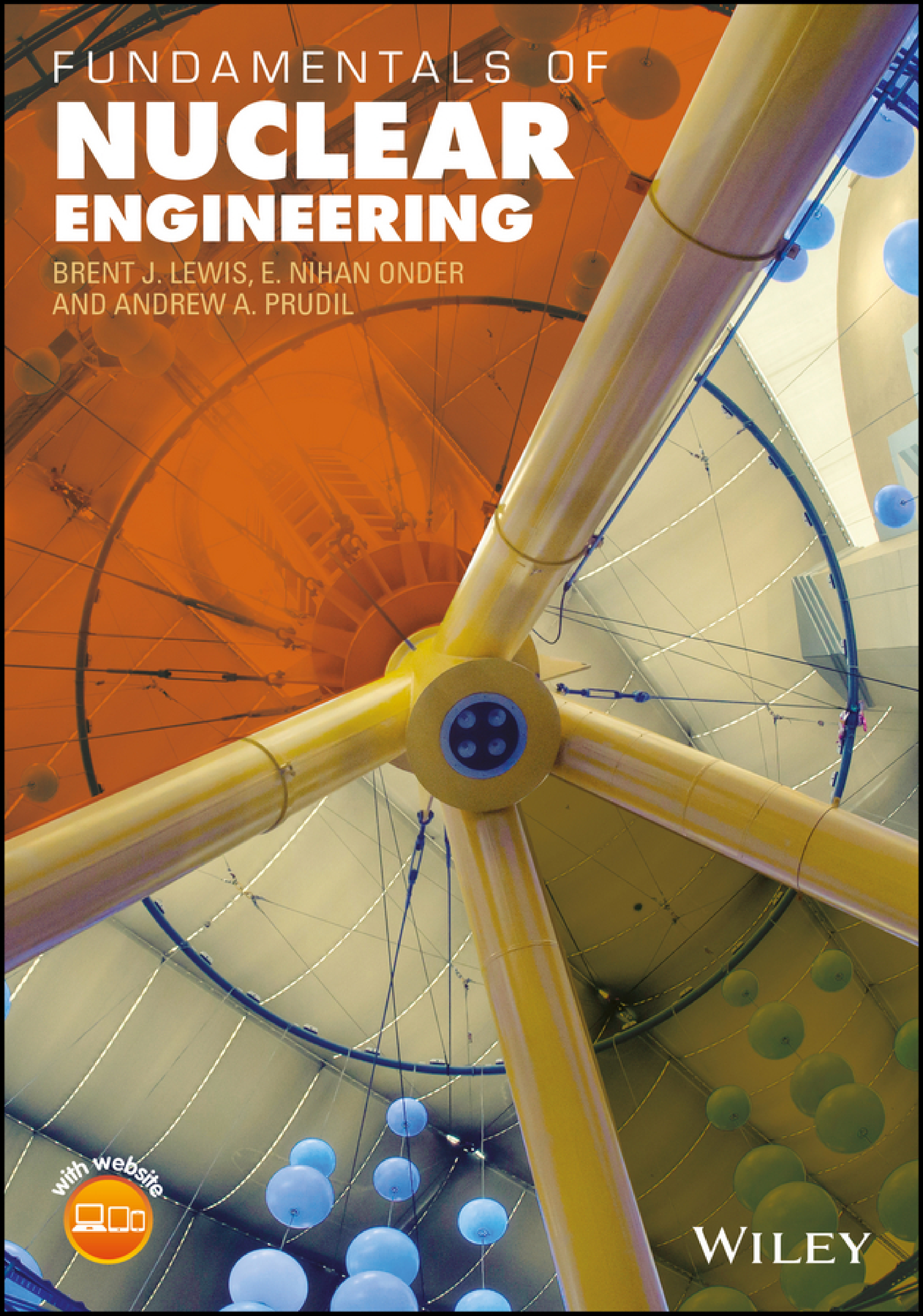
FUNDAMENTALS OF NUCLEAR ENGINEERING

BRENT J. LEWIS, E. NIHAN ONDER
AND ANDREW A. PRUDIL



WILEY

Fundamentals of Nuclear Engineering

Fundamentals of Nuclear Engineering

Brent J. Lewis, PhD, PEng, FCNS
Emeritus Professor and Past COG/UNENE/NSERC Industrial Research Chair in Nuclear Fuel
Royal Military College of Canada, Kingston, Ontario, Canada

