On the EU-Japan roadmap for experimental research on corium behavior

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ABSTRACT

A joint research roadmap between Europe and Japan has been developed in severe accident field of light water reactors, focusing particularly on reactor core melt (corium) behavior. The development of this roadmap is one of the main targets of the ongoing EU project SAFEST. This paper presents information about ongoing severe accident studies in the area of corium behavior, rationales and comparison of research priorities identified in different projects and documents, expert ranking of safety issues, and finally the research areas and topics and their priorities suggested for the EU Japan roadmap and future bilateral collaborations. These results provide useful guidelines for (i) assessment of long term goals and proposals for experimental support needed for proper understanding, interpretation and learning lessons of the Fukushima accident; (ii) analysis of severe accident phenomena; (iii) development of accident pre vention and mitigation strategies, and corresponding technical measures; (iv) study of corium samples in European and Japanese laboratories; and (v) preparation of Fukushima site decommissioning.

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1. Introduction

The Western European Nuclear Regulators' Association (WENRA) defines the Safety Objective for 'accidents with core melt' (WENRA, 2013) as "accidents with core melt which would lead to early or large releases have to be practically eliminated". According to WENRA, deterministic and probabilistic analyses should be used to show that conditions leading to failure of the containment function due to physical phenomena or system failures are practically eliminated. Experimental data is necessary for clarification of the relevant phenomena and validation of the analysis codes.

One of the general goals of the European Commission funded SAFEST project is to establish EU Japan coordination activities in experimental research on corium behavior through the development of a common research roadmap not only to address national and international research priorities but also to acquire the knowledge, expertise and lessons learned from the Fukushima Daiichi NPP accident in Japan and the stress tests in EU countries.

The Atomic Energy Society of Japan (AESJ) has developed a Problem Identification and Ranking Table (PIRT) in 2013 (Suehiro et al., 2015; Sakai et al., 2014) for the Fukushima Daiichi NPP accident in order to understand the severe accident event progression, radioactive materials' environmental release and to prepare decommissioning. After 6 years, a lot of additional information for this accident has been revealed, including robot observation inside the pedestal supporting the pressure vessel. An improvement of the Fukushima PIRT will be required for further research and development.

The EU Japan roadmap is developed in order to link the existing EU, OECD, IAEA, Japanese and European national projects and programs, so that they can more effectively use the existing experimental infrastructure and plan new facilities more rationally, as well as receive additional benefits from combined efforts of the many experimentalists. The EU experimental research on corium behaviour will also be coordinated with what is planned under the OECD and the IAEA programs.

An additional objective of the EU Japan roadmap is to support national plans and efforts for decommissioning of the Fukushima Daiichi NPP, in particular, by joint studies on Fukushima corium relocation, development of corium debris removal and reprocessing technologies. Furthermore, analysis of plant data characterizing severe accident and corium behavior at full scale BWR units, will also provide useful insights for all other light water reactors.

2. Sources of references

In order to initiate the EU Japan roadmap on corium behaviour, the following documents, which specify the priorities established for severe accident research at the different levels of collaboration, have been reviewed:

- The European corium experimental research roadmap (Journeau, et al., 2018) recently developed in the SAFEST project, which is based on the research priorities determined in the European Sustainable Nuclear Energy Technology Platform (SNE TP) (Brunna et al., 2013), the SARNET Severe Accident Research Priorities (SARP) (Klein Heßling, 2013, 2014) following the EURSAFE PIRT (Magallon, 2005), and NUGENIA Technical Area N°2 on severe accidents (Van Dorsselaere, 2012) and NUGENIA Global Vision Report (NUGbENIA, 2015);
- The Phenomena Identification and Ranking Table (PIRT) identified by the Research Expert Committee on Evaluation of Severe Accident of Atomic Energy Society of Japan (AESJ) based on the findings of the Fukushima Daiichi NPP accident (Suehiro et al., 2015; Sakai et al., 2014), whose objectives are to evaluate the source term and debris removal from the Fukushima reactors, respectively.
- The draft version of IAEA recommendations and suggestions for further R&D (Report on Training Meeting, 2015) prepared at the Training Meeting on "Post Fukushima Research and Development Strategies and Priorities" held on 15 18 December 2015.

