Kirk-Othmer Encyclopedia of Chemical Technology.

NUCLEAR REACTORS, WASTE MANAGEMENT, INTRODUCTION

The nuclear reactor is a device in which a controlled chain reaction takes place involving neutrons and a heavy element such as uranium. Neutrons are typically absorbed in uranium-235 [15117-96-1], ^{235}U, or plutonium-239 [15117-48-3], ^{239}Pu, nuclei. These nuclei split, releasing two fission fragment nuclei and several fast neutrons. Some of these neutrons cause fission in other uranium nuclei in a sequence of events called neutron multiplication. The fission fragments are stopped within the nuclear fuel, where their kinetic energy becomes thermal energy. The thermal energy is removed by a cooling agent and converted into electrical energy in a turbine-generator system. Many of the fission fragments are radioactive, releasing radiation and decay heat. Some of the radioactive materials have useful purposes; others form nuclear waste (see Nuclear reactors, waste management).

Nuclear reactors as a source of heat energy and radiation were the outgrowth of World War II defense applications. Research and development was pursued on several fronts in the Manhattan Project. Success of a graphite and uranium pile built and tested at the University of Chicago in 1942 prompted construction of production reactors at Hanford, Washington, to accumulate plutonium for the atomic bomb. A second approach to obtaining weapons material involved uranium isotope separation methods. Two techniques were successful: the electromagnetic process at the University of California and gaseous diffusion at Columbia University. Oak Ridge, Tennessee, became the enriched-uranium production center, utilizing both methods. At the same time, knowledge was gained at Los Alamos, New Mexico, about conditions for controlled chain reactions in uranium and plutonium assemblies (see Diffusion separation methods; Nuclear reactors, isotope separation).

The Manhattan Project culminated in the use of nuclear weapons. After the war, the U.S. Atomic Energy Commission (AEC), the predecessor of the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE), was formed. The AEC led U.S. research and development programs on nuclear naval vessels and central station power plants, in cooperation with industry. Excellent accounts of the history of the nuclear enterprise have been provided, including the period 1939–1961, during which the designs of newer reactors came into being (1).

A variety of nuclear reactor designs is possible using different combinations of components and process features for different purposes (see Nuclear reactors, reactor types). Two versions of the lightwater reactors were favored: the pressurized water reactor (PWR) and the boiling water reactor (BWR). Each requires enrichment of uranium in ^{235}U. To assure safety, careful control of coolant conditions is required (see Nuclear reactors, water chemistry of lightwater reactors; Nuclear reactors, safety in nuclear facilities).

1. Power Generation

The principal application of the nuclear reactor is as a heat source for electrical power generation. Growth in the relative contribution of nuclear energy to the electricity supply of the United States since 1949 is shown in Figure 1. As of 1995 there were 109 nuclear power reactors in operation in the United States, generating almost 100 GW of electrical power. Outside of the United States, there were 313 reactors producing 236 GW.

