Federal Environmental, Industrial and Nuclear Supervision Service

Scientific and Engineering Centre
for Nuclear and Radiation Safety

MODELING OF SEVERE ACCIDENTS FOR SODIUM AND LEAD COOLED REACTORS

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Technical Meeting on the Safety Approach for Liquid Metal Cooled Fast Reactors and
the Analysis and Modelling of Severe Accidents
13–17 Mar 2023 IAEA

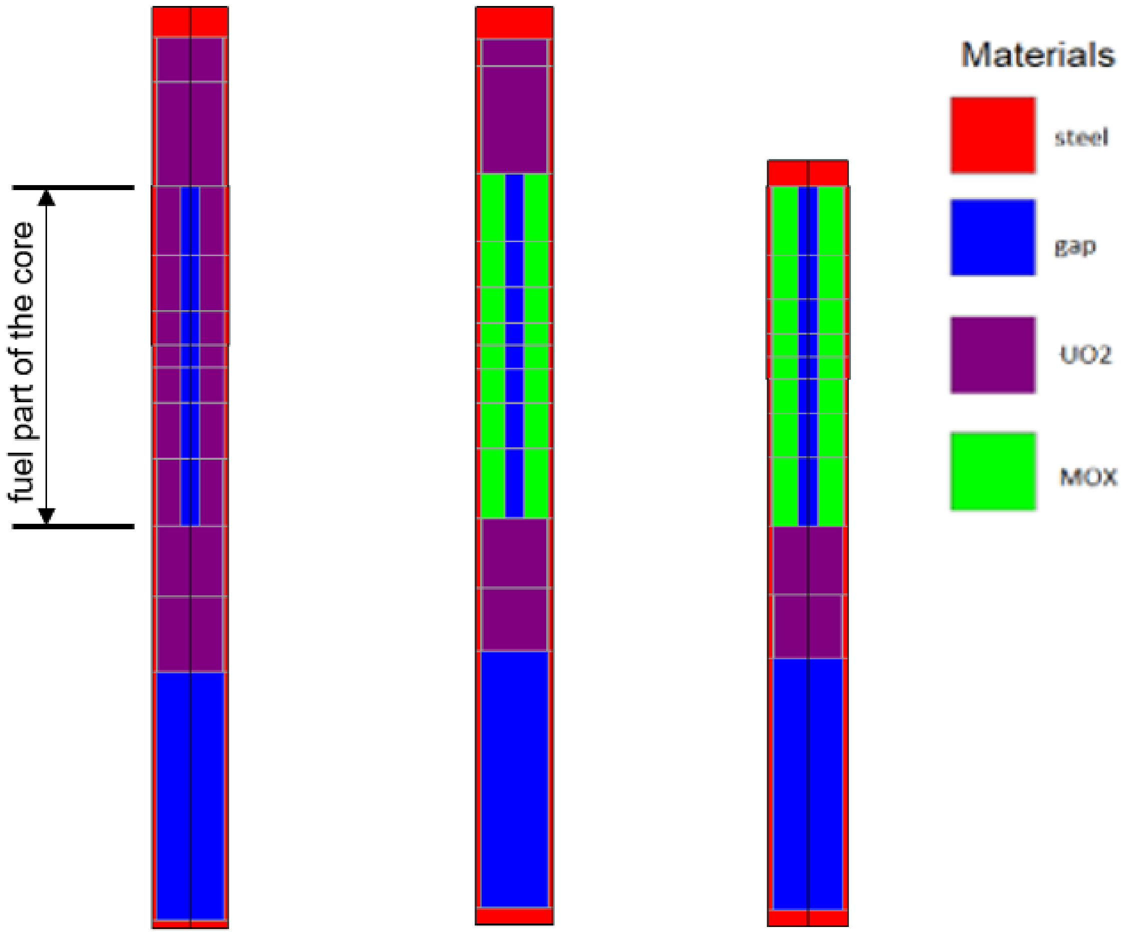
Objectives of the work

- Creation of computational models of reactors with sodium and lead coolant;
- Evaluation of the veracity of the results obtained using the developed computational models;
- Application of the calculation results to assess the safety review of fast neutron reactors with sodium and lead coolant.

1) https://strana-rosatom.ru/2020/10/29/dolgaya-doroga-prometeya-istoriya-bys
2) https://www.ippe.ru/nuclear-power/fast-neutron-reactors/138-bn-800

Reactor BN-800 with sodium coolant model

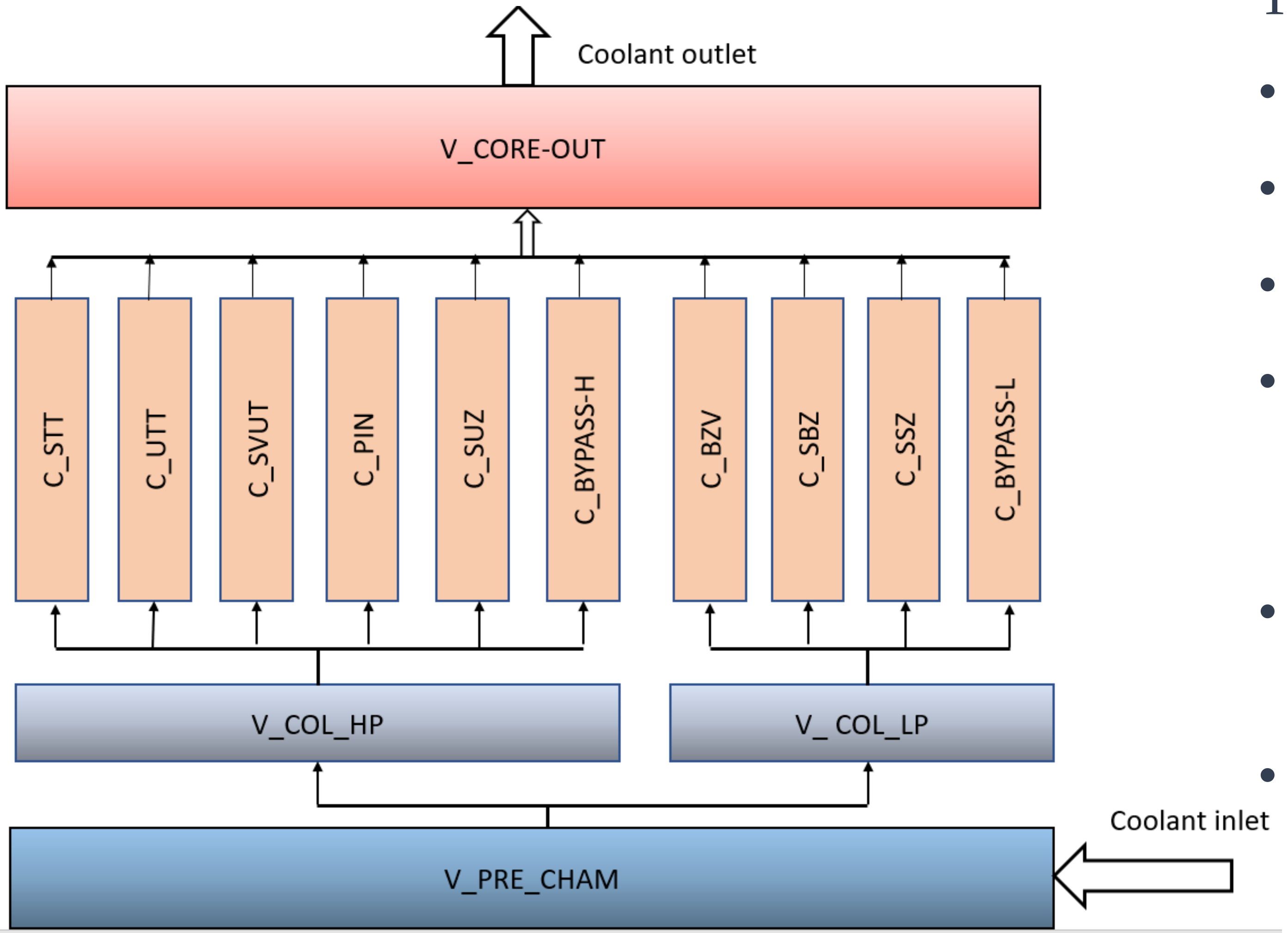
Models of fuel elements for fuel assemblies of the core of BN-800



a) fuel rod of FA UTT *b) fuel rod of FA SVUT* *c) fuel rod of FA STT*

- FA with enriched uranium dioxide pellets and depleted uranium dioxide pellets in the upper and lower breeding zones (FA UTT);
- FA with vibrocompacted MOX fuel and depleted uranium dioxide pellets in the upper and lower breeding zones (FA SVUT);
- FA with pellet MOX fuel and pellets of depleted uranium dioxide in the lower breeding zone (FA STT);
- The height of the layers was chosen in accordance with the axial profile of the energy release in the reactor.

