reversed.

Beyond these broad decisions, there have been several major closures of nuclear power plants in Europe involving special circumstances:

- After the reunification of Germany, the government in 1990 shut down five Soviet-manufactured reactors (1.7 GWe total).
- The four reactors at Chernobyl have all been shut down, the first by the accident in 1986 and the last by the decision of the Ukrainian government in December 2000 (3.8 GWe total).
- France closed its 1200-MWe breeder reactor, Superphenix, in 1998 following a troubled operational history and a lack of an immediate need for a breeder program.

There have been other reactor closures throughout the world, but in most cases, these have involved relatively old and small reactors.

2.5.3 Planned Construction of New Reactors

The pace of reactor construction is now quite slow. According to an IAEA compilation, 32 reactors were under construction as of November, 2003 with a total capacity of 26 GWe. Completion of all these reactors would add 7% to the then existing capacity of 360 MWe, and if accomplished within 5 years, the

Table 2.5. Nuclear reactors under construction as of November, 2003.

Country	No. of Units	Capacity (GWe)	Mean Cap. (MWe)
Asia			
Japan	3	3.70	1232
India	8	3.62	453
China	3	2.61	870
Taiwan	2	2.70	1350
Iran	2	2.11	1056
South Korea	2	1.92	960
North Korea	1	1.04	1040
TOTAL ASIA	21	17.70	843
Eastern Europe			
Ukraine	4	3.80	950
Russian Federation	3	2.83	942
Slovak Republic	2	0.78	388
Romania	1	0.66	655
TOTAL E. EUR.	10	8.06	806
Other: Argentina	1	0.69	692
WORLD TOTAL	32	26.45	827

Source: Ref. [2].

average annual rate of increase would be about 1.4%. Details of the construction plans, subdivided by country and region, are summarized in Table 2.5.

Consistent with the small number of reactors under construction, the IAEA estimated in 2002 that worldwide nuclear capacity will grow at an average rate of only 0.8–1.6% per year for the period from 2001 to 2010 [29, p. 17]. A 2002 U.S. DOE summary projected even slower growth, with world capacity changing from 350 GWe in 2000 to 385 GWe in 2010 in the “high growth case” and to 340 GWe in 2010 in the “low growth case” [30, p. 93]. The “high” figure represents an average annual growth rate of 1.0%.

Table 2.5 clearly shows Asia’s dominance in the planned construction. About two-thirds of the reactors listed as being constructed are in Asia. The remainder are almost entirely in Eastern Europe. Even these reactors are not necessarily a sign of vitality in their nuclear programs. Construction on the Eastern Europe reactors was begun in 1987 or earlier, and the current plans therefore reflect projects that have been long delayed and, in most cases, have no announced completion dates [3]. In contrast, with the exception of the Iranian reactors, all the reactors in Asia were started after 1996. Typically, their expected time from the start of construction to commercial operation is 7 years or less.

The only definite move in recent years to start construction of a new reactor outside Asia was in Finland, where the Parliament in May 2002 voted to build a fifth reactor. This plant is not reflected in the IAEA listing in Table 2.5 because actual construction had not yet been started. It is noteworthy that no new reactors are presently slated for the United States or Western Europe. Here, there is either a pause or a planned retraction. Among the leading countries in this group, the United States, France, and the United Kingdom are standing pat, whereas Germany, Sweden and Belgium are scheduled to phase out nuclear power, absent a change in national policy.

However, this may be an incomplete picture. In a number of countries, there are reactors that have been ordered but are not now actively under construction. Some of them could be completed before 2010, given a decision to move ahead. In addition, with a 5-year construction time, additional reactors could be ordered and completed by 2010. For example, Russia has announced plans that call for putting nine additional plants into operation by 2010, primarily by completing delayed projects (see Section 2.6.3), and the U.S. DOE has adopted the goal of having a new commercial nuclear reactor completed by 2010. Conversely, additional plants may be shut down. In particular, there is pressure to shut down two Chernobyl-type reactors that are still operating in Lithuania.

2.6 National Programs of Nuclear Development

2.6.1 France

France is widely cited as the leading success story for nuclear power. Each year since 1986, nuclear power has accounted for over 70% of electricity generation in France. Another large fraction, averaging about 15%, but with considerable year-to-year variations, has come from hydroelectric power. Therefore, France is virtually saturated in terms of the replacement of fossil fuels. Taking advantage of its ample nuclear capacity, France now exports substantial amounts of electricity to its neighbors.

