ANALYSIS OF MAIN STEAM LINE BREAK AT HOT ZERO POWER USING ATHLET, COCOSYS and DYN3D

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Main Steam Line Break at Hot Zero Power (MSLB at HZP) is a design basis accident for VVER-1000 reactors. This accident scenario involves a significant cooling of the affected loop and the corresponding section of the reactor core. As a result, return to power occurs due to negative moderator temperature feedback. The steam released into the containment increases the pressure in it, leading to the initiation of safety signals that influence the behaviour of both the primary and secondary circuit equipment. Consequently, the event encompasses complex thermal-hydraulic and 3D neutron kinetics phenomena that must be addressed in the analysis.

Three distinct approaches were employed in this investigation to analyse MSLB at HZP:

1. Fully coupled ATHLET-COCOSYS-DYN3D calculation: This approach integrates all three codes to provide a comprehensive simulation of the event.

2. Hybrid ATHLET-COCOSYS + DYN3D approach: This approach begins with an ATHLET-COCOSYS calculation with a point kinetics model accounting for the average coolant temperature in each of four reactor sectors. Subsequently, the results for reactor pressure, reactor flow rate and temperatures at the reactor inlet for each of the four sectors are utilized as boundary conditions in a DYN3D calculation. This allows to determine the power of each fuel assembly, considering its position in the core, as well as its enrichment and burnup. In addition, a hot FR is modelled.

3. ATHLET-COCOSYS coupled calculation. This is the first part of the previous approach. To cover the uncertainties of the point kinetics model, hot FA and hot FR are modelled.

ATHLET code

- Developed by the German Society for Safety of installations and Reactors (Gesellschaft für Anlagen- und Reaktorsicherheit, GRS)
- Advanced best-estimate system code for simulation of design basis and beyond design basis accidents in light water reactors, including VVER
- One-dimensional, two-phase fluid dynamics models based on six conservation equations
- Heat conduction and heat transfer module allow a flexible simulation of fuel rods and structures
- Nuclear heat generation calculated by a point-kinetics model
- A general control simulation module is provided for a flexible modelling of auxiliary plant systems and controllers
- Applied in ENPRO since 2003
- VVER-1000 input deck for KNPP 5 and 6 verified and validated against operational events and via code-to-code validation
- Applied recently in the framework of RWFA licensing project for:
  - Dynamic stability
  - Anticipated operational occurrences (category 2)
  - Anticipated transients without scram
  - Accidents with fuel melting for evaluation of the SAMG

COCOSYS code

- Developed by the German Society for Safety of installations and Reactors (Gesellschaft für Anlagen- und Reaktorsicherheit, GRS)
- Simulation of all processes and conditions in the containments of PWR in the course of both design and beyond design basis accidents, including severe accidents
- Calculation of the mass and energy release of radioactive products into the environment (source term)
- Applied in ENPRO since 2003
- Applied recently in the framework of RWFA licensing project for:
    - Containment analysis during LBLOCA
    - Containment analysis during MSLB

ATHLET-COCOSYS coupling

- Applied in ENPRO since 2010
    - LBLOCA for Kozloduy NPP
    - MSLB for Belene NPP

DYN3D code

- Developed by the Helmholtz-Zentrum Dresden-Rossendorf, Germany
- 3D-neutron kinetics model and thermal-hydraulic calculation module, the connection of which is given by a parameterized dependence of the neutron group constants on the fuel temperature, moderator temperature, moderator density and boron acid concentration
- Applied in ENPRO since 2002
- Applied recently in the framework of RWFA licensing project for:
  - Reactivity initiated accidents
  - including generation of library with diffusion and kinetics parameters in NEMTAB format using the Westinghouse code PHOENIX5

ATHLET-DYN3D coupling

- Common development of GRS and HZDR
- Validation performed in HZDR both for VVER-440 and VVER-1000 by means of operational events and code-to-code comparison
  (see *Y.Kozmenkov, S.Kliem, U.Rohde, HZDR, Validation and verification of the coupled neutron kinetic/thermal hydraulic system code DYN3D/ATHLET*)
- Available in ENPRO since November 2023

Why it is advisable to use ATHLET-COCOSYS-DYN3D coupling for the analysis of MSLB

