

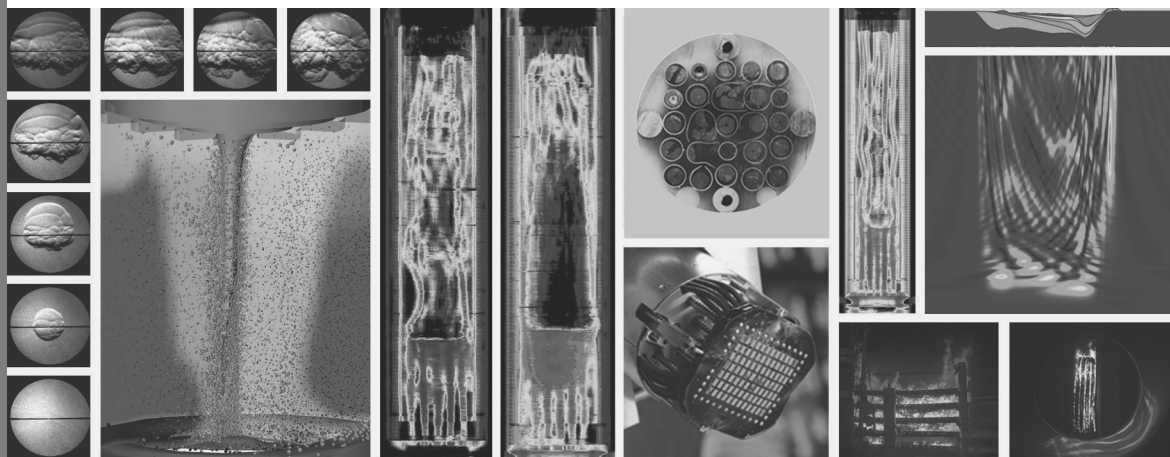
# IRSN

INSTITUT  
DE RADIOPROTECTION  
ET DE SÛRETÉ NUCLÉAIRE

*Enhancing nuclear safety*

Jean Couturier, Michel Schwarz

## Current State of Research on Pressurized Water Reactor Safety



**edp sciences**



Science and Technology Series

# **Current State of Research on Pressurized Water Reactor Safety**

Jean Couturier, Michel Schwarz



**Cover illustrations:** photographs showing research and development in pressurized water reactor safety at IRSN. From left to right: the hydrogen risk in nuclear reactors © IRSN Institut Icare; image from a 3D simulation by the MC3D code of corium dispersion in the water in a reactor pit in the event of a central reactor vessel failure © IRSN; states of degradation of fuel assemblies from the Phébus-PF program © IRSN; a prototype of the conformable transducer – IRSN/CEA patent © IRSN/CEA (bottom); Phébus-LOCA – section view (post-mortem) of a test fuel cluster following a temperature transient typical of a LOCA © IRSN (top); an experiment involving a fire in a stack of cable raceways © Florent-Frédéric Vigroux/IRSN (bottom); 2D model of the Nice basin; below, amplification of seismic waves calculated by a numerical simulation of seismic wave propagation in this model © Fabien Peyrusse/Inria; fire test on electrical cables © Florent-Frédéric Vigroux/IRSN (bottom).

Printed in France

ISBN (print): 978-2-7598-2164-8 – ISBN (ebook): 978-2-7598-2165-5

DOI: 10.1051/978-2-7598-2164-8

All rights relative to translation, adaptation and reproduction by any means whatsoever are reserved, worldwide. In accordance with the terms of paragraphs 2 and 3 of Article 41 of the French Act dated March 11, 1957, “copies or reproductions reserved strictly for private use and not intended for collective use” and, on the other hand, analyses and short quotations for example or illustrative purposes, are allowed. Otherwise, “any representation or reproduction - whether in full or in part - without the consent of the author or of his successors or assigns, is unlawful” (Article 40, paragraph 1). Any representation or reproduction, by any means whatsoever, will therefore be deemed an infringement of copyright punishable under Articles 425 and following of the French Penal Code.

© IRSN 2018

# Preface

---

This publication sets out to provide an overview of much of the research and development work carried out over the past forty years in the field of pressurized water reactor safety, in particular by the Institut de Protection et de Sûreté Nucléaire (IPSN), later becoming the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), whether alone or in collaboration with other organizations. This work – and the lessons that can be learned from it – is set in front of the safety issues raised during assessments of French nuclear power plants, or following incidents and accidents that have occurred, such as those affecting reactor 2 at the Three Mile Island nuclear power plant in 1979, reactor 4 at the Chernobyl nuclear power plant in 1986 and, more recently, at the Fukushima Daiichi nuclear power plant in 2011.

The safety of nuclear facilities is part of a continuous improvement process that is based on:

- national and international operating experience feedback,
- and knowledge acquired through research and development, with assessment and research activities fueling each other.

Since the 1980s, safety reviews have been carried out at nuclear power plants operated by Électricité de France (EDF), the national power utility, as part of a ten-yearly outage program. These provide an opportunity to ensure that lessons learned from operating experience feedback and R&D work flow down to the operational level.

The research and development themes relating to pressurized water reactor safety in which IRSN has been – and for the most part still is – particularly involved are part of the general initiative to prevent and mitigate the impact of postulated events. These include internal events, such as the loss of coolant or an uncontrolled increase of reactivity in the core until it melts, and "hazards" such as earthquakes, external flooding, and fires inside or outside facilities. The knowledge acquired through research on core melt accidents is

fed into ASTEC, an IRSN computer code used for simulation purposes, and internationally recognized as a reference tool.

The authors also wished to provide a panorama of studies and research work relating to human and organizational factors, a theme that has been of concern to the international community since the accidents at Three Mile Island and Chernobyl. The safety issues raised by the growing tendency of licensees to work with subcontractors have become major themes of studies and research today. Furthermore, since the accident at the Fukushima Daiichi nuclear power plant, and the conclusions drawn from the event – in particular those of the National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission, according to which various social factors contributed to the accident – studies and research initiatives have covered topics in the human and social sciences.

For each of the research and development themes addressed, the remaining uncertainties and the new knowledge required are highlighted. Research in new areas, such as topics relating to new reactor designs (passive safety, the possibility of retaining the corium in the reactor vessel in the event of a core melt accident, etc.) is also discussed.

