DOI 10.1007/s10512-023-00941-4
Atomic Energy, Vol. 132, No. 5, September, 2022 (Russian Original Vol. 132, No. 5, September, 2022)

MCU–RELAP SOFTWARE PACKAGE FOR ANALYZING ACCIDENTS AND NON-STATIONARY PROCESSES IN THE PIK REACTOR

A. A. Apresov, A. M. Degtyarev, M. A. Kalugin, A. N. Kuznetsov, A. A. Myasnikov, S. S. Pylev, and D. A. Shkarovskii

UDC 621.039.51+621.039.514+621.039.51...17

The purpose of this work is to elaborate the MCU-RELAP software package for modeling transient regimes in the PIK reactor by way of a self-consistent description of neutronics and thermohydraulic processes. The scheme of the developed MCU–RELAP software package is described, and the application of the package is shown for the example of a beyond design-basis accident in which an element of the CPS is ejected. The reactivity adjustment procedure implemented in the scheme makes it possible to detect and smooth the deviations that appear because of the imprecision of the reactivity characteristics used in dynamic calculations performed within the scope of the point-kinetics approximation used in the RELAP5/MOD3.2 code.

A calculation of transient processes in the PIK reactor during design basis and beyond-design basis accidents is one of the stages of safety substantiation [1]. A reactor is characterized by a complicated geometric structure with a significant spatial dependence of the neutron spectrum, which requires an accurate description of the power density. A high average power density of the core ~2 MW/L requires computer modeling with heightened accuracy. At the same time, in transient regimes, the small core volume ~50 L affords moderate manifestation of spatial effects. Under these conditions, the MCU–RELAP software package was developed based on an adiabatic approximation of neutron kinetics in order to simulate transient regimes.

In the RELAP5/MOD3.2 general-loop thermohydraulic program, the calculation of a change of reactor power is based on the point kinetics model, in which the change in the shape of the power density cannot be taken into account [2]. The Monte Carlo method implemented in the MCU program code makes it possible to improve the simulation accuracy of transient processes by refining the power density and system reactivity calculated using the RELAP5/MOD3.2 computer code [3].

The RELAP5/MOD3.2 program is used to calculate the position of the control rods and the spatial distribution of the fuel temperature and the temperature and density of the coolant. The obtained values are used in the MCU calculation of reactivity and power density, which are then transferred to the RELAP5/MOD3.2 program in order to continue the calculation.

One of the main problems of the interrelated neutronic and thermohydraulic calculations is conformity of different approaches to model building. A consistent description of the PIK reactor separately for each code with data exchange aided by tables of correspondence, which are given, was used to combine the MCU and RELAP5/MOD3.2 codes into a single software package. For MCU, a full-scale 3D model of the PIK reactor is specified, including the core, CPS rods, and reflector (Fig. 1). Uranium dioxide enriched with ^{235}U up to 90 wt.% serves as fuel, the first two rows containing inner (along the radius) hexagonal fuel assemblies – fuel rods with a reduced load of uranium. The nodalization model for RELAP5/MOD3.2 makes it possible to simulate the flow of liquid inside the reactor pressure vessel, taking the design into consideration. The movement of liquid from the top to the bottom of the core is modeled taking into account the gaps between the central experimental channel tube and the core, the inner-row fuel assemblies and a hexagonal guide, the outer-row fuel assemblies and the reactor vessel, the shell of the support grid and the reactor vessel, and the gaps between the fuel assemblies. The space between the FA and the support grid and the sampler tubes and the support grid are also taken into account.

National Research Center Kurchatov Institute, Moscow, Russia; e-mail: degtyarev_am@nrcki.ru. Translated from Atomnaya Energiya, Vol. 132, No. 5, pp. 264–268, May, 2022. Original article submitted January 23, 2021.

