Chapter 1
Introduction

1.1. General objectives of the book

The operation of nuclear power reactors utilising nuclear fission involves risks of possible radioactive substance dispersion and human and environmental exposure to radiation. In order to mitigate these risks, the nuclear industry attaches the greatest importance to the safety of its facilities. The nuclear facilities are therefore designed, constructed and used in such a way as to prevent potential abnormal and emergency situations and limit their consequences. Furthermore, measures are taken to continuously improve the facilities' level of safety by acting upon feedback on their design and operation, periodically reassessing their safety and integrating advances in scientific knowledge and the applicable techniques.

Despite all the measures taken, however, the possibility of an accident resulting in partial or complete melting of the nuclear fuel contained in the reactor core and, over the relatively long term, large quantities of radioactive substances being released into the environment cannot be excluded, as the Fukushima Daiichi accident in Japan in March 2011 has shown. Studying this type of accident, which is commonly classified as a "severe accident", is an important element of the safety approach adopted for nuclear fission power reactors. It is done with the aim of setting up suitable measures to reduce the probability of such an accident and, should one nevertheless occur, to mitigate its impact upon populations and the environment. All stakeholders in the nuclear industry have conducted considerable research in France and worldwide with the aim of achieving this objective and so improving the equipment and procedures of the reactors currently in operation.

The objective of this book is to present the scientific aspects of core melt accidents, and notably the knowledge acquired through the research carried out over the course of the last thirty years in order to understand and model the physical phenomena that can occur in such an accident. It is intended for any reader wishing to obtain an overview of the knowledge acquired, any remaining gaps and uncertainties, and past and present research in the field of core melt accidents.

It therefore reviews the current state of knowledge and prospects regarding research in the field, little more than thirty years after the Three Mile Island (TMI) accident in the United States which resulted in the partial melting of the core but fortunately caused very minor radioactive releases, nearly four years after the Fukushima Daiichi accident which resulted in a core melt in three reactors and major radioactive releases, and during the construction of the first third-generation pressurised water reactors (PWRs) in France; in the case of these reactors, core melt accidents are being addressed at the design stage.

The preliminary lessons learned from the Fukushima Daiichi accident do not seem to fundamentally challenge the existing state of knowledge regarding the phenomenology of core melt accidents or highlight new, hitherto unknown phenomena. Four years after the accident, however, the full sequence of events is still not exactly known. Feedback from the TMI accident, in which the damage to the reactor core could only be seen when the damaged reactor pressure vessel was opened around seven years after the accident, leads us to suppose that it will take several years to reconstruct the detailed scenario of the accident that caused the radioactive releases. As long as the cores of the three damaged reactors remain inaccessible, the available data will be too limited to allow the progression of the damage to be reconstructed. It therefore seems too early to present any lessons learned from the Fukushima accident regarding the phenomenology of nuclear core melt accidents at this stage[1].

It should be noted that although the physical phenomena described in this book can occur in different models of French or foreign pressurised water reactors currently in operation or under study as well as widely in the boiling water reactors such as those at the Fukushima Daiichi site, this book focuses more specifically on the reactors currently in operation and under construction or planned in France: the second-generation 900, 1300 and 1450 MWe pressurised water reactors and third-generation 1600 MWe European Pressurised Water Reactors (EPRs).

1. Following the Fukushima Daiichi accident, the consequences of external hazards such as flooding and earthquakes have been assessed in greater detail with a view to preventing and mitigating the effects of a core melt accident. In France, the Prime Minister asked the President of the French Nuclear Safety Authority (ASN) to conduct a safety audit of the French nuclear facilities in 2011, giving priority to the power reactors, regarding the following five points: the flooding risks, the seismic risks, the loss of electrical power, the loss of the heat sink, and the operational management of accident situations. ASN therefore asked the nuclear facility operators to conduct additional safety assessments on their facilities with the aim of learning the first lessons from the events that occurred at the Fukushima Daiichi nuclear power plant, firstly in order to assess the robustness of the French nuclear facilities in confronting severe external events, and secondly in order to reinforce the existing safety measures to increase their robustness.

