SEVERE ACCIDENT RESEARCH PRIORITY RANKING: A NEW ASSESSMENT EIGHT YEARS AFTER THE FUKUSHIMA DAIICHI ACCIDENT

D. Manara
European Commission, Joint Research Centre (JRC), Karlsruhe (Germany)
P.O. Box 2340, 76125 Karlsruhe, Germany
dario.manara@ec.europa.eu

D . Jacquemain, J.P. Van Dorsselaere
Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Cadarache, France
didier.jacquemain@irsn.fr

P.D. Bottomley
Japanese Agency for Atomic Energy (JAEA) - CLADS Laboratory,
Iwaki, Japan
dboksb3@gmail.com

M. Adorni
Bel V, Rue Walcourt 148, 1070 Bruxelles, Belgium
martina.adorni@Belv.be

C. Journeau, Y. Pontillon
CEA, DEN, Cadarache, 13108 Saint-Paul-lès-Durance, Cedex, France
christophe.journeau@cea.fr
yves.pontillon@cea.fr

T. Lind
Paul Schrerrer Institute (PSI)
Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
terttaliisa.lind@psi.ch

L.E. Herranz
CIEMAT
División of Nuclear Fission
Avda. Complutense 40 28040 Madrid, Spain
luisen.herranz@ciemat.es

F. Rocchi
Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA)
CR ENEA Bologna, via Martiri di Monte Sole 4, 40136 Bologna, Italy
federico.rocchi@enea.it

A. Schaffrath
Gesellschaft für Reaktorsicherheit (GRS)
Boltzmannstraße 14, 85748 Garching b. München, Germany
andreas.schaffrath@grs.de

J.C. de la Rosa Blul
European Commission, Joint Research Centre (JRC), Petten (The Netherlands)
Westerduinweg 3, 1755 LE Petten, The Netherlands
juan-carlos.de-la-rosa-blul@ec.europa.eu

S. Bechta
Kungliga Tekniska Högskolan (KTH)
10691 Stockholm, Sweden
bechta@safety.sci.kth.se

J. Duspiva
Nuclear Research Centre (UJV) REZ a.s.
Hlavni 130, 250 68 Husinec Rez, Czech Republic
jiri.duspiva@ujv.cz

I. Kljenak
Jozef Stefan Institute (JSI),
Ljubljana, Slovenia
Ivo.Kljenak@ijs.si

P. Dejardin
Tractebel
Boulevard Simon Bolivar 34-36 1000 Brussels, Belgium
philippe.dejardin@tractebel.engie.com

ABSTRACT

In the final step of the SARNET Euratom projects in 2013, an assessment of the ranking of research priorities for severe accidents was elaborated by a group of European experts (named SARP), based on gaps of knowledge and needs identified in SARNET and taking into account the first outcomes of the 2011 Fukushima Daiichi Nuclear Power Station (FDNPS) core meltdown accident. In the autumn of 2017, a group of experts from fifteen NUGENIA TA2/SARNET partners was formed again to perform an update of such ranking, accounting for recent advances on knowledge coming from research initiatives launched in the international frame (mainly EC H2020 and OECD/NEA) and in particular linked to a deeper analysis of the FDNPS accidents. Thirty-five topics were addressed in the following domains: in-vessel accident progression, risk of early containment failure, risk of late containment failure, release and transport of fission products, accident in spent fuel pool storages and other topics (e.g. instrumentation or thermodynamic databases). No big change has been observed with respect to the 2013 ranking, with for instance a very high priority still given to knowledge consolidation on corium behaviour in the lower head and on ex-vessel corium coolability in relation to SA mitigation strategies. Nonetheless, a few new possible research areas have been identified mostly related to long term management of severe accidents.

KEYWORDS
Euratom, NUGENIA, Nuclear Safety, Severe Accidents

1. INTRODUCTION

Severe Accident Research (SAR) in nuclear power plants has been broadly boosted in the aftermath of the core meltdown events occurred in the unfortunate 2011 mishap of the Fukushima Daiichi Nuclear Power Station (FDNPS). A great number of different topics and side effects need to be thoroughly analysed in order to obtain a satisfactory description of the series of processes that may lead to and result in a nuclear power plant core meltdown. The earlier accidents happened at Three Mile Island (USA, 1979) and Chernobyl (USSR 1986) already highlighted the importance of a deep understanding of such events, in order to prevent their occurrence and, in the worst case, manage and mitigate their consequences. The 2011 FDNPS accident and its long-term consequences demonstrate that further research is needed in this direction. In this scenario, a recent Directive by the European Council [1] requires EU countries to give highest priority to nuclear safety at all stages of the lifecycle of a nuclear power plant. This includes safety assessments before the construction of new nuclear power plants and also significant safety enhancements for existing reactors [2].

On the other hand, it is up to the scientific community to ensure that research conducted on severe accidents be efficient and focusing on truly relevant topics, among the numerous aspects calling for investigation. The Severe Accident Research Priority (SARP) work that started already in the first SARNET FP6 project [3] and updated in 2013 [4], is being upgraded [5, 6] by evaluating more recent experimental results and considering the remaining safety issues. These evaluation activities are being conducted in close relation with the work performed both in existing international organizations - mainly the OECD/NEA/CSNI Working Group on Analysis and Management of Accidents (WGAMA) [7, 8] and the International Science and Technology Centre (ISTC) Projects [9-15] – and in the Sustainable Nuclear Energy Technology Platform (SNE-TP) [16], including NUGENIA platform dedicated to the research and development of Generation II-III nuclear fission technologies, whereby Technical Areas (TAs) 2.1, 2.2, 2.3 and 2.4 deal with severe accident analysis [17-19].

In the autumn of 2017, a group of experts from fifteen NUGENIA TA2/SARNET partners was formed again to perform an update of the 2013 SA research topic ranking, accounting for recent advances on knowledge coming from research initiatives launched in the international frame (mainly EC H2020 and OECD/NEA research projects) and in particular linked to a deeper analysis of the FDNPS accidents.

Thirty-five topics were addressed in the following domains: in-vessel accident progression, risk of early containment failure, risk of late containment failure, release and transport of fission products, accident in spent fuel pool storages and other topics (e.g. instrumentation or thermodynamic databases). The present paper summarizes the main outcome of this latest survey.

2. RANKING OF RESEARCH PRIORITIES

Table 1 presents a list of the research priorities that constituted the basis for the 2017 SARP survey and the 2018 revised status. The voting participants were requested to indicate whether each topic was to be considered as H (=1, high priority), M (=2, medium priority), L (=3, low priority) or CL (=4, closed). The status results reported in Table 1 are based on the average vote for each topic, using the following convention to define a topic's status: H = 1 to 1.3; M to H = 1.4 to 1.6; M = 1.7 to 2.2; L to M = 2.3 to 2.6; L= 2.7 to 3; CL = 4 (a value of 4 (closure) is only when all partners agree.).
The basis for evaluation was the opinion of severe accident experts representing the participating organisations or research institutes active in Technical Area 2 (SA). It was considered as the best means to get the expert’s opinions (technical, analytical or regulatory) with detailed knowledge of future needs to update the list of priorities of severe accident research for the EU and its partners. An advantage is a consistency of methodology with that previously used and it offered the most rapid return on SA research results in Europe. This also assisted the overall aim of improving operational reactor safety, given the recent events. Furthermore, this evaluation promotes the networking of costly SA research (eg under SAFEST). In addition, the series of roadmaps produced under SAFEST provide a means to examine work outside the SARP participants.
Some issues have been refined, sub-divided, or included with another topic (eg. transfer of topic 2.5: BWR wetwell heat removal to topic 3.6) in the re-evaluation as progress has been made in this area and so clarify the topics, especially those of high priority.

