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Phenomena Identification and Ranking Table

R&D Priorities for Loss-of-Cooling and Loss-of-Coolant Accidents in Spent Nuclear Fuel Pools

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) is responsible for NEA programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

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EXECUTIVE SUMMARY

Following the 2011 accident at the Fukushima Daiichi nuclear power station, the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) launched several activities to help contribute to the post-Fukushima accident decision-making process. Among other deliverables, a status report on spent fuel pools (SFPs) under loss-of-cooling and loss-of-coolant accident conditions [1] was produced in order to summarise the current state of knowledge about such accidents. One of the recommendations given in the report was to produce a Phenomena Identification and Ranking Table (PIRT) in order to systematically identify phenomena that are of both high importance and high uncertainty, and thus of primary interest for further studies. The CSNI endorsed the recommendation and a PIRT was produced from early 2016 to mid-2017 by an international panel of experts consisting of members of the NEA CSNI Working Group on Fuel Safety (WGFS) and Working Group on Analysis and Management of Accidents (WGAMA) as well as invited experts from industry, research organisations and nuclear regulatory bodies. Altogether, 23 organisations from 15 countries were represented in the panel. The resulting "Phenomena Identification and Ranking Table (PIRT) on Spent Fuel Pools under Loss-of-Cooling and Loss-of-Coolant Accident Conditions" report, here presented, is summarised below by chapter.

Chapter 1: Introduction

The main objective of the report is to identify research and development priorities related to loss-of-cooling and loss-of-coolant accidents in spent fuel pools. This is done by applying a PIRT process methodology to identify phenomena that are both of high safety importance and of high uncertainty and therefore deserve further comprehensive analytical and/or experimental studies.

The PIRT process is applied on at-reactor SFPs. The study is generic with regard to reactor and fuel design, it covers boiling water reactor (BWR), pressurised water reactor (PWR), Russian-type pressurised water reactor (VVER) and Canada Deuterium Uranium (CANDU) reactor power plants. Two general types of accidents are studied: a loss-of-coolant accident with fast drainage of the pool water, and a loss-of-cooling accident with slow uncovery of the spent fuel by gradual water evaporation and boil-off. Three separate sub-PIRTs are developed for three consecutive phases of the considered accident scenarios: the pre-uncovery phase, the uncovery phase and the fuel damage phase. This temporal subdivision is made, since the three phases can be dominated by different phenomena.

The study is restricted to phenomena that occur in the spent fuel pool. Phenomena occurring predominantly outside the SFP, e.g. heat and mass transfer in the pool building, are beyond the scope of the study. However, these phenomena are discussed in terms of boundary conditions to the SFP, when they are deemed to be important to the in pool accident progression.

Chapter 2: Expected accident progression and phenomena

The first phase of the accident (the pre-uncovery phase) is dominated by thermal-hydraulic phenomena. Safety issues concern increased release of radiolytic hydrogen, tritium and radioactive contaminants from the pool water as it heats up, and the strong radiation field that would arise if the pool water level dropped to less than about half a metre above the spent fuel assemblies (FAs). Furthermore, the increasing water temperature and decreasing water level in the SFP could make it impossible to recover cooling of the SFP by restarting the normal cooling system, e.g. because of pump cavitation or loss of suction to the intake strainers in the upper part of the pool.

As the accident enters into the second phase, the spent fuel assemblies start to get uncovered. The elevated temperature experienced by the fuel during the uncovery phase will accelerate the exothermic oxidation of the cladding and its creep deformation that reduces the cross-sectional area for coolant flow through the fuel assembly. For high burnup light water reactor (LWR) fuel, fine fragments of the fuel pellets can relocate axially downward within the distending cladding tube, therefore increasing the risk for cladding failure and the amount of ejected fuel material. When the spent FAs get completely uncovered, natural convection by air and radiation are the dominating cooling mechanisms. Analyses suggest that a large-scale flow pattern develops inside the pool building.

During the fuel damage phase of the accident, the phenomena are expected to be similar to those in reactor loss-of-coolant accidents, but since the decay heat is much lower, damage phenomena occurring at relatively low temperature (< 1 200 K) become comparatively more important. Moreover, fuel in an SFP accident may be exposed to air, which speeds up UO_2 fuel degradation and volatilisation of fission products by oxidation, and may increase the release. As damage progresses in the upper part of the fuel assembly, debris may relocate downward and obstruct the axial flow through the fuel assembly. If melting occurs, the molten material will flow downwards and solidify in cooler regions of the fuel assembly. If water remains at the bottom of the pool, hot relocated material may cause a strong steam production and possibly energetic interaction if it drops into water. Uncertainty exists whether the specific decay heat of spent fuel would be sufficient to cause degradation of the concrete floor in the pool. If degradation occurs, the phenomena would be similar to those known for molten corium concrete interaction.

Chapter 3: Methodology

The step-wise procedure applied in the study follows the generally accepted methodology for PIRT development. During the application of the different steps, the international panel of experts have defined the SFP designs (a generic at-reactor SFP of rectangular shape and a length/width/depth of about 12/8/11 m), the spent fuel inventories (two postulated inventories of spent fuel, representing a worst case and a typical heat load of the pool, respectively) and two general accident scenarios that may lead to loss of adequate cooling of the spent fuel in a SFP: sudden loss of pool water inventory (loss-of-coolant accident) and failure of the pool cooling system (loss-of-cooling accident). Since the relative importance of phenomena changes with time as the accident progresses, accident scenarios were partitioned into three temporal phases: the pre-uncovery phase, the uncovery phase and the fuel damage phase leading to three separate sub-PIRTs.

All panellists were asked to identify phenomena that they deemed relevant to each of the three temporal phases of the accident, and propose them for subsequent ranking and inclusion in the three sub-PIRTs. To ensure completeness, this was done in a brainstorming manner and no screening or ranking of the suggested phenomena were attempted at this stage. The study was restricted to phenomena that occur in the spent fuel pool.

Evaluation criteria for the ranking were selected with the aim to address safety issues, while at the same time being generic with regard to fuel and SFP design. The expert panel decided to use the following evaluation criteria: source term (release of radionuclides and hydrogen from the SFP), fuel damage (loss of cladding integrity, loss of geometry, melting), accident progression (timing of events that lead to a new phase of the accident) and water density (important primarily to the sub-criticality margin in the SFP, but also to the operation of SFP cooling systems). In the ranking process, three-level scales were used with regard to the importance level (High, Medium, Low importance) and the knowledge level (Adequate, Some, None) of each phenomenon. The knowledge level was assessed with regard to availability of both data and models.

The importance level and the knowledge level for each phenomenon were determined by averaging the panellists' votes. As a panellist may be an expert in some of the identified phenomena, but less familiar with others, all panel members were invited to consult with other experts in their home organisations and instructed to vote only if they had sufficient knowledge with the phenomenon in question. The panellists were also instructed to focus solely on the importance of the phenomenon relative to the evaluation criteria when casting their votes. Only one vote per participating organisation was accepted, which means that each organisation had to internally agree on a specific vote.

Chapter 4: Results and discussion

The three sub-PIRTs developed for the three phases of the considered accident gather 31 phenomena for the pre-uncovery phase, 38 for the uncovery phase, and 61 for the fuel damage phase. These numbers reflect the complexity of the fuel damage phase in comparison with the early stages of the accident. Based on the PIRTs, the expert panel identified 18 unique phenomena that are of both high importance and low knowledge level, and thus of primary interest for further research. These phenomena are distributed among the three phases of the accident as follows:

Pre-uncovery phase:

- non-uniform natural circulation cooling flow distribution between FAs;
- flow instabilities within the spent FAs at low liquid level;
- multi-dimensional interaction of different temperature zones within the pool;
- radioactive aerosol formation due to bubble breakup processes at the free surface;
- leakage due to pool concrete and liner deterioration and cracking by temperature rise;

Uncovery phase:

- development of two-phase natural circulation in FAs, storage racks and SFP;
- air cooling of the FAs and storage racks after complete pool drainage;
- fuel fragmentation and relocation during ballooning, before cladding rupture;
- cladding oxidation under air and/or (steam+hydrogen)-mixture environment;
- nitrogen-assisted oxide breakaway at low temperature;
- fuel cooling by water spray: water injection above the FAs.

Fuel damage phase:

- stop of natural circulation of air through the FAs by water, injected or sprayed as mitigation measure;
- air cooling of the FAs and storage racks after complete pool drainage;
- coolability of almost completely uncovered FAs, with their bottom ends immersed in water;
- influence of geometry changes during degradation on heat transfer;
- radiative heat transfer from uncovered fuel assemblies to other FAs, racks and SFP structure;
- re-oxidation of ZrN by steam/oxygen;
- fuel volatilisation and behaviour of fuel fines;
- loss of subcriticality due to relocation of absorber materials;
- fuel cooling by water spray: water injection above the fuel assemblies;

In order to assess the consistency of the votes, a dispersion analysis of the results was performed. The analysis showed that there is a significant dispersion in the votes for many of the ranked phenomena. In some cases, the spread may be explained by the phenomenon being design dependent, and that panellists have different views of its importance and level of knowledge, depending on the SFP technology that they are familiar with. In other cases, the dispersion of votes suggests that the phenomenon is poorly known.

In the pre-uncovery phase, the most dispersed phenomena are associated with the pool concrete and liner deterioration. The high relative dispersion is due to disagreement among the panellists regarding both the importance level and the availability of data and models. For the uncovery and fuel damage phases, the criticality-related phenomena are the most dispersed. For the uncovery phase, the dispersion seems to be caused mainly by an inconsistent view on the availability of data among the voters. For the fuel damage phase, the dispersion also includes disagreement on the importance level for some criticality phenomena.

Chapter 5: Conclusions and recommendations

About half of the phenomena identified in Chapter 4 as having priority research needs are related to thermal-hydraulics and heat transfer in the SFP, and they are judged to be important to the coolability of the spent fuel in the considered accident scenarios. Since experimental studies of these phenomena in most cases call for costly large-scale integral tests, it is expected that associated computer models and their supporting databases will evolve slowly. However, another group of phenomena identified as having urgent research needs concern the degradation of the fuel rod cladding tubes by chemical reactions with the mixed steam-air environment. Since these phenomena can be studied experimentally by use of fairly simple separate effect tests, and the results can be used to extend and improve oxidation models used in today's severe accident codes, there is a potential for improving the applicability of these models to SFP accident conditions within a reasonable time and with moderate efforts.

The expert panel also opines that phenomena related to spent fuel emergency cooling by water spray are among those with priority research needs and that the efficiency of spray cooling for mitigating different SFP accidents should be further assessed; see the recommendations below.

Quite a few of the phenomena identified by the expert panel as having priority research needs are currently being investigated in ongoing research projects or will be studied in near-term programmes. Hence, the ranking results reflect the current (early 2017) understanding of involved phenomena and the current perception of their importance. This implies that the PIRTs include only phenomena for which there exists some knowledge base. It also implies that the ranking of certain phenomena will most likely change as the results of new research become available. Hence, it should be recognised that the PIRTs in this report are inevitably based on incomplete information and that they have to be re-evaluated as the knowledge base is extended.

The dispersion of the panellists' votes was used for assessing the confidence of the ranking results for each phenomenon. While most of the phenomena that were identified as having priority research needs were ranked with a high degree of agreement among the panellists, the votes on phenomena that may potentially lead to loss of subcriticality in the SFP were generally extremely dispersed. A plausible reason is that criticality phenomena have a particularly strong dependence on the SFP and storage rack design and/or accident scenario. More design specific and/or scenario specific studies would be needed to produce useful PIRTs for the SFP criticality issues.

Based on the results of the presented study, the following recommendations are given:

- A CSNI state-of-the-art report on SFP loss-of-cooling and loss-of-coolant accidents should be written as the results of ongoing and planned research programmes become available. An appropriate starting time for this activity would be 2020–2022.
- Ongoing separate effect tests that address cladding chemical reactions with mixed steam-air environments should be supported, and it should be ensured that the testing programmes cover all type of fuel cladding present in SFPs and also the low temperature range, which is of interest for many SFP accident scenarios.
- Integral tests at and above the scale of fuel assemblies should be conducted to further investigate thermal-hydraulic and heat transfer phenomena with importance to the coolability of partly or completely uncovered fuel assemblies. The need for such tests is most apparent for CANDU fuel and rack designs, for which the results of recently conducted Sandia tests on LWR fuels and racks do not apply.
- Properly scaled experiments should be carried out to study the thermal-hydraulic behaviour and the large-scale natural circulation flow pattern that evolves in the SFP under the pre-uncovery phase of loss-of-cooling accidents. These experiments are needed, in the first instance for validating 3D models in thermal-hydraulic system codes, and later, for formulating and validating models in computational fluid dynamics codes under development.
- Spray cooling of uncovered spent fuel assemblies in typical storage rack designs should also be experimentally studied. Experiments are needed at and above the scale of fuel assemblies and they should be done with heat loads typical for spent fuel. In a first step, the tests should address the coolability of the fuel, with the aim to generate suitable data for development and/or validation of empirical spray cooling models in severe accident codes and thermal-hydraulic system codes. Later, more detailed experiments are needed, on several length scales, for formulation and validation of mechanistic models for spray cooling.
- Sensitivity and uncertainty analyses should be considered an integral part of computer code applications for SFPs in loss-of-cooling and loss-of-coolant accidents conditions. These analyses should be directed towards submodels and phenomena for which the most substantial uncertainties are known to exist. The results presented in the report provide some general guidance in identifying these phenomena.

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LIST OF ABBREVIATIONS AND ACRONYMS

All acronyms and abbreviations are explained as they first appear in the text. To ease a non-linear reading of the report, the acronyms are also listed below.

BEL V	Technical Safety Organisation of the Belgian Nuclear Safety Authority (Belgium)
BWR	Boiling water reactor
CANDU	Canada Deuterium Uranium (Canadian-type pressure tube heavy water reactor)
CEA	Commissariat à l'Énergie Atomique et aux Énergies Alternatives (France)
CFD	Computational fluid dynamics
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)
CNL	Canadian Nuclear Laboratories (Canada)
CSN	Consejo de Seguridad Nuclear (Spain)
CNSC	Canadian Nuclear Safety Commission (Canada)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
D	Relative dispersion
EDF	Electricité de France (France)
FA	Fuel assembly
FD	Fast drainage
FP	Fission product
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
IAE	Institute of Applied nergy (Japan)
IAEA	International Atomic Energy Agency
IL	Importance level
IRSN	Institut de radioprotection et de sûreté nucléaire (France)
JAEA	Japan Atomic Energy Agency (Japan)
JRC	Joint Research Centre (European Commission)
JSI	Institut Jožef Stefan (Slovenia)
KAERI	Korea Atomic Energy Research Institute (Republic of Korea)
KL	Knowledge level (KL^D for data and KL^M for models)
LOCA	Loss-of-coolant accident
LWR	Light water reactor
MCCI	Molten corium concrete interaction
MNF	Mitsubishi Nuclear Fuel (Japan)
MOX	Mixed oxide; $(U,Pu)O_2$
MTA-EK	Hungarian Academy of Sciences Centre for Energy Research (Hungary)

NEA	Nuclear Energy Agency
NINE	Nuclear and Industrial Engineering S.r.l. (Italy)
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (United States)
NRCKI	National Research Centre Kurchatov Institute (Russia)
OECD	Organisation for Economic Co-operation and Development
PIRT	Phenomena identification and ranking technique/table
PSI	Paul Scherrer Institut (Switzerland)
PWR	Pressurised water reactor
QT	Quantum Technologies AB (Sweden)
R	Relative relevance
SA	Severe accident
SD	Slow drainage
SFP	Spent fuel pool
UJV	UJV Rez a.s. (Czech Republic)
VVER	Russian-type pressurised water reactor (Vodo-Vodyanoi Energetichesky Reaktor)
WGAMA	Working Group on Analysis and Management of Accidents (NEA/CSNI)
WGFS	Working Group on Fuel Safety (NEA/CSNI)

1. INTRODUCTION

1.1. Background

Spent fuel pools (SFPs) are large accident hardened structures that are used to temporarily store irradiated nuclear fuel. Because of the robustness of the structures, severe accidents involving SFPs are generally regarded as highly improbable events. The safety and security of spent fuel pools are continuously re-assessed as new information becomes available or the operating conditions of the plants or pools change. For example, the terrorist attacks in the United States on 11 September 2001, prompted studies on the vulnerability of spent fuel storage facilities to potential terrorist attacks in many countries [2]. More recently, the Fukushima Daiichi nuclear accident [3] that followed the Tohoku earthquake in Japan on 11 March 2011, has renewed international interest in the safety of spent nuclear fuel stored in SFPs under prolonged loss-of-cooling conditions, although the SFPs and the fuel stored in the pools remained safe during the accident.

The Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) launched several activities to help contribute to the post-Fukushima accident decision making process. Among other things, a status report on spent fuel pools under loss-of-cooling and loss-of-coolant accident conditions [1] was produced in order to summarise the current state of knowledge about such accidents. Past accidents and precursor events were reviewed, in particular the behaviour of the Fukushima Daiichi spent fuel facilities during and after the accident. Important aspects of possible accident scenarios and involved phenomena were addressed, such as the thermal-hydraulic behaviour of the pool, the issue of criticality, the accident progression under partial or complete loss of coolant, the hydrogen production and the fission product release. The report provided a brief assessment of current experimental knowledge about these phenomena. It also reviewed state-of-the-art computer codes used for analyses of SFP accidents, and discussed strengths and weaknesses of models and methods used in these codes.

One of the recommendations given in the status report was to produce a Phenomena Identification and Ranking Table (PIRT) in order to systematically identify phenomena that are both of high importance and high uncertainty, and thus of primary interest for further studies. The overall objective of the PIRT is to guide future experimental and modelling efforts relating to SFP loss-of-cooling and loss-of-coolant accidents in order to reduce uncertainties. The CSNI endorsed the recommendation in December 2014 and approved the development of a PIRT in December 2015. The present report documents the PIRT activity that followed upon this decision.

1.2. Objectives and scope

The main objective of the work in this report is to identify research and development priorities relating to loss-of-cooling and loss-of-coolant accidents in spent fuel pools. This is done by applying a PIRT process methodology to systematically identify phenomena that are both of high safety importance and of high uncertainty, and therefore pose sufficient risk to merit new comprehensive analytical and/or experimental studies.

The study in this report is generic with regard to reactor and fuel design in that it considers accidents in an at-reactor spent fuel pool of typical design. Virtually all reactors at nuclear power plants have some form of at-reactor pool that allows storage of spent fuel after core offload until the residual power is sufficiently low to allow transport of the fuel to intermediate storage, which can be either dry storage or wet storage in an away-from-reactor pool [1]. The at-reactor pool is also used during reactor refuelling operations for temporary storage of fresh and spent fuel assemblies. The reason for considering an at-reactor rather than an away-from-reactor SFP is that the fuel residing in the former has significantly higher decay power. Since the progression rate and severity of a loss-of-cooling/coolant accident relates with the power of the stored fuel, the most challenging accident scenarios are expected in at-reactor storage pools.

More specifically, the study is applicable to at-reactor SFPs in boiling water reactor (BWR), pressurised water reactor (PWR), Russian-type pressurised water reactor (VVER) and Canada Deuterium Uranium (CANDU) reactor power plants. Yet, some of the phenomena dealt with in the report inevitably are design specific. For example, natural (non-enriched) uranium is used in CANDU fuel, which means that there are no criticality concerns in CANDU SFPs. Moreover, contrary to light water reactor (LWR) spent fuel, CANDU spent fuel is stored horizontally and in storage racks that are open to both horizontal and vertical flow. This means that the thermal-hydraulic behaviour differs between CANDU and LWR spent fuel pools, especially when the fuel racks are partially uncovered.

The study covers the behaviour of the generic at-reactor SFP under two general types of accidents, which are here represented by two different postulated accident scenarios: a loss-of-coolant accident with fast drainage of the pool water, and a loss-of-cooling accident with slow uncovery of the spent fuel by gradual water evaporation and boil-off. At the time of the accident, the SFP is assumed to have either of two postulated inventories of spent fuel, representing a worst case and a typical heat load of the pool, respectively.

The study is restricted to phenomena that occur in the spent fuel pool, i.e. thermal-hydraulics, heat transfer and fuel heat up, degradation and damage mechanisms for the fuel and storage racks, release of fission products, hydrogen production, re-criticality, mitigation measures and phenomena anticipated during recovery of normal cooling. Phenomena occurring predominantly outside the SFP, e.g. heat and mass transfer in the pool building, are beyond the scope of this study. However, these phenomena are discussed in terms of boundary conditions to the SFP, when they are deemed to be important to the in pool course of events.

1.3. Procedure

The PIRT is produced by an international panel of experts, representing 23 organisations from 15 countries. The generic nature of the PIRT is reflected in the composition of the panel: the panellists' expertise ranges over various disciplines relating to phenomena expected in the considered SFP accidents, and also over the different power plant designs covered by the study.

Separate PIRTs are produced for three consecutive phases of the considered accident scenarios: the pre-uncovery phase, the uncovery phase and the fuel damage phase. This temporal subdivision is made, since the three phases are dominated by different phenomena. Phenomena in each phase are ranked with regard to importance and current (June 2017) state of knowledge. The state of knowledge is assessed using two separate criteria: the availability of relevant experimental data and the availability of adequate computational models. Phenomena that are both of high importance and high uncertainty are identified based on the PIRTs. These phenomena, which are deemed to merit special recognition in future research, are discussed in conjunction with each PIRT and technical justifications are given for why they deserve further study. The discussion addresses the importance as well as the current knowledge base of these high-rank phenomena, with the aim to delineate what kind of experiments and/or model development efforts are needed to bridge existing knowledge gaps.

1.4. Organisation of the report

The outline of the report is as follows:

Chapter 2. is an introduction to SFP accidents and provides a brief description of the anticipated accident progression. Key phenomena involved in the different phases of the accident are described, with the intention to introduce the reader to the subject and to help understand the phenomena listed in the PIRTs.

Chapter 3. presents the methodology used for developing the PIRTs in this report. The considered SFP designs and accident scenarios are defined, and the applied process of identifying and ranking physical phenomena in different phases of the accident is described.

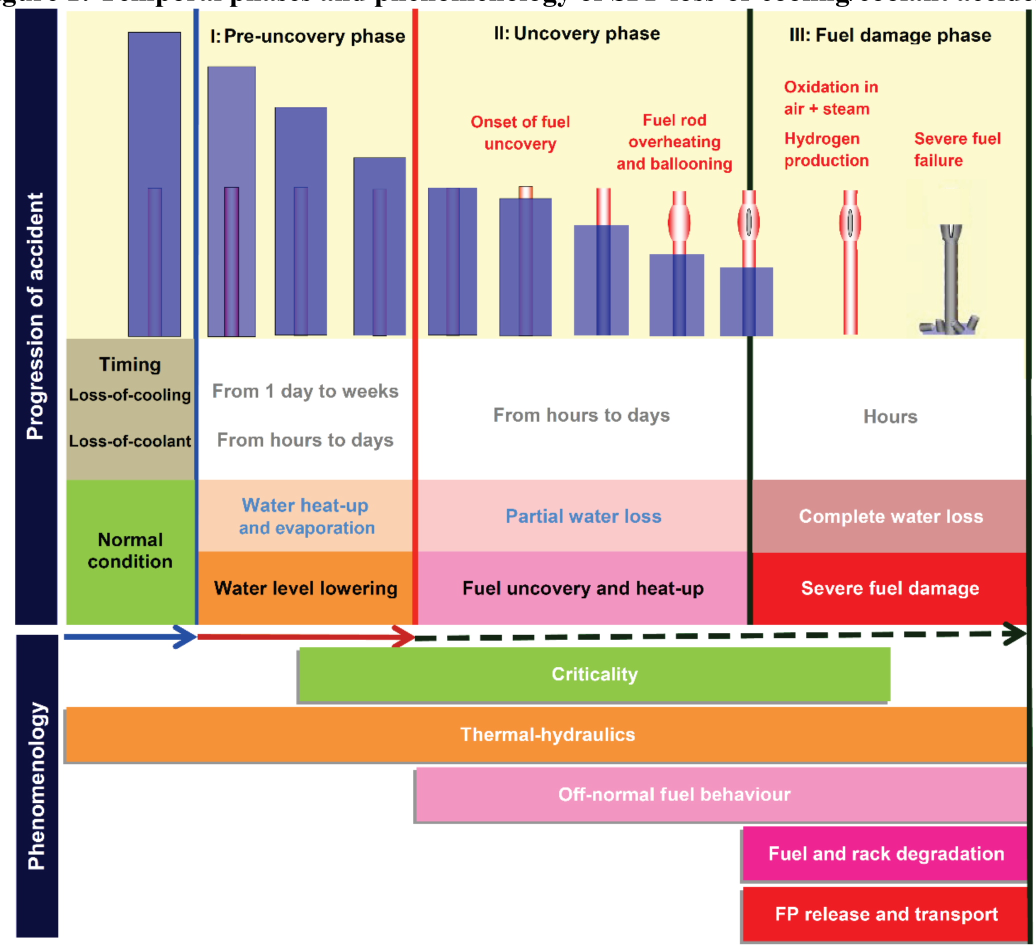
Chapter 4. presents the main results in the form of three PIRTs, corresponding to the three temporal phases of the accidents. Phenomena deemed to be of primary interest for further research are identified and discussed and the dispersion of the panellists' votes are used for assessing the confidence of the results.

Chapter 5. presents the main conclusions of the study and recommendations for future research and activities are given.

