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Thermal assessment of new Ignalina NPP casks for spent nuclear fuel storage at some abnormal conditions

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1. Introduction

For interim storage of spent nuclear fuel (SNF) at the Ignalina Nuclear Power Plant (INPP), the so-called "dry" storage technology has been chosen. In this case, SNF after a cooling (pre-storage) period in water pools (no less than 5 years) is placed into GNS (Germany) manufactured metal CASTOR® RBMK-1500 or reinforced concrete CONSTOR® RBMK-1500 casks and may be stored for at least 50 years in an open or a closed storage facility. The SNF open storage facility, constructed in the vicinity of the INPP, currently stores 120 CASTOR and CONSTOR type casks, which contain over 6 000 SNF assemblies. The storage is already full.

After the final shutdown of the INPP, up to 18 000 SNF assemblies will have to be appropriately placed into casks and stored. Presently, a new closed type storage facility for RBMK SNF from the INPP Units 1 and 2 is in the final stage of construction. The facility will be capable to store up to 200 of GNS design CONSTOR® RBMK-1500/M2 type casks for storage of all the remaining SNF. The casks of the new design are of much greater capacity in comparison with those already in use.

Design stage of any nuclear facility includes comprehensive assessment of possible design and beyond design basis accidents arising as a consequence of various external and internal events or due to human errors. Such assessment has been performed for the new SNF storage facility as well. The environmental impact assessment [1], safety analysis and justification of the basic design consider various factors and conditions that may affect the safety of SNF handling at the reactor units and at the storage facility, casks transportation and long-term storage.

From thermal point of view, the main parameters determining safe storage of SNF and handling of casks are the maximum allowed fuel rod (FR) cladding temperature and the maximum allowed cask external surface temperature. Temperatures for the cask construction materials may also by limited. The designers have established that for long-term storage in the inert helium or nitrogen environment (i.e. for normal conditions), the RBMK SNF cladding maximum temperatures should not exceed 300°C [2] or 350°C [3]. External surface temperature of the cask during their transportation, according to the IAEA requirements [4], should not exceed 85°C. In case of accidents, the allowed temperatures are higher: maximum FR cladding temperatures should not exceed 570°C [5], and concrete temperatures should not exceed 177°C [6]. However, the SNF and the cask cannot be kept under these extreme conditions for a long time. The measures have to be taken in order to reduce temperatures of SNF and the cask materials to values that correspond with the long-term storage requirements.

Assurance of safe storage of SNF for such a long period of time requires understanding of different processes that may take place in the cask and also how they can be influenced by the environment at normal and abnormal conditions.

The thermal regime of cask is determined by the release of decay heat from stored SNF, the construction of cask and the storage conditions. Nuclear fuel of various enrichment – from 2.0% to 2.8%, without and with erbium absorber – was used at the INPP [7]. The release of decay heat most significantly changes within the first 7 years, when the fuel is mostly stored in water pools; later, the release of decay heat stabilizes, and monotonically reduces during the subsequent SNF storage time.

In previous studies [8, 9], thermal modeling results of CASTOR® RBMK-1500 and CONSTOR® RBMK-1500 type casks, by use of the numerical calculation code ALGOR (USA), are presented. In the recent study [10], the thermal modeling results of new CONSTOR® RBMK-1500/M2 type casks, which will be stored in the new INPP storage facility, are provided. It has been determined, that from the thermal point of view casks of all investigated types are suitable for long-term storage of SNF, which have been cooled in water pools for at least 5 years. Methodically similar calculations are described in the study [11] where calculation code FLUENT (USA) was applied for the analysis of casks with SNF from pressurized water reactors (PWR).

In this study thermal assessment of new design heavy concrete casks of CONSTOR® RBMK-1500/M2 type is presented for a some, even though very unlikely, but hypothetically possible abnormal conditions – when the cask becomes leaky and looses helium filler, when the cask is erroneously loaded with inner basket containing SNF of the highest enrichment (having maximum decay heat power), and when the ventilation regulation system of the storage hall fails to open shutter grids for a long period of time under extremely hot weather conditions.

The occurrence of the above selected accidents is considered to be very unlikely. The engineering and managerial measures preventing from occurrence of such events are foreseen by designs of the cask and of the storage facility. The selected abnormal conditions, therefore, could be allocated to the category of hypothetical events. Nevertheless understanding the potential impacts and possibilities to detect and mitigate consequences in case of such improbable accidents would occur, gives some additional information on cask behavior.