The research and development work discussed in this publication illustrates IRSN's policy of opening up to the international community and the many ties it has developed with it. Examples include direct ties with similar organizations (such as the United States NRC or GRS in Germany) research operators (in particular the Commissariat à l'énergie atomique et aux énergies alternatives [CEA] and universities) as well as involvement in knowledge sharing organizations (such as the OECD Nuclear Energy Agency) and the many projects funded in France by the Agence nationale de la recherche (ANR) and at the European level by the European Commission through its multi-year Framework Programs (FP) for research and development. In addition, IRSN is closely involved in defining European research strategies within the European Sustainable Nuclear Energy Technology Platform (SNETP) and, since 2012, as a member of the NUGENIA association.

I would especially like to thank the two main contributors, Jean Couturier and Michel Schwarz, for this impressive summary (representing more than three years' work) and, more generally, all the IRSN experts for their invaluable assistance in this work.

Jean-Christophe Niel  
IRSN Director-General

## The authors

---

Jean Couturier works at the office of IRSN's Director General, supporting the roll-out of a knowledge management program. He is also a senior expert (safety policies, risk analyses). He began his career working on the design of fast reactors. From 1982, his work focused on nuclear safety not only for this type of reactor (PHENIX, SUPERPHENIX) but also for research reactors, pressurized water reactors, etc. He is a member of the Standing Group of experts for Reactors and the Standing Group of experts on Nuclear Pressurized Equipment.

Michel Schwarz retired from IRSN in 2012. He spent his career in nuclear safety research. In particular, he ran the Phébus-PF international research program on core melt accidents in light water reactors. He was director of major accident prevention and then IRSN's scientific director. He is a member of ASN's Scientific Committee.



# List of abbreviations

---

## Glossary of institutions

AEC: Atomic Energy Commission, USA (forerunner of the U.S.NRC)

AECL: Atomic Energy of Canada Limited, a nuclear science and technology research institute

AFPS: Association française du génie parasismique (French Earthquake Engineering Association)

ANDRA: Agence nationale pour la gestion des déchets radioactifs (French National Radioactive Waste Management Agency)

ANL: Argonne National Laboratory, USA

ANR: Agence nationale pour la recherche (French National Research Agency)

AREVA: French nuclear operator

ARMINES-SPIN: Institut Carnot M.I.N.E.S – Centre des Sciences des processus industriels et naturels de l'École des Mines de Saint-Étienne, France (Carnot M.I.N.E.S Institute – Center for Industrial and Natural Processes of the École des Mines in Saint-Etienne)

ASME: American Society of Mechanical Engineers, USA (commonly used to refer to the design and construction rules drawn up by this American society and used by American designers [Westinghouse, etc.]

ASN: Autorité de sûreté nucléaire (French Nuclear Safety Authority)

BelV: Belgian Federal Agency for Nuclear and Radiological Inspections of nuclear installations

BETCGB: Bureau d'études techniques et de contrôle des grands barrages (French Technical and Inspection Office for Large Dams)

BRGM: Bureau de recherche géologique et minière (French Geological Research Mining Bureau)



C3R: Laboratoire de cinétique chimique, combustion et réactivité (Laboratory of Chemical Kinetics, Combustion and Reactivity is a French joint research laboratory established by IRSN, CNRS and the University of Lille 1 Science and Technology)

CEA: Commissariat à l'énergie atomique et aux énergies alternatives (French Alternative Energies and Atomic Energy Commission)

CEBTP: Centre d'essais du bâtiment et des travaux publics (the French Construction and Public Works Test Center is a center of expertise in soil engineering, materials and structural engineering, and construction)

CEGB: Central Electricity Generating Board, UK

CEMAGREF: Centre national du machinisme agricole, du génie rural, des eaux et des forêts (French National Center for Agricultural Machinery, Rural Engineering, Water and Forestry, research institute)

CERIB: Centre d'études et de recherches de l'industrie du béton (French Concrete Industry Study and Research Center)

CETMEF: Centre d'études techniques maritimes et fluviales (French Technical Maritime and River Study Center)

CNL (formerly AECL): Canadian Nuclear Laboratories

CNPP: Centre national de prévention et de protection (French National Center for Prevention and Protection)

CNR: Compagnie nationale du Rhône (French National Company of the Rhone)

CNRS: Centre national de la recherche scientifique (French National Center for Scientific Research)

CNSC: Canadian Nuclear Safety Commission

CORIA: Complexe de recherche interprofessionnel en aérothermochimie (French Aero-thermochemistry Research Complex)

CRL: Chalk River Laboratories, Canada

CSNI: Committee on the Safety of Nuclear Installations, OECD

CSN: Consejo de Seguridad Nuclear (Spanish Nuclear Safety Council)

CSO: Centre de sociologie des organisations (French Center for Sociology of Organizations, a joint research unit of Sciences Po and CNRS)

CSTB: Centre scientifique et technique du bâtiment (French Construction Science and Technology Center)

CTICM: Centre technique industriel de la construction métallique (French Industrial Technology Center for Construction in Metal)

DCNS: French hi-tech company specializing in defense naval systems

DGA: Direction générale de l'armement (Ministère de la Défense) (French General Directorate for Armament, [French Ministry of Defence])

DGPR: Direction générale de la prévention des risques (French General Directorate for Risk Prevention, a government department reporting to the Ministry of Ecology, Sustainable Development and Energy)

DMT: Département de mécanique et thermique (Mechanical and Thermal Engineering Department at CEA's research platform in Saclay, France)

- EDF: Électricité de France (French power utility)
- ENEL: Ente Nazionale per l'Energia Elettrica, Italian power utility
- ENS Cachan: École nationale supérieure de Cachan (a prestigious French higher National School)
- ENSI: Eidgenössisches Nuklearsicherheitsinspektorat (Swiss Federal Nuclear Safety Inspectorate)
- ENSREG: European Nuclear Safety Regulators Group
- EPRI: Electric Power Research Institute, USA
- ETIC: Laboratoire d'étude des incendies en milieux confinés (Laboratory for the Study of Fire in a Contained Environment, IRSN, France)
- Euratom: European Atomic Energy Community
- Fzk: Forschungszentrum Karlsruhe (Karlsruhe Institute of Technology, Germany)
- Framatome: nuclear steam supply system manufacturer, France
- GDF: Gaz de France (French gas utility)
- GeM: Institut de recherche en génie civil et mécanique, unité mixte CNRS/École centrale de Nantes/Université de Nantes (French Civil and Mechanical Engineering Research Institute, a joint CNRS/École Centrale de Nantes/University of Nantes unit)
- GFH: Groupe facteurs humains (Human Factors Group, EDF, France)
- GrDF: Gaz, réseau, distribution France (French Gas, Network management, Distribution Company)
- GRS: Gesellschaft für Anlagen – und Reaktorsicherheit (reactor safety organization, Germany)
- HAMMLAB: Halden Man-Machine Laboratory (Norwegian laboratory researching man-machine interactions and control processes)
- HSE: Health and Safety Executive, UK
- IAEA: International Atomic Energy Agency, Vienna, Austria
- IBRAE: Nuclear Safety Institute of the Russian Academy of Sciences, Russia
- ICARE: Institut de combustion aérothermique réactivité et environnement (Institute for Combustion, Aerothermal Engineering, Reactivity and Environment, CNRS, Orléans, France)
- IFE: Institutt for energiteknikk (Institute for Energy Technology, Norway)
- IFREMER: Institut français de recherche pour l'exploitation de la mer (French Research Institute for Exploitation of the Sea)
- IFSTTAR: Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (French Institute of Science and Technology for Transport, Development and Networks)
- INERIS: Institut national de l'environnement industriel et des risques (French National Institute for the Industrial Environment and Risks)
- INL: Idaho National Laboratory, USA
- Inria: Institut national de recherche dédié au numérique (French National Research Institute for the Computational Sciences)

