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Assessment and Application of RELAP5-3D to Gen-II,III,IV Reactor Designs

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OUTLINES

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1) INTRODUCTION

- **Growing demand for deterministic safety analyses in the Czech Republic**
  - **Extension of analyses for existing NPPs (more comprehensive elaboration of SA, events in shutdown conditions, design extension conditions DEC-A, assessment of I&C diversity, EOP support etc.)**
  - **Independent analyses for new PWR build (candidates: AP1000, EPR1200, APR1400)**
  - **Analyses of SMR and GenIV**
- **Continuous computer codes validation**
- **Licensing of computer codes to be used for NPP safety analyses (regulatory body SUJB guide BN-JB-2.4)**
- **The RELAP5 computer code (both the Mod3.3 and the 3D version) is the main working horse in this area**

1) INTRODUCTION

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Suite of computer codes used in UJV Rez for safety analyses of DBA:

Type of code	Modeled systems							Additional info	
	Core NK	**Core TH**	**RCS TH**	**ECCS**	**FWS + MSS**	**I&C**	**Containment**	Comment to physical models	Typical size of comp. cell
System TH codes (RELAP, ATHLET, APROS)	**YES** (0D/1D/3D)	**YES** (1D/ 3D)	**YES** (1D/3D)	**YES**	**YES**	**YES**	Simplified	Verified model of 2-phase flow.	0,25÷2 m
NK codes (DYN3D, NESTLE)	**YES** (3D)	**YES**	Bound. cond.	-	-	Part.	-	Diffusion 3D model of neutron flux	0,02÷0,25 m
Coupled TH-NK codes (RELAP5-3D, ATHLET-DYN3D, APROS)	**YES** (1D or 3D)	**YES** (1D/ 3D)	**YES** (1D/3D)	**YES**	**YES**	**YES**	Simplified	3D 2-phase TH model of RPV + 3D diffusion model of neutron flux	TH: 0,25÷2 m NK: 0,02÷0,25 m
CFD (FLUENT, NEPTUNE, TRIO)	-	**YES** (3D incl. turb.)	**3D** , RCS partially	Bound. cond.	-	-	Bound. cond.	Turbulent mixing models	0,01 m
Subchannel codes (VIPRE)	-	**YES** (3D)	Bound. cond.	-	-	-	-	Core mixing models	0,01÷0,1 m
Fuel thermo-mech. (TRANSURANUS)	-	**-**	-	-	-	-	-	TM model of fuel	0,01÷0,1 m
Containment codes (COCOSYS, MELCOR,GOTHIC)	-	-	Bound. cond.	Sprays	Bound. cond.	Part.	**YES** (1D/3D)	Special models for containment phenomena	1÷10 m
Radiolog. conseq. (JRODOS)	-	-	-	-	(ST)	-	(ST)	RIMPUSS dispersion model	100m ÷10 km

1) INTRODUCTION

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Methods of safety analyses applied in the Czech Republic
(based on IAEA SSG-2, Rev.1, 2019)

Methodology of licensing analysis	Computer code type	Initial and boundary conditions	Assumptions on systems availability	Application in the Czech Rep.
1) Conservative methodology	Conservative	Conservative	Conservative	N/A nowadays
2) Combined methodology	**Best estimate**	**Conservative**	**Conservative**	**AOO and DBA**
3) Best estimate plus uncertainty evaluation (BEPU)	**Best estimate**	**Best estimate + uncertainty**	**Conservative**	**AOO and DBA**
4) Realistic	**Best estimate**	**Best estimate**	**Best estimate**	**DEC-A**

2) Overview of RELAP5-3D assessment in UJV Rez

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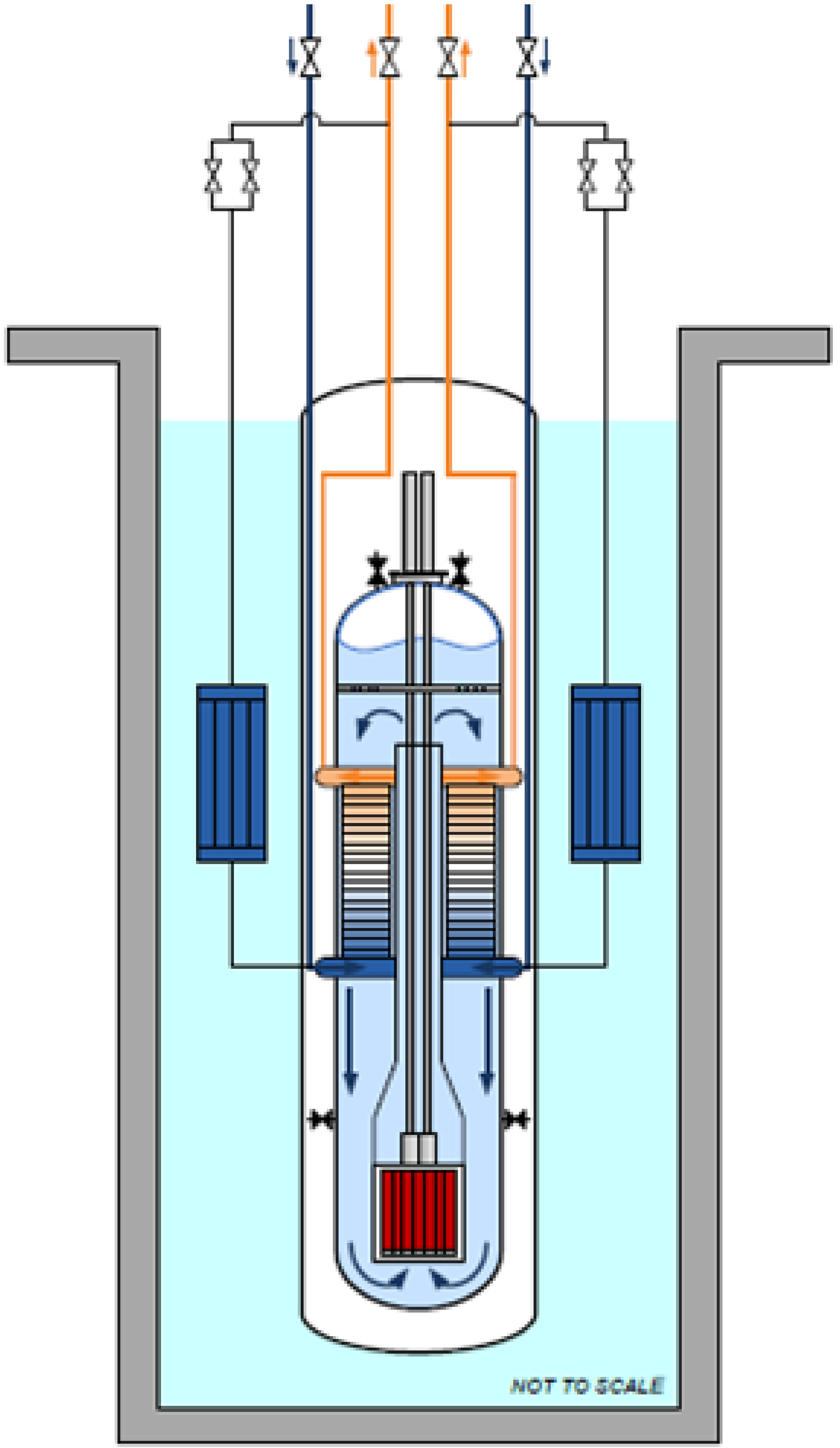
- **Introductory analysis with RELAP5-3D and comparison with RELAP5/MOD3.2.1, SBLOCA in VVER-1000, 2004**
- **Pre-test analysis of LBLOCA in the PSB-VVER experimental facility, OECD, 2007**
- **Validation of the VVER-440 thermal-hydraulic model for RELAP5-3D on mixing test from NPP Dukovany, 2009**
- **Participation in the 6th AER Dynamic Benchmark (VVER-440, MSLB), 2003,** (see https://doi.org/10.13182/NSE07-A2728)
- **Participation in the 7th AER Dynamic Benchmark (VVER-440, reactivity insertion due to connection of isolated loop), 2012** (see https://doi.org/10.3139/124.110702)
- **Validation analysis of SBLOCA in the PSB-VVER experimental facility, OECD, 2013**
- **Validation analysis of SBLOCA in the PKL experimental facility, OECD, 2013**
- **Comparison analysis of PTS events with RELAP5/MOD3.3 and CFD code, 2018**
- **Analysis of MSLB in NuScale and intercomparing between codes, EU McSAFER project, 2022**
- **Post-test analyses of reflood tests on RBHT facility, OECD, 2023**

3) Analyses of NuScale and intercomparison between codes

- EU project McSafer Task 4.2 Boron dilution in NuScale (UJV was the task leader)
- Computer codes and organizations:
    - RELAP5-3D (UJV)
    - TRACE (JRC)
    - TRACE (UMP)
    - ATHLET (HZDR)
- Point-kinetics models used in Task 4.2 (3D neutronic models to be used in following Task)
- Deliverable D4.4: Analysis of NuScale plant with 3D system code and intercomparing between codes



