Florian Fichot – Jean-Michel Bonnet – Bernard Chaumont
IRSN – PSN-RES/SAG

IRSN views and perspectives on in-vessel melt retention strategy for severe accident mitigation

Outline

1. Key points for the feasibility of In-Vessel retention strategy
2. Impact of reactor power on the robustness of the approach
3. A research program for In-Vessel retention in high power reactor: the H2020 IVMR project
4. Innovations to improve the robustness of the in-vessel retention approach
5. Conclusion

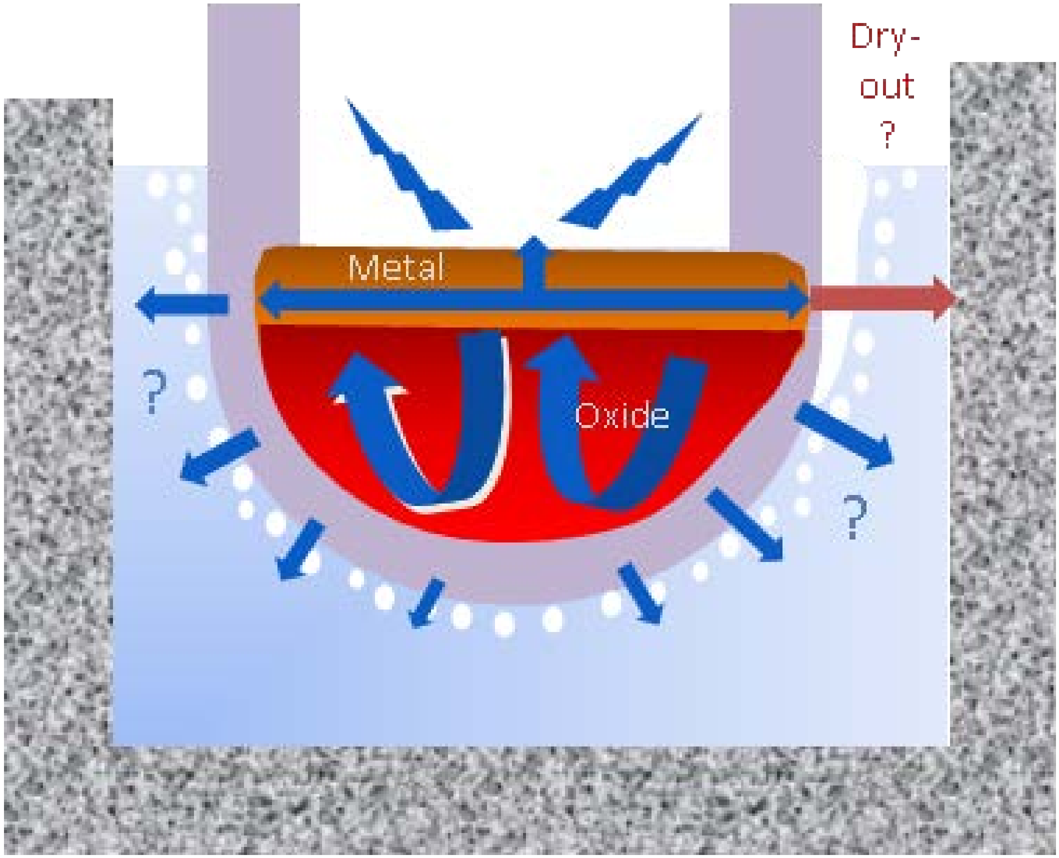
Key points for the feasibility of an In-Vessel retention strategy – Concept and Approach

- The strategy of in-vessel retention of corium, as it was implemented in existing reactors (Loviisa, Paks, Dukovany, Mochovce) or as proposed in possible designs (AP600, VVER-640, AP1000, APR-1400) relies on:
  - Flooding of reactor cavity.
  - Natural circulation of water (passive system) thanks to the presence of an external baffle designed to optimize the extraction of power (convective boiling).
  - Condensation of steam produced in the containment and cooling of water in the reactor pit.

First concepts : Henry & Fauske (1993), Tuomoisto & Theofanous (1994)

Key points for the feasibility of an In-Vessel retention strategy – Concept and Approach

- The approach is considered valid and robust if it can be shown that, everywhere along the vessel, the heat flux from the corium and molten metal is lower than the maximum that can be extracted by boiling (CHF), by a reasonable margin.



