Corium In-Vessel Retention stakes as regards the safety demonstration

Garo Azarian
Bertrand de L’Epinois

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Introduction

1. Reachable CHF by external water circulation

2. Corium layering in transient conditions

3. Possible reduction of vessel failure risks by in-vessel injection

Conclusion
Introduction (1/2)

▶ Objectives for GEN 3 PWR as regards severe accident:
  - a fourth level of defense in depth dedicated to SA mitigation
  - deterministic safety approach
  - practical elimination of phenomenon susceptible to lead to large & early releases
    - e.g. ex-vessel steam explosion

▶ Current solution: dry pit and ex-vessel corium retention (EPR, ATMEA)

- dry reactor pit at vessel failure (steam explosion prevention)
- temporary corium retention to collect corium,
- spreading in dry condition and flooding
- metallic core catcher cooled from below, lateral and top.
- spreading, relocation and initial cooling: passive.

What are the questions to address in order to consider an IVR strategy on PWR > 600 Mwe?
R&D stakes as regards IVR uncertainties and feasibility:

- **Critical Heat Flux (CHF)** by vessel outside cooling
  - CHF # 1.5 – 2 MW/m² can be reached
- **Heat flux** by focusing effect from corium stratification
  - still significant uncertainties
  - non negligible likelihood of vessel failure
- **Ex-vessel steam explosion**
  - if vessel failure occurs in a flooded pit
  - large uncertainties: triggering, energy, mechanical effect on containment
  - early containment failure risk is to be practically eliminated.

*IVR would require to overcome uncertainties; IVR reliability, steam explosion in case of IVR failure*
1- Reachable CHF by external cooling (1/2)

- **Residual vessel thickness** is a factor limiting CHF enhancement
  - 1.5 MW/m²-2MW/m² currently reachable
  - possible margins could allow more than 2 MW/m²
  - but reduction of vessel thickness (1cm <600°C for 1.5MW/m²)

- **Design optimization related to thermo-hydraulics**
  - vessel insulation to optimize natural circulation with two legs, thus increasing liquid flow.
  - passive openings and arrangements to improve steam venting and prevent steam blockage.
1- Reachable CHF by external cooling (2/2)

**Nucleate boiling** physics optimization

- **Vessel material surface**
  - AREVA’s Technical Center Le Creusot,
  - real oxidation conditions,
  - porosity characteristics
  - nucleate boiling sites

- **Water solution in the pit:**
  - to prevent film boiling by increasing Leidenfrost temperature.

2 MW / m2 can be reached by outside cooling optimization
2- Corium layering in transient conditions (1/2)

- Phenomena in transient conditions could reduce the upper steel layer thickness and worsen focusing effect (MASCA, CORDEB1).

  - Reduction of thickness of top metal layer in contact with RPV due to metal flow through upper crust

  - Upward migration (due to driven forces) of molten steel behind lateral crust (assumed to be stable)

  - Upward relocation of superheated molten steel from heavy steel layer, through horizontal crust
2- Corium layering in transient conditions (2/2)

- Transient models addressing the thermochemistry effects in the lower head are developed (e.g. CEA PROCOR code).
  - Scale effects will have to be justified

- New tests are needed to consolidate knowledge of some phenomena:
  - Crusts behavior, permeability, impact of oxidation level on chemical interaction with molten steel
  - Kinetics of mass transfers between layers
  - Molten steel pathways

- 2D/3D thermal conduction to be assessed
  - In the metal layer (natural convection cells)
  - In vessel wall (could lower flux)

Complex phenomenon might worsen the focusing effect: R&D needed to reduce significant uncertainties and reasonably bound phenomenon.
3- IVR dedicated in-vessel injection

- In-vessel injection goal depends on core status:
  - to delay before corium relocation (it)
  - to cover the top metal layer (reduce focusing effect)
  - to enhance Zr oxidation and impact corium stratification thermochemical phenomena

- Among the passive systems:
  - dedicated accumulators (pressurized tanks)
  - dedicated core make-up tanks, both sides of which are connected with the primary circuit
  - elevated gravity tanks

Injection efficiency requires a rapid actuation (< 1H). The open issues are therefore mainly related to safety analysis (assumption of both core melt and capability of fast actuation of a safety injection in the vessel)
Conclusions (1/2)

- Core melt to be taken into account
  - as shown on TMI and FKSH
  - even with improved prevention

- Safety objectives for severe accident mitigation
  - practical elimination of phenomenon leading to large & early release
  - robust corium retention, to avoid long term & important contamination

- Important uncertainty regarding heat flux were recently identified
  - in-vessel corium stratification transient phenomenon?
  - top metal layer thickness, relevance of worsened focusing effect (very high thermal fluxes on the vessel)?
  - on-going EU IVMR project will provide insights

- Uncertainties concerning CHF can be mastered
Conclusions (2/2)

- In-vessel injection in case of severe accident is a question mark concerning the safety demonstration.

- Should a vessel failure occur with a flooded pit, the steam explosion safety case is to be resolved.
  - likelihood, efficiency and energy of steam explosions?
  - ex-vessel steam explosion mitigation by design?
  - (early containment failure which must be practically eliminated)

*To consider IVR as a robust severe accident mitigation solution, much R&D is still needed to overcome uncertainties. Ex-vessel steam explosion risk appreciation appears as a major driver as regards IVR: continued R&D and international consensus are much needed.*