COMPARATIVE ANALYSIS OF NUMERICAL METHODS USED FOR THERMAL MODELING OF SPENT NUCLEAR FUEL DRY STORAGE SYSTEMS

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Management of spent nuclear fuel is a very important part in the whole cycle of nuclear energy generation. Usually “dry” storage technology in casks is selected for the interim storage of spent nuclear fuel for up to 50 years after pre-storage time in water pools. In this paper, two case studies were carried out to highlight the differences and similarities between Ukraine and Lithuania in spent nuclear fuel storage.

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INTRODUCTION

Interim dry storage in containers is one of the rather widely used technologies for the management of spent nuclear fuel (SNF) in countries with an open fuel cycle.

In Ukraine, it is planned to use two types of storage facilities: at the Zaporizhska NPP, SNF from WWER-1000 reactors is stored in concrete ventilated containers VSC-24, produced by Sierra Nuclear Corporation and Duce Engineering and Services (USA); at the Chernobyl NPP, the SNF of RBMK-1000 reactors will be stored in containers placed in ventilated concrete modules developed by Holtec Int. (USA). In both cases, the storage facilities are open type facilities; the SNF is placed in containers after storing in pools for at least 5 years. The service life of the storage facilities is at least 50 years.

Lithuania decided to use the dry storage method and to store spent nuclear fuel from RBMK-1500 reactors of the Ignalina NPP after storage in pools for at least 5 years in an open-type storage facility using initially unventilated containers of the CASTOR RBMK-1500 type and further – CONSTOR RBMK-1500 type. CASTOR containers are made from metal, CONSTOR containers from reinforced concrete. In 1999, a storage facility was built that can hold up to 120 containers and is now completely full. In 2017, the operation of a new, closed-type intermediate storage facility was started, where SNF is stored in new type reinforced concrete containers CONSTOR RBMK-1500/M2. The total storage capacity is about 190 containers. The life of both storage facilities is 50 years.

The determination of the thermal state of containers with SNF is an important component in ensuring the safety of the SNF dry storage during the entire service life of the storage facility. Therefore, a number of thermal state studies have been carried out for storage containers with SNF from WWER-1000 [1, 2] (the method will be transformed for storage modules with RBMK-1000 fuel) and RBMK-1500 [3, 4] reactors.

This paper presents the modeling methodology and results of decay heat removal from CONSTOR RBMK-1500 and storage modules used for the Chernobylska NPP dry SNF storage facility.

1. METHODOLOGY

VENTILATED STORAGE MODULE

In Ukraine, the SNF of RBMK-1000 reactors is stored in concrete modules (Fig. 1). The cooling of a cask with spent fuel assemblies is conducted by atmospheric air, which goes through the module due to natural draught. The module includes a storage cask, which is covered by a thermal shield; the entry port of the module is closed by a concrete lid.

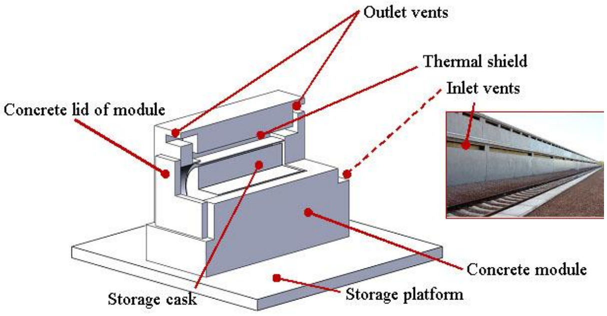

Fig. 1. The storage module used for SNF of RBMK-1000

The multi-stage approach [5] for the current problem consists of the components shown in Fig. 1. At the first stage, the storage basket with spent fuel assemblies was considered as a solid unit with equivalent thermal properties [6, 7] and the thermal state of the whole storage module is defined.

Then, the thermal conditions on the surface of the basket were obtained on the basis of the calculated information about heat transfer processes inside the storage container. These conditions include the temperature of the basket surface or the heat transfer rate through the basket surface or the temperature of the cooling air in the ventilating channels together with the heat-transfer coefficient on the basket surface. This information is used as boundary conditions at the next stage. At the second stage, the basket alone is considered with more detailed geometry than at the previous stage: the helium domain and domains of solid parts of the basket are taken into account, but each SNF assembly is considered as a solid unit with equivalent thermal properties. The thermal state of the basket is

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calculated with the boundary conditions on its surface that were obtained at the first stage, and the thermal conditions on the surfaces of the solid units corresponding to the SNF assemblies are calculated similar to the conditions on the basket surface at the first stage. At the third stage, each SNF assembly is modeled with more detailed geometry and the boundary conditions obtained at the second stage. Finally, this approach (Fig. 2) allows determining the temperature fields of each fuel element.

