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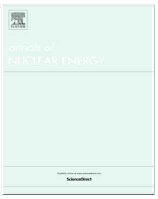

Thermal analysis of CASTOR RBMK-1500 casks during long-term storage of spent nuclear fuel

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ABSTRACT

In this paper, thermal analysis of German CASTOR RBMK-1500 casks for long-term (up to 300 years) storage of spent nuclear fuel at the Ignalina Nuclear Power Plant was performed. The numerical modeling code ALGOR (USA) which allows modeling temperature and heat flux distributions inside a cask (in fuel load) and in a cask body, was used. The modeling was performed for a cask in an open storage facility in summer and winter conditions. A detailed analysis was performed including previous results about casks with just loaded fuel (pre-stored in water pools for 5 years) and after 50 years of interim cask storage. Also, a local sensitivity analysis of parameters that mostly influence the temperature distribution was performed.

1. Introduction

The Ignalina Nuclear Power Plant (INPP) in Lithuania operated two RBMK-1500 water-cooled graphite-moderated channel-type power reactors. The first reactor was shutdown at the end of 2004, and the second one was closed at the end of 2009. For storage of spent nuclear fuel (SNF), the so-called “dry” storage technology was selected. Using this technology, SNF is pre-stored in water pools (at least for 5 years) and then loaded into metal CASTOR RBMK-1500 or metal-concrete CONSTOR RBMK-1500 casks, and then stored in the open-type SNF storage facility that was commissioned in 1999; the planned interim storage period is 50 years. A new closed-type storage facility for larger capacity CONSTOR RBMK-1500/M2 casks where the remaining SNF will be stored is under construction.

However, commissioning of the geological repository for disposal of SNF is foreseen later than the planned interim storage period ends. In relation to this, the possibility to extend the long-term storage period (up to 300 years) needs to be considered. For safe storage of SNF for such a long period of time, it is necessary to ensure nuclear safety, radiation safety, and safe thermal conditions. In order to fulfill the requirements set for the safety of fuel bundles, casks and storage facilities where casks are stored, deep understanding of different processes that take place in a cask and also its interaction with the environment is crucial.

From the thermal point of view, the main parameters determining the safe storage of SNF in casks are the maximum allowed fuel rod cladding temperature and the maximum allowed cask external surface temperature. It is established that in the case of long-term storage in an inert helium or nitrogen environment (i.e. for normal conditions), the RBMK SNF cladding maximum temperatures should not exceed 300 °C (Kalinkin et al., 2010) or 350 °C (Vatulin et al., 2003).

A cask's thermal regime is determined by the decay heat release from the stored SNF, the cask construction, and the storage conditions. Nuclear fuel with enrichment of 2–2.8%, with and without erbium absorber, was used at the INPP. Radiological characteristics and decay heat of the fuel used at the INPP were analyzed in detail in Šmaižys et al. (2014). The most significant changes of the decay heat release occur during the first five years while the fuel is stored in the water pools. During the subsequent storage period, the release of decay heat monotonically decreases.

The previous study (Poškas et al., 2006) presented the thermal modeling results of CASTOR RBMK-1500 and CONSTOR RBMK-1500 casks in the stage of the interim storage for up to 50 years using the numerical modeling code ALGOR (USA). Characteristic temperatures of the casks at different storage conditions (a single cask or a cask in a storage facility just loaded with SNF but

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pre-stored for not less than 5 years in water pools, or after 50 years of storage, in summer/winter conditions, with/without assessment of solar insolation) were presented.

Other codes and approaches have also been used for thermal analysis of the casks. In Lee et al. (2009), the code FLUENT (USA) was applied for the analysis of the casks with SNF from pressurized water reactors (PWR). In Alyokhina et al. (2015), a Computational Fluid Dynamics model developed by the authors was used for the analysis of the containers with SNF from reactors WWER-1000. Comparison of different methods for assessment of maximum cladding temperature was presented in Kim et al. (2014).

This study presents a thermal assessment of CASTOR casks for long-term – up to 300 years – storage of RBMK-1500 SNF at the INPP using the numerical modeling code ALGOR. Also, the parameters that mostly influence the temperature distribution are selected, and a local sensitivity analysis is performed.

2. Methodology

The CASTOR RBMK-1500 cask (Fig. 1) is a cylindrical vessel (cask body) (1) made of special metal alloy; its height is more than 4 m, the diameter is about 2 m and the wall thickness is about 0.3 m. A special cylindrical stainless steel basket (2) with SNF bundles is placed in such a cask. The basket holds 51 half-cut SNF assemblies, i.e. 102 fuel rod bundles (7). The cask is tightly closed with a cask lid (3), then it is covered with a guard plate (4) and, after pumping-out the water, drying-out and vacuumization, the cask is filled with helium. The cask is then simply set on a concrete basis in an open storage facility and additionally is covered with a reinforced concrete cover (5). The mass of such a loaded cask is about 75 tons.

The general-purpose software (code) ALGOR (ALGOR, 1992) was used for the thermal analysis of the casks. This multipurpose code allows performing two- and three-dimensional thermal modeling using the finite element method. In this paper, the basket with SNF is modelled as a homogeneous body; therefore, there are no variations of heat transfer around the perimeter of the cask, and a two-dimensional symmetrical cask model can be used in a cylindrical r-z axes system under stationary conditions. Large thickness of the barriers (walls) of the cask causes only small variation of the SNF temperatures in time (day and night time); therefore, the assumption can be made that the process is stationary. All cask elements in the model are modeled as separate zones (Fig. 2).