E. Nihan Onder, PhD
Thermalhydraulics Engineer/Analyst and Nuclear Fuel Research Scientist
Canadian Nuclear Laboratories
Chalk River, Ontario, Canada

Andrew A. Prudil, PhD, PEng
Nuclear Fuel Safety Scientist
Canadian Nuclear Laboratories
Chalk River, Ontario, Canada

WILEY

This edition first published 2017

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data
Names: Lewis, Brent J., 1955- author. | Onder, E. Nihan, 1972- author. | Prudil, Andrew A., 1987- author.
Title: Fundamentals of nuclear engineering / Brent J. Lewis, PhD, PEng, FCNS, Emeritus Professor and Past COG/UNENE/NSERC Industrial Research Chair in Nuclear Fuel, Royal Military College of Canada, Kingston, Ontario, Canada, E. Nihan Onder, PhD, Thermalhydraulics Engineer/Analyst and Nuclear Fuel Research Scientist, Canadian Nuclear Laboratories, Chalk River, Ontario, Canada, Andrew A. Prudil, PhD, PEng, Nuclear Fuel Safety Scientist, Canadian Nuclear Laboratories, Chalk River, Ontario, Canada.
Description: Chichester, West Sussex, United Kingdom : John Wiley & Sons, Inc., [2017] | Includes bibliographical references and index.
Identifiers: LCCN 2016039544 (print) | LCCN 2016048630 (ebook) | ISBN 9781119271499 (cloth) | ISBN 9781119271543 (pdf) | ISBN 9781119271550 (epub)
Subjects: LCSH: Nuclear engineering.
Classification: LCC TK9145 .L49 2017 (print) | LCC TK9145 (ebook) | DDC 621.48--dc23
LC record available at https://lccn.loc.gov/2016039544

Hardback ISBN: 9781119271499

Cover image: © Martin Turner/Gettyimages
Cover design by Wiley

Set in 10/12pt Warnock by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

Contents

Preface

This book is developed from course lecture notes given in the graduate programme in Nuclear Engineering at the Royal Military College of Canada (RMC), Kingston, ON, and École Polytechnique, Montreal, QC, and an undergraduate course at Queen's University, Kingston, ON. It is further based on subject research in nuclear fuel behaviour, thermal hydraulics and radiation protection (for aircrew and space crew) as research scientists at the Canadian Nuclear Laboratories [formally the Chalk River Laboratories of Atomic Energy of Canada Limited (AECL)] and as a university educator and Industrial Research Chair in Nuclear Fuel sponsored by the CANDU Owners Group (COG), University Network of Excellence in Nuclear Engineering (UNENE) and Natural Sciences and Engineering Research Council (NSERC). This book focuses on undergraduate and graduate-level teaching in nuclear engineering with the development of concepts in a systematic manner. It is relevant to the nuclear professional summarizing some key research developments in the fields of nuclear fuel behaviour, health physics and reactor thermal hydraulics. Moreover, it especially fills an important need and niche as a modern and comprehensive textbook for undergraduate and graduate instruction and the learning of core subjects in atomic and nuclear theory, nuclear reactor physics, nuclear reactor dynamics and control, nuclear fuel engineering, thermal hydraulics, nuclear reactor safety, and health physics and radiation protection. The textbook also contains extensive nuclear and reactor physics data, and fundamental constants detailed in several Appendices as developed from recent data libraries. Solved exercises are provided to augment the learning of the text material. In addition, a number of solved problems used for various tests and examinations in the courses are also included at the end of each chapter. This package therefore provides a complete set of source material and problems with a single textbook for undergraduate and graduate course instruction.

