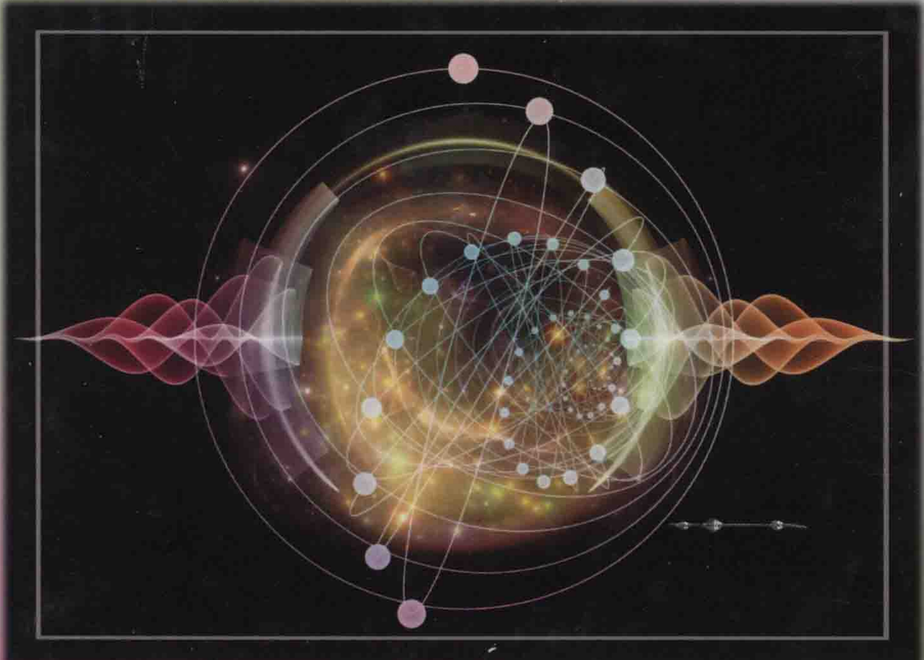
Nuclear Engineering Fundamentals

A PRACTICAL PERSPECTIVE



Robert E. Masterson

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Nuclear Engineering Fundamentals
A Practical Perspective

This book is dedicated to the great men and women who created the nuclear power industry and helped to make it what it is today.

This book is further dedicated to my old friend and colleague John Cowley, who claims that he will read every line of it even though he may not understand all of it.

Finally, this book is dedicated to my late wife, Carol, who encouraged me to undertake this effort but never lived to see it completed.

Preface

P.1 Book Overview

This book endeavors to provide a modern alternative to classical nuclear engineering textbooks that have not been updated over the last 20 years. It discusses a wide range of topics of interest to anyone who is interested in learning about how reactors work as well as anyone who is interested in pursuing a career in nuclear science and engineering. To achieve these goals, it makes extensive use of color images, the Internet, computer graphics, and other innovative techniques to make the process of learning about nuclear energy as interesting as possible. As such, it may be used for a one-semester, a two-semester, or a three-semester course in the fundamentals of nuclear power.

P.2 Topics Covered

All major reactor types including PWRs, BWRs, gas reactors, military reactors, and LMFBRs are discussed. There are also several chapters devoted to the interaction of radiation with matter, radiation detection and protection, and radiation shielding. Radioactivity is discussed in Chapter 6 and the nuclear chain reaction is introduced in Chapter 7. In addition to these subjects, a great deal of attention is paid to the nuclear fuel cycle, the uranium enrichment process, various uranium enrichment technologies, and the mining and extraction of uranium ore. The pros and cons of different types of nuclear waste disposal and fast and thermal breeder reactors are discussed. The thorium fuel cycle is presented and it is compared and contrasted to conventional uranium and plutonium fuel cycles. The economic trade-offs associated with these fuel cycles are discussed. The extraction of uranium from seawater is explored. This book also describes the neutron life cycle, nuclear cross sections and reaction rates, single-group and multigroup cross sections, compound nucleus formation, the liquid drop model and the shell models of nuclear structure, and the mass defect of the nucleus. It is the first mainstream nuclear engineering textbook the publisher is aware of that presents a modern view of the theory of radioactive decay (including the weak force and Feynman diagrams). As a bonus, it also presents the first derivation of Einstein's famous equation $E = mc^2$ in a mainstream nuclear engineering textbook. The Heisenberg uncertainty principle and its effect on particle confinement are also explored.