INQUA: International Union for Quaternary Research (organization responsible for promoting international collaboration in the earth sciences)

INSA: Institut national des sciences appliquées (French National Institute of Applied Sciences)

IPSN: Institut de protection et de sûreté nucléaire (French Institute for Nuclear Safety and Protection)

IREX: Institut pour la recherche appliquée et l'expérimentation en génie civil (French Institute for Applied Research and Experimentation in Civil Engineering)

IRSN (formerly IPSN): Institut de radioprotection et de sûreté nucléaire (French Institute for Radiological Protection and Nuclear Safety)

ISTC: International Science and Technology Center

IUSTI: Institut universitaire des systèmes thermiques industriels (French University Institute for Industrial Thermal Systems, a joint research unit of CNRS/Universities of Provence and the Mediterranean)

JAEA: Japan Atomic Energy Agency

JAERI (formerly JAEA): Japan Atomic Energy Research Institute

KAERI: Korea Atomic Energy Research Institute, South Korea

KEPCO: Kansai Electric Power Company, Japan

Kfj: Forschungszentrum Jülich (Jülich Research Center, Germany)

KfK: Kernforschungszentrum Karlsruhe (Karlsruhe Institute of Technology, Germany)

KIT (formerly FzK and KfK): Karlsruhe Institut für Technology (Karlsruhe Institute of Technology, Germany)

KWU: Kraftwerk Union (German nuclear power plant construction company)

Labra: Laboratoire des rayonnements appliqués (Laboratory for Applied Radiation, CEA, France)

LaMCoS: Laboratoire de mécanique des contacts et des structures (Laboratory for the Mechanics of Contacts and Structures, a joint research unit of INSA in Lyon and CNRS, France)

LCPC: Laboratoire central des ponts et chaussées (French Central Laboratory for Bridges and Roads)

LEFH: Laboratoire d'étude des facteurs humains (Laboratory for the Study of Human Factors, IPSN, France)

LEMTA: Laboratoire d'énergétique et de mécanique théorique et appliquée (Laboratory of Energy and Theoretical and Applied Mechanics, jointly run by the University of Lorraine and CNRS, France)

LEPMI: Laboratoire d'électrochimie et de physico-chimie des matériaux et des interfaces (Laboratory of Electrochemistry and Physico-chemistry of Materials and Interfaces in Grenoble, France)

LMA: Laboratoire de mécanique et d'acoustique, (Mechanics and Acoustics Laboratory, France)

LMDC: Laboratoire matériaux et durabilité des constructions (Construction Materials and Durability Laboratory, France)

LNE: Laboratoire national de métrologie et d'essais (French National Laboratory for Metrology and Testing)

LSHS: Laboratoire des sciences humaines et sociales (Human and Social Sciences Laboratory, IRSN, France)

LVEEM: Laboratoire Vellave sur l'élaboration et l'étude des matériaux (Vellave Laboratory on the Development and Study of Materials in Le Puy-en-Velay, France)

MAI: Materials Ageing Institute, France (an international research and development institute set up by EDF, specializing in research into the ageing of materials used in power plants)

MIST: Laboratoire de micromécanique et intégrité des structures, laboratoire "sans mur" commun au CNRS et à l'IRSN (Micromechanics and Structural Integrity Laboratory, jointly funded by the CNRS and IRSN, could be described as a laboratory "without walls", France)

NEA: Nuclear Energy Agency, OECD

NEI: Nuclear Energy Institute, USA

NIIAR: Scientific Research Institute of Atomic Reactors, Russia

NIST: National Institute of Standard and Technology, USA

NITI: Aleksandrov Scientific Research Technological Institute, Saint-Petersburg, Russia

NRA: Nuclear Regulation Authority, Japan

NUGENIA: NUClear GENeration II & III Association (international association dedicated to the safety of generation II and III reactors)

NUPEC: Nuclear Power Engineering Center, Japan

OECD: Organization for Economic Co-operation and Development

NGO: Non-Governmental Organization

ORNL: Oak Ridge National Laboratory, USA

PC2A: Laboratoire de physico-chimie des processus de combustion et de l'atmosphère (Laboratory for the Physical Chemistry of Combustion Processes and the Atmosphere, Lille, France)

PNNL: Pacific Northwest National Laboratory, USA

PROMES: Procédés, matériaux et énergie solaire (Processes, Materials and Solar Energy, laboratory in Perpignan, France)

PSI: Paul Scherrer Institute, Switzerland

RESIF: Réseau sismologique & géodésique français (French Seismologic and Geodesic Network)

ROSATOM: Federal Agency on Atomic Energy, Russia

SHOM: Service hydrographique et océanographique de la marine (French Naval Hydrographic and Oceanographic Service)

SNCF: Société nationale des chemins de fer (French rail operator)

SNL: Sandia National Laboratory, USA

STUK: Radiation and Nuclear Safety Authority, Finland

U.S.NRC: United States Nuclear Regulatory Commission, USA

VTT: Technical Research Center, Finland

WGAMA: Working Group on Analysis and Management of Accidents, OECD/NEA/CSNI

WGELE: Working Group on Electrical Power, OECD/NEA/CSNI

WGEV: Working Group on External Events, OECD/NEA/CSNI

WGFCs: Working Group on Fuel Cycle Safety, OECD/NEA/CSNI

WGFS: Working Group on Fuel Safety, OECD/NEA/CSNI

WGHOFF: Working Group on Human and Organizational Factors, OECD/NEA/CSNI

WGIAGE: Working Group on Integrity and Ageing of Components and Structures, OECD/NEA/CSNI

