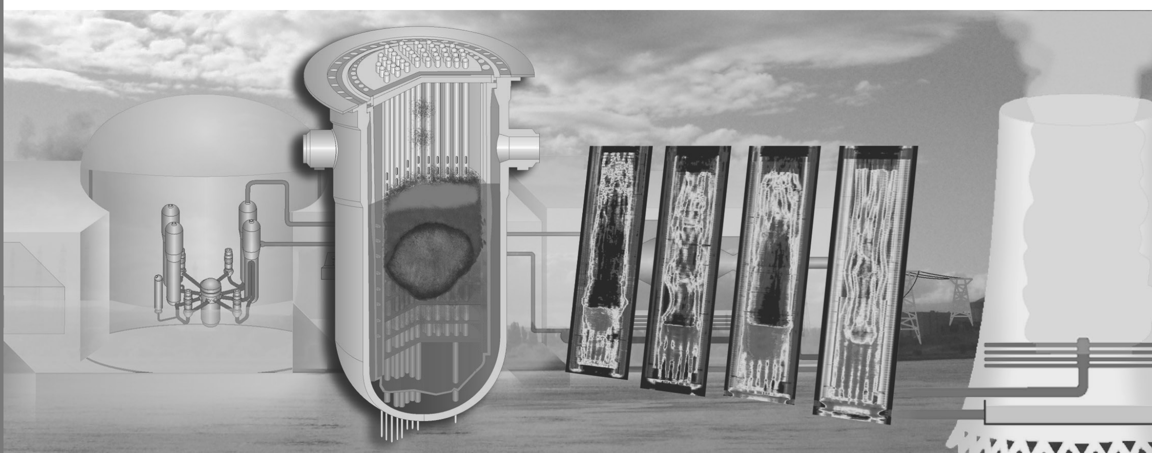
IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

Didier Jacquemain, Coordinator

Nuclear Power Reactor Core Melt Accidents

Current State of Knowledge



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Science and Technology Series

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Cover illustration: Radiographic image of Phebus FP test devices and an artist's impression of the TMI-2 reactor core after fuel melt.

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Preface

This new publication on what are referred to as “severe” core melt accidents, which may occur in pressurised light-water reactors, is the result of one of the most comprehensive surveys ever conducted on this subject. The knowledge it contains is presented with a strong educational focus. I would like to take this opportunity to thank all those mentioned in the foreword who contributed to this vast project, with a special mention for its coordinator D. Jacquemain.

Although the project was not yet completed, considerable headway had already been made when the Fukushima Daiichi disaster struck. This was the world’s third severe accident and resulted in the destruction of three nuclear power reactors and the release of large quantities of radioactive material to the sea and atmosphere. It raised the question as to whether the project should be postponed to take into account feedback from these major events. It was however decided to complete the book as soon as possible as it would be several years before any detailed scientific information from the Fukushima Daiichi accident became available. Furthermore, the knowledge and models already available within IRSN on the phenomenology of this type of accident had enabled the Institute to carry out valuable real-time assessments of changes in the state of the reactors.

For more than thirty years, IRSN has been carrying out experimental studies on the phenomena that lead to reactor core melt and those induced by this type of event. Back in the 1960s when the first nuclear power reactors were designed, a core melt was considered impossible because of the design measures taken to prevent it, such as design margins and redundant safety systems to halt the chain reaction and remove the heat generated in the reactor core. Consequently, no measures were included in reactor design to mitigate the impact of this type of event. This approach had to be rethought following the accident at the Three Mile Island nuclear power plant in the United States in 1979. It was then necessary to determine how fuel could be damaged in a reactor core and, more especially to understand the melting process induced by a loss of cooling that could ultimately lead to failure of the reactor coolant system – and the reactor vessel in particular. The next step was to grasp how chemical or radiolytic reactions could induce a significant release of hydrogen and many fission products exhibiting varying degrees of volatility and toxicity.

An experimental programme unlike any other in the world was then launched using Phebus, a reactor built by the CEA at Cadarache in the south of France. As part of the programme, fuel melt tests were performed on a reduced scale, representative of the actual operating conditions in a pressurised water reactor. New knowledge was to emerge from this impressive programme, including some surprises that called into question certain theoretical predictions. Models aimed at simulating these extreme phenomena in a full-scale reactor were then developed and incorporated in computer tools and validated during these tests.

