1

Introduction

1.1 Background and Context

Beginning in the early 1950s, the nuclear power industry in the United States grew to become second only to coal in its electrical generation capacity. By 1990, there were 111 commercial nuclear power plants with a combined capacity of 99,000 MW, representing about 19 percent of the nation's electric power. Nuclear power production in the United States was then 530×10^9 kWh, much more than in France and Japan combined, although these two countries were among the nations most reliant on nuclear power. France produced 77 percent of its electricity by nuclear power; in West Germany and Japan, the percentages were 33 percent and 26 percent, respectively. However, in the United States, no new nuclear plants were ordered after 1978, and the expansion of the U.S. commercial nuclear power industry ceased shortly thereafter. Other countries saw a similar drastic decline in the growth of nuclear power capacity.

The reasons for this abrupt transition are several. First, the rate of growth of demand for electric power was less than expected. Second, the capital costs associated with new nuclear power plants rose dramatically in the 1970s and 1980s, in part because of more stringent regulatory activity. And third, public opposition to nuclear power also rose substantially in the aftermath of the Three Mile Island accident (see Section 7.5.1) in 1979, a reaction that was further amplified by the Chernobyl accident in 1986 (see Section 7.5.2). These accidents greatly heightened the public fear of nuclear power plants based on three major concerns, two reasonable and one unreasonable. The unreasonable concern was that a nuclear generating plant might explode like a nuclear weapon, an event that can be dismissed on fundamental physical grounds (see, e.g., Nero 1979). However, the other two concerns that continue to have validity are the fear of the release of harmful radioactive material and the concern over the storage of nuclear waste. While Chernobyl rightly increased the concern over radioactive release, the improvements introduced as a result of the lessons learned from the nuclear accidents over the past half-century (see Sections 7.5 and 7.6) have greatly reduced the risk of such events. Specifically, it is now recognized that, in the past, a lack of standardization in the design and operation of nuclear power plants significantly impaired their safety margins and that worldwide cooperation, oversight, and standardization will radically improve safety margins in the future. Great strides have been made in this regard since the end of the Cold War. Similarly, plans for waste storage and/or recycling continue to be developed both nationally and globally. As von Hippel (2006) has pointed out, there is no hurry to recycle nuclear waste because many temporary storage options are possible given how small a volume of waste is produced, and temporary storage is advisable when a number of reprocessing options may be found to be advantageous in the years ahead.

Of course, no power-generating process is devoid of risks and consequences, and, although complex, it is necessary to balance both the long- and short-term effects while seeking an appropriate mix of energy resources. In 2011, 63 percent of the world's electricity generation was produced by coal and gas combustion; 12 percent was from nuclear power (Shift Project Data Portal 2011). This 12 percent is significantly smaller than in the year 2006, when nuclear power amounted to about 20 percent of global generation. It is projected that nuclear power generation will remain relatively constant in the decades ahead, while the overall demand and generation will continue to grow. This growth is in part caused by population increase and in part by economic development, particularly in the developing countries. Efforts to conserve energy in the developed countries have been more than offset by population increases in the less-developed world. Consequently, worldwide energy consumption per capita continues to rise and increased by approximately 20 percent between 1980 and 2010 (Shift Project Data Portal 2011).

However, it is now becoming clear that the increase in the use of combustible fuels, primarily coal and gas, has serious consequences for the earth's atmosphere and climate, because worldwide emissions of CO_2 from electricity production will continue to rise in the decade ahead. Moreover, greenhouse gas emissions are primarily caused by the burning of the combustible fuels coal, natural gas, and oil, which far exceeds that from the other power sources. The emissions advantage of nuclear power generation has led a number of environmental groups to begin to advocate for nuclear power (see, e.g., Duffey et al. 2006) as a preferred *green solution* to the energy challenge. Whatever the preferred means of electricity production might be in the future, it seems clear that nuclear power must remain an option. One of the disturbing consequences of the antinuclear public sentiment in the past 30 years is that nuclear engineering has become quite unpopular in universities (at least in the United States), and hence the numbers of nuclear engineering programs and their students dwindled. If nuclear power generation were to become an important national or global objective, there would have to be a radical increase in that component of our engineering educational effort.

