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FINITE ELEMENT ANALYSIS FOR THE LEAK DETECTION IN VESSELS OF SODIUM-COOLED FAST REACTORS IN CASE OF BEYOND DESIGN BASIS ACCIDENTS

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ABSTRACT

3D simulation considers the process of non-standard deformation of the liquid sodium-cooled fast reactors in case of an emergency shutdown of main circulation pumps in the primary circuit aggravated with the emergency protection system failure (beyond design basis accident of ULOF type). Coolant circulation loss causes melting of the reactor core and generates increased pressure in the power density area filled with sodium evaporations. Progressing expansion of the power density area in the coolant increases the reactor vessel stress level and may cause its destruction. Under such circumstances, ensuring the radiation safety of the Nuclear Power Plant personnel and the surrounding environment requires localization of the accident consequences within the reactor pressure vessel, which is impossible in case of its seal failure.

The current Langrangian formula analyses the coolant and reactor structure motions. The equation of motion is derived from the virtual power balance. Elastic-plastic deformation of structure materials is fitted to the plastic flow theory correlation to the isotropic hardening. In case of liquid coolant, the relation of the hydrostatic pressure and density is fitted to the quasi-acoustic type equation of state. The contact of the coolant with the reactor structural elements is simulated in the nonponetrating conditions. The solution is based on the moment scheme of the finite element method and explicit finite-difference scheme of time integration of a "cross" type implemented on the "Dinamika-3" computer system. The 8-node finite elements with poly-linear functions of the form are used to discretize the defining equations system for spatial variables.

The change in the stressed-strained state of the fast reactor vessel in the conditions of the beyond design basis accident of ULOF type. The authors analyse the possibility of localizing the consequences of the beyond design basis accident within the reactor pressure vessel.

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Environmental and health radiation safety assessment is one of the leading determinants for the prospects in the development of nuclear power industry [1-4]. Pursuant to the regulation acts [5], the analysis of the beyond design basis accidents (BDBA) forms an integral part of the safety justification any nuclear power plant (NPP). In particular, the power scenario of the ULOF BDBA [6, 7] provides for the NPP blackout with the loss of energy supply sources, including the reserve ones with the simultaneous failure of all means to impact the reactivity. In these circumstances, the construction of the integral fast reactors of the BN type shall provide for the solidity of the pressure vessel.

The beyond design basis accident is characterized by the generation of increased pressure in the reactor core power density area (PDA) filled with sodium vapours. The power density area transmits the stress waves able to cause a large displacement of the coolant, elastic plastic deformations or fractures in the constructive elements of the reactor. The most important aspect in safety assurance in the emergency under consideration becomes the dynamic strength analysis of the reactor vessel and in-core instrumentation equipment in their interaction with the coolant. Methods and program codes for the simulation of thermal phenomena in nuclear power plants are described in [7-11]. Below are the methods and results of numerical solution of a three dimensional task for elastic-plastic deformation of fast reactor under hydrodynamic effects in the ULOF type BDBA.

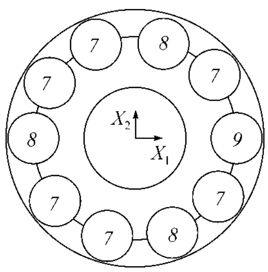

Fig. 1. Design model (top view)

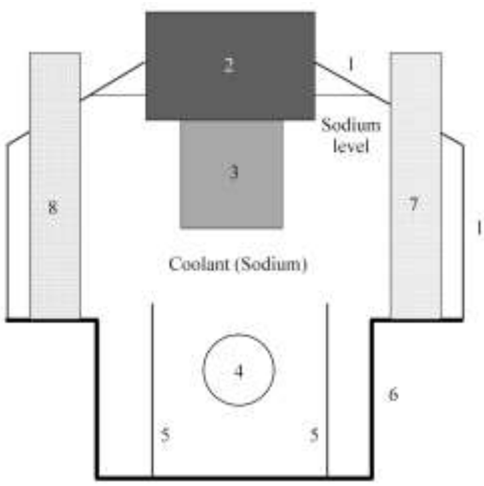

Fig. 2. Design model (side view)

Design model of BN-type reactor is shown in Fig. 1, 2, where the figures indicate the following: 1) reactor vessel; 2) big rotating plug; 3) central column; 4) power density area (PDA); 5) neutron-reflecting block; 6) support skirt; 7) intermediate heat exchanger (IHX); 8) main circulation pump (MCP); 9) riser. Reactor design elements are made of steel 08XI8H9, the physical and mechanical properties of which at the temperature of 450 °C are given in [6]. It was assumed that the time moment t = 0 corresponds to the completion of a reactor power excursion phase and the formation of a spherical power density area. The power density source is located in the core center. The change in the time of pressure P in the power density area calculated with the account of the heat exchange with a cold metal structure of the vessel is shown in Fig. 3, where P_0 = 3 MPa is the maximum pressure value [6].

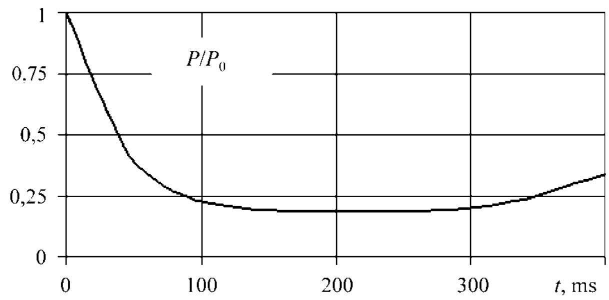

Fig. 3. Relation of pressure in the coolant to the time at the power density area borderline

The reactor vessel and coolant motion is described using the current Langrangian formula. The equation of motion is derived from the virtual power balance [12, 13]:

$$\int_{\Omega} \sigma_{ij}\delta\dot{\varepsilon}_{ij}dV + \int_{\Omega} \rho\ddot{U}_i\delta\dot{U}_i dV =$$

$$= \int_{\Gamma_p} P_i\delta\dot{U}_i d\gamma + \int_{\Gamma_q} P_i^q\delta\dot{U}_i d\gamma \quad \left(i, j = \overline{1, 3}\right), \qquad (1)$$

where $\dot{U}_i$ are the components of the motion speed vector in the common Cartesian coordinates system X; σ_{ij}, $\dot{\varepsilon}_{ij}$ are the Cauchy stress tensors components and deformations speed (symmetric part of the velocity gradient); ρ is density; P_i^q is the contact pressure on the border of Γ_q interaction of the coolant and reactor structural elements; P_i is the load distributed on the surface of the power density area Γ_p; Ω is the area under analysis (coolant, reactor vessel and in-core equipment); $\delta\dot{\varepsilon}_{ij}$, $\delta\dot{U}_i$ are variations $\dot{\varepsilon}_{ij}$, $\dot{U}_i$ (on the surface with the set kinematic boundary conditions $\delta\dot{U}_i = 0)$; the point over the symbol means the partial differential coefficient by the time t; the summing up is performed by the repeated indexes. Tensor components of the strain rate are defined in the current state:

$$\dot{\varepsilon}_{ij} = \left(\dot{U}_{i,j} + \dot{U}_{j,i}\right)/2 \quad \left(i, j = \overline{1, 3}\right), \quad \dot{U}_{i,j} = \partial\dot{U}_i / \partial X_j ,$$

$$X_i = X_i\big|_{t=0} + \int_0^t \dot{U}_i dt\,. \qquad (2)$$

The equations of the plastic flow theory are employed as the physical ratios for metals [15, 16].

$$\sigma'_{ij} = \sigma_{ij} + \sigma^V \delta_{ij},\ \ \dot{\sigma}^V = -3K\dot{\varepsilon}^V,\ \ \dot{\varepsilon}^V = \dot{\varepsilon}_{ii}/3,$$

$$\dot{\varepsilon}'^e_{ij} = \dot{\varepsilon}_{ij} - \dot{\varepsilon}^V\delta_{ij} - \dot{\varepsilon}^p_{ij},\ \ \dot{\varepsilon}^p_{ii} = 0,\ \ D_J\sigma'_{ij} = 2G\dot{\varepsilon}'^e_{ij},$$

$$\dot{\varepsilon}^p_{ij} = \dot{\lambda}\partial f/\partial\sigma'_{ij},\quad f = \sigma'_{ij}\sigma'_{ij} - \frac{2}{3}\sigma_T^2 = 0;$$

$$\sigma_T = \sigma_T(\chi),\quad \chi = \sqrt{\frac{2}{3}}\int_0^t \sqrt{\dot{\varepsilon}'^p_{ij}\dot{\varepsilon}'^p_{ij}}\,dt; \qquad (3)$$

Here, σ'_{ij}, $\dot{\varepsilon}'_{ij}$, σ^v, $\dot{\varepsilon}^v$ are the deviatoric and spherical stress tensors components and strain rates; $\dot{\varepsilon}^p_{ij}$ is the plastic strain rates; G, K are the shear modulus and volumetric compression; δ_{ij} are Kronecker symbols; D_J is the Jaumann derivative [17]: $D_J\sigma'_{ij} = \dot{\sigma}'_{ij} - \sigma'_{ik}W_{kj} - \sigma'_{jk}W_{ik}$, where $W_{ij} = \left(\dot{U}_{i,j} - \dot{U}_{j,i}\right)/2$; f is the Mises yield surface, σ_T is the dynamic yield stress; $\dot{\lambda}$ is the parameter equal to zero at the elastic deformation and defined at elastic plastic deformation based on the conditions of momentary yield surface through the end of the additional loading vector.

This paper examines the non-stationary stage of the BDBA characterized by the highest level of pressure in the power density area. The duration of the non-stationary stage according to the numerical task solution in the axially symmetric simulation [6] is about 10 ms. The deviation from the temperature of 450 ^{0}C is not material. The strain rate in the constructive elements of the reactor does not exceed 10s^{-1}. Thus, the effect of changing the strain rate and temperature on deformation characteristics of the material are not taken into account.

The coolant is modeled as a liquid media, in which the deviatoric stress components are assumed to be equal to zero, and the relation of the hydrostatic pressure to the density is taken as a quasi-acoustic equation of state [6].

The contact between the coolant and the reactor structural elements are simulated in the nonponetrating conditions along the normal and free glide along the tangent to the contact surface [18]

$$\dot{u}^1_n = \dot{u}^2_n,\ \ q^1_n = -q^2_n,\ \ q^1_i = q^2_i = 0,\ \ i = \tau_1, \tau_2. \qquad (4)$$

Here n, τ_1, τ_2 are single vectors of local orthogonal basis, n is the vector of normal to the contact surface, τ_1, τ_2. are orthogonal to n; the inferior index i means projection of the vector onto the axis of the mobile coordinate system, the upper indices 1 and 2 mark the numbers of the corresponding subdomains, whose surfaces are in contact. The relation of the contact subdomains is assumed to be one-sided, i.e. the separation of surfaces and repeated contact are possible. Thus, the conditions (4) are applied to compressing forces only $\left(q^i_n, n^i\right) < 0.$ The system of equations (1)-(4) is supplemented with initial conditions and kinematic boundary conditions.

The solution of 3D nonlinear dynamics task is based on the finite element method and explicit finite-time integration scheme of differential type of a "cross" type [16, 18-21]. The deformed construction is replaced by a Lagrangian frame consisting of 8-node finite element (FE). The acceleration $\{\ddot{U}\}$, velocity $\{\dot{U}\}$ and displacement in a common coordinate system are defined in the frame nodes $\{U\}$ $\{X\} = \{X_1 X_2 X_3\}^T$. The shear elements and bending deformations in the finite elements are supposed to be small, while the shear and rotation angles of the FE as a rigid solid unit are random. In each final element, there is an introduced local basis $\{x\} = \{x_1 x_2 x_3\}^T$ tracking its rotation as a rigid solid unit [20]. The finite element is displayed on the cube using poly-linear isoparametric transformation $-1 \le \xi_i \le 1$ $(i = \overline{1,3})$:

$$x_i = \sum_{k=1}^{8} x_i^k N_k\left(\xi_1 \xi_2 \xi_3\right)$$
$$N_k = \left(1+\xi_1/\xi_1^k\right)\left(1+\xi_2/\xi_2^k\right)\left(1+\xi_3/\xi_3^k\right)/8. \qquad (5)$$

In (5) x_i^k, ξ_i^k the coordinates of nodes in the basic sets x, ξ; N_k is the form functions. To prevent the development of the spurious energy mode, the strain rate components $\dot{\varepsilon}_{ij}$ in FE are approximated by linear functions:

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^0_{ij} + \dot{\varepsilon}^1_{ij}\xi_1 + \dot{\varepsilon}^2_{ij}\xi_2 + \dot{\varepsilon}^3_{ij}\xi_3. \qquad (6)$$

By analogy with the theory of shells, $\dot{\varepsilon}^0_{ij}$ are the values of strain rate components in the FE center are further referred to as momentless components and their gradient $\dot{\varepsilon}^k_{ij} = \partial\dot{\varepsilon}_{ij}/\partial\xi_k = \mathrm{const}$ are the moment components. Not to overstate the shear stiffness of the element, (6) includes only the components $\dot{\varepsilon}^k_{ij}$ corresponding to the bending and torque moments in the theory of shells [21]. On the basis of (6) there has been developed a family of finite elements for modeling complex composite structures including deformable media, massive bodies and shells [16].

The power of virtual work in each of the final elements in equation (1) is expressed through the matrix of the masses, node acceleration, and statically equivalent nodal forces. The replacement of integration in the area Ω by summing up the elements allowed obtaining the analog of the motion equations:

$$[M]\{\ddot{U}\} = \{F\}, \qquad (7)$$

where $[M]$ is the diagonal matrix of masses; $\{\ddot{U}\},\{F\}$ are the vectors made of accelerations of FE frame and resulting node forces in the common coordinates system. The system of ordinary differential equations (7) is integrated in the explicit finite differential scheme of a "cross" type.

Numerical determination of the contact pressure in the interaction zones of deformable bodies and statically equivalent to it forces in FE frame is made of nonponetrating conditions and laws of mass conservation and kinetic momentum [18]. The methodology above is implemented using "Dinamika-3" computing system (CS) certified in the Research and Technology Center for Nuclear and Radiation Safety [22] and Federal Agency on Technical Regulating and Metrology of Russia [23]. The appraisal completed on the "Dinamika-3" CS allowed studying the research accuracy, convergence and stability of a mathematical model and solution methodology implemented in it [16, 18, 20]. Research results confirmed their effectiveness in the tasks of the class under consideration.

In the course of the numerical analysis over the stress-strain state of the BN type reactor in the BDBA conditions, the riser, main circulating pumps and intermediate coolants are modeled with non-deformed cylindrical shells of the same geometric parameters. Given the cyclic symmetry of the design under consideration (Fig. 1) and loading conditions, the computational domain was selected to be 1/20 part of the reactor. The total number of nodes in the discrete model of a computational domain amounted to 13325. 1212 nodes of the latter are in the reactor vessel and protection rim. The use of a relatively coarse design discretisation was made possible by the adopted approximation for strain rate and stresses [16], which is in its essence the numerical realization of a 6 variant model of the theory of a Timoshenko type [21] and allows simulating the dynamics of thin shells on frames with one element in thickness. Comparing the results of the numerical solution of the axially symmetric task without taking into account the intermediate coolants and the main circulating pumps of reactor in 3D and axially symmetric simulations [6] proved that the applied methodology [16, 18, 20] provides for the acceptable accuracy at such a finite element frame.

Results of numerical research are presented in Fig. 4-6 in the form of graphs of time relation to: a) contact force $\tilde{F} = F/(P_0 S_P)$ impacting the bottom of the central column and rotating plug (S_P is the area of the central column bottom and rotating plug); b) vertical displacement velocity V of the rotating plug; c) stress intensity calculated in the average vertical cross section of a cylindrical shell vessel. The dotted and solid lines in these figures highlight the results of finite element solutions axially symmetric and non-axially symmetric tasks in a 3D simulation with and with no account for the innertank equipment.

The analysis of the results of the numerical simulation revealed the following.

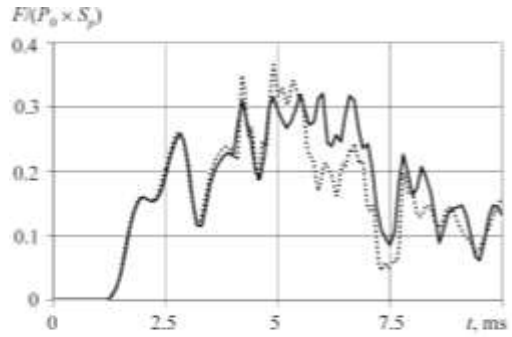

Fig. 4. Variation in time for the contact force impacting the bottom of the central column and rotating plug

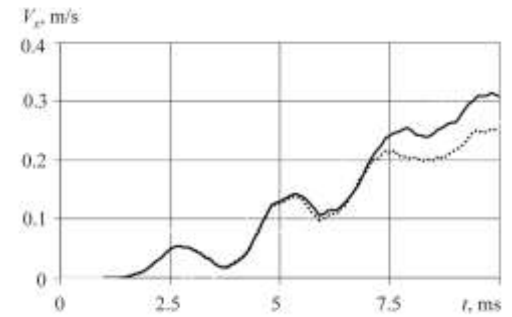

Fig. 5. Variation in time of the vertical displacement velocity in the rotating plug

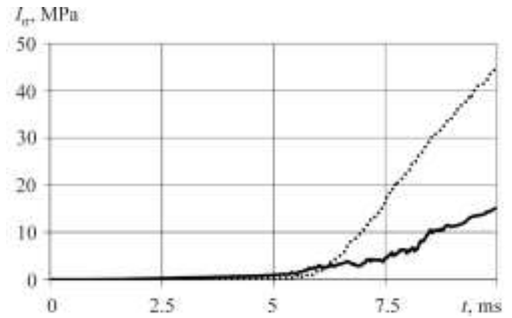

Fig. 6. Variations in time for the stress intensity calculated in the average along the vertical cross section of a cylindrical shell of the vessel

Within the time interval under consideration the MCP and intermediary coolant reduce the hydrodynamic load on the reactor vessel and stresses intensity in the vessel. Thus, the maximum value of the stress intensity, resulting in an average vertical cross-section of the cylindrical shell reduced by 3 times. The impact of MCP/Intermediary coolant on hydrodynamic loads on the bottom of the central column is not material. The maximum value of the integral hydrodynamic load $F(t) = F_k + F_p$, that impacts the bottom of the central column (F_k) and rotating plug (F_p) slightly changes. This is due to the fact that the increase in the load on the rotating plug bottom is caused by the waves reflected from the MCP/Intermediary coolant occurs during the period, when the load impacting the bottom of the central column from the power density area side is already decreasing.

The in-core equipment causes increase in the pressure generated on the rotating plug and in the velocity of its vertical displacement by approximately 16 %. Under the influence of vertical displacement of the rotating plug and increase in the longitudinal tensile stresses in the middle part of the cylindrical shell in the pressure vessel, the motion stops and radial strain rate sign changes.

The impact produced by the innertank equipment on the hydrodynamic loading on the bottom of the central column and rotating plug are revealed at the non-stationary stage of the BDBA development $(8 \le t \le 10\ \text{ms})$. Therefore, studying a more prolonged development stage of the BDBA is acceptable to be completed in the 2D (axially symmetric) simulation.

The maximum level of stress in the reactor vessel during the BDBA progress does not exceed the permitted norms set for the strength [24]. Thus, the completed analysis demonstrated the potential to localize the consequences of BDBA inside the reactor pressure vessel and prevent hazardous radiation exposure on the NPP personnel and the environment.

Conclusions

Main circulation pumps and intermediary coolants reduce hydrodynamic load on reactor pressure vessel in the middle part of the reactor and increase stresses in the location of mounting the rotating plugs to the neck. The numerical study of the BDBA developmental stage after reaching the maximum pressure on the rotating plug is acceptable to be conducted in 2D (axially symmetric) simulation. Nuclear Power Plant blackout with a loss of energy supply sources, including the reserve ones, with the simultaneous failure of all means to impact the reactivity do not result in the depressurization of the fast reactor, which confirms the high safety level of the reactor.

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