Annals of Nuclear Energy 74 (2014) 4–11

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Conclusions on severe accident research priorities

W. Klein-Heßling [a,*], M. Sonnenkalb [a], D. Jacquemain [b], B. Clément [b], E. Raimond [b], H. Dimmelmeier [c], G. Azarian [d], G. Ducros [e], C. Journeau [e], L.E. Herranz Puebla [f], A. Schumm [g], A. Miassoedov [h], I. Kljenak [i], G. Pascal [j], S. Bechta [k], S. Güntay [l], M.K. Koch [m], I. Ivanov [n], A. Auvinen [o], I. Lindholm [o]

[a] Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)mbH, Köln, Germany,
[b] Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses or Cadarache, France
[c] AREVA NP GmbH, Erlangen, Offenbach, Germany
[d] AREVA NP SAS, France
[e] Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), Cadarache, France
[f] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[g] Electricité de France, EDF R&D, Chatou, France
[h] IKET, KIT, Karlsruhe, Germany
[i] Jožef Stefan Institute (JSI), Slovenia
[j] Joint Research Centre (JRC), Petten, Netherlands
[k] Kungliga Tekniska Högskolan (KTH), Sweden
[l] Paul Scherrer Institut (PSI), Switzerland
[m] Ruhr-Universität Bochum (RUB), Germany
[n] Technical University of Sofia (TUS), Bulgaria
[o] Technical Research Centre of Finland (VTT), Finland

A R T I C L E   I N F O

Article history:
Received 13 January 2014
Accepted 7 July 2014
Available online 15 August 2014

Keywords:
Severe accidents
Research priorities
SARNET

A B S T R A C T

The objectives of the SARNET network of excellence are to define and work on common research programs in the field of severe accidents in Gen. II–III nuclear power plants and to further develop common tools and methodologies for safety assessment in this area. In order to ensure that the research conducted on severe accidents is efficient and well-focused, it is necessary to periodically evaluate and rank the priorities of research. This was done at the end of 2008 by the Severe Accident Research Priority (SARP) group at the end of the SARNET project of the 6th Framework Programme of European Commission (FP6). This group has updated this work in the FP7 SARNET2 project by accounting for the recent experimental results, the remaining safety issues as e.g. highlighted by Level 2 PSA national studies and the results of the recent ASAMPSA2 FP7 project. These evaluation activities were conducted in close relation with the work performed under the auspices of international organizations like OECD or IAEA. The Fukushima-Daiichi severe accidents, which occurred while SARNET2 was running, had some effects on the prioritization and definition of new research topics. Although significant progress has been gained and simulation models (e.g. the ASTEC integral code, jointly developed by IRSN and GRS) were improved, leading to an increased confidence in the predictive capabilities for assessing the success potential of countermeasures and/or mitigation measures, most of the selected research topics in 2008 are still of high priority. But the Fukushima-Daiichi accidents underlined that research efforts had to focus still more to improve severe accident management efficiency.

1. Introduction

Severe accidents can cause significant damage to reactor fuel resulting in more or less complete core meltdown. Although such accidents are highly unlikely in the light of the preventive measures implemented by operators they are indeed possible as recently happened at Fukushima-Daiichi I plant in Japan. Therefore, they are continuously in the focus of considerable research because of their serious consequences due to possible releases of radioactive products into the environment. This research also reflects a commitment to the defence-in-depth approach.

To be sure that the research conducted on severe accidents is efficient and focusing on relevant topics, the Severe Accident

* Corresponding author.
E-mail address: walter.klein-hessling@grs.de (W. Klein-Heßling).

http://dx.doi.org/10.1016/j.anucene.2014.07.015
0306-4549/

Research Priority (SARP) work that started already in the first SARNET FP6 project (Schwinges et al., 2008a) is being updated, evaluating the most recent experimental results and taking into account the remaining safety issues, as those highlighted by Level 2 PSA studies as being of high priority for reducing uncertainties (link between SARNET2 FP7 and the ASAMPSA2 FP7 project that ended in early 2013 (Raimond et al., 2013). These evaluation activities are being conducted in close relation with the work performed both in existing international organizations – mainly the OECD/NEA/CSNI Group on Analysis and Management of Accidents (GAMA) and the International Science and Technology Centre (ISTC) Projects – and in the Sustainable Nuclear Energy Technology Platform (SNETP), including the new NUGENIA association (see www.nugenia.org), dedicated to the research and development of Generation II–III nuclear fission technologies. NUGENIA gathers stakeholders from industry, research, safety organizations and academia, committed to develop joint R&D projects in the field.

The SARP work, led by GRS, was performed in close collaboration with 14 partners representing Technical Safety Organizations (TSO), R&D centers, universities, industry and utilities (IRSN, CEA, EDF, KIT, GRS, AREVA NP GmbH, KTH, TUS, VTT, JSI, PSI, CIEMAT, JRC and RUB). It should be further noted that the collaboration among those who perform the research and those who use its results is essential to correctly address the problem which may lead to the closure.

The work of the SARP group is originally based on the results of the EURSAFE FP5 project (Magallon et al., 2005). The objectives of the EURSAFE thematic network were to establish a large consensus on the severe accident issues where large uncertainties still subsist, and to propose a structure to address these uncertainties by appropriate R&D programs making the best use of the European and national resources. It incorporated issues related to existing European plants (PWR, BWR and VVER), lifetime extension of these plants, evolutionary concepts (higher burn-up and MOX fuels), and safety and efficiency of future systems. In EURSAFE the first Priority Identification and Ranking Table (PIRT) was realized for severe accidents as an initial step towards the objectives. It integrated all the severe accident issues from core degradation up to release of fission products (FP) from the containment, taking into account any possible counter-measures and the evolution of fuel management. Two evaluation parameters, the safety importance ratio and the knowledge ratio, were established. Starting with 1016 identified phenomena, the list was reduced to 239 items, important for safety, of which 106 were found with a significant lack of knowledge. These items have been regrouped and summarized in 21 items, the so-called EURSAFE Research Issues (ERI).