Key points for the feasibility of an In-Vessel retention strategy – Concept and Approach

- **LB LOCA is considered as the worse scenario, leading to a massive corium relocation after 1h or 2h.**
  - For a PWR of 1000 MWe, it corresponds to 20-30MW that must be extracted by external cooling.
- **It is conservatively assumed that all the core inventory is relocated to the lower plenum.**
  - For a PWR of 1000 MWe, it corresponds approximately to 80t UO_2 and 20t Zr partly oxidized (ZrO_2).
  - Molten steel is also present (lower plenum structures, ablated vessel wall, molten core structures)

Key points for the feasibility of an In-Vessel retention strategy – Aggravating factors

- When the top metal layer is « thin » (between 10 and 50cm), the heat flux along that layer may be greater than the maximum flux along the oxide pool (« **focusing effect** »)
- Extracting a high heat flux can only be done through a thin wall → vessel wall is significantly ablated.
- Residual thickness is only a few cm and the « mechanically resistant » part is only 1cm for a heat flux of 1.5MW/m2
- Therefore, it is useless to look for CHF values higher than 3 or 4 MW/m2 because the residual thickness will be too small.

Key points for the feasibility of an In-Vessel retention strategy – Favourable factors

- **A part of the fuel remains in the core region, at least for a few hours** (results of PSA2 for PWR-900):
  - SBO sequence: between 40% and 70% of the core is molten at the time of first massive relocation in lower plenum
  - LB sequence : between 60% and 90% of the core is molten at the time of first massive relocation in lower plenum
- **Volatile fission products are likely to have escaped from the molten pool →** residual power would be 20% lower, at least at the beginning of the sequence
- **Consequence: heat load is lower (with respect to conservative approach) at the beginning of the sequence.**

Impact of reactor power on robustness of the approach - Changes in timing and maximum heat load

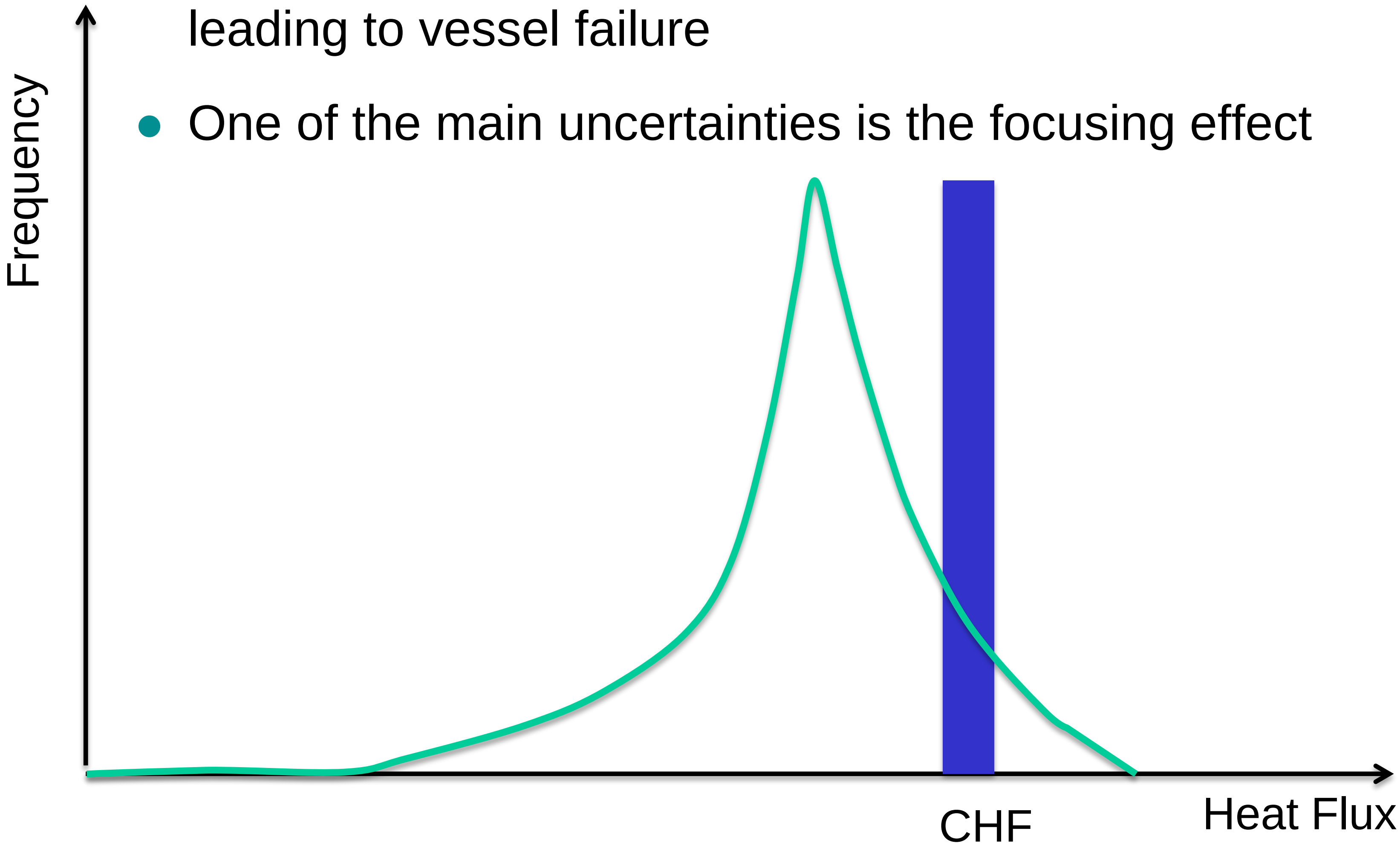
- For high power reactors, there are 2 cumulative factors which increase the maximum heat load
  - The time of corium arrival in the lower plenum is shorter (for similar sequences) → residual power is higher
  - The mass of fuel is larger → average heat flux is higher
- The maximum heat flux from corium to vessel wall (estimated with standard correlations), for a PWR of 1000MWe, would be in the range from1.7 to 2.5MW/m2, for the worst cases.