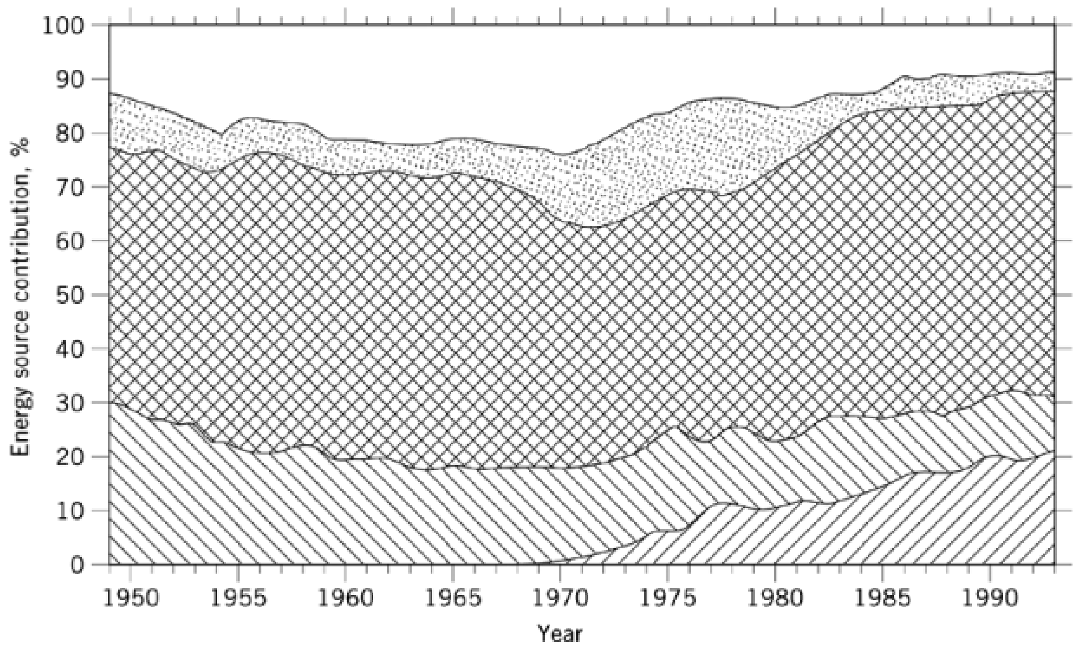

Fig. 1. U.S. utility net electricity generation, where ☒ represents coal, hydro power and other energy sources, □ natural gas, nuclear, and petroleum. Data from Reference 2.

Table 1 lists power reactors by country (3). Table 2 gives the worldwide distribution by reactor type (3). The United States and Europe have the greatest number of nuclear facilities. There are few in South America or Africa and none in Australia. The fraction of total electricity that is derived from nuclear reactors varies greatly among countries. Notable approximate figures are France, 75%; Japan, 30%; and the United States, 21%. Some of the characteristics of the PWR and BWR, ie, the pressurized lightwater reactor and the boiling water reactor, which are the most widely used reactor types, are given in Table 3.

1.1. Safety

A large inventory of radioactive fission products is present in any reactor fuel where the reactor has been operated for times on the order of months. In steady state, radioactive decay heat amounts to about 5% of fission heat, and continues after a reactor is shut down. If cooling is not provided, decay heat can melt fuel rods, causing release of the contents. Protection against a loss-of-coolant accident (LOCA), eg, a primary coolant pipe break, is required. Power reactors have an emergency core cooling system (ECCS) that comes into play upon initiation of a LOCA.

Nuclear power has achieved an excellent safety record. Exceptions are the accidents at Three Mile Island in 1979 and at Chernobyl in 1986. In the United States, safety can be attributed in part to the strict regulation provided by the Nuclear Regulatory Commission, which reviews proposed reactor designs, processes applications for licenses to construct and operate plants, and provides surveillance of all safety-related activities of a utility. The utilities seek continued improvement in capability, use procedures extensively, and analyze any plant incidents for their root causes. Similar programs intended to ensure reactor safety are in place in other countries.

Table 1. World Nuclear Power Plants[a]

Nation	Operative units	Power, net MWe	Total number of units	Power, net MWe
Argentina	2	935	3	1,627
Belgium	7	5,527	7	5,527
Brazil	1	626	3	3,084
Bulgaria	6	3,420	6	3,420
Canada	22	15,442	22	15,442
China	2	1,800	5	3,300
Cuba	0	0	2	834
Czech Republic	4	1,632	6	3,412
Finland	4	2,310	4	2,310
France	56	57,623	61	64,033
Germany	21	22,703	21	22,703
Hungary	4	1,729	4	1,729
India	9	1,834	16	3,874
Japan	47	36,946	54	43,692
Kazakhstan	1	135	1	135
Korea	9	7,220	16	13,083
Lithuania	2	2,760	2	2,760
Mexico	1	654	2	1,308
the Netherlands	2	507	2	507
Pakistan	1	125	2	425
Philippines	0	0	1	605
Romania	0	0	5	3,100
Russia	25	19,799	29	23,174
Slovakia	4	1,632	8	3,296
Slovenia	1	620	1	620
South Africa	2	1,840	2	1,840
Spain	9	7,085	15	12,832
Sweden	12	10,002	12	10,002
Switzerland	5	2,985	5	2,985
Taiwan, China	6	4,884	6	4,884
Ukraine	14	12,095	20	17,795
United Kingdom	34	11,540	35	12,728
United States	109	99,510	116	107,994
Total	*422*	*335,920*	*494*	*395,060*

[a]Ref. 3. Courtesy of *Nuclear News*.