January 2017

Brent J. Lewis
E. Nihan Onder
Andrew A. Prudil

Acknowledgements

We would like to recognize the use of some source material selected from several nuclear engineering courses. In particular, we would like to acknowledge the use of lecture material derived from the CHE1521S course of Professor R. Jervis at the University of Toronto in the area of nuclear and radiochemistry for Chapter 1 and lecture material from the CHE1531S course of Professor J. Luxat at the University of Toronto on nuclear reactor control systems for Chapter 3. In addition, we are indebted to Dr. Altan Tapucu from École Polytechnique for providing some of his lecture notes from the ENE 6002 and ENE 6107 courses and comments on Chapter 5 and Professor Alberto Teyssedou from École Polytechnique for his contribution to the ENE 6002 and ENE 6107 course materials, and Professor H.W. Bonin of the Royal Military College of Canada for some of his course material and problems on health physics and radiation protection from the CC511 course for Chapter 7. We would like to further acknowledge and thank Professor P. Chan for some lecture material on nuclear fuel design and nuclear safety, Dr. Diana Wilkinson from the Defence Research Development Canada (Ottawa) on radiation biology and Kirsten Avarmaa for her diligent work on the book illustrations.

PowerPoint slides developed from material in this book for courses CC511 (Health Physics and Radiation Protection), CC523 (Nuclear Reactor Engineering) and CC533 (Nuclear Fuel Engineering) were graciously provided by Professors E. Corcoran and P. Chan from the Royal Military College of Canada for use on the Wiley web site.

The book is dedicated to the many graduate students we have had the pleasure to supervise and mentor over the many years. Finally, we would like to thank our colleagues for their continual friendship and collaboration, and especially our families for their patience and loving support.

About the Companion Website

Don’t forget to visit the companion web site for this book:
www.wiley.com/go/lewisnuc

There you will find valuable material designed to enhance your learning, including:

- Problem solutions
- Teaching slides
- Course outlines

Scan this QR code to visit the companion web site

Prologue

Introduction

Nuclear technology was first developed in the 1940s during research on weapons production during the World War II. Attention turned to commercial nuclear power in the 1950s. Today, nuclear energy is an important source of electricity production for three main reasons: (i) supply, (ii) environmental footprint (i.e., climate change) and (iii) economics.

As shown in Figure P.1, nuclear power provides about 11% of the global electricity needs. In particular, as of 2015, there have been 16 000 reactor years of experience with 436 commercial power reactors in 31 countries that supply 378 000 MW (electrical) of total capacity; in addition, 67 nuclear power reactors are also under construction with 166 reactors being planned (Table P.1). Fifty-six countries operate a total of 240 research reactors as a source of neutrons for scientific research and for the production of medical and industrial isotopes. Moreover, there are about 180 nuclear reactors that power ships and submarines.

From 1990 to 2010, the world electricity (e) capacity rose by 57 GWe (17.75%), with a rise in electricity produced from nuclear power of 755 TWh (40%), as shown in Figure P.2, due to new plant construction (36%), uprating of other plants (7%) and an increase in availability of plants (57%). The USA itself accounts for nearly one third of the world's nuclear electricity (see the first column of Table P.1), where nuclear power plant performance has increased over the past twenty years with capacity factors over 90% in five of the seven years up to 2013. In 2011 and 2012, both capacity and output diminished, with cutbacks in Germany and Japan (i.e., in Japan dropping from 13 TWh in 2010 to 0 TWh in 2015 as seen in Table P.1) following the Fukushima reactor accident (see Chapter 6).

Nuclear power is important because of its relatively low environmental footprint in terms of climate change. The lifecycle greenhouse gas (GHG) emissions from different forms of electricity generation for all phases of the process including construction, operation, and decommissioning are shown in Figure P.3 based on the analysis of twenty studies. This analysis shows that generating electricity from fossil fuels results in much greater emissions than that from nuclear or renewable generation.