2. EXPECTED ACCIDENT PROGRESSION AND PHENOMENA

There are two principal categories of accidents that may lead to loss of adequate cooling of the spent fuel in a spent fuel pool (SFP): malfunction of the pool cooling system (loss-of-cooling accident) and sudden loss of the pool water inventory by leaking (loss-of-coolant accident) [1]. The two types of accidents are similar with regard to involved phenomena, but the progression may be significantly faster for the loss-of-coolant accidents. This is indicated in Figure 1, which schematically illustrates the phenomenology of SFP accidents. Unmitigated accidents are expected to evolve from a single dominant phenomenon in the early stages to a progressively more complex situation with several interdependent phenomena.

Figure 1: Temporal phases and phenomenology of SFP loss-of-cooling/coolant accidents



As indicated in Figure 1, the accidents can be partitioned into three temporal phases, in which different phenomena dominate the course of events. During the first, pre-uncovery, phase, the spent fuel assemblies (FAs) are covered with water and the phenomenology is dominated by the thermal-hydraulics of the SFP. The second phase involves uncovery of the stored fuel, which leads to significant heat up of the

FAs and the storage racks, and possibly also to criticality issues in the SFP by changes of the coolant density/coolant levels. The third phase is dominated by damage and degradation of the spent fuel, storage racks and possibly also other structures in the pool. The duration of each phase depends strongly on the type of accident and on the decay power of the spent fuel, and for the second phase in particular, it also depends on the type and status of the fuel. In the following subsections, the dominant phenomena expected for each phase are briefly described. The presentation is intended to provide the reader with a background and brief explanation to the phenomena included in the PIRTs. For a more thoroughgoing presentation of the phenomena and a review of the current knowledge base, the reader is referred to the NEA/CSNI status report on SFP loss-of-cooling/coolant accidents [1].

2.1. Pre-uncovery phase (Phase I)

The first phase of the accident, whatever the scenario, involves loss of water from the SFP until the spent fuel assemblies start to get uncovered. Since the fuel is immersed in water and effectively cooled, it will not experience any damage or degradation during this phase, leading to release of radioactive fission products, provided that subcriticality is maintained in the pool. Criticality in the SFP would provide an additional source of heat and radiation, and also generate an inventory of short-lived fission products in the fuel that could add to the radioactivity release later in the accident [1]. In addition to the risk for criticality, safety issues for the pre-uncovery phase concern increased release of hydrogen, tritium and radioactive contaminants from the pool water as it heats up, and the strong radiation field that would arise if the pool water level drops to less than about half a metre above the spent fuel assemblies. The loss of the biological shielding function could prevent access to the SFP building and hamper mitigation measures, surveillance and control. Furthermore, the increasing water temperature and decreasing water level in the SFP could make it impossible to recover cooling of the SFP by restarting the normal cooling systems, e.g. because of pump cavitation or loss of suction to the intake strainers in the upper part of the pool.

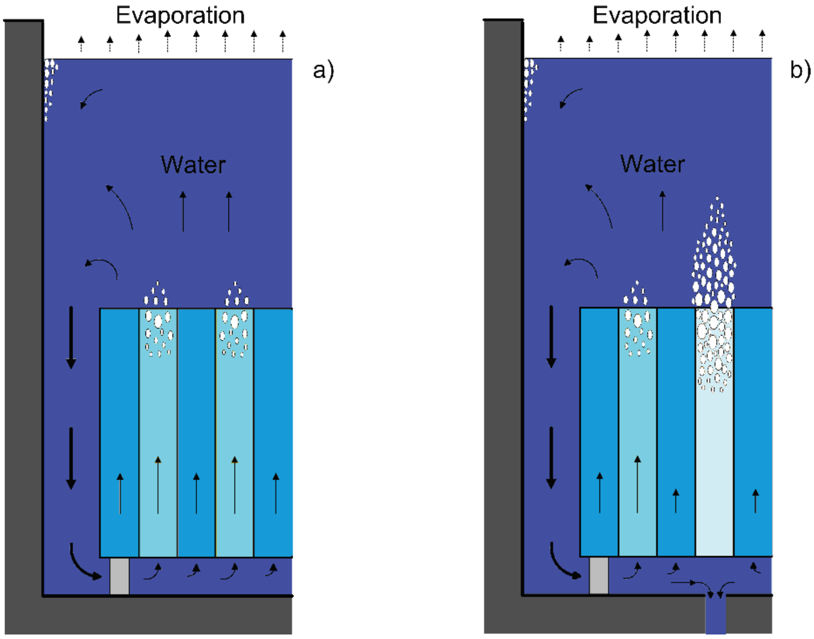
2.1.1. Thermal-hydraulics

By its nature, the pre-uncovery phase is dominated by thermal-hydraulic phenomena. Analyses by use of computational fluid dynamics (CFD) [4-6] show that natural convection loops develop in the pool, as illustrated in Figure 2. Most modern storage rack designs for spent LWR fuel have a closed-cell design, in which each fuel assembly is enclosed in a separate cell with walls made of stainless steel or aluminium, sometimes combined with boron-containing neutron absorbing materials. Since this closed-cell design allows lateral cross-flow only in the regions below and above the racks, the overall shape of the natural convection flow pattern in the pool depends largely on the location of free paths for water to flow downwards and on the distribution of fuel assemblies with regard to their power generation [5, 6]. The power generation stems from radioactive decay of unstable fission products and actinides [7]. The decay heat in a specific fuel assembly depends mainly on its power density at end of life, its burnup and its storage time in the SFP. The dependencies are complex, and the decay heat must be calculated with dedicated computer programs for individual FAs or groups of FAs with similar in-reactor operating life and storage time [8, 9].

As the pool water heats up, the evaporation rate at the pool surface will increase. Evaporation of water from the pool surface is considered the dominating mechanism for heat removal from an SFP with inoperable cooling system, and it increases dramatically with temperature when the water temperature exceeds about 340 K at atmospheric pressure in the SFP building [5, 10, 11]. Several models and correlations are presently available for the evaporation. Among them, the Stefan model, combined with appropriate closure relations for the mass convection within the gas phase, yields accurate predictions of evaporation flow rates for a wide scope of configurations, including those reached during a SFP-LOCA [11]. Measured data on pool temperature and water loss for the SFPs at the Fukushima Daiichi nuclear power station after the 2011 accident have been used for validating the models [10, 12]. The results suggest that bulk boiling does not necessarily occur in an SFP with inoperable cooling system if the heat load is low and the pool building well ventilated, since heat removal by evaporation becomes significant at pool temperatures well below the boiling point. On the other hand, if the building is poorly ventilated and saturated with steam, the boiling point will be reached even for a low heat load. It should also be recognised that the evaporation rate depends on the natural convection heat transfer from the lower part of the pool to the pool surface.

Figure 2: Schematic illustration of thermal-hydraulic conditions expected in the pre-uncovery phase

Fuel assemblies with high decay power and/or water temperature are indicated with brighter colour. In (b), the natural convection loop is locally disturbed by a pool leak, leading to reduced flow, higher water temperature and more extensive boiling in some FAs.



The contribution of boiling mechanisms to the overall SFP loss of mass (in addition to the free-surface evaporation), depends both on the possible vapour bubble nucleation within the pool and on the vapour bubble flow across the pool. Bubble nucleation is possible by different physical processes, each corresponding to specific conditions. One of the most common processes, wall heterogeneous nucleation on heated structures, is likely to occur first in the upper part of high-power FAs. Bulk nucleation processes by homogeneous nucleation (sometimes referred to as bulk or surface boiling) or heterogeneous nucleation (on suspended solid particles or on free-moving non-condensable gas bubbles) are unlikely to contribute significantly to the SFP loss of mass. Homogeneous nucleation would require very large liquid superheats, and heterogeneous nucleation would require high concentrations of suspended particles or non-condensable gas bubbles. Bubble nucleation along unheated solid surfaces (pool walls or immersed solid structures) has to be considered as a possible mechanism of vapour formation, if the local liquid temperature well exceeds the saturation temperature. This condition could be reached nearby the pool surface [5, 6]; see Figure 2.

From a general point of view, the occurrence of nucleate boiling in an SFP depends on the liquid temperature distribution within the pool (and hence, on convective thermal mixing and on power distribution between the FAs) and on local conditions (wall heat flux and wall temperature for heated structures, surface roughness and wettability for unheated structures), as well as on the water content in non-condensable gases, and the pool water level. Quantitative estimates of these processes are required to consider them as significantly contributing to the SFP loss of mass, but corresponding models are not always applicable to SFP conditions and/or require some assumptions on the material properties that are difficult to verify.

If the pool water level is high above the fuel racks, the impact of steam generated by bubble nucleation processes on the SFP loss of mass could be weakened, since bubbles may condense before reaching the pool surface. This is because the hot water that exits from high-power FAs and initiates nucleation processes is mixed with colder water as the fluid rises. When the pool water level approaches the top of the racks, the non-boiling region of the pool will shrink and the void fraction in the upper part of the FAs will increase as a result of lower hydrostatic pressure at that location. It is worth pointing out that, even though bubble nucleation processes do not contribute directly to the SFP loss of mass, they could contribute significantly to the overall heat transfer from FAs to the pool surface, since bubbling is understood as strongly enhancing the convective heat transfer in comparison with single phase natural convection in the pool.

With natural convection in a large number of parallel heated channels that are fed by the same down comer, flow reversal is possible in low-power FAs [13]. This may lead to unstable natural circulation flow [14], and in some channels, the flow could be reduced and the cooling of the FAs perturbed, possibly leading to local nucleate boiling [15]. Another potential reason for local boiling is that the natural convection flow in some FAs is perturbed by outflow of water through a nearby leak, as illustrated in Figure 2b). This scenario would require a concentrated leak at the bottom of the pool, which is unlikely because of the general design principles for SFPs [1].

If it occurs, boiling in the SFP under the pre-uncovery phase could have several potential consequences. Firstly, it would increase the release of hydrogen and radionuclides from the pool water to the building. Hydrogen is produced in the pool mainly by radiolysis of water, and the radiolytic yield of H_2 increases in boiling compared with non-boiling conditions [16]. Moreover, the solubility of hydrogen and other gases in the pool water decreases as the pool heats up, which means that pre-existing gaseous species in dissolution will be released to the building. Radionuclides in the pool stem from activated corrosion products deposited on the spent fuel, leaking fuel rods (if any) and tritium. Any bubble flux breaking through the pool free surface increases the release rate of these contaminants, since aerosols (droplets) are formed when bubbles collapse as they reach the surface. Tritium (^3H) poses a particular problem, since it cannot be removed from the pool water by the normal purification system. In PWR and VVER plants, where boric acid is used for reactivity control in both the reactor and the SFP [17], tritium is formed mainly by ^{10}B neutron capture. It can also be formed in the SFP, but most of the tritium is carried over from the reactor cooling circuit to the pool during refuelling. Since it has a half-life of 12.4 year, the SFP tritium inventory builds up over time.

Secondly, spent fuel pools and their cooling systems are not designed for high temperatures [1]. The cooling system is usually not designed to operate with superheated or boiling water at the intake. In an SFP, water superheat at the intake may result from the change of local hydrostatic pressure experienced by a rising hot water volume. Because of the significant depth of the pool, usually around 10 m, there is a large difference in static pressure between the top and bottom of the pool, which leads to a saturation temperature difference of about 20 K. With superheated water or boiling at the intake, the normal pool cooling system may prove difficult to restart because of pump cavitation and/or loss of suction at the intake strainers. Moreover, damage to the lined concrete structure cannot be precluded if the pool is operated in boiling conditions for some time. The technical safety limit for the SFP water temperature is typically around 65 °C (338 K). This limit is to ensure proper operation of the pool cooling and purification system and to keep the SFP building environment acceptable for the personnel. Thirdly, boiling may lead to loss of subcriticality in case the storage racks are of low density design; see Section 2.1.2 below.

With regard to the water level in the SFP, two critical events can be identified for the accident progression during the pre-uncovery phase. Firstly, when the water level drops below the intake strainers at the top of the pool, suction to the SFP cooling system will be lost and it will be impossible to restart the pool cooling system. Secondly, when the pool water level drops to less than about half a metre above the spent FAs, analyses show that the increased radiation field would prevent access to the spent fuel building [18]. For a loss-of-cooling accident, the time needed for evaporating the pool water down to a certain level depends mainly on the total heat load of the spent fuel, the pre-accident pool water volume and water temperature, possible loss of water through leaks, the atmospheric boundary conditions above the pool free surface, and any corrective actions in terms of make-up water injection or forced cooling. Fairly simple methods can be used for estimating the time to fuel uncovery, but the methods differ with respect to how heat and mass transfer by evaporation is modelled [10-12, 19, 20].

Mitigation measures for the pre-uncovery phase include SFP building ventilation, to evacuate steam and heat, and pool water injection, to make up for the evaporation and leakage.

2.1.2. Criticality

Subcriticality may possibly be lost during the pre-uncovery phase if neutron absorption is lowered by an increase in coolant void fraction and/or a decrease in coolant soluble boron concentration. The coolant void fraction increases by boiling, which may lead to loss of subcriticality in case the storage racks are of low density design, i.e. a design with large pitch between the stored fuel assemblies that make no use of borated structural materials. In this rack design, the water between the FAs provides the main neutron absorption, and a reduction in the effective water density by boiling reduces the subcriticality margin. Computational studies have been performed to assess the criticality margin of SFPs under diverse accident conditions. These studies have focused on scenarios with partially uncovered fuel assemblies or scenarios with reflooding of severely damaged and geometrically distorted fuel assemblies and storage racks [1]. Although these scenarios do not apply directly to the pre-uncovery phase, the results in general suggest that criticality may be reached in undamaged low density storage racks, but only if they contain fresh or low burnup (< 10 MWd/kgU) fuel with high reactivity, and only if the coolant void fraction exceeds about 60 %.

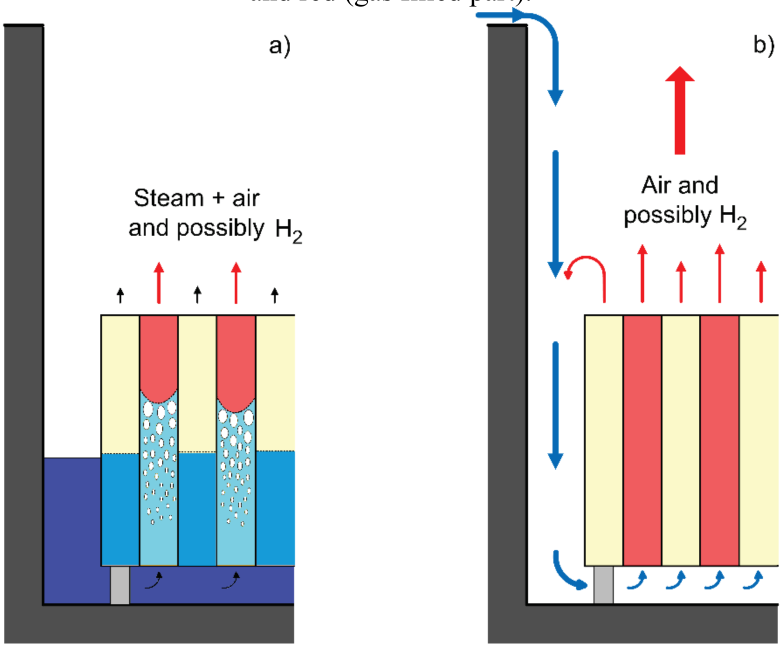
The possible injection of un-borated water into an SFP that normally uses boric acid for criticality control would reduce the subcriticality margin in case the original pool water was lost by leakage. However, in case the pool water has evaporated or boiled off, most of the boron will still remain in the pool and the injection of un-borated water will not substantially reduce the original subcriticality margin [1]. Yet, there is a risk that slugs of injected un-borated water enter the storage racks temporarily, prior to sufficient mixing with the borated water remaining in the pool.

2.2. Uncovery phase (Phase II)

2.2.1. Thermal-hydraulics

As the accident enters into the second phase and the spent fuel assemblies start to get uncovered, it does not necessarily result in immediate heat up of the uncovered part of the fuel: for a fuel assembly with low or moderate decay power, the uncovered part may be cooled by steam flow and water level swell from boiling in the lower part, as long as the water level is not too far below the top of the FA; see Figure 3a). Calculations suggest that cladding peak temperatures in the uncovered part of the fuel assembly may be kept < 800 K even when the collapsed water surface is 1.5–2.0 m below the top of the FA [18, 21, 22]. However, for a fuel assembly with high decay power, or for situations with low water levels, the steam production will not be sufficient to cool the upper part of the FA, and much higher temperatures will be reached. It should also be recognised that the thermal-hydraulic phenomena occurring in the partly uncovered fuel assemblies are complex. The swell level is dependent on the bubble rise velocity inside the closed rack area, on the flow resistance of the spacer grids and on the pitch and the diameter of the fuel rods. Hence, fuel assemblies with identical heat load may have different swell levels, depending on the assembly design.

Figure 3: Partly (a) and completely (b) uncovered fuel assemblies in undamaged state
Fuel assemblies with high decay power are indicated with brighter shades of blue (water filled part) and red (gas filled part).



The steam generation and the water swell in a particular fuel assembly, and hence, the effectiveness of cooling in the uncovered upper part, depend on the extent of boiling below the water surface. This, in turn, depends on the immersed length of the FA and its decay power. As the water level drops, the cladding peak temperature in the uncovered part of an FA increases for two reasons; less steam is produced by boiling in the bottom part, and the steam overheating increases in proportion to the uncovered length. Computational analyses suggest that, for certain water levels, the peak cladding temperature can in fact be *lower* in high-power fuel assemblies than in neighbouring medium-power assemblies, since the former have higher steam production that gives better cooling of the uncovered part [22, 23]. However, there are uncertainties in the predicted temperatures for the uncovered part, as calculated by computational models, mainly because of the complex two-phase flow pattern. At high temperature, heat transfer by radiation in the lateral direction between adjacent FAs and between FAs and the rack structure, as well as heat generation by oxidation of the fuel cladding, add further complexity to the calculations.

When the spent fuel assemblies get completely uncovered and the water level drops below the base plate of the storage racks, natural convection by air is the dominating cooling mechanism; see Figure 3b). Experiments on the behaviour of completely uncovered BWR and PWR fuel assemblies in air have recently been carried out at Sandia National Laboratories in the USA [24-26]. These experiments used electrically heated prototypic FAs in a prototypic storage rack, with the overall objective to provide data for validation of severe accident (SA) computer codes. These codes are originally intended for analyses of reactor accidents, but are now being extended for application to SFP accidents [27]. In earlier computational studies, software developed specifically for the problem [19, 28, 29], as well as general-purpose CFD programmes [23, 30], have been used to analyse the natural circulation airflow in completely drained SFPs and the surrounding building. These analyses suggest that a large scale flow pattern develops inside the pool building: hot air exiting the top of the fuel assemblies forms a plume that rises to the ceiling. It then spreads laterally within a hot layer. If the layer of hot air beneath the ceiling is evacuated by the ventilation system or by opening roof hatches, the air in the building may remain thermally stratified as cool air enters at lower elevation to replace the hot air that exits through the ceiling. The cool air is then drawn into the SFP, where it spreads laterally under the racks and enters the FAs from below. However, if the building ventilation is inadequate, the analyses suggest that the room will gradually heat up and the hot gas layer will ultimately drop into the SFP, hampering the natural convection and resulting in significant fuel heat up. Hence, the aforementioned computational analyses suggest that the boundary conditions related to the design of the SFP building are important for the long-term fuel coolability in air.

With prevalent closed-cell rack designs for storage of spent LWR fuel, the worst possible scenario with regard to fuel coolability is deemed to arise with nearly completely uncovered storage racks, when only the bottom inlets of the rack cells are immersed in non-boiling water [28]. This scenario is considered worse than a situation with a completely drained SFP, in which natural convection of air provide some cooling to the spent fuel. The water will plug the bottom inlets to the storage racks and prevent air circulation, and if non-boiling, the water will emit negligible steam for cooling the uncovered part of the FAs. This worst-case scenario would occur if the SFP is drained through a leak at an elevation corresponding to the rack inlet level. It would also occur transitionally if the leak is below this elevation, and when refilling a completely drained SFP by injecting cold water into the bottom of the pool. In the latter case, natural circulation of air through the FAs would stop as soon as the water level reaches the bottom inlets of the rack cells and fuel temperatures would start to increase.

2.2.2. Thermal-mechanics

The elevated temperature experienced by the fuel during the uncovery phase will accelerate cladding creep and oxidation. Both are time dependent, thermally activated processes, which may lead to loss of cladding integrity. The creep deformation, which is driven by the internal gas overpressure in the fuel rod, will cause the cladding tube to expand in its radial direction. This deformation may ultimately become unstable: if the diameter of the tube increases at any axial position, the local stress is increased due to the larger diameter and the reduced wall thickness, provided that the rod internal pressure does not reduce significantly. This positive feedback enhances the creep rate, which may lead to a local runaway deformation (“ballooning”) that results in cladding creep rupture. However, also in cases with stable and limited creep deformation, the expansion reduces the cross-sectional area for coolant flow through the fuel assembly, increases the cladding surface area exposed to oxidants, and leads to cracking and/or spallation of the protective oxide layer at the cladding outer surface.

At fabrication, fuel rods are commonly pre-pressurised with helium gas. With accumulation of gaseous fission products and helium released from the fuel to the rod free volume during reactor operation and subsequent storage, the internal gas pressure at room temperature may reach as high as 3.5 MPa and 7.5 MPa in spent BWR and PWR/VVER fuel rods, respectively [1]. The magnitude of the end-of-life gas pressure, which varies significantly between fuel rods, will affect the time to cladding creep rupture. When the fuel is overheated in the spent fuel pool, the internal gas pressure will increase in proportion to the absolute temperature. In fuel with very high burnup, the overheating may also cause a burst type release of gas-phase fission products, which further adds to the rod internal overpressure. This kind of fast fission gas release has been observed in UO_2 fuel with a pellet average burnup above 65-70 $MWd(kgU)^{-1}$, when heated to temperatures above about 900 K [31, 32]. It seems to occur by overpressurisation of gas bubbles in the fuel grain boundaries, which are broken concurrently with the gas release [33]. The high burnup fuel is thereby turned into very fine fragments, which can relocate axially downward within the distending cladding tube. The fuel relocation may localise the heat load to “ballooned” parts of the rod, which increases the risk for cladding failure. It may also increase the amount of ejected fuel material, should the cladding fail in the balloon. In summary, the fuel burnup, the temperature distribution in the pellet, and the cladding distension are expected to be the governing parameters for fuel fragmentation, relocation and dispersal [34].

2.2.3. Oxidation of structural materials

The main oxidising agents in the SFP environment are steam, oxygen and nitrogen. These species may oxidise structural materials in the FAs and storage racks, among which zirconium alloys are the most abundant. The following exothermic reactions between the oxidants and zirconium may occur (the released energy per mole oxidised Zr at standard temperature and pressure is indicated):

$$Zr + O_2 \rightarrow ZrO_2 + 1101 \text{ kJ/mol}, \quad (1)$$

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + 528 \text{ kJ/mol}, \quad (2)$$

$$Zr + \tfrac{1}{2}N_2 \rightarrow ZrN + 365 \text{ kJ/mol}. \quad (3)$$

The reactions (2) and (3) are strongly suppressed in presence of oxygen. Under conditions of oxygen starvation, followed by oxygen recovery, additional so-called back reactions will take place:

$$2H_2 + O_2 \rightarrow 2H_2O + 573 \text{ kJ/mol}^{1}, \quad (4)$$

$$ZrN + O_2 \rightarrow ZrO_2 + \tfrac{1}{2}N_2 + 736 \text{ kJ/mol}. \quad (5)$$

In the presence of steam and under oxygen starved conditions, the zirconium nitride will be oxidised by:

$$ZrN + 2H_2O \rightarrow ZrO_2 + \tfrac{1}{2}N_2 + 2H_2 + 163 \text{ kJ/mol}. \quad (6)$$

In principle, all six reactions will take place in parallel, according to the availability (partial pressure) of the oxidants and according to their temperature dependent reaction rates. The oxidation rates depend not only on temperature and pressure, but also on interaction between species. For example, experiments show that oxidation rates in air-steam and nitrogen steam mixtures are higher than in single-gas environments, and that reaction (3) is slow with pure zirconium, but comparatively rapid with sub-stoichiometric zirconium oxide and with oxygen-stabilised α-zirconium. The formation of ZrN increases the porosity of the oxidised layer, which therefore loses its protectiveness [35]. The oxidation processes in gas mixtures are thus complex, and there is a paucity of experimental data for steam-air mixtures [1]. Moreover, the chemical environment in a partly uncovered fuel assembly at high temperature is expected to be complex: steam will dominate close to the water, but as the rising steam reacts with the zirconium metal, the steam gradually becomes starved of oxygen. The uppermost part of the FA may therefore contain a mixture of steam, hydrogen and air. The environment is more complex than for a completely uncovered fuel assembly, and the risks involved with hydrogen production must be considered.

During long-term oxidation in steam at temperatures below 1 300 K, the oxide layer formed on zirconium alloy cladding materials is known to break when it reaches a certain thickness [36]. This so-called breakaway thickness increases strongly with temperature, from about 10 µm at 900 K to 70-100 µm at 1 300 K [37]. The broken oxide layer presents a much weaker barrier to the diffusion of oxygen atoms (from steam or oxygen molecules), and it is known from separate effect tests that the oxide breakaway increases the oxidation rate significantly. No oxide breakaway occurs at temperatures above 1 300 K by oxidation in steam or pure oxygen, but exposure of the oxidising cladding to nitrogen can trigger a breakaway-like behaviour at all temperatures. The reason is that nitrogen penetrates any defect in the oxide scale and forms porous nitrides beneath the oxide and breaks up the overlying oxide, if the oxide is not completely stoichiometric. The zirconium nitride thus formed breaks up the microstructure and increases the porosity, allowing the reacting gases to penetrate more readily, making the process self-perpetuating or even self-enhancing. It should also be remarked that re-oxidation of the nitride, according to equation (6), may occur very rapidly and energetically during reflooding of the nitrided material [38, 39].