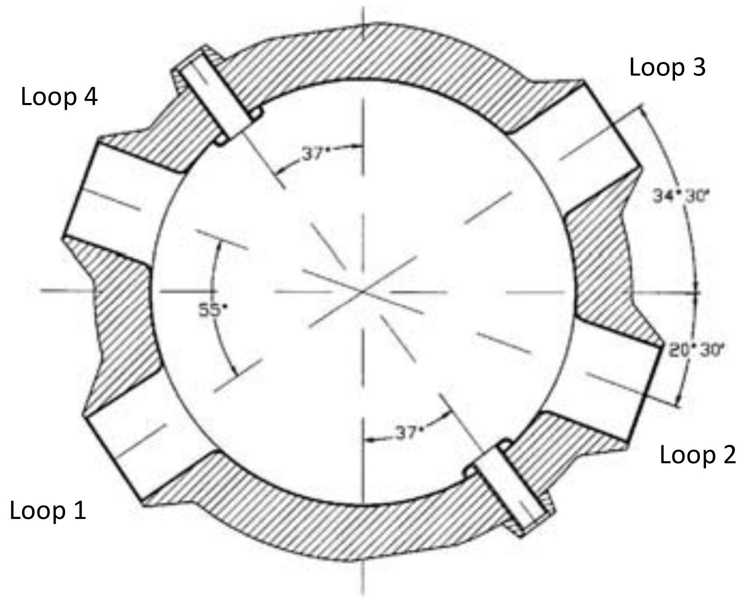
DYN3D is used to overcome the following deficiencies of the point kinetics:

- Not precise in case of scenarios with unsymmetrical behaviour of the core
  MSLB causes significant cooling in one sector of the core related to the affected steam generator
- Constant reactivity coefficients
  MSLB at HZP starts at 0 power and leads to return to power, while reactivity coefficients are defined constant either for HZP or HFP
- Constant radial and axial power profile; does not account for the enrichment and burning of the FAs and for the insertion the control rods

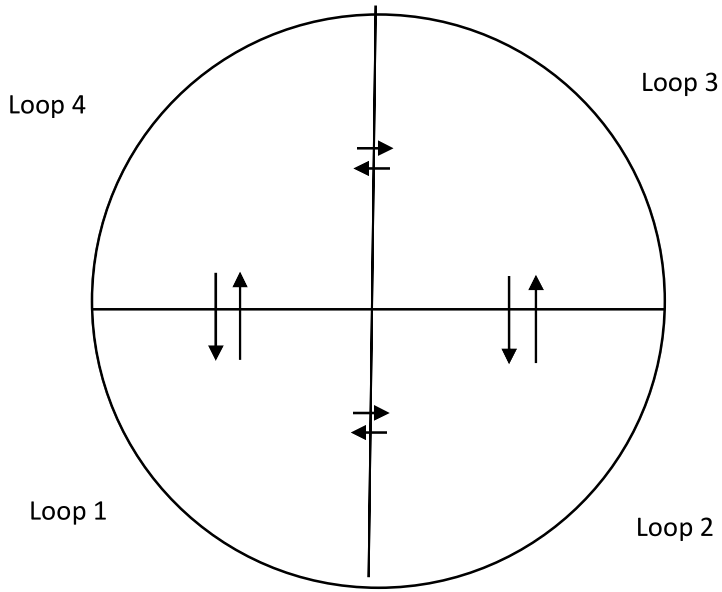
COCOSYS is used for correct determination of the moment when the containment pressure reaches the set-point for containment isolation

