RELAP5/M3.3 – RELAP5/3D – FLUENT Calculations and Comparison of Reactor Downcomer Parameters in PTS Analyses

Pavel Kral

Marek Bencik

Ladislav Vyskocil

International RELAP5-3D Users Group Meeting

Idaho Falls, May 3-4, 2018

Skupina ÚJV

TECHNOLOGIE I INOVACE I LIDÉ

Outline

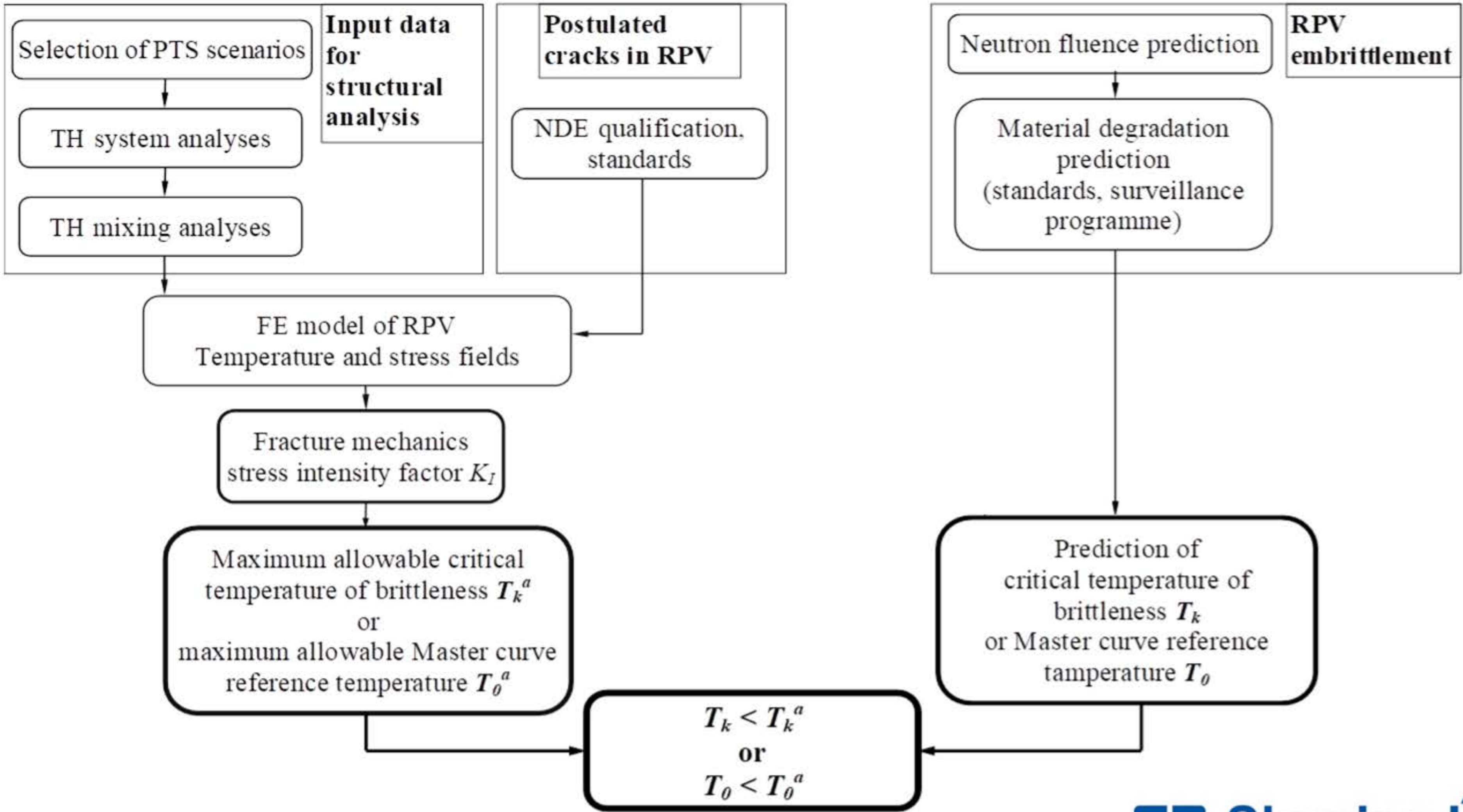
- Introduction and background
- TH remarks to PTS issue
- Relap5/Mod3.3 Input Model of VVER-440 for PTS calculations
- Relap5-3D Model of VVER-440 Reactor for PTS calculations
- CFD Fluent Model of VVER-440 for PTS calculations
- Comparison of R5/M3 – FLUENT results of analyses of various PTS cases in VVER-440
- Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg
- Conclusions

Introduction and background

- ❑ Radiation embrittlement due to neutron fluence is the most significant aging mechanism for reactor pressure vessel (RPV)
- ❑ For the RPV lifetime assessment, material degradation limit (i.e. limits that are allowed to be approached by material degradation, without endangering the RPV integrity) has to be established
- ❑ This limit is established on the basis of pressurised thermal shock (PTS) analyses
- ❑ PTS is an event in NPP that is characterized by rapid cooldown in the primary coolant system with (usually) high primary pressure
- ❑ Thermal hydraulic analyses of PTS relevant events are the basis for PTS evaluation
- ❑ Application of advanced computational tools and method in system and mixing TH analyses has substantial effect on final PTS results
- ❑ Advanced system TH code RELAP (NRC 1D version implemented in UJV in 1990, DOE 3D version in 2004) is in UJV widely assessed and validated - more than 25 pre- and post-tests
- ❑ UJV Rez also cooperates in code development (DNBR correlations, end-valves, model of model for condensation of steam and steam-gas mixture in horizontal and inclined tubes) and in preparation of code couplings (containment code, CFD code etc.)

Introduction and background (cont'd)

General scheme of PTS evaluation:



Introduction and background (cont’d)

Computer codes used for PTS analyses of Czech NPPs in 1995-2005:

system TH analysis: RELAP5 (later with 2D downcomer)

mixing calculation: REMIX/NEWMIX
CATHARE 2D (for 2-phase cases)

structural calculation: SYSTUS
COSMOS/M

Note: For some minor or special purposes UJV had used also the ATHLET, MELCOR, COCOSYS, FLUENT and FLUTAN computer codes.

Computer codes used for PTS reevaluation of Czech NPPs in 2016-2020:

system TH analysis: RELAP5 (2D DC) or RELAP5-3D

mixing calculation: CFD FLUENT for predominantly single-phase cases
Direct transfer of results from system RELAP5 / RELAP5-3D calculation of reactor DC (2D) to structural analysis

structural calculation: SYSTUS

Introduction and background (cont'd)

Major UJV Rez PTS projects:

PTS study for NPP Dukovany (VVER-440/213)

- Started in 1995, finished in 2004
- System TH analyses of 69 cases → final PTS analyses of the 41 worst cases

PTS study for NPP Temelin (VVER-1000)

- Started in 2001, finished in 2005
- System TH analyses of 72 cases → final PTS analyses of the 24 worst cases

PTS analyses for Mochovce NPP in Slovakia (VVER-440)

- Independent analyses for SAR, 2007-2008

PTS study for Armenian NPP (VVER-440)

- IAEA project, 2012-2013

PTS studies for South-Ukraine NPP (VVER-1000), Rovno NPP (VVER-1000, VVER-440), Khmelnitska NPP (VVER-1000)

- In frame of complex reassessment of RPV lifetime and LTO, 2012-2018

PTS re-evaluation for Czech NPPs Dukovany and Temelin (2016 – 2020)

- The most significant PTS scenarios have been / will be recalculated according to current methodology, approaches and models

Introduction and background (cont'd)

UJV co-authoring in preparation of PTS guidelines:

- Guidelines on Pressurized Thermal Shock Analysis for WWER Nuclear Power Plants, IAEA-EBP-WWER-08, 1997 (Revision 2006)
- Unified Procedure for Lifetime Assessment of Components and Piping in VVER NPPs, VERLIFE project of the 5th Framework Programme of the EU, 2003 (Revision 2008)
- Preparation of "PTS Textbook", IAEA→NUGENIA. Draft version.

UJV participation in PTS benchmarks and other assessment work:

- IAEA Pressurized Thermal Shock Benchmark (PRZ SV inadvertent opening), 1997-1999 (UJV system TH analysis selected as reference results for following mixing and structural calcs)
- Unsymmetrical cooldown of 1 loop of VVER-440 (measured test from Dukovany NPP)

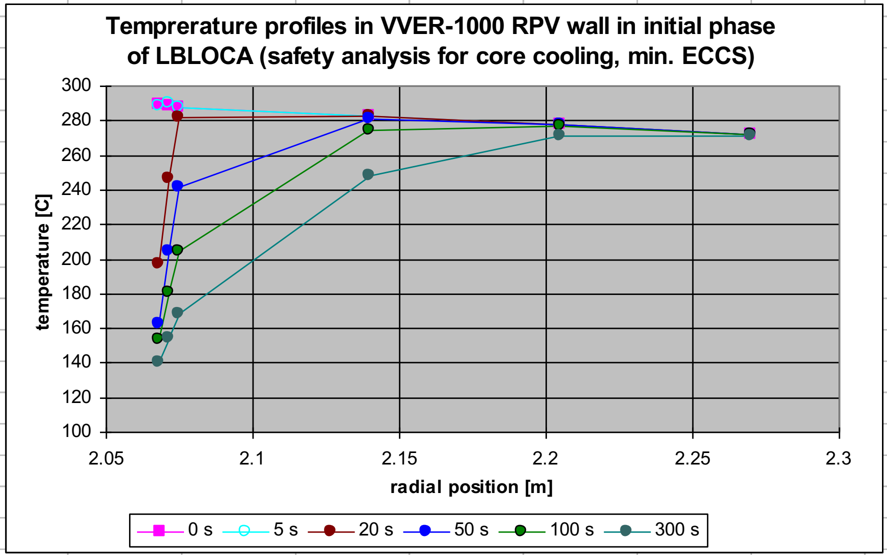
Papers:

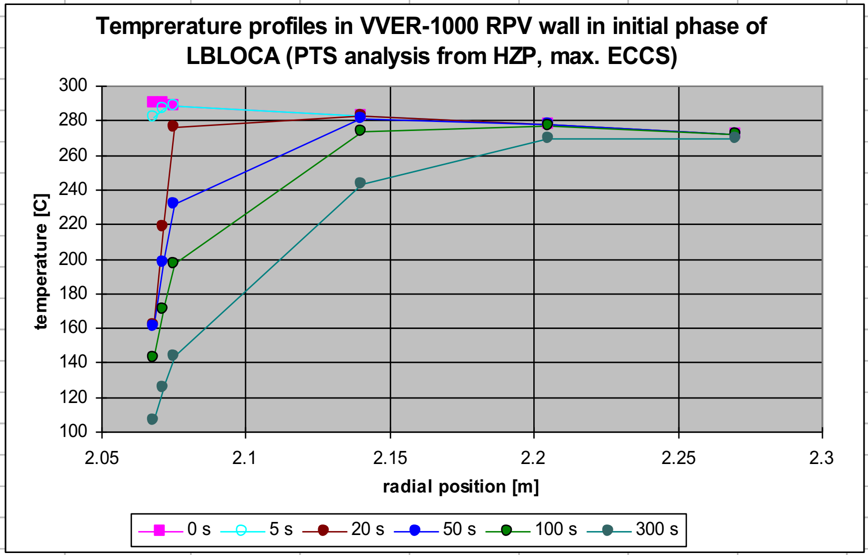
- Macek, Muhlbauer, Krhounková, Král, Malačka: Thermal Hydraulik Analyses of NPPs with VVER-440/213 for the PTS Condition Evaluation. NURETH-8. 1997
- Král, Pištora: Impact of ECCS Design of VVER Reactors on PTS Issue. Internatioinal Topical Meeting 2004 - Prague. October 2004.
- Pištora V, Král P.: PTS Evaluation for Czech Nuclear Power Plants of WWER Type. 2009 ASME Conference. Prague July 2009.
- Pistora, Zamboch, Král, Vyskocil: PTS Re-Evaluation Project for Czech NPPs. Fourth International Conferences on NPP Life Managment (PLiM), IAEA, October 2017, Lyon

Thermal Hydraulic Remarks to PTS issue

TH remarks to PTS issue

The pressurized thermal shock (PTS) events are characterized by rapid temperature decrease of the primary coolant, particularly in the reactor downcomer, and by subsequent cooldown of the reactor pressure vessel (RPV) wall leading to thermal stresses in the RPV wall, that could be loaded at the same time by inner pressure.



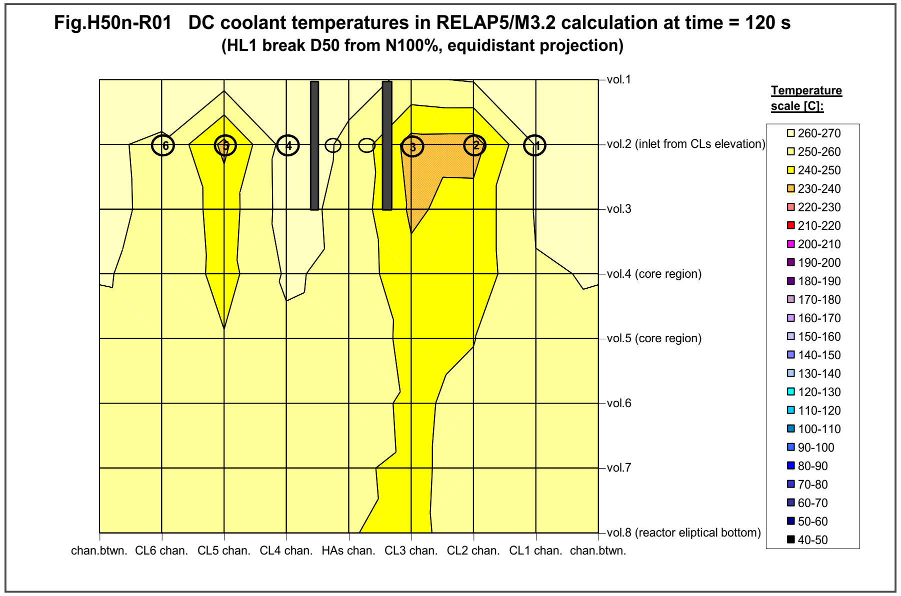


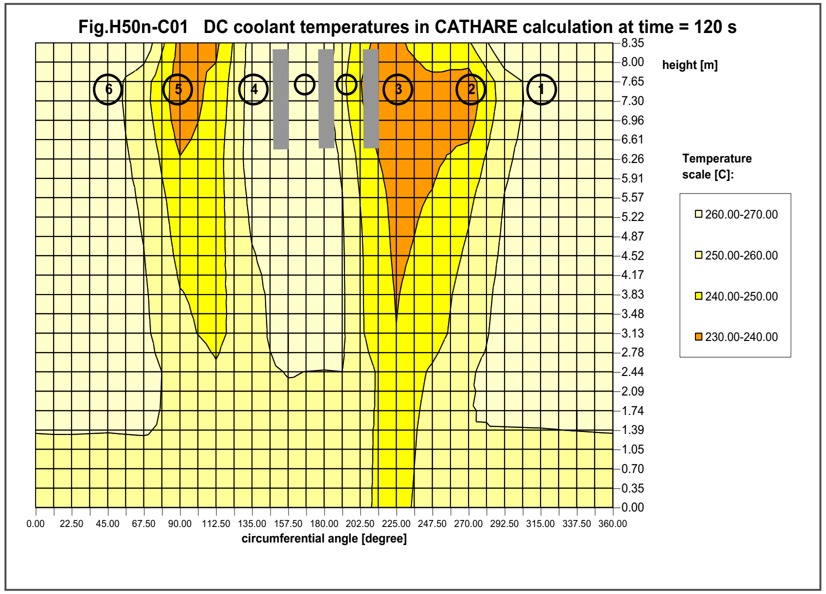
Fast changes of temprerature profile in reactor vessel wall during LBLOCA analyses

TH remarks to PTS issue (cont'd)

The RPV <u>cooldown is often nonuniform</u>, which is caused either by ECCS injection or by rapid asymmetric cooldown via a steam generator (plus symmetrical cooldown due to RCS rapid depressurization and coolant evaporation in LOCA).

So-called „<u>cold plumes</u>“ (typical for SBLOCA etc.), respectively „<u>cold stripes</u>“ (typical for early phase of LBLOCA) or „<u>cold sectors</u>“ (typical for MSLB) could be formed and consequently increase the thermal stresses in the RPV wall.