[1] This is the energy released per mol O_2.

As indicated by equations (1)–(6), all the oxidation reactions are exothermic. The reaction rates, and thus the rate of heat released in the reactions, increase exponentially with temperature. When the cladding temperature reaches 1100–1200 K, the chemical heat released by the oxidation reactions provides a significant contribution to the total heat load. Temperature feedback effects on the oxidation processes may then initiate a runaway reaction, resulting in a strong temperature escalation and a self-sustained zirconium fire. The aforementioned experiments on electrically heated prototypic BWR and PWR fuel assemblies in air environment at Sandia National Laboratories showed that this runaway reaction started already at a cladding temperature around 1 150 K in FAs with small lateral temperature gradients, but at higher temperature in FAs with large gradients [24-26]. After complete oxidation of metallic materials in the SFP, the chemical heat will be missing and the decay heat of remaining fission products alone will drive the accident further.

2.2.4. Criticality

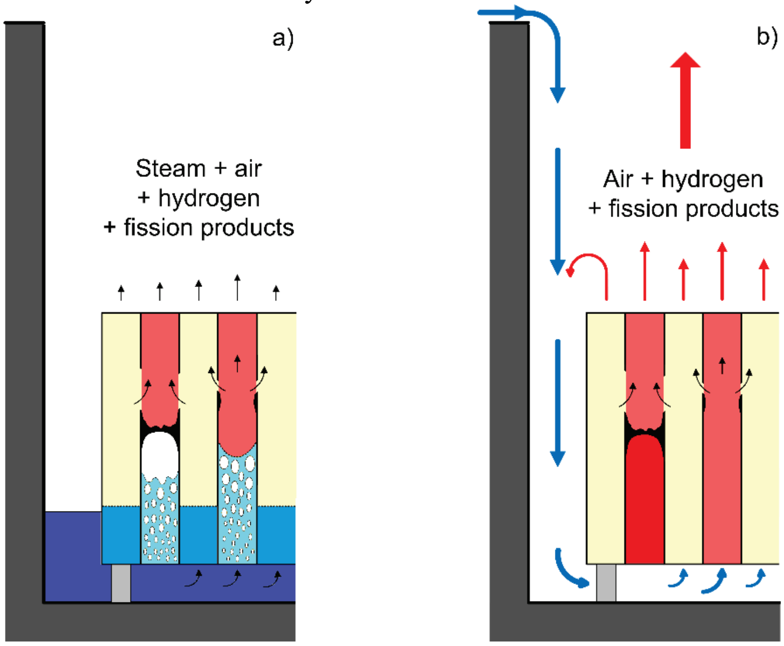
Subcriticality may be lost during the uncovery phase by reduced neutron absorption, either caused by a decrease in coolant soluble boron concentration or by partial loss of the coolant water itself. Hence, the criticality issues for the uncovery phase are principally the same as for the pre-uncovery phase, see Section 2.1.2, but the partially uncovered fuel assemblies pose a particular risk. The reason is that a significant difference in water level may arise between the interior of the stored fuel assemblies, where boiling may occur and non-boiling water outside the storage rack. The water level difference reduces the neutron absorption in the gap between the partly uncovered fuel assemblies, which enhances the neutron coupling between neighbouring FAs [1, 40]. An additional issue is the possibility of early relocation of absorber materials. In certain rack designs, neutron absorbing materials are used in the rack cell walls [1]. Some of these materials are known to degrade at lower temperature than the stored fuel assemblies. For example, the widely used BORAL absorber, which is a laminated composite material with aluminium clad that encloses an inner core of compacted aluminium and boron carbide powders, is expected to melt already at 933 K [41]. If the SFP is reflooded with un-borated water in the time interval between absorber relocation and the loss of structural integrity of the stored FAs, subcriticality may no longer be guaranteed by the rack design.

2.3. Fuel damage phase (Phase III)

The transition point from the uncovery to the fuel damage phase of the accident is somewhat indeterminate. In this report, we define the transition as the time when cladding tube integrity is lost and gaseous fission products are released from the fuel rods (“gap release”). The rod integrity may be lost by cladding creep rupture and/or excessive oxidation. If the accident remains unmitigated, the damage may progress, leading to severe consequences. The damage phenomena are expected to be similar to those in reactor loss-of-coolant accidents (LOCAs) [42], but it should be recognised that the conditions are significantly different in SFP accidents. For example, the decay heat is much lower and neighbouring fuel assemblies may have very different heat loads, depending on their storage time. These factors reduce the heat-up rate, which means that damage phenomena occurring at relatively low temperature (< 1 200 K) become comparatively more important for the SFP accidents. Another important difference is that the fuel assemblies in an SFP accident may be exposed to air. This accelerates zirconium alloy oxidation by nitriding and ensuing breakup of the protective oxide layer [35]. Air also speeds up UO_2 fuel degradation and volatilisation of fission products by oxidation, and may increase the release of otherwise less volatile fission products, e.g. ruthenium, and the fuel matrix itself [43].

Figure 4: Schematic illustration of partly (a) and completely (b) uncovered fuel assemblies in damaged state

Pathways for lateral cross-flow between adjacent fuel assemblies are opened in the damaged racks,while axial flow is obstructed by relocated material in some assemblies.



2.3.1. Thermal-hydraulics

The thermal-hydraulic conditions in the SFP may change considerably during the fuel damage phase. As damage progresses in the upper part of the FA, debris may relocate downward and obstruct the axial flow through the fuel assembly. At the same time, melting and candling of the rack material in the damaged region may open pathways for cross-flow between adjacent rack cells, as illustrated in Figure 4. The flowpaths and thermal-hydraulic conditions in the damaged fuel rack thus become complex and difficult to model in computer simulations. In addition, the exothermic oxidation reactions described in Section 2.2.3 will significantly add to the local heat load in case a zirconium fire breaks out. Axial relocation of oxidising and/or heat emitting radioactive material would also change the heat distribution in the SFP during the fuel damage phase.

2.3.2. Fission product release

When UO_2 fuel is discharged from the reactor at end of life, about 95 % of the spent fuel mass still consists of UO_2. The rest includes fission products (FPs) and transuranium elements, many of them being radioactive. With regard to their release behaviour in reactor accidents, the fission products are usually divided into the following groups [44]:

- *Volatiles*: release of volatiles (Xe, Kr, Cs, I) from the fuel is usually complete before the fuel starts to melt. The release is not significantly influenced by reducing/oxidising (redox) conditions, unless the oxidation leads to structural changes of the fuel matrix.
- *Semi-volatile and low-volatile FPs*: the release rate of semi-volatile FPs (Mo, Rh, Ba, Pa, Tc) and low-volatile FPs (Ru, Ni, Sr, Y, La, Ce, Eu) is very sensitive to the redox conditions.
- *Non-volatile FPs*: negligible release before the fuel melts (Zr, Nd, Pr).

Although Xe and Kr can be released even at low temperature by oxidation of UO_2 fuel in air [45], the main controlling factor for release of volatile fission products is the fuel temperature. Release of volatiles from the SFP during the accident is therefore proportional to the extent of fuel heat up and degradation, i.e. the fraction of fuel exposed to high temperature and the duration of this exposure. The cladding tube has a constraining effect on the release of volatiles, also after the cladding integrity has been lost. Air ingress into the SFP during the accident increases the risk of large release of semi-volatiles and low volatiles like ruthenium, and also increases the risk for significant release of fuel fines.

When the cladding tube loses its integrity, it is generally assumed that the complete inventory of free noble gas (Xe, Kr) in the fuel rod plenum and gap volume is immediately released, the so-called gap release. In fact, some delay in this release is expected in high burnup fuel rods, due to pellet-cladding bonding that obstructs the gas outflow [46]. Certain amounts of volatile iodine and caesium might be released directly upon cladding failure as well. Data from experiments [47] and real accidents with overheated spent fuel [48] suggest that 1–3 % of the total inventory of iodine, caesium and noble gases can be expected to be released directly upon cladding failure. A small amount of solid fuel fragments may also be ejected through the cladding breach [34].

Once the cladding is broken, the fuel pellets may be exposed to air and oxidised in an oxygen-rich atmosphere. Below 450 K, exposure of UO_2 fuel to air is not an issue [49]. However, at a temperature of only 800 K, UO_2 oxidation is particularly fast. Oxygen penetrates rapidly the grain boundaries, converting them to U_3O_8, which occupies about 30 % more volume than the parent UO_2. As a consequence, the grain boundaries split and the grains separate from the matrix. The grains can then be attacked from all sides, continue to oxidise and fragment further. The final particle size, typically with 50 % of the mass in particles less than 10 μm in diameter, can be small enough that the particles (also called fuel fines) become airborne [50]. U_3O_8 is the equilibrium phase in air at 1 400 K. At higher temperatures, fuel fragmentation is less severe, partly because oxidation proceeds more as a front moving through the fuel pellet and partly because U_3O_8 becomes less brittle. Air oxidation above 1 500 K results in UO_3, which is a gas under these conditions [50]. Particles released during fuel volatilisation at relatively low temperature may still contain large fractions of their initial FP inventory, even volatiles.

If the fuel is oxidised to compositions close to U_3O_8, the high oxygen potential permits to oxidise semi-volatile and low-volatile elements that are normally in the metallic state, e.g. Mo, Tc or Ru and eventually makes the formation of complex phases more likely, e.g. $(Ba,Sr)MoO_3$, Cs_2MoO_4, RuO_3, RuO_4 or MoO_2 [43, 51]. These compounds are much more volatile than the elements, so that high release fractions would be expected under strongly oxidising conditions. Also the release of volatile FPs will be enhanced by the formation of U_3O_8, as a result of increased FP diffusivity, and by the structural transformation of the fuel. Additionally, the very high volatility of the matrix itself and fuel fragmentation, as described above, will boost the release of volatile fission products. Otherwise, the influence of redox conditions on volatile FP release is minor. Fission product release experiments in air-rich environments are reviewed in [1].

If the fuel melts, release of volatile fission products from the molten fuel will be (almost) complete. For other fission products, release from the molten fuel is governed by vapourization of species from the melt. The equilibrium vapour pressure above the melt obeys Henry's law [52], and the vapourization rate is thought to be surface limited [53].

Transport of released fission products to the environment above the pool is driven by the bulk flow of gas from the pool. For a partly drained pool as in Figure 4a), the flow would be dominated by steam produced by boiling, whereas for a completely drained pool when the water level drops below the base plate of the storage racks as in Figure 4b), the flow would result from thermal expansion and buoyancy of air that passes through the FAs. In case of a zirconium fire, the flow driven by thermal expansion of gas and its buoyancy may be able to transport large aerosols and fuel fines to the environment. The possibility of retention of released material above the release point in the assembly would be very limited. Fuel fines and larger aerosols might be trapped by turbulent impaction on obstacles, such as spacer grids or upper nozzles. Significant deposition of Ru compounds can also be expected, even on relatively hot surfaces [44]. However, the deposits would probably be re-suspended if the FAs collapse.

Further transport of released FPs to the environment outside the pool building would be different for an SFP located inside the reactor containment than for an SFP in a non-hermetic building or non-isolated (open or failed) containment. In case the SFP is inside the reactor containment, the involved phenomena would be the same as for severe reactor accidents [54]. If the SFP is located in a non-hermetic building, the escape of FPs to the free environment would depend on the design and possible damage to the building. Key parameters are the size and position of openings, and also the free volume of the building; it is known that retention of FPs is more effective in larger buildings [1].

2.3.3. Melting and severe damage

Because of the relatively low heat loads and heating rates involved in SFP loss-of-cooling and loss-of coolant accidents, it is expected that metal in the pool inventory will be oxidised before reaching melting temperatures. However, this will depend on the storage rack design and the stored material. For example, aluminium, with a melting point as low as 930 K, is used in some rack designs as structural material or in combination with boron as neutron absorber [1]. The SFP may also contain spent Ag-In-Cd and B_4C-bearing control rods, which makes eutectic reactions between the absorber material, stainless steel and zirconium alloys possible. These eutectic reactions may lead to liquefaction at lower temperature than 1700K, which is the melting point of austenitic stainless steel [55]. Eutectic reactions are also known to occur between UO_2 fuel, partially oxidised zirconium alloys and stainless steel, potentially leading to large-scale liquefaction at a temperature of 2 500±200 K [56]. It should be remarked that the structural material in the storage racks loses much of its strength well before melting, and that the racks may be unable to maintain the fuel assemblies in their original configuration even though the material is entirely in solid phase.

If melting occurs, the molten material will flow downwards (“candle”) and solidify in cooler regions of the FA. The accompanying loss of support may also lead to relocation of partially degraded cladding and fuel material, and it will open pathways for lateral cross-flow due to failure of the rack. If water remains at the bottom of the pool, hot relocated material may cause a strong steam production and possibly energetic interaction if it drops into the water. If there has been oxygen starvation in the upper regions of the stored FAs, this steam production could cause a strong temperature increase due to renewed oxidation through the reaction described by equation (6); see Section 2.2.3. Finally, uncertainty exists whether the specific decay heat of spent fuel would be sufficient to cause degradation of the concrete floor in the pool [1]. If degradation occurs, the phenomena would be similar to those known for molten corium concrete interaction (MCCI) [42, 57].

2.3.4. Criticality

Computational analyses at hand suggest that criticality may be reached in the SFP as a result of displaced fuel assemblies and/or neutron absorbing material in partly damaged rack structures, if water is present in the pool [1]. If the pool is completely drained, the analyses tend to show that it will remain subcritical. The same is true if the fuel assemblies are damaged to the extent that they have lost their integrity and transformed into rubble [1].

3. METHODOLOGY

3.1. Summary of the Phenomena Identification and Ranking Table procedure

3.1.1. Background and related PIRTs

The Phenomena Identification and Ranking Table (PIRT) process was developed in the late 1980s by the US Nuclear Regulatory Commission (NRC) and its contractors to support the introduction of the best estimate plus uncertainty analysis method as a new licensing option for emergency core cooling systems in the United States [58-60]. More precisely, the PIRT process was aimed to help establish relevant regulatory requirements to be imposed on phenomenological models used in the best-estimate computational tools. In its original form, the process involved systematic identification and ranking of physical phenomena that dominate the response of a reactor system under a postulated accident scenario, based on their influence on safety criteria.

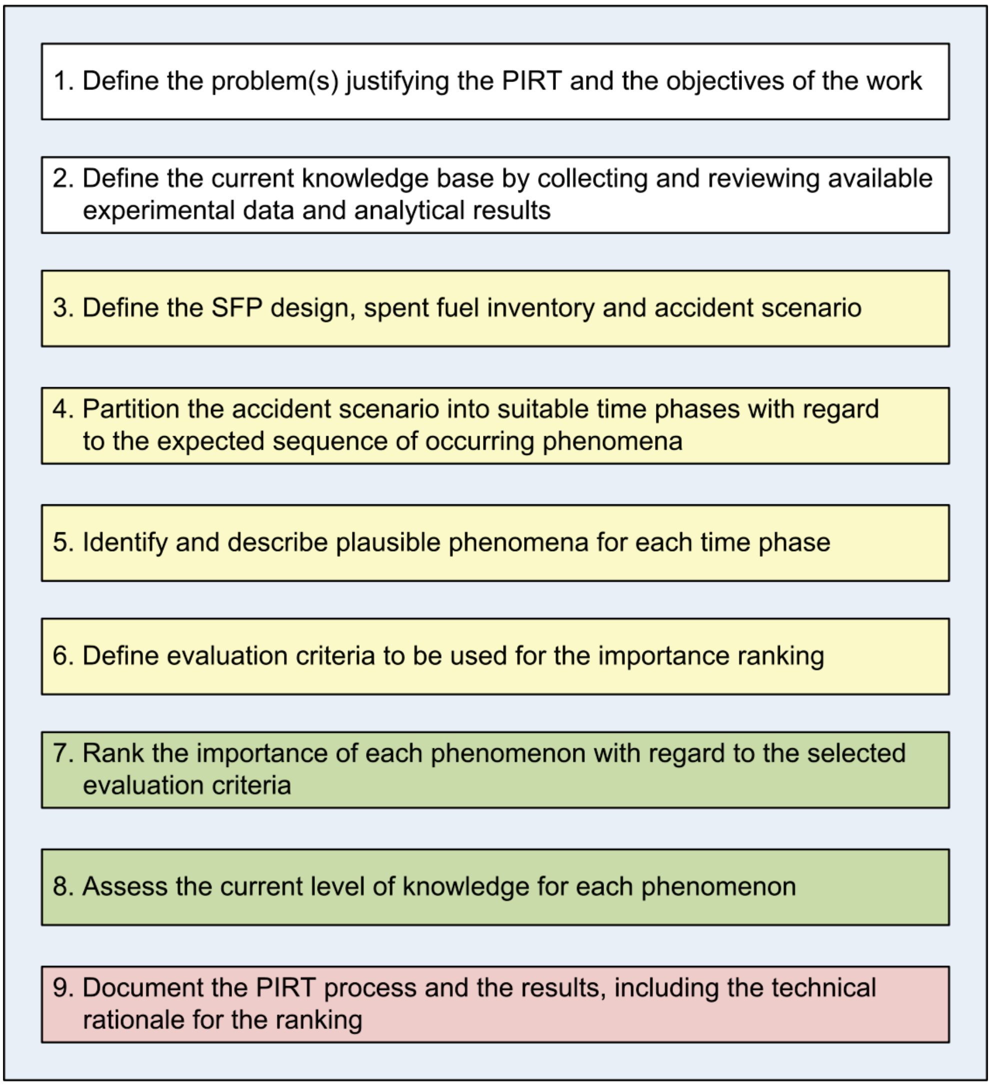
Since its inception, the PIRT process has evolved from being just a systematic method for defining modelling requirements. It has been refined, extended and applied in many other contexts; see e.g. [58, 61] and references therein for examples. One of the most important extensions is that phenomena are nowadays ranked not only with regard to their importance, but also with regard to their current state of knowledge. This has made the PIRT process useful for identifying and prioritizing research needs, and for setting up cost-effective and focused experimental and/or analytical research programmes. Examples of such applications of the PIRT process can be found in [62, 63]. A few PIRTs have also been produced in the wake of the 2011 Fukushima Daiichi nuclear power plant accident [64, 65]. With regard to spent fuel pool accidents, a PIRT has recently been produced for a postulated loss-of-cooling accident in a CANDU SFP [66]. Moreover, a PIRT-like procedure has in the past been used for identifying and ranking phenomena related to spent fuel heat up, following instantaneous and complete drainage of the SFP in a generic LWR plant [29].

3.1.2. Applied procedure

The step-wise procedure applied in the present study, schematically illustrated in Figure 5, follows the generally accepted methodology for PIRT development [58]. Although the procedure in Figure 5 is depicted as consisting of nine consecutive steps, it should be recognised that iterations between the steps are not unusual. This is particularly true for steps 3 to 6, which are difficult to carry out in a completely sequential order.

Most of the work related to the first two steps in Figure 5 was accomplished already in the process of composing the NEA/CSNI status report on spent fuel pools under loss-of-cooling and loss-of-coolant accident conditions [1]. Steps 3–9 in Figure 5 were carried out from early 2016 to the middle of 2017 by an international panel of experts; see Section 3.1.3. During this period, four panel meetings were arranged in Paris, France. In the first two meetings, the panel discussed and agreed upon the organisation of the PIRT (steps 3–6), whereas the last two meetings were focused on evaluation, interpretation and documentation of the results (step 9). The actual ranking of the importance and knowledge level of each phenomenon (steps 7–8) was done individually by the panellists, and the overall ranking was determined by averaging the votes. Steps 1–8 in Figure 5 are documented in Section 3.2 of the report and the results (Step 9) are presented in chapter 4. .

Figure 5: Procedure for developing the PIRT on SFP loss-of-cooling/coolant accident



3.1.3. The international panel of experts

The international panel of experts responsible for the PIRT consisted of members of the NEA CSNI Working Group on Fuel Safety (WGFS) and Working Group on Analysis and Management of Accidents (WGAMA) as well as invited experts from industry, research organisations and nuclear regulatory bodies. Altogether 23 organisations from 15 countries were represented in the panel; see Table 1. As indicated by the list of contributors to the report, some organisations were represented by more than one panellist, but each organisation had only one vote in the ranking process; see section 3.2.7.3. The panellists’ expertise ranged over various disciplines relating to phenomena expected in the considered SFP accident, and they also had experience with different nuclear reactor and spent fuel pool designs. Some of the panellists had their primary focus on experimental programmes and facilities, while others were experts in development or application of computer models and simulation tools for the anticipated phenomena. About half of the panellists contributed to the aforementioned status report on spent fuel pools under loss-of-cooling and loss-of-coolant accident conditions [1].

Table 1: Organisations represented in the international panel of experts

Country/organisation	Participating organisations
Belgium	BEL V
Canada	CNL, CNSC
Czech Republic	UJV
European Commission	JRC
France	CEA, EDF, IRSN
Germany	GRS
Hungary	MTA-EK
Italy	NINE
Japan	IAE, JAEA, MNF, S/NRA/R*
Republic of Korea	KAERI
Russian Federation	NRCKI
Slovenia	JSI
Spain	CIEMAT, CSN
Sweden	QT
Switzerland	PSI
USA	U.S. NRC

* As for Japan, experts are selected from researcher organisations (JAEA, CRIEPI, IAE), PWR vendors (MHI, MNF), BWR vendors (Hitachi-GE, TOSHIBA, GNFJ) and regulatory body (S/NRA/R). JAEA, MNF, IAE and S/NRA/R are representatives of those organisations.

3.2. Step-wise application of the PIRT procedure

3.2.1. Justification of the PIRT and definition of objectives

The first step in Figure 5 was accomplished in the process of composing the NEA/CSNI status report on spent fuel pools under loss-of-cooling and loss-of-coolant accident conditions [1]. In that report, it was concluded that our current understanding of these accidents is based on experiments that have been done predominantly to study reactor cores in loss-of-coolant accidents and on analyses with computational tools that are intended primarily for studies of reactor accidents. Hence, it was concluded that there is a need to assess to what extent these experiments and computational tools are applicable to SFP accidents, in order to find possible knowledge gaps. These knowledge gaps must be bridged by future experimental and model development efforts that are specifically targeted to SFP accidents, and it was recommended that a PIRT should be used to systematically identify phenomena that are both of high importance and high uncertainty, and thus, of primary interest for such studies [1]. This is the objective of the present work.

3.2.2. Definition of the current knowledge base

Also the second step in Figure 5 was to a large part carried out already when preparing the NEA/CSNI status report [1], since the material in the status report served as a common knowledge base when developing the PIRT. The status report is a comprehensive review of accidents and precursor events, relevant experimental data and results from computational analyses. The report covers material published in the open literature up to 2014, but results from more recent works (published up to early 2017) were also considered when developing the PIRT. An example of the latter is the NUGENIA+ AIR-SFP project on spent fuel pool behaviour in loss-of-cooling/coolant accidents, which is a co-ordinated research project among 14 European countries. The main objectives of the project are to assess the applicability of severe accident computer codes to analyses of SFP accidents and to lay out a roadmap for future research and development for these accidents [67]. Among other things, the NUGENIA+ AIR-SFP project comprises a benchmark of SA codes with regard to loss-of-cooling and loss-of-coolant SFP accident scenarios and investigations of the potential for criticality during such scenarios.

3.2.3. Examined SFP designs, spent fuel inventories and accident scenarios

3.2.3.1 SFP design

For the purpose of this study, we consider a generic at-reactor SFP of rectangular shape and a length/width/depth of about 12/8/11 m, which are typical dimensions for this kind of pools in most LWR power plants (see the review of existing at-reactor pool designs in Appendix A of [1]). A notable exception is the VVER-440 plant design, in which the at-reactor SFP is significantly deeper and has pentagonal rather than rectangular cross section [1]. Spent fuel pools in CANDU plants generally have larger lateral dimensions than SFPs in LWR plants [1].

In current power plant designs, there are three principally different locations for the at-reactor SFP [1]. The pool may be (i) in a separate building, adjacent to the reactor building, (ii) inside the reactor building, but outside the reactor containment, (iii) inside the reactor containment. While these differences in pool location can have a strong effect on the transport and release of steam and radioactive fission products to the environment during an SFP accident, they are not expected to significantly affect the phenomena occurring within the pool itself. The exact location of the SFP is therefore deemed relatively unimportant for the present study, which is restricted to phenomena that occur within the pool. Phenomena occurring outside the SFP, such as heat and mass transfer in the pool building, are discussed in terms of boundary conditions to the SFP, when they are deemed to be important to the in pool course of events. Another important design difference is the elevation of the spent fuel pool. BWR plants usually have elevated SFPs, whereas other plant designs have the pools near grade. Although the elevation may affect the likelihood ratio for complete versus partial drainage of the SFP, it is assumed not to affect the accident scenarios studied in this report.

Although a wide variety of configurations exists for the SFP cooling systems in various power plants, the design principles are similar [1, 68]: the pool water is cooled by a dedicated system, which pumps the water through heat exchangers that reject the heat to an ultimate heat sink through an intermediate cooling circuit. In addition, there is a non-safety related purification system for the pool water, which is often integrated with the cooling system. There are different degrees of redundancy for the SFP pumps, heat exchangers and intermediate cooling circuits, but in the accident scenarios considered here, we assume that the normal systems for cooling, purification and water makeup are unavailable. Emergency systems, providing emergency make-up water or spray cooling of the pool, are operable. The actions of these systems are considered as phenomena in the PIRT; see Section 3.2.3.4.