1.2. Structure of the book

Following this introduction, which describes the structure of this book and highlights the objectives of R&D on core melt accidents, this book briefly presents the design and operating principles (Chapter 2) and safety principles (Chapter 3) of the reactors currently in operation in France, as well as the main accident scenarios envisaged and studied (Chapter 4). The objective of these chapters is not to provide exhaustive information on these subjects (the reader should refer to the general reference documents listed in the corresponding chapters), but instead to provide the information needed in order to understand, firstly, the general approach adopted in France for preventing and mitigating the consequences of core melt accidents and, secondly, the physical phenomena, studies and analyses described in Chapters 5 to 8.

Chapter 5 is devoted to describing the physical phenomena liable to occur during a core melt accident, in the reactor vessel and the reactor containment. It also presents the sequence of events and the methods for mitigating their impact. For each of the subjects covered, a summary of the physical phenomena involved is followed by a description of the past, present and planned experiments designed to study these phenomena, along with their modelling, the validation of which is based on the test results. The chapter then describes the computer codes that couple all of the models and provide the best current state of knowledge of the phenomena. Lastly, this knowledge is reviewed while taking into account the gaps and uncertainties, and the outlook for the future is presented, notably regarding experimental programmes and the development of modelling and numerical simulation tools.

Section 5.1 provides a detailed description of the sequence of events of a core melt accident in the reactor vessel; it discusses the core damage in the reactor vessel (Section 5.1.1), the behaviour of the corium[2] at the bottom of the reactor vessel (Section 5.1.2), the reactor vessel failure (Section 5.1.3) and high-pressure core melt (Section 5.1.4). Section 5.2 concerns the phenomena that can result in an early[3] failure in the containment, consisting of direct heating of the gases within the containment building (Section 5.2.1), the "hydrogen risk" (Section 5.2.2) and the "steam explosion" risk (Section 5.2.3). Corium erosion of the concrete basemat of the containment building, which is one of the phenomena that can result in the containment failing later[4], is discussed in Section 5.3. Section 5.4 focuses on the phenomenology of corium retention and cooling, both within the reactor vessel by reflooding the reactor coolant system and outside it by reflooding the reactor pit (Section 5.4.1), as well as of the under-water cooling of the corium during the corium-concrete interaction (Section 5.4.2) and of corium spread (Section 5.4.3). Section 5.5 discusses the release and transport of the fission products (FPs). It covers the release of FPs both within the vessel (Section 5.5.2) and outside the vessel (Section 5.5.4), the transport of FPs within the primary and secondary coolant

2. The mixture of melt materials resulting from the degradation of the structures comprising the reactor core (the fuel rods, control rods, spacer grids and plates within the core).
3. The word "early" means within such a very short time that it is not possible to set up measures to limit the spread of the radioactivity in the environment and its potential consequences upon the populations.
4. "Later" is used as the opposite of "early".

systems (Section 5.5.3), the behaviour of the aerosols (Section 5.5.5) and the chemistry of the FPs (Section 5.5.6) within the containment building.

Chapter 6 focuses on the behaviour of the containment enclosures during a core melt accident. After summarising the potential leakage paths of radioactive substances through the different containments in the case of the accidents chosen in the design phase, it presents the studies of the mechanical behaviour of the different containments under the loadings that can result from the hazards linked with the phenomena described in Chapter 5. Chapter 6 also discusses the risks of containment building bypass[5] in a core melt accident situation.

Chapter 7 presents the lessons learned regarding the phenomenology of core melt accidents and the improvement of nuclear reactor safety from:

– the Three Mile Island accident that occurred on 28 March 1979 in the United States;
– the Chernobyl accident that occurred on 26 April 1986 in the Soviet Union's Ukrainian territory;
– the integral simulation testing of core melt accidents in the Phebus FP international research programme, which took place between 1993 and 2004.

