



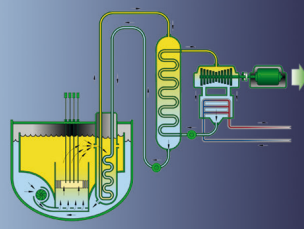
Nuclear Engineering
Series

Bertrand Barré,
Pascal Anzieu, Richard Lenain, Jean-Baptiste Thomas



Nuclear Reactor Systems

A technical, historical and dynamic approach



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GÉNIE ATOMIQUE

Nuclear reactor systems

A technical, historical and dynamic approach

**Bertrand Barré,
Pascal Anzieu, Richard Lenain, Jean-Baptiste Thomas**



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17, avenue du Hoggar
Parc d'activités de Courtabœuf, BP 112
91944 Les Ulis Cedex A, France

Printed in France
ISBN : 978-2-7598-0669-0

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Introduction to the *Nuclear Engineering* book series

INSTN, the National Institute for Nuclear Science and Technology, is a higher education institution founded in 1956 as part of French Alternative Energies and Atomic Energy Commission (CEA). INSTN is specialized in nuclear education and training, and contributes to the human resources development required by nuclear research and industry, from operators to engineers, and researchers. INSTN's main objective is to contribute to disseminating CEA's expertise through specialized courses and continuing training, not only on a national scale, but across Europe and worldwide.

Bolstered by the CEA's efforts to build partnerships with universities and engineering schools, the INSTN has developed links with other higher education institutions, leading to the organisation of more than thirty jointly-sponsored Masters graduate diplomas. There are also courses covering disciplines in the health sector: nuclear medicine, radio-pharmacy and also a specific degree for hospital physicists.

Continuous education is another important sector of INSTN's activities that relies on the expertise developed within the CEA and by its industry partners.

INSTN's "Génie Atomique" known as "GA" course is a specialised course in nuclear engineering that can be considered as a master after the master course. The course was first taught in 1954 at the CEA Saclay research centre, where the first experimental piles were built, and since 1978 it has also been taught in CEA Cadarache research centre, where the fast neutron research reactors were developed. Starting from 1958, the "GA" course is taught at the School for the Military Applications of Atomic Energy (EAMEA), under the responsibility of the INSTN. Since its creation, the INSTN has graduated over 5000 engineers who did work in major companies or public-sector bodies in the French nuclear industry: CEA, EDF, AREVA, Marine Nationale (the French navy), IRSN (French TSO)... Many foreign students from a variety of countries have also studied for this diploma.

There are two categories of student: civilian and military. Civilian students will obtain jobs in the design, the construction or the operation of nuclear power plants or research establishments as well as in the fuel processing facilities. They can aim to become expert consultants, analysing nuclear risks or assessing environmental impact. The EAMEA provides education for officers assigned to French nuclear submarines or the aircraft carrier.

The teaching faculty comprises CEA research scientists, experts from the Nuclear Safety and Radiation Protection Institute (IRSN), and engineers working in industry (EDF, AREVA, etc.). The main subjects are: nuclear and neutron physics, thermal hydraulics, nuclear materials, mechanics, radiological protection, nuclear instrumentation, operation and safety of Pressurized Water Reactors (PWR), nuclear reactor systems, and the nuclear fuel cycle. These courses are taught over a seven-month period, followed by a final project that rounds out the student's training by applying it to an actual industrial situation. These projects take place in the CEA's research centres, companies in the nuclear industry (EDF, AREVA, etc.), and even abroad (USA, Japan, Canada, United Kingdom, etc.). A key feature of this programme is the emphasis on practical work carried out using the INSTN facilities (ISIS training reactor, PWR simulators, radiochemistry laboratories, etc.).

Even now that the nuclear industry has reached full maturity, the “Génie Atomique” diploma is still unique in the French educational system, and affirms its mission: to train engineers who will have an in-depth, global vision of the science and the techniques applied in each phase of the life of nuclear installations from their design and construction to their operation and finally, their dismantling.

The INSTN has committed itself to publishing all the course materials in a series of books that will become valuable tools for students, and to publicise the contents of its courses in French and other European higher education institutions. These books are published by EDP Sciences, an expert in the promotion of scientific knowledge, and are also intended to be useful beyond the academic context as essential references for engineers and technicians in the nuclear industrial sector.

Joseph Safieh
“Génie Atomique” Course Director 2000–2014

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Foreword

This book incorporates the core knowledge of the lectures given in the framework of the “Atomic Engineering” specialization, as well as of the Nuclear Energy / Nuclear Reactor Physics and Engineering (M2), under the heading: **Nuclear reactor systems: a technical, historical and dynamic perspective.**

Prerequisite knowledge is about neutronics, core and system thermal-hydraulics, fuel and fuel cycle, as well as about PWRs, which are considered as the reference system. This is the logic of the integration of the lectures in the curriculum, where a series of book [1] is dedicated to PWRs.

The conferences (and thus the present book) combine four approaches.

