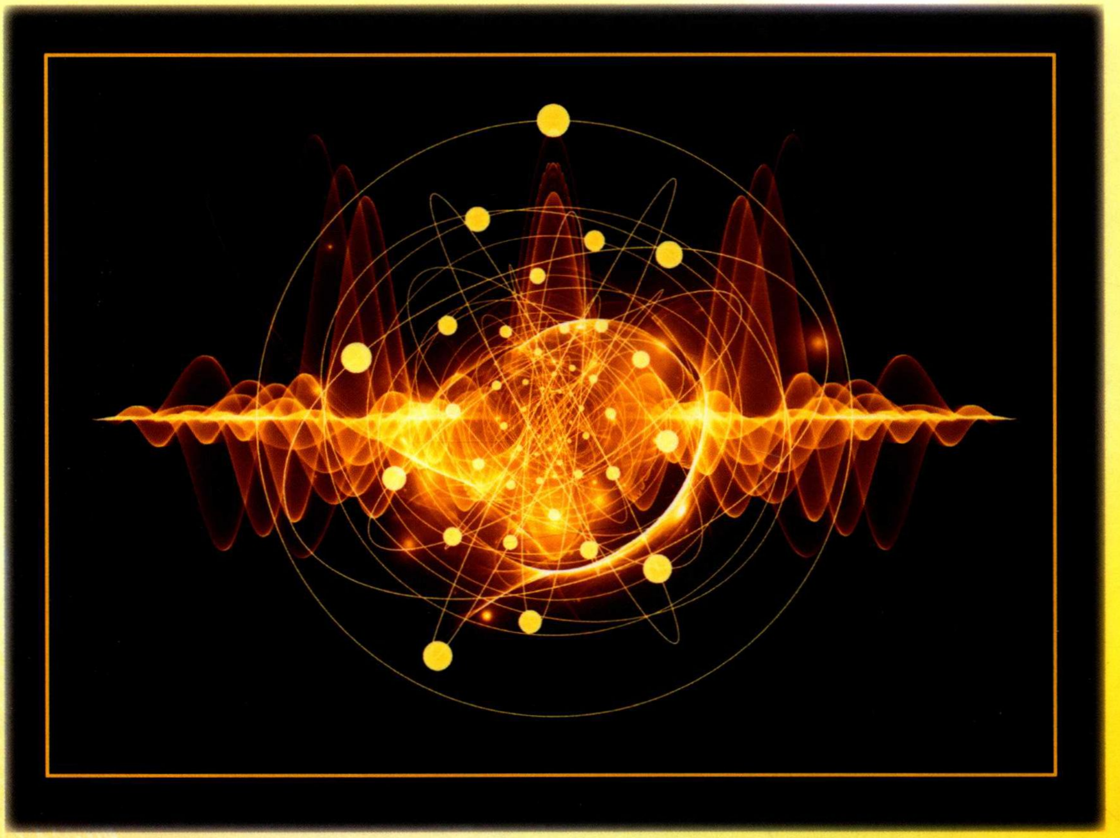
Introduction to NUCLEAR REACTOR PHYSICS



Robert E. Masterson

CRC Press
Taylor & Francis Group

Engineering - Mechanical

Introduction to NUCLEAR REACTOR PHYSICS

Robert E. Masterson

"A modern reactor physics book is long overdue. There are many classic texts, but they lack regular updates, ease of use, or a more extensive nuclear physics introduction for undergraduate courses. Following a detailed yet accessible comparison of modern reactor types, and a chapter introducing the basic nuclear physics underpinning nuclear power generation, the book steadily builds up the tools required in a clear and non-presumptive way. The lay-out of the text is uncluttered and clean, and the diagrams included are colorful and appropriate."

—**Carl Wheldon**, University of Birmingham, United Kingdom

Nuclear engineering is in the midst of a long overdue renaissance, but few reactor physics books have been written to support the needs of specific curricula tailored to comprehensive overviews of reactor physics, diffusion theory, and other fundamental principles of nuclear reactor design.

