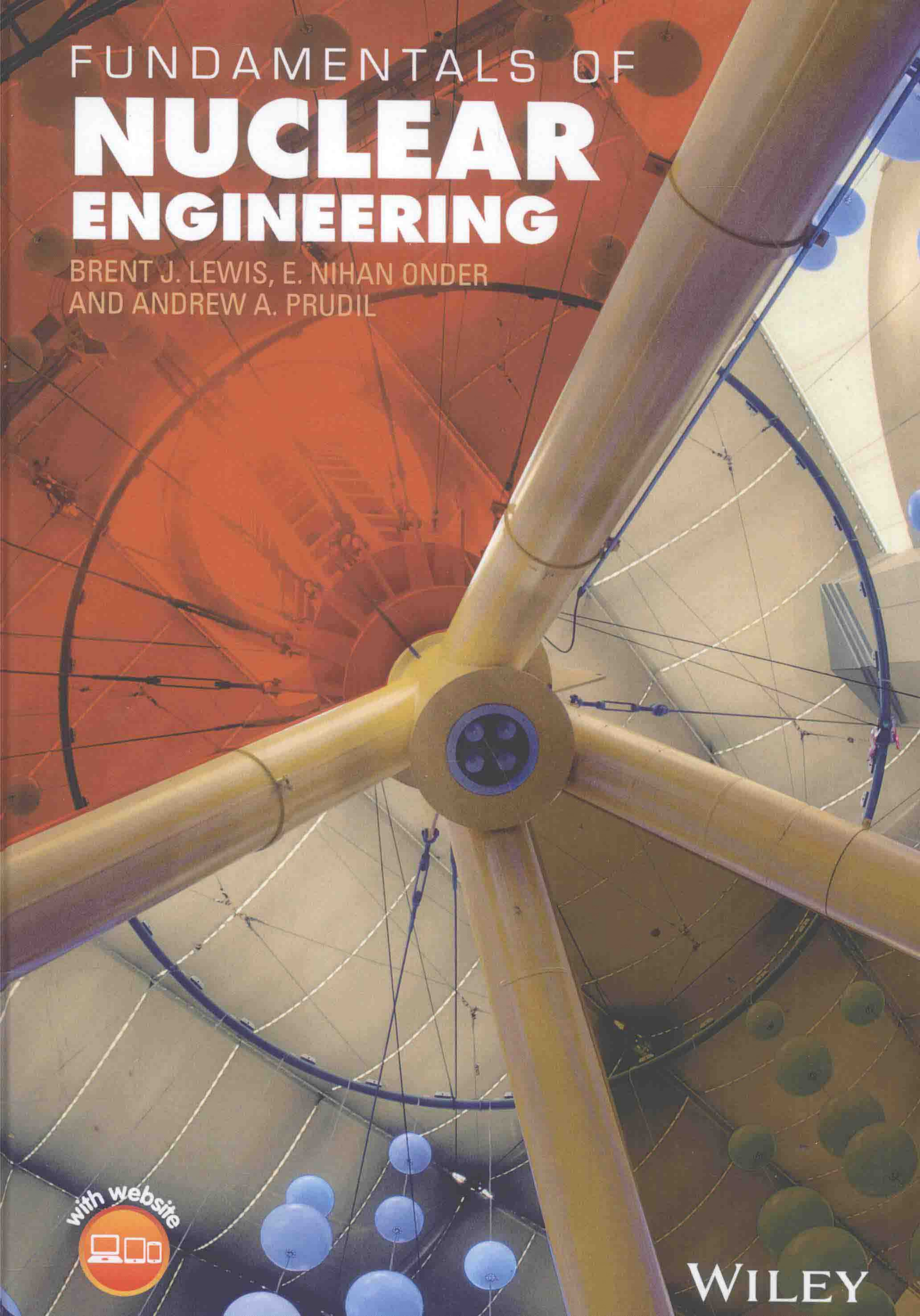

FUNDAMENTALS OF NUCLEAR ENGINEERING

BRENT J. LEWIS, E. NIHAN ONDER
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Fundamentals of Nuclear Engineering

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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

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

- Problem solutions
- Teaching slides
- Course outlines

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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.

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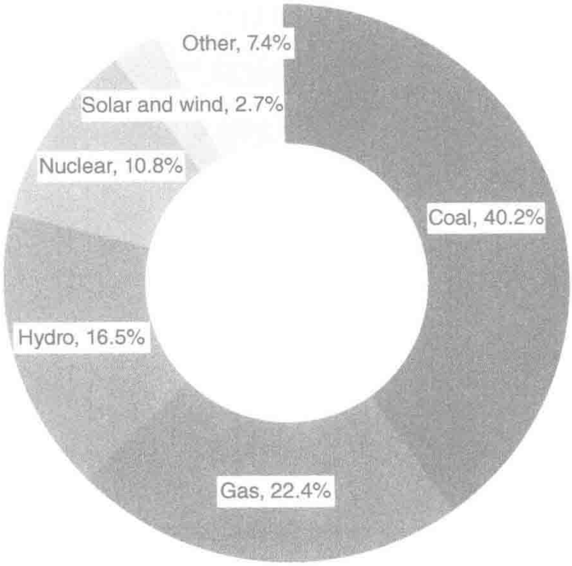

Figure P.1 World electricity production in 2012. Source: World nuclear association.

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.