Coolant mixing in the Lower plenum

Cross-section at the elevation of inlet nozzles



Modeling of the Lower plenum

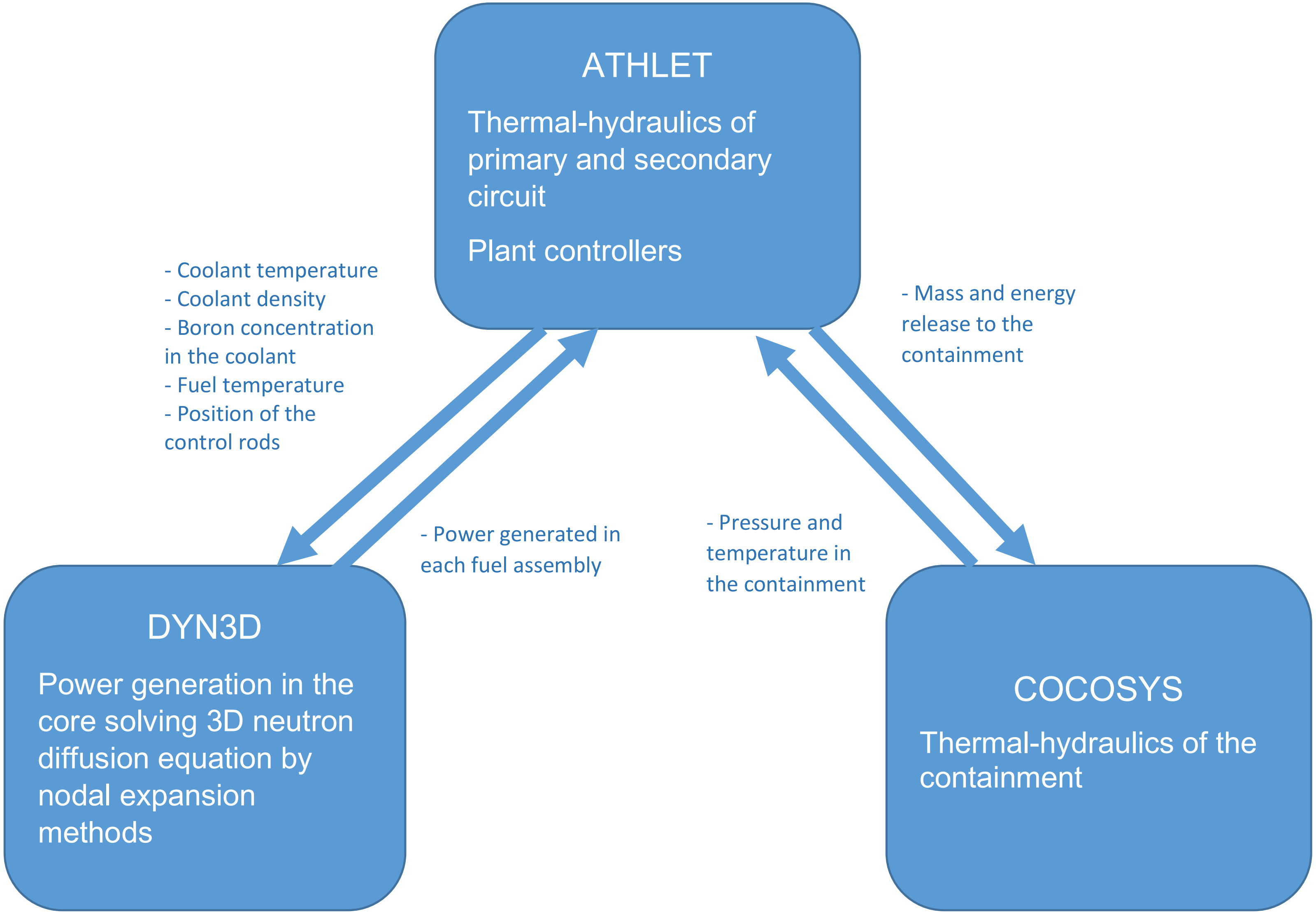


The cross-connectuons are validated against KNPP 6 operational event 747 *Trip of MCP 3*

