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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

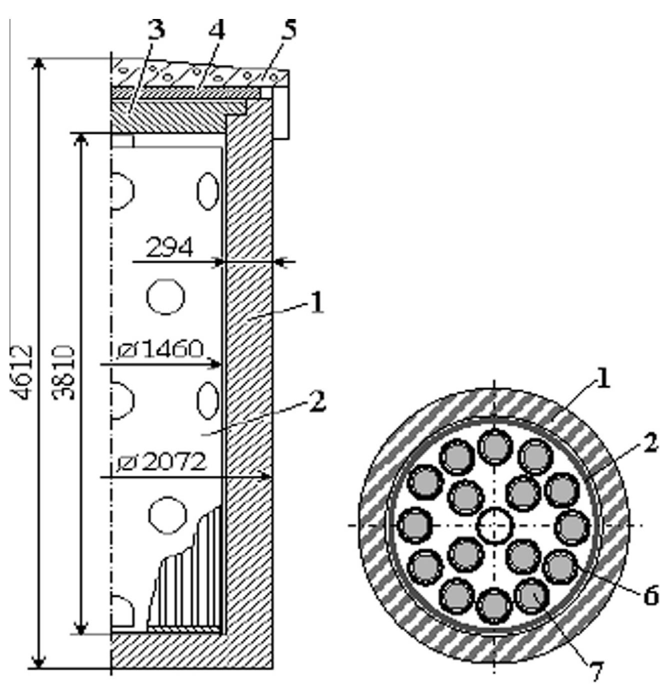

Fig. 1. Scheme of the cask: 1 – cask body, 2 – basket, 3 – cask lid, 4 – guard plate, 5 – concrete cover, 6 – basket tube, 7 – fuel rod bundles 102 pcs.

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).

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; $g = 9.81\ \mathrm{m/s^2}$ – 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 $\sigma = 5.67 \cdot 10^{-8}\ \mathrm{W(m^2\,K^4)}$ – 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

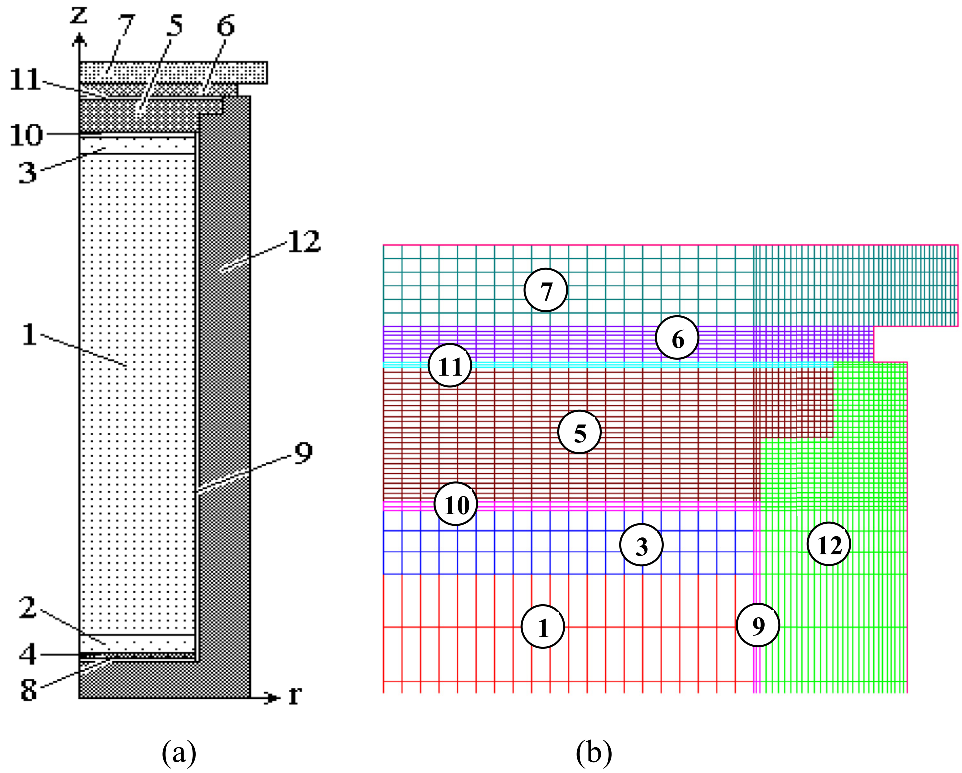

Fig. 2. Schemes of the cask computer model (a) and enlarged mesh (b): 1 – active fuel load part, 2, 3 – lower and upper fuel load parts, 4 – basket bottom, 5 – cask lid, 6 – guard plate, 7 – concrete cover, 8–10 – lower, vertical and upper He gaps, 11 – air gap, 12 – cask body.