Table I. List of the research priorities that constituted the basis for the 2017 SARP survey and the 2018 revised status

N	Topic	Topic description	2013 status	2018 revised status	Remarks
1. Phenomena during In-Vessel Accident Progression					
1,1	**Hydrogen generation during reflooding of slightly degraded cores**	Rapid generation of hydrogen; improve knowledge about the magnitude of hydrogen generation.	L	L	
1,2	**Hydrogen generation during reflooding of strongly degraded cores**	Rapid generation of hydrogen due to oxidation of metals; improve knowledge about the magnitude of hydrogen.	M	M	

1,3	**Core coolability during reflooding and thermal-hydraulics within particulate debris**	Termination of the accident by reflooding of the core while maintaining RCS integrity. Increase predictability of core cooling during re-flooding.	H	M to H	Ranking considers expected progress from on-going SAFEST [20, 21] and IVMR [22-24] programs
1,4	**Corium behaviour in lower head**	Improve predictability of corium behaviour and the thermal loading on RPV lower head to assess RPV integrity. BWR: Consideration of specific BWR boundary conditions.	H	H	
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.	H	M to H	Ranking considers expected progress from on-going EC IVMR [22-24] program
1,6	**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.	L	L	Interest in FCI topic is now considered under 2.3 for the Ex-Vessel Scenario. Also some aspects of In-vessel FCI is also included in 1,5
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.	L for PWR H for BWR (→1,5; 2,2)	M (LWR geometry) to H (BWR geometry)	
1,8	**Integrity of RCS, especially integrity of SGT in HP 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).	M	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 countermeasures.	H	M to H	M for mixing, H for combustion
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.	H (→1,7)	H	
2,3	**FCI incl. steam explosion: melt into water, in-vessel and ex-vessel**	Increase the knowledge of parameters affecting steam explosion energetics during corium relocation into water and determine the risk of vessel or containment failure.	CL-in vessel H ex-vessel	M to H	Needed further research on spreading underwater and related steam explosion risks
2,4	**Direct containment Heating (DCH)**	Increase the knowledge of parameters affecting the pressure build-up due to DCH and determine the risk of containment failure.	M	L	Existing knowledge considered sufficient to assess DCH risks in different designs and so reduce the priority at this point in time
2,5	**Long term loss of heat removal from wetwell in a BWR**	In Fukushima the heat removal from the wetwell was lost after the tsunami. The heat released by steam from the RCS heated the wetwell water to saturation.	M (→ 4,8)	L to M	Replaced by new topic in domain 3 (3,6)

3. Phenomena that could lead to late containment failure					
3,1	**MCCI: 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.	M oxidic melt H stratified oxidic/ metallic melt	M oxidic melt H stratified oxidic/ metallic melt	
3,2	**Ex-Vessel corium coolability, top flooding**	Increase knowledge of cooling mechanisms by top flooding the corium pool to demonstrate termination of accident progression and maintenance of containment integrity.	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.	L Bilateral projects	L	New knowledge may be needed for new designs
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.	L Bilateral projects	L	New knowledge may be needed for new designs
3,5	**External corium catcher device**	Improve predictability of corium catcher devices to maintain their integrity.	L Bilateral projects	L	New knowledge may be needed for new designs
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.	M	M to H	Knowledge needed to improve evaluations of releases

4. Phenomena of release and transport of fission products					
4,1	**Core reflooding impact on source term (early phase)**	Characterise and quantify the FP release during core reflooding in early phase of core degradation (more or less intact core geometry).	L (→1,1)	L	Partly closed
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).	M (→1,2)	M	
4,3	**Oxidizing environment impact on source term**	Quantify the source term, in particular for Ru, under oxidative conditions / air ingress for HBU and MOX.	H	M to H	Significant knowledge increase expected from ongoing research programs (ISTP, OECD/NEA, THAI3 [25], BIP3 [26], STEM2 [27])
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.	H	H	See above (4,3)
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.	H	H	See above (4,3)
4,6	**Aerosol behaviour impact on source term**	Quantify the source term for aerosol retention in the secondary side of steam generator and leakage through cracks in the containment wall as well as the source into the containment due to re-volatilization in RCS	L	L to M	Chemical revolatilisation of FPs deposited on surfaces and in pools to be further addressed Iodine chemistry in the environment to be further addressed

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	M	Significant results obtained from EC PASSAM program [28].
4,8	**Pool scrubbing under different conditions**	Estimation of pool scrubbing efficiency under different (e.g. boiling) conditions inside the pool.	M	M	New knowledge expected from the NUGENIA IPRESCA project [29].
5. Phenomena in spent fuel pool storages					
5,1	**Fuel Assembly (FA) 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	H	Existing research programmes on this topic. A future review can refine and subdivide the areas of main interest.
6. Other topics related to severe accidents (proposed as "new topics" in 2013)					
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	M	
6,2	**Instrumentation for severe accidents**	Development and qualification of specific instrumentation for SA conditions	H	M to H	Increased knowledge on instrumentation survivability, on-going development of SA robust instruments in many countries

6,3	**MCCI aerosol effect on chemistry**	Effect of MCCI aerosols on iodine gaseous concentration chemistry in the sump.	L	L	
6,4	**Thermodynamic and thermo-physical databases**	Improvement of the thermo-dynamic and thermo-physical data-base for corium and fission products.	M	M	

2.1. 2018 Analysis and Synthesis of SARP Votes

The analysis and synthesis process led to select the topics with an average vote below or close to 1.5 and to check (through histograms) that the votes are not too much scattered. The selection threshold of the average vote has been set at 1.6. In the following, topics with average vote equal to or below 1.3 are said to “high priority” and those between 1.4 and 1.6 “medium-to-high priority”.

Topic rankings are summarised domain by domain along with the relative vote histograms.
The conclusions on each of the selected topics are summarized in Table 1 and in the following sub-sections. Appendix 1 presents a more detailed synthesis of comments.

2.1.1. Domain 1: “Phenomena during in-vessel accident progression”

Four topics have been selected, in the following decreasing priority:

- Vote 1.1: “Corium behaviour in lower head” (1,4)
- Vote 1.4: “Core coolability during reflooding and thermal-hydraulics within particulate debris” (1,3)
- Vote 1.5: “Integrity of RPV due to external vessel cooling” (1,5)
- Vote 1.6: “RPV failure mode” (1,7)

The 1st topic gets a high priority (as in 2013) mainly due to its importance for the progression of the accident (in particular for potential vessel failure), although results of the IVMR [22-24] and SAFEST [20, 21] projects are expected to significantly improve knowledge in the next years. This situation is, naturally, consistent with the priority to complete SA current projects. The main uncertainties still concern the transient configurations of corium layers in the vessel lower head and the coolability of debris with a prototypical morphology. The three others get a medium-to-high priority (with a slight decrease with respect to 2013) also in close relation with the IVMR project.
For the 2nd topic the main uncertainties concern the coolability of debris with a prototypical morphology.
For the 3rd topic the demonstration of the possibility to maintain the RPV integrity by simultaneous external vessel cooling, water injection within the vessel and related safety margins need to be consolidated. Also thermal properties data of corium need improvement to enable more accurate modelling.
The 4th topic remains important since it has an impact on ex-vessel potential steam explosion and corium coolability through the corium release characteristics. It will also directly impact on the safety requirements of some current LWR designs. The main uncertainties concern on one hand the overall integrity of an ablated vessel and on the other hand the local failure of PWR and BWR vessels with penetrations.

