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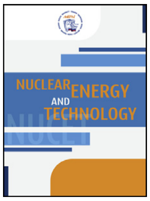

Testing of the system code designed for simulation of hypothetical beyond design-basis accident on fast breeder reactor

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Abstract

The purpose of the present study was to develop integrated system of codes (ISC) for performing continuous self-consistent calculation of the whole life cycle of fission products (FP) in the nuclear power plant with nuclear reactor unit (RU) equipped with fast reactor (BN) starting from accumulation of FPs in the reactor core to their exit in the environment and migration outside the NPP site territory. SOKRAT-BN integrated code was used in the calculations in combination with KUPOL-BN and NOSTRADAMUS codes.

Practical importance of the study is attributed to the development of the ISC for substantiation of BN RU safety. Simulation of hypothetical beyond design-basis accident at the NPP equipped with BN RU accompanied with escape of radioactive isotopes in the reactor premises was performed as the test task. Results of solution of the test problem confirm practical applicability of the developed ISC. Development of the methodology for simulation of migration and precipitation of radioactive impurities in the sodium coolant represents scientific novelty. Software module TRANS-FR designed for simulation of transport of radioactive fission products (RFP) and radioactive corrosion products (RCP) in the primary cooling circuit and in the gas system of the RU was developed and integrated in the SOKRAT-BN ISC taking into account the main physical processes taking place during transport and accumulation of RFP and RCP.

Software interface modules for data exchange between the SOKRAT-BN, KUPOL-BN and NOSTRADAMUS codes were developed and tested.

Keywords: Severe beyond design-basis accident; KUPOL-BN code; NOSTRADAMUS code; SOKRAT-BN integrated code; Fast reactor; Fission products; Substantiation of BN reactor safety.

Introduction

Russia has a long waiting list of foreign orders for construction of nuclear power generation facilities – more the fifty countries would like nuclear power reactors to be built on their territories, and fast reactors are also found in this list. A complex of studies needed to substantiate safety of the nuclear power unit has to be performed for obtaining the license to implement construction works, commissioning, operation and decommissioning of the power unit of nuclear power installation on the specific site. In order to prove safety of the RU and to obtain permits from oversight agencies supporting calculations must be made using licensed computer codes.

Dedicated codes were developed at the SSC RF-IPE in the process of design and substantiation of Russian fast reactors BN-350, BN-600 and BN-800. Review of some of these codes is contained in the monograph [1]. BOS-TWC codes calculating in two-dimensional approximation sodium

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boiling in reactor fuel assemblies, COREMELT code for calculation of melting of reactor fuel assemblies and melt drainage, TWOCOM code for calculation of yield of gaseous fission products from fuel pins, BRUT code for simulation of molten matter retention inside the reactor vessel and ANPEX code for investigation of reactor runaway on prompt fission neutrons in case of secondary criticality were developed. KUPOL code [2] for analysis of hydrogen safety and its subsequent version KUPOL-BN intended for fast reactor simulation were developed as well.

At present requirements imposed on reactor safety and, consequently, requirements imposed on computer codes are steadily becoming more and more stringent. Increasing computer capacities allowed practically addressing the task of development of multi-physics codes. Integrated software tool which in the field of nuclear engineering combines neutron physics calculation module, thermal hydraulics loop module, as well as modules for calculation of yield of fission products (FP), activation of corrosion products (CP), containment module for analysis of hydrogen safety, module describing transfer and deposition of radioactivity in the environment surrounding the NPP and analysis of exposure loads, etc. is understood under the term multi-physics code. In order to satisfy international safety requirements pertaining to reactor safety substantiation it is necessary to perform analysis of consequences of initiating events (IE) leading to severe accidents (SA) or to beyond design-basis accidents (BDBA). Experimental simulation of such processes is usually extremely expensive, hazardous and hardly feasible in practical terms.

In pursuance with Paragraph 6.2, RB-044-09 Standard [5]: “Studies of beyond design-basis accident are recommended to be implemented using system software describing in an integrated manner the development of different processes (from the initiating event to the emergency radioactivity release) and the events during the design-basis accident”. The above listed domestically developed software instruments, although they are capable to calculate the processes in the BN-type reactor facility in emergency operation mode, do not allow implementing the integrated once-through calculation of severe accidents in reactor facilities of BN type. Integrated software tool (IST) SOKRAT-B1 [3] designed to calculate VVER reactors developed at the Nuclear Safety Institute of the Russia Academy of Sciences was used in the substantiation of safety of VVER-100 reactors in China, India, etc.

