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ANALYSIS OF PROCESSES IN SPENT FUEL POOLS IN CASE OF LOSS OF HEAT REMOVAL DUE TO WATER LEAKAGE

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ABSTRACT

Safe storage of spent fuel assemblies in the facilities for intermediate storage (spent fuel pools) is very important. These facilities are not covered with a leak-tight containment, thus the consequences of overheating and melting of fuel in the spent fuel pools can be very severe. On the other hand, due to low decay heat of fuel assemblies, the processes in pools are very slow. Therefore, the accident management measures play a very important role in case of some accidents in spent fuel pools.

This paper presents the analysis of possible consequences of fuel overheating due to the leakage of water from a spent fuel pool. Also the accident mitigation measure, i.e. the injection of water was evaluated. The analysis was performed for the Ignalina NPP Unit 2 spent fuel pool, using system thermal-hydraulic code RELAP5/MOD3 and the code for severe accident analysis ASTEC. The phenomena taking place during such accident are discussed.

INTRODUCTION

The Tsunami that followed the earthquake at the Fukushima Daiici nuclear plants in Japan [1] showed that a loss of coolant can occur with the resultant effect on the spent fuel in the spent fuel pools. The consequences of such an event can be very serious creating a possibility of significant amount of radioactive material release to the environment. The consequences of such an accident can possibly be equivalent to the Chernobyl accident, which has been rated at 7 on the International Nuclear Event Scale (INES), because spent fuel pools are in general not housed in a containment with the same integrity as the containment around the reactor core and primary pressure boundary.

As it is noted in the Operating Experience Feedback Report “Assessment of Spent Fuel Cooling” [2], during the operation time two losses of spent fuel pool coolant inventory events occurred and a decrease of water level by 1.5 m was registered. These real events were terminated by the operator action when approximately 6 m of water remained above the stored fuel. In a case without operator actions, the water loss could have continued, which could have led to a severe accident in the spent fuel pool. The last accident at Fukushima NPP showed that the loss of ventilation due to loss of power supply can lead to the explosion of hydrogen in SFP hall and additional damage of SFP building and system. The possible consequences of water loss due to the leakage and water injection to the spent fuel pool after fuel heat up are evaluated in this paper. The evaluation of this accident was performed for Ignalina NPP Unit 2 spent fuel pool, but it can be applied for SFP of other reactor types. In order to apply it to other reactor type SFP, real characteristics of SFP, such as water volume, possible leakage rate and decay heat of fuel assemblies groups in SFP, etc. should be evaluated.

At the Ignalina NPP (Lithuania) two Russian design channel-type graphite-moderated boiling water reactors (RBMK-1500) were commissioned in 1983 and 1987. At present both units are shutdown for decommissioning (in 2004 and 2009). According to the design, the spent fuel should be returned for reprocessing to Russia. However, no fuel assemblies have been taken out from the territory of the Ignalina NPP: all assemblies of spent fuel are stored in the spent fuel pools (SFP) and in dry storage facility on-site of the Ignalina NPP. Thus, the safety justification of facilities for intermediate spent fuel assemblies storage in Ignalina NPP is very important.

NOMENCLATURE

ASTEC	Accident Source Term Evaluation Code
INES	International Nuclear Event Scale
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission
RBMK	Russian abbreviation for “Large-power channel-type reactor”
SFA	Spent fuel assembly
RELAP5	Code for the Reactor Excursion and Leak Analysis Program
SFP	Spent fuel pool

The design of the RBMK reactor fuel rods differs very little from fuel elements manufactured for standard BWR-type reactors [3]. The core height of RBMK-1500 reactor is 7 m. In order to achieve the required height, the RBMK fuel assembly consists of two fuel bundles placed one above the other. Each fuel bundle includes 18 fuel elements placed in two circles around the carrying rod. The outer diameter of the fuel assembly is 79 mm. For safe disposal of spent fuel bundles into the spent fuel pools and later in the dry storage facility, the leak-tight fuel assemblies should be cut separating the fuel bundles and placed in the shipping casks.

The main goal of this paper is to discuss the processes in SFP during the loss of water due to leakage in pools and to describe the accident mitigation measure, i.e. the water injection to the spent fuel pool after fuel heat up.