As a result of the SARP Group in SARNET FP6, thus at the end of 2008, six of these 21 issues were still considered as "high priority" ones, four issues were re-assessed with medium and five with low priority. Three issues were marked as "issue could be closed". New issues (in total seven topics have been discussed), such as combustion of hydrogen jets in the containment with pre-existing hydrogen atmosphere in conjunction with Direct Containment Heating (DCH) were identified, and the final SARP/FP6 report (Schwinges et al., 2008b) have been the basis of the follow-up SARNET2 FP7 project.

The understanding of severe accident phenomena is today quite important. This was underlined again regarding the consequence of the severe accidents in Japan. Although a considerable progress has been gained in the recent decades, it is still necessary to reduce further the uncertainties of simulation results, to investigate new phenomena not regarded in detail before and to improve further severe accident management (SAM) measures under extreme boundary conditions.

In addition, the improvement of computer codes, in particular integral codes like ASTEC, is not explicitly included in all these issues but obviously it remains a continuous and essential line of R&D.

This paper summarizes the concluding results of the work in the SARP group at the end of the SARNET2 FP7 activity.

2. Ranking of research priorities

The resulting decisions and reassessments performed in the SARP group are an attempt to reach, in a reasonable time an agreed decision considering all aspects of innovation and economic efficiency.

The ERI issues used in the previous SARP FP6 report were a collection of different severe accident phenomena. It has to be pointed out that the details and content these different issues have been changed partly and/or the safety requirements and assumed boundary conditions may have been changed. Therefore, a new numbering was set-up and issues have been sorted in a more logical order as a result of the SARP work in SARNET2.

Comparing the priority level with the original levels decided in SARNET FP6, most of the levels have not been changed or even received again higher priorities (Table 1). This could lead to the misleading impression that, during the last period, the progress in severe accident research was quite low. On the contrary, the progress on severe accident phenomenology understanding was important but during SARNET2 FP7 it was noticed that more efforts are needed to increase the knowledge necessary for a better appreciation of existing – or for the development of new – mitigation means: in- and ex-vessel corium and debris cooling, steam and hydrogen explosions mitigation, reduction of FPs releases (scrubbing, filtered containment venting systems or FCVS). The same need applied to the source term towards the external environment for all accident scenarios. Especially the new issues related to FCVS and pool scrubbing phenomena under boiling conditions underline that an improved assessment of SAM measures gets a higher relevance.

The SARP final report has formed the basis of the R&D roadmap established in 2013 in NUGENIA that will be used as a guideline for the definition of future European R&D projects.

The definition of ranking (see Table 1) includes the level of safety importance and the knowledge level, based on the consensus found in the SARP group. In addition the old ERI numbering of issues is provided in the third column of this table.

2.1. Phenomena during in-vessel accident progression

The **1,1 issue** concerns the in-vessel H_2 generation (by oxidation of metal-rich melt mixtures) during the core re-flooding accident phase in a slightly degraded core. During this phase, the hydrogen is generated rapidly and may not be totally recombined by passive autocatalytic recombiners in the containment in this short time frame. This may increase the risk of hydrogen combustion and the potential consequences of an early containment failure. This issue is of **low priority** as several validated models exist to properly evaluate the phenomenon.

In a later accident phase with highly degraded core or in case of melt relocation into water in the RPV lower head (**1,2 issue**) the prediction of hydrogen generation during in-vessel re-flooding is much more uncertain. Therefore this issue is still of **medium priority**. It has to be pointed out that the risk significance of both situations depends strongly on the considered sequence and the degraded core geometry.

The **1,3 issue** concerns the core and debris coolability (rod failure, molten pool formation, molten pool and debris cooling, crust failure) and thermal-hydraulics within particulate debris during re-flooding. This research item addresses the re-flooding of a core

Table 1
Ranking of research issues.