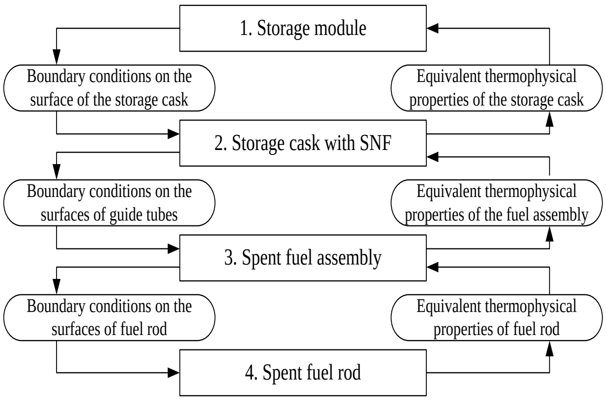


Fig. 2. Methodology of SNF thermal state simulation in modular storage

NON-VENTILATED CASKS

This paper presents the modeling results of decay heat removal from metal-concrete CONSTOR non-ventilated casks that are used only for RBMK-1500 SNF at the Ignalina NPP. Modeling is performed for casks in an open type storage facility for summer conditions.

The body of a CONSTOR cask contains 2 low-alloy steel cylinders of different inner and outer dimensions. The annular space is filled with heavy concrete. The heavy concrete is also poured into the space between panels and at the bottom of the cask. A massive metal ring is welded at the top of cask steel cylinders. The cask lid and two guard plates are fastened and fixed to the ring.

The cask described is a storage vessel for a stainless steel basket where the SNF bundles are placed. The basket contains 51 assemblies cut in halves (102 fuel rod bundles). Once the basket is within the cask, the cask lid and the guard plates are tightly closed. When the water is pumped out, the cask dries out and helium is pumped in. Then the cask is put onto a concrete base at the open storage facility and a reinforced concrete cover is used as additional cover. A shock-absorbing damper is fastened to the bottom of the cask to prevent possible shocks during its transfer to the storage site. A loaded concrete cask weights approx. 88 tones.

For thermal analysis, the ALGOR code [8] was used. It is a general-purpose code which can be used for two- and three-dimensional modeling using the finite element method. The ALGOR code is widely used for modeling the mechanical stress and structural integrity of the equipment and thermal processes**.** The cask in this paper was modeled as two-dimensional in cylindrical r-z coordinates assuming steady state conditions (Fig. 3). Modeling is performed based on effective thermal conductivities and thermal conductivities. So, in such a case, the ALGOR code is a rather effective tool.

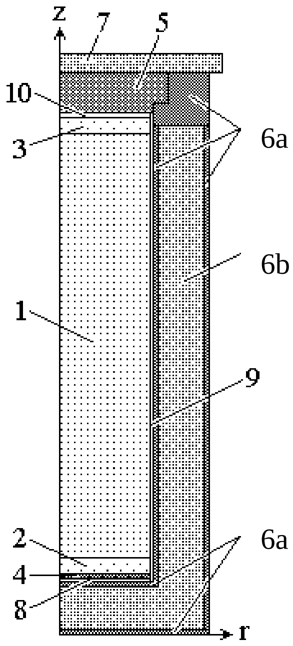


Fig. 3. Schematic view of the cask computer model: 1 – fuel load active part; 2, 3 – fuel load lower and upper parts; 4 – basket bottom; 5 – lid; 6a – metal parts of the body, 6b – heavy concrete; 7 – reinforced concrete cover; 8–10 – horizontal lower, vertical and horizontal upper helium gaps

The elements of the cask are meshed separately. The grid of the computer model was created following ALGOR code recommendations for the effective conductivity/conductivity cases. To demonstrate the grid independence, the modelling was also performed using a 1.5 times finer grid. In such a case the maximum rod cladding temperature decreased by ~ 2% but the cask body outer surface temperature increased by ~ 1%. This demonstrates that the selected grid is reasonable and gives conservative values for rod cladding temperatures.