2. Methods of investigation

The sidewall of heavy concrete CONSTOR® RBMK-1500/M2 cask (Fig. 1) consists of two steel cylinders of different size: inner *1a* and outer *1b* with thickness of wall equaling 40 mm. The annulus space is filled with

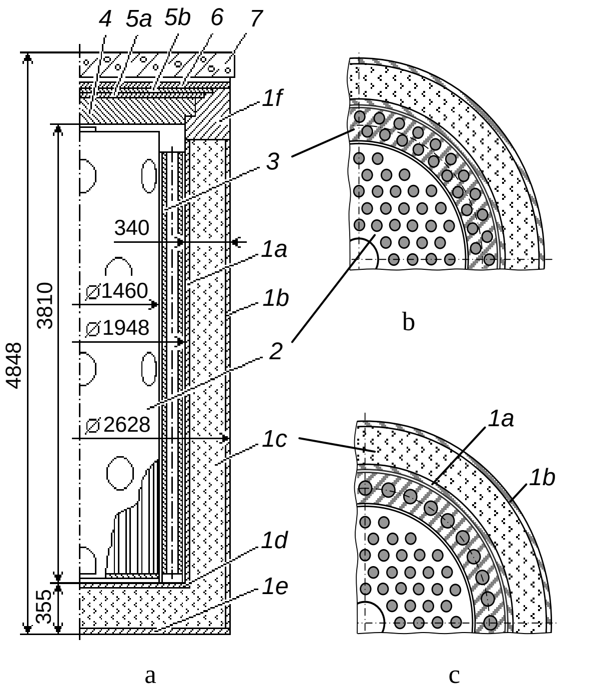


Fig. 1 Principal schemes of new-type cask (a) and ring basket (b, c): *1a*, *1b* – inner and outer cylinders of cask body; *1c* – filler of cask body; *1d*, *1e* – bottom plates; *1f* – metal ring; *2* – inner basket; *3* – ring basket; *4* – cask lid; *5a* – seal plate; *5b* – secondary lid; *6* – protection plate; *7* – concrete cover

shielding material – heavy concrete CONSTORIT *1c*. The bottom of the cask body is made similarly – by filling the space between two plates *1d* and *1e* with heavy concrete. The general thickness of the wall equals 340 mm. The top of the cask body is formed by massive metal ring *1f*, which is welded to the edges of cylinders. The cask body is closed with a triple lid system – a bolted cask lid *4*, welded seal plate *5a* and secondary lid *5b*. The protection plate *6* is bolted to the ring and in primary is used as cask lid protection during cask transfer to the storage facility. In the storage position the cask is additionally covered from the top by concrete cover *7*. Two baskets with SNF are placed inside the cask: 32M type inner basket *2* also used in casks of other types and an additional ring basket *3* used only in this type of cask. Inner basket (IB) is a stainless steel basket of cylindrical form with closed bottom and 102 tubes, in which 102 SNF rod bundles (arising from dismantling of 51 SNF assemblies) are placed. Ring basket (RB) is an aluminum alloy ring with 80 or 40 apertures in the body, depending on the configuration (Fig. 1, b and c), where intact or damaged SNF rod bundles are placed. Therefore, maximally 102 + 80 = 182 SNF rod bundles can be loaded into this cask (in casks of other types in use at the INPP only 102 SNF rod bundles can be loaded). Dimensions of the cask are: diameter – ∅2630 mm and height – 4850 m, and mass of the loaded cask is up to 116 tons.

All cask loading operations at the reactor units are performed under water. After placing of both baskets with SNF into the cask, the cask body is closed with a cask lid. The water then is pumped out, the cask inner cavity is vacuum dried and the cask is filled with helium. The cask is covered with a protection plate and is transported to the storage facility. Here, the cask is finally prepared for the storage – the protection plate is removed, seal plate and secondary lid are welded, the protection plate is bolted again and the cask is covered with a concrete cover. The cask then is moved to its permanent storage place in the storage hall of the storage facility.

The new storage facility will be located at the distance of approximately 1 km from the power units. The facility is a reinforced concrete structure with walls, roof and a firm foundation. The storage facility consists basically of two halls: the cask reception hall and the cask storage hall for 200 casks. In order to maintain the necessary thermal regime, the storage hall is naturally ventilated through orifices in the walls and the roof. The air flow can be regulated by closing/opening shutter grids fitted to orifices. The storage facility will also have a “hot cell”, where, if necessary, a reloading of SNF from one cask into another can be performed.

