Computational methods developed to propose a new methodology for IVR assessment

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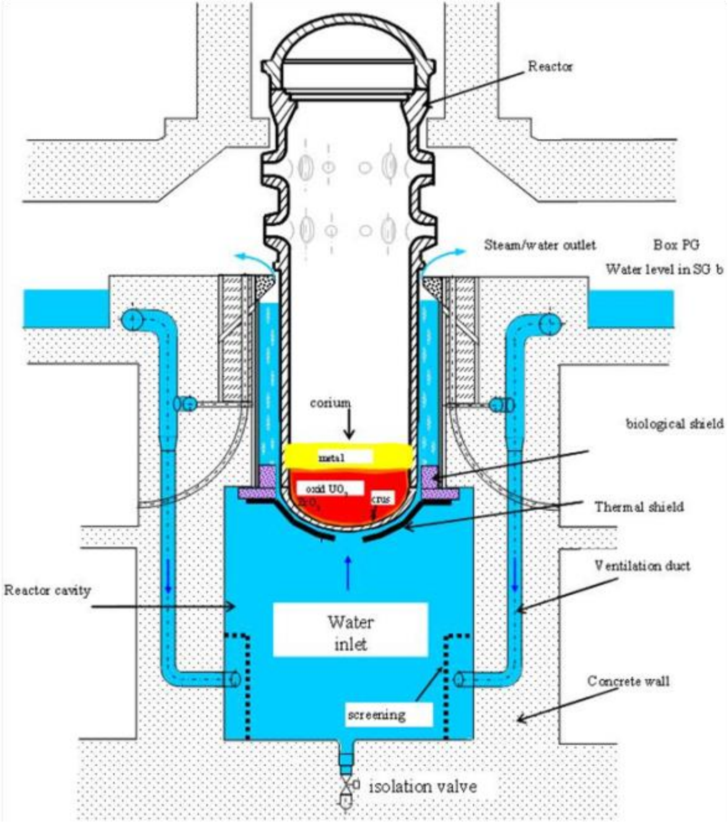
The IVR strategy: context and facts

IVR is a Severe Accident strategy that aims at stopping corium progression inside the vessel, by external cooling.

IVR first implemented in Finland, then Hungary, Slovakia, Czech Republic, for VVER-440 reactors

Safety margin is sufficient because of low power and large amount of steel:

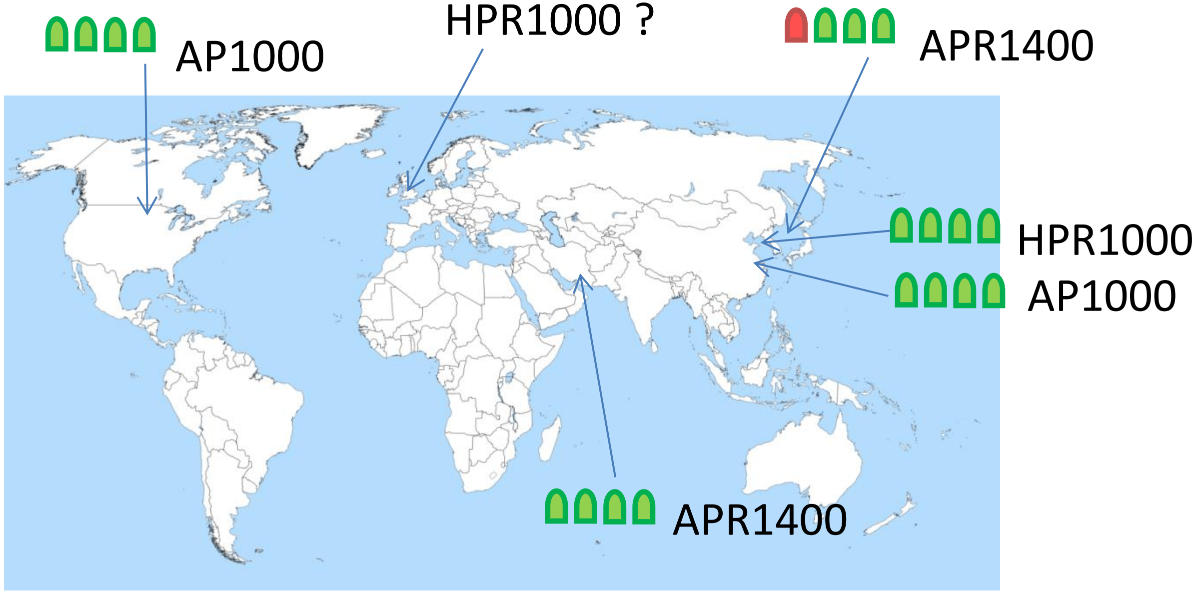
- Average heat flux 0.5MW/m² (maximum 1MW/m²)
- External cooling up to (CHF) 1,5MW/m² (CHF) thanks to hydraulic channel
- Residual vessel thickness > 7cm
- Large amount of water in circuits → significant time before corium arrival in lower plenum



