Comparison of MYRRHA RELAP5 mod 3.3 and RELAP5-3D models on steady state and PLOF transient

Diego Castelliti
SCK•CEN

diego.castelliti@sckcen.be

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

IRUG 2013 Meeting
12-13 September 2013
INL – Idaho Falls

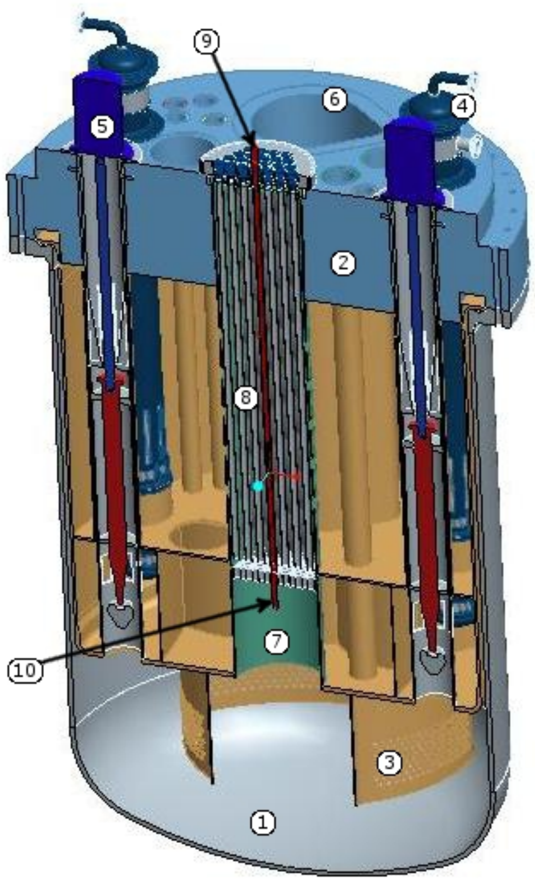
Contents

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 irradiation facility
  - Minor Actinides (MAs) transmutation demonstration in support of R&D on a "closed fuel cycle" (Generation IV requirement)
  - ADS demonstrator
  - Lead Fast Reactor demonstrator
  - (Pre-) Gen IV plant
- MYRRHA project recognized as high priority infrastructure for nuclear research in Europe

MYRRHA plant: purposes and general design

- MYRRHA primary system design state of the art (developed in FP7 Central Design Team project):



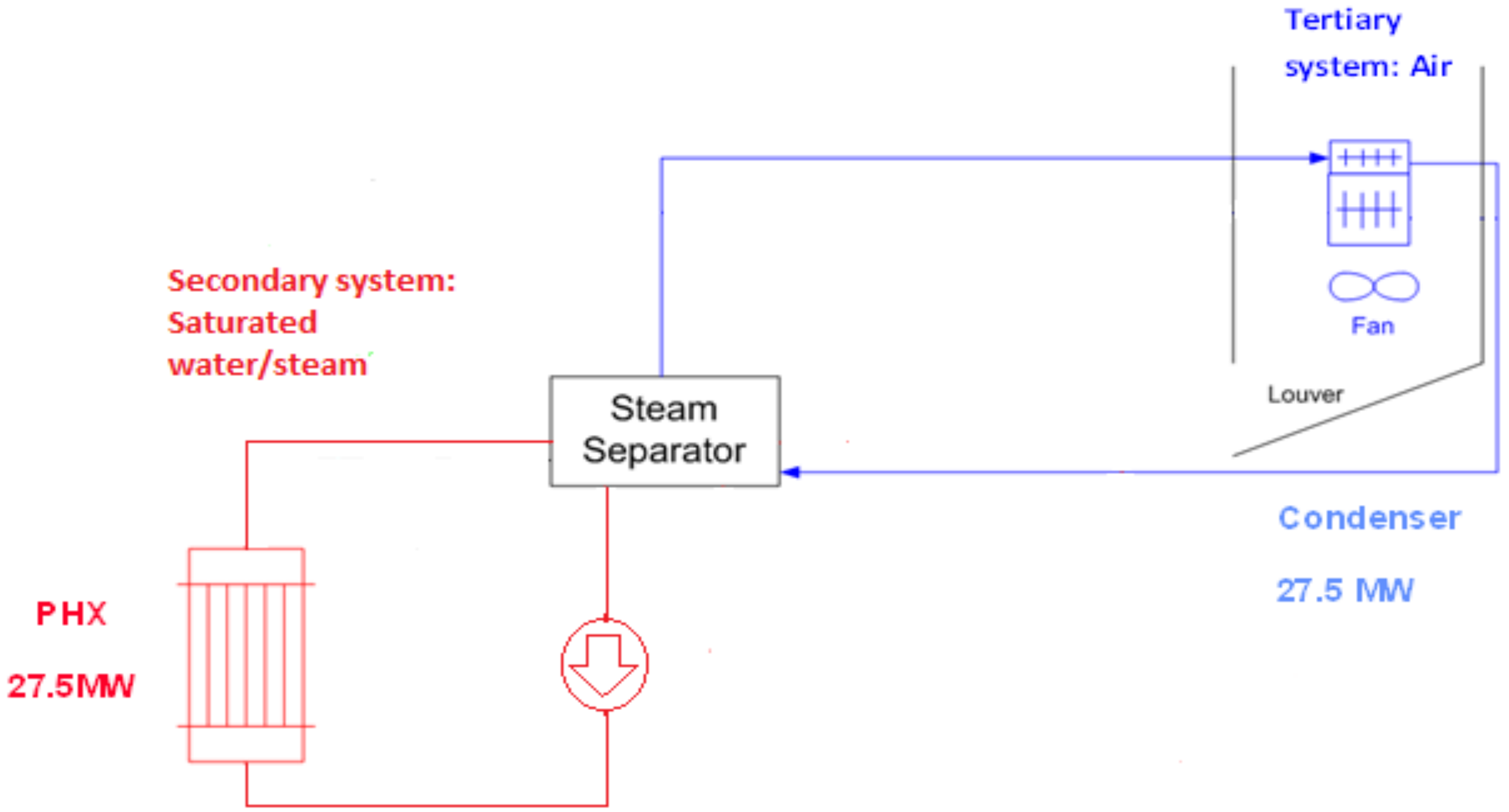
1. Reactor vessel
2. Reactor cover
3. Diaphragm
4. Primary heat exchanger
5. Pump
6. In-Vessel Fuel Handling Machine
7. Core barrel
8. Above Core Structure
9. Core plug
10. Spallation window