For thermal analysis of cask, as in previous studies [8–10], the general-purpose software (code) ALGOR developed in USA [12] was used. It is a multipurpose code, which allows performing two- and three-dimensional thermal modeling. In this study two-dimensional symmetric cask model in cylindrical r-z system of axes for stationary conditions is analyzed (Fig. 2). In the calculation model, all cask elements are modeled by separate zones. The IB load zone (inner basket with SNF excluding basket bot-

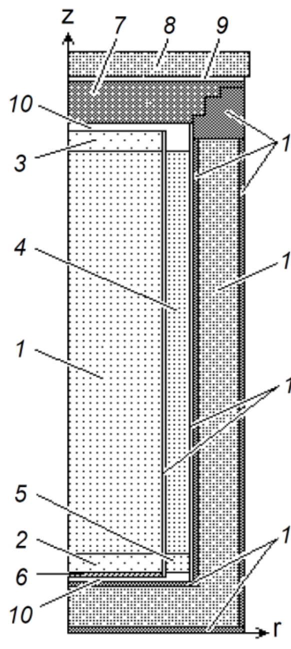


Fig. 2 Conceptual thermal calculation model of cask: *1* –active load zone of IB; *2*, *3* – lower and upper inactive load zones of IB; *4* – active load zone of RB; *5* – lower inactive load zone of RB; *6* – basket bottom; *7* – lids system; *8* – concrete cover; *9* – air gap; *10*, *11* – horizontal and vertical helium gaps; *12a* – metal parts of cask body; *12b* – filler of cask body

tom plate) is modeled by three homogeneous zones: 1 – the main active load zone *1*, which generates heat, and 2, 3 – the lower *2* and upper *3* inactive load zones, which consist of bottom and top ends of fuel assemblies. The bottom of the basket has the thickness of approximately 0.05 m and is modeled as a separate zone *6*. The RB load zone is modeled by two homogeneous zones: 1 – the main active load zone *4*, which generates heat, and 2 – the lower inactive load zone *5* with ends of fuel assemblies.

The metal parts of cask body are modeled by one zone *12a*, and the heavy concrete filler – by the other zone *12b*. The cask lid, seal plate, secondary lid and protection plate are modeled by one zone *7* and concrete cover – by the other zone *8*. The horizontal helium gaps *10*, vertical helium gaps *11* and air gap *9* are modeled as separate zones also.

Actually, the heat generated in SNF is transferred through IB and RB load zones and helium gaps by conduction, radiation and convection processes. Through cask body heat is transferred only by conduction and from the surface of cask – by radiation and natural convection. During modeling, heat transfer through load zones is calculated using effective thermal conductivity coefficients of each homogeneous zone, and through other zones – using real thermal conductivity coefficients of each respective zone. Coefficients of effective conductivity for IB load zone, which account for the complex conditions of conduction, radiation and convection heat transfer, are established experimentally by designers of the nuclear reactor. However, effective conductivity coefficients for RB load zone are unknown. Therefore, two limiting cases of heat transfer in the RB load zone were analyzed, assuming that: 1 – effective conductivity coefficients are the same as thermal conductivity coefficients of the basket body material, i.e. of aluminum alloy; 2 – effective conductivity coefficients are the same as those of the IB load zone, where materials of lower thermal conductivity prevail. The actual effective conductivity coefficients for the RB load zone are expected to be between these two limiting cases.

Heat transfer through helium gaps was calculated considering only conduction process. However, to account for other heat transfer processes, heat conduction coefficients for vertical gaps, according to [13] recommendations, were increased by the factor of two.

Heat transfer by natural convection from cask vertical cylindrical surface and concrete cover horizontal upper surface (the bottom of the cask is assumed being in adiabatic conditions) is defined from the equation:

$$q_{conv} = \alpha_{conv}\left(T_{cask} - T_a\right), \tag{1}$$

where: α_{conv} is heat transfer coefficient; T_{cask} is cask surface temperature; T_a is ambient air temperature.

Heat transfer coefficient for natural convection from vertical cylindrical surface of cask is calculated from a criterion equation [14]:

$$Nu = 0.13Ra^{1/3},\ \text{if}\ Ra > 4\times10^{10},\ Pr > 0.5, \tag{2}$$

where: $Nu = \alpha_{conv}\, l/\lambda_0$ is Nusselt number; $Ra = Gr \times Pr$ is Rayleigh number; $Gr = g\beta l^3\left(T_{cask} - T_a\right)/\nu_0^2$ is Grashof number; $Pr = \nu_0/a$ is Prandtl number; $g = 9.81$ m/s^2 is gravitational acceleration; β is coefficient of volumetric expansion; λ_0 and ν_0 are coefficients of air conductivity and dynamic viscosity, respectively; l is reference geometrical parameter in *Nu* and *Ra* numbers – in this case it is height of the cask.

Heat transfer coefficient for natural convection from cask concrete cover horizontal upper surface is calculated from a criterion equation [14]:

$$Nu = 0.15Ra^{1/3},\ \text{if}\ Ra > 8\times10^{6},\ Pr > 0.5. \tag{3}$$

Reference geometrical parameter l in this case is half of the cask radius. Values of heat transfer coefficients and surface temperatures are interdependent, therefore calculation of these parameters is an iterative process.