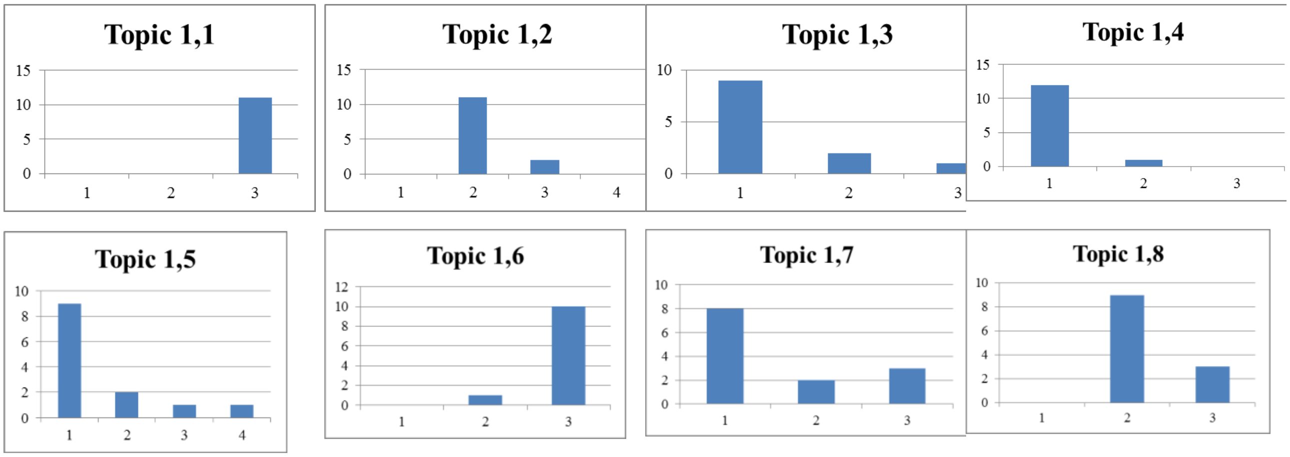


Figure 1: Ranking vote distribution for the various Topics of Domain 1 (x axis: 1=high priority; 2=medium priority; 3=low priority; 4= closed topic.; y axis: number of votes).

One new topic is proposed on progression of degradation in reactor core: prediction of progressive relocation of molten material or formation of extended molten pool, depending on accident scenario and core design. This is in close relation with recent crosswalk exercises done between MAAP, MELCOR and ASTEC codes and in particular for BWR, as shown by Fukushima-Daiichi accident analysis [30, 31, 32].

2.1.2 Domain 2: “Phenomena that could lead to early containment (or reactor building) failure”

Three topics have been selected, in the following decreasing priority:
- Vote 1.3: “Melt relocation into water and particulate formation” (2,2)
- Vote 1.4: “Hydrogen combustion / detonation and countermeasures” (2,1)
- Vote 1.4: “FCI incl. steam explosion: melt into water ex-vessel” (2,3)

The 1st and 3rd topics, closely linked together, get a high- and a medium-to-high priority respectively:
- For the 1st topic, improvements of knowledge are important for understanding fuel fragmentation in FCI and predicting the formation and characterisation of ex-vessel debris beds, which is an essential input to evaluate the possibility of ex-vessel corium coolability.
- The 3rd topic is today restricted to ex-vessel corium configurations since the in-vessel FCI consequences, for both PWR and BWR, are judged unanimously lower. It remains an important topic since it addresses the risk and modes of containment failure. New KTH experimental data obtained in SAFEST underline the need to better understand stratified steam explosions, including spontaneous ones.

The 2nd topic gets a high priority when suppressing the gas distribution issue that was included in the 2013 ranking since major uncertainties are today attributed to the combustion and detonation aspects. Despite new knowledge (e.g. on behaviour of Passive Autocatalytic Recombiners (PAR)) and ongoing new projects (e.g. OECD/NEA THAI3 [25]), efforts are still needed to close research gaps, enhance capability of simulation codes, and reduce code uncertainty on application to real plant geometries.

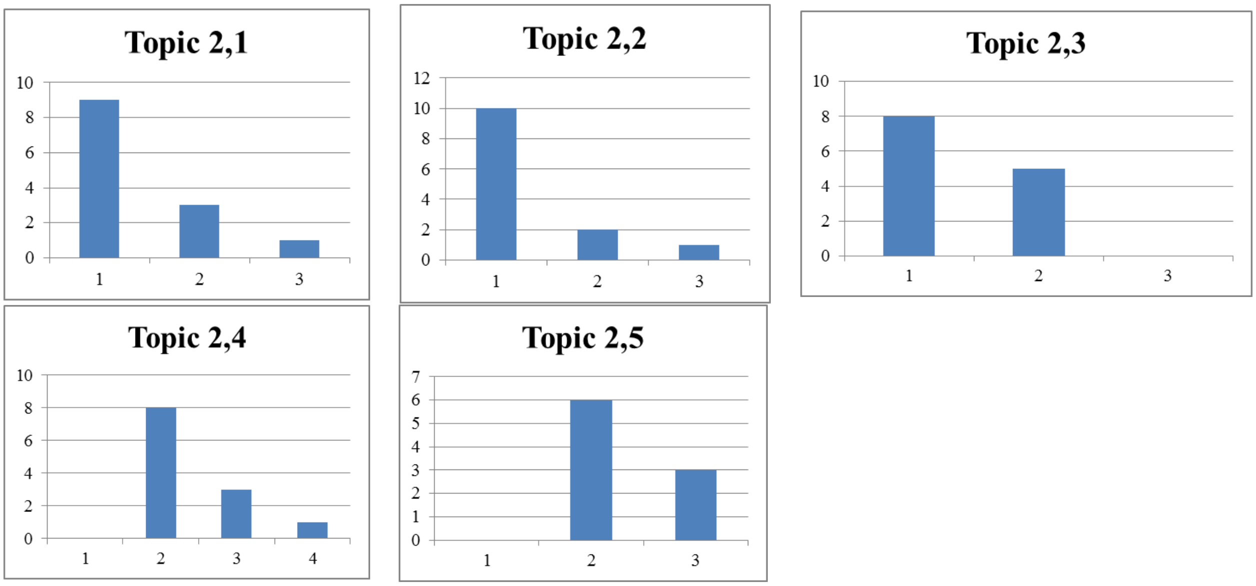


Figure 2: Ranking vote distribution for the various Topics of Domain 2 (x axis: 1=high priority; 2=medium priority; 3=low priority; 4= closed topic.; y axis: number of votes).

2.1.3 Domain 3: "Phenomena that could lead to late containment failure"

Three topics have been selected, in the following decreasing priority:

- Vote 1.0: "Ex-Vessel corium coolability, top flooding" (3,2)
- Vote 1.6: "MCCI: molten pool configuration and concrete ablation" (3,1)
- Vote 1.6: "Dynamic and static behaviour of containment, crack formation and leakage at penetrations" (3,6)

The priorities of 2013 are mostly confirmed.

The 1st topic gets unanimously a very high priority. Despite additional results in recent years in ANL CCI tests [33], the knowledge of cooling mechanisms by top flooding the ex-vessel corium pool remains crucial to demonstrate possibilities of termination of MCCI and of maintaining containment integrity.

The 2nd topic is still considered as medium-to-high priority, mainly because high uncertainties are expected to remain on termination of MCCI progression with oxide-metallic melts, in particular with the incorporation in melts of steel from rebars. The mechanisms of melt concrete interaction remain difficult to model.

The 3rd topic has received a slightly higher priority with respect to 2013, i.e. a medium-to-high priority. It is proposed mainly for long term accident situations and also in relation with the limited knowledge on leakage paths.

A new topic is proposed on the failure risks of Emergency Core Cooling System on the long term under SA conditions.

