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An Introduction to Nuclear Power Generation

It has been more than three decades since the first nuclear reactor achieved a critical fission chain reaction beneath the old Stagg Field football stadium at the University of Chicago. Since that time an extensive worldwide effort has been directed toward nuclear reactor research and development in an attempt to harness the enormous energy contained within the atomic nucleus for the peaceful generation of power. Nuclear reactors have evolved from an embryonic research tool into the mammoth electrical generating units that drive hundreds of central-station power plants around the world today. The recent shortage of fossil fuels has made it quite apparent that nuclear fission reactors will play a dominant role in meeting man's energy requirements for decades to come.

For some time electrical utilities have been ordering and installing nuclear plants in preference to fossil-fueled units. Such plants are truly enormous in size, typically generating over 1000 MWe (megawatts-electric) of electrical power (enough to supply the electrical power needs of a city of 400,000 people) and costing more than one billion dollars. It is anticipated that some 500 nuclear power plants will be installed in the United States alone by the year 2000 with an electrical generating capacity of about 500,000 MWe and a capital investment of more than $600 billion,[1] with this pattern being repeated throughout the world. The motivation for such a staggering commitment to nuclear power involves a number of factors that include not only the very significant economic and operational advantages exhibited by nuclear plants over conventional sources of power, but their substantially lower environmental impact and vastly larger fuel resources as well.[2-7]

The dominant role played by nuclear fission reactors in the generation of electrical power can be expected to continue well into the next century. Until at least A.D. 2000, nuclear power will represent the only viable alternative to

fossil-fueled plants for most nations.[2,3] The very rapid increase in fossil-fuel costs that has accompanied their dwindling reserves has led to a pronounced cost advantage for nuclear plants which is expected to widen even further during the next few decades.[4,6] Of course, there are other longer-range alternatives involving advanced technology such as solar power, geothermal power, and controlled thermonuclear fusion. However the massive practical implementation of such alternatives, if proven feasible, could probably not occur until after the turn of the century since experience has shown that it takes several decades to shift the energy industry from one type of fuel to another,[2] due both to the long operating lifetime of existing power machinery and the long lead times needed to redirect manufacturing capability. Hence nuclear fission power will probably be the dominant new source of electrical power during the productive lifetimes of the present generation of engineering students.

I. NUCLEAR FISSION REACTORS

The term *nuclear reactor* will be used in this text to refer to devices in which controlled nuclear fission chain reactions can be maintained. (This restricted definition may offend that segment of the nuclear community involved in nuclear fusion research, but since even a prototype nuclear fusion reactor seems several years down the road, no confusion should result.) In such a device, neutrons are used to induce nuclear fission reactions in heavy nuclei. These nuclei fission into lighter nuclei (*fission products*), accompanied by the release of energy (some 200 MeV per event) plus several additional neutrons. These *fission neutrons* can then be utilized to induce still further fission reactions, thereby inducing a chain of fission events. In a very narrow sense then, a nuclear reactor is simply a sufficiently large mass of appropriately fissile material (e.g., ^{235}U or ^{239}Pu) in which such a controlled fission chain reaction can be sustained. Indeed a small sphere of ^{235}U metal slightly over 8 cm in radius could support such a chain reaction and hence would be classified as a nuclear reactor.

However a modern power reactor is a considerably more complex beast. It must not only contain a lattice of very carefully refined and fabricated nuclear fuel, but must as well provide for cooling this fuel during the course of the chain reaction as fission energy is released, while maintaining the fuel in a very precise geometrical arrangement with appropriate structural materials. Furthermore some mechanism must be provided to control the chain reaction, shield the surroundings of the reactor from the intense nuclear radiation generated during the fission reactions, and provide for replacing nuclear fuel assemblies when the fission chain reaction has depleted their concentration of fissile nuclei. If the reactor is to produce power in a useful fashion, it must also be designed to operate both economically and safely. Such engineering constraints render the actual nuclear configuration quite complex indeed (as a quick glance ahead to the illustrations in Chapter 3 will indicate).

