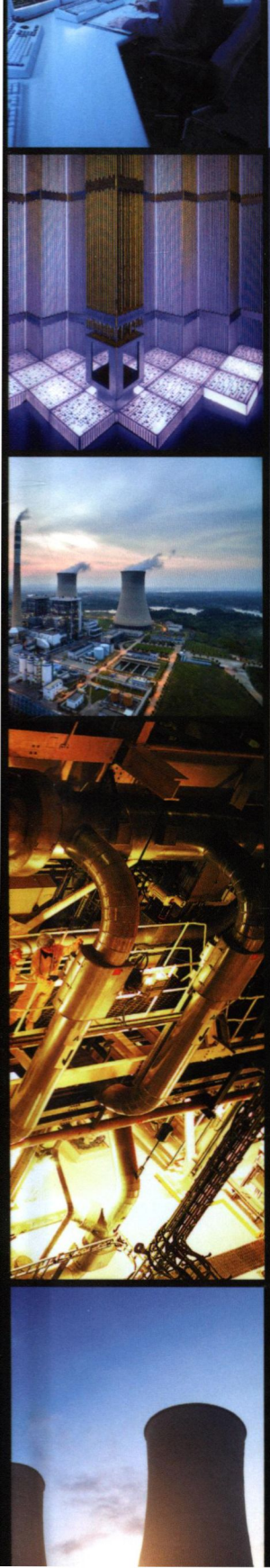

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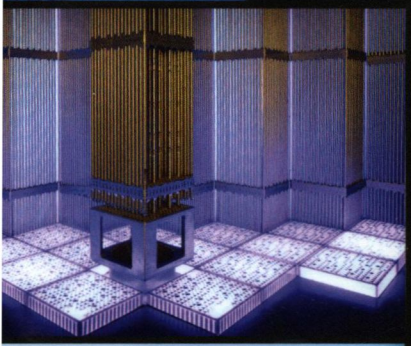
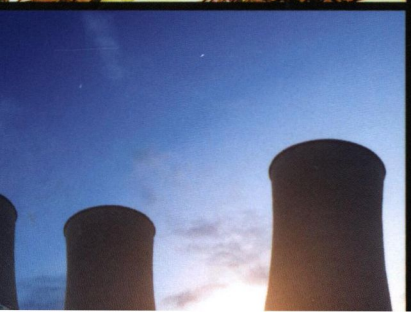
Nuclear Reactor Thermal-Hydraulics: Past, Present and Future

Pradip Saha





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Nuclear Reactor Thermal-Hydraulics: Past, Present and Future

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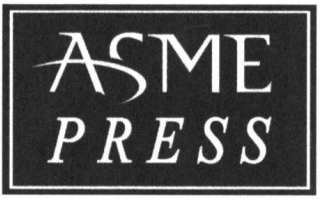

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Series Editors' Preface

Nuclear Engineering and Technology for the 21st Century—Monographs Series

Nuclear engineering and technology play a vital role in achieving low carbon emission goals worldwide, while providing reliable, baseload power to the world economy. Presently over 12 percent of the world's energy needs are satisfied by nuclear power—with 30 countries operating 436 nuclear power plants and 3 countries (France, Slovakia, and Belgium) using nuclear power to provide over half their power needs (source: Nuclear Energy Institute: http://www.nei.org).

The country with the largest number of operational nuclear power plants (the United States) has 102 plants and uses nuclear power to provide over 19 percent of its needs. Concurrently, the advanced nuclear power plant designs are the basis for extensive, ongoing research and development efforts in many countries with the promise of enhanced sustainability, safety, and proliferation-free power-sources with ever-higher operational efficiencies and capacity factors. Consequently, there are many fruitful topics of interest in the nuclear engineering field to be addressed in this exciting monograph series.

The *Nuclear Engineering and Technology for the 21st Century* monograph series provides current and future engineers, researchers, technicians and other professionals and practitioners with practical, concise but key information concerning the nuclear technologies from areas of medical applications, mining, processing and manufacturing, environmental monitoring to safe and energy-efficient plant operation and electricity generation. Each monograph should provide a well rounded and definitive state-of-the-art review of its subject, with a focus on applied research and development, and best industry practices, processes and related technological applications. The series is envisaged as a collection of 80 to 100 pages monograph publications which can stand as the most authoritative source of information on current state of a topic, application or discipline. Core topics include, but are not limited to:

- best practices in power plant operation
- nuclear science and technology in medicine,
- irradiation technologies and applications,