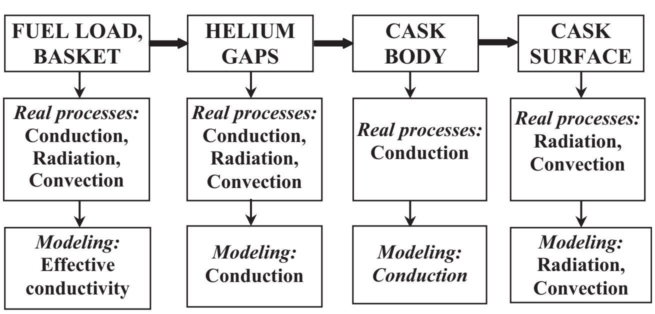

Fig. 3. Scheme of heat transfer through the cask.

case radiation from the cylindrical surface of the cask to the environment was ignored since the wall temperature of all casks is similar. The influence of solar insolation to the cask's cover and the cylindrical part was distributed proportionally to the radiated areas.

Further, as a result of the modeling by the ALGOR code, the distributions of temperature and heat flux in the cask's fuel load and the cask body were determined. It was assumed that the maximal fuel load temperatures comply with the surface temperature of the cladding of the heat generating central rod.

Modeling in this study was performed under extreme conditions of cask storage. It was assumed that the cask is in an open storage facility, in summer influenced by solar insolation and the ambient temperature is 37 °C. Such temperature complies with the average temperature of the hottest season and is enlarged by 10° because of the influence of the adjacent casks. When the cask is in the open storage facility in winter and without solar insolation, the possible ambient temperature is −42 °C. The modeling was performed for characteristic periods of container storage: after 100, 200 and 300 years of storage.

After the parameters that can mostly influence the temperature distribution in the cask had been identified, a sensitivity analysis was performed changing the parameter values ±20%.

3. Investigation results

Fig. 4 presents the temperature distribution inside the cask (in fuel load) and in the cask body in summer conditions (ambient temperature 37 °C) after 100 and 300 years of storage. As the Fig. 4(a) shows, after 100 years of storage, the maximum temperature is in the center of the fuel load and reaches almost 100 °C. The temperatures decrease receding from the center in axial as well as in radial directions; however, the temperature gradients are substantially higher in radial direction. The temperatures are varying similarly in the cask body. The highest temperatures are also in the center of the inner surface of the cask's body, of the protective cover and of the cask's bottom. The lowest temperatures are in the corners of the body.

After 300 years of storage (Fig. 4(b)), the maximum fuel load temperature decreases till approx. 80 °C. Also, it shifts axially to the top of the cask due to solar influence. The surface temperatures are similar, and they decrease approx. by 1–3 °C in comparison to the temperatures after 100 years of storage.

The typical feature for both storage periods is that because of the influence of solar insolation, the temperatures of the upper surface of the protective cover are even higher than the temperatures of the fuel load. This happens because the evaluation of the solar insolation is sufficiently conservative; the insolation will never last half a day by the specified intensity (Regulations, 2009). Certainly, the temperatures of the upper surface of the protective cover in comparison to the temperatures of the cylindrical surface are higher because of different solar intensity on the horizontal and vertical cask surfaces and different radiated areas.