Nodalization scheme of the reactor core (BN-800)

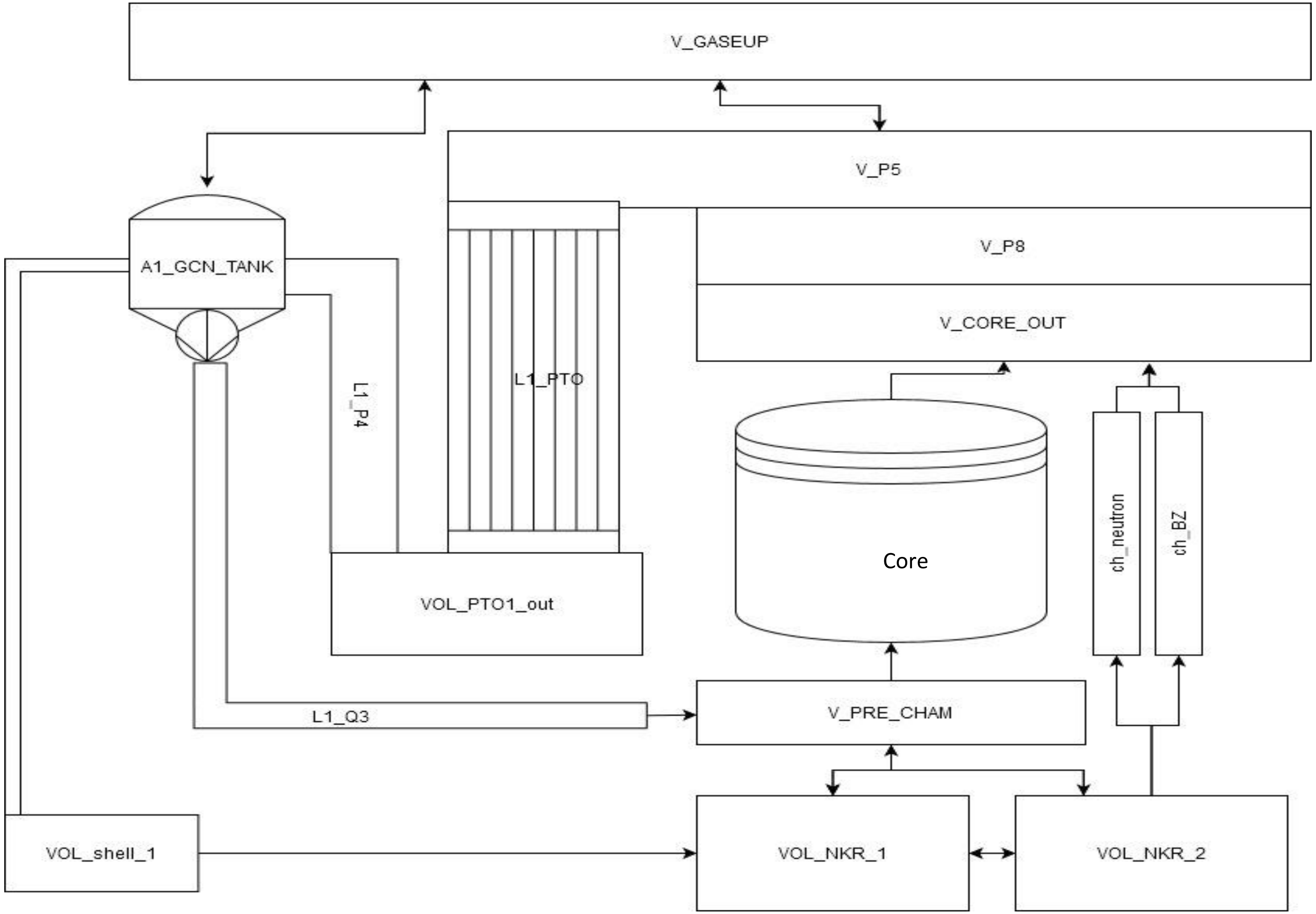


The nodalization scheme includes :

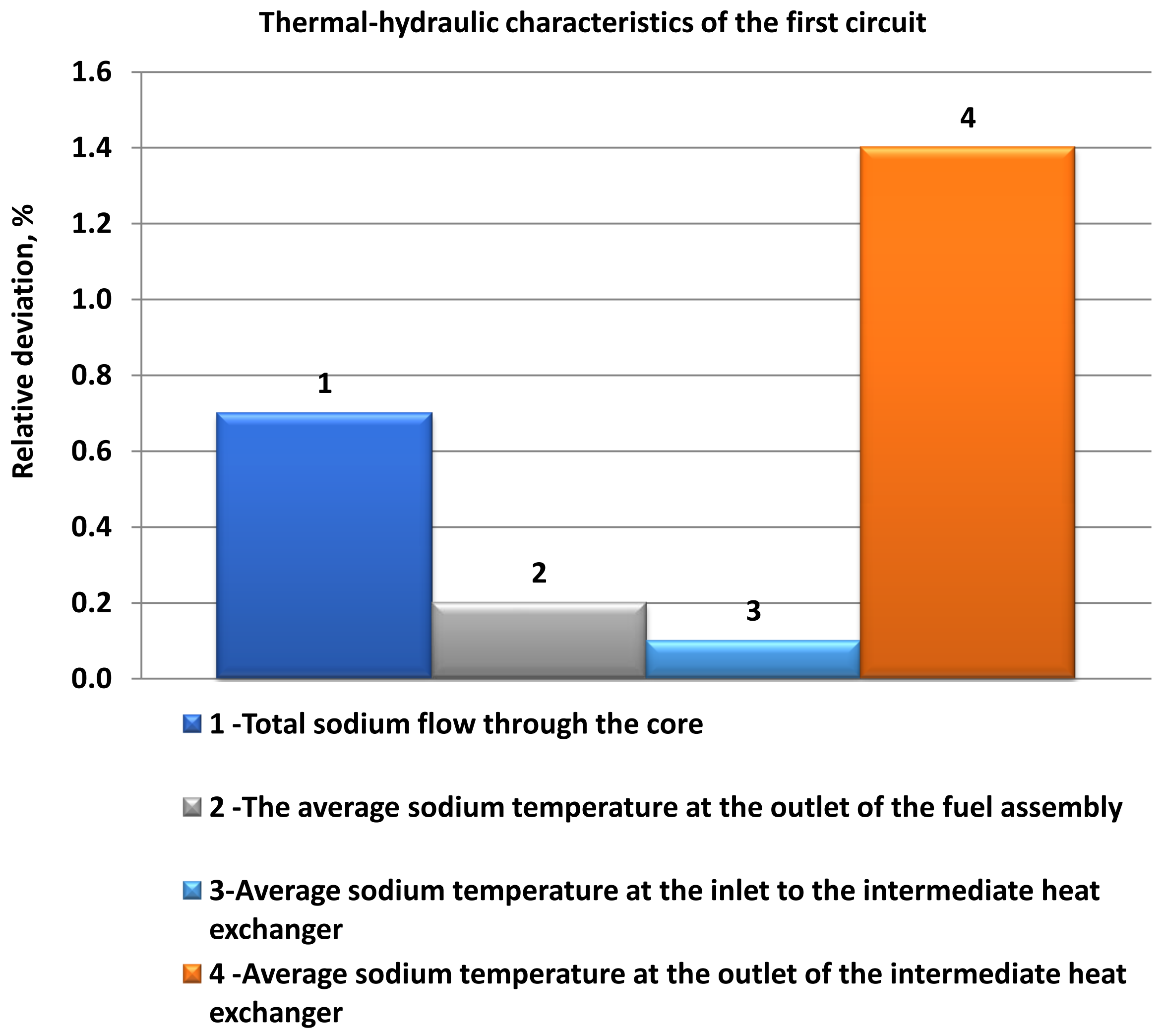
- Pressure chamber
- Upper drain cavity
- High and low pressure collectors
- Channels of fuel assemblies of the core and fuel assemblies of the side breeding zone
- CPS and trigger neutron source cooling channels
- Leaks channels in the space between cassettes and steel and boron protection assemblies

