IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

Jean Couturier, Hassan Abou Yéhia
& Emmanuel Grolleau

Elements of nuclear safety
Research reactors

Elements of Nuclear Safety, Radiological Protection and Security series

edp sciences

Science and Technology Series

Elements of nuclear safety – Research reactors

Jean Couturier and Hassan Abou Yéhia
with the help of Emmanuel Grolleau
and contributors to the IRSN's Nuclear Safety Pole

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Cover image: mosaics of photographs related to the subjects dealt with the different volumes of the Elements of nuclear safety, radiological protection and security series. Highlighted, outlined in purple, are those illustrating the themes developed in this second volume of the series.

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Preface

As part of IRSN's Science and Technology Series, the aim of the new "Elements of nuclear safety, radiological protection and security" series is, like the 1996 publication entitled *Elements of nuclear safety* by Jacques Libmann, to provide all those whose work involves ionizing radiation, primarily in the nuclear industry, with information regarding the technological culture relative to prevention and management of the related risks. This new series is the result of the desire not only to update the 1996 publication, but also to extend its scope to areas previously not covered or only touched upon.

In its collection of scientific works, IRSN promotes the most advanced knowledge acquired either within the Institute or in the context of national or international collaborations, focusing particularly on the educational value of its presentation. With this in mind, the specifications for this new series include clear explanations through recounting the history of developments in techniques, ideas, approaches, organizations and regulations, or through questions raised and lessons learned from accidents and operating feedback in general.

The series also aims to provide access for all those interested in these issues to technical knowledge and information that has been properly established and that can be checked in the subject areas referred to, thereby applying IRSN's three core values, Knowledge, Independence and Accessibility, as defined in its Code of Ethics and Professional Conduct.

We hope that this "Elements of nuclear safety, radiological protection and security" series, coordinated by Jean Couturier, will contribute to disseminating knowledge, especially as a new generation of nuclear scientists and technicians takes over from the old.

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The first part of this publication gives a broad international overview of the diversity and complementarity of research reactors. It describes the many uses of these reactors,

not least their significant contribution to research for power reactors' industrial development and safety – whether related to the development of more efficient fuels or the study of the types of accident affecting these reactors –, and it discusses some safety issues specific to research reactors. Although the objectives, principles and safety (and radiological protection) approaches adopted for the design and operation of research reactors are similar to those developed over time and used for power reactors, research reactors are very diverse in terms of design and use very varied quantities of radioactive material. Some of them are operationally flexible enough to be used for a wide variety of experiments, with experimental devices that pose varying levels of risk (from the irradiation of inert materials in a capsule to tests of nuclear fuel melt in a loop, in liquid sodium, in pressurized water, etc.).

In addition, many of the research reactors around the world are old and have been through periods of temporary shutdown. Appropriate measures are necessary to manage the ageing and obsolescence of some of their components and, on an organizational and human level, to keep them operating safely. There are also different types of operators involved either in the operation of these reactors or their use; this can have an impact on safety and radiological protection, and therefore also needs to be taken into consideration.

Two specific chapters are devoted to the safety standards established under the aegis of the IAEA for research reactors and to criticality and reactivity accidents at research reactors.

These safety and radiological protection issues are discussed in more detail and illustrated in the case of French research reactors, in the second part of the publication. There are also specific chapters on the French regulatory system and the official texts applicable to these reactors, on experience feedback from significant events and accidents — including the Fukushima Daiichi nuclear power plant accident in 2011 —, on the account taken of reactivity accidents in the design of French research reactors, and on the ten-yearly safety reviews carried out in France.

I would particularly like to thank Jean Couturier, the coordinator and main editor of this publication with Hassan Abou Yéhia, for this important – and unparalleled – synthesis of the subject, as well as Emmanuel Grolleau and everyone else who gave their valuable support.