For the reasons stated above (Section 1.1), it is too early to draw detailed lessons from the core melt accidents during the Fukushima Daiichi accident; as a result, this book does not contain a specific section on this accident. Further information on this accident is contained in the public report listed as reference document [1], which describes the initial analyses of the accident and its consequences one year after the accident.

Lastly, Chapter 8 presents a review of development and validation efforts regarding the main computer codes dealing with "severe accidents", which draw on and build upon the knowledge mainly acquired through the research programmes: ASTEC, which is jointly developed by IRSN and its German counterpart, GRS (*Gesellschaft fűr Anlagen- und Reaktorsicherheit*), MAAP-4, which is developed by FAI (Fauske & Associates, Inc.) in the United States and used by EDF and by utilities in many other countries, and MELCOR, which is developed by SNL (Sandia National Laboratories) in the United States for the US Nuclear Regulatory Commission (US NRC).

1.3. Objectives and approach of R&D on core melt accidents

1.3.1. Objectives

Analysis of the feedback, which includes an analysis of the incidents and, therefore, of the accidents, must be supplemented by research on safety notably relating to core melt accidents, as this is essential in maintaining and improving the safety of the nuclear reactors currently in operation.

5. An accident in which the containment building is bypassed can result in the direct release of radioactive products into the environment.

Research and studies of core melt accidents will undoubtedly not only provide a better understanding of the conditions under which the accidents occur as well as their sequence of events, but also improve our knowledge of their phenomenology with the aim of developing measures to stop them progressing and limit their effects. The results of this research can therefore be used to develop, on the basis of existing experience and knowledge, simulation tools and models that can predict the accidents' sequence of events and consequences, as these tools are used in the nuclear facilities' safety studies.

The knowledge acquired as a result of this research can also help to develop new concepts for improving safety and thereby reduce the risks and consequences of core melt accidents. This research includes that relating to the "core catcher" developed for the EPR with the aim of limiting the consequences of a core melt accident, which are described in Section 5.4.3.

1.3.2. International R&D

Even before the Three Mile Island accident, which occurred in 1979 in the United States (Section 7.1), probabilistic safety assessments were performed on core melt accidents that occurred in the United States, with the aim of assessing the risks of radioactive releases into the environment and the consequences of these releases upon the populations [2]. At the time, these studies were widely considered to be theoretical.

More advanced research programmes on core melt accidents began at the beginning of the 1980s, following the awareness caused by the Three Mile Island accident, which clearly demonstrated that a nuclear reactor core melt accident was possible. Most of the countries using nuclear reactors (United States, Finland, France, Japan, Germany, Belgium, Canada, South Korea, United Kingdom, Netherlands, Switzerland, Sweden, Russia as well as some central Europe and eastern European countries [Hungary, Czech Republic, Slovakia, Slovenia, Lithuania and Ukraine]) have conducted research programmes in the field of core melt accidents. The Chernobyl accident, which occurred in 1986 in the Ukraine (Section 7.2), has merely underlined the need to continue and extend the research in this field. In general, each of these countries has focused on one or more particular aspects of the issue, as the field is too vast to allow the investigation of all phenomena in any one national programme.

The United States was the first country to conduct major research in the field. The research programmes were directed by the US NRC and based on national laboratories including the Electric Power Research Institute (EPRI), SNL and the Oak Ridge National Laboratory (ORNL) [3].

In France, the first major research programmes on core melt accidents began at the beginning of the 1980s and include the Phebus CSD (severely degraded fuel) programme. Bearing in mind the number of its nuclear power plants, France, like the United States, has developed national or international programmes on almost all subjects relating to core melt accidents. This research is primarily conducted by IRSN, CEA, EDF and AREVA. All these entities either develop or help to develop simulation software and have facilities in which they conduct testing.

