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ASSESSMENT OF THE CONDITIONS OF HEAT EXCHANGE IN A POOL OF SPENT NUCLEAR FUEL FROM THE ACCOUNT OF EFFECT OF EVAPORATION

Provides a model for the assessment of processes of heat transfer in the basins of excerpts of spent nuclear fuel, with various levels of flooding and the effects of evaporation. To heat flow due to surface evaporation can be significant (up to 20–30%) the amount of total heat sink and must be taken into account in the analysis of accidents and for the first time after unloading spent nuclear fuel from the reactor. The results of this work can be used to analyze the security of storage of spent nuclear fuel in some reactor basins excerpts.

Introduction. Storage of spent nuclear fuel (SNF) is one of the final stages of the fuel cycle a nuclear power plant. Unloaded from the reactor SNF originally sent for storage in a pond in the basins of excerpts (BE) for reduction of residual heat, and then transferred to dry storage [1].

Complexity of the problems of spent nuclear fuel (SNF linked to its high activity, availability of a large number of fissionable substances and considerable heat release after unloading from the reactor.

Storage of spent nuclear fuel should provide removal of the residual heat of spent fuel assemblies (SFA), the protection of personnel and the environment from ionizing radiation or release of radioactive substances into the environment, physical protection of spent fuel. These requirements fully meet the storage of spent nuclear fuel in the aquatic environment ("wet" method of storage), in which there is a reduction of the residual heat and the disintegration of the most active short-lived radionuclides such as iodine-131, xenon-133, etc. The time this takes is 1–3 years depending on the type of nuclear fuel [2].

Long-term experience of the "wet" storage of SNF has proved its reliability and convenience, particularly to reduce the level of radiation loads and heat generation of the spent fuel directly after unloading from the reactor [3, 4]. Basins of excerpts (Fig. 1) is intended:

– for storage of spent fuel assemblies in order to downturn of their activity and residual heat;

– overload sustained TVs from VWD in the transport container;

– overload of fresh TVs from the holster in the basins of excerpts reactor;

– overload of spent TVs from the reactor core in racks BE;

– overload of fresh TVs from the shelves BV in the reactor.

To control the condition of the assemblies during the storage of used industrial television set. Indrect control is exercised with the help of measuring a specific radioactivity and analysis of chemical composition of water. With the planned refueling for on-water heat from the spent fuel assemblies in reactor spent fuel pools has a cooling system that cycles on maintaining the temperature of the pool water to 30°C. The maximum temperature in the BE should not exceed 70°C at full unloading SFA in basins of excerpts of the active zone of the reactor [2].

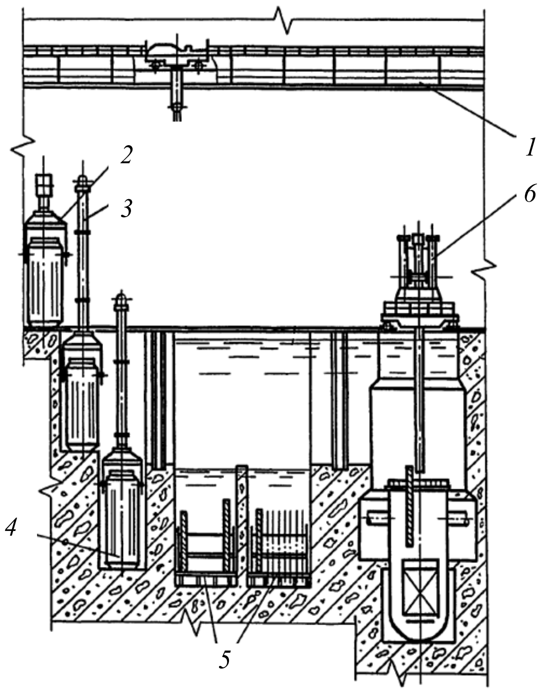

Fig. 1. Scheme some reactor basin extracts of spent nuclear fuel from VVER-1000 [2]:
1 – circular crane; *2* – gantry container for spent nuclear fuel; *3* – pole for container; *4* – transport container; *5* – racks BE; *6* – fuel-handling machine

Decay heat from the fuel assemblies are in BE is forced circulation of water in the compartments of BE. Running pump cooling water circulation BE creates a closed loop. The pump delivers water to the pressure line where it enters the pressure manifold, which supplies the compartments pond. BE of water flows into the drain pipe and the heat exchanger. Going through the annulus with multiple cross-flow tube bundle, the water is cooled to a temperature of ≤45° C, and its circulation by the cooling circuit BV repeated.

Statement of the problem of the study. The accident at the Fukushima nuclear power plant basins of excerpts (BE) was the Achilles heel of nuclear power plants, as the vast majority of new fuel assemblies (FA) was in BW, but not in the reactor. As a result of leaks and boiling water in BE FA stripped and began to melt.

Certainly, SFA emit less heat la than new build, but still enough to bring in their inefficient cooling to heating BE zirconium rods and shells, respectively, to the possible destruction of their integrity. In this case, as a result of pressure from the shells begin to escape FA radioactive gases (for example, a pair of iodine-131) that has accumulated in the rods during their stay in the reactor.

In connection with the above, the safety case "wet" storage of spent fuel due to development of analysis of the effectiveness of cooling systems BE reliable methods of calculating their thermal parameters. And, in particular, in emergency situations, when the partial or full off forced circulation in the cooling circuit.

The basis of these techniques can serve as a numerical analog systems 2-D and 3-D time-dependent conservation equations for the initial and boundary conditions corresponding to the real conditions of storage of spent nuclear fuel in BE.

These equations have to be built in relation to the complex spatial geometric structures and describe the various modes of heat transfer considering both convection and evaporation effect.

Method of analysis. In this paper, in the framework of formal templates software package COMSOL Multiphysics model designed analog system for temporary storage and cooling of spent fuel in reactor spent fuel pools (Fig. 2).

When building a computational model of BE, the following key assumptions:

1) the motion of the gas phase is described in the two-vapor mixture;

2) the physical properties of water and solid media are assumed constant, and the properties Vapor – depending on the temperature, pressure and relative humidity;

3) the bottom and sides pond are considered to be insulated, and the removal of heat of committed, respectively, only through vents.

This takes into account two mechanisms of heat removal: by convection and by evaporation. Radiation heat transfer was not considered.

Consequently, the overall model for the description of transport processes was based on the unsteady equations of conservation of momentum, mass and thermal energy in the form of

$$\rho\frac{\partial U}{\partial t}-\nabla\left[\eta\left(\nabla U+(\nabla U)^{T}\right)\right]+\rho U\nabla U+\nabla P=0,$$

$$\nabla U=0,\ \ \rho C_p\left(\frac{\partial T}{\partial t}+\vec{u}\cdot\nabla T\right)=\nabla\left(\lambda\nabla T\right)+Q_V,$$

where ρ – density of the medium; U – flow rate; η – coefficient of dynamic viscosity; P – hydrostatic pressure; T – temperature range in RA; C_p – specific heat; u – velocity vector of STI; λ – thermal conductivity; Q_V – volumetric heat source. Upper indeks T – turbulence component, defined according to k-ε turbulence model in the interpretations of COMSOL Multiphysics.

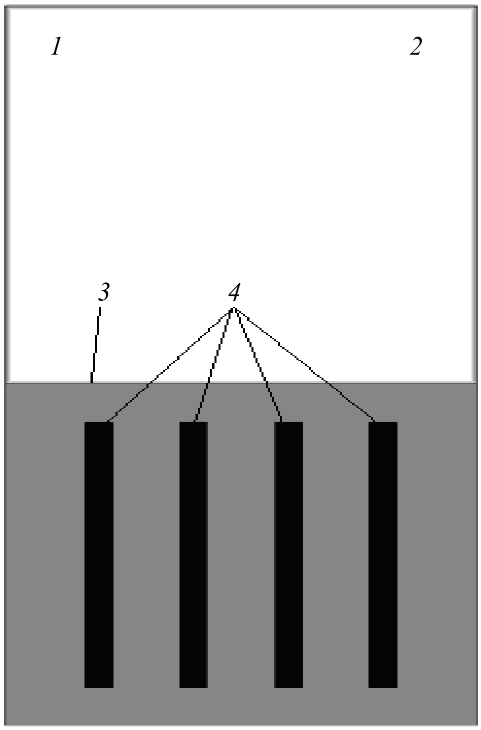

Fig. 2. Model analog BE:
1 – input vent; *2* – closed vent;
3 – water level; *4* – SFA

Additionally the equation of moose and vapor mass's preservation was solved:

$$\frac{\partial c''}{\partial t}+\vec{u}\cdot\nabla c''=\nabla\left(D''\nabla c''\right),$$

where c'' – concentration of vapor; D'' – diffusion coefficient of vapor in the air.

The total heat flow through the surface of the phases was taken as equal:

$$q_{sum}=q_{ev}+q_{con},$$

where q_{ev} – heat flux due to evaporation; q_{con} – heat flow by convection.

Heat flux due to evaporation of one gas molecula (proposed by Landau [5]) is:

$$q_{ev} = \kappa\left(c_s'' - c_{sf}''\right)\left(\frac{m''}{2\pi K T_{sf}}\right)^{0.5},$$

where κ – latent heat of vaporization; c_s'' – the concentration of vapor saturation; c_{sf}'' – the vapor concentration at the border areas; m – the mass of vapor molecules; K – constant Boltsmana; T_{sf} – saturation temperature.

The total heat flow in the approximation method of effective film near the surface of the STI was defined as BE [6]:

$$q_{sum} = \frac{Nu}{L}\left[\lambda_{mix}\left(T_{sf} - T_{\infty}\right) + \right.$$

$$\left. + D''\rho_{mix}\kappa \cdot \ln\left(\frac{\left(m_{mix}\left(1-c''\right)\right)_{\infty}}{\left(m_{mix}\left(1-c''\right)\right)_{sf}}\right)\right],$$

where Nu – Nusselt number; L – typical lineal scale of the processes at the surface; λ_{mix} – thermal conductivity of the air and vapor mixture; T_{sf} – saturation temperature (at the surface of the STI); T_{∞} – the temperature at a distance from the surface of the STI; D'' – diffusion coefficient of vapor in air; ρ_{mix} – density of air and vapor mixture; κ – latent heat of vaporization; m_{mix} – the weight of the air and vapor mixture; c'' – the concentration of vapor.

For numerical implementation of BE model counterpart BE the method of finite elements in the interpretation of COMSOL Multiphysics was used. During this action there was being fulfilled the task to install non-stationary process.

The results of computational experiment. As part of the computational experiment there was considered the case of the BE cooling system failure. This heat removal from the SFA ensures was ensured only through the natural convection and evaporation of water from the surface of the pool, warm curve of the flow through the bottom and sides of BE was not considered due to its small contribution to the overall warm on rent.

In the calculation we used the following initial conditions: and water temperature in the BE – 30°C, the temperature and humidity of the input flow of the air respectively – 20°C and 10%, SFA temperature – 80°C, power heat release of one SFA – 1 kW.

These parameters and characteristics of the BE room comply with engineering solutions, and that allows to speak about the practical significance of the received results to justify no danger in SNF' storage.

Numerical modeling of heat and mass exchange processes while storage of spent nuclear fuel in a pool was implemented for three cases:

– a rather high level of water in the BE;
– low water level in the BE;
– partial exposure of the SFA.

The taken computing experiments have helped to qualitatively and quantitatively evaluate the process of heat and mass exchange processes in the system of SFA storage.

In the numerical implementation of the described above three-dimensional model of the transmission processes in reactor spent fuel pools there was received a complex pattern of gasdynamic flows that determine heat flows with regard to the effect of evaporation. Gradient view of temperature fields and vapor concentrations in the BE for the given above initial and boundary conditions is shown on Fig. 3, 4.

Profiles of the vertical temperature distribution of BE for the three cases it is filled with water are shown on Fig. 5.

Analysis of the estimated temperature fields showed that with a decrease in the fill level of BE there occurs a small (a few degrees) rise in steam and gas temperature of gas mixture above the water surface. In this case there is registered the mixture of the incoming air flow with vapor flow from the heating and evaporation of water.

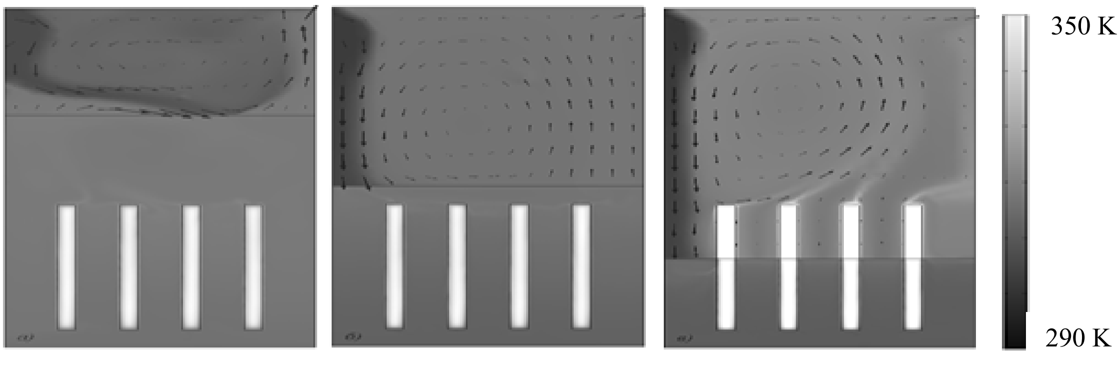

Fig. 3. The spatial distribution of temperature in the BE at different levels of its completion. Provides fields of temperatures in the range from 290 to 350 K

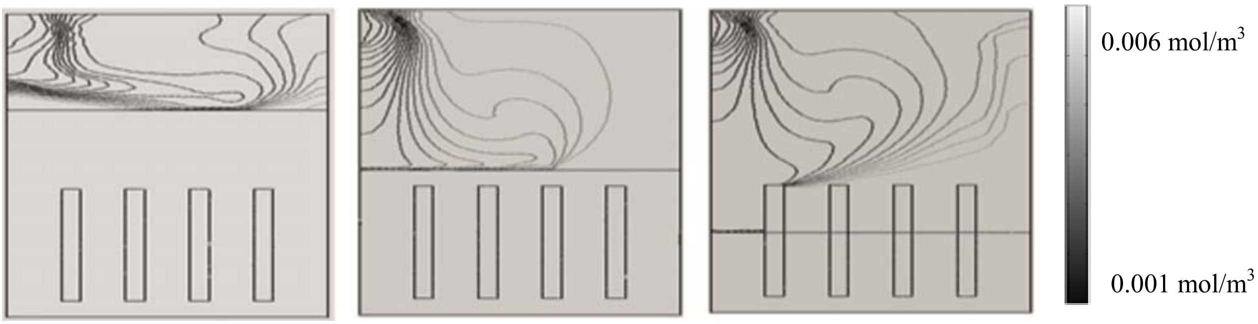

Fig. 4. The spatial distribution of the concentration of steam in the BE at different levels of fill it out. Shows the contours of molar concentrations of vapor in the vapor mixture in the range from 0.001 up to 0.006 mol/m^3

The intensity of the heat flow resulted from evaporation is determined by the field of the concentration of vapor phase and is the most intensive in the area of contact between the convective flow and the water surface.

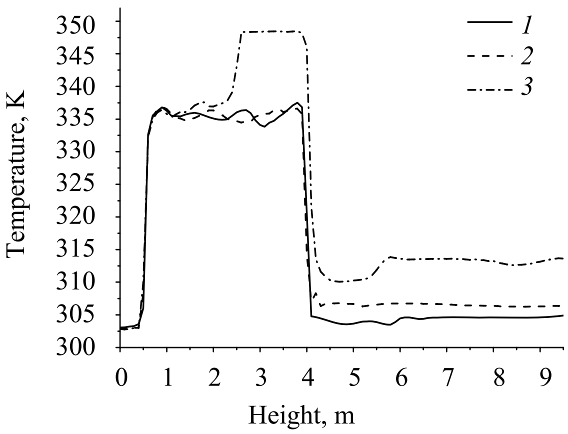

Fig. 5. Profiles of temperature at a height of BE for the three cases of filling: *1* – the relatively high level of water in the BE; *2* – the lower the water level in the BE; *3* – partial denudation of the SFA

The concentration profiles of the vapor phase in BE at a height of 7.87 in above the water level for the three cases of filling of BE are presented in Fig. 6.

The presence of a minimum concentrations in the beginning of the graphs (at the entrance to the BE), given in Fig. 6, due to the downward flow of cold air from the vent.

In case of high level of BE further growth and exit to the stable value of the concentration of vapor phase is connected with the formation of the vortex, which applies to all of the area above the surface of the water in BE. In the case of low level of BE the resulting vortex moves to the right, which leads to a corresponding shift of the maximum concentration of vapor phase. Disconnected nature of the curve in Fig. 7, referred to the case of partial exposure of SFA is associated with the description of the concentration in the vapor phase of the interval between the bare SFA.

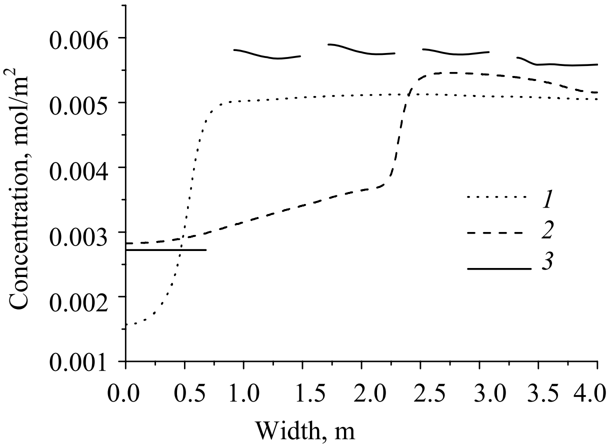

Fig. 6. Concentration profiles of the vapor phase in BE at 20 cm above the water in three cases it is full: *1* – a high level of water in the BE; *2* – lower the water level in BE; *3* – partial exposure of the SFA

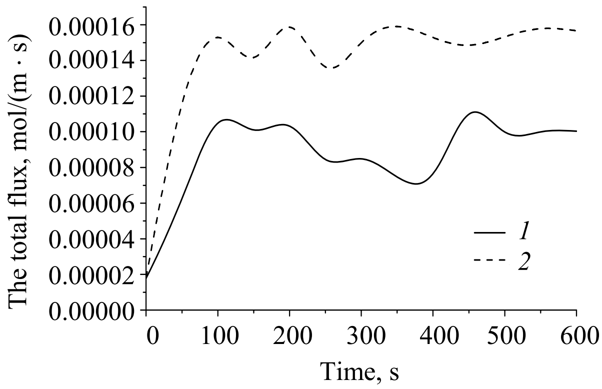

Fig. 7. A normal to the surface of the total BE heat and vapor mixture flow: *1* – a rather high level of water in the BE; *2* – low water level in the BE

Of the three cases of BE fill in Fig. 7 the maximum concentration of the vapor phase is observed in SFA exposure, which testifies to a minimum in this case the contribution of the evaporation to the total heat removal.

The intensity of the heat flow in the result of evaporation is defined by a field of vapor phase concentration and, as follows from Fig. 7, has the maximum figure in the in the area of contact between the convective flow and the water surface.

On fig. 7 there is a “task to establish”, i.e. entering the quasistationary regime of the value of the total mass flow of air and vapor mixture normal to the liquid surface, which characterizes the total heat flow resulted from the convective transition and the effect of evaporation.

As is evident from the nature of the curves in Fig. 7, the maximum mass flow rate, and correspondently, the heat removal of BE (~5 W/m^2) is reached in the case of low water level, which is associated with the intensification of convective mass transition.

Conclusion. As part of the formalized patterns of COMSOL Multiphysics software package there was developed a three-dimensional model analogue of heat and mass transition processes in fuel pool with the SFA taking into consideration convective heat transition and evaporation effect. The contribution of the heat flow due to the surface evaporation may contribute significantly (up to 20–30%) to the value in the total heat removal from the pond surface, and therefore it must be considered in the analysis of accidents. It is shown that the associated with the evaporation value of the total heat flow constituent is determined with the gradient of vapor concentration in air and vapor mixture near the evaporation surface, which in its turn depends on the intensity of convective flows.

The possible emergency situation due to a water level decrease in the pool with the SFA and their possible exposure in the result of partial or full failure of the circulation circuit of regular cooling system.

It is shown that m Maximum temperature in the pond with SFA doesn’t much depend on the level of the coating layer of water, but increases greatly with partial exposure of the SFA. However, dramatic increase in the maximum and the minimum temperature is observed only in the case of full exposure SFA.

The developed calculator pattern and the results of this study can be used for safety analysis of spent nuclear fuel storage in STI-reactor storage pools, and in particular, Belarusian NPP.

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