Jean-Christophe Niel
IRSN Director-General

Main contributors

Jean COUTURIER has worked for the office of IRSN's Director General since 2012, supporting the roll-out of a knowledge management programme. He is also a senior expert in safety policy and risk analysis. He began his career working for Novatome on the design of fast neutron reactors, in the areas of fuel and safety analysis. He joined IPSN in 1986 to assess the safety aspects of the PHENIX and SUPERPHENIX fast neutron reactors. His activities then broadened to the nuclear safety of research reactors and pressurized water reactors. From 2003 to 2005 he was Strategic Programme Director for Generation IV systems. He is a member of the standing group of experts for nuclear reactors.

Hassan ABOU YEHIA retired from IRSN in 2017. Having completed a doctorate in physical sciences, from 1980 he held various technical and managerial posts at the CEA followed by IPSN and IRSN, including safety assessment for different types of nuclear facilities in France – and throughout the world as part of assignments for the IAEA. From 2006 to 2012 he was responsible for the IAEA's Research Reactor Safety Section (which also covers nuclear fuel cycle facilities). Until the end of 2016 he coordinated IRSN's nuclear safety training activities and participated in the training courses organized by the European Nuclear Safety Training & Tutoring Institute (ENSTTI).

Emmanuel GROLLEAU, has been, since the middle of 2018, assistant head of the service responsible for confinement and aerodispersion of polluants. Previously, he spent several years within the criticality studies and computation service at SGN, part of the AREVA group. He joined IRSN in 2004 to work for the assessment service responsible for research reactor safety. In particular, he directed a number of assessments on which presentations were given to the Advisory Committee for Nuclear Reactors. From 2007 to 2011 he worked for IRSN's Strategy and Partnerships Department. From 2012 to the middle of 2018, he has been assistant head of the service responsible for conducting safety assessments of research-related facilities and reactors undergoing dismantling within IRSN's Nuclear Safety Expertise Directorate.

List of abbreviations

Glossary of institutions

AFCEN: French association producing rules for the design, construction and in-service inspection of nuclear power plant components
AISI: American Iron and Steel Institute
ANCCLI: French national association of local information commissions
ANL: Argonne National Laboratory, USA
AREVA: French nuclear designer and operator (which subsequently became Orano and Framatome)
ARILL: Institut Laue–Langevin Retirees Association
ASME: American Society of Mechanical Engineers (ASME is often used to refer to the design and construction rules drawn up by this American society and used by nuclear reactor designers [Westinghouse, etc.])
ASN: Autorité de sûreté nucléaire (French nuclear safety authority)
AVN: Association Vinçotte-Nucléaire, Belgium
CEA: Commissariat à l'énergie atomique et aux énergies alternatives (Alternative Energies and Atomic Energy Commission), France
CERCA: Compagnie pour l'étude et la réalisation de combustibles atomiques (nuclear fuel design and manufacturing company), France
CI: Information commission
CIS: Internal security committee
CLI: Local information commission
CNRS: Centre national de la recherche scientifique (National Centre for Scientific Research), France
CSIA: Commission de sûreté des installations atomiques (nuclear facility safety commission), France
DAE: Department of Atomic Energy, India
DEP: Nuclear Pressure Equipment Department, ASN

DOE: Department of Energy, USA
DSN: Nuclear Safety Department, CEA
DSND: representative in charge of nuclear safety and radiological protection for French defence-related activities and facilities
EDF: Electricité de France (French power utility)
ENSREG: European Nuclear Safety Regulators Group (a European Commission consultative group of independent experts)
FzK: Forschungszentrum Karlsruhe (Karlsruhe Institute of Technology, Germany)
GAAA: Groupement Atomique Alsacienne Atlantique, a French company
GRS: Gesellschaft für Anlagen- und Reaktorsicherheit (safety organization for nuclear reactors and facilities, Germany)
HCTISN: Haut comité pour la transparence et l'information sur la sécurité nucléaire (High Committee for Transparency and Information on Nuclear Security), France
IAEA: International Atomic Energy Agency, Vienna, Austria
ICRP: International Commission on Radiation Protection
ILL: Institut Laue-Langevin, France
INL: Idaho National Laboratory, USA
IPSN: Institut de protection et de sûreté nucléaire (Institute for Protection and Nuclear Safety), France
IRSN: Institut de radioprotection et de sûreté nucléaire (Institute for Radiological Protection and Nuclear Safety), France
JRC: Joint Research Centre, European Commission
KIT (formerly FzK and KfK): Karlsruhe Institute of Technology, Germany
LLB: Laboratoire Léon Brillouin (joint CEA/CNRS research unit)
LSTC: Livermore Software Technology Corporation, USA
NEA: Nuclear Energy Agency, OECD
OECD: Organisation for Economic Co-operation and Development
PNC (formerly JAEA): Power reactor and Nuclear fuel development Corporation, Japan
SCK CEN: Studiecentrum voor Kernenergie – Centre d'étude de l'énergie nucléaire (nuclear energy research centre), Belgium
SCSIN: Service central de sûreté des installations nucléaires (central nuclear facility safety service), France
SODERA: Société pour le développement de la recherche appliquée (company for the development of applied research), France
WENRA: Western European Nuclear REgulators Association