- (i) **The descriptive one.** The benefit is a better understanding of how reactors are designed by combining “genetic chunks” taken from a common “library”, just like living beings are. Compatibility constraints play a major role in the designer’s choice. This gives a first insight into the design issue. It also gives an overview of the main strengths and weaknesses of the different reactor systems, tightly related to the design choices.

A series of examples show how recent choices are connected to events like those at Three Mile Island, Chernobyl and Fukushima, and how some problems can be fixed by incremental adaptation, while some generic solutions are proposed for future designs, with an increasing emphasis on the thorough implementation of defense in depth principles.

Finally, one can get a fresh look on biodiversity, in the worldwide current fleet as well as in Generation-4 systems. The latter resemble the earlier ones but fulfil an extended set of specifications, thanks to a few but significant innovations in technology and design. There are well known pedagogical limits of the plain descriptive approach: it can lead to get lost in the maze of the details. To get the whole picture, the book provides also the following approaches, tightly intertwined and complementing each other.

- (ii) **The axiomatic approach.** Starting with a focus on a specific set of long term criteria concerning the fuel cycle sustainability, a conceptual solution is established, and then a family of reactor systems is selected for development and qualification. That is the way fast breeders were selected from the early days of nuclear engineering and are still dominating the Generation IV competition. When combined with the “market pull, technology push” paradigm which led to the supremacy of LWRs, this approach gives a binocular view, thus a perception of the depth of the landscape, even if the set of axioms has not to be trusted in blindly, as the past history has shown.
- (iii) **A historical approach,** from the 1940’s to nowadays, with an extrapolation to the near future. This approach, extensively developed in the Introduction, sheds light on the Heraclitean/Darwinian process which is at work on the “market”, as well as on

innovations or efficient industrialization considered as game changers. This has been the case with the emergence of a competitive enrichment capability paving the way to the triumph of the LWR. The LWR dominance being firmly established, what is the next step? This is the purpose, for instance, of the Generation IV International Forum, launched in 2001, as well as of the INPRO programme at the IAEA. The driver is a set of specifications requested for the nuclear energy sustainability. A worldwide cooperative effort is needed to achieve a jump from the “business as usual” stimulation by the market to the higher level rules fixing the roadmap for the future. Actually, combining competition and cooperation is a big challenge.

- (iv) **A dynamic approach.** In the early 2000s, the prevailing image combined a “nuclear renaissance”, a quick implementation of rules - enabling the worldwide energy consumption increase to keep compatible with a strong limitation of the greenhouse gases (GHG) concentration - and a strong growth of the world economy. Undertaking a deep mutation of the energy paradigm thanks to a high and sustainable investment would clear the way for low carbon power production systems, including a high share of competitive base-load nuclear. The last decade main events and trends damped some hopes and dissipated some illusions.

In a few years, the financial then economic crisis has slowed down the global growth and made the capital less available for long term, moderate Return On Equity (ROE) ratio projects. The construction costs of nuclear plants soared in most occidental countries, when compared with those of fossil-fuel plants.

The Fukushima accident put temporarily a cap on nuclear growth. Moreover, Europe seems to overreact when compared to other regions, and the “new energetic paradigm” is often (up to now) oriented against nuclear despite the strong pro-nuclear commitment of many European countries and the fact that nuclear is the most “scalable” low carbon power source, competitive in base-load operation, and flexible enough to accommodate a large share of intermittent renewables in the power fleet. The risk assessment and perception are the core topics of a fierce debate.

This series of events has fostered a dynamic approach involving, beyond the “market” viewpoint on the one hand and a long term, cooperative approach on the other hand, a deeper knowledge of actors and forces at work. This approach relies on strategic prospective studies, on “humanities”, as well as on the design process from a conceptual viewpoint. The design key point, at the moment, is the coolant issue. These topics are not addressed in depth in the present book. They provide a framework for future investigation and modeling.

As a consequence of this fourfold approach of the nuclear reactor system issue, **the plan is as follows.**

Chapter 1 – Introduction

The evolution of nuclear reactors since the 1942 Fermi experiment can be described along the lines of natural history, with an initial flourish of uninhibited creativity followed by a severe selection process leading to a handful of surviving species, with light water reactors occupying most of the biotope today. The criteria which drove this selection have evolved with time and might not all be relevant in the future. The recent interesting development of the Generation IV International Forum and INPRO comes from a desire to rationalize

and formalize the selection process for the future nuclear systems. Will these attempts be successful? Will “natural” selection still prevail? In any case, in the context of a growing demand for energy for the developing world and of the need to reduce greenhouse gas emission, the nuclear reactor “species” is here to stay.

Chapter 2 – CO₂ Gas-cooled Reactors: MAGNOX, UNGG, AGR

This chapter dedicated to first generation of European reactors: MAGNOX, UNGG and AGR, is aimed at focusing on major architecture characteristics imposed by knowledge and industrial capabilities reached in the 1950's; solutions were found based on natural uranium fuel, graphite moderator, gas coolant, concrete caisson, large core and continuous fuel reloading and permanent in-core instrumentation. A very brief overview of some reactor architectures (dramatically different from LWR ones) envisaged at the early stage of nuclear power development can be found through examples presented. Some important common core physic parameters are described according to their general design options such as: heterogeneous lattice design, reactivity coefficient, power density... AGRs present an effective solution for graphite gas reactors compatible with the mainstream fuel concept share with other reactors types.