In LWRs, spent fuel assemblies are stored vertically in racks at the bottom of the SFP, while in CANDUs, the fuel bundles are stored horizontally [1]. The racks provide mechanical support and allow efficient cooling of the spent fuel by water flow, and for LWR fuel, they also ensure subcriticality in the pool. This is achieved either by neutron absorbing material (boron) in the racks, or by the pool water alone, which can be either borated (PWRs and VVERs) or demineralised (BWRs). The latter requires a sufficient spacing of the FAs, which is provided by the rack design. The natural uranium fuel used in CANDUs cannot go critical in light water or air, which means that there are no criticality issues with this fuel design.

A wide variety of storage rack configurations are currently in use [1]. In this report, we make no explicit assumptions or postulates regarding the rack configuration, but try to cover the existing designs generically.

3.2.3.2 Fuel inventories and storage configurations

The inventory and storage configuration of the spent fuel are important, since they define the distributions of heat load and fission products in the SFP. In this study, we consider three different scenarios with regard to fuel inventory and storage configuration. Two of them pertain to reactor outage, when FAs are being moved back and forth from pool, whereas the third scenario represents post-outage conditions. The scenarios are:

A. A worst-case scenario, corresponding to a nearly completely filled SFP, where a substantial part of the spent fuel inventory originates from a recent full core offload, carried out shortly after reactor shutdown. The total thermal power released from the spent fuel is therefore at the maximum allowable heat load for the SFP, which is typically around 10 MW for a 1 GWe reactor [1]. Moreover, the recently discharged (hot) fuel assemblies are stored such that they are concentrated in one end of the pool.

B. A scenario with the same challenging inventory of spent fuel as described above, but with a dispersed storage configuration: hot, recently discharged, FAs are distributed across the entire SFP. The hot fuel assemblies are stored either in a checkerboard or a 1×4 configuration, meaning that each hot FA is surrounded by at least four neighbouring FAs with significantly lower power [1].

C. A typical post-outage scenario, representing a half-filled SFP that contains spent fuel from 3–4 past refuelling operations. The most recent refuelling, corresponding to one third of the reactor core, took place about four months ago. This scenario, which gives a total heat load less than 1 MW, is similar to the status of the SFPs in units 2 and 3 of the Fukushima Daiichi nuclear power plant at time of the Tohoku earthquake on March 11, 2011 [1, 3].

3.2.3.4 Accident scenarios

As already mentioned in chapter 2. , there are two principal categories of accidents that may lead to loss of adequate cooling of the spent fuel in an SFP: sudden loss of the pool water inventory by leakage (loss-of-coolant accident) and malfunction of the pool cooling system (loss-of-cooling accident). In the present study, these two categories are represented by two different postulated accident scenarios, as described below. For each scenario, we consider the three postulated fuel inventories and storage configurations defined in Section 0.0.0.2. Hence, we consider six different cases in total, as shown in Table 2.

Table 2: Combinations of accident scenarios, SFP fuel inventories and storage configurations considered in this study

SFP fuel inventory and storage configuration	SFP accident scenario	
	FD – Fast Drainage (loss-of-coolant accident)	SU – Slow Uncovery (loss-of-cooling accident)
A: Maximum heat load and concentrated storage pattern	FD-A	SU-A
B: Maximum heat load and dispersed storage pattern	FD-B	SU-B
C: Moderate heat load and dispersed storage pattern	FD-C	SU-C

Hypothetically, scenarios involving a combination of fast drainage and slow uncovery are possible. For example, a severe seismic event could lead to fast *partial* draindown of the pool by failure of gates or connected piping systems, followed by a period with no or reduced SFP cooling. Such scenarios are, with regard to the occurring phenomena, deemed to be covered by the two considered scenarios.

For all the combinations in Table 2, the SFP is assumed to be at nominal operating conditions and hydraulically disconnected from the reactor well when the accident occurs, meaning that all gates between the SFP and the reactor well are firmly closed, the pool water level is normal and the water temperature is around 325 K for fuel inventories A and B, and around 310 K for inventory C; see Table 2. Prior to the accident, the water purification system is in normal operation and the concentration of contaminants is low. For simplicity, we do not consider the possibility of a reactor accident occurring simultaneously with the SFP accident, as was the case in some of the Fukushima Daiichi units [3], since it is not believed to be important to the phenomenology. Moreover, the spent fuel and storage racks are assumed to be undamaged when the accident occurs. Hence, whatever the initiating event, it has not damaged the stored fuel or storage racks. Likewise, we do not consider the possibility of debris, poolside equipment or larger building parts falling into the pool and obstructing flow paths by piling up at the top of the storage racks. We also neglect the possibility of immediate pool water loss by sloshing during the initial event. Safety systems, such as emergency supply of make-up water and spraying of the SFP, are assumed to be either fully operable or completely inoperable for all the considered scenarios in Table 2. More precisely, the actions of these safety systems are considered as phenomena in the PIRT.

Loss-of-coolant accident scenario: Fast Drainage (FD)

Sudden accidental loss-of-coolant water from the SFP to such an extent that the spent fuel is uncovered is highly unlikely [1]. The pool itself is a robust structure in concrete, lined with stainless steel and/or fibreglass reinforced epoxy, designed to withstand severe external events. Gates between the pool and the reactor well, as well as all connected piping systems, are designed such that the potential water loss is limited in case the components fail or are misaligned [1]. Past studies in the USA [19, 69] have suggested that a large seismic event (well beyond the design basis for the plant) would be the most likely reason for sudden drainage of the SFP in LWRs. The estimated likelihood of pool liner failure by such events ranged from 0.2 to 6 per million reactor year in these studies [19, 69]. Even though fast drainage of the SFP is highly unlikely, we have chosen to consider it, since it is a worst-case scenario with regard to fuel uncovering rate that could possibly trigger other phenomena than in loss-of-cooling accidents with slow uncovery of the spent fuel.

In the aforementioned studies of fast drainage, no estimates of the resulting leak rates were given. However, a more recent study by the NRC [18] included detailed structural analyses of a typical BWR SFP under a severe beyond-design-basis seismic event, in order to estimate the resulting damage to the pool and to provide leak rates for further analyses of the loss-of-coolant accident progression. The worst calculated damage state, involving a 3–4 mm wide through-wall crack along the SFP perimeter at the bottom of the pool walls, was estimated to result in complete drainage of the pool within 6 to 9 hours, in absence of mitigation measures. The estimated average leak rate down to a height of about 5 m above the SFP pool floor was about 0.1 m^3/s [18]. These numbers are subject to considerable uncertainty, but are used in our study to define the leak kinetics. To our knowledge, they are currently the only estimates of this kind. Other reported analyses of SFP loss-of-coolant accidents have usually assumed instantaneous draindown [19, 29, 70], but some analyses with various postulated leak rates are also available [71, 72].

Loss-of-cooling accident scenario: Slow Uncovery (SU)

There are two classes of events that may lead to loss of SFP cooling. The first class involves loss-of-coolant flow, e.g. caused by pump failure, loss of electrical power to the pumps, flow blockage or diversion in the SFP cooling system, or loss of suction caused by a low water level in the pool. The second class is related to the loss of heat sink, e.g. caused by damage or fouling of the heat exchangers. Examples of past events that have resulted in momentary loss of SFP cooling are given in [1].

Loss of cooling results in heat up of the pool, and if no corrective actions are taken, the pool water will gradually evaporate and eventually uncover the fuel assemblies. The time needed for evaporating the pool water level down to the top of the fuel assemblies depends mainly on the total heat load of the spent fuel, the pre-accident pool water volume and temperature, and any corrective actions in terms of make-up water injection or forced cooling [1]. Here, we study an accident scenario that involves complete loss of the normal SFP cooling system, initiating from a state of nominal operating conditions for the pool.

3.2.4. Partitioning of the accident into temporal phases

Since the relative importance of phenomena changes with time as an accident progresses, it is common practice to divide accident scenarios into temporal phases, in which different phenomena come into play (see step 4 in Figure 5). For the work in this report, the panel agreed to partition the considered accident scenarios into three phases, as illustrated in Figure 1, and to develop a specific PIRT for each phase. The transition from Phase II to Phase III is somewhat indeterminate: the panel decided to define it as the time when cladding tube integrity (tightness) is lost by creep rupture or excessive oxidation and gaseous fission products are released from the fuel rods.

3.2.5. Identification of phenomena and influential initial/boundary conditions

All panellists were initially encouraged to identify phenomena that they deemed relevant to each of the three temporal phases of the accident and to propose them for subsequent ranking and inclusion in the three PIRTs. To ensure completeness, this was done in a brain-storming manner and no screening or ranking of the suggested phenomena were attempted at this stage. Since it was realised that the relative importance of a phenomenon could depend on the assumed initial conditions or boundary conditions for the accident, it was decided to identify the most dominant initial/boundary conditions in the same manner as the phenomena considered in the PIRTs. However, the initial/boundary conditions were not subsequently ranked; see Section 4.4. Some of the most important initial/boundary conditions, such as the assumed SFP fuel inventory, fuel storage configuration, pool leak rate and the operability of SFP cooling and emergency systems during the accident, were explicitly postulated; see Section 3.2.3.

Once the panellists were satisfied with the completeness of the identified phenomena and initial/boundary conditions, three structured tables were created by condensing and grouping the phenomena proposed by the panellists. In addition, succinct definitions of the phenomena were included in the tables. This work was distributed among three subgroups of panellists, formed according to their expertise, and each subgroup was given the responsibility to prepare the list of phenomena for a particular temporal phase of the accident.

3.2.6. Definition of evaluation criteria (figures of merit)

The sixth step in Figure 5, i.e. the definition of evaluation criteria, is an essential part of the PIRT process. The evaluation criteria are the key figures of merit against which the relative importance of each phenomenon is to be judged. Hence, the importance rank of a particular phenomenon is a measure of its relative influence on the selected evaluation criteria. In the present study, it was agreed by the expert panel to apply evaluation criteria that focused on the main safety issues related to spent fuel pools.

3.2.6.1 Safety issues related to spent fuel pools

Spent fuel pools generally contain a large and diversified radionuclide inventory (potential source term). The most important safety issue related to SFPs is that all or part of this inventory may be released to the SFP building atmosphere and possibly to the environment during an accident, and potentially, endanger both the biosphere (personnel, public) and the geosphere. For the purpose of minimising the radiological consequences of any release, some basic spent fuel pool design features and operational practices have been defined. For example, the International Atomic Energy Agency (IAEA) has issued general guidelines regarding the design and operation of SFPs [73, 74]. Above all, the best practice ensuring safe storage in spent fuel pools consists in minimising the magnitude of the source term and in maintaining a minimum of two independent barriers between the fuel and its direct environment [75].

With regard to the source term, most of the radionuclide inventory is retained within the fuel rods and consists of fission and activation products that were generated during fuel irradiation. In addition, though smaller than the in-fuel inventory, a substantial radioactivity is usually contained within the SFP water. This activity may be due to fission and activation products coming from leaking fuel rods in the pool or from the reactor primary coolant system water during outage. Moreover, activation and corrosion products deposited on the fuel are transported to the SFP during core offload and may later be released to the pool water. When boiling starts in the SFP, the temperature inside of leaking fuel rods will also increase. The coolant which fills large part of the internal gas volume of the leaker will be released from the fuel together with the dissolved fission product, and it creates an additional source term. From Section 2.1.1, we recall that tritium may represent an important part of the SFP water inventory in plants where boric acid is used as an in reactor neutron absorber, but other fission products (e.g caesium) released directly from the leaking fuel rods during the accident should be also considered.

Regarding the barriers between the fuel inventory and the environment, the most important barrier is the fuel cladding itself, as long as fuel integrity is ensured. In addition, the pool water, structure and systems act as a second barrier, containing the substantial pool water inventory. Specific to some nuclear power plants, a third barrier may be achieved by locating the SFP within a containment building with a dedicated ventilation and filtration system, thereby minimising the transfer of airborne radioactivity off-site as long as the containment remains intact. Moreover, a secondary hydraulic containment system may be set up in order to avoid any radioactivity release to the environment through a liquid state. During accidents, the design and operation measures related to the safety of the SFP may possibly prove insufficient and the integrity of each barrier may be lost. In particular, the loss of pool water, structure and systems containment is closely linked with the Phase I thermal-hydraulic phenomenology (e.g. pool boiling may lead to airborne radioactivity releases to the pool building atmosphere), whereas the integrity loss of fuel cladding and pool containment building (if any) is mostly related to processes in Phase II and III. Accident scenarios are usually classified according to postulated initiating events and consequences, and their specification is to be acceptable to the regulatory body for the spent fuel pool facility [74]. In addition, safety analyses applied to SFPs commonly include an assessment and quantification of the processes leading to loss of integrity for the containment barriers and its consequences.

3.2.6.2 Selected evaluation criteria

The evaluation criteria were selected with the aim to address the aforementioned safety issues, while at the same time being generic with regard to fuel and SFP design. The expert panel decided to use the following evaluation criteria:

1. Source term, referring to the release of radionuclides and hydrogen from the SFP to the pool building. The radionuclides can be released both from the fuel and the SFP water, and the hydrogen may be produced by radiolysis of the SFP water, high-temperature metal-water reactions and melt-concrete interactions.
2. Fuel damage. Loss of cladding integrity by creep rupture or excessive oxidation, loss of rod-like geometry, melting, etc.
3. Accident progression, as manifested by the timing of events that lead to a new phase of the accident, i.e. fuel uncovery for Phase I and loss of cladding integrity for Phase II.

4. Water density, referring to the effective density of a two-phase (water-steam) mixture. The water density is important primarily to the subcriticality margin in the SFP, but also to the operation of SFP cooling systems.
5. These evaluation criteria were used for all three phases of each accident scenario. We note that the criteria are not entirely independent of each other. For example, the source term in Phase III of the accident is strongly correlated to the extent of fuel damage.

3.2.7. Ranking of phenomena and assessment of level of knowledge

3.2.7.1 Definition of importance ranks

Based on its simplicity and proven success in many previous PIRT efforts [58, 62, 64, 76], the expert panel decided to adopt a three-level scale for the importance ranking; see Table 3 for a definition of the ranks and their implications. A ranking scale with only three levels was deemed sufficient, since the panel was large and the final rank of a phenomenon was determined by averaging the panellists' votes, using the weights defined in Table 3; see also Section 0.0.0. Due to the relatively large size of the panel and the averaging procedure, the final ranks became sufficiently distributed that there was no need to introduce additional levels in the primary ranking scale to further distinguish the phenomena.

Since it was recognised that a panellist may be an expert in some of the identified phenomena, but less familiar with others, the panel members were encouraged to consult with other experts in their organisations and instructed to vote only if they had sufficient experience with the phenomenon in question. The panellists were also instructed to focus solely on the importance of the phenomenon relative to the evaluation criteria when casting their votes.

Table 3: Three-level scale used for phenomena importance ranking [58]

Rank	Weight	Definition	Implication
High (H)	1.0	The phenomenon has a dominant impact on any of the evaluation criteria	The phenomenon should be explicitly considered in experimental programmes and modelled with high accuracy in computational tools
Medium (M)	0.5	The phenomenon has only a moderate impact on the evaluation criteria	Experimental studies and analytical modelling are required, but the scope and accuracy may be compromised
Low (L)	0.0	The phenomenon has small or no impact on the evaluation criteria	The phenomenon should be exhibited experimentally mentally and considered in computational tools However, almost any model will be sufficient

3.2.7.2 Definition of knowledge ranks

The knowledge level of each phenomenon was ranked according to the three-level scale defined in Table **4**. The ranking was done with regard to the current (early 2017) availability of both relevant experimental data and computational models. As seen from Table 4, the word "adequate" was used to define the availability of data and models, and the panel of experts recognised that a suitable reference level must be defined for this word to be meaningful. Therefore, it was agreed that the word adequate in this context means that the data and/or models are adequate for performing safety analyses of SFP loss-of-cooling/coolant accidents with accuracy comparable to that achieved with state-of-the-art severe accident computer codes in applications to reactor accidents.

Table 4: Three-level scale used for ranking the current knowledge level of phenomena.
The ranking was performed with regard to both experimental data and computational models

Rank	Weight	Definition – data	Definition – models
Adequate (A)	1.0	The phenomenon is well understood Data obtained for SFP accident conditions are available in sufficient range, quantity and quality	Models that are validated for application to SFP accident conditions are available
Some (S)	0.5	Data obtained for SFP accident conditions are available, but not in sufficient range, quantity or quality. Alternatively, data pertinent to other conditions exist and can be extrapolated to SFP conditions	The phenomenon can be app-approximately modelled, e.g. by lower order models or models for similar phenomena that can be extrapolated to SFP conditions
None (N)	0.0	No relevant data exist, and the phenomenon is poorly known	No validated models exist

When assessing the availability and status of models, the panel considered models in different categories of computer codes, depending on the temporal phase of the accident. For Phase I, system codes and CFD codes for thermal-hydraulic analyses were considered. For Phase II, system codes and CFD codes were considered together with severe accident and transient fuel rod performance codes. Finally, for Phase III, the panel considered models available in system codes and SA codes. The modelling capacity of nuclear criticality codes was assessed for all phases of the accident. As with the importance ranking, the panellists were instructed to vote on the knowledge level only if they had sufficient experience with the availability of data and models for the phenomenon in question.

3.2.7.3 *Evaluation of overall importance and knowledge ranks*

The three tables with identified phenomena for the three temporal phases of the accident were distributed to all panellists, who were asked to individually rank the phenomena with regard to importance and knowledge level, as defined in the foregoing sections. The panellists were given about a month's time to do the ranking, which allowed them to consider the phenomena in depth and to consult colleagues and experts within their home organisations; see Table 1. Only one vote per participating organisation was accepted, which means that each organisation had to agree on a specific vote.

The overall importance level (*IL*) for a phenomenon was then calculated from the votes of each participating organisation through

$$IL = \frac{1.0\,N_H + 0.5\,N_M + 0.0\,N_L}{N_H + N_M + N_L}, \qquad (7)$$

where N_H, N_M and N_L refer to the numbers of "High", "Medium" and "Low" importance votes, respectively and the numerical values are the weights defined for these importance levels; see Table 3. Likewise, the overall knowledge levels (*KL*) with regard to data and models were calculated separately through

$$KL = \frac{1.0\,N_A + 0.5\,N_S + 0.0\,N_N}{N_A + N_S + N_N}, \qquad (8)$$

where N_A, N_S and N_N refer to the numbers of “Adequate”, “Some” and “None” knowledge votes for the availability of either data or models; see Table 4. In addition, the standard deviations of the weighted votes for the importance and knowledge levels were evaluated for each phenomenon and used as indicators for the agreement between panellists.

Following the voting, the panel was convened to discuss the outcome. The discussion focused on phenomena that had received high importance level (IL) and/or low knowledge level (KL), and for which there seemed to be significant disagreement between the panellists. These phenomena were identified by use of two screening parameters. The first one, defined through

$$R_i = \frac{IL_i\left(1-KL_i^D\right)\left(1-KL_i^M\right)}{\underset{i}{\mathrm{Max}}\left[IL_i\left(1-KL_i^D\right)\left(1-KL_i^M\right)\right]}, \qquad (9)$$

was used as a measure for the *relative relevance* of each phenomenon. Here, IL_i is the importance level of the i:th phenomenon, whereas KL_i^D and KL_i^M are the knowledge levels for data and models. The screening was done for each of the three tables separately, which means that the maximum in the denominator refers to the maximum for a specific phase of the accident.

The second screening parameter addressed the *relative dispersion* of votes for each phenomenon, i.e. the scatter in experts’ opinion regarding importance level and knowledge level. It was defined by

$$D_i = \frac{\sigma\left(IL_i\right)\sigma\left(KL_i^D\right)\sigma\left(KL_i^M\right)}{\underset{i}{\mathrm{Max}}\left[\sigma\left(IL_i\right)\sigma\left(KL_i^D\right)\sigma\left(KL_i^M\right)\right]}, \qquad (10)$$

where $\sigma(x)$ alludes to the standard deviation of x. Phenomena that received highly dispersed votes by the panel, as indicated by high values for D_i, were brought up to discussion. The intention was to refine their definition and to ensure that all panellists had a consistent conception of these phenomena.

Following the discussions, minor revisions were made to the three tables with identified phenomena for the three phases of the accident: descriptions of some phenomena were refined, other phenomena were re-grouped or moved from one table to another, but no entirely new phenomena were introduced in the revised tables. Finally, the revised tables were distributed to the panellists, who were asked to rank the phenomena anew. The results of the second ranking are presented in Chapter 4.

4. RESULTS AND DISCUSSION

The PIRTs developed for the three phases of the considered accident scenarios are presented in Sections 4.1–4.3 below. The tables have a similar structure in that the phenomena are listed by category. We note that 31 phenomena were identified and ranked for Phase I, 38 for Phase II and 61 for Phase III. These numbers reflect the complexity of the fuel damage phase in comparison with the early phases of the accident, as illustrated in Figure 1.

The PIRTs presented in Sections 4.1–4.3 contain the ranking results for each phenomenon. Results are presented separately for the fast drainage (FD) and slow uncovery (SU) accident scenarios, since the importance of some phenomena were ranked very differently for the two scenarios. The heat load of the SFP and the storage pattern for the spent fuel assemblies were found to have a weaker influence on the ranking. Consequently, separate results for the sub-scenarios A-C in Table 2 are not presented in the PIRTs.

The ranking may also depend on the particular design: significant differences in fuel and SFP design exist, especially between LWRs and CANDUs. Moreover, initial and boundary conditions may impact the importance ranking of some phenomena. Initial/boundary conditions with relevance for the ranking were identified by the expert panel in the same manner as the phenomena considered in the PIRT, but they were not subsequently ranked. The most important initial/boundary conditions, such as the SFP fuel inventory and storage configuration, were postulated as part of the PIRT process; see Section 3.2.3. Other initial and boundary conditions identified as influential for the considered accident scenarios are presented in Section 4.4.

For each phenomenon and accident scenario, the PIRTs in Sections 4.1–4.3 contain the panellists' votes on importance level (*IL*) and state of knowledge with regard to data (KL^D) and models (*KLM); see* Section 3.2.7.3 *The letters L/M/H and N/S/A in the table headings refer to the ranks defined in Section 3.2.7, and the number of votes given to each rank by the expert panel are given in the tables together with the screening parameters used to quantify the relative relevance (R) and the relative dispersion (D). The results obtained for the importance level and state of knowledge are colour-coded in the tables, and the range*s for *IL* and *KL* used in this coding are defined in Table 5. Likewise, the results for the screening parameters *R* and *D* are also colour-coded, as defined in the same table. The colour coding is not intended to categorise the phenomena, but merely to help the reader to identify at a glance the most interesting phenomena with regard to importance or lack of knowledge.

Table 5: Key for the colour coding used in the PIRTs

Parameter range	**Importance/knowledge level** *IL*	*KL*	**Screening parameters** *R*	*D*
< 1/3	Green	Red	Green	Green
1/3 – 2/3	Yellow	Yellow	Yellow	Yellow
> 2/3	Red	Green	Red	Red

Based on the PIRTs, the expert panel identified phenomena that are of both high importance and high uncertainty, and thus of primary interest for further research. These phenomena are presented and discussed in conjunction with each PIRT, and technical justifications are given for why they are deemed to deserve further study. The discussion addresses the importance as well as the current knowledge base of these high-rank phenomena, with the aim to delineate what kind of experiments and/or model development efforts are needed to bridge existing knowledge gaps.

4.1. Pre-uncovery phase

4.1.1. Phenomena Identification and Ranking Table

Table 6 is the PIRT developed for the pre-uncovery phase of the accident. It contains the ranking results for the 31 identified phenomena, with detailed information on the distribution of votes from the expert panel. The colour coding used for the importance and knowledge levels is defined in Table 5.

The most important results in the PIRT are presented graphically in Figure 6, where each phenomenon and accident scenario is plotted in the (*IL*,*KL*)-plane. The knowledge level shown in the figure is the arithmetic average of the knowledge levels with regard to data and models, i.e. $KL = (KL^D+KL^M)/2$. The scatter plot is useful for identifying the most relevant phenomena, i.e. phenomena that are ranked important and at the same time deemed poorly known. The colour coding of the markers in Figure 6 reflects the relevance (*R*) of each phenomenon, as defined through eq. (9) and the colour key in Table 5. It is clear from the figure that *R* is a fairly good indicator for phenomena with high importance and low knowledge level. However, in contrast to *IL* and *KL*, *R* is a normalised and relative measure, and a high value for *R* does not necessarily mean that the phenomenon is important or poorly known in absolute terms. We note that most of the phenomena identified for the pre-uncovery phase have $IL < 0.5$.

4.1.2. Phenomena with priority research needs

The expert panel identified five phenomena in the pre-uncovery phase, for which further research should be given priority. These phenomena are discussed below. They are highlighted in Figure 6, from which it is clear that the five high-priority phenomena are important primarily for the slow uncovery accident scenario. Their importance level ranges from 0.38 to 0.71 and their knowledge level (average of KL^D and KL^M) falls between 0.23 and 0.48 for this scenario. We note from Figure 6 that there are other phenomena (e.g. I.1–I.3) with high importance level, but they were deemed to be sufficiently well known.