As knowledge of severe accidents grew over the years, some countries took concrete steps to improve the safety of power reactors – whether existing or planned.

SARNET, an international network of experts and researchers led by IRSN from 2004 to 2013, coordinated continuous improvement of knowledge and the standards of models used to simulate severe accident phenomena in various types of reactor. This collaboration is being continued as part of the European NUGENIA association. Further experiments are needed, however, to reduce uncertainty on various phenomena with a significant impact on the consequences (especially for health) of a severe accident, although, based on data from the Phebus programme, such experiments are now designed as analytical tests, known as separate-effect tests. These are designed to target individual phenomena for which greater knowledge is required: what happens if an attempt is made to "reflood" a severely damaged, partially melted reactor core? What happens to the corium – the chemically and thermally aggressive mixture of fuel and molten metal – once it is released from the reactor core? Another question, of prime importance for radiation protection, concerns the behaviour of the different chemical species of radioactive iodine and ruthenium which are produced in large quantities inside the reactor containment, with varying degrees of volatility.

IRSN and its national and international research partners will continue to devote considerable resources in these areas over the coming years. For the past fifteen years, the Institute has never lost sight of the fact that severe accident research is vital. Unfortunately, the accident at Fukushima proved it right. The knowledge already acquired, as well as that yet to come, should be used not only to go on improving existing reactors wherever possible, but also to ensure that in the future, the nuclear industry at last develops reactors that no longer expose countries opting for nuclear energy to the risk of accidents, and the ensuing radioactive contamination of potentially large areas, that most human societies consider unacceptable. I hope that this publication helps to disseminate existing knowledge on this crucial topic as the new generation of nuclear engineers takes over from the old. I also hope it serves to illustrate how important it is to continue research and industrial innovation, without which no essential progress can be made in the field of nuclear safety.

Jacques Repussard
IRSN Director-General

List of abbreviations

Institutions

AEAT: Atomic Energy Authority Technology, UK (AEC Technology plc)

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

AEKI: Atomic Energy Research Institute, Budapest, Hungary

ANCCLI: *Association nationale des comités et commissions locales d'information* (French National Association of Local Information Commissions and Committees)

ANL: Argonne National Laboratory, USA

ANR: *Agence nationale de la recherche* (National Research Agency, France)

ASN: *Autorité de sûreté nucléaire* (Nuclear Safety Authority, France)

AVN: *Association Vinçotte nucléaire* (Vinçotte Nuclear Association, Belgium)

BARC: Bhabha Atomic Research Centre, India

BNL: Brookhaven National Laboratory, USA

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

CLI: *Commission locale d'information* (French Local Information Commission)

CNL (formerly AECL): Canadian Nuclear Laboratoires

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

CSNI: Committee on the Safety of Nuclear Installations, OECD

EDF: *Électricité de France* (French power utility)

EPRI: Electric Power Research Institute, USA

FAI: Fauske & Associates, Inc., USA

FzD: *Forschungszentrum Dresden-Rossendorf* (research laboratory in Dresden, Germany)

FzK: *Forschungszentrum Karlsruhe* (Karlsruhe Institute of Technology, Germany)

GRS: *Gesellschaft für Anlagen – und Reaktorsicherheit*, (reactor safety organisation in Germany)

IAEA: International Atomic Energy Agency, Vienna, Austria

IAE-NNC-RK: Institute of Atomic Energy – National Nuclear Centre – Republic of Kazakhstan

IBRAE: Nuclear Safety Institute of Russian Academy of Sciences

ICRP: International Commission on Radiological Protection

IKE: *Institut für Kernenergetik und Energiesysteme*, *Universität Stuttgart* (Institute for Nuclear Technology and Energy Systems, University of Stuttgart, Germany)

INEL: Idaho National Engineering Laboratories, Idaho, USA

INL: Idaho National Laboratory, USA

INSA: *Institut national des sciences appliquées* (National Institute of Applied Science, France)

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

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

IRSN: *Institut de radioprotection et de sûreté nucléaire* (Institute for Radiological Protection and Nuclear Safety, France)

ISS: Innovative Systems Software, USA

ISTC: International Science and Technology Centre, EC

JAEA: Japan Atomic Energy Agency

JAERI: Japan Atomic Energy Research Institute

JNES: Japan Nuclear Energy Safety

JRC: Joint Research Centre, EC

JSI: Jozef Stefan Institute, Slovenia

KAERI: Korea Atomic Energy Research Institute, South Korea

KAIST: Korea Advanced Institute of Science and Technology, South Korea

KINS: Korea Institute of Nuclear Safety, South Korea

KIT (ex-FzK): *Karlsruher Institut für Technologie* (Karlsruhe Institute of Technology, Germany)