A technique called probabilistic safety assessment (PSA) has been developed to analyze complex systems and to aid in assuring safe nuclear power plant operation. PSA, which had its origin in a project sponsored by the U.S. Atomic Energy Commission, is a formalized identification of potential events and consequences leading to an estimate of risk of accident. Discovery of weaknesses in the plant allows for corrective action.

Reactors are designed to be inherently safe based on physical principles, supplemented by redundant equipment and special procedures. Nuclear power benefits from the application of the concept of defense in depth, ie, by using fuel form, reactor vessel, building containment, and emergency backup procedures to ensure safety.

Table 2. Worldwide Nuclear Power Units by Reactor Type[a]

Reactor type	Units in operation	Power, net MW	Total number of units	Power, net MW
pressurized lightwater reactors (PWR)	243	214,234	286	253,872
boiling lightwater reactors (BWR)	91	74,941	99	83,243
gas-cooled reactors, all types	36	12,239	36	12,239
heavy-water reactors, all types	33	18,645	49	26,540
graphite-moderated lightwater reactors (LGR)	15	14,785	16	15,710
liquid-metal-cooled fast-breeder reactors (LMFBR)	3	928	7	3,308

[a]Ref. 3. Courtesy of *Nuclear News*.

Table 3. Characteristics of Reactors

Parameter	Reactor type	
	PWR	BWR
heat power, MWt	3425	3579
electrical power, MWe	1150	1220
coolant temperatures, °C	292 (326)[a]	216 (285)[a]
pressure, MPa[b]	15.5	7.0
reload fuel, wt % ^{235}U	4.0–5.0	3.5–3.8

[a]In (out).
[b]To convert MPa to psia, multiply by 145.

The accident in 1979 at Three Mile Island Unit 2 (TMI-2), although highly publicized and very costly to clean up, resulted in minimum hazard to the public. The design included a thick steel reactor vessel and a tight containment building. The incident resulted from mechanical failure compounded by misinterpretation of events by the operating crew. The TMI-2 accident, which prompted a number of improvements in equipment and procedures, also led the nuclear industry to create the Institute of Nuclear Power Operations (INPO), a self-regulatory organization. The INPO maintains extensive safety-related databases, conducts power plant visits, and oversees operator training programs.

The steam explosion of the Chernobyl reactor in Ukraine in 1986 caused scores of immediate deaths and released large amounts of radioactivity, with resultant contamination and radiation exposure. The accident occurred because of inadequate inherent safety, improper operating practices, and lack of containment. The Chernobyl accident resulted in some design and operation changes in the reactor, making it less vulnerable in future operation. Countries of the former USSR have been encouraged by the International Atomic Energy Agency (IAEA) and the United States to shut down the reactors, but as of early 1995 demands for electrical power have prevented such action.

The public perceives the risk of nuclear power to be much greater than that determined by experts (4). Among explanations for the discrepancy are the belief in the possibility of a disaster and the association of reactors with weapons. Living 50 years within five miles of a nuclear power plant has been shown to be comparable in terms of risk to smoking 1.4 cigarettes during the same period (5).

2. Environmental Aspects

In contrast to power plants using fossil fuel, nuclear reactor plants emit no compounds of carbon, nitrogen, or sulfur, and thus do not contribute to acid rain, ozone layer depletion, or global warming (see Air pollution; Atmospheric modeling). Emissions of radioactive materials during regular operations are within regulatory requirements based on medical knowledge. These emissions do include radionuclides of the noble gases xenon and krypton, which readily disperse throughout the atmosphere. Small quantities of soluble radionuclides are released into lakes or streams that provide very large dilution factors. Plant and animal life are monitored regularly at such facilities. On the other hand, the potential, however small, of radioactive contamination of the environment in case of a reactor accident in which containment is breached does exist.

As the result of many years of nuclear reactor research and development and weapons production in U.S. defense programs, a large number of sites were contaminated by radioactive materials. A thorough cleanup of this residue of the Cold War is expected to extend well into the twenty-first century and cost many billions of dollars. New technologies are needed to minimize the cost of the cleanup operation.

