RELAP5-3D two-phase behavior and predictions at low pressures

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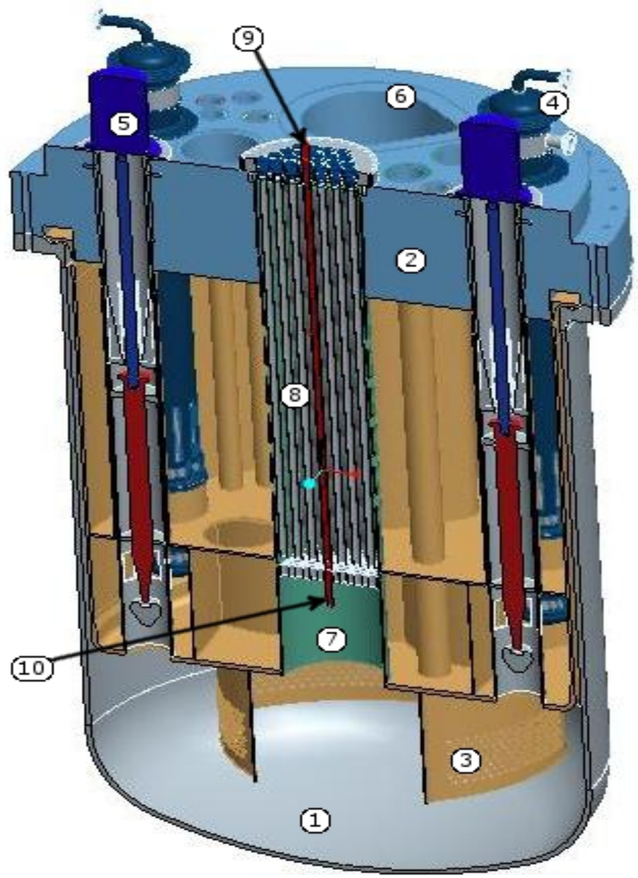
MYRRHA plant: purposes and general design

- MYRRHA: Multi-purpose hYbrid Research Reactor for High-tech Applications
- Pool-type Accelerator Driven System (ADS) with ability to operate also as critical reactor
- Liquid Lead-Bismuth Eutectic (LBE) as primary coolant
- Main purposes:
  - Flexible fast-spectrum irradiation facility
  - Minor Actinides (MAs) transmutation demonstrator
  - ADS demonstrator
  - GEN-IV European Technology Pilot Plant (ETPP) in the roadmap for Lead Fast Reactor (LFR)
- MYRRHA project recognized as high priority infrastructure for nuclear research in Europe

MYRRHA plant: Primary Cooling System

- MYRRHA primary system design current status:

- Completely enclosed in primary vessel (pool-type)
- Design power: 110 MW
- Primary LBE:
  - Lower plenum (270 °C)
  - Upper plenum (~325 °C)
- Cold plenum separated from hot plenum by Diaphragm supporting core barrel and components' penetrations
- Above LBE free surface: Nitrogen layer



Reactor vessel

Reactor cover

Diaphragm

4 Primary Heat Exchangers

2 Primary Pumps

In-Vessel Fuel Handling Machine

Core barrel

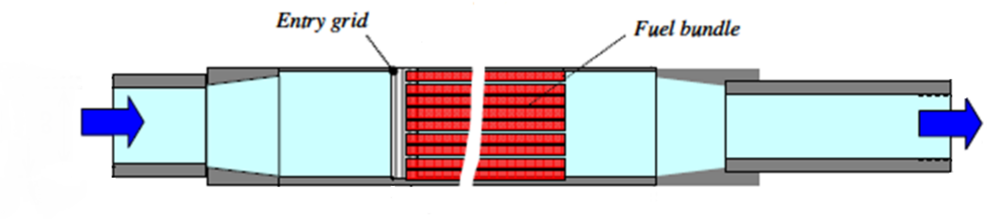
Above Core Structure

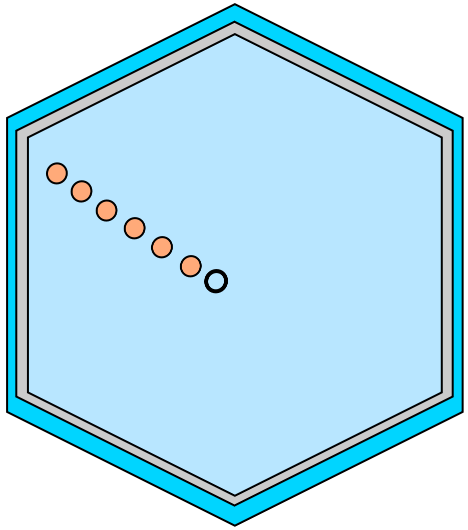
Core plug

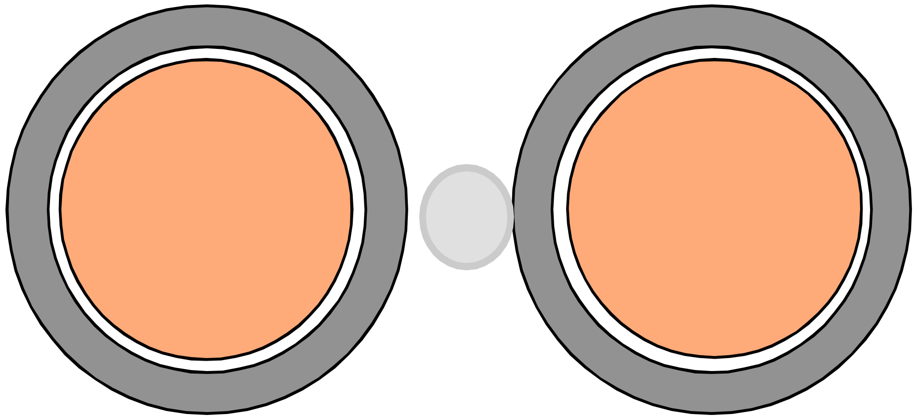
Spallation window

MYRRHA plant: Fuel Assembly

- MOX fuel, 30% wt. Pu
- Fuel pin with wire spacer in 15-15Ti
- 127 pins per Fuel Assembly
- External wrapper