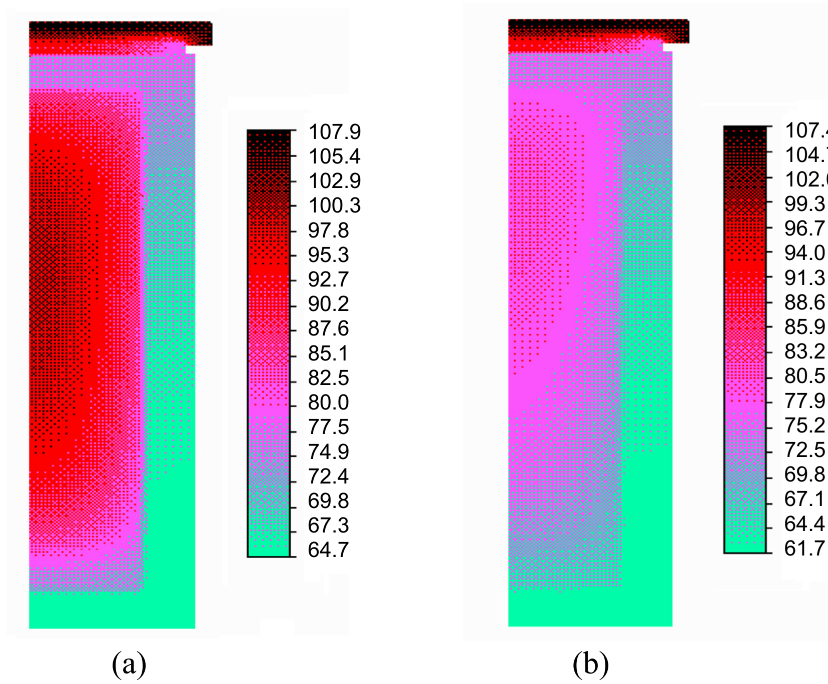

Fig. 4. Temperature distribution inside the cask and in the body of the cask in summer conditions: (a) after 100 years of storage and (b) after 300 years of storage.

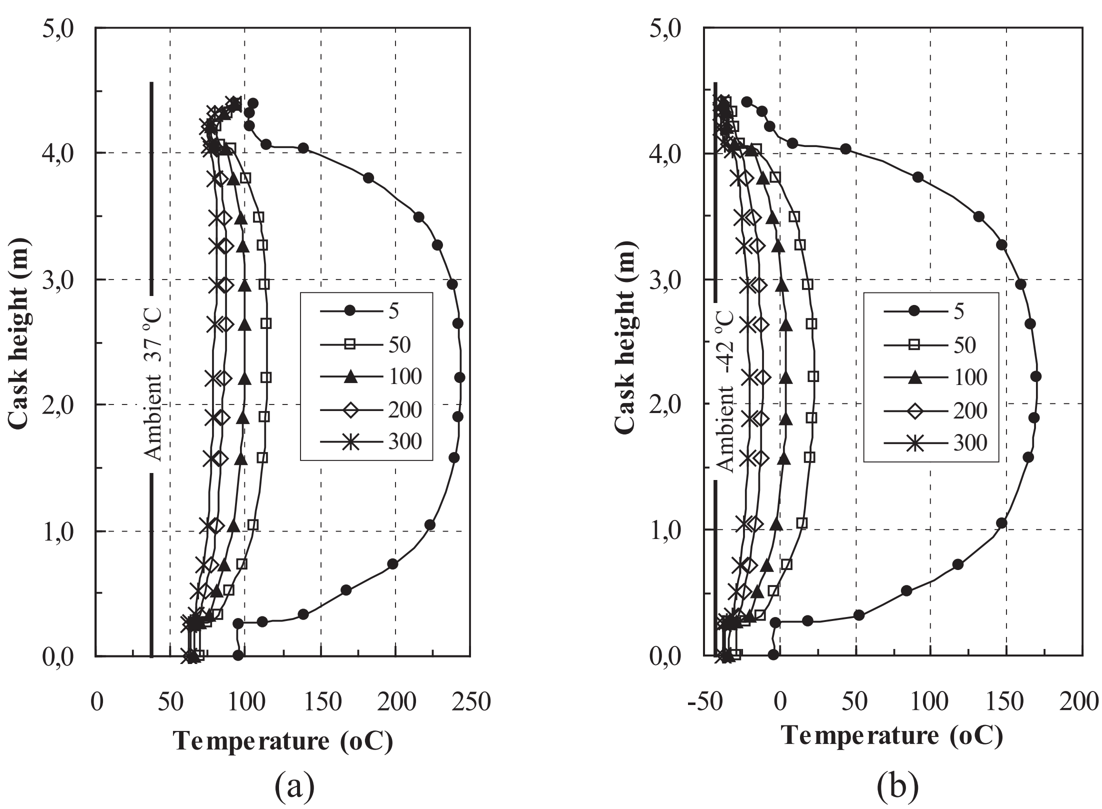

Fig. 5. Temperature distribution in the axial direction in the center of the cask depending on storage time: (a) in summer conditions and (b) in winter conditions. 5 and 50 years – from Poškas et al. (2006); 100, 200 and 300 years – this study.