Heat transferred by radiation from cask surface to the environment is defined from the equation:

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

where: $\sigma = 5.67\times10^{-8}$ W/(m^2 K^4) is radiation constant; $\varepsilon = 0.93$ is the emissivity coefficient for cask painted surface.

The assessment of solar insulation impact to casks in the new storage facility is not necessary, because the casks are stored in a closed facility and direct solar radiation is not relevant.

The following parameters are used in calculations: values of decay heat power in IB and RB load zones, temperature dependent thermal conductivity (or effective thermal conductivity) coefficients for materials constituting the cask, ambient air temperature, heat transfer coefficients for natural convection from cask surfaces and emissivity coefficient for the cask external surface.

In the calculation code ALGOR, physical properties of all elements constituting the cask model are logged in electronic tables. Further, differential heat conduction equations are solved by finite element method. The calculation results provide temperature and heat flux distribution in the modeled load zones and the body of the cask.

Various SNF loading schemes for the IB and RB are foreseen by the cask design. However, only SNF of 2.0% enrichment, which forms the bulk amount from all the INPP SNF [1], and which is currently stored in water pools from 7 to 10 years and longer, will be actually placed into the IB. The remaining fuel (including the SNF of maximum 2.8% enrichment) can be stored in the pools for a shorter time. These types of SNF are foreseen to be placed into the RB. The study [10] provides calculations that addresses normal SNF storage conditions, i.e. the IB load zone locates SNF of 2.0% enrichment, cooled in water pools for 7 years, and the RB load zone locates SNF of the highest 2.8% enrichment, cooled in water pools for 5 years (reference designation 7(5)). Therefore, the results [10] provide a basis, which can be used for comparison of results at normal and abnormal conditions.

Several very unlikely, but hypothetically possible abnormal conditions are analyzed in this study. First of all, it is the loss of the cask containment leading to loss of helium filler (cask leakage). Normally, the cask is filled with helium at the power units and confinement provided by primary lid is thoroughly tested. However, during transportation of the cask to the storage facility and handling in the reception hall or cask service station, during welding of seal plate and during long-term storage, loss of the cask containment is hypothetically possible. Once seal plate and secondary lid are welded, no confinement control is foreseen during cask storage. Only ambient air and cask surface temperatures will be permanently measured and radiological monitoring will be performed. In case of cask leakage, helium filler would escape from the cask and the cask internal cavity would be filled with air. Heat transfer from fuel bundles would change, moreover, release of airborne radionuclides into the environment is possible.

Other analyzed abnormal conditions could be caused mainly by the human factor – it is an erroneous cask loading with 32M basket containing SNF of maximum decay heat power. Normally, the cask is loaded using the above described scheme 7(5). However, if during of the SNF management and tracking at the power units a very unlikely sequence of events, leading to misidentification of SNF status would be realized, then loading of the cask with IB containing SNF of the highest 2.8% enrichment with maximum decay heat power is hypothetically possible.

The last addressed abnormal conditions are failure of the ventilation regulation system of the storage hall. Normally, the storage hall is ventilated by natural air draught through orifices in the walls and the roof. The air flow is regulated by closing/opening shutter grids fitted to orifices. In case of malfunction in operation of the grids for a sufficiently long time under extremely high ambient air temperature, the air temperature in the storage hall may increase above the design values.

3. Investigation results

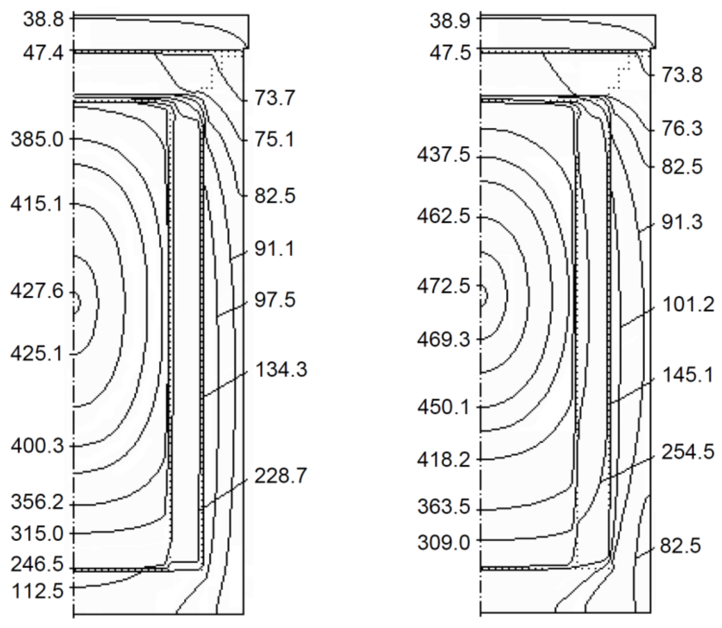
As it has been stated before, calculations were performed for maximally loaded with SNF cask located in the storage facility together with other casks. Two limiting cases of heat transfer in the RB load zone were considered, assuming that: 1 – effective conductivity coefficients are the same as thermal conductivity coefficients of the basket body material, i.e. of aluminum alloy (maximum possible conductivity); 2 – effective conductivity coefficients are the same as those of the IB load zone (minimum credible conductivity). Specific assumptions and calculation results obtained for each investigated abnormal conditions are discussed below.