The IVR strategy: Gen III reactors

AP1000, APR1400, HPR1000, CAP1400

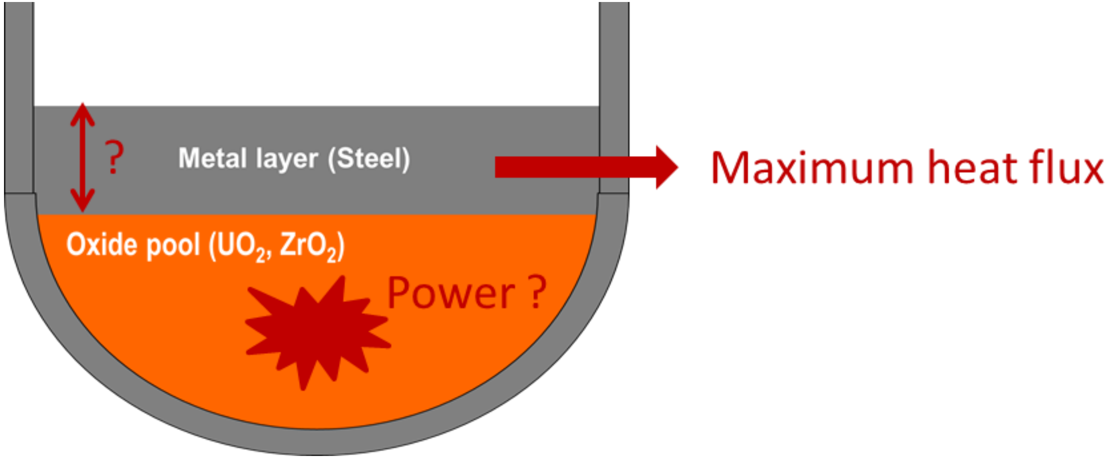
- 9 in operation
- 15 under construction



IVR safety evaluation: “bounding cases”

Approach proposed initially for AP600 and VVER440 (Theofanous et al. 1997):

- All core inventory is molten and relocated in the lower plenum → oxide pool
- Molten steel forms a layer located above the oxide pool
- This configuration is assumed to be conservative w.r.t. heat flux φ_{max}



The “steady-state heat flux” criterion

- The standard criterion for IVR evaluation is:

$$K_\varphi = \varphi_{max}/\varphi_{CHF}$$

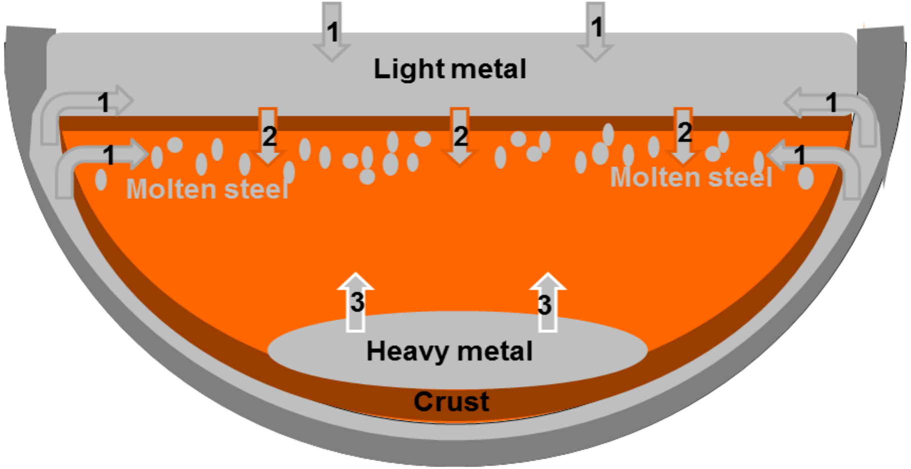
- Acceptance corresponds to $K_\varphi < 1$

- But it does not allow to define a safety “margin” because:
    - There is no absolute “reference value” (it is only relative to the local CHF which is not constant)
    - It is not obvious to define an “acceptable distance” between 2 heat fluxes

Oxide/metal stratification: several kinetics

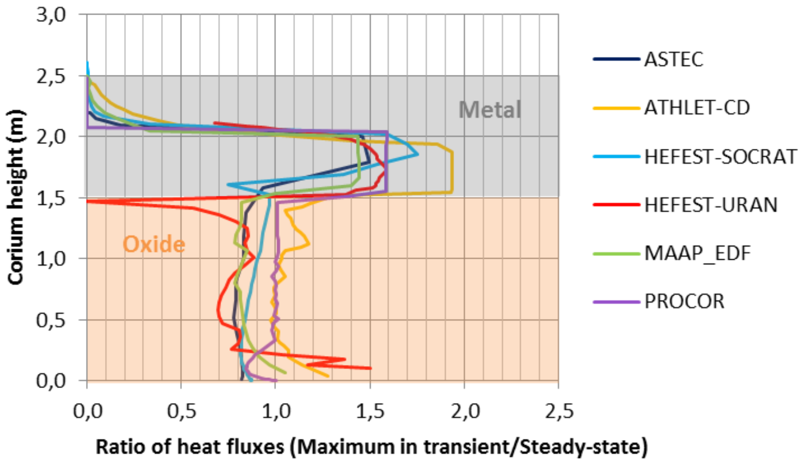
In reality, stratification may start with a heavier metal, becoming progressively lighter.

- ‘1’ steel addition from melting (vessel and internal structures)
- ‘2’ : steel transfer through crust
- ‘3’ mass transfer between heavy metal and oxide pool



IVR safety evaluation: “really bounding”?