No.	Issue	Explanation	ERI	Ranking at SARNET FP6's end	Revised ranking
1. *Phenomena during in-vessel accident progression*					
1,1	Hydrogen generation during re-flooding of *slightly* degraded cores	Rapid generation of hydrogen; improve knowledge about the magnitude of hydrogen generation	1,1a	M*	L(→4,1)
1,2	Hydrogen generation during re-flooding of *strongly* degraded cores	Rapid generation of hydrogen due to oxidation of metals; improve knowledge about the magnitude of hydrogen generation	1,1b	M	M(→4,2)
1,3	Core coolability during re-flooding and thermal-hydraulics within particulate debris	Termination of the accident by re-flooding of the core while maintaining RCS integrity. Increase predictability of core cooling during re-flooding	1,2	H	H
1,4	Corium behaviour in lower head	Improve predictability of corium behaviour and the thermal loading on the lower head of the Reactor Pressure Vessel (RPV) to assess RPV integrity. BWR: Consideration of specific BWR boundary conditions	1,3a	M	H(→1,5)
1,5	Integrity of RPV due to external vessel cooling	Improve database for critical heat flux and external cooling conditions to evaluate and design AM strategies of external vessel cooling for in-vessel melt retention	1,4	M	H(→1,4; 1,7)
1,6	Fuel Coolant Interaction (FCI) incl. steam explosion in stratified situation	Investigate the risk of weakened vessel failure during re-flooding of a molten pool in the lower head.	3,3	CL	L
1,7	RPV vessel failure mode	Improve predictability of mode and location of RPV failure to characterise the corium release into the containment L for PWR, H for BWR, especially failure of penetrations	1,6	L	L for PWR H for BWR(→1,5; 2,2)
1,8	Integrity of Reactor Coolant System (RCS), especially integrity of steam generator (SG) tubes in high pressure scenarios	Improve predictability of heat distribution in the RCS to quantify the risk of RCS failure and possible containment bypass. The effect has an influence on accident progress. There is a link to FP transport (e.g. iodine flashing)	1,5	CL	M
2. *Phenomena that could lead to early containment (or reactor building) failure*					
2,1	Hydrogen mixing, combustion/detonation	Identify the risk of hydrogen accumulation leading to deflagration/ detonation and to identify counter-measures	3,4	H	H(→5,1)
2,2	Melt relocation into water and particulate formation	Determine characteristics of jet fragmentation during melt relocation into water in RPV and cavity, debris bed formation and debris coolability towards maintenance of vessel and containment integrity, respectively	3,1	H	H(→1,7)
2,3	FCI incl. steam explosion: melt into water, in-vessel and ex-vessel	Increase the knowledge of parameters affecting steam explosion energetic during corium relocation into water and determine the risk of vessel or containment failure	3,2	H	CL in-vessel H ex-vessel
2,4	Direct containment heating	Increase the knowledge of parameters affecting the pressure build-up due to DCH and determine the risk of containment failure	4,1	M	M
2,5	Long term loss of heat removal from wet-well in a BWR	In Fukushima the heat removal from the wet-well was lost after the tsunami. The energy released by condensing steam from the RCS heated the wet-well water to saturation. In addition non-condensable gases from core degradation led to containment over-pressure	–	–	M(→4,8)
3. *Phenomena that could lead to late containment failure*					
3,1	MCCI (Molten Corium Concrete Interaction): molten pool configuration and concrete ablation	Improve predictability of axial versus radial ablation up to late phase MCCI to determine basement material failure time and loss of containment integrity	2,1	H	M oxidic melt H stratified oxidic/ metallic melt
3,2	Ex-vessel corium coolability, top flooding	Increase the knowledge of cooling mechanisms by top flooding the corium pool to demonstrate termination of accident progression and maintenance of containment integrity	2,2	H	H
3,3	Ex-Vessel corium catcher: corium ceramics interaction and properties	Demonstrate the efficiency of specific corium catcher designs by improving the predictability of the corium interaction with corium catcher materials	2,3	CL	L bilateral projects
3,4	Ex-vessel corium catcher: coolability and water bottom injection	Demonstrate the efficiency of water bottom injection to cool corium pool and its impact on containment pressurisation	2,4	CL	L bilateral projects
3,5	External corium catcher device	Improve predictability of corium catcher devices to maintain their integrity	1,3b	L	L bilateral projects
3,6	Dynamic and static behaviour of containment, crack formation and leakage at penetrations	Estimate the behaviour of penetrations, sealing, hatches and so on leading to leakages of fission products into the environment. Here aging and severe accident conditions have to be considered	3,5	L	M
4. *Phenomena of release and transport of fission products*					
4,1	Core re-flooding impact on source term (*early phase*)	Characterise and quantify the FP release during core re-flooding in early phase of core degradation (more or less intact core geometry)	5,5a	L	L(→1,1)
4,2	Core re-flooding impact on source term (*late phase*)	Characterise and quantify the FP release during core re-flooding in late phase of core degradation (with highly degraded core; loss of geometry)	5,5b	L	M(→1,2)
4,3	Oxidizing environment impact on source term	Quantify the source term, in particular for Ru, under oxidation conditions/air ingress for high burn-up and Mixed Oxide fuel (MOX)	5,1	H	H
4,4	RCS high temperature chemistry impact on source term	Improve predictability of iodine and ruthenium species exiting RCS to provide the best estimate of the source into the containment	5,2	H	H
4,5	Containment chemistry impact on source term	Improve the predictability of iodine and ruthenium chemistry in the containment to reduce the uncertainty in iodine source term	5,4	H	H
4,6	Aerosol behaviour impact on source term	Quantify the source term for aerosol retention in the SG secondary side and leakage through cracks in the containment wall as well as	5,3	L	L

Table 1 (*continued*)

No.	Issue	Explanation	ERI	Ranking at SARNET FP6's end	Revised ranking
		the source into the containment due to re-volatilization in RCS			
4,7	Existing and innovative filtered containment venting systems	Re-evaluation of the efficiency of the implemented filters accounting for progresses in source term evaluations and valorisation of the R&D on source term evaluation to propose innovative filtering devices	–	–	H
4,8	Pool scrubbing under different conditions	Estimation of pool scrubbing efficiency under different (e.g. boiling) conditions inside the pool	–	–	M
5. *Phenomena in spent fuel pool (SFP) storages*					
5,1	Fuel assembly behaviour in spent fuel pool scenarios	Thermal hydraulics of SFP accidents, physico-chemical and mechanical behaviour of claddings under air and air/steam mixtures, zirconium fire risks, release of fission products, possibility of mitigation	–	–	H
6. *New topics related to severe accidents*					
6,1	Effect of impurities in water on core degradation, chemistry and FCI	Effect of injection of water not prepared for RCS and containment (e.g. "hard" water, salt water, river water) on long term cooling and fission product behaviour	–	–	M
6,2	Instrumentation for severe accidents	Development and qualification of specific instrumentation for SA conditions	–	–	H
6,3	MCCI aerosol effect on chemistry	Effect of MCCI aerosols on iodine gaseous concentration chemistry in the sump	–	–	L
6,4	Thermodynamic and thermo-physical databases	Improvement of the thermo-dynamic and thermo-physical database for corium and fission products	–	–	M

* Definition of ranking levels: High: The phenomenon (or the aspect) is highly important for safety and the probability of occurrence is high, medium or unknown. The uncertainties on this phenomenon should be reduced to the minimum possible. Medium: The phenomenon (or the aspect) is important for safety and the probability of occurrence is medium or unknown. Low: The phenomenon (or the aspect) has low importance for safety, or has medium importance for safety and its probability of occurrence is low. Close: The existing knowhow, experience and database related to the phenomena (or the aspect) are accepted by the end-users and research organizations and when the issue as addressed does not constitute a challenge to the safety of the plants regardless of the design.

not yet totally degraded, with the potential of stopping the core degradation process. This topic is still a point of discussion inside Level 2 PSA studies. Because of multidimensional effects the models are quite poor. Therefore, users have to be cautious in using the models for reactor applications. The topic is still of **high priority**.

