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THERMAL CHARACTERISTICS OF CONTAINER FOR ON-SITE IRRADIATED NUCLEAR FUEL TRANSPORTATION

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ABSTRACT

An object of analysis in this paper is the container, which was developed for transportation of irradiated RBMK-1500 nuclear fuel assemblies at the Ignalina Nuclear Power Plant (NPP). Ignalina NPP (Lithuania) comprises two Units with RBMK-1500 reactors. After the Unit 1 of the Ignalina Nuclear Power Plant was shut down in 2004, approximately 1000 fuel assemblies from Unit 1 were safely transported and reused in the reactor of Unit 2 before final shutdown of the Unit 2 reactor in 2009. The RBMK reactor is continuously reloaded at power. Therefore the reactor core contains fuel assemblies with different burn-up level. After permanent reactor shutdown hundreds of fuel assemblies in the reactor core have considerably less burn-up than their design value. Such fuel assemblies have high energetic potential and can be reused. The fuel-transportation container, vehicle, protection shaft and other necessary equipment were designed in order to implement the process for on-site transportation of Unit 1 Fuel Assemblies for reuse in the Unit 2. The developed equipment can be used also in decommissioning phase for fuel transportation to fuel storage facilities. The set of this equipment can be applied for NPP-s with RBMK type reactors. The structural integrity, thermal, radiological and nuclear criticality safety calculations were performed to assess the acceptance of the proposed set of equipment.

The purpose of this paper is to present the results of thermal analysis of new developed container, which was used for transportation of irradiated RBMK-1500 nuclear fuel assemblies.

Using finite element code the irradiated fuel transportation container model was developed and influence of an environment temperature and influence of different axial fuel power density profiles over container temperatures field was determined. Performed analysis demonstrated that the temperatures in proposed nuclear fuel transportation container do not exceed acceptance limits for both normal operation and accident conditions.

INTRODUCTION

RBMK is a water-cooled graphite-moderated channel-type power reactor. One of the specific features of the RBMK type reactor is that refueling is performed during power operation. Therefore the reactor core contains fuel assemblies with different burn-up level. After permanent reactor shutdown hundreds of fuel assemblies in the reactor core have considerably less burn-up than their design value. Such fuel assemblies have high energetic potential and can be reused.

The project was implemented at Ignalina Nuclear Power Plant (NPP) in order to develop the process and set of equipment intended for reuse of Unit 1 fuel (which remains in the reactor after its shutdown) in the Unit 2 reactor. It is important to note that implementation of this project has two benefits: it reduces the amount of fuel to be imported to Lithuania, and reduces the amount of radioactive waste to be stored.

During implementation of the project, first of all, the technological process scheme, which covers all steps of fuel transportation from reactor of Unit 1 to the reactor of Unit 2, was developed. The implementation of the technological scheme required some modification of existing equipment and development of new equipment. The container for fuel transportation on rails, transport vehicle, protection shaft and other necessary new equipment were designed, manufactured and delivered to the INPP in order to implement the proposed technological scheme. The developed equipment can be used also in decommissioning phase for fuel transportation to fuel storage facilities. The set of this equipment can be applied for other NPP-s with RBMK type reactors.

The safety justification of fuel reuse in the reactor of Unit 2 and safety assessment of equipment, intended for on-site transportation of RBMK fuel, are the issues of highest importance. Therefore, the safety analysis report is developed to demonstrate that the reactor core parameters are safely kept within the required limits and that the proposed set of equipment performs all functions and assures the required level of safety. In the Safety Analysis Report (SAR), the structural integrity, thermal, radiological and nuclear safety calculations are performed and the calculation results are compared with safety criteria and principles to assess the acceptance of fuel reloading mode and of the proposed set of equipment.