This comprehensive textbook is intended to provide the reader with a complete introduction to the subject of reactor physics. Intended for one-semester or two-semester courses in the physics of nuclear power, the text explains reactors, fuel cycles, radioisotopes, radioactive materials, design, and operation. In contrast to many reactor physics books intended for undergraduates, the author discusses in greater depth the multi-group neutron diffusion equation and multi-group neutron diffusion theory and its applications, as well as chain reaction and fission reactor concepts. The neutron diffusion equation, Fick's Law of Diffusion, and steady state/time-dependent reactor behavior are also explained in depth. This text:

- Covers all major topics needed for undergraduate and graduate nuclear reactor physics courses
- Provides the most up-to-date information on current reactor designs
- Written in a student-oriented style with full-color diagrams and photographs throughout
- Offers numerous examples, questions, problems, and boxed features
- Includes a complete solutions manual and electronic versions of figures for instructors

K27257

ISBN: 978-1-4987-5148-3

90000

9 781498 751483

CRC Press
Taylor & Francis Group
an informa business

6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

www.crcpress.com

Masterson

Introduction to NUCLEAR REACTOR PHYSICS

CRC

Introduction to Nuclear Reactor Physics

Robert E. Masterson, ScD

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

MIX
Paper from responsible sources
FSC® C014174
FSC www.fsc.org

Printed on acid-free paper

International Standard Book Number-13: 978-1-4987-5148-3 (Hardback)

Library of Congress Cataloging-in-Publication Data

Names: Masterson, Robert, 1950- author.
Title: Introduction to nuclear reactor physics / Robert Masterson.
Description: Boca Raton : Taylor & Francis, a CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa, plc, [2017]
Identifiers: LCCN 2016052983 | ISBN 9781498751483 (hardback : acid-free paper)
Subjects: LCSH: Nuclear reactors. | Nuclear physics. | Nuclear power plants.
Classification: LCC QC786.5 .M375 2017 | DDC 621.48/31--dc23
LC record available at https://lccn.loc.gov/2016052983

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Printed and bound in the United States of America by Sheridan

Introduction to Nuclear Reactor Physics

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 fully completed.

PREFACE

P.1 Overview of This Book

Nuclear engineering is in the midst of a long overdue renaissance, but few reactor physics books have been written to support this renaissance on a worldwide scale. Instructors are often asked to choose between books that are either too advanced or too elementary to meet the needs of a specific curriculum. Thus, many instructors have chosen to develop their own course notes or to ask students to buy several reactor physics books in order to cover the material that is required to fulfill the needs of a specific curriculum. In addition, many reactor physics books intended for undergraduates do not discuss the multigroup neutron diffusion equation or multigroup neutron diffusion theory and its applications. Instead, simple analytical solutions are presented to the diffusion equation for idealized reactor geometries with a single energy group. These solutions do not account for the presence of the reflector, and at an undergraduate level, they do not discuss the neutron transport equation or the Monte Carlo method. In addition, their computational underpinnings are almost never discussed.

To provide the attention these important areas deserve, this book endeavors to cover many subjects of interest to the reactor physicist as well as anyone interested in pursuing a career in nuclear science and engineering. The subject matter is inclusive enough to meet the needs of junior and senior undergraduates, but it is also broad enough and advanced enough to meet the needs of first-year graduate students. Thus this book is intended to be a comprehensive, accessible, and easy-to-use reference that will be an excellent addition to any nuclear engineering curriculum. It may also be used as an introductory or intermediate level textbook that the student can read prior to taking more advanced courses in the field. To achieve these goals, this book makes extensive use of color images, links to the Internet, computer graphics, and other innovative techniques to illustrate the concepts that are important to a modern nuclear engineer. The subject matter is broad enough and deep enough to support a nuclear engineering degree program at the B.S. or M.S. level.

P.2 Topics Covered: Reactor Physics, Reactor Dynamics, and Nuclear Particle Transport

P.2.1 Basic Reactor Physics

Holistically speaking, this book is designed to be used for a one-semester or two-semester course in the physics of nuclear power. To achieve this objective, considerable attention is paid to the behavior of the neutron and its interaction with matter. The nature of elastic, inelastic, head-on, and glancing collisions is explored. X-rays, gamma rays, and other nuclear particles of interest to the field of reactor physics are also discussed. Various reactor types, reactor fuel cycles, radioisotopes, radioactive materials, and various aspects of reactor design and operation are explored. Chapter 7 is devoted to the nuclear chain reaction as well as other important concepts required to understand how fission reactors work. In addition to these topics, other important topics such as neutron diffusion theory, the neutron diffusion equation, Fick's Law of Diffusion, and both steady state and time-dependent reactor behavior are explored. Both steady state and time-dependent solutions to the neutron diffusion equation are presented. The Inhour equation, the Point Kinetics Approximation, and Xenon transients are explored. These subjects are enhanced by a discussion of reactor accidents, the INES Scale of accident severity, the neutron transport equation, and the Monte Carlo method. Single-group, two-group, and multigroup neutron diffusion theories are also discussed.