- **The bounding case does not bound all intermediate states**
  - transient situations where the peak heat flux is higher than the heat flux at final state



- **The bounding case does not represent the final state**
  - the shape of the ablated vessel may significantly differ from the shape deduced from the final state

Drawbacks of bounding case approach

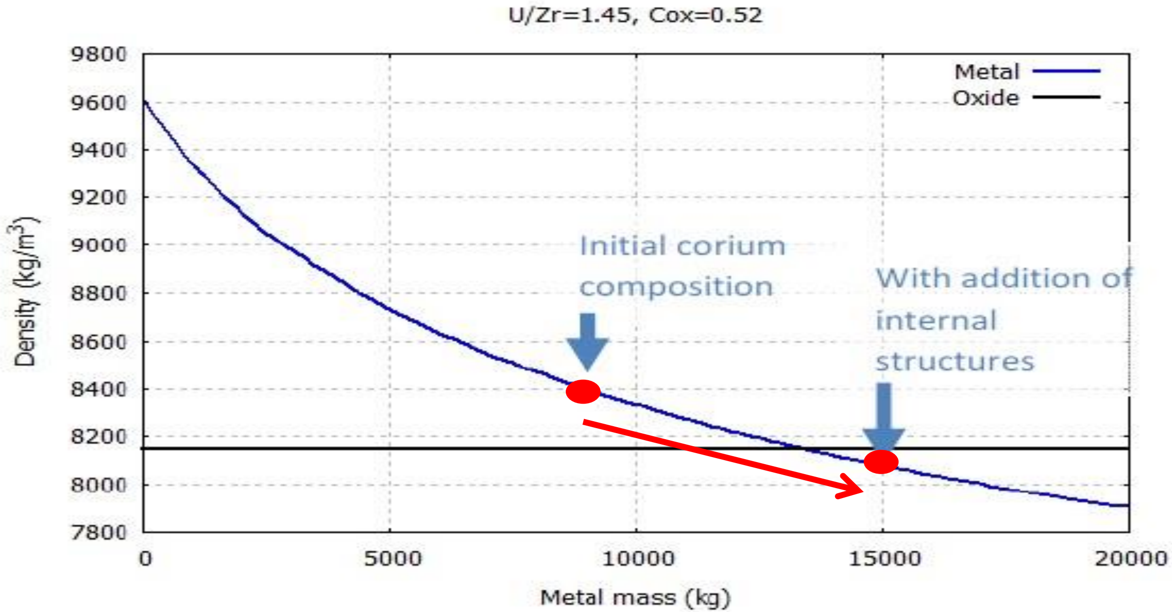
- **Critical parameter “mass of steel” includes too many sources of uncertainties**
  - Design
  - Scenario
  - Modelling

  → its distribution function is more complex than usually assumed

- **No independence of uncertain variables**
  - Some variable are related :
    - mass of steel and power,
    - FP distribution and oxidation degree of Zr,
    - …

- **Unlikely combinations of uncertain variables**
  - This may lead to overestimate the probability of “favorable” cases

Final mass of steel and impact on density



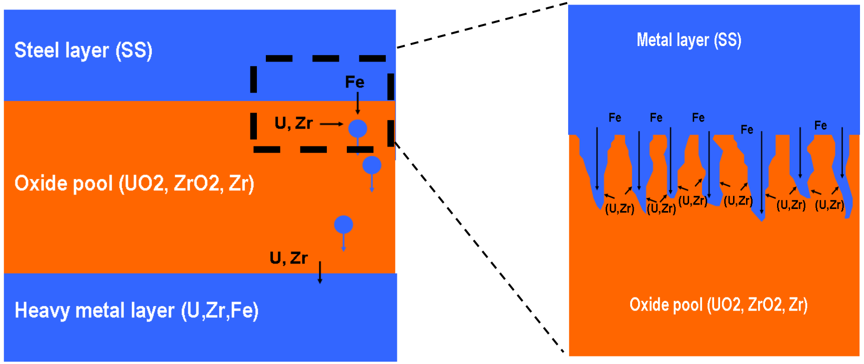
- What is the kinetics of evolution between heavy and light metal?
- How does the configuration change?

From Almjashev et al., deliverable D3.2 of IVMR project

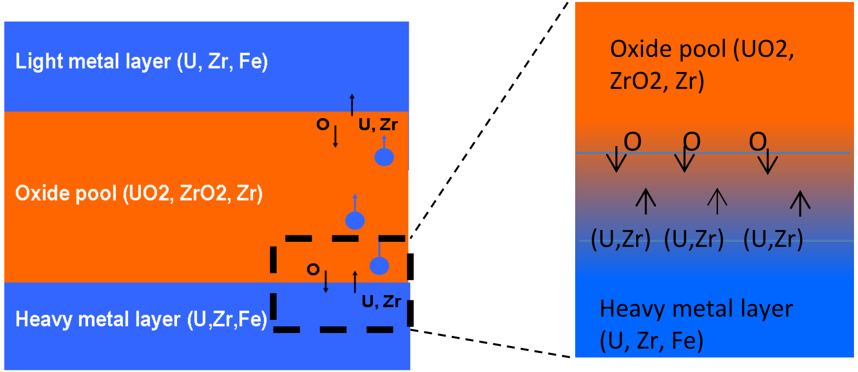
Species transport near the metal-oxide interfaces