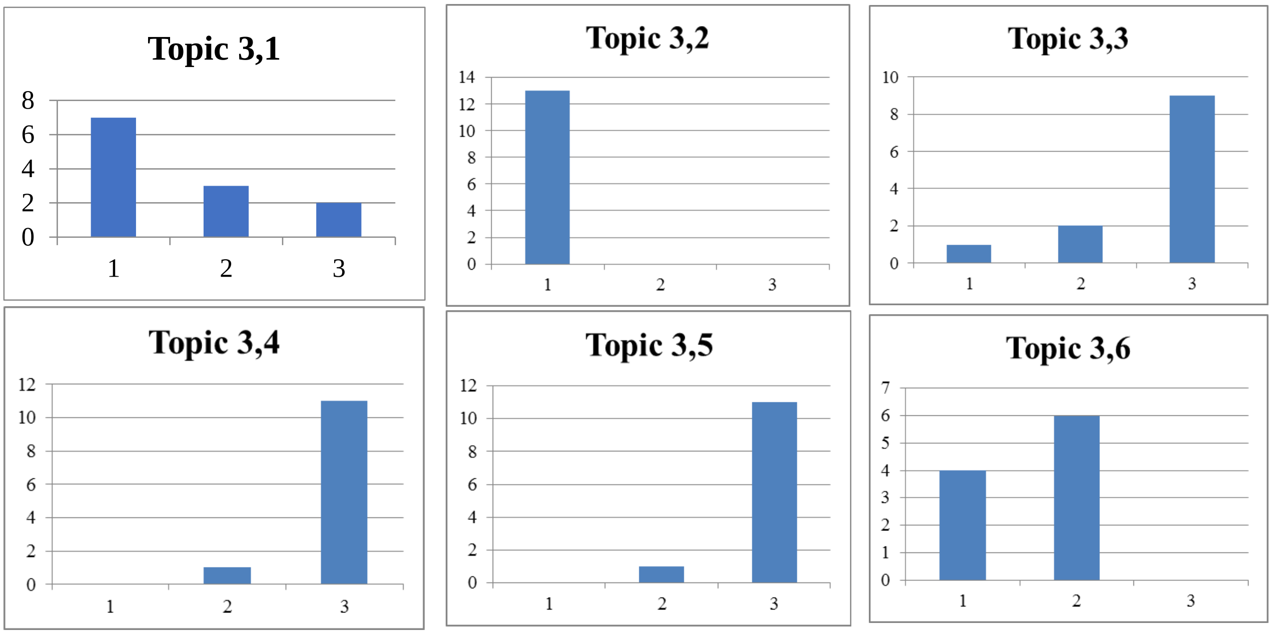


Figure 3: Ranking vote distribution for the various Topics of Domain 3 (x axis: 1=high priority; 2=medium priority; 3=low priority; 4= closed topic.; y axis: number of votes).

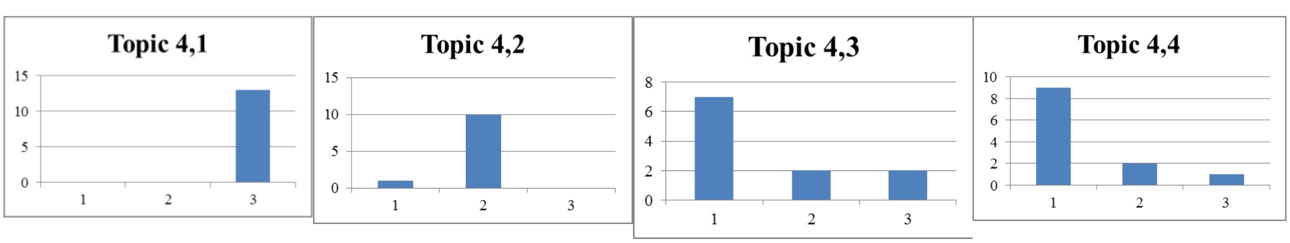
2.1.4 Domain 4: "Phenomena of release and transport of fission products"

Three topics have been selected, in the following decreasing priority:

- Vote 1.3: "Impact of high-temperature chemistry in the RCS" (4,4)
- Vote 1.3: "Impact of chemistry in the containment" (4,5)
- Vote 1.5: "Impact of the oxidizing environment" (4,3)

For these 3 topics, although the priority has decreased with respect to the previous vote in 2013 (vote 1 for each topic), reflecting that substantial experimental investigations have been conducted since then (ISTP, SARNET, OECD) with improvements of the corresponding modelling, the ranking remains high as partners still expect new significant results from on-going research programs (e.g. OECD/NEA BIP3, THAI3, STEM2) and as some partners consider that *methods and tools for severe accident evaluation should be consolidated implementing new knowledge, treating scaling issues and uncertainties* (see new topics proposed in Domain 6 below).

A new topic is proposed by several partners, in close relation to the Fukushima-Daiichi accident analyses, on long term fission product remobilization processes. One partner proposed also another new topic on iodine chemistry in the environment.



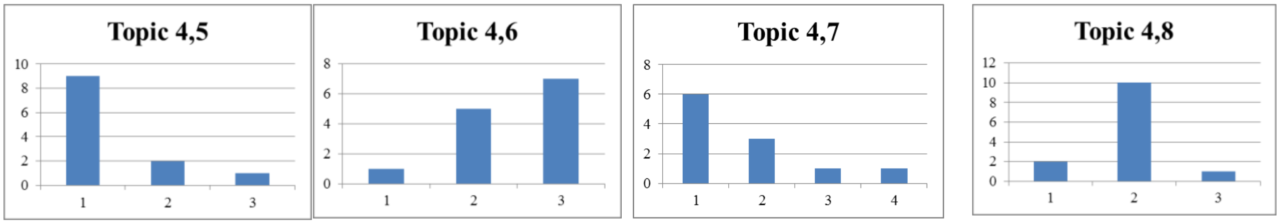


Figure 4: Ranking vote distribution for the various Topics of Domain 4 (x axis: 1=high priority; 2=medium priority; 3=low priority; 4= closed topic.; y axis: number of votes).

2.1.5 Domain 5: "Phenomena in spent fuel pool storages"

Only one unique topic was defined in this domain: it gets with quasi-unanimity a high priority.

- Vote 1.3: "Fuel Assembly (FA) behaviour in spent fuel pool scenarios" (5,1)

Consistently with the outcomes of the recent OECD SFP PIRT [34], this domain could be subdivided in the following topics:

- Cladding chemical reactions with mixed steam-air environments for the low temperature range relevant for SFP and for all types of fuel claddings present in SFPs,
- Thermal-hydraulic and heat transfer phenomena for the coolability of partly or completely uncovered fuel assemblies,
- Thermal-hydraulic behaviour and large-scale natural circulation flow pattern that evolves in the SFP with fuel assemblies covered with water,
- Spray cooling of uncovered spent fuel assemblies in typical storage rack designs.

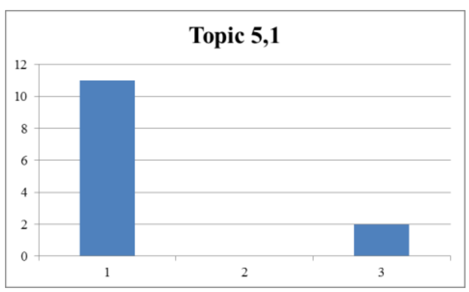


Figure 5: Ranking vote distribution for Domain 5 (x axis: 1=high priority; 2=medium priority; 3=low priority; 4= closed topic.; y axis: number of votes).

2.2.6 Domain 6: "Other topics related to severe accidents"

Only one the topics proposed as "new" in 2013 has been selected in 2018:

- Vote 1.5: "Instrumentation for severe accidents" (6,2)

This topic gets a medium-to-high priority, mainly due to importance to optimise future SAM and strategy (in particular for the accident long term) and the needs of R&D include innovative technologies and robustness of instrumentation in the long term.
New additional topics have been proposed by some partners:

- "Consolidation of tools and methodologies for SA analysis and SAMG validation (treatment of scaling and uncertainties)",

- "Long term management of SA", which is closely linked to a few new topics proposed above and to the Fukushima-Daiichi sample analysis and interpretation,
- "Re-criticality of in- and ex-vessel debris bed". This point has high priority in the FDNPS corium management.

They are reformulated and listed together with other new possible SA research topics in Table II below.

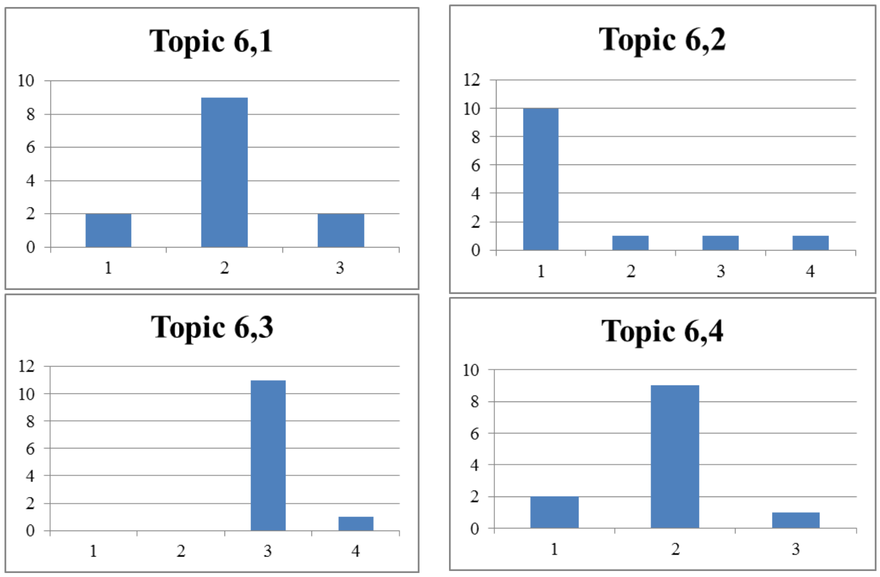


Figure 6: Ranking vote distribution for Domain 6 (x axis: 1=high priority; 2=medium priority; 3=low priority; 4= closed topic.; y axis: number of votes).