Technical glossary

ADS: Accelerator Driven System (subcritical hybrid reactor)
ALARA: As Low As Reasonably Achievable (a radiological protection principle)
ALIZÉ: name of a CEA nuclear research reactor (now permanently shut down)
APOLLO: name of a 2D neutron simulation software used for establishing multi-parameter libraries of effective neutron cross-sections
AQUILON: name of a CEA nuclear research reactor (now permanently shut down)

ARS: seismic reactor shutdown (high flux reactor in Grenoble)
ASTEC: Accident Source Term Evaluation Code (system of simulation codes for evaluating the physical phenomena occurring during a core melt accident in a pressurized water reactor)
ASTER: Analyses des Structures et Thermomécanique pour des Etudes et des Recherches (thermomechanical and structural analysis simulation software system for studies and research)
ASTRID: Advanced Sodium Technological Reactor for Industrial Demonstration
ATPu: Atelier de technologie du plutonium (plutonium technology facility, now closed; its main activity was the production of MOX [mixed oxide fuel] fuel for nuclear reactors)
ATWS: Anticipated Transients Without Scram (automatic reactor shutdown without insertion of control absorbers or transients with failure of the automatic reactor shutdown system – also known as ATWR for anticipated transient without reactor trip)
AZALEE: name of a shaking table at CEA Saclay
BCS: control and safety rods (CABRI reactor)
BDBA: Beyond Design Basis Accident
BNCT: Boron Neutrons Capture Therapy (cancer treatment)
BORAX: BOiling water ReActor eXperiment (experimental reactor in the USA)
BR2: Belgium Reactor 2 (at the Mol research centre in Belgium)
CABRI: name of a CEA test reactor at Cadarache used to study accident situations in reactors (PWRs, SFRs)
CASHIMA: name of a research project looking at seismic "site effects"
Cast3M: name of a simulation software using the finite element method for structural and fluid mechanics
CATHARE: Code Avancé de THermohydraulique pour l'Etude des accidents de Réacteurs à Eau (advanced thermohydraulic simulation software used for water reactor accident analyses)
CDS: seismic depressurization system (RHF)
CEN: groundwater supply system (RHF)
CERES: name of a software for calculating the radiological impact of a release in an accident situation
CES: emergency cooling system (RHF)
CESAR: name of a CEA research reactor (now permanently shut down) or name of a thermohydraulics module in the ASTEC software system
CFD: Computational Fluid Dynamics
CIP: Cabri International Program (an international program to study the behaviour of nuclear fuel rods and cladding during a reactivity injection accident in pressurized water reactors)
CPA: name of a module in the ASTEC software system
CRISTAL: name of a calculation route developed jointly by IRSN, CEA and AREVA to evaluate the risk of criticality in all nuclear facilities and transport casks containing fissile materials
CRONOS: name of a simulation software for 3D core neutronics calculation