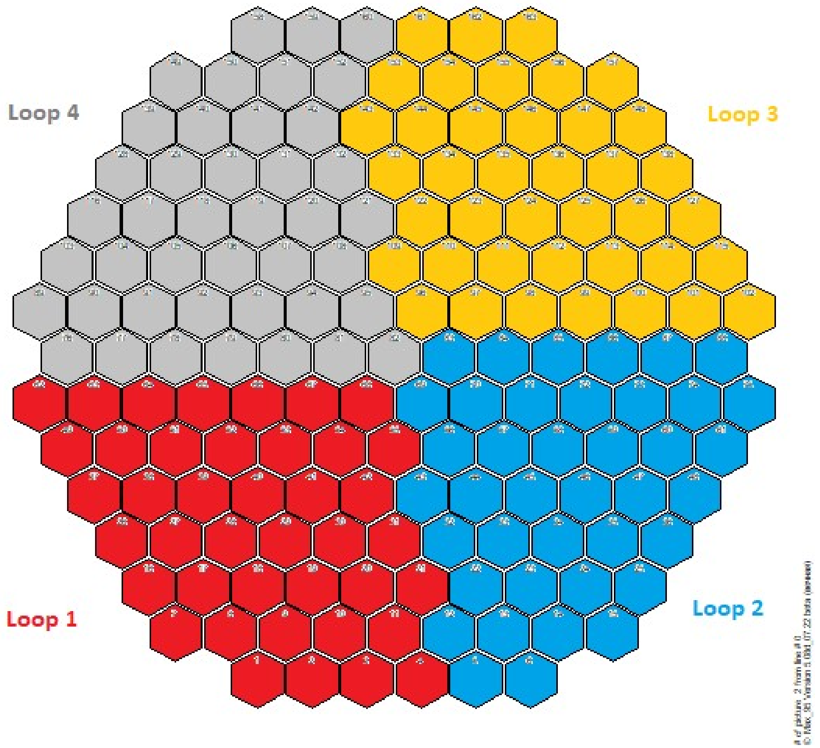
Three different approaches applied

1. ATHLET-COCOSYS-DYN3D coupling
    - TH parameters in the primary and secondary circuit calculated by ATHLET
    - Insertion of control rods determined by ATHLET
    - Containment parameters calculated by COCOSYS
    - Power of each FA calculated by DYN3D with account for the enrichment, burnup and position of control rods
2. ATHLET-COCOSYS coupling + DYN3D
    - Results obtained with ATHLET-COCOSYS are used as boundary conditions in DYN3D:
        - pressure in the primary circuit
        - coolant flowrate by four sectors
        - temperatures at the inlet of the four core sectors
    - DYN3D calculation is performed with a hot FR modelled in the FA found to be "hottest" in the ATHLET-COCOSYS-DYN3D coupled calculation with rod relative power equivalent to the max hot rod peaking factor Kr determined by the core design
3. ATHLET-COCOSYS coupling
    - reactivity determined separately for each part of the core, in this way accounting for the different coolant and fuel temperatures in the sectors
    - hot FA modelled with assembly relative power of the FA identified to be "hottest" in the ATHLET-COCOSYS-DYN3D coupled calculation
    - hot FR modelled in the hot FA with rod relative power equivalent to the max hot rod peaking factor determined by the core design