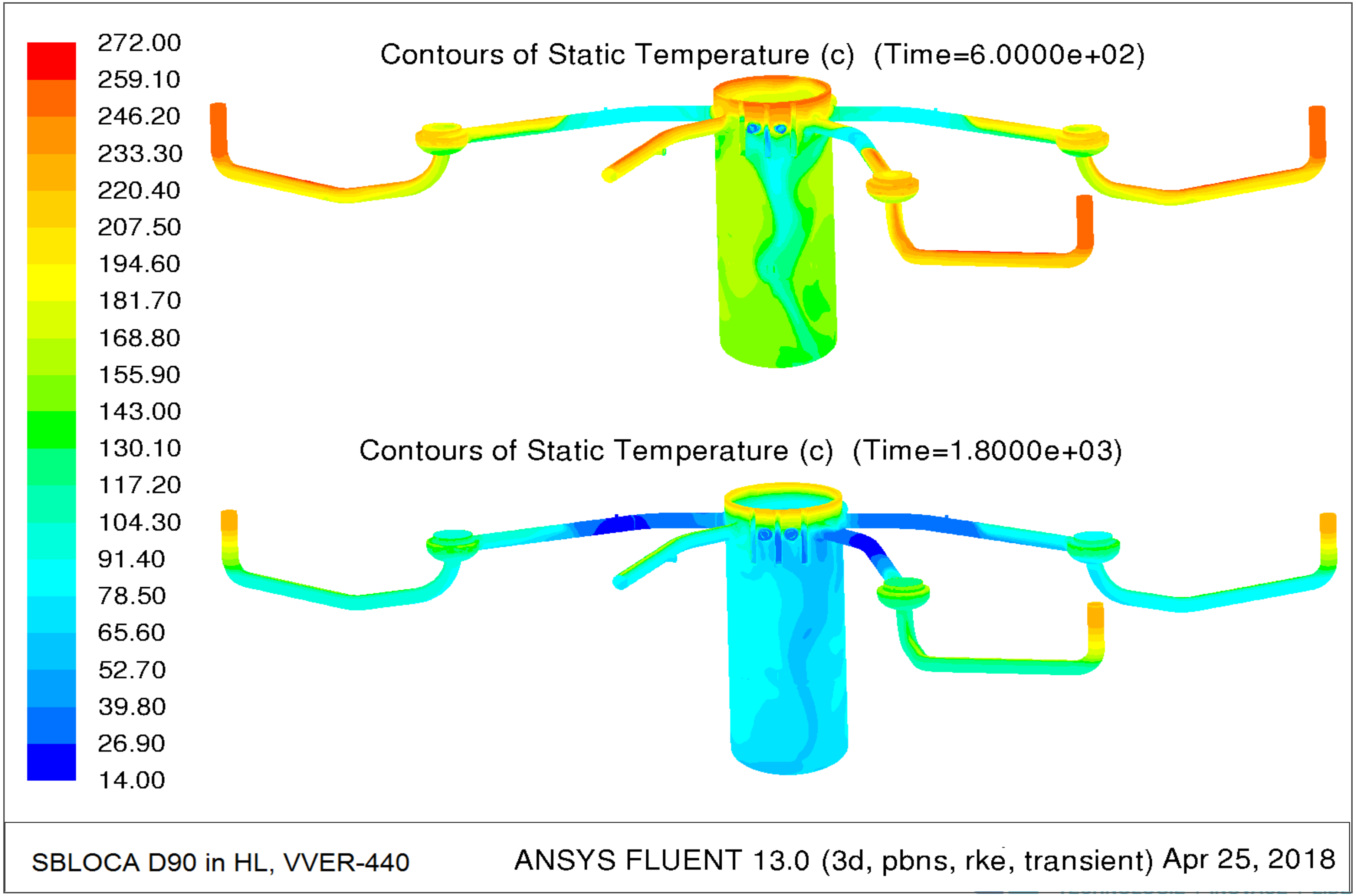




RELAP5/M3.3 and CATHARE.2D temperature fields at inner surface of reactor vessel in SBLOCA (VVER-440, break D50 in hot leg, time 120 s with injection of 3 HPSI, 2001)

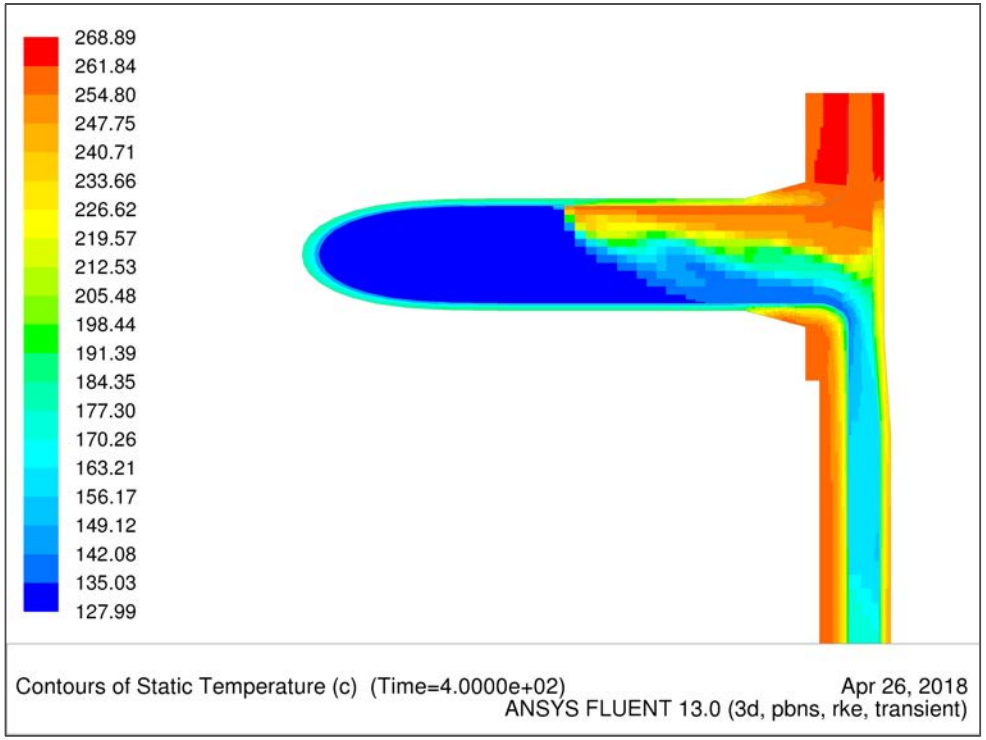
Skupina ÚJV
TECHNOLOGIE I INOVACE I LIDÉ

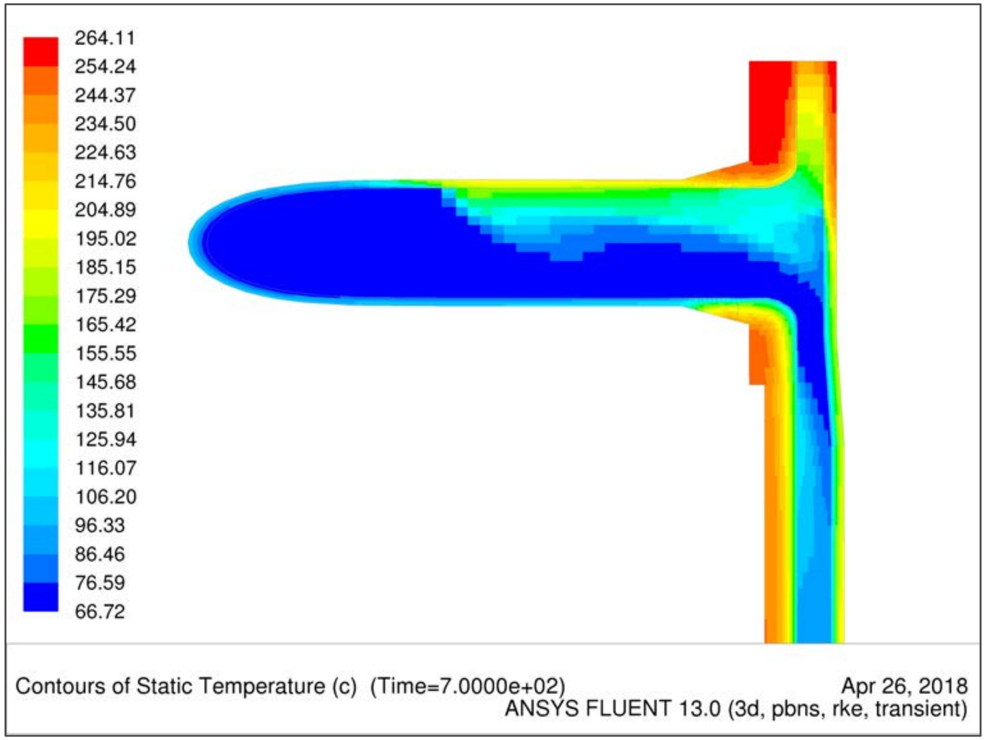
TH remarks to PTS issue (cont'd)



TH remarks to PTS issue (cont'd)

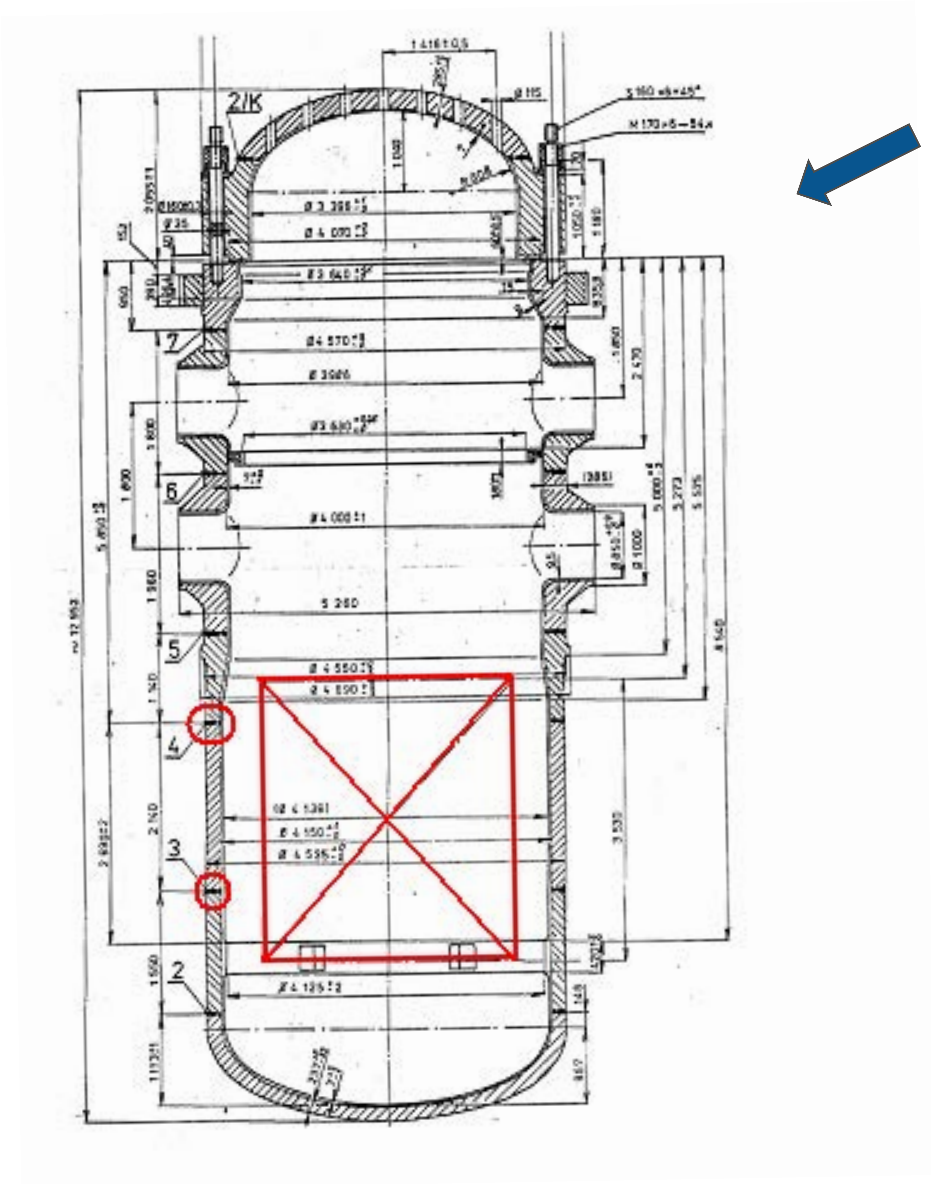
SBLOCA D90 in hot leg – CFD predicted contours of static temperature in axial section:





Skupina ÚJV
TECHNOLOGIE I INOVACE I LIDÉ

TH remarks to PTS issue (cont'd)



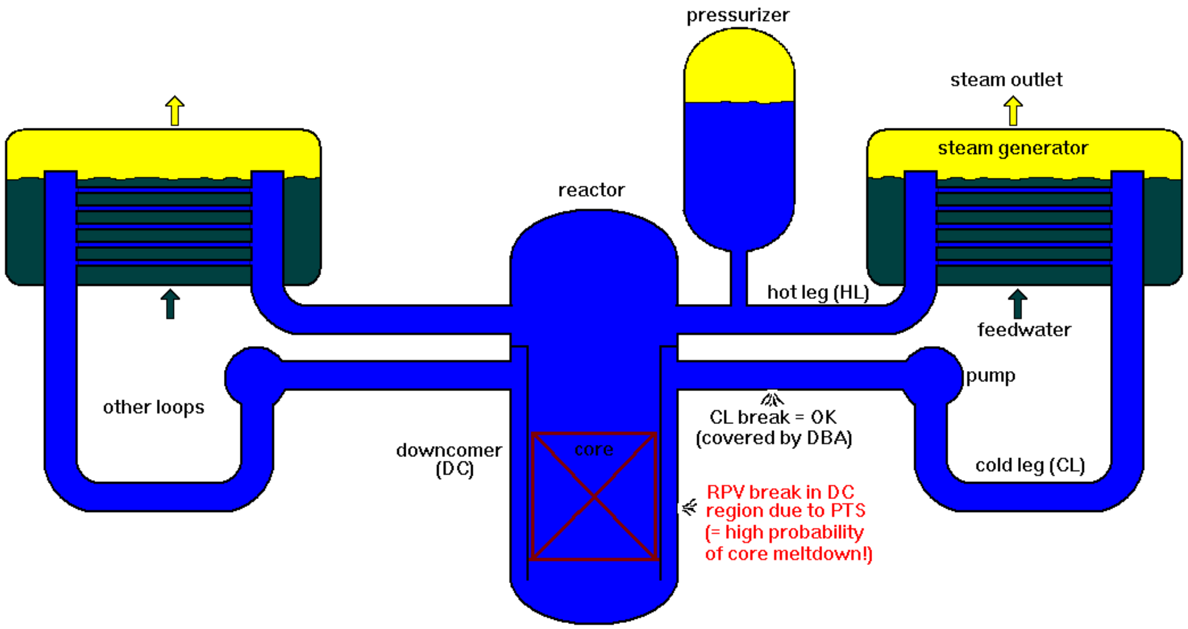
Reactor pressure vessel of VVER-1000 with position of welds No. 3 and 4 versus core elevation

Skupina ÚJV
TECHNOLOGIE I INOVACE I LIDÉ

TH remarks to PTS issue (cont'd)

Reactor pressure vessel (RPV) is the most important component of a nuclear power plant. Its lifetime is a limiting factor for the lifetime of the entire NPP. So the evaluation of PTS is a crucial task of the nuclear safety.

Rupture of RPV and consequent LOCA with break in middle or lower part of the downcomer could lead to LOCA with nearly impossible cooling of the core (= inevitable core damage).



Schematics of VVER (PWR) primary circuit and steam generators during normal operation

Skupina ÚJV
TECHNOLOGIE | INOVACE | LIDÉ

TH remarks to PTS issue (cont'd)

Main TH phenomena deteriorating pressurized thermal shock:

- (-) Fast temperature decrease in reactor downcomer (DC).
- (-) Low final temperature in DC (especially with: high initial temperature).
- (-) High primary pressure during the process.
- (-) Low flowrate or flow stagnation in loops with ECCS connection.
- (-) Nonhomogeneous coolant temperature field in reactor downcomer from SI injection (cold plumes, cold stripes) or from non-symmetric cooldown (cold sectors).
- (-) Big differences in heat transfer coefficients (HTC) at inner wall of RPV.
- (-) Interactions of neighboring cold plumes.

These general deteriorating TH factors are important in selecting conservative initial and boundary conditions for TH calculations.

