NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 9(1): 71–76
DOI 10.3897/nucet.9.102912

Research Article

A spatial dynamic model of the SHELF-M reactor facility with fuel and coolant temperature feedbacks*

Denis A. Plotnikov[1], Aleksey L. Lobarev[1], Ivan N. Krivoshein[2], Pavel B. Kuznetsov[2], Anastasia N. Ivanyuta[2]

1 *MEPhI, 31 Kashirskoye sh., 115409, Moscow, Russia*

2 *NIKIET JSC, 2/8 Malaya Krasnoselskaya Str., 107140, Moscow, Russia*

Corresponding author: Denis A. Plotnikov (pda1995@gmail.com)

Academic editor: Yury Kazansky ♦ **Received** 1 April 2022 ♦ **Accepted** 27 October 2022 ♦ **Published** 17 March 2023

Citation: Plotnikov DA, Lobarev AL, Krivoshein IN, Kuznetsov PB, Ivanyuta AN (2023) A spatial dynamic model of the SHELF-M reactor facility with fuel and coolant temperature feedbacks. Nuclear Energy and Technology 9(1): 71–76. https://doi.org/10.3897/nucet.9.102912

Abstract

The evolution of nuclear power is inseparably linked with the development of breakthrough solutions in the field of economic development of new territories. A pressing issue in this connection nowadays is generation of power for remote and hard-to-reach areas with decentralized power supply. To resolve this issue, JSC NIKIET is developing a version of the SHELF-M modular water-cooled water-moderated reactor facility as a source of power for offshore installations, including the Arctic coast areas, as well as localities with practically no power and transport infrastructure. One of the stages in justifying the safety of the reactor facility operation is to investigate the behavior of the reactor facility in dynamic transient modes at various power levels. To this end, a spatial dynamic model has been developed for the reactor facility with fuel and coolant temperature feedbacks. The dynamic model development process is a complex task that includes both preparation of constants for subsequent calculations and generation of the reactor neutronic and thermophysical models. The paper describes the development stages of the SHELF-M reactor facility spatial dynamic model and the results of coupled neutronic and thermophysical calculations for transients using the developed dynamic model of the reactor. Shim rod movement in the cold and hot states of the SHELF-M reactor facility is considered as transients.

Keywords

pressurized water-cooled water-moderated reactor, dynamics, feedbacks, simulation

Introduction

Recent years have seen a growing interest worldwide in developing and using small nuclear power plants (SNPP). SNPPs offer an efficient substitute for the existing hydrocarbon-based power supply systems in remote hard-to-reach areas in Russia (Voropay et al. 2015; Goltsov and Molokanov 2019; Pimenov et al. 2019).

Highly reliable, safe and ecofriendly reactor facilities have been developed by now at JSC NIKIET reaching different design stages (Dragunov et al. 2011; Alekseev et al. 2015; Goltsov et al. 2016). One of the most promising designs in this field is a version of the SHELF-M, a modular water-cooled water-moderated reactor facility for SNPPs for a spectrum of applications (Andreeva et al. 2020).

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2022, n. 3, pp. 30–41.

As part of the SHELF-M project, it was required to justify computationally the safety of the reactor facility operation during transients at different power levels. A spatial dynamic reactor model with fuel and coolant temperature feedbacks was developed to this end.

The dynamic model development process involved the following stages: preparation of a two-group library of macroconstants using an MCU-family code (Alekseev et al. 2011), generation of the SHELF-M model in a diffusive approximation using the FACT code, an adaptation of the certified FACT-BR code (FACT-BR 2018) for the SHELF-M reactor facility, and integration of the IVIS thermophysical software module, developed based on the IVIS-BR thermophysical module described in Ivanyuta et al. 2021 into the FACT code. As a result, coupled neutronic and thermophysical calculations were undertaken using the generated model for transients at different reactor power levels. The transients considered include movement of shim rods in the SHELF-M cold and hot states.

Preparation of the two-group macroconstant library

To analyze the SHELF-M transients, a two-group library of macroscopic cross-sections and diffusion coefficients was formed depending both on the position of the shim rods and on the values of the fuel and coolant temperature in the computational cell of interest. To this end, a precision reactor model was developed in an MCU-family code with the MDB650 neutron data library to be used for design of thermal reactors. This code allows precision neutronic Monte Carlo calculations with solving the gas-kinetic neutron transport equation and describing continuously the neutron spectrum.

