Recent Progress in Phenomenology and Technologies Relevant to In-Vessel Melt Retention and Ex-Vessel Corium Cooling

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BACKGROUND AND OBJECTIVE
Background

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

- The IAEA held, in cooperation with the OECD/NEA, International Experts’ Meeting (IEM) on Strengthening R&D Effectiveness, February 2015, to facilitate the exchange of information on R&D activities and to further strengthen international collaboration.

- It has been highlighted at the IEM that the R&D area regarding IVMR and EVCC is one of the highest priority areas, and that better understanding of accident progression should be gained.
Technical Meeting (TM) on IVMR&EVCC

• The IAEA TM on “Phenomenology and Technologies Relevant to In-Vessel Melt Retention and Ex-Vessel Corium Cooling” was hosted by the Government of China through SNERDI, Shanghai, China, October 2016.

• Attended by 63 experts from 18 Member States.

https://www.iaea.org/NuclearPower/Meetings/2016/2016-10-17-10-21-NPTDS.html
Objective

• The objective of this presentation is to summarize and disseminate the major outcomes from the Technical Meeting, especially the consensus established among the participating experts.
PHENOMENOLOGY AND TECHNOLOGIES RELEVANT TO IN-VESSEL MELT RETENTION (IVMR)
Phenomenology and Technologies relevant to IVMR

- The IVMR strategy achieved by external reactor vessel cooling and/or in-vessel flooding is one of the most effective measures to prevent the progression of SAs in WCRs.
- Several operating nuclear power reactors and new ones use or aim to use IVMR strategy, and some of them have dedicated systems.
- Success/failure of the IVMR strategy depends on how the core melt can be effectively cooled to prevent the RV melt-through.
Phenomenology inside the RV:

- Molten pools are considered to separate into 2 or 3 layers in the lower plenum.
- Behaviour of the upper metal layer and impact of its thickness on heat flux focusing, so-called ‘focusing effect’, is a subject of research in many organisations because it determines the maximum heat flux from the RV, $q_{RV}$. 
Phenomenology outside the RV:

- Main factors affecting the maximum heat flux to be removed by external water flow (i.e., critical heat flux, $q_{\text{CHF}}$) include:
  - stability of the natural circulation;
  - outer surface conditions of RV lower head (LH);
  - geometry of the flow path; and
  - water subcooling at the inlet of the flow path.

- The most effective measures to increase $q_{\text{CHF}}$ might be optimisation of the flow path and outer surface conditions.
Two Success Criteria of IVMR:

• ‘Thermal criterion’ to make sure the heat flux from in-vessel molten pool \( q_{RV} \) is less than the critical heat flux \( q_{CHF} \) at the outer surface of the RV LH that is determined by external cooling conditions; and

• ‘Structural criterion’ to ensure the long-term integrity of the RV, including survivability of penetrations and welds at the RV LH.
Application of IVMR Strategy and Technologies:

- The application of IVMR strategy requires the following design considerations such as:
  - Depressurization of the RCS;
  - Initial flooding, followed by a long term water supply; 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.

- Probability of successful retention of melted core in the RV is generally higher in lower power reactors, but it also highly depends on specific designs.
Remaining Challenges on IVMR (1/4)

**Phenomenology inside the RV:**

- Behaviour of stratified molten pools is still a key issue and requires additional information.
- 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.
- Uncertainties mainly come from insufficient knowledge in key phenomena related to accident progression and limitations of experimental facilities and instrumentation.
- Larger scale corium pool tests are desirable to provide more realistic data.
Phenomenology outside the RV:

- A lot of CHF data are available now, but some of them are contradictory (e.g., the effect of surface oxidation).
- 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.
Remaining Challenges on IVMR (3/4)

**Code Improvement/Validation:**

- 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.
Application of IVMR Strategy and Technologies:

• Regarding structural integrity of RV, there are not enough analyses made for different shapes of vessel and different pressure and temperature conditions.