2.1. Wastes

Nuclear reactors produce unique wastes because these materials undergo radioactive decay and in so doing emit harmful radiation. Spent nuclear fuel has fission products, uranium, and transuranic elements. Plans call for permanent disposal in underground repositories. Geological studies are in progress at the Yucca Mountain site in Nevada. Until a repository is completed, spent fuel must be stored in water pools or in dry storage casks at nuclear plant sites.

Nuclear wastes are classified according to the level of radioactivity. Low level wastes (LLW) from reactors arise primarily from the cooling water, either because of leakage from fuel or activation of impurities by neutron absorption. Most LLW will be disposed of in near-surface facilities at various locations around the United States. Mixed wastes are those having both a hazardous and a radioactive component. Transuranic (TRU) waste containing plutonium comes from chemical processes related to nuclear weapons production. These are to be placed in underground salt deposits in New Mexico (see Actinides and transactinides).

Mill tailings are another form of nuclear waste. The residue from uranium ore extraction contains radium, the precursor of short-lived radon and its daughters. Piles of tailings must be properly covered.

Other wastes are expected to arise from the decontamination and decommissioning of existing nuclear facilities. These include reactors at the time of life extension or at the end of their operating life. Whereas technologies are available for waste disposal, as of this writing (ca 1995) there is much public resistance to the establishment of disposal facilities.

3. Economic Aspects

In the early years of reactor development, electricity from nuclear sources was expected to be much cheaper than that from other sources. Whereas nuclear fuel cost is low, the operating and maintenance costs of a nuclear facility are high. Thus on average, electric power from coal and nuclear costs about the same.

Optimism about economic growth in the period 1960–1975 led to a large number of reactor orders. Many of these were canceled even after partial completion in the period after the 1974 oil crisis, as the result of a reduction in energy demand. Inflation, high interest rates, long construction periods, and regulatory delays resulted in severe cost overruns. Moreover, the reactor accidents of TMI and, later, Chernobyl produced an atmosphere of public concern. As a consequence, there is a general reluctance in the financial community to support the construction of new nuclear plants.

4. Resources

Predictions in the 1960s of the growth in nuclear power indicated the need for recycling (qv) of nuclear fuels. Radionuclides involved are uranium-235, uranium-238 [24678-82-8], and plutonium-239. This last is produced by neutron absorption in the reactions:

$$^{238}_{92}\mathrm{U} + n^1_0 \longrightarrow {}^{239}_{92}\mathrm{U}$$

$$^{239}_{92}\mathrm{U} \longrightarrow {}^{239}_{93}\mathrm{Np} + e^0_{-1}$$

$$^{239}_{93}\mathrm{Np} \longrightarrow {}^{239}_{94}\mathrm{Pu} + e^0_{-1}$$

Uranium-239 [13982-01-9] has a half-life of 23.5 min; neptunium-239 [13968-59-7] has a half-life of 2.355 d. Recycling or reprocessing of spent fuel involves separation of plutonium from uranium and from bulk fission product isotopes (see Nuclear reactors, chemical reprocessing).

Uranium resources were originally expected to be rapidly depleted in a growing economy. There were, however, ample supplies of uranium as of 1995.

The breeder reactor, which would produce and burn plutonium and gradually increase the inventory of fissionable material, requires reprocessing of nuclear fuel. As of 1995 only limited research and development was in progress on breeder reactors, mainly in France and Japan.

The importance of nuclear power for meeting growing U.S. energy needs in an environmentally sound manner has been highlighted (6). The role of nuclear power for the world in the twenty-first century has also been discussed (7).

In the hope of stimulating interest in the building of nuclear power plants, the nuclear industry is designing advanced lightwater reactors. These are of two types, known as simplified and enhanced safety. The first takes advantage of knowledge gained in the operation of previous nuclear reactor designs. It has lower (ca 600 MW) power levels than the 1200 MW reactors of the 1970s and 1980s. The second uses passive features such as natural convection and the force of gravity for enhanced safety. The U.S. government is funding limited development of liquid-metal and gas-cooled advanced reactors.

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