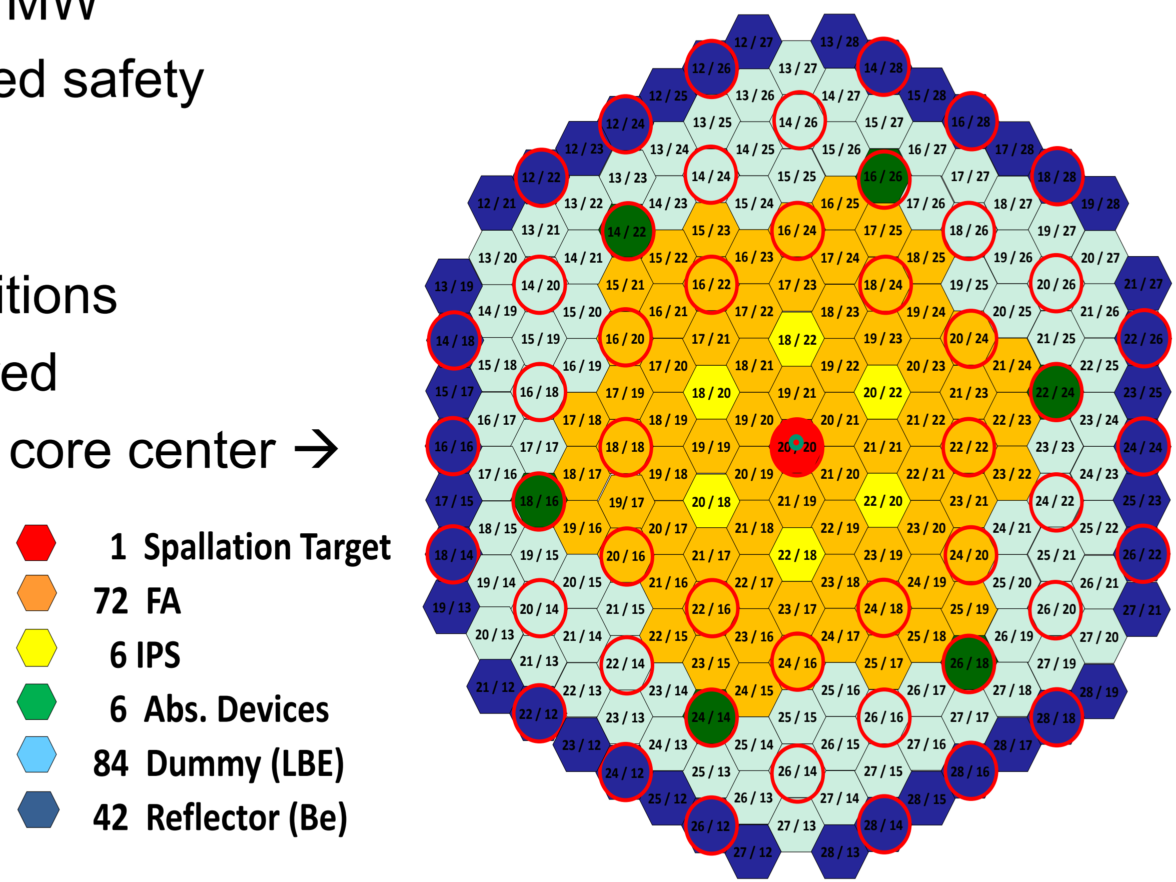






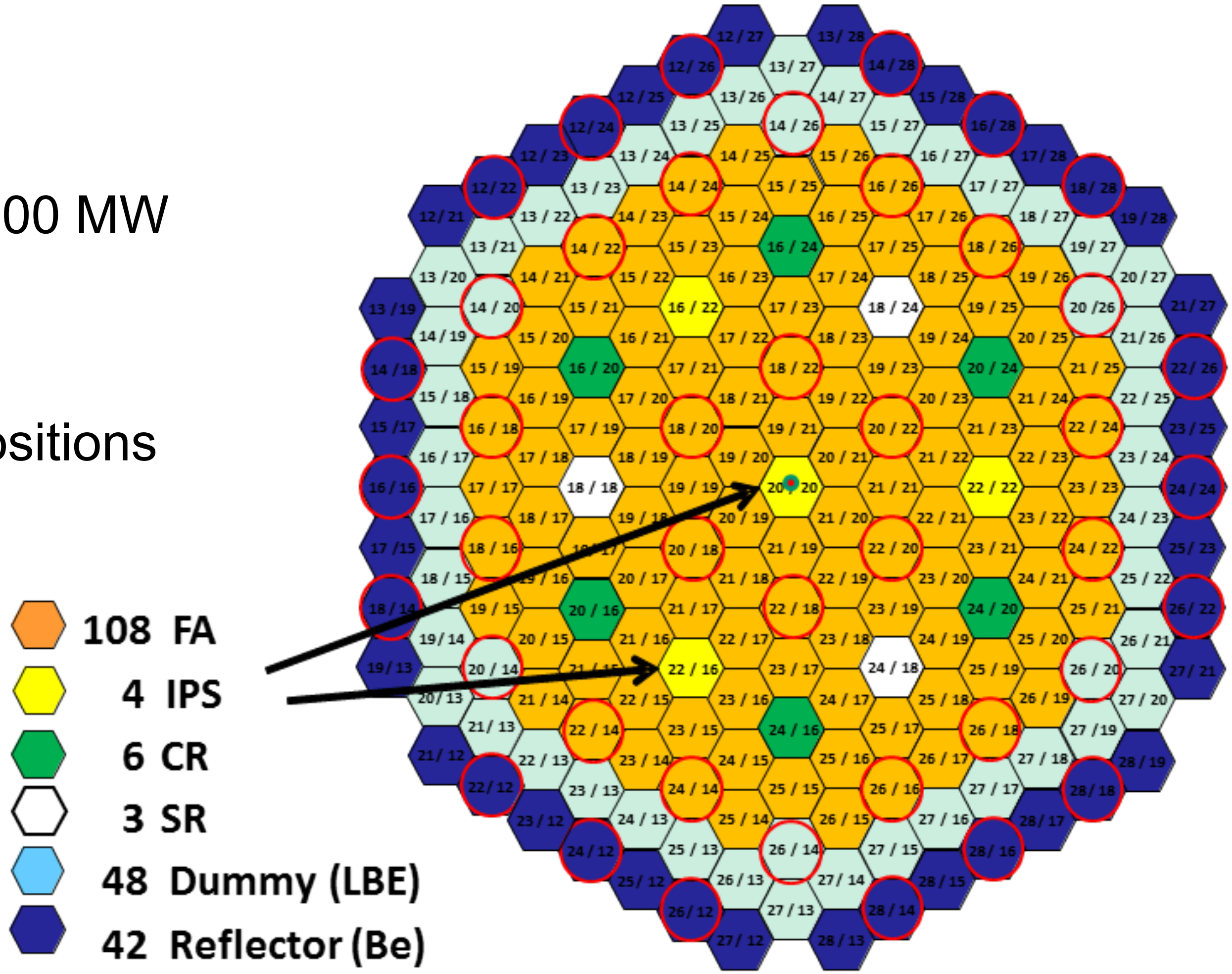
MYRRHA plant: Sub-Critical Core Layout

- Sub-critical core:
  - 72 FAs
  - Maximum Power: 75 MW
  - K_{eff} = 0.95 → improved safety characteristics
  - 6 Control Rods
  - 6 In-Pile Section positions
  - No safety rods required
  - High and hard flux in core center → MA transmutation