WGRISK: Working Group on Risk Assessment, OECD/NEA/CSNI

### Technical glossary

AAR: Alkali-Aggregate Reactions

ABI: name of a program of tests conducted as part of research into reactor vessel failure and basemat erosion due to corium in a reactor core melt accident

ACHILLE: name of an experimental program to study the behavior of fuel rods

ACRR: Annular Core Research Reactor (experimental reactor run by SNL to study core temperature rise and core melt in a reactor vessel)

AGORAS: *Amélioration de la gouvernance des organisations et des réseaux d'acteurs pour la sûreté nucléaire* (Improving Governance of Organizations and Networks involved in Nuclear Safety, research project)

AIC: *Argent-Indium-Cadmium* (Silver-Indium-Cadmium)

ALPHA: name of an experimental facility run by JAERI to study steam explosions in a reactor

ALPS: Advanced Light water reactor Performance and Safety (international research program)

APHRODITE: name of a series of analytical tests to study two-phase thermal hydraulics

ARTEMIS: name of a test program conducted as part of research into reactor vessel failure and basemat erosion due to corium in a reactor core melt accident

ARTIST: Aerosol Trapping in a Steam Generator (experimental facility run by PSI – study of aerosol retention in a steam generator)

ASTEC: Accident Source Term Evaluation Code (system of simulation codes for evaluating the physical phenomena that occur during a core melt accident in a pressurized water reactor)

ASTRID: Advanced Sodium Technological Reactor for Industrial Demonstration (demonstration sodium-cooled fast reactor project)

AZALEE: name of a CEA shake table

BALI: name of a series of tests conducted as part of research into reactor core melt accidents

BALISE: name of a test program conducted as part of research into reactor vessel failure and basemat erosion due to corium in a reactor core melt accident

- BETA: name of a KIT experimental facility used to study corium/concrete interaction as part of research into reactor core melt accidents
- BETHSY: name of a CEA experimental facility – tests used to check the ability of the CATHARE code to predict satisfactorily the behavior of a nuclear steam supply system in an accident situation
- BFC: Bottom of Fissile Column
- BILLEAU: name of tests to study steam explosion in a reactor (study of the dispersion of a jet of solid spheres in a test section filled with water)
- BIP: Behavior of Iodine Project (international program to study iodine behavior in a reactor containment)
- BK: fuel building
- BWR: Boiling Water Reactor
- CABRI: name of a CEA test reactor used to study accident situations in reactors (PWR, FNR)
- CAD: Computer-Aided Design
- CADUCEE: name of an experimental apparatus on the GALAXIE platform for research into controlling fire risks in nuclear facilities
- CALIST: Characterization and Application of Large and Industrial Spray Transfer (IRSN experimental facility for studying spray mechanisms)
- CANON: name of a series of analytical tests to study two-phase thermal hydraulics
- CARAIDAS: name of an IRSN experimental facility – study of the behavior of radioactive products in a reactor containment
- CAIMAN: name of a CEA experimental facility – study of iodine behavior in a reactor containment
- CARINEA: name of an experimental facility on the GALAXIE platform used for research into controlling fire risks in nuclear facilities
- Cast3M: name of a finite-element computer code used for the mechanics of structures and fluids
- CATHARE: *Code avancé de thermohydraulique pour les accidents de réacteurs à eau* (Advanced Thermohydraulics Code for Water Reactor Accidents, a simulation code used for safety analyses)
- CATHODE: name of some analytical test programs conducted as part of research into controlling fire risks in nuclear facilities
- CAV: Cumulative Absolute Velocity
- CCI: Corium Concrete Interaction
- CCM: Cold Crucible Melting (test program to study the fragmentation of molten mixtures)
- CCWS: Component Cooling Water System
- CEOS.fr: *Comportement et évaluation des ouvrages spéciaux* (Behavior and Evaluation of Special Structures, a French research project)
- CESAR: name of a module of the ASTEC code

CIP: CABRI International Program (international program to study the behavior of nuclear fuel rods and their cladding in a reactivity injection accident in PWR)

CIR: Cooperative Irradiation-assisted stress corrosion cracking Research (an international research and development program on the corrosion of stainless steels under stress and under irradiation)

CIVA: name of a numerical simulation platform for non-destructive testing

CFD: Computational Fluid Dynamics

CFR: Code of Federal Regulations

CHIP: *Chimie de l'iode dans le circuit primaire* (Iodine Chemistry in the Reactor Coolant System, an IRSN facility or research program contributing to better evaluation of the quantity of iodine that can be released in a reactor core melt accident)

CHRS: Containment Heat Removal System

CIRCE: name of a research program on the corrosion of nickel-based alloys under stress

CLARA: name of a test program conducted as part of research into reactor vessel failure and basemat erosion due to corium in a reactor core melt accident

CODAZIR: research program to study the fuel rod behavior in a LOCA

COMET: name of an experimental facility and a concept developed by KIT to research reactor core melt accidents

COPAT: *Centre opérationnel de pilotage des arrêts de tranche* (EDF), see OCC

COPO: Corium Pool Facility (Finnish experimental facility – research into the potential for retaining the corium in the reactor vessel in a reactor core melt accident)

CORA: name of a research program on core temperature rise and core melt in the reactor vessel

CORDEB: Corium-Debris (experimental program of research into reactor core melt accidents)

CROCO: name of a code for simulating corium spreading

CSD: *Combustible sévèrement dégradé* (Severely Degraded Fuel)

CSS: Containment Spray System

CVCS: Chemical and Volume Control System

DA: *diagnostic automatique* (automatic diagnostics)

DANAIDES: *Dispositif analytique pour l'étude, en cas d'incendie, du dysfonctionnement électrique par les suies* (Analytical Equipment for Studying Electrical Malfunctions caused by Soot during a Fire, an experimental facility on the GALAXIE platform)

DBE: Design Basis Earthquake (used during the design of nuclear facilities)

DCH: Direct Containment Heating

DDF: *durée de fonctionnement* (Operating Life [EDF project])

DDT: Deflagration–Detonation Transition

DEBORA: name of a series of analytical tests for research into two-phase thermal hydraulics