3) Analyses of NuScale and intercomparison between codes

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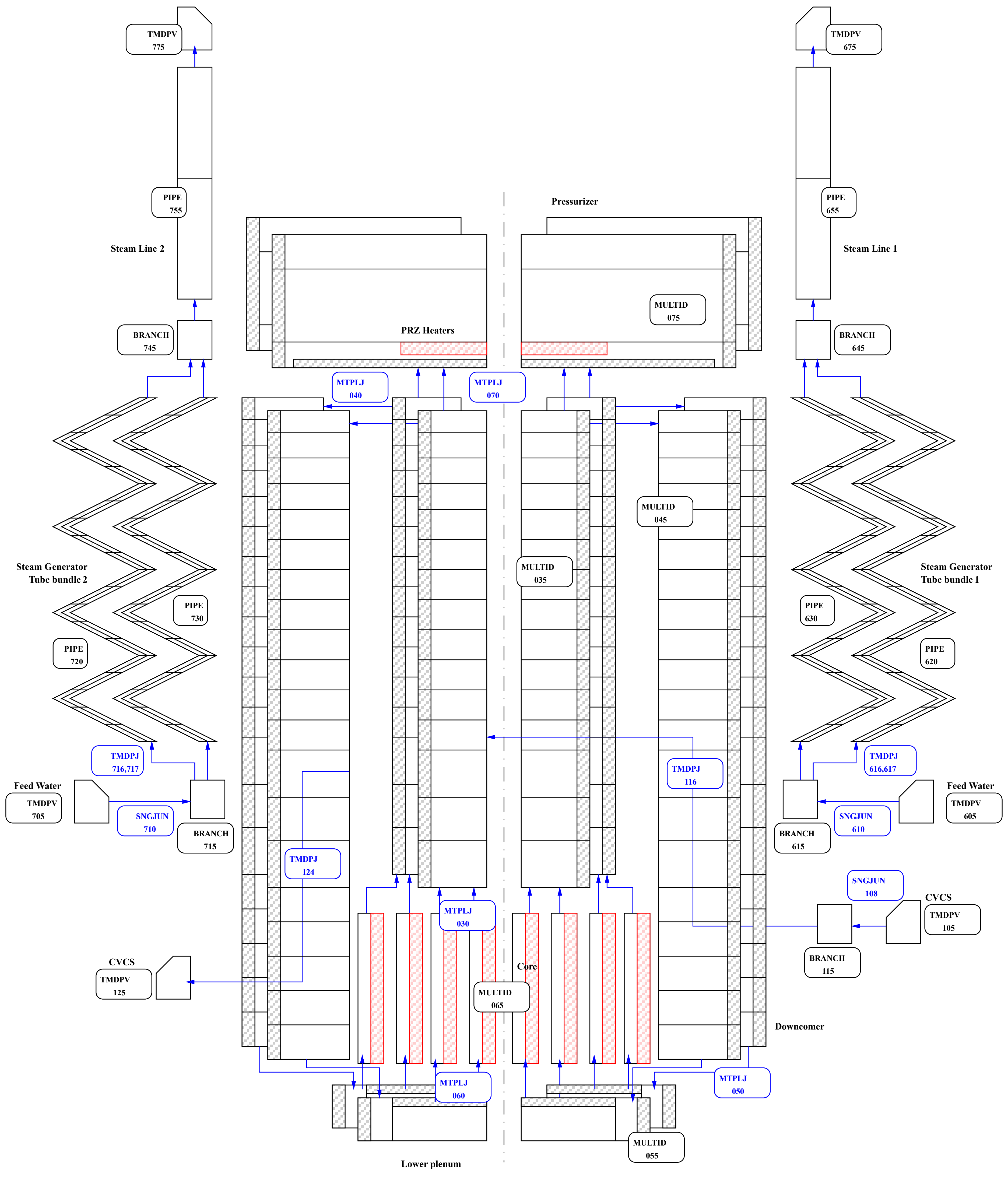
UJV model of NuScale for RELAP5-3D

- The vessel is modelled three-dimensionally in cylindrical geometry with 4 azimuthal sectors by interconnected MULTID components:
  - Riser
  - Downcomer
  - Lower plenum
  - Pressurizer
- The core is modelled by 3D component MULTID. All 37 fuel assemblies are simulated with cartesian matrix 7×7. Active height is divided into 10 axials levels. Each fuel assembly is modelled by one heat structure except for those with maximum power, where a hot pin is also considered with peak linear power 16.4 kW/m. For hot pins CHF is evaluated by using Groeneveld look up tables.
- The core bypass is simulated by four PIPE components (in each azimuthal sector).



3) Analyses of NuScale and intercomparison between codes

Steady-state parameters	DCA	UJV (error%)	HZDR (error%)	JRC (error%)	UPM (error%)
RCS pressure (bar)	127.55	127.57 (0.02)	126.45 (-0.86)	127.55 (0.0)	127.80 (0.19)
Core Power (MW)	160	160.01 (0.0)	159.98 (0.01)	160.00 (0.0)	160.0 (0.0)
Core inlet T (K)	531.48	531.39 (-0,02)	526.87 (-0.86)	531.67 (0.04)	527.34 (-0.78)
Core outlet T (K)	-	591.68	588.08	591.68	588.13
RCS mass flow rate (kg/s)	535.24	535.27 (0.0)	531.97 (-0.61)	535.31 (0.01)	536.49 (0.23)
Core mass flow rate (kg/s)	496.17	496.24 (0.01)	490.89 (-1.06)	501.75 (1.12)	494.6 (-0.32)
PRZ level (%)	60	60.01 (-0,02)	58.82 (-1.96)	60.07 (0.12)	59.99 (-0.02)
Initial boron concentration (ppm)	1600	1599.9 (0.0)	1600.25 (0.01)	1600.00 (0.0)	1601.83 (0.11)
Primary inventory (kg)	-	47403.0	47836	46890.45	49513.43
FW mass flow rate (kg/s)	67.07	67.07 (0.0)	67.07 (0.0)	67.07 (0.0)	67.07 (0.0)
SG1 mass flow rate (kg/s)	-	35.22	35.22	35.22	35.22
SG2 mass flow rate (kg/s)	-	31.85	31.85	31.85	31.85
SG1 inlet T (K)	421.87	421.87 (0.0)	421.44 (-0.10)	421.88 (0.0)	421.88 (0.0)
SG2 inlet T (K)	421.87	421.87 (0.0)	421.45 (-0.09)	421.88 (0.0)	421.87 (0.0)
SG1 outlet T (K)	580.04	582,03 (0.34)	583.88 (0.66)	583.57 (0.61)	565.48 (-2.51)
SG2 outlet T (K)	580.04	583,34 (0.57)	583.93 (0.67)	586.68 (1.14)	571.72 (-1.43)
SG1 outlet pressure (bar)	34.47	34.52 (0.14)	33.58 (-2.58)	34.88 (1.19)	35.34 (2.52)
SG2 outlet pressure (bar)	34.47	34.49 (0.06)	33.47 (-2.90)	34.87 (1.16)	34.34 (-0.38)

3) Analyses of NuScale and intercomparison between codes

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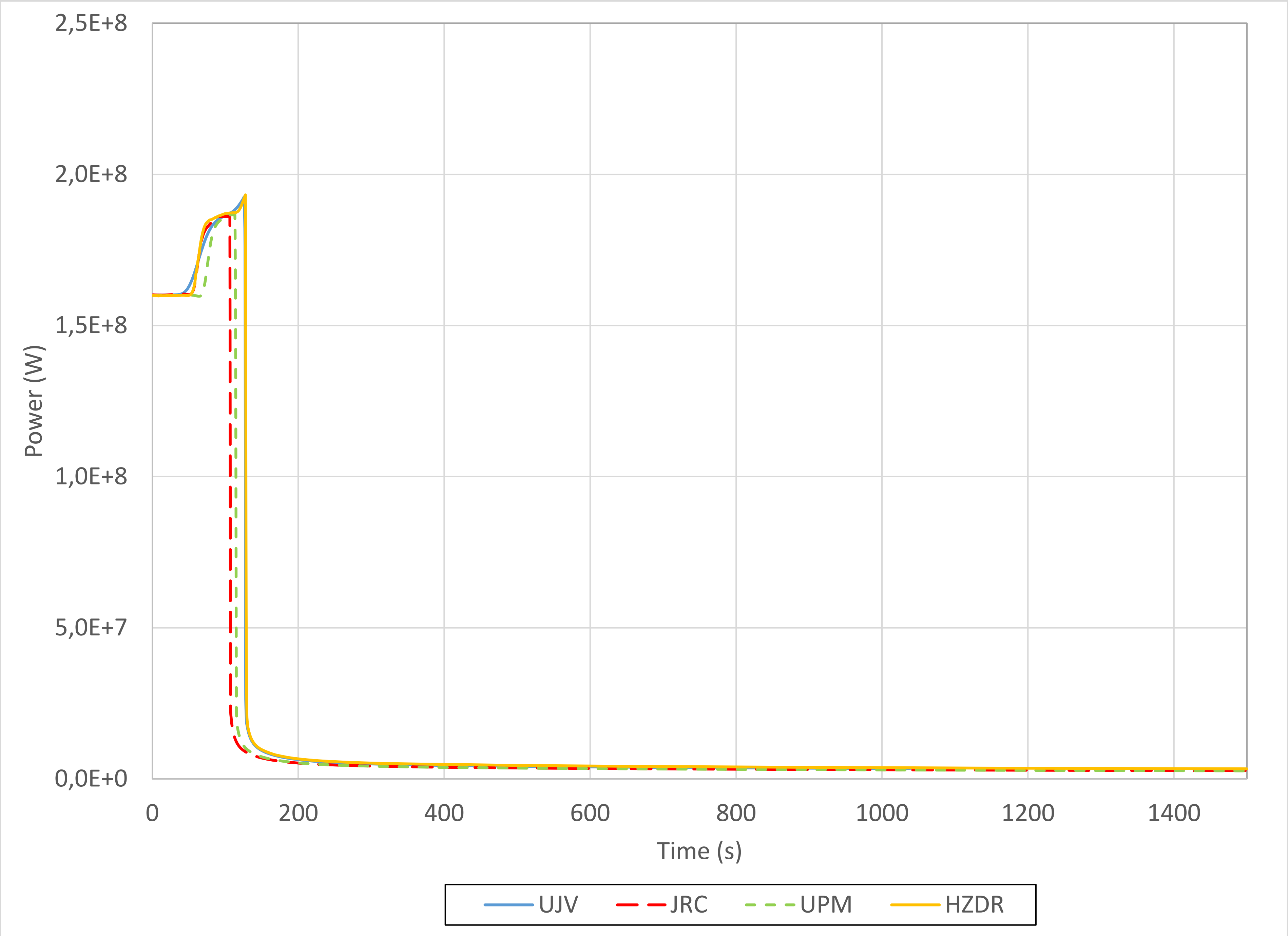
Timing of main events in UJV and HZDR calculations:

Event	UJV Time (s)	HZDR Time (s)	Comment
Steady state calculation	< 0	< 0	
Initial event	0.0	0.0	CVCS malfunction, injection of unborated water
SCRAM signal set point: High Power Range Linear Power	124.7	129.6	Reactor thermal power > 120%
CRs start to move	126.7	131.6	2 s signal delay
CVS isolation	133.7	138.6	7 s delay after SCRAM
ESFAS signal set point: Low pressurizer level	194.7	231.0	Pressurizer level < 35%
Pressurizer heaters trip	197.7	233.0	3 s signal delay
ESFAS signal set point: Low Low Pressurizer Pressure	203.0	228.0	Pressurizer pressure < 11.032 MPa
Secondary system isolation	205.0	230.0	2 s signal delay
MSIVs and FWIVs fully closed	210.0	235.0	Valve closing time = 5 s
ESFAS signal set point: High Main Steam Pressure	1036.3	1575.0	SG outlet pressure > 5.516 MPa
DHRS activated	1038.3	1577.0	2 s signal delay