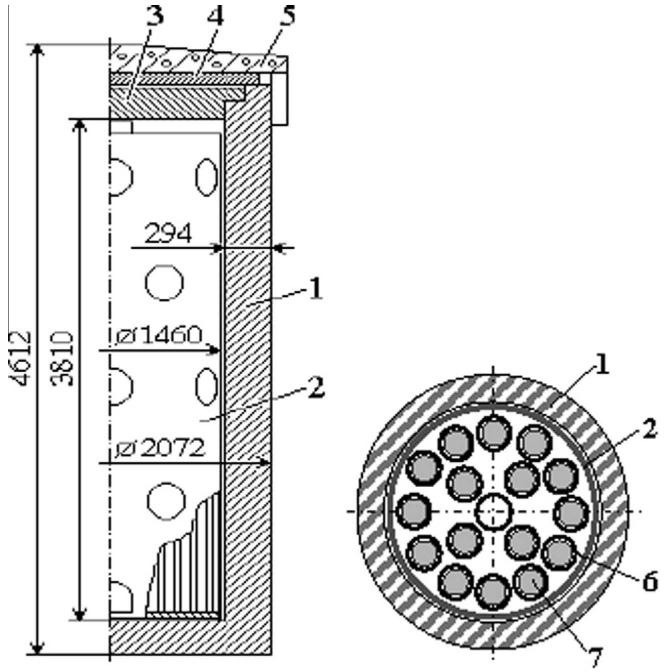

Fig. 1. Scheme of the cask: 1 – cask body, 2 – basket, 3 – cask lid, 4 – guard plate, 5 – concrete cover, 6 – basket tube, 7 – fuel rod bundles 102 pcs.

The decay heat power of a basket just loaded with 102 SNF rod bundles pre-stored in water pools for at least 5 years is about 6.1 kW. Conservatively taking into account the decay heat power variation in the axial direction (the maximum deviation constitutes 17%), the decay heat power of the fuel load homogeneous zone enlarged by 17% is assumed in the modeling, i.e. Q = 7.14 kW. As mentioned above, the decay heat power monotonically decreases during the subsequent SNF storage period, and this condition is accepted based on Šmaižys et al. (2014) results.

A transfer scheme of the heat generated in fuel rods is presented in Fig. 3. Heat is transferred by conduction, convection and radiation through fuel load and He gaps. In the case of a cask body, heat is transferred only by conduction, and from the surface of the cask, heat is transferred by radiation and natural convection. During the modeling, heat transfer through the fuel load is evaluated using effective radial and axial heat conductivity coefficients experimentally defined by design institutions (NUKEM, 2008).

The heat transfer coefficient for natural convection from the upper surface of the cask's protective concrete cover (treated as from horizontal surface) and from the vertical cylindrical surface of the cask is calculated from a criterial equation (Kutateladze, 1990):

$$Nu = c\,Ra^{1/3} \tag{1}$$

where $Nu = \alpha_{conv}\, l/\lambda_0$ – Nusselt number; $c = 0.13$ for a vertical surface and $c = 0.15$ for a horizontal surface; $Ra = Gr\,Pr$ – Rayleigh number; $Gr = g\,\beta\,l^3\,(T_{cask}–T_a)/\nu_0^2$ – Grashof number; $Pr = \mu_0\,c_{p0}/\lambda_0$ – Prandtl number; β – the coefficient of volumetric expansion; $g = 9.81$ m/s^2 – gravitational acceleration; λ_0, ν_0 and μ_0 – coefficients of air conductivity and dynamic and kinematic viscosity, respectively; c_{p0} – air specific heat; l – the reference geometrical parameter. The reference geometrical parameter in the case of the horizontal surface is half of the cask's radius, and in the case of the vertical surface, it is the height of the cask. The reference temperature is the ambient temperature.

The radiation-transferred heat from the surface of a cask into the environment is defined from the following classical equation:

$$q_{rad} = \sigma\varepsilon(T_{cask}^4 - T_a^4) \tag{2}$$

where $\sigma = 5.67 \cdot 10^{-8}$ W(m^2 K^4) – the Stefan-Boltzman radiation constant; ε – the emissivity coefficient of a specially painted cask's surface equal to 0.8.

In the modeling, heat transfer through He gaps was assumed only by conduction because after 50 years of cask storage, the temperature differences in the He gaps will be rather small. Therefore, according to Heat (1991), the parameter Ra, characterizing natural convection, is less than 1000, and an increase in heat transfer by natural convection is negligible. Heat transfer by radiation through He gaps is also negligible due to relatively small temperature differences in the He gaps.

Modeling also allows evaluating the heat received by a cask from solar insolation. This is evaluated using the IAEA recommendations (Regulations, 2009). It is assumed that during the daylight in the case of solar insolation, heat flux to the horizontal surface (to the protective cover of the cask) equals to 800 W/m^2 and to the vertical surface (the cylindrical surface of the cask) it is 200 W/m^2. When casks are placed in a storage facility, they are arranged by the step 3 × 3 m; therefore, during the modeling the influence of the adjacent casks was taken into account. In this