Models of VVER-440:

- Relap5/Mod3.3
- Relap5-3D
- Fluent

Relap5/Mod3.3 Input Model of VVER-440

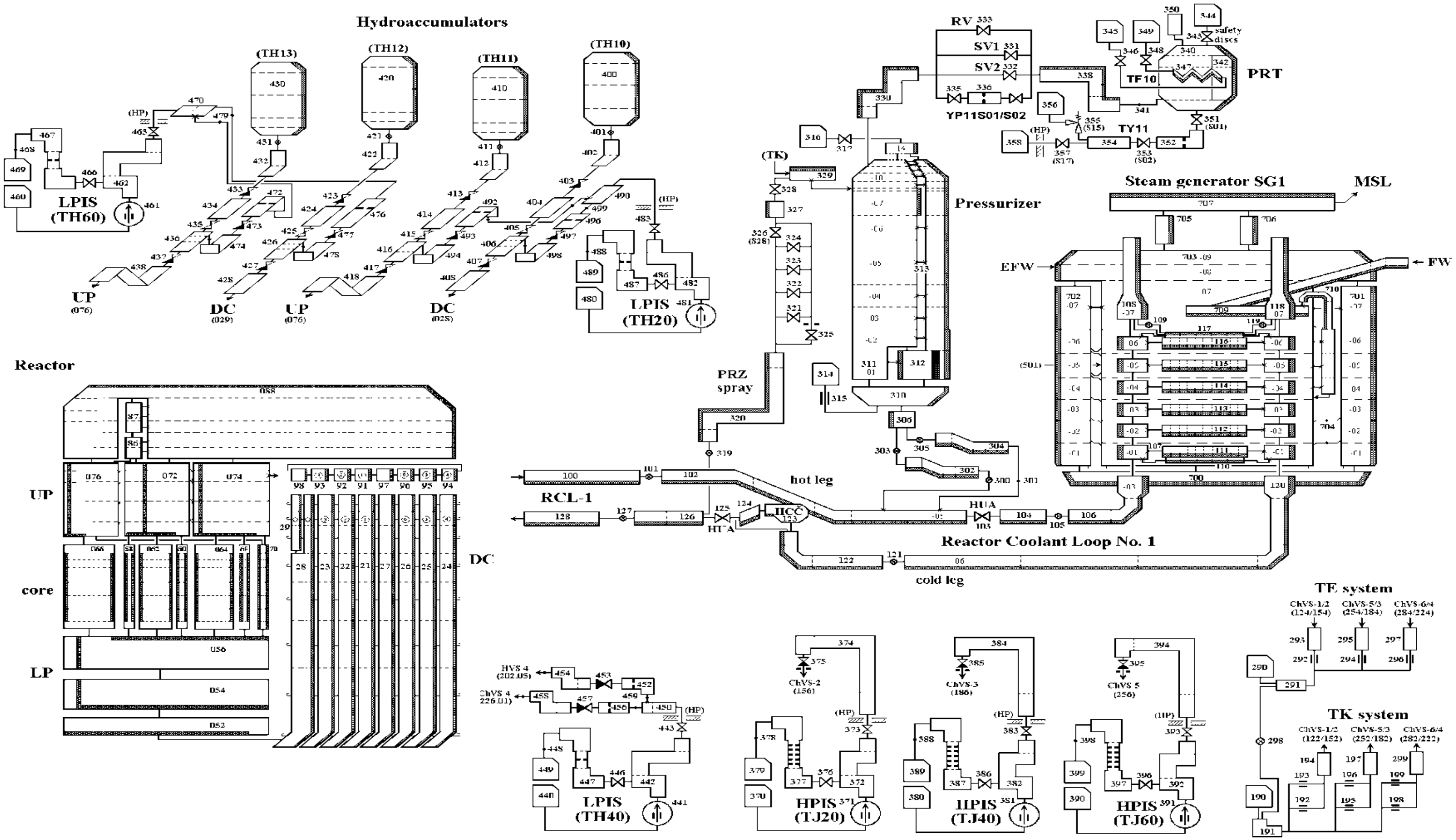
Important features of the model from the PTS point of view:

- Detailed and complex model of RCS, ECCS, SGs, MSS, FW systems
- 1800 hydraulic control volumes and 2200 junctions, 1800 heat structures with 9800 mesh points, 2700 control variables with 1800 trips
- Nodalization based on R5 manual guide, know-how of wide R5 users community, experience from own code validation against VVER-design experimental facilities, modelling of NPP tests etc.

Important features of the model from the PTS point of view:

- Individual modeling of all primary loops (i.e. 6 loops in case of VVER-440)
- 2-D nodalization of reactor downcomer applied in selected transients (for correct prediction of flow coastdown in individual loops etc.)
- Detailed modeling of ECCS system (hydroaccumulators + HA lines, SI tanks, SI pumps, discharge lines)
- Detailed modeling of SGs (multi-layer tubing) and Main Steam System (important for the MSLB)

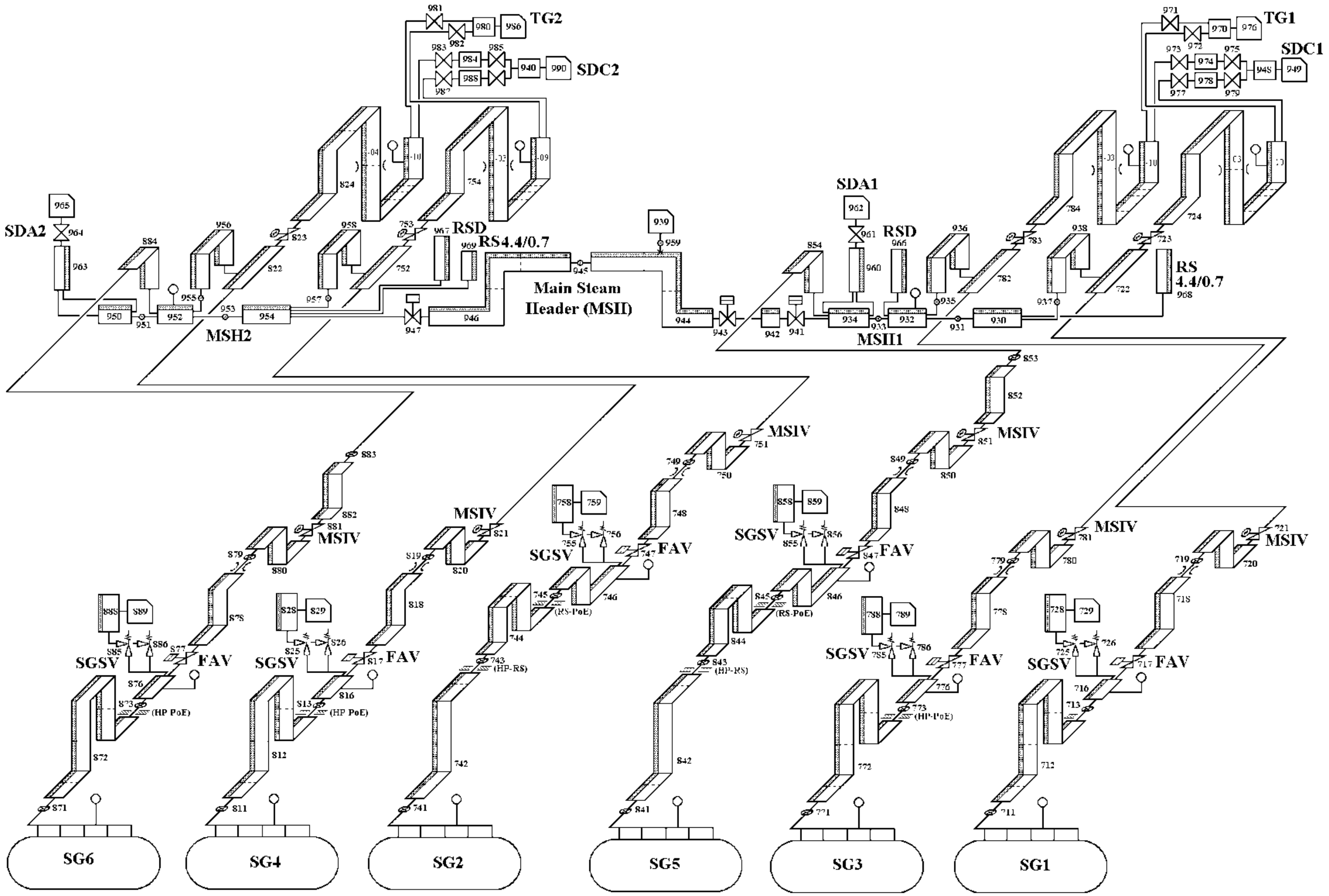
Relap5/Mod3.3 Input Model (cont'd)



Nodalization of NPP Dukovany Reactor Coolant System and ECCS
(VVER-440/213, version with 2D downcomer, only 1 of 6 loops depicted)

Skupina ÚJV
TECHNOLOGIE | INOVACE | LIDÉ

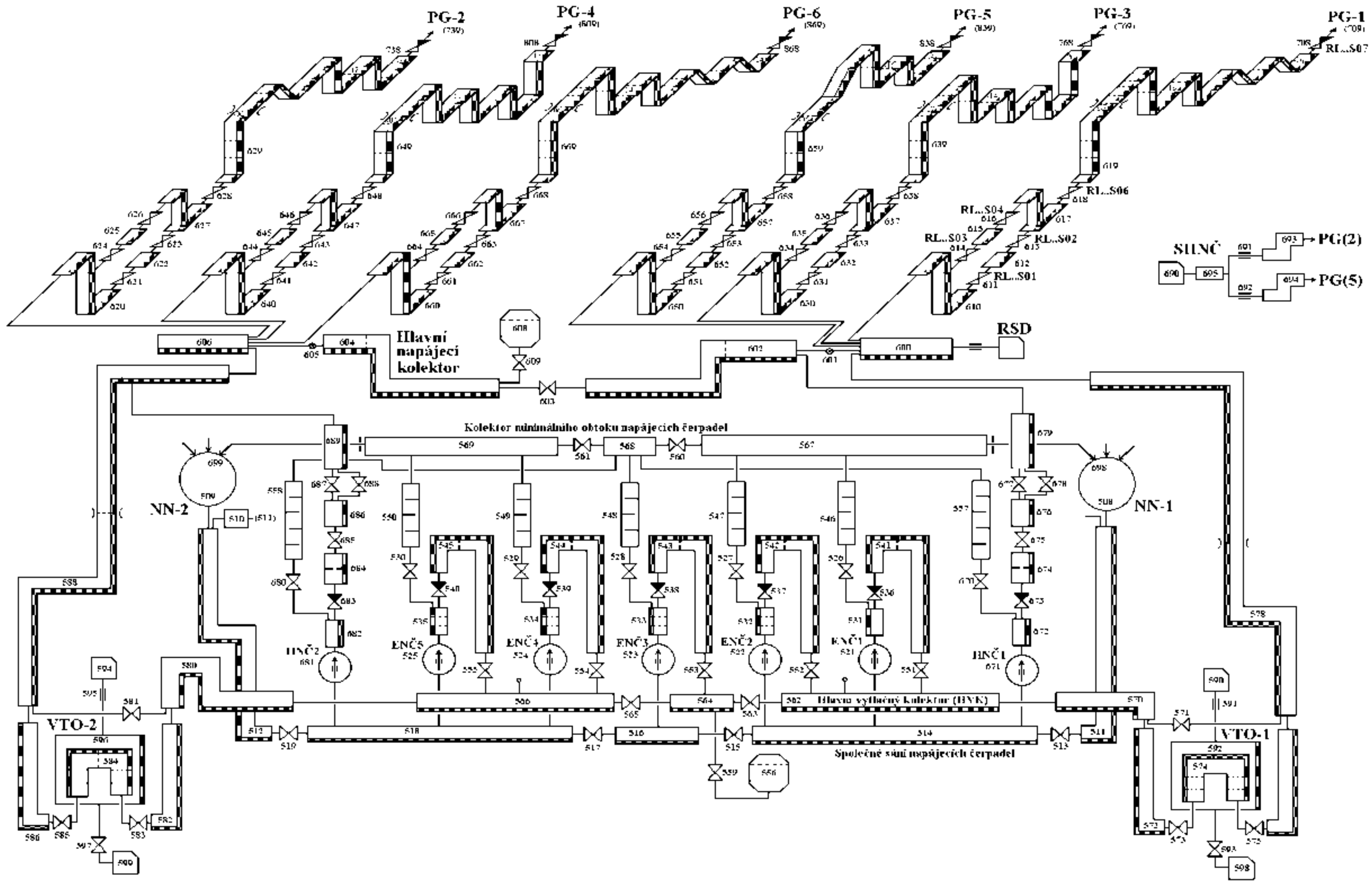
Relap5/Mod3.3 Input Model (cont'd)



Nodalization of Main Steam System (MSS) of NPP Dukovany with VVER-440/213

Skupina ÚJV
TECHNOLOGIE | INOVACE | LIDÉ

Relap5/Mod3.3 Input Model (cont'd)



Nodalization of Feedwater System of NPP Dukovany with VVER-440/213

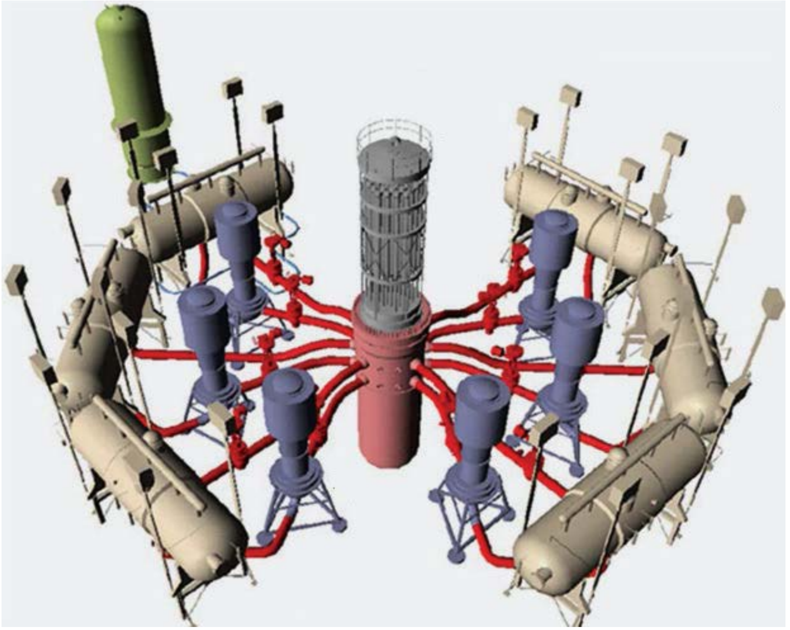
Skupina ÚJV
TECHNOLOGIE | INOVACE | LIDÉ

Relap5_3D Model of VVER-440

- The RELAP5/MOD3 input model for VVER-440 created in UJV Rez was used as a base for the RELAP5-3D input deck.