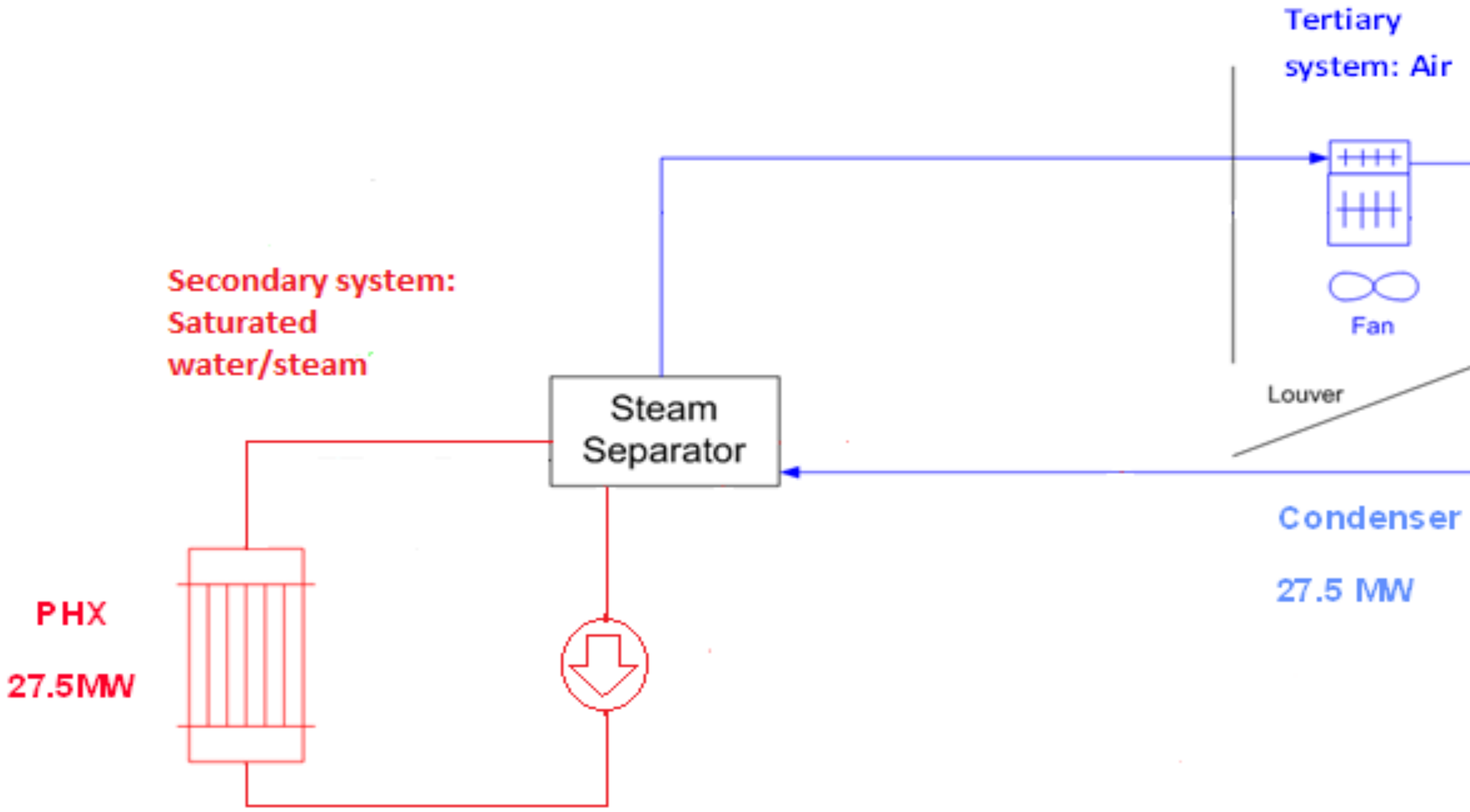
MYRRHA plant: Critical Core Layout

- Critical core:
  - 108 FAs
  - Maximum Power: 100 MW
  - 6 Control Rods
  - 3 Safety Rods
  - 4 In-Pile Section positions



MYRRHA plant: Secondary and Tertiary Cooling System

- MYRRHA secondary system (one loop out of four) conceptual diagram:

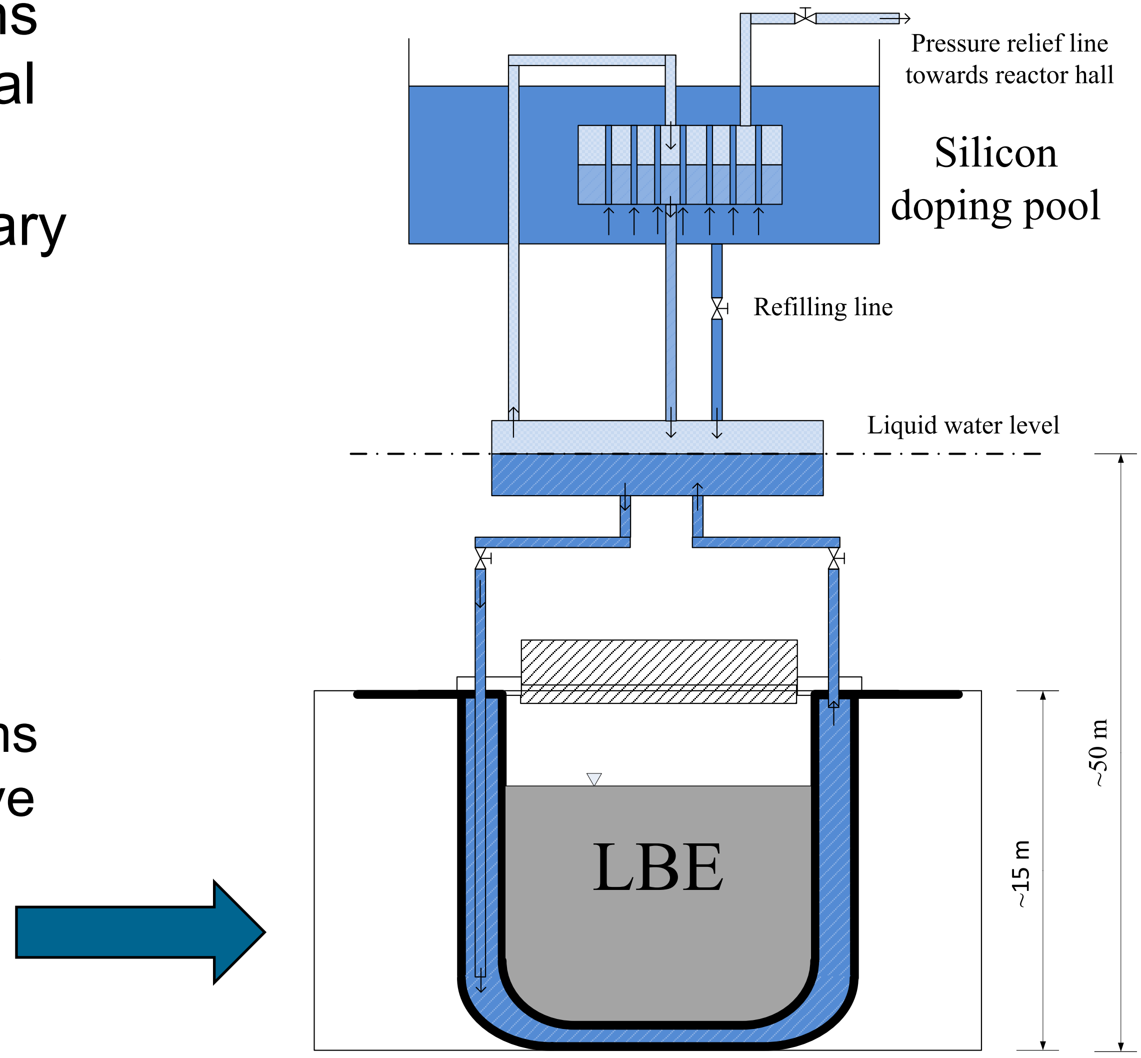


MYRRHA plant: Secondary and Tertiary Cooling System

- Secondary system:
  - Four independent secondary loops (linked through PHXs)
  - Operated with forced flow two-phase water mixture (16 bar, 200 °C)
  - Secondary water flow path:
    - PHX inlet (~saturated conditions)
    - PHX outlet ($x \sim 0.3$, $\alpha \sim 0.9$)
    - Moisture separated in steam drum
  - In normal operation, secondary water temperature kept constant by control system (primary LBE temperature changing as a function of core loading)
- Tertiary system: dissipating heat to external environment through air condensers (forced circulation air fans)
- Condensed steam recirculated into steam drum

MYRRHA plant: Decay Heat Removal

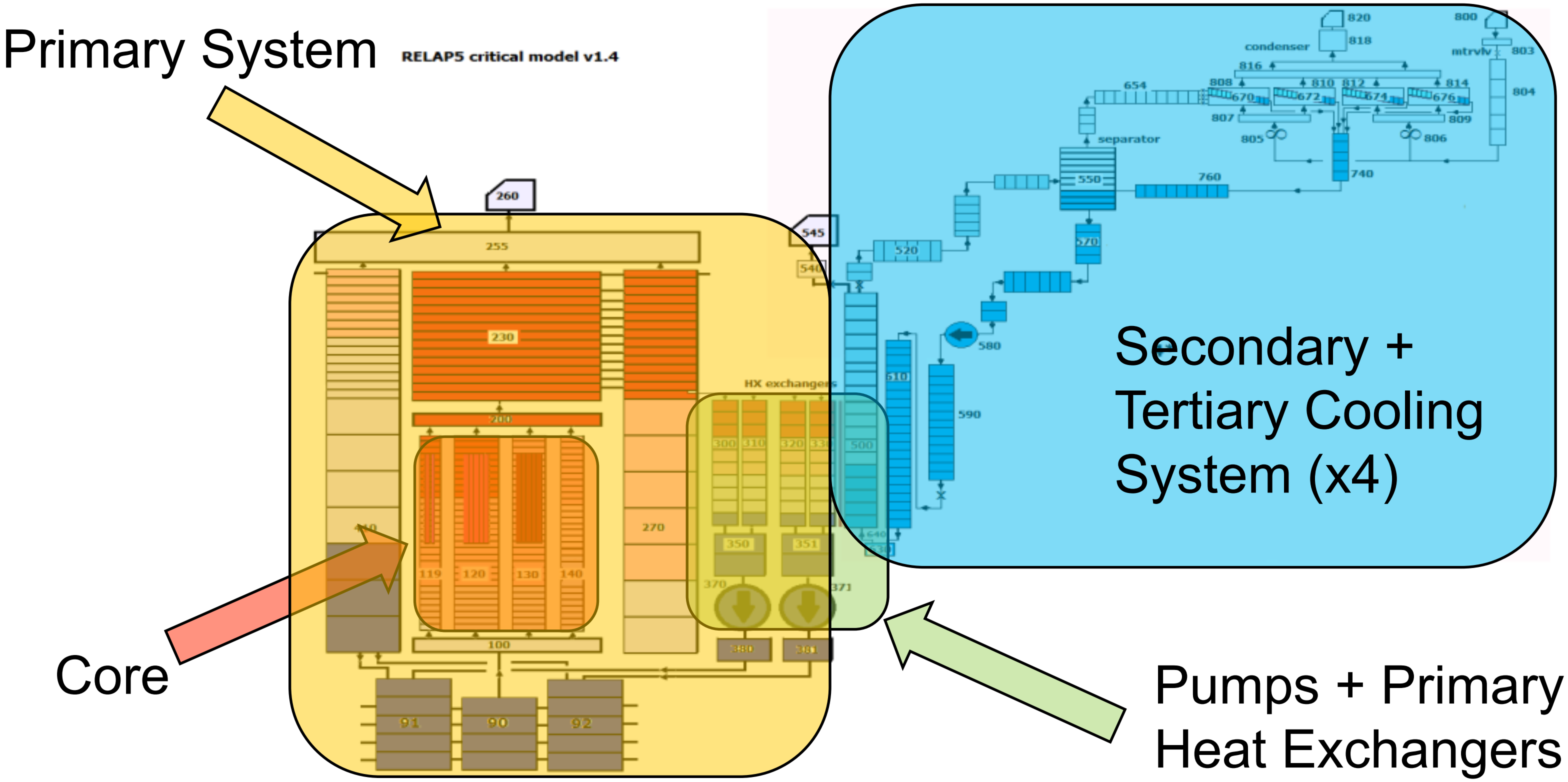
- Accidental conditions → DHR in full natural circulation (primary, secondary and tertiary able to operate in passive mode)
- Two systems to remove decay heat power:
  - DHR-1: secondary and tertiary systems operating in passive mode
  - DHR-2: Reactor Vessel Auxiliary Cooling System