4.1.2.1 Non-uniform natural circulation cooling flow distribution between fuel assemblies (I.5)

With regard to the evaluation criteria in Section 3.2.6, the flow distribution between fuel assemblies is important mainly for its effect on local boiling, which may potentially lead to loss of subcriticality in low density storage racks. As mentioned in Section 2.1.1, most modern storage racks for spent LWR fuel have a closed-cell design that prevents lateral cross-flow between the vertically stored FAs within the rack. Hence, the natural convection flow through the fuel assemblies is nearly one-dimensional and driven by buoyancy. This flow may differ significantly from one rack cell to another, depending on the heat load and hydraulic design of the stored FA, the design of the rack, and the local fluid conditions at the inlet and outlet of the cell. The inlet/outlet conditions depend on neighbouring fuel assemblies, i.e. the storage configuration, and will also change as the accident pre-uncovery phase progresses. The same kind of multi-channel one-dimensional flow is expected also in open cell rack designs if they are loaded with BWR fuel; in this case, the fuel assembly boxes constitute the parallel flow channels.

In situations with the SFP water close to saturation, the local flow rate and decay power in the stored fuel assembly would be decisive for whether local boiling would occur in a specific cell. The large-scale natural circulation flow patterns that develop in SFPs under postulated accidents are generally analysed by CFD tools, using fairly crude models and approximations. For example, the storage racks are usually modelled as anisotropic porous media [5, 77]. These models are inadequate for determining the flow distribution among the FAs stored in the racks. More elaborate representations of the racks and stored fuel assemblies are needed for this purpose [78], and experiments are needed for validation of the CFD models for SFP accident conditions [6].

4.1.2.2 Flow instabilities within the spent fuel assemblies at low liquid level in the pool (I.6)

Also this phenomenon pertains specifically to BWR fuel assemblies and/or to closed-cell storage rack designs, where the cells can be viewed as parallel and independently heated vertical channels that are connected to common volumes at their top and bottom. Natural circulation flow may become unstable in this configuration, and flow reversal is possible in rack cells with low-power fuel assemblies [13, 14]. The main safety concern is that these flow instabilities could contribute to local boiling in cells with perturbed flow [15], which may potentially lead to loss of subcriticality by void generation.

Although the phenomenon is qualitatively well known from heat exchangers and other applications, the knowledge level for it is very low for flow geometries pertinent to spent fuel storage racks and conditions expected for SFP accidents. Some models exist, but adequate experimental data are missing; see Table 6.

4.1.2.3 Multi-dimensional interaction of different temperature zones within the pool (I.15)

This phenomenon includes transfer of heat, mass and momentum between thermal plumes and stagnant zones in the SFP, local erosion of thermally stratified zones, and interaction of adjacent thermal plumes, whose interests stand, most of all, in the prediction of liquid local boundary conditions for an estimation of boiling and flashing mass flow rates and the contribution of the above phenomena to the overall loss of mass. It is closely related to phenomenon I.3, “Single and two-phase natural convection within the pool at a large scale”, which also received a high importance rank; see Figure 6. The natural circulation loops that develop in the SFP will depend, in large, on the heterogeneous water heating caused by the distribution of hot/cold fuel assemblies in the pool and fluid dynamics interaction between zones with different water temperature. The interaction is complex, especially when boiling occurs in part of the pool, and properly scaled experiments are needed to support existing CFD models as well as 2D/3D models in lumped parameter computer codes.

4.1.2.4 Radioactive aerosol formation due to bubble breakup processes at the free surface (I.23)

Before boiling occurs at the pool surface, the radioactivity transferred from the surface to the SFP building is limited to gaseous species and tritiated steam. If and when boiling occurs at the surface, the radioactivity release rate may increase significantly by aerosol formation: bubbles bursting at the surface eject droplets a few centimetres into the air. The droplets, which are carried away by convection or evaporating steam, may contain dissolved radionuclides as well as suspended insoluble particles. The phenomenon is thus important with regard to the source term in the pre-uncovery phase, as it changes both the release rate and the type of released radionuclides.

The mechanisms for radioactive aerosol formation are qualitatively understood, mainly from experiments that address containment sump boiling in reactor accidents [79]. These experiments show that the radioactivity release rate depends on the type (dissolved/suspended) and concentration of radioactive contaminants in the water, the boiling state (bubble size, velocity and arrival rate at the surface), and the environment above the free water surface (dry/condensing, air velocity). Quantitative data from experiments targeted at boiling SFPs are, however, unavailable, and mechanistic models are scarce.

4.1.2.5 Leakage due to pool concrete and liner deterioration and cracking by temperature rise (I.28)

For the slow uncovery accident scenario, the SFP is assumed to be intact when cooling is lost and the water starts to heat up. During the pre-uncovery phase, any deterioration and cracking of the pool concrete walls or liner would be caused by the water temperature rise and the abnormal temperature and temperature gradients induced in these structures. The expert panel found it unlikely that these temperature effects would damage the pool to such an extent that substantial leakage would occur. However, the panel also recognised that there are few data in support of this judgement; see Figure 6 and Table 6. There are also large differences in pool wall and liner designs among nuclear power plants [1], which may merit further studies of the phenomenon for particular designs. These design differences are reflected in the relatively large dispersion in the panellists' votes for the concrete and liner deterioration; see Section 4.5.2. If leakage is found to be possible due to temperature-induced deterioration, experiments would be needed to support leak rate estimates.

Table 6: PIRT for Phase I (pre-uncovery phase) of the considered accident scenarios; slow uncovery (SU) and fast drainage (FD)

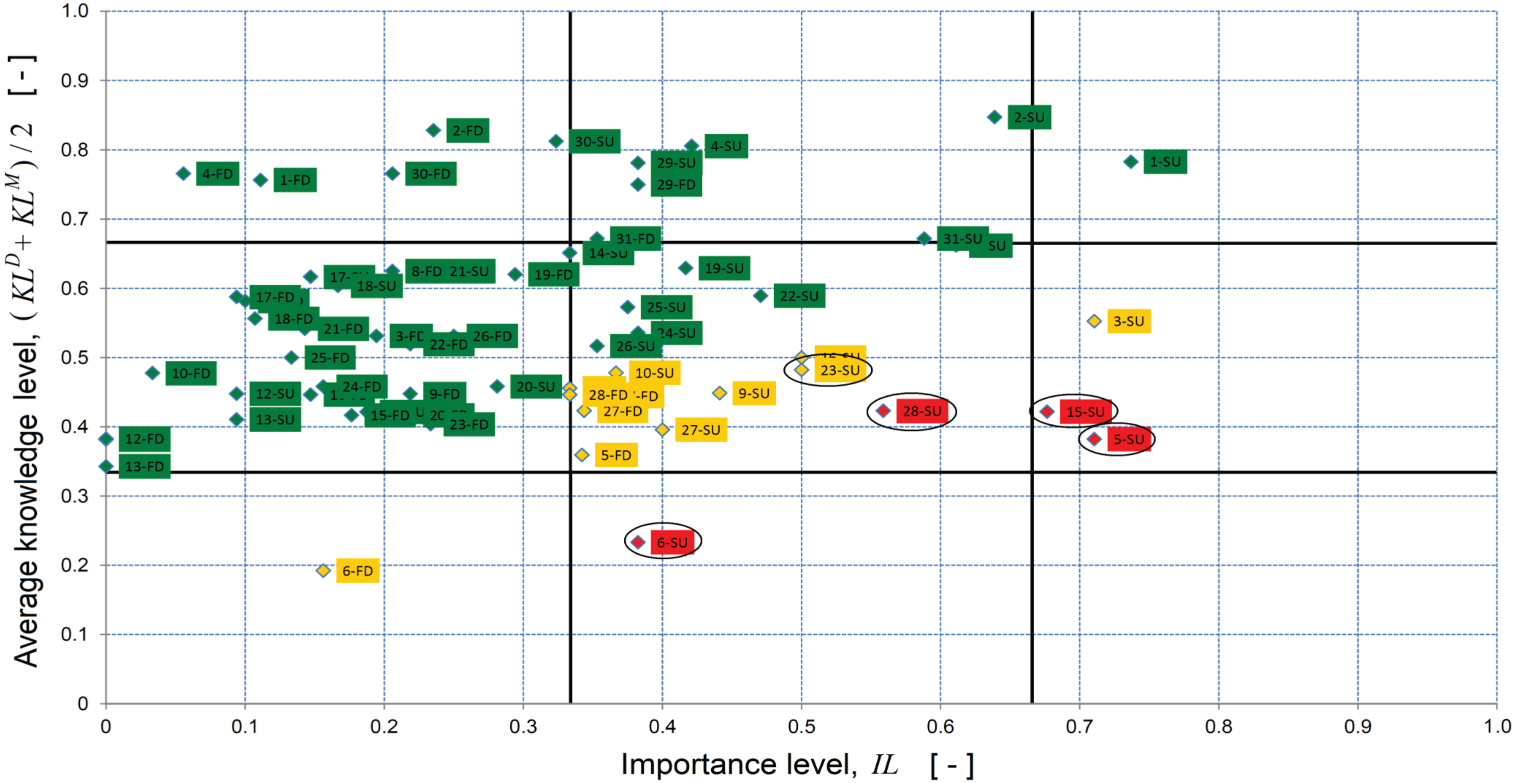
Phenomena by category	#	Scenario	Importance ranking				State of knowledge								Screening-parameters	
							Availability of data				Availability of models					
			L	M	H	IL	N	S	A	KL^D	N	S	A	KL^M	R	D
1. Thermal-hydraulics																
Water evaporation process at the free surface.	I.1	SU	1	8	10	0.737	2	5	11	0.750	1	5	13	0.816	0.130	0.352
		FD	14	4	0	0.111	3	3	10	0.719	2	3	12	0.794	0.025	0.335
Nucleate boiling on the spent fuel rods.	I.2	SU	3	7	8	0.639	1	4	13	0.833	0	5	13	0.861	0.057	0.279
		FD	11	4	2	0.235	2	2	12	0.813	1	3	12	0.844	0.026	0.418
Single and two-phase natural convection within the pool at large scale, including formation of thermal plumes due to heterogeneous water heating as a consequence of the spent fuel arrangement.	I.3	SU	1	9	9	0.711	7	6	6	0.474	1	12	6	0.632	0.527	0.395
		FD	12	5	1	0.194	6	5	5	0.469	2	9	5	0.594	0.161	0.458
Heat losses to the pool structure. Includes walls and floor.	I.4	SU	5	12	2	0.421	3	5	10	0.694	0	3	15	0.917	0.041	0.244
		FD	16	2	0	0.056	4	5	7	0.594	0	2	14	0.938	0.005	0.124
Non-uniform natural circulation cooling flow distribution between fuel assemblies.	I.5	SU	2	7	10	0.711	8	9	0	0.265	3	11	3	0.500	1.000	0.296
		FD	9	7	3	0.342	8	8	0	0.250	4	9	3	0.469	0.522	0.355
Flow instabilities within the spent FAs at low liquid level. Includes flow reversal and flow excursions.	I.6	SU	7	7	3	0.382	12	3	0	0.100	5	9	1	0.367	0.834	0.248
		FD	12	3	1	0.156	11	2	0	0.077	6	6	1	0.308	0.382	0.194
Impact of siphoning/leakage on natural flow convection.	I.7	SU	10	4	4	0.333	9	5	3	0.324	4	6	7	0.588	0.355	0.723
		FD	9	5	4	0.361	9	6	3	0.333	5	6	7	0.556	0.410	0.716
Bubble swarm rise and level swell. Includes bubble dynamics within the pool, condensation.	I.8	SU	1	12	5	0.611	2	10	5	0.588	0	9	8	0.735	0.255	0.243
		FD	12	3	2	0.206	2	8	4	0.571	1	7	6	0.679	0.109	0.399
Impact of cold water injection on the efficiency of natural circulation cooling.	I.9	SU	6	7	4	0.441	5	6	3	0.429	2	13	1	0.469	0.513	0.357
		FD	10	5	1	0.219	5	6	3	0.429	2	12	1	0.467	0.255	0.296
Water superheating resulting from its rise within the pool, from high to low hydrostatic pressure regions.	I.10	SU	6	7	2	0.367	7	2	4	0.385	2	8	4	0.571	0.370	0.572
		FD	14	1	0	0.033	6	2	4	0.417	3	6	4	0.538	0.034	0.242
Nucleation of superheated water onto unheated pool structures. Heterogeneous nucleation.	I.11	SU	11	4	1	0.188	5	6	2	0.385	2	9	1	0.458	0.239	0.305
		FD	16	0	0	0.000	6	5	2	0.346	3	8	1	0.417	0.000	0.000

Phenomena by category	#	Scenario	Importance ranking				State of knowledge: Availability of data				State of knowledge: Availability of models				Screening-parameters	
			L	M	H	IL	N	S	A	KL^D	N	S	A	KL^M	R	D
Nucleation of superheated water onto free non-condensable bubbles. Heterogeneous nucleation.	I.12	SU	13	3	0	0.094	6	6	2	0.357	1	10	2	0.538	0.106	0.192
		FD	16	0	0	0.000	6	6	1	0.308	2	9	1	0.458	0.000	0.000
Nucleation of superheated water onto flowing solid particles. Heterogeneous nucleation.	I.13	SU	13	3	0	0.094	7	5	2	0.321	2	9	2	0.500	0.122	0.230
		FD	16	0	0	0.000	7	5	1	0.269	3	8	1	0.417	0.000	0.000
Bulk nucleation of superheated water. Homogeneous nucleation.	I.14	SU	7	6	2	0.333	5	2	7	0.571	1	5	7	0.731	0.147	0.600
		FD	12	3	0	0.100	5	2	6	0.538	2	5	5	0.625	0.066	0.391
Multi-dimensional interaction of different temperature zones within the pool.	I.15	SU	1	9	7	0.676	5	11	0	0.344	2	12	2	0.500	0.850	0.202
		FD	12	4	1	0.176	5	10	0	0.333	2	11	2	0.500	0.225	0.212
Return of condensate to the pool.	I.16	SU	6	6	6	0.500	8	5	3	0.344	1	9	6	0.656	0.432	0.541
		FD	13	3	1	0.147	7	5	2	0.321	2	8	4	0.571	0.164	0.387
2. Hydrogen issues																
Hydrogen production by radiolysis and radiation-induced electrolysis.	I.17	SU	14	1	2	0.147	3	5	5	0.577	2	7	7	0.656	0.082	0.516
		FD	14	1	1	0.094	4	3	5	0.542	3	5	7	0.633	0.060	0.518
Degassing of hydrogen from the pool, as a result of gas solubility decrease with increasing water temperature.	I.18	SU	11	3	1	0.167	3	5	6	0.607	2	8	5	0.600	0.100	0.445
		FD	12	1	1	0.107	4	3	6	0.577	3	7	4	0.536	0.081	0.501
3. Radioactivity release issues																
Radionuclide releases from leaking fuel rods into the pool.	I.19	SU	7	7	4	0.417	2	6	5	0.615	1	8	5	0.643	0.219	0.464
		FD	10	4	3	0.294	2	5	5	0.625	2	6	5	0.615	0.162	0.574
Radionuclide releases from eroded CRUD into the pool.	I.20	SU	9	5	2	0.281	5	4	3	0.417	3	6	3	0.500	0.314	0.589
		FD	11	3	2	0.219	6	3	3	0.375	4	5	3	0.458	0.283	0.656
Tritium production from neutron capture processes, e.g. neutron capture by boric acid.	I.21	SU	8	7	0	0.233	4	2	6	0.583	2	4	6	0.667	0.124	0.494
		FD	10	4	0	0.143	5	2	5	0.500	3	4	5	0.583	0.114	0.488
Pool scrubbing. Includes capture from pool on bubbles, and capture from bubbles by pool.	I.22	SU	7	4	6	0.471	1	10	3	0.571	1	9	4	0.607	0.303	0.371
		FD	12	1	3	0.219	2	9	2	0.500	2	8	3	0.538	0.193	0.398
Radioactive aerosol formation due to bubble breakup processes at the free surface.	I.23	SU	5	7	5	0.500	4	7	3	0.464	3	8	3	0.500	0.513	0.522
		FD	10	3	2	0.233	5	6	2	0.385	4	7	2	0.423	0.317	0.490

Phenomena by category	#	Scenario	Importance ranking				State of knowledge: Availability of data				Availability of models				Screening-parameters	
			L	M	H	IL	N	S	A	KL^D	N	S	A	KL^M	R	D
Gaseous radionuclide releases by change of solubility when water temperature increases. Includes tritium (HT).	I.24	SU	7	7	3	0.382	3	7	3	0.500	3	6	5	0.571	0.314	0.545
		FD	12	3	1	0.156	4	6	2	0.417	4	5	4	0.500	0.174	0.465
Tritiated steam (HTO) releases by water evaporation.	I.25	SU	7	6	3	0.375	4	4	5	0.538	3	5	6	0.607	0.260	0.710
		FD	11	4	0	0.133	5	5	4	0.464	4	5	5	0.536	0.127	0.417
4. Pool concrete and liner effects																
Pool concrete deterioration and cracking by pool temperature rise.	I.26	SU	9	4	4	0.353	7	2	6	0.467	4	5	6	0.567	0.312	0.911
		FD	12	3	3	0.250	7	2	7	0.500	5	4	7	0.563	0.209	0.906
Pool liner deterioration and cracking by pool temperature rise.	I.27	SU	7	4	4	0.400	7	2	3	0.333	4	5	3	0.458	0.553	0.795
		FD	10	1	5	0.344	7	2	4	0.385	5	4	4	0.462	0.436	1.000
Leakage due to pool concrete and liner deterioration and cracking by pool temperature rise.	I.28	SU	4	7	6	0.559	7	3	3	0.346	5	5	5	0.500	0.699	0.752
		FD	10	4	4	0.333	7	3	4	0.393	6	4	6	0.500	0.387	0.900
5. Criticality issues																
Loss of subcriticality by boric acid dilution with fresh water supply.	I.29	SU	7	7	3	0.382	2	5	9	0.719	1	3	12	0.844	0.064	0.443
		FD	7	7	3	0.382	2	5	9	0.719	1	5	10	0.781	0.090	0.463
Loss of subcriticality by decrease in water density (due to temperature rise only).	I.30	SU	11	1	5	0.324	1	6	9	0.750	0	4	12	0.875	0.039	0.354
		FD	12	3	2	0.206	2	5	9	0.719	0	6	10	0.813	0.042	0.349
Loss of subcriticality by an increase in coolant void fraction within the spent fuel assemblies.	I.31	SU	6	2	9	0.588	3	7	6	0.594	1	6	9	0.750	0.229	0.607
		FD	9	4	4	0.353	3	6	7	0.625	1	7	8	0.719	0.143	0.557

Figure 6: Graphical presentation of ranking results for the Phase I phenomena in the (*IL*,*KL*)-plane

Phenomena with priority research needs are circled. The colour coding of the markers reflects the relative relevance (*R*) of each phenomenon, as defined through eq. (9) and the colour key in **Table 5**.



4.2. Uncovery phase

4.2.1. Phenomena Identification and Ranking Table

Table 7 is the PIRT developed for the uncovery phase of the accident. It contains the ranking results for the 38 identified phenomena, with detailed information on the distribution of votes from the expert panel. The colour coding used for the importance and knowledge levels is defined in Table 5. The most important results in the PIRT are presented graphically in Figure 7, where each phenomenon and accident scenario is plotted in the same way as in Figure 6. We note that quite a few phenomena in Phase II have an importance level above 0.7, which is not the case for the Phase I phenomena. We also note from Figure 7 that phenomena ranked with a low knowledge level are generally ranked to be of intermediate importance by the expert panel.

4.2.2. Phenomena with priority research needs

The expert panel identified six phenomena in the uncovery phase, for which further research should be given priority. These phenomena, which are highlighted in Figure 7, are discussed below. It is clear from Figure 7 that most of the six high-priority phenomena are deemed important for the fast drainage accident scenario. Their importance level falls between 0.58 and 0.87 and their knowledge level falls between 0.37 and 0.58.

4.2.2.1 Development of two-phase natural circulation in FAs, storage racks and SFP (II.3)

The expert panel judged that this is a poorly known phenomenon with moderate importance level. As can be seen from Figure 7, the knowledge level is deemed among the lowest for the phenomena considered in the uncovery phase. This is mainly due to the lack of experiments involving two-phase natural circulation in conditions representative for SFP loss-of-coolant/cooling accident scenarios. Such experiments, which are essential for developing and validating CFD models, are underway for PWR fuel in the French DENOPI Project [80]. Similar experiments should be done on other fuel and rack designs, since the design is expected to have a strong impact on the natural circulation flow.

4.2.2.2 Air cooling of the FAs and storage racks after complete pool drainage (II.9)

This phenomenon, which received a very high importance level for the fast drainage accident scenario, includes cooling of the completely uncovered FAs by convection as well as radiation. Hence, it represents the combined effects of phenomenon II.11 “Convective heat transfer between air/steam and structures in the SFP” and phenomenon II.14 “Radiative heat transfer from uncovered FAs to other FAs and the SFP structure”. The safety concern is that air cooling of the completely uncovered fuel assemblies would be insufficient to keep the cladding temperature below 1100–1200 K. At higher temperature, the exothermic oxidation of the cladding may initiate a runaway reaction, resulting in a significant temperature rise and a self-sustained zirconium fire [1].

From Figure 7, it is clear that the phenomenon received a fairly high knowledge level. Pertinent experiments have recently been carried out at the Sandia National Laboratories, United States, on electrically heated prototypic BWR [24] and PWR [25, 26] fuel assemblies in prototypic storage racks. Non-destructive separate effect tests, intended to study the hydraulics and thermal-hydraulics of the FAs, were followed by destructive integral tests to study ignition phenomena and the axial and radial propagation of zirconium fires. The test results have been used for validation of SA computer codes [27].

Further work of this kind is warranted, especially for CANDU fuel and rack designs, for which the Sandia tests do not apply.

4.2.2.3 Fuel fragmentation and relocation during ballooning, before cladding rupture (II.18)

Downward axial relocation of fuel pellet fragments, driven by gravity, may occur when the overheated and internally overpressurised cladding tube distends due to creep. Fuel pellet fragmentation and axial relocation are of safety concern, since the two phenomena in combination may localise the heat load to "ballooned" parts of the rod, thereby reducing the time to cladding rupture. Also, when the balloons finally rupture, the amount of fuel material dispersed into the SFP is increased. These phenomena were observed already in the early 1980s, when in reactor LOCA tests were done on low to medium burnup fuel rods, but more recent tests suggest that fragmentation, relocation and dispersal are far more pronounced for high burnup fuel [81]. The reason is that high burnup fuel, when overheated, may crack and form very fine fragments with a high potential for axial relocation and subsequent dispersal from failed rods [34]. This presumed high burnup issue is currently being studied both by experiments and modelling [34]. The work is focused on fuel behaviour during reactor LOCAs, and the models are developed for application in computer codes for fuel rod thermal-mechanical analyses of design-basis LOCA rather than severe accident codes. We note from Figure 7 that the fragmentation-relocation phenomenon is deemed moderately important for SFP accidents (*IL*=0.61–0.64); the main concern is its fairly low level of knowledge (*KL*=0.44–0.47).

4.2.2.4 Cladding oxidation under air and/or (steam+hydrogen)-mixture environment (II.23)

High-temperature oxidation of the fuel rod cladding tubes by steam, air or a mixture thereof, is important for two reasons: it leads to significant degradation of the material strength and to heat generation. If the oxidation occurs in steam, it also leads to hydrogen production. The main oxidising species in the SFP environment are steam, oxygen and nitrogen and the reactions between these species and zirconium are described by eqs. (1)–(3) in Section 2.2.3. The oxidation kinetics is different in steam than in air (oxygen+nitrogen). Oxidation of zirconium alloys in steam is relevant to reactor accidents and has been extensively studied in the past [82]. Oxidation in air has received less attention, although it is much faster than in steam. The presence of air causes temperature runaway reactions from lower temperature than in steam, and the cladding degradation is also more severe in air. For these reasons, a fairly large experimental database for air oxidation of zirconium alloys has been produced during the last decade [1], and validated computational models exist for zirconium alloy oxidation in air [83].

For mixed air+steam environments, however, the database is scarce and no well-established models for high-temperature oxidation of zirconium alloys in mixed environments exist. As of today, the available data on air+steam oxidation are predominantly from tests on unirradiated Zircaloy-4 cladding in bare (non-preoxidised) condition [1], but separate effect tests are underway at several research institutes that will extend the database to preoxidised cladding materials of different designs and to a wider range of air-steam mixture compositions [6, 84, 85]. The new data will support the development of oxidation models that are applicable to spent nuclear fuel and to gas compositions expected in SFP accidents.

4.2.2.5 Nitrogen-assisted oxide breakaway at low temperature (II.24)

Oxide breakaway involves the loss of protectiveness of the oxide scale formed at the metal surface, due to its mechanical failure. The broken oxide layer presents a much weaker barrier to diffusion of oxygen atoms (from steam or oxygen molecules) to the metal surface, and it is known from separate effect tests that the oxide breakaway increases the oxidation rate of zirconium alloys significantly [37].

Oxide breakaway for zirconium alloys exposed to steam or oxygen environment is known to occur by a phase transformation from meta-stable tetragonal to monoclinic oxide and corresponding change in density at temperatures below about 1 300 K. No oxide breakaway occurs at higher temperatures by oxidation in steam or pure oxygen, but exposure of the oxidising cladding to nitrogen can trigger a breakaway-like behaviour at all temperatures. The reason is that nitrogen penetrates any defect in the oxide scale and forms porous nitrides beneath the oxide. This breaks up the overlying oxide, if the oxide is not completely stoichiometric. The zirconium nitride leads to a disordered microstructure and increases the oxide porosity, allowing the reacting gases to penetrate more readily [37]. It is also known that nitrogen exposure at high temperature leads to a breakup of protective oxide scales formed over long time at low temperature, which are typical for spent nuclear fuel cladding. The aforementioned catalytic effects of nitrogen are thus important for cladding oxidation in air or air+steam mixtures and must be properly understood when developing oxidation models for application to spent nuclear fuel and gas compositions expected in SFP accidents.