Reference: Fichot & Carénini, 2015

First stage: ablation of steel layer driven by the diffusion of Iron across the two-phase interaction layer



Second stage: "oxidation" of the bottom layer driven by interaction at the top interface



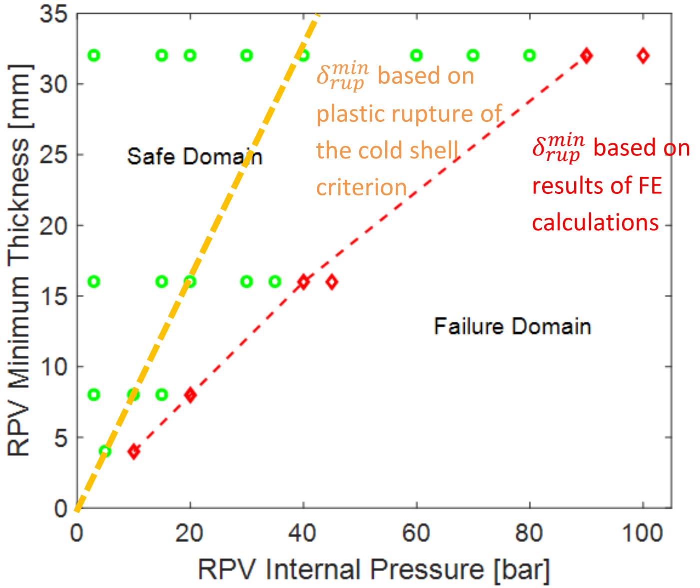
A new generic safety criterion (1/2)

- **Vessel thickness** $'\delta'$
  - **Integrates all the peaks of heat flux** (additional ablation whenever the internal heat flux exceeds the external one)
  - Is a **measure of the mechanical resistance** of the vessel → it is a "natural" safety criterion

- **A straightforward safety margin**
  - $\sigma \leq \sigma_{max} = \frac{\sigma_{fail}}{m} \rightarrow \ \delta \geq m\,\delta_{fail}$, where 'm' is the margin

A new generic safety criterion (2/2)

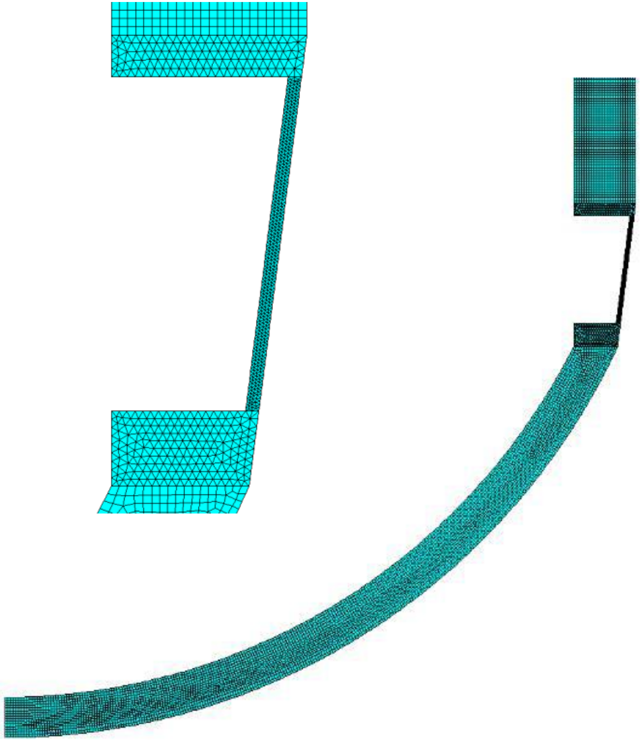
- **Possible evaluations of** $'\delta_{fail}'$
  - "Cold shell approach" $\delta_{fail} = \frac{R\,\Delta P_{max}}{2\sigma_{cr}}$
  - Detailed FE calculation (2D) (less conservative)