The **1,4 issue** concerns the corium behaviour in a RPV lower head. This research item clearly addresses the details of the phenomena to be investigated for in-vessel melt pool behaviour. These are preconditions for possible in-vessel melt retention considerations. The in-vessel melt retention aspects and the improvement of the predictability of the thermal loading are a matter of high interest, especially also for BWRs because of the control rod guide tubes (CRGTs) that influence the behaviour of melt in the lower head significantly and for reactors with low power density. Two main phenomena are still of interest: heat flux to metal layer in layered melt configuration and 3-layer configurations including the transient stages. Further points are the evolution of the thicknesses of light and dense metallic layers and the formation of an insulating oxidic crust at the upper surface. The simulation of the oxide pool is quite understood. However, the simulation of transient corium behaviour inside BWR and PWR lower heads must still be improved. It was suggested to change to **high priority** level, due to the increased current interest on IVR, especially after Fukushima.

The **1,5 issue** concerns the RPV integrity by external vessel cooling. The database for critical heat flux on RPV outside wall and external cooling conditions needs to be improved in order to evaluate and design SAM measures for external vessel cooling with the aim of in-vessel melt retention. This possibility for SAM depends on the local special conditions in each plant. Especially the influence of BWR lower head penetrations on melt and RPV cooling and their influence on the water/steam convection flows in the cavity should be examined. Relevant topics under investigation are: use of additives to the water or nano-particles on the RPV outer wall (or even of corroded vessel surface states) to enhance the heat transfer, evaluation of pressure dependence, consequences caused by "dirty" water, consideration of local effects like "hot spots". This issue is still of **high priority** caused also by the link to issue 1,4.

The **1,6 issue** concerns Fuel-Coolant-Interaction (FCI) including a possible steam explosion in a weakened vessel during re-flooding of a molten corium pool in lower head. On the basis of available experimental results the probability of an in-vessel steam explosion that would be energetic enough to rupture an quite intact vessel is very low: therefore the state of knowledge on this issue was discussed to be regarded as sufficient in comparison to other more important issues and, with respect to its low probability, it can be regarded with **low priority**. Minor open questions concerning in-vessel steam explosion are treated together with the ex-vessel aspects under issues 2,2 and 2,3.

The **1,7 issue** concerns the RPV vessel failure mode and the following corium release from the failed vessel. The predictability of the failure mode and of the location of RPV failure to characterize the corium release into the cavity/containment should be improved. The information on the break location is regarded as sufficient for PWR but not for BWRs with a large number of bottom head penetrations. There is currently no solution for the prediction of the break size. Due to the hole ablation during the outflow this lack of knowledge is regarded as less significant, although the hole size is a relevant starting condition for possible DCH or for ex-vessel steam explosion and debris bed formation and coolability. Since the resolution of the issue of bottom head break size evolution during and between corium pours is considered to be beyond reach at short or medium term, the issue, initially ranked with medium priority for PWR, is being classified with **low priority for PWR** now and no further intensive research in the near future is needed. It shall be re-evaluated when a R&D program is proposed having been assessed to have sufficient probability to tackle this last remaining issue. For BWRs, KTH has developed a coupled thermo-mechanical approach to analyse the different modes of vessel failure. Analyses of BWR severe accident scenarios suggest that quite likely a few penetrations (instrumentation tubes and

CRGT) out of about two hundred in the vessel lower head will fail before a large molten corium pool will be formed. Corium conditions at the time of penetration failure will determine melt release conditions which have a tremendous impact on the ex-vessel accident progression, namely on (i) debris bed formation and coolability, (ii) ex-vessel steam explosion. Therefore, gradual re-melting of corium debris, which can contain a significant amount of metallic zirconium, interaction of debris with vessel penetrations, failure of penetrations are considered as important phenomena which define RPV failure mode, melt ejection mode and thus ex-vessel consequences. Remarkably, in none of the past experiments the interactions of gradually re-melting debris, containing high and low melting temperature materials, with vessel penetrations were considered. Thus, there is a need to investigate the issue of RPV penetration failure in order to provide necessary data for resolving ex-vessel severe accident progression phenomena and issues. Therefore, the **1,7 issue** is ranked with **high priority for BWR**, and further intensive research in the near future is needed.

The **1,8 issue** concerns the RCS) integrity in high pressure scenarios. It addresses the predictability of heat distribution in the RCS, especially in the affected pressuriser loop and the SG, in order to quantify the risk of RCS failure and possible containment bypass by a failed SG tube. The effect of high thermo-mechanical loads on SG tubes is still a point of investigation. Different projects are already launched (e.g. experiments in WENKA facility at KIT) and AM measures are typically in place to depressurize the RCS before core degradation. Nevertheless caused by a renewed interest of some partners and results of some PSA level 2 studies for PWRs, the priority level is increased to **medium priority**.