The chief avenues for further major nuclear growth are through increased exports or a greater electrification of the French energy economy, but there are no visible indications that this is a high priority for France. The last new reactors to go into operation in France were four large PWRs each with a capacity of about 1450 MWe, and no new reactors are under construction. The French and German nuclear industries are continuing to consider a large next-generation reactor, the European Pressurized Water Reactor (EPR), a version of which has been ordered as Finland's fifth reactor.

Over the past two decades, nuclear power has greatly changed the structure of French energy supply. It was an almost negligible contributor in 1970, but in 2001, nuclear power provided 39% of all primary energy in France [1]. The period from 1971 to 1995, in which most of the nuclear growth was achieved, has been described in some detail in Section 1.3.3. It was marked by decreases in fossil fuel use and CO_2 emissions while gross domestic product and energy consumption rose. Total electricity generation more than tripled, accompanied by a change from almost total reliance on fossil fuels and hydroelectric power to a dominant reliance on nuclear power (see Table 1.3). The French experience has been pointed to as demonstrating the impact that nuclear power can have in curbing dependence on fossil fuels and on the emission of greenhouse gases.

There have been a number of attempts to explain why French nuclear history has developed so differently from that of other major countries. Several factors have been advanced, although many of them need not have been unique to France:

- France is poor in fossil fuels, and nuclear power was seen as the most expeditious way to reduce French dependence on oil and coal imports.
- There has been a concentration on a single type of reactor (a PWR originally modeled on Westinghouse designs), operated under the aegis of a single utility, Electricité de France, and built by a single reactor manufacturer, Framatome. This has allowed for standardization to a few PWR types, with resulting economies in design, construction, and operation.
- Although France has open political debate, there were few mechanisms whereby opposition to nuclear power could impede its development, short of changing the policy of the central government. In the United States, on the other hand, individual state governments have considerable independent authority and often have taken positions against nuclear development. Further, fewer opportunities for intervention through the courts are available in France than in the United States, especially as the state structure in the United States provides an extra layer of courts.
- The Communist party, which in the early years of nuclear power was still an important political force in France, supported nuclear power. In most other European countries, the political left opposed nuclear power.
- With the initial success of the French nuclear program, the maintenance of French leadership became a matter of national pride.

Despite these factors, there exists some opposition to nuclear power in France. There is no suggestion that this opposition will reverse the French use of nuclear power, but it may inhibit France from increasing its electricity exports to other European countries.

2.6.2 Japan

Japan is another country with a continuing strong nuclear program, although a smaller one than that of France, especially when adjusted for its larger population and economy. Its nuclear program is particularly driven by Japan's dependence on energy imports, which account for virtually all of Japan's fossil fuels. The chief domestic resources are nuclear energy and hydroelectric power.[22] An increase in the nuclear share of the total energy budget is the most direct way of moving toward greater energy independence. As part of this general strategy, Japan is taking steps toward a self-contained fuel cycle, which could eventually rely on breeder reactors.

To date, Japan has depended for reprocessing on a small domestic plant and reprocessing contracts with facilities in France and Great Britain. Japan's own reprocessing facilities will be greatly expanded with the construction of the Rokkasho-mura plant, started in 1993 and now scheduled for completion in 2005 (see Section 9.4.2). The plant will have a capacity of 800 tonnes per year, sufficient to handle the output of about 25 1000-MWe reactors, each discharging about 30 tonnes of fuel per year. A uranium enrichment plant at Rokkasho-Mura began operation in 1992 and now has an annual capacity sufficient to produce about one-fifth of Japan's requirements of enriched uranium [31, pp. 30–31].