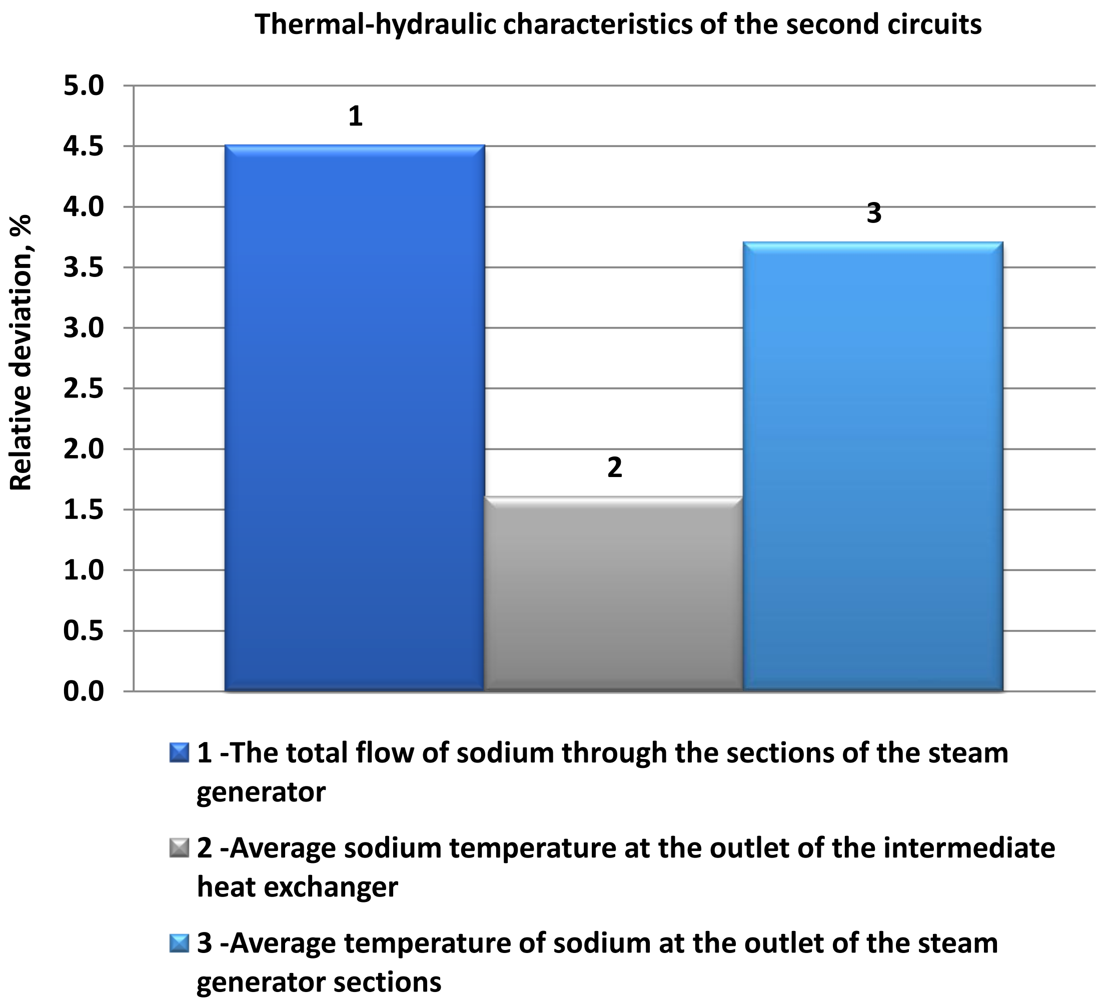
Thermal-hydraulic model of BN-800

- Three circulation loops with a common tract in the section between the pressure chamber of the core and the reactor tank;
- The regions of the reactor in which the pressure vessel and internal protection are cooling;
- Second and third circuits of the reactor were prepared.



Relative deviations of the results of the thermal-hydraulic characteristics calculating between SOCRAT-BN and design data





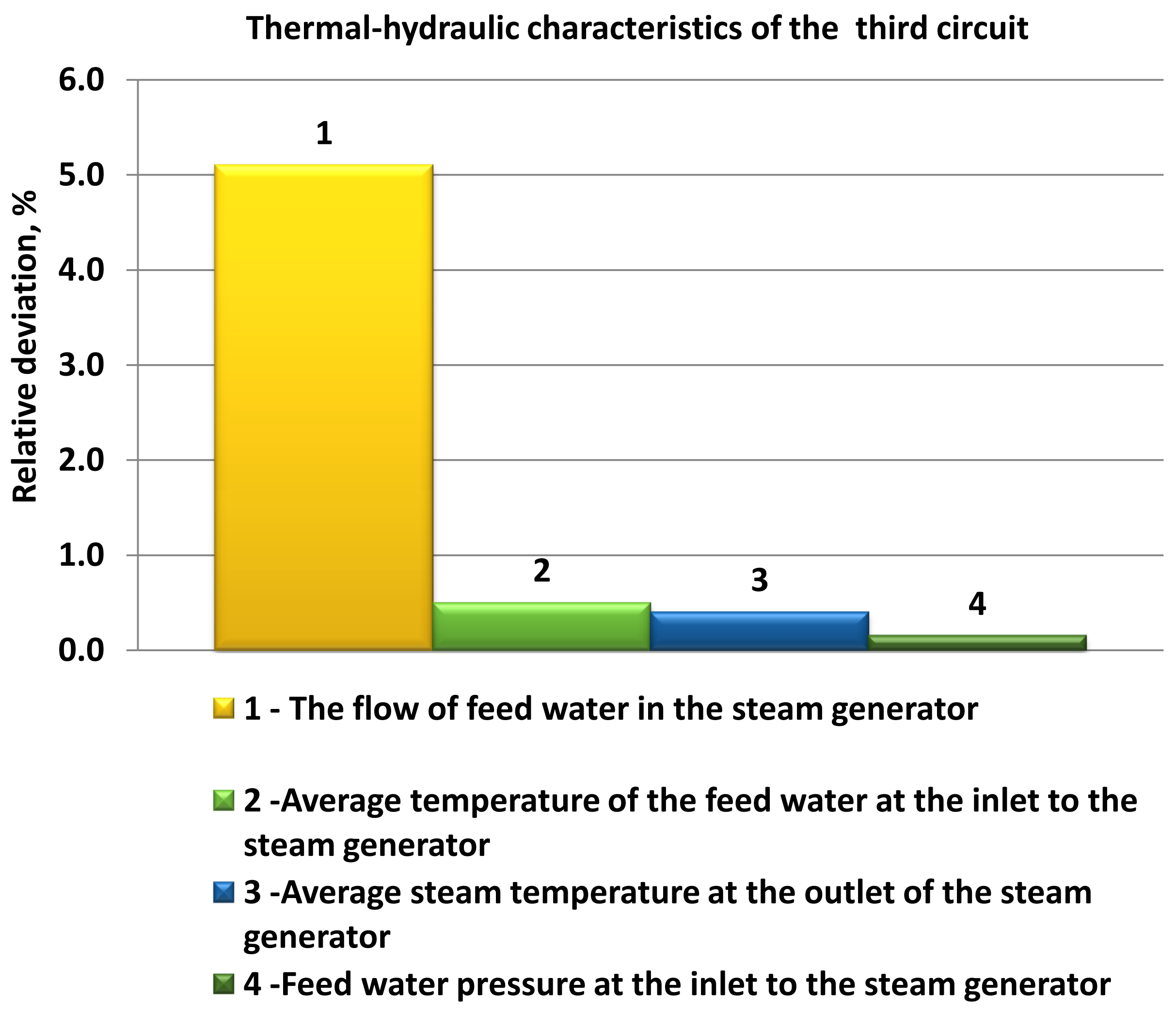
Relative deviations of the results of the thermal-hydraulic characteristics calculating between SOCRAT-BN and design data