DESIGN OF SPENT FUEL POOLS AT IGNALINA NPP AND RELAP5 MODEL

It was already mentioned that the RBMK fuel assembly consists of two fuel bundles placed one above the other. The reloaded fuel assemblies with two fuel bundles remain in the pool for at least a year, after which they may be removed to be cut in a "hot" cell. During this procedure the fuel bundles are separated and placed into the 102 shipping casks. The shipping casks with spent fuel assemblies are stored in the storage pools until they are loaded into the protective casks CASTOR or CONSTOR to be further transported to the dry spent fuel storage facility. The fuel assemblies with fuel rods, which lose whey leak-tightness, are placed in a special individual sheaths (for single assembly – two fuel bundles) and stored together with other non-cut fuel assemblies.

Each reactor unit at Ignalina NPP is equipped with a system of spent fuel pools (Figure 1). All process operations related to the handling of the spent fuel are performed in the central hall or in the spent storage pools hall. Spent Fuel Pools of Ignalina NPP are designed for the following:

- storage of non-cut Spent Fuel Assemblies (SFAs) in deep compartments of storage pool (Rooms 236/1 and 236/2);
- storage of spent nuclear fuel in shipping casks in shallow compartments of the storage pool after cutting SFAs (Rooms 336, 337/1, 337/2, 339/1, and 339/2).

The spent fuel assemblies prepared to be cut in the "hot" cell are accumulated in a separate pool (Room 234). The loading of the shipping casks is performed in two pools (Rooms 338/1 and 338/2). Also, there is a transport corridor (Room 235) for the transportation of SFAs and shipping casks between the pools and the transport corridor (Room 157) for transportation of fuel assemblies between the spent fuel hall and reactor hall. The whole complex of storage pools of the spent fuel storage and handling system comprises 12 pools (Figure 1). The detailed description of spent fuel pools in Ignalina NPP is presented in [4, 5].

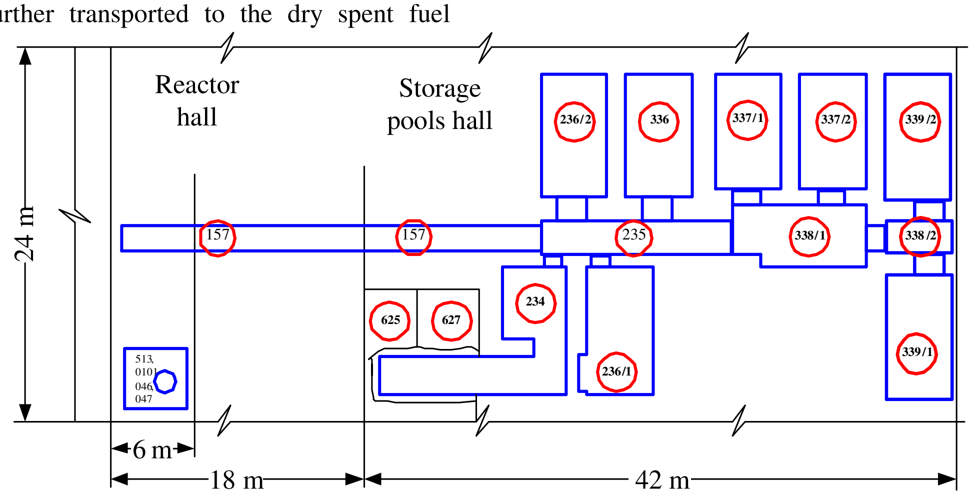

Figure 1 Layout of buildings in SFPs hall of Ignalina NPP Unit 2

At first, to understand the processes in the spent fuel pools, the best-estimate system thermal hydraulic code RELAP5/MOD3 was used for the development of SFP model. RELAP5 code [6] has been used in Lithuanian Energy Institute since 1995 for Ignalina NPP licensing purposes.

RELAP5 model of Ignalina NPP Unit 2 spent fuel pool consists of 3 representative spent fuel pools ("201", "202" and "203" in Figure 2 and Figure 3), which model the real rooms of SFP:

- "201" is used for the modelling of the most energy rated room of SFP (room 236/2).
- "202" is used for the modelling of all the other SFPs (Room 234 and Room 236/1 loaded with non-cut SFAs; Room 235, Room 336, Room 337/1, Room 337/2, Room 338/1, Room 338/2, Room 339/1 and Room 339/2, where the spent fuel bundles are loaded into the shipping casks).
- In pool "201" two groups of non-cut SFAs: Heat Structure "12111" and Heat Structure "12211" are modelled (see Figure 2).
- In pool "202" one group of non-cut SFAs – Heat Structure "12121" and one group – Heat Structure "12221" for spent fuel bundles in the shipping casks are modelled.
- By pool "203" the gap between SFA and SFP walls are modelled.