In addition to these important topics, neutron slowing down theory is discussed. This theory includes how fission neutrons are converted into thermal and epithermal neutrons and how neutron moderators are used to perform this function. Slowing down theory is applied to many different moderators and reactor coolants. The average energy loss per collision is determined for elastic scattering events. The dependence of neutron energy loss on the scattering angle is also discussed. Useful parameters such as the lethargy and moderating ratio are defined and applied to practical problems. The "energy staircase" that illustrates how neutrons lose energy as they move through a reactor lattice is illustrated pictorially in Chapter 8. Next, this book describes the differences between neutron transport theory and neutron diffusion theory. The neutron transport equation and the neutron diffusion equation are derived from first principles. The angular neutron flux is compared to the isotropic neutron flux, and for isotropic particle flows, the current is expressed as the gradient of the particle flux. This discussion is preceded by a derivation of the Four-Factor formula, the Six-Factor formula, and Fick's Law of Diffusion. Each factor in the four- and six-factor formulas is derived and discussed. Representative values are provided for these factors. Control rods, burnable poisons, chemical shim, burnup and depletion, and long-term changes to the isotopic composition of the core are discussed.

P.2.2 Reactor Dynamics and Nuclear Particle Transport

Next, the text attempts to provide a broad and relatively practical overview of reactor dynamics and nuclear particle transport. Time-dependent reactor behavior is initially discussed at an elementary level, which includes a presentation of the Prompt Jump and the

Prompt Drop approximations. Then it is extended to more advanced topics including the Point Kinetics approximation, the two-root Inhour equation, and the seven-root Inhour equation. (Other introductory textbooks only discuss the two-root Inhour equation.) The origins of the Inhour, the Infinite multiplication factor, and the Effective multiplication factor are discussed. The fast and thermal nonleakage probabilities are derived from first principles. The reactivity is defined using both absolute and relative units. Several equations are presented for the control rod worth, and its value is expressed as a function of the delayed neutron fraction. The relationship between the reactivity and the reactor period is explored. Temperature feedback and other forms of thermal feedback such as the nuclear Doppler effect, the fuel temperature coefficient, the moderator temperature coefficient, and the void coefficient of the reactivity are examined for different reactor types. The time frames associated with these feedback mechanisms are discussed as well. Regulatory issues are explored, and important reactor design parameters, such as the Moderator Fuel Ratio (or MFR), are added to the discussion. The coverage of reactor physics is extensive, and in many cases it exceeds the level of coverage presented in far more expensive reactor physics books.

P.3 Sources of Nuclear Data

This text also provides an extensive discussion of nuclear cross-section libraries and valuable sources of nuclear data. The cross sections used are based on the ENDF and JENDL databases, although other sources of nuclear data are referenced as well. The text then attempts to create an operational multigroup cross-section library from raw experimental nuclear data. It discusses ultrafine libraries, course libraries, and how the process of cross-section collapsing is implemented. It illustrates how cross-section data can be plotted using ENDFPLOT and other online plotting tools. As a bonus, it describes the process of fuel assembly and fuel rod homogenization. It starts with a discussion of bare reactors and then extends this discussion to include reactors with both radial and axial reflectors. The concept of the reflector savings is discussed. Particular attention is paid to the temperature dependence of nuclear cross sections, diffusion coefficients, and leakage rates. Once the neutrons become thermal neutrons, the Maxwell–Boltzmann probability distribution is discussed. (Here it is also derived, while in most other textbooks, it is simply discussed.)

P.4 Other Important Topics

On a nuts-and-bolts level, real nuclear engineering is discussed. Many topics are presented that build on the foundation created in our companion book (see Section P.7). These topics include 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 at both an operational level and at a design level. The containment buildings that failed at Fukushima and Chernobyl are discussed as well. The role of suppression pools and passive heat removal systems are explored. Modern reactor designs, such as the Westinghouse AP-1000, the AREVA EPR, and the GE Advanced Boiling Water Reactor (ABWR) and Simplified Boiling Water Reactor (SBWR), are also discussed. In our companion book, the Zirconium–water reaction and the buildup of hydrogen gas during a severe reactor accident or LOCA is explored. The energetics of the Zirconium–water reaction is discussed. Other topics of interest include radioactivity, radioactive decay, decay heat generation, and the Wigner–Way equation. 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. The nuclear fuel cycle is presented for both fast and thermal reactors. The attributes and drawbacks of various nuclear fuels are discussed.

