Foreword

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Professor Cumo's book *Nuclear Plants* enriches the literature on the production of industrial-scale electricity from nuclear reactors by bringing under one roof all of the major concepts and components underlying this production, from uranium enrichment processes and nuclear fuel fabrication to waste disposal and decommissioning of old installations. The book contains a wealth of up to date information presented clearly and objectively, covering the entire nuclear fuel cycle, nuclear reactors technologies, operation of the major types of reactors, instrumentation and control, radiation protection, plant components and safety, and analyses of severe accidents in fast and thermal reactors, including a detailed analysis of the well-known Chernobyl accident in the former Soviet Union and the most recent accident at the Fukushima-Daiichi plant in Japan. The contents of the book's ten chapter and one appendix are briefly summarized below.

The book's first chapter, entitled *Nuclear Energy in the Worldwide Outlook*, highlights the interplay between energy consumption and industrial development, economic growth and quality of human life. Since the invention of the steam engine, energy consumption has risen exponentially through the present, although optimistic forecasts scenarios predict that the rate of consumption growth will progressively diminish through the twenty-first century. The growth of energy consumption demands a corresponding growth in energy production, which needs to be carefully balanced against other fundamental factors, such as ecological considerations and the limited availability and non-uniform geographical distribution of energy sources. This chapter discusses the advantages and drawbacks not only of nuclear energy sources, but also of fossil sources (coal, natural gas, oil) and renewables (hydro, solar, aeolian, geothermal, tidal and ocean thermal gradients), and identifies the major factors that contribute to the end-cost of electricity, which is the common standard for comparing the figure of merit of the various energy sources. The environmental effects of fossil, conventional renewable and nuclear energy are discussed in detail. The chapter concludes by using recent (up to 2013) data in conjunction with transition and equilibrium scenarios extrapolated to 2040 to assess pragmatically the future potential development and practical implementation of the major renewable, fossil, and nuclear energy sources.

The book's second chapter, *entitled Uranium Resources and Fuel Cycle Facilities*, reviews of the status of global conventional and unconventional uranium and thorium, as of 2014. After mining, the uranium ore is processed, in several steps, into uranium hexafluoride which is delivered in crystalized form to isotope separation and enrichment facilities. For many years after the discovery of the fission process, gaseous diffusion and centrifuge separation and enrichment processes have been, and still are used for producing industrial quantities of enriched uranium. The performance parameters of such facilities are presented semi-quantitatively in this chapter, while the more recent, but not yet industrialized, separation processes using the chemical exchange, the nozzle diffusion, and the atomic vapor laser separation processes are also mentioned briefly.

The issues related to the fabrication of reactor fuel rods containing either uranium or plutonium are also briefly mentioned. Subsequently, the narrative in Chapter 2 changes from the front-end to the back-end of the fuel cycle, presenting the construction of the casks for transporting spent nuclear fuel, the wet and dry reprocessing routes, and the treatment and disposal of radioactive waste products. The treatment of the various waste categories (low-, medium-, and high-level) and forms (solid, liquid, gaseous) is discussed expertly and comprehensively, noting that the overall reprocessing strategy (no reprocessing, reprocessing with recycling in thermal reactors, reprocessing with recycling in fast reactors) makes a huge difference the amount and time durations of the residual waste that would need to be disposed permanently in adequate repositories. Without any reprocessing, the radiotoxicity of the directly-disposed spent fuel elements would require over 200 000 years to decay to the level of the natural uranium ore, whereas a completely closed fuel cycle in conjunction with separation of minor actinides and irradiation in fast reactors would reduce the toxicity (as well as the amount) of the left-over radioactive waste by a factor of about 500.

Following a short presentation of the methods and tools of post-irradiation analysis of spent fuel elements, Chapter 2 also presents the activities necessary for decommissioning nuclear plants, highlighting decontamination and dismantling technologies. The last major issues presented in this chapter reflect the trends, as of 2014, in the countries peacefully using nuclear energy, regarding the technological options for the fuel cycles (open, partially closed, fully closed, with or without partitioning and transmutation) and the consequences of the various options on the sustainability of uranium and thorium resources, radioactive waste disposal options, afferent safety, non-proliferation and safeguards, and (ultimately), the economics of nuclear energy.