CRP: Coordinated Research Project
CRU: emergency core cooling (reflood) system (RHF)
CSA: Complementary Safety Assessment (post Fukushima Daiichi accident)
CSS: Commission on Safety Standards (IAEA)
DBA: Design Basis Accident
DEC: Design Extension Conditions
DIRAS: information package related to the cleanup of structures
DISCO: DIspersion of Simulated COrium (KIT experimental facility to study airborne contamination/dispersion of corium, using inactive powders)
DULCINEE: name of a software used to simulate core thermohydraulics and the thermal behaviour of fuel in a reactor
ECS: évaluation complémentaire de sûreté (see CSA)
EFPD: Equivalent Full Power Days
EIP: element important for protection (of "interests", concept in French regulations)
EL2: Eau Lourde 2 (a CEA research reactor, now dismantled)
EL3: Eau Lourde 3 (a CEA research reactor currently being dismantled)
EL4: Eau Lourde 4 (Brennilis nuclear power plant, France)
EOLE: name of a CEA nuclear research reactor
EPIC: French industrial and commercial public undertaking
EPR: European Pressurized Water Reactor
ESPN: nuclear pressure vessel
ETRR-2: Egypt Test and Research Reactor Number two
EUROPLEXUS: name of a finite element simulation software
FINAS: Fuel Incident Notification and Analysis System (run by the IAEA)
FLICA: name of a software that calculates the thermohydraulics of a reactor core during transients
FP: fission products
FRM-II: Forschungsreaktor München II (research reactor in Garching, Germany)
GAZAXI: name of a software used for calculating the radiological impact of a release in an accident situation
GCR: gas-cooled, graphite-moderated reactor
GOR: General Operation Rules
GPD: standing group of experts for waste
GPDEM: standing group of experts for dismantling
GPE: standing group of experts
GPESPN: standing group of experts for nuclear pressure equipment
GPMED: standing group of experts for medical exposure
GPR: standing group of experts for nuclear reactors
GPRAD: standing group of experts for radiation protection (non-medical)
GPT: standing group of experts for transport
GPU: standing group of experts for laboratories and factories
GUS: ultimate diesel generator (JHR)
HARMONIE: name of a CEA nuclear research reactor (now dismantled)

HEMERA: Highly Evolutionary Methods for Extensive Reactor Analyses (software chain for simulating the thermohydraulics and neutronics of transients in a nuclear reactor)
HFR: High Flux Reactor (high flux reactor at the JRC in Petten, Netherlands)
HIFAR: High Flux Australian Reactor
HTR: High Temperature Reactor
IAEA: International Atomic Energy Agency, Vienna, Austria
IEA-R1: Instituto de Energia Atômica-Reactor 1 (Brazilian research reactor)
IGORR: International Group on Research Reactors
INB: basic nuclear installation
INES: International Nuclear Event Scale (developed by the IAEA)
INSAG: International Nuclear Safety Group
INSARR: Integrated Safety Assessment of Research Reactors
IODE: name of a module in the ASTEC software system
IRR1: Israel Research Reactor-1
IRS: International Reporting System for operating experience (system run by the IAEA for reporting incidents at power reactors)
IRSRR: Incident Reporting System for Research Reactors (system run by the IAEA for reporting incidents at research reactors)
ISIS: name of the critical assembly of the OSIRIS nuclear research reactor at Saclay
ISTP: International Source Term Program
ITER: International Thermonuclear Experimental Reactor (under construction at Cadarache)
JHR: Jules Horowitz Reactor (CEA nuclear research reactor currently under construction)
LOOP: loss of off-site power
LS-DYNA: name of a finite element simulation software for dynamic structural analysis
MARIUS: name of a CEA nuclear research reactor (now permanently shut down)
MASURCA: critical assembly of the CEA at Cadarache
MC3D: name of a 3D multi-phase thermohydraulic software used to simulate the interaction between molten materials and coolant
MCNP: Monte Carlo N-Particle transport code (3D simulation software for particle transport based on the Monte Carlo method)
MELUSINE: name of a CEA nuclear research reactor (now dismantled)
MHPE: Maximum Historically Probable Earthquake
MINERVE: name of a CEA nuclear research reactor at Cadarache
MNSR: Miniature Neutron Source Reactor
MORET: simulation software that solves the neutron transport equation using Monte Carlo methods, mainly used for criticality studies
MOX: Mixed Oxide Fuel (UO_2 + PuO_2)
MTR: Material Testing Reactors (used for testing various materials and nuclear fuels)
NGO: non-governmental organization
NRU: National Research Universal (research reactor of Chalk River Laboratories, Canada)
NRX: National Research eXperimental (research reactor of Chalk River Laboratories, Canada)