3.1. Cask leakage

Under these abnormal conditions it is assumed that helium filler has been leaked out from the cask and is replaced with the air. The normally expected cask loading scheme 7(5) [10] has been considered in the calculations: IB is loaded with 2.0% enrichment SNF, cooled in water pools for 7 years, and RB – with 2.8% enrichment SNF, cooled in water pools for 5 years. The decay heat power of 102 fuel rod bundles in IB constitutes Q_i = 4.77 kW and of 80 fuel rod bundles in RB – Q_r = 6.21 kW. The ambient air temperature in the storage facility is assumed to be t_a = 35°C, which, in comparison with the single cask storage conditions, is by 5° higher to account for heat release from the neighboring casks.

Distribution of temperatures in the leaky cask for the first and the second calculation cases is presented in Fig. 3. Maximum temperature is calculated in the center of the IB load zone and is approximately 428°C for the first calculation case (a) and approximately 473°C for the second calculation case (b). It is assumed, that these temperatures correspond with maximum temperature of FR cladding. With increasing of distance from the center of the cask, both in axial and in radial directions, temperatures decrease. Temperature gradients in radial direction are higher than in axial direction. As it can be seen, calculated temperatures in the IB load zones exceed maximum allowed FR cladding temperature for normal conditions (300°C), but do not exceed maximum allowed short-term temperature in case of an accident conditions (570°C).

Calculated maximum temperature in the RB load zone is up to 255°C for the first (a) and up to 324°C for the second (b) calculation cases. Therefore, it can be expected that actual FR cladding temperature in the RB load zone practically will not exceed the maximum allowed tempera-



a b

Fig. 3 Distribution of isotherms in leaky cask filled with air for the first (a) and the second (b) calculation cases ture for normal conditions (300°C). Calculated maximum temperatures of the cask side surface in both cases do not exceed 90°C, and temperatures of the concrete cover surface reaches 40°C. Moreover, temperatures in the concrete cover are significantly lower than the temperatures in the cask bottom. This is due to assumption of adiabatic conditions for the cask bottom, although in reality, there will be a 20 mm air gap between the bottom of cask and the floor of the storage hall. Actually, due to the natural convection, temperatures at the cask bottom will be lower by 35–40°C.

Comparing calculated maximum temperatures in the cask for normal and abnormal conditions (see Table), it can be seen, that under investigated abnormal conditions maximum temperatures in the IB load zone may increase by approximately 160°C. The same temperature increase in the RB load zone constitutes approximately 120°C. Meanwhile, temperatures of the cask body filler, cask side and concrete cover surfaces almost do not change. This is due to significant reduction of heat transfer in the cask cavity, which is assumed being filled up with the air. Therefore, it will be practically impossible to detect helium leakage by measurement of temperatures of the cask outer surfaces. This may only be detected by registering airborne radionuclide release from the leaking cask.

Evaluation of the leaky cask thermal behavior for the long-term storage period (Fig. 4) shows, that temperatures in the SNF and the cask components most significantly change within the first 7 years after SNF loading. Later on, gradient of temperature change stabilizes. Maximum temperatures in the IB load zone will decrease to the maximum allowed FR cladding temperature for normal conditions (300°C) in approximately 20 years. This indicates that if the cask becomes leaky after storage for 20 years, the increase of SNF cladding temperatures will not exceed permissible safe storage limits. It is also seen, that temperatures of the cask body concrete filler practically do not exceed 100°C and are much lower than the maximum allowed concrete temperature of 177°C.

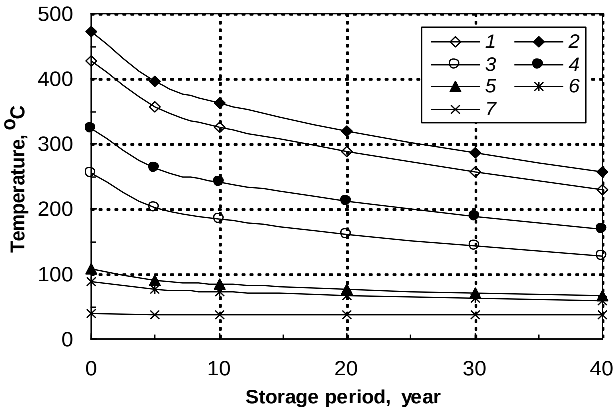


Fig. 4 Change of maximum temperatures in leaky cask components and SNF during long-term storage for the first (*1, 3*) and the second (*2*, *4*, *5-7*) calculation cases: *1*, *2* – IB load zone; *3*, *4* – RB load zone; *5* – cask body filler; *6* – cask body outer side surface; *7* – concrete cover surface

Summarizing, it may be noted that the most impacting conditions occur if the cask would leak within the first 20 years of storage. After detecting of the cask leakage, it is necessary during a quite short period of time to eliminate the leakage cause and refill the cask with helium. In the case of helium leakage at the later time, the SNF cladding temperatures will not exceed the maximum allowed temperature for normal conditions.