The SHELF-M precision model is a 3D computational reactor model which describes heterogeneously all core and side reflector components. The end reflector is defined in the model homogeneously. The fuel in the computational model is divided axially into 10 material zones. To record the functionalities, the FA is broken down into 18 layers, including three bottom reflector layers, ten layers at the core level, and five top reflector layers. A portion of the SHELF-M computational model prepared in the MCU code is shown in Fig. 1.

To generate the two-group library of macroconstants in the prepared computational model, the positions of the shim rods and the fuel and coolant temperature and nuclear concentration values was varied among respective computational cells. The calculation of the coolant nuclear concentrations took into account the dependence of the coolant (light water) density on the coolant temperature at the same pressure as the reactor primary circuit pressure. This dependence is presented in Fig. 2.

A matrix of the macroconstant values was formed in each computational cell based on the neutronic calculation results. The least square method was further used

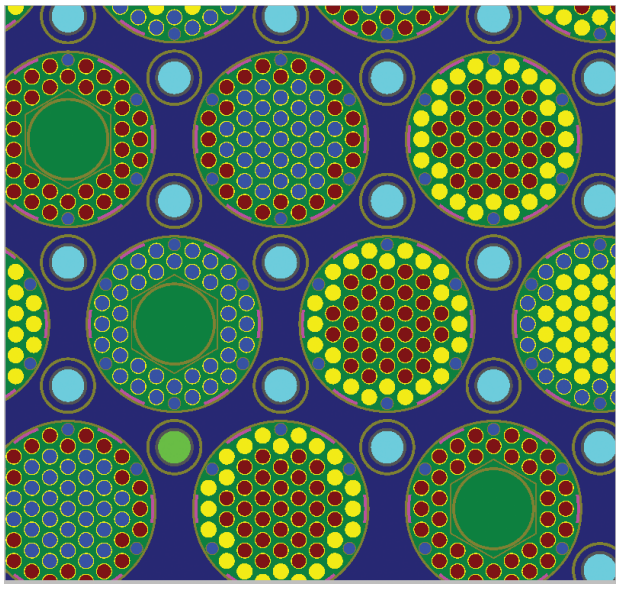

Figure 1. A portion of the SHELF-M computational model core in the MCU code.

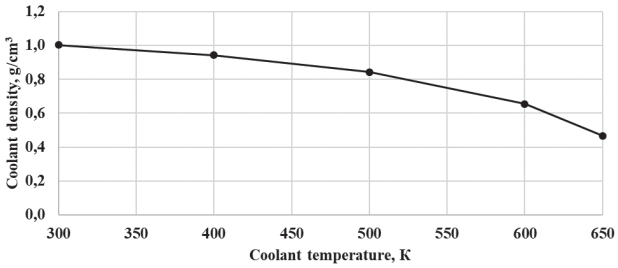

Figure 2. Coolant density change as a function of temperature.

to calculate quartic polynomials depending on the fuel and coolant temperature. The obtained polynomials were normalized against the macroconstant values that corresponded to the fuel and coolant temperature, equal to 300 K, which fits the reactor cold state.

The so obtained two-group macroconstant library was used at further stages of developing the dynamic spatial model of the reactor facility.

Simulation of the SHELF-M reactor facility in the FACT code

The prepared two-group library of macroscopic cross-sections and diffusion coefficients was used to generate the SHELF-M model in the FACT code. The model represents a set of 19 calculation cell types divided axially into 18 layers (ten layers for the core, and eight layers for the bottom and top end reflectors). The cells were divided according to type depending on the number and type of the surrounding shim rods and on the type of the FAs in the cell under consideration. In the considered model, the shim rods were arranged as three banks, including a peripheral shim rod bank (PSG), a middle shim rod bank (MSB), and a central shim rod bank (CSB).

A map of the SHELF-M computational model in the FACT code is shown in Fig. 3. A description of the cell types in the computational model is presented in Table 1.

