RECENT PROGRESS IN PHENOMENOLOGY AND TECHNOLOGIES RELEVANT TO IN-VESSEL MELT RETENTION AND EX-VESSEL CORIUM COOLING

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Abstract

The IAEA recently held the Technical Meeting on “Phenomenology and Technologies Relevant to In-Vessel Melt Retention and Ex-Vessel Corium Cooling”. It provided international experts with a platform for detailed presentations and technical discussions on recent progress in R&D activities on in-vessel melt retention and ex-vessel corium cooling during severe accidents in water cooled reactors.

This paper summarizes the major outcomes from the Technical Meeting focusing on recent progress and current status of related R&D, and remaining challenges and open issues, mainly based on the presentations and the discussion at the meeting.

1. INTRODUCTION

The Fukushima Daiichi accident highlighted some areas where the knowledge and understanding regarding severe accidents (SAs) in water cooled reactors could be strengthened to enhance nuclear safety.

The IAEA held, in cooperation with the OECD/NEA, the International Experts’ Meeting (IEM) on “Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant”, February 2015, to facilitate the exchange of information on these R&D activities and to further strengthen international collaboration among Member States and international organizations.

It was one of the main conclusions at the IEM that the Fukushima Daiichi accident had not identified completely new phenomena, but it highlighted several challenges that should be addressed by reconsidering R&D strategies and priorities. It has been highlighted that the R&D area regarding in-vessel melt retention and ex-vessel corium cooling/stabilization is one of the highest priority areas, and that better understanding of accident progression should be gained to reduce uncertainties as to the effectiveness of these strategies.

As one of the follow-up meetings for the IEM, the IAEA held the Technical Meeting (TM) on “Phenomenology and Technologies Relevant to In-Vessel Melt Retention and Ex-Vessel Corium Cooling”, Shanghai, China, October 2016. More than 60 experts from 18 Member States exchanged information on their activities, discussed the recent progress and current status of related R&D, and highlighted remaining challenges and open issues.

2. OBJECTIVE

The objective of this paper is to summarize and disseminate the major outcomes from the above-mentioned TM, especially the technical consensus established among the participating experts.

The TM included 6 Technical Sessions (TSs): 4 TSs on in-vessel melt retention (IVMR) and 2 TSs on ex-vessel corium cooling (EVCC). In total, 33 presentations were given, each of which was followed by active technical discussion. General issues related to the two main topics, i.e., IVMR and EVCC, were discussed at Discussion Sessions (DSs), respectively. A draft meeting summary of the highlights from the TSs and DSs was reviewed, discussed and agreed by the participants at Summary Sessions. All presentations and the meeting summary are available on the IAEA website [1], and an IAEA Technical Document (TECDOC) summarizing the TM outcomes will be prepared in 2017.
3. PHENOMENOLOGY AND TECHNOLOGIES REGARDING IVMR

It is commonly recognized that the IVMR strategy achieved by external reactor vessel (RV) cooling and/or in-vessel flooding is one of the most effective measures to prevent the melt-through of RVs during severe accidents in water cooled reactors. Several operating nuclear power reactors and new ones use or aim to use IVMR strategy, and some of them have dedicated systems.

When a SA occurs, the core melt usually relocates into the lower plenum and forms a molten pool. The radioactive fission products in the molten pool continue to generate decay heat. One of the two success criteria of the IVMR strategy is ‘thermal criterion’ to make sure that the heat flux from in-vessel molten pool is less than the critical heat flux (CHF) at the outer surface of the RV lower head (LH) that is determined by external cooling conditions with water pooled in the reactor cavity. The other success criterion is ‘structural criterion’ to ensure the long-term integrity of the RV taking into account ablation (i.e., thinning of the RV wall) by the molten pool and survivability of penetrations and welds at the RV LH.

3.1. Recent Progress and Current Status of R&D on IVMR

A lot of R&D activities have been done and are still on-going to develop IVMR strategy and technologies at national, regional and international level, and the Fukushima Daiichi accident revitalized it. Most of the efforts have been made in understanding of key phenomena, both inside and outside of the RV, with experiments and numerical analyses, code improvement/validation, and application of IVMR strategy to specific reactors and its optimization.

It is understood that molten pools can separate into either 2 layers (i.e., lower oxidic and upper light metal layers, or upper oxidic and lower heavy metal layers) or 3 layers (i.e., heavy, metal oxidic and light metal layers). Behaviour of the upper metal layer and impact of its thickness on heat flux focusing (so-called ‘focusing effect’) has been a subject of research in many organisations because it determines the maximum heat flux from the RV.

During the past years a significant progress has been achieved in understanding and modelling of behaviour of molten pools in the RV, and new tests are expected to provide data for the validation of computer codes allowing them to be used at reactor-scale conditions, which was difficult to achieve.