MYRRHA safety analysis: FP projects participation

- Participation to several European FP projects in last decade:
  - FP6 IP-EUROTRANS, leading to finalization of MYRRHA/XT-ADS version of MYRRHA in June 2008
  - FP7 Central Design Team (CDT), defining MYRRHA/FASTEF version in March 2012
  - FP7 MAXSIMA (started in November 2012, ongoing), more focused on the MYRRHA safety analyses and component qualification
- European FP projects outcome partly used to define the latest version of MYRRHA design (currently in verification phase)
- Current version not definitive
  - MYRRHA design still evolving taking into account results from parallel R&D program

MYRRHA safety analysis: RELAP5-3D model



- RELAP5-3D MYRRHA plant model:
  - 2518 volumes, 2590 junctions
  - All cooling systems (primary, secondary, tertiary) simulated
  - Main control systems (Control Rods, secondary pressure) included

MYRRHA safety analysis: Steady State

- First step: steady state analysis
  - Main steady state results reported:

Parameter	Unit	RELAP5-3D value	Design value
Lower plenum temperature	°C	270.1	270
Upper plenum temperature	°C	322.9	325
Maximum core outlet temperature	°C	424.6	430.7
Primary flow rate	kg/s	13829	13800
Core flow rate	kg/s	7716	7711
Secondary water pressure	bar	16	16
Secondary water PHX inlet temperature	°C	198.2	200
Secondary water PHX outlet quality	-	0.30	0.3

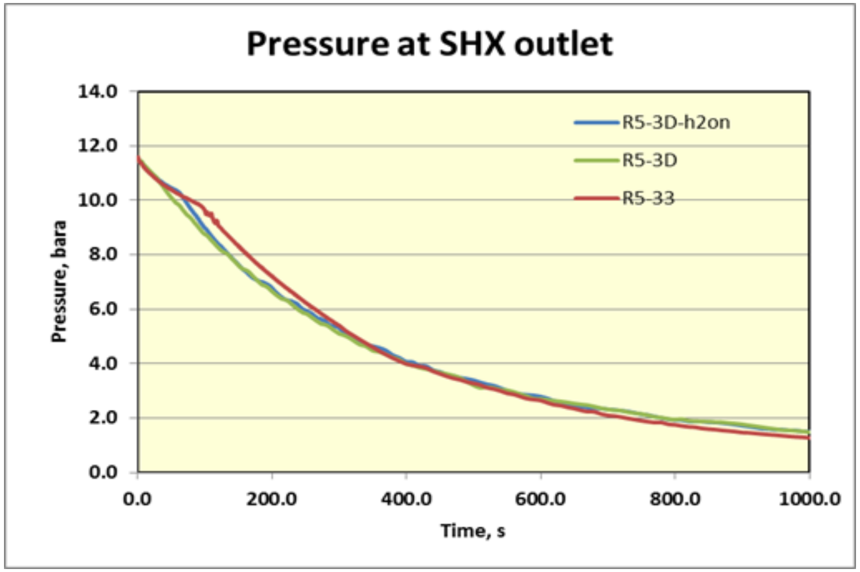
  - Very good agreement between code-calculated values and design values
    - Limited differences due to different LBE physical properties (mainly C_p)
  - Maximum clad temperature ~470 °C
  - Maximum fuel temperature ~1600 °C (low value due to low linear power ~110 W/cm)

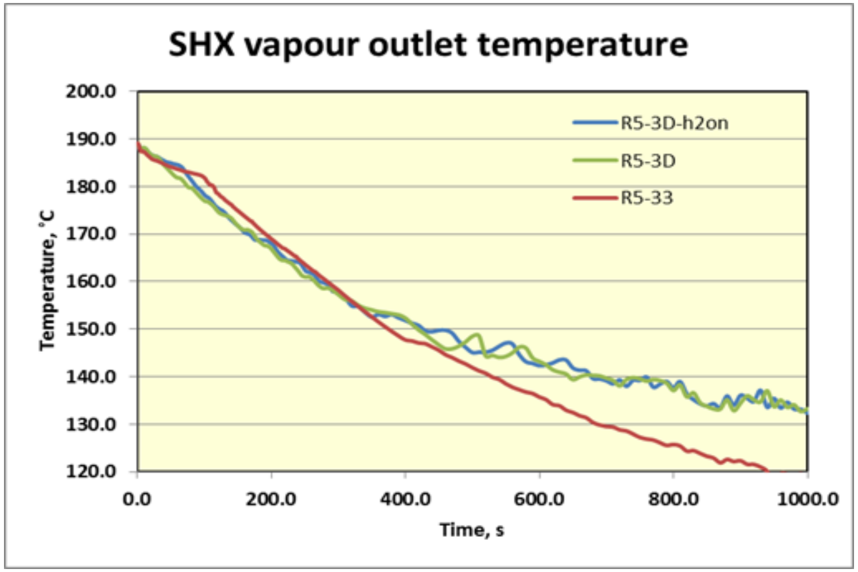
MYRRHA safety analysis: SCS depressurization transient