4.2.2.6 Fuel cooling by water spray: water injection above the FAs (II.37)

This phenomenon is actually a mitigation measure, which involves cooling of uncovered fuel assemblies by water injection or spraying from the top.[2] This is in contrast to phenomenon II.38, "Fuel cooling by recovery of water makeup; reflood of FAs from below". Both these mitigation measures are essential for recovering the uncovered fuel to normal conditions and both were ranked important by the expert panel. However, spray cooling was deemed to be of somewhat higher importance and to have a lower level of knowledge; see Figure 7. Additionally, spraying is deemed to result in higher circumferential gradients in cladding temperature, which may aggravate fuel rod deformation and promote failure. Past experimental studies on spray cooling have been focused on reactor LOCA and the efficiency of either containment spray systems or core spray emergency cooling systems in BWRs [86]. Spray models implemented in SA computer codes are not developed and validated for SFP conditions and storage rack geometries. Some experimental programmes that specifically address spray cooling in SFP accident conditions are underway, e.g. in France and Japan.

The expert panel noted that there are currently no well-established evaluation criteria for the efficiency of SFP emergency cooling systems, comparable to the acceptance criteria on cladding peak temperature and oxidation that are widely used for emergency core cooling systems in safety analyses of LOCA [82]. Such evaluation criteria could be useful, not only for assessing the efficiency of SFP emergency cooling systems, but also for comparing different mitigation measures in a given accident situation.

[2] Here, water injection refers to improvised means of applying water to the uncovered FAs from above, e.g. by use of fire fighting equipment. Spraying alludes to the use of a dedicated emergency cooling system with properly designed and positioned spraying nozzles.

Table 7: PIRT for Phase II (uncovery phase) of the considered accident scenarios; slow uncovery (SU) and fast drainage (FD)

Phenomena by category	#	Scenario	Importance ranking				State of knowledge								Screening-parameters	
							Availability of data				Availability of models					
			L	M	H	IL	N	S	A	KL^D	N	S	A	KL^M	R	D
1. Thermal-hydraulics																
Water loss by boiling and evaporation.	II.1	SU	0	3	16	0.921	2	5	12	0.763	0	4	15	0.895	0.086	0.193
		FD	6	8	5	0.474	2	4	12	0.778	0	4	14	0.889	0.044	0.414
Development of single phase natural circulation in FAs, storage racks and SFP.	II.2	SU	2	10	7	0.632	4	12	1	0.412	1	10	7	0.667	0.464	0.361
		FD	5	8	6	0.526	4	11	2	0.441	1	8	9	0.722	0.306	0.507
Development of two-phase natural circulation in FAs, storage racks and SFP. Including liquid water, steam and H_2.	II.3	SU	4	8	7	0.579	7	10	0	0.294	3	14	1	0.444	0.850	0.321
		FD	9	6	4	0.368	6	9	1	0.344	3	12	2	0.471	0.479	0.472
Water level difference between FA and storage rack (for criticality calculation).	II.4	SU	0	11	3	0.607	3	8	2	0.462	0	9	4	0.654	0.424	0.223
		FD	7	4	2	0.308	4	5	3	0.458	0	6	6	0.750	0.156	0.536
Parallel channel flow instability, including counter current flow and dryout.	II.5	SU	4	9	4	0.500	6	9	1	0.344	2	10	4	0.563	0.538	0.459
		FD	10	4	3	0.294	6	8	2	0.375	2	9	5	0.594	0.280	0.620
Effect of flow blockage due to fuel rod ballooning and rack geometry degradation.	II.6	SU	1	13	4	0.583	3	11	3	0.500	2	10	5	0.588	0.450	0.351
		FD	4	8	6	0.556	3	11	3	0.500	2	10	5	0.588	0.428	0.517
Multi-dimensional neutronic-thermal hydraulic coupling.	II.7	SU	3	8	2	0.462	3	7	2	0.458	2	8	2	0.500	0.468	0.436
		FD	7	5	1	0.269	4	5	3	0.458	2	6	4	0.583	0.228	0.634
Return of condensate to pool.	II.8	SU	7	5	6	0.472	5	6	5	0.500	2	10	4	0.563	0.387	0.770
		FD	10	7	1	0.250	4	6	4	0.500	2	9	3	0.536	0.217	0.516
2. Heat transfer																
Air cooling of the FAs and storage racks after complete pool drainage.	II.9	SU	1	10	8	0.684	4	10	4	0.500	1	13	5	0.605	0.506	0.387
		FD	1	3	15	0.868	4	8	6	0.556	1	13	5	0.605	0.571	0.402
Convective heat transfer between water and structures in the SFP (fuel cladding, canister, storage rack cell).	II.10	SU	5	6	7	0.556	2	6	9	0.706	1	4	12	0.824	0.108	0.630
		FD	9	4	5	0.389	2	5	9	0.719	1	4	11	0.813	0.077	0.690

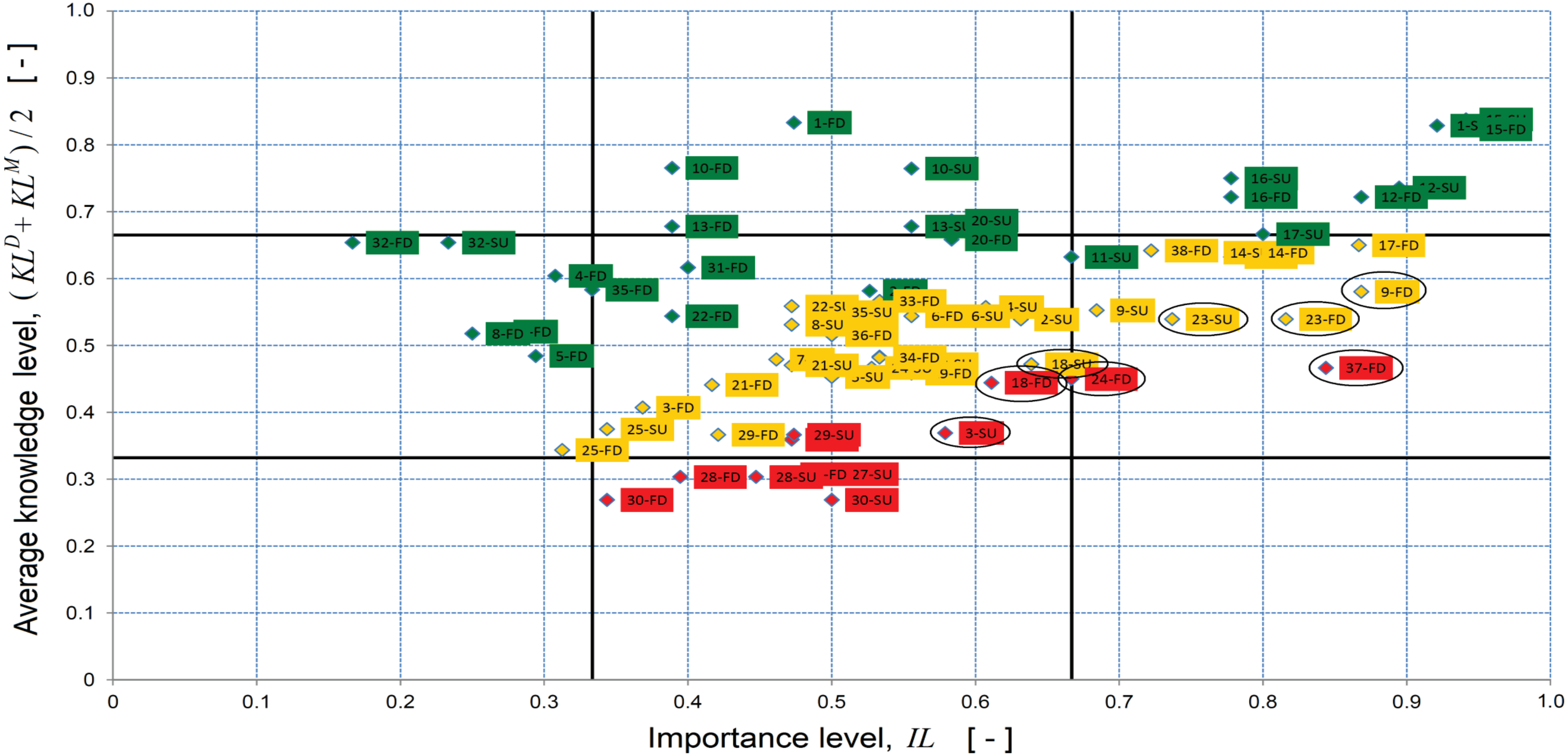
Phenomena by category	#	Scenario	Importance ranking				State of knowledge								Screening-parameters	
							Availability of data				Availability of models					
			L	M	H	*IL*	N	S	A	KL^D	N	S	A	KL^M	*R*	*D*
Convective heat transfer between air/steam and structures in the SFP (fuel cladding, canister, storage rack cell).	II.11	SU	2	8	8	0.667	3	10	4	0.529	1	7	9	0.735	0.311	0.494
		FD	1	6	11	0.778	3	10	4	0.529	1	7	9	0.735	0.363	0.444
Heat generation from oxidation of cladding, storage racks, etc.	II.12	SU	0	4	15	0.895	4	3	11	0.694	1	6	11	0.778	0.228	0.386
		FD	0	5	14	0.868	4	3	11	0.694	1	7	10	0.750	0.248	0.419
Heat generation from H_2 + O_2 combustion.	II.13	SU	6	4	8	0.556	2	7	7	0.656	1	7	7	0.700	0.215	0.698
		FD	9	4	5	0.389	2	7	7	0.656	1	7	7	0.700	0.150	0.681
Radiative heat transfer from uncovered FAs to other FAs and the SFP structure.	II.14	SU	0	9	10	0.763	2	10	6	0.611	0	12	6	0.667	0.370	0.283
		FD	1	6	12	0.789	2	10	6	0.611	0	12	6	0.667	0.383	0.335
3. Fuel behaviour																
Fuel/cladding heatup.	II.15	SU	1	0	16	0.941	1	6	10	0.765	1	1	15	0.912	0.073	0.280
		FD	1	0	16	0.941	0	8	9	0.765	1	2	14	0.882	0.098	0.245
Cladding creep and ballooning.	II.16	SU	0	8	10	0.778	0	9	9	0.750	1	7	10	0.750	0.182	0.286
		FD	0	8	10	0.778	0	10	8	0.722	1	8	9	0.722	0.225	0.283
Burst of fuel rod cladding tubes	II.17	SU	1	4	10	0.800	0	9	6	0.700	0	11	4	0.633	0.330	0.254
		FD	0	4	11	0.867	0	10	5	0.667	0	11	4	0.633	0.397	0.177
Fuel fragmentation and relocation during ballooning, before cladding rupture.	II.18	SU	2	9	7	0.639	0	17	1	0.528	5	11	2	0.417	0.659	0.171
		FD	2	10	6	0.611	1	16	1	0.500	5	12	1	0.389	0.699	0.214
Burst fission gas release, i.e. release of retained fission gases due to fuel fragmentation within the sound cladding.	II.19	SU	4	8	6	0.556	4	11	3	0.472	4	11	3	0.472	0.580	0.545
		FD	4	8	6	0.556	4	12	2	0.444	4	11	3	0.472	0.610	0.497
Heat transfer in fuel rods; temperature distribution and resulting strains and stresses.	II.20	SU	6	3	9	0.583	2	9	7	0.639	1	7	9	0.735	0.209	0.677
		FD	6	3	9	0.583	3	8	7	0.611	1	8	8	0.706	0.250	0.734
Cladding hydrogen pick-up under steam + air + hydrogen environment.	II.21	SU	6	7	5	0.472	0	17	0	0.500	3	13	1	0.441	0.494	0.000
		FD	8	5	5	0.417	1	16	0	0.471	4	12	1	0.412	0.486	0.193
Zirconium hydride formation and dissolution in the cladding.	II.22	SU	5	9	4	0.472	0	14	3	0.588	2	12	3	0.529	0.343	0.278
		FD	7	8	3	0.389	0	14	3	0.588	3	11	3	0.500	0.300	0.309
Cladding oxidation under air or/and (steam + hydrogen)	II.23	SU	2	6	11	0.737	1	14	4	0.579	2	15	2	0.500	0.581	0.291

Phenomena by category	#	Scenario	Importance ranking				State of knowledge								Screening-parameters	
							Availability of data				Availability of models					
			L	M	H	IL	N	S	A	KL^D	N	S	A	KL^M	R	D
mixture environment, influence of nitriding.		FD	0	7	12	0.816	1	14	4	0.579	2	15	2	0.500	0.643	0.207
Nitrogen-assisted oxide breakaway at low temperature.	II.24	SU	5	7	6	0.528	2	9	4	0.567	4	11	0	0.367	0.542	0.408
		FD	3	6	9	0.667	3	8	4	0.533	4	11	0	0.367	0.738	0.429
Pellet-cladding de-bonding in high burnup fuel.	II.25	SU	7	7	2	0.344	5	9	2	0.406	5	11	0	0.344	0.502	0.384
		FD	7	8	1	0.313	6	8	2	0.375	6	10	0	0.313	0.503	0.368
Spallation of initial cladding oxide layer.	II.26	SU	4	11	3	0.472	3	12	1	0.438	8	7	1	0.281	0.715	0.351
		FD	4	11	3	0.472	3	12	1	0.438	8	7	1	0.281	0.715	0.351
Power excursion and fuel damage in specific FAs with high decay power.	II.27	SU	3	10	3	0.500	6	7	0	0.269	5	7	1	0.346	0.895	0.354
		FD	4	9	3	0.469	6	7	0	0.269	5	7	1	0.346	0.839	0.381
4. Pool concrete and liner effects																
Pool concrete deterioration and cracking by temperature rise.	II.28	SU	6	9	4	0.447	5	9	0	0.321	6	8	0	0.286	0.812	0.326
		FD	7	9	3	0.395	5	9	0	0.321	6	8	0	0.286	0.717	0.315
Pool liner deterioration and cracking by temperature rise.	II.29	SU	7	6	6	0.474	5	9	1	0.367	5	9	1	0.367	0.712	0.520
		FD	8	6	5	0.421	5	9	1	0.367	5	9	1	0.367	0.633	0.512
Leakage due to pool concrete and liner deterioration and cracking by temperature rise.	II.30	SU	5	6	5	0.500	7	5	1	0.269	6	7	0	0.269	1.000	0.479
		FD	9	3	4	0.344	7	5	1	0.269	6	7	0	0.269	0.688	0.512
5. Criticality issues																
Loss of subcriticality by boric acid dilution with injected fresh water.	II.31	SU	6	6	3	0.400	5	3	7	0.567	3	4	8	0.667	0.216	1.000
		FD	5	8	2	0.400	5	3	7	0.567	3	4	8	0.667	0.216	0.873
Loss of subcriticality by loss of coolant.	II.32	SU	9	5	1	0.233	3	5	5	0.577	2	3	8	0.731	0.100	0.679
		FD	11	3	1	0.167	4	4	5	0.538	2	2	9	0.769	0.066	0.706
Loss of subcriticality by pool refilling; reflood of FAs from below.	II.33	SU	3	8	4	0.533	5	5	5	0.500	3	5	7	0.633	0.366	0.821
		FD	3	8	4	0.533	5	5	5	0.500	3	5	7	0.633	0.366	0.821
Loss of subcriticality by water spray injection; water injection above the FAs.	II.34	SU	2	10	3	0.533	6	7	2	0.367	3	6	6	0.600	0.506	0.559
		FD	2	10	3	0.533	6	6	2	0.357	3	5	6	0.607	0.504	0.594

Phenomena by category	#	Scenario	Importance ranking				State of knowledge								Screening-parameters	
							Availability of data				Availability of models					
			L	M	H	IL	N	S	A	KL^D	N	S	A	KL^M	R	D
Loss of subcriticality by an increase in coolant void fraction.	II.35	SU	4	7	4	0.500	4	7	4	0.500	3	6	6	0.600	0.375	0.764
		FD	7	6	2	0.333	5	5	5	0.500	3	4	8	0.667	0.208	0.863
Loss of subcriticality due to deformation of fuel storage racks or/and spent fuel assemblies.	II.36	SU	4	9	4	0.500	5	7	4	0.469	3	8	5	0.563	0.435	0.683
		FD	4	9	4	0.500	5	7	4	0.469	3	8	5	0.563	0.435	0.683
6. Mitigation																
Fuel cooling by water spray; water injection above the FAs.	II.37	SU	0	5	11	0.844	3	11	1	0.433	2	11	2	0.500	0.895	0.229
		FD	0	5	11	0.844	3	11	1	0.433	2	11	2	0.500	0.895	0.229
Fuel cooling by recovery of water makeup; reflood of FAs from below.	II.38	SU	2	6	10	0.722	2	9	6	0.618	1	10	7	0.667	0.345	0.488
		FD	2	6	10	0.722	2	9	6	0.618	1	10	7	0.667	0.345	0.488

Figure 7: Graphical presentation of ranking results for the Phase II phenomena in the (*IL*,*KL*)-plane

Phenomena with priority research needs are circled. The colour coding of the markers reflects the relative relevance (*R*) of each phenomenon, as defined through eq. (9) and the colour key in **Table 5**.



4.3. Fuel damage phase

4.3.1. Phenomena Identification and Ranking Table

Table 8 is the PIRT developed for the fuel damage phase of the accident. It contains the ranking results for the 61 identified phenomena, with detailed information on the distribution of votes from the expert panel. The colour coding used for the importance and knowledge levels is defined in Table 5.

The most important results in the PIRT are presented graphically in Figure 8, where each phenomenon and accident scenario is plotted in the same way as for Phase I in Figure 6 and Phase II in Figure 7. Obviously, a significant fraction of the phenomena in Phase III have an importance level above 0.7. This is to some part a consequence of the evaluation criteria used in the study: we recall from Section 0.0.0 that one of them concerned fuel damage.

4.3.2. Phenomena with priority research needs

The expert panel identified nine phenomena in the fuel damage phase, for which further research should be given priority. Two of the phenomena are identical to high-priority phenomena identified for the uncovery phase of the accident. Here, however, these two phenomena could be made more complex by fuel damage, such as geometrical distortion of the fuel assemblies and storage racks. Most of the identified high-priority phenomena are deemed important both for the slow uncovery and the fast drainage accident scenario, which suggests that the phenomena in this late phase of the accident are not much affected by the scenario. The importance level of the high-priority phenomena ranges from 0.56 to 0.95, whereas the knowledge level falls between 0.28 and 0.50; see Figure 8.

4.3.2.1 Stop of natural circulation of air through the FAs by water, injected or sprayed as mitigation measure (III.3)

This phenomenon is specific to BWR fuel assemblies and/or to LWR fuel storage racks of closed-cell design, where the cell walls prevent lateral cross-flow. The worst possible scenario with regard to fuel coolability in these racks is deemed to arise when the racks are nearly completely uncovered and only the bottom inlets of the rack cells are immersed in water; see Section 2.2.1. The scenario is considered worse than a completely drained pool, in which natural circulation of air would provide some cooling. The scenario may occur transitionally during uncovery (see phenomenon III.8, Section 0.0.0), but also when refilling a completely drained pool. In the latter case, the natural circulation of air would stop temporarily when the airflow through the rack inlet is blocked by the rising water, and the temperature of the stored fuel would increase. To limit the temperature rise, it is believed that refilling a completely drained pool is sometimes better done by spraying from the top than by injecting water from below, especially if the water injection rate is limited and the refilling slow [18, 23]. Experiments and modelling are needed to confirm this conjecture.

4.3.2.2 Air cooling of the FAs and storage racks after complete pool drainage (III.7)

This phenomenon was identified also for the uncovery phase of the accident; see Section 4.2.2.2. However, for the fuel damage phase, where the fuel may not be intact, the knowledge level for air cooling is deemed lower, especially with regard to modelling. The main reason is the uncertainty associated with geometry distortion of damaged fuel and storage racks and its effects on convective flow. These effects are difficult to model; see also Section 4.3.2.4.

4.3.2.3 Coolability of almost completely uncovered FAs, with their bottom ends immersed in water (III.8)

The coolability of partly uncovered fuel assemblies is a complex issue that involves convective heat transfer between water and degraded fuel for the immersed part and convective, conductive and radiative heat transfer for the uncovered part; see Section 2.2.1. Hence, this phenomenon represents the combined effects of several heat transfer mechanisms in Table 8 (III.9, III.10, III.12, III.14), and must be addressed by integral tests on prototypic fuel assemblies and rack designs. Such tests are underway for PWR fuel, but similar tests are needed for other technologies. The main safety concern is that insufficient cooling of the uncovered part of the fuel assemblies would lead to runaway zirconium-steam-air reactions, resulting in a significant temperature rise and ultimately in a self-sustained zirconium fire [1].

4.3.2.4 Influence of geometry changes during degradation on heat transfer (III.11)

This phenomenon covers heat transfer implications from a broad spectrum of degradation induced geometry changes, ranging from fuel rod ballooning to formation of debris beds. It refers to heat transfer mechanisms between degraded fuel and steam/air, as well as interaction with liquid water, if present. As mentioned in Section 2.3.1, the thermal-hydraulic conditions in different parts of the SFP may change considerably as the fuel damage phase progresses. Debris from oxidised and collapsed fuel rods may block axial flow paths in the lower part of the storage racks, while melting and candling may open new paths for lateral cross-flow between adjacent rack cells in the upper part. These geometry changes and their effects on thermal-hydraulics and heat transfer are difficult to model mechanistically, and relevant data for model validation are needed. The difficulties in modelling heat transfer after the fuel geometry is lost is not specific to SFP accidents, but pertain also to reactor accidents. The current modelling approach for these phenomena in severe accident codes is considered to be state-of-the-art. As evidenced by the ranking results in Table 8, the estimated knowledge level for the heat transfer effects of geometry changes is low, especially with regard to data. The current data base consists of the aforementioned Sandia tests on completely uncovered fuel assemblies [24-26] and results from reactor LOCA tests [82].

4.3.2.5 Radiative heat transfer from uncovered FAs to other FAs, racks and SFP structure (III.12)

This phenomenon refers to radiative heat from uncovered and possibly damaged fuel assemblies, as opposed to convective and conductive heat transfer. From Table 8, we note that radiation (III.12) is in fact deemed to be slightly less important than convective heat transfer by air (III.10), but the knowledge level is considered to be lower: the scarcity of relevant data, e.g. for emissivities, is the main concern. The phenomenon also includes radiative heat transfer between other uncovered structures (notably racks) in the SFP, water and the pool walls and floor. The radiative heat transfer between uncovered FAs and these structures is expected to depend strongly on rack geometry, pool design and storage configuration of the spent fuel. A considerable difficulty in this context is that view factors may change with progressing fuel damage as a result of deformation and collapse, and surface emissivities of the involved structures may also change by oxidation or deposition. These phenomena are difficult to assess quantitatively by experiments. In calculations with severe accident codes, they are usually accounted for by sensitivity analysis.

4.3.2.6 Re-oxidation of ZrN by steam/oxygen (III.22)

When zirconium nitride, which has formed at high temperature by air-zirconium reactions in oxygen starved environment, is exposed to steam and/or oxygen, e.g. by rewetting the cladding, the nitride will be oxidised through exothermic reactions; see eqs. (5) and (6) in Section 2.2.3. Some integral LOCA tests, which involve reflooding of fuel assemblies that have been severely oxidised and nitrided in air/steam environment, give evidence of energetic and damaging reactions during the reflooding phase [38, 39]. Part of the released energy stems from oxidation of the remaining zirconium metal, part from oxidation of the zirconium nitride. As of today, computer codes used for analyses of severe accidents have models for oxidation of the zirconium metal, but usually not for the zirconium nitride [1]. This explains the very low knowledge level with regard to models for this phenomenon; see Table 8. Separate effect tests on re-oxidation of nitrided zirconium alloy cladding are required for developing the missing models.

4.3.2.7 Fuel volatilisation and behaviour of fuel fines (III.49)

Fuel volatilisation and behaviour of fuel fines was deemed to be a moderately important phenomenon by the expert panel, but on the other hand, it received one of the lowest knowledge levels among phenomena identified for the fuel damage phase; see Table 8. Contribution of fuel fines to the source term depends both on fuel fines production rate and on presence of sufficient driving force for their transport from the pool to the environment. We recall from Section 2.3.2 that air ingress into the SFP changes the redox conditions such that the potential for release of semi/low-volatile fission products and fuel fines increases in comparison with the steam environment associated with reactor accidents. The increase is related to the oxidation and volatilisation of the UO_2 fuel matrix into U_3O_8 or UO_3, but also to oxidation of metallic semi-volatile and low-volatile fission products into more volatile oxides or complex compounds [43, 50, 52]. There is a very limited amount of quantitative data on fission product release from UO_2 and $(U,Pu)O_2$ mixed oxide (MOX) fuel in air or air-steam environment; most of the data are for steam and applicable mostly to reactor accident conditions [1]. Source term estimates for SFP accidents that involve loss of cladding integrity and fuel pellet exposure to air are therefore uncertain.

4.3.2.8 Loss of subcriticality due to relocation of absorber materials (III.58)

This phenomenon was judged to be of moderate importance by the expert panel. Yet, it is considered here because of its low level of knowledge with regard to data; see Table 8. The phenomenon pertains only to LWR fuel and to high density storage racks, i.e. rack designs where the fuel assembly spacing alone is inadequate to provide the required margin to criticality. High density racks are either made of structural materials (stainless steel, aluminium) alloyed with boron or contain boron-bearing absorbers as additional sheaths or sheets within the structure [1].