1.2 This Book

This book, which is intended as an introduction to the thermo-hydraulics of nuclear power generation for graduates or advanced undergraduates, clearly focuses on just one aspect of the design of nuclear reactors for electricity generation, namely, thermo-hydraulics and issues that affect thermo-hydraulics. The term *thermo-hydraulics* refers to all the flow processes involved in the removal of heat generated in the reactor core and the use of that heat to drive generators that produce electricity. Note that although the use of the word *hydraulics* might imply only water flows, in fact the fluids involved range over many coolants and their liquid and vapor phases, including complex multiphase flows. In the present context, the word *thermo-hydraulics* also refers to a whole collection of possible flow processes that might occur due not only to normal reactor operation but also to any operational irregularities or accidents.

Clearly, then, any review or analysis of the thermo-hydraulics must include a description of how the heat is generated within the nuclear reactor core and, consequently, must include description and quantification of the nuclear physics processes that generate the heat. Thus, following a brief introduction of the background and context of nuclear power generation, Chapter 2 provides a review of the fundamental physics of nuclear fission and radioactivity. This leads into Chapter 3, which covers some of the basic features of the neutronics of nuclear reactors. This is followed in Chapter 4 by a description of the structure of the fission reactors presently used or envisaged for nuclear power generation. With that structure in mind, the reader is then equipped to absorb, in Chapter 5, how the heat generated by nuclear fission is transferred to the reactor core coolant and thus transported out of the core to be used to drive the turbines and generators that complete the structure of the power station. Chapter 6 reviews some of the basic multiphase flow phenomena that may be associated with those heat transfer processes during both normal operation of a nuclear power plant and during postulated accidents within that reactor. This leads naturally to a discussion in Chapter 7 of nuclear reactor safety, including descriptions of the three major accidents that dominate the public's impression of the dangers of nuclear power, namely, the accidents at Three Mile Island, Chernobyl, and Fukushima. That discussion naturally includes the important lessons learned from those accidents and other experiences.

There are, of course, many fine textbooks on nuclear power generation and on the engineering of nuclear power systems (see, e.g., Gregg King 1964). Those interested in more detailed treatments of the analytical methods should consult one of the classic texts, such as Glasstone and Sesonske (1981) or Duderstadt and Hamilton (1976). Other texts, such as Winterton (1981) or Collier and Hewitt (1987), have strong focus on thermo-hydraulics. Of course, many additional aspects associated with nuclear power are also important, such as waste disposal (see, e.g., Knief 1980) and the political and economic issues. Other texts are referenced at the conclusion of each chapter. Moreover, today a great deal can be learned from the pages of the Internet, for example, those constructed by the American Nuclear Society or the World Nuclear Association (WNA 2011). Indeed, any single book attempting to review the entire field of electricity generation by nuclear power would be huge; even many of the more narrowly focused books include excessive detail. The present text attempts to narrow thermo-hydraulics down to its essentials without eliminating essential analytical and practical approaches.

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2

Basic Nuclear Power Generation

2.1 Nuclear Power

Nuclear energy is released when atoms are either split into smaller atoms (a phenomenon known as fission) or combined to form a larger atom (a phenomenon known as fusion). This monograph will focus on the production of power by harnessing atomic fission since that is the principle process currently utilized in man-made reactors.