- fuel cycle processes, engineering and technologies,
- nuclear reactor thermal hydraulics and/or neutronics
- materials for current and advance power generation
- nuclear safety and environmental impact
- next generation of nuclear power plants
- radiation in our environment
- radioecology, radiobiology, radiation chemistry

Series Editors:

Dr. Jovica Riznic, Canadian Nuclear Safety Commission
Dr. Richard Schultz, Idaho National Laboratory

Abstract

This monograph summarizes the major developments on nuclear reactor thermal-hydraulics over the last fifty years, primarily for the water-cooled reactors, and provides a direction for the future thermal-hydraulic developments for water-cooled, including small modular reactors or SMR, and Generation IV reactors. This includes discussion on the steady-state reactor thermal hydraulics including subchannel analysis, evolution of emergency core cooling systems (ECCS) from active to fully passive systems to remove the decay heat, and development and consolidation of the best-estimate safety analysis methodology. With substantial increase in computing power, the computational fluid dynamics (CFD) tools for single-phase and multi-phase flows are being used more these days to address some of the important reactor thermal-hydraulics phenomena which could not be analyzed earlier using the traditional one-dimensional or coarse three-dimensional analysis tools. Development of multi-physics methodology encompassing neutronics, thermal-hydraulics, thermal-mechanical and coolant chemistry has also started.

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1. Introduction

Nuclear power plants, which produce electricity with almost zero greenhouse gas or carbon emissions at stable and competitive costs, are operating in more than thirty countries throughout the world. According to International Atomic Energy Agency (IAEA) Reference Data Series No. 1 2015 Edition [1], in 2014, 438 nuclear power reactors with the total installed capacity of 376 GWe produced about 2410 TWh of electricity representing 11.1% of the total electricity produced in the world from all energy sources. Some countries in Europe (e.g., France, Slovakia, Hungary, Ukraine, Belgium, and Sweden) produced more than 40% of their electricity from nuclear. The United States of America (USA) produced about 800 TWh of electricity, representing 19.5% of total U.S. electricity production, from its 99 nuclear reactors. This represented over 60% of electricity produced from low carbon-emission sources including hydro, solar and wind [2]. Percentage of electricity from nuclear is also increasing in Asia, particularly in China, Korea and India. Thus nuclear power constitutes an element of the solution to global warming and a means of delivering electricity to both developed and emerging countries.

Figure 1-1 (reproduced from Ref. 1 with permission by the IAEA) shows the nuclear share of electricity in various countries in 2014. Generation of electricity from nuclear reactors started in 1950's with rapid growth in 1960's to 1980's. After the Three Mile Island Unit 2 accident in 1979 [3–6] and Chernobyl Unit 4 accident in 1986 [7, 8], the growth of nuclear power in developed countries slowed down; however, the growth increased in large Asian countries, namely, China and India. It is estimated [1] that the world electricity generation by nuclear will slowly increase in the future and its share will be around 9–11% in 2030. Thus nuclear power will remain a significant contributor to the world's electricity generation as more countries pledge to reduce the greenhouse gas emissions to combat the climate change. In the USA, nuclear's share of electricity generation in 2040 is estimated to be around 16% [9] as shown in Figure 1-2.

There are many types of nuclear power reactors operating in the world today to generate electricity. However, the basic principles of these operating reactors are the same. In simple words, heat is generated in the reactor core by sustaining a fission chain reaction in nuclear fuel.