Nuclear reactors have been used for over 30 years in a variety of applications. They are particularly valuable tools for nuclear research since they produce copious amounts of nuclear radiation, primarily in the form of neutrons and gamma rays. Such radiation can be used to probe the microscopic structure and dynamics of matter (neutron or gamma spectroscopy).

The radiation produced by reactors can also be used to transmute nuclei into artificial isotopes that can then be used, for example, as radioactive tracers in industrial or medical applications. Reactors can use the same scheme to produce nuclear fuel from nonfissile materials. For example, ^{238}U can be irradiated by neutrons in a reactor and transmuted into the nuclear fuel ^{239}Pu. This is the process utilized to "breed" fuel in the fast breeder reactors currently being developed for commercial application in the next decade.

Small, compact reactors have been used for propulsion in submarines, ships, aircraft, and rocket vehicles. Indeed the present generation of light water reactors used in nuclear power plants are little more than the very big younger brothers of the propulsion reactors used in nuclear submarines. Reactors can also be utilized as small, compact sources of long-term power, such as in remote polar research stations or in orbiting satellites.

Yet by far the most significant application of nuclear fission reactors is in large, central station power plants. A nuclear power plant is actually very similar to a fossil-fueled power plant, except that it replaces the coal or oil-fired boiler by a nuclear reactor, which generates heat by sustaining a fission chain reaction in a suitable lattice of fuel material. Of course, there are some dramatic differences between a nuclear reactor and, say, a coal-fired boiler. However the useful quantity produced by each is high temperature, high pressure steam that can then be used to run turbogenerators and produce electricity. At the center of a modern nuclear plant is the nuclear steam supply system (NSSS), composed of the nuclear reactor, its associated coolant piping and pumps, and the heat exchangers ("steam generators") in which water is turned into steam. (A further glance at the illustrations in Chapter 3 will provide the reader with some idea of these components.) The remainder of the power plant is rather conventional.

Yet we must not let the apparent similarities between nuclear and fossil-fueled power plants overshadow the very significant differences between the two systems. For example, in a nuclear plant sufficient fuel must be inserted into the reactor core to allow operation for very long periods of time (typically one year). The nuclear fuel cycle itself is extremely complex, involving fuel refining, fabrication, reprocessing after utilization in the reactor, and eventually the disposal of radioactive fuel wastes. The safety aspects of nuclear plants are also quite different, since one must be concerned with avoiding possible radiological hazards. Furthermore the licensing required by a nuclear plant before construction or operation demands a level of sophisticated analysis totally alien to fossil-fueled plant design.

Therefore even though the NSSS contributes only a relatively modest fraction of the total capital cost of a nuclear power plant (presently about 20%), it is of central concern since it not only dictates the detailed design of the remainder of the plant, but also the procedures required in plant construction and operation. Furthermore it is the low fuel costs of the NSSS that are responsible for the economic advantages presently enjoyed by nuclear power generation.

The principal component of the NSSS is, of course, the nuclear reactor itself. A rather wide variety of nuclear reactors are in operation today or have been proposed for future development. Reactor types can be characterized by a number of features. One usually distinguishes between those reactors whose chain reactions are maintained by neutrons with characteristic energies comparable to the energy of thermal vibration of the atoms comprising the reactor core (*thermal reactors*) and reactors in which the average neutron energy is more characteristic of the

much higher energy neutrons released in a nuclear fission reaction (*fast reactors*).

Yet another common distinction refers to the type of coolant used in the reactor. In the United States, and indeed throughout the world, the most popular of the present generation of reactors, the light water reactor (LWR) uses ordinary water as a coolant. Such reactors operate at very high pressures (approximately 70–150 bar) in order to achieve high operating temperatures while maintaining the water in its liquid phase. If the water is allowed to boil in the core, the reactor is referred to as a boiling water reactor (BWR), while if the system pressure is kept sufficiently high to prevent bulk boiling (155 bar), the reactor is known as a pressurized water reactor (PWR). Such reactors have benefited from a well-developed technology and performance experience achieved in the nuclear submarine program.