The pace of deployment of new reactors has slowed since the 1990s. However, reactor construction times are relatively short in Japan, averaging under 5 years, so that rapid changes in the program are possible [3, p. 50]. Conversely, political opposition to nuclear power in Japan could interfere with present plans. This opposition has been growing in recent years, exacerbated by incidents that have reflected adversely on the management of Japan's nuclear enterprise.[23]

2.6.3 Other Countries

The Former Soviet Union

The breakup of the Soviet Union left nuclear reactors in a number of the new states, mostly in Russia and Ukraine, but also two in Lithuania and one each in Armenia and Kazakhstan. The 1986 Chernobyl accident led to a cutting back of reactor construction in Russia. Nonetheless, six reactors that had been started before the accident were connected to the grid in Russia between the time of the accident and the end of 2001—five of which were 950-MWe PWRs and one was a 925-MWe RBMK reactor (Smolensk-3 in 1990) [3].[24] From 1988 to 1990, nine older reactors with capacities of 100 MWe to 336

[22] In this discussion, use of imported oil to generate electricity is not counted as indigenous production, but electricity generated from imported uranium is counted as indigenous. This is not symmetric, but it is not unreasonable given that the cost of the fuel in the case of nuclear energy is a small fraction of the total cost.

[23] The most notable of these was an accident at the Tokaimura facility in 1999, when two workers died of radiation exposure due to carelessness in their handling of enriched ^{235}U that was to be used in fuel for a research reactor.

[24] The Chernobyl reactor was an RBMK reactor. These reactors have design features that make them more vulnerable to accidents than are the light water reactors more commonly used (see Sections 8.1.4 and 15.3.1).

MWe were taken out of operation. There was also a considerable scaling down of plans. The number of operating plants in Russia rose from 24 in 1992 to 27 in 2002, but over the same period, the number of plants listed as being under construction or on order dropped from 16 to 6 [4, 32].[25] Of the six, two were 750-MWe breeder reactors and it is not clear when, if ever, these will be built.

It is possible that there will be a substantial development of nuclear power in Russia during the next two decades. Several reactors were under construction in Russia in 2003, and Russia is actively engaged in the export market, including reactors under construction in China, India, and Iran. Following a plan formulated by the Russian Ministry of Atomic Energy (MiniAtom) in 2000, the Russian government has adopted a strategy to raise nuclear capacity (which is now 21 GWe) to a level of 52 GWe by 2020 in their "optimistic" economic scenario and to about 35 GWe in their "pessimistic" scenario [33, pp. 171–190]. In the first instance, this will be accomplished by extending the lives of existing plants beyond the originally scheduled 30 years and completing some projects begun earlier. The next phase calls for the construction of 31 GWe of new capacity [33, p. 187]. However Russia is rich in fossil fuels and, for reasons of geography, may be less concerned than most countries about the effects of global warming.

Ukraine was the site of the 1986 Chernobyl accident. The response has been to shut down the three undamaged Chernobyl reactors—the last not until December 2000—but continue with nuclear power. Six PWRs that had been under construction at the time of the accident were completed by 1989, before the Ukraine separated from the USSR. One additional PWR went into commercial operation in 1996, giving a total of 13 operating reactors by the beginning of 2003. Four more reactors are officially under construction (see Table 2.5).

Lithuania led the world in dependence on nuclear electricity in 2002, obtaining 80% of its electricity from two 1380-MWe RBMK reactors that went into operation in 1985 and 1987. However, it has been under pressure to shut these reactors down, given the fears created by their design similarity to the Chernobyl reactors. Lithuania's admission to the European Union, scheduled for 2004, has been made contingent on the subsequent closure of these reactors.

The two other FSU countries with nuclear reactors at the time of Chernobyl were Armenia and Kazakhstan. Armenia had two 376-MWe PWRs, one of which was shut down in 1989 (before the breakup of the FSU) while the other continues to operate, providing 40% of Armenia's electricity in 2002. The one Kazakhstan reactor was a 50-MWe fast breeder that was shut down in 1999, leaving no operating reactors in that country.

[25] Note: These numbers, from *Nuclear News*, differ from the IAEA data of Table 2.1. A major reason for the difference is that the IAEA, but not *Nuclear News*, includes four Russian 11-MWe reactors.

Former Soviet Bloc Countries

With only a few exceptions, nuclear power has been at a standstill in Europe since the late 1980s. The main exception, other than France, has been in countries in which there has been construction directed toward completing reactors started in the 1980s under Soviet influence. The operating reactors in the former Soviet bloc as well as those under construction are primarily PWRs of the Russian VVER series. The quality of construction and performance of these reactors has varied among countries, and some of these reactors have been viewed as constituting safety hazards. However, problems of air pollution from coal burning are severe in Eastern Europe, and this may favor nuclear power. Further, a number of these countries are heavily dependent on nuclear energy for their electricity, and it would be difficult to abandon it. For example, the share of electricity in 2002 from nuclear power was 55% in the Slovak Republic, 47% in Bulgaria, and 36% in Hungary (see Table 2.1).