When modeling the following processes and parameters are accepted: the decay heat of the fuel, heat conduction (or effective conductivity) coefficients of all materials of the cask (which depend on the temperature), ambient temperature, the influence of adjacent casks in the storage facility, the heat transfer coefficient by natural convection from the cask's outer surface, the emissivity for external radiation from the cask surfaces and the heat fluxes from solar insolation.

A cask just loaded with 102 SNF rod bundles that had been stored in water pools for 5 years emits approximately 6.1 kW of decay heat. Since our model doesn't take into account decay heat variation in axial direction (the maximum deviation is 17%), therefore in modeling the 17% enlarged decay heat of fuel load homogeneous zone is assumed to be Q = 7.14 kW. The decay heat gradually decreases during the succeeding period of SNF storage.

A scheme of heat transfer from the fuel rods through the cask is presented in Fig. 4. The heat from the fuel load by conduction is transferred to the outer surfaces of the cask, and then by radiation and natural convection to the environment. For the modeling, effective axial and radial heat conductivity coefficients were used to evaluate the heat transfer through the fuel load. They were obtained experimentally by research institutions.

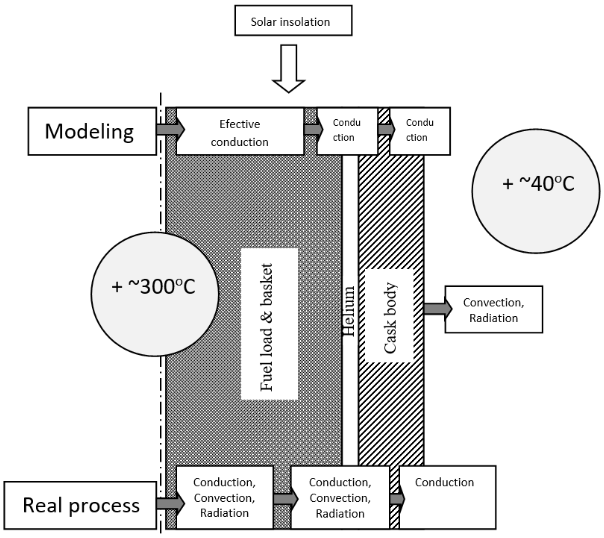


Fig. 4. Processes of decay heat removal from the cask in summer time. Solar insolation was taken into account only for the reinforced concrete cover

For the determination of the heat transfer coefficient from the vertical cylindrical surface of the cask by natural convection an empirical correlation [9] was used:

$$\mathrm{Nu} = 0.13\mathrm{Ra}^{1/3}, \qquad (1)$$

where Nu = $\alpha_{conv}\, l/\lambda_0$ is the Nusselt number; Ra = Gr·Pr is the Rayleigh number; Gr = $g\cdot\beta\cdot l^3\,(T_{cask}-T_a)/\nu_0^2$ is the Grashof number; Pr = $\mu_0 c_{p0}/\lambda_0$ is the Prandtl number; g = 9.81 m/s^2 is the gravitational acceleration; β is the coefficient of volumetric expansion; λ_0, ν_0, and μ_0 are coefficients of air conductivity and dynamic and kinematic viscosity, respectively; c_{p0} is air specific heat; l is a reference geometrical parameter. The reference geometrical parameter here is the cask's height, and the reference temperature is the ambient temperature.

For the upper horizontal surface of the protective concrete cover of the cask the heat transfer coefficient is calculated from the empirical correlation [9]:

$$\mathrm{Nu} = 0.15\mathrm{Ra}^{1/3}. \qquad (2)$$

The reference geometrical parameter here is half of the cask's radius, and the reference temperature is the ambient temperature. The calculation of the parameters mentioned is a iterative process since the values of heat transfer coefficients and surface temperatures depend on each other.

For evaluating heat transfer through the He gaps, only conduction was taken into account. Based on [10], an increase in heat transfer by natural convection is negligible when the Rayleigh number, characterizing natural convection, is less than 1000. Heat transfer by radiation through the He gaps also can be neglected conservatively because the temperature differences in the He gaps are relatively small and He thermal conductivity is rather high.

In the modeling, heat from solar insolation was taken into account. This was evaluated based on IAEA recommendations [11]. It is recommended that the heat flux from solar insolation during daylight (12 h) to horizontal surfaces is 800 W/m^2, and to vertical surfaces is 200 W/m^2. In this study heat fluxes from solar insolation were distributed during 24 h. So, heat flux to the horizontal surface was 400 W/m^2 and to the vertical surface 100 W/m^2. Also, the effect of neighboring containers for vertical surfaces was taken into account, since, in a storage facility, casks are arranged at intervals of 3 m.