DEF: Delayed Ettringite Formation

- DELTA: name of some analytical test programs run as part of research into controlling fire risks in nuclear facilities
- DENOPI: *Dénoyage piscines* (Spent Fuel Pool Water Uncovery, a research program on accidental water uncovery of a nuclear fuel storage pool)
- DEVAP: *Dépôt en phase vapeur des produits de fission volatils sur les surfaces des circuits* (Volatile Fission Product Deposits in the Vapour Phase on Reactor System Surfaces, an analytical test program to study the transfer of radioactive products in reactor systems during a core melt accident)
- DF: Damage Fuel (a research program to study core temperature rise and core melt in a reactor vessel)
- DISCO: DISpersion of simulated COrium (KIT experimental facility to study airborne contamination/corium dispersion, using inert powders)
- DIVA: *Dispositif incendie ventilation et aérocontamination* (Fire, Ventilation and Airborne Contamination Device, IRSN experimental facility for conducting fire tests in laboratories and factories or in a pressurized water reactor)
- DNB: Departure from Nucleate Boiling
- DRACCAR: *Déformation et renoyage d'un assemblage de crayons de combustible pendant un accident de refroidissement* (Deformation and Reflooding of a Fuel Rod Assembly during a Loss-Of-Coolant Accident, simulation code)
- DRIVER: name of a KIT experimental facility for studying hydrogen risk
- ECO: Experiments on energy CONversion during a steam explosion
- ECOA: *Étude du confinement des ouvrages en béton armé* (Study of Reinforced Concrete Containment Structures, a research project to improve the assessment of containment integrity in pressurized water reactors during a core melt accident)
- ECS: Complementary Safety Evaluation
- EDGAR: name of a CEA experimental facility – study of fuel rod behavior
- ELISA: name of an experimental loop for research into cooling water recirculation under accident conditions
- EMAIC: *Émission de l'argent, de l'indium et du cadmium* (Silver, Indium and Cadmium Emission, a series of tests to study the release of products from Ag-In-Cd control rods during accident transients)
- EMIS: *Émission de produits de fission* (Fission Product Emission, a code for simulating the release of fission products [a forerunner of ELSA])
- ENACCEF: *Enceinte accélération de flamme* (Flame Acceleration Enclosure, an experimental facility run by CNRS/ICARE, Orléans, France)
- ENISTAT: Experimental and Numerical Investigation of Shear wall reinforced concrete buildings under Torsional effects using Advanced Techniques (a European program of experimental and numerical studies)
- EPICUR: *Études physico-chimiques de l'iode confiné sous rayonnement* (Physical and Chemical Studies of Contained Iodine under Radiation, an IRSN facility or research program to validate models of iodine chemistry in the containment of a pressurized water reactor in an accident situation)



EPR: European Pressurized Water Reactor

ERCOSAM-SAMARA: Containment thermal-hydraulics of current and future LWRs for Severe Accident Management (a research program on hydrogen risk)

ESSOR: *Essai orgel* (ORGEL Reactor Test, research reactor at the Ispra Joint Research Centre, Italy)

EVA: *étude du vieillissement des aciers* (Study of the Ageing of Steel)

FABIME: name of a series of tests on thermal fatigue and their test equipment

FALCON: name of a program of analytical tests to study the transfer of radioactive products in reactor systems during a core melt accident

FARO: name of a test program to study interactions between fuel and coolant (steam explosions)

FAT3D: name of a series of tests on thermal fatigue and their test equipment

FDS: Fire Dynamics Simulator

FEBA: Flooding Experiments with Blocked Arrays (experimental program to study fuel rod behavior in a loss-of-coolant accident)

FGD: Fission Gas Dynamics (analytical tests to study reactivity accidents)

FITS: Fully Instrumented Test Series (Sandia National Laboratories experimental facility used to study steam explosion in a reactor)

FLECHT-SEASET: Full-Length Emergency Core Cooling Heat Transfer–Separate Effects tests And System-Effects Tests (experimental program – study of fuel rod behavior in a loss-of-coolant accident)

FLHT: Full Length High Temperature (research program on core temperature rise and core melt in a reactor vessel)

FLIP: *Feux de liquide en interaction avec une paroi* (Interaction of Liquid Fires with a Wall, research program on solvent fires for fuel reprocessing plant safety)

FLUENT: name of a numerical fluid mechanics code

FNR: Fast Neutron Reactor

FP: Fission Products

FP: Framework Program, European Commission

FPCPS: Fuel Pool Cooling and Purification System

FPT: Fission Product Test (acronym associated with the tests run as part of the Phébus-PF program)

GALAXIE: name of an IRSN platform of experimental facilities for research into controlling fire risks in nuclear facilities

GONDOLÉ: name of a research program – swelling of steel under irradiation

GMR: Giant Magnetoresistance

GPS: Global Positioning System

H2-PAR: Hydrogen Passive Autocatalytic Recombiners (test program)

HEPA: High Efficiency Particulate Air

HEVA: *Hélium, vapeur* (Helium, Steam – experimental program)

- HI: Horizontal Induction (tests as part of a study of fission product emission by fuel when its temperature rises)
- HOF: Human and Organizational Factors
- HRO: High Reliability Organizations
- HRP: HALDEN Reactor Project (research aimed at improving nuclear power plant safety)
- HT: High Temperature
- HYCOM: integral large scale experiments on HYdrogen COMbustion for severe accident code validation (European project)
- HYDRA: name of an experimental device on the GALAXIE platform for research into controlling fire risks in nuclear facilities
- HYDRAZIR: research program to study fuel rod behavior in a loss-of-coolant accident
- ICE: *Interaction corium-eau* (Corium-Water Interaction, experimental program)
- IGR: Impulse Graphite Reactor (Russian research reactor – study of reactivity accidents)
- IMPACT: name of an experimental program as part of research and development on the behavior of engineered structures subject to an impact
- INB: *installation nucléaire de base* (Basic Nuclear Installation)
- INCEFA: INcreasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment, European project
- INSAG: International Nuclear Safety Group
- InSa: Interferometric Synthetic aperture radar (technique used in geodesy and remote sensing)
- IRIS 2010: Improving Robustness assessment of structures Impacted by missileS (international benchmarking on the behavior of engineered structures subject to an impact)
- IRMA: *Irradiation matériaux* (IRradiation of MATerials, a CEA experimental facility for studying radiation/material interaction mechanisms)
- IRWST: In-containment Refueling Water System Tank (borated water tank located inside the EPR containment building)
- ISAFES: Interactive Seismic Analysis of Fragilities of Equipment and Structures
- ISIS: name of a software system for analysing the ventilation of a fire and airborne contamination
- ISP: International Standard Problem
- ISR: *ingénieur de sûreté-radioprotection* (Safety and Radiation Protection Engineer)
- ISTP: International Source Term Program
- ITER: International Thermonuclear Experimental Reactor
- IVANA: name of a VUEZ experimental facility used for research into cooling water recirculation in accident conditions
- IVMR: In-Vessel Melt Retention
- IVR: In-Vessel Retention
- KALI H2: name of a CEA experimental facility for studying hydrogen risk