Extensive research has been carried out in the field of core melt accidents, involving very considerable human and financial resources as a result of their great complexity, as well as collaboration between nuclear stakeholders, industry groups, research centres and safety authorities, at both the national and the international levels. In France, IRSN, CEA, EDF and AREVA have conducted joint programmes on many subjects and participate in international programmes, including those supported by the European Commission through its Framework Programmes for Research and Development and those conducted under the auspices of the OECD. In particular, IRSN has jointly conducted the Phebus FP integral test programme with CEA from the end of the 1980s onwards, thereby structuring international research efforts regarding core melt accidents (Section 7.3).

As part of the Sixth Framework Programme, a Network of Excellence called SARNET (Severe Accident Research NETwork of excellence) was set up to optimise the use of the available resources and increase the knowledge acquired in Europe regarding core melt accidents, coordinated by IRSN. Between 2004 and 2008, SARNET consisted of around fifty organisations belonging to 19 European Union countries as well as Switzerland. As well as increasing the scientific knowledge acquired regarding core melt accidents, it has also defined new research programmes and set up the resources needed to ensure the sustainability of the knowledge gained and to transfer the knowledge on a wider level. In 2008, operation of the SARNET network ensured the consistency of the current state of knowledge and of the main remaining uncertainties regarding core melt accidents. As a result, the highest-priority areas for improvement have been identified and new research programmes proposed in order to fill in the remaining gaps [4]. The activities of the network, which include the new proposed subjects of research, have continued as part of the Seventh Framework Programme, as the network has now been joined by the US NRC, Canadian Nuclear Laboratories (CNL, formerly AECL) and two South Korean organisations (KINS and KAERI). This book benefits from the scientific consensus reached in this field [4].

Many international collaborative projects have also been set up with the help of the OECD. The work of the OECD Nuclear Energy Agency Committee for the Safety of Nuclear Installations (CSNI) encourages the kick-off and implementation of research programmes intended to reach a consensus regarding scientific and technical issues of joint interest, notably in the field of core melt accidents [5]. Their subjects are chosen as part of its working groups, which identify questions that have not been fully resolved as well as programmes or facilities that could be the subject of international collaborative projects (for example, see reference [6]). Since the OECD does not have its own budget for this type of action, it relies on contributions from participants.

In the field of simulation tools, CSNI has formed expert working groups with the aim of setting up validation matrices; it also organises International Standard Problems (ISPs), which compare the experimental results obtained by teams using different computer software for a given problem, improving the software concerned as a result [7]. Lastly, State-of-the-Art Reports (SOARs) are produced on subjects of joint interest, such as hydrogen distribution, hydrogen combustion and aerosol behaviour. These SOARs provide the widest possible view of a given problem by reviewing current knowledge and the remaining uncertainties, and may recommend areas for further research [5].

1.3.3. Approach

The objective of core melt accident research is to produce and collect scientific information that enables us to improve our understanding and description of the physical phenomena that take place when such an accident occurs. The characteristics of these physical phenomena are generally rarely experienced and studied outside the nuclear field. They involve specific materials whose chemistry and interactions are complex and must be studied under extreme temperature — and sometimes, radioactivity — conditions. In addition, the physics of core melt accidents combine the disciplines of energy with those of material physics, as well as those of aerosol physics and of fission product physics and chemistry. Couplings between elementary phenomena involving different technical or scientific disciplines must also be taken into account. These special characteristics complicate both the experimental approach and the theoretical approach.

The experimental approach is further complicated by a particular difficulty: accurately reproducing all or part of an accident transient can rarely be envisaged, both for questions of scale as well as for various technological reasons including the radioactivity of the materials involved, which can only be used experimentally in small quantities. As it is impossible to perform full-scale testing in this field and reproduce all accident situations, elementary tests (so-called "analytical" experiments) aimed at providing a detailed understanding of the elementary phenomena contributing to the situation under study must be conducted instead, and more general tests must be performed to confirm that nothing has been forgotten, considering the many interactions between the different physical phenomena. All this must be done at scales that are compatible with the facilities' technical and economic capacities while also maintaining the highest possible level of representativeness, allowing the acquired knowledge to be extrapolated to the full-scale power reactor — often using qualified models.