MYRRHA plant: purposes and general design

- Primary system:
  - Completely enclosed in primary system (pool-type)
  - Primary LBE flow path:
    - Lower plenum (270 °C)
    - Core (100 MW)
    - Upper plenum (~350 °C)
    - 4 Primary Heat eXchanger (PHX) units
    - 2 Primary Pumps (PPs)
    - Lower plenum
  - Cold plenum separated from hot plenum by Diaphragm supporting core barrel and components' penetrations
  - Above LBE free surface: Argon layer

MYRRHA plant: purposes and general design

- MYRRHA secondary system (single loop) design state of the art (developed in FP7 Central Design Team project):



MYRRHA plant: purposes and general design

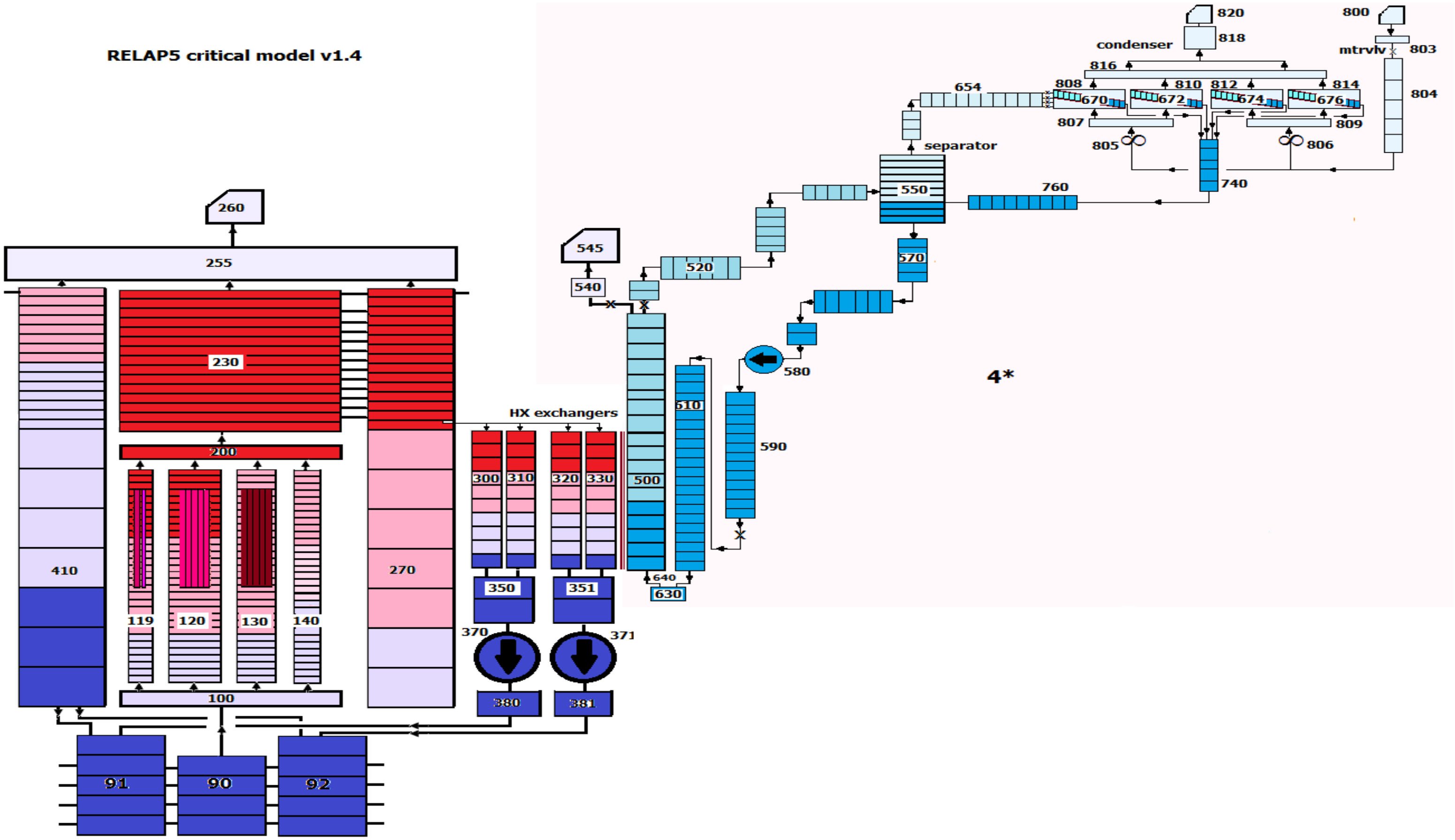
- Secondary system:
  - Four independent secondary loops (linked through PHXs)
  - Operated with forced flow two-phase water mixture (16 bar, 200 °C)
  - Secondary water flow path:
    - PHX inlet (~saturated conditions)
    - PHX outlet ($x \sim 0.3$, $\alpha \sim 0.9$)
    - Moisture separated in steam drum:
      - Steam: towards air condenser (one per secondary loop)
      - Liquid: recirculated to PHX inlet
  - In normal operation, secondary water temperature kept constant by control system (primary LBE temperature changing in 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: purposes and general design

- MYRRHA plant designed for 110 MW as nominal power:
  - 100 MW → core power
  - 10 MW → additional heat sources:
    - In Vessel Storage Tank (IVST)
    - Pump power
    - Po decay heat
    - γ heating
    - Spallation target power
- Normal operation → all three systems designed to operate in forced circulation
- Accidental conditions → DHR in full natural circulation (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 (RVACS)

MYRRHA RELAP5 model description

- RELAP5 mod 3.3 model for MYRRHA steady-state and transient simulations (schematic representation):