The results of structural integrity, radiological and nuclear safety calculations showed compliance with acceptance limits [1]. The results of the structural integrity calculations showed that all constructive elements (spent fuel assembly, the container) maintain their structural integrity even in the case of dropping a fuel-loaded basket from the maximal possible height (17 m). The performed criticality calculations proved that a nuclear criticality safety is assured with large margin. The radiological safety calculations showed that the maximal calculated dose rate value on the container external surface is 214 μSv/h. This calculated value is almost ten times lower even than the limit of 2 mSv/h, which is defined in the International Atomic Energy Agency Safety Standard TS-R-1 [2] as the maximum radiation level at any point on the external surface of a package for radioactive material transportation on public roads and railways (in our case the container is used for on-site fuel transportation). The radiation levels at a distances of 1 m and 2 m from the external surface of the package is also well below the limits prescribed by the IAEA Safety requirements No TS-R-1 [2].

The objective of this paper is to present the results of thermal analysis of new developed container, which was used for transportation of irradiated RBMK-1500 nuclear fuel assemblies. The acceptance limits for temperatures in the nuclear fuel transportation container shall not be exceeded for both normal operation and accident conditions. The most dangerous accident from the point of view of thermal characteristics is fire. The calculations of temperatures are performed and results are presented in this paper for normal operation conditions and in the case of fire.

NOMENCLATURE

IAEA	International Atomic Energy Agency
NPP	Nuclear Power Plant
RBMK	Russian acronym for 'Large Channel Type Water Cooled Graphite Moderated Reactor'
SAR	Safety Analysis Report
SFAs	Spent nuclear fuel assemblies

DESCRIPTION OF PROCESS AND CONTAINER FOR IGNALINA NPP UNIT 1 FUEL REUSE IN UNIT 2 REACTOR

In the first phase of the project, the process, which covers all the steps of transporting fuel from the Unit 1 reactor to the reactor of Unit 2, was developed. Technological process on fuel reuse includes following main stages:

- preparation and loading of spent fuel assemblies (SFAs) into the transportation container, when container is in vertical position on Unit 1,
- transportation of on-site container from Unit 1 to Unit 2, when container is in horizontal position,
- unloading SFAs from the transportation container, when container is in vertical position on Unit 2.

The fuel transportation container, vehicle, protection shaft for biological shielding, equipment for container movement from horizontal to vertical position and vice versa, tools for handling of SFAs and other necessary special equipment were designed to implement the proposed process.

The SFAs are transported from Unit 1 to Unit 2 in the *container* designed for the maintenance of radiation and nuclear safety at transportation of SFAs between power plant units. The container is placed on the transportation vehicle and is the steel thick-walled cylindrical vessel (Figure 1), providing the arrangement of basket with six SFAs, protection from ionizing radiation, retention of radionuclides within the container and SFAs integrity during transportation. The transportation container is one of the most important components of the developed equipment set.

Figure 1 Container for SFAs in vertical position for fuel loading

METHOD DESCRIPTION

The original design calculations for thermal characteristics evaluation of spent nuclear fuel transport container were performed by employing three-dimensional programme ANSYS version 5.5.1. Calculations were performed for vertical and horizontal position of container. In vertical position container is during fuel loading/unloading operations. Additionally, verification calculations were performed by employing finite elements code ALGOR (USA). The calculations taken into account the heat transfer by conduction through materials, convection and radiation. This study invokes a non-linear heat transmission method which considers the dependence of heat conduction and heat transfer by radiation on temperature by applying iterative calculation.

The cross-section of SFAs transportation container and its model is given in Figure 2. At one time SFAs container may be used to transport up to 6 fuel assemblies arranged in a concentric circle in the same distance from each other. There is a tube with 102 mm diameter in the centre of the basket. In the developed numerical model (Figure 2, b), fuel assemblies and basket construction form a ring of 30.5 mm width (pos. *2* in Figure 2) with a cross-section area equal to the sum of areas of six fuel assemblies (together with 6 tubes in the basket construction). The heat source (fuel) is defined as a 27 mm width circular zone. The 1.75 mm walls on the both sides represent the walls of the six tubes (95x3) of the basket (1.75+27+1.75=30.5 mm). The thickness of the wall of the container (pos. *1* in Figure 2) is 337.5 mm, whereas the active height of the fuel assembly is 6.85 m and the height of the whole container is ~ 11.5 m.