NSRR: Nuclear Safety Research Reactor (Japanese research reactor used for safety tests)
NUSSC: NUclear Safety Standards Committee (IAEA)
OLC: Operational Limits and Conditions
OPAL: Open Pool Australian Lightwater (an Australian research reactor)
ORPHÉE: name of a CEA nuclear research reactor at Saclay
OSIRIS: name of a CEA nuclear research reactor at Saclay (now permanently shut down)
OTHELLO: name of an experimental loop in the OSIRIS reactor
PAI: iodine filter
pcm: per cent mille
PSA: Probabilistic Safety Assessment
PCS: emergency control room (RHF)
PEGASE: name of a CEA research reactor (now permanently shut down)
PEGGY: name of the critical assembly of the PEGASE research reactor
PGA: Peak Ground Acceleration
PHEBUS: name of a CEA experimental reactor in Cadarache
Phebus-FP: international research programme to study the behaviour of fission products in core melt situations in a pressurized water reactor
PHENIX: name of a CEA prototype nuclear power (and experimental) reactor at Marcoule, a sodium-cooled fast neutron reactor (currently being dismantled)
PROSERPINE: name of a CEA research reactor (now permanently shut down)
PSA: Probabilistic Safety Assessment
PUI: on-site emergency plan
PWR: Pressurized Water Reactor
RA-2: name of an Argentinian research reactor
RADIOSS: name of a finite element simulation software
RAPSODIE: name of a CEA experimental sodium-cooled fast neutron reactor at Cadarache (now permanently shut down)
RASSC: Radiation Safety Standards Committee (IAEA)
RCC-CW: rules for design and construction of French PWR nuclear civil works
RCC-E: design and construction rules for electrical components of French PWR nuclear islands
RCC- M: design and construction rules for mechanical components of French PWR nuclear islands
RCC-MRx: design and construction rules for mechanical components of nuclear installations high-temperature, research and fusion reactors
RERTR: Reduced Enrichment for Research and Test Reactors (US program)
RFS: fundamental safety rule
RGEP: guillotine break of a “particular element” (concept used in the safety analysis of the Jules Horowitz reactor)
RGSE: general surveillance and maintenance rules

RHF: high flux reactor at Grenoble, France (nuclear research reactor of the Institut Laue-Langevin)
RIA: Reactivity Injection Accident
RLC: risk limitation conditions (concept used in the safety analysis of the Jules Horowitz reactor)
RRDB: Research Reactor DataBase (run by the IAEA)
RSE-M: equipment in-service surveillance rules of French PWR nuclear islands
RSG-GAS: Reaktor Serba Guna – Gerrit Augustinus Siwabessy (Indonesian research reactor)
RUS: Strasbourg university reactor or emergency secondary cooling system of the Jules Horowitz Reactor, in construction at Cadarache, France
SAFARI-1: South African Fundamental Atomic Research Installation 1 (nuclear research reactor)
SBO: station blackout
SCANAIR: software for simulating the thermomechanical behaviour of the fuel rods in pressurized water reactors during power transients
SCARABEE: name of a CEA research reactor at Cadarache (now dismantled)
SFRs: sodium-cooled fast neutron reactors
SIGMA: Seismic Ground Motion Assessment
SILOE: name of a CEA nuclear research reactor at Grenoble (currently being dismantled)
SILOETTE: name of a CEA thermal nuclear research reactor in Grenoble (critical assembly of the SILOE nuclear reactor) (now dismantled)
SIMMER: name of a simulation software combining neutronics and fluid mechanics, used to simulate a fuel melt accident in a fast neutron reactor
SIREX: instrumentation and control electronic racks or cabinets in French research reactors
SL-1: Stationary Low Power Reactor Number One (Idaho National Laboratories, Idaho, USA)
SME: Safe Shutdown Earthquake
SND: hardened safety core design earthquake
SOFIA: Simulateur d'Observation du Fonctionnement Incidentel et Accidentel (simulator of the operation of PWRs used by IRSN)
SPERT: Special Power Excursion Reactor Tests, pressurized water type, operated by Phillips Petroleum Company as part of the U.S. Atomic Energy Commission program, USA
SSC: Structures, Systems and Components
TECDOC: TEChnical DOCument (IAEA)
TECV: French Act No 2015-992 on energy transition for green growth, adopted on 17 August 2015
HEPA: high efficiency particulate air (filter)
TRANSSC: TRANsport Safety Standards Committee (IAEA)
TREAT: Transient Reactor Test Facility (research reactor developed by Idaho National Laboratories, Idaho Falls, USA)