3. SUMMARY AND DISCUSSION

A second review of the severe accident research priorities was obviously needed seven years after the FDNPS accident and five years after the last review of this kind. This enabled the immediate impact of the FDNPS accident on research activities to be assessed by the research institutions themselves. The results reported in table 1 show that most SA research topics continue with the same priority level, however, with a few exceptions. These are mostly linked to ongoing research projects that are already providing some answers to previously open questions. Particularly, one can mention the research carried out in the last few years on in-vessel melt retention (IVMR) and on the development and pooling of research facilities in the EU (SAFEST). This is naturally consistent with the priority-based methodology adopted in the SAFEST project. High priority remains for topics like the corium behaviour in the lower head, the melt relocation, fuel-coolant interaction (ex-vessel), MCCI mixed molten pool configurations and ex-vessel corium coolability with top flooding. Certain source term issues remain top-priority such as oxidising environmental impact, RCS high temperature chemistry impact and containment chemistry. Additional issues are still important like fuel assembly behaviour in spent fuel pool systems while filtering containment venting systems for example maintain medium priority. Severe accident instrumentation also requires some further development.

Moreover, a number of new possible research topics were proposed. They are summarised and briefly commented in Table II here below. They relate to long term aspects of FP chemistry and corium and filtering in containment systems and overall management; in addition, some specific accident site issues such as Fukushima sampling but also general improvement of tools and methodologies for SA analysis. Iodine environmental impact is also proposed.

Table II: New possible SA research topics.

Topic	**Topic description**	**Proposed ranking**	**Partner's justification**
Long term chemistry in containment and filtered containment venting systems	Quantify the long term chemistry in containment and its impact on the containment performance as well as on the filtered containment venting systems. Quantify the long term chemistry in the filtered containment venting systems.	M or H	There is the need to improve knowledge on FP remobilisation phenomena in a damaged plant. Fukushima-Daiichi analysis has evidenced this as an important issue. Important for accident management
Long term behaviour of corium	Leaching, radiation stressed corrosion, fragmentation, evolution of properties, which are necessary to know for prediction of corium behaviour and for preparation of corium removal and reprocessing	M or H	See conclusions of the LTMNPP OECD/NEA action (to be published in 2018). Some aspects are already in the OECD/TCOFF project [35] (leaching). This could be high priority for long term management of a SA as leaching could affect liquid ST and damaged fuel behaviour (possible dusting in particular during damaged fuel retrieval operations). Corrosion/erosion of critical metallic parts may also be an issue for safety systems on the LT.
Iodine chemistry in the environment	Better characterize the evolution of iodine species when released to the environment and related radiological consequences	M	No iodine chemistry in the environment is presently considered in tools calculating radiological consequences. Existing models (reaction schemes) indicate that speciation evolution could significantly affect radiological consequences. Research is required to consolidate these models.
Long term management of SA	In addition to maintaining a stable state (sub-critical and cooled fuel, combustion risk and radioactive releases mitigated), recovery actions to be prepared and conducted safely (e.g. cleaning, fuel retrieval, waste management).	L or M	See conclusions of the LTMNPP OECD/NEA action (report to be published in 2018). At this stage, it is important to capitalize knowledge and experience from past accidents LTM (Fukushima-Daiichi, Chernobyl).

Re-criticality in debris bed	This is one of the main issues for the corium management at FDNPS.	M	The current OECD PreADES project [36] is considering this aspect in its proposals for future FDNPS sampling.
Sampling and analysing FDNPS corium samples	Addressing technical issues related to sampling and analysing FDNPS corium in an ultra-highly radioactive environment.	M or H	Data evaluation for sampling priorities and analytical techniques is a main subject of the current OECD PreADES project [36].
Consolidation of tools and methodologies for SA analysis and SAMG validation	Mostly treatment of scaling and uncertainties	M-H	Consistent with OECD Nuclear Innovation 2050 plans [37]

However, at the present time of writing it has not been possible to obtain any proper feedback about the shared interest of these new topics, and therefore no new ranking can be officially reported, besides the one proposed in Table II.

4. CONCLUSIONS

A second review of the severe accident research priorities was obviously needed seven years after the FDNPS accident and five years after the last review of this kind. This enabled the immediate impact of the FDNPS accident on research activities to be assessed by the research institutions themselves. The results reported in Table I show that most SA research topics continue with the same priority level, however, with a few exceptions. These are mostly linked to ongoing research projects that are already providing some answers to previously open questions. While only a couple of topics have been closed since 2013, most of them are still object of research. A few new severe accident research topics have been proposed, which shall be reviewed in the near future. They mostly involve long-term severe accident management, corium sampling and recriticality in accident sites (Fukushima, Chernobyl), and the consolidation of tools and methodologies for SA analysis.

NOMENCLATURE

AM	Accident Management
ANL	Argonne National Laboratory
ASTEC	Accident Source Term Evaluation Code
BIP	Behaviour of Iodine Project
BSAF	Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station
BWR	Boiling Water Reactor
CCI	Core-Concrete Interactions
CEA	Commissariat à l'Énergie Atomique et aux énergies alternatives
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CSNI	Committee on the Safety of Nuclear Installations
DCH	Direct Containment Heating
CLADS	Collaborative Laboratories for Advanced Decommissioning Science in JAEA
EC	European Commission
ECCS	Emergency Core Cooling System
EDF	Electricité De France
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EU	European Union
Euratom	European Atomic Energy Agency
FA	Fuel Assembly
FCI	Fuel Coolant Interaction
FCVS	Filtered Containment Venting System
FDNPS	Fukushima Daiichi Nuclear Power Station
FP	Framework Program / Fission Products (depending on context)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
H2020	Horizon 2020 (Commission Framework Programme)
HBU	High Burn-Up (fuel)
HP	High Pressure
IPRESCA	Integration of Pool scrubbing Research to Enhance Source-term Calculations
INVECOR	(In-VEssel COrium Retention) in accidents of water reactors – ISTC project, K1265)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
ISTC	International Science and Technology Centre,
ISTP	International Source Term Program
IVMR	In-Vessel Melt Retention
JAEA	Japan Atomic Energy Agency
JRC	Joint Research Centre
JSI	Jožef Stefan Institute
KIT	Karlsruher Institut für Technologie
KTH	Kungliga Tekniska Högskolan
LCS	Limestone-Common-Sand
LTM	Long Term Management
LTMNPP	Long Term Management of Nuclear Power Plant
LWR	Light Water Reactor
MAAP	Modular Accident Analysis Program
MCCI	Molten Core-Concrete Interactions
MELCOR	Methods for Estimation of Leakages and Consequences Of Releases
MOX	Mixed Oxide (fuel)
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NUBIKI	Hungarian Nuclear Safety Research Institute
NUGENIA	NUclear GENeration II. and III.Association
OECD	Organisation for Economic Co-operation and Development
PAR	Passive Autocatalytic Recombiner
PASSAM	Experiments on Passive and Active Systems on Severe Accident source term Mitigation
PIRT	Problem Identification and Ranking Table
PreADES	Preparatory Study on Analysis of Fuel DEbriS Project
PSI	Paul Scherrer Institute
PWR	Pressurized Water Reactor
R&D	Research and Development
RCS	Reactor Cooling System