Maximum relative deviations of sodium and feed water temperature calculation:

- ✓ the first circuit - 1.4%
- ✓ second circuit - 3.7%
- ✓ third circuit - 0.5%

Maximum relative deviations of sodium and feed water flow calculation:

- ✓ the first circuit - 0.7%
- ✓ second circuit - 4.5%
- ✓ third circuit - 5.1%

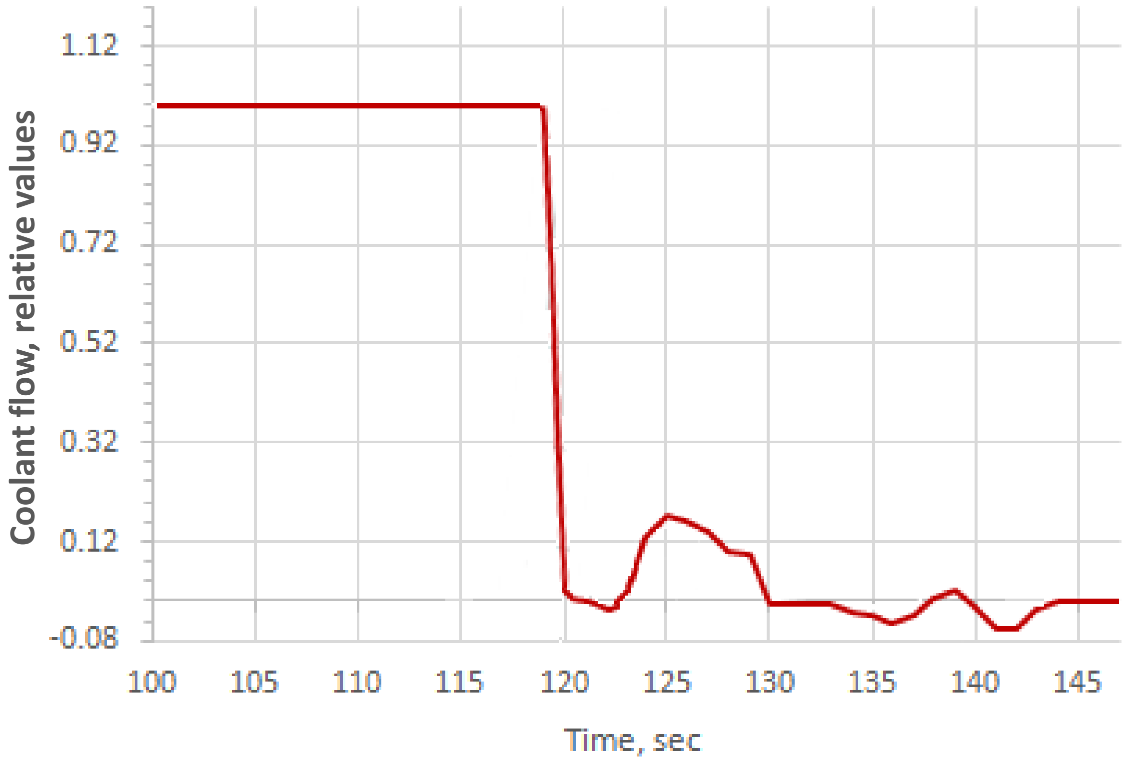


Calculation of a severe accident with core elements melting in a sodium cooled reactor

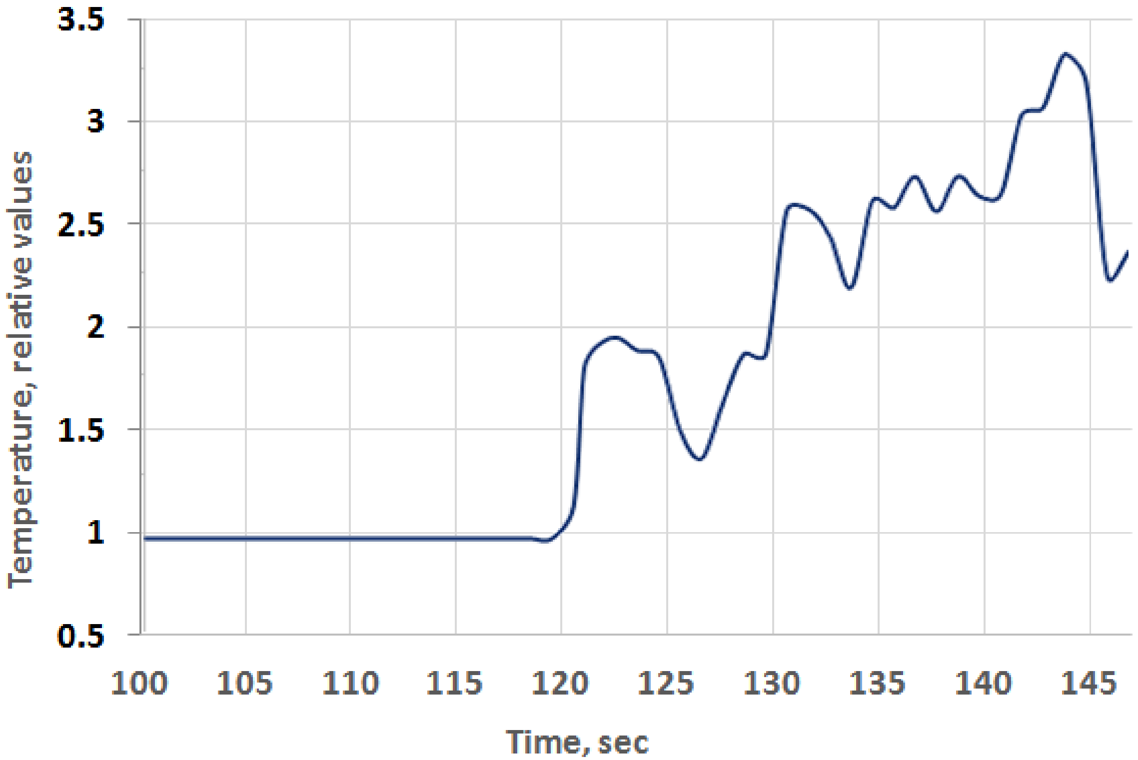
The accident modeling

- The design basis accident calculation with blocking of the flow pass section of one FA when the reactor is operating at the nominal power level was performed;
- Blocking of the flow pass section at the inlet part of one FA with MOX pellet fuel was modeled;
- It is postulated that the blocking of the flow pass section of the FA starts from 118 sec from the start of the calculation;
- Complete blocking of the flow pass section of the FA happens for 120 sec.