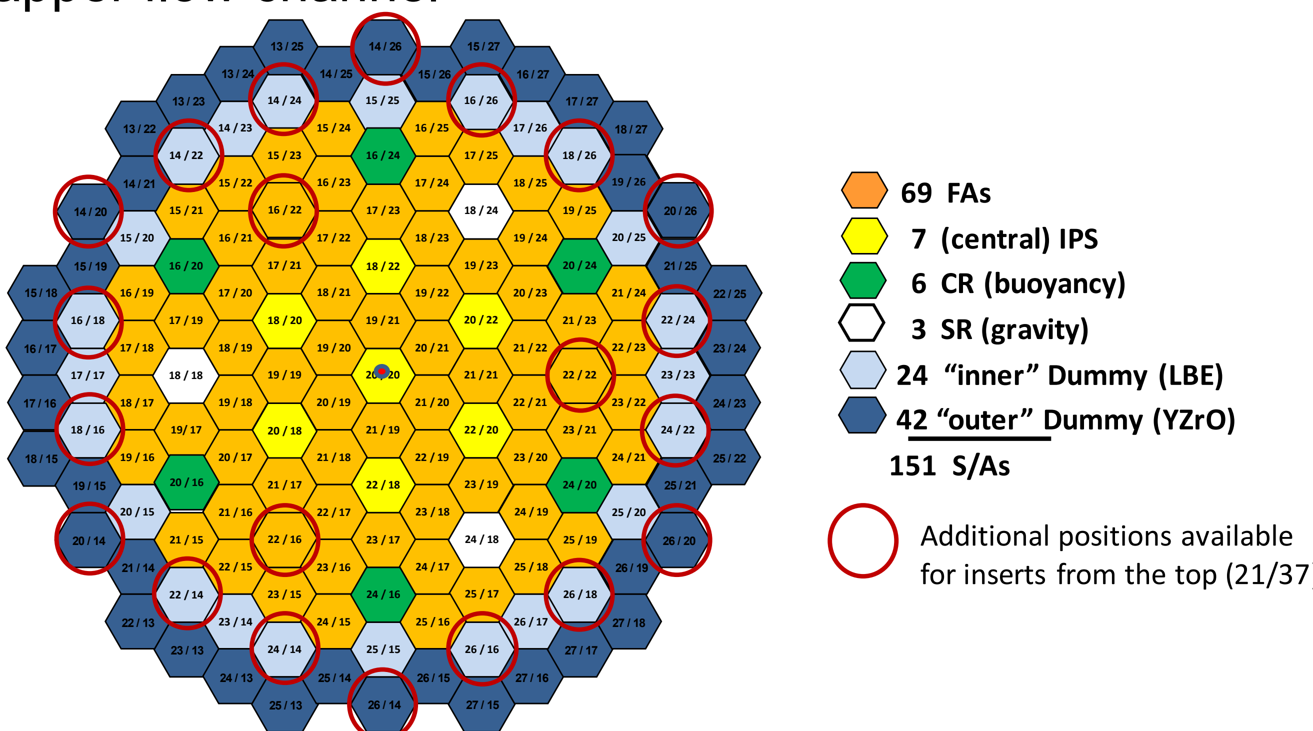


MYRRHA RELAP5 model description

- Original RELAP5 mod 3.3 not including LBE as working fluid → version used for simulation modified by ENEA, Ansaldo Nucleare and University of Pisa (Italy) to allow use of LBE:
  - LBE physical properties
  - HLM heat transfer correlations
- Model built according to latest design specifications, with full simulation of primary, secondary, tertiary and RVACS system:
  - 2551 volumes
  - 2609 junctions
- All circuits able to operate in forced and natural circulation
- Extended use of cross-flow junctions in primary pool for better simulation of 3-D velocity and temperature fields in plena
- Preliminary regulation linking tertiary fan velocity to steam pressure in steam drum to maintain constant pressure (16 bar)

MYRRHA RELAP5 model description

- Core modelled with 4 hydraulic channels:
  - Hot channel
  - Average channel (simulating 68 FA)
  - Dummy channel (simulating 24 inner dummy + 48 outer dummy)
  - Inter-wrapper flow channel



MYRRHA RELAP5 model description

- Heat structures has been used to simulate:
  - Core fuel pins
  - PHX tube bundles
  - Air condenser tube bundles
  - Core barrel
  - Diaphragm
  - Reactor vessel
- 10 MW from additional heat sources generated into core dummy channels
- RELAP5 model confronted against:
  - Validation matrix proposed for qualification of T-H codes nodalizations
  - Results obtained by FP7-CDT project participants using RELAP5, TRACE

RELAP5 mod 3.3 vs. RELAP5-3D

- Model used for Framework Programme European projects developed with RELAP5 mod 3.3 code version (LBE properties inserted by third party)
- MYRRHA licensing process → RELAP5-3D v 4.0.3 acquired by SCK•CEN for:
  - Full 3-D TH and NK capabilities
  - LBE official working fluid
- First step: running of latest version of MYRRHA model input deck on RELAP5-3D → RELAP5 mod 3.3 output difference comparison
- Comparison performed in Steady State and Protected Loss Of Flow (PLOF) conditions
- No NK module used for this comparative study

RELAP5 mod 3.3 vs. RELAP5-3D: Steady State

- Main steady state parameters from two code versions:

Parameter	Unit	RELAP5 mod 3.3 value	RELAP5-3D value
Thermal power	MW	110	110
LBE total mass	kg	3086190	2957260
Hot channel mass flow rate	kg/s	71.57	70.15
Active core mass flow rate	kg/s	4926	4827
Total mass flow rate	kg/s	9578	9427
PHX LBE mass flow rate	kg/s	2394	2356
Core inlet temperature	°C	273.6	263.7
Core hot channel outlet temperature	°C	477.4	467.3
Core average channel outlet temperature	°C	410.4	400.5
Core hot channel clad temperature	°C	498.9	501.2
Core average channel clad temperature	°C	425.3	423.7
Core hot channel fuel temperature	°C	2059	2067.3
Core average channel fuel temperature	°C	1851.2	1853.5
ΔT clad-bulk hot channel	°C	21.5	33.9
ΔT clad-bulk average channel	°C	14.9	23.2
Core average ΔT	°C	136.8	136.8
Upper plenum temperature (above core)	°C	351.4	341.1
Plena ΔT	°C	77.8	77.4
Hot plenum level	m	4.84468	4.41477
Core total Δp (friction+gravity)	Pa	4.70E+05	4.66E+05
Pump head	Pa	2.35E+05	2.38E+05
Pump torque	Nm	2692.3	2679.2
PHX water mass flow rate	kg/s	48.9	48.9
PHX water inlet pressure	Pa	1.78E+06	1.78E+06
PHX water inlet temperature	°C	201.6	201.6
PHX water outlet temperature	°C	205.7	205.7
PHX water exit quality	-	0.28	0.28
PHX water exit void fraction	-	0.89	0.89