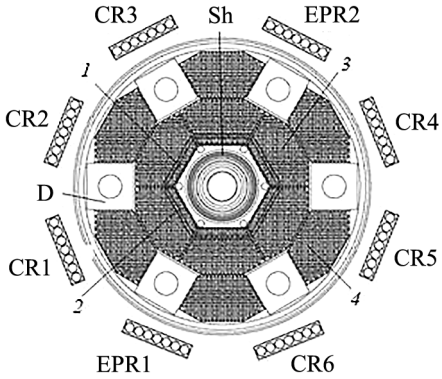

Fig. 1. Model of the PIK reactor with 12 fuel assemblies, 6 displacers, and the following groups of fuel rods selected for the RELAP5 program: *1*) first group of fuel rods (first two rows of the fuel rods of inner hexagonal fuel assemblies); *2*) second group (third row of fuel rods of the inner hexagonal fuel assemblies); *3*) third group (other fuel rods of inner hexagonal FA; *4*) fourth group (fuel rods of inner hexagonal FA); KS – compensating rods, AZ – emergency protection rods, Sh – shutters, D – displacer.

In the model, the core is divided into layers along height, and the fuel rods are combined into four groups. On data exchange the MCU receives information averaged for each layer of each fuel assembly, and RELAP5/MOD3.2 receives information averaged over the nodes of each group of each layer. The coolant pressure at the reactor entrance and the water flow through the reactor were assumed to be constant. The power release in water and structural materials was not taken into account.

To check correctness, the calculations were performed using the complex and separately using RELAP5/MOD3.2, i.e., using the MCU program without specifying the reactivity and density. In both calculations, on solving the point kinetics equation in RELAP5/MOD3.2, the same data set was accepted, including the reactivity coefficients, calibration curves of the CPS rods, and the parameters of the point kinetics equation. The reactivity coefficients and calibration curves were determined from preliminary calculations performed with the MCU program.

The MCU–RELAP complex was tested for the example where the lower absorbing shutter is ejected with the reactor operating at power 10 MW and load 12 hexagonal FA with very low fuel burnup. In addition, six displacers were situated in the core; these are hydraulic simulators of standard square fuel assemblies. This core state corresponds to the onset of the reactor start-up phase with 12 fuel assemblies and is characterized by a 2% reactivity margin distributed between the absorbing shutters and lateral compensating rods: the shutters are in a symmetrical position relative to the central plane of the core with a 34.4 cm window between them, KS4 is submerged by 90 cm to the level at the center of the core, and KS1 is fully inserted.

It was assumed that 0.1 sec is required in order for the lower curtain to be fully ejected on introduction of a positive reactivity of 0.95 β_{eff}, resulting in a rapid increase in the reactor power on reaching the emergency protection set-point for the reactor period. The signal is passed. The emergency protection is activated when the reactor power reaches the emergency setting. Jamming of the most effective emergency protection element (top shutter) is considered as an independent failure signal.

The emergency power alarm is generated within 0.5 sec. Taking into account an additional delay of 0.05 sec, in computational modeling the movement of lateral CPS rods starts with a 0.55 sec delay from the set-point. Lateral rods are introduced – six compensating rods and two emergency protection rods. The travel distance of a CPS rod from the upper limit switch to the upper boundary of the core requires 1 sec, the full insertion time is equal to1.3 sec.

According to the data in Table 1, the introduction of positive reactivity ~0.95 β_{eff} for 0.1 sec effects a reactor power increase to ~65 MW within 0.15 sec. The maximum supercriticality of the reactor is reached by 0.1 sec and, taking negative feedbacks into account, it is equal to ~0.9 β_{eff}. After that, feedback powers the reactivity and power begins to decrease. In the time interval of 0.1–0.6 sec the input of negative reactivity comes from feedback on the temperature of the fuel and water. After 0.6 sec, the CPS rods start to move. Since half of a KS4 rod was inserted into the core before the onset of the initiating event, its movement without additional time delay effects the introduction of negative reactivity ~0.2 β_{eff} within the full immersion time ~0.7 sec from the initial state. The six remaining CPS rods situated on the upper limit switch reach the upper core level 1 sec after the start of movement, i.e., by 1.55 sec. The reactivity introduced within their complete insertion time

TABLE 1. Change in Power and Reactivity on Ejection of the Lower Shutter in the PIK Reactor