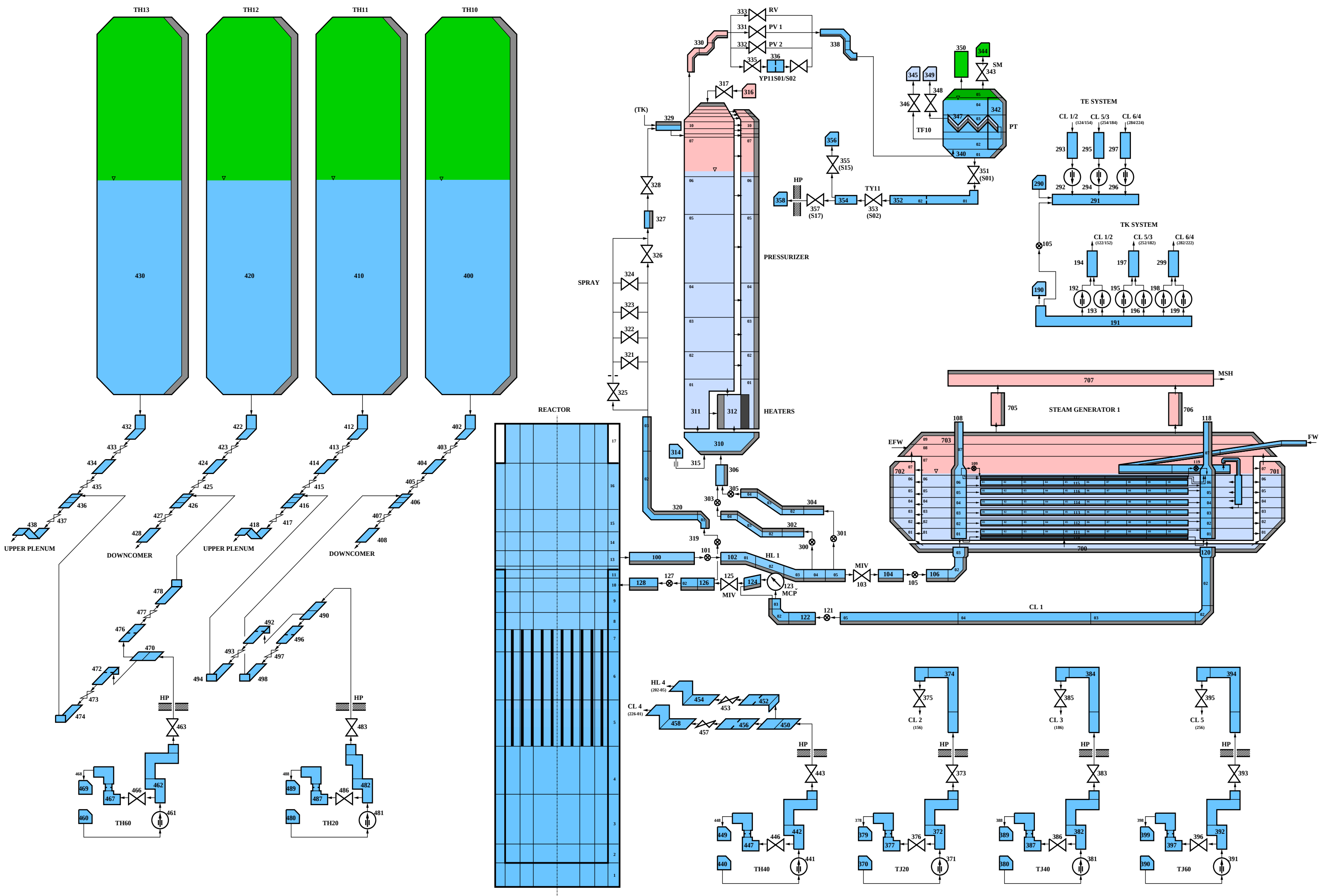
- The reactor vessel is described by the following R5-3D components:
  - 1 MULTID (3D) object representing reactor DC, LP, core bypass, UP, UH (17 axial levels, 4 radial sectors, 8 azimuthal sectors)
  - 49 PIPES representing 349 fuel assemblies

- The model prepared for PTS analyses uses point-kinetics model of reactor core (no need for 3D neutron kinetics in PTS analyses)



Skupina ÚJV
TECHNOLOGIE I INOVACE I LIDÉ

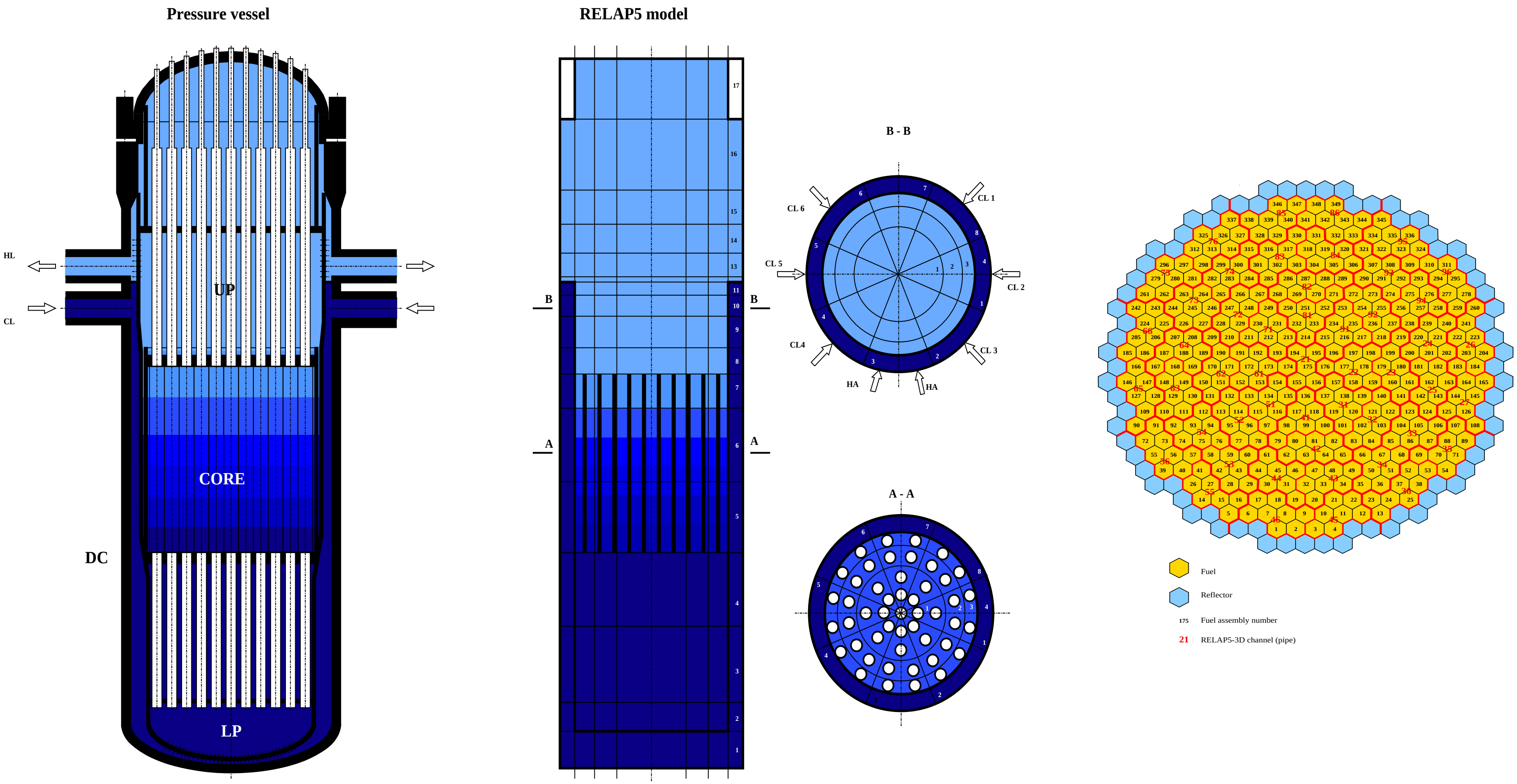
Relap5_3D Model of VVER-440



Nodalization of VVER-440 RCS with 3D model of reactor
(only 1 of 6 primary loops depicted)

Skupina ÚJV
TECHNOLOGIE | INOVACE | LIDÉ

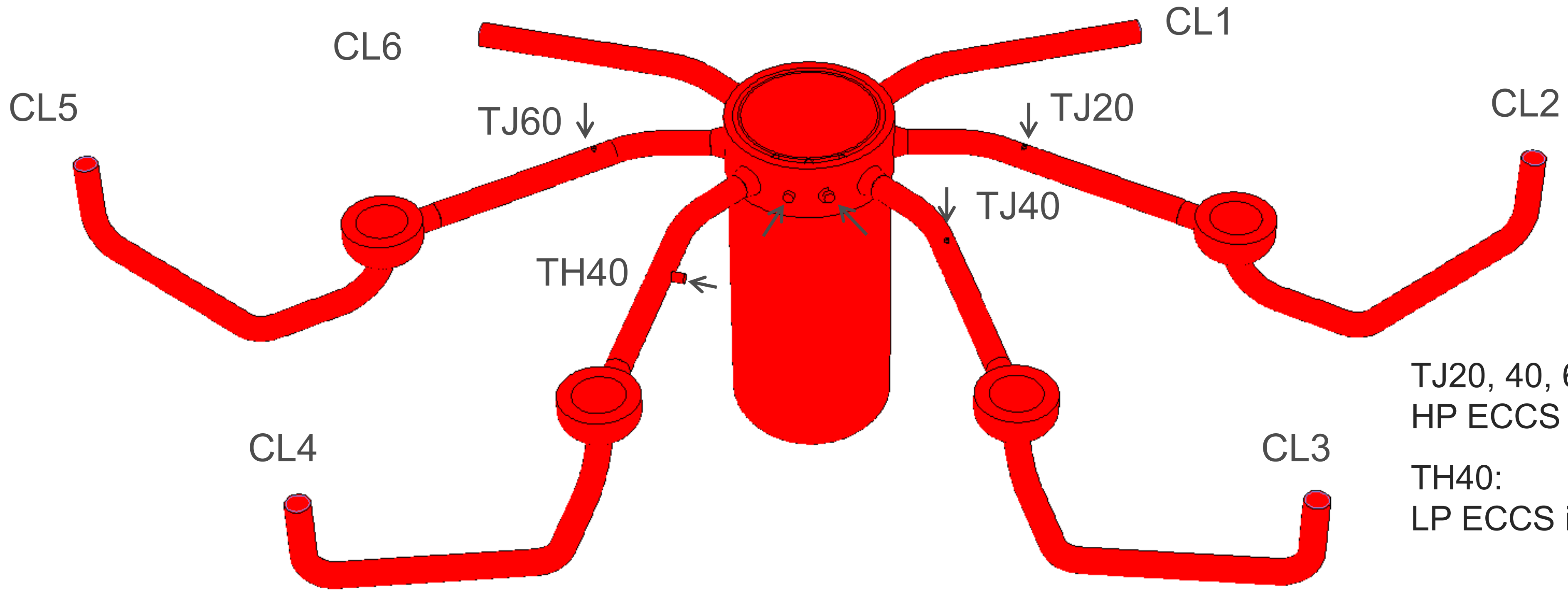
Relap5_3D Model of VVER-440



Reactor vessel and core nodalization

CFD Fluent Model of VVER-440 for PTS Calculations

Computational Domain

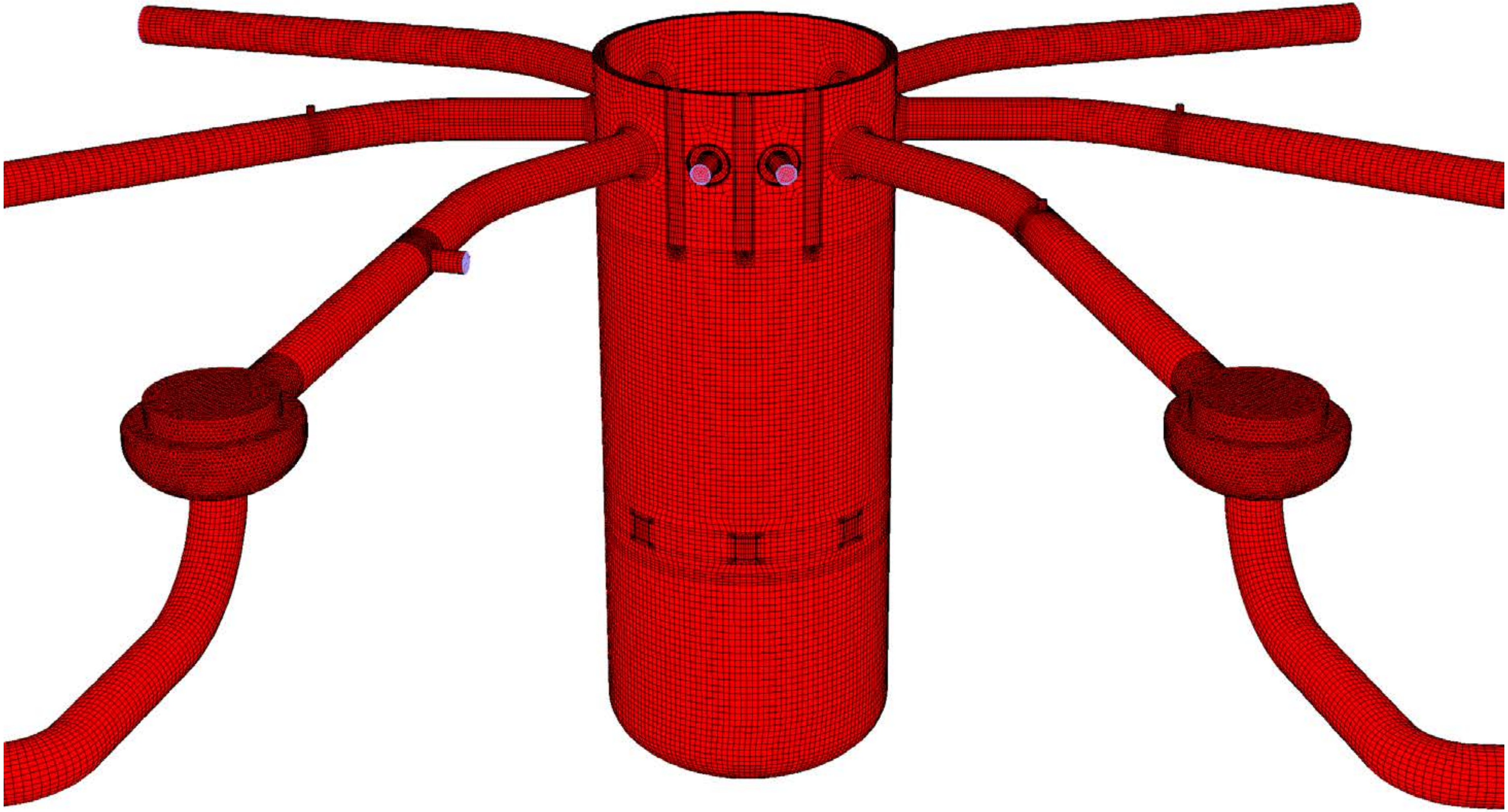


TJ20, 40, 60:
HP ECCS injections

TH40:
LP ECCS injection

- 2.1M computational cells, 1.4M cells in fluid domain, 0.7M cells in solid walls
- Calculations of long transients (~1hour or longer)
- Initial and boundary conditions for CFD are taken over from RELAP5 simulation.
- Goal of the CFD simulation: temperature fields on wetted walls in cold legs and on RPV wall in downcomer
- Depending on the solved case, some parts can be deleted from the computational domain, e.g. cold legs without operating injections.

CFD Fluent Model of VVER-440 for PTS Calculations



Computational mesh in the fluid domain

Wall-adjacent cells are 1mm thin.
Turbulence is modelled with the realizable k-ε model.

Comparison of R5/M3 – FLUENT results of various PTS analyses for VVER-440

Comparison of R5/M3 – FLUENT results of various PTS analyses for VVER-440

Parameters transferred from system TH analysis to mixing CFD calculation:

- **Reactor pressure and temperature (lower plenum)**
- **Coolant velocity, temperature and void at SG outlet**
- **Coolant velocity, temperature and void at reactor inlet**
- **HPIS flow to cold legs and temperature (3+3 par.)**
- **LPIS flow to cold leg and temperature**
- **Hydroaccumulators flow to downcomer and temperature**

Comparison of R5/M3 – FLUENT results of various PTS analyses for VVER-440

SBLOCA with 90 mm break in hot leg from full power with 3/3 HPIS in operation:

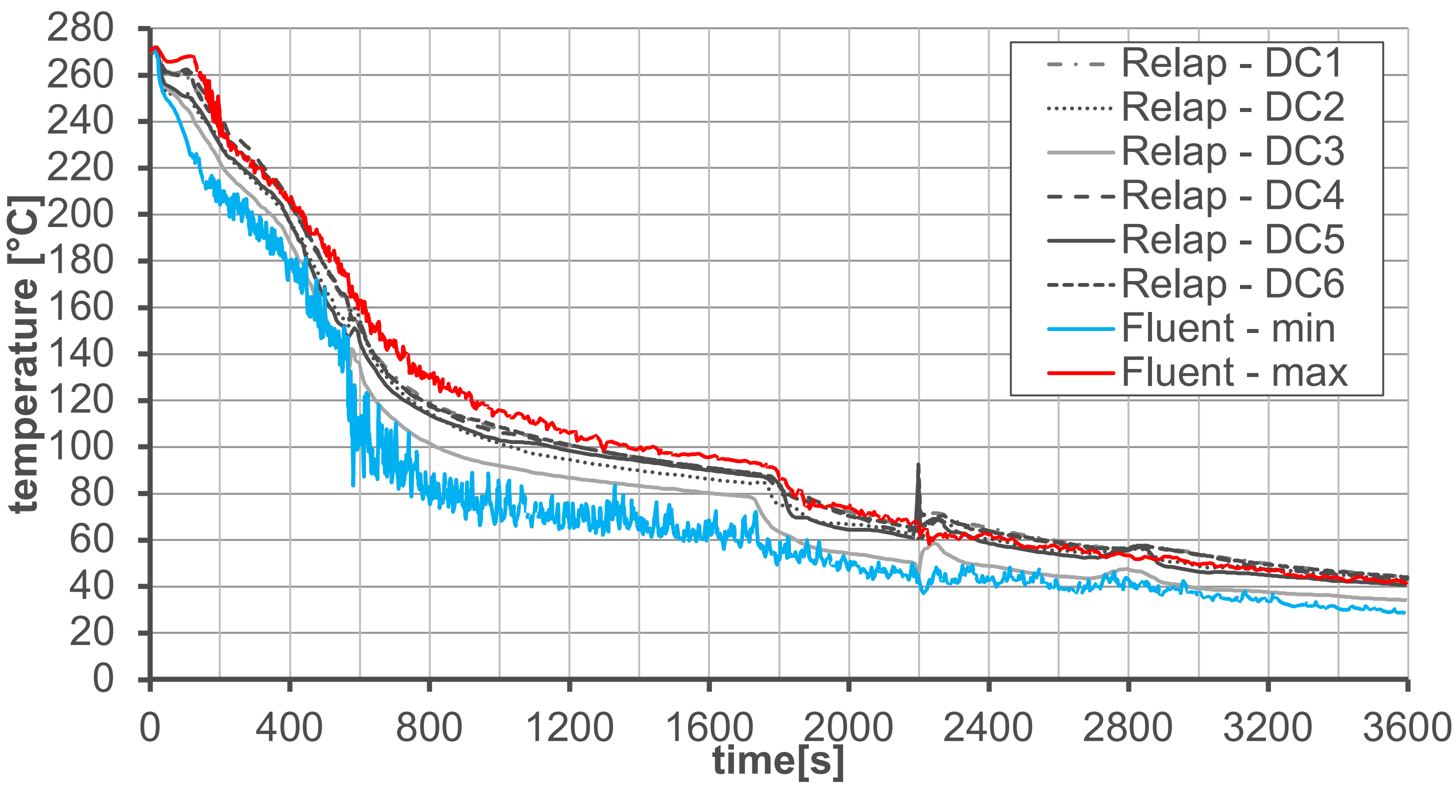


Fig. 22 Temperatures of wetted surface on the RPV weld 5/6

Note: The weld 5/6 is located next to the reactor core, 3.74 m below axes of the cold legs.