KTH, see RIT

LUCH: Scientific Manufacturer Centre, Russia

MIT: Massachusetts Institute of Technology, USA

NEA: Nuclear Energy Agency, OECD

NIIAR: Scientific Research Institute of Atomic Reactors, Russia

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

NRC-KI (formerly RRC-KI): National Research Centre Kurchatov Institute, Moscow, Russia

NUPEC: Nuclear Power Engineering Corporation, Japan
OECD: Organisation for Economic Co-operation and Development
ORNL: Oak Ridge National Laboratory, USA
PSI: Paul Scherrer Institute, Switzerland
RIT (formerly KTH): Royal Institute of Technology, Stockholm, Sweden
SKI: Swedish Nuclear Power Inspectorate
SNL: Sandia National Laboratory, USA
UCLA: University of California, Los Angeles, USA
UCSB: University of California, Santa Barbara, USA
UJV: Nuclear Research Institute Rez, Czech Republic
US NRC: United States Nuclear Regulatory Commission, USA
VTT: Technical Research Centre, Finland

Technical abbreviations

Ag-In-Cd: Silver-Indium-Cadmium
AICC: Adiabatic Isochoric Complete Combustion
ARTIST: Aerosol Trapping in a Steam Generator (experimental programme carried out by the Paul Scherrer Institute [PSI])
ATWS: Anticipated Transient Without Scram (automatic reactor shutdown without insertion of control rods or transients with failure of the automatic reactor shutdown system – also known as ATWR for anticipated transient without (reactor) trip)
AVS: Annulus Ventilation System (1300 MWe, 1450 MWe reactors and EPR)
BIP: Behaviour of Iodine Project (international programme on iodine behaviour under the auspices of the OECD)
BL: Electrical Building
BWR: Boiling Water Reactor
CANDU: CANada Deuterium Uranium reactor (a heavy-water reactor)
CCWS: Component Cooling Water System
CFD: Computational Fluid Dynamics
CHF: Critical Heat Flux
CHRS: Containment Heat Removal System (a reactor spraying system in the EPR designed for use in severe accidents)
CODIR-PA: French Post-accident Management Steering Committee
CRP: Coordinated Research Programme on Severe Accident Analysis, IAEA
CSA: Complementary Safety Assessment
CSARP: Cooperative Severe Accident Research Programme (coordinated by the US NRC)
CSD: Severely Degraded Fuel
CSS: Containment Spraying System
CVCS: Chemical and Volume Control System
DAC: Facility construction licence

DCH: Direct Containment Heating (of gases)

DDT: Deflagration-Detonation Transition

E3B: Extension of the third containment barrier

EEE: Containment annulus (1300 MWe, 1450 MWe reactors and EPR)

EFWS: Emergency Feedwater System

ENACEEF: Flame acceleration facility, an experimental installation of the CNRS/ICARE in Orleans, France

EPR: European Pressurised Water Reactor

EPS: Emergency Power Supply

ESWS: Essential Service Water System

ETY: Hydrogen Reduction and Measurement System

FB: Fuel Building

FNR: Fast Neutron Reactor

FP: Fission Products

FP + number: European Commission Framework Programme for research and technological development (e.g., FP6, FP7 for the sixth and seventh framework programmes)

FPCPS: Fuel Pool Cooling and Purification System

FWLB: Feedwater Line Break

GAEC: Assistance Guide for Emergency Response Teams

GCR: Gas-Cooled, Graphite-Moderated Reactor

GIAG: Severe Accident Operating Guidelines

HHSI: High Head Safety Injection

HRA: Human Reliability Analysis

HTR: High Temperature Reactor

IRWST: In-containment Refuelling Water Storage Tank (borated water tank located inside the EPR containment building)

ISP: International Standard Problem

ISTP: International Source Term Programme

LHF: Lower Head Failure (failure in the lower part of the reactor vessel)

LHSI: Low Head Safety Injection (or Low Head Safety Injection System according to context)

LOCA: Loss-of-Coolant Accident

LUHS (H1): Loss of Ultimate Heat Sink (H1 in France)

