Power Systems

Sustainable and Safe Nuclear Fission Energy

Technology and Safety of Fast and Thermal Nuclear Reactors

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Preface

This book was written in an effort to present a complete description and evaluation of the current power generation technology by means of nuclear fission reactions. Similar to an earlier book by the author[1] it covers the entire nuclear fuel cycle, from mining of natural uranium, uranium conversion and enrichment, to the fabrication of fuel elements for the cores of various types of commercial nuclear power plants.

Numerically, light water reactors (LWRs) outweigh all other types of reactors, generating electricity. In most countries of the world applying nuclear energy, electricity is generated in nuclear power plants at a lower cost than in fossil-fueled power plants. Most likely, LWRs will continue to hold the largest share of the market in the coming decades, when the contribution of nuclear power for the generation of electricity in most industrialized countries will rise from its present level. The enrichment of natural uranium as fuel for these nuclear power plants is still achieved by about 50% in gaseous diffusion plants, but gas ultracentrifuge enrichment is becoming more dominating. Only in the future decades will laser enrichment be able to secure a certain share of the uranium enrichment market.

Assessments of the world uranium resources by international organizations such as OECD and IAEA as well as analyses on the natural uranium consumption by nuclear power reactors in the world point to a growing scarcity of natural uranium in the second half of this century. This threat can be counteracted by the replacement, in due time, of today's light water reactors (highest uranium consumption), by advanced reactors, and, above all, by breeder reactors. This will drastically reduce the consumption of natural uranium. Especially, fast breeder reactors operated in symbiosis with light water reactors can curb the uranium requirement enough to assure the world's energy generation. It is technically feasible to introduce fast breeder reactors commercially during the second half of this century. In such a case even today's assured world uranium reserves would be sufficient to meet the requirements over thousands of years. However, the

[1] Nuclear Fission Reactors, Springer Verlag Wien New York, 1983.

commercialization of advanced reactor lines will imply further development efforts and costs, in particular for the development of advanced technologies and processes for fuel fabrication and reprocessing.

Advanced converter and breeder reactors require a closed nuclear fuel cycle in order to get started with plutonium or U-233. These man-made fissile materials must be produced by chemical reprocessing of the spent fuel elements of the present line of commercial nuclear power plants. This directly links with the decision to be taken on the construction of internationally operated reprocessing and refabrication centers and installations for subsequent waste conditioning and final storage of the radioactive waste. The technical availability of reprocessing and refabrication facilities, and the development of chemical processes for the separation of the different minor actinides opens possibilities for transmutation and incineration of plutonium and of the minor actinides. Analyses show that plutonium and the minor actinides can be incinerated except for the chemical losses during reprocessing and refabrication of less than 1% going to the high active nuclear waste. After multi-recycling this eventually results, depending on the reprocessing losses, in an overall utilization of 60–80% of the resources of natural uranium.

Recent results of research programs show that the incineration of the actinides by transmutation processes is technically feasible. However, this requires the development of new chemical separation processes for the spent fuel and advanced fuel fabrication technologies. This is accompanied by advanced material research for high burnup fuels.

The environmental impacts and risks associated with the different types of nuclear power plants and nuclear fuel cycle facilities must remain below the limits set by the International Commission for Radiation Protection (ICRP) and by national authorities. The environmental impacts are due to the release of radioactive substances from various stages of the nuclear fuel cycle, such as uranium ore mining, uranium conversion, enrichment plants, fuel fabrication plants, nuclear power plants, reprocessing plants, and waste conditioning installations.

The objective of reactor safety concepts is to protect the operational personnel, the environment, and the population against radioactivity releases during normal operation and accidents. The safety concept is based on multiple containment structures as well as engineered safeguards components. In addition, other safety measures combined in a staggered-in-depth concept of four safety levels must be incorporated. Design basis accidents must be accommodated by design features of the protection and safety systems, as well as by the emergency cooling systems of the nuclear plant.

Probabilistic safety analysis is a supplement to this deterministic approach. Reactor risk studies which were performed during the 1970s (USA) and 1980s (Europe) had shown that the risk arising from light water reactors as a result of core melt down is well below the risk of other power generating systems or traffic systems. However, the Chernobyl accident in 1986 (water cooled, graphite moderated 1,000 MW(e) reactor of Soviet RBMK design) resulted, in addition to severe radiation exposures to the rescue personal and to the population, also in large-scale land contamination by radioactive cesium isotopes.

As a consequence, new research programs were initiated on severe accident consequences. Their results led to a revision of the results of the early risk studies of the 1980s and to the application of a new safety concept for modern light water reactors, e.g., the European Pressurized Water Reactor (EPR) and the European Boiling Water Reactor (SWR-1000).

The safety design concept of future liquid metal cooled fast breeder reactors (LMFBRs) will also have to follow the basic safety principles (multiple barrier concept and staggered in-depth four level safety concept) as developed for light water reactors. This holds despite the fact that LMFBRs have different design characteristics (fast neutron spectrum, liquid metal as coolant, plutonium–uranium fuel). It has been shown that LMFBRs have a strong negative power coefficient and good power control stability. The main design characteristics of control and shut-off systems do not differ much from those of light water reactors. The excellent cooling and natural convection properties of liquid metals as well as the low system pressure of about 1 bar allow the safe decay heat removal in a number of ways. The consequences of sodium fires or sodium water reactions can be prevented or limited by special design provisions. On the other hand, lead or lead-bismuth-eutecticum (LBE) as coolant do not chemically react either with oxygen in the atmosphere or with water in the failing tubes of a steam generator.

The safety concept of fuel cycle plants, e.g., spent fuel storage facilities, reprocessing facilities, and waste treatment facilities is based on similar multiple barrier and engineered safeguards measures as they are applied to nuclear reactors. However, the risk of these fuel cycle facilities is smaller than for nuclear power plants as the fuel is at much lower temperatures and atmospheric pressure in reprocessing and refabrication plants.

In covering the many interdisciplinary aspects discussed in this book the author was able to make use of the excellent library facilities of the Karlsruhe Institute of Technology. A number of former colleagues of the former Institute of Neutron Physics and Reactor Technology of the former Forschungszentrum Karlsruhe (FZK) now part of KIT, the Karlsruhe Institute of Technology, assisted considerably in completing this work. Their help and support is much appreciated. The author would like to thank explicitly the following scientists and former staff members of this former Institute:

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The author hopes that this publication will make a helpful contribution to the understanding and advancement of the further nuclear fission reactor deployment.

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