- Unbalance between power delivered by PHXs and removed by aero-condensers → SCS depressurization (16 bar → 1 bar and below)
- Overcooling transient:
  - 4 (out of 4) tertiary fans accidentally restarting at full speed with DH power level in the core
  - SCS depressurization
  - SCS feedwater pumps active
- Transient evaluation performed with RELAP5-3D and RELAP5/ Mod3.3

MYRRHA safety analysis: SCS depressurization transient

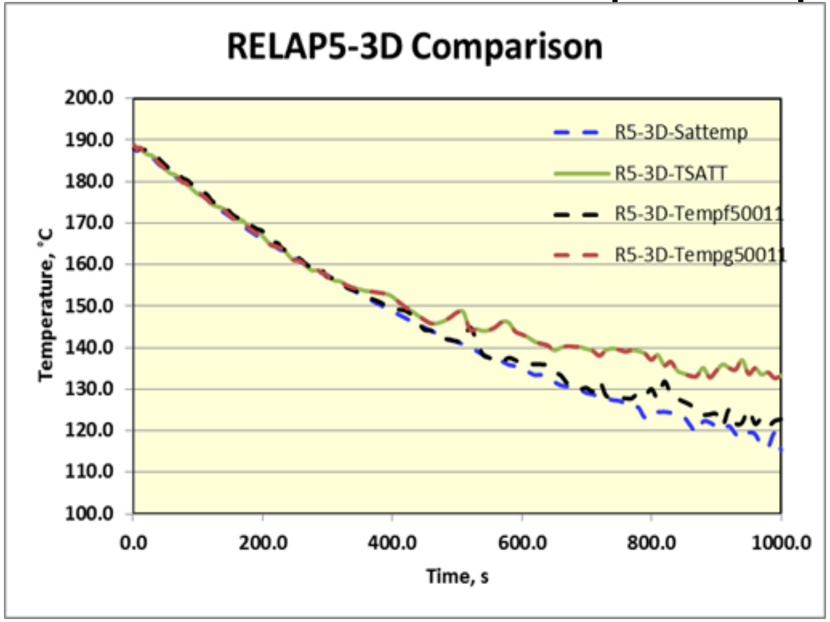
- Different transient evolution evaluation by the two codes:
  - Above 5 bar: ~same evaluation
  - Below 5 bar:
    - Nearly no differences in pressure evolution
    - Diverging liquid and vapor temperatures

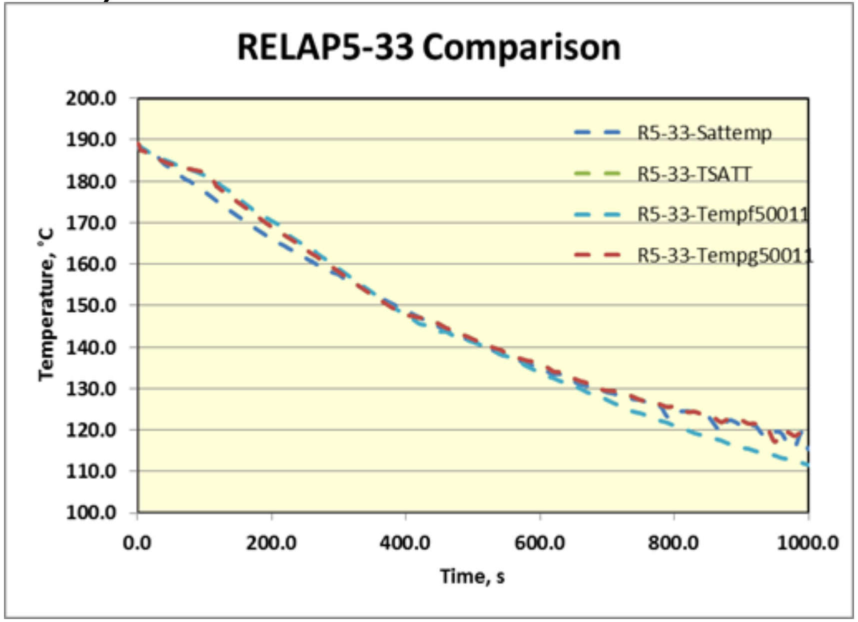




MYRRHA safety analysis: SCS depressurization transient

- Minor edit "sattemp" and "tsatt" plotted (supposed to coincide if no non-condensable species present) for both codes:



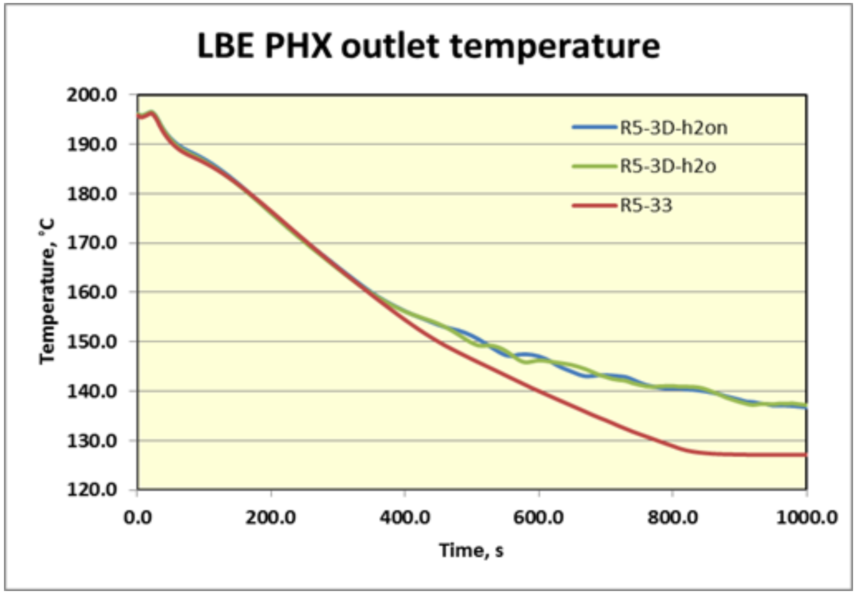


- Different trends for "sattemp" and "tsatt"
- "tsatt" provides same profile as vapor phase
- "sattemp“ lower than the liquid phase