Chapter 3, entitled *Fuel Cycles*, commences by reviewing the classification of nuclear reactors according to the respective neutron spectrum (thermal, intermediate, fast) and neutron moderator material (light water reactors, liquid metal reactors, gas cooled reactors), which often serves as the respective reactor's coolant, as well. Although the reactor physics analysis is kept at a minimum, the major types of reactors are presented as an integral part of the respective fuel cycle, thus providing an excellent overall perspective of the role of reactors, which actually transcends their traditionally depicted role as "generators of heat from nuclear fission processes." This departure from more narrow perspective presented in the extant textbooks on nuclear engineering enables the presentation of the potential development strategies not just for a single type of reactor but for "reactor families," including symbiotic uses of light water reactors in combination with fast breeder reactors, or light water and gas cooled reactors. Such symbiotic uses of different types of reactors could, in principle, extend significantly the sustainability of nuclear energy while minimizing the amount and radiotoxicity of the long-lived radioactive waste products.

Entitled *Plant Schemes of Main Reactor Types*, Chapter 4 presents a comparative discussion of the advantages and disadvantages of various reactor types when considered as heat sources within in a thermodynamic cycle which includes all of the other nuclear plant components. After recalling the main features of the Rankine and Brighton cycles, this chapter presents the main characteristics of the major light water reactors, (LWR) comprising various boiling water reactor (BWR) and pressurized water reactor (PWR) concepts, functionally integrated within their respective nuclear island complexes. The main characteristics of the various types of gas cooled reactors (GCR) are presented next, followed by the presentation of heavy water (moderated) reactors (HWR). The presentation continues with the discussions of the characteristics of fast reactors (FR), highlighting the relative advantages and disadvantages of the various possible coolants (sodium, helium, lead or lead-bismuth). The uses of fast reactors as either net breeders or net burners of fissile materials is also discussed.

Reactors are classified according to their uses in Chapter 5, which is entitled *Power and Research Reactors, Nuclear Energy Applications*. Reactors can broadly be distinguished as being used for research (research reactors), for industrial production of electricity, heating or both (power reactors), or for special purposes (test reactors for investigation of materials under reactor conditions, reactors for production of medical and industrial isotopes). Also discussed in this chapter are various liquid-fueled and/or liquid-cooled reactors, of which some molten-salt fueled and molten-salt cooled reactor concepts may continue to be developed in the future. Reactors for marine and space propulsion are reviewed next, highlighting several particular features regarding safety and power density. This chapter also presents the fundamental issues underlying magnetic and, respectively, inertial confinement of the deuterium-tritium plasma needed to sustain a fusion reaction. After a brief discussion of conversion systems that directly transform heat into electricity, this chapter presents a thorough exposition of the reactor concepts selected by the international community as worthy of being pursued in the future, called "Generation IV reactors", which includes the following six types: sodium fast reactor (SFR), gas-cooled fast reactor (GFR), lead fast reactor (LFR), supercritical water reactor (SCWR), very high-temperature gas-cooled reactor (VHTR), and molten-salt (fueled) reactor (MSR). These reactors must demonstrate improvements over the current generation (Generation-III) of reactors, in the following areas: economic competitiveness, improved safeguards against proliferation, improved safety and waste reduction, and end-products other than just electricity (e.g., hydrogen production, process heat, desalination). A very informative presentation of the issues of importance for the current Generation-III reactors, particularly the quest for introducing commercially competitive small modular reactors (SMR), concludes Chapter 5.

Chapter 6 is entitled *Nuclear Thermal Hydraulic and Technological Design of Fuel Elements* and highlights the fundamental fact that designing a nuclear reactor involves a process of multi-objective optimization of occasionally conflicting goals and requirements. After briefly discussing the sources of positive and negative contributions to the reactor's overall reactivity, the chapter qualitatively summarizes the reactor core design phases and fuel loading patterns. It includes formulas for qualitative computations of the temperature distribution within the fuel element and flow channels, and reviews the commonly used criteria and correlations for the thermal-hydraulic design of light water reactors. The presentation continues with elements of technological reactor design, including an exposition of the transformations undergone by fuel and structural materials under neutron irradiation. Means for controlling and mitigating adverse effects of water radiolysis and corrosion are also discussed. This chapter ends by discussing the safety criteria for in-service inspection and repair (ISIR) to control plant ageing and, hence, possible path to extending the useful "life" of a nuclear power plant (NPP).

A summary of the relative advantages and disadvantages of liquid versus solid fuels is presented in Chapter 7, *Nuclear Fuels*. After presenting the most important types of solid fuels (metallic, dispersion, ceramic), the chapter reviews the issues underlying the fabrication of fuel rods and fuel assemblies. The thermo-mechanical design of fuel rods and corresponding cladding is revisited in more detail, addressing phenomena in addition to those discussed in the previous chapters, including the very important pellet-cladding interactions. This chapter concludes by listing the most important computer code systems used in various countries for simulating the performance of fuels for light water, heavy water, and liquid-metal cooled reactors. In particular, the European code TRANSURANUS, which is representative of this class of simulation tools, is described in some detail.