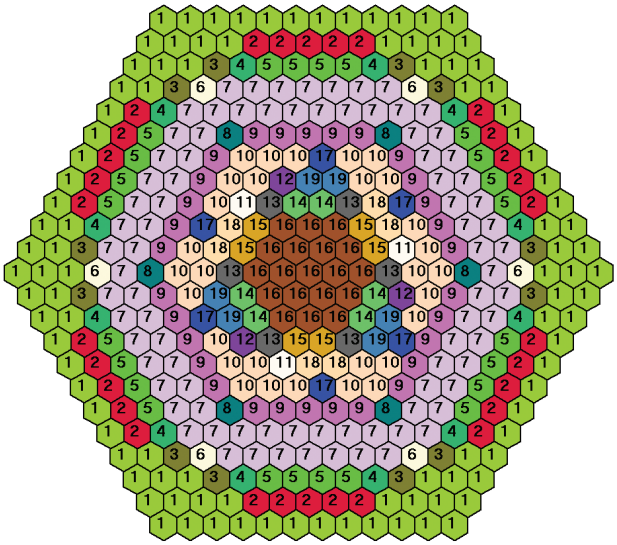

Figure 3. SHELF-M computational model in the FACT code.

Table 1. Cell types in the SHELF-M computational model in the FACT code

Cell numbers	Cell types
1–4	Reflector cells
5–19	FA cells (the number is defined by the FA type and the quantity of the shim rods around the FA)

The cell numbers are defined both by the FA type (for fuel cells) and by the rods of one of the shim banks residing (taken into account) in the computational cell. Thus, for example, the computational cell that represents a reflector and does not contain any shim rods is numbered 1, and the computational cell that represents a reflector surrounded by three PSB rods is numbered 4.

The FACT code is an adaptation of the FACT BR code for the SHELF-M reactor facility (FACT-BR 2018) and is designed for 3D neutronic and thermal-hydraulic calculations for the nuclear reactor steady states and transients taking into account the operation of control systems. A small-group diffusive approximation (2 to 26 energy groups) is used to calculate the 3D field of the neutron flux density and power distribution in the code. The diffusion equations are solved either by the finite-difference method or by the Askew-Takeda nodal method. A two-group diffusive approximation was used for the SHELF-M transient calculations based on the Askew-Takeda nodal method.

To check if the reactor model was defined correctly, the FACT code was used to calculate the reactor steady states prepared with the fuel and coolant temperature values equal to 300 K (reactor cold state). The reactor steady states match particular positions of the peripheral (PSB), middle (MSB) and central (CSB) shim rods. The adequacy of the model definition was checked using relative deviations of the K_{eff} values and the root-mean-square (RMS) power deviations between the calculation results for the MCU and FACT steady states calculated using the power values in each computational fuel cell (FA).

The obtained deviations are presented in Table 2. The relative K_{eff} deviations are in a range of –0.26% to 0.35%, and the RMS power deviations are in a range of 2.1% to 4.8%.

Table 2. Relative K_{eff} and RMS power deviations

State number	Insertion depth, cm				K_{eff}^{MCU}	K_{eff}^{FACT}	Relative K_{eff} deviations (FACT-MCU), %	RMS power deviations, %
	PSB	MSB	CSB	EP				
1	0	0	0	0	1.262	1.263	0.05	2.1
2	87	0	0	0	1.213	1.210	-0.26	4.4
3	0	87	0	0	1.153	1.154	0.07	3.0
4	0	0	87	0	1.225	1.230	0.35	4.8
5	0	0	0	92	1.238	1.238	0.04	4.2
6	87	87	87	0	0.990	0.992	0.22	2.7
7	87	87	87	92	0.976	0.976	0.02	3.9

Integration of the IVIS thermophysical module into the FACT code

To simulate thermophysical processes, a thermophysical software module called IVIS was used, designed to simulate and justify computationally the behavior of a single multilayer cylindrical object, including a fuel element with different fuel types and gas and liquid-metal layers flown over by liquid-metal coolant or pressurized water. The IVIS thermophysical module was developed based on the IVIS-BR thermophysical module (Ivanyuta et al. 2021). To develop the SHELF-M dynamic model, the IVIS thermophysical module was integrated into the FACT code.

No hydraulic processes have been calculated. The coolant flow through the FA was assumed to be constant and did not vary in the simulated transients. The SHELF-M thermophysical parameters were calculated for the condition of no coolant boiling.