The accident with blocking of the flow pass section

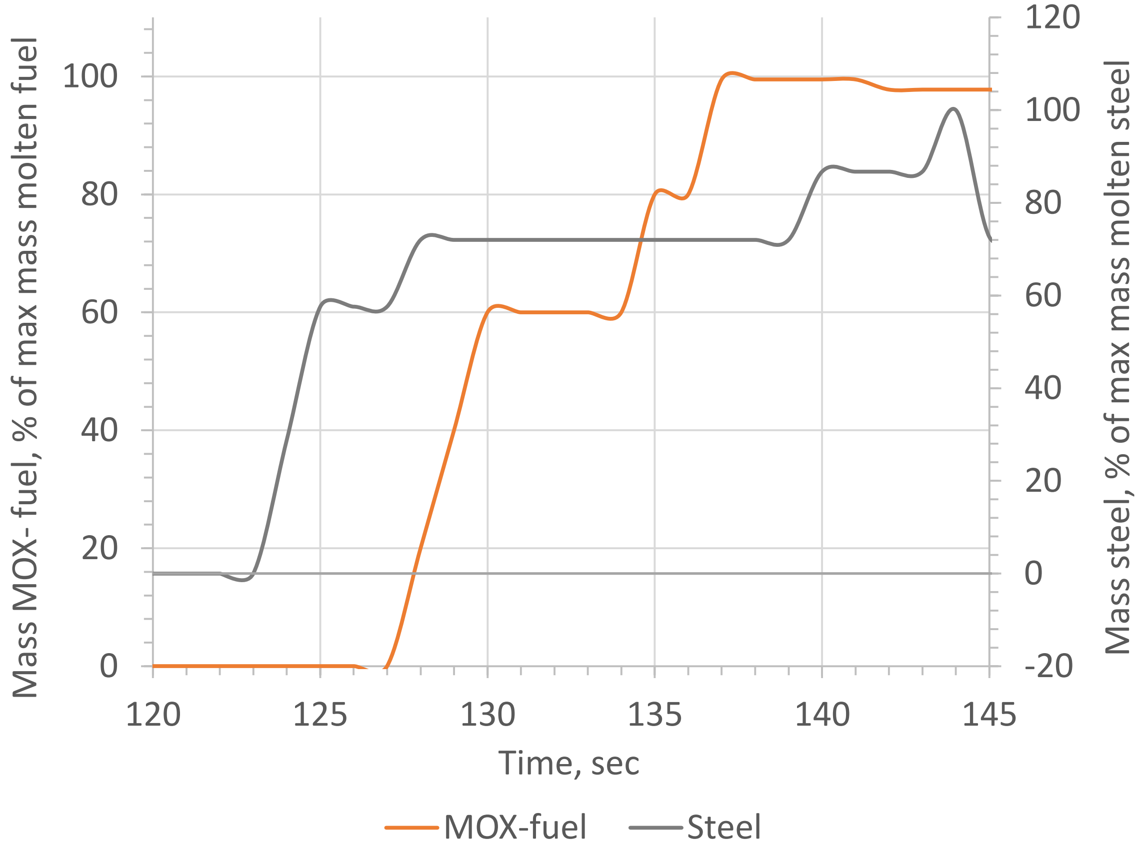


Coolant flow rate at the outlet of the emergency fuel assembly



Coolant temperature at the outlet of the emergency fuel assembly

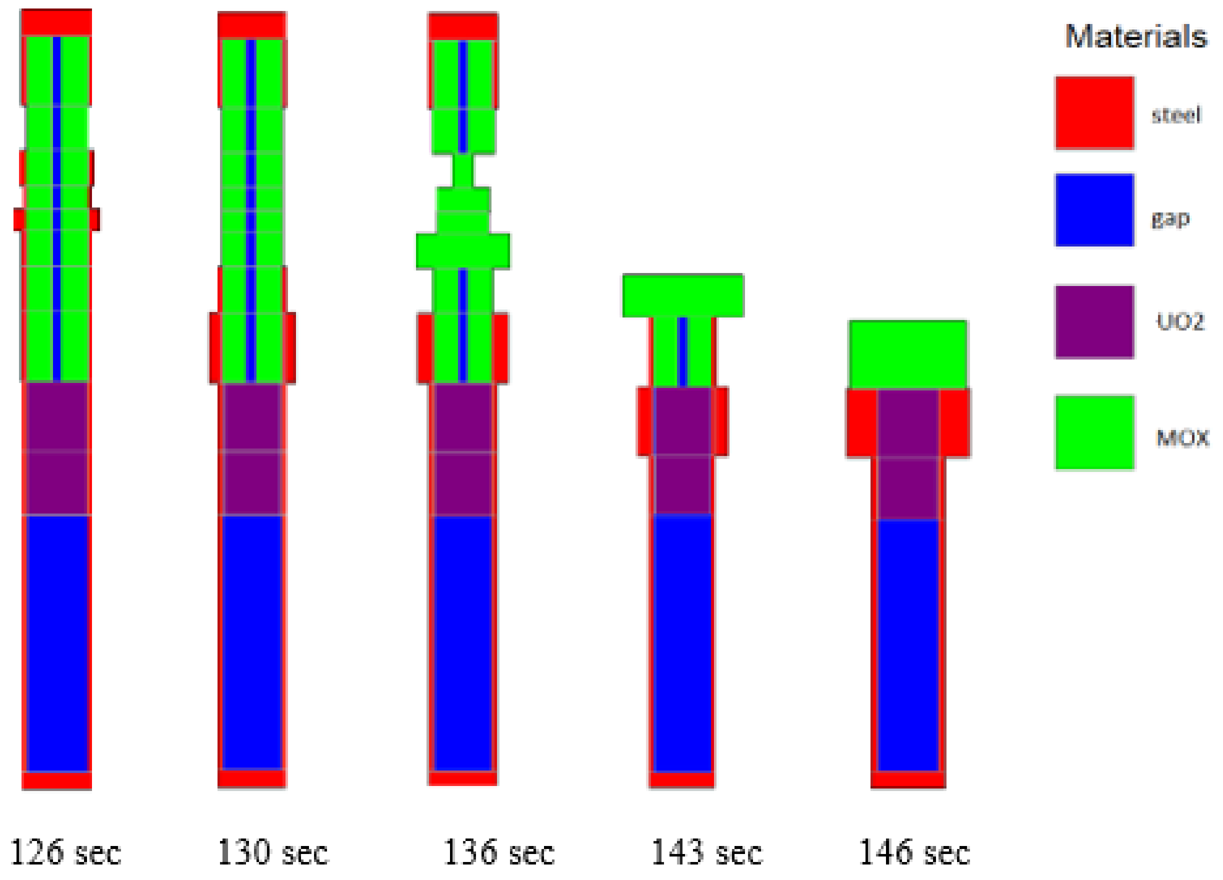
The accident with blocking of the flow pass section



Mass of molten fuel and molten steel

- Boiling of sodium in the inter fuel rod space of the FA as a result of blocking the flow pass section happens at 1.78 seconds after the complete blocking of the flow pass section;
- Fuel cladding melting begins at the 4 second after the complete blocking of the flow pass section of the FA;
- Fuel melting begins at the 7 second after the complete blocking of the flow pass section of the FA.