At present the base version of the SOKRAT-BN IST developed on the basis of the SOKRAT-B1 IST and intended for calculation of physical processes taking place during the phases of heavy and severe accidents at the liquid-metal cooled nuclear power installations is available. For ensuring the unified self-consistent calculation of the behavior of fission products (FP) in sodium-cooled reactor facilities (BN RF), release of FPs in the environment for different BN RF operation conditions and calculation of FP behavior in the environment the SOKRAT-BN IST in combination with KUPOL-BN software complex and NOSTRADAMUS software complex are expected to simulate the following chain of events:

It is necessary to calculate generation and accumulation of FP isotopes in fuel pins in the reactor core, release of FPs in the fuel pin gas gap, destruction of the fuel pin cladding, release of FPs in the primary cooling circuit, transport of FPs along the RF circulation loops, deposition and washing away of the FPs, release of FPs inside the NPP buildings, transport of FPs to the places in the buildings and structures with loss of containment tightness formed as the result of the accident, and FP migration in the environment. Results of testing the SOKRAT-BN IST modules ensuring simulation of the whole chain of development of events described above are presented in the present study.

Simulation of migration of radioactive impurities in the SOKRAT-BN IST

The task of simulation of penetration of radionuclides in the coolant, their transfers and behavior within the circulation loops of the RF is allowed to be implemented by the SOKRAT-BN IST. In particular, the TRANS-FP computation module is included in the above IST designed to calculate the transfer and behavior of radioactive fission products (RFP) and radioactive corrosion products (RCP) in the primary circuit and in the reactor facility gas system.

The original version of the TRANS-FP module included empirical models of transfer and behavior of RCP and gaseous RFP (described in [6]) and simplified models of behavior of volatile and non-volatile FPs. Transfer equation is applied for description of FP and CP transport in the following form:

$$\frac{dC_i(t)}{dt} = S_i(t) - C_i(t)(R_i(t) + \lambda) - C_i(t) \sum_{\substack{j=1 \\ j \neq 1}}^{Ncomp} Q_{ij}(t) + \frac{1}{V_i} \sum_{\substack{j=1 \\ j \neq 1}}^{Ncomp} C_{ij}(t) Q_{ij}(t) V_j + \frac{S_i}{V_i} C_i^p(t) R_i^p(t).$$

The equation is solved jointly with equation describing the variation of concentration.

$$\frac{dC_i^p(t)}{dt} = \frac{V_i}{S_i} C_i(t)\ (R_i(t) - C_i^p(t) R_i^p(t + \lambda)$$

Here, j and i are the indices corresponding to channels; R_i is the rate of deposition; N_{comp} is the number of channels; $S_i(t)$ is the source of impurities in the channel; S_i is the total surface area of channel walls; R_i^p is the rate of resuspension of impurities; Ci is the concentration of impurity in the suspended state; C_i^p is the concentration of impurity in the deposited state; and Q_{ij} is the rate of gas (liquid) exchange between the channels i and j.

Existing models are suggested to be supplemented with improved model of behavior of cesium isotopes in sodium coolant. Cesium may be present in the form of easily dissolvable metal impurity, it can be accumulated in depositions on the walls of elements of the first cooling loop of the RF, as well as released in the gas system [7]. Results of experimental studies of cesium behavior in sodium loops [8–10]

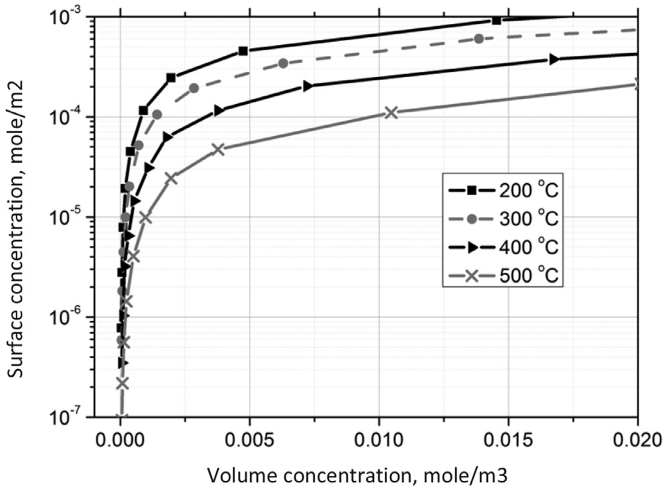

Fig. 1. Curves of cesium sorption on steel from liquid sodium within temperature interval of 200–500 °C.

evidence that physical adsorption is the main mechanism of cesium deposition.

Based on the particular shape of experimental curves of cesium sorption (Fig. 1, [8]) assumption was made on the predominantly monomolecular character of adsorption at coolant temperatures and within the range of cesium concentrations in sodium which can be expected to be found in BN RF.

Beside that the following assumptions were made: uniform surface of walls of the loop; effects of sediments of CP and FP on the walls on the cesium sorption process are not taken into consideration.

Within the framework of the above assumptions the Langmuir's model of monomolecular adsorption is used. The process of adsorption is described by the equation of kinetics of sorption process on the wall C as follows:

$$dx/dt = k_{ads} \cdot C_S \cdot (1 - x) - k_s \cdot x. \quad (1)$$

The equation contains the rates of adsorption and desorption determined from the following relations:

$$k_{ads} = k^0_{ads} \cdot \exp[-E_{act}/(R \cdot T)], \quad (2)$$

$$k_{des} = k^0_{des} \cdot \exp[-(E_{act} + \Delta H)/(R \cdot T)]. \quad (3)$$

In (1)–(3) C_S is the cesium concentration in the suspended state near the wall; $x = \rho_p/\rho_c$ is the relative concentration of occupied adsorption centers; ρ_p is the density of occupied adsorption centers; k^0_{ads} and k^0_{des} are the constants not dependent on the coolant temperature; E_{act} is the energy of adsorption activation; ΔH is the heat of adsorption; T is the coolant temperature near the wall or near the phase contact surface.

Parameters in Eqs. (1)–(3) were determined in the course of analysis of results of loop experiments described in [8,10].

The phenomenon of mass transfer between the phases is taken into account in the developed model of transfer and behavior of cesium isotopes. Transfer and behavior of cesium isotopes between the phases is described as the combination of processes of diffusion transfer of cesium from the main coolant flow to the surface separating phases, and processes of evaporation and condensation on the surface separating phases. The resulting rate of cesium transfer between the phases is determined according to the following relation [11]:

$$\omega = \alpha \cdot (PS - P) \cdot a \cdot [M/(2\pi RT)]^{1/2},$$

where α is the condensation coefficient (for the case of evaporation from sodium in argon the value can be taken to be equal to 0.03 [12]); PS is the partial pressure of saturated cesium vapors at the given temperature; P is the partial pressure of cesium vapors; a is the relative activity of cesium in the solution; and M is the cesium molar mass.

Testing the complex of software modules describing FP transfer between the coolant loop and the NPP buildings using SOKRAT-BN IST

BN-600 nuclear reactor has pool-type configuration and, therefore, the possible place of leakage from the primary cooling loop in the containment is the leakage from the pipeline in the rooms where cool traps are located. The problem of calculation of FP transport from the place of leakage inside the NPP premises to the place of their escape in the environment through the destroyed walls of NPP buildings (as the result of hypothetical severe accident) or through the ventilation stack must be solved using the KUPOL-BN computational complex. NOSTRADAMUS code [4] originally developed for VVER-type RF and additionally refined to take into account the specific features of the BN-type RF is used for numerical simulation of FP migration in the environment after accident at the NPP. In particular, modules of behavior of non-stable sodium isotopes (^{22}Na, ^{24}Na) as the products of coolant activation in humid atmosphere were added.

It is assumed that the FPs escape the primary cooling loop in the premises of cold traps together with coolant (liquid sodium). Values of flow rates through the leak and sources of fission products were output using the transmitter of SOKRAT-BN code via the developed interface in the output file of the KUPOL-BN module.

The criterion of correctness of operation of the interfaces is the equality between the readings of program transmitters of the SOKRAT-BN code and the values in the control printout in the output file of the KUPOL-BN module.

Flow rates of sodium in the leak calculated using the SOKRAT-BN code (black curve), and those transmitted via interface by the KUPOL-BN module (round dots) are shown in Fig. 2 for the conditions of hypothetical leak through the small diameter tube. It is clear from the figure that leakage from the small-diameter pipeline of the primary coolant loop produces little effect on the primary loop parameters and, therefore, it remains intact during extended time periods (within the framework of the selected scenario of the accident).

Correctness of transmission of remaining thermal and hydraulic parameters (pressure, temperature, flow rates of liquid and gaseous components and concentrations of

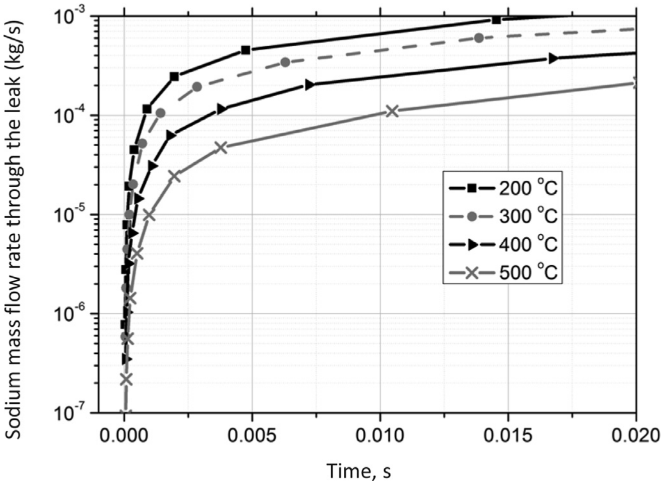

Fig. 2. Results of calculation of mass flow rate through the leak. Test of transmission of sodium flow rate from SOKRAT-BN code (solid line) to the KUPOL-BN module (markers).

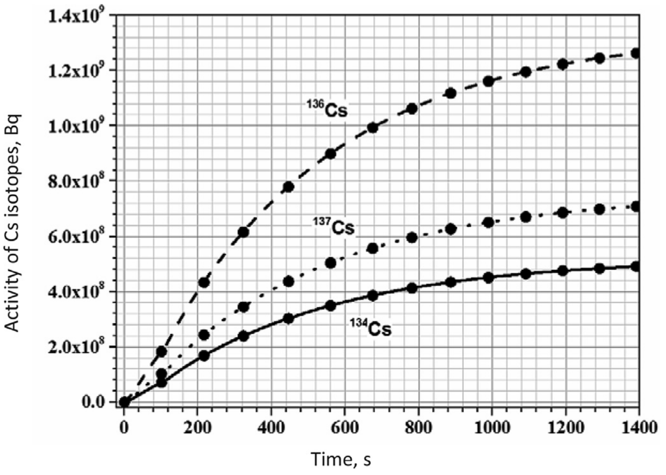

Fig. 3. Activities of Cs isotopes transmitted from the SOKRAT-BN code (solid line) to the KUPOL-BN module: lines refer to the SOKRAT-BN code; and markers refer to the KUPOL-BN module.

non-condensing gases) was checked in the process of testing. Cesium isotopes (^{134}Cs, ^{136}Cs and ^{137}Cs) and isotopes of noble gases, xenon and krypton (^{85m}Kr, ^{88}Kr, ^{133}Xe, ^{135}Xe and ^{138}Xe) were selected in order to test correctness of transmission by interfaces of activities of dose-shaping isotopes from the SOKRAT-BN to the KUPOL-BN software. Activities of Cs, Xe and Kr isotopes calculated using the SOKRAT-BN code (curves) and the KUPOL-BN module (markers) are shown in Figs. 3 and 4. It is clear that transmission of values of activities for radioactive decay chains of from the SOKRAT-BN to the KUPOL-BN code is operated correctly.

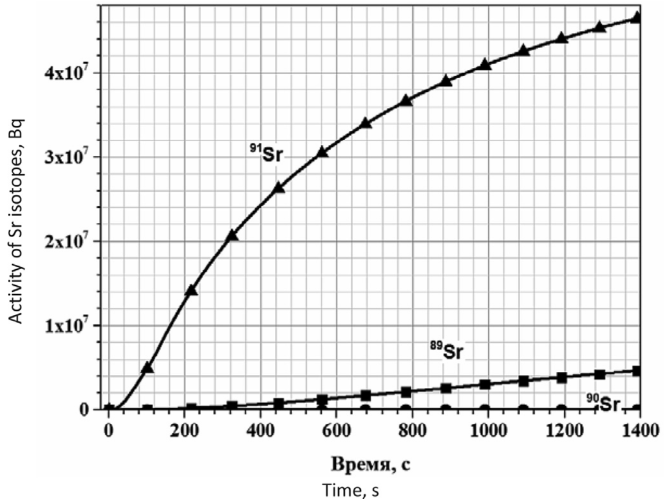

Fig. 4. Activities of xenon and krypton isotopes transmitted from the SOKRAT-BN code (solid line) to the KUPOL-BN module: lines refer to the SOKRAT-BN code; and markers refer to the KUPOL-BN module.

Testing modules for calculation of releases of FPs and their migration in the environment

Inclusion of the NOSTRADAMUS code in the calculations finalizes the solution of the radiation safety analysis problem. It has to be noted that different meteorological conditions (direction and force of wind, presence of precipitation, atmospheric stability) must be accounted for in the analysis of safety within the framework of a single hypothetical accident at the NPP. Therefore, several calculations made using the NOSTRADAMUS code will be required for a single scenario of development of accident at the RF simulated using the SOKRAT-BN ISC and the KUPOL-BN ISC. The possibility to perform such calculations is ensured by the fact that calculations of typical grids performed by the NOSTRADAMUS code are faster than the development of events in real time.

Transmission of data from the KUPOL-BN software complex to the NOSTRADAMUS software complex was achieved via the external data files. Release height, mass flow rate from the leak and, as well, parameters of the medium acting as the carrier of FPs, including dry deposition rate, gravity velocity and the washout rate are additionally transmitted from the KUPOL-BN code to the NOSTRADAMUS code as the input data.

Test calculation of radiation environment with sequential automatic data transmission was performed for testing joint run of the SOKRAT-BN–KUPOL-BN–NOSTRADAMUS software complex. In this exercise the data on the release of radionuclides in atmosphere prepared by the KUPOL-BN code are used by the NOSTRADAMUS code for estimating the radiation environment during such radioactivity release. Is was conventionally assumed in the calculation that release of radionuclides in atmosphere occurs through the ventilation stack and mounts to 50% of the quantity of activity penetrating from the reactor loop in the power plant premises.

Source of radioactivity release in the environment for the examined example is described in Table 1.

It was accepted in the calculation of migration of radioactivity in the atmosphere that the third power unit of the Beloyarskaya NPP (BN-600) serves as the source of the radioactivity release and, correspondingly, performance characteristics

Table 1
Integral yield of radioactivity in the test calculation.

Nuclide	^{134}Cs	^{136}Cs	^{137}Cs	^{90}Sr	^{89}Sr	^{91}Sr
Activity, Bq	$2.3 \cdot 10^{12}$	$0.8 \cdot 10^{13}$	$4 \cdot 10^{12}$	$0.6 \cdot 10^{10}$	$1.1 \cdot 10^{11}$	$1.5 \cdot 10^{11}$
Nuclide	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	
Activity, Bq	$0.8 \cdot 10^{14}$	$1.3 \cdot 10^{14}$	$1.8 \cdot 10^{14}$	$2.3 \cdot 10^{14}$	$1.7 \cdot 10^{14}$	

Table 2
Set of conditions for calculation of the radiation environment.

Parameter	Value	Comments
Wind velocity	2 m/c	Such wind velocity is typical for stable stratification
Category of stability of the atmosphere	F	
Atmospheric precipitation	No	
Wind direction	350°	Wind direction towards the Town of Zarechny located at the distance of ~4 km from the BNPP
Average roughness of the underlying surface	0.4 m	
Duration of the discharge	0.1 h	

Input data presented in the table were input in the NOSTRADAMUS code manually through the dialog input system, while data on the source were transmitted in automatic mode.

of the territory surrounding the NPP site were used in the calculations.

It is assumed in the estimation of effective radiation exposure values that meteorological conditions are the most favorable for areas removed from the source by several kilometers, i.e. for the group of population residing in the region of the NPP site. Such conditions are the following: stable stratification of atmosphere and not high wind velocity. Due to the first factor maximum of radionuclide concentration appears to be found several kilometers from the stack because of weak vertical turbulence. The second factor (slow wind) facilitates development of high concentrations at all distances. Input data for the calculation are presented in Table 2.

Evaluation of radiation exposure for population in the vicinity of the NPP

Results of the implemented analysis of radiation environment can be formulated as follows:

- Exposure of humans to external irradiation from radioactive cloud at the distance of 4 km (on the territory of the Town of Zarechny) amounts to 2 mSv;
- Adolescent exposure from inhalation irradiation of thyroid (children one-two years of age) amounts to 25 mSv;
- Maximum exposure from external irradiation from the cloud equal to approximately 0.1 mSv is reached at the distance of 2.6 km from the source.

In accordance with “Criteria for decision making on the measures for protection of population in case of nuclear reactor accident” no evacuation of residents of the Town of Zarechny is required.

Conclusion

Integrated computer software tool allowing performing once-through calculation of fission products for NPP equipped with BN RF starting from their accumulation in the reactor core to their release in the environment and migration beyond the limits of the NPP site was developed. Interface software modules for exchange of data describing parameters of fission products between the SOKRAT-BN, KUPOL-BN and NOSTRADAMUS software codes were developed and tested. Capacities of the integrated software tool were demonstrated. Obtaining licenses to use the developed software tools is planned to be achieved in the nearest future – in 2014–2016. Therefore, the numerical results presented in the present paper must be regarded as preliminary data corresponding to the current state of development of software codes.

References

[1] I.A. Kuznetsov, V.M. Poplavsky, in: V.I. Rachkov (Ed.), Corresponding Member of the RAS, IzDat, Moscow, 2012, p. 635. (in Russian).
[2] KUPOL-M. Certificate of software product No. 199, Dated 23.06.2005, Science and Technical Nuclear Safety Center (NTTs YaRB) (developed by the SSC RF-IPPE) (in Russian).
[3] SOKRAT/B1 Certificate of software product No. 275 dated 13.05.2010, (developed by the Nuclear Safety Institute of the Russia Academy of Sciences) (in Russian).
[4] NOSTRADAMUS. Certificate of software product No. 158 dated 28.03.20023, Science and Technical Nuclear Safety Center (NTTs YaRB) (in Russian).
[5] RB-044-09, Nucl. Radiat. Saf. 3 (53) (2009) 44–67 (in Russian).
[6] A.S. Zhilkin, S.L. Osipov, Salyaev, et al., Bull. RAS (Izvestiya RAN): Power Gener. Ser. (Energetika) 3 (2014) 1–9 (in Russian).
[7] Yu.V. Chechetkin, V.D. Kizin, V.I. Polyakov, Radiation Safety of NPPs Equipped With Fast Reactor and Sodium Coolant, Energoatomizdat, Moscow, 1983, p. 128. (in Russian).
[8] Yu.G. Bobkov, I.A. Efimov, Yu.I. Zagoroul’ko, et al., in: Proceedings of the Annual Meeting of International Working Group on Fast Reactors, May 5–8, 1987, Karlsruhe, FRG, 1987, pp. 41–60.
[9] N. Mitsutsuka, H. Shimojima, Y. Gohshi, J. Nucl. Sci. Technol. 14 (2) (1977) 135–146.
[10] N. Sagawa, H. Iba, Y. Yato, et al., J. Nucl. Sci. Technol. 10 (9) (1973) 523–532.
[11] O. Knacke, I.N. Stransky, Physics-Uspekhi (Adv. Phys. Sci.) 68 (2) (1959) 261–305.
[12] M.F. Zhukov, A.S. Koroteev, B.A. Uryukov, Applied Dynamics of Thermal Plasma, Nauka Publishers, Novosibirsk, 1975, p. 297.