The IVIS calculation results are the fuel and coolant temperature values in the computational cells of the SHELF-M model. The obtained temperature values were used to calculate two-group macroscopic cross-sections and diffusion coefficients. The calculations did not include the power density in the reflector, so the temperatures in the reflector's bottom layers are constant and equal to the reactor core inlet coolant temperature, and do not vary in the transient, as the reflector's top layers assume the core outlet coolant temperature values.

Simulation of transients

The shim rod movement in the reactor critical state (starting state) in the reactor cold and hot states is considered

as the demonstration of the coupled neutronic and thermophysical calculation results for transients.

A transient is calculated in two stages. The calculation's stage 1 is to establish the reactor steady state. In the process of recalculating the neutron flux density, the fuel and coolant temperatures are recalculated, and the macroscopic cross-sections and diffusion coefficients are respectively recalculated in each computational cell. The transient is simulated at the second stage.

Six groups of delayed neutrons are used to simulate transients. Table 3 presents the data of six delayed neutron emitter groups for the spatial kinetics calculation obtained as the result of the SHELF-M calculation in the MCU code.

Table 4 presents a description of the starting state corresponding to the SHELF-M hot state. The hot state corresponds to the reactor operation at the rated power level.

Table 3. Data for six groups of delayed neutron emitters

Emitter group number	Fraction of delayed neutrons	Delayed neutron emitter decay constant, s^{-1}
1	2.56×10^{-4}	0.012
2	1.46×10^{-3}	0.033
3	1.306×10^{-3}	0.121
4	2.843×10^{-3}	0.303
5	9.37×10^{-4}	0.849
6	2.02×10^{-4}	2.85

Table 4. Starting state description

Parameter	Value
Fuel temperature, K	590
Core inlet coolant temperature, K	544
Reactor power, MW	35.2
K_{eff}	0.9988
PSB rod position, cm	53
MSB rod position, cm	65
CSB rod position, cm	78

To demonstrate the operation of the IVIS code, the maximum fuel temperature, the maximum coolant temperature, and the maximum fuel element temperature drop reached in the process of establishing the steady-state temperature field in the reactor in the course of the steady-state calculation are presented in Table 5.

Table 5. SHELF-M thermophysical parameters

Parameter	Value
Maximum fuel temperature, K	659.9 K
Maximum coolant temperature, K	584.6 K
Maximum fuel element temperature drop, K	140.08 K

After the reactor steady state is established, the transient is simulated. The transient was simulated as follows:

- at time t = 5 s, the CSB rods start to move from position 78 cm to position 81 cm (CSB rod insertion);
- at time t = 35 s, the CSB rods stop at position 81 cm (the CSB rod stop);
- at time t = 55 s, the CSB rods start to move from position 81 cm to position 78 cm (CSB rod withdrawal);
- at time t = 85 s, the CSB rods stop at position 78 cm (CSB rod stop);
- the CSB rod movement rate is 0.1 cm/s;
- the transient duration is 100 s.

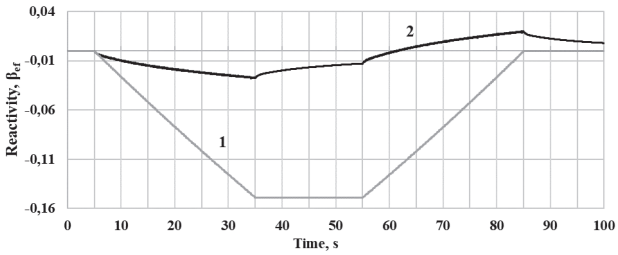

Figure 4. Reactivity change for models without feedbacks (1) and with feedbacks (2) for fuel and coolant temperature.

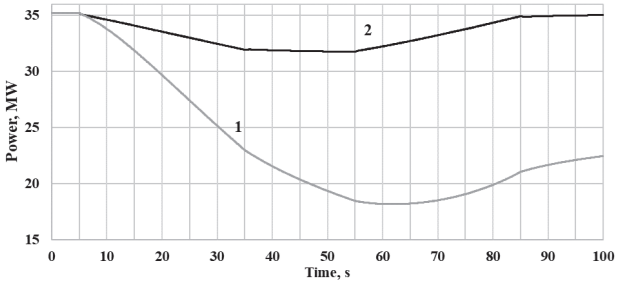

Figure 5. Power change for models without feedbacks (1) and with feedbacks (2) for fuel and coolant temperature.