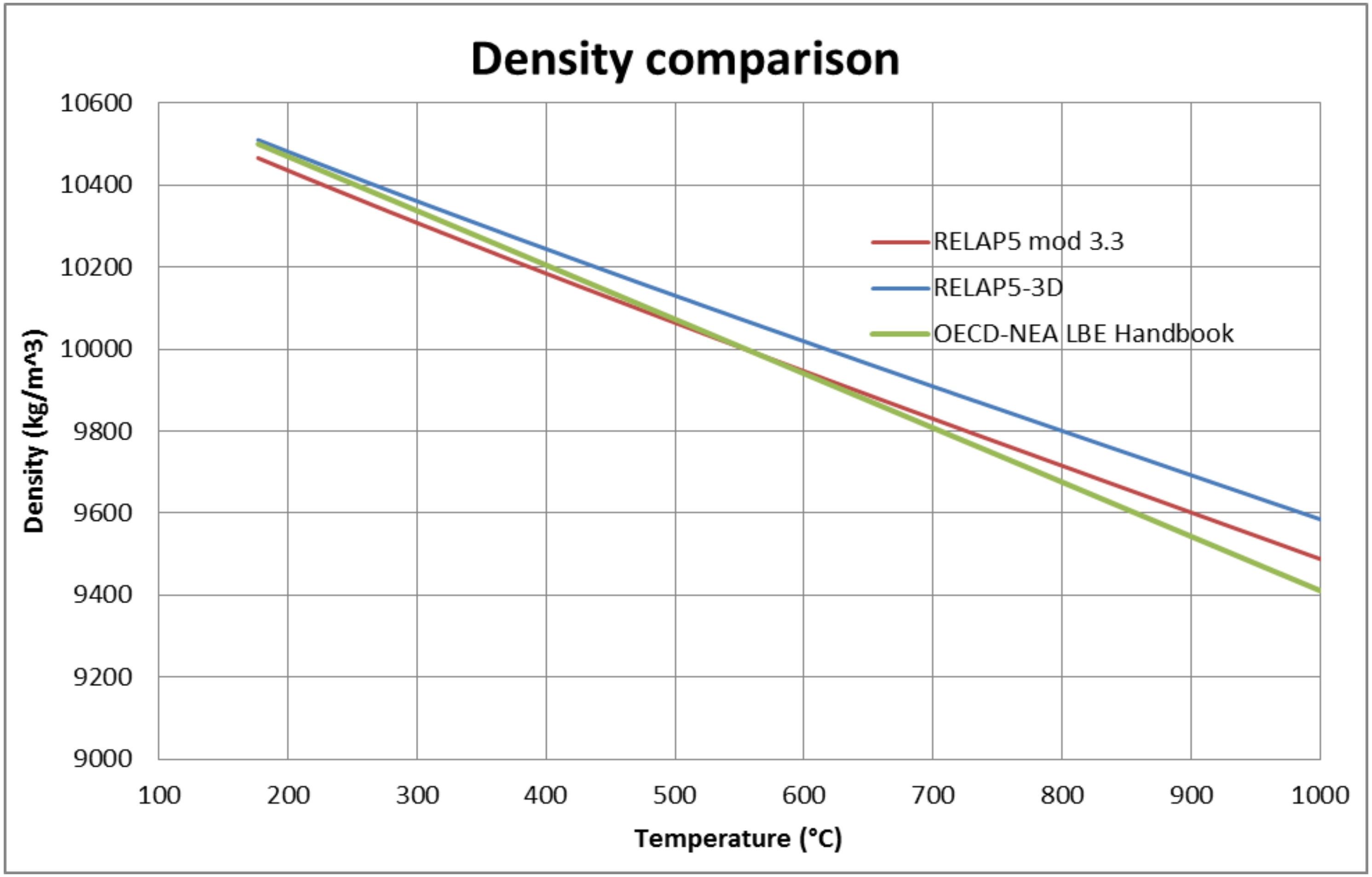
RELAP5 mod 3.3 vs. RELAP5-3D: Steady State

- Different physical models used
- Main differences:
  - Total mass
  - Mass flow rate
  - Temperature distribution
- Differences mainly located into primary pool
- Great similarity in secondary two-phase water loops behavior
- Comparison studies focused on:
  - LBE physical properties
  - Non-condensable gases input
  - LBE Heat Transfer Coefficient (HTC) correlations

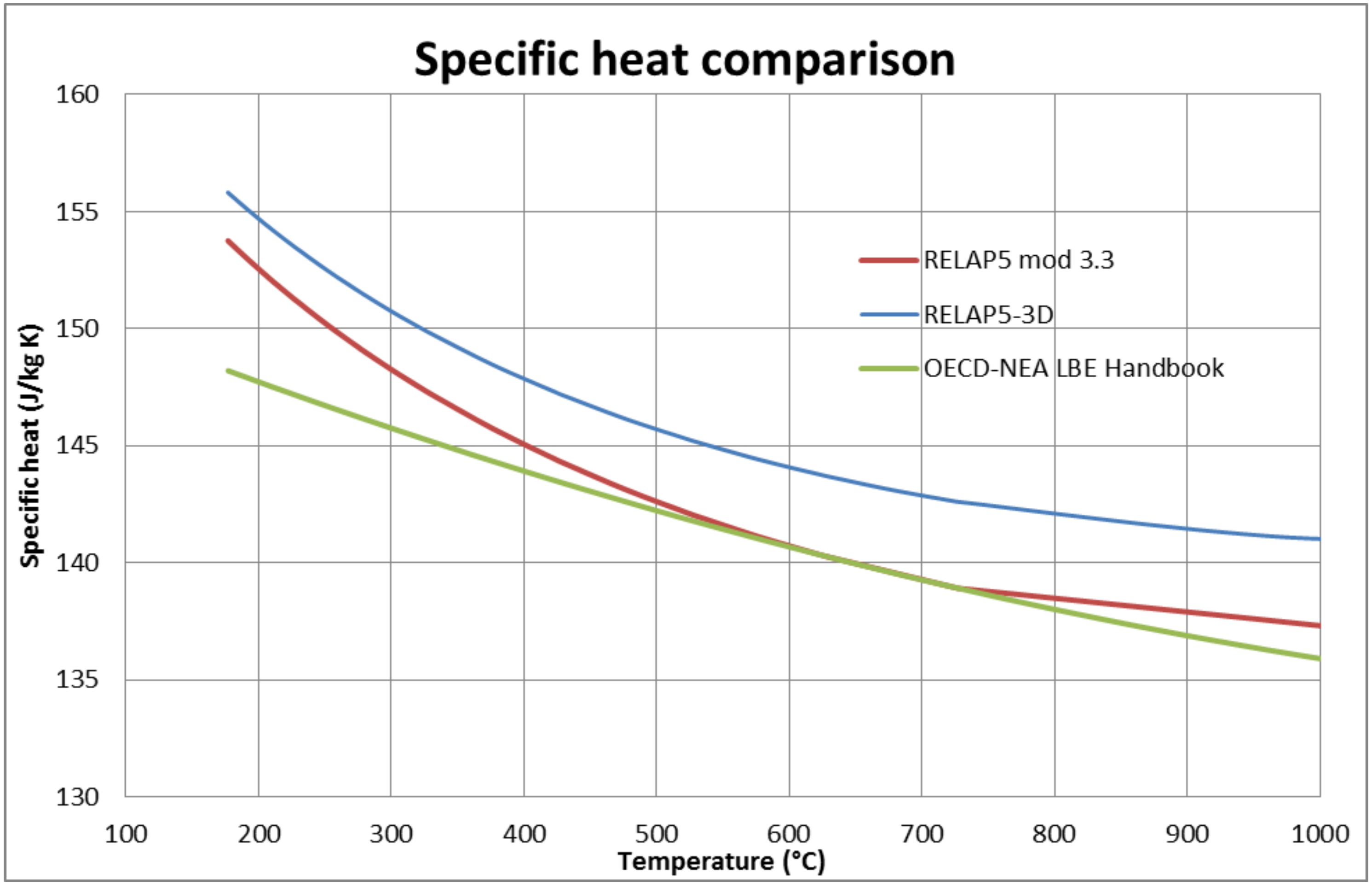
RELAP5 mod 3.3 vs. RELAP5-3D: Physical properties