- "sattemp" and "tsatt" profiles match
- "sattemp" and "tsatt" profiles ~equal to vapor phase
- Liquid phase lower than saturation temperature

MYRRHA safety analysis: SCS depressurization transient

- SCS temperature evolution important towards primary PbBi coolant freezing risk:

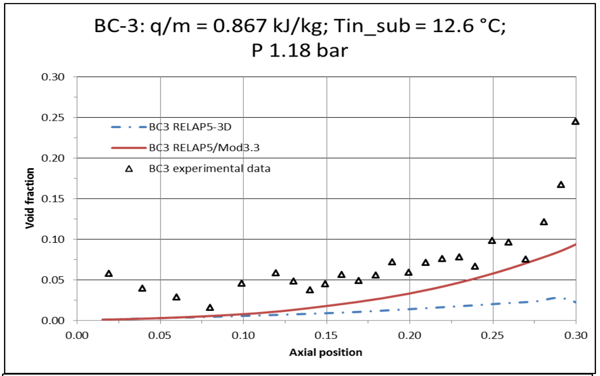


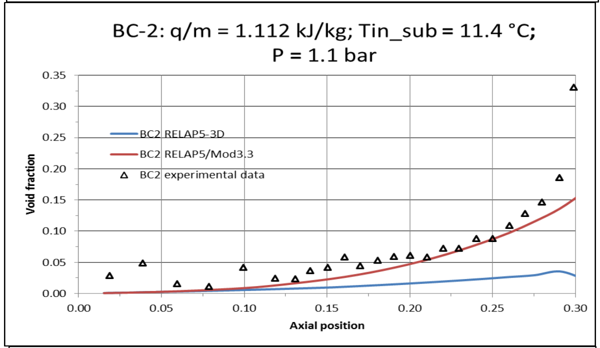
- RELAP5-3D and RELAP5/Mod3.3 predicts LBE freezing time of ~1600 s and ~800 s respectively. This difference can have a certain impact for the safety case.

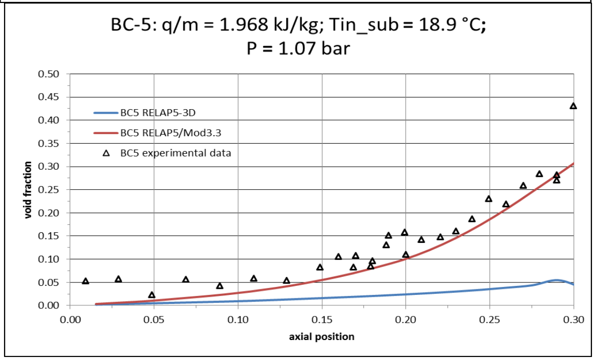
Experimental validation at low pressures: Zeitoun and Choukri

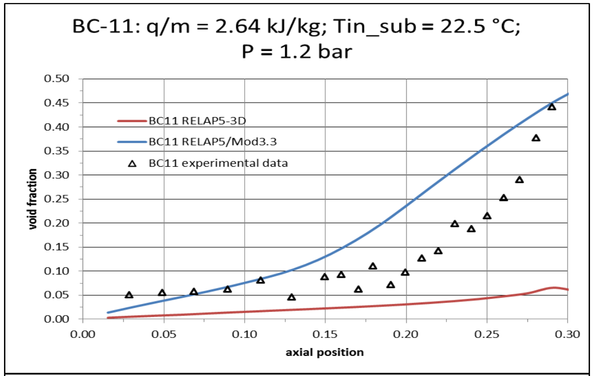
- Preliminary review of available benchmarks: Zeitoun and Choukri experiment:
  - Void generation in heated channel
  - Sensitivity parameters:
    - Pressure (1.07 bar - 1.56 bar)
    - Heat flux and mass flow rate (q/m: 0.867 kJ/kg – 2.64 kJ/kg)
    - Inlet subcooling temperature (11.4 °C – 23.5 °C)
- Experiments included in RELAP5/Mod3.3 Validation matrix (volume 3) but not in RELAP5-3D developmental assessment documents (volume 3)

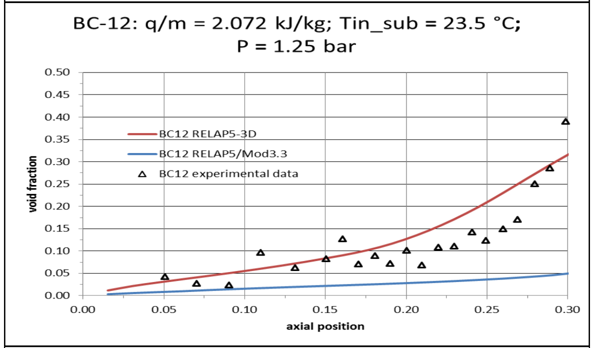
Experimental validation at low pressures: Zeitoun and Choukri

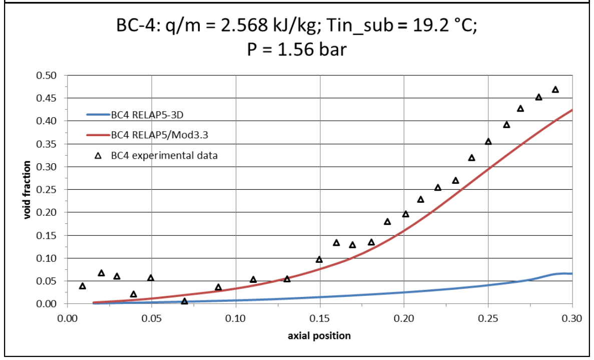












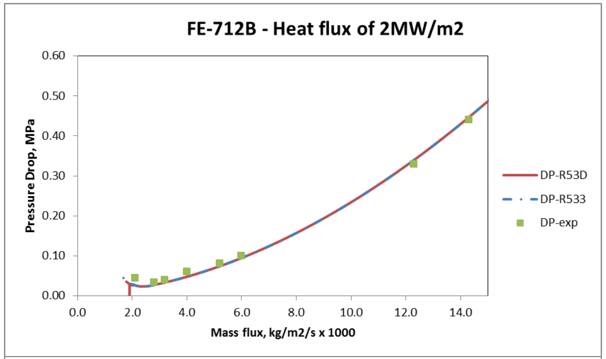
Experimental validation at low pressures: Zeitoun and Choukri