The concern is that relocation of absorber material would lead to loss of subcriticality. The very few available studies on this issue in the open literature [87, 88] show that relocation of absorber material does not pose a criticality problem in completely drained parts of the SFP. Criticality seems possible only if un-borated water is present as a neutron moderator. This suggests that refilling a drained SFP with un-borated water, in which absorber material has been lost from high density storage racks, could be a problem. Also, in a partially drained pool, subcriticality could possibly be lost if absorber material relocates in regions where water is still present or being re-filled. Further studies are needed on these issues.

4.3.2.9 Fuel cooling by water spray: water injection above the FAs (III.59)

This phenomenon was identified also for Phase II; see Section 4.2.2.6. For the fuel damage phase, spray cooling is deemed more important, while the knowledge level is lower. The reason is that effects of fuel damage and geometry distortion of fuel and storage racks on spraying efficiency are largely unknown.

Table 8: PIRT for Phase III (fuel damage phase) of the considered accident scenarios; slow uncovery (SU) and fast drainage (FD)

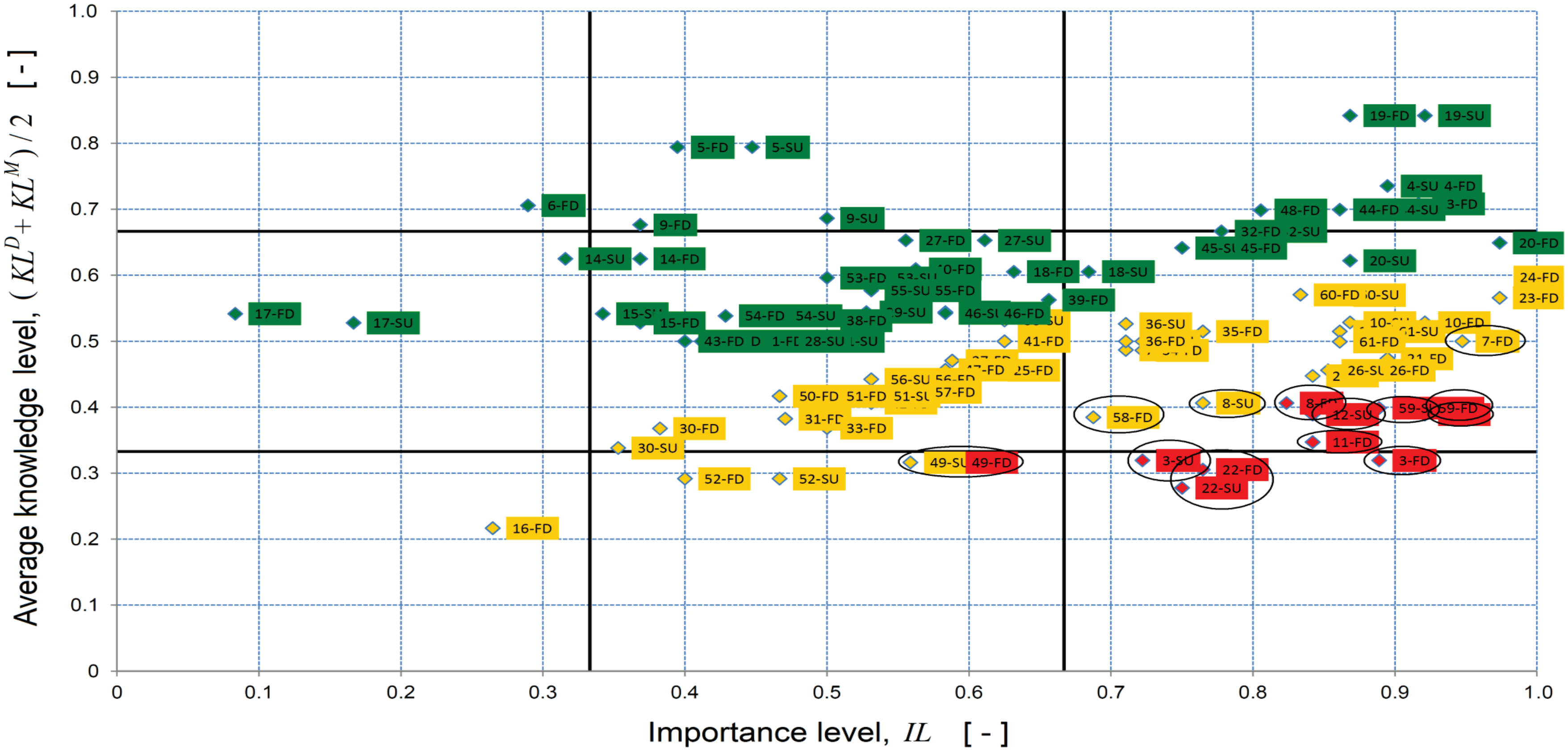
Phenomena by category	#	Scenario	Importance ranking				State of knowledge								Screening-parameters	
							Availability of data				Availability of models					
			L	M	H	*IL*	N	S	A	KL^D	N	S	A	KL^M	*R*	*D*
1. Thermal-hydraulics																
Pathways for cross-flow between adjacent rack cells	III.1	SU	3	13	3	0.500	8	6	4	0.389	2	10	6	0.611	0.289	0.537
		FD	5	11	3	0.447	8	6	4	0.389	2	10	6	0.611	0.258	0.612
Natural circulation by air in the pool, including open downward flow paths into FAs	III.2	SU	2	6	10	0.722	6	9	2	0.382	2	9	6	0.618	0.414	0.550
		FD	1	3	14	0.861	5	10	2	0.412	2	9	6	0.618	0.471	0.430
Stop of natural circulation of air through the FAs by water, injected or sprayed as mitigation measure	III.3	SU	2	6	10	0.722	8	9	1	0.306	6	12	0	0.333	0.813	0.369
		FD	0	4	14	0.889	8	9	1	0.306	6	12	0	0.333	1.000	0.224
2. Power generation																
Heat generation from oxidation of cladding, storage racks, etc.	III.4	SU	1	2	16	0.895	2	7	8	0.676	1	5	11	0.794	0.145	0.412
		FD	1	1	17	0.921	2	7	8	0.676	1	5	11	0.794	0.149	0.386
Heat generation from H_2 + O_2 combustion	III.5	SU	7	7	5	0.447	1	5	11	0.794	2	3	12	0.794	0.046	0.632
		FD	7	9	3	0.395	1	5	11	0.794	2	3	12	0.794	0.041	0.557
Heat generation from released fission products	III.6	SU	10	7	2	0.289	2	6	9	0.706	1	8	8	0.706	0.061	0.541
		FD	10	7	2	0.289	2	6	9	0.706	1	8	8	0.706	0.061	0.541
3. Heat transfer																
Air cooling of the FAs and storage racks after complete pool drainage	III.7	SU	3	5	11	0.711	6	8	5	0.474	4	11	4	0.500	0.454	0.713
		FD	0	2	17	0.947	5	9	5	0.500	4	11	4	0.500	0.576	0.280
Coolability of almost completely uncovered FAs, with their bottom ends immersed in water (partial drain down)	III.8	SU	3	2	12	0.765	5	10	1	0.375	5	8	3	0.438	0.653	0.584
		FD	2	2	13	0.824	5	10	1	0.375	5	8	3	0.438	0.704	0.513
Convective heat transfer between water and structures in the SFP (fuel cladding, canister, rack cell)	III.9	SU	6	7	6	0.500	1	10	7	0.667	1	8	8	0.706	0.119	0.533
		FD	10	4	5	0.368	1	10	6	0.647	1	8	8	0.706	0.093	0.562
Convective heat transfer between air/steam and structures in the SFP (fuel cladding, canister, rack cell)	III.10	SU	1	3	15	0.868	4	12	3	0.474	2	11	5	0.583	0.463	0.385
		FD	1	1	17	0.921	4	12	3	0.474	2	11	5	0.583	0.491	0.343
Influence of geometry changes during degradation on heat transfer (both in water and air/steam)	III.11	SU	0	6	13	0.842	9	8	1	0.278	4	13	1	0.417	0.862	0.269
		FD	0	6	13	0.842	9	8	1	0.278	4	13	1	0.417	0.862	0.269
Radiative heat transfer from uncovered fuel assemblies to other FAs, racks and SFP structure	III.12	SU	0	6	13	0.842	7	11	0	0.306	2	15	1	0.472	0.750	0.177
		FD	0	3	16	0.921	7	11	0	0.306	2	15	1	0.472	0.820	0.139
Fuel/cladding heat up	III.13	SU	1	1	16	0.917	3	5	10	0.694	1	8	9	0.722	0.189	0.437
		FD	1	1	16	0.917	3	5	10	0.694	1	8	9	0.722	0.189	0.437

Phenomena by category	#	Scenario	Importance ranking				State of knowledge: Availability of data				State of knowledge: Availability of models				Screening-parameters	
			L	M	H	*IL*	N	S	A	KL^D	N	S	A	KL^M	*R*	*D*
Heat conduction in different components. e.g. storage racks, SFP walls and floor.	III.14	SU	8	10	1	0.316	3	8	7	0.611	2	9	7	0.639	0.108	0.520
		FD	7	10	2	0.368	3	8	7	0.611	2	9	7	0.639	0.126	0.569
Outlet fluid sensible heat. Influences the buoyancy of the bulk steam/gas flow in the SFP, and in turn, the transport of released fission products to the environment	III.15	SU	8	9	2	0.342	5	9	4	0.472	1	12	5	0.611	0.171	0.475
		FD	8	8	3	0.368	5	9	4	0.472	2	11	5	0.583	0.197	0.585
4. Fuel behaviour																
Effect of sea water injection on the fuel degradation and coolability	III.16	SU	8	9	0	0.265	9	5	1	0.233	9	6	0	0.200	0.395	0.293
		FD	8	9	0	0.265	9	5	1	0.233	9	6	0	0.200	0.395	0.293
Water radiolysis and hydrogen production	III.17	SU	13	4	1	0.167	5	7	6	0.528	5	7	6	0.528	0.090	0.679
		FD	16	1	1	0.083	4	8	6	0.556	5	7	6	0.528	0.043	0.556
Fuel cladding embrittlement due to hydriding and oxidation	III.18	SU	4	4	11	0.684	1	12	6	0.632	2	12	5	0.579	0.258	0.502
		FD	5	4	10	0.632	1	12	6	0.632	2	12	5	0.579	0.238	0.526
Zr oxidation in steam. Includes heat/hydrogen generation and kinetics (oxide breakaway)	III.19	SU	1	1	17	0.921	2	2	15	0.842	0	6	13	0.842	0.056	0.287
		FD	1	3	15	0.868	2	2	15	0.842	0	6	13	0.842	0.053	0.321
Zr oxidation in air by oxygen. Includes heat generation and kinetics (oxide breakaway)	III.20	SU	1	3	15	0.868	4	7	8	0.605	2	9	7	0.639	0.301	0.527
		FD	0	1	18	0.974	3	8	8	0.632	1	10	7	0.667	0.291	0.178
Nitride formation in air	III.21	SU	0	6	13	0.842	4	12	3	0.474	5	12	2	0.421	0.624	0.319
		FD	0	4	15	0.895	3	13	3	0.500	4	13	2	0.447	0.601	0.245
Re-oxidation of ZrN by steam/oxygen	III.22	SU	0	9	9	0.750	6	11	1	0.361	11	7	0	0.194	0.938	0.263
		FD	0	8	9	0.765	5	12	1	0.389	10	8	0	0.222	0.883	0.256
Zr oxidation in steam/air mixtures. Includes oxygen starvation during oxidation in steam/air and oxide breakaway	III.23	SU	0	1	18	0.974	4	9	6	0.553	2	12	5	0.579	0.446	0.182
		FD	0	1	18	0.974	4	9	6	0.553	2	12	5	0.579	0.446	0.182
Cladding ignition	III.24	SU	1	3	14	0.861	3	9	6	0.583	2	12	4	0.556	0.388	0.421
		FD	0	0	18	1.000	2	10	6	0.611	1	13	4	0.583	0.394	0.000
Oxidation of debris	III.25	SU	4	5	8	0.618	4	11	2	0.441	2	14	1	0.471	0.444	0.378
		FD	4	5	8	0.618	4	11	2	0.441	2	14	1	0.471	0.444	0.378
Fuel-steam/air reaction: Ruthenium release	III.26	SU	1	3	13	0.853	3	13	1	0.441	3	12	2	0.471	0.613	0.280
		FD	1	2	14	0.882	3	13	1	0.441	3	12	2	0.471	0.634	0.268
Stainless steel-steam reaction: oxidation and hydrogen production	III.27	SU	1	12	5	0.611	3	8	7	0.611	2	7	9	0.694	0.176	0.497
		FD	3	10	5	0.556	3	8	7	0.611	2	7	9	0.694	0.160	0.614
B_4C (boron carbide)-steam reaction: oxidation and gas production (H_2, CO, CO_2, CH_4, etc.)	III.28	SU	6	6	5	0.471	4	10	3	0.471	2	12	3	0.529	0.285	0.535
		FD	8	4	5	0.412	4	10	3	0.471	2	12	3	0.529	0.249	0.571
Stainless steel-air reaction: oxidation	III.29	SU	3	11	4	0.528	6	4	7	0.529	5	5	7	0.559	0.266	0.872
		FD	1	13	4	0.583	6	4	7	0.529	5	5	7	0.559	0.294	0.702
B_4C-air reaction: oxidation and gas production	III.30	SU	8	6	3	0.353	8	8	1	0.294	7	7	3	0.382	0.374	0.634

Phenomena by category	#	Scenario	Importance ranking				State of knowledge								Screening-parameters	
							Availability of data				Availability of models					
			L	M	H	IL	N	S	A	KL^D	N	S	A	KL^M	R	D
		FD	7	7	3	0.382	7	9	1	0.324	6	8	3	0.412	0.370	0.587
Oxidation in molten pool geometry	III.31	SU	6	6	5	0.471	4	13	0	0.382	5	11	1	0.382	0.436	0.359
		FD	6	6	5	0.471	4	13	0	0.382	5	11	1	0.382	0.436	0.359
5. Fuel assembly and storage rack degradation																
Start of melting: fuel pellets, cladding and rack material, and mixtures of stainless steel and B_4C	III.32	SU	1	5	12	0.806	2	9	7	0.639	0	11	7	0.694	0.216	0.362
		FD	2	4	12	0.778	2	9	7	0.639	0	11	7	0.694	0.209	0.420
Fuel fragmentation and axial relocation of the fuel pellet fragments inside the ballooned fuel rods	III.33	SU	5	9	5	0.500	6	12	1	0.368	6	12	1	0.368	0.485	0.420
		FD	5	9	5	0.500	6	12	1	0.368	6	12	1	0.368	0.485	0.420
Debris formation and relocation	III.34	SU	2	6	10	0.722	5	12	1	0.389	1	13	4	0.583	0.447	0.353
		FD	2	6	10	0.722	5	12	1	0.389	1	13	4	0.583	0.447	0.353
Formation of molten pools and relocation of molten materials	III.35	SU	2	4	11	0.765	3	13	1	0.441	1	12	4	0.588	0.428	0.325
		FD	2	4	11	0.765	3	13	1	0.441	1	12	4	0.588	0.428	0.325
Eutectic reactions, e.g. between stainless steel and B_4C	III.36	SU	2	7	10	0.711	3	13	3	0.500	2	13	4	0.553	0.386	0.405
		FD	2	7	10	0.711	4	12	3	0.474	3	12	4	0.526	0.430	0.477
Channel blockage by collapsed fuel rods	III.37	SU	2	10	5	0.588	5	10	2	0.412	2	12	3	0.529	0.396	0.397
		FD	2	10	5	0.588	5	10	2	0.412	2	12	3	0.529	0.396	0.397
6. Molten material issues																
Molten material – water interaction	III.38	SU	1	10	5	0.625	2	10	4	0.563	1	14	1	0.500	0.332	0.229
		FD	5	6	5	0.500	2	10	4	0.563	1	14	1	0.500	0.266	0.324
Heat generation from molten material – concrete interaction (reaction)	III.39	SU	1	9	6	0.656	2	9	5	0.594	2	11	3	0.531	0.304	0.397
		FD	1	9	6	0.656	2	9	5	0.594	2	11	3	0.531	0.304	0.397
Gas generation (H_2, CO, CO_2, etc.) from molten material – concrete interaction (reaction)	III.40	SU	3	8	5	0.563	3	7	6	0.594	1	10	5	0.625	0.208	0.547
		FD	3	8	5	0.563	3	7	6	0.594	1	10	5	0.625	0.208	0.547
Aerosol generation from molten fuel-concrete interaction (reaction)	III.41	SU	1	10	5	0.625	3	10	2	0.467	1	12	2	0.533	0.378	0.274
		FD	1	10	5	0.625	3	10	2	0.467	1	12	2	0.533	0.378	0.274
Crust porosity and coolability at MCCI	III.42	SU	4	7	5	0.531	3	13	0	0.406	3	13	0	0.406	0.455	0.220
		FD	4	7	5	0.531	3	13	0	0.406	3	13	0	0.406	0.455	0.220
Convection in molten pools	III.43	SU	6	6	3	0.400	4	9	2	0.433	2	9	4	0.567	0.239	0.553
		FD	6	6	3	0.400	4	9	2	0.433	2	9	4	0.567	0.239	0.553
7. Fission product release and transport																
Transport of released fission products	III.44	SU	0	4	14	0.889	0	11	6	0.676	0	10	8	0.722	0.194	0.191
		FD	0	5	13	0.861	0	11	6	0.676	0	10	8	0.722	0.188	0.206
Fission product deposition	III.45	SU	1	7	10	0.750	1	12	4	0.588	0	11	7	0.694	0.229	0.291

Phenomena by category	#	Scenario	Importance ranking				State of knowledge: Availability of data				Availability of models				Screening-parameters	
			L	M	H	*IL*	N	S	A	KL^D	N	S	A	KL^M	*R*	*D*
		FD	0	8	10	0.778	1	12	4	0.588	0	11	7	0.694	0.238	0.240
Fission product chemistry	III.46	SU	2	11	5	0.583	2	12	3	0.529	1	14	3	0.556	0.296	0.287
		FD	1	12	5	0.611	2	12	3	0.529	1	14	3	0.556	0.311	0.255
Fission product re-suspension	III.47	SU	2	11	5	0.583	4	11	2	0.441	4	11	3	0.472	0.418	0.421
		FD	1	13	4	0.583	4	11	2	0.441	4	11	3	0.472	0.418	0.350
Release of fission products from the fuel	III.48	SU	2	3	13	0.806	0	12	5	0.647	0	9	9	0.750	0.173	0.299
		FD	1	5	12	0.806	0	12	5	0.647	0	9	9	0.750	0.173	0.260
Fuel volatilisation, behaviour of fuel fines	III.49	SU	5	5	7	0.559	8	8	0	0.250	6	9	2	0.382	0.629	0.519
		FD	4	6	7	0.588	8	8	0	0.250	6	9	2	0.382	0.662	0.489
8. Pool concrete and liner effects																
Pool concrete deterioration and cracking by temperature rise	III.50	SU	4	7	4	0.500	3	8	1	0.417	3	8	1	0.417	0.413	0.432
		FD	5	6	4	0.467	3	8	1	0.417	3	8	1	0.417	0.386	0.456
Pool liner deterioration and cracking by temperature rise	III.51	SU	4	6	5	0.533	4	7	1	0.375	2	9	1	0.458	0.439	0.438
		FD	5	5	5	0.500	4	7	1	0.375	2	9	1	0.458	0.411	0.464
Leakage due to pool concrete and liner deterioration and cracking by temperature rise	III.52	SU	6	4	5	0.467	6	6	0	0.250	4	8	0	0.333	0.567	0.389
		FD	6	6	3	0.400	6	6	0	0.250	4	8	0	0.333	0.486	0.341
9. Criticality issues																
Loss of subcriticality by boric acid dilution with injected fresh water	III.53	SU	4	5	5	0.536	5	3	5	0.500	2	4	7	0.692	0.200	1.000
		FD	4	6	4	0.500	5	3	5	0.500	2	4	7	0.692	0.187	0.947
Loss of subcriticality by an increase in coolant void fraction	III.54	SU	4	7	3	0.464	4	6	3	0.462	2	6	5	0.615	0.234	0.692
		FD	5	6	3	0.429	5	5	3	0.423	2	5	6	0.654	0.208	0.797
Loss of subcriticality by pool refilling; reflood of FAs from below	III.55	SU	4	7	5	0.531	4	5	4	0.500	2	5	6	0.654	0.223	0.819
		FD	4	6	6	0.563	4	5	4	0.500	2	5	6	0.654	0.237	0.855
Loss of subcriticality by water spray injection; injection above the FAs	III.56	SU	5	5	6	0.531	7	4	2	0.308	3	5	5	0.577	0.378	0.908
		FD	5	4	7	0.563	7	4	2	0.308	3	5	5	0.577	0.400	0.941
Loss of subcriticality due to deformation of fuel storage racks or/and spent fuel assemblies	III.57	SU	5	4	7	0.563	6	5	2	0.346	3	7	3	0.500	0.447	0.813
		FD	5	4	7	0.563	6	5	2	0.346	3	7	3	0.500	0.447	0.813
Loss of subcriticality due to relocation of absorber materials	III.58	SU	2	6	8	0.688	9	2	2	0.231	4	4	5	0.538	0.593	0.832
		FD	2	6	8	0.688	9	2	2	0.231	4	4	5	0.538	0.593	0.832

Figure 8: Graphical presentation of ranking results for the Phase III phenomena in the (*IL*,*KL*)-plane
Phenomena with priority research needs are circled. The colour coding of the markers reflects the relative relevance (*R*) of each phenomenon, as defined through eq. (9) and the colour key in **Table 5**



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4.4. Influential initial conditions and boundary conditions

Influential initial conditions and boundary conditions were identified by the expert panel in the same manner as the phenomena considered in the PIRTs, but they were not subsequently ranked. Some of the most important initial/boundary conditions, such as the assumed SFP fuel inventory, fuel storage configuration, pool leak rate and the operability of SFP cooling and emergency systems during the accident, were postulated as part of the PIRT process; see Section 3.2.3. Others, that were deemed less important, were not explicitly defined, but treated generically. Table 9 is a list of all the initial and boundary conditions identified as influential by the expert panel. The conditions are grouped in categories, starting with the fuel assemblies and moving progressively outward. It should be remarked that the conditions listed in categories 6–7, concerning the SFP building and conditions outside the building, have only indirect effects on the in pool phenomena addressed in this report. These conditions are included for completeness, since they do in fact affect the conditions inside the SFP building; see category 5 in Table 9.

Table 9: Initial conditions and boundary conditions deemed influential for the considered SFP accident scenarios

Initial conditions and boundary conditions listed by category
1. Fuel assemblies and other objects stored in the SFP
Type and design of individual FAs (FA geometry, type and enrichment of fuel pellets)
Decay heat of individual FAs and total heat load in the pool
State of stored FAs (burnup, cladding corrosion, rod internal overpressure)
Presence of FAs with leaking or damaged fuel rods
Type and number of stored control elements (B_4C, Ag-In-Cd)
Presence of other pool contents (transport cask, equipment)
2. Storage racks and fuel storage configuration in the racks
Rack geometry (low/high density, FAs stored vertically/horizontally, open/closed rack cells)
Rack material (aluminium, stainless steel, borated stainless steel, neutron absorbers)
Arrangement of FAs in the racks (random, uniform, checkerboard, 1×4, 1×8)
Availability of open downward flowpaths to the bottom of the SFP
3 .Initial (pre-accident) conditions of the SFP water
Water level and volume
Water temperature
Water chemistry (dissolved H_2, radionuclide inventory, boric acid concentration)
4 .Design and status of the SFP and auxiliary systems
Design of the SFP (geometry, wall structure, liner material, location relative to the grade, storage capacity)
Status of the pool structure (leakage rate)
Design of auxiliary systems (location of cooling system intakes, high-temperature operability)
Status of auxiliary systems (cooling capacity, make-up water capacity)
Alternative means of water injection (design and status)
5 .Conditions inside the SFP building
Pressure
Gas temperature
Gas composition (steam, air, H_2)

Initial conditions and boundary conditions listed by category
Gas circulation flow pattern (in particular the velocity above the SFP surface)
6 .Design and status of the SFP building
Design of the SFP building (type of containment, dimensions, material, location relative to reactor building)
Status of the SFP building (leakage/ventilation)
7. Conditions outside the SFP building
Meteorological conditions (temperature, humidity, precipitation, wind velocity)
Radiologic conditions onsite

4.5. Summary and interpretation of results

4.5.1. Summary of results

Altogether 130 phenomena were identified and ranked by the expert panel. The phenomena are distributed over the three consecutive phases of the considered accident scenarios as 31/38/61. About 25 of the phenomena are common to Phase II and III, meaning that they initiate with undamaged fuel and continue after cladding integrity is lost, possibly with increasing complexity as the fuel damage progresses.

Twenty phenomena were identified by the panellists as having priority research needs, since they were judged to be important and at the same time having a low level of knowledge with regard to available data and/or computational models. The identified high-priority phenomena are listed in Table 10 and presented graphically in Figure 9. Two of the phenomena are common to Phase II and III of the accident (II.9-III.7 and II.37-III.59). Ten of the phenomena in Table 10 are important to both of the considered accident scenarios, while the remaining ten are specific to either the fast drainage or the slow uncovery scenario. The differences between these accident scenarios are relevant mostly for phenomena pertaining to the early phases of the accident: for Phase III, most of the identified high-priority phenomena are deemed important to both scenarios.