Comparison of R5/M3 – FLUENT results of various PTS analyses for VVER-440

SBLOCA with 30 mm break in hot leg from zero power with 3/3 HPIS in operation:

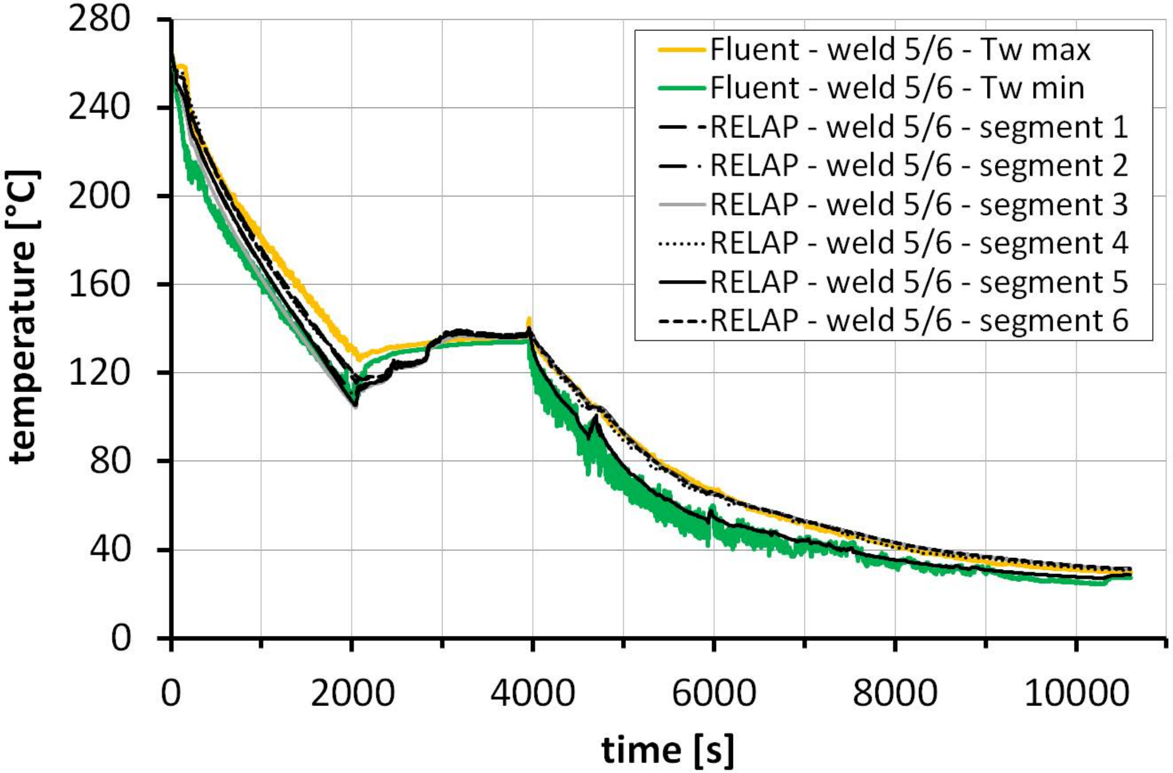


Fig. 22 Temperatures of wetted surface on the RPV weld 5/6

Comparison of R5/M3 – FLUENT results of various PTS analyses for VVER-440

MSLB at zero power with 3/3 HPIS

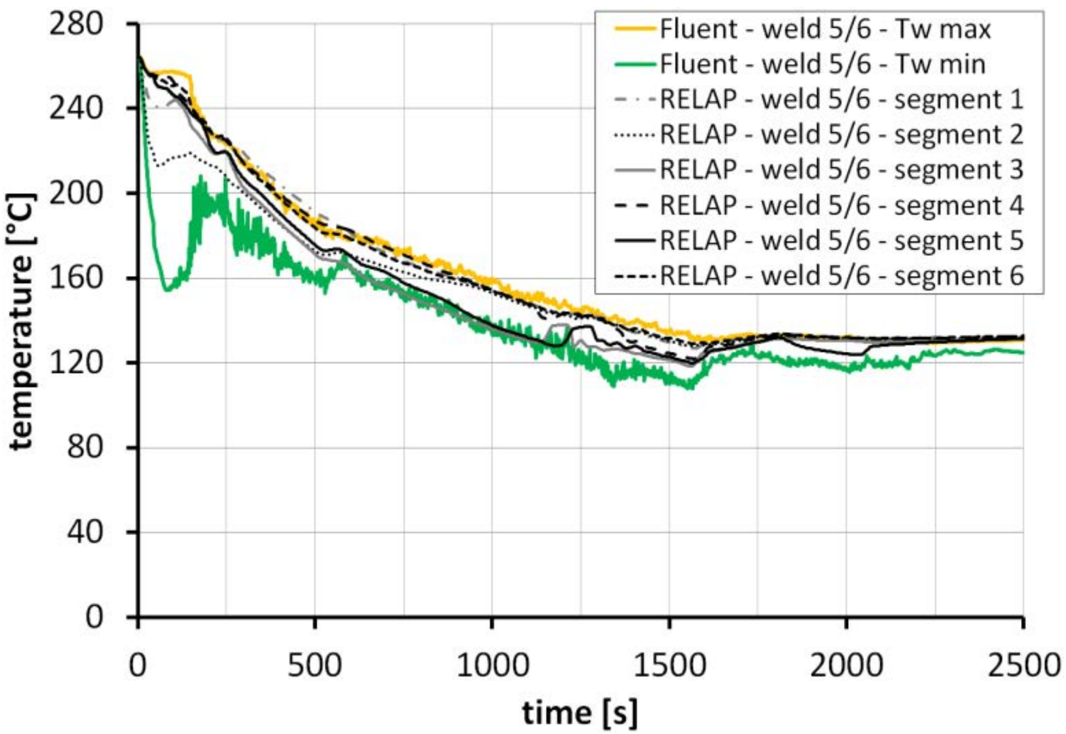


Fig. 22 Temperatures of wetted surface on the RPV

Comparison of R5/M3 – FLUENT results of various PTS analyses for VVER-440

PRISE with SG internal manifold failure from HZP and with 1/3 HPIS

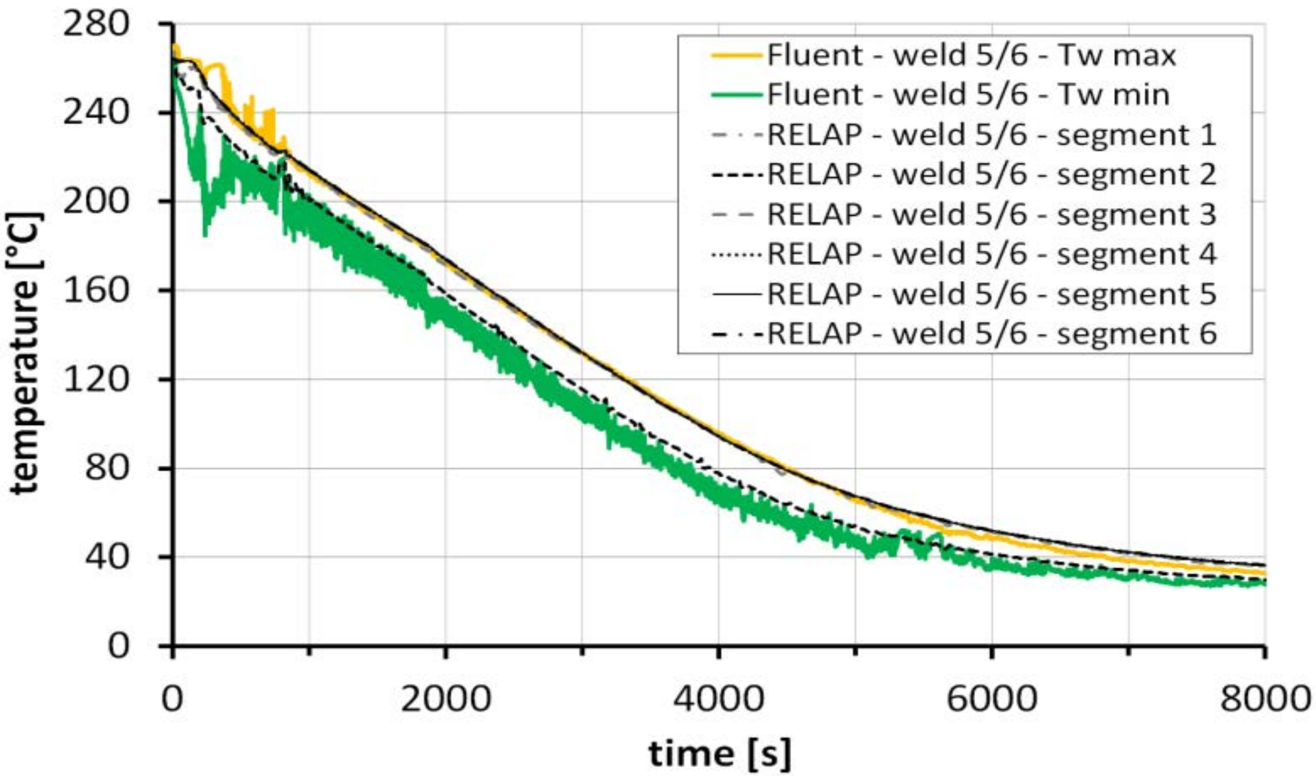


Fig. 22 Temperatures of wetted surface on the RPV

Comparison of R5/M3 – FLUENT results of various PTS analyses for VVER-440

Inadvertent opening of PRZ SV at full power and its re-closure at 1800 s with 3/3 HPIS

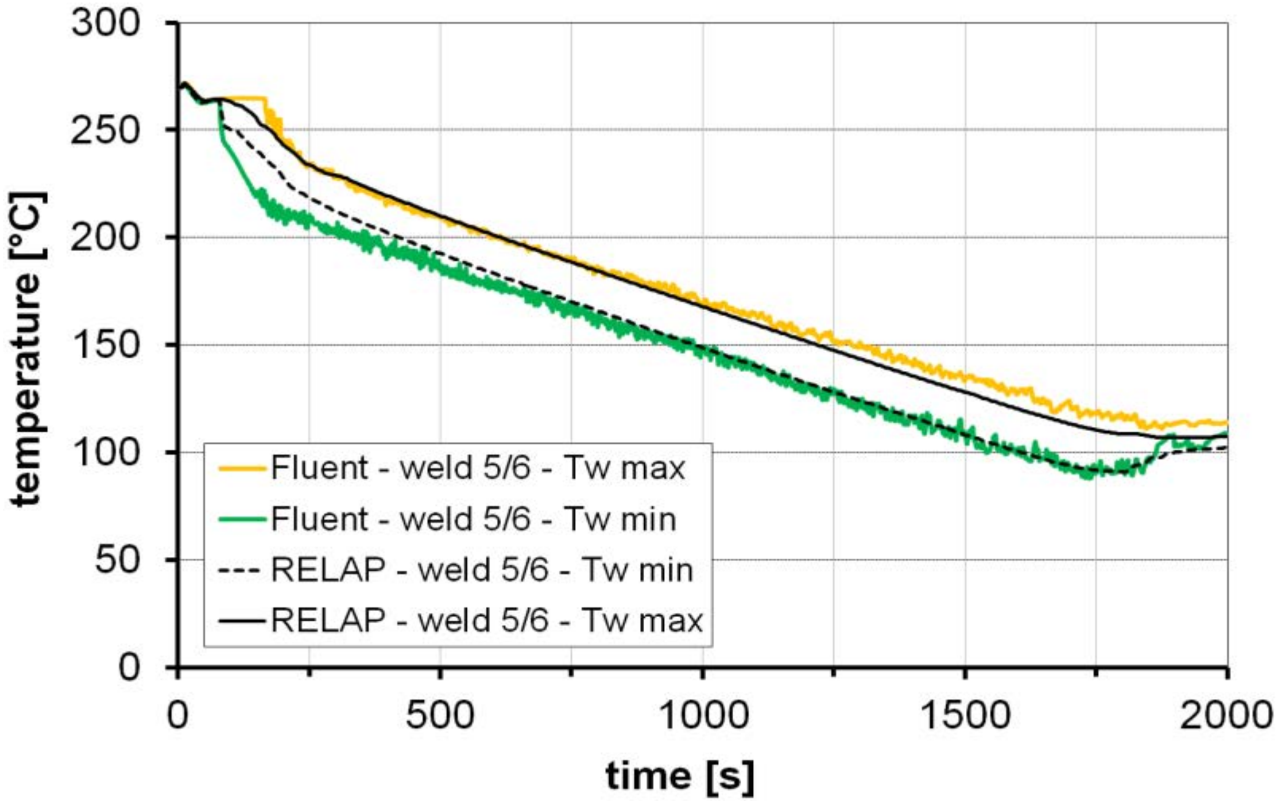


Fig. 22 Temperatures of wetted surface on the RPV

Comparison of results of R5/M3 – R5/3D analysis of medium break LOCA with break D200 mm in hot leg

Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

System TH calculation of medium-break LOCA in VVER-440 with 2D model of DC:

- **Starting from full power (1502 MWt)**
- **Break D200 mm in hot leg of loop No.1**
- **Full availability of ECCS (3/3 HPIS, 4/4 ACCU, 3/3 LPIS)**
- **Conservative assumptions for PTS analysis**

- **Calculations with RELAP5/MOD3.3 and with RELAP5-3D**

Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Initial parameters

PARAMETR	UNIT	VALUE R5/M3.3	VALUE R5-3D
Reactor power	MW	1501,8	1502,0
Reactor inlet coolant temperature	°C	270,1	270,1
Reactor outlet coolant temperature	°C	303,0	304,0
Reaktor coolant flow	kg/s	8623	8636
Core bypass	kg/s	733,3 (8,5 %)	734 (8,5 %)
Primary pressure (HL)	MPa	12,66	12,66
PRZ heaters power	kW	180	360
Pressurizer level	m	6,90	7,02
SG pressure	MPa	4,90 ÷ 4,93	4,91 ÷ 4,97
MSH pressure	MPa	4,72	4,72
FW pressure	MPa	6,63	6,45
FW temperature	°C	229,2	223,4
SG collapsed level	m	1,86 ÷ 1,90	1,92
Steam output	kg/s	137,6 ÷ 138,9	135,2 ÷ 137,0

Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

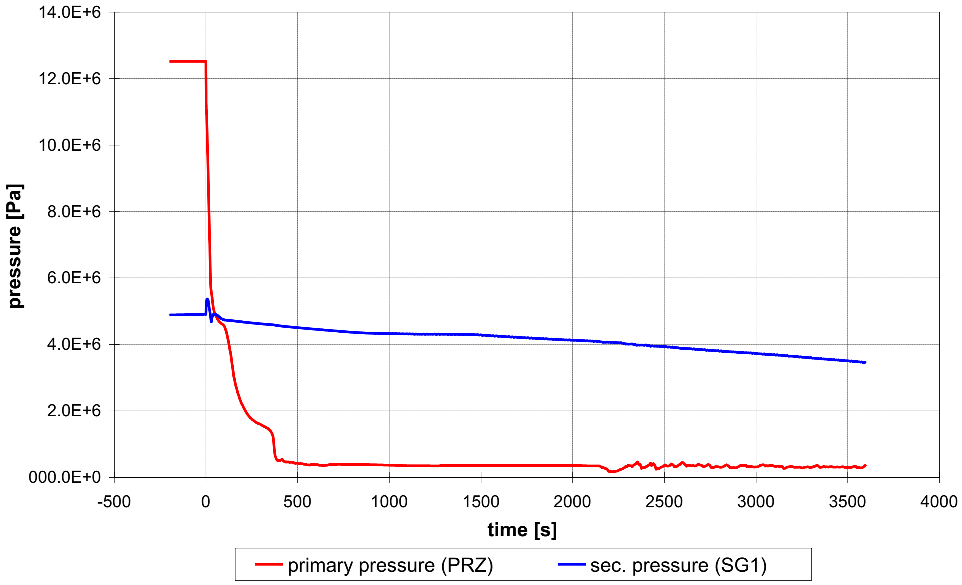
Timing of main events:

Event	Time [s] RELAP5-3D	Time [s] RELAP5-3D
Initial event = break D200 mm in hot leg of loop No.1	0	0
LOOP	0	0
Reactor SCRAM	0,5	0,5
Start of 3/3 HPIS injection	22	30
Start of 4/4 ACC injection	131	126
End of ACC injection	352	280
Start of 3/3 LPIS injection	367	300
End of calculation	3600	3600

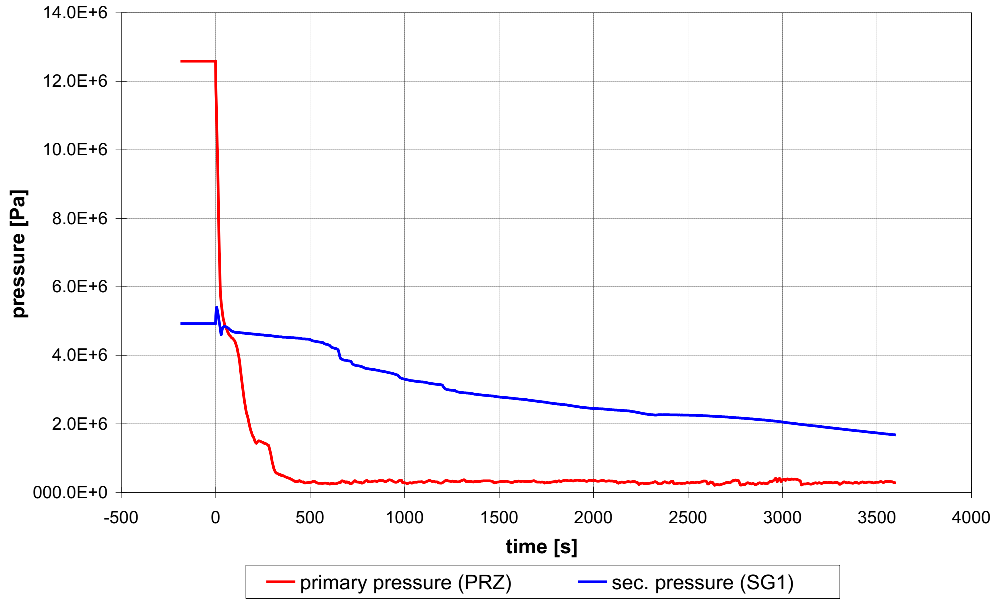
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Primary and secondary pressure

RELAP5/MOD3



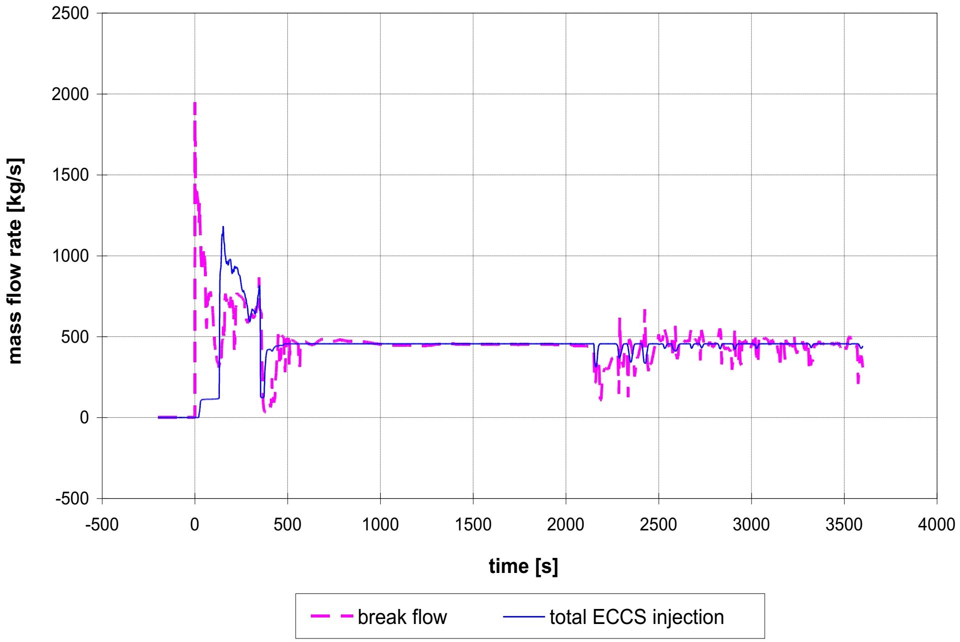
RELAP5-3D



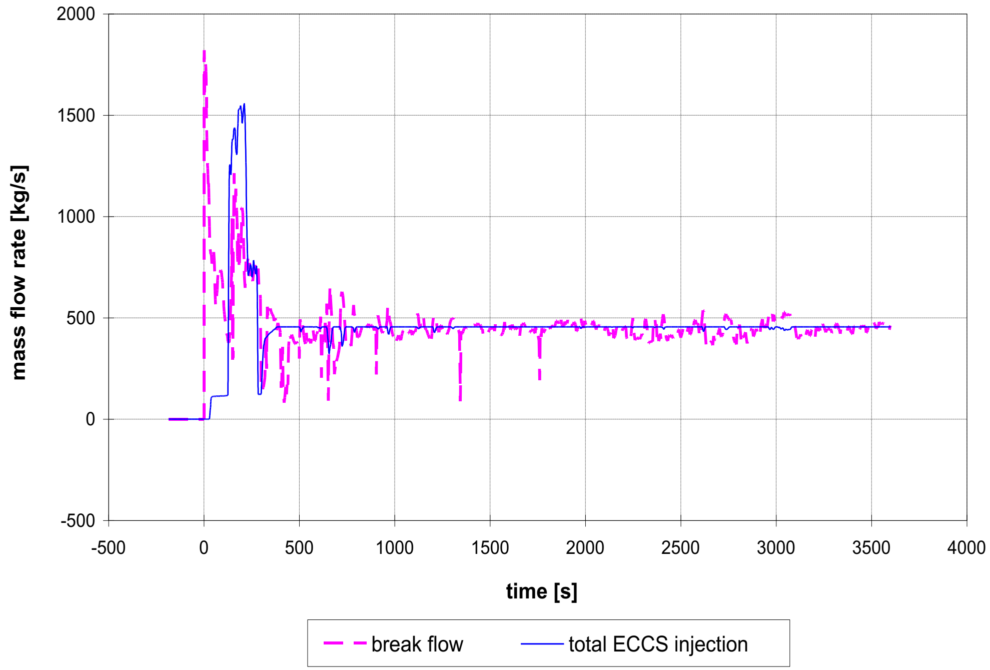
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Break and ECCS flow

RELAP5/MOD3



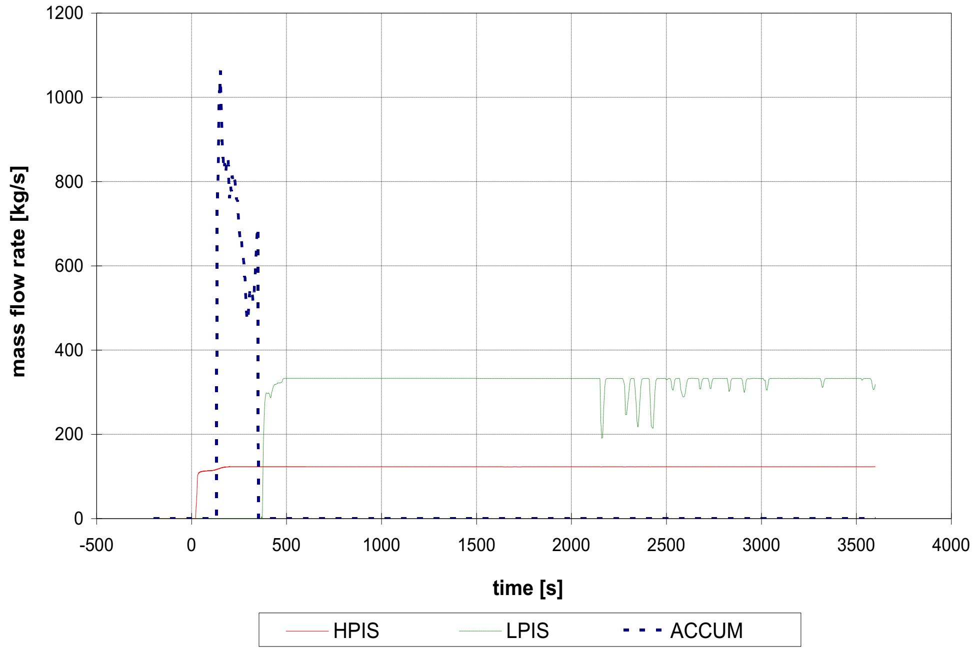
RELAP5-3D



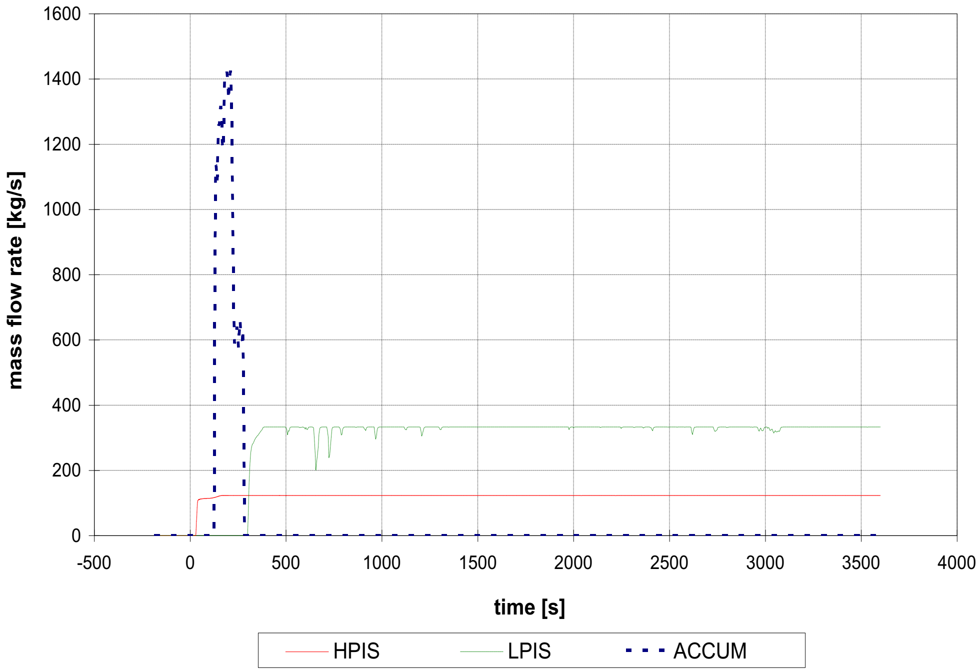
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Injection of individual ECCS systems

RELAP5/MOD3



RELAP5-3D

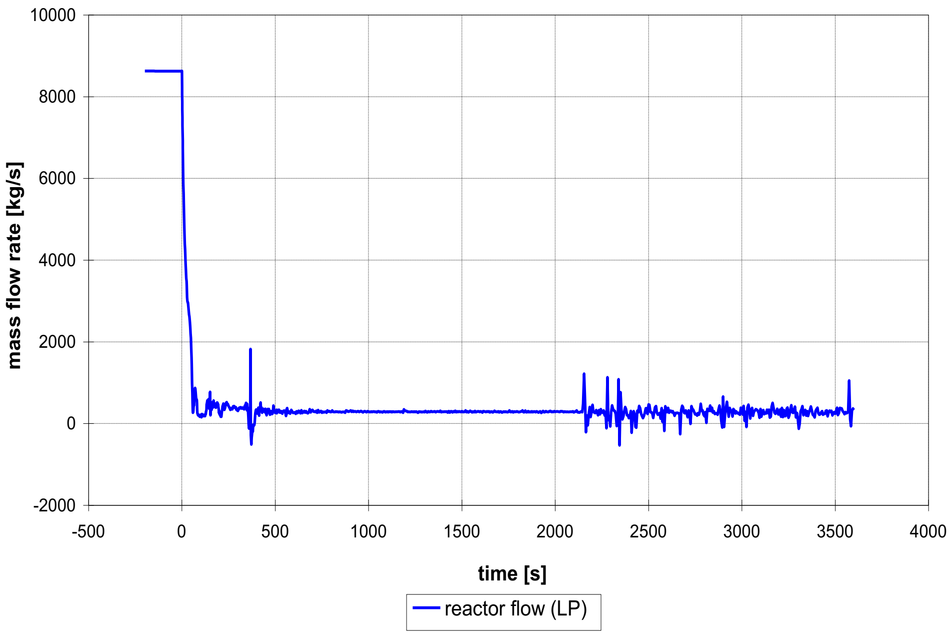


Skupina ÚJV
TECHNOLOGIE | INOVACE | LIDÉ

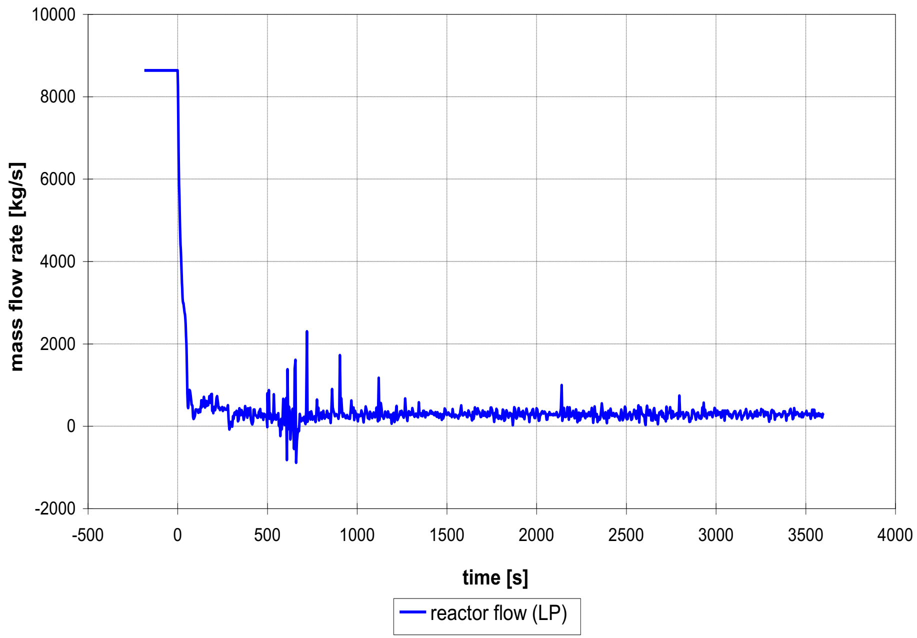
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Reactor flow