MCCI: Molten Core-Concrete Interaction

MFWS: Main Feedwater System

MHPE: Maximum Historically Probable Earthquake

MHSI: Medium Head Safety Injection

MOX: Mixed Oxide Fuel (fuel composed of a mixture of UO2 + PuO2)

MPL: Maximum Permissible Level (of radioactivity)

NAB: Nuclear Auxiliary Buildings

OLHF: OECD Lower Head Failure (OECD research programme on failure in the lower part of the reactor vessel)

ORSEC: French emergency response plan

PBMR: Pebble Bed Modular Reactor (a type of high-temperature reactor or HTR)

PDS: Plant Damage State

PHWR: Pressurised Heavy Water Reactor

PPI: Off-site Emergency Plan

PRT: Pressuriser Relief Tank

PSA: Probabilistic Safety Assessment

PUI: On-site Emergency Plan

PWR: Pressurised Water Reactor

RB: Reactor Building

RBMK: *Reactor Bolshoy Moshchnosty Kanalny* (high-power Russian reactor with pressure tubes)

RCS (transients): Transients on the Reactor Coolant System

RCS: Reactor Coolant System

RFS: Basic Safety Rule

RHRS: Residual Heat Removal System

SAB: Safeguard Auxiliary Buildings

SARNET: Severe Accident Research NETwork of excellence, a European research project to study core melt accidents in water reactors

SBO (H3): Station Blackout

SERENA: Steam Explosion REsolution for Nuclear Applications (an OECD research programme)

SG: Steam Generator

SGTR: Steam Generator Tube Rupture

SI: Safety Injection

SIS: Safety Injection System

SLB: Steam Line Break

SME: Seismic Margin Earthquake

SOAR: State-of-the-Art Report

TAM: Equipment hatch

TGT: Thermal Gradient Tube

TGTA-H2: Accident with total loss of steam generator feedwater supply and failure of “feed and bleed” operating mode (or transients on the secondary system)

TMI: Three Mile Island, USA

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

VCI: Pre-service Inspection

VD: Ten-Yearly Outage Programme

V-LOCA: Loss of Coolant Accident (containment bypass accidents or loss-of-coolant accidents outside the containment building)

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

ZPP: Population Protection Zone

ZST: Reinforced Environmental Monitoring Zone

Foreword

This summary of knowledge on core melt accidents is a collective work written for the most part by authors from the *Institut de Radioprotection et de Sûreté Nucléaire* (French Institute for Radiological Protection and Nuclear Safety or IRSN). Some sections include contributions from authors from the *Commissariat à l'énergie atomique et aux énergies alternatives* (French Alternative Energies and Atomic Energy Commission or CEA). Experts from both these organisations and from EDF, a French power utility, also took part in carefully proofreading various chapters. We would like to express our thanks to all those who contributed in one way or another to this publication.

Didier Jacquemain from IRSN, who was the project coordinator.

Contributions were made by the following authors:

- Chapters 1, 2, 3 and 9: Didier Jacquemain;
- Chapter 4: Gérard Cénérino, François Corenwinder, Didier Jacquemain and Emmanuel Raimond from IRSN;
- Chapter 5: Ahmed Bentaïb from IRSN (Section 5.2.2), Hervé Bonneville from IRSN (Section 5.1.4), Bernard Clément from IRSN (Section 5.5), Michel Cranga from IRSN (Sections 5.3, 5.4.2 and 5.4.3), Gérard Ducros from CEA (Section 5.5), Florian Fichot from IRSN (Sections 5.1.1, 5.1.2 and 5.4.1), Christophe Journeau from CEA (Section 5.4.3), Vincent Koundy from IRSN (Section 5.1.3), Daniel Magallon from CEA (Section 5.2.3), Renaud Meignen from IRSN (Sections 5.2.1 and 5.2.3), Jean-Marie Seiler from CEA (Section 5.4.1) and Bruno Tourniaire from CEA (Sections 5.3 and 5.4.2);
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– Chapter 7: Bernard Clément (Section 7.3) and Didier Jacquemain (Sections 7.1 and 7.2);

– Chapter 8: Jean-Pierre Van-Dorsselaere from IRSN.

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Georges Goué, Odile Lefèvre and Sandrine Marano from IRSN prepared the work for publication.

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Tim Haste from IRSN largely contributed to improve the quality of the present English version by proof-reading minutely many chapters.