2.2. Phenomena that could lead to early containment (or reactor building) failure

The **2,1 issue** concerns the mixing of hydrogen in the containment (and reactor building) atmosphere, possible hydrogen combustion/detonation processes and the influence of countermeasures like recombiners or the effect of spray systems. The items of flame acceleration, the produced pressure loads and the scaling effect for accelerated flames up to Detonation-to-Deflagration-Transition (DDT) are points of increased interest. Especially analytical activities are necessary to improve the predictability of the codes, mainly Computational Fluid Dynamics (CFD) codes to simulate hydrogen combustion under realistic accident conditions. One specific topic is the hydrogen combustion during the DCH process (link to 2,4). The influence of CO released during MCCI on hydrogen combustion has been discussed. Here, the specific MCCI conditions (high temperature, lack of oxygen, CO addition) may have an effect on flammability limits which is of major interest. Due to the risk of early containment failure or the risk of combustions in the reactor building where hydrogen countermeasures are sparse, the issue is still of **high priority**. There are on-going activities within the OECD: the THAI2 experimental project and the status report on hydrogen countermeasures.

The **2,2 issue** concerns the melt relocation into water in the RPV lower head and/or the cavity and consequent particulate formation. While the **2,3 issue** concerns FCI including steam explosion in the in- and ex-vessel phase, in presence of water in the RPV bottom head or cavity. Both issues are related to each other. In-vessel steam explosion is no longer regarded as a significant threat, but for the ex-vessel situation in the cavity the situation is different because of the relatively low pressure resistance of the structures. Melt relocation into water determines the boundary conditions for a possible steam explosion. In many BWR lay out a water pool is located under the RPV, either from containment design or as result of an early SAM measure, so that the boundary conditions for a possible steam explosion need urgently to be known. Flooding the cavity is also used for many western PWR concepts. The investigations performed in SARNET aimed at getting the characteristics of jet fragmentation, debris bed formation and debris coolability and at increasing the knowledge of parameters affecting the steam explosion energetic during corium relocation into water in order to determine better the risk of containment failure. Different experimental facilities like KROTOS (CEA), TROI (KAERI), MISTE and DEFOR (KTH) are available. Two successive OECD projects cover this area: SERENA and then SERENA 2 that provided new data on the premixing phase. The fragmentation and dynamic loading by FCI, the energy conversion, propagation and jet break up in deep pools are regarded of first priority. Recently KTH performed experiments in the PULiMS facility with up to 80 kg of different high temperature corium simulant materials resulted in quite repeatable self-triggered steam explosions in stratified melt-coolant configuration. Measured dynamic forces and impulses were comparable to those usually observed in “conventional” melt-jet coolant pool configuration. These observations suggest that the stratified steam explosion, previously considered as of low importance due to assumed low energetics, should be reconsidered and explanations to the recent results with high energetics should be provided. Some analytical efforts have been conducted within the related OECD projects. There is still a need for the transposition of the experimental results to plant conditions and plant application, especially since reactor pit flooding is considered for some plants as a SA countermeasure. Due to the high risk significance for the containment integrity, the **2,3 issue** is classified with **high priority** regarding ex-vessel and could be **closed** for in-vessel aspects. The ranking for the **2,2 issue** related to corium fragmentation remains **high priority**, due to the quite high uncertainties still existing.

The **2,4 issue** concerns the melt ejection under elevated pressure from the failed vessel into the cavity and further into the upper containment or neighbouring compartments (DCH) even under moderate pressure in the vessel. The phenomenon is combined with hydrogen production due to oxidation processes of the melt droplets with steam in the cavity, adjacent compartments and the containment dome atmosphere and its combustion together with pre-existing hydrogen. The DCH phenomena are investigated e.g. in the DISCO experiments (KIT) at reactor scale. Main open issues are the influence of water inside the cavity on the DCH process and the H_2 combustion during the DCH process (link to 2,1). Concerning break location, the failure at the lowest point of the RPV bottom is the most dangerous one. The issue is still classified with **medium priority**, although SAM measures exist to depressurize the RCS before RPV failure reducing the risk for DCH.

2.3. Phenomena that could lead to late containment failure

The **3,1 issue** concerns the ex-vessel melt pool configuration in the cavity during the MCCI process and the concrete ablation, which affect the containment integrity. The **3,2 issue** – to be treated together with 3,1 because phenomena are coupled – concerns the ex-vessel corium coolability in the cavity by top flooding and all the encountered phenomena dealing with heat transfer, crust formation, sparging gas and cracking of crust.

Concerning “dry” MCCI, calculations of experiments related to the interaction of oxidic corium with a limestone-rich concrete have shown very good results. The issue of oxidic corium-siliceous concrete interaction is still open with uncertainties that remain high, as calculations showed a wide spread of results caused also by the non-isotropic erosion front found in experiments. In general the ranking was set to **medium priority** for oxidic melt concrete interaction. Reactor scale calculations indicate that the major sources of uncertainties lie now with the oxide-metal corium interactions (evolution of layer configuration). This topic included in **3,1 issue** should be considered with a **high priority** although at the limits of current experimental capabilities. Further on, the knowledge of the cooling mechanisms by top flooding of the ex-vessel corium pool ("wet" MCCI) needs to be increased, because they affect the containment integrity with a possible basemat erosion stop or not. The corium coolability by top flooding is currently investigated with first priority on the heat transfer between the upper crust and the water on top, including water ingression and melt eruption phenomena. Due to the risk significance, the **issue 3,2** is classified with **high priority**, although PSAs for different plants result in different importance rankings.