The accident with blocking of the flow pass section



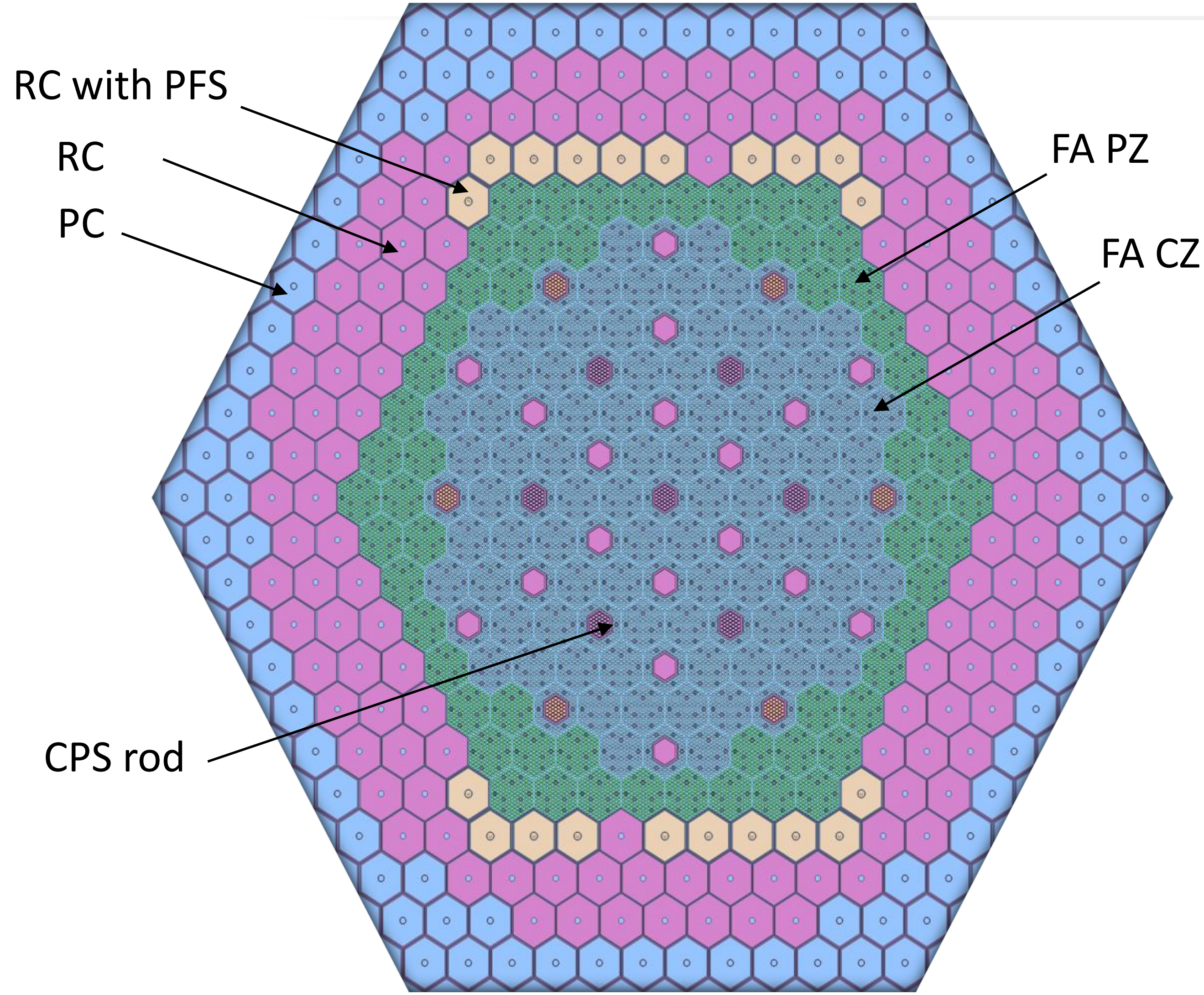
Distribution of materials in the fuel rods of emergency fuel assembly with MOX pellet fuel

- The change in the mass of the molten fuel and steel of the fuel element cladding during the accident occurs due to the transfer of part of the melt by the sodium flow to the sections of the fuel element with a lower temperature;

- The collapse of the upper layer of the fuel part due to the moving down of fuel and fuel cladding steel occurs at 143 seconds.

Modeling of severe accidents for lead cooled reactor (BREST)

Lead cooled reactor core model (BREST)



The core of the BREST consists of:

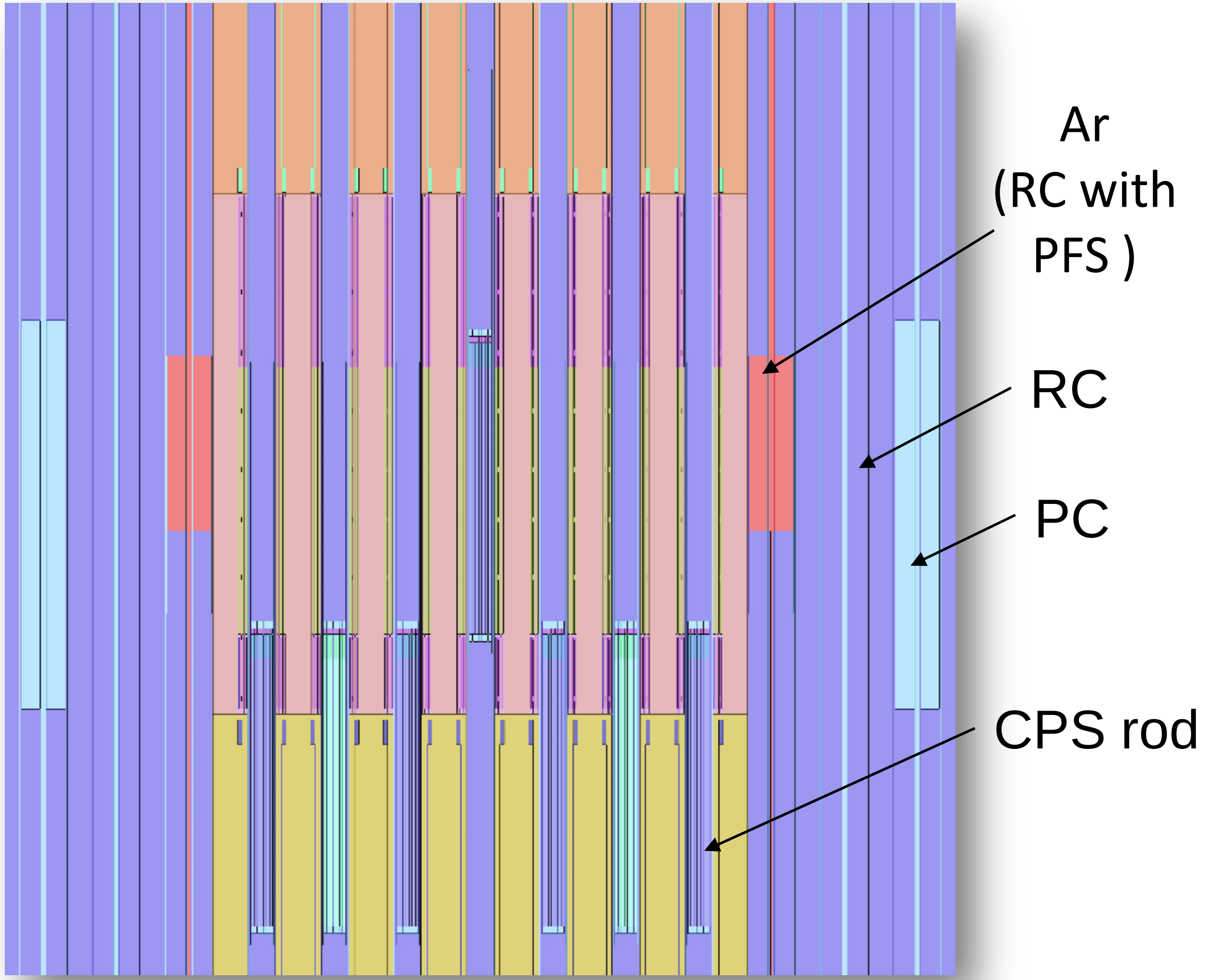
- FA of the central zone (FA CZ)
- FA of the peripheral zone (FA PZ)
- the rods of the control and protection system (CPS)
- reflector channels (RC)
- reflector channels with a passive feedback system (RC with PFS)
- steel channels of radiation protection (PC)

BALOVNEV, A., DAVYDOV, V., ZHIRNOV, A., KALUGINA, K., MOISEEV, A., UMANSKY, A., SMIRNOV, V., Analysis of reactivity effects in emergency situations with steam entering the core of a lead-cooled fast reactor, Conference of young professionals. Innovations in nuclear energy, JSC "NIKIET", Moscow, 2019.