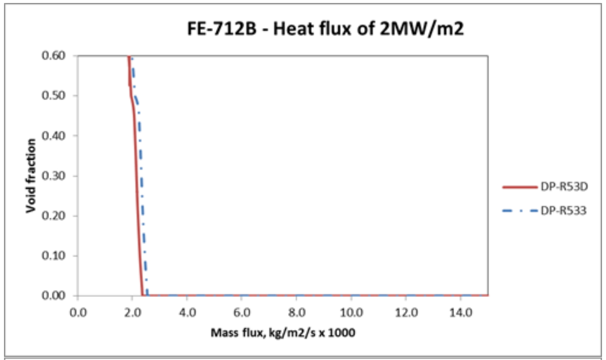
- RELAP5-3D predictions underestimated, especially for high q/m
- RELAP5-3D void fraction estimation quite less sensitive to experiments condition: void fraction prediction very limitedly affected by experimental boundary conditions
- Approaching the experimental channel top, RELAP5-3D predictions often present a maximum in the void fraction function (void fraction decreasing while channel is still heated)
- Other parameters such as wall temperature and water outlet temperature are in acceptable agreement
- Possible reason:
  - RELAP5-3D two-phase SNB model based on former RELAP5/Mod3.2 model (mainly based on high pressure subcooled boiling data)

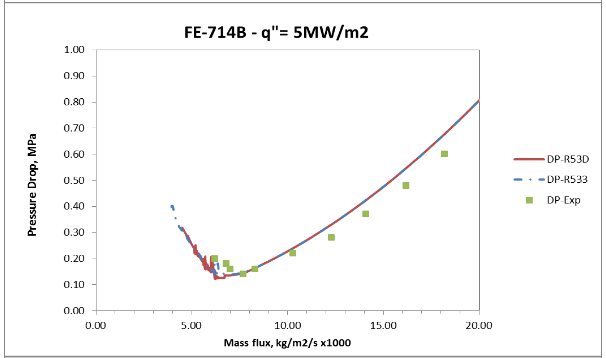
Experimental validation at low pressures: THTL

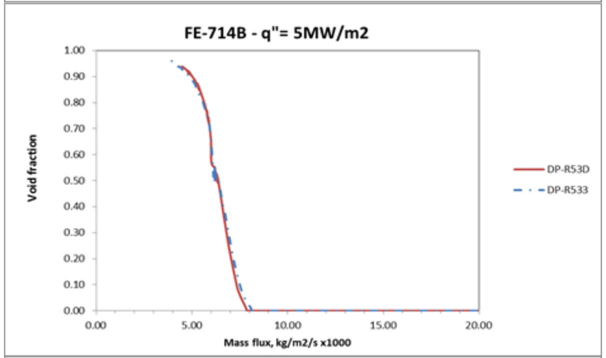
- Different experiment: Thermal-Hydraulic Test Loop
  - Void generation in heated channel
  - Experimental conditions:
    - Coolant: light water, upward flow
    - Inlet coolant temperature: 45°C
    - Outlet pressure: 1.7 MPa
    - Local heat flux range: 0.7–18 MW/m2
    - Corresponding exit velocity range: 2.8–28.4 m/s

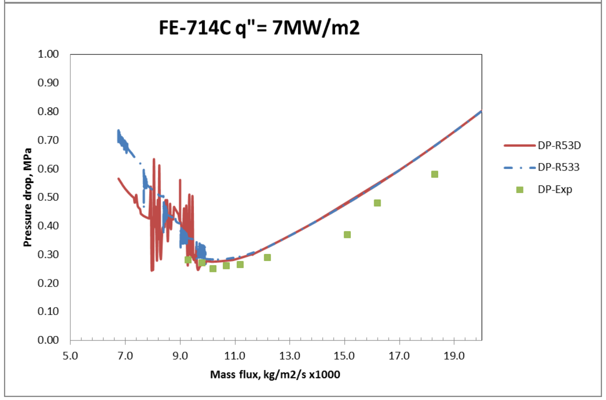
Experimental validation at low pressures: THTL

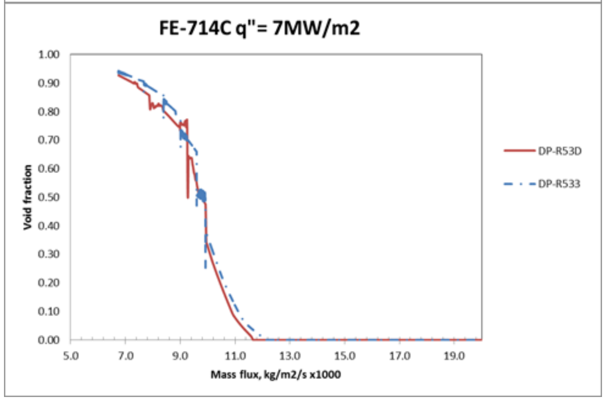












Experimental validation at low pressures: THTL

- Difference with respect to experimental data increases with applied heat flux
  - Above 8 MW/m^2: code simulation crashes with Onset of Fluw Instability
  - This behavior is common for both RELAP5-3D and RELAP5/Mod3.3 codes
- At higher pressure (similar to MYRRHA SCS normal operating conditions) there is no observed divergence between the two codes
- Void fraction plotted in function of mass flow rate shows also a good agreement between the two codes
  - Some disturbances only arising when operating at higher heat fluxes
- Two codes found in good agreement at a pressure of ~17 bar (~MYRRHA SCS operation)

Conclusions

- Several transients studied for MYRRHA reactor pre-licensing involve the depressurization of the Secondary Cooling System (SCS), cooled by low pressure two-phase water mixture
- RELAP5-3D overestimates, with respect to RELAP5/Mod3.3, the freezing time (~1600 s vs. ~800 s), with potential consequences on the LBE freezing conservative predictions. This is caused by the SCS temperature prediction between the two codes
- The code benchmarking for low pressure showed some shortcomings and limitations of RELAP5-3D subcooled model at low pressures
- Predictions of the two codes are found to be in good agreement with experiments at pressures above ~10 bar. In particular, experimental evidence proves the correct behavior at 17 bar.

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