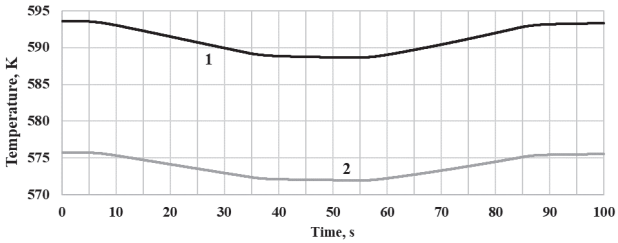

Figure 6. Fuel (1) and coolant (2) temperature change in the selected central group FA layer.

The transient is shown in the diagrams of the change in reactivity (Fig. 4), power (Fig. 5), and the fuel and coolant temperature (Fig. 6). For comparison with the spatial kinetics model without feedbacks, diagrams of the transient have been added to the reactivity and power change diagrams (Fig. 4 and Fig. 5 respectively) without considering the fuel and coolant temperature feedbacks.

To check the serviceability of the prepared SHELF-M model at different power levels, the transient was also calculated for the reactor's cold state. The reactor cold state matches the reactor power equal to 1.0 MW. The transient simulation process in the event of the reactor cold state was similar to that in the event of the reactor hot state. A description of the starting state in the event of the SHELF-M cold state is presented in Table 6.

Table 6. Description of the starting state

Parameter	Value
Fuel temperature, K	300
Core inlet coolant temperature, K	300
Reactor power, MW	1.0
K_{eff}	0.9999
PSB rod position, cm	68
MSB rod position, cm	82
CSB rod position, cm	68

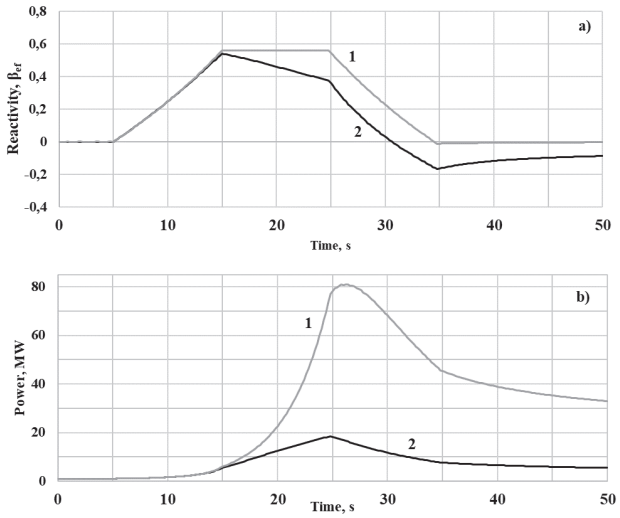

Figure 7. Reactivity (**a**) and power (**b**) change in the models without feedbacks (1) and with feedbacks (2) for fuel and coolant temperature.

The transient was simulated as follows in the event of the cold state:

- at time t = 5 s, the MSB rods start to move from position 82 cm to position 79 cm from the core top (MSB rod withdrawal);
- at time t = 15 s, the MSB rods stop at position 79 cm from the core top (MSB rod stop);
- at time t = 25 s, the MSB rods start to move from position 79 cm to position 82 cm from the core top (MSB rod withdrawal);
- at time t = 35 s, the MSB rods stop at position 82 cm from the core top (MSB rod stop);
- the MSB rod movement rate is 0.3 cm/s;
- the transient duration is 50 s.

The transient is shown in the diagrams for the change in reactivity (Fig. 7a), power (Fig. 7b), and the fuel and coolant temperature (Fig. 8). For comparison, diagrams of the transient have been added to the reactivity and power change diagrams without considering the fuel and coolant temperature feedbacks.