Data for costs in the United States for various sources of electricity production from 1995 to 2012 (Figure P.4) show nuclear generation (i.e., for the fuel plus operation and maintenance) at 2.40 cents/kWh, as compared with coal at 3.27 cents/kWh and gas at 3.40 cents/kWh. These costs exclude indirect costs and capital costs that are plant/utility specific and also depend on the age of the plant.

Fundamentals of Nuclear Engineering, First Edition. Brent J. Lewis, E. Nihan Onder and Andrew A. Prudil.

Companion Website: www.wiley.com/go/lewisnuc

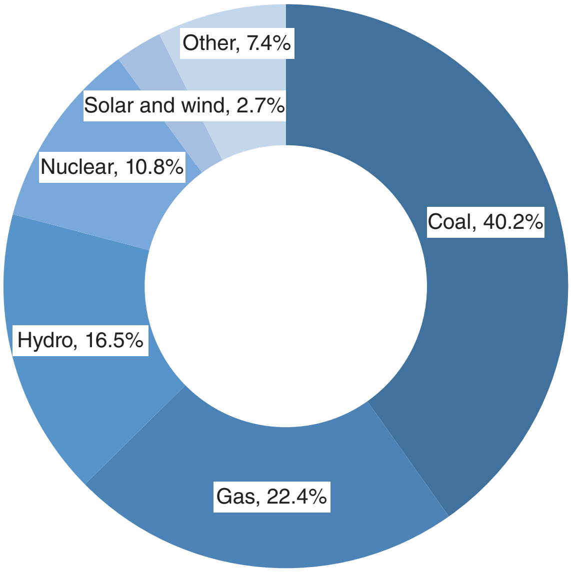


Figure P.1 World electricity production in 2012. Source: World nuclear association.

A finish study for projected electricity costs in 2003 suggested nuclear production at €2.37 cents/kWh, coal at €2.63 cents/kWh and natural gas at €3.22 cents/kWh (Figure P.5). This study assumed a 91% capacity factor, 5% interest rate and 40-year plant life. The relative effects of capital and fuel costs are depicted. Nuclear production specifically has a relatively high capital cost that depends importantly on the financing costs and length of time for construction. On the other hand, the fuel costs are much lower, so that once a nuclear plant is built its costs are more predictable compared to gas or coal. In addition, a carbon tax can impact costs, that is, with carbon emissions trading at €20/t CO_2, the electricity costs for coal and gas increase to €4.25 and 3.92 cents/kWh, respectively. Finally, in 2015, a report from the Institute for Energy Research on the levelized cost of electricity from existing generation resources suggested nuclear production at slightly over $90/MWh, compared with coal at almost $100/MWh and gas just over $70/MWh.

Organization of the book

The book covers a broad range of key areas in the field of nuclear engineering and is organized into seven chapters, consisting of: Chapter 1: Atomic and Nuclear Theory; Chapter 2: Nuclear Reactor Design and Physics; Chapter 3: Nuclear Reactor Dynamics and Control; Chapter 4: Nuclear Reactor Materials and Fuel Engineering; Chapter 5: Thermal Hydraulics; Chapter 6: Nuclear Reactor Safety; and Chapter 7: Health Physics and Radiation Protection. Information in the book is provided at both an introductory and a more advanced level and also draws on, in part, recent state-of-the-art research in nuclear fuel behaviour, reactor safety and thermal hydraulics. The book chapters are presented in a logical manner from basic theory to design, construction, operation, control and safety of nuclear reactors, including the need for health physics and radiation protection. It also contains nine appendices of relevant nuclear and reactor physics data as well as fundamental constants, cross-sections and fission product yields. This work also includes a complete exercise manual with solved problems for the exercises and problems presented at the end of each chapter.