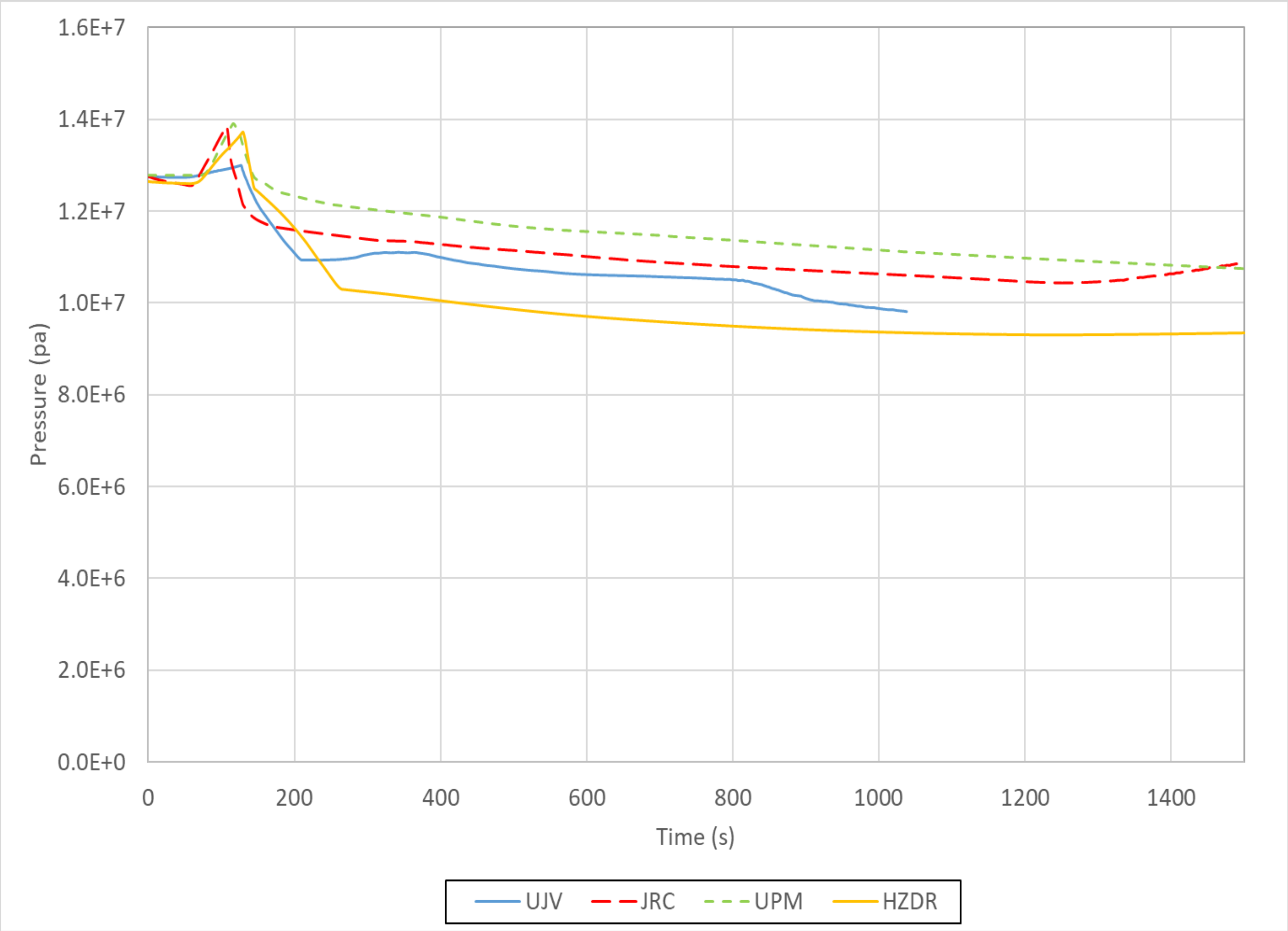
In the UJV and HZDR calculations, the reactor is shut down from the "High Power Range Linear Power" SCRAM signal. The secondary circuit is not isolated, so heat removal from the primary circuit is ensured.

In the JRC and UPM calculations, the pressure increases so much that the SCRAM / ESFAS "High Pressurizer Pressure" signal is initialized, which leads to reactor shutdown, secondary circuit isolation and DHRS activation. DHRS then ensures long-term heat removal from the primary circuit.

3) Analyses of NuScale and intercomparison between codes



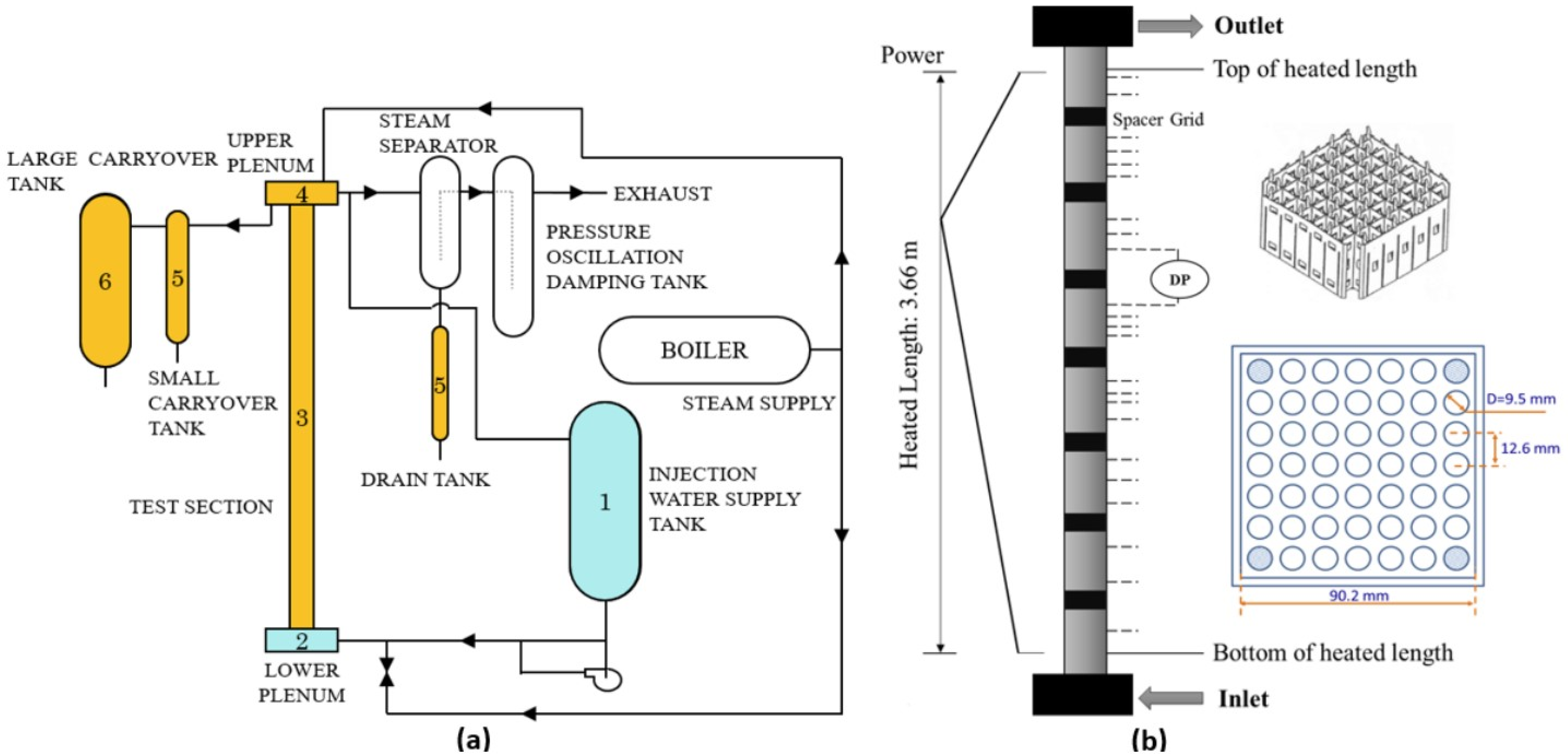
Reactor power



Pressurizer pressure

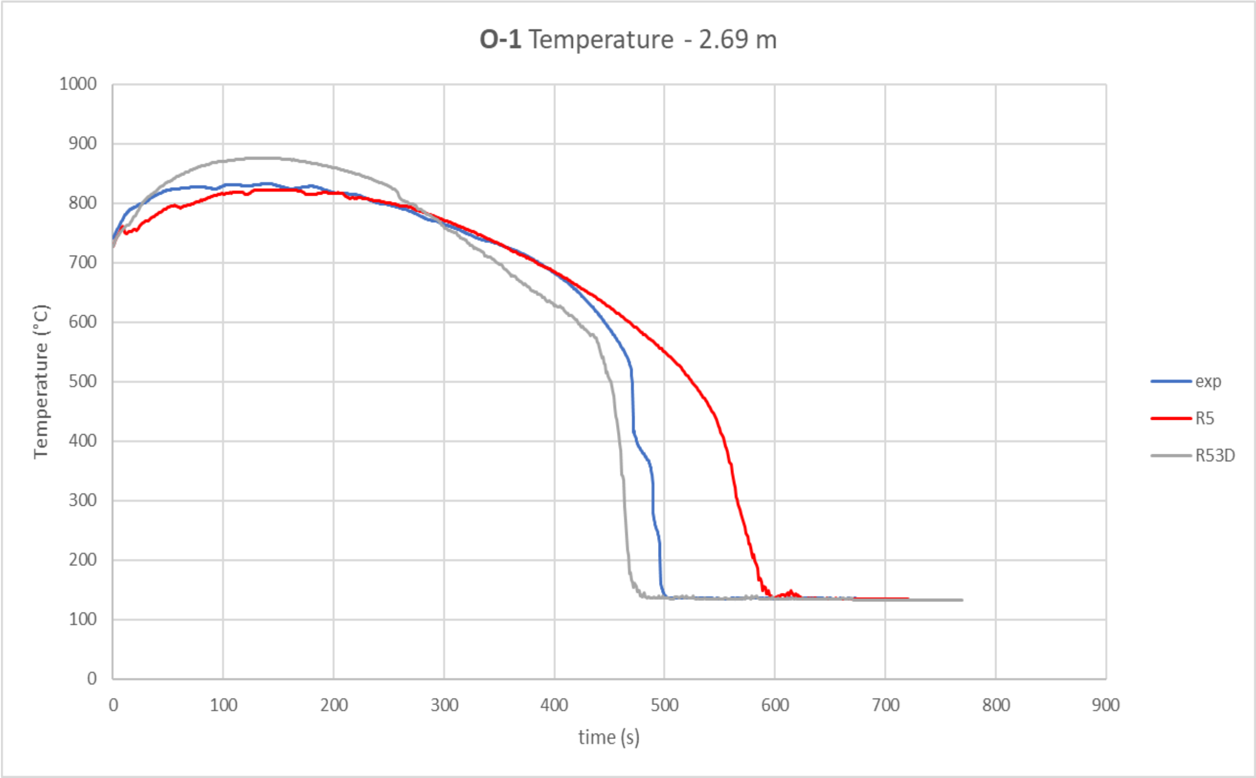
4) Code assessment based on RBHT reflood tests