Characteristic temperature distribution in the axial direction of the casks during cask storage from 100 to 300 years in summer and winter conditions including the data of the previous studies (Poškas et al., 2006) for cask storage after 5 and 50 years is presented in Fig. 5. As the Fig. 5(a) shows, the maximum temperature in summer is in the center of the fuel load. The temperatures decrease monotonically when receding from the center of the cask. The highest temperature gradients are in the zones of He gaps.

The temperatures remain almost unchanged over the bottom of the cask due to good conductivity of the metal cask body. The most significant decrease in the temperature in the center of the cask is in the period from 5 to 50 years. Later changes in the temperature are rather small.

Temperature distributions in the axial direction in winter (Fig. 5(b)) are quantitatively similar to those in summer; however, they are much lower and even become negative after 100 years of storage.

Characteristic temperature distribution in the radial direction of the casks during cask storage from 5 to 300 years in summer and winter conditions is presented in Fig. 6. Radial cross-sections are chosen at the positions of the largest fuel load temperature locations (at 2–2.5 m) (Fig. 5). As it is shown, in the radial direction, the qualitative view of temperature distributions in summer (Fig. 6(a)) and in winter (Fig. 6(b)) are similar. However, the temperatures differ quantitatively. As it has been already indicated above, the most significant changes in the temperature are during the first 5–50 years of storage period. Receding from the center of the cask, the temperatures are decreasing, and at the He gap position (between the basket and the cask body) at radius 0.7–0.75 m, there are rather large temperature gradients for both summer and winter conditions. The temperatures remain almost unchanged over the cask body due to good conductivity of the metal body.

Characteristic temperature variations during long-term cask storage (from 5 to 300 years) including the data of the previous study (Poškas et al., 2006) for casks storage till 50 years in summer and winter conditions is presented in Fig. 7. As the Fig. 7(a) shows, in summer the fuel load temperatures mostly change during the first 5–50 years of storage. Later the temperatures monotonically decrease and after 300 years of storage reach approx. 80 °C. Changes in the surface temperatures of the cask are much smaller, especially after 50 years of storage. The temperatures of all cask elements in winter conditions (Fig. 7(b)) are much lower and after about 120 years of storage become negative even for the fuel load. After 300 years of storage, the fuel load temperatures are about −20 °C. From the structural point of view, such negative temperatures are not critical and satisfy the design criteria.

4. Sensitivity analysis

To assess the impact of the parameter uncertainties on the cask temperatures, a local sensitivity analysis was performed. The selected parameters and their justification are presented below:

– *Decay heat of SNF*. It depends on fuel enrichment, position in the reactor during the operation, etc.