Practically speaking, this book can be viewed as the first book of a two-book set. Its companion book, titled *An Introduction to Nuclear Reactor Physics* is also available from CRC Press, and it explores neutron diffusion theory, the neutron diffusion equation, Fick's law of diffusion, and steady-state and transient reactor behavior. Both numerical and analytical solutions to the steady-state and time-dependent neutron diffusion equations are presented. The Inhour equation, the point kinetics approximation, and the effects of xenon transients are discussed. These topics are further augmented by a discussion of reactor accidents, the INES scale of accident severity, and an introduction to neutron transport theory and the Monte Carlo method. The origins of one-group theory, two-group theory, and multigroup theory are explored. The coverage of reactor physics and nuclear physics is extensive, and in many cases, the coverage exceeds the amount of coverage available in classical reactor physics books.

In its companion book, the areas of reactor physics, reactor dynamics, neutron slowing down theory, and nuclear particle transport are discussed. Neutron transport theory is introduced and it is compared and contrasted to neutron diffusion theory. The neutron transport equation and the neutron diffusion equation are derived from first principles. This derivation is preceded by a discussion of the four-factor formula, the six-factor formula, and Fick's law of diffusion. Formulas for calculating the neutron leakage rates in the six-factor formula are derived. Control rods, burnable poisons, chemical shim, burnup and depletion, and long-term changes to the isotopic composition of the core are then discussed from both an operational perspective and a reactor safety perspective. Time-dependent reactor behavior is discussed on several different levels. This discussion includes a presentation of the prompt jump and drop approximations, the point kinetics equations, and both the two-root and seven-root Inhour equations. The origins of the Inhour, the infinite multiplication factor, the effective multiplication factor, and the reactivity are presented. Both absolute and relative units are discussed for measuring the reactivity. The relationship between the reactivity and the reactor period is explored. Temperature feedback and other forms of thermal feedback are also explored for both PWRs and BWRs. The nuclear Doppler effect, the fuel temperature coefficient, the moderator temperature coefficient, and the void coefficient of the reactivity are all discussed. The time frames for these various nuclear phenomena are discussed as well.

P.3 Nuclear Data and Reactor Design

On a nuts-and-bolts level, real nuclear engineering is discussed. This includes a discussion of reactor core design, fuel rod design, and fuel assembly design. Containment buildings, power plant thermal cycles, and nuclear steam supply systems are discussed both at an operational level and at a design level. The containment buildings that failed at Fukushima and Chernobyl are discussed. The role of suppression pools and passive heat removal systems are explored. Modern reactor designs such as the Westinghouse AP-1000, the AREVA EPR, the GE advanced boiling water reactor (ABWR) and the GE simplified boiling water reactor (SBWR) are discussed. The zirconium-water reaction and the buildup of hydrogen gas during a severe reactor accident or LOCA are explored. The energetics of the zirconium-water reaction is reviewed. Chapters 6 and 11 present an extensive discussion of the process of radioactive decay heat. The Wigner–Way equation and Cherenkov radiation are also included in this discussion. The decay heat generated by both the fission products and the actinides is explored. Radioactive decay chains, the Bateman equations, and secular equilibrium are discussed. Radiocarbon dating and other methods are presented for dating organic materials.