RPV	Reactor Pressure Vessel
SA	Severe Accident
SAFEST	Severe Accident Facilities for European Safety Targets
SAM	Severe Accident Management
SAMG	Severe Accident Management Guidelines
SARNET	Severe Accident Research NETwork of excellence
SAR	Severe Accident Research
SARP	Severe Accident Research Priorities
SFP	Spent Fuel Pool
SGT	Steam Generator Tube
SGTR	Steam Generator Tube Rupture
SNE-TP	Sustainable Nuclear Energy Technology Platform
STEM	Source Term Evaluation and Mitigation Project
TA	Technical Area
TCOFF	Thermodynamic Characterization Of Fuel debris and Fission products based on scenario analysis of severe accident progression at Fukushima Daiichi NPS
THAI	Thermal-hydraulics, Hydrogen, Aerosols and Iodine Project
ÚJV	Ústav Jaderného Výzkumu Rez, a. s.
USA	United States of America
USSR	Union of Soviet Socialist Republics
VVER	Water-water energetic reactor
WGAMA	Working Group on Analysis and Management of Accidents

ACKNOWLEDGMENTS

The Authors acknowledge the contribution of other researchers who were directly involved in the Severe Accident Research Priority survey, although they haven't directly contributed to the present paper, in particular: E. Sauvage and B. Tourniaire (EDF) A. Miassoedov (KIT), G. Lajtha (NUBIKI), M. Auglaire (Tractebel).

REFERENCES

1. Council Directive 2014/87/Euratom, " Directive establishing a Community framework for the nuclear safety of nuclear installations", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2014.219.01.0042.01.ENG.
2. J. P. Van Dorsselaere, J. Mustoe, S. Power, M. Adorni, A. Schaffrath, A. Nieminen, "ETSON views on R&D priorities for implementation of the 2014 Euratom Directive on safety of nuclear installations", *KERNTECHNIK* **81**(5), pp. 527 – 534 (2016).
3. D. Magallon, et al., "European expert network for the reduction of uncertainties in severe accident safety issues (EURSAFE)", *Nucl. Eng. Design* **235**, pp. 309–346 (2005).
4. W. Klein-Hessling, M. Sonnenkalb, D. Jacquemain, B. Clément, E. Raimond, D. Dimmelmeier et al., "Conclusions on Severe Accident Research Priorities", *Proceedings of the 6th European Review meeting on Severe Accident Research (ERMSAR-2013)* Avignon (France), Palais des Papes, 2-4 October, 2013, “Conclusions and Perspectives” Session, pp. 1-14 (2013).
5. W. Klein-Heßling, , M. Sonnenkalb, D. Jacquemain, B. Clément, E. Raimond, H. Dimmelmeier, G. Azarian, G. Ducros, C. Journeau, L.E.H. Puebla, A. Schumm, A. Miassoedov, I. Kljenak, G. Pascal, S. Bechta, S. Güntay, M.K. Koch, I. Ivanov, A. Auvinen, I. Lindholm, "Conclusions on severe accident research priorities", *Annals of Nuclear Energy* **74** (C) pp. 4-11 (2014).
6. J.-P. Van Dorsselaere, A. Auvinen, D. Beraha, P. Chatelard, L.E. Herranz, C. Journeau, W. Klein-Hessling, I. Kljenak, A. Miassoedov, S. Paci, S., R. Zeyen, "Recent severe accident research synthesis of the major outcomes from the SARNET network", *Nucl. Eng. Design*, **291**, pp. 19-34 (2015)

7. "NEA Working Group on Analysis and Management of Accidents", https://www.oecd-nea.org/nsd/csni/wgama.html.
8. L. E. Herranz, D. Jacquemain, N. Sandberg, "Recent Contributions of OECD-WGAMA to the Severe Accident Field", http://www.sar-net.eu.
9. "The International Science and Technology Center", http://www.istc.int.
10. D. Bottomley, J. Stuckert , P. Hofmann et al., "Severe accident research in the core degradation area: An example of effective international cooperation between the European Union (EU) and the Commonwealth of Independent States (CIS) by the International Science and Technology Center", *Nucl. Eng. Design* **252**, pp. 226– 241 (2012).
11. L. Tocheny, A. Gozal, "ISTC: International collaboration in nuclear technologies research —results, trends and prospective", *FISA-2009 Conference on EU Research and Training in Reactor Systems*, Post-FISA Workshop # 5, Corinthia Towers Hotel, Prague, Czech Republic, 22–25 June 2009.
12. S.V. Bechta, V.B. Khabensky, S.A. Vitol, E.V. Krushinov, V.S. Granovsky, D.B. Lopukh, V.V. Gusarov, A.P. Martinov, V.V. Martinov, G. Fieg, W. Tromm, D. Bottomley, H. Tuomisto, "Corrosion of vessel steel during its interaction with molten corium. Part 1: Experimental", *Nucl. Eng. Des.* **236**, pp. 1810–1829 (2006). Part 2: Modelling development", *Nucl. Eng. Des.* **236**, pp. 1362–1370 (2006).
13. S.V. Bechta, V.S. Granovsky, V.B. Khabensky, E.V. Krushinov, S.A. Vitol, A.A. Sulatsky, V.V. Gusarov, V.I. Almiashev, D.B. Lopukh, D. Bottomley, M. Fischer, P. Piluso, A. Miassoedov, W. Tromm, E. Altstadt, F. Fichot, O. Kymalainen, "VVER vessel steel corrosion at interaction with molten corium in oxidizing atmosphere", *Nucl. Eng. Des.* **239**, pp. 1103–1112 (2009).
14. M.S. Veshchunov, "Modelling of U–Zr–O corium/vessel steel interactions". ISTC Project #3876 THOMAS. In: *15th International QUENCH Workshop*, Karlsruhe, November 3–5 2009, ISBN 978-3-923704-71-2. (2009).
15. A.E. Kiselev, V.F., Strizhov, A.D. Vasiliev, "Application of thermal hydraulic and severe accident code SOCRAT/V2 to bottom water reflood experiment PARAMETER-SF4", *Nucl. Eng. Design* **246**, pp. 175–184 (2012).
16. "Sustainable Nuclear Energy Technology Platform", http://www.snetp.eu.
17. "Nuclear Generation II and II Association", http://nugenia.org.
18. "NUGENIA Roadmap 2013". NUGENIA Association, http://nugenia.org/wp-content/uploads/2017/12/NUGENIA_roadmap.pdf
19. S. Bakardjieva, M. Barrachin, S. Bechta, D. Bottomley, L. Brissoneau, B. Cheynet, E. Fischer, C. Journeau, M. Kiselova, L. Mezentseva, P. Piluso, T Wiss, "Improvement of the European thermodynamic database NUCLEA", *Prog. Nucl. Energy* **52**, 84–96 (2010).
20. C. Journeau, V. Bouyer, N. Cassiaut-Louis, P. Fouquart, P. Piluso, G. Ducros, S. Gossé, C. Guéneau, A. Quaini et al., "Safest roadmap for corium experimental research in Europe", *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering* **4**, Article number 030901 (2018).
21. S. Bechta, W. Ma, A. Miassoedov, C. Journeau, K. Okamoto, D. Manara, D. Bottomley, M. Kurata, B.R. Sehgal, J. Stuckert, M. Steinbrueck, B. Fluhrer, T. Keim, M. Fischer, G. Langrock, P. Piluso, Z. Hozer, M. Kiselova, F. Belloni, M. Schyns, " On the EU-Japan roadmap for experimental research on corium behaviour", *Annals of Nuclear Energy* **124**, pp. 541-547(2019).
22. "In-Vessel Melt Retention strategy for high power nuclear reactors", Funded by the European Commission under the Grant N° 662157 (Research and Innovation action of the HORIZON 2020 programme), https://gforge.irsn.fr/gf/project/ivmr.
23. V. Zhdanov, V. Baklanov, et al., "Study of the processes of corium-melt retention in the reactor pressure vessel (INVECOR)" In: *Proceedings of ICAPP 2011*, Nice, France, May 2–5th, Paper 11375 (2011).
24. F. Fichot, L. Carénini, M. Sangiorgi, S. Hermsmeyer, A. Miassoedov, S. Bechta, J. Zdarek, D. Guenadou, "Some considerations to improve the methodology to assess In-Vessel Retention strategy for high-power reactors", *Annals of Nuclear Energy* **119** 36-45 (2018).