In addition to PWRs, BWRs, gas reactors, and LMFBRs, the neutronic characteristics of mobile power reactors (MPRs) and military reactors are explored. Their refueling cycles are also compared to those of commercial power reactors. Because of its novel design and unusual stability, the design of the TRIGA reactor is discussed in some detail (see Chapter 17). The advantages of heavy water are compared and contrasted to those of light water. Various reactor safety analysis and reactor licensing codes such as RELAP, TRAC, and TRACE are discussed within the framework of modern reactor physics. Monte Carlo, Transport Theory, and Neutron Diffusion Theory codes are discussed as well.

P.5 Neutron Transport Theory and the Monte Carlo Method

On a somewhat more advanced level, several chapters (including Chapters 22 and 23) are dedicated to a discussion of neutron transport theory and the Monte Carlo method. The neutron transport equation is derived from first principles. The angular neutron flux is then discretized using the discrete ordinates method and the S_N method. The P_N method for solving the neutron transport equation is presented in addition to the P_1 approximation. The Monte Carlo method is then introduced to the reader in Chapter 23. Since Monte Carlo methods require the use of random numbers, both hardware and software random number generators are discussed. Algorithms for generating random numbers are provided for reactor physicists. Practical applications of PDFs, CDFs, and inverse CDFs are presented in Chapter 23. The characteristic features of statistical probability distributions are explored. The primary differences between neutron transport theory and neutron diffusion theory are discussed. The angular neutron current and the angular neutron flux are defined and compared to the conventional neutron current and the conventional neutron flux. The transport cross section and the transport mean free path are directly derived from the P1 approximation. Finally, variance reduction methods and other error reduction schemes are introduced for reducing the statistical uncertainties in a Monte Carlo calculation. As far as the author and the publisher are aware, this is the only introductory reactor physics book that attempts to discuss these subjects at a working level. The relationship between the Monte Carlo method and neutron game theory is explored.

P.6 Topics of Historical Interest to Nuclear Scientists and Engineers

This book, as well as its companion book *Nuclear Engineering Fundamentals: A Practical Perspective*, provides a unique historical perspective on the nuclear power industry that is not available in other textbooks. This perspective may be of interest to anyone seeking to know how the nuclear industry was founded, and which people were responsible for creating it. Its origins dating back to the early days of the Manhattan Project are explored in the companion book. The use of the first PWR in the Nuclear Navy is discussed. The history of the U.S. Nuclear Navy is discussed from the viewpoint of a reactor physicist.

The text also presents a historical narrative of how the nuclear power industry originated in the United States and then became prevalent throughout the rest of the world. For example, in its companion book, the relationship between George Westinghouse and Nicola Tesla, which led to the founding of the Westinghouse Nuclear Energy Corporation, is explored. The Borax experiments that led to the creation of the first BWR are discussed. Finally, the origins of the modern LMFBR, dating back to the Clementine reactor at Los Alamos, are discussed. This includes a discussion of the design of modern containment buildings, including the GE Mark I, Mark II, and Mark III containments, and the containment buildings used for the Westinghouse AP-1000. The contributions of the many great men to the field of nuclear engineering are explored within the context of its companion 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 (one of the inventors of the modern computer, computer game theory, and the Monte Carlo method). Several other figures of historical importance in the field, such as Gordon Moore (the cofounder of Intel and one of the inventors of the modern microprocessor), are also discussed.