Time, sec	Power, MW			Reactivity, β		
	RELAP	MCU–RELAP	Δ, %	RELAP	MCU–RELAP	Δ, %
0	10	10	0.01	0.13	0.13	0.02
0.1	44.83	48.54	8.27	0.89	0.92	3.04
0.15	64.89	65.27	0.57	0.81	0.8	–1
0.2	51.11	50.46	–1.28	0.73	0.73	–0.44
0.3	45.08	42.75	–5.18	0.71	0.69	–2.68
0.4	47.57	46.1	–3.1	0.7	0.69	–1.32
0.5	49.05	49.17	0.24	0.69	0.69	0.57
0.7	50.23	50.09	–0.28	0.68	0.68	0
0.8	49.93	47.77	–4.32	0.66	0.64	–2.39
0.9	48.31	46.68	–3.37	0.63	0.62	–1.64
1	45.67	45.83	0.34	0.59	0.6	0.83
1.1	42.86	42.51	–0.82	0.55	0.55	–0.05
1.2	39.91	39.37	–1.36	0.51	0.5	–1.64
1.3	38.81	38.03	–2.01	0.49	0.48	–1.70
1.4	38.61	36.34	–5.88	0.48	0.45	–5.59
1.5	38.57	36.41	–5.61	0.47	0.45	–5.04
1.6	36.56	35.85	–1.93	0.42	0.41	–0.87
1.7	25.2	24.71	–1.96	0.14	0.13	–3.58
1.8	13.85	14.01	1.14	–0.56	–0.53	–6.48
1.9	8.66	8.67	0.15	–1.46	–1.42	–2.35
2	7.53	7.67	1.89	–1.73	–1.64	–5.23

~0.3 sec from the upper boundary of the core into the core is ~2.4 βeff. The subcriticality of the reactor by the 2nd second reaches ~1.7 βeff, and the power decreases to ~8 MW.

The agreement between the calculation results for the MCU–RELAP and RELAP5/MOD3.2 computer codes as shown in Figs. 2, 3 confirms the legitimacy of using the point approximation, which is implemented in RELAP5/MOD3.2. The maximum deviation of power was less than 7%, water temperature – less than 1°C, and fuel – less than 10°C. The transient regime is characterized by moderate deformation of the power density (Fig. 4). However, the MCU-RELAP program will have to be used if on the introduction of significant reactivity spatial effects must be taken into account in transient modes.

The RELAP5/MOD3.2 program can be used to analyze transient processes occurring in the PIK reactor with a known joint manifestation of reactivity characteristics: density and temperature coefficients of reactivity, efficiency of CPS organs. At the same time, it is not always possible to assess in advance the degree of their reliability in relation to the process being modeled.

Two additional calculations show the ability of MCU-RELAP to assess and adjust the impact of inaccuracies in determining the reactivity characteristics of the reactor on calculation of transientients. In the first calculation, the density coefficient of reactivity is reduced by 20%; in the second calculation, a coarsened dependence of the CPS rod efficiency on the insertion depth is used. Due to the high sensitivity of the reactor power to reactivity, especially in the supercritical state, in order to reduce fluctuations in characteristics, the time intervals between MCU calculations must be reduced to a minimum. In this case, the high time cost for each such calculation must be taken into account.

TABLE 2. Change in the Power and Reactivity on 20% Reduction of the Density Coefficient of Reactivity Reduced by 20% in the PIK Reactor

Time, sec	Power		Reactivity	
	ΔRELAP, %	Δ(MCU–RELAP), %	ΔRELAP, %	Δ(MCU–RELAP), %
0	0.02	0.01	0.2	0.17
0.25	8.99	8.54	2.48	2.63
0.5	8.13	1.12	2.08	0.53
0.75	8.45	–4.67	2.16	–2.92
1	7.88	–1.38	2.32	–0.98
1.25	7.32	–2.97	2.35	–2.39
1.5	7.25	–3.28	2.61	–3.07
1.75	5.12	–0.04	–0.37	–1.94

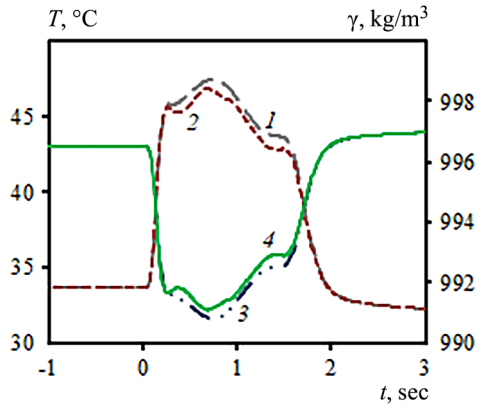

Fig. 2. Average temperature (*1*, *2*) and coolant density (*3*, *4*) on ejection of the lower shutter, calculated using the RELAP5/MOD3.2 and MCU–RELAP programs, respectively.