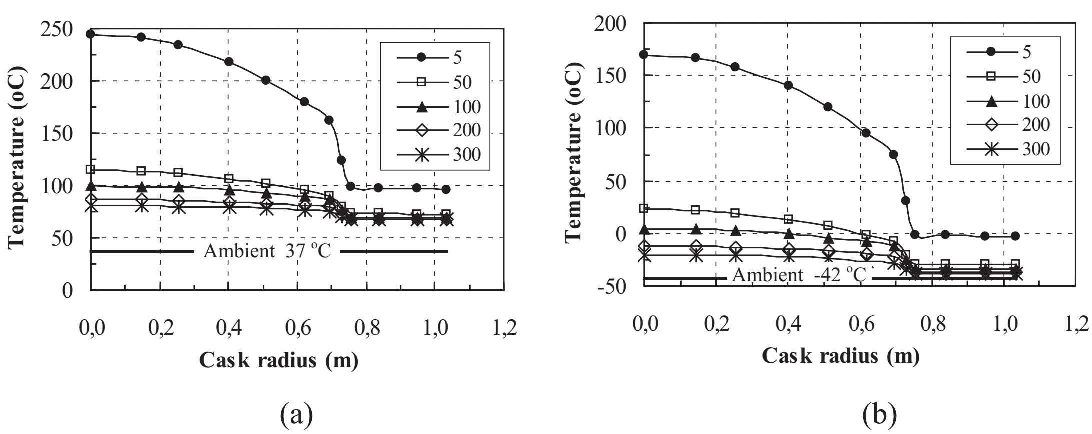

Fig. 6. Temperature distribution in the radial direction of the cask depending on storage time: (a) in summer conditions and (b) in winter conditions. 5 and 50 years – from Poškas et al. (2006); 100, 200 and 300 years – this study.

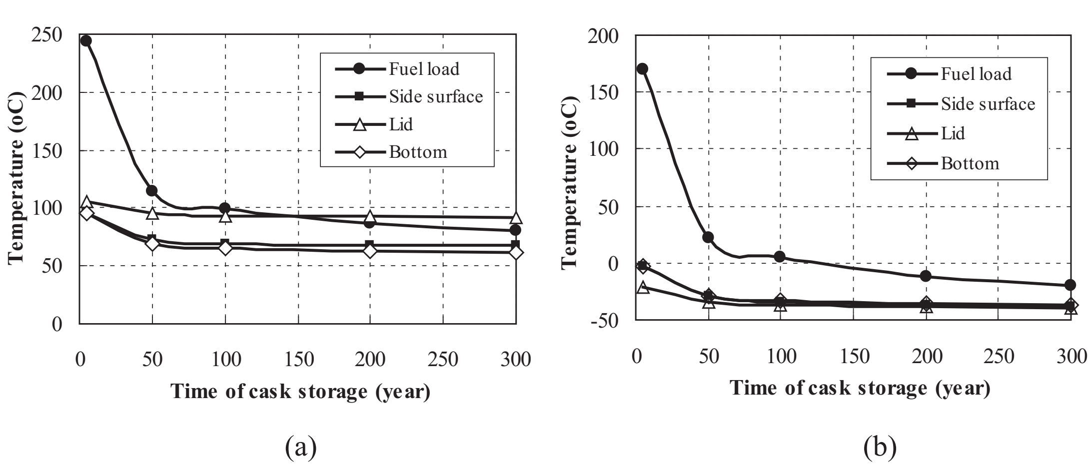

Fig. 7. Temperature variation with time in the characteristic locations: (a) in summer conditions and (b) in winter conditions.

– *Effective thermal conductivity coefficient of fuel load*. It is defined by a special basket with fuel rod bundles and surrounding He. Its effective conductivity coefficient is defined experimentally with certain uncertainties.
– *Thermal conductivity coefficient of He gaps*. Through He gaps heat is transferred not only by conduction but also by natural convection and radiation. This was not taken into account in the modeling.
– *Ambient temperature*. This temperature is not strongly defined; it may vary due to climate change, the impact of the adjacent casks, etc.
– *Solar insolation*. Assessment of solar insolation in the modeling is rather conservative but it can vary with climate change.

Realistically, possible deviations by ±20% of the identified parameters were adopted, and their influence on the maximal temperatures of the fuel load and the side cylindrical surface after 5 and 100 years of cask storage was estimated. The results are presented as Tornado diagrams in Figs. 8 and 9. As Fig. 8(a) shows, the uncertainty of the decay heat has the largest influence on the maximal fuel load temperature after 5 years of cask storage (approx. ±13%), and the uncertainty of solar insolation has the smallest impact (approx. ±1%). After 100 years of cask storage (Fig. 8(b)), the uncertainty of the ambient temperature has the largest (approx. ±8%) impact on the maximal fuel load temperature, and the uncertainty of the conductivity of He gaps has the smallest impact (approx. ±2%). In the case of 5 years storage period, uncertainty of the effective conductivity of the fuel load is also important (approx. −6%, +8%). The uncertainty of the decay heat is important in the case of 100 years storage period (about ±6%).