The **3,3 issue** concerns the ex-vessel corium catcher (without any specific design) and its related phenomena relevant to interaction of corium and ceramics. This issue was regarded as closed in respect of EPR. The simultaneous interaction of corium with ceramic and concrete must be reassessed in view of the recent results of MCCI. The modelling of the transition between a mainly lateral ablation to a preferential ablation of the bottom concrete is not well simulated and the experience of the erroneous predictions of an isotropic 2D MCCI leads to the recommendation of a reasonable R&D program on this issue. Moreover, new designs (in terms of geometry and materials) are being proposed and should be assessed but this may lead to the problem of industrial confidentiality. Therefore, it was decided to change to **low priority** with bilateral projects for interested partners.

The **3,4 issue** concerns the corium coolability by bottom water injection in the core catcher. These items might affect the containment integrity. The efficiencies of different corium catcher designs and the efficiency of water bottom injection were demonstrated for Gen. III applications, owing to experiments at ex-FZK (now KIT), ANL, KTH and CEA and modelling mainly at IKE. Further investigations for plant specific geometrical conditions can be performed on a bilateral basis (see above). In the view of Gen. II plant back-fitting, the technical solutions that were considered must be modified in order to adapt to the constraint of an implementation in a highly radioactive environment. This will lead to renewed research activities on these issues with a focus on the risks of coolant bypass, the control of the maximal steam rates and the elimination of steam explosion risks. Therefore, it is proposed to reassess this issue to **low priority** with bilateral projects for interested partners.

The **3,5 issue** concerns the unique item of corium coolability in an external corium catcher. The predictability of the thermal loading on the core catcher device needs further improvement. The issue was treated already in SARNET FP6 for the EPR design and was experimentally closed. Related to other new plant concepts it is also of interest for the ESBWR, APR1400 and VVER 1200 core catchers. Due to proprietary reasons, specific questions should be investigated on a bilateral basis. The WCB1 experiment within the OECD MCCI-2 project using sacrificial concrete and water cooled basemat (as used in the EPR concept) showed the presence of hot spots which must be further investigated, too. This issue is therefore maintained as **low priority** with bilateral projects for interested partners.

The **3,6 issue** concerns the containment behaviour and the formation of cracks and leakages at penetrations in the containment shells. One goal is the estimation of FP leakages and their possible retention in the cracks, another one the release of non-condensable into the secondary containment. This issue 3,6 was reassessed as **medium priority**, since programs related to the study of leak-tightness of penetrations and seals under SA conditions (temperature, pressure, dose-rate) will be performed.

2.4. Phenomena of release and transport of fission products

The **4,1 and 4,2 issues** concern the characterisation and quantification of FP release due to re-flooding of the degraded core. It is suggested to separate between the early phase (4,1) (**low priority** – according to the results of ISTC VVER QUENCH project) and the late phase (4,2) (**medium priority** – according to uncertainties on corium leaching process emphasized by Fukushima and leading to significant strontium release) of the core degradation.

The **4,3 issue** concerns the characterisation and quantification of FP release under oxidation conditions and in particular air ingress for high burn-up and MOX fuel. Important concerns are relative to ruthenium release as well as volatile fission products revolatilisation in the RCS following air ingress (link with 4,4). Few projects are on-going related to these issues: new data are expected on FP release from MOX fuel in the VERDON tests at CEA in the frame of ISTP, as well as on volatile FP revolatilisation. KIT studies underline that the Ba and Ru releases depend on the oxidation of cladding. Furthermore it depends on the oxygen potential in the fuel (HCE, VERCORS/VERDON, Phébus. FP tests). Concerning the cooling impact on FP release, the FP release can be simulated if the temperatures are simulated correctly. Experiments related to FP release through fuel cracks provide no usable answer. Additionally, the FP release during re-flooding of large degraded core (with loss of geometry) with a potential high risk was discussed. Only little experimental data are available. Concerning 4,3 issue it is recommended to keep a **high priority** due to the remaining uncertainties and high safety impact of this issue, associated with still scarce experimental data to validate the models.

The **4,4 issue** concerns the high temperature chemistry in the RCS and its impact on the source term to the environment. The prediction of the FP species exiting the RCS shall be improved to provide the best estimate of FP source into the containment. The **4,5 issue** concerns the chemistry of FP in the containment and its impact on the source term to the environment. Both issues are related notably since the external source term is strongly dependent on RCS and containment chemistry and induced volatility of FPs. Iodine and ruthenium are of special interest since they form stable gaseous species at containment temperature and may be the main contributors to the radiological consequences in the days following an accident. Further, re-suspension or re-volatilisation of FP deposited on RCS and containment surfaces can also constitute a delayed source of activity which shall be quantified.

Concerning FP chemistry in the RCS, significant experimental activity has been taken in order to solve open issues in iodine chemistry, notably to develop models able to simulate gaseous iodine fractions exiting the RCS as evidenced in Phébus FP tests (Bottomley et al., 2014). Iodine chemistry in the RCS has been examined in ISTP CHIP and GAEC separate effect tests (at IRSN) and in EXSI PC (VTT) experiments. Thermodynamic and kinetic modelling of the I, Cs, Mo, B, O, H chemical system were developed and implemented in the SOPHAEROS FP transport module of ASTEC. These developments highlight the role of B and Mo (due to their reactivity with Cs) and of kinetic limitations in explaining the formation of gaseous iodine in the RCS as observed in Phébus FP tests, notably in Phébus FPT3 where the RCS chemistry was influenced by the degradation of a boron carbide control rod. Experimental and theoretical work is continuing at IRSN to take into account the role of silver, indium and cadmium since Phébus FP tests performed with silver-indium-cadmium control rod showed these elements can influence the iodine volatility in the RCS.