These characteristics lead us to choose a research approach that combines the following:

- analytical experiments that study the elementary phenomena while limiting the effects of other phenomena as much as possible within a range of parameters that is representative of can be expected in a core melt accident; the obtained results can be used to develop and qualify the models and determine the associated uncertainties;
- the assembly and coupling of all elementary models within computer codes with predictive capabilities;
- more global experiments intended to simulate as accurately as possible the situations that can be met in a power reactor in an actual accident scenario. These global experiments are used to validate the calculation tools in order to ensure that no important phenomena have been forgotten and the coupling of the phenomena has been modelled correctly. If any unexpected behaviour is noticed, the modelling is reviewed or a new campaign of analytical experiments may even be run. Due to their complexity and their generally high cost, few global tests are performed. As each of the tests involves a set of coupled

phenomena, the results are often difficult to interpret. The Phebus FP programme is a notable example of this type of testing, and its lessons are presented in Section 7.3 of this book.

The computer codes contain the knowledge produced by analysing the experimental data. The transposition of the experimental results to the power reactors is therefore based on these codes. Considering the importance of these computer codes, it is essential to assess their ability to correctly describe the accident. This explains the importance attached to physically qualifying the computer codes.

All of the experimental data used (analytical experiments and global experiments) form the experimental basis of the physical qualification of the computer code. Despite the degree of sophistication presently achieved by the computer codes developed in the field of core melt accidents (Chapter 8), these computer tools all still suffer from many uncertainties that must be carefully considered when used in safety studies. These uncertainties are of two main types:

– those resulting from the simplification of the physical models introduced in the calculation software, the representativeness limits of the software experimental qualification base and the lack of precision in the numerical resolution schemes;
– those resulting from the simplification introduced in the simulation tools used to describe an actual facility.

This somewhat theoretical description should enable the reader to form an idea of how core melt accident research operates. The approach described here will be illustrated in Chapter 5 of this book for each of the phenomena involved.

Reference documents

[1] "Fukushima, one year later – Initial analyses of the accident and its consequences" IRSN/DG report 2012-001, www.irsn.fr, 2012.

[2] N. Rasmussen *et al*., Reactor Safety Study. An Assessment of Accident Risks in US Commercial Nuclear Power Plants, WASH-1400 (NUREG-75/014), Washington DC, US Nuclear Regulatory Commission, 1975.

[3] See the US NRC website containing the NUREG reports on core melt accidents: http://www.nrc.gov/reading-rm/doc-collections/nuregs/.

[4] (a) T. Albiol *et al.*, SARNET: Severe accident research network of excellence, *Progress in Nuclear Energy* **52**, 2-10, 2010.

(b) B. Schwinges *et al.*, Ranking of severe accident research priorities, *Progress in Nuclear Energy* **52**, 11-18, 2010.

(c) W. Klein-Hessling *et al*., Conclusions on severe accident research priorities, *Annals of Nuclear Energy*, available on-line, http://dx.doi.org/10.1016/j.anucene.2014.07.015.

[5] See the OECD/NEA/CSNI website containing the NEA/CSNI reports on core melt accidents: http://www.oecd-nea.org/nsd/docs/.

[6] Nuclear Safety Research in OECD Countries: Support Facilities for Existing and Advanced Reactors (SFEAR), Nuclear Safety, NEA/CSNI/R(2007)6, ISBN 978-92-64-99005-0, 2007.

[7] CSNI International Standard Problems: Brief Description (1975-1999), NEA/CSNI/R(2000)5, 2000.