- Most notable differences in LBE physical properties comparison:
  - LBE density
  - LBE specific heat
- Density:
  - Discrepancies between RELAP5 mod 3.3 and RELAP5-3D at temperature values close to MYRRHA working condition: ~0.5%
- Specific heat:
  - Discrepancies between RELAP5 mod 3.3 and RELAP5-3D at temperature values close to MYRRHA working condition: ~2% (increasing at higher temperatures)

RELAP5 mod 3.3 vs. RELAP5-3D: Physical properties



RELAP5 mod 3.3 vs. RELAP5-3D: Physical properties



RELAP5 mod 3.3 vs. RELAP5-3D: Non-condensable input

- Difference found in output → Total LBE mass in the primary system:
  - 3086190 kg in RELAP5 mod 3.3
  - 2957260 kg in RELAP5-3D
  - Difference = 128930 kg (4.3%)
- Density difference not enough to justify this variation (-4.3% vs. +0.5%)
- Output and problem initialization analysis proven how:
  - Non-condensable gas quality “x” initialized to 1 (volume filled with 100% gas) by RELAP5-3D in all volumes marked with flag "t=4“ on control word determining initial thermodynamic state
  - Full gas initialization regardless of actual non-condensable mass quality specified in input deck
- Code version initial mass difference explained

RELAP5 mod 3.3 vs. RELAP5-3D: Non-condensable input

- For more valuable further version comparisons → mass controller addition to stabilize LBE mass to desired value
- Steady state results thus modified as follows:

Parameter	Unit	RELAP5 mod 3.3 value	RELAP5-3D revised value	RELAP5-3D value
Thermal power	MW	110	110	110
LBE total mass	kg	3086190	3086150	2957260
Hot channel mass flow rate	kg/s	71.57	71.36	70.15
Active core mass flow rate	kg/s	4926	4911	4827
Total mass flow rate	kg/s	9578	9585	9427
PHX LBE mass flow rate	kg/s	2394	2396	2356
Core inlet temperature	°C	273.6	263.8	263.7
Core hot channel outlet temperature	°C	477.4	463.9	467.3
Core average channel outlet temperature	°C	410.4	398.2	400.5
Core hot channel clad temperature	°C	498.9	497.6	501.2
Core average channel clad temperature	°C	425.3	421.3	423.7
Core hot channel fuel temperature	°C	2059	2064.9	2067.3
Core average channel fuel temperature	°C	1851.2	1851.9	1853.5
ΔT clad-bulk hot channel	°C	21.5	33.7	33.9
ΔT clad-bulk average channel	°C	14.9	23.1	23.2
Core average ΔT	°C	136.8	134.4	136.8
Upper plenum temperature (above core)	°C	351.4	340	341.1
Plena ΔT	°C	77.8	76.2	77.4
Free surfaces level difference	m	2.088	2.102	2.127
Core total Δp (friction+gravity)	Pa	4.70E+05	4.73E+05	4.66E+05
Pump head	Pa	2.35E+05	2.37E+05	2.38E+05
Pump torque	Nm	2692.3	2699.8	2679.2

RELAP5 mod 3.3 vs. RELAP5-3D: LBE HTC correlations

- Temperatures show still considerable differences
- HTC correlations analysis required
- HTC correlations used by both code versions for vertical tube bundles:
  - RELAP5 mod 3.3: Ushakov correlation

    $$\mathrm{Nu} = 7.55\,\frac{p}{d} - 20.0\left(\frac{p}{d}\right)^{-13} + 0.041\left(\frac{p}{d}\right)^{-2}(\mathrm{Pe})^{0.56+0.19\frac{p}{d}}$$

    - Validity range: 1.0 < P/D < 2.0; 1 < Pé < 4000
  - RELAP5-3D: Kazimi-Carelli correlation

    $$\mathrm{Nu} = 4.0 + 0.33\left(\frac{p}{d}\right)^{3.8}\left(\frac{\mathrm{Pe}}{100}\right)^{0.86} + 0.16\left(\frac{p}{d}\right)^{5}$$