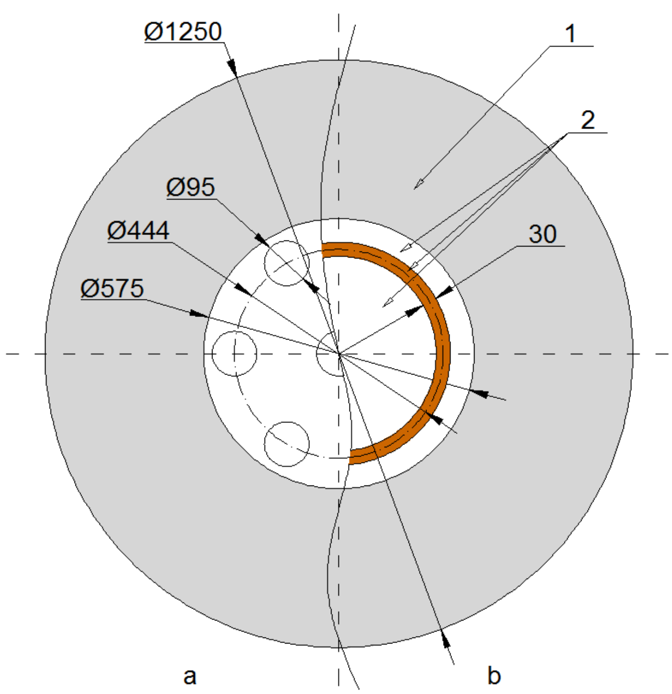

Figure 2 Cross-section (a) and numerical model (b) of SFAs transportation container: 1- container vessel, 2 – inner part of container with basket and SFAa

The heat generated in the matrix of the fuel assembly is transmitted to the basket construction and massive vessel by radiation, convection and conduction. The heat is further directed from the container surface to the surrounding environment by convection and radiation. The temperature profiles in SFAs transportation container were determined at the environment temperatures of -6 °C, 16.4 °C and 38 °C which respectively correspond to the average winter temperature and average summer temperature in Ignalina region, and possible maximal summer temperature increased by 10 degrees taking into account the influence of solar radiation. The emissivity coefficients of homogeneous fuel zone and external wall of the container was assumed as 0.45 and 0.8 respectively, whereas the equivalent emissivity coefficient between external surface of fuel basket and internal surface of container vessel as 0.46 [3, 4].

In order to determine the residual heat, calculations were carried out applying SCALE 4.4a software package. The calculations were performed for all types of nuclear fuel used at the Ignalina NPP – i.e. for fuel with 2 %, 2.4 %, 2.6 % and 2.8 % enrichment by ^{235}U. The maximal burnup level of fuel was assumed in the calculations in order to receive conservative result regarding residual heat. The calculations were performed for up to 10 years of fuel cooling after reactor shutdown. Residual heat sharply decreases during first 3 years of cooling (Figure 3). The fuel for reuse was transported after at least 1.5 years of cooling period. The Figure 3 shows that maximal residual heat of fuel assembly after 1.5 years of cooling is equal to 600 W.