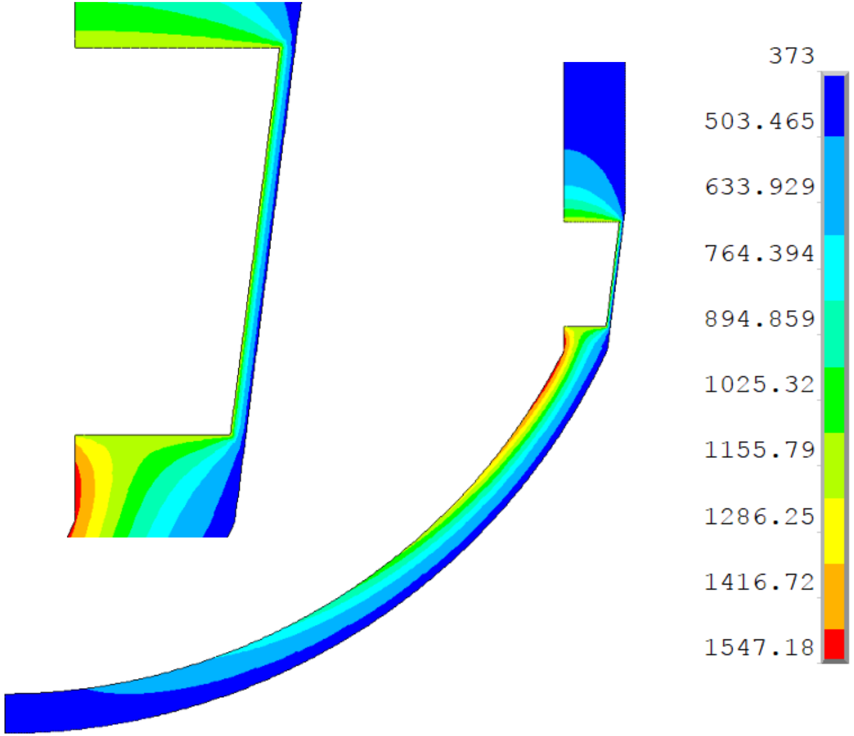


- **New safety criterion**
  - $K_\delta = m\delta_{fail}/\delta_{min}$ where 'δ_{min}' is the minimum residual thickness
  - Acceptance corresponds to $K_\delta < 1$

2D Finite-Elements approach

Evaluation of δ_{fail} as a function of internal pressure load in simplified geometry





Simplification of the problem: “cold shell” approximation

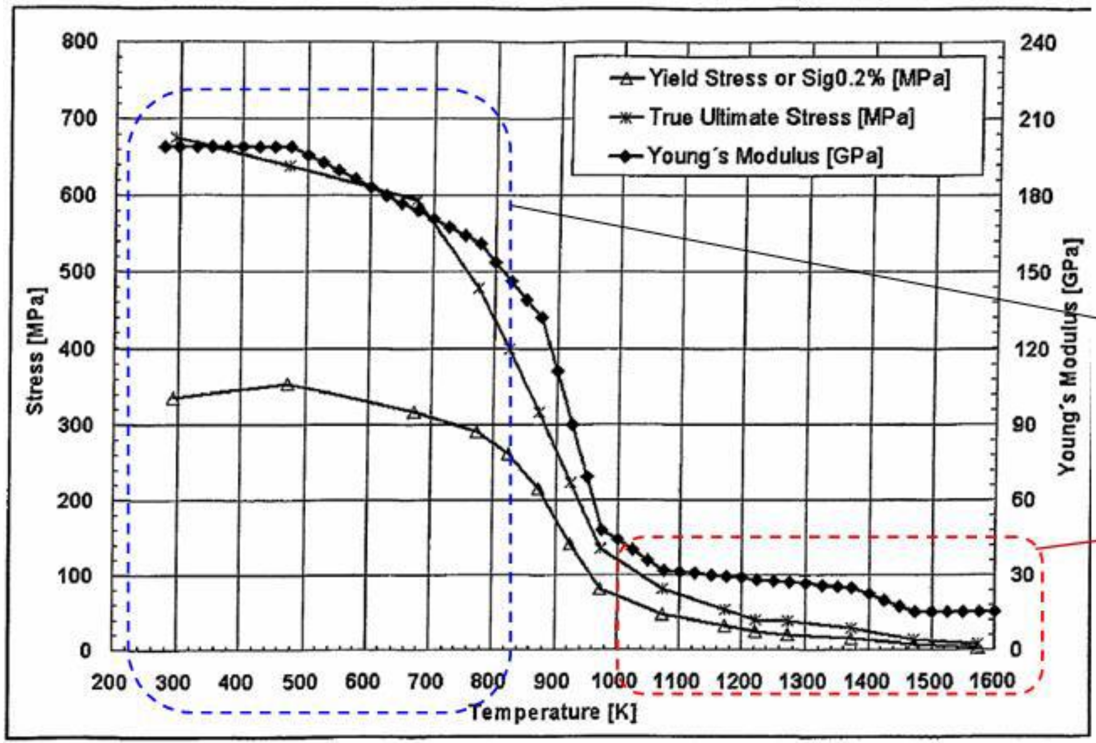
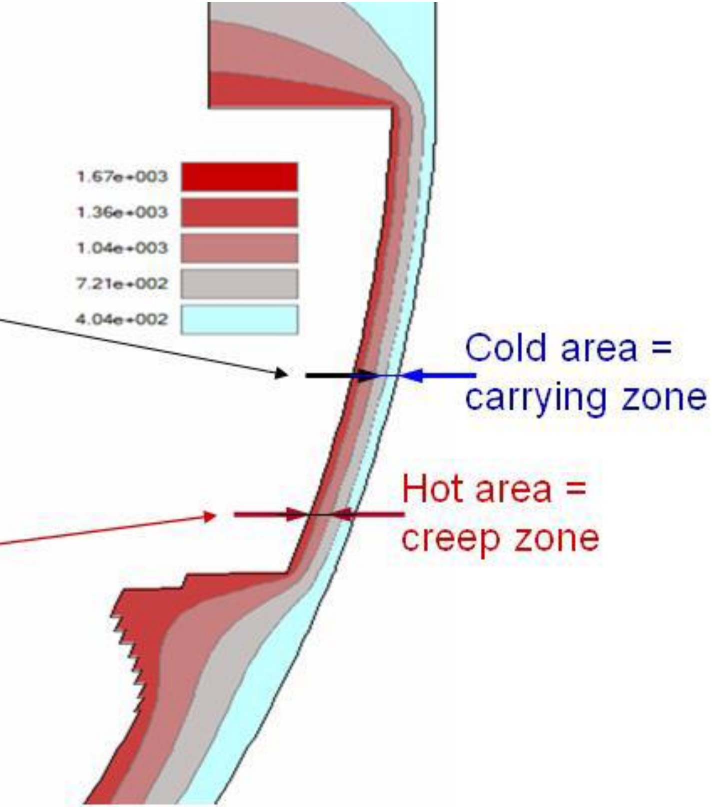