3.2. Erroneous cask loading

Under these abnormal conditions it is assumed that the cask is erroneously loaded with IB containing SNF of maximum decay heat power. Therefore, calculations consider that the both IB and RB contain SNF of the highest enrichment (2.8%), that has been cooled in water pools for 5 years, i.e. the considered cask loading scheme is 5(5). The decay heat power of 102 fuel bundles in IB constitutes Q_i = 7.92 kW, and of 80 fuel bundles in RB – Q_r = 6.21 kW. As in previous case, the assumed ambient air temperature is t_a = 35°C.

Fig. 5 presents temperature distribution in radial and axial directions of the cask for the first and the second calculation cases. As it can be seen, under these abnormal conditions the calculated maximum temperature of the IB load zone reaches 330°C for the first and 400°C for the second calculation cases. However, the maximum allowed short-term FR cladding temperature in case of an accident conditions (570°C) is not exceeded. In this case, maximum temperatures are calculated in the center of the cask also. With increasing of distance from the center of cask, both in axial and in radial directions, temperatures decrease. Temperature gradients in radial direction are higher than in axial direction. Temperatures at the bottom of the cask are higher than in the concrete cover. Sharp drops of temperature along ~1 m radius in the radial direction and along distance of ~0.4, ~4.1 and ~4.6 m in the axial direction, are due to enhancement of heat transfer in the helium and the air gaps.

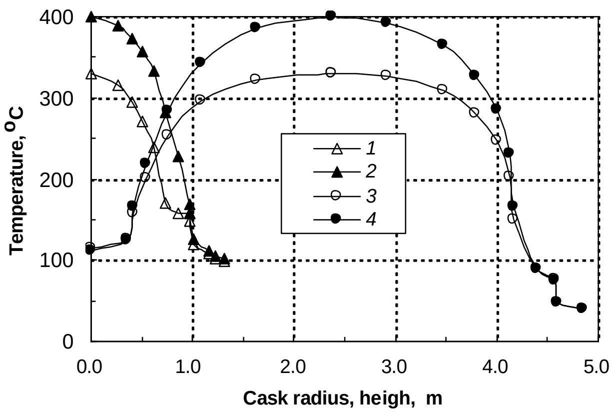


Fig. 5 Temperature distribution in radial (*1*, *2*) and axial (*3*, *4*) directions of erroneously loaded cask for the first (*1*, *3*) and the second (*2*, *4*) calculation cases

Comparing calculated maximum temperatures in the cask for normal and abnormal conditions (see Table), it can be seen, that under investigated abnormal conditions maximum temperatures increases not only in the IB and RB load zones (up to 80°C in the IB load zone and up to 45°C in the RB load zone), but also at the outer side surface of the cask (increase is up to 12°C). Therefore, the state of erroneously loaded cask may be detected from measurement of cask outer side surface temperatures and appropriate measures can be applied to eliminate the abnormal conditions (e.g. by reloading of part of the SNF into a new cask).

3.3. Failure of ventilation regulation system

Under these abnormal conditions it is assumed that shutter grids of ventilation orifices are closed and the ambient air temperature of $t_a = 45°C$ stays in the storage hall for a sufficiently long time. This temperature is close to the registered maximum air temperature during the hottest season in the Ignalina region. The normally expected cask loading scheme 7(5) [10] has been considered in the calculations: IB is loaded with 2.0% enrichment SNF, cooled in the water pools for 7 years, and RB – with 2.8% enrichment SNF, cooled in the water pools for 5 years. Decay heat power is $Q_i = 4.77$ kW and $Q_r = 6.21$ kW for IB and RB load zones, respectively.

Comparing the calculated maximum temperatures in the casks for normal and abnormal conditions (see Table), it can be seen, that under investigated abnormal conditions maximum temperatures of the IB and RB load zones will increase by only 6–10°C and practically do not exceed maximum allowed FR cladding temperature for normal conditions (300°C). Maximum temperatures of other cask components, i.e. cask body filler, concrete cover, bottom and side surfaces, increase by approximately 10°C. Therefore, if these abnormal conditions would not be eliminated for a sufficiently long time, this will not lead to increase of FR cladding temperatures considerable above the safe storage limits. Presence of the abnormal conditions will be detected by increased ambient air temperature in the storage hall and by increased surface temperatures of the stored casks.