    - Validity range: 1.1 < P/D < 1.4; 10 < Pé < 5000

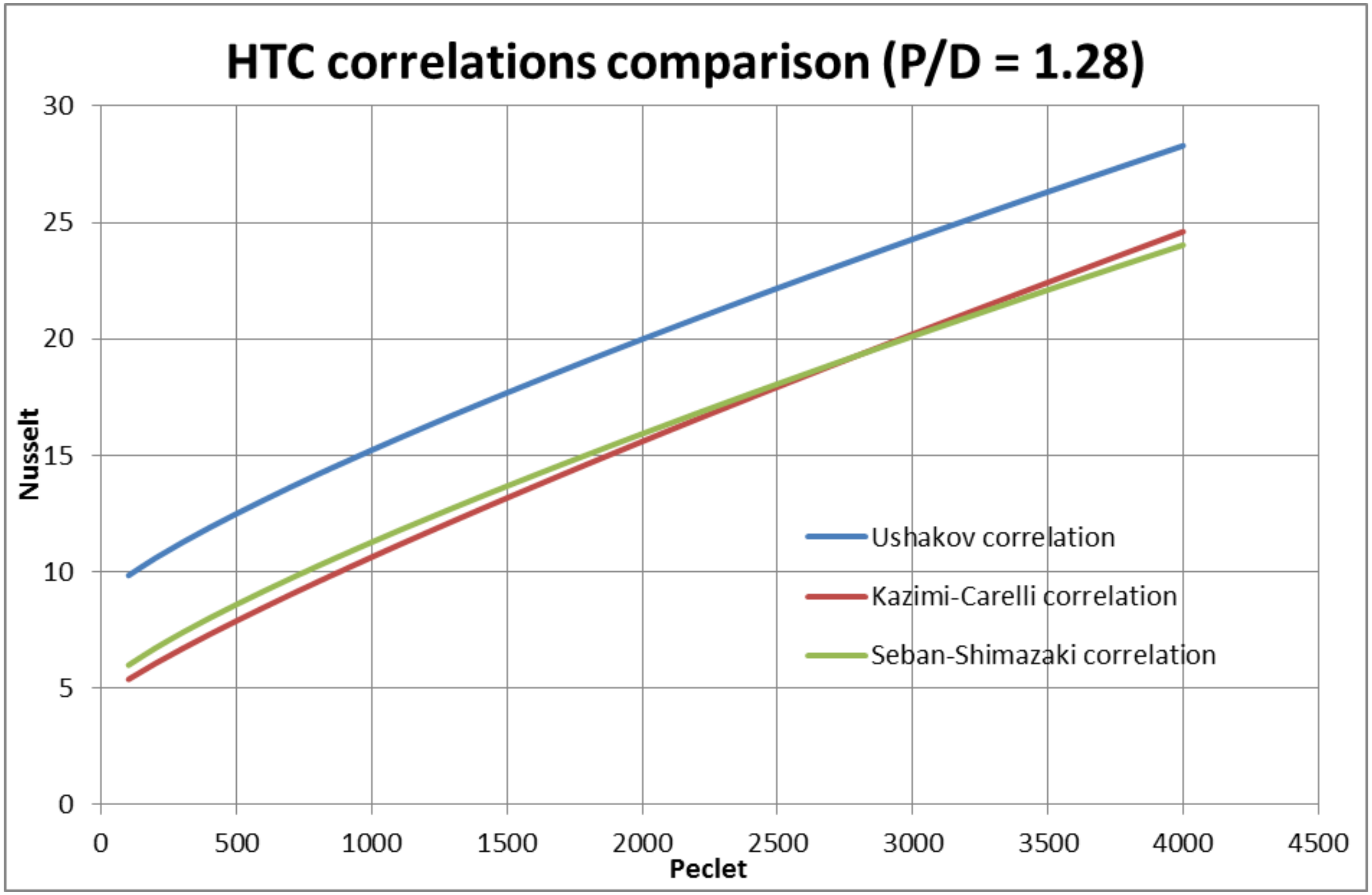
RELAP5 mod 3.3 vs. RELAP5-3D: LBE HTC correlations

- HTC correlation for plates and tubes (same for both code versions):
  - Seban-Shimazaki correlation:

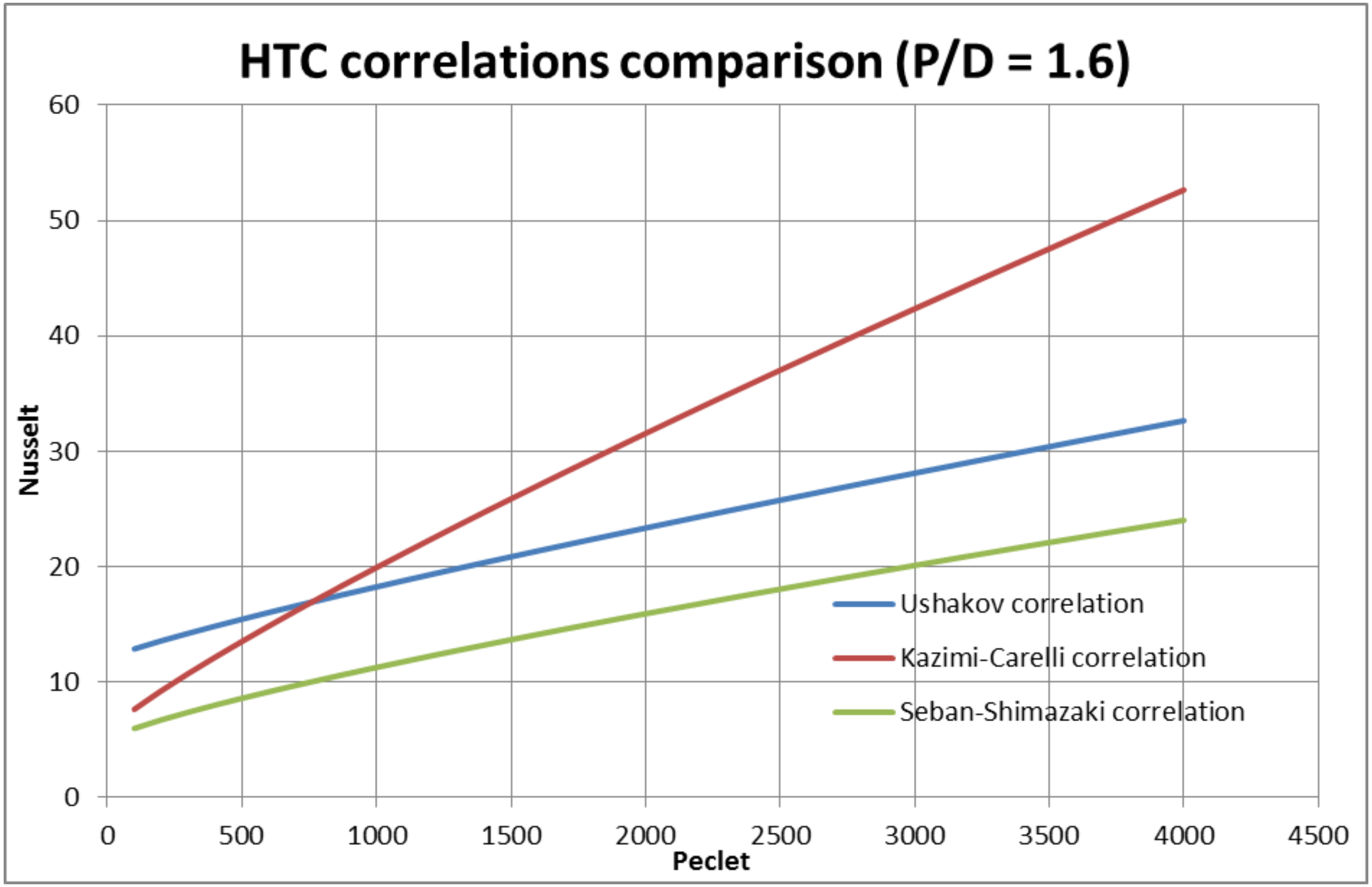
$$Nu = 5.0 + 0.025\, Pe^{0.8}$$

    - Validity range: $0 < Pr < 0.1$; $10^4 < Re < 5*10^6$
- Comparison between the three correlations in function of the variation of Pé number assuming two different P/D value (corresponding to core and PHX values) has been made