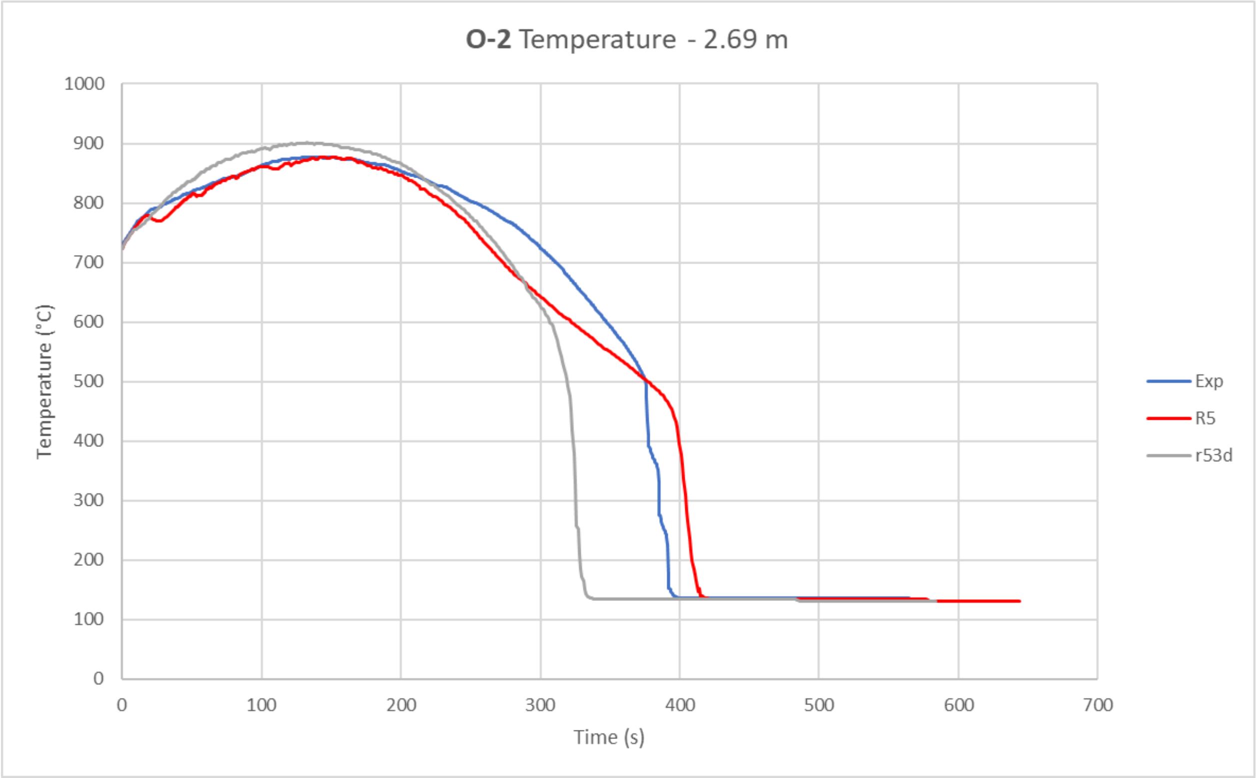
- OECD/NEA Rod Bundle Heat Transfer (RBHT) Project
- Participants: RBHT: Belgium, Czechia, Finland, France, Germany, Italy, Japan, Korea, Spain, Sweden, Switzerland and United States.
- RBHT Phase2 is just starting

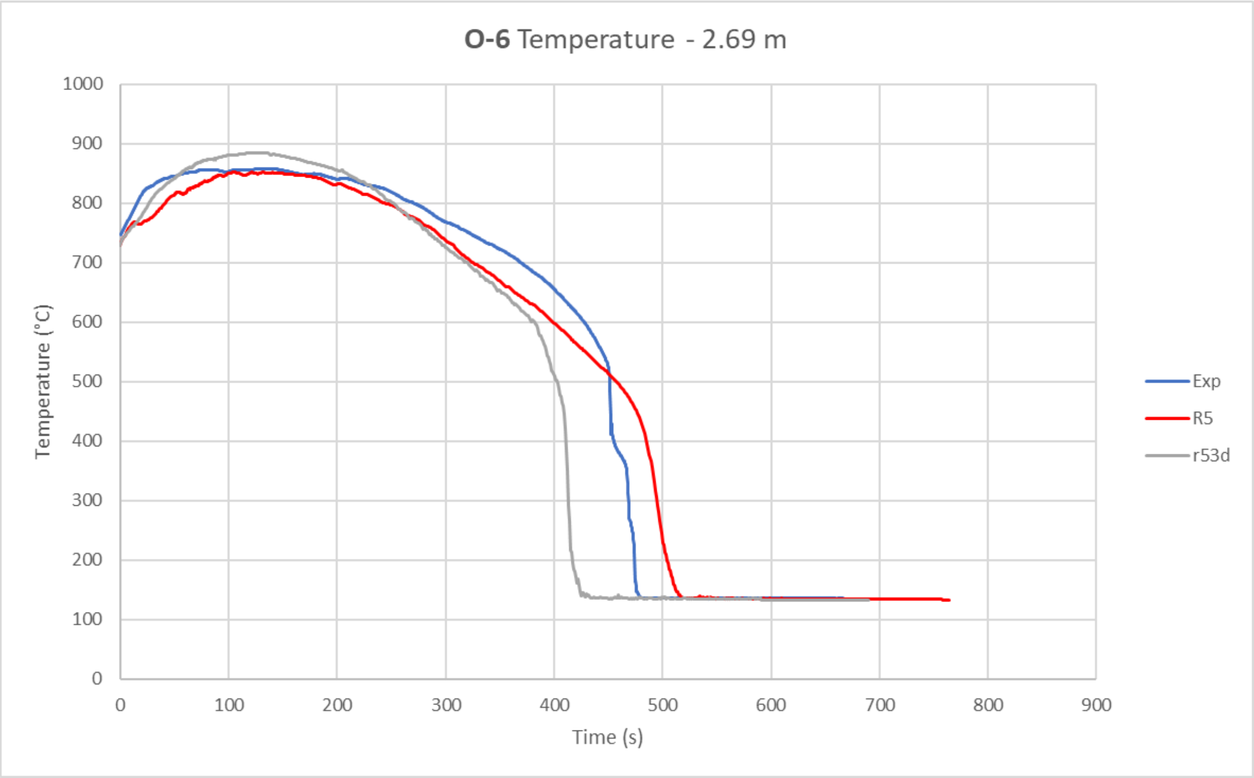


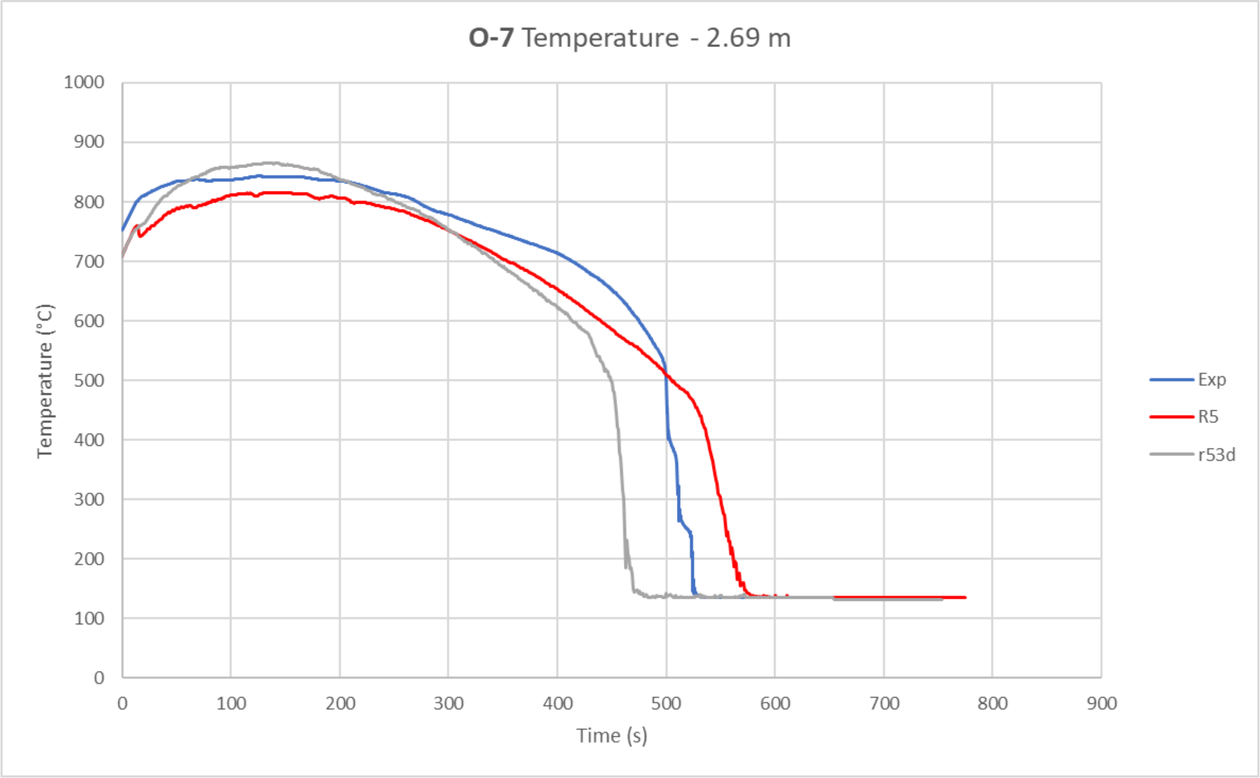
4) Code assessment based on RBHT reflood tests