Due to one-dimensional code specifics, it was assumed that pools "201" and "202" are in the concentric geometry as it is shown in Figure 3. It means that “201” does not have radial heat losses to the SFP walls. “201” is connected only to “202” and “202” is connected to “203’ by special connections, presented in Figure 2 by arrows. These cross connections between the channels “201”, “202” and “203” models the water mixing in the pools. The bottom part of SFP below the fuel assembly in RELAP5 model is modelled by a branch element “100”, the top part of SFP is modelled by branches “301” and “302”. To model the atmospheric pressure in SFP, the top part of the pools is connected to a time dependent volume “400” with atmosphere air conditions. The leakage of water through the rupture in the wall of SFP is modelled by a junction “011”. In the severe accident management guidelines of Ignalina NPP [5], it was shown that the water leakage in the case of SFP floor break is limited by the capacity of drainage system and the maximal uncompensated leakage may not be higher that 21.1 kg/s. The flow area and flow energy coefficients of this junction are selected in such a way that the maximal flow rate from the pools (when the water level in pools is nominal) is 21.1 kg/s. The supply of water is modelled using a junction “021” ant volume “020” with the steady state conditions. The temperature of water which is supplied to SFP is assumed to be 50 ^{o}C.

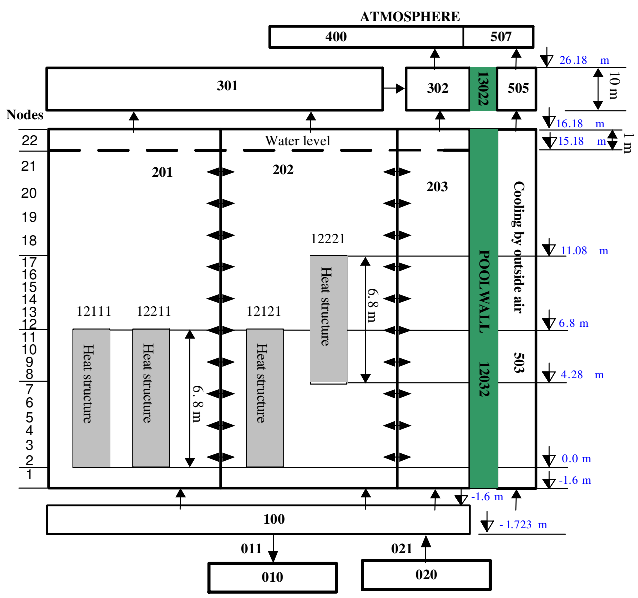

Figure 2 SFP and SFAs nodalization scheme in RELAP5 model

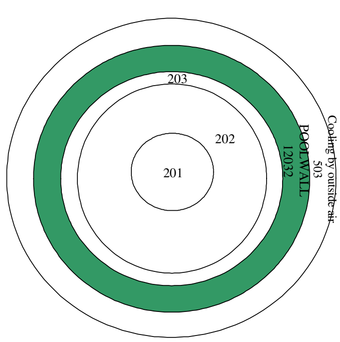

Figure 3 Pools and walls scheme in RELAP5 model

It was assumed that shipping casks with spent fuel bundles are placed in SFP in two layers one above the other, according to the real shipping casks loadings in the SFP [5, 7]. Therefore, in the model, Heat Structure “12221” is described in same way like non-cut SFAs (Heat Structures “12111”, “12211” and “12121”). Elevations of the shipping casks loading in SFP are different from the non-cut SFAs, thus Heat Structure “12221” is placed higher, comparing to Heat Structures “12111”, “12211” and “12121” (see Figure 2).

The ring POOLWALL – heat structure “12032” models the walls of SFP from ferroconcrete. The outer ring – channel “503” models the outside air, which is around the SFP. Total cross sectional area equals to “201” + “202” + “203” = 30 + 240 + 30 = 300 m^2. Total volume of water in the SFP is 300 m^2 * (15.18 + 1.723) = 5070 m^3. To model the area of the wall and roof in SFP compartment above water, which are connected to the environment, the heat structure “13022” was used. In the model, it was assumed that the area of concrete walls (heat structure “12032”) around the pools with spent fuel assemblies (pool “203”) is 1000 m^2 from the inner side and 1050 m^2 form the outer side; the area of concrete walls (heat structure “13022”) around the top part of SFP building (volume “302”) is assumed to be 615 m^2 from the inner side and 645 m^2 form the outer side; the total area of concrete walls is 1613 m^2 from the inner side and 1692 m^2 form the outer side of the walls; the thickness of concrete wall is assumed to be 0.5 m.