• 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.
PHENOMENOLOGY AND TECHNOLOGIES RELEVANT TO EX-VESSEL CORIUM COOLING (EVCC)
Phenomenology and Technologies relevant to EVCC

- The EVCC strategy, combined with other measures, remains the ultimate means to limit MCCI in case IVMR is not applied or fails.
- SA ex-vessel progression depends on many factors and can follow several different paths.
- Some paths may end in a manageable situation that is a situation in which the melt/debris has been cooled and quenched and kept in this state for a long time.
RV Failure

Gravity driven corium discharge

Water in the cavity?

Yes

Ex-vessel FCI

No

Steam explosion?

Yes

Early Containment Failure (C.F.)

Is the RCS pressurized?

Yes

Corium jet discharge

Depressurization possible?

No

MCCI

Corium/debris coolable?

No

Concrete ablation

Yes

Concrete thick enough?

No

Manageable situation

Yes

Delayed C.F.

Early C.F.
Lessons learned from experiments:

• For dry reactor cavity conditions:
  – Melt temperature evolution and concrete ablation shape are influenced by concrete composition.
  – A few tests show a more pronounced ablation in areas where metal is in direct contact with concrete.

• Under wet reactor cavity conditions:
  – Several corium cooling mechanisms were identified; and
  – Potential enhancement of coolability by early containment flooding was observed.
Capabilities of current computer codes and models, and plant applications:

• For current plant applications, MCCI are analysed with idealization of plant geometry and configuration:
  – Corium assumed to be instantaneously and uniformly spread over the entire floor of a dry reactor cavity; and
  – Empirical correlations needs to be introduced for ablation anisotropy.

• Computer model limitations:
  – In addressing local corium accumulations, in particular, in the case of initially flooded reactor cavity; and
  – In modelling the impact of top flooding, as very few codes can model this impact, mainly due to the lack of data for the top flooding of metal-oxide melt.
Remaining Challenges on EVCC (1/3)

Lack of data to support analysis of long duration transients:

- Due to facility design and operational constraints, past MCCI experiments with prototypic melt have relatively short duration.
- Need to obtain longer duration experimental data in order to extrapolate to reactor situations.
Remaining Challenges on EVCC (2/3)

Data gaps in the experimental database:

- There are gaps in experimental data related to EVCC concerning:
  - high metal content in the melt;
  - rebar in the concrete;
  - non-uniform melt accumulations, crust formation/failure mechanisms and their effect on MCCI; and
  - the effect of raw water on coolability.

- Further investigation is needed regarding corium bed formation and coolability, and MCCI phenomenology.
Remaining Challenges on EVCC (3/3)

Application of EVCC Strategy and Technologies:

- Depending on reactor design and accident scenario, debris coolability may not be ensured for all situations. Additional engineered features may be needed to ensure the coolability.
- Recriticality in debris beds formed from MOX fuel should be considered.
- EVCC back-fitting measures might be more complicated for operating reactors.
INTERNATIONAL COLLABORATION
Current Status:

• Several national and regional R&D programmes are ongoing or planned to start soon.
• Importance of international scientific cooperation in having better and common understanding of IVMR and EVCC.
• Information exchange in existing bilateral and multilateral cooperation is useful, but limited among contracting parties for confidentiality reasons or funds involved. It is difficult to disseminate the information beyond them.
Proposed Cooperation:

- Although different types of reactors have different designs, accident sequences and operational procedures, the following suggestions were made for common efforts:
  - Molten pool behaviour experiments with higher fidelity and representativeness;
  - Top cooling of corium for both IVMR and EVCC;
  - RV integrity assessment including characterization of material properties at SA conditions and improvement of the mechanical modelling;
  - Code benchmarking, including blind test calculations, against well-defined experiments;
  - Education and Training of young nuclear professionals.
SUMMARY
Summary

• The IAEA Technical Meeting was held on In-Vessel Melt Retention and Ex-Vessel Corium Cooling in Shanghai, China, October 2016.

• Active discussions took place on recent progress and remaining challenges, as well as on related activities that could be performed in the frame of international collaboration.

• The IAEA will continue to play an essential role in fostering the exchange of information on recent progress and challenges and its dissemination to Member States.
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Thank you for your attention!