Furthermore, heat radiation from the outer cylindrical surface of the cask to the environment was not taken into consideration because the wall temperatures of surrounding casks are similar. The summary of the real and modeled processes is presented in Fig. 4.

In this study, when the modeled cask is in an open storage facility in summer time, it is affected by solar insolation and the ambient temperature is 37 °C. Such a temperature was evaluated by taking into account the average temperature of the hottest season in Lithuania and adding 10 °C due to the effect of the adjacent casks. A decrease of the temperature during the night was conservatively not taken into account.

Further, the temperature and the heat flux distributions in the fuel load and the cask's body were modeled and an assumption was made that the maximum fuel load temperature coincides with the central heat generating rod temperature. Modeling was performed till 300 years of container storage. Validation of the numerical model was performed by comparing modelling results of cask surface temperatures with surface temperature measurements of a commercial cask for winter conditions (ambient temperature -6 °C) taking into account real burnup of the loaded fuel bundles [12]. The surface temperature difference between modelling results and measurements was till 2.0 °C.

2. RESULTS DISCUSSION

VENTILATED STORAGE MODULE

At the beginning of the research on the Ukrainian SNF storage system, only the first level of the calculation methodology was used. One concrete module with a storage cask was considered. The atmospheric air comes to the module and, already cooled, flows up the cask, which is placed horizontally (Fig. 5). The heated ventilating air then flows out through two outlet vents. The outlet vent placed above the entry port conducts more air than the other due to the specifics of the cooling channels inside the storage module.

The existing velocity field organizes relevant temperature field (Fig. 6). The maximum temperature is observed inside the storage cask but above the central axis. It is caused by the structure of the cooling flow, which is stopped by the thermal shield placed above the storage cask.

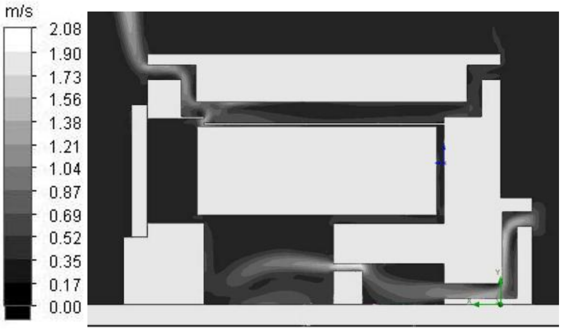


Fig. 5. Velocity contour of ventilated air inside storage module with SNF of RBMK-1000

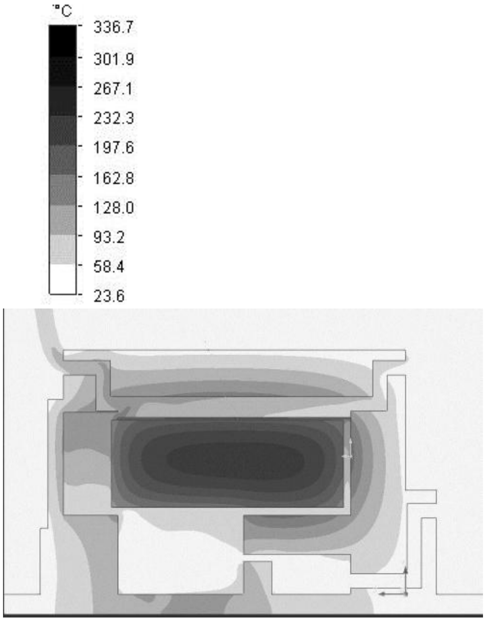
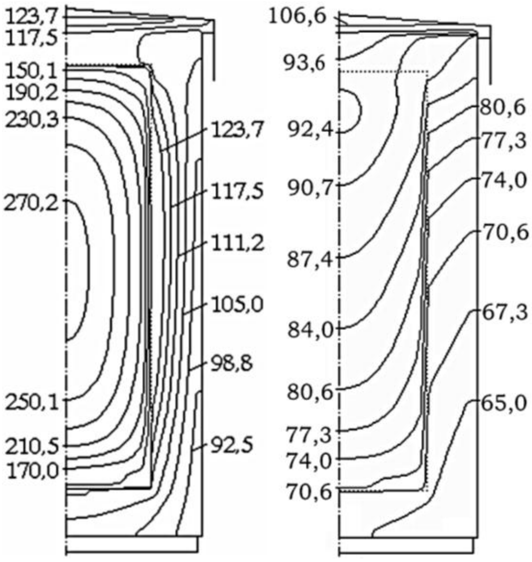


Fig. 6. Temperature field of storage module with SNF of RBMK-1000

The velocity and the thermal contours are physically correct and therefore the problem formulation is correct too and could be used in real simulation of the storage module for the Chernobyl NPP.