ATHLET-COCOSYS-DYN3D internal coupling

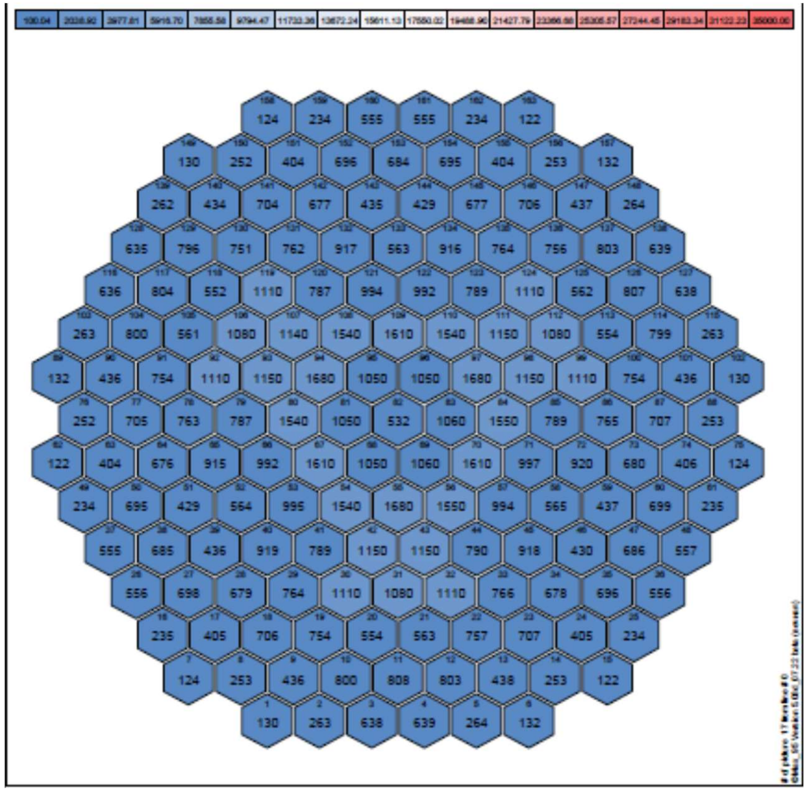


ATHLET-COCOSYS-DYN3D with TH 163 channels in the core

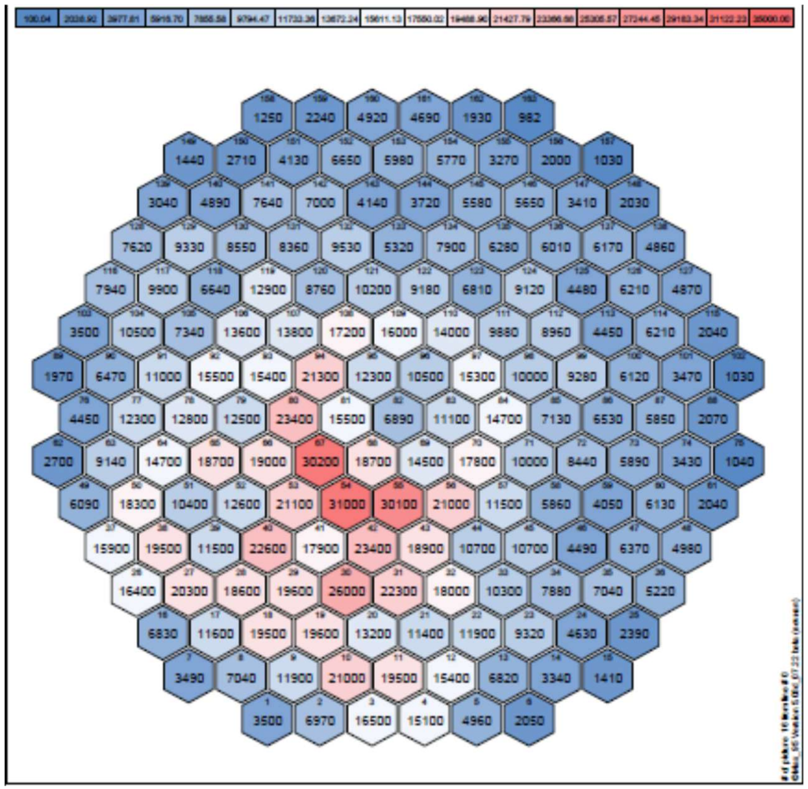


ATHLET-COCOSYS-DYN3D coupling

Results for the power distribution



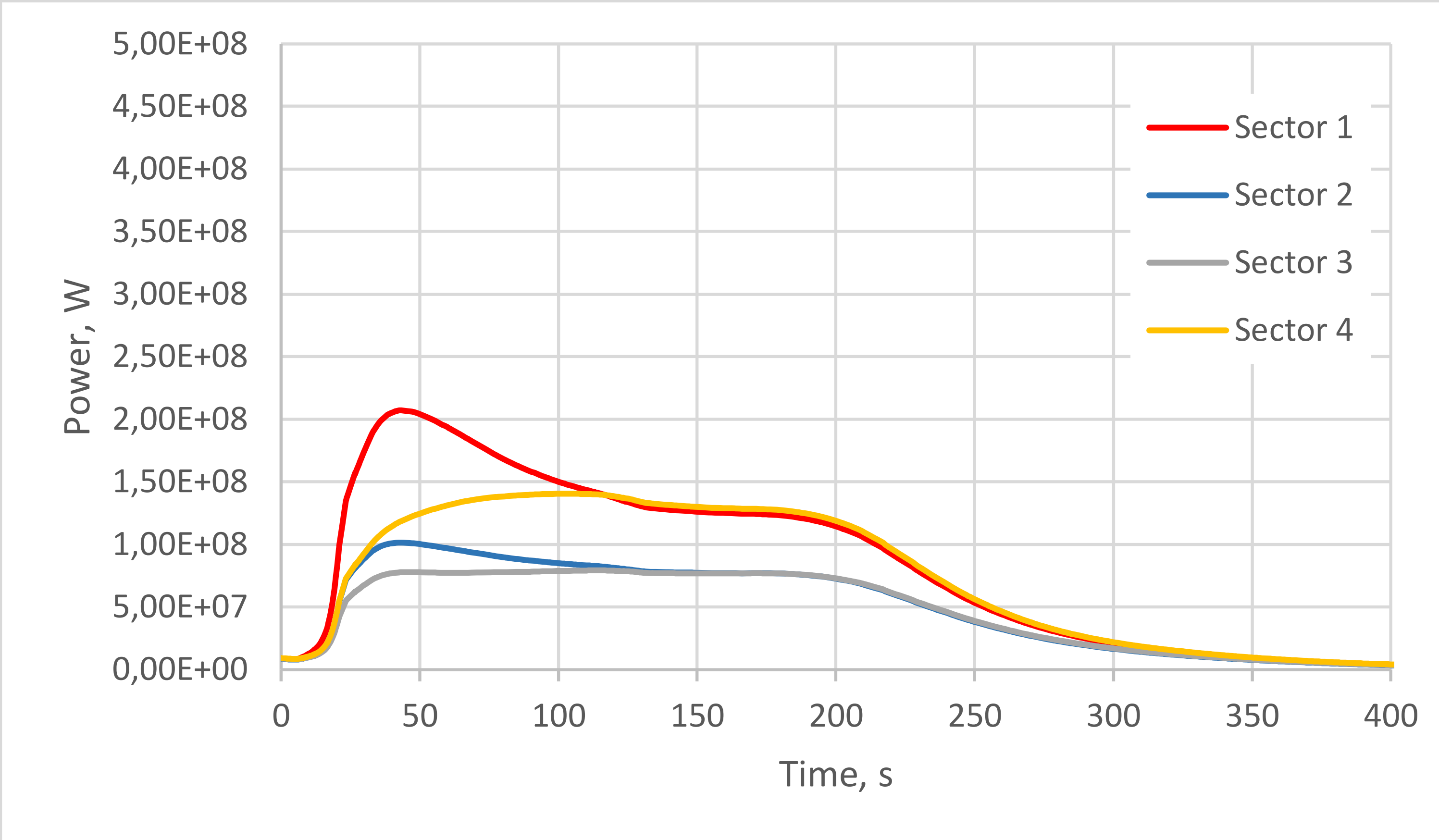
T = 0 seconds



T = 47 seconds

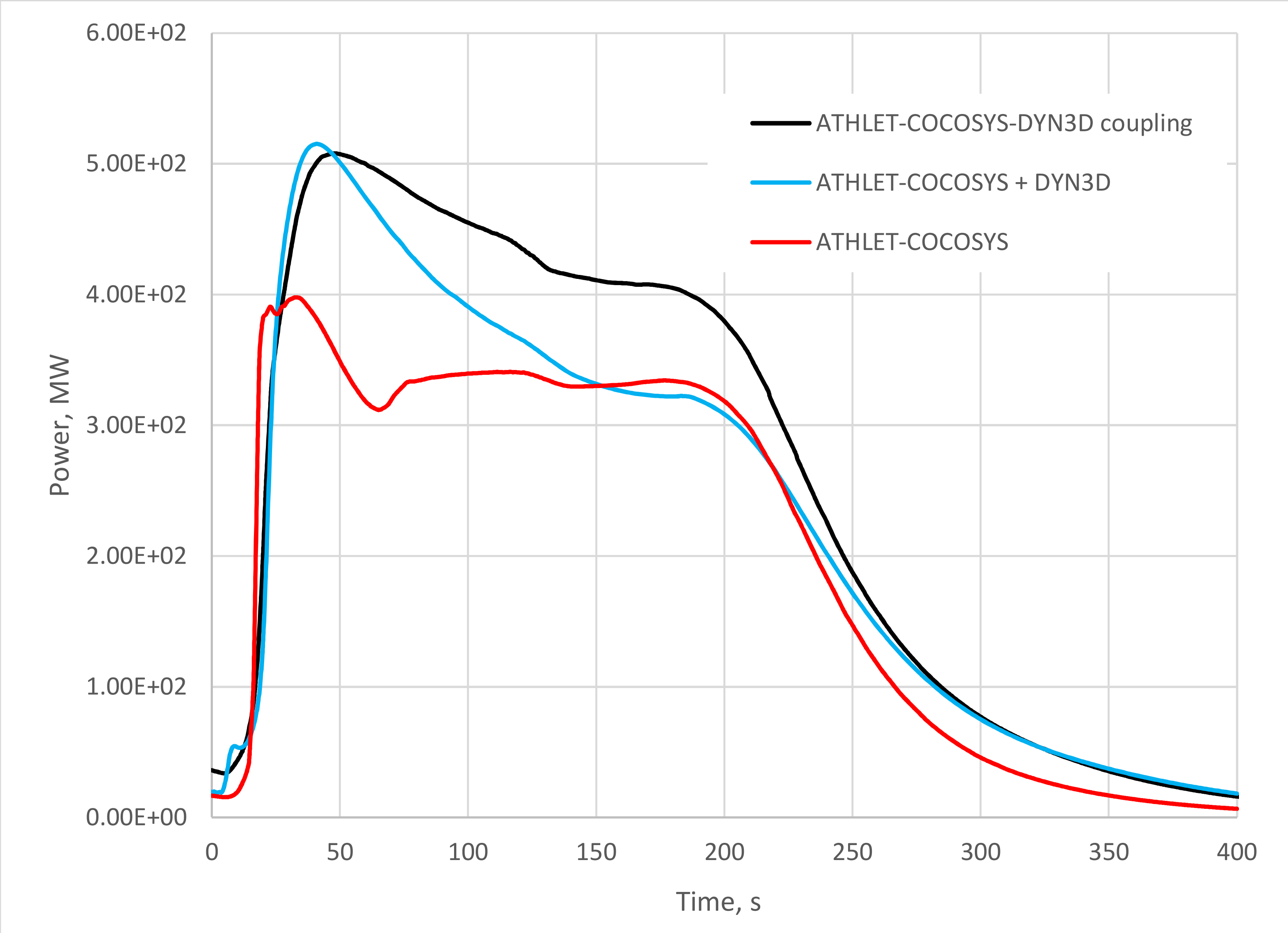
ATHLET-COCOSYS-DYN3D coupling

Results for the power distribution by sectors

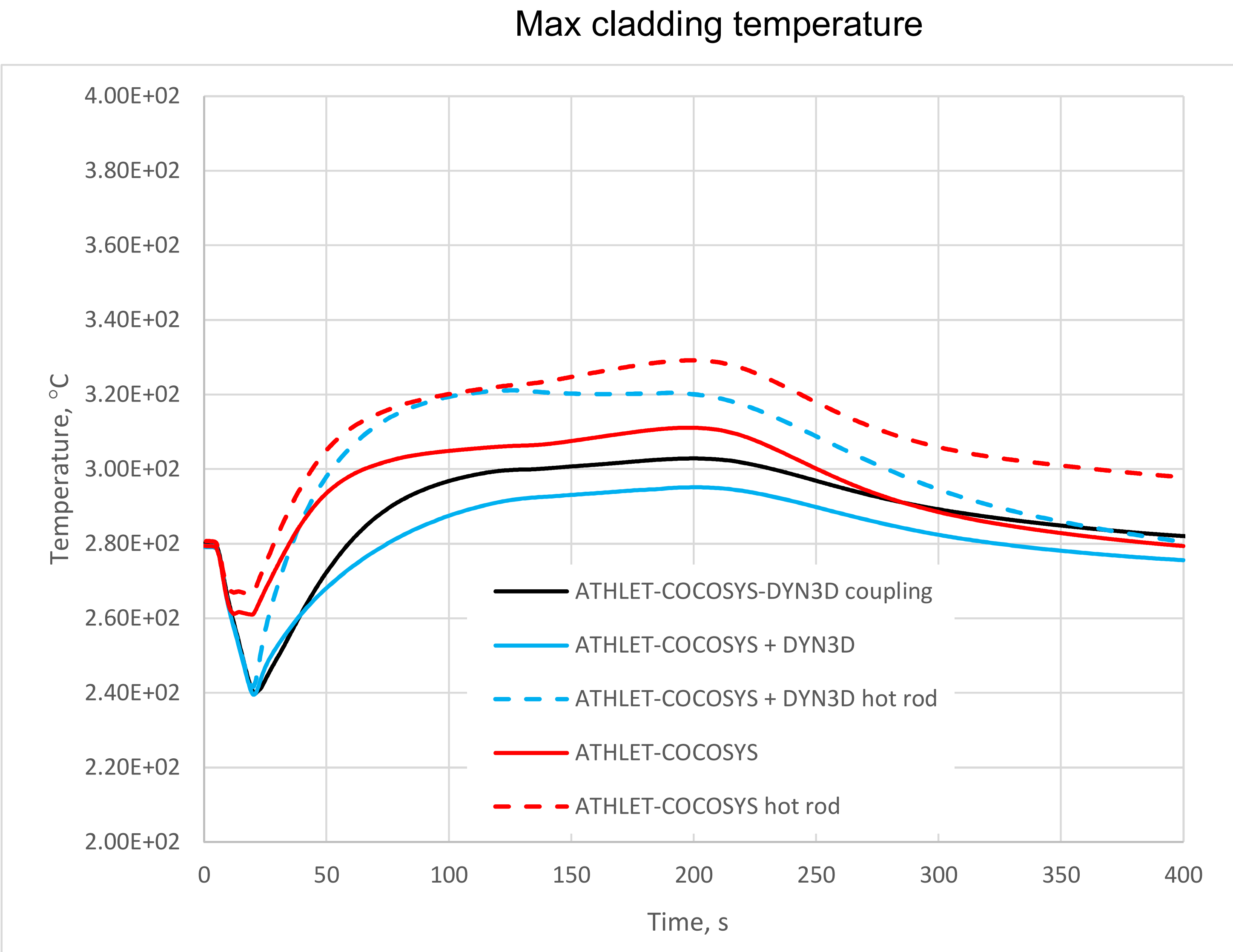


Results from the tree approaches

Reactor power