KARISMA: KAshiwazaki-Kariwa Research Initiative for Seismic Margin Assessment (international benchmarking carried out following an earthquake affecting the Kashiwasaki Kariwa nuclear power plant in Japan)

KMS: Russian experimental facility – hydrogen risk

KONVOI: name of a pressurized water reactor of German design

KROTOS: name of a CEA experimental facility for studying the interactions between a molten mixture and a coolant (steam explosions)

LDV: Laser Doppler Velocimetry

LI: Laser Induced Incandescence

LOBI: name of an experimental facility at the Ispra Joint Research Centre, used for studying the thermohydraulic behavior of a nuclear reactor in an accident situation

LOCA: Loss-of-Coolant Accident

LOFT-FP: Loss Of Fluid Tests–Fission Product (research project on core temperature rise and core melt in a reactor vessel due to a loss of coolant)

LS-DYNA: name of a rapid dynamic simulation code for studying structures

LSTF: Large Scale Test Facility (Japanese experimental facility – study of the thermohydraulic behavior of a nuclear reactor in an accident situation)

MAAP: Modular Accident Analysis Program (software [or software system] for the simulation of physical phenomena that occur during a core melt accident in a pressurized water reactor)

MACE: Melt Attack and Coolability Experiments (test program on corium-concrete interaction as part of research into reactor core melt accidents)

MAEVA: *Maquette échange vapeur air* (Steam Air Exchange Model, EDF experimental model for studying on a large scale the behavior of a containment in a loss-of-coolant accident)

MAFFé: name of an oven on the EDF experimental platform used for research into controlling fire risks in nuclear facilities

MANON: name of an experimental loop used for research into cooling water recirculation in accident conditions

MARC: *Masse, amortisseur, raideur, critère* (Weight, Damper, Stiffness, Criterion)

MASCA: name of a test program conducted as part of research into reactor core melt accidents

MC3D: name of a 3D multi-phase thermal hydraulics code for simulating the interaction between molten materials and a coolant

MCCI: Molten Core-Concrete Interaction

MELCOR: name of a software (or software system) for simulating the physical phenomena that occur during a core melt accident in a pressurized water reactor

MFPR: Module for Fission Product Release (code for simulating fission product behavior)

MILONGA: name of an experimental platform developed by EDF for research into controlling fire risks in nuclear facilities

MIRE: *Mitigation des rejets à l'environnement en cas d'accident nucléaire* (Mitigation of Releases into the Environment in the Event of a Nuclear Accident, research program to

study and improve the mitigation of radioactive releases in the event of a reactor core melt accident)

MISS3D: *Modélisation de l'interaction sol-structure en trois dimensions* (3D Modelling of Ground-Structure Interaction, a simulation software)

MISTRA: name of a CEA experimental facility – studies of hydrogen risk

MITHYGÈNE: *Mitigation hydrogène* (Hydrogen Mitigation, improving knowledge of hydrogen risk and how to manage it in a reactor core melt accident)

MIT3BAR: *Évaluation et mitigation du risque de percement de la troisième barrière de confinement des centrales nucléaires* (Assessment and Mitigation of the Risk of Third Containment Barrier Breakthrough at Nuclear Power Plants)

MOCKA: name of a KIT experimental facility – study of corium-concrete interaction in a reactor core melt accident

MOBY DICK: name of a series of analytical tests conducted as part of the study of two-phase thermal hydraulics

MOX: Mixed Oxide Fuel ( $\text{UO}_2 + \text{PuO}_2$ )

MOZART: *Mesure de l'oxydation du zirconium par l'air en température* (Measurement of Zirconium Oxidation by Air at Temperature, a program of analytical tests to study the oxidation of fuel rod cladding in the presence of air)

MPE: Maximum Probable Earthquake

MRBT: Multi-Rod Burst Test (ORNL experimental facility – study of fuel rod behavior)

NORS: NOkia Research Simulator

NPPs: Nuclear Power Plants

NUREG: Nuclear Regulatory Report, U.S.NRC

NUSMOR: NUgenia Small Modular Reactor with passive safety features, European research project

NRU: National Research Universal (Canadian research reactor)

NSRR: Nuclear Safety Research Reactor, Japan

NYX: name of an experimental device on the GALAXIE platform, used for research into controlling fire risks in nuclear facilities

OCC: Outage Control Centers

ODOBA: *Observatoire de durabilité des ouvrages en béton armé* (Monitoring Center for the Durability of Reinforced Concrete Structures, a research project to study the ageing of structures and the pathologies affecting them)

OLHF: OECD Lower Head Failure (research program to study failure of the lower part of a reactor vessel)

OMEGA: name of a series of analytical tests conducted as part of studies of two-phase thermal hydraulics

OSIRIS: name of a CEA research reactor

PACTEL: Parallel Channel Test Loop (Finnish experimental facility for studying the thermohydraulic behavior of a nuclear reactor in an accident situation)

PANDA: name of a PSI experimental facility used for research into hydrogen risk

PARIS: name of an experimental program conducted as part of the study of radioactive iodine behavior in a reactor core melt accident

PASSAM: Passive and Active Systems on Severe Accident source term Mitigation (multi-partner research project on passive and active systems to mitigate releases in a reactor core melt accident)

PATRICIA: name of a research program on reactivity accidents

PBF: Power Burst Facility, INL, USA

PCCV: Prestressed Concrete Containment Vessel (SNL experimental model – assessment of leaks of air and steam through cracks in conditions representative of a reactor containment)

PCMI: Pellet-Cladding Mechanical Interaction

PEARL: name of an IRSN experimental facility for testing debris bed reflooding

PERFECT: name of a European research program – corrosion of stainless steel under stress and under irradiation

PERFORM60: Prediction of the Effects of Radiation FOR Pressure Vessel and in-core Materials using multi-scale Modelling – 60 years foreseen plant lifetime (irradiation European research and development project on metallic components subject to irradiation)

PERFROI: *Étude de la perte de refroidissement* (Loss-of-Coolant Study, an experimental project aimed at filling the gaps in knowledge of reactor core cooling in a loss-of-coolant accident)

PERICLES: name of a series of analytical tests conducted as part of a study of two-phase thermal hydraulics

PGA: Peak Ground Acceleration

PHEBUS: name of a CEA experimental reactor

Phebus-CSD: international research program to study severe fuel degradation, using tests carried out in the PHEBUS reactor

Phebus-FP: international research program to study the behavior of fission products, using tests carried out in the PHEBUS reactor

PHENIX: name of a CEA prototype nuclear power reactor (and experimental reactor), a fast neutron reactor using liquid sodium as a coolant