Impact of reactor power on robustness of the approach - Changes in timing and maximum heat load

- The maximum heat flux that can be extracted by external cooling (CHF) is estimated from experimental data obtained in « 2D slices» at full scale
  - ULPU: up to 2MW/m2 (optimised design for AP1000)
  - SULTAN: from 1.2 to 1.5MW/m2
  - KAIST: up to 1.5MW/m2
- Some scenarios would lead to vessel failure.
- The maximum heat flux from corium to vessel wall would become lower than the CHF between after 10h for a PWR of 1000 MWe (excluding a possible focusing effect).

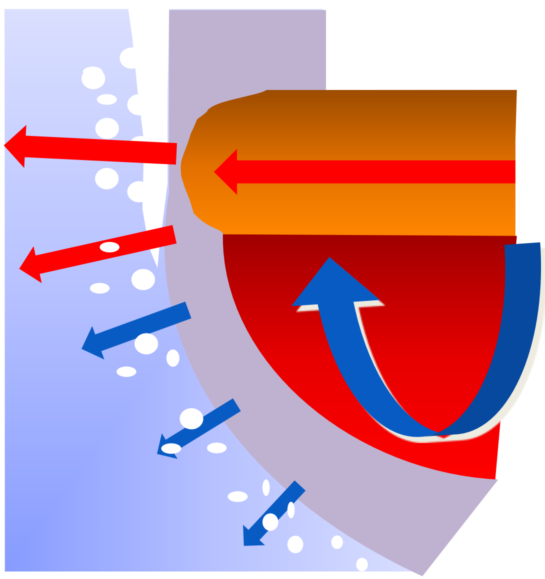
Impact of reactor power on robustness of the approach - Evaluation of residual risk of vessel failure