Figure 6: Temperature dependent Young's Modulus and yield stress and true ultimate stress as measured in tensile tests.



Cold area = carrying zone

Hot area = creep zone

Relations between both criteria K_δ and K_φ

- **A "critical mechanical heat flux"** $'\varphi_{fail}'$ may be defined
    - $\varphi_{fail} = \dfrac{k\Delta T_{fus}}{m\delta_{fail}}$
    - It may be interpreted as the heat flux for which, at steady-state, the vessel would fail mechanically, even if it is not completely ablated

  → $K_\delta \approx \varphi_{max}/\varphi_{fail}$

- **Integrity of the vessel requires to fulfill both criteria**

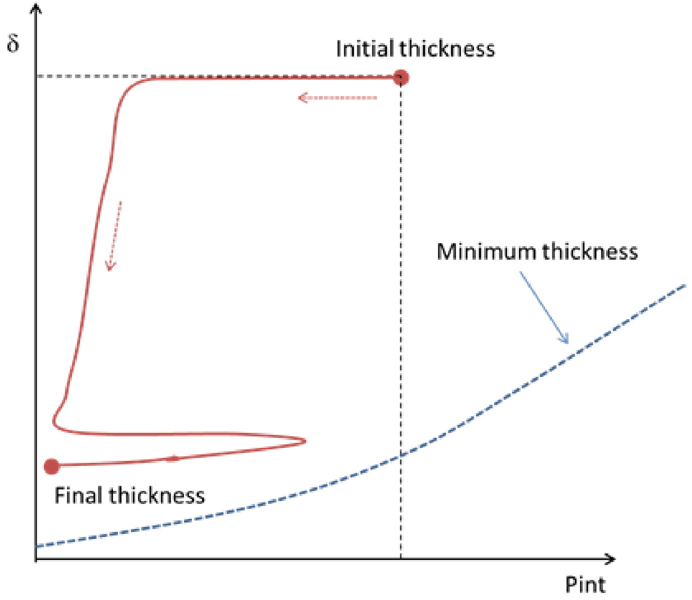
- φ_{fail} **includes the impact of** ΔP_{max} **whereas** φ_{CHF} **is independent of it**
    - $\varphi_{fail}(\Delta P_{max} = 1bar) \approx 4.5\ MW/m^2$ **with** $m = 10$
    - $\varphi_{fail}(\Delta P_{max} = 5bar) \approx 0.9\ MW/m^2$ **with** $m = 10$

A “best-estimate transient” methodology (1/2)

- Tabulation of minimum vessel thickness δ_{fail}
  - Function of vessel material
  - Function of internal load: $\delta_{fail} = f(P_{int})$
- Evaluation of internal loads as a function of time
  - Primary pressure
  - Corium weight
- Evaluation of “cumulated” wall ablation as a function of time → $\delta(\theta, t)$ for each angular position θ
  - Taking into account short peak transient heat flux
  - Taking into account variation of the angular position of maximum heat flux
- Check that $\delta(\theta, t) \gg m\delta_{fail}$
  - At any location θ along the vessel
  - At any time t