Another unique feature of this book is an extensive discussion of nuclear cross sections, reaction rates, and modern sources of nuclear data. Several cross section libraries are used in this book. These libraries are based on the ENDF and JENDL databases, although other sources of nuclear data are used as well. This book is one of only a hand full of nuclear engineering books that actually show how to create an operational multigroup cross section library from experimental nuclear data. It discusses ultrafine libraries, course libraries, and how the process of cross section collapsing works. It shows how raw cross section data can be plotted using *ENDFPLOT* and other important Internet tools. It also describes the process of fuel assembly and fuel rod cross section homogenization. It begins with a discussion of bare reactor geometries and then extends this discussion to include reflected reactor cores. The concept of the reflector savings is discussed. Some attention is also paid to the temperature dependence of nuclear cross sections, diffusion coefficients, and neutron leakage rates. The Maxwell–Boltzmann probability distribution is derived and discussed. (In other books, it is simply discussed but not derived.)

In addition to common reactor types such as PWRs, BWRs, gas reactors, and LMFBRs, mobile power reactors and military reactors are also discussed. Because of its inherent safety features, the design of the TRIGA reactor is presented and discussed in some detail. Reactor coolants and neutron moderators are compared and various ways of measuring their efficiency are discussed. The design of the Canadian CANDU pressurized heavy water reactor (or PHWR) is explored. Its nuclear fuel cycle is also discussed. The advantages of heavy water are compared and contrasted to those of light water. The process of heavy water production is explained. The Brayton and Rankine thermal cycles are discussed. In its companion book (which is also available from CRC Press), various reactor analysis, safety analysis, and licensing codes such as RELAP, TRAC, and TRACE are discussed. Popular Monte Carlo, transport theory, and neutron diffusion theory codes are discussed as well. The discrete ordinates method and the S_N method are discussed as well as their computational underpinnings. The P_N method is presented in addition to the P_1 approximation. The philosophy of the Monte Carlo method and neutron transport theory are explained. The neutron transport equation and the angular neutron flux are derived from first principles. Since Monte Carlo methods rely heavily on the use of random numbers, both hardware and software random number generators are explored. Algorithms for generating random numbers are presented. Practical applications for PDFs, CDFs, and inverse CDFs are discussed as well.

P.4 Topics of Historical Interest

For the interested reader, this text endeavors to provide an interesting historical perspective of the nuclear power industry that is not available in other books. This discussion may be of interest to those seeking to understand how the modern nuclear power industry originated. Its origins dating back to the Manhattan Project are explored. The use of the first PWR in the U.S. nuclear navy is explored, and history of the U.S. nuclear navy is discussed.

From a somewhat different perspective, this book presents a historical overview of how the nuclear power industry originated in the United States and then spread to the rest of the world. In Chapter 12, the relationship between George Westinghouse and Nicola Tesla is explored. This relationship subsequently led to the founding of the Westinghouse Nuclear Corporation, which is the largest supplier of commercial nuclear reactors in the world today. The Borax experiments that led to the creation of the modern BWR are discussed in Chapter 14. Chapter 15 discusses the origins of the modern LMFBR, dating back to the Clementine reactor at Los Alamos in the late 1940s. Chapter 16 discusses the design of modern containment buildings, such as the GE Mark I, Mark II, and Mark III containments, and the containment building used for the Westinghouse AP-1000.

The contributions of many great people to the field of nuclear science and engineering are also explored within the context of this book. These historical figures include Hyman Rickover, James Maxwell, Ludwig Boltzmann, Albert Einstein, Enrico Fermi, Robert Oppenheimer, Edward Teller, Glenn Seaborg, Freeman Dyson, Nikola Tesla, Richard Feynman, George Westinghouse, and John Von Neumann. Several other notable figures of historical importance to the field are discussed as well.

Consequently, we hope the reader will find this book to be an excellent introductory textbook for teaching modern nuclear engineering to many different types of nuclear scientists and engineers. The book contains literally thousands of homework problems, worked examples, and illustrations to explain the principles of nuclear power. As opposed to other textbooks, a great deal of work has gone into ensuring that the writing style is warm and inviting rather than classical and dry. While this may seem to be a bit unorthodox at first, we believe that it will ultimately broaden the appeal of the book and make it easier for the general public to embrace the concept of nuclear power as a whole.