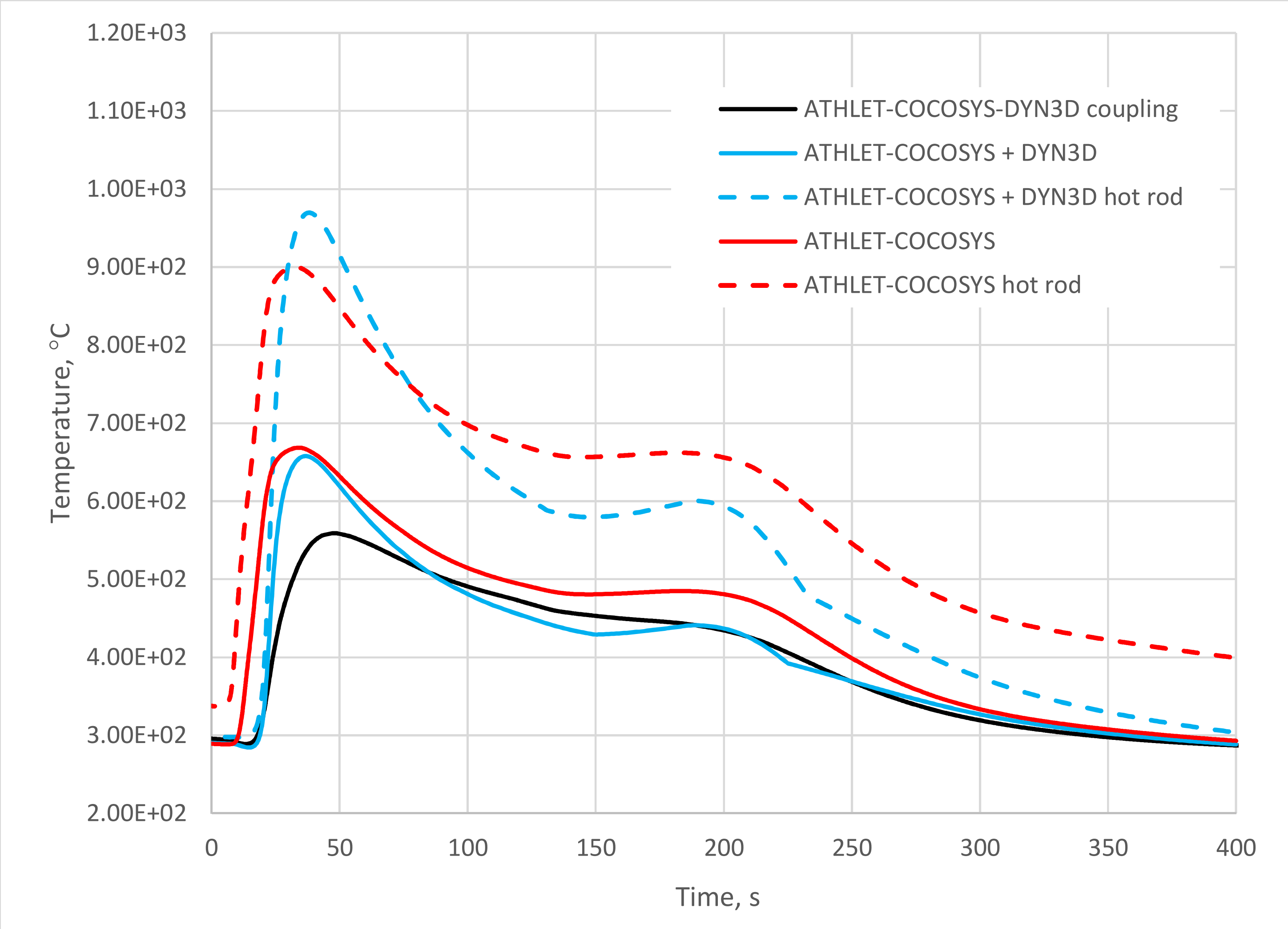


Results from the tree approaches



Results from the tree approaches

Max fuel temperature in the centre of the rod



Scenario of the event

	Event	Time, s		
		A-C-D	A-C+D	A-C
1	Double-ended break of the main steam line of SG1 inside the containment	0	0	0
2	Signal for tripping of RCP1 due to low pressure in the steam line and low ΔP over the check valve. The pump remains in operation Closing of the check valve on steam line 1	0.2	0.2	0.2
3	Signal for low pressure in MSL 1, high ΔTs I-II and coolant temperature in any of the hot legs above 200 °C – Actuation of ASSS – FAIV-1 starts to close	0.2	0.2	0.2
4	Signal for isolation of the feedwater line. Only the safety-graded valves start to close.	2.5	1.9	1.9
5	Signal for containment isolation	4.3	4.4	4.4
6	Tripping of all RCPs due to containment isolation	19.3	19.4	19.4
7	Max reactor thermal power reached	47	40	33

CONCLUSIONS

	Criteria	A-C-D	A-C+D	A-C
1	Peak cladding temperature, C	303	320	329
2	Peak fuel centre line temperature	559	961	899

1. ATHLET-COCOSYS-DYN3D coupling is a best estimate approach allowing for a realistic modelling of RIA with asymmetrical behaviour of the reactor installation

2. The system thermal-hydraulic code with point kinetics may underestimate the power due to using constant reactivity feedbacks for the whole range of power from HZP to return to power. Applying system code and 3D kinetics code afterwards leads to correct determination of the peak power.

3. A conservative modelling approach in point kinetics is capable to compensate for the deficiencies of the method.

Acknowledgements

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