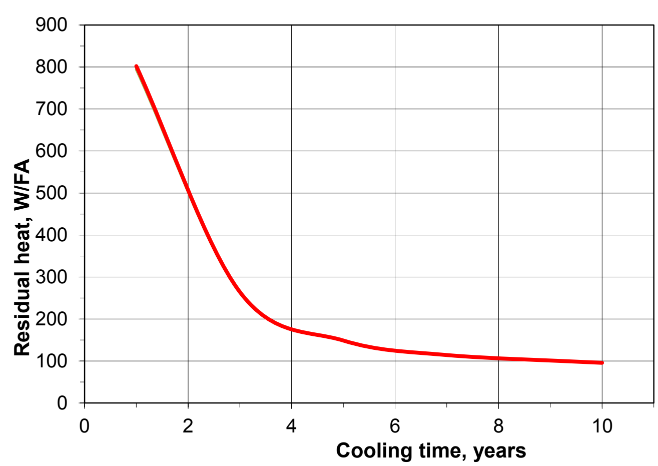

Figure 3 Residual heat of fuel assembly depending on the cooling time

In reality the residual heat distribution profile by height of fuel assembly is not uniform (Figure 4). Such distribution of heat in fuel assembly is influenced by the positions of control rods in the active zone of the RBMK reactor. Since normally the control rods are not fully inserted into the reactor active zone during almost the whole operation time of a fuel assembly, the power peak has moved to the bottom part of the fuel bundle.

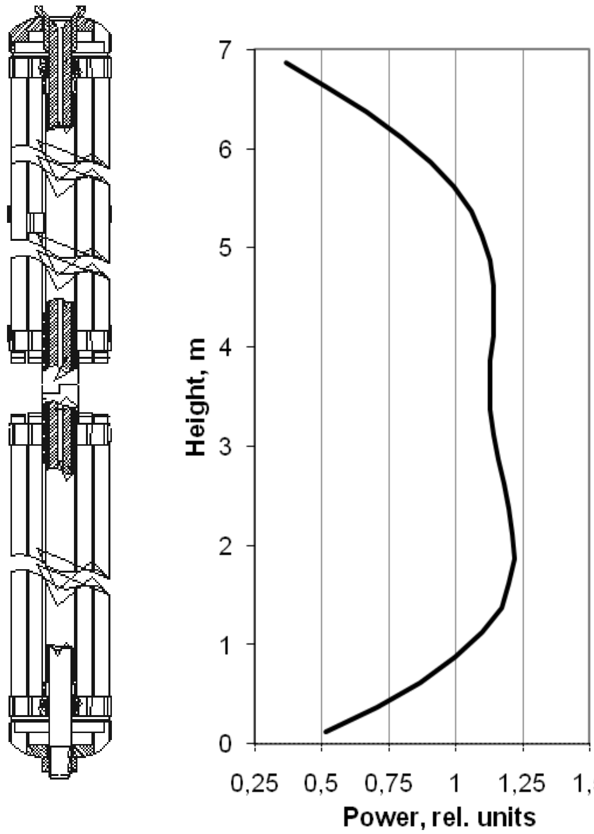

Figure 4 Non-uniform distribution of residual heat by height of the RBMK-1500 fuel assembly [5]

In order to determine the impact of heat distribution profile, the analysis of temperature distribution in SFAs transportation container was carried out by considering both uniform and non-uniform heat release profiles by height of fuel assembly (Figure 4). When the uniform fuel assembly heat distribution profile is used in modelling, the total heat release from all 6 fuel assemblies (6x600=3600 W) is regarded as uniform at full height of the assembly. In the second case (non-uniform profile), the residual heat is the same, but the heat release by height of container varies as it is presented in Figure 4. Then, the non-uniformity coefficient of heat release by height is 1.2.

RESULTS

Container Temperatures during Normal Operation

By employing ALGOR software package, the influence of different environment temperatures on the temperature of SFAs container vessel (external wall) surface was determined when the total heat release from all 6 fuel assemblies (3600 W) is uniform at full height of the assemblies. Figure 5 shows the temperature profiles of the SFAs container vessel external surface. When the environment temperature increases, the temperature profile of the container external surface becomes flatter. The increase of container surface temperature is directly proportional to the increase of environment temperature. Temperature distribution calculated using the non-uniform heat release profile is presented for environment temperature of 38 ^{o}C for comparison. It shows that the curve indicating the maximal temperature of SFAs container vessel external surface bends towards the bottom part of the container. This is determined by a greater heat release at the bottom part of the fuel bundle assembly (Figure 4). A drop of heat release may be observed in the middle part of the fuel bundle due to the 3 cm connector between the top and bottom bundles of the SFA.