A majority of the phenomena identified as having priority research needs are related to Phase III of the accident. This is partly a consequence of the evaluation criteria used for ranking the importance level of each phenomenon; see Section 3.2.6.2. Since two of these criteria are related to fuel damage and source term, many phenomena occurring in the fuel damage phase inevitably become important. Nevertheless, five phenomena from Phase I and six phenomena from Phase II are included in Table 10 and Figure 9. Most of these phenomena have a moderate importance level, but, on the other hand, also a low level of knowledge. Since it is generally difficult to accurately assess the importance of poorly known phenomena, the expert panel preferred to give some priority to these phenomena when identifying those with high research needs. It should also be remarked that not only the importance and knowledge levels, but also the dispersion in the panellists' votes regarding these levels was accounted for when identifying phenomena with priority research needs. The high-priority phenomena in Table 10 and Figure 9 were generally identified with a fairly high consistency among the panellists' votes; see Section 4.5.2.

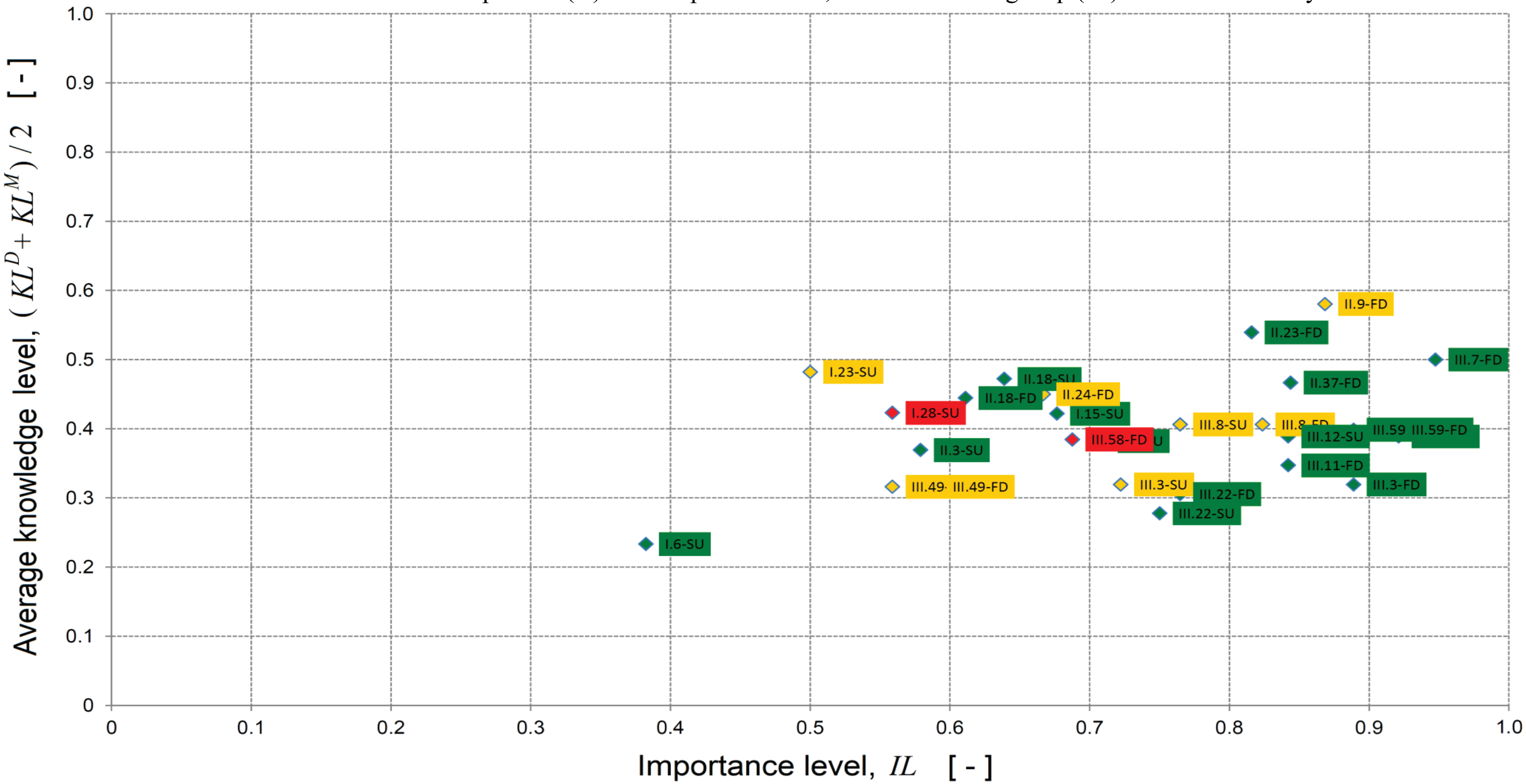
Half of the phenomena in Table 10 concern thermal-hydraulics and heat transfer. From the table, it is clear that these disciplines are important for all phases of the accident. The situation is somewhat different for the phenomena related to fuel behaviour in Table 10, which are important mainly for Phase II of the accident. The reason is that the listed fuel behaviour phenomena are expected to affect the time to cladding tube rupture, and hence, will be important to the accident progression rate for Phase II; see Section 3.2.6.2.

Table 10: Phenomena with priority research needs

Phenomena by category	#	Scenario	Importance ranking				State of knowledge: Availability of data				State of knowledge: Availability of models				Screening-parameters	
			L	M	H	*IL*	N	S	A	KL^D	N	S	A	KL^M	*R*	*D*
1. Thermal-hydraulics																
Non-uniform natural circulation cooling flow distribution between fuel assemblies.	I.5	SU	2	7	10	0.711	8	9	0	0.265	3	11	3	0.500	1.000	0.296
Flow instabilities within the spent FAs at low liquid level. Includes flow reversal and flow excursions.	I.6	SU	7	7	3	0.382	12	3	0	0.100	5	9	1	0.367	0.834	0.248
Multi-dimensional interaction of different temperature zones within the pool.	I.15	SU	1	9	7	0.676	5	11	0	0.344	2	12	2	0.500	0.850	0.202
Development of two-phase natural circulation in FAs, storage racks and SFP. Including liquid water, steam and H_2.	II.3	SU	4	8	7	0.579	7	10	0	0.294	3	14	1	0.444	0.850	0.321
Stop of natural circulation of air through the FAs by water, injected or sprayed as mitigation measure.	III.3	SU	2	6	10	0.722	8	9	1	0.306	6	12	0	0.333	0.813	0.369
		FD	0	4	14	0.889	8	9	1	0.306	6	12	0	0.333	1.000	0.224
2. Heat transfer																
Air cooling of the FAs and storage racks after complete pool drainage.	II.9	FD	1	3	15	0.868	4	8	6	0.556	1	13	5	0.605	0.571	0.402
Air cooling of the FAs and storage racks after complete pool drainage.	III.7	FD	0	2	17	0.947	5	9	5	0.500	4	11	4	0.500	0.576	0.280
Coolability of almost completely uncovered FAs, with their bottom ends immersed in water (partial drain down).	III.8	SU	3	2	12	0.765	5	10	1	0.375	5	8	3	0.438	0.653	0.584
		FD	2	2	13	0.824	5	10	1	0.375	5	8	3	0.438	0.704	0.513
Influence of geometry changes during degradation on heat transfer (both in water and air/steam).	III.11	SU	0	6	13	0.842	9	8	1	0.278	4	13	1	0.417	0.862	0.269
		FD	0	6	13	0.842	9	8	1	0.278	4	13	1	0.417	0.862	0.269
Radiative heat transfer from uncovered fuel assemblies to other FAs, racks and SFP structure.	III.12	SU	0	6	13	0.842	7	11	0	0.306	2	15	1	0.472	0.750	0.177
		FD	0	3	16	0.921	7	11	0	0.306	2	15	1	0.472	0.820	0.139
3. Fuel behaviour																
Fuel fragmentation and relocation during ballooning, before cladding rupture.	II.18	SU	2	9	7	0.639	0	17	1	0.528	5	11	2	0.417	0.659	0.171
		FD	2	10	6	0.611	1	16	1	0.500	5	12	1	0.389	0.699	0.214
Cladding oxidation under air or/and (steam + hydrogen)	II.23	FD	0	7	12	0.816	1	14	4	0.579	2	15	2	0.500	0.643	0.207

Phenomena by category	#	Scenario	Importance ranking				State of knowledge: Availability of data				Availability of models				Screening-parameters	
			L	M	H	*IL*	N	S	A	KL^D	N	S	A	KL^M	*R*	*D*
mixture environment, influence of nitriding.																
Nitrogen-assisted oxide breakaway at low temperature.	II.24	FD	3	6	9	0.667	3	8	4	0.533	4	11	0	0.367	0.738	0.429
Re-oxidation of ZrN by steam/oxygen.	III.22	SU	0	9	9	0.750	6	11	1	0.361	11	7	0	0.194	0.938	0.263
		FD	0	8	9	0.765	5	12	1	0.389	10	8	0	0.222	0.883	0.256
4. Radioactivity release issues																
Radioactive aerosol formation due to bubble breakup processes at the free surface.	I.23	SU	5	7	5	0.500	4	7	3	0.464	3	8	3	0.500	0.513	0.522
Fuel volatilisation, behaviour of fuel fines.	III.49	SU	5	5	7	0.559	8	8	0	0.250	6	9	2	0.382	0.629	0.519
		FD	4	6	7	0.588	8	8	0	0.250	6	9	2	0.382	0.662	0.489
5. Pool concrete and liner effects																
Leakage due to pool concrete and liner deterioration and cracking by pool temperature rise.	I.28	SU	4	7	6	0.559	7	3	3	0.346	5	5	5	0.500	0.699	0.752
6. Criticality issues																
Loss of subcriticality due to relocation of absorber materials.	III.58	SU	2	6	8	0.688	9	2	2	0.231	4	4	5	0.538	0.593	0.832
		FD	2	6	8	0.688	9	2	2	0.231	4	4	5	0.538	0.593	0.832
7. Mitigation																
Fuel cooling by water spray; water injection above the FAs.	II.37	SU	0	5	11	0.844	3	11	1	0.433	2	11	2	0.500	0.895	0.229
		FD	0	5	11	0.844	3	11	1	0.433	2	11	2	0.500	0.895	0.229
Fuel cooling by water spray; water injection above the FAs.	III.59	SU	0	4	14	0.889	5	12	0	0.353	3	14	1	0.444	0.776	0.168
		FD	0	3	15	0.917	5	12	0	0.353	3	14	1	0.444	0.801	0.151

Figure 9: Graphical presentation of identified phenomena with priority research needs in the (*IL*,*KL*)-plane see Table 10. The colour coding of the markers reflects the relative dispersion (D) of each phenomenon, as defined through eq. (10) and the colour key in **Table 5**.



4.5.2. Uncertainty and dispersion of votes

We recall from Section 3.2.7 that the panellists were instructed to vote on the importance and knowledge levels of a phenomenon only if they had sufficient experience with the phenomenon in question. The number of votes received for each phenomenon in Table 6 to Table 8 is typically 13–17, which should be compared with the number of voting organisations (23).

The fairly large number of votes (i.e. 23, one for each organisation) made it possible to use the standard deviation of the votes as an indicator of uncertainty in the ranking results. To identify phenomena that received conflicting votes from the panellists, the standard deviation of the weights was calculated for each kind of vote and used for defining a screening parameter, *D*, that addresses the overall relative dispersion of votes for each phenomenon; see Section 3.2.7.3. To help the reader to identify the phenomena with largest relative dispersion at a glance, the colour coding defined in Table 5 is applied. Phenomena with highly dispersed ($D > 2/3$) votes appear in red in the PIRTs and with a red label in Figure 9. We note that 13–21 % of the ranked phenomena fall into this category, depending on the considered phase of the accident. Most phenomena, 50–58 %, have relative dispersion in the intermediate ($1/3 \leq D \leq 2/3$) range. The differences in these percentages are moderate between the three phases of the accident, which indicates that the consistency of given votes is similar for all phases.

A plausible reason for the dispersion of votes for a phenomenon is that it is design dependent, and that panellists have different views of its importance and level of knowledge, depending on the SFP technology that they are familiar with. This could most likely explain why about 20 % of the phenomena receive highly dispersed votes, but it is unlikely that design differences can explain why as much as 50 % of the phenomena fall into the intermediate dispersion category. Indeed, the discussions held by the expert panel revealed that, except for the Canadian members, participating organisations had their focus on LWR SFPs that have fairly small variations in design [1]. Instead, the results may suggest that some phenomena were still poorly known by voting panellists, and/or that available data and models were not properly identified.

Table 11 is a list of all phenomena that received high relative dispersion ($D > 2/3$) in the panellists' votes. The standard deviations for IL, KL^D and KL^M are given for each phenomenon, with the aim to identify which of these parameters have the largest spread in the votes. A standard deviation larger than 0.4 is indicated by red colour in Table 11. For Phase I, it is clear that phenomena that are associated with concrete and liner deterioration at elevated temperature received the most dispersed votes. The high relative dispersion is due to disagreement among the panellists regarding both the importance level and the availability of data and models. This could suggest that design differences exist, but another explanation is that this kind of deterioration, occurring already in the pre-uncovery phase of the accident, is a rather new issue that was raised during the PIRT activity. For Phase II and III, the criticality-related phenomena are the most dispersed. A plausible reason is that these phenomena have a particularly strong dependence on the design and/or accident scenario. We recall that our study covers SFPs using both borated and un-borated water, all kinds of storage rack designs, all kinds of LWR fuel, and even CANDU fuel, for which criticality in the SFP is not an issue at all. More design specific and/or scenario specific studies are obviously needed to produce useful PIRTs for criticality issues under SFP accidents. For Phase II, the dispersion seems to be caused mainly by an inconsistent view on the availability of data among the voters, and it is possible that available data may not have been clearly identified as existing for some voting panellists. For Phase III, the dispersion also includes disagreement on the importance level for some criticality phenomena.

Finally, we note that the phenomena identified as having priority research needs by the expert panel generally have low relative dispersion. From Table 10 and Figure 9, it is clear that only two of the twenty identified phenomena had $D > 2/3$, while thirteen had $D < 1/3$. Hence, the high-priority phenomena were identified with a high degree of agreement among the panellists, which lends confidence to the results.

Table 11: Phenomena that received votes with high relative dispersion (D > 2/3)

Phenomena by accident phase	#	Scenario	Relativedi sp. D	Standard deviations $\sigma(IL)$	$\sigma(KL^D)$	$\sigma(KL^M)$
Phase I:						
Impact of siphoning/leakage on natural flow convection.	I.7	SU	0.723	0.408	0.381	0.392
		FD	0.716	0.402	0.373	0.404
Tritiated steam (HTO) releases by water evaporation.	I.25	SU	0.710	0.375	0.414	0.386
Pool concrete deterioration and cracking by pool temperature rise.	I.26	SU	0.911	0.412	0.464	0.403
		FD	0.906	0.382	0.468	0.428
Pool liner deterioration and cracking by pool temperature rise.	I.27	SU	0.795	0.416	0.425	0.380
		FD	1.000	0.458	0.445	0.414
Leakage due to pool concrete and liner deterioration and cracking by pool temperature rise.	I.28	SU	0.752	0.379	0.411	0.408
		FD	0.900	0.408	0.430	0.433
Phase II:						
Return of condensate to pool.	II.8	SU	0.770	0.424	0.395	0.300
Convective heat transfer between water and structures in the SFP	II.10	FD	0.690	0.427	0.352	0.300
Heat generation from H_2 + O_2 combustion.	II.13	SU	0.698	0.437	0.306	0.306
		FD	0.681	0.427	0.306	0.306
Heat transfer in fuel rods; temperature distribution and resulting strains and stresses.	II.20	SU	0.677	0.449	0.325	0.303
		FD	0.734	0.449	0.356	0.300
Loss of subcriticality by boric acid dilution with injected fresh water.	II.31	SU	1.000	0.374	0.442	0.394
		FD	0.873	0.327	0.442	0.394
Loss of subcriticality by loss of coolant.	II.32	SU	0.679	0.309	0.385	0.373
		FD	0.706	0.298	0.414	0.373
Loss of subcriticality by pool refilling; reflood of FAs from below.	II.33	SU	0.821	0.340	0.408	0.386
		FD	0.821	0.340	0.408	0.386
Loss of subcriticality by an increase in coolant void fraction.	II.35	SU	0.764	0.365	0.365	0.374
		FD	0.863	0.350	0.408	0.394
Loss of subcriticality due to deformation of fuel storage racks or/and spent fuel assemblies.	II.36	SU	0.683	0.343	0.374	0.348
		FD	0.683	0.343	0.374	0.348
Phase III:						
Air cooling of the FAs and storage racks after complete pool drainage.	III.7	SU	0.713	0.374	0.380	0.324
Water radiolysis and hydrogen production.	III.17	SU	0.679	0.289	0.390	0.390
Stainless steel-air reaction: oxidation.	III.29	SU	0.872	0.311	0.436	0.416
		FD	0.702	0.250	0.436	0.416
Loss of subcriticality by boric acid dilution with injected fresh water.	III.53	SU	1.000	0.399	0.439	0.369
		FD	0.947	0.378	0.439	0.369
Loss of subcriticality by an increase in coolant void fraction.	III.54	SU	0.692	0.352	0.365	0.348
		FD	0.797	0.371	0.385	0.361
Loss of subcriticality by pool refilling; reflood of FAs from below.	III.55	SU	0.819	0.374	0.392	0.361
		FD	0.855	0.390	0.392	0.361
Loss of subcriticality by water spray injection; injection above the FAs.	III.56	SU	0.908	0.413	0.369	0.385
		FD	0.941	0.428	0.369	0.385
Loss of subcriticality due to deformation of	III.57	SU	0.813	0.428	0.361	0.340

Phenomena by accident phase	#	Scenario	Relativedi sp. D	Standard deviations $\sigma(IL)$	$\sigma(KL^D)$	$\sigma(KL^M)$
fuel storage racks or/and spent fuel assemblies.		FD	0.813	0.428	0.361	0.340
Loss of subcriticality due to relocation of absorber materials.	III.58	SU	0.832	0.348	0.373	0.414
		FD	0.832	0.348	0.373	0.414

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The PIRTs presented in this report were developed with the overall objective to guide future experimental and modelling efforts relating to spent fuel pool (SFP) loss-of-cooling and loss-of-coolant accidents. An international panel of experts identified and ranked more than a hundred physical phenomena with regard to their safety importance and current level of knowledge, with the aim to identify phenomena that should be prioritised in future experimental and/or analytical studies. A well-established PIRT methodology was used to identify these phenomena, which are deemed to be of high potential safety importance and low level of knowledge as measured by the availability of experimental data and/or computational models. The study was generic with regard to reactor and fuel design, but restricted to phenomena that occur in the spent fuel pool. Phenomena occurring predominantly outside the SFP, e.g. heat and mass transfer in the pool building or to the environment, were beyond the scope of the study.

Altogether, 18 unique phenomena were identified as having priority research needs; see Section 4.5.1. About half of these phenomena are related to thermal-hydraulics and heat transfer in the SFP, and they are judged to be important to the coolability of the spent fuel in loss-of-cooling and/or loss-of-coolant accidents. Experimental studies of these phenomena generally call for costly large-scale integral tests, and it is therefore expected that associated computer models and supporting databases will evolve slowly. However, there are also phenomena with high-priority research needs that can be studied in fairly simple separate effect tests, for example fuel volatilisation, cladding oxidation in mixed steam-air environment and nitrogen-assisted oxide breakaway at moderate temperature.

The expert panel also opines that phenomena related to spent fuel emergency cooling by water spray are among those with priority research needs. Quite a few of the phenomena identified by the expert panel as having priority research needs are currently being investigated in ongoing research projects or will be studied in near-term programmes. This is no coincidence, since many of the panellists are involved in or aware of these programmes. Hence, the ranking results reflect the current (early 2017) understanding of involved phenomena and the current perception of their importance. This implies that the PIRTs include only phenomena for which there exists some knowledge base. It also implies that the ranking of certain phenomena will most likely change as the results of new research become available. Hence, it should be recognised that the PIRTs in this report are inevitably based on incomplete information and that they have to be re-evaluated as the knowledge base is extended. Most of the knowledge base behind the PIRTs in this report is documented in [1].

The study in this report addresses the research needs on SFP accidents from a general point of view. It has a wide scope in that it is generic with regard to the design of the considered at-reactor SFP, the storage racks and the spent fuel. It also considers two general types of accidents, each taking place with a spectrum of postulated initial and boundary conditions in terms of fuel heat load and storage configuration. In general, there is a risk that results of generic PIRTs tend to become inconclusive or too imprecise to be useful [58]. In the present study, the confidence of the ranking results can be assessed through the dispersion of the panellists' votes. As shown in Section 4.5.1, most of the eighteen phenomena that were found to have priority research needs were identified with a high degree of agreement among the panellists, which lends confidence to the main results of the PIRTs. It is therefore likely that further research on these eighteen phenomena will improve our understanding and modelling capacity of SFP accidents for a wide range of designs and accident scenarios.

On the other hand, there is a large dispersion of the votes on phenomena that may potentially lead to loss of subcriticality in the SFP; see Section 4.5.2. A plausible reason is that these phenomena have a particularly strong dependence on the design and/or accident scenario. We recall that our study covers SFPs using both borated and un-borated water, all kinds of storage rack designs, all kinds of LWR fuel, and even CANDU fuel, for which criticality in the SFP is not an issue at all. More design specific and/or scenario specific studies are needed to produce useful PIRTs for criticality issues under SFP accidents.

5.2. Recommendations

In the 2015 CSNI status report [1] on spent fuel pools under loss-of-cooling and loss-of-coolant accident conditions, it was concluded that our understanding of these accidents, at that time, was based on past experiments that were done predominantly to study reactor cores in loss-of-coolant accidents and on analyses with computational tools that were intended primarily for studies of reactor accidents. Considering that many experiments, specifically targeted to SFP accidents, are underway or planned and that validation of computer programs and models will continue against the produced data, **it is recommended that a CSNI state-of-the-art report on SFP loss-of-cooling and loss-of-coolant accidents be written as the results of the ongoing and planned research become available. An appropriate starting time for this activity would be 2020–2022, and a suitable starting point would be the CSNI status report from 2015 [1].**

Three of the phenomena identified as having priority research needs (II.23, II.24, and III.22) concern cladding chemical reactions with mixed steam-air environments, including re-oxidation of nitrided cladding. These phenomena can be studied experimentally by use of fairly simple separate effect tests, and the results can be used to extend and improve oxidation models used in today's severe accident codes. Hence, there is a potential for improving the applicability of these models to SFP accident conditions within a reasonable time and with moderate efforts. Separate effect tests of this kind are underway in France, Germany and Japan. **These ongoing research programmes should be supported, and it should be ensured that they cover all type of fuel cladding present in SFPs and also low (< 1 200 K) temperatures, which are of particular interest for many SFP accident scenarios.**

Five of the high-priority phenomena (III.3, III.7, III.8, III.11, III.12) are related to thermal-hydraulics and heat transfer in the SFP with importance to the coolability of partly or completely uncovered fuel assemblies. Experimental studies of these phenomena require integral tests at and above the scale of fuel assemblies. Such tests have recently been performed on completely uncovered BWR and PWR fuel assemblies at the Sandia National Laboratory in the USA [24-26]. It is recommended that similar tests be carried out for CANDU fuel and storage rack designs, and also for partly uncovered LWR fuel assemblies. Pre-test sensitivity analyses with severe accident codes are believed to be valuable for prioritizing the research needs and for identifying the most relevant test parameters. **When new experimental data become available from these tests, post-test benchmarks of severe accident codes against the data are also recommended. However, the expert panel deems that there is currently no need for a CSNI-co-ordinated SA code benchmark, since some activities of this kind are ongoing [67] and others have recently been completed [27].**

Three of the phenomena identified as having priority research needs (I.5, I.6, I.15) pertain to the pre-uncovery phase of the accident and concern the thermal-hydraulic behaviour and the large-scale natural circulation flow pattern that evolves in the SFP under loss-of-cooling accidents. Properly scaled experiments are needed that address these phenomena, in the first instance for validating 3D models in existing thermal-hydraulic system codes, and later, for formulating and validating models in CFD codes under development. **Some experiments of this kind are underway in a reduced scale mock-up of a typical at-reactor SFP [6], but additional studies are needed.**

It is also recommended that experiments be carried out on spray cooling of uncovered spent fuel assemblies in typical storage rack designs; see phenomena II.37 and III.59 in Table 10. Systems for spray cooling of the SFP are installed or considered in many countries as part of post-Fukushima action plans for improving SFP safety. Experiments are needed at and above the scale of fuel assemblies and they should be done with heat loads typical for spent fuel and with various storage configurations for the fuel assemblies. In a first step, tests should be done that address the coolability of the fuel, e.g. what spray water mass flux is needed for cooling fuel assemblies with given heat load and uncovered length. The resulting data will help to develop and/or validate empirical spray cooling models in severe accident codes and thermal-hydraulic system codes. **Experiments of this kind are underway for PWR fuel [6], and similar studies are warranted for other fuel designs. Later, more detailed experiments are needed, on several length scales, for formulation and validation of mechanistic models for spray cooling.**

Finally, sensitivity and uncertainty analyses should be considered an integral part of computer code applications. These analyses should be directed towards submodels and phenomena, for which the most substantial uncertainties are known to exist. The results presented in this report provide some general guidance in identifying these phenomena for SFP loss-of-cooling and loss-of-coolant accidents, but must be complemented with information on the specific submodels used in the applied computer code.

6. REFERENCES

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