Chapter 1
Introduction

Preventing accidents liable to affect a nuclear facility and, in keeping with a defense-in-depth approach, mitigating their impact, call for robust methods based on the state of the art, operating experience feedback and regulations, and the demonstration by the licensee that the provisions and measures it implements are effective. This demonstration and its assessment, carried out in France by IRSN as part of its assessment activities[1], draw on a body of scientific knowledge that has grown considerably after nearly forty years of research and the related development work, particularly in the field of simulation codes.

This publication describes the current state of this research and development conducted by IRSN, alone or in collaboration with other organizations, the lessons learned and how they have contributed to safety at French nuclear power reactors and, lastly, the work that is still underway or planned to consolidate and push back the boundaries of knowledge. This summary does not claim to be exhaustive, and some R&D work is only quoted or mentioned briefly at the end of this publication. Also, some of the research discussed here, such as the work on seismic, flooding and fire hazards, is of benefit to all nuclear facilities, not only to nuclear power reactors.

Nuclear reactors are large, complex machines. Many complex physical phenomena interact as an accident unfolds. Studying these phenomena requires knowledge in many fields of physics, including neutronics, heat transfers, fluid mechanics, structural mechanics, metallurgy, radiation chemistry, etc. That being the case, it is clear that the results of experimental research, which is generally carried out at a reduced scale and is simplified to varying degrees, cannot be used directly for demonstration purposes. Physical models

1. Defined in Decrees No. 2002-254 of February 22, 2002 and No. 2016-283 of March 10, 2016.

must therefore be developed, based on academic knowledge or targeted experiments, also called separate effects experiments (see the Focus at the end of this introduction). These models must then be integrated in computer codes used to simulate all the phenomena considered essential for a clear understanding of how the accident unfolds at reactor scale.

More complex experiments simulating real conditions as closely as possible, but carried out at an intermediate scale, also known as integral experiments (see the Focus at the end of this introduction) are conducted to assess the relevance of the calculations performed using these simulation codes. In some cases, the experiments highlight areas where further research is required to supplement and deepen knowledge. Accidents such as those that occurred in reactor 2 of the Three Mile Island nuclear power plant in the United States on March 28, 1979, and in the reactors of the Fukushima Daiichi nuclear power plant in Japan on March 11, 2011, have also provided unique data. Despite gaps due to lack of instrumentation, this data nonetheless helps to assess the performance of simulation codes in terms of their ability to predict how real accidents unfold. The accident that occurred in reactor 4 of the Chernobyl nuclear power plant on April 26, 1986 raised questions as to the suitability of models – and therefore the ability of computer codes – for predicting radioactive release from western nuclear power plants in the event of core melt, as well as the validity of the safety criteria adopted until then for reactivity-initiated accidents.

In spite of the considerable progress made over the past forty years in understanding the phenomena involved, more in-depth knowledge is still required in some areas relating to nuclear safety because of changes in reactor operating conditions, the use of innovative technology, and the search for more accurate scientific approaches, all in an environment of increasingly fierce industrial competition. Assumptions thought to be prudent have often been made at the design stage, sometimes making it necessary to check and determine how conservative they are and what margins they really allow.

Furthermore, the possible occurrence of core melt was taken into account right from the design stage of new-generation reactors, like the European Pressurized water Reactor (EPR), which was not the case for reactors commissioned during the 20th century, even if they did subsequently benefit from improvements aimed at taking this risk into consideration. Consequently, extending the operating life of these reactors beyond forty years cannot be contemplated without a significant improvement in safety, in terms of preventing core melt accidents and mitigating their impact. This heightens the need for research in this area. The complementary safety evaluation (ECS) carried out in the wake of the accident at the Fukushima Daiichi nuclear power plant underscored the need for further research on external hazards that could potentially lead to core melt accidents, the risk and consequences of hydrogen explosions, and radioactive release filtering.

In France, the main organizations involved in nuclear safety research are IRSN, the French Alternative Energies and Atomic Energy Commission (CEA), EDF – French power utility – and, to a lesser degree, AREVA (Framatome before 2006), the designer. Academic research organizations, such as universities, engineering schools and CNRS[2], the

2. French National Center for Scientific Research.

French National Center for Scientific Research, are also involved in promoting a fuller understanding of basic phenomena.