A very similar type of reactor uses heavy water (D_2O) either under high pressure as a primary coolant or simply to facilitate the fission chain reaction. This particular concept has certain nuclear advantages that allow it to utilize low-enrichment uranium fuels (including natural uranium). It is being developed in Canada in the CANDU series of power reactors and in the United Kingdom as steam generating heavy water reactors (SGHWR).

Power reactors can also utilize gases as coolants. For example, the early MAGNOX reactors developed in the United Kingdom used low-pressure CO_2 as a coolant. A particularly attractive recent design is the high-temperature gas-cooled reactor (HTGR) manufactured in the United States which uses high-pressure helium. Related gas-cooled reactors include the pebble-bed concept and the advanced gas cooled reactors (AGR) under development in Germany and the United Kingdom, respectively.

All of the above reactor types can be classified as thermal reactors since their fission chain reactions are maintained by low-energy neutrons. Such reactors comprise most of the world's nuclear generating capacity today, and of these the LWR is most common. It is generally agreed that the LWR will continue to dominate the nuclear power industry until well into the 1980s, although its market may tend to be eroded somewhat by the successful development of the HTGR or advanced heavy water reactors.

However as we will see in the next chapter, there is strong incentive to develop a fast reactor which will breed new fuel while producing power, thereby greatly reducing nuclear fuel costs. Such fast breeder reactors may be cooled by either liquid metals [the liquid metal-cooled fast breeder reactor (LMFBR)] or by helium [the gas-cooled fast breeder reactor (GCFR)]. Although fast breeder reactors are not expected to make an appreciable impact on the nuclear power generation market until after 1990, their development is actively being pursued throughout the world today.

Numerous other types of reactors have been proposed and studied—some even involving such exotic concepts as liquid or gaseous fuels. Although much of the analysis presented in this text is applicable to such reactors, our dominant concern is with the solid-fuel reactors cooled by either water, sodium, or helium, since these will comprise the vast majority of the power reactors installed during the next several decades.

II. ROLE OF THE NUCLEAR ENGINEER

The nuclear engineer will play a very central role in the development and application of nuclear energy since he is uniquely characterized by his ability to

assist in both the nuclear design of fission reactors and their integration into large power systems. In the early days of the reactor industry a nuclear engineer was usually regarded as a Ph. D.-level reactor physicist primarily concerned with nuclear reactor core research and design. Today, however, nuclear engineers are needed not only by research laboratories and reactor manufacturers to develop and design nuclear reactors, but also by the electrical utilities who buy and operate the nuclear power plants, and by the engineering companies who build the power plants and service them during their operating lifetimes.

Hence an understanding of core physics is not sufficient for today's nuclear engineer. He must also learn how to interface his specialized knowledge of nuclear reactor theory with the myriad of other engineering demands made upon a nuclear power reactor and with a variety of other disciplines, including mechanical, electrical, and civil engineering, metallurgy, and even economics (and politics), just as specialists of these other disciplines must learn to interact with nuclear engineers. In this sense, he must recognize that the nuclear analysis of a reactor is only one facet to be considered in nuclear power engineering. To study and master it outside of the context of these other disciplines would be highly inadvisable. In the same sense, those electrical, mechanical, or structural engineers who find themselves involved in various aspects of nuclear power station design (as ever increasing numbers are) will also find some knowledge of nuclear reactor theory useful in the understanding of nuclear components and interfacing with nuclear design.

Future nuclear engineers must face and solve complex problems such as those involved in nuclear reactor safety, environmental impact assessment, nuclear power plant reliability, and the nuclear fuel cycle, which span an enormous range of disciplines. They must always be concerned with the economic design, construction, and operation of nuclear plants consistent with safety and environmental constraints. An increasing number of nuclear engineers will find themselves concerned with activities such as quality assurance and component standardization as the nuclear industry continues to grow and mature, and of course all of these problems must be confronted and handled in the public arena.