P.7 Relationship of This Book to Its Companion Book

As alluded to previously, this text book is intended to be the second book of a two-book set. Its companion volume, *Nuclear Engineering Fundamentals: A Practical Perspective* (which is also available from CRC Press), provides the introductory material that students should be exposed to before taking a reactor physics class. It begins by discussing common types of reactors (including PWRs, BWRs, gas reactors, Military Reactors, and LMFBRs) as well as their various design and operational parameters. It discusses 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 discussed in Chapter 7. In addition to these important topics, a great deal of attention is paid to the nuclear fuel cycle, the uranium enrichment process, various uranium enrichment technologies, and the interaction of radiation with matter. The advantages (and drawbacks) of different types of nuclear waste disposal and fast and thermal breeder reactors are discussed. The Thorium fuel cycle is also presented and compared to conventional uranium and plutonium fuel cycles. The economic trade-offs associated with each of these fuel cycles are discussed. The extraction of uranium from sea water 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 nature of the weak force and the application of Feynman diagrams). As a bonus, it also presents the first publicly available derivation of Einstein's famous equation $E = mc^2$ in an introductory nuclear engineering textbook.

Consequently, we believe the reader will find this two-book set to be an excellent introductory set of books for teaching modern nuclear engineering to many different types of nuclear scientists and engineers. Combined together, these two books contain literally thousands of homework problems, worked examples, and illustrations to explain the principles of reactor physics. As opposed to many 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 population to embrace the concept of nuclear power as a whole.

P.8 Potential for Course and Curriculum Customization

This textbook takes a slightly different approach than classical reactor physics 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 match the needs of a specific curriculum. In other words, *it allows the subject of reactor physics to be taught on many different levels and* *to many different audiences*. The initial chapters (Chapters 1 through 12) can be used for an introductory reactor physics class (at a level similar to that employed by Lamarsh), and the later chapters are appropriate for a more advanced class (at a level similar to that used by Duderstadt or Stacy). Hence, this 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 type of presentation for a specific curriculum. This extensive 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. Several customized courses can also be developed from the material provided.

P.9 Modularity, Cost Effectiveness, and Flexibility

In conclusion, we hope that you will find this book to be a thoroughly modern alternative to classical reactor physics books that are much more expensive or much harder to read. It provides a thorough introduction to the subject of reactor physics that is wide-ranging in its intended scope and cuts a broad swath across many areas of interest to the nuclear scientist and engineer. This book and its companion book are the first mainstream nuclear engineering textbooks to be printed in full color. Taken together, *they contain more than 3000 worked homework problems, examples, questions, and sample problems* for the interested student or reader. This is between *five and ten 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 their inherent flexibility and modularity, these books can provide a modern and cost-effective way to teach nuclear engineering courses to undergraduates and first-year graduate students. In some cases, a three-semester or four-semester course can be fashioned from the subject matter 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 it to *orders@taylorandfrancis.com* 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)

Credits and Acknowledgments

The author wishes to thank the many faculty, students, and industry professionals who contributed their thoughts and comments to the completion of this book. In particular, he would like to thank:

- Kord Smith and Lulu Li from the Nuclear Engineering Department of MIT
- Igor Bolotnov and Maria Avramova from the North Carolina State University
- Jim Turso from Pennsylvania State University
- Harry Goodman from Louisiana State University
- Shripad Revankar from Purdue University
- Yaron Danon from Rensselaer Polytechnic Institute
- Mahmoud Massoud from the University of Maryland, College Park
- Dr. Tom Boulette, previously from Boston Edison and the US NRC
- Eddy Cardentey from the Westinghouse Nuclear Corporation
- Mark Pierson and Dewey Spangler from Virginia Polytechnic University
- William L. Dunn from Kansas State University
- Mike Driscoll, previously from the Nuclear Engineering Department at MIT
- The students and staff of Virginia Tech
- And lastly for his inspiration and support, Ken Ball, now dean of engineering at George Mason University

Finally, I would like to express my gratitude to the editors at CRC Press and in particular to Jonathan Plant, whose vision and perseverance has made a book of this scope, color, depth, and breadth possible.

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 (the American Nuclear Society) and has been a member of the society for many years.

Dr. Masterson has also served over the years as affiliate professor of nuclear science and engineering at the Virginia Polytechnic Institute and 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. The author has more than 20 years of experience in the field of nuclear science and engineering and worked for Westinghouse Nuclear Energy Systems at the Hanford site. He is president of a major technology consulting firm and is also the author of *Nuclear Engineering Fundamentals: A Practical Perspective*, which can also be obtained from CRC Press.

In addition to his work in nuclear science and engineering, he has founded and cofounded several companies and has held many noteworthy management, advisory, and strategic positions. His global e-mail address is drbobmasters@gmail.com, where he welcomes feedback and suggestions regarding his books.

TABLE OF CONTENTS

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7