RELAP5 model description is presented in the paper [4] in more detail. During the modelling of loss of water from the spent fuel pools due to a leakage accident, for the evaluation of the worst possible case, the following main assumptions in the model were used:

- The maximal amount of spent fuel assemblies is placed in the spent fuel pools.
- The situation before the final shutdown of Ignalina NPP Unit 2 reactor in 2009 is modelled: it is assumed that some accidents in the reactor occur and some fuel assemblies from the reactor were unloaded into SFPs. This assumption results a much higher decay-energy content in the spent fuel pools. Such assumption was made evaluating the situation in Fukushima Daiichi NPP Unit 4.
- According to the regulation at Ignalina NPP, at any moment spent fuel pools should have an opportunity to receive 166 SFAs of the emergency unloading. These SFAs from the reactor are placed in individual sheaths in room 236/2 (Figure 1).
- 2074 SFAs can be placed without sheaths in the rooms: (in room 234 - 108 SFAs; in room 236/1 - 784 SFAs; in room 236/2 - 1182 SFAs).
- Maximal permissible number of shipping casks in SFP of Unit 2 of Ignalina NPP is 111. Because SFA consist of two bundles, 102 bundles are stored in one shipping cask after cutting. 111*51=5661 SFAs can be stored in all shipping casks. Therefore, if emergency unloading of 166 SFAs occurred, the maximal possible number of SFAs in SFP of Ignalina NPP Unit 2 was 166+2074+5661=7901. Total power generated due to the decay heat of SFAs in SFPs is 4253 kW.

- Total mass of uranium in SFPs (in 7901 SFA) is equal to 752,400 kg.

In RELAP5 model all SFAs in SFP are divided into 4 groups (Heat Structures "12111", "12211", "12121" and "12221"). The decay heat of different SFAs groups was calculated according to the assumed storage time in the pools (see Table 1).

Table 1 Parameters of groups of SFAs in the RELAP5 and ASTEC models

Groups	Groups of SFAs in RELAP5 and ASTEC models	Assumed storage time in SFP	SFA decay heat, kW	Amount of SFAs in group	Group power, kW
SFAs in 236/2 room	Heat Structure "12111"; ROD1	8 days	5.21	166	864.9
SFAs in 236/2 room	Heat Structure "12211"; ROD2	137 days	1.281	1182	1514.1
SFAs in 236/1 and 234 rooms	Heat Structure "12121"; ROD3	2 years	0.489	892	436.2
SFBs in shipping casks	Heat Structure "12221"; ROD4	3 year	0.254	5661	1437.9
			Total:	7901	4253

ANALYSIS OF WATER LEAK FROM SPENT FUEL POOL BY EMPLOYING RELAP5 CODE

For the modelling of nominal initial conditions, the following assumptions were made:

- initial water level is 15.18 m from the very bottom of the fuel assemblies (15.18 + 1.723 m from the bottom of SFP - Figure 2);
- initial water temperature in SFPs is 50 °C;
- air ventilation system in the SFP is switched off;
- heat removal by outside air is not taken into account;
- the maximal water leakage from SFP is 21.1 kg/s;
- at the time moment t = 304,000 s (84.4 h) the leakage from the SFP is terminated;
- the supply of water into SFP starts at 400,000 s (111.1 h) after the beginning of an accident. The flow rate of the emergency injected water 27.8 kg/s was selected taking into account the capacity of water make-up system in Ignalina NPP [5].

In the modelling it was assumed that the leakage in the SFP starts at the time moment t = 0 s (Figure 4). Due to the water leakage from the pools, the water level, the hydrostatic pressure of water column and flow rate through the junction, which models the rupture in SFP, decrease. As it is presented in Figure 5, at the time moment t = 59,700 s (16.6 h), the uncovering of the fuel bundles, placed into a higher level in the 102 shipping casks (in the RELAP5 mode these fuel assemblies are modelled by heat structure "12221") begins. The uncovering of non-cut spent fuel assemblies placed in the lower level (heat structures "12211", "12121") and fuel assemblies of the emergency unloading (heat Structure "12111") starts at t = 134,000 s (37.2 h). The water level decreases down to the very bottom of SFA at t = 304,000 s (84.4 h). After the start of water injection with flow rate 27.8 kg/s (Figure 4), the water level in the SFP starts to increase. All fuel assemblies are re-covered by water after approximately 33 hours from the beginning of water supply (at time moment t = 519,000 s).