An important indicative study, which is the DOE report on the US Efforts in Support of Examinations at Fukushima Daiichi for Light Water Reactor Sustainability Program (Rempe, et al., 2015), has also been reviewed.

There are several projects supported by OECD/NEA to study the Fukushima accident and to learn its lessons (Years, 2016):

- Ongoing BSAF 2 project Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant, which improves severe accident modeling and understanding of the core/corium progression.
- Completed SAREF project Senior Expert Group on Safety Research Opportunities Post Fukushima, which identified research gaps and opportunities related to this accident but also supported plans for safe decommissioning.
- New project PreADES Preparatory Study on Analysis of Fuel Debris, which will prepare scientific basis and knowledge necessary for corium debris study, removal and reprocessing.
- New project TCOFF Thermodynamic Characterization of Fuel Debris and Fission Products based on scenario analysis of severe accident progression at the Fukushima Daiichi Nuclear Power Plant, which will improve databases and thermodynamic modelling of phase equilibrium in multi component systems at different stages of severe accident of accidental units.

The information available from the above listed projects was considered and discussed during the preparation of the EU Japan roadmap on experimental research on corium behaviour. More importantly, many experts from EU and Japan, who are active in the field, are involved in the creation and review of the roadmap.

3. Comparison of R&D priorities

A complete comparison of the research priorities between the EU roadmap and the Fukushima PIRT of Japan is given in Tables 1, 2 and 3, which list common and complementary research areas and topics related to safety issues. The comparison shows that there are many common research areas (Table 1), such as core and debris coolability, corium behavior in a lower head, RPV failure mode and corium release scenario, direct containment heating, ex vessel corium behaviour and recriticality.

The EU roadmap complements severe accident research priorities as shown in Table 2, which are not identified in the Fukushima PIRT of Japan, including the areas of containment integrity, development of ex vessel core catchers, study of spent fuel pools and some other areas, such as development of new accident tolerant fuels, study of human and organizational factors during emergency actions.

The Japanese research roadmap is primarily concentrated on the debris removal/reprocessing and Fukushima Daiichi NPP units 1 3 decommissioning, and therefore the ranking of some research priorities differs from the EU research roadmap which has a limited consideration of certain post accident activities.

The Fukushima PIRT complements the EU roadmap in the areas of corium removal, corium reprocessing and disposal, as well as RPV and containment integrity by the study of the impact of addition of salt water in the primary circuit and reactor containment and examination of sea salt effects on corium behavior and thermochemistry.

Table 1
Common research topics between EU and Japan.

Area	Issue	Topic
Core and debris coolability	H_2 generation	• H_2 generation from molten/re-solidified fuel • H_2 generation from control rods (influence of B_4C)
	Core reflooding and its impact on source terms	• Early-phase (core intact) reflooding • Late-phase (degraded core) reflooding
Corium behaviour in lower head	In-vessel coolability and retention	• Premixing (corium jet fragmentation and debris formation) • Steam explosion • Fragmentation of corium in water pool and rapid steam generation • Temperature/pressure increase by FCI • Scattering of materials and corium in lower head by FCI • Non-uniform molten and particulate corium spreading • Corium oxidation including H2 production • Change in mixing state and physical properties of corium • Formation of molten pool • Metal/oxide stratification in the molten pool
RPV failure mode and corium release	Leakage via instruments/penetration/gasket/ RPV damage	• Vessel failure and its timing • Corium /water/ gas flow through failed CRGT guide tube from/to lower plenum • Melt release modes through single and multiple breaches. • Ablation and plugging of the vessel breach during melt release. • Corrosion of lower head by corium pool • Corium melting and crystallization behavior, equilibrium and non-equilibrium corium phases • Properties of solid and liquid corium, particulate debris and structural materials
Ex-vessel corium behaviour	Direct containment heating FCI	• High-pressure melt ejection • Fragmentation of corium in water pool and rapid steam generation • Pressure wave due to FCI and steam explosion • Pedestal failure due to FCI • Dispersal of corium and pedestal internal material due to FCI • Effect of impurities in water (including sea water effect) • Debris formation
	MCCI and coolability	• Corium flow spread in pedestal cavity, drywell • Corium stratification • Mixing of concrete with corium flow and internal gas generation • Corium flow into sump pit and reaction • Heat transfer between sump floor and corium/crust/corium particle • Deposition condition of corium in pedestal floor • Corium leak into connecting pipe inside sump • Dry MCCI (single oxidic phase) • MCCI (oxide-metal configurations; top-flooding)
	Aerosol behavior in containment	• Gas distribution inside containment • Gaseous ruthenium transport and delayed releases from iodine deposits in circuits • Oxidizing environment impact on FP release
	Pool scrubbing	• Scrubbing by steam flow, with vent • Scrubbing by water injection
Other relevant areas	Re-criticality Fukushima corium samples	• Coupled TH/NK analysis of in- and ex-vessel debris • Characterization of corium chemical/isotope/phase compositions and properties