NON-VENTILATED CASKS

Fig. 7 gives the distribution of isotherms inside casks (in fuel load) and in a body of cask for summer conditions after 5 (just loaded SNF into cask) and 300 year of storage. In Fig. 7,a it can be observed that the maximum temperature is in the center of fuel load. As it mentioned above, this temperature coincides with the central heat generating rod temperature. Receding from the center in axial, as well as in radial direction, the temperature decrease, but in radial direction the temperature gradients are substantially higher. The temperatures are varying similarly in the cask body. The highest temperatures are in the center of the inner surface of cask body and protective cover. The lowest temperatures are in the body corners. The typical feature is that because of the influence of solar insolation the temperatures of the upper surface of protective cover are higher than the temperatures of cylindrical surface.



a *b*

Fig. 7. Distribution of isotherms inside the casks for summer conditions: a – in case of 5 year of storage; b – in case of 300 years of storage

In the case of 300 years of storage (see Fig. 7,b), the maximum fuel load temperature is about 180 °C lower due to decreased decay heat, and it reaches about 92 °C but it is displaced to the top of the cask because of the effect of solar insolation. The maximum surface temperature is about 40 °C lower in comparison with the maximum temperature in the case of 5 year of storage.

CONCLUSIONS

After the thermal analysis of two SNF storage casks, the following conclusions have been drawn:

- The techniques used by Lithuanian and Ukrainian scientists in the study of the thermal state of the spent fuel of the RBMK-1500 and RBMK-1000 reactors are similar. Both groups have used CFD-methods, effective thermal conductivity of some elements and showed good results in the analysis of the thermal safety of dry storage facilities.
- Simulation of heat removal from the CONSTOR RBMK-1500 container with rather conservative assumptions has shown that the temperature of the hottest fuel element does not exceed the allowable temperature (300…350 °C).
- The temperature in the fuel storage module of RBMK-1000 reactors does not exceed the limits for thermal safety either.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ ЧИСЛЕННЫХ МЕТОДОВ, ИСПОЛЬЗУЕМЫХ ДЛЯ ТЕПЛОВОГО МОДЕЛИРОВАНИЯ СИСТЕМ ХРАНЕНИЯ ОТРАБОТАВШЕГО ЯДЕРНОГО ТОПЛИВА

С. Алёхина, Ю. Мацевитый, В. Дудкин, Р. Пошкас, А. Сирвидас, К. Рачкайтис, Р. Зуюс

Управление отработанным ядерным топливом является очень важной частью всего цикла производства ядерной энергии. Обычно технология «сухого» хранения в контейнерах выбирается для временного хранения отработанного ядерного топлива в течение до 50 лет после времени предварительного хранения в водных бассейнах. В этой статье были проведены два тематических исследования, чтобы подчеркнуть различия и сходства между Украиной и Литвой в области хранения отработавшего ядерного топлива.

ПОРІВНЯЛЬНИЙ АНАЛІЗ ЧИСЕЛЬНИХ МЕТОДІВ, ЩО ВИКОРИСТОВУЮТЬСЯ ДЛЯ ТЕПЛОВОГО МОДЕЛЮВАННЯ СИСТЕМ ЗБЕРІГАННЯ ВІДПРАЦЬОВАНОГО ЯДЕРНОГО ПАЛИВА

С. Альохіна, Ю. Мацевитий, В. Дудкін, Р. Пошкас, А. Сірвідас, К. Рачкайтис, Р. Зуюс

Управління відпрацьованим ядерним паливом є дуже важливою частиною всього циклу виробництва ядерної енергії. Зазвичай технологія «сухого» зберігання в контейнерах вибирається для тимчасового зберігання відпрацьованого ядерного палива протягом до 50 років після часу попереднього зберігання у водних басейнах. У цій статті були проведені два тематичних дослідження, щоб підкреслити відмінності і подібності між Україною та Литвою в області зберігання відпрацьованого ядерного палива.