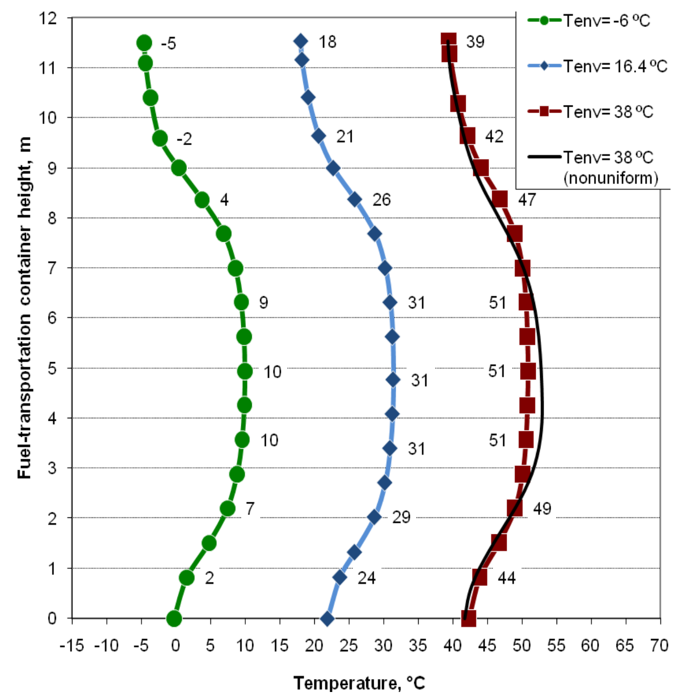

Figure 5 Temperature profiles of external surface of the SFAs container vessel at different environment temperatures (curves with points - uniform heat release by height; black line – non-uniform heat release)

The comparison of the calculation results (Figure 6), obtained by employing uniform and non-uniform residual heat release of fuel assemblies, shows that the maximum temperature of external surface of container differs by 2 ^{o}C when the environment temperature is 38°C. In the case of non-uniform fuel assembly heat release profile at 38°C environment temperature, the maximum temperature of container external surface, calculated by the ANSYS software package, is 53 ^{o}C [4] – i.e. it corresponds to the temperature calculated by the ALGOR software package.

Figure 7 presents the comparison of temperature distribution at uniform and non-uniform heat release in the basket with 6 fuel assemblies, placed in SFAs transportation container. Residual heat release profiles have a considerable influence on the maximum temperature inside the container. Thus, in the case of non-uniform residual heat release in the fuel assemblies, the maximum temperature is 126 ^{o}C, which is 18 ^{o}C higher than in the case of uniform profile.