TRIDENT: name of a simulation software
TRIGA: TRaining, Isotope, General Atomics (pool-type research reactor developed by General Atomics, USA)
TRIPOLI: TRIdimensionnel POLYcinétique (3D simulation software that uses the Monte Carlo method to solve the coupled neutron/photon transport equation)
TSN: French Act No 2006-686 of 13 June 2006 on nuclear security and transparency
ULYSSE: name of a CEA nuclear research reactor (now dismantled). This was an Argonaut class reactor, a research reactor model developed by the Argonne National Laboratory in the USA (ARGONAUT stands for ARGOnne Nuclear Assembly for University Training)
VARMA: acceptable modelled value for residual activity
VENUS: Vulcan Experimental Nuclear System (JRC research reactor in Mol, Belgium)
WASSC: WAste Safety Standards Committee (IAEA)
ZEPHYR: Zero power Experimental PHYsics Reactor (a CEA reactor still in the planning phase)
ZOÉ: ZerO Energy, an alternative name for the EL1 reactor. France's first research reactor, located at the CEA centre in Fontenay-aux-Roses

Foreword

This publication on nuclear research reactors and particularly on specific characteristics and issues of research reactors in terms of nuclear safety and radiological protection, was written by authors from IRSN, the French Institute for Radiological Protection and Nuclear Safety.

It assumes that the reader already has a basic knowledge of the physics of nuclear reactors and their operation; however, reminders are provided throughout the text on these subjects in the form of *notes* or *focus* texts.

Jean Couturier is the main author – and the project coordinator – with contributions from Hassan Abou Yéhia on international aspects, and assistance from Emmanuel Grolleau and the unit in charge of assessing safety and radiological protection at French research reactors. Specific contributions were made by Maud Corbel, Stanislas Massieux, Ludovic Maas, Vincenzo Tiberi, Patrice François, Sandrine Soares, Elodie Cahen, Florence Gupta, Stéphanie Kanamori, Mathieu Derotte, Céline Gelis, Eric Dumonteil, Bertrand Cochet, Tonino Sargeni and Jacques Ducau.

An effort has been made to ensure that external sources of information, including illustrations, have been credited. This was the case for the "monographs" by the Nuclear Energy Directorate of the French Alternative Energies and Atomic Energy Commission (of the greatest interest), and for publications produced for conferences, official texts, presentations available on websites, etc.

Daniel Quéniart carefully proofread the publication in its draft version. His contribution was important to the production of the final version.

Thierry Bourgois, Martial Jorel, Gianni Bruna and Michel Bourguignon also proofread draft versions of the whole text or sections of it. Their comments were taken into account when it was finalized.

Odile Lefèvre and Georges Goué prepared the work for publication.

Finally, during the production of this text we were keen to do more than simply describe research reactors and their objectives and general principles in terms of nuclear safety and radiological protection, which would have duplicated the work of many other French and international publications; this would have produced a much less useful document, especially from an educational point of view. Technical substance was necessary to illustrate these objectives and principles. The authors would like to thank in this regard the Division operating the high flux reactor (RHF) in Grenoble (Institut Laue Langevin [ILL]) for providing information and illustrations and allowing us to publish them. This material gives a practical illustration, in the case of this particular reactor, of a number of (French) nuclear safety and radiological protection principles and practices (particularly the ten-yearly safety reviews and the experience feedback from the Fukushima Daiichi accident).