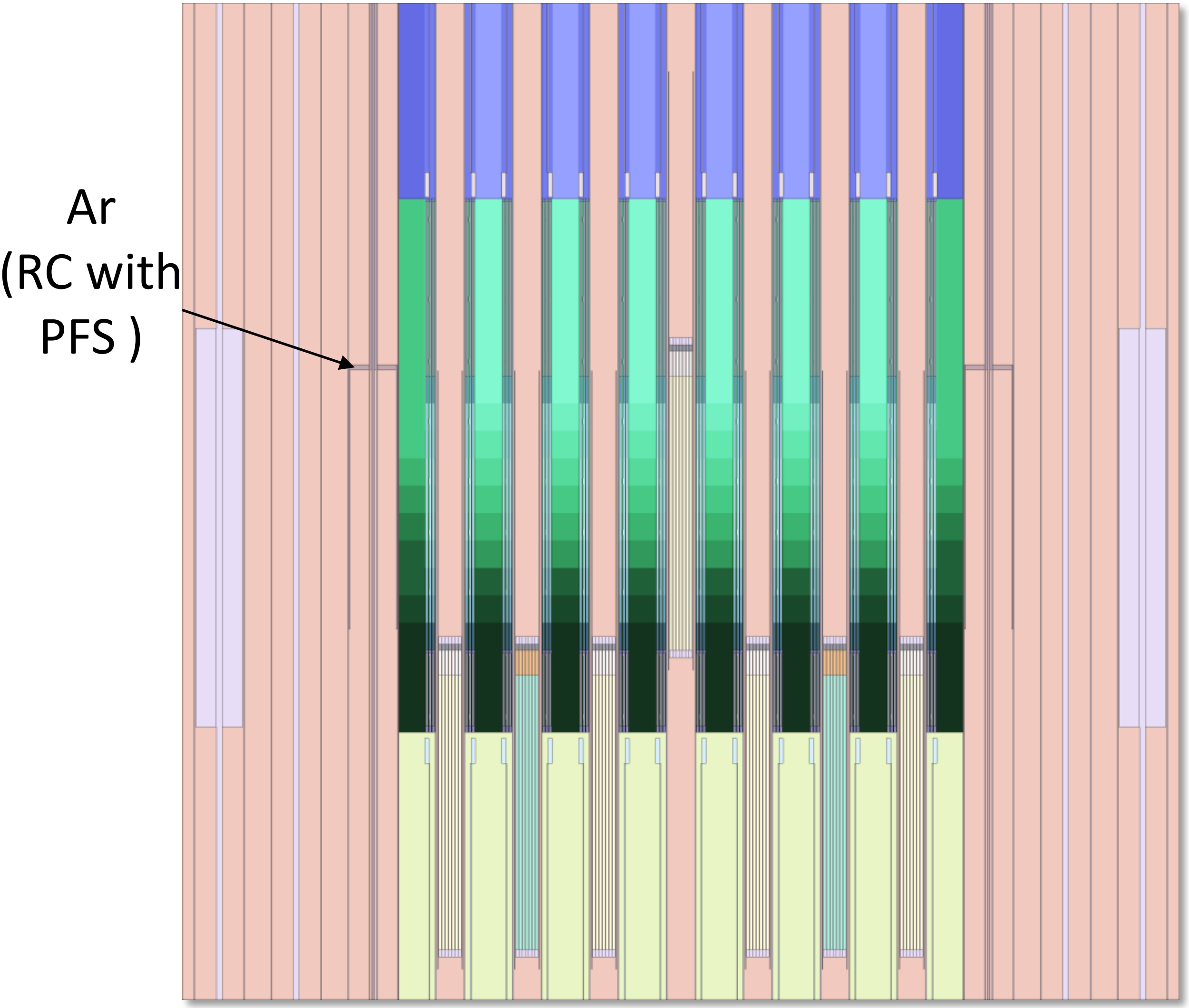
Neutron-physical model of the core

1. “Cold" state

- The temperature of the fuel, lead coolant and all constructional elements are set the identical;
- The coolant level in reflector channels with a passive feedback system is set minimum (the space is filled with argon);
- Thermal-hydraulic calculation for this state was not carried out.