Most of the energy produced by nuclear fission appears as heat in the nuclear reactor core, and this heat is transported away from the core by conventional methods, namely, by means of a cooling liquid or gas. The rest of the power generation system is almost identical in type to the way in which heat is utilized in any other generating station, whether powered by coal, oil, gas, or sunlight. Often the heat is used to produce steam that is then fed to a steam turbine that drives electric generators. In some plants, hot gas rather than steam is used to drive the turbines. In the case of steam-generating nuclear power plants, the part of the plant that consists of the reactor and the primary or first-stage cooling systems (pumps, heat exchangers, etc.) is known as the *nuclear steam supply system*, and the rest, the conventional use of the steam, is called the *balance of plant*. This monograph does not deal with this conventional power generation technology but focuses on the nuclear reactor, its production of heat, and the primary coolant loop that cools the reactor core.

2.2 Nuclear Fuel Cycle

Though it is possible that power might be derived from nuclear fusion at some point in the distant future, all presently feasible methods of nuclear power generation utilize the energy released during nuclear fission, that is to say, the process by which a neutron colliding with an atom causes that atom to split and, as a by-product, produces heat. With atoms known as fissile atoms, additional neutrons are released at the same time, thus allowing a continuing, naturally regenerating process of fission and a source of heat. The only naturally occurring fissile material is the uranium isotope, ^{235}U, but it only occurs along with a much greater quantity of the common

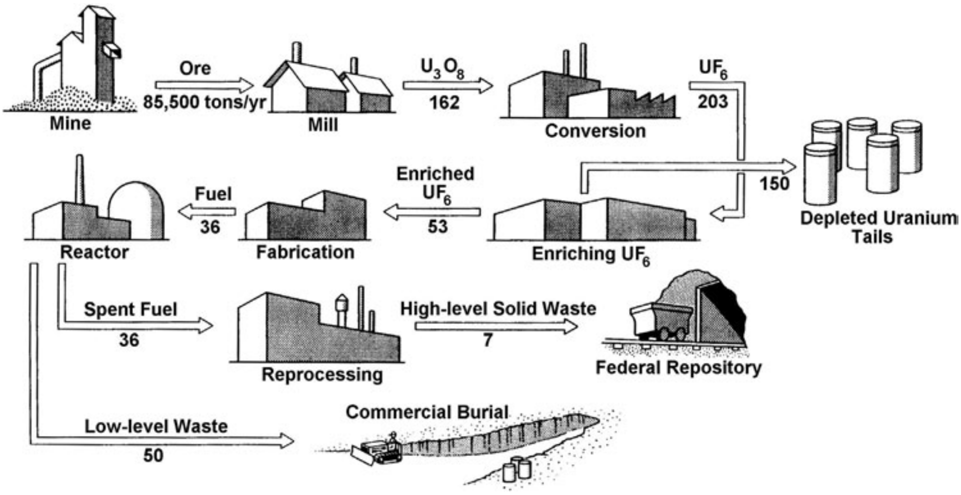

Figure 2.1. Uranium requirements for a typical pressurized water nuclear reactor (see Section 4.3.2). The numbers refer to the number of tons of each material required per year for a 1000 MW electric power plant. From USAEC (1973).

isotope, ^{238}U. Specifically, naturally occurring uranium contains 99.29 percent of ^{238}U and only 0.71 percent of ^{235}U (138 atoms of ^{238}U for every atom of ^{235}U). With a singular exception, these proportions are the same everywhere on earth because they date from the original creation of uranium by fusion and the similar decay of these isotopes since that time. The exception is a location in Oklo, Gabon, Africa, where, approximately 1.7 billion years ago, a uranium-rich mineral deposit became concentrated through sedimentation and, with the water acting as moderator (see Section 2.8.1), formed a natural nuclear reactor (Gauthier-Lafaye et al. 1996; Meshik 2005). The reactor became subcritical when water was boiled away by the reactor heat (though it restarted during subsequent flooding). The consequence was a uranium ore deposit that contained only 0.60 percent or less of ^{235}U (as opposed to 0.71 percent elsewhere).