The results of calculated maximum temperatures for all investigated cases are summarized in Table. Table includes calculated maximum temperatures of the IB and RB load zones (FR cladding), maximum temperatures in the cask body filler (heavy concrete) and maximum temperatures of the cask outer surfaces – cask side, concrete cover and bottom. It can be seen, that the most significant temperature increase in the SNF load zones may be expected in case of cask leaking leading to loss of helium filler. Calculated temperatures indicate, that temperature in the IB load zone will exceed the maximum allowed FR cladding temperature for normal conditions (300°C), but will not exceed the maximum allowed short-term temperature in case of an accident conditions (570°C). Temperatures in the RB load zone practically will not exceed the maximum allowed temperature for normal conditions. Temperatures of the cask body filler and the cask outer surfaces are most significantly impacted by erroneous loading of cask IB with SNF of maximum decay heat power. Nevertheless, temperatures of concrete filler will not exceed the maximum allowed temperature for concrete in case of an accident conditions (177°C). The concrete cover experiences maximum temperature increase in case of failure of the ventilation regulation system. However, this temperature increase is insignificant from impacting point of view.

Table

Calculated maximum temperatures for analyzed casks conditions

Conditions and calculation case		Temperature, °C				
		IB/RB load (FR cladding)	Filler of cask body	Cask side surface	Concrete cover surface	Cask bottom surface
Cask in storage facility at normal operation conditions [10]; SNF load 7(5): $Q_i = 4.77$ kW, $Q_r = 6.21$ kW; $t_a = t_{conv} = t_{rad} = 35°C$	I	256.7/135.6	104.3	87.2	39.2	98.8
	II	317.7/227.4	109.1	89.8	39.1	95.4
Leaky cask in storage facility; SNF load 7(5): $Q_i = 4.77$ kW, $Q_r = 6.21$ kW; $t_a = t_{conv} = t_{rad} = 35°C$	I	427.6/254.5	104.4	87.1	38.9	106.3
	II	472.5/323.4	108.2	89.0	39.0	100.2
Erroneously loaded cask in storage facility; SNF load 5(5), enrichment 2,8%: $Q_i = 7.92$ kW, $Q_r = 6.21$ kW; $t_a = t_{conv} = t_{rad} = 35°C$	I	329.4/158.4	119.9	98.1	40.1	115.5
	II	399.7/271.5	126.0	101.5	40.0	112.1
Cask in storage facility with failed ventilation regulation system; SNF load 7(5): $Q_i = 4.77$ kW, $Q_r = 6.21$ kW; $t_a = t_{conv} = t_{rad} = 45°C$	I	263.6/145.5	114.8	97.7	49.1	109.3
	II	323.5/234.8	119.8	100.6	49.0	105.9

4. Conclusions

1. Thermal assessment of new design heavy concrete casks CONSTOR® RBMK-1500/M2 for SNF storage at the INPP new storage facility has been performed for a some, even though very unlikely, but hypothetically possible abnormal conditions – when the cask becomes leaky and looses helium filler, when the cask is erroneously loaded with IB containing SNF of maximum decay heat power, and when the ventilation regulation system for the storage hall fails to open shutter grids for a long time under extremely hot weather conditions. Calculations have been performed using the ALGOR calculation code (USA) for the conditions when cask is in the storage facility.

2. Calculations revealed that in the case of cask leakage leading to loss of helium filler, temperatures in the IB load zone will increase by approximately 160°C and will exceed the maximum allowed FR cladding tempera-

ture for long-term storage (normal) conditions (300°C), but will not exceed the maximum allowed short-term temperature in case of an accident conditions (570°C). Temperatures in the RB load zone practically will not exceed the maximum allowed temperature for normal conditions. Temperatures of cask outer surfaces will change negligible, therefore, it will be practically impossible to detect helium leakage from temperature measurements, and only the release of airborne radionuclides from leaking cask might be registered.

3. In the case of cask leakage, the most impacting conditions occur if cask would leak within the first 20 years of storage. After detecting of the cask leakage, it is necessary during a quite short period of time to eliminate the leakage cause and refill the cask with helium. In case of helium leakage at the later time, the FR cladding temperatures will not exceed the maximum allowed temperature for normal conditions.

4. In the case of cask erroneous loading with IB containing SNF of maximum decay heat power, temperature increase in the IB load zone will be less significant than in previously investigated case and will constitute approximately 80°C. Nevertheless, temperatures in the IB load zone will exceed the maximum allowed FR cladding temperature for normal conditions (300°C). Temperatures in the RB load zone will always be lower the maximum allowed temperature for normal conditions. Temperatures of cask outer side surface will increase up to 12°C, therefore, the state of erroneous cask loading may be detected from side temperature measurements, and appropriate measures can be applied to eliminate the cause of abnormal conditions.