All analysed time intervals can be divided into five stages:

- 1st stage – water leakage up to the beginning of the uncovering of the bigger part of spent fuel assemblies in SFP (t = 0 – 59,700 s); within this stage the SFAs are still covered by water;
- 2nd stage – dry-out of fuel bundles and start of fuel heat up (t = 59,700 – 304,000 s);
- 3rd stage – fuel heat up and overheating in the empty SFP (t = 304,000 – 400,000 s);
- 4th stage – start of water injection and reflooding of overheated fuel (t = 400,000 – 519,000 s);
- 5th stage – final filling of SFP by increasing the amount of water up to the initial level (t = 519,000 – 550,000 s).

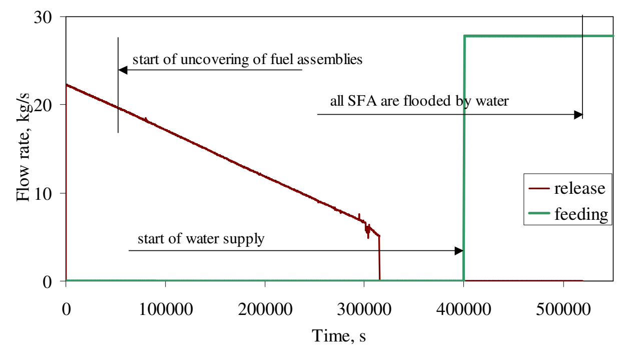

Figure 4 Water leak from SFP and feeding

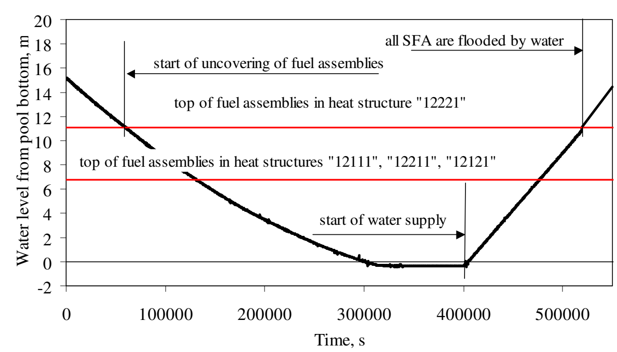

Figure 5 Water level in SFP

As it is shown in Figure 6, within the 1st stage (t = 0 – 59,700 s) the increase of fuel temperature is insignificant. After the start of uncovering the fuel bundles, placed into the higher level in the 102 shipping casks (heat structure "12221"), the temperature of these fuel rods starts to increase (t = 59,700 – 134,000 s) during the 2nd stage. The heat up of the remaining groups of fuel rods starts at the time t > 134,000 s. The temperature increases much faster in the heat structure “12111”, which models the fuel assemblies of the emergency unloading with the highest decay heat.

The heat from the hot fuel rods by steam-air mixture is transferred to the walls of SFP. The behaviour of SFP wall temperatures on the inner and outer surface of the wall is presented in Figure 7.

After the beginning of water injection in the 4th stage (t = 400,000 s), the slow process of fuel cooldown begins. The fuel rods, placed in the lower level, are cooled faster, the top part of the fuel rods (heat structure “12221”) is cooled the latest (Figure 6). The increase of water level within the 5th stage in SFP is indicated by a fast decrease of the wall inner surface temperature (Figure 7), but the temperature of the outer surface is decreasing very slowly. The modelling shows that the significant part of the heat from the SFA is transferred to the concrete walls (Figure 8). As it was mentioned, an assumption was made that in the calculation the total area of concrete walls is 1613 m^2 from the inner side and 1692 m^2 form the outer side of the walls; the thickness of concrete wall is assumed to be 0.5 m. The heat accumulated in the concrete is later removed by supplied water. Heat removal by outside air was not taken into account.