25. "NEA Thermal-hydraulics, Hydrogen, Aerosols and Iodine Project Phase 3 (THAI-3)", https://www.oecd-nea.org/jointproj/thai3.html.
26. "NEA Behaviour of Iodine Project Phase 3 (BIP-3)", https://www.oecd-nea.org/jointproj/bip-3.html.
27. "NEA Source Term Evaluation and Mitigation Project Phase 2 (STEM-2)", https://www.oecd-nea.org/jointproj/stem2.html.
28. T. Albiol, L. Herranz, E. Riera, C. Dalibart, T. Lind, A. Del Corno, T. Kärkelä, N. Losch, B. Azambre), C. Mun, L. Cantrel,, "Passive and Active Systems on Severe Accident source term Mitigation (PASSAM project) Final Synthesis Report" PASSAM–DKS-T28 [D5.5] IRSN/PSN-RES/SEREX/2017- 00165, available at https://cordis.europa.eu/result/rcn/197119_en.html (2017).
29. S. Gupta, L.E. Herranz, J.-P. Van Dorsselaere, "Integration of Pool scrubbing Research to Enhance Source-term Calculations (IPRESCA)", *The 8th European Review Meeting on Severe Accident Research - ERMSAR-2017* Warsaw, Poland, 16-18 May 2017. DOI: 10.13140/RG.2.2.13085.20962 (2017)-
30. N. Andrews, T. Haskin and C. Faucett, Modular Accident Analysis Program (MAAP) – MELCOR Crosswalk: Phase II, Analyzing a Partially Recovered Accident Scenario, contract DE-NA0003525. https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2017/1711975.pdf
31. Luxat D., Hanophy J. & Kalinich D., “Modular Accident Analysis Program (MAAP) - MELCOR Crosswalk Study Phase 1,” EPRI Technical Report, Report 3002004449, (2014).
32. OECD Nuclear Energy Agency (NEA), “Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant - (BSAF Project) - Phase 1 Summary Report,” NEA Technical Report, NEA/CSNI/R(2015)18, (2015).
33. M. T. Farmer, M. Corradini, J. Rempe, R. Reister, D. Pekod, "United States Department of Energy Severe Accident Research Following the Fukushima Daiichi Accidents", *Nuclear Tech.* **196**, pp.141–148 (2016).
34. "Phenomena Identification and Ranking Table", Nuclear Safety NEA/CSNI/R(2017)18 June 2018 JT03433323 www.oecd-nea.org (2018).
35. "Thermodynamic Characterisation of Fuel Debris and Fission Products Based on Scenario Analysis of Severe Accident Progression at Fukushima-Daiichi Nuclear Power Station (TCOFF)", https://www.oecd-nea.org/science/tcoff.
36. "NEA Preparatory Study on Analysis of Fuel Debris (PreADES) Project", https://www.oecd-nea.org/jointproj/preades.html
37. "Nuclear Innovation 2050 (NI2050) – A Roadmap to a Carbon-free Energy Future", https://www.oecd-nea.org/ndd/ni2050.

APPENDIX A: DETAILED ANALYSIS OF MAIN COMMENTS AND SYNTHESIS

Only the topics with a high or medium-to-high priority (votes under 1,7) are addressed in this Appendix.

-Domain 1: "Phenomena during in-vessel accident progression"

The topic "Core coolability during reflooding and thermal-hydraulics within particulate debris" gets a medium-to-high priority for most partners, mainly because some R&D results are still expected from the IVMR and SAFEST current European projects. But a few uncertainties remain because most of the research has been done with idealized geometries of debris beds and of debris shapes. More prototypical morphology of the debris should be investigated. The future inspections of Fukushima-Daiichi degraded cores should provide additional information.
The topic "Corium behaviour in lower head" gets the highest priority (very close to 1.0) with quasi-unanimity, although results of the IVMR and SAFEST projects are still expected in the next years. Uncertainties remain on transient multi-layer configurations and their evolution that could be more problematic than the steady-state "bounding case", for instance on the focusing effect. Same for the behaviour of vessel steel after it has been molten and how it mixes with corium layers. The Fukushima Daiichi inspections should indicate possible mechanisms.
The topic "Integrity of RPV due to external vessel cooling" gets a medium-to-high priority, in close relation with the ongoing IVMR project. Although some demonstration was effective for some low power reactors with properly designed external circulating cooling, such as VVER-440, it has yet to be done for higher power reactors (1000 MWe and more). For many existing reactors the existing knowledge is not sufficient to demonstrate that this measure, in addition of water injection within the vessel, is effective in preserving in all cases the RPV integrity.
The topic "RPV failure mode" gets a medium-to-high priority, also in close relation with the ongoing IVMR project. The failure mode and corresponding characteristics of melt release into the flooded reactor pit govern risk and energy of steam explosion, as well as properties and coolability of ex-vessel corium, i.e. risk of debris re-melting and late containment bypass. RPV resilience with thinned wall under thermal shock is investigated in H2020 IVMR. The issue should be addressed for PWR having in-vessel melt retention based SAM. In addition, the OECD/NEA BSAF benchmark has shown that there is still a very large uncertainty in the prediction of lower head failure in a BWR.
One new topic is proposed by 2 partners: "Progression of degradation in reactor core (prediction of progressive relocation of molten materials or formation of extended molten pool, depending on accident scenario and core design)", in close relation with recent crosswalk exercises done between MAAP, MELCOR and ASTEC. One of these partners underlined the case of BWR where analyses of the Fukushima-Daiichi accidents have shown large uncertainties in the code predictions of the BWR core melt progression.

-Domain 2: "Phenomena that could lead to early containment (or reactor building) failure"

The topic "Hydrogen mixing, combustion / detonation" gets a high priority but only when cancelling the word "mixing" from the topic's title. Indeed all partners agree that main remaining uncertainties are related to the combustion and detonation phenomena. The topic's title could include in addition the word "countermeasures". Although the knowledge increased (OECD/NEA THAI2 and current 3) and new projects are starting such as SAMHYCO-NET in TA2/SARNET frame on SA long-term aspects (effect of H_2/CO mixtures due to MCCI…), efforts are still needed to close research gaps, enhance capability of simulation codes, and reduce code uncertainty on application to real plant geometries. Note that a small number of partners consider that the installation of Passive Autocatalytic Recombiners (e.g. in some VVER-440) allows reducing strongly R&D needs in that domain.
The topic "Melt relocation into water and particulate formation" gets a medium-to-high priority. New data from DEFOR and MISTEE experiments at KTH are available in SAFEST European project. But

improvements of knowledge are important for understanding FCI initial phases, e.g. fragmentation of corium in water pool and rapid steam generation (with melt oxidation and hydrogen formation during melt quenching). This should help predicting the formation and characterisation of debris beds, which is an essential input to evaluate the possibility of ex-vessel corium coolability. One partner underlined the lack of data (experiments and models) on corium interaction with BWR-typical ex-vessel structures.
The topic “FCI incl. steam explosion: melt into water in ex-vessel” gets a medium-to-high priority for BWRs but only for ex-vessel situations. The consequences on in-vessel FCI, for both PWR and BWR, are judged unanimously lower and it is thus considered that R&D must focus on ex-vessel situations. It remains an important topic to address the risk and modes of containment failure. Uncertainties remain on the application of knowledge to realistic reactor scenarios, including the transposition of experimental results to plant scale and to prototypical materials. Besides, new data from SES tests at KTH on stratified steam explosions, including spontaneous ones, were recently obtained in the SAFEST project, and this is a configuration to study in details. One partner underlined that, due to the complexity and difficulty to predict FCI consequences, the priority should focus on potential prevention / mitigation means.