Table 2
Main research topics not mentioned in the Fukushima PIRT of Japan.

Area	Topic
RPV integrity	• External RPV cooling
Reactor building or containment integrity	• Dynamic and static behaviour of containment, crack formation and growth. • Influence of countermeasures like Passive Autocatalytic Recombiners (PARs) or the effect of spray systems
Core catchers	• Corium-ceramics interaction • Melt enclosure in an outside cooled metallic container • Melt enclosure in high-temperature-resistant material • Enforced melt fragmentation and volumetric cooling by water • Quenching and fragmentation during melt pouring into water or flooded MCCI
Spent fuel pool	• Fuel Assembly (FA) behavior in spent fuel pool severe accident scenarios
Other areas	• Development of new accident tolerant fuels • Understanding of human and organizational factors during emergency

Table 3
Main research topics not mentioned in the EU roadmap.

Area	Topic
Decommissioning of Fukushima Daiichi NPP	• Corium removal • Corium reprocessing and disposal • Phenomena important for development of technology, equipment and control for decommissioning efforts
RPV and containment integrity	• Study of the impact of addition of salt water in the primary circuit and reactor containment • Examination of sea salt effects on corium behavior and thermochemistry

Some US DOE interests (Rempe, et al., 2015) in examinations of Fukushima Daiichi NPP units 1 4 could also be relevant for the EU Japan roadmap. The following near term R&D tasks can be considered:

Establishment of point of contact (POC);
Information evaluations;

Code evaluations of new information;
Obtaining detailed inspection information;
Facilitation of reactor examinations.

The specification of existing information needs has been deter mined in the report (Rempe, et al., 2015) mainly for the reactor building, the primary containment vessel and the reactor pressure vessel.

Being focused mainly on industrial needs of US Light Water Reactor Sustainability Program, the joint US Japan program can contribute to the further development of severe accident research priorities by the results obtained in the following three areas:

Component inspection (based on industry prioritized list and code analysis);
Radiological sampling and swiping;
Core debris location evaluations.

The most comprehensive list of R&D topics of severe accident safety, which includes technology development, experimental and analytical research and analysis, has been recently proposed by IAEA and the member states. The main activities include:

External and internal events (assessment of external and inter nal events and the associated issues);
Technology development to prevent/mitigate severe accidents (understanding safety margins, measures for preventing severe accidents, measures for mitigating the consequences of severe accidents including SAM);
Severe accident analysis (forensic analysis of the Fukushima Daiichi accident), severe accident phenomenology, severe acci dent analysis models and code development including bench marking, management of corium, melt progression, knowledge of the source term, spent fuel safety issues, etc.).

According to the IAEA mission report (Report on Training Meeting, 2015): "*The completed table of recommendations and sug gestions for further R&D will help not only mapping the activities of interest but also identifying activities that Member States wish the IAEA to facilitate. The discussion on possible international collabora tion in R&D activities on severe accidents identified some activities that IAEA may sponsor or facilitate in cooperation with other organi zations; these include in particular:*

severe accident training under the sponsorship of IAEA, possibly in cooperation with other organizations;
management by IAEA of the dissemination of the information from Fukushima Daiichi forensics; and
development of guidance for prioritizing R&D."