P.5 Potential for Course and Curriculum Customization

This textbook uses a slightly different approach than classical nuclear engineering books because it is designed to be *as modular as possible*. This inherent modularity allows the instructor to mix, match, and interchange the chapters in a variety of different ways to suit the needs of a specific curriculum. For example, Chapters 1 through 19 can be taught in a different order than they are presented because the chapters are more or less self-contained. This allows an instructor to create a customized fuel cycle, radiation protection, or radiation detection course. This also allows the instructor to create a customized nuclear physics or a reactor design course by mixing the chapters in a different way. For example, Chapters 1 through 8 can be used to create a nuclear physics course, Chapters 9 through 11 (with some additional material from its companion book) can be used to create a fuel cycle course, and Chapters 12 through 16 can be used to create a reactor design course. A radiation protection and detection course can be constructed from Chapters 17 through 19, with some additional coverage being provided by Chapters 2 through 6.

Its companion book then allows the subject of reactor physics to be taught to many different audiences on many different levels. The initial chapters can be used for an introductory reactor physics class (at a level similar to that presented in Lamarsh), and its later chapters are appropriate for a more advanced class (at a level similar to that presented in Duderstadt). Hence, its companion book can be used to create *two separate reactor physics courses* (an introductory course and an advanced course) that can be used for a two-semester curriculum. This inherent modularity allows the instructor to find the most appropriate level of presentation for a specific curriculum.

In other words, the inherent modularity designed into both books allows them to be used to create many different nuclear engineering courses that can be customized to the needs of an individual student or instructor. Because of this, the reader does not have to purchase several different nuclear engineering textbooks (i.e., a reactor physics book, a fuel cycle book, a reactor design book, a nuclear physics book, and a radiation protection or detection book) to cover the same amount of material. This inherent modularity may also be of some benefit to those who would like to vary their core curriculum from time to time. The overall text is broad enough and deep enough to accommodate most of these needs.

P.6 Cost-Effectiveness, Modularity, and Flexibility

In conclusion, we hope you will find this book to be a thoroughly modern introduction to nuclear science and engineering that is wide-ranging in its intended scope and cuts a broad swath across many areas of interest to the modern nuclear scientist and engineer. This is the first mainstream nuclear engineering textbook to be printed in *full color*. Together with its companion book, *it contains over 3000 worked homework problems, examples, questions, and sample problems* for the interested student or reader. This is between *5 and 10 times* the number of homework problems that are provided in other comparable textbooks. A solution key for these problems is also available to accredited faculty members and instructors. Because of its inherent modularity, this book can provide a very modern and cost-effective way to teach nuclear engineering to undergraduates and first year graduate students. In some cases, a three- or four-semester course can be created from the material provided.

Every effort has been made to make the information presented in this book as accurate as possible. In the event an error is found, please report this error to the following website: *http://www.crcpress.com/product/isbn/9781482221497* and it will be corrected in the next edition.

Finally, we sincerely hope that you will enjoy the warm and inviting writing style and the beautiful color images. We hope that it will inspire you to embrace the renaissance in the nuclear power industry that is occurring in the world today. We hope that you will enjoy reading this book and that you will find it to be an interesting and rewarding experience.

Robert E. Masterson, ScD (MIT)

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AUTHOR

Robert E. Masterson earned an MS and a Phd (ScD) in nuclear science and engineering at the Massachusetts Institute of Technology and a BS in physics at the University of Notre Dame. He has published extensively in the *Transactions of the ANS* and is a member of the American Nuclear Society.

Dr. Masterson has served over the years as an affiliate professor of nuclear science and engineering at the Virginia Polytechnic Institute, and he has an extensive background in the fields of reactor safety, reactor design and analysis, reactor thermal hydraulics, numerical analysis, reactor physics, reactor dynamics, nuclear medicine, and nuclear particle transport. He has over 20 years of experience in the field of nuclear science and engineering and also worked for Westinghouse Nuclear Energy Systems at the Hanford, Washington, site. He is president of a major technology consulting firm, and he is also the author of the book *An Introduction to Nuclear Reactor Physics*, which is also available from CRC Press.

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