While it is for the licensee to provide the French Nuclear Safety Authority (ASN) with the technical bases used in its safety demonstration, including the related research results, it is essential for IRSN to also carry out its own research. It is this work that allows it to develop and maintain its expertise in complex scientific themes that must be perfectly mastered in order to perform relevant, independent assessments of the licensee's safety demonstrations, and make a positive contribution to advancing safety. IRSN conducts experimental research programs in its laboratories, or has them carried out at partner laboratories (CEA's in particular), benefits from partners' work and, whenever possible, develops its own models and simulation codes. It validates the simulation codes (or has them validated) that are vital to the research work and studies carried out in support of its assessment activities.

The knowledge thus acquired and the developed and validated simulation codes also enable IRSN to provide the public authorities with scientific and technical support in the event of emergency. It was thus able to provide the authorities, general public and media with precise updates on events at the Fukushima Daiichi nuclear power plant following the accident.

Some research allows IRSN to clarify or consolidate its technical examination of topics that could help to significantly enhance safety, in nondestructive testing of reactor systems and components for example.

One specific feature of nuclear safety research is the period of time required before results can be used for assessment purposes. In general, this is relatively long, about ten years, for example, for research involving the use of a nuclear reactor, or requiring the design of a technologically innovative experimental setup. This is due to the complexity of the experimental facilities to be designed and implemented, particularly those that must be installed in nuclear research reactors, and to the time required for post-mortem (or post-test) examinations at specialized laboratories, especially when testing involves the use of radioactive material. It is therefore important to plan ahead to ensure that the required knowledge and simulation codes are available when needed. For licensees and IRSN experts alike, such forward planning is crucial if they are to be ready for major milestones such as reactor safety reviews during periodic outage programs, or examinations of safety conditions for extending the operating life of reactors beyond forty years (EDF's DDF project on "operating life").

With regard to its cost, a great deal of this research – especially experimental programs – is carried out under cooperation agreements between industry and IRSN and its foreign counterparts, with each partner being free to use the results of the research for its own purposes.

IRSN is a partner in more than a dozen projects selected by the French National Research Agency (ANR), notably in the framework of the call for projects "Nuclear Safety and Radiation Protection Research" launched in the wake of the Fukushima Daiichi accident. But the cooperative research is not limited to France. It will be seen later that the main countries that designed and built nuclear power reactors – the United States, Canada, Japan, Germany, the United Kingdom, Switzerland and Russia – carried out research programs on nuclear safety and continue to do so. IRSN receives funding from international partners under various bilateral and multilateral agreements for most of its research programs and, in exchange, has access to the results of foreign programs to which it makes a financial contribution.

The Organization for Economic Co-operation and Development/Nuclear Energy Agency[3] (OECD/NEA) plays a very important role by assisting "*its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes*". It works to achieve a consensus among experts on the current state of knowledge (e.g. State-Of-the-Art Reports [SOAR]), gaps to be filled, and future research priorities. It organizes international benchmark exercises to compare various simulation codes with experimental results (International Standard Problems [ISP]). These exercises always provide a great deal of information. It also helps to structure international research projects – referred to as Joint Projects, proposed by one of its members – by bringing together other partner members to obtain the required funding, and thus advance knowledge in areas where it considers this is necessary. With regard to OECD/NEA activities, IRSN is particularly involved in the work of the Committee on the Safety of Nuclear Installations (CSNI), whose mission is to assist member countries in maintaining and further developing the scientific and technical knowledge base required to assess the safety of nuclear reactors and fuel cycle facilities and, more directly in its various working groups:

- Working Group on Risk Assessment (WGRISK),
- Working Group on Fuel Safety (WGFS),
- Working Group on Analysis and Management of Accidents (WGAMA),
- Working Group on Integrity and Ageing of Components and Structures (WGIAGE),
- Working Group on Human and Organizational Factors (WGHOF),
- Working Group on Fuel Cycle Safety (WGFCS),
- Working Group on External Events (WGEV),
- Working Group on Electrical Power Systems (WGELE).

The European Commission also makes a substantial contribution to the funding of international research and development projects relating to nuclear safety. Calls for projects on what are considered as priority themes are issued in the Euratom part of the multi-year research and development Framework Programs (FP), which began in 1984. These are carried out within a cooperative framework, and generally involve industrial partners, nuclear reactor operators, assessment organizations, and research laboratories.