Table P.1 World nuclear power reactors and uranium requirements

Country	Nuclear electricity generation 2014	Reactors operable August 2015		Reactors under construction August 2015		Reactors planned August 2015		Reactors proposed August 2015		Uranium required 2015	
	Billion kWh (or TWh)	% electricity	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross	tonnes U
Argentina	5.3	4.0	3	1627	1	27	2	1950	2	1300	215
Armenia	2.3	30.7	1	376	0	0	1	1060			88
Bangladesh	0	0	0	0	0	0	2	2400	0	0	0
Belarus	0	0	0	0	2	2388	0	0	2	2400	0
Belgium	32.1	47.5	7	5943	0	0	0	0	0	0	1017
Brazil	14.5	2.9	2	1901	1	1405	0	0	4	4000	326
Bulgaria	15.0	31.8	2	1906	0	0	1	950	0	0	324
Canada	98.6	16.8	19	13 553	0	0	2	1500	3	3800	1784
Chile	0	0	0	0	0	0	0	0	4	4400	0
China	123.8	2.4	26	23 144	25	27 393	43	49 970	136	153 000	8161
Czech Republic	28.6	35.8	6	3904	0	0	2	2400	1	1200	566
Egypt	0	0	0	0	0	0	2	2400	2	2400	0
Finland	22.6	34.6	4	2741	1	1700	1	1200	1	1500	751
France	418.0	76.9	58	63 130	1	1750	0	0	1	1750	9230
Germany	91.8	15.8	8	10 728	0	0	0	0	0	0	1889
Hungary	14.8	53.6	4	1889	0	0	2	2400	0	0	357
India	33.2	3.5	21	5302	6	4300	22	21 300	35	40 000	1579
Indonesia	0	0	0	0	0	0	1	30	4	4000	0
Iran	3.7	1.5	1	915	0	0	2	2000	7	6300	176
Israel	0	0	0	0	0	0	0	0	1	1200	0
Italy	0	0	0	0	0	0	0	0	0	0	0
Japan	0	0	43	40 480	3	3036	9	12 947	3	4145	2549
Jordan	0	0	0	0	0	0	2	2000			0
Kazakhstan	0	0	0	0	0	0	2	600	2	600	0
Korea DPR (North)	0	0	0	0	0	0	0	0	1	950	0
Korea RO (South)	149.2	30.4	24	21 677	4	5600	8	11 600	0	0	5022

(Continued)

Table P.1 (Continued)

Country	Nuclear electricity generation 2014	Reactors operable August 2015		Reactors under construction August 2015		Reactors planned August 2015		Reactors proposed August 2015		Uranium required 2015	
	Billion kWh (or TWh)	% electricity	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross	tonnes U
Lithuania	0	0	0	0	0	0	1	1350	0	0	0
Malaysia	0	0	0	0	0	0	0	0	2	2000	0
Mexico	9.3	5.6	2	1600	0	0	0	0	2	2000	270
Netherlands	3.9	4.0	1	485	0	0	0	0	1	1000	103
Pakistan	4.6	4.3	3	725	2	680	2	2300	0	0	101
Poland	0	0	0	0	0	0	6	6000	0	0	0
Romania	10.8	18.5	2	1310	0	0	2	1440	1	655	179
Russia	169.1	18.6	34	25 264	9	7968	31	33 264	18	16 000	4206
Saudi Arabia	0	0	0	0	0	0	0	0	16	17 000	0
Slovakia	14.4	56.8	4	1816	2	942	0	0	1	1200	466
Slovenia	6.1	37.2	1	696	0	0	0	0	1	1000	137
South Africa	14.8	6.2	2	1830	0	0	0	0	8	9600	305
Spain	54.9	20.4	7	7002	0	0	0	0	0	0	1274
Sweden	62.3	41.5	10	9487	0	0	0	0	0	0	1516
Switzerland	26.5	37.9	5	3333	0	0	0	0	3	4000	521
Thailand	0	0	0	0	0	0	0	0	5	5000	0
Turkey	0	0	0	0	0	0	4	4800	4	4500	0
Ukraine	83.1	49.4	15	13 107	0	0	2	1900	11	12 000	2366
UAE	0	0	0	0	3	4200	1	1400	10	14 400	0
United Kingdom	57.9	17.2	16	9373	0	0	4	6680	7	8920	1738
USA	798.6	19.5	99	98 792	5	6018	5	6063	17	26 000	18 692
Vietnam	0	0	0	0	0	0	4	4800	6	6700	0
World	***2411***	***11.5***	***436***	***378 995***	***67***	***70 107***	***166***	***186 704***	***322***	***364 920***	***66 883***