PICSEL: *Propagation de l'incendie de combustibles solides dans un environnement laboratoires et usines* (Propagation of Solid Fuel Fires in Laboratories and Factories, research programs into fires in electrical cabinets, looking at safety in fuel reprocessing plants)

PIA: *plan d'investissement d'avenir* (Investment in the Future Program)

PIV: Particle Image Velocimetry

PKL: Primärkreislauf (reactor coolant system, German research projects and large-scale test facility for studying the thermohydraulic behavior of a nuclear reactor in an accident situation)

PLUTON: name of an experimental facility on the GALAXIE platform used for research into controlling fire risks in nuclear facilities

- PRELUDE: *Préliminaire sur le renoyage expérimental d'un lit de débris* (Preliminary Study on the Experimental Reflooding of a Debris Bed, an IRSN experimental facility for conducting feasibility studies and qualification studies of the instrumentation used by the PEARL program on reflooding debris beds)
- P2REMICS: name of a simulation code for studying hydrogen risk
- PREMIX: name of a KIT experimental facility for studying steam explosion in a reactor
- PRENOLIN: *Amélioration de la prédiction des effets non linéaires induits par les mouvements sismiques forts* (Better Prediction of Non-Linear Effects Induced by Strong Seismic Motion, benchmarking process)
- PRISME: *Propagation d'un incendie pour des scénarios multi locaux élémentaires* (Spread of a Fire for Multi-Room Elementary Scenarios, international research program)
- PROGRES: *Program expérimental analytique sur le renoyage de lits de débris* (Analytical Experimental Program on Debris Bed Reflooding)
- PROMETRA: *Propriétés mécaniques en transitoire* (Mechanical Properties in a Transient, research program to study the mechanical behavior of fuel cladding in a reactivity accident)
- PSB-VVER: Russian experimental facility used to study the thermohydraulic behavior of a nuclear reactor in an accident situation
- PSA: Probabilistic Safety Assessments
- PTR: *système de traitement et refroidissement de l'eau des piscines* (FPCPS water tank)
- PWR: Pressurized Water Reactor
- QUENCH: name of a KIT experimental facility used for integral core reflooding tests
- RADIOSS: name of a fast dynamic code for analysing structures
- RASPLAV: name of a test program run as part of research into reactor core melt accidents
- RB: Reactor Building
- RCC-G: *règles de conception et de construction des ouvrages de génie civil* (Rules on the Design and Construction of Civil Engineering Structures)
- RCC-M: *règles de conception et de construction des matériels métalliques* (Rules on the Design and Construction of Metallic Equipment)
- RCCV: Reinforced Concrete Containment Vessel (SNL experimental model – assessment of leaks of air and steam through cracks in conditions representative of a reactor containment)
- RCS: Reactor Coolant system
- REBEKA: name of a KfK experimental facility (Germany) – study of fuel rod behavior in a LOCA
- RECI: *Recombineur et iode* (Recombiner and Iodine, tests to quantify experimentally the conversion rate of metal iodides into iodine on the basis of temperature)
- REKO: name of a KfJ experimental facility – study of hydrogen risk
- REPASS: Reliability Evaluation of Passive Safety Systems (European research project)
- RESOH: *Recherche en sûreté, organisation et hommes* (Research on Safety, Organization and Humans, a chair devoted to safety management in hazardous industries, particularly nuclear)

RG: Regulatory guide, USA

RHRS: Residual Heat Removal System

RIA: Reactivity Injection Accident

RJH: *réacteur Jules Horowitz* (Jules Horowitz Reactor, France)

ROSA: Rig Of Safety Assessment (research projects to study the thermohydraulic behavior of a nuclear reactor in an accident situation)

ROSCO: name of a series of analytical tests to study two-phase thermal hydraulics

RSE-M: *règles de surveillance en exploitation des matériels mécaniques* (Rules for the Monitoring of Mechanical Equipment in Operation)

RSNR: *Recherche en matière de sûreté nucléaire et de radioprotection* (Research Projects in the Field of Nuclear Safety and Radiation Protection)

RT: Release of Transuranics

RTF: Radioiodine Test Facility (AECL experimental facility – study of radioactive iodine behavior in a reactor containment during a core melt accident)

RUT: name of a Russian experimental facility – study of hydrogen risk

RWST: Refueling Water Storage Tank

SAFEST: Severe Accident Facilities for European Safety Targets

SARNET: Severe Accident Research NETWORK of excellence (international network of excellence on core melt accidents)

SATURNE: name of an experimental facility on the GALAXIE platform used for research into controlling fire risks in nuclear facilities

SCANAIR: *Système de codes pour l'analyse d'accidents d'insertion de réactivité* (System of Simulation Software for Analysing Reactivity Injection Accidents)

SCARABEE: name of a CEA research reactor (used for studying accident situations in FNRs)

SEFLEX: (Fuel Rod) Simulator Effects in Flooding Experiments (experimental program to study fuel rod behavior in a LOCA)

SERENA: Steam Explosion RESolution for Nuclear Applications (research program to study and develop simulation tools for steam explosion)

SETH: SESAR THERmalhydraulics (international research program on hydrogen risk)

SFD: Severe Fuel Damage (experimental program on core temperature rise and core melt inside a reactor vessel)

SFP: Spent Fuel Pool

SFR: Sodium-cooled Fast neutron Reactors

SG: Steam Generator

SIGMA: Seismic Ground Motion Assessment (research and development program)

SILOE: name of a CEA research reactor

SIMIBE: name of tests conducted on leaks through a crack in a reactor containment

SINAPS@: *Séisme et installations nucléaires, améliorer et pérenniser la sûreté* (Earthquakes and Nuclear Facilities, Improving and Protecting Safety, a research project on seismic hazards and the vulnerability of nuclear components and structures)