However, it is complicated at the moment to identify possible resources of IAEA and other organizations, which can be spent for such a program or for its separate parts, and the time frames linked to the program activities.

Finally, the initiatives related to Collaborative Laboratories for Advanced Decommissioning Science (CLADS) should be men tioned. The CLADS laboratory has been recently established by JAEA to promote international collaboration for support the decommissioning of the Fukushima Daiichi NPP. During the recent CLADS Workshop "International Collaboration Toward Advanced Decommissioning of Fukushima Daiichi NPP" held at the JAEA headquarters on 10 November 2015 and CLADS workshop at Fukushima Research Conference for "Dialog on Fuel/Core Degrada tion in Severe Accident among Experts of Material Science, Thermodynamics, Severe Accident Analysis and Modeling" held at Japan during 5 6 July 2017, the following main activities were discussed:

Severe accident analysis;
Characterization of fuel debris and creation of debris/corium database;
FP and aerosol behaviour;
MCCI;
Thermodynamic database for corium;
Core degradation high temperature tests including experiments with plasma heating of fuel assemblies;
Radioactive waste management.

The timely interactions of CLADS with the partners of the EU SAFEST project shall create new horizons in EU collaboration with Japan for severe accident research.

4. Possible R&D areas of the EU-Japan roadmap

One of the possible approaches in the development of the EU Japan collaborative research roadmap can be realized through the synthesis of research priorities listed in the Tables 1 3 with partic ular attention to the analyses given in (Journeau, et al., 2018) about existing EU experimental facilities, which can address specific experimental research areas included in the EU roadmap.

Three prioritized experimental studies are currently not "ad dressed" by the existing facilities:

Core late re flooding impact on source term;
RPV vessel failure mode and corium release scenario;
Remelting of the multi component (low/high melting tempera ture) corium debris.

Also, there are several experimental priorities with poor infras tructural support, e.g., core coolability, core late reflood and debris formation during the stage of corium relocation from the core region into the lower head. Moreover, there are no more large scale facilities available for prototypical corium research in Europe and Japan.

There are several activities related to the Fukushima accident, which received some interest from the JAEA/CLADS during discus sion at the workshop mentioned above:

Study of the simulated and the actual Fukushima debris, includ ing experimental studies in EU hot cells, and characterization of corium properties;
Testing of various methods of debris sampling, characterization and reprocessing;
Separate effect experiments to study various local phenomena during accident progression of Fukushima units #1 3. (Gener ally from core degradation to MCCI, including FP release/trans port/scrubbing, B_4C effects on core degradation and molten pool behaviour);
Development and validation of models with the experimental data collected.

The addition of the above listed R&D areas to the EU Japan roadmap can be beneficial for the both parties.

Finally, we proposed Table 4 to integrate the topics of severe accident safety and the ranking of their priorities, which can be suggested for the EU Japan roadmap for experimental research on corium behavior. The table also indicated the comparison with the SARP, and the difference in priority level between PWR and BWR.

Table 4
EU-Japan roadmap of experimental research on corium behaviour.