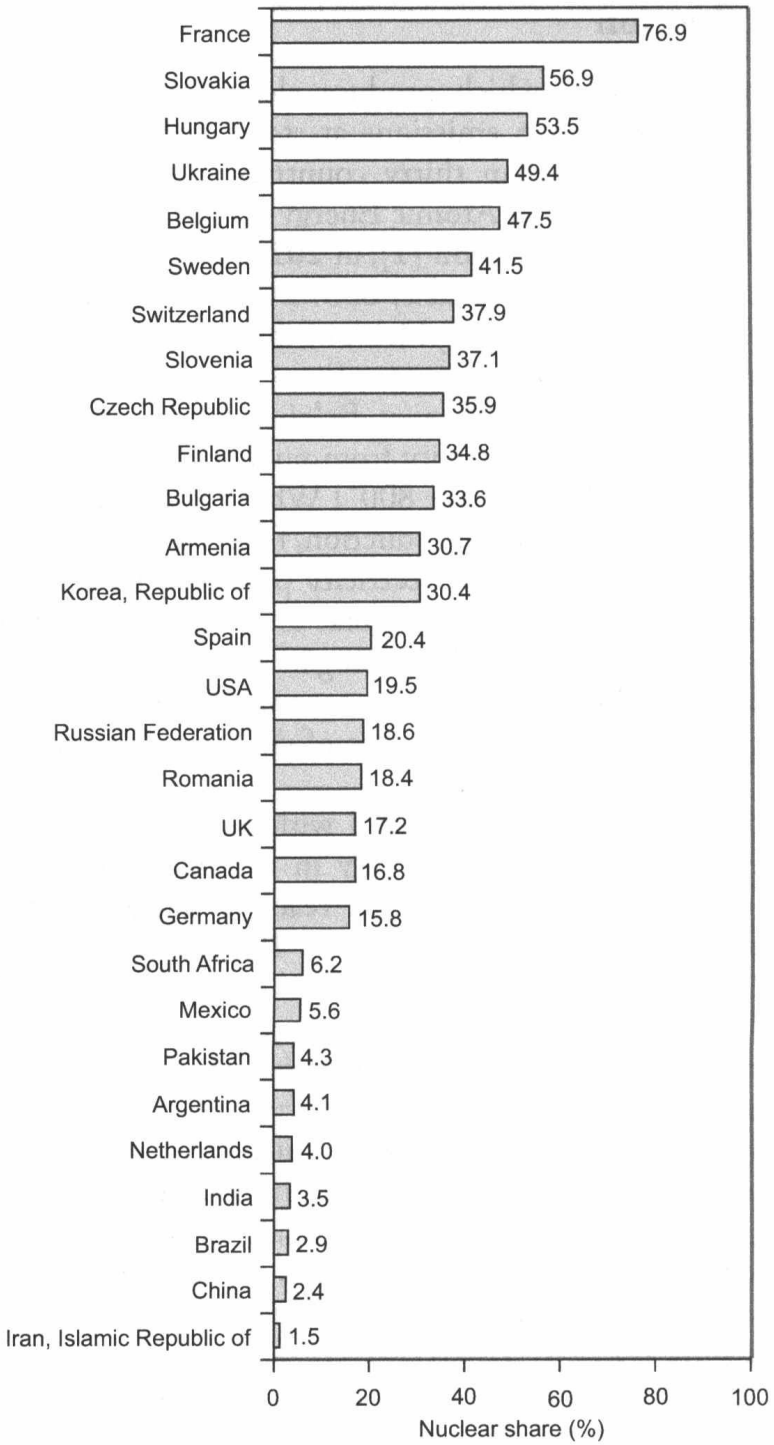

Figure 1-1 Nuclear share of total electricity generation in 2014 (reproduced from Ref. 1 with permission by the IAEA).

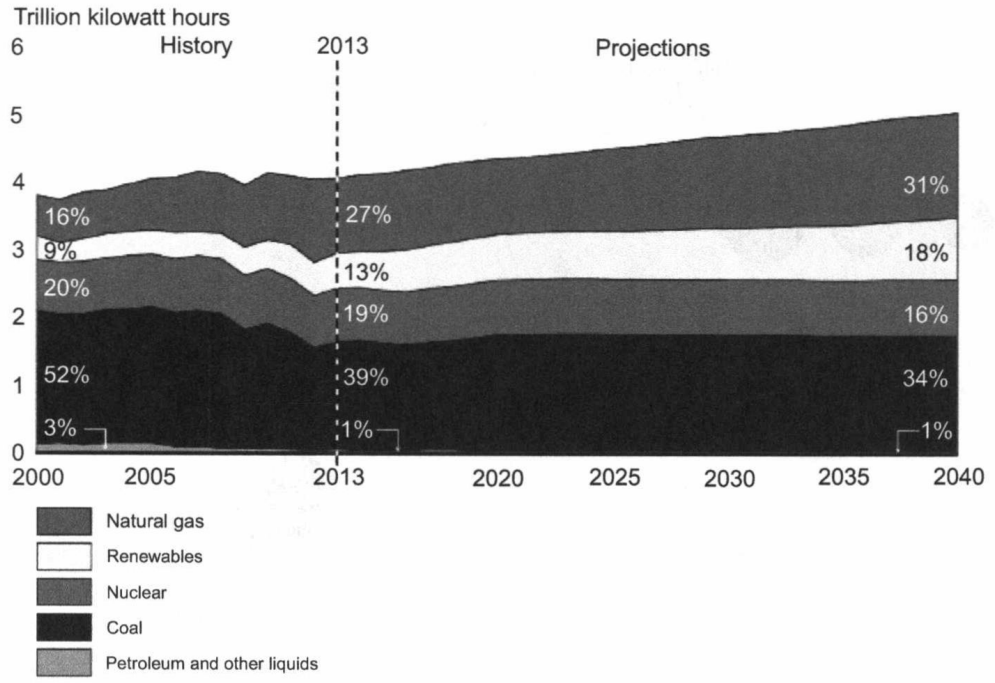

Figure 1-2 Forecast of U.S. electricity generation by fuel type (reproduced from Ref. 9 with permission by the USGAO).