- SIROCCO: name of an oven on the GALAXIE platform, used for characterizing malfunctions of electrical equipment subjected to thermal stress
- SIS: Safety Injection System
- SMA: Seismic Margins Assessment
- SMART: name of an instrumented CEA model used for assessing seismic motion transferred to equipment
- SMD: SUPER MOBY DICK (name of a series of analytical tests conducted as part of the study of two-phase thermal hydraulics)
- SME: Seismic Margin Earthquake
- SMR: Small Modular Reactors
- SNETP: Sustainable Nuclear Energy Technology Platform
- SOA: State-Oriented Approach
- SOAR: State-of-the-Art-Report, OECD/NEA
- SOFIA: *Simulateur d'observation du fonctionnement incidentel et accidentel* (Observation Simulator for Incidental and Accidental Operation, an engineering simulator to improve the nuclear safety of pressurized water reactors)
- SPARK: software for simulating the operation of passive autocatalytic recombiners
- SPERT: Special Power Excursion Reactor Tests (American research reactor used for studying reactivity accidents)
- SPLASH: name of a series of tests on thermal fatigue and their test equipment
- SPOT: name of a Russian experimental facility – study of hydrogen risk
- SSI: Soil-Structure Interaction
- SSG: Specific Safety Guide, IAEA
- SSWICS: Small Scale Water Ingression and Crust Strength (ANL experimental platform for research into reactor vessel failure and basemat erosion due to corium)
- STARMANIA: name of an IRSN experimental facility for conducting research into controlling fire risk in nuclear facilities
- STEM: Source Term Evaluation and Mitigation (research program on the behavior of radioactive products likely to be released into the environment during a core melt accident)
- STORM: name of an Ispra Joint Research Centre experimental facility used for studying the transfer of radioactive products into reactor systems in a core melt accident
- STL: *sonde tournante longue* (Long Rotating Probe)
- STT: *sonde tournante transversale* (Transverse Rotating Probe)
- STYX: name of an experimental facility on the GALAXIE platform used for research into controlling fire risks in nuclear facilities
- SUPERCANON: name of a series of analytical tests conducted as part of the study of two-phase thermal hydraulics
- SUPERPHENIX: name of an EDF nuclear power reactor, a fast neutron reactor using liquid sodium as a coolant



SUW: Scale-Urania-Water (Winfrith experimental facility – study of steam explosion in a reactor)

SYLVIA: *Système de logiciels de simulation pour l'étude de la ventilation, de l'incendie et de l'aérocontamination* (Software System for Analysing the Ventilation of a Fire and Airborne Contamination)

TAGCIS: *Trempe en APRP de gaine de combustible à irradiation simulée* (Quench during a LOCA of fuel rod cladding that has undergone simulated irradiation, a research program)

TAGCIR: *Trempe en APRP de gaine de combustible irradiée* (Quench during a LOCA of irradiated fuel rod cladding, a research program)

TAMARIS: *Tables et moyens d'analyses des risques sismiques* (Tables and Means of Analysing Seismic Risks, a CEA experimental platform)

TANDEM: Tsunami in the Atlantic and the English Channel: Definition of the Effects through numerical Modeling

THAI: Thermal-hydraulics, Hydrogen, Aerosols and Iodine (experimental installation of Becker Technologies)

THETIS: name of an experimental program to study fuel rod behavior

THINS: Thermal-hydraulics of Innovative Nuclear Systems (European research project)

TIB: Total Instantaneous Blockage

TMI: Three Mile Island, USA

TMI-2: Reactor 2 at the Three Miles Island NPP, USA

TOFD: Time Of Flight Diffraction

TONUS: name of a simulation code for assessing hydrogen risk in core melt accident conditions

TORPEDO: name of a KIT experimental facility – study of hydrogen risk

TOSQAN: name of an IRSN experimental facility used for simulating the thermohydraulic conditions in a nuclear reactor containment during a core melt accident

TRANSAT: name of a program of analytical tests conducted as part of research into the transfer of radioactive products into reactor systems during a core melt accident

TREPAM: name of an experimental program to study corium-concrete interaction

TRIGA: Training, Research, Isotopes, General Atomics (pool-type research reactor)

TROI: Test for Real Corium Interaction with water (KAERI experimental facility used to study the interaction between fuel and coolant)

TSO: Technical Safety Organization

TUBA: name of a program of analytical tests to study the transfer of radioactive products into reactor systems during a core melt accident

ULPU: An IVR-related full-scale boiling heat transfer facility at University of California, Santa Barbara (a UCSB experimental facility for research on the possibility of retaining the corium in the reactor vessel during a reactor core melt accident)

UMR: *unité mixte de recherche* (Joint Research Unit)

UNGG: *uranium naturel-graphite-gaz* (Natural Uranium-Graphite-Gas, gas-cooled reactor type)

VD: *visite décennale* (Ten-Yearly Outage Program)

VEGA: Verification Experiments of radionuclides Gas/Aerosol release (tests to study the emission of fission products by fuel when its temperature rises)

VERCORS: CEA facility in Grenoble, used to study the release of fission products by irradiated fuel subjected to a temperature increase

VERCORS: *Vérification réaliste du confinement des réacteurs* (Realistic Verification of the Containment of Reactors, an EDF model and a series of tests to assess leaks through a containment in an accident situation)

VERDON: name of the CEA experimental facility that replaced VERCORS in Grenoble

VI: Vertical Induction (tests to study the emission of fission products by fuel when its temperature rises)

VIKTORIA: name of an experimental loop for conducting research into cooling water recirculation in accident conditions

VITRA: name of an experimental loop for conducting research into cooling water recirculation in accident conditions

VULCANO: Versatile UO<sub>2</sub> Laboratory for COrium ANalysis and Observation (CEA experimental facility for research into reactor vessel failure and basemat erosion due to corium in a reactor core melt accident)

VVER: *Vodo-Vodianoï Energeticheski Reaktor* (Russian water-cooled, water moderated nuclear power reactor)

VWU: VULCANO Water-Uranium

WUMT: tests to study steam explosion in a reactor

XRD: X-Ray Diffraction



# Foreword

---

This summary on the current state of research in the field of pressurized water reactor safety is a collective effort by a team of authors from IRSN, the French national Institute for Radiological Protection and Nuclear Safety. Jean Couturier and Michel Schwarz (retired from IRSN) are the main authors.

Jean Couturier was responsible for coordinating the project.

The following authors contributed to the work:

- Chapter 5: Sébastien Roubaud, Caroline Lavarenne, Jean-Marie Mattei,
- Chapter 7: Laurence Rigollet,
- Chapter 8: Oona Scotti, Christophe Clément, Maria Lancieri, Céline Gelis,
- Chapter 9: Didier Jacquemain, Ahmed Bentaib,
- Chapter 10: Georges Nahas, François Tarallo, Gilbert Guilhem, Gérard Cattiaux, Benoît Durville, Christian Mun, Christine Delaval, Thierry Sollier, Jean-Marc Stelmaszyk,
- Chapter 11: François Jeffroy, Nicolas Dechy, Olivier Chanton, Daniel Tasset, Isabelle Pichancourt.

The following experts were involved in proofreading in their specialist fields: François Barré, Gianni Bruna, Jean-Michel Évrard, Richard Gonzalez, Olivier Loiseau, Daniel Quéniart, Didier Vola.

Georges Goué and Odile Lefèvre prepared the work for publication.