RELAP5 mod 3.3 vs. RELAP5-3D: LBE HTC correlations



RELAP5 mod 3.3 vs. RELAP5-3D: LBE HTC correlations



RELAP5 mod 3.3 vs. RELAP5-3D: LBE HTC correlations

- Conclusion from bundle HTC correlation comparison:
  - P/D = 1.28 (core Pé = 845):
    - Ushakov correlation provides higher Nu values over whole range
    - Kazimi-Carelli correlation ~ Seban-Shimazaki correlation
  - P/D = 1.6 (PHX Pé = 3100):
    - Ushakov correlation provides higher Nu values for Pé < 800
    - Kazimi-Carelli provides higher Nu values for Pé > 800
- HTC correlations comparison explained results previously found:
  - RELAP5-3D found lower primary system temperature (~10 °C) because of higher PHX efficiency → lower ΔT_{LM} between the two fluids (secondary water temperature kept constant by control system)
  - Clad temperature ~same because of "compensation effect" between lower heat transfer in core and higher heat transfer in PHX

RELAP5 mod 3.3 vs. RELAP5-3D: LBE HTC correlations

- Kazimi-Carelli correlation application range does not match the PHX ($P/D = 1.6$, range: $1.1 < P/D < 1.4$) → PHX efficiency overestimated
- Current RELAP5-3D version incomplete for MYRRHA plant analysis and model validation

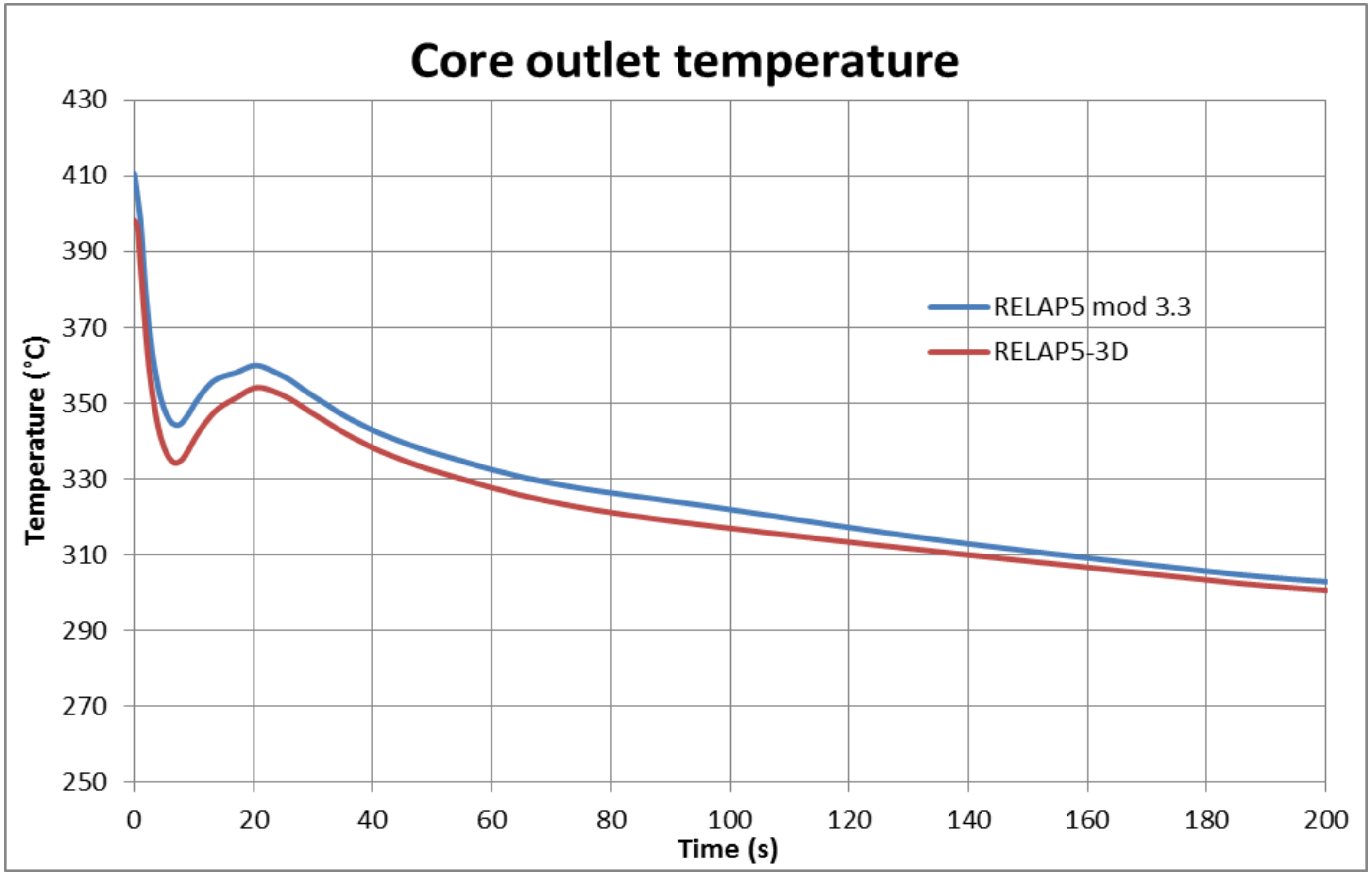
RELAP5 mod 3.3 vs. RELAP5-3D: LBE HTC correlations

- Two final comparison cases:
  - Replacing bundle HTC correlation (option 110) with plate HTC correlation (option 101) in both PHX and core
  - Replacing bundle HTC correlation (option 110) with plate HTC correlation (option 101) in PHX only
- Core HTC correlation variation causes very limited effect on primary system temperatures distribution (only important to determine clad temperature)
- Lower HTC correlation in PHX → PHX efficiency lowered → higher primary system temperature
- Finally, using same mass and same HTC correlation:
  - Results much closer than initially seen
  - Differences still retrievable coherently due to physical properties differences