Each of these countries has followed its own path, and we describe these developments briefly (with the number of operating reactors, as of the end of 2003, shown in parentheses):

- *East Germany* (0). The most draconian remedial measures were taken following the merger of East and West Germany in 1990. The East German reactors—primarily VVERs—were all removed from service, as not meeting Western safety standards.
- *Czech Republic* (6). The division of Czechoslovakia into the Czech Republic and Slovakia left four operating reactors in each, and two reactors under construction in the Czech Republic (each about 900 MWe). One of these reactors, Temelin 1, was connected to the grid in 2000. It was located near the Austrian border and its operation was a source of contention with Austria. The second, Temelin 2, was connected to the grid in December 2002.
- *Slovakia* (6). Slovakia completed construction of two 388-MWe VVERs in the late 1990s and has put them both into commercial operation. Two more remain nominally under construction.
- *Bulgaria* (4). Four 440-MWe PWRs of Soviet design were in operation in Bulgaria at the time of Chernobyl, and two new 953-MWe Soviet-type PWRs were brought on line in 1988 and 1992. The two oldest were permanently shut down in December 31, 2002, reducing the total number of reactors to four.
- *Romania* (1). Romania is an anomaly in Eastern Europe, and for that matter a rarity in the world, in opting exclusively for Canadian-type heavy water reactors. Five 625-MWe pressurized heavy water reactors of the CANDU design were under construction in the early 1990s. One went into operation in 1996, but only one of the other four reactors was listed as being under construction in 2003 [3].

Other European Countries

Beyond this activity in Eastern Europe—essentially a cleanup of long-standing projects—nuclear power development has almost stopped, or is in regression, in Europe. Outside of France, the one new reactor built in Western Europe in the 1990s was a 1188-MWe PWR (Sizewell B) that started operation in the United Kingdom in 1995. The only other further step toward European development of nuclear power was the decision of Finland in May 2002 to build its fifth reactor. There have been no tangible signs of other countries following suit, as of early 2004.

Western Hemisphere (Other Than the United States)

Canada embarked on a large program of nuclear construction, mostly in the late 1970s, and in 1995 had 22 operating reactors, all based on the CANDU reactors, which have made Canada a leading country in nuclear capacity and generation. However, in the 1990s, 8 of the 22 reactors in Canada were put into a temporary "laid-up" status, one in 1995 and 7 in late 1997 and early 1998. These eight were the oldest ones in operation, all having started up in the 1970s. This step was taken at the behest of Canada's nuclear regulatory authority to avoid a degradation of the "long-term safety and performance" of Canada's nuclear fleet [34, p. 248]. However a 2003 IAEA summary suggested that the eight closed plants "might re-start in the future" [3, p. 46], and three of these reactors were back in service by early 2004 (Bruce 3 and 4 and Pickering 4). There are also nuclear reactors in use in Argentina, Brazil, and Mexico, but these are small programs, with no imminent expansion plans except for one reactor nominally under construction in Argentina.

Other Asian Countries

Beyond Japan, there are active ongoing nuclear programs in other Asian countries (with number of operating reactors in parentheses):

- *South Korea* (18). South Korea is a relative late-comer to nuclear power, but in recent years, it has had rapid growth. Since 1990, it has been second only to Japan in the addition of new nuclear capacity and it plans further expansion. It uses PWRs and heavy water reactors.
- *India* (14). India has followed a path of its own, and now has 12 small heavy water reactors in operation—the largest with a capacity of 202-MWe—and two small BWRs. Its eight plants now under construction include four reactors similar to the existing ones and four that are larger, including—in a new departure—two Russian designed 905-MWe PWRs.
- *China* (8). China's civilian nuclear power program started comparatively late. Its first three reactors went into operation in 1994 and its next five in 2002 and 2003. China has drawn on many different foreign companies in these first stages, but is developing its own national capabilities.