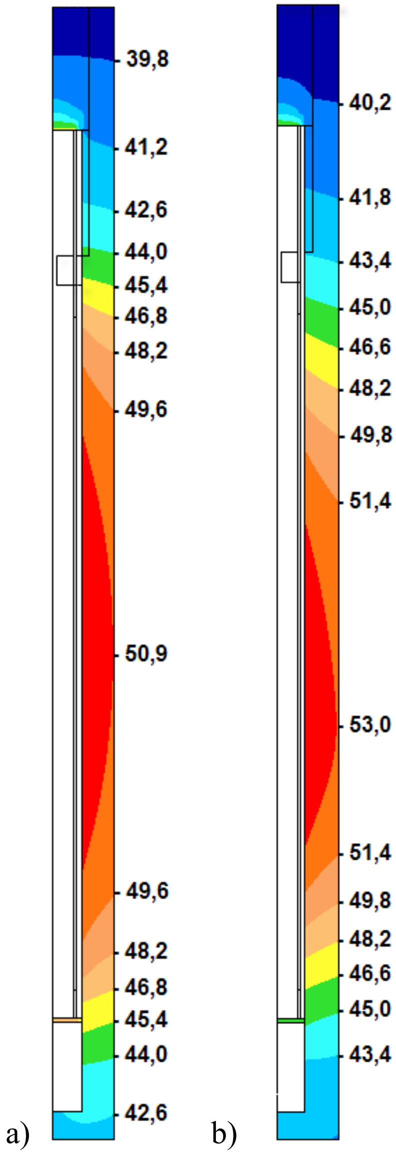

Figure 6 Temperature profiles on the container external surface a) at uniform and b) non-uniform residual heat release profile (T_{env}=38 °C)

Judging from the calculation results, both the temperature of container external surface and maximal SFA temperature inside container do not exceed the accepted limit of temperatures, i.e. 85 °C [2] and 300 °C [6] respectively.

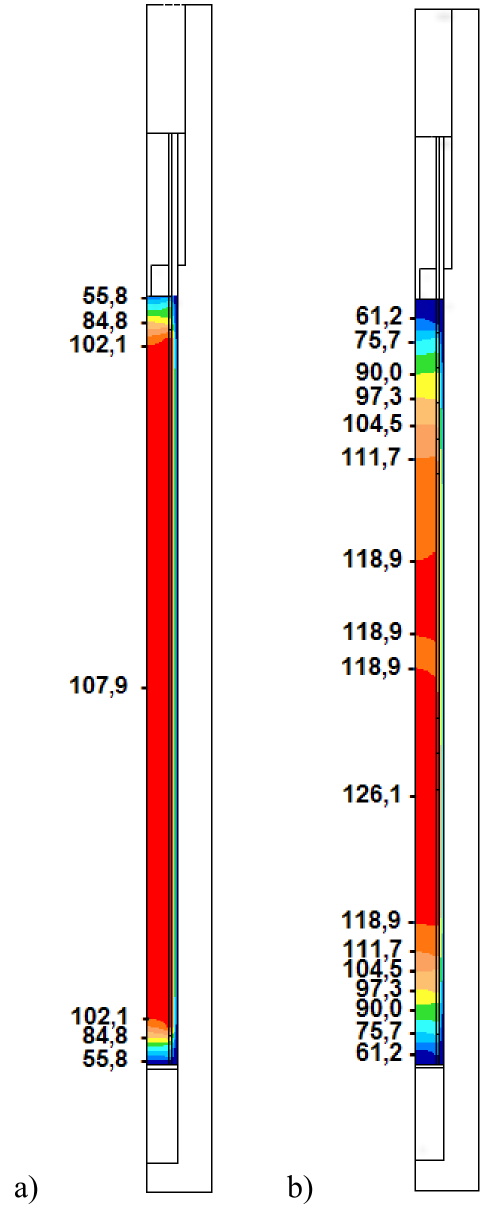

Figure 7 Temperature profiles of the basket with 6 fuel assemblies placed in SFAs container a) at uniform and b) non-uniform residual heat release profile (T_{env}=38 °C)

Container Temperatures in the case of fire

To meet the requirements of regulations, fuel roads shall not exceed the permissible temperature (300 °C) not only for normal operation conditions, but also during the fire. Therefore, the safety analysis of fuel transportation in case of fire is also provided in the SAR. For thermal characteristics calculation in the case of fire, the parameters of fire are accepted in accordance with the Regulations OPBZ [7] and TS-R [2] when fire temperature is equal to 800°C, whereas duration of fire is 0.5 h. Such fire could be caused by the spilt of liquid fuel during the accident. An additional scenario of fire was analysed in the case of container storage. In this case flame temperature is assumed to be 600°C, whereas fire duration – 1 hour, like in the case of the simulation of the CONSTOR RBMK-1500 container.