Source: World nuclear association.

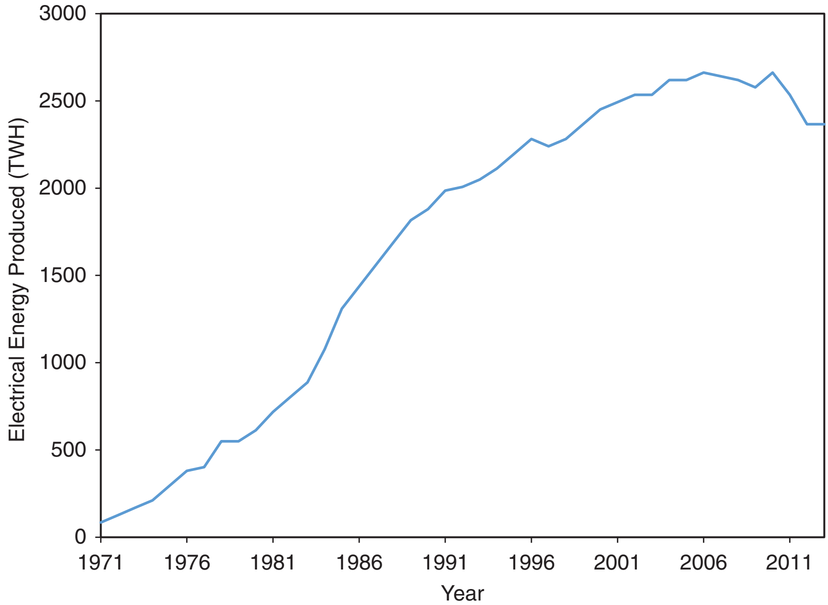


Figure P.2 Nuclear electricity production in the world. Source: World nuclear association.

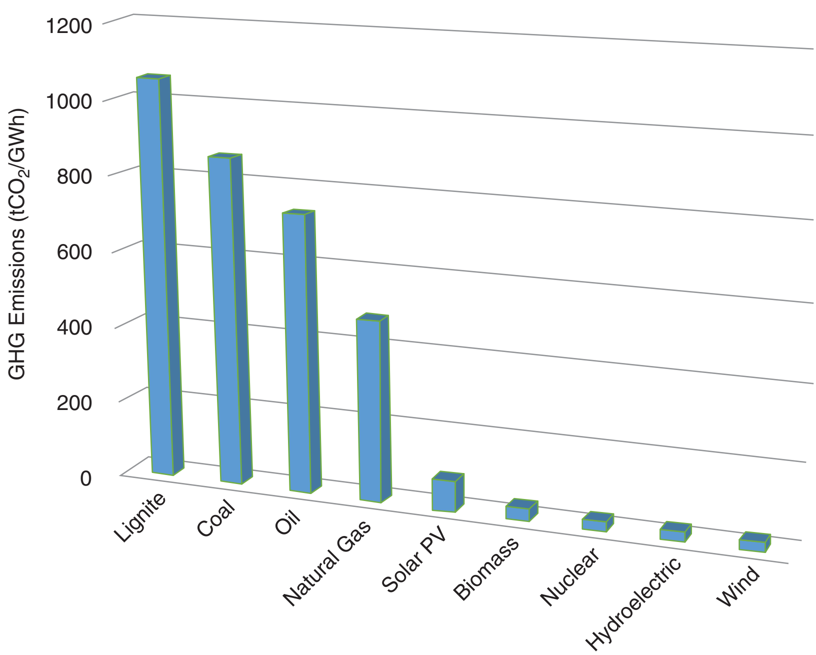


Figure P.3 Average lifecycle greenhouse gas emissions from different sources of electricity generation. Source: World nuclear association.