Chapter 3 – RBMK

RBMKs combine different design options that can be found in CANDU (water channel type reactor), in BWRs (boiling water coolant and energy production systems) and in AGRs: (moderated with graphite and continuous fuel reloading). The chapter presents the general reactor design and emphasizes on some design options that involved core physics parameters peculiar to RBMK. Attention is given to RBMK design modifications carried out during the decade after Chernobyl disaster that is shortly reported. In Russia RBMK remain work-horse reactors for electricity production even if no more reactors will be ever built in the future.

Chapter 4 – Heavy Water Moderated Nuclear Reactors

Heavy water is the best neutron moderator. It allows operating a nuclear reactor with natural uranium and eliminates the need for fuel enrichment industry, thus simplifying the fuel cycle to the simplest technology, and reducing proliferation risk.

Nevertheless, the volume of heavy water needed is 10 times the one with light water. This generates several design constraints that the design of a CANDUTM reflects. This technology is the main representative of heavy water moderated reactor systems. It is based on reactors of large volume and moderate power, separated horizontal fuel channels with pressure and vessel tubes, a big amount of static moderator in a calendar. Each fuel channel is filled with several rods assembly made of Zircaloy clad oxide pellets. Fuel is loaded during operation.

The size of the core and the costly heavy water induce an important construction cost which reduces the advantage gained by the good loading factor. This reactor system is the third to produce nuclear electricity worldwide.

Chapter 5 – Nuclear Marine propulsion

Nuclear marine propulsion was the first motivation for the development of a nuclear reactor industry, this chapter illustrates how large was the field of a priori solutions. This period permits to put in place theoretical core physics basis that oriented design solutions,

16.15. Optimisation of a multi-strata nuclear fleet achieving “smart recycling” is the new frontier

The strata structure and the right blend make the Gen-IV fleet.

Some requirements must be fulfilled whatever the reactor type. This is the case for safety. On the other hand, some qualities can be brought by specific “enablers” (transmuters (?), breeders). Competitiveness must be achieved thanks to the “workhorse” of the fleet and with a high support ratio, meaning that more costly enablers support a large number of cheaper “power reactors”.

For the current century, the Gen-IV fleet will be composed of **a blend of Gen-3⁺**, post-Fukushima LWRs, potentially capable of efficient multi-recycling during their lifetime, and of genuine Gen-IV reactors, the leaders of the current competition, namely **SFRs**, while some of their challengers will be developed and qualified.

The fleet composed of different “**strata**” and of their related reactor types, capable of complementary functions through specific features, can be built up incrementally, giving time to the newcomers: time for more operation feedback and credibility (industrial operation and safety); time for optimisation. This process benefits from the formidable operation feedback of LWRs. LWR limits can be pushed further by incremental improvements, even for the fuel cycle. The objective is not to modify the LWR role during the century (power reactors, advanced converters) but to help the fleet as a whole come closer to the objectives (because power reactors form the main part of the fleet), before specialised systems help make the final jump, bridge the gap. That is the only way to value newcomers which can’t win the contest on their own.

LWRs should thus be able to reach a multi-recycling regime, as “rectifiers” and “savers”, keeping the built-up plutonium in good condition for its future, when it would enter the breeding regime into FBRs, while thorium and ²³³U could be introduced stepwise and with cross-valorisation into both reactor systems.

Beyond improvements of the reactor systems and of the fuel cycle processes and facilities, optimisation relies on the (slow) evolution of the composition of the fleet and of the related support ratios.

16.16. Qualification (including substantial operation feedback) of all efficient enablers, with an updated design fulfilling the post-Fukushima requirements, must be started ASAP

There is no time left. There is no contradiction between resuming the massive construction of Gen-3⁺ LWRs and launching ASAP the demonstration, then “NOAK” operation, of SFRs and of promising alternatives. Presently, in the wake of Fukushima, safety improvements, followed by stabilisation, are the top drivers.

Epilogue: J.D. Salinger: the carrousel (“going around and around”) and the gold ring.

The playing field of nuclear energy is reminiscent of the final scene in “The Catcher in the Rye” by J.D. Salinger:

On the carrousel, “**All the kids kept trying to grab for the gold ring** and so was old Phoebe, and I was sort of afraid she’d fall off the goddam horse, but I didn’t say anything or do anything. The thing with kids is, if they want to grab for the gold ring [...] If they fall off, they fall off, but it’s bad if you say anything to them.”

Whatever the field (design and safety, operation, dismantling, R&D, teaching, etc.), knowledge and understanding of reactor systems will be a valuable resource in trying to grab for the gold ring, reducing the risk of falling off and increasing the pleasure to play as well as the chance to win (contributing to decisive improvements).