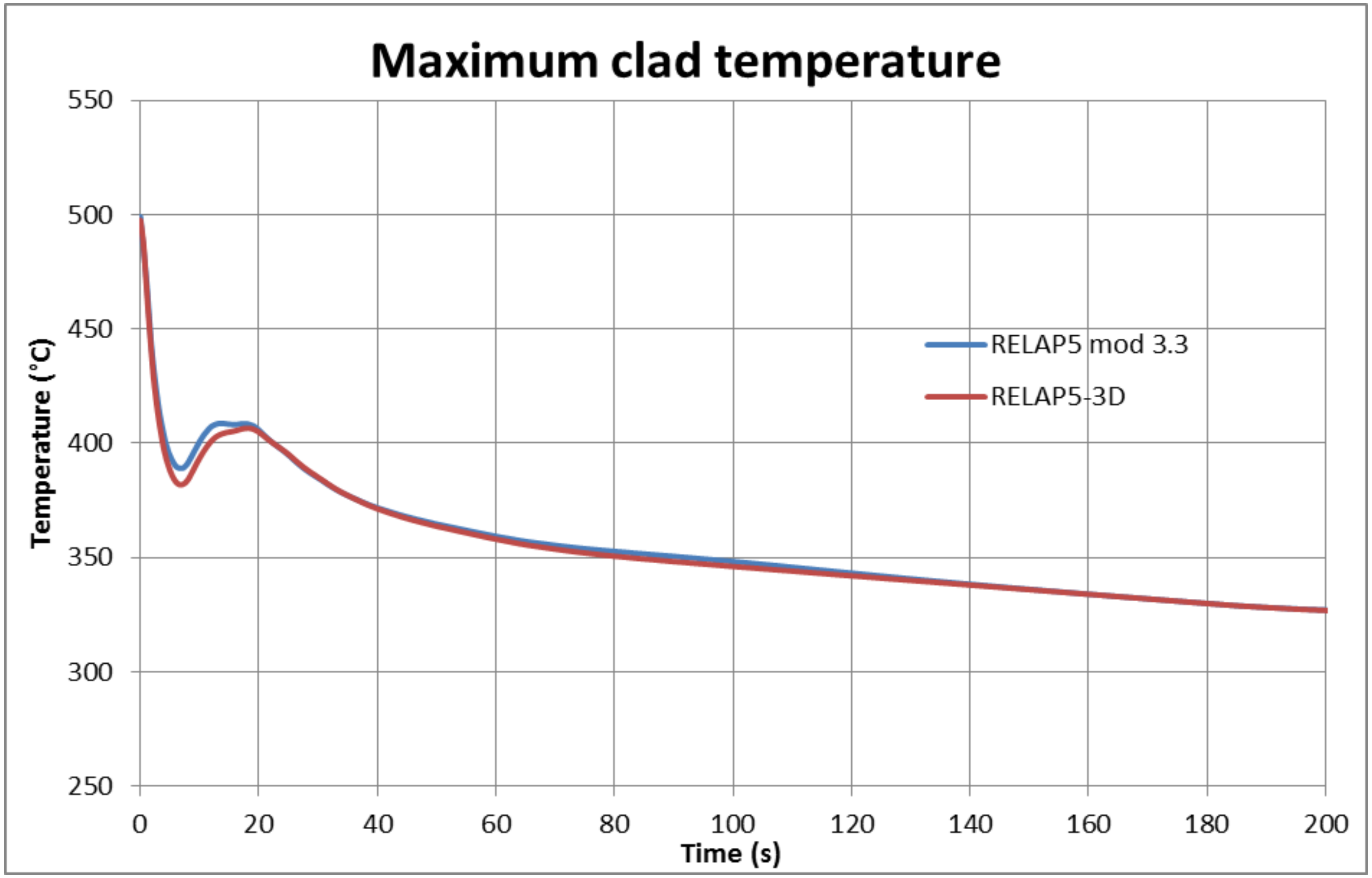
RELAP5 mod 3.3 vs. RELAP5-3D: PLOF transient

- Preliminary transient comparison run on Protected Loss Of Flow (PLOF) accidental sequence:
  - Initiating event: sudden trip of both primary pumps
  - Immediate reactor shutdown → reactor switched in DHR mode
  - Natural circulation set in primary pool
  - Secondary and tertiary systems maintaining active operations
  - Control system maintained operative
- PLOF transient run on both code versions
- Input deck with mass controller and vertical bundle HTC correlation (option 110)

RELAP5 mod 3.3 vs. RELAP5-3D: PLOF transient



RELAP5 mod 3.3 vs. RELAP5-3D: PLOF transient



RELAP5 mod 3.3 vs. RELAP5-3D: PLOF transient

- Core outlet temperature (steady state difference: ~10 °C) maintains a difference roughly proportional to LBE NC mass flow rate during transient evolution
- Maximum clad temperature evolution almost equal because of the counterbalancing effect between core and PHX HTC correlations already noticed in steady state
- Secondary water system pressure re-stabilized on nominal value after ~80 s:
  - Sudden pressure drop (~0.8 bar) in the first 5 seconds due to power decrease
  - Control system reacting by slowing tertiary fans down
  - Pressure returning to set-point value

Conclusions

- SCK•CEN acquired RELAP5-3D v 4.0.3 for MYRRHA reactor pre-licensing procedure
- First step: comparison between RELAP5 mod 3.3 (modified for LBE use) and RELAP5-3D using same input deck to discover differences between code versions
- Several differences identified concerning:
  - LBE physican properties
  - Non-condensable gas initialization
  - HTC correlations
- LBE physical properties: notable differences mainly in density and heat capacity → non negligible influence in steady state

Conclusions

- Non condensable initialization: possible inconsistency in RELAP5-3D input deck definition found leading to different mass inventory computation → notable mass flow differences well beyond property-generated mismatch
- HTC correlations: RELAP5-3D vertical bundle HTC correlation for liquid metals (Kazimi-Carelli) predicting higher Nu number in PHX → lower primary system temperatures (~10 °C)
  - Kazimi-Carelli not applicable to MYRRHA PHX analysis because of its P/D validity ranges
  - A more suited HTC correlation for bundles advisable
- PLOF transient comparison: same conclusions drawn for steady state extended in transient condition → core outlet temperature maintains difference ~proportional to LBE natural circulation mass flow rate

SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE