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Thermal Analysis of Vertical Dry Storage Cask for Nuclear Spent Fuel in Off-Normal Conditions

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One of the key aspects for safety assessment of spent fuel dry storage systems is evaluation of the temperature profile for spent fuel in various storage conditions. In this effort, a three-dimensional model of a vertical dry storage HI-STORM 190 UA system for VVER-1000 fuel is developed for ANSYS CFX code. This model is then used for the analysis of spent fuel thermal state in normal conditions and in a hypothetical case of a loss of the fuel canister integrity. Canister depressurization with helium leakage and its substitution with air lead to degradation of heat removal and increase of spent nuclear fuel temperature.

The results presented in this article demonstrate that the maximum cladding temperature of spent fuel does not exceed the design limit in normal storage conditions. In the case of loss of the fuel canister integrity, the maximum cladding temperature exceeds this design limit for normal storage conditions, but remains below the limit for short-term off-normal conditions. The results also demonstrate that loss of the fuel canister integrity leads to insignificant change in vents outlet temperature and cannot be reliably identified by temperature monitoring according to the existing procedures.

Keywords: ANSYS CFX, CFD simulation, dry storage cask, HI-STORM, spent fuel, thermal analysis.

Introduction

The centralized storage facility for spent nuclear fuel (SNF) constructed in the Chornobyl exclusion zone for intermediate storage of SNF from VVER reactors operating in Ukraine utilizes the dry storage system (DSS) designed by Holtec International. The system consists of a vertical steel canister with SNF, which is placed inside of a concrete overpack with inner and outer steel liner (see Figure 1). The principal construction follows the design of the HI-STORM 100 system [1], [2], which was adapted for VVER hexagonal fuel assemblies taking into account Ukrainian regulations and requirements of the regulatory authority.

Since the majority of degradation mechanisms of SNF (e.g., cladding creep, oxidation in a non-inert atmosphere [4]) and DSS components are temperature-dependent (usually, with a degradation rate increasing with the temperature), the analysis of their thermal state is an essential part of DSS safety assessment to be performed to demonstrate that the canister and fuel cladding temperatures remain within the limits specified for normal, off-normal and accident conditions [5], [6].

For this purpose, the computational fluid dynamics (CFD) codes (e.g., ANSYS CFX, FLUENT, STAR-CCM+) are increasingly used both in Ukraine and worldwide. These codes provide numerical solution of the governing equations that describe fluid flow, i.e. the set of the Navier-Stokes equations, mass continuity, and additional conservation equations, such as for heat and species concentration. The solution is done on scales down to those of the largest turbulence eddies and boundary layer widths [7], [8].

The normal conditions of VVER SNF storage in HI-STORM DSS were evaluated with ANSYS CFX in [9] and [10]. In article [9], heat transfer from the outer canister surface was defined by the boundary conditions, while in [10] more detailed simulation with modelling of the entire DSS including the concrete overpack was performed.

This article analyzes a hypothetical case with loss of integrity of the SNF canister and substitution of internal helium volume with air with the focus on thermal SNF state. The analyses are conducted with ANSYS CFX code ver. 2019R1.

1. HI-STORM Dry Storage System

HI-STORM 190 UA is a ventilated vertical cask designed to ensure intermediate storage (up to 100 years) of Multi-Purpose Canister (MPC) with VVER spent fuel assemblies. HI-STORM 190 UA consists of carbon steel inner and outer shells with concrete between them, bottom plate and top lid (see Figure 1). Ventilation openings at the upper and lower parts of HI-STORM provide air flow for passive cooling of MPC placed inside the storage cask.

The multipurpose spent fuel canister MPC-31 (see Figure 2) is designed for storage of 31 spent fuel assemblies of VVER-1000 reactor [11] and consists of the fuel basket, which is placed inside the double wall hermetic case.

The hermetic case provides two independent barriers consisting of the inner and outer shells, closure lids and base plates. In order to improve heat removal from the spent fuel assemblies, the MPC is filled with helium.

The fuel basket forms 31 hexagonal cells for VVER-1000 spent fuel assemblies, which are separated by spacers. To allow helium circulation inside the MPC, the lower part of fuel basket has openings for helium passage through the spacers, which are welded to the inner MPC bottom (see Figure 2).

The following design limits are established for VVER-1000 SNF storage in HI-STORM 190 UA: the fuel cladding temperature shall not exceed 350 °C in normal storage conditions and shall remain below 450 °C in short-term off-normal conditions (for 8 hours as a maximum, once per storage period).

2. 3-D model

Geometric 3-D model of the HI-STORM system was developed using the ANSYS Design Modeler module based on the DSS design drawings [13]-[15]. Figure 3 presents a model of 1/4 section of the HI-STORM system. The major model components include a concrete overpack enclosed in carbon steel shells, MPC, cask lid with radiation shielding, base plate and air inlet and outlet vents that provide passive cooling of the MPC by natural convection.

The fuel assemblies are not modeled explicitly. Instead (for the simplification purposes) they are represented as solid bodies with effective thermal conductivity. This approach with the use of a homogenized model for simulating the spent fuel assembly reduces significantly the required number of cells and computation time. For the same purpose, the triangular metallic insets installed at the upper and lower parts of the basket between the fuel assembly's cells are not modeled. Correspondent volume is assigned to the fill gas.

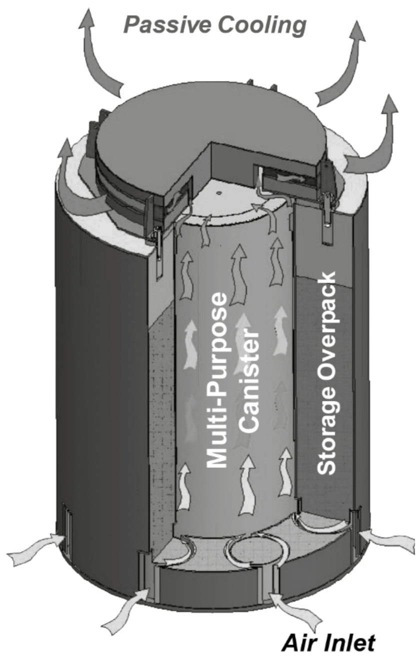

Figure 1 – HI-STORM storage system [3]

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Figure 4 presents the mesh for the 1/4th section of the MPC and HI-STORM. The total number of cells is ~5.49 million. The grid is generated by using a meshing module implemented in the ANSYS Workbench, which is a platform that facilitates meshing, solving (CFX) and data transfer in 3D simulation. More fine mesh representation of the physical model can be obtained automatically by tuning the mesh control parameters in the Workbench. In the case of fluid channels, the mesh is generated with the value of y+ parameter equal to or less than 5.

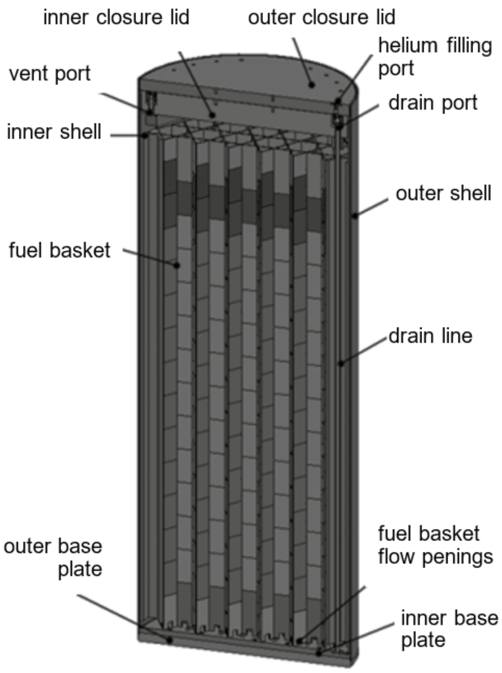

Figure 2 – General view of MPC-31 [11], [12]

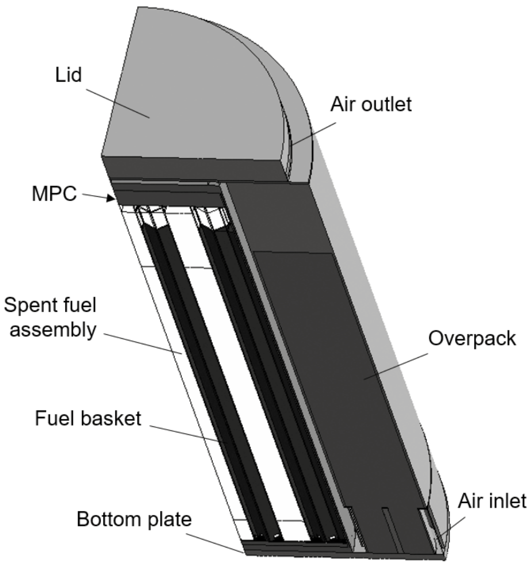

Figure 3 – Cross section of a 1/4th section of the HI-STORM 3D model.

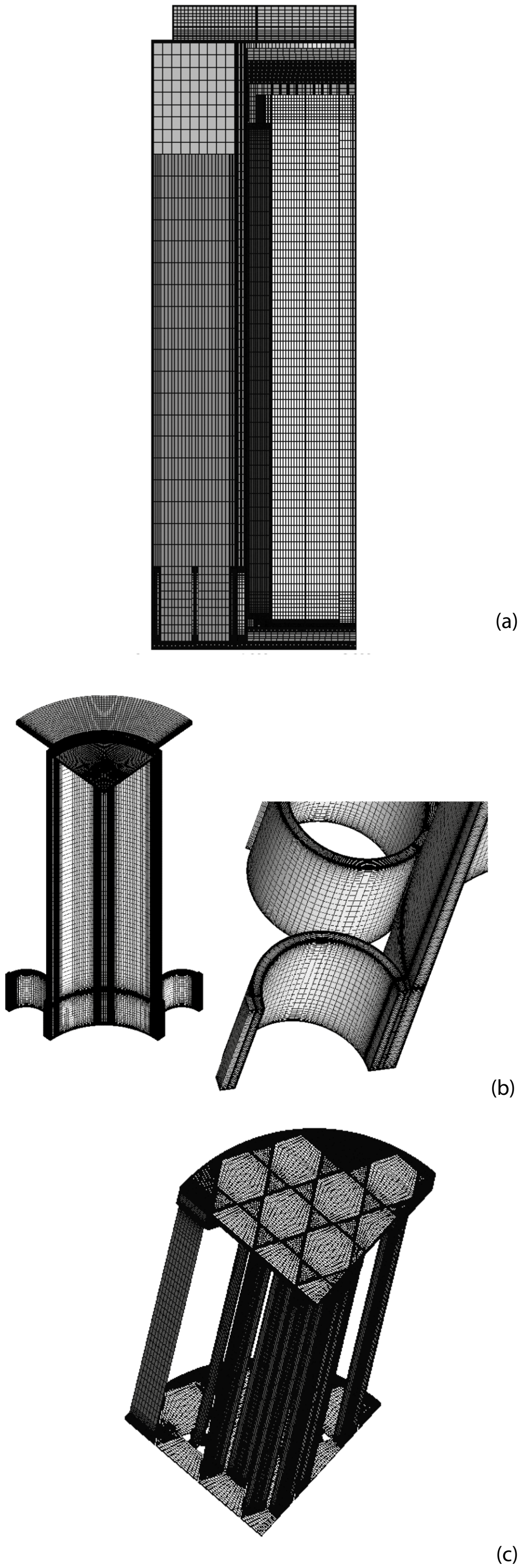

Figure 4 – Cross section of a 1/4th section of MPC and HI-STORM 3D model showing mesh representation, (a) for solid part, (b) fluid part – ventilation channel, (c) fluid part – in MPC.

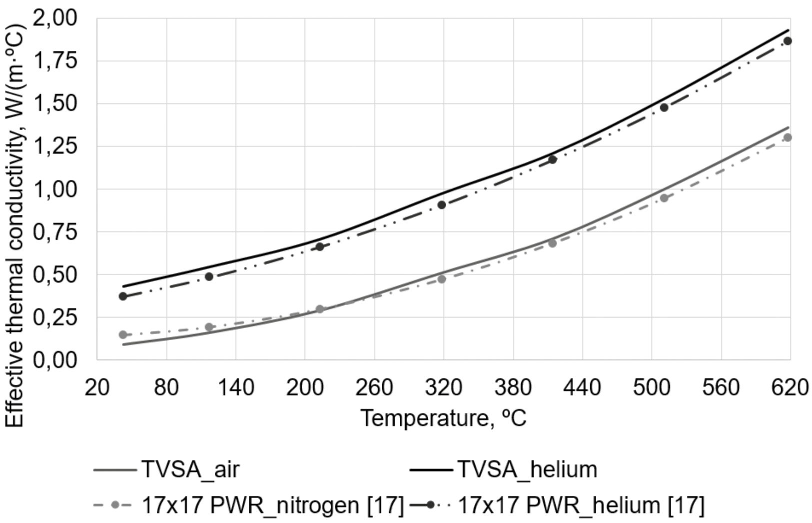

Figure 5 – Transverse (planar) effective thermal conductivities

3. Thermal modeling

3.1. Effective thermal conductivity

The method of determining the effective thermal conductivity for a spent fuel assembly cooled by helium in a hexagonal pipe is described in [9]. Based on the results in [9], the effective thermal conductivity of the VVER-1000 spent fuel assembly of TVSA type cooled by air was calculated using the approach described in [16]. In general, this approach includes the following main steps:

1) estimate a part of helium conductivity in the total effective thermal conductivity of spent fuel assembly;

2) estimate a part of thermal conductivity due to radiation by subtracting helium conductivity from the total effective thermal conductivity;

3) calculate the total effective thermal conductivity of homogenized air and fuel rods.

Figure 5 presents obtained values of transverse (planar) effective thermal conductivities for the TVSA spent fuel assembly cooled by air and helium in a hexagonal pipe and transverse (planar) effective thermal conductivities of the 17×17 PWR spent fuel assembly cooled by helium and nitrogen (see Figure 3 [17]). It can be seen that the results obtained for TVSA are comparable with similar data for PWR fuel assemblies.

3.2. Material properties

The physical properties of DSS components and gases are obtained from [18], [19]. These properties include density, thermal conductivity, heat capacity, viscosity, and surface emissivity, which are temperature dependent. Gas density is an important parameter in simulating heat transfer by natural convection, because it is the temperature-induced density difference that drives buoyance flow. Gas density is calculated using the ideal gas law. The approach is applicable to density calculation when the pressure variation is small.

3.3. Initial and Boundary Conditions

The total decay heat load of the 38 kW canister is assumed to be non-uniformly distributed among 31 VVER-1000 spent fuel assemblies as shown in Figure 6, while the axial profile is assumed to be uniform for each fuel assembly.

Fluid flow is modeled with the SST turbulence model. Heat transfer on the internal overpack surfaces contacting with air and inside the canister accounts for natural convection and thermal radiation. The latter is determined with the Discrete Transfer model (surface-to-surface option) implemented in the code.

The boundary conditions on the storage container surface depend on the environment surrounding the storage container. The mechanisms for heat transfer from the storage container surface usually include natural (free) convection and thermal radiation.

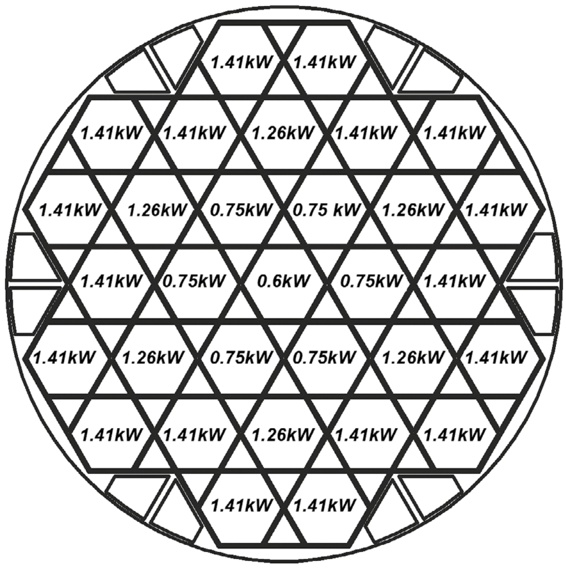

Figure 6 – Radial heat distribution for 31 VVER-1000 spent fuel assemblies

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The heat flux from the storage container surface is defined as:

$$Q = Q_{insol} - Q_{rad} - Q_{conv}, \quad (1)$$

were Q_{insol} – solar insolation, W/m^2;
Q_{rad} – heat flux due to radiation, W/m^2;
Q_{conv} – convective heat flux, W/m^2;
Q – total heat flux, W/m^2.

$$Q_{rad} = \varepsilon \cdot \sigma \cdot \left(T^4 - T_{ex}^4\right), \quad (2)$$

were ε – emissivity coefficient;
σ – Stefan-Boltzmann constant, 5,670367(13)·10^{-8} W/(m^2·K^4);
T – surface temperature, K;
T_{in} – environment temperature, K.

$$Q_{conv} = \alpha \cdot \left(T - T_{in}\right), \quad (3)$$

where α – heat transfer coefficient, W/(m^2·K).

Solar insolation on the outer overpack surfaces is selected according to the preliminary safety analysis report [18]: 447 W/m^2 for the cask vertical outer surface and 800 W/m^2 for the horizontal surface of the lid.

To estimate the contribution of thermal radiation to HI-STORM cooling, the cases with and without thermal radiation were studied. For the latter case, two different emissivity values were used, namely 0.85 and 0.66, corresponding to the painted and unpainted carbon steel surface, respectively. The simplified 3D model of the HI-STORM container and MPC-31 without internals and spent fuel was used for these calculations. The constant heat flux was specified as a boundary condition for the inner MPC-31 surface. The results of the case studies presented in Table 1 indicate more than 40° C temperature difference for HI-STORM external wall temperature for the cases with and without thermal radiation that demonstrates the need to account radiation when performing the thermal analysis of spent fuel storage conditions.

The final calculations of the HI-STORM system thermal behavior in normal and off-normal conditions were performed with the emissivity coefficient equal to 0.85.

Table 2 summarizes the boundary conditions used in the simulation. A symmetry boundary conditions are applied to the mid-plane of the model.

The convergence criteria used in the simulation are as follows: the first criterion checked is the scaled residuals below the user-defined thresholds (namely, 10^{-4} for the mass, momentum, and turbulence equations, and 10^{-6} for the energy equation). To achieve a reasonable computational time, the second criterion checked is the calculated temperatures (e.g., cladding temperatures) to ensure that steady state has been reached (i.e., a variation of <1°C in 1000 iterations).

Table 1 – Maximum temperature of HI-STORM and MPC walls

Parameter	Temperature, °C			
	Conv	Insol+Conv	Insol+Conv+Rad (ε=0.85)	Insol+Conv+Rad (ε=0.66)
HI-STORM internal wall	118.12	151	130.156	132.75
HI-STORM external wall	64.644	129.15	79.897	85.318
MPC internal wall	205.36	221	211.503	212.81
MPC external wall	192.13	209.12	198.392	199.73

Table 2 – Boundary conditions

Parameter		Value
External temperature	air	28 °C
Pressure	Inlet/outlet vents	1 atm
	MPC: helium air	6.37 atm 1 atm
External convection heat transfer coefficient	Top, side	4.6 W/(m^2·K)
	Bottom	adiabatic wall

4. Simulation results

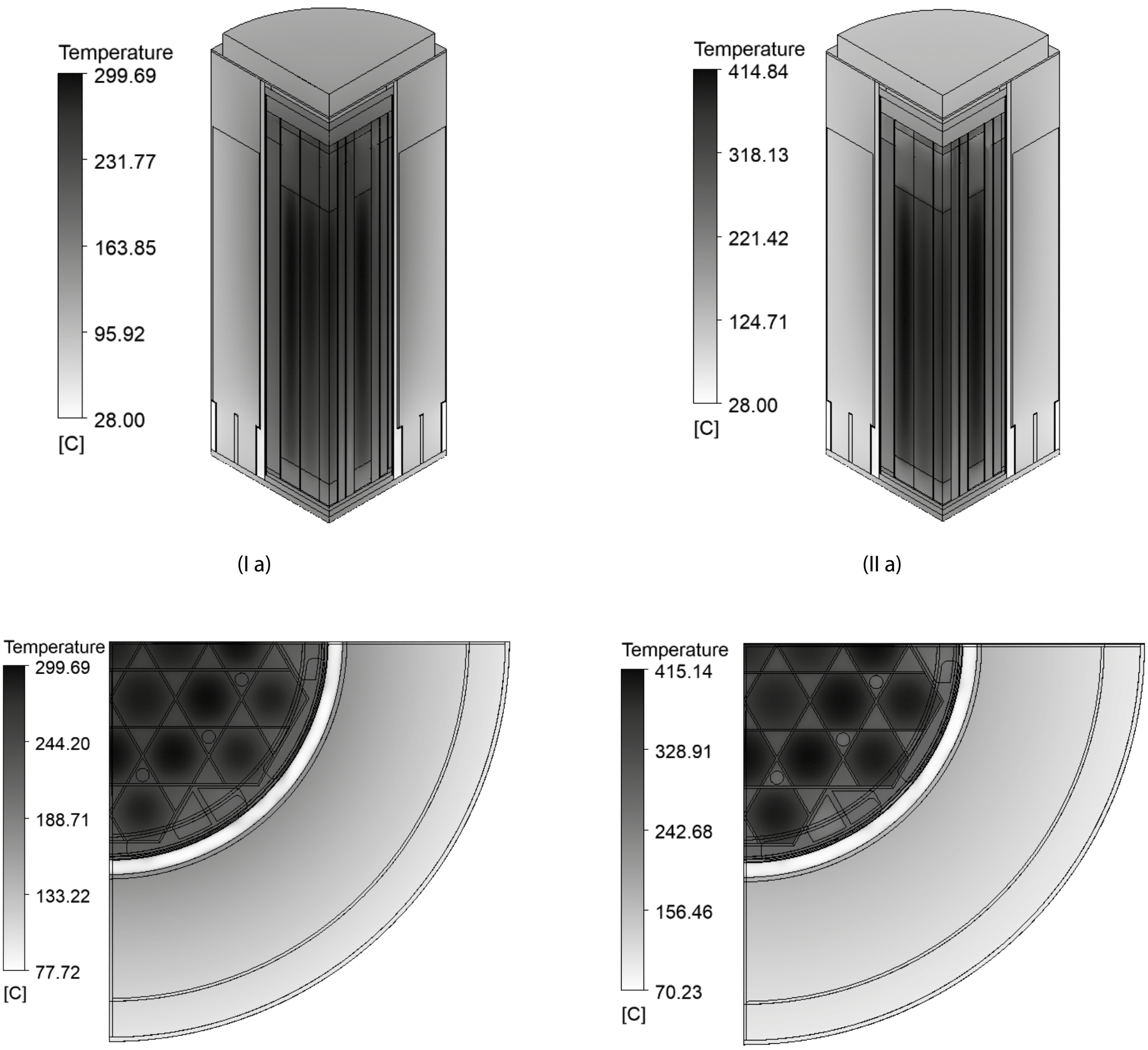
Calculations were performed for two types of storage conditions: normal storage conditions and off-normal conditions (complete depressurization of MPC-31).

The results are obtained from the 3D simulations for the helium-filled vertical storage cask with internal pressure of 6.37 atm and the air-filled vertical storage cask with internal pressure of 1 atm (complete depressurization of MPC-31). For both cases a basket containing 31 spent fuel assemblies with a total decay heat load of 38 kW was used.

Figure 7 shows temperature distribution at the symmetry boundaries of HI-STORM 190 UA (a) and temperature distribution in DSS cross-section near the center of the canister (b) for normal (I) and off-normal (II) conditions.

Radial temperature profiles across the spent fuel assemblies, fuel basket, and other DSS components and the longitudinal section displaced from the one-quarter model boundary for 0.0 (corresponds to the model boundary), 0.1263 and 0.2526 m obtained for normal and off-normal conditions are shown in Figures 8 and 9, respectively.

The results of simulation demonstrate that the calculated maximum fuel cladding temperature for off-normal conditions is ~415 °C, which is above the design limit of 350 °C for normal storage of spent fuel assemblies, but below the allowed short-term temperature for off-normal conditions [18]. The maximum air temperature at the outlet of ventilation ducts is ~132 °C and ~130 °C for normal and off-normal conditions, respectively.



(I b) z=3.0942 m (II b) z=2.7342 m

Figure 7 – Temperature distribution at the symmetry boundaries of HI-STORM 190 UA (a) and maximum temperature of spent fuel (b) for normal (I) and off-normal (II) conditions

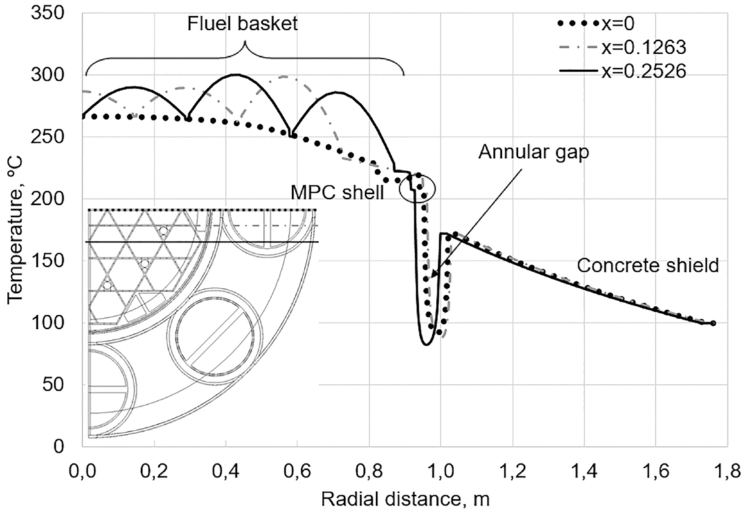


Figure 8 – Radial temperature profile corresponding to x = 0, 0.1263 and 0.2526, at z = 3.0942 m for normal conditions

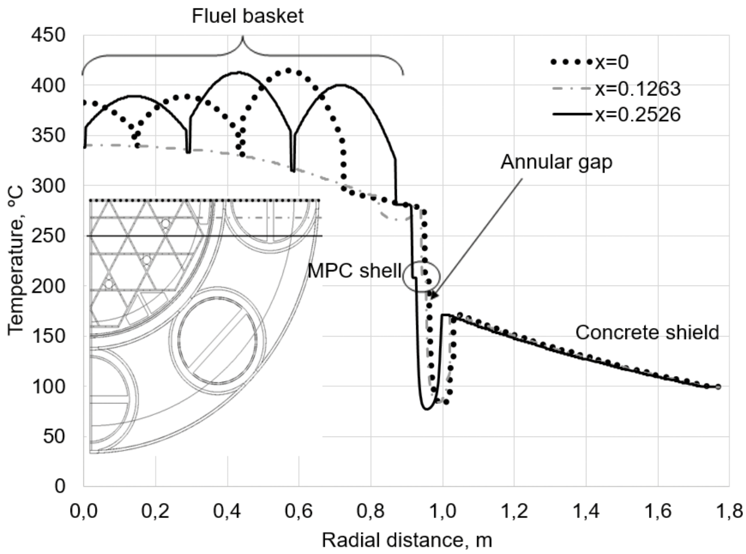


Figure 9 – Radial temperature profile corresponding to x = 0, 0 .1263 and 0.2526, at z = 2.7342 m for off-normal conditions

Conclusions

The thermal analysis of the HI-STORM 190 UA dry storage system loaded with 31 VVER-1000 spent fuel assemblies with total decay heat of 38 kW is performed with ANSYS CFX for the hypothetical case with loss of the SNF canister integrity. The analysis results show that helium leakage from the canister and its substitution with air leads to degradation of heat removal from SNF and increase of the fuel cladding temperature up to ~415 °C. This temperature value is above the design limit of 350 °C for normal storage conditions, but below the allowed short-term temperature for off-normal conditions. It shall be noted that this hypothetical case cannot be identified by the outlet air temperature measurement system, and will be detected by the radiation monitoring system only after a failure of fuel cladding.

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Тепловий аналіз вертикального контейнера для сухого зберігання відпрацьованого палива в запроєктних умовах

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Державне підприємство «Державний науково-технічний центр з ядерної та радіаційної безпеки», м. Київ, Україна

Одним із ключових аспектів оцінки безпеки систем сухого зберігання відпрацьованого ядерного палива (ВЯП) є визначення температурного профілю ВЯП для різних умов зберігання. У цій статті розглянуто розроблену для розрахункового коду ANSYS CFX тривимірну модель вертикальної системи сухого зберігання ВЯП HI-STORM 190 UA для палива реакторів типу ВВЕР-1000. Ця розрахункова модель надалі використовується для аналізу теплового стану ВЯП за нормальних умов зберігання та за гіпотетичного сценарію з втратою герметичності багатоцільового контейнера (БЦК), де його внутрішнє середовище (гелій) заміщається повітрям. Через виникнення такої події відбувається погіршення умов теплообміну внаслідок гірших теплофізичних властивостей повітря, що призводить до зростання температури оболонок твел ВЯП.

Наведені в цій статті результати демонструють, що отримане максимальне значення температури ВЯП для нормальних умов зберігання не перевищує встановлену допустиму проєктну межу за температурою оболонки твел 350 °С. Зі свого боку, для сценарію із втратою герметичності БЦК, отримане максимальне значення температури ВЯП перевищує проєктну межу для нормальних умов зберігання, однак, є нижчим за значення, встановлене для короткочасного підвищення температури внаслідок аварійних та перехідних процесів. Отримані результати також демонструють, що розгерметизація БЦК призводить до незначної зміни температури повітря на виході з вентиляційних каналів системи зберігання HI-STORM і, відповідно, до неможливості надійної ідентифікації такої події за допомогою моніторингу цього параметра відповідно до існуючих процедур.

Ключові слова: відпрацьоване ядерне паливо, контейнер сухого зберігання, тепловий аналіз, HI-STORM, CFD моделювання, ANSYS CFX.

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