- *Taiwan* (6). Taiwan's six operating reactors are a mix of PWRs and BWRs with capacities ranging from 604 to 948 MWe [4]. They were all in operation by 1985, giving Taiwan a relatively early nuclear program. There was a subsequent lull, but construction is now underway on two 1350-MWe advanced BWRs.
- *Iran and North Korea* (0). The plans to build civilian nuclear power plants in these countries are intertwined with nuclear weapons proliferation issues, and we discuss them further in Section 18.2.3.

Although recent construction activity in Asia has far exceeded that in Europe and North America, it has not been very rapid compared either to the size of the populations involved or to earlier history elsewhere. The United States and Western Europe each still has a larger total nuclear capacity than does Asia. The Asian countries that are pursuing nuclear power appear to be doing this in a deliberate manner, not in the spirit of "crash programs." However, Asian nuclear leaders have an optimistic view of the future Asian role (see Section 20.4.3).

2.7 Failures of Prediction

In the preceding discussions, the trends of events for nuclear power has been reviewed, and such discussions may appear to suggest the nature of future trends. However, any suppositions as to how nuclear power will develop over

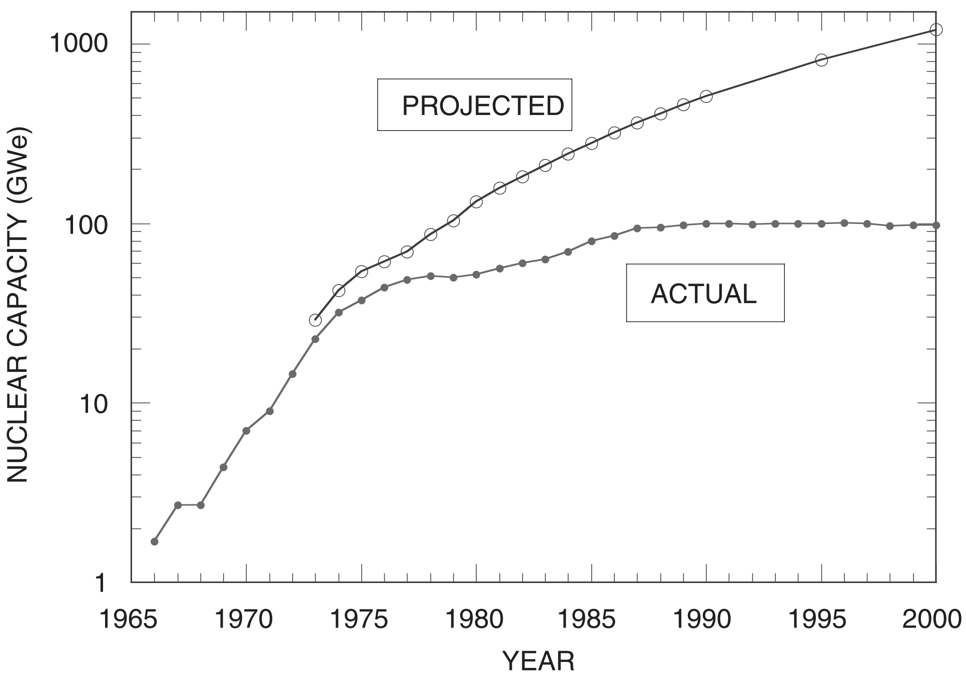

Fig. 2.5. Comparison of U.S. nuclear capacity, projected in 1972 and actual.

the next several decades should be viewed with caution. Past predictions have been rife with errors, and there is no reason to assume we will do better today.

The changing fortunes of nuclear power in the United States offers a cautionary lesson. In Figure 2.5, we compare an early projection for the growth of U.S. nuclear power with the actual subsequent developments. In 1972, the Forecasting Branch of the AEC's Office of Planning and Analysis made a projection for future growth in nuclear capacity, based on past trends in energy use and electricity capacity [35]. Its forecast for the "most likely" case are shown in Figure 2.5, together with the actual history. The projected capacities for 1990 and 2000 were 508 GWe and 1200 GWe, respectively. The actual capacities for 1990 and 2000 were 100 GWe and 98 GWe, respectively [20, p. 113].

This was a spectacular failure of prediction, but one that was in tune with the conventional wisdom of the time. It is natural to speculate on the implications for today. Alternatively, we can believe we now have the wisdom to avoid comparable errors, or we can wonder what new predictive errors are being made. We will return to considering the future of nuclear power in Chapter 20.

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