RELAP5/MOD3



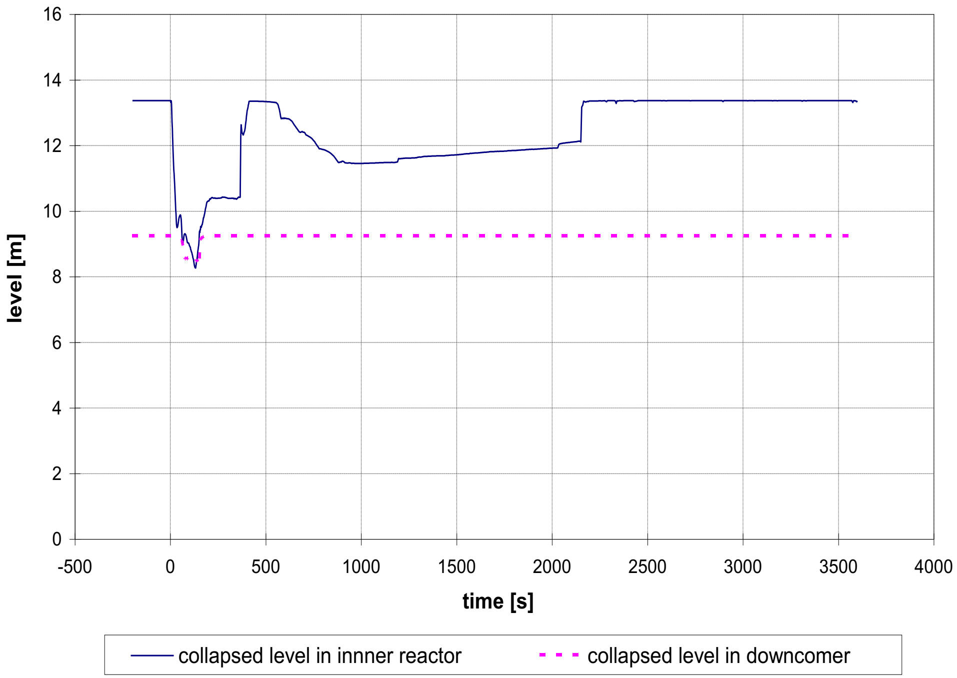
RELAP5-3D



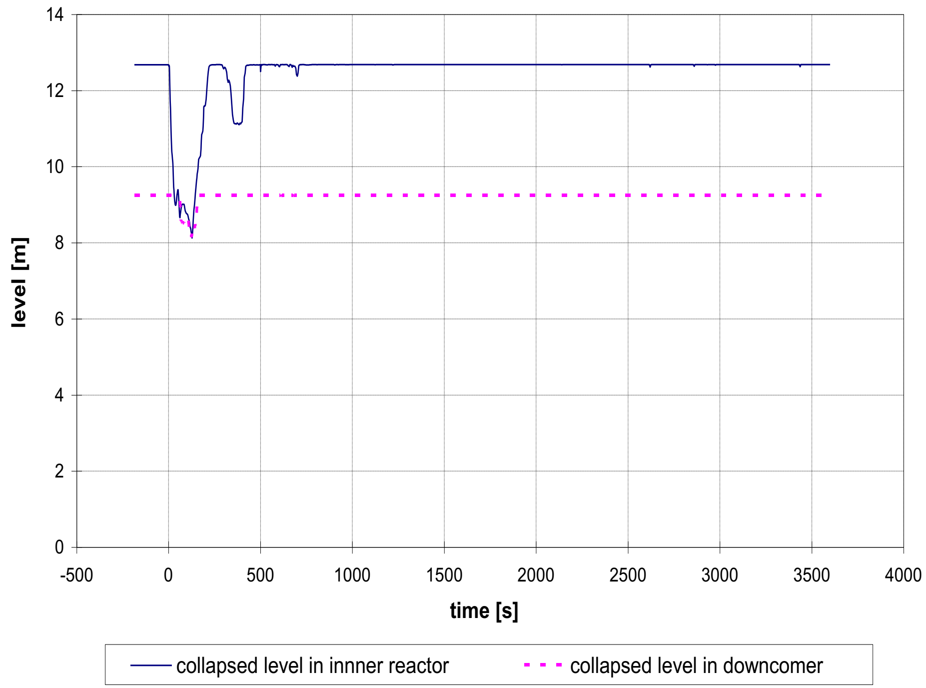
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Reactor level

RELAP5/MOD3



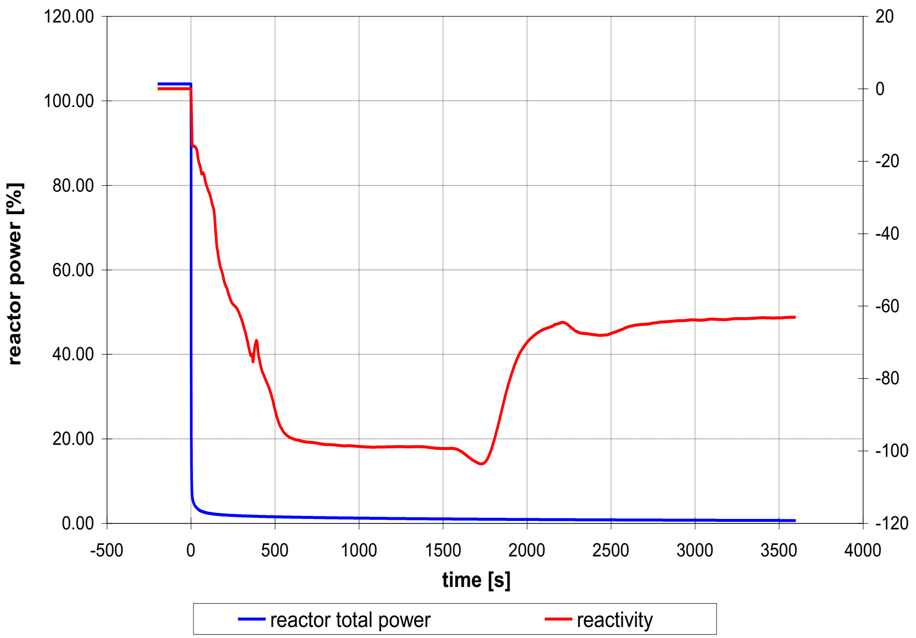
RELAP5-3D



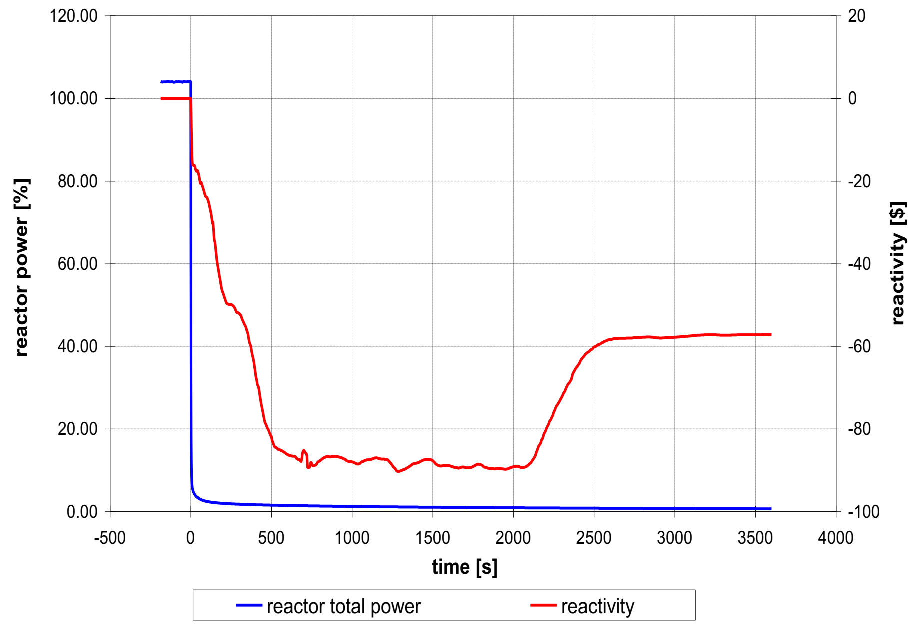
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Reactor power and reactivity

RELAP5/MOD3



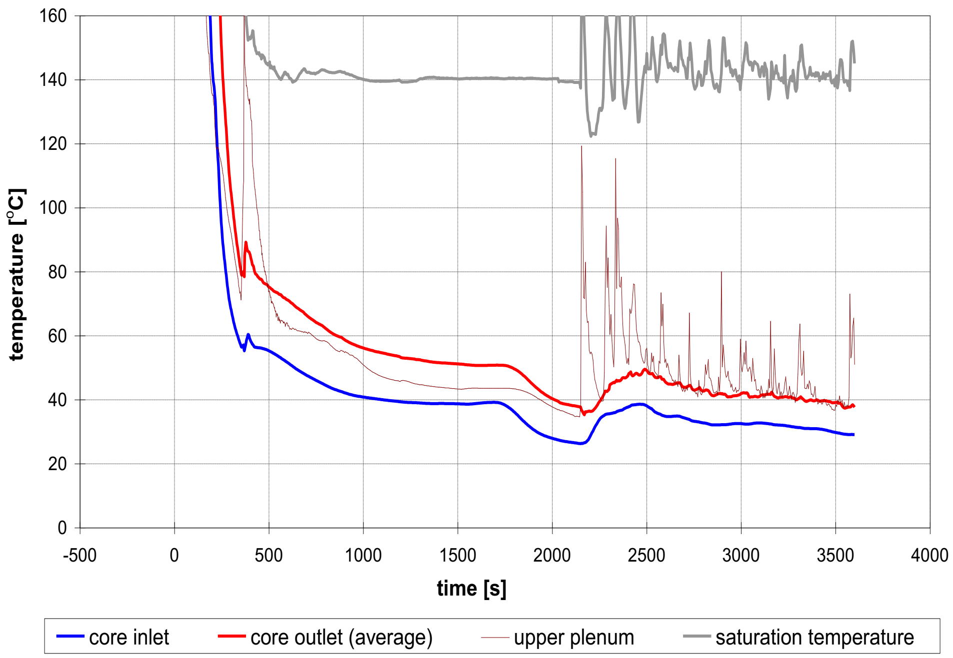
RELAP5-3D



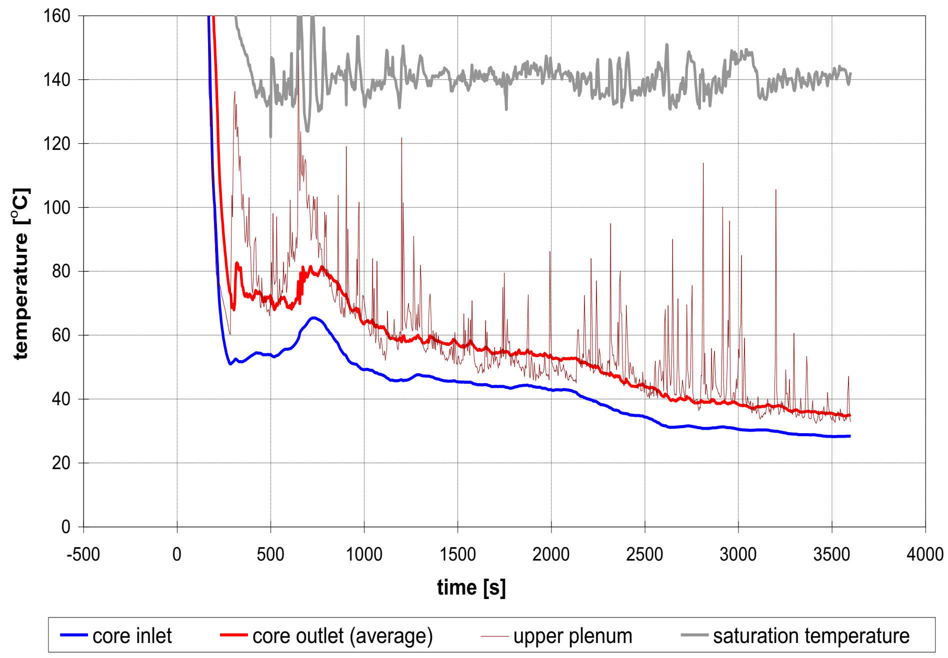
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Coolant temperatures in reactor

RELAP5/MOD3



RELAP5-3D

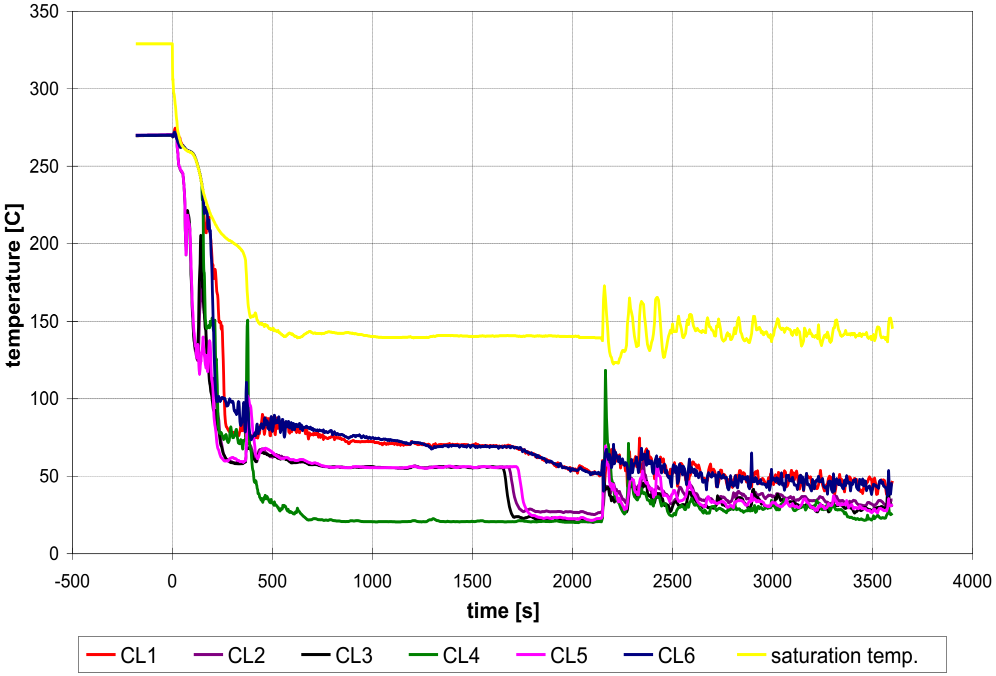


Skupina ÚJV
TECHNOLOGIE I INOVACE I LIDÉ

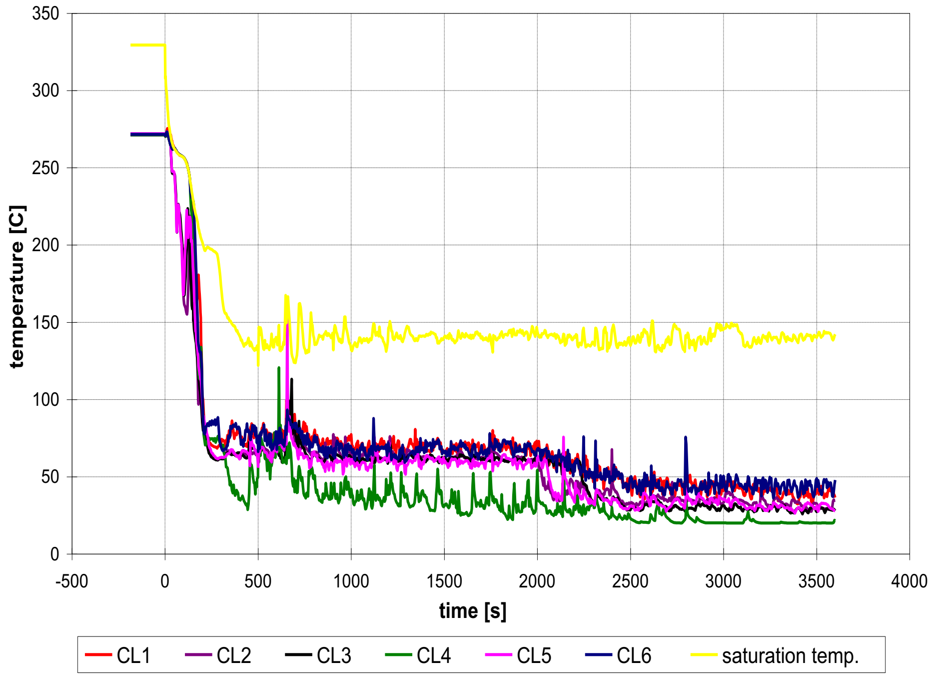
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Coolant temperatures at reactor inlet