Area	Issue	Topic	Priority	Differences for BWRs or in the SARP	Priority for Fukushima
Fukushima corium	Corium final state	• Debris sampling, characterization and reprocessing • Database on Fukushima	H	Not seen in SARP but added in SNE-TP	H
Corium properties and physical chemistry	In- and ex-vessel corium	• Phase diagrams • Thermo-physical properties • Physicochemical properties • Data for optimization of thermodynamic databases	M		H
Core and debris coolability	Hydrogen generation from molten / re-solidified fuel	• Influence of B_4C	M	BWR: H SARP Issues #1.1 & #1.2: M	M
	Core reflooding impact on source term	• Early phase (core intact)	L	BWR: M	L
		• Late phase (degraded core)	M		M
	Core coolability during re-flooding	• Late phase (degraded core)	H		M
Corium relocation and behavior in lower head		• Corium relocation from the core region into the lower head	M	BWR: H SARP: H	H
	FCI and debris/molten pool formation	• Premixing (corium jet fragmentation)	L	SARP: CL	L
		• Steam explosion	L	BWR: M SARP: CL	L
		• Fragmentation of corium in water pool and rapid steam generation	L	BWR: M Not seen in SARP	M
		• Temperature/pressure increase by FCI	L	SARP Issue #1.6: L	L
		• Scattering of materials and corium in lower head by FCI	L	Not seen in SARP	L
		• Debris formation and bed packing	M		M
		• Non-uniform corium and particulate corium spreading	H		H
		• Reflooding of debris bed	H		H
		• Cooling of porous debris bed	H		H
		• Dryout and reheating of debris bed	H		H
		• Corium debris oxidation and H2 production	M		M
		• Changes of composition and physical properties of corium	M/L	BWR: H	H
		• Interactions between liquid metallic melt in porous oxidic debris.	M/L	BWR: H	H
		• Formation of molten pool	H		H
		• Metal/oxide stratification in the molten pool and crust behaviour	H		H
	In-vessel corium retention	• Moten pool formation and behavior • Thermomechanical loads on the RPV lower head • Cooling of the vessel external surface Melt top flooding during IVR • Behavior of penetrations during IVR In-vessel core catchers	H		L
RPV failure mode and corium release	Leakage via instruments/ penetration/gasket/RPV damage	• Vessel failure modes and its timing	H	SARP: L	H
		• Corium /water/ gas flow through failed CRGT, instrumentation guide tube (IGT), from/to lower plenum.	H		H
		• Melt release modes through single and multiple breaches. • Ablation and plugging of the vessel breach during melt release.	H	SARP Issue #1.7: H for BWR; L for PWR	H
		• Corrosion of lower head by corium pool	M/L	BWR: M Not seen in SARP	L
		• Corium melting and crystallization behavior, equilibrium and non-equilibrium corium phases	M/L	BWR: H A part of SARP Issue #1.4: H	H
		• Properties of solid and liquid corium, particulate debris and structural materials	M/L	BWR: H A part of SARP Issue #6.6: M	H
Ex-vessel / pedestal cavity	FCI	• Fragmentation of corium jet in water pool and rapid steam generation	H		M
		• Pressure wave due to FCI, Steam explosion	H		M
		• Pedestal failure due to FCI	L	BWR: H	M
		• Failure of access hatches and tunnels due to FCI	M	BWR: H	M
		• Effect of uncertainty in the triggering time.	H		M
		• Dispersal of corium and pedestal internal material due to FCI	H		M
		• Effect of impurities in water (including sea water effect)	M		H
	Direct containment heating		M	BWR: L	L
	Ex-vessel debris bed formation and cooling	• Formation of debris	M	BWR: H SARP: H	H
		• Melt jet penetration depth and agglomeration of debris	M	BWR: H A part of SARP Issue #2.2: H	H
		• Spreading of the debris in the pool	M	BWR: H A part of SARP Issue #2.2: H	H
	Ex-vessel debris bed formation and cooling	• Stratified steam explosion	H		H
		• Formation and packing of the bed	H		H

(*continued on next page*)

Table 4 (*continued*)