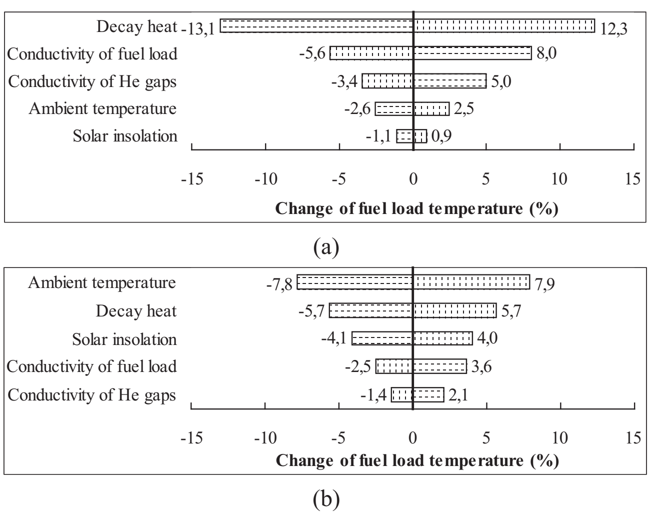

Fig. 8. Tornado diagrams for maximal fuel load temperatures in summer conditions: (a) after 5 years of storage and (b) after 100 years of storage.

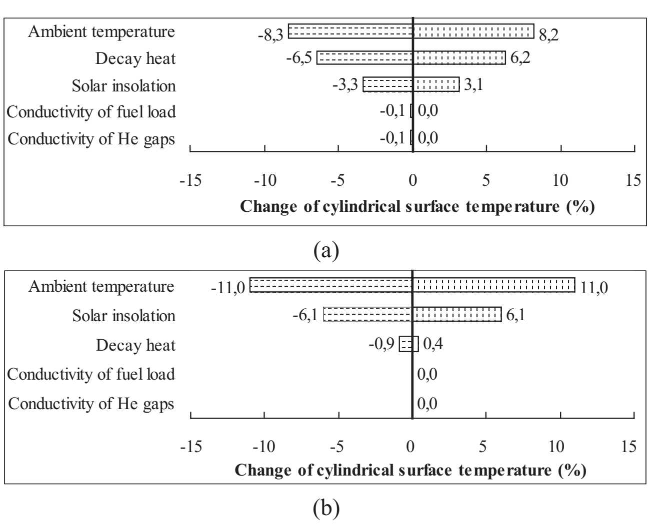

Fig. 9. Tornado diagrams for cylindrical surface temperatures in summer conditions: (a) after 5 years of storage and (b) after 100 years of storage.

A different impact of uncertainties of the influencing parameters was identified for the temperature of the casks' side cylindrical surfaces. Here, in both cases, i.e. after 5 years of cask storage (Fig. 9(a)) and after 100 years of cask storage (Fig. 9(b)), the uncertainty of the ambient temperature has the largest influence on the change of the side cylindrical surface temperature, approx. ±8% and ±11%, respectively. Impact of the uncertainty of the decay heat temperature after 5 years of cask storage is approx. ±6%, and the impact of solar insolation after 100 years of storage is also approx. ±6%. The uncertainty of the effective conductivity of the fuel load and the conductivity of He gaps are not important.

In general, it is possible to state that the uncertainties of the decay heat and of the ambient temperature have the largest impact on the fuel load and the cask surface temperatures. However, the considered deviations of the parameters do not exceed the limiting thermal conditions for safe long-term cask storage, i.e. the fuel load (fuel cladding) temperatures do not exceed the limiting temperature of 300 °C.

5. Conclusions

The detailed thermal analysis of German CASTOR RBMK-1500 casks intended for storage of SNF at the Ignalina NPP during a long-term period of up to 300 years in an open storage facility in summer and winter conditions allows the following conclusions to be drawn:

1. The most significant decrease of the fuel load temperature is during the first 5–50 years of SNF storage. Later changes in the temperature are less significant.
2. Uncertainties of the decay heat and of the effective conductivity of the fuel load have the largest impact on the maximal fuel load temperatures in the first 5–50 years of SNF storage.
3. Uncertainties of the ambient temperature have the largest impact on the cask surface temperatures during the whole storage period and even on the maximal fuel load temperatures at later stages of the storage (after 100 years).
4. Even taking into account the uncertainties, the fuel load (fuel cladding) maximal temperature does not exceed the limiting temperature of 300 °C.

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