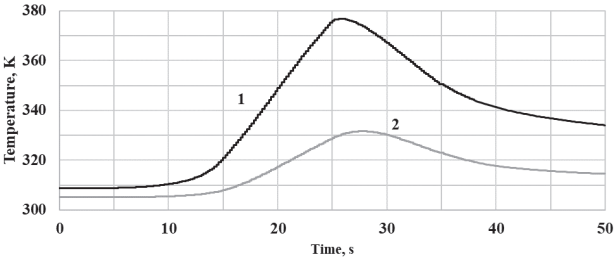

Figure 8. Fuel (1) and coolant (2) temperature change.

Conclusion

As the result of the study, a technology has been implemented in the FACT code to calculate the SHELF-M reactor facility transients using a spatial dynamic model of the reactor with fuel and coolant temperature feedbacks.

Coupled neutronic and thermophysical calculations were undertaken for the SHELF-M transients involving the shim rod movement in the reactor cold and hot state. Simulation results are shown for the transients under investigation.

Therefore, the obtained spatial dynamic model of the SHELF-M reactor facility makes it possible to analyze the reactor behavior in transients at different power levels.

Further activities will aim at improving the SHELF-M model, developing thermal-hydraulic and thermomechanical model of the reactor, and integrating respective software modules into the FACT code.

References

- Alekseev AI, Goltsov EN, Grechko GI, Eremeev DV, Pepa VN (2015) SMR Uniterm is One of Actual Directions in the Development of Nuclear Energy. Proc. of the Conference «Small Nuclear Power Reactors: A New Direction for Energy Development». Moscow. Academ-Print Publ., 219–219. [in Russian]
- Alekseev NI, Bolshagin SN, Gomin EA, Gorodkov SS, Gurevich MI, Kalugin MA, Kulakov AS, Marin SV, Novoseltsev AP, Oleinik DS, Pryanishnikov AV, Sukhino-Khomenko EA, Shkarovsky DA, Yudkevich MS (2011) MCU-5 status. VANT. Ser. Fizika Yadernykh Reaktorov 4: 5–23. [in Russian]
- Andreeva LA, Goltsov EN, Kaplienko AV, Kudinov VV, Kulikov DG, Molokanov NA, Pimenov AO (2020) Actual Developmental Problems of Small Energy Installations: SNPP Based on the SHELF-M Reactor Installation. Atomic Energy 129(4): 201–207. https://doi.org/10.1007/s10512-021-00734-7
- Dragunov YuG, Shishkin VA, Grechko GI, Goltsov EN (2011) Small Nuclear Power: Problems and Answers, Atomnaya Energiya 111(5): 293–297. http://elib.biblioatom.ru/text/atomnaya-energiya_t111-5_2011/go,56/ [accessed Mar. 29, 2022] [in Russian]
- FACT-BR (2018) «FACT-BR» (Version 1.1) Certification Passport of the Software No 433 dated 02.27.2018. [in Russian]
- Goltsov AE, Molokanov NA (2019) Assessment of SMRs Competitiveness Based on the SHELF Nuclear Facility for Isolated Territories on the Example of the Republic of Sakha (Yakutiya). In: Scien-

tific and Technical Annual Report NIKIET-2019. NIKIET JSC Publ., Moscow, 260–263. [in Russian]

- Goltsov EN, Kulikov DG, Pimenov AO, Rapnitsky VA (2016) SHELF-M Modular Reactor Facility for Small Nuclear Power Plants. Proc. of the International Scientific and Technical Conference «Innovative Nuclear Power Designs and Technologies (NIKIET-2016)», September 27–30, Vol. 1: 582–586. [in Russian]
- Ivanyuta AN, Ionov AI, Sakharova TYu (2021) Certificate of State Registration of the Software «IVIS-BR»: No 2021610722 dated 01.02.2021. [in Russian]
- Pimenov AO, Kulikov DG, Vasiliev AP, Molokanov NA (2019) Small Nuclear Power Reactors in the Arctic Territories: Issues of Economic Feasibility and Environmental Safety. Arktika: Ecologiya i Ekonomika 2(34): 120–128. https://doi.org/10.25283/2223-4594-2019-2-120-128 [in Russian]
- Voropay NI, Saneev BG, Ivanova IYu, Izhbuludin AK (2015) Comparative Efficiency of Using Small Nuclear Power Reactors in Local Energy Systems in the East of Russia. Proc. of the Conference «Small Nuclear Power Reactors: A New Direction for Energy Development». Academ-Print Publ., Moscow, 59 pp. [in Russian]