That heat is extracted by a coolant flowing through the reactor core to produce steam and drive a steam turbine to generate electricity.

1.1 Nuclear fission and heat generation

Nuclear fission reactions can occur when a neutron strikes the nucleus of a large fissile atom, typically the fissile isotopes uranium-235 or plutonium-239, causing that nucleus to split or fission. The result of a fission reaction is typically two fission fragments or smaller nuclei, two or more fast-moving high-energy neutrons, and significant heat. The new neutrons produced by a fission reaction initiate new fission reactions, resulting in a sustained fission chain reaction. This is depicted in Figure 1-3.

Nuclear reactors typically fall into one of two types – Thermal or Fast reactors – based on the neutron spectrum or neutron energies at which the fission reactions occur:

- Thermal reactors optimize the fission reaction rate in their fuel by slowing down, or moderating, the high-energy fast neutrons that are produced as a result of fission reactions. This "moderation" of

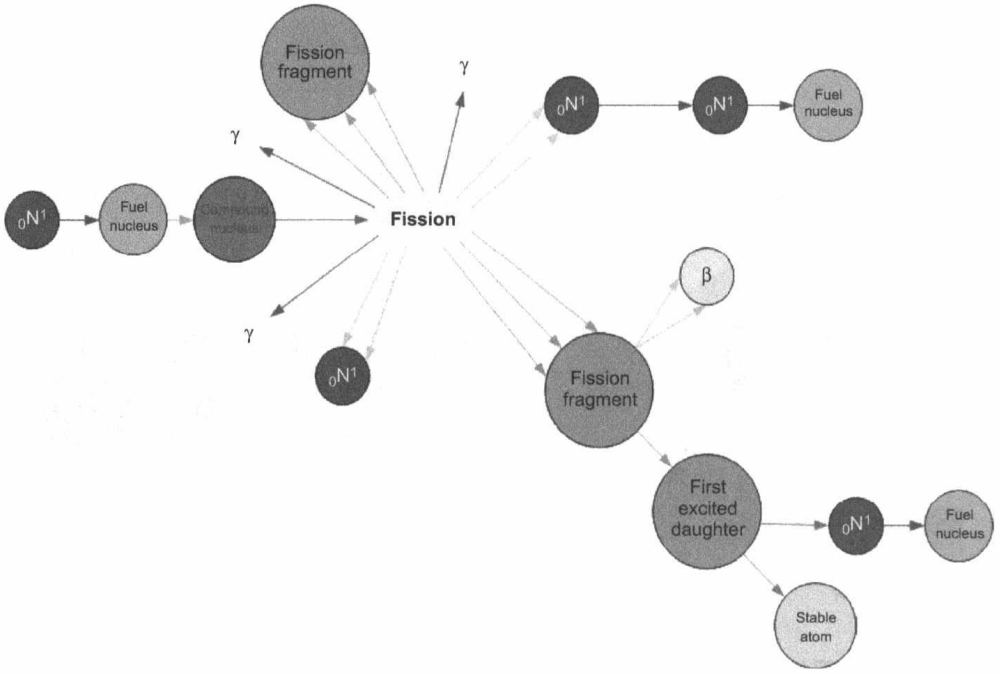

Figure 1-3 Depiction of nuclear fission process.

the fast neutrons increases the likelihood that a "new" neutron will initiate fission to sustain the chain reaction. Most of the operating nuclear power reactors today are "thermal" reactors and the process of neutron moderation is depicted in Figure 1-4.

- Fast reactors do not moderate the fission neutrons, instead leaving them fast at high energy. Fast neutrons allow these reactors to be more effective than thermal reactors at creating or breeding new fuel through neutron absorption in uranium-238, creating more fissile material plutonium-239.

For both thermal and fast reactors, the fission reaction occurs in the central region of a reactor called the reactor core, which typically contains the following components:

- *Nuclear fuel:* Nuclear reactors need fissile isotopes, such as uranium-235 or plutonium-239 to sustain a chain reaction and generate heat. Most of the commercial power reactors are light water reactors (LWRs), which need slightly enriched (<5%) uranium-235 as their fissile fuel, the rest of the fuel being non-fissile uranium-238, some of which is converted to fissile

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