Area	Issue	Topic	Priority	Differences for BWRs or in the SARP	Priority for Fukushima
		• Self levelling of the packed bed	M	BWR: H A part of SARP Issue #2.2: H	H
		• Cooling of the debris. The effects of debris agglomerations on cooling.	H	A part of SARP Issue #2.2: H	H
	MCCI included	• Corium flow spread in dry and wet pedestal cavity, drywell	H	Not considered in SARP	H
		• Corium stratification	H	A part of SARP Issue #3.1: H	H
		• Mixing of corium, stratification due to corium flow and gas generation	H	A part of SARP Issue #3.1: H	H
		• Corium flow into sump pit and reaction	M/L		H-L
		• Heat transfer between sump floor and corium / crust / corium particle	M/L	BWR: M	H
		• Deposition condition of corium in pedestal/reactor pit floor	M/L	BWR: M	H
		• Corium leak into connecting pipe inside sump	M/L	BWR: M	L
		• Corium interactions with cable penetrations in the containment floor	M/L	BWR: M	L
		• Dry MCCI (Single oxidic phase)	M	A part of SARP Issue #3.1: M	M
		• MCCI (oxide-metal configurations)	H	A part of SARP Issue #3.1:H	H
	MCCI related coolability	• Wet MCCI	H	A part of SARP Issue #3.2:H	H
	Ex-vessel core catchers	• Corium relocation from RPV to the core catcher	L	BWR: M SARP: L (as it must be bilateral R&D)	L
		• Interactions of corium with protective and sacrificial materials	M	SARP: L (bilateral R&D)	L
		• Melt quenching and fragmentation during melt pouring into water or flooded MCCI	M	SARP: L (bilateral R&D	L
		• Corium molten pool/layer formation and coolability	M	BWR: M-L SARP: L (bilateral R&D)	L
		• Catcher vessel cooling and integrity	M	SARP: L(bilateral R&D)	L
		• COMET	M	SARP: L(bilateral R&D)	L
Ex-vessel / pedestal cavity	FP and aerosol behavior in containment	• Gas distribution inside containment	H	H	H
		• Gaseous ruthenium transport and delayed releases from iodine deposits in circuits	H	A part of SARP Issues #4.3 and #4.4: H	M
		• Oxidizing environment impact on FP release	H	A part of SARP Issue #4.3: H	M
		• MCCI (SiO_2) aerosol effect on FPs	L	A part of SARP Issue #6.3: L	M
	Containment or reactor building integrity	• Dynamic and static behaviour of containment, crack formation	M	SARP Issue #3.6	M/H
		• Influence of countermeasures like Passive Autocatalytic Recombiners (PARs) or the effect of spray systems	M/L	A part of SARP Issue #2.1: H	L
	Pool scrubbing	• Scrubbing by steam flow, with vent	L	BWR: M SARP Issue #4.8: M	H
		• Effect of stratification/mixing on scrubbing	L	BWR: M SARP Issue #4.8: M	M
		• Scrubbing by water injection	L	BWR: M SARP Issue # 4.8: M	L
	Filtered containment venting systems	• Early activation of containment venting	M	SARP: H	L
		• Low pressure in the containment with activated venting, possibility of air ingress.	M	SARP: H	L
Re-criticality	In and ex-vessel debris bed	• Distribution of fuel and absorber materials • Effects of fuel, water/void, temperature and containment pressure • MOX fuel debris	L	BWR: M Not seen in SARP	M
Spent fuel pool	Spent fuel degradation and FP/ hydrogen release into containment	• Fuel Assembly (FA) behavior in spent fuel pool severe accident scenarios	M	BWR: H SARP Issue #5.1: H	H
Other areas		• Development of new accident tolerant fuels	M-L	Not seen in SARP	L
		• Human and organizational factors during emergency	H	Not seen in SARP	H
		• Sea salt intake to corium, • Sea salt impact on corium thermodynamic properties • RPV integrity	M	SARP Issue #6.1: M	H
		• Instrumentation under severe accident conditions	H	A part of SARP Issue 6.2: H	H
		• Improvement of the thermo-dynamic and thermo-physical database for corium and fission products.	M	SARP Issue #6.4: M	H/M

5. Conclusions

Based on an extensive review of ongoing severe accident studies in the area of corium behavior, comparison of research priorities identified in different projects and documents, as well as expert ranking of safety issues, the research priorities particularly on reac tor core melt (corium) behavior were finally suggested for the EU Japan roadmap which prioritizes research topics most relevant to safety issues of existing and future LWRs and to Fukushima decom missioning. This relevant R&D can be materialized in the collabora tion between EU and Japan, which was promoted by the recent arrival of CLADS/JAEA which participated in ranking of the research issues starting from the SARP activities and continuing within the SAFEST project.

The review and the resulting roadmap provide useful guidelines for (i) assessment of long term goals and proposals for experimen tal support needed for proper understanding, interpretation and learning lessons of the Fukushima accident; (ii) analysis of severe accident phenomena; (iii) development of accident prevention and mitigation strategies, and corresponding technical measures; (iv) study of corium samples in European and Japanese laborato ries; and (v) preparation of Fukushima site decommissioning

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