3. As of January 1, 2015, NEA membership included 31 countries in Europe, North America and the Asia-Pacific region.

It should also be noted that IRSN is involved in European bodies whose task is to steer prestandardization research in various fields (metal structural mechanics, civil engineering, instrumentation and control software).

The European Sustainable Nuclear Energy Technology Platform (SNETP), which brings together representatives from the nuclear industry, research, safety organizations, associations, and NGOs[4], was set up in 2007 to formulate a collective vision of the contribution that nuclear fission could make towards the transition to a low-carbon energy mix by 2050. Within this context, the SNETP has published various documents, including a "Strategic Research Agenda" (January 2009) and a "Strategic Research and Innovation Agenda" (February 2013), which addresses a number of safety issues relating to Generation II and III water reactors, as well as a special document entitled "Identification of Research Areas in Response to the Fukushima Accident" (January 2013). These documents are used to help the European Commission to define its research and development Framework Programs. Note that in 2012, SNETP stakeholders (except for the NGOs) working on Generation II and III reactors joined with other existing organizations or networks (including SARNET (Severe Accident Research NETwork of excellence) for core melt accidents, NULIFE, and ETSON), to form NUGENIA (NUclear GENeration II & III Association), an association under Belgian law. Two publications of this association are worthy of mention: "NUGENIA Roadmap – Challenges & Priorities" (October 2013) and "NUGENIA Global Vision" (April 2015). IRSN is closely involved in both SNETP and NUGENIA.

There now follows an overview of the main safety-related research programs, in particular those carried out by IPSN then IRSN, as well as an outline of the lessons learned from results. The main foreign research programs in the same field are also presented, although by no means exhaustively.

The first chapter of this publication is devoted to research on the design-basis accident taken into account for engineered safety equipment used in pressurized water reactors (PWR), namely a main pipe break in the reactor coolant system (loss-of-coolant accident [LOCA]). The first research programs on nuclear safety, which started in the 1970s, focused on this area with the aim of improving knowledge and developing computer tools for studying this accident.

For each of the research and development themes discussed in this publication – positioned in the "deterministic" safety demonstration in Figure 1.1 on the next page – the safety objectives of the safety demonstration are indicated, together with the issues or difficulties that the demonstration might have raised, or still raises today given the current state of knowledge.

First, a brief description is provided of some of the research instruments favored by IRSN in the field of nuclear power reactor safety and which will be mentioned later in the publication.

As a general rule, it was decided to refer only to a few documents regarded as the most significant, or as having the advantage of providing an overview of the knowledge acquired in some of the areas of interest (e.g. some OECD State-Of-the-Art Reports), and which generally include references to many scientific documents.

4. Non-Governmental Organization.

► Research carried out as part of strategic guidelines and programs

The research themes and topics referred to in this publication concern strategic guidelines and scientific programs aimed at ensuring that first IPSN, then IRSN, has had access to the best available knowledge for their assessments and other activities. These scientific guidelines and programs have, of course, been determined by issues raised during safety analysis, by changes in reactor design, lesson learned from operating experience feedback (from incidents in particular), the accidents that have occurred (TMI, Chernobyl and, more recently Fukushima Daiichi), as well as research results. IRSN's scientific strategy can now be consulted by the public. Pressurized water reactor safety is directly addressed in reference [1], published in October 2015, which considers it in terms of seven "priority scientific issues", including one concerning cross-cutting human and organizational aspects, corresponding to the themes and topics discussed in the present publication.

#FOCUS

Separate-effects or Analytical Experiments *versus* Integral Experiments

Separate-effects experiments are very well-instrumented experiments used for the detailed study of a particular physical phenomenon to precisely determine the physical laws that govern it. The "experimental designs" allow systematic variation of the important physical parameters. For example, the oxidation kinetics of fuel rod cladding is determined by placing a cladding sample in a test section with steam flowing through it inside a controlled temperature oven. The sample is hung from scales and the required information is obtained by measuring the increase in its weight at different temperatures over time.

Integral experiments, on the other hand, are more concerned with reproducing the complexity of the phenomena under study, even if this often means that the measurement of the physical variables is broader and less precise. For example, the damage to a fuel assembly following loss of cooling was studied by irradiating a bundle of 20 fuel rods in the PHEBUS reactor, in a heat-insulated test section with steam flowing through it. The physical phenomena involved are: nuclear fission reactions that cause the fuel to overheat; cladding oxidation beyond a certain temperature, which has the result of consuming steam, releasing hydrogen, and generating heat; and heat transfers in the bundle through conduction, convection and radiation. The phenomena can only be studied by measuring the reactor power, the flow of steam passing through the test section, local temperatures in the fuel and the test section, as well as total hydrogen production.