Surface reactions (FPs chemisorption and physisorption, re-suspension and re-volatilisation) have been studied via re-vaporisation tests performed with Phébus FP RCS surface samples at JRC/ITU and via a theoretical approach (ab initio calculations) modelling surfaces at the atomic scale at IRSN. Large re-vaporisation of FPs was evidenced in ITU tests depending on the tested conditions. The theoretical approach of surface processes provides promising results, however existing modelling in severe accident codes is insufficient to account for the delayed release of FPs due to such processes. Experimental work to study iodine and ruthenium re-volatilisation from deposits is underway in the OECD/STEM program.

Concerning FP chemistry in the containment, iodine chemistry under irradiation was and is still experimentally studied in small-scale experiments at IRSN (ISTP/EPICUR and OECD/STEM), at AECL (OECD/BIP1 and BIP2) and at PSI. Experiments performed at IRSN and at AECL focussed on the formation of gaseous organic iodides since these compounds may contribute significantly to the iodine source term notably when SAM measures involve filtered containment venting (organic iodides are difficult to remove by filtration systems). The modelling of organic iodides formation in severe accident codes has greatly benefited from these programs; experimental work is still on-going in OECD/STEM and BIP2 programs to develop a more mechanistic approach notably to take account of paint ageing (due to normal and accidental conditions). Experiments performed at PSI focused on the effects of some impurities (nitrate, nitrite and chloride) on the iodine volatility under irradiation in the sump. Data are available to model the corresponding reactions.

Air radiolysis reactions, with the formation of iodine oxides, were shown through experiments (PARIS, OECD/BIP and EXSI projects) and interpretation of Phébus FP tests to influence significantly gaseous iodine amounts in suspension in the containment. Iodine oxides formation and destruction under radiation are currently being studied in the OECD/STEM project to develop the corresponding modelling.

The long term stability under radiation of deposited iodine aerosols and the deposits delayed release are currently being looked at in the OECD/STEM project. These processes may contribute significantly to a delayed iodine source term.

Gaseous iodine interaction with aerosols (Ag and SnO_2 particles) and of iodine aerosols with hydrogen recombiners were studied in the OECD/THAI and THAI2 projects (in the Becker Technologies facility) in larger scale experiments. Data were obtained to assess the potential effect of these processes on the iodine source term. These assessments are currently underway to appreciate if additional experiments should be performed in the future on these topics.

In relation with issue 4.3, IRSN studied ruthenium chemistry in the containment under radiation in the ISTP program and developed relevant modelling for the ASTEC code to appreciate potential ruthenium releases notably for scenarios involving oxidant conditions.

Experimental data related to issues 4.4 and 4.5 have been used for the development and validation of the major modelling codes such as ASTEC, MELCOR, COCOSYS/AIM and INSPECT/IODAIR. Both issues are still of high relevance for the source term and risk significance, although the predictability of iodine and ruthenium volatility has made a large progress. The on-going R&D work shall further reduce the uncertainties on the iodine and ruthenium release and transport phenomena.

In the recent Fukushima accidents, volatile FPs have contributed significantly to the activity released from the plants. The release of volatile FPs has continued weeks after the initiation of the accident. Moreover, radioactive particles deposited within the plants have hindered repair crews from entering the buildings. In the near future, possible means to retain more efficiently FPs from contaminated air and water should be studied (cf. issues 4.7 and 4.8).

All the activities for both issues **4,4 and 4,5** are further on classified with **high priority**.

The **4,6 issue** concerns the aerosol behaviour and its impact on the source term. The effect of uncertain key aerosol phenomena on the source term shall be quantified. The work should be continued with **low priority**.

The **4,7 issue** related to filtered venting systems has been set to **high priority**. The experiences of Fukushima underline the need of such systems which have already been implemented in several nuclear plants. Beside the reduction of uncertainties of simulation results, the requirements on venting systems under more severe boundary conditions including the long-term operation of the venting filters should be investigated. As well more data are needed to develop detailed filter models for the integral codes like ASTEC. Research is underway in the PASSAM FP7 project.

The **4,8 issue** concerns the pool scrubbing topic. Research is underway in the PASSAM project. The work is important especially for BWR and should be regarded with **medium priority**. The models implemented in codes like ASTEC need a re-evaluation and further improvement, notably in the "Code for European Severe **Accident** Management (CESAM)" FP7 project.

2.5. Phenomena in spent fuel pool storages

The new **5,1 issue** is linked to fuel assembly behaviour inside Spent Fuel Pools (SFP), with its specific thermo-hydraulics and with physico-chemical and mechanical behaviour of claddings under air and air/steam mixtures. It is regarded with **high priority**. In the short and mid-term, the high priority concerns small/medium scale experiments on convection in prototypical SFPs and assembly scale experiments to study the thermal-hydraulic conditions representative of a loss of coolant accident, with and without dewatering. CFD codes could be used to interpret these experiments and be further validated. Phenomenological models should also be elaborated for integral codes such as ASTEC.

2.6. New topics related to severe accidents (underlined after Fukushima)

The new **6,1 issue** regards the effect of impurities in water on core degradation, chemistry and FCI. During the Fukushima accidents, raw sea water has been used to cool the reactor cores, although this had never been considered in previous severe accident studies. Since it is not possible to exclude totally the use of untreated water (sea water but also hard-calcareous-water or dirty water pumped somewhere in the NPP) during a postulated future severe accident, investigations must be conducted to define possible R&D needs. In particular, studies should include the effects on FP release (notably by leaching) and on corium chemistry (low temperature eutectics or volatile species, e.g. effects of chloride) and the study of precipitate formation. The effects of impurities on FCI should be studied, too. In the US, Sandia National Laboratories is actively working on chemistry models for water from raw sources for T below 320 °C. Considerable progress has been made regarding the inorganic chemistry and further work is conducted for organics. This work will be reported to the SARNET community and should be taken into account in planning future activities in this topic. This issue is regarded with **medium priority**.