The nuclear fuel cycle refers to the sequence of steps in a nuclear power generation system, from the mining or acquisition of the raw ore to the refining and enrichment of that material, to its modification during power production and thence to the management of the nuclear waste. Many of the steps in a nuclear fuel cycle involve complex engineering and economics that are beyond the scope of this book (the reader could consult Knief 1992, for a comprehensive summary). However, a brief summary of commonly, envisaged fuel cycles is appropriate at this point. A basic feature of those cycles is an assay of the mass of the essential material during each step (as well as the waste). Another is the power consumption or generation during each step. One example of a nuclear fuel cycle is shown in Figure 2.1, which presents the uranium requirements for a 1000 MW pressurized water reactor.

Because ^{235}U is the only naturally occurring fissile material, the nuclear fuel cycle must necessarily begin with the mining and milling of uranium ore. Uranium ore is relatively common, and additional recoverable resources are being discovered at a significant pace; indeed, the known resources have increased by a factor of about 3 since 1975. Some 40 percent of the known recoverable resources are found in Canada and Australia, while Russia and Kazakhstan hold another 21 percent (the highest-grade uranium ore is found in northern Saskatchewan). Thorium, an alternate nuclear reactor fuel (see Sections 2.11 and 2.2.1), is reputed to be about 3 times as abundant as uranium (WNA 2011).

Uranium is usually removed from the ore by chemical milling methods that result in the production of U_3O_8, known as yellowcake. The waste or *tailings* present some, primarily chemical, disposal problems. With the exception of the CANDU reactor described in Section 4.8, all other current reactors require the uranium to be *enriched*, a process in which the fraction of ^{235}U is increased. In preparation for enrichment, the uranium is converted to a gaseous form, namely, from U_3O_8 to UF_6, in a process known as *conversion*. Several possible methods have been used to enrich the UF_6, and this requires the separation of $^{235}UF_6$ from the $^{238}UF_6$, a process that cannot be accomplished chemically because these isotopes are chemically identical. The separation must therefore be accomplished physically by recourse to the small physical differences in the molecules, for example, their densities or diffusivities. The most common conversion process uses a gas centrifuge in which the heavier $^{238}UF_6$ is preferentially driven to the sides of a rapidly rotating cylinder. Another is the gaseous diffusion method, in which the gas is forced through a porous filter that the $^{235}UF_6$ penetrates more readily. In either case, a by-product is a waste known as the *enrichment tailings*.

Whether enriched or not, the fuel must then be formed into fuel ready for loading into the reactor. In most reactors this fuel fabrication stage involves conversion to solid pellets of UO_2 or, less commonly, UC. These cylindrical pellets are then packed into long fuel rods (as described in Section 4.3.4) whose material is referred to as *cladding*. The rods are then loaded into the reactor. The fuel cycle continues when the fuel rods are spent and removed from the reactor and the spent fuel is reprocessed.

However, before resuming this review with a description of the fuel changes that occur in a uranium reactor, it is appropriate to briefly digress to mention the other naturally available fuel, thorium, and its fuel cycle.

2.2.1 Thorium Fuel Cycle

The other naturally abundant element that can be used in a nuclear reactor fuel cycle is thorium, Th, whose stable isotope and fertile material is ^{232}Th. Unlike natural uranium, natural thorium contains only trace amounts of fissile material, such as ^{231}Th, that is insufficient to initiate a chain reaction. In a thorium-fueled reactor, ^{232}Th absorbs neutrons to produce ^{233}Th and eventually ^{233}U that either fissions in the reactor or is processed into new nuclear fuel. Advantages of the thorium fuel cycle include thorium's greater abundance, better physical properties and reduced plutonium production. Though thorium fuel features in a number of proposed future reactor designs (see Section 4.9.1) and in the high-temperature gas-cooled reactor (HTGR) (see Sections 2.11 and 4.6), thorium cycles are unlikely to significantly displace uranium in the nuclear power market in the near future (IAEA 2005). However, both China and India have plans for thorium cycle use in the future (Thorium Cycle Plans 2015).