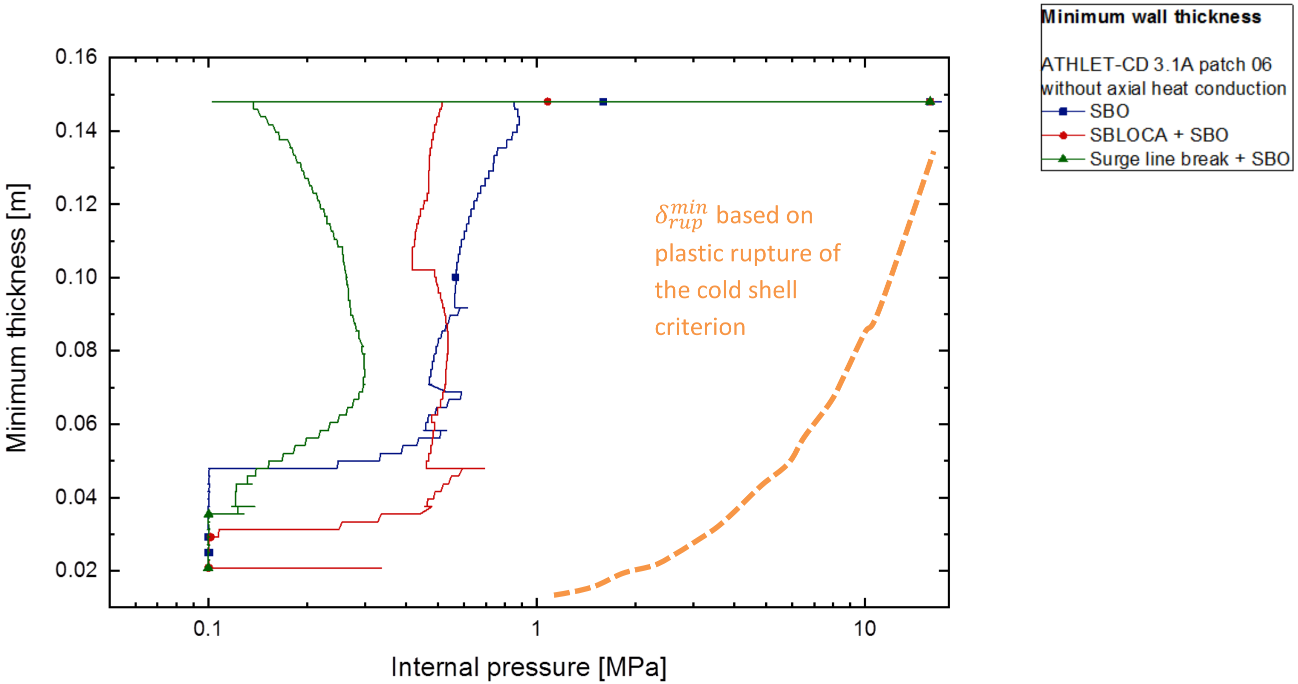
A “best-estimate transient” methodology (2/2)

Graphical illustration of the method



fast depressurization followed by a late pressure peak when significant ablation is reached

Illustration with a reactor case, for 3 scenarios



from HZDR results, Sangiorgi et al., 2019 (IVMR deliverable)

Conclusions (1/2)

- In order to be general and take into account both risks of mechanical failure and thermal melt-through, it is necessary to consider two safety criteria :
  - Based on the evaluation of two parameters φ_{max} and δ_{min}
  - Using 2 reference values φ_{CHF} and δ_{fail}
- This analysis may be done in the classical frame of steady-state “bounding case” approach → but may be non-conservative or inaccurate
- A straightforward and more accurate way to do this analysis is to use a “transient best-estimate” approach which calculates the progressive ablation of the vessel following the scenario evolution (pressure variations)

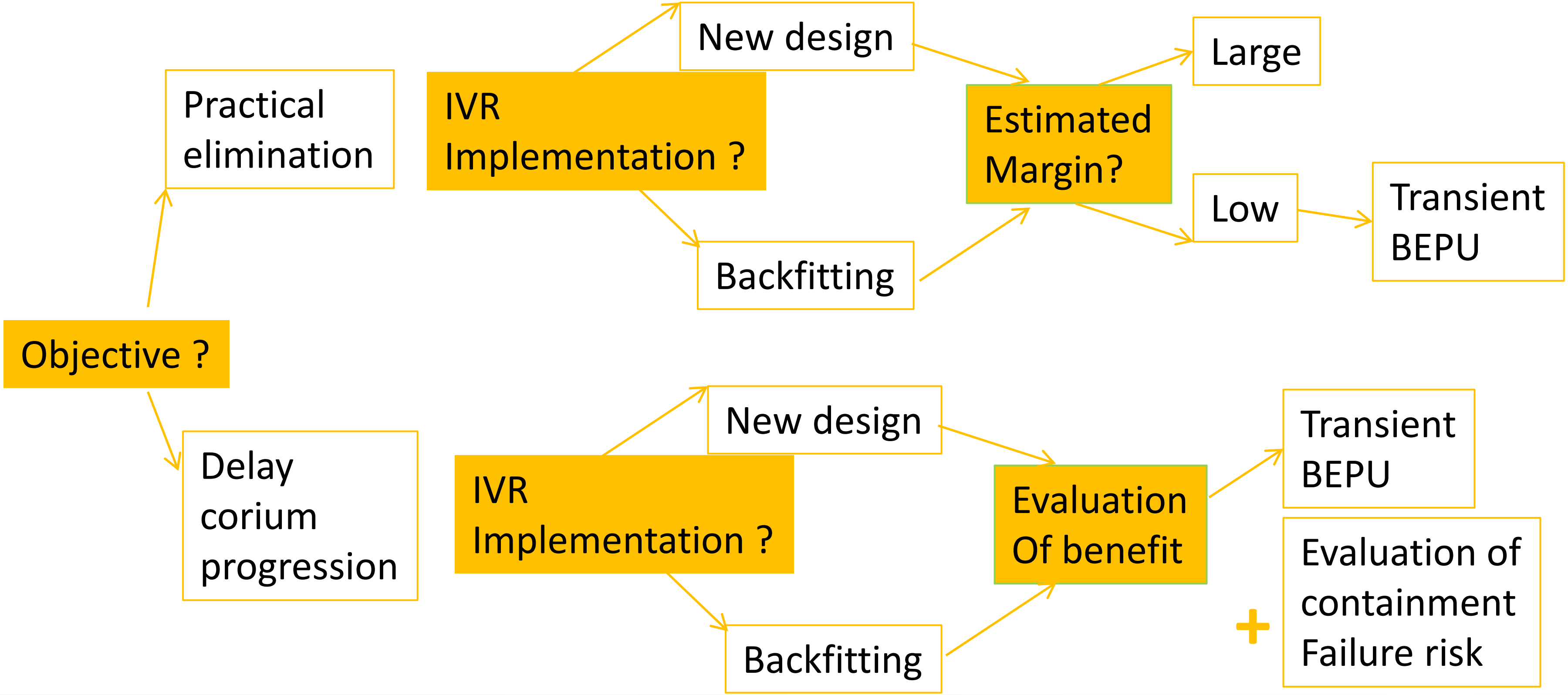
Conclusions (2/2)