The new **6,2 issue** regards the instrumentation for severe accidents. The TMI2, Chernobyl and Fukushima accidents have shown a lack of efficient instrumentation, which should have helped to get a reliable diagnosis of the core and SFP status over the weeks following the accident. Even after more than two and a half years passed from Fukushima accident we do not know yet the location of corium debris of damaged reactors. SAM Guidelines (SAMG) implementation and effective use require accident progression to be correctly detected and consequences of different SAM to be well predicted. It appears clearly that the current instrumentation available to cope with a severe accident is not sufficient for effective SAM and needs to be further developed and reinforced. The main function of the additional instrumentation is to assess the level of the core degradation and, in particular, to be able to identify the different increasing degraded states of fuel and reactor safety barriers, such as water core uncovering, massive fuel cladding ruptures, fuel rod damage and fragmentation, in-core molten pool formation, corium relocation in the lower head, rupture of the lower head, ex-vessel corium spreading and basemat concrete ablation. Rapid development of diagnosis and research on instrumentation during last decades enable new methods for accident diagnosis and management to be used and novel systems potentially can be installed even at operating units. Several approaches can be recommended for reliable operation of SA instrumentation including use of optical fibres with remote electronic systems outside of the containment or remotely operated devices at key points, preferential use of passive systems, able to work during complete station blackout. This new issue is regarded as **high priority**.

The new **6,3 issue** regards the possible influence of aerosols on the iodine chemistry. Most of the iodine experiments have been performed under more or less "clean" conditions. One exception is the Phébus FP experiment series. In a real severe accident the situation is much more complex. Not investigated is the possible influence of aerosols and chemical species released during an MCCI process on the iodine chemistry as well as on the containment venting filters. Especially if top flooding is considered this situation should be evaluated in more detail. This **6,3 issue** was set to **low priority** since the relative importance of these processes with respect to FP chemistry needs to be further assessed.

The new **6,4 issue** is related to thermodynamic and thermophysical databases. In and ex-vessel corium behaviour is modelled with a strong coupling between thermal-hydraulics and thermochemistry. Improved knowledge of corium phase diagrams is necessary to determine if observed discrepancies between models and experiments are due to uncertainties in models or in the material database. The current level of uncertainties is one of the large sources of error in the calculation of severe accident sequences involving corium. Although the European Nuclear Database NUCLEA (Bakardjieva et al., 2008) is a very useful tool and is implemented e.g. in ASTEC through a look-up table, there are still many uncertainties. Some important data are missing such as the properties of molten zirconia. Furthermore, the mixing laws are not validated. This **6,4 issue** is regarded with **medium priority**.

3. Conclusions

The need of a deeper understanding of severe accident phenomena and accident progression is still quite important notably concerning the appreciation of SAM efficiency. This was underlined again by the assessment of the consequences of the Fukushima severe accidents. Although considerable progress has been gained in many areas in the recent decades and in particular during the last 4 years in SARNET2 FP7, it is still necessary to reduce further the uncertainties of simulation results, to investigate new phenomena not regarded in detail before, to reinvestigate phenomena which gained enhanced interest after Fukushima and to improve further possible SAM measures under extreme boundary and environmental conditions.

Comparing the priority level of issues with the original levels decided in SARP of SARNET FP6, most of the levels have not been changed or even received higher priorities again. The progress on understanding the severe accident phenomenology was important but during SARNET2 FP7 it was seen, notably after Fukushima's accidents that more efforts had to be made to increase the knowledge necessary to better appreciate – or develop new – severe accident mitigation means and radioactive releases to the environment for relevant accident scenarios.

Under the umbrella of the Sustainable Nuclear Energy Technological Platform (SNETP), the NUGENIA Association, gathering all types of organizations, in particular industry and utilities, has been recently created to deal with R&D on the Gen. II/III water reactors in Europe. The SARNET network has been integrated as one of its 8 topics about severe accidents. This results in a strong link between the results of the SARP group and the roadmap on short/medium/long term R&D drawn up by NUGENIA. This roadmap (NUGENIA Roadmap, 2013) will be used as a frame to define and launch new R&D projects in the next years, in particular in the HORIZON 2020 European Commission frame that starts in 2014.

References

Bakardjieva, S., et al., 2008. Improvement of the European thermodynamic database NUCLEA in the frame of EU-funded experiments. 3rd European Review Meeting on Severe Accident Research (ERMSAR-2008) Nesseber, Vigo Hotel, Bulgaria, 23–25 September 2008.

Bottomley, P.D.W., et al., 2014. Revaporisation of fission product deposits in the primary circuit and its impact on accident source term. Ann. Nucl. Energy 74, 208–223.

Final synthesis report of EURSAFE or Magallon, D., et al., 2005. European expert network for the reduction of uncertainties in severe accident safety issues (EURSAFE). Nucl. Eng. Des. 235, 309–346.

NUGENIA Roadmap, 2013. NUGENIA Association (http://www.nugenia.org/docs/NUGENIA_roadmap.pdf).

Raimond, E., et al., 2013. ASAMPSA2, Best practices guidelines for L2PSA development and applications, volume 1 – general. Technical report ASAMPSA2/ WP2-3-4/D3.3/2013-35, Rapport IRSN-PSN/RES/SAG 2013–0177 (www.asampsa2.eu).

Schwinges, B., et al., 2008. Ranking of severe accident research priorities. ERMSAR 2008, Nesseber (Bulgaria).

Schwinges, B., et al., 2008. Final Evaluation of Severe Accident Research Priorities and Proposed Research Activities. SARNET-SARP-D96, EC-SARNET/FI6O-CT-2004-509065, August 2008.