2.2.2 Fuel Changes in the Reactor

It is appropriate to briefly review the changes in the fuel that occur during its life in the reactor core. In a typical 1000 MW light water reactor for power generation, the core contains 75,000 kg of low-enriched uranium usually in the form of UO_2 pellets (1000 kg of fuel typically generates about 45 kWh of electricity). During operation in a critical state, the ^{235}U fissions or splits producing heat in a chain reaction that also produces plutonium, other transuranic elements, and fission products. The fission fragments and heavy elements increase in concentration so that, after 18–36 months, it becomes advantageous to replace the fuel rods. At this point the fuel still contains about 96 percent of the original uranium (the term *burnup* is used to refer to the 4 percent used), but the fissionable ^{235}U is now less than 1 percent compared with the initial, enriched 3.5–5 percent. About 3 percent of the used fuel is waste product and 1 percent is plutonium. It is worth noting that much greater burnup (up to 20 percent) can be achieved in a fast neutron reactor (see Section 4.7).

2.2.3 The Postreactor Stages

Upon removal from a reactor, the fuel in the fuel rods is highly radioactive and is still producing decay heat as described in Section 2.4.2. At the time of shutdown of the reactor, the decay heat is about 6.5 percent of the full power level. This declines rapidly, falling to about 1.5 percent after an hour, 0.4 percent after a day, and 0.2 percent after a week. Spent fuel rods are therefore normally stored in isolated water pools near the generation site for several months not only to keep them cool but also to allow for the radioactive elements with short half-lives to decay substantially before further processing. The water absorbs the decay heat and prevents overheating of the fuel rods. They can be transferred to dry storage after about 5 years.

At the present time there are two subsequent strategies. The fuel may be reprocessed to recycle the useful remnants, or it may remain in long-term storage to await reevaluation of its potential use or disposal in the future. Reprocessing involves separating the uranium and plutonium from the waste products by chopping up the fuel rods (cladding and all) and dissolving them in acid to separate their components (see, e.g., Nero 1979). This enables the uranium and plutonium to be reused in fuel while the remaining 3 percent of radioactive waste is disposed of as described later. The recovered uranium is usually a little richer in ^{235}U than in nature and is reused after enrichment. The plutonium can be combined with uranium to make so-called *mixed oxide* (MOX) fuel that can be used as a substitute for enriched uranium in mixed oxide reactors.

All the waste from the nuclear cycle and fuel processing is classified according to the radiation it emits as either low-level, intermediate-level or high-level waste.

The high-level waste from reprocessing is reduced to powder and entombed in glass (*vitrified*) to immobilize it. The molten glass is poured into steel containers ready for long-term storage. One year of high-level waste from a 1000 MW reactor produces about 5000 kg of such high-level waste. Currently there are no disposal facilities for used fuel or for reprocessing waste. These are deposited in storage to await future use or treatment or for the creation of more permanent disposal facilities. The small mass of the material involved makes this wait not only feasible but wise.

Parenthetically, we note that the end of the Cold War created a new source of nuclear fuel from the Russian stockpiles of highly enriched weapons-grade uranium. Under a U.S.–Russian agreement, this has been diluted for use in nuclear power plants and, since then, has provided fully half of the nuclear fuel used in the United States for the generation of electricity.

2.3 Nuclear Physics

2.3.1 Basic Nuclear Fission

To proceed, it is necessary to outline the basic physics of nuclear fission. The speed of individual neutrons is quoted in terms of their kinetic energy in eV or *electron-volts*, where 1 eV is equivalent to 4.44×10^{-26} kWh (kilowatt hours) of power. These energies range from those of so-called *fast neutrons* with energies of the order of $0.1 \rightarrow 10$ MeV down to those of so-called *thermal neutrons* with energies of the order of 0.1 eV or less. As described later, both fast and thermal neutrons play important roles in nuclear reactors.