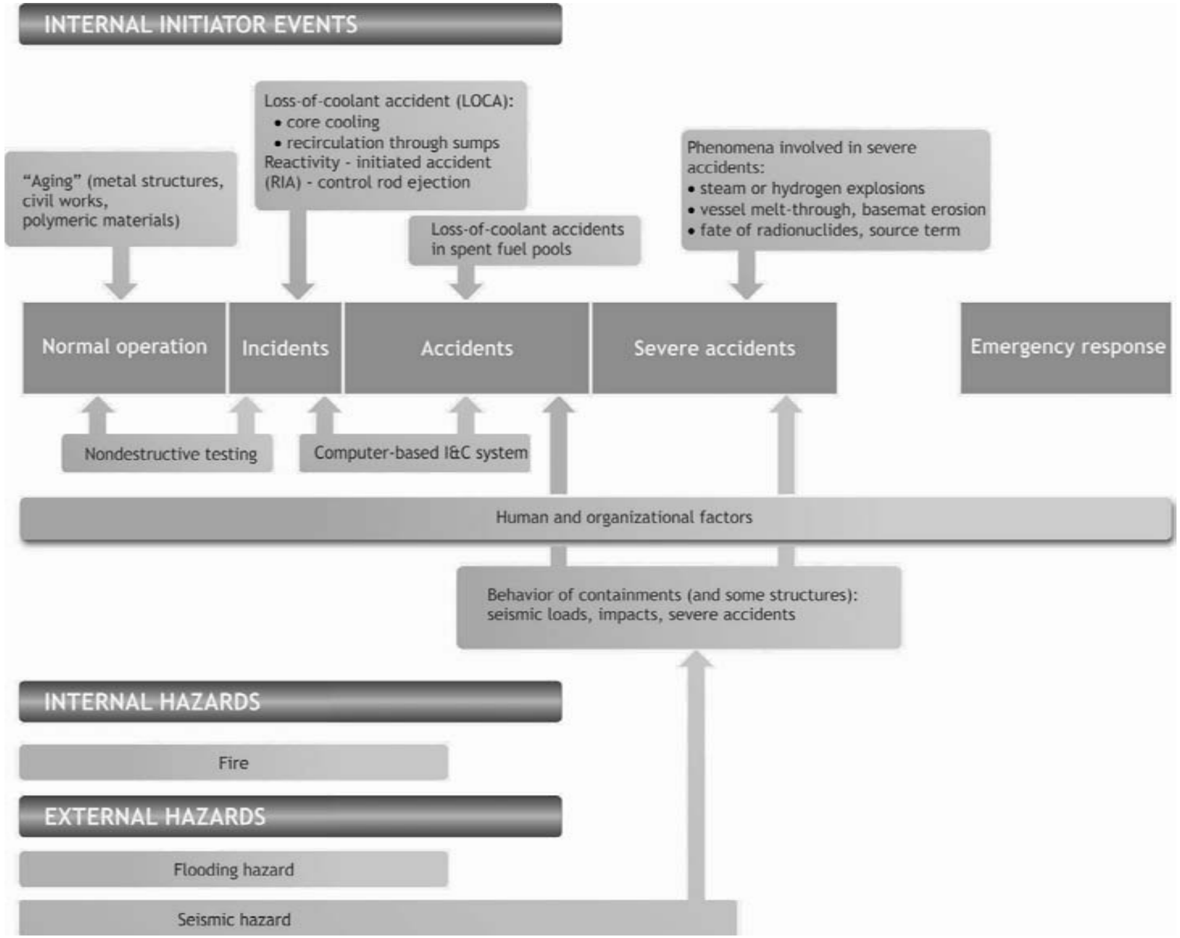

Figure 1.1 Research and development themes discussed (or simply mentioned) in this publication. © Georges Goué/IRSN.

Reference

[1] *La stratégie scientifique de l'IRSN*, October 2015: http://www.irsn.fr/FR/IRSN/presentation/Documents/IRSN_Strategie-scientifique_2015.pdf