Chapter 8 is entitled *Main Nuclear Reactor Components and Plants Layout* and commences by discussing the design criteria underlying the standard requirements for reactor pressure vessels constructed either of steel (for most reactor types) or pre-stressed concrete (for gas-cooled reactors). The design requirements for the reactor core's structural support bottom and top plates are presented next. These internal structures are subject to mechanical stresses and to various types of corrosion (i.e., fretting-, stress-, crevice-, fatigue-corrosion), highlighting the importance of controlling the vibrations undergone by these structures. Following a brief exposition of the heat conduction through the thermal shield protecting the inside of the pressure vessel, the chapter continues by describing briefly the mechanical aspects of positioning the control rods in LWRs. The main characteristics of various types of pumps, blowers and circulators are described next. These components keep the coolant in forced convection during normal operation, while the overall piping design must guarantee adequate emergency core cooling of the reactor core under natural convection circulation if pumping power becomes unavailable. This chapter concludes by presenting the main design requirements and characteristics of steam generators for PWRs, BWRs, HWRs and SFRs.

The requirements for controlling the most important physical quantities that affect the behavior of the nuclear plant when starting or stopping it, under normal operating conditions, and under anomalous conditions stemming from malfunctioning, incidents or accidents are presented in Chapter 9, entitled *Instrumentation, Control and Protection System for Nuclear Reactors*. The physical phenomena underlying the time-dependent control of the reactor's reactivity are qualitatively described by considering the reactor plant as a time-dependent system with feedback that can be modeled by using concepts of control theory applied to the point kinetics equations driven by small (operational) or large (accident conditions) reactivity insertions. Following a brief description of devices needed to control the plant's status at any stage, the chapter outlines the functioning of the reactor's safety control systems. Protection against sources of neutron and gamma radiation by means of thermal and biological shielding layers is discussed subsequently. These shielding layers must ensure that the radiation is adequately attenuated, so that any escaping radiation remains below the levels deemed safe for humans by the International Commission for Radiological Protection. This chapter concludes by discussing the challenges remaining to be overcome while developing instrumentation and control systems for future reactors (small modular reactors, Generation-III+ and Generation-IV reactors).

The fundamental principles underlying the *defense in depth* doctrine, which marshals the criteria of *redundancy*, *diversity*, *physical separation*, *fail-safe*, and *multiple barriers* into *preventive*, *protective*, and *mitigating* measures are reviewed in Chapter 10, entitled *Safety of Nuclear Plants*. The influence of human factors and the methods for performing risk assessment are discussed in conjunction with the so-called "stress tests," which were introduced after the Fukushima accident for the purpose of verifying the prediction of various probabilistic safety assessment models. This chapter also summarizes the classical approach to safety assessment following the methodology originated in the well-known Rasmussen report, and describes in detail the sequence of events that led to the Fukushima-Daiichi accident. The "beyond design basis accidents" are reviewed qualitatively for both PWRs and BWRs. In particular, the loss of coolant accident (LOCA) and the steam explosion accident are described semi-quantitatively. Accident scenarios in SFRs are described next, starting with the classical Bethe-Tait core disruptive scenario, sodium fire accidents and sodium-water reactions. Special attention is subsequently devoted to the criteria for locating nuclear power plants, so as to preserve the local ecosystem and ensure safe levels of maximum discharges of radioactive, chemical and thermal pollution. Finally, this chapter summarizes the international perspective offered in the document "Technical Roadmap for Nuclear Energy (2015)" published jointly by the International Energy Agency and the OECD Nuclear Energy Agency.

The book concludes with an Appendix that describes in detail the well-known Chernobyl Accident.

As underscored by the above review of the book's contents, Professor Cumo's *Nuclear Plants* touches upon all of all major considerations regarding the construction, operation and decommissioning of nuclear reactor power plants. The mathematics is minimal, but this may be a benefit for non-engineers interested in learning about the fundamental truths regarding nuclear power plants and the afferent fuel cycles, since Professor Cumo's accessible qualitative description of complex issues makes his book useful not only as an introduction to nuclear engineering for aspiring engineers, but also for interested non-engineers. In this regard, Professor Cumo's *Nuclear Plants* responds elegantly and eloquently to a need for a comprehensive yet easily accessible book on nuclear engineering.

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