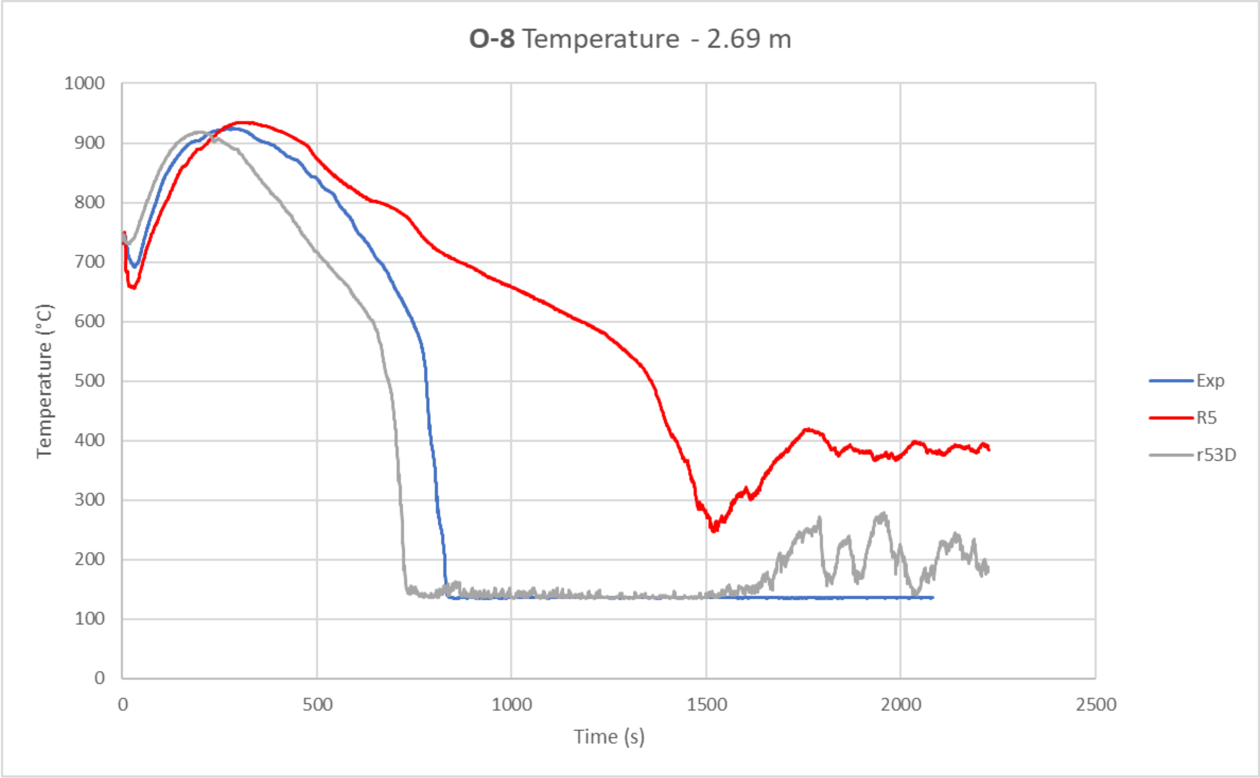
UJV assessment of RELAP5/MOD3.3 and RELAP5-3D based on RBHT Phase I tests:

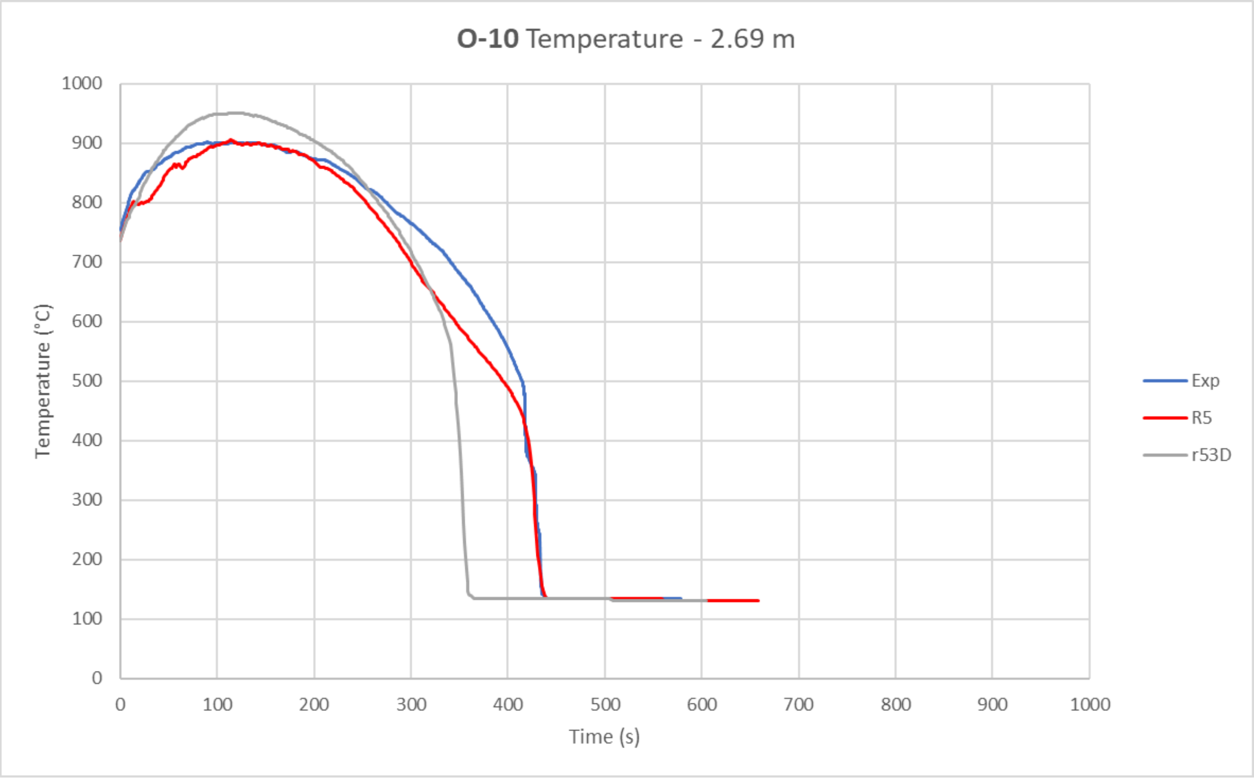




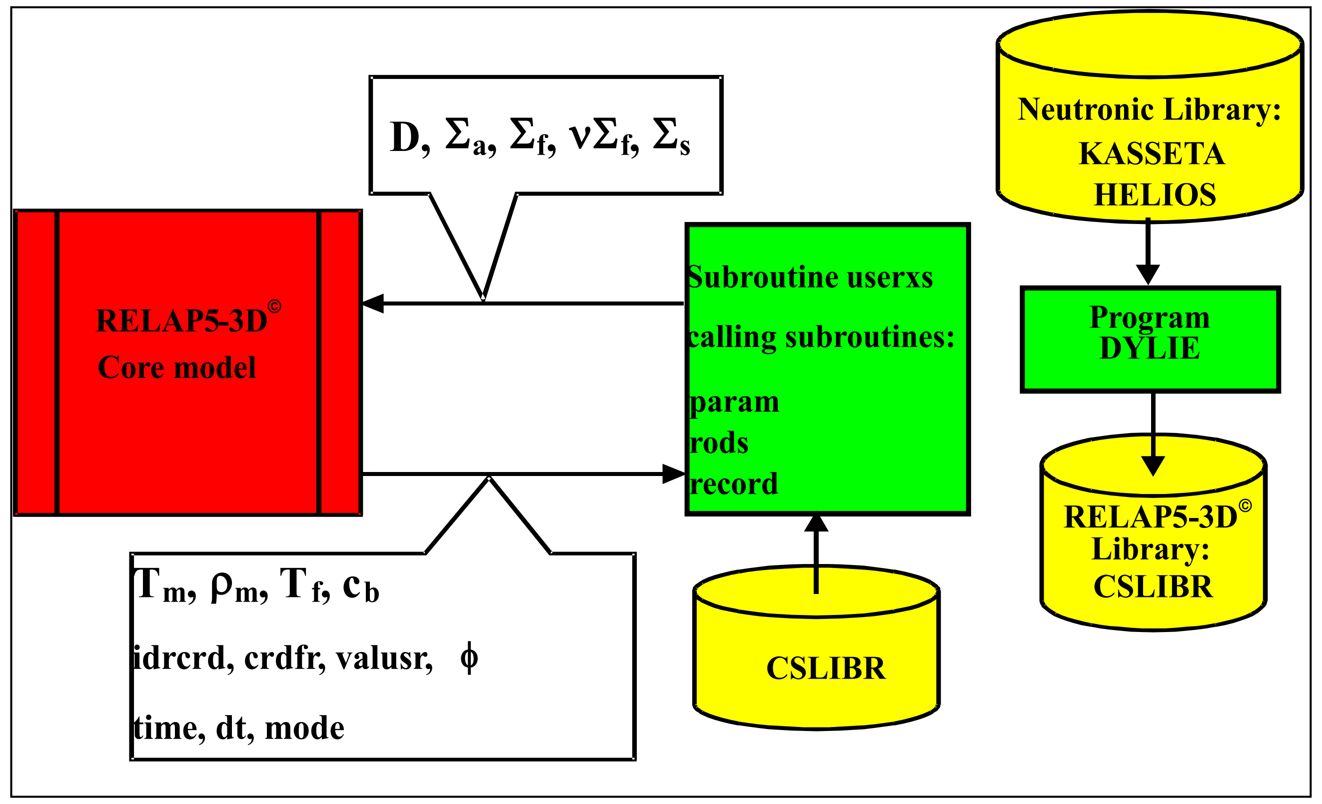


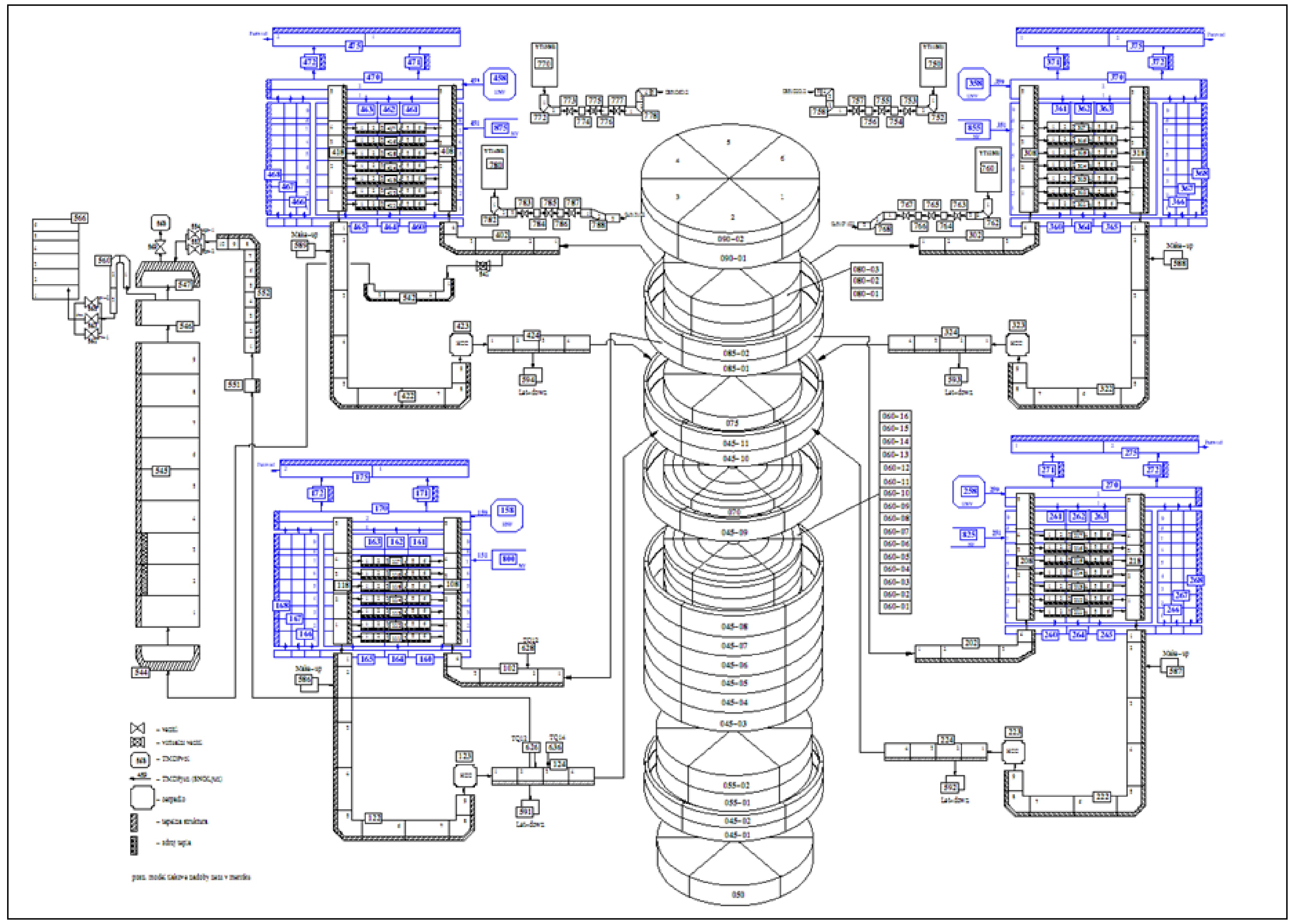






5) Analysis of post-accident reactivity insertion in VVER-1000





Description of the analyzed event:

- LBLOCA with double-ended rupture of hot leg from full power
- Operator actions according to EOP (step-wise stop of HPSI and LPSI)
- After stop of injection of the last LPIS pump assumption (1 hr 15 min of original accident) of operator restart of RCP in loop-2 full of non-borated water = time 0 s of the post-accident analyses
- Realistic analysis assumptions (DEC-A)

5) Analysis of post-accident reactivity insertion in VVER-1000

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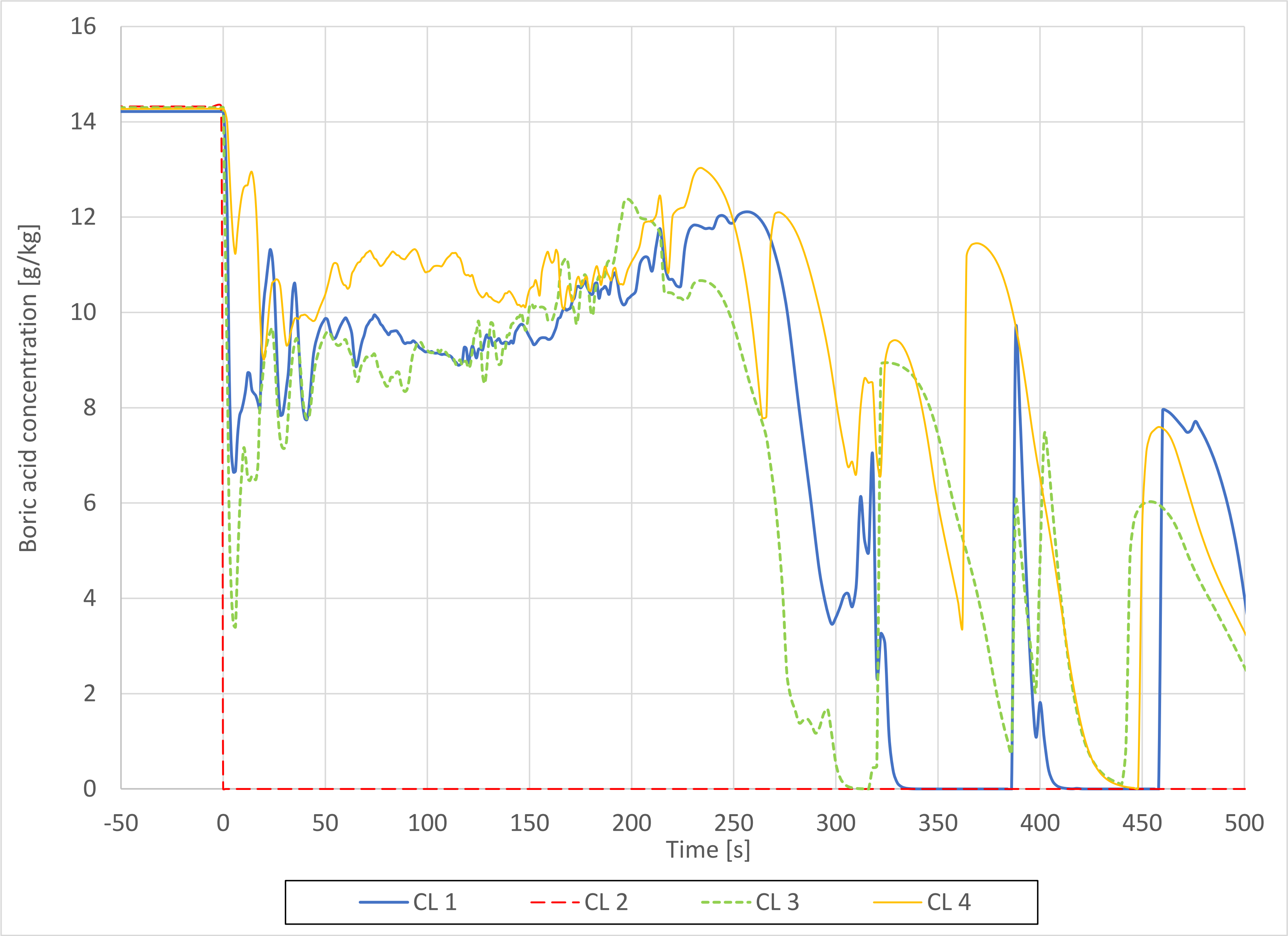
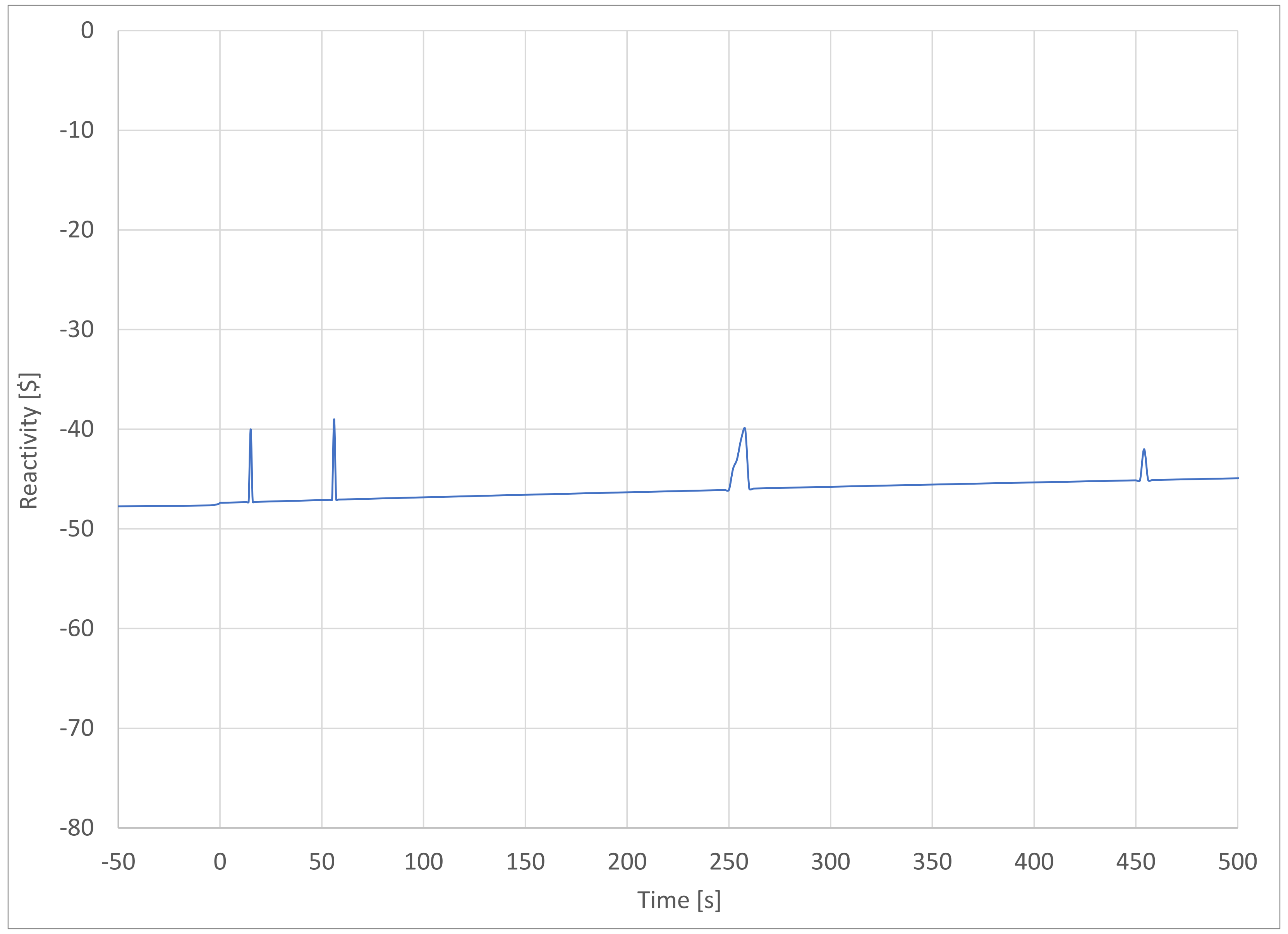