5. In case of failure of ventilation regulation system of the storage hall for a sufficiently long time under extremely hot weather conditions, maximum temperature increase in the IB and RB load zones will constitute approximately 6–10°C and practically will not exceed maximum allowed FR cladding temperature for normal conditions (300°C).

6. Temperatures of the cask body filler (heavy concrete) in all investigated cases will never exceed the maximum allowed temperature for concrete in case of an accident conditions (177°C).

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NAUJŲJŲ IGNALINOS AE PANAUDOTO BRANDUOLINIO KURO SAUGOJIMO KONTEINERIŲ ŠILUMINIS ĮVERTINIMAS TAM TIKROMIS NENORMALIOMIS SĄLYGOMIS

R e z i u m ė

Straipsnyje pateiktas naujos konstrukcijos konteinerių CONSTOR® RBMK-1500/M2, skirtų panaudotam branduoliniam kurui saugoti naujojoje Ignalinos AE tarpinio saugojimo saugykloje, šiluminis įvertinimas tam tikromis mažai tikėtinomis, bet hipotetiškai galimomis avarinėmis sąlygomis – kai konteineris tampa nesandarus ir iš jo išteka helio užpildas, kai į konteinerį klaidingai pakraunamas vidinis krepšys su maksimalaus liekamojo šilumos išsiskyrimo panaudotu branduoliniu kuru ir kai karščiausiu metų laiku saugojimo salės ventiliacijos reguliavimo sistema ilgam uždaro ventiliacijos groteles. Skaitinis temperatūros laukų modeliavimas atliktas naudojant JAV sukurtą programų paketą (kodą) ALGOR saugykloje esančiame konteineryje su pakrautu panaudotu branduoliniu kuru, prieš tai laikytu vandens baseinuose 5–7 metus.

Skaičiavimai parodė, kad nesandaraus ir klaidingai pakrauto konteinerių atvejais maksimalios vidinio krepšio įkrovos temperatūros viršys maksimalią leistiną ŠIEL'ų paviršiaus temperatūrą ilgalaikio saugojimo (normaliomis) sąlygomis (300°C), bet neviršys maksimalios leistinos trumpalaikio saugojimo temperatūros avarinėmis sąlygomis (570°C). Žiedinio krepšio įkrovos temperatūros abiem atvejais praktiškai neviršys maksimalios leistinos temperatūros normaliomis sąlygomis. Saugyklos saugojimo salės ventiliacijos sistemos reguliavimo sutrikimas didelės įtakos neturės. Maksimalios vidinio ir žiedinio krepšių įkrovų temperatūros praktiškai neviršys maksimalios leistinos temperatūros normaliomis sąlygomis. Visais atvejais konteinerio korpuso betoninio užpildo temperatūros neviršys maksimalios leistinos betono temperatūros avarinėmis sąlygomis (177°C).

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THERMAL ASSESSMENT OF NEW IGNALINA NPP CASKS FOR SPENT NUCLEAR FUEL STORAGE AT SOME ABNORMAL CONDITIONS

S u m m a r y

Thermal assessment of new design casks CONSTOR® RBMK-1500/M2 for interim storage of spent nuclear fuel in the new storage facility at the Ignalina Nuclear Power Plant has been performed for a some even thought very unlikely, but hypothetically possible abnormal conditions – when the cask becomes leaky and looses helium filler, when the cask is erroneously loaded with inner basket containing spent nuclear fuel of highest decay heat power, and when the ventilation regulation system of the storage hall fails to open shutter grids for a long time under extremely hot weather conditions. The ALGOR numerical calculation code (USA) was used for modeling of temperature fields in the cask located in the storage facility and loaded with spent nuclear fuel cooled in water pools for 5–7 years.

The calculations showed, that in the cases of cask leakage and cask erroneous loading, the maximum temperatures in the inner basket zone will exceed the maximum allowed fuel rod cladding temperature for long-term storage (normal) conditions (300°C), but not exceed the maximum allowed short-term temperature in case of an accident conditions (570°C). Temperatures in the ring basket zone practically will not exceed the maximum allowed temperature for normal conditions in both investigated cases. Failure of the ventilation regulation system of the storage hall will not lead to significant consequences. Maximum temperatures in the inner and ring basket zones practically will not exceed maximum allowed fuel rod cladding temperature for normal conditions. Temperatures of the cask body concrete filler in all investigated cases will never exceed the maximum allowed temperature for concrete in case of an accident conditions (177°C).

Keywords: RBMK-1500 spent nuclear fuel, cask, storage facility, fuel rod, temperature, decay heat flux.

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