Main factors affecting the maximum heat flux able to be removed by external water flow (i.e., CHF) include: stability of the natural circulation; outer surface conditions of RV LH; geometry of the flow path; and water subcooling at the inlet of the flow path. Recent R&D results suggest that the most effective measures to increase CHF might be optimisation of the flow path and outer surface conditions.

The application of IVMR strategy requires the following design considerations such as: depressurization of the reactor coolant system (RCS); water source for external reactor vessel cooling and/or in-vessel flooding; initial flooding, followed by a long term water supply; venting and condensation of generated steam; and management of potential negative impacts if the IVMR with external cooling fails (e.g., threat of steam explosion in the containment). Various kinds of active and passive systems have been designed. It is agreed among experts that the probability of successful retention of melted core in RVs is generally higher in lower power reactors, but it also highly depends on the specific designs.

3.2. Remaining Challenges and Open Issues on IVMR

Regarding phenomenology inside the RV, behaviour of stratified molten pools is still a key issue and requires additional information in terms of experimental data and material properties. Especially, transient behaviour of molten pools is important to determine local heat flux values which may result in larger threat to
the integrity of the RV than the fully-developed (steady) state. Larger scale corium pool tests are desirable to provide more realistic data.

There are still uncertainties in phenomenology inside the RV, and they mainly come from insufficient knowledge in key phenomena related to accident progression and limitations of experimental facilities and instrumentation.

Larger scale corium tests are desirable to provide more realistic data, and it is still open how to compare results obtained in facilities having different scales and what is the influence of geometry of test facilities.

Phenomenology outside the RV is much clearer than that inside the RV: a lot of CHF data are available now. However, some of them are contradictory (e.g., the effect of surface oxidation), and experimental results should be classified and presented in a consistent way to be used easily by analysts, designers and regulators. Two new large experimental facilities are designed to measure CHF at the outer surface of the RV LH under more realistic configurations and flow conditions.

Code improvement and validation is important to simulate transient behaviours of molten pools inside the RV, water flow outside the RV and their interaction, which will give an assessment of the IVMR strategy under the given conditions. At present, different models and codes produce quite different results partly due to the absence of a proper validation matrix for IVMR-related phenomena. The current models for focusing effect and transient behaviour of molten pools need to be improved. Full height experimental facilities to measure CHF are necessary for validation data, and they should be designed as closely as possible to the real conditions.

Concerning application of IVMR strategy and technologies to reactor designs, there is a consensus among TM participants that there are not enough analyses of structural integrity made for different shapes of RVs and different pressure and temperature conditions. Hence, the structural integrity should be evaluated based on detailed phenomenology and material properties at realistic severe accident conditions. Probabilistic approaches are considered necessary as complement for deterministic approach in the analysis of IVMR strategy effectiveness.

4. PHENOMENOLOGY AND TECHNOLOGIES REGARDING EVCC

It is recognized that EVCC strategy, combined with other measures, remains the ultimate means to limit molten corium-concrete interaction (MCCI) in case IVMR is not applied or fails. Several NPPs under operation or under construction apply or aim to apply EVCC strategy.

Ex-vessel progression of SAs depends on the RCS pressure at the moment of RV failure, the possibility of containment over-pressurization, presence of water in the reactor cavity, corium cooling (e.g., by flooding), thickness of the concrete, and accident management measures to address non-condensable gases generation. There can be several paths which end by early containment failure, delayed containment failure or a manageable situation. An ex-vessel manageable situation is a situation in which the melt/debris has been cooled and quenched and kept in this state for a long time. In this paper, we focus on the phenomena related to ex-vessel corium cooling to stop MCCI and reach a manageable situation after a significant amount of the in-vessel corium inventory would pour by gravity in the reactor cavity.

When presence of water in the reactor cavity is allowed, the following melt fuel-coolant interaction can occur: (i) if an energetic steam explosion occurs outside the RV, the melt involved in the explosion may be dispersed out of the reactor cavity while the one not directly involved in the explosion can still form a particle debris bed; (ii) otherwise, the melt jet can break up in the water pool and a portion of the initial melt may form a particle debris bed and the remaining part may form a cake.

In case of dry reactor cavity conditions, the poured debris accumulates at the bottom, transfers heat to the atmosphere by radiation and convection and ablates the concrete substrate, possibly leading to containment melt-through. Reactor cavity flooding and/or corium spreading to reduce the heat flux are necessary to reach a manageable situation. Melt coolability may be improved by top flooding.