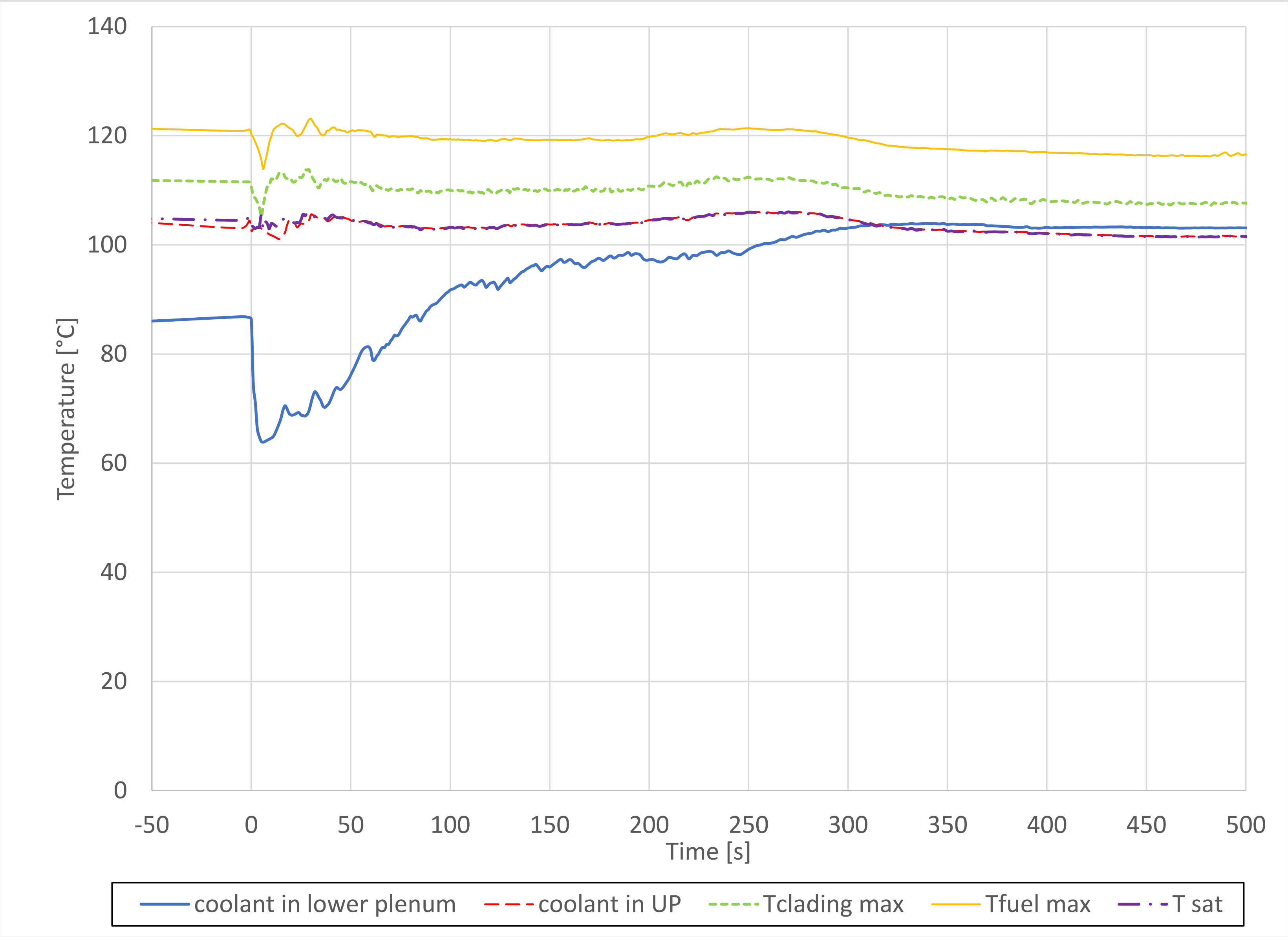
Boric acid concentration at reactor inlet from cold legs

Boric acid concentration at core inlet

5) Analysis of post-accident reactivity insertion in VVER-1000



Reactivity



Temperatures in reactor core

6) Code Analyses for MSR concept EnergyWell

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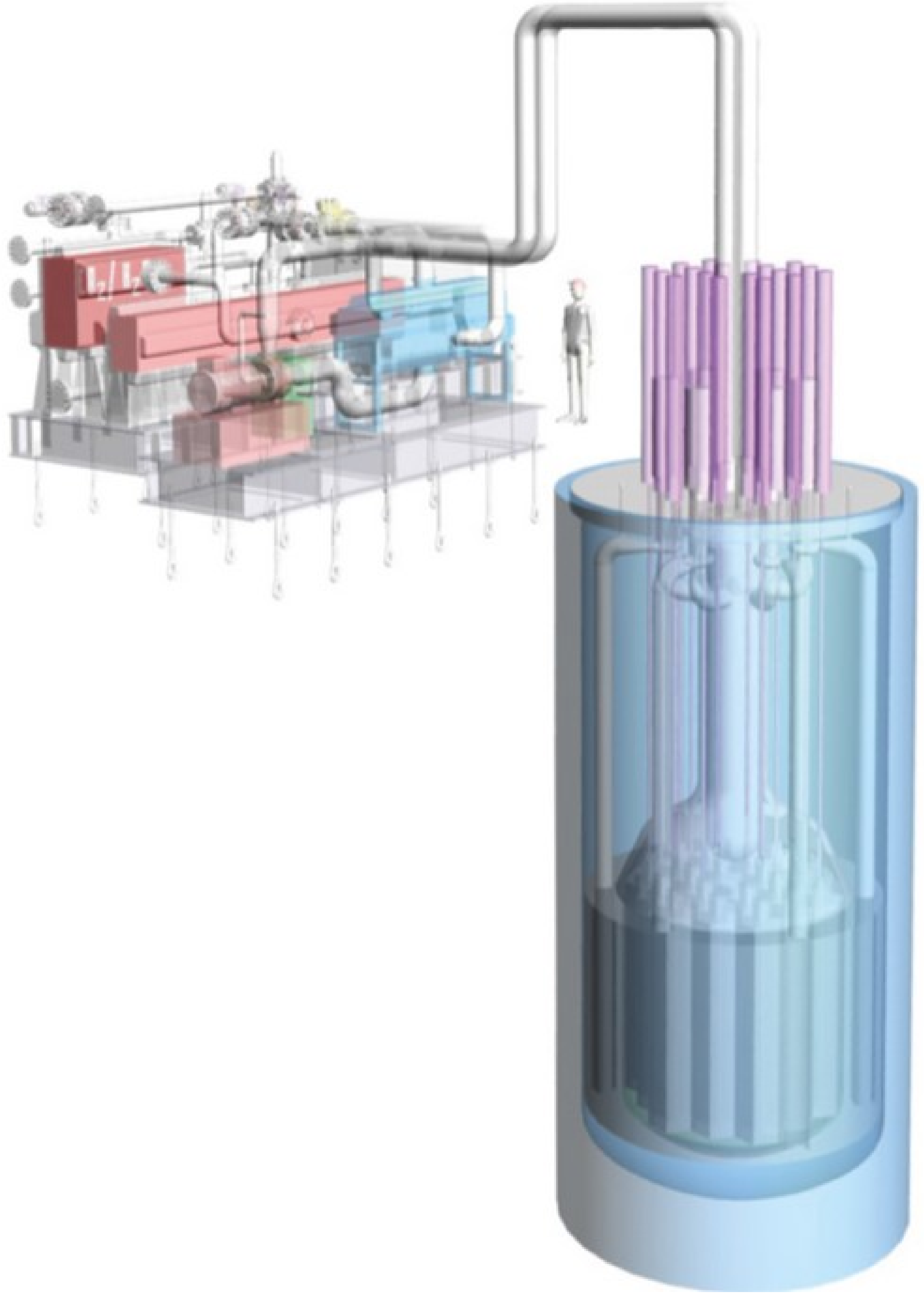
- **Energy Well** is a patented small modular reactor developed by the Research Center Řež.
- The power plant includes three cooling circuits. Liquid fluoride salts are used as a heat transfer medium (FLiBe, $NaBF_4$) in the primary and secondary circuits. Carbon dioxide in a supercritical state (sCO_2) is used in the tertiary circuit.
- The primary circuit removes the heat generated in the core of the reactor, while the secondary circuit separates the active primary and the highpressure tertiary circuit while ensuring the heat transfer.
- The tertiary circuit uses an optimized Ericsson-Brayton cycle configuration to transform heat into electricity.