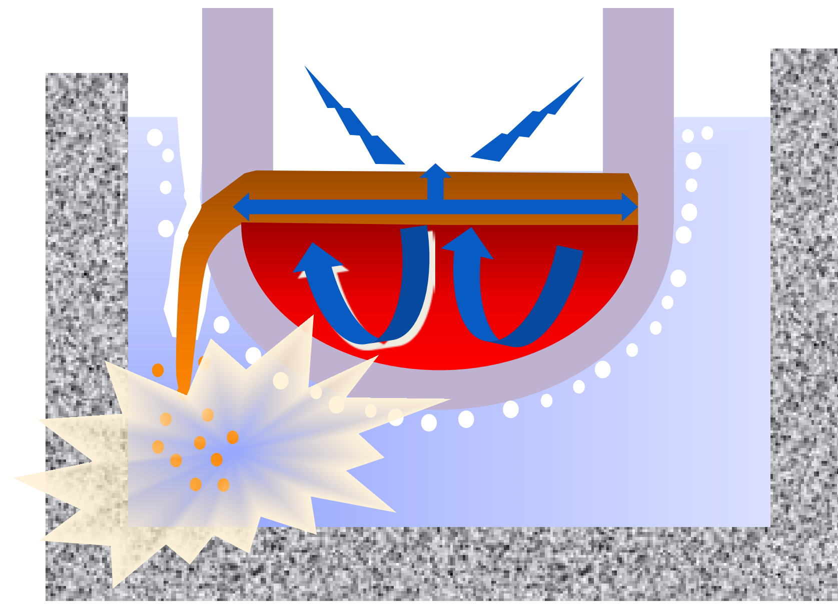
- Considering several uncertainties, there are situations leading to vessel failure
- One of the main uncertainties is the focusing effect



Impact of reactor power on robustness of the approach - Evaluation of residual risk of vessel failure

- Main consequence of vessel failure with ERVC: energetic corium-water interaction outside the vessel → risk of steam explosion and early containment failure





Impact of reactor power on the robustness of the approach - The case of VVER-1000 reactors in Europe

- As a result of the stress tests analysis requested by EC after Fukushima accidents, it was concluded that there was a probablity of early containment failure for that type of reactor.
- In that situation, the implementation of a strategy for in-vessel retention of corium would provide more benefits than risks.
- This is why in-vessel retention in VVER-1000 is actively studied in Europe.
- This has led to the proposal of several projects on in-vessel corium stabilisation and in particular the European H2020 project IVMR which will be coordinated by IRSN

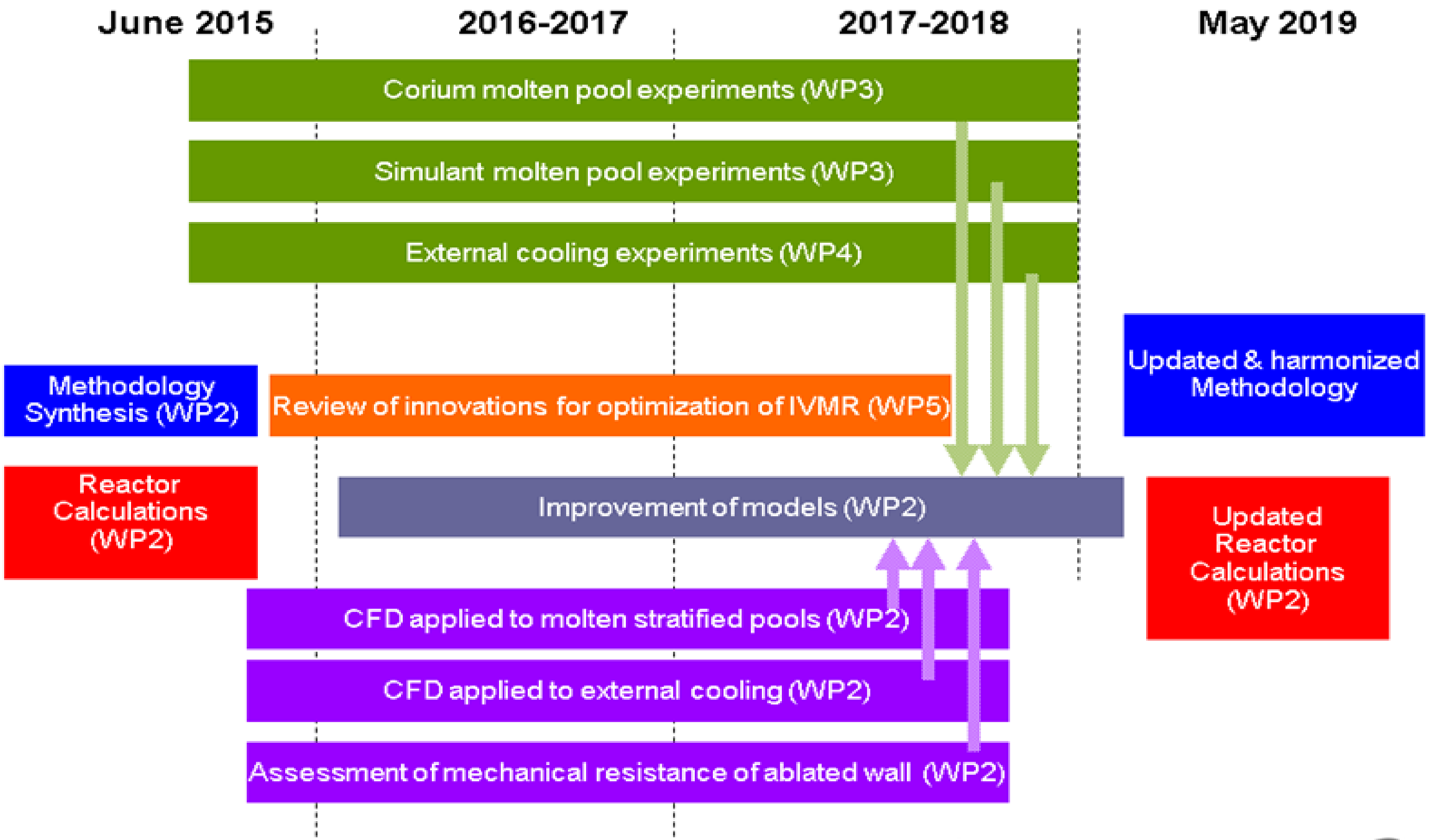
A research project for In-Vessel retention in high power reactor: H2020-IVMR - Objectives