RELAP5/MOD3



RELAP5-3D

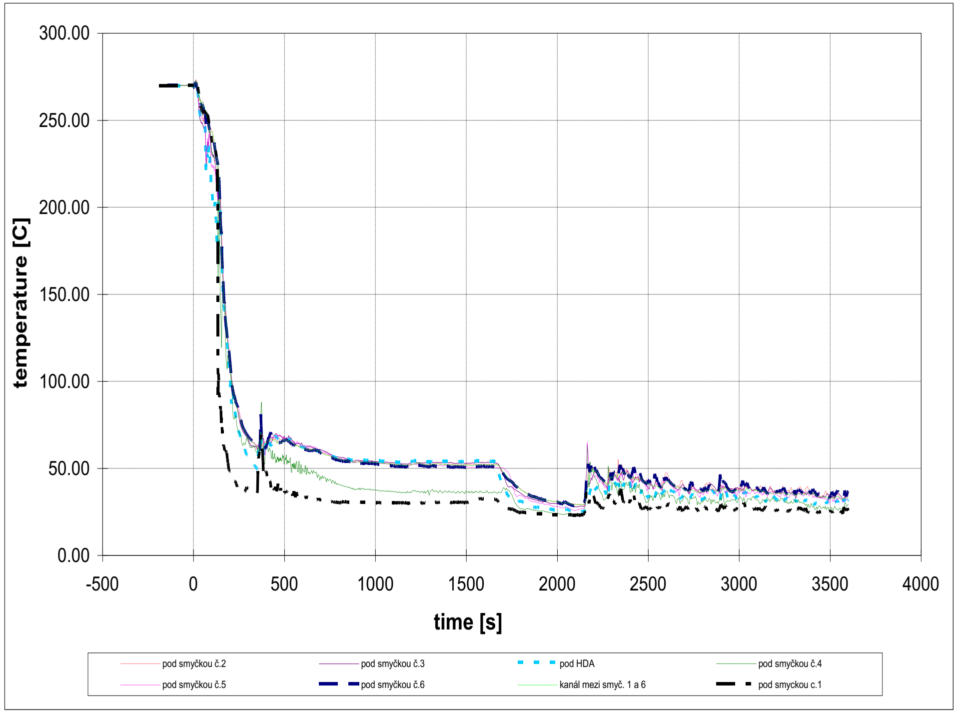


Skupina ÚJV
TECHNOLOGIE | INOVACE | LIDÉ

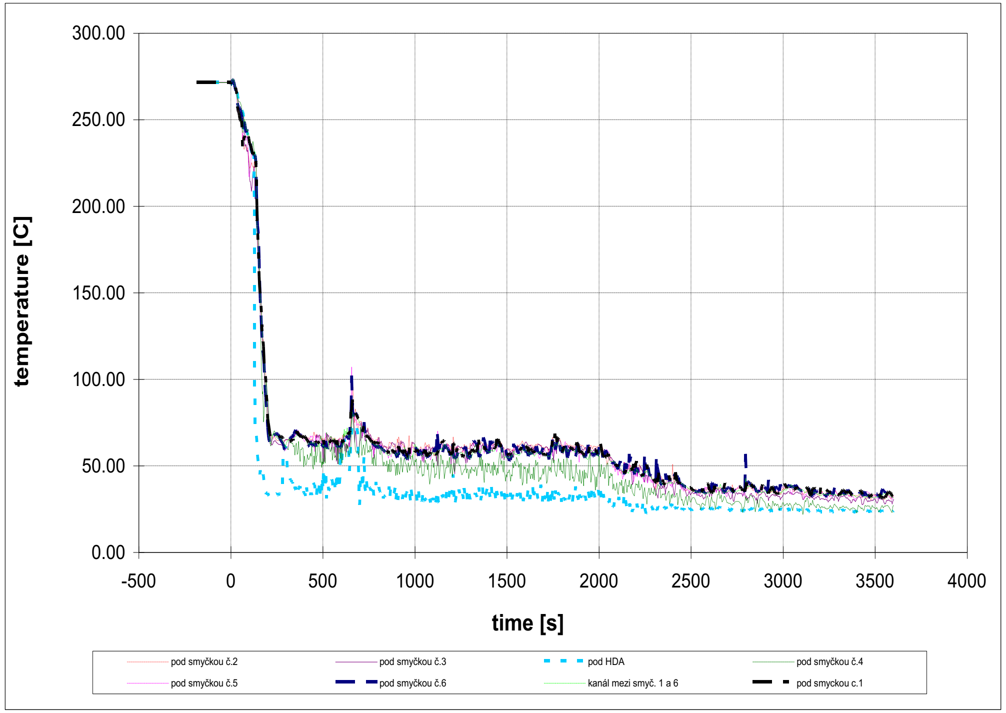
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Coolant temperatures around downcomer (at core elevation)

RELAP5/MOD3



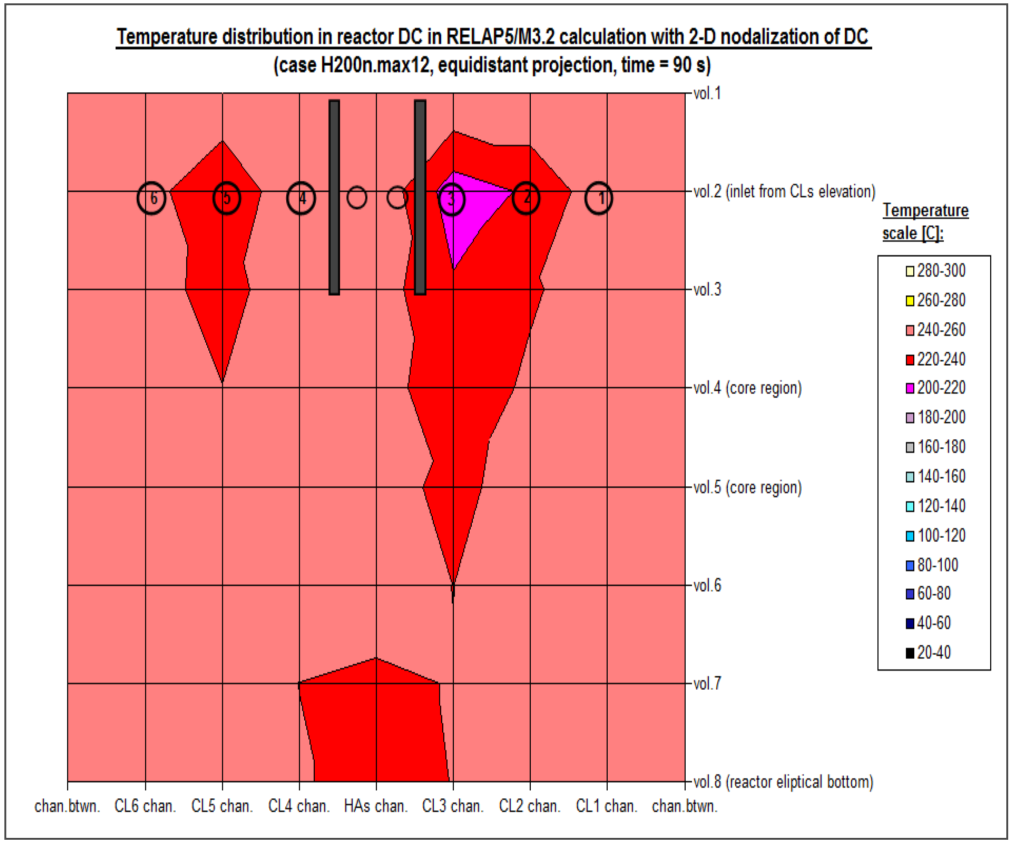
RELAP5-3D



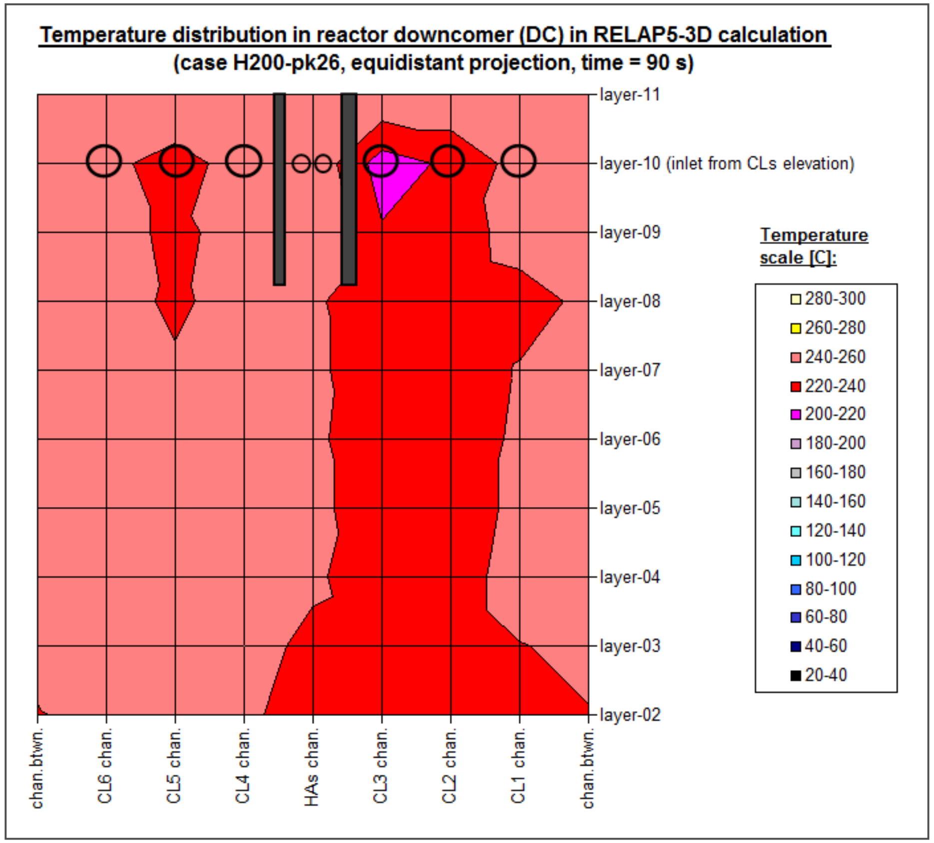
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Coolant temperatures field in downcomer at 90 s (HPSI dominating)

RELAP5/MOD3



RELAP5-3D

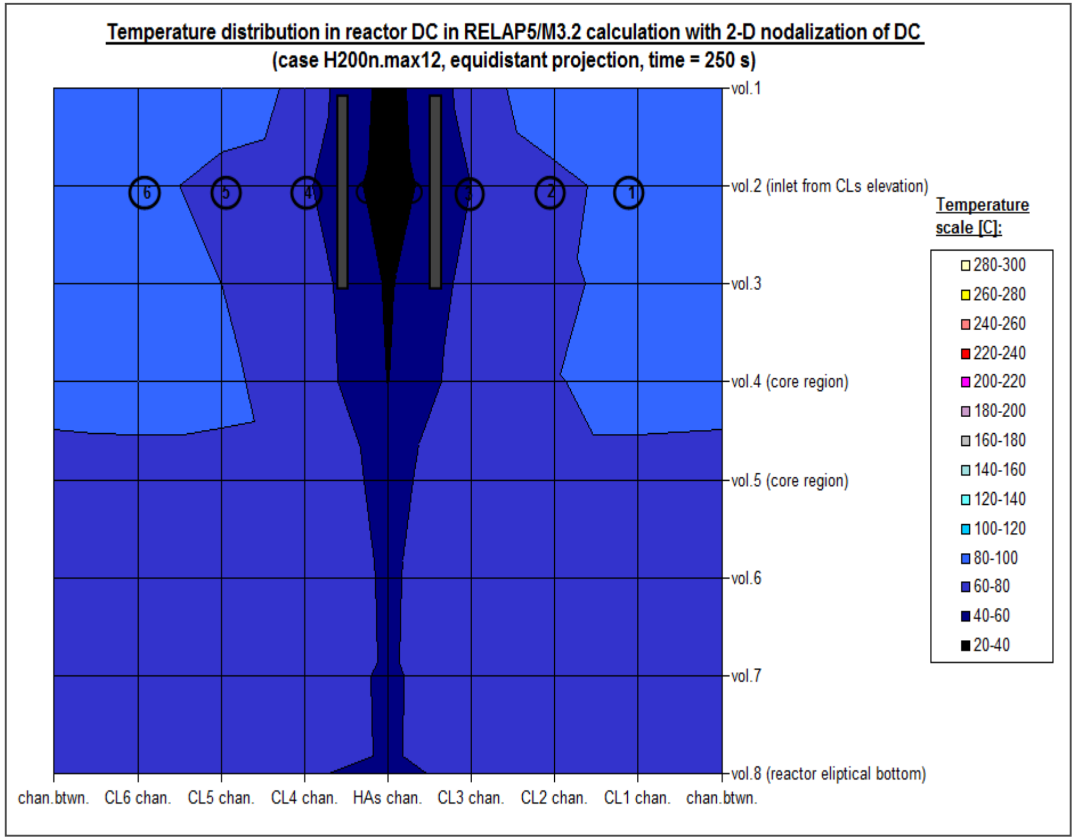


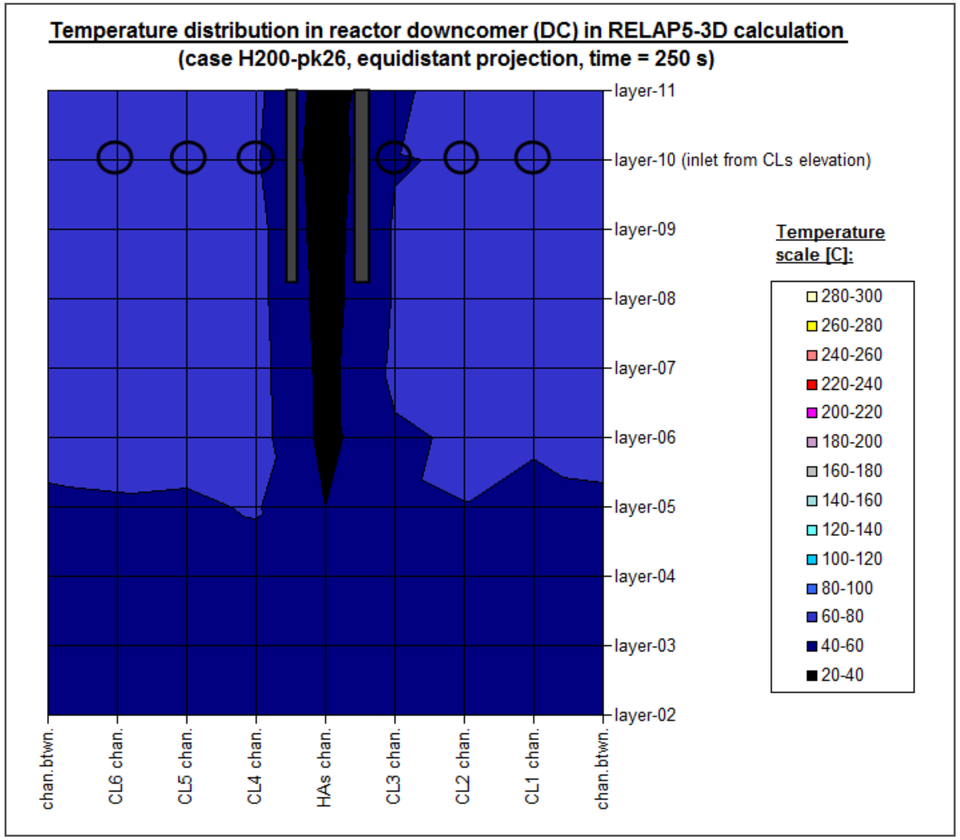
Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Coolant temperatures field in downcomer at 250 s (ACCUM injection dominating)

RELAP5/MOD3

RELAP5-3D





Skupina ÚJV
TECHNOLOGIE I INOVACE I LIDÉ

Comparison of R5/M3 – R5/3D results of analysis of MBLOCA with break D200 mm in hot leg

Preliminary conclusions from calculations of MBLOCA D200 with Relap5/Mod3.3 and Relap5-3D and comparison of results:

- **Good overall agreement**
- **Major difference is the stronger ACCUM injection and faster filling of reactor vessel UP and UH – probably due to differences in predicted condensation in UP – which may be caused by finer nodalization of UP in Relap5-3D model**
- **Further analysis of results needed**

Conclusions

- The paper presents briefly overall UJV approach to PTS evaluation
- Increasing computational power enables wider deployment of CFD in PTS analyses
- For predominantly single-phase cases, the system TH analysis with Relap5/Mod3.3 (and 2D nodalization of reactor DC) is followed by CFD mixing calculation of downcomer and cold legs domain
  - Surprisingly good agreement between Relap5 and Fluent in prediction of temperature field in DC
- For two-phase cases the result from system TH analysis with 2D downcomer nodalization (Relap5/Mod3.3) have been directly transferred to integrity calculations
- Application of Relap5-3D is a new progressive step in PTS method applied to Czech NPPs (just started)

- *Another direction of progress in UJV Rez thermal-hydraulic methods for PTS evaluation is the coupling of system TH code and CFD code – for predominantly single phase cases (not presented in the paper)*

Thank you for your attention

www.ujv.cz

Skupina ÚJV
TECHNOLOGIE I INOVACE I LIDÉ