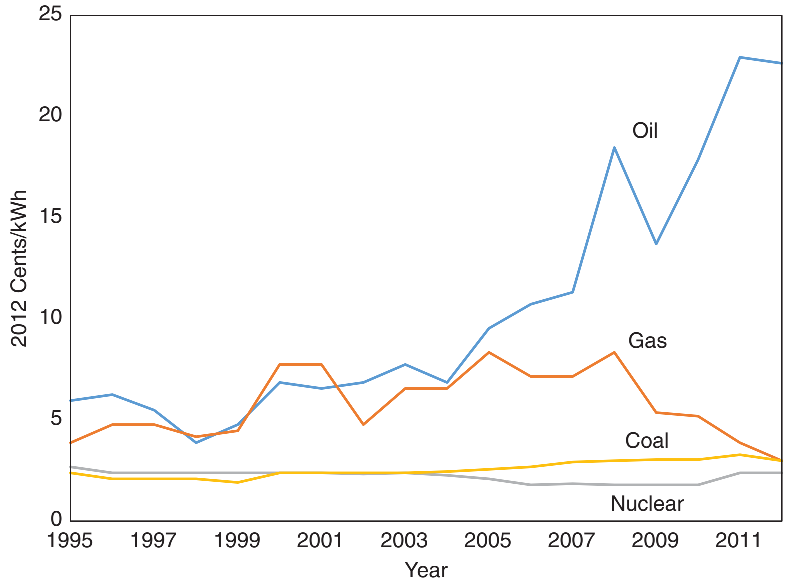


Figure P.4 US electricity production costs from 1995 to 2012. Source: World nuclear association.

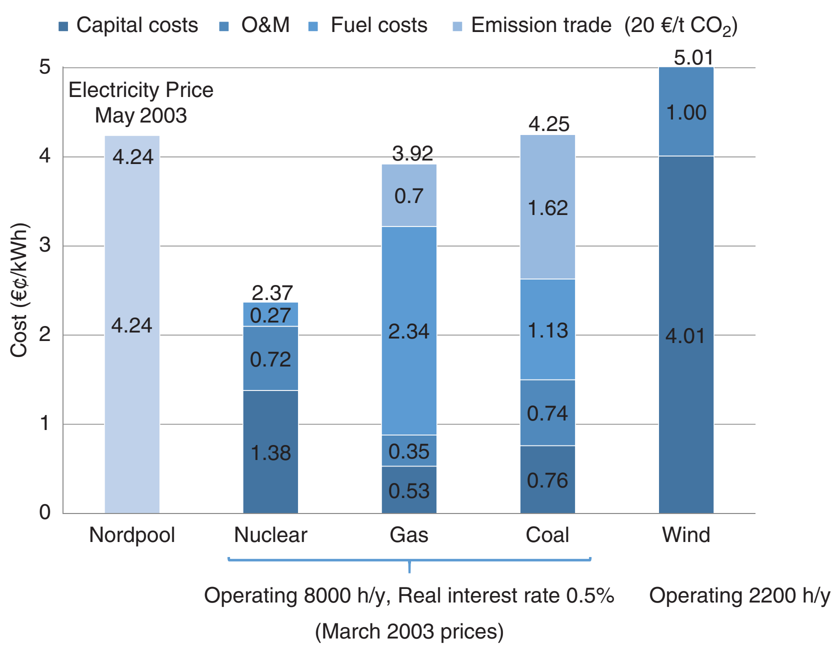


Figure P.5 Projected electricity costs for Finland in 2003. Source: World nuclear association.