In 1938–39 Hahn, Meitner, Strassman, and Frisch (Hahn and Strassman 1939; Meitner and Frisch 1939; Frisch 1939) first showed that any heavy atomic nucleus would undergo fission if struck by a *fast* neutron of sufficiently high kinetic energy, of the order of $1 \rightarrow 2$ MeV. Shortly thereafter, Bohr and Wheeler (1939) predicted that only very heavy nuclei containing an odd number of neutrons could be fissioned by all neutrons with kinetic energies down to the level of *thermal* neutrons (order 0.1 MeV). The only naturally occurring nucleus that meets this condition is the isotope U^{235} that has 92 protons and 143 neutrons. However, the isotope ^{235}U is rare; in nature it only occurs as one atom for every 138 atoms of the common isotope ^{238}U or, in other words, as 0.71 percent of natural uranium. The consequences of this are discussed shortly.

When a neutron strikes a heavy nucleus, there are several possible consequences:

- *radiative capture* or absorption, in which the neutron is captured by the nucleus and essentially lost
- *elastic scattering*, during which the neutron rebounds from the collision without any loss of kinetic energy
- *inelastic scattering*, during which the neutron is momentarily captured and then released without fission but with considerable loss of kinetic energy
- *fission*, in which the heavy nucleus is split into several *fission fragments*, energy is generated, and several *secondary* neutrons are released

When a heavy nucleus such as ^{235}U is fissioned by a colliding neutron, several important effects occur. First and most fundamentally for our purposes is the release of energy, mostly in the form of heat (as a result of the special theory of relativity, there is an associated loss of mass). On average, the fission of one ^{235}U nucleus produces approximately 200 MeV (2×10^8 eV) of energy. Thus a single fission produces roughly 8.9×10^{-18} kWh. Because a single ^{235}U atom weighs approximately 3.9×10^{-22} g, it follows that the fission of one gram of ^{235}U produces approximately 23 MWh of power. In contrast, 1 g of coal when burned produces only about 10^{-5} MWh, and there is a similar disparity in the waste product mass.

The second effect of a single ^{235}U fission is that it releases two or three neutrons. In a finite volume consisting of ^{235}U, ^{238}U, and other materials, these so-called *prompt* neutrons can have several possible fates. They can

- collide with other ^{235}U atoms, causing further fission
- collide with other ^{235}U atoms and not cause fission but rather undergo radiative capture
- collide with other atoms, such as ^{238}U, and be absorbed by radiative capture
- escape to the surroundings of the finite volume of the reactor

As a consequence, it is useful to conceive of counting the number of neutrons in a large mass in one generation and to compare this with the number of neutrons in the following generation. The ratio of these two populations is known as the *reproduction factor* or *multiplication factor*, k, where

$$k = \frac{\text{Number of neutrons in a generation}}{\text{Number of neutrons in the preceding generation}} \tag{2.1}$$

In addition to k, it is useful to define a multiplication factor that ignores the loss of neutrons to the surroundings, in other words, the multiplication factor for a reactor of the same constituents but infinite size, k_∞. In the section that follows the process by which k and k_∞ are used in evaluating the state of a reactor is detailed.

An alternative to k is the frequently used *reactivity*, ρ, defined as

$$\rho = \frac{(k-1)}{k} \tag{2.2}$$

and this quantity is also widely used to describe the state of a reactor. Further discussion on k (or ρ) and k_∞ and the role these parameters play in the evaluation of the criticality of a reactor is postponed until further details of the neutronics of a reactor core have been established.

2.3.2 Neutron Energy Spectrum

The neutrons that are released during fission have a spectrum of energies as shown in Figure 2.2, where $n(E)dE$ is the fraction of neutrons with energies in the range E to $E + dE$. The distribution in Figure 2.2 is often described by empirical formulae