- The selected methodology of IVR evaluation depends on:
  - The objective of IVR implementation (practical elimination of vessel failure or not)
  - The expected safety margin
- “Transient best-estimate” approach:
  - Is more accurate and gives a clearer picture of the situation
  - Is now possible with some SA codes (models are more mature)
  - Requires more detailed models and an associated uncertainty analysis (BEPU)

This work was funded by the IVMR grant agreement number 662157 (H2020)

Appendices

Choice of evaluation method



Objective ?

Practical elimination

IVR Implementation ?

New design

Backfitting

Estimated Margin?

Large

Low

Transient BEPU

Delay corium progression

IVR Implementation ?

New design

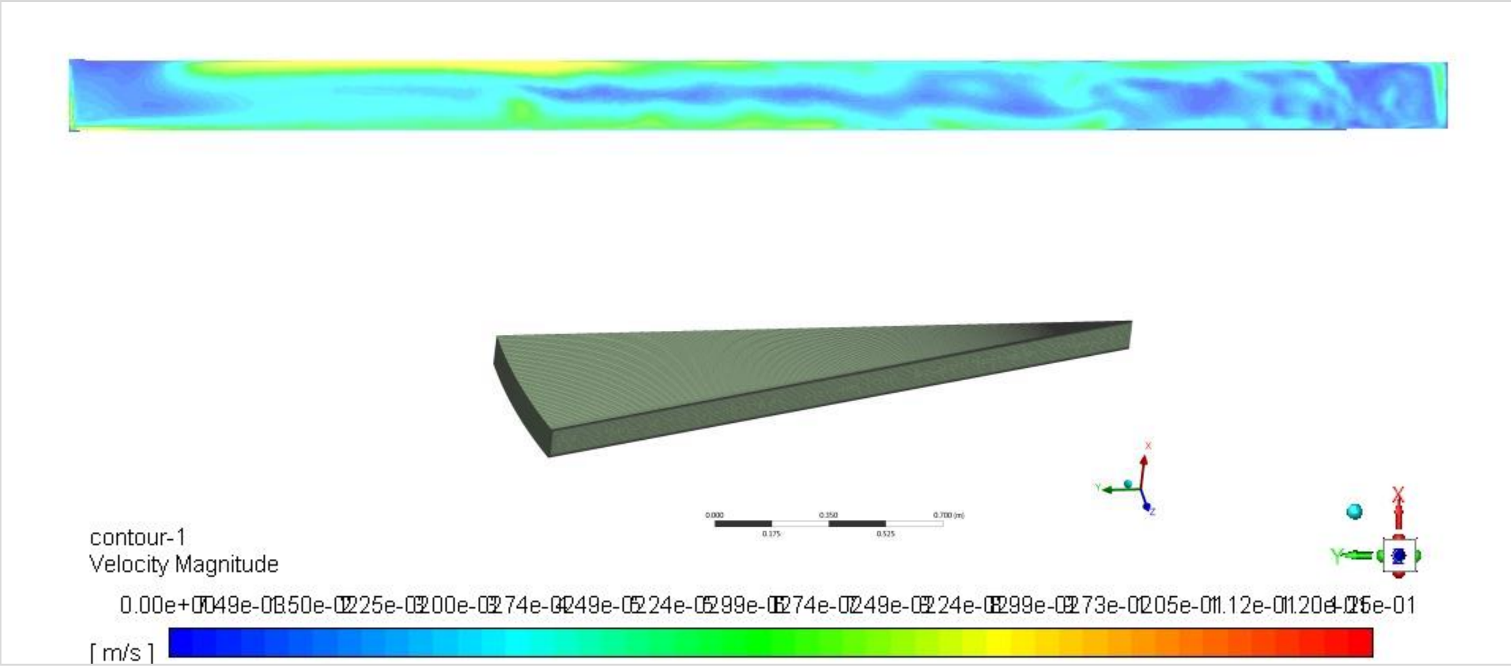
Backfitting

Evaluation Of benefit

Transient BEPU

+ Evaluation of containment Failure risk

Heat transfer in the top metal layer: CFD approach



From NBCJ calculations, WP2.3 of IVMR project

Relations between both criteria K_δ and K_φ

"critical mechanical heat flux" $'\varphi_{fail}'$

- $\varphi_{fail} = \dfrac{k\Delta T_{fus}}{m\delta_{fail}}$

$\rightarrow K_\delta = \dfrac{1}{\varphi_{fail}} \dfrac{k\Delta T_{fus}}{\delta_{min}} = \varphi_{max}/\varphi_{fail}$