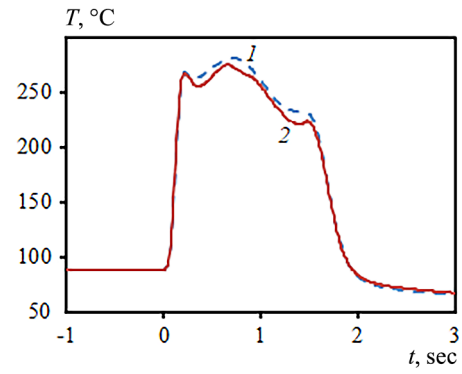

Fig. 3. Maximum fuel temperature calculated using the RELAP5/MOD3.2 (*1*) and MCU–RELAP (*2*) programs on ejection of the lower shutter.

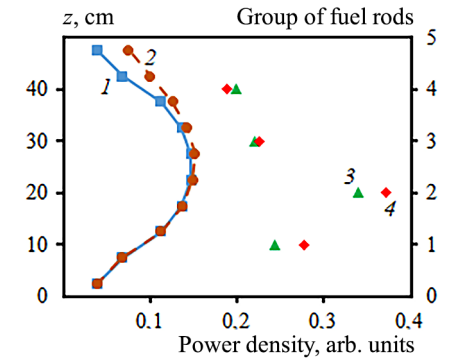

Fig. 4. Axial (*1*, *2*) and radial distribution of the power density (*3*, *4*) at the start of the process and up to 1.85 sec, respectively, calculated using the MCU-RELAP program.

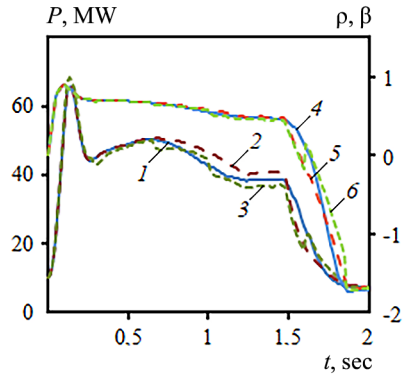

Fig. 5. Power (*1*, *2*, *3*) and reactivity (*4*, *5*, *6*) with a rough description of the dependence of the CPS rod efficiency on the insertion depth, calculated using the RELAP5/MOD3.2 programs with initial and perturbed characteristics and the MCU–RELAP, respectively.

Thirteen MCU calculations were performed in each problem considered: two to determine the equilibrium state before the accident and 11 directly in the accident simulation process. The effective multiplication factor, which is used in the calculation of the reactivity adjustment for the RELAP5/MOD3.2 program, was calculated with an error of 0.004%.

The calculations given in Table 2 and Fig. 5 show that MCU-RELAP levels out the effect of perturbations in the reactivity characteristics of the reactor, bringing the results closer to the distributions calculated using the RELAP5/MOD3.2 program with unperturbed characteristics. This effect is achieved by adjusting the reactor reactivity based on a Monte Carlo calculation.

The developed MCU-RELAP software package makes it possible to increase the modeling reliability and accuracy of non-stationary processes in the PIK reactor, including emergency regimes with the introduction of significant positive reactivity. The automatic exchange of information between the MCU and RELAP5/MOD3.2 codes implemented in the complex provides a consistent three-dimensional description of the dynamics of neutronic and thermophysical characteristics.

This work was performed using the equipment at the Center for Collective Use "Complex for Modeling and Processing Data of Mega-Class Research Installations" at the National Research Center Kurchatov Institute (subsidy from the Ministry of Education and Science, work identifier RFMEFI62117X0016).

REFERENCES

1. A. N. Erykalov, A. S. Zakharov, K. A. Konoplev, et al., *Design of the Core and Reflector of the PIK Reactor*, Preprint PNPI 2472 (2002).
2. *RELAP5/MOD3.2 Code Manual*, NUREG/CR5535, INEL-95/0174, Vol. I–VII (1995).
3. M. A. Kalugin, D. S. Oleinik, and D. A. Shkarovskii, "Overview of the MCU Monte Carlo Software Package," *Ann. Nucl. Energy*, **82**, 54–62 (2015).