The calculations for the fire conditions are performed for horizontal position of container. The calculation of thermal characteristics of the container is carried out using the method of finite-elements employing three-dimensional programme ANSYS version 5.5.1. Designed finite-element model of the container contains 3933 finite elements and 3694 junctions.

The heat generated in the SFA active zone is transferred to the basket elements and then to the container vessel by heat radiation and conduction. Natural air circulation (intensifying heat exchange) into the inside of the container was not taken into account when determining the initial conditions for fire accident and this increases conservatism of the calculations. Heat exchange between the environment and external surfaces of the vessel emerge due to free convection and heat radiation. The heat in the hearth of fire affects the whole external surface of the container. At normal operation conditions (which are the initial conditions), the side surface of the container is affected by insolation, which is 400 W/m^2 for curved surfaces as determined by the IAEA documentation. Since the effect of insolation may last for only 12 hours a day and only a half of container surface may be sunlit, the insolation flow is conservatively accepted as 200 W/m^2 for the whole side surface of the container for 24 hours.

The performed calculations demonstrated that decay heat is efficiently removed from SFAs to the container vessel and further to the environment by the natural convection and radiation and during fuel transportation at normal operation conditions the temperature of fuel roads does not exceed 153° C.

Calculation results show the available margin to the maximum permissible temperature of fuel rods in the case of fire. In case of container appearance in the fireplace with the flame temperature of 600°C, at fire duration of 1 hour and the maximum temperature of fuel rods is achieved in 4.3 hours after entering the fireplace and comprises 188°C. In case the container enters the fireplace with temperature of 800°C at fire duration of 0.5 hour and the maximum temperature of fuel rods is achieved in 3.7 hours after entering the fireplace and comprises 201°C (Figure 8).

Level of temperatures of metal elements in case of fire (approximately 200 ^{0}C) and insignificant duration of such temperatures do not have a negative impact on the equipment in general. The simulation showed that maximum temperature gradients occurring in thick-walled elements of the casing in especially unfavorable time spans and due to that obtained thermal stresses do not reduce the strength of these constructive elements. Obtained calculation results confirmed that in case of transportation container entrance into fire the failure of fuel cladding integrity does not occur.

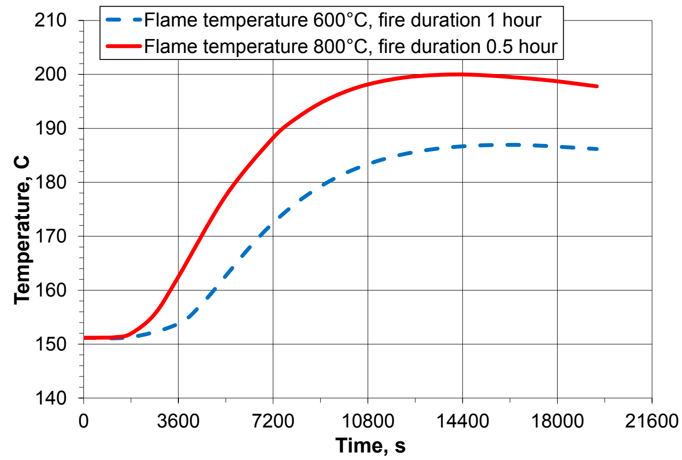

Figure 8 Maximal temperature of fuel rods in the case of fire

CONCLUSION

A considerable influence of external environment temperature on the temperature of SFAs container surface was determined.

Application of different fuel assembly heat release profiles noticeably affects the internal temperature of SFAs transportation container. In the case of non-uniform axial heat release profile, the maximum temperature of spent fuel assemblies in the container is higher by 18 ^{o}C, whereas the temperature of container vessel external surface is higher by 2 ^{o}C. In all analysed cases of normal operation, the temperature of external surface of SFAs transportation container does not exceed the limit of 85 ^{o}C. Using the non-uniform axial heat release profile enables a more exact evaluation of SFAs temperatures inside the container. In the analysed cases, they did not exceed the limit of 300 ^{o}C.

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