Neutron-physical model of the core



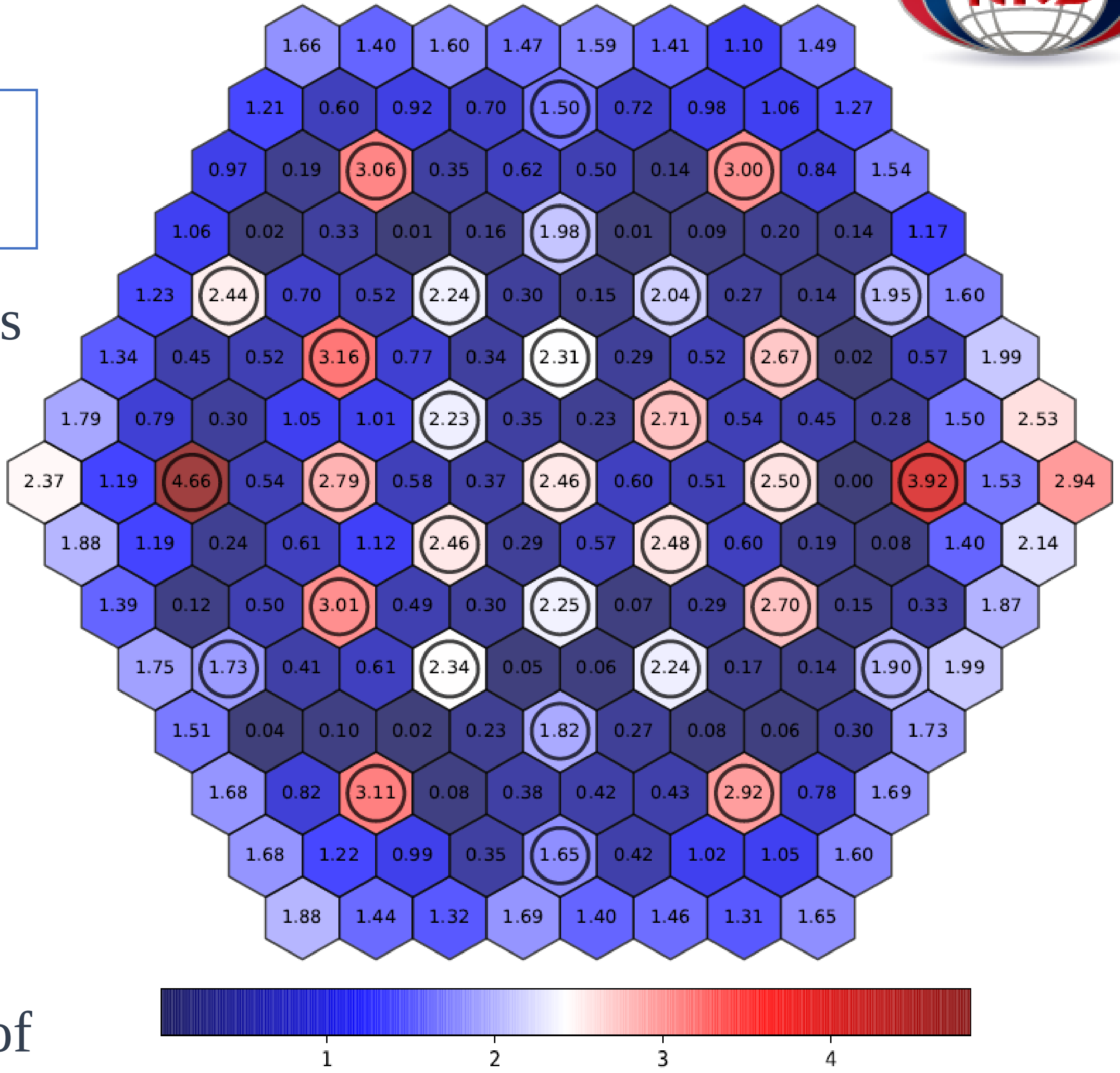
2. Operating ("hot") state

- Nominal level of thermal power is 700 MW;
- The critical state provided by the position of the automatic control rods;
- The level of lead coolant in reflector channels with a passive feedback system is set maximum;
- The temperature distribution is set in accordance with the thermal-hydraulic calculation.

Cross-verification of the reactor calculated values

Deviations cartogram of the calculated results between SERPENT and MCU-BR

- The largest relative energy release deviations are observed in FA with CPS rod with a dysprosium titanate absorber;
- Deviations of the efficiencies of shutdown systems and spatial energy release are not more 7% and 4%, respectively;
- The results obtained demonstrate the correctness of the application of the models developed using the codes SERPENT/ATHLET for safety assessment of the lead cooled reactor.



Calculation of lead cooled reactor under conditions of possible accidents

Choice of states for calculations

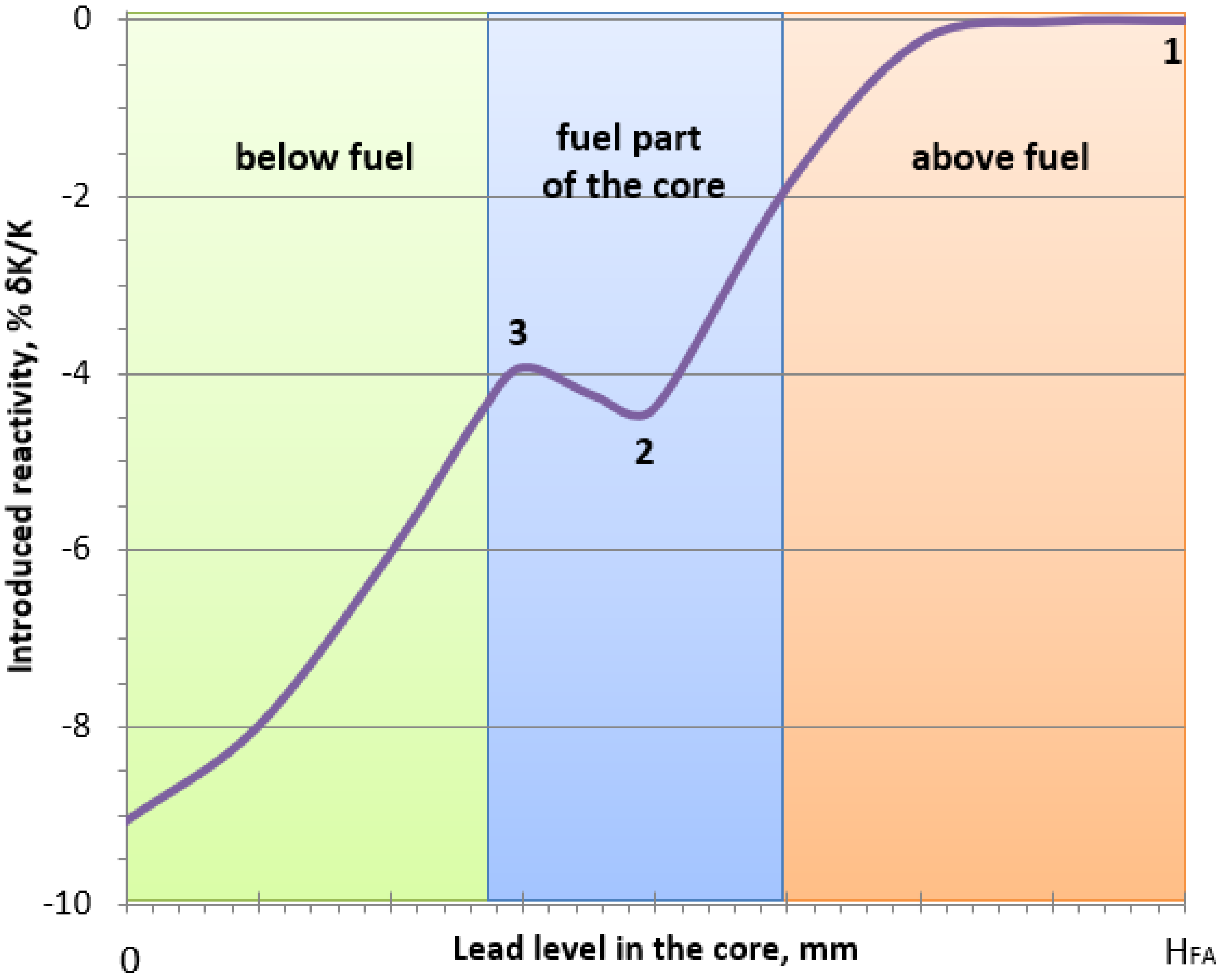
The following states were analyzed:

1) Core cooling followed by coolant freezing;
2) Coolant level changes in the reactor and core;
3) Removing (floating) of fuel claddings from the core.

1. Cooling of the core with freezing of the coolant

State characteristic	Calculation results
Cooling of the core with freezing of the coolant can also occur at the reactor commissioning stage;	The introduced positive reactivity reduces the subcriticality of the shutdown reactor for 6.81% from the initial value;
Temperature change (to final temperature 20°C) and coolant density.	The efficiency of the CPS rods is sufficient to hold the subcriticality of the reactor.

2. Coolant level change in the reactor and core



Calculation results:

- The introduced reactivity has a variable character;
- Maximum introduced negative reactivity is -9,17 % δK/K;
- The efficiency of CPS rods is sufficient to maintain the reactor subcriticality in all states with the loss of coolant without changing the configuration of the core.

3. Floating of fuel claddings from the core

State characteristic	Calculation results
➢ Lead boiling temperature (1745°C) exceeds the melting temperature of fuel claddings (1400–1500°C) for reactors with a lead coolant; ➢ Were carried two calculations: 1) for seven central FAs (fuel rods number is 2,26% of all fuel rods in the core); 2) for all FAs in the central zone (fuel rods number is 61,97% of all fuel rods in the core).	➢ When fuel claddings floating up, a positive effect of reactivity is appears; ➢ The introduced positive reactivity during the melting and floating of the claddings of all fuel rods in the central zone is 2.3% δK/K. ➢ Finding: 1) More than 2% subcriticality is provided; 2) The introduced reactivity can have a significant impact during accidents such as ULOF and UTOP.

Conclusion

- Calculation models of reactors with sodium and lead coolant have been created
- Cross-verification was carried out to evaluate the calculations of the stationary characteristics of the core
- The results of the calculations confirm the correctness of the developed calculation models for the stationary states and accidents in BN-800 and BREST reactors

1) https://proryv2020.ru/smi/bn-800-sdan-v-promyshlennuyu-ehkspluataciyu
2) The ninth national report of the Russian Federation on the fulfillment of commitments resulting from the convention on nuclear safety. To the Joint Eighth/Ninth Review Meeting of the Contracting Parties under the Convention on Nuclear Safety

Thank you for your attention!

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