- Review existing approach for in-vessel retention
- Extend it to various designs
- Improve it by considering more scenarios and by justifying less conservative assumptions
- Investigate possible innovations for in-vessel retention

A research project for In-Vessel retention in high power reactor: H2020-IVMR - Objectives

- Review, from an analytical point of view, the possibility to retain the corium inside the vessel thanks to external cooling, for several kinds of reactors in Europe (existing or under project), following the standard methodology
- Provide new experimental results to assess the models used in the methodology, in particular to cover all possible configurations of corium and all geometries of lower head (VVER-1000 and BWR).
- Investigate several options to improve the IVMR methodology by reducing conservatism in order to derive more realistic safety margins, which is necessary when considering high power reactors.
- Elaborate an updated and harmonized methodology for the analysis of IVMR that will be used for various types of reactors and implemented in various codes used in Europe

A research project for In-Vessel retention in high power reactor: H2020-IVMR – Main Outcomes



A research project for In-Vessel retention in high power reactor: H2020-IVMR – Main Outcomes

- Methodology - Modelling – CFD - Reactor calculations - Evaluations of safety margins (analysis) (Leader: JRC-Petten, co-leader: IRSN)
- Experimental and analytical assessment of heat flux into RPV wall during the IVMR and possible measures to reduce it. Corium and simulant experiments (Leader: KTH, coleader: KIT)
- Experimental and analytical assessment of vessel external cooling and long term stabilization (Leader: UJV)
- Innovation and technical engineering research – New ideas for the efficiency and optimal management of IVMR (this WP has the ambition to promote the emergence of new concepts) (Leader: CEA)

Innovations to improve the robustness of the in-vessel retention approach

- **Delaying the arrival of corium in the lower plenum**
  - Passive/active in-vessel safety injection
- **Limiting the maximum internal heat load**
  - Increasing the mass of steel
  - Increasing the volume of corium (dilution)
  - Increasing the vessel radius
- **Improving the efficiency of external vessel cooling**
- **Mitigating the consequences of vessel failure**
  - Avoiding highly energetic corium-water interaction

Conclusion

- For reactors below 600 MWe, current knowledge makes it possible to adopt an in-vessel corium retention strategy.
- Beyond this level of power, given the current state of knowledge, there is a risk of vessel failure, in particular for sequences leading to a very fast arrival of corium to the lower plenum → risk of early containment failure following steam explosion.
- In-vessel corium retention strategy for high power reactors remains an option that deserves to be studied but this requires additional R&D.
- Since June 2015, IRSN coordinates the H2020 European project IVMR which should bring new experimental data and a revised methodology for the IVMR strategy.

Annoucement

- IRSN will organize an International Workshop on « In-Vessel Corium Retention Strategy: Status of knowledge and perspectives »
- Dates: June 6-7, 2016
- Venue: Aix en Provence