4.1. Recent Progress on and Current Status of R&D on EVCC

During the last three decades, there have been many tests (both integral and separate effect) and analyses completed and significant progress has been made towards understanding phenomenology related to MCCI and corium coolability [2].
Lessons learned from these tests and associated analyses are being applied in severe accident management planning for operating plants and in the design of new plants. They highlighted the following:

- For dry cavity conditions, melt temperature evolution and concrete ablation shape are influenced by concrete composition (radial ablation rate is faster than the axial ablation rate for siliceous concrete while a more isotropic ablation is observed for limestone-rich concrete). In a few tests, ablation appears to be more pronounced and faster oxidation kinetics in the areas where metal is in direct contact with concrete are observed.

- Under wet cavity conditions, several corium cooling mechanisms (e.g., bulk cooling, water ingression, melt ejection and crust breaching) were identified, and potential enhancement of coolability was observed.

For current plant applications, MCCI phenomena are analysed based on conservative assumptions with respect to the weakness of the containment design. In general, extrapolating the results of experiment results at plant scale requires some idealization of plant geometry and configuration; as a matter of fact, dedicated MCCI computer codes can currently analyze idealized cases where corium is spread uniformly over a dry reactor cavity. In addition, empirical correlations are needed as ablation anisotropy cannot be explained by existing phenomenological code models.

A few physics-based models for debris cooling mechanisms and debris beds have been developed and implemented in system codes to support accident management planning and plant safety analyses. However, there are limitations in addressing local corium accumulations in the case of an initially flooded reactor cavity, and very few codes model the impact of top flooding, in particular due to the lack of data for the top flooding of metal-oxide melt.

4.2. Remaining Challenges and Open Issues on EVCC

In spite of the significant progress mentioned above, the following challenges and open issues are still to be addressed:

- The lack of data to support analysis of long duration transients. As a matter of fact, tests are typically limited to a few hours while Fukushima Daiichi accident indicated that plant accident conditions can last for several days before reaching a controlled state;

- The need to perform more realistic plant simulation. Most codes are unable to address non-uniform core debris distributions and/or particle beds as initial conditions in real plant configurations. Also, realistic containment features such as deep sumps, sump drains, and cable penetrations need to be considered in analysis and testing activities;

- Data gaps in the experiment database related to EVCC concerning: (i) high metal content in the melt, (ii) rebar in the concrete, (iii) non-uniform melt accumulations, crust formation/failure mechanisms and their effect on MCCI, and (iv) the effect of raw water on coolability;

- Depending on reactor design and accident scenario, debris coolability might not be ensured for all situations. Therefore, additional engineered features might be needed to ensure coolability in some plants;

- Recriticality in debris beds formed for MOX fuel should be considered.

It is recognized from the presentations and discussions that the implementation of EVCC backfitting measures may be more complicated for operating reactors, in particular due to already existing design and layout and radiation protection issues induced by possible modifications.

5. INTERNATIONAL COLLABORATION

The TM underlined the importance of the international scientific cooperation in having better and common understanding of IVMR and EVCC phenomenology and technologies, and hence in increasing the safety level of operating and new nuclear power plants.
Several national and regional R&D programmes both on IVMR and EVCC are ongoing or planned to start soon. However, information exchange in existing bilateral and multilateral cooperation is limited among contracting parties for confidentiality reasons and funds involved, and it is difficult to disseminate the information beyond them.

The following activities could be carried out, as a complement, in the frame of international cooperation:
- Code benchmarking against well-defined experiments, including blind test calculations, will be useful for code/model development and validation;
- In the case of IVMR, RV integrity including characterization of material properties at severe accident conditions and improvement of the mechanical modelling could be an interesting topic for cooperation;
- A R&D activity on top cooling may be interesting for both IVMR and EVCC; and
- Education and training of young nuclear professionals should be a key element of future planned activities to ensure knowledge transfer in the area of severe accidents from senior to younger generations.

6. SUMMARY

The IAEA TM on “Phenomenology and Technologies Relevant to In-Vessel Melt Retention and Ex-Vessel Corium Cooling”, Shanghai, China, October 2016, gathered more than 60 experts from 18 Member States, and from regulatory bodies, technical support organizations, operators, vendors/designers, research institutes and universities. Based on the presentations, active discussions took place on recent progress and remaining challenges and issues related to IVMR and EVCC, as well as on related activities that could be performed in the frame of international cooperation.

The IAEA will continue to play an essential role in providing a platform to foster the exchange of information on recent progress and challenges in the addressed topics and its dissemination to Member States by using its different means (e.g., TMs, Coordinated Research Projects (CRPs), International Collaborative Standard Problems (ICSPs)) to support international collaboration.

ACKNOWLEDGEMENTS

The authors express their gratitude to the consultants who attended the consultancy meeting to plan the TM for their suggestions and advice. The authors also thank the participants in the TM for their contribution in presentations and discussion, and especially for their cooperation to explore consensus.

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