Chapter 1 provides an overview of atomic and nuclear theory, including historical developments and a modern understanding of the underlying forces of nature. It particularly explains nuclear composition and stability in nature and how energy release is "thermodynamically" favoured in the fission process. This energy release occurs through a mass loss between the reactants and products as a result of Einstein's mass-energy equivalence relationship and is the source of energy in nuclear power. The chapter also details generalized schemes and systematics for alpha, beta and gamma decay and transition processes. Importantly, by utilizing nuclear models, it explains *why* specific decay systematics are observed for isotopes in accordance with nuclear selection rules. The theory provides a fundamental understanding of decay processes and their energies as well as the observed nuclear spin and parity of nuclides. It also details the important concepts of nuclear reactions and cross sections as needed for reactor physics analysis in the design of the critical reactor core in Chapter 2.

Chapter 2 illustrates the overall design of reactors, including past, present and future concepts. It describes the physics of criticality, including introductory reactor theory, design and operation. In the steady-state, sources and losses of neutrons in the reactor are examined for the critical state employing diffusion theory for leakage of neutrons from the core. Diffusion theory in itself is an approximation of the more generalized neutron transport equation. The development of this latter equation from advanced reactor theory is also presented, as is its simplification to diffusion theory with the assumption of isotropic neutron scattering. Moreover, the solution of the more detailed neutron transport equation using modern computational methods is explained.

Chapter 3 examines the dynamical nature of the reactor using a "point kinetics" approach. This chapter involves a discussion of the overall reactivity of the system for control of the reactor. The time-dependent behaviour of the reactor for start-up, shutdown or a change in power is discussed as a further extension of the steady-state development in Chapter 2. It details how the reactor can be controlled solely from the production of delayed neutrons that are produced by radioactive decay of some fission products. The effects of the loss of fissile material and the production of fission product "poisons" are discussed. Engineered devices used to control the reactor are further detailed. Also, the specifics for the fuelling of the reactor as well as different fuel management schemes are examined.

Chapter 4 details nuclear reactor materials, including the properties of structural materials, and irradiation effects on materials that can lead to corrosion and materials degradation/deformation. Such degradation includes irradiation hardening, creep and growth, embrittlement and crud formation. It provides a complete description of fuel rod materials, including advanced fuel designs and state-of-the-art efforts for development of accident tolerant fuels following the Fukushima accident as described in Chapter 6. This chapter covers new additives in fuels to improve performance, as well as metallic and ceramic fuels (e.g., nitrides, silicides, carbides and mixed-oxide fuels). It also describes the fuel cycle with nuclear fuel fabrication and production, operation, fuel chemistry, restructuring and fission product behaviour, thermophysical properties of the fuel, fuel performance and reprocessing of spent fuel. Severe fuel damage phenomena are covered later in the book (in Chapter 6 on reactor safety).

Chapter 5 includes a treatise on reactor thermal hydraulics to describe heat transport from the core as well as flow conditions in the reactor coolant system. It details the different flow regimes, pressure drop, critical heat flux and condensation phenomena. This discussion includes modern correlations with a broadened review of single- and two-phase flow, including viscous/inviscid, internal (pipe)/external (tank) flow, and forced and natural convective flow. This more complete treatment is important to better understand both normal operating conditions, as well as abnormal reactor operations as detailed later in Chapter 6.

Chapter 6 provides an understanding of nuclear reactor safety and reactor behaviour under abnormal conditions. It includes a discussion on reactor licensing and regulation as adopted in various countries. The chapter also discusses engineered safety features with emergency core coolant systems and reactor containment, various civil and military reactor accidents, radioactive plume migration and radiation dose analysis, nuclear emergency response and severe core damage phenomena.

Chapter 7 provides a description of the interaction of radiation with matter and fundamental concepts of health physics and radiation protection. Moreover, this chapter includes radiation dose assessment, the biological effects of radiation as well as radiation contamination treatment. It also describes the evolving subject of space-radiation protection.