6) Code Analyses for MSR concept EnergyWell

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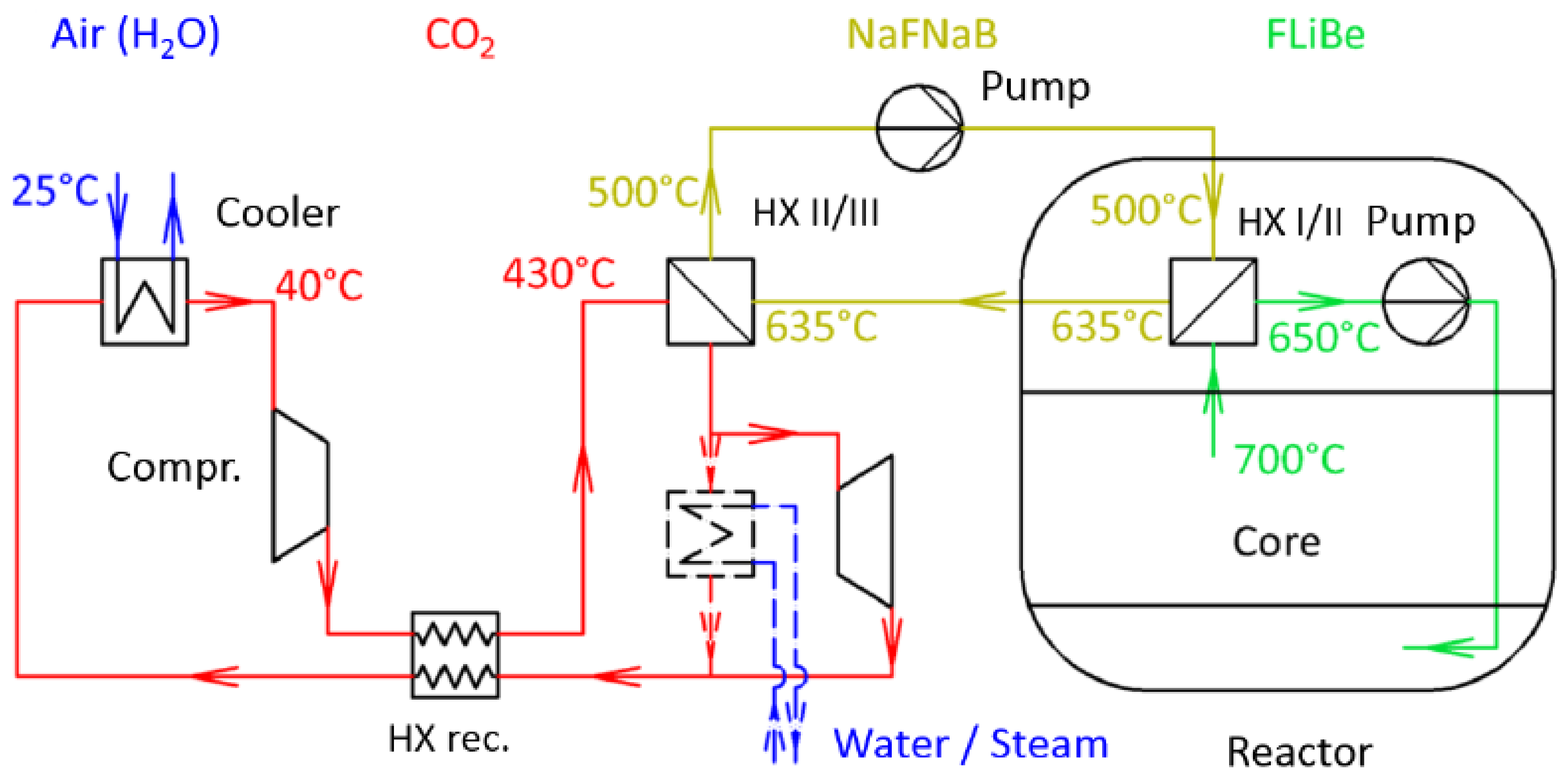
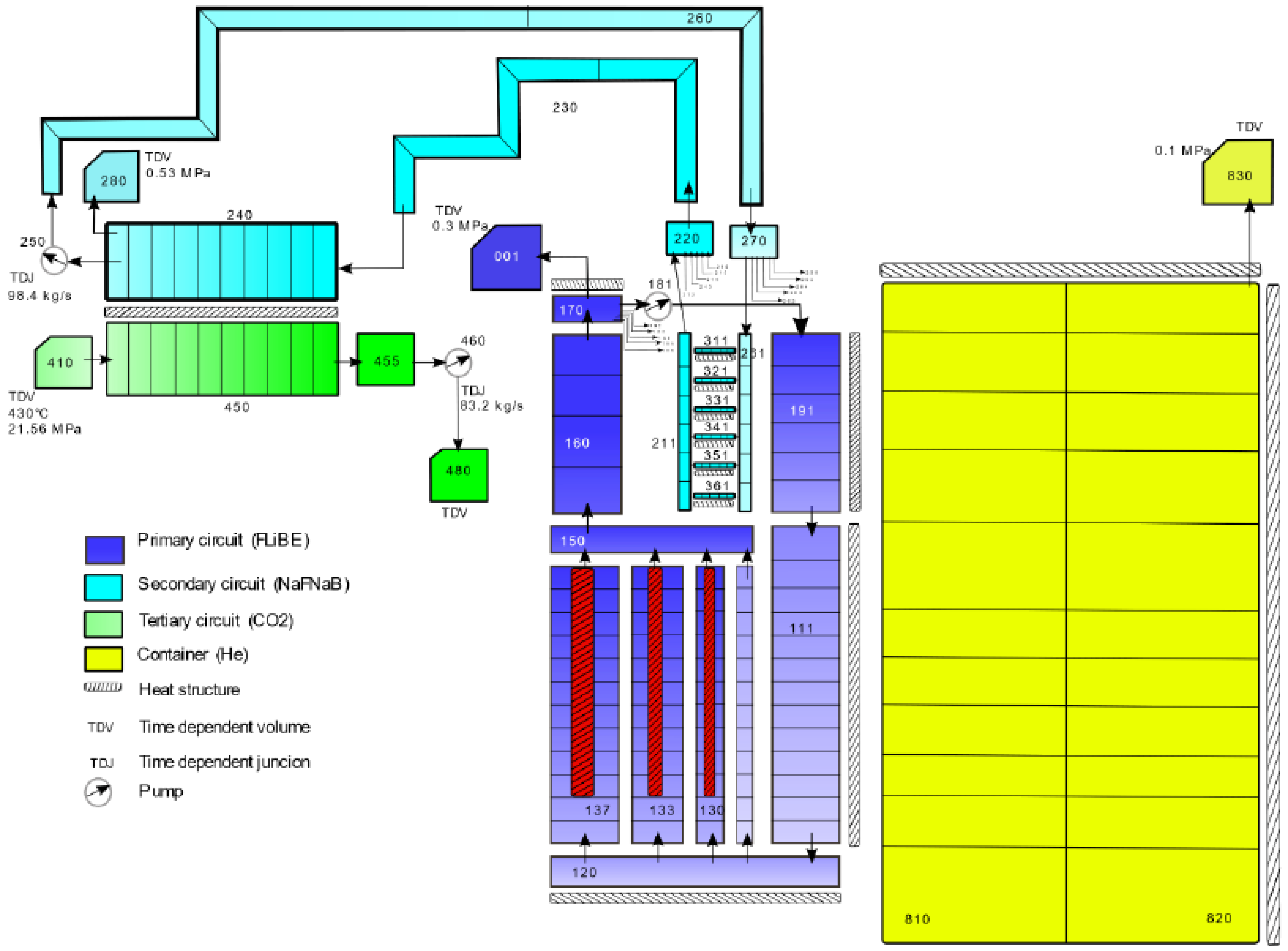
Process Flow Diagram of the EnergyWell concept:



EnergyWell model for RELAP5-3D:



6) Code Analyses for MSR concept EnergyWell

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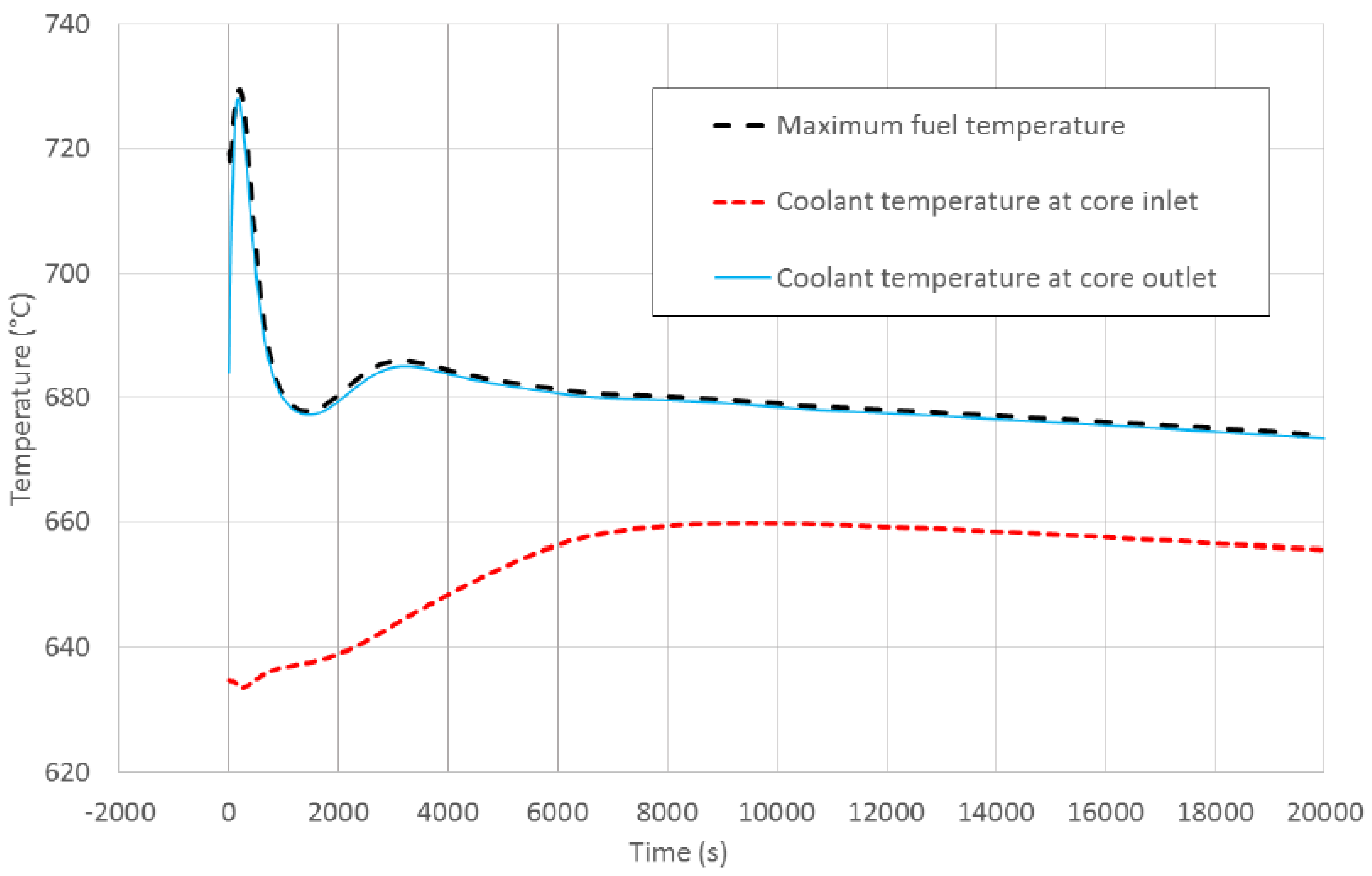
EnergyWell core temperature in case of loss of flow event:



SUMMARY

- The presentation describes increasing role of deterministic safety analyses for safety of existing and new NPPs in the Czech Republic
- UJV Rez has long tradition in assessment both RELAP5/MOD2(3) and RELAP5-3D and their application of safety analyses of VVER reactors
- New challenge is the safety assessment of planned new builds – big PWR units and LW-SMRs
- Thanks to its unique features, the RELAP5-3D can play an important role in this effort
- The international cooperation – both European and trans-Atlantic – is more than important for the safe development of nuclear energy

Thank you for your attention

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Appendix A - Notes to application of RELAP5-3D to safety analyses

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- The XS library for RELAP5-3D (NESTLE) is generated in UJV Rez by the HELIOS code and contains primarily realistic values from a reference campaign
- For a conservative safety analysis of a reactivity-initiated event (from MSLB to control rod withdrawal and ejection), the analyst needs tools to modify the realistic XS library to a conservative one.
- We would like to discuss with INL and other code users their approach to conservative analyses with the RELAP5-3D and NESTLE
- The USER option (available in earlier versions of RELAP5-3D) has been very useful for safety analysis, especially for tuning conservative reactivity coefficients.
- Also, minor modifications to the code input/output could significantly improve the ability to use RELAP5-3D for conservative safety analysis.