III. SCOPE OF THE TEXT

Our goal in this text is to develop in detail the underlying theory of nuclear fission reactors in a manner accessible to both prospective nuclear engineering students and those engineers from other disciplines who wish to gain some exposure to nuclear reactor engineering. In every instance we attempt to begin with the fundamental scientific principles governing nuclear fission chain reactions and then carry these fundamental concepts through to the level of realistic engineering applications in nuclear reactor design. During this development we continually stress the interplay between the nuclear analysis of a reactor core and the parallel nonnuclear design considerations that must accompany it in any realistic nuclear reactor analysis.

We must admit a certain preoccupation with nuclear power reactors simply because most nuclear engineers will find themselves involved in the nuclear power industry. This will be particularly apparent in the examples we have chosen to discuss and the problems we have emphasized. However since our concern is always with emphasis of fundamental concepts over specific applications, most of the topics we develop have a much broader range of validity and would apply

equally well to the analysis of other types of nuclear reactors. And although our principal target is the prospective nuclear engineer, we would hope that engineers from other disciplines would also find this text useful as an introduction to the concepts involved in nuclear reactor analysis.

The present text develops in four progressive stages. Part 1 presents a very brief introduction to those concepts from nuclear physics relevant to nuclear fission reactors. These topics include not only a consideration of the nuclear fission process itself, but also a consideration of the various ways in which neutrons, which act as the carrier of the chain reaction, interact with nuclei in the reactor core. We next consider from a qualitative viewpoint the general concepts involved in studying nuclear chain reactions. Part 1 ends with an overview of nuclear reactor engineering, including a consideration of the various types of modern nuclear reactors, their principal components, and a qualitative discussion of nuclear reactor design.

Parts 2–4 are intended to develop the fundamental scientific principles underlying nuclear reactor analysis and to apply these principles for derivation of the most common analytical tools used in contemporary reactor design. By way of illustration, these tools are then applied to analyze several of the more common and significant problems facing nuclear engineers.

Part 2 develops the mathematical theory of neutron transport in a reactor. It begins with the most general description based on the neutron transport equation and briefly (and *very* qualitatively) reviews the standard approximations to this equation. After this brief discussion, we turn quickly to the development of the simplest nontrivial model of a nuclear fission reactor, that based upon one-speed neutron diffusion theory. This model is used to analyze both the steady state and time-dependent behavior of nuclear reactors, since although the model has very limited validity in practical reactor analysis, it does illustrate most of the concepts as well as the calculational techniques used in actual reactor design.

In Part 3, we develop the principal tool of modern nuclear reactor design, the multigroup diffusion model. Particular attention is devoted to the calculation of the multigroup constants appearing in these equations, as well as to the practical numerical solution of the equations themselves.

In Part 4, we attempt to give an overview of the methods used in nuclear reactor core design. In particular, we consider the application of the concepts and tools developed in the earlier sections to a variety of problems faced by the nuclear engineer, including criticality calculations, the determination of core power distributions and thermal-hydraulics analysis, burnup and control studies, and fuel-loading requirements. While certainly incomplete, we do feel that the problems we have chosen to examine are representative of those encountered in nuclear reactor design and serve to illustrate the concepts developed in the earlier chapters of the text.

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Nuclear Engineering International (Europressatom): A British journal distinguished by its elaborate, multicolored diagrams of nuclear power plants.

Nuclear Industry (Atomic Industrial Forum): A monthly news magazine written more from the viewpoint of the consumer of nuclear power products—namely, the electrical utilities.

Nuclear News (American Nuclear Society): A monthly news magazine published by the American Nuclear Society, the principal technical organization of nuclear engineering in the United States.

Nuclear Safety (Office of Information Services, U. S. Atomic Energy Commission): A journal highlighting recent developments in the field of nuclear reactor safety.

Nuclear Science and Engineering (American Nuclear Society): The principal technical research journal of nuclear engineering.

Other more research-oriented journals in the field of nuclear science and engineering include:

Annals of Nuclear Science and Engineering (formerly *Journal of Nuclear Energy*) (Pergamon, New York).

Journal of Nuclear Science and Technology (Atomic Energy Society of Japan).

Nuclear Engineering and Design (North-Holland, Amsterdam).

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