-Domain 3: “Phenomena that could lead to late containment failure”

The priorities of 2013 are mostly confirmed.
The highest priority topic remains the "Ex-Vessel corium spreading and coolability, top flooding” with unanimity on the maximal possible priority. Knowledge of cooling mechanisms by top flooding the corium pool is needed in order to define measures to terminate the accident progression and maintain the containment integrity. Focus is recommended on long term effects like for example the sustainability of cooling mechanisms, achievement of coolable configuration, fission product release with evaporating water and steam, by mechanical forces, droplets, resuspension. Another open question in this respect is the metal content impact on coolability, as most of the available experimental data concern fully oxidic melts. Another important issue still to be solved is the ability to correctly transpose experimental data from the laboratory scale to the reactor scale. A better understanding on the topic can be obtained from future studies to be performed in the coming years on the Fukushima-Daiichi corium.
The topic "MCCI, molten pool configuration and concrete ablation" is mostly considered to be of medium-to-high priority as long as metallic or oxide-metallic melts are concerned. Knowledge acquired until now on oxidic melts is considered to be rather satisfactory, which makes this topic a medium priority one for such oxidic melts. In particular, interaction of an oxide (Al_2O_3, ZrO_2, CaO, SiO_2) and metal melt (Fe) on SiO_2, LCS and basaltic concrete with and without reinforcement has been studied within the MOCKA experiments at KIT. The results suggest that further investigations are needed in order to better establish the concrete decomposition temperature and the progression of the encrusted metal melt into the concrete. Moreover, the different concrete compositions should be taken into account.
The topic "Dynamic and static behaviour of containment, crack formation and leakage at penetrations" has been given a slightly higher priority with respect to 2013, i.e. now with a medium-to-high priority. Some partners remark that this topic should be given high priority in the long term after the accident initiation if the plant is severely damaged. In fact, no data exist on the long term behaviour under accident conditions. This point becomes even more relevant in the frame of existing NPP lifetime extension. Moreover, the knowledge level is not sufficient to allow development of algorithms for integral codes.
Like in 2013, topics concerning corium catcher issues are currently given low priorities by most of the partners, essentially due to the low number of nuclear power plants equipped with ex-vessel core catchers. However, one should consider that research topics dealing with core catcher are design-specific. In this situation, corresponding R&D should be performed by vendors and utilities and could lead to innovation for future designs, as proposed in draft NI2050 SA template. One partner proposed to group the three items into a single one dealing with innovations on ex-vessel corium cooling systems for future designs.
As a perspective, a new topic is proposed by one partner on the failure risks of Emergency Core Cooling System (ECCS) on the long term under SA conditions (e.g. clogging risks, mechanical failure risks by radio-catalysed corrosion reactions…), in consistence with the current OECD NEA LTMNPP action.

- Domain 4: "Phenomena of release and transport of fission products"

The topics "Impact of chemistry in the RCS on source term" and "Impact of chemistry in the containment on source term" remain as high priority topics (with average votes 1.3). Substantial experimental investigations have been conducted in the past years (e.g. International Source Term Program and EXSI/VTT programs discussed within SARNET2 network and OECD/NEA BIP2, THAI2 and STEM projects) and new data have been produced to improve the corresponding modelling. Outcomes of major programs in the field have been discussed in 2016 in an international workshop (OECD/NEA/CSNI Report, NEA/CSNI/R(2016)5). The ranking remains high as partners still expect new significant results from on-going research programs (e.g. OECD/NEA BIP3, THAI3, STEM2) and as some partners consider that methods and tools for accident source term evaluation should be consolidated implementing new knowledge, treating scaling issues and uncertainties.
The topic "Impact of the oxidizing environment on source term" gets a medium-to-high priority (average vote 1.6). Some partners highlight that FP release in oxidizing environment is of high interest for SFP accidents.
The topic "Existing and innovative filtered containment venting systems" is now considered of medium priority (average vote 2.0) while it got a high priority in 2013 (vote 1.0). This reflects that significant knowledge was gained mostly through the EU PASSAM project that was completed in 2017. Also, partners that have selected design options for their FCVS implementation consider that the issue is closed. Some however consider that additional investigations related to possible FP remobilization from the filters on the long term should be performed and some consider that innovative filtering media that provided promising results should be further tested for challenging SA conditions.
The topic "Pool scrubbing" remains of medium priority (average vote 2.0, no change related to 2013). Despite knowledge gained through the EC PASSAM project, partners still consider that pool scrubbing modelling has to be improved in various situations (pools in reactor, liquid pool in FCVS, flooded secondary side of steam generator in SGTR accidents). Besides, the newly started IPRESCA initiative within NUGENIA/TA2 should foster knowledge sharing in the field and promote new modelling development.
The topic "FP release during late reflooding" remains of medium priority (average vote 1.9 to be compared to vote 2.0 in 2013). Some partners interestingly commented that FP release from fuel in relation to ex-vessel corium cooling first when corium and debris mix with water in containment and then on the long term by corium and debris leaching should be further investigated in relation to ex-vessel corium cooling strategies.
About new topics,

- 5 partners underlined that outcomes of Fukushima-Daiichi accident analyses, particularly through the BSAF2 project, should be considered for future investigations in the field. Long term FP remobilization processes are highlighted as important phenomena that deserve further investigations: remobilization from radioactive deposits onto surfaces, remobilization from pools after an accident and LT leaching of corium and debris (classified either H or M priorities). Comments reflect that the OECD/NEA post-Fukushima-Daiichi initiative should foster knowledge sharing in the field and promote research development.
- 1 partner suggested the topic of iodine chemistry in the environment.

- Domain 5: "Phenomena in spent fuel pool storages"

There is quasi-unanimity (all but 2 partners) to consider a high priority for this single topic "Fuel Assembly (FA) behaviour in spent fuel pool scenarios". Consistently with the outcomes of the recent OECD SFP PIRT, this domain could be subdivided in the following topics:

- Cladding chemical reactions with mixed steam-air environments for all type of fuel claddings present in SFPs and also the low temperature range,

- Thermal-hydraulic and heat transfer phenomena for the coolability of partly or completely uncovered fuel assemblies,
- Thermal-hydraulic behaviour and large-scale natural circulation flow pattern that evolves in the SFP with fuel assemblies covered with water,
- Spray cooling of uncovered spent fuel assemblies in typical storage rack designs.

- Domain 6: "Other topics related to severe accidents"

The topic "Effect of impurities in water on core degradation, chemistry and FCI" gets a medium priority, like in 2013. Only 2 partners recommended a high priority on the following aspects: understanding effects for Fukushima-Daiichi corium & FP behaviour and long term reliability of corium cooling.
The topic "Instrumentation for severe accidents" gets a medium-to-high priority, mainly due to its Importance to optimise future SAM (in particular long term one) and to needs of R&D complements including innovative technologies and robustness of instrumentation on the long term. The qualification of newly installed instrumentation and the assessment of survivability for the existing one should be addressed. Note that 2 partners recommended a "Low" or "To be closed" vote.
The topic "Thermodynamic and thermo-physical databases" gets a medium priority but with some scattering of votes. Although the importance of the issue and the need to carry on improvement of the databases are recognized, the medium votes (and a few low ones) are mainly linked to the existence of current international projects like TCOFF in OECD frame. Two partners, with a high vote, underlined that the associated uncertainties are becoming the major uncertainty source of the SA calculations (even larger than uncertainties on models as models are improving).
New topics have been proposed by some partners:

- "Consolidation of tools and methodologies for SA analysis and SAMG validation (treatment of scaling and uncertainties)", which is consistent with OECD NI2050 plans;
- "Long term management of SA", which is closely linked to a few above new proposed topics (long term FP remobilization, long term failure risks of Emergency Core Cooling System) and which is also consistent with OECD NI2050 plans. It covers also the long term management of Fukushima-Daiichi damaged unit and defueling (long term release due to leaching, resuspension, fragmentation of contaminated materials including products of MCCI, mobility of fuel fragments, etc…) and its sample analysis and interpretation, which is linked to several OECD projects, under way (PreADES, ARC-F);
- "Re-criticality in in- and ex-vessel debris bed".