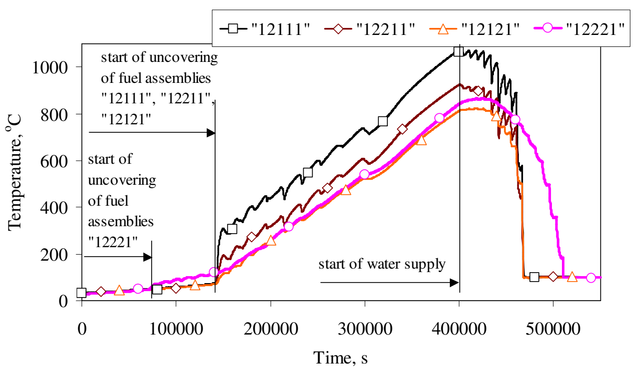

Figure 6 Behaviour of fuel temperatures in SFP

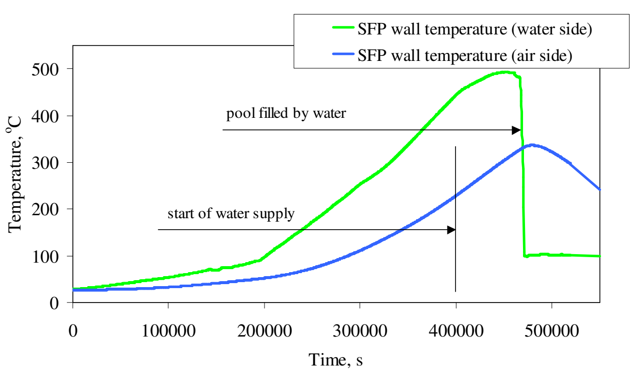

Figure 7 Behaviour of SFP wall temperatures

The maximal fuel temperature 1060 °C in SFA with the highest decay heat is reached in the 3rd stage before the water injection (Figure 6). At such high temperature, the steam-zirconium and zirconium-air reactions should take place; however, they were not evaluated in this case.

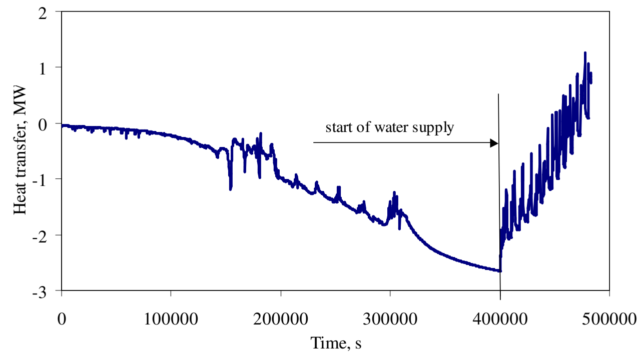

Figure 8 Heat transfer from the water-steam-air mixture to the concrete walls of SFP (total area of 1692 m^2 from the outer side of walls)

The additional calculation was performed activating a special option of RELAP5/MOD3.3, when water-metal reaction was evaluated. In this last case, the reaction of zirconium and steam is treated using the correlation developed by Cathcart [6]. The model assumes that there is an unlimited amount of steam available for the metal-water reaction. The chemical equation being modelled is the following:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + 5.94*10^8 J/(kg*mole) \quad (1)$$

The amount of heat added to the outer surface of the cladding between time point n and n-1 is given by multiplying the volume of the cladding undergoing reaction by the density of zirconium and the reaction heat release:

$$Q = \rho\pi[(r_0 - dr_{n-1})^2 - (r_0 - dr_n)^2]H/W \quad (2)$$

where:
Q = heat addition per unit length (J/m),
ρ = density of zirconium = 6500 Kg/m^3,
r_o = cladding outer radius (m),
H = reaction heat release = 5.94*10^8 J/(kg*mole),
W = molecular weight of zirconium = 91.22 kg/(kg*mole).

Similar equations are used for the inner surface of the cladding if its rupture occurs. The total hydrogen mass generated by the metal-water reaction is calculated by multiplying the mass of zirconium reacted by the ratio of the molecular weight of 4 hydrogen atoms to 1 zirconium atom.

The calculated peak fuel temperatures in SFP, when the steam-zirconium reaction is evaluated, are presented in Figure 9. The RELAP5/MOD3.3 does not evaluate the specific severe accident phenomena as fuel melting. Thus, in the calculation, it is assumed that the released heat due to the steam-zirconium reaction is used only for the heating of fuel. This explains very high (not realistic) fuel temperatures in Figure 9. Comparing the maximal fuel temperatures calculated without evaluation of steam–zirconium reaction and when this exothermic reaction was taken into account (Figure 10), it can be seen that a significant increase of the temperature starts after the fuel cladding temperature exceeds 800 – 900 °C, when the exothermic reaction starts. The generation of hydrogen and exothermic reaction starts in the 3rd stage, before the emergency water injection. The calculated total amount of generated hydrogen is presented in Figure 11. As it is shown in the figure, the total amount of hydrogen generated from 7901 SFAs is 9100 kg.

Because the RELAP5 model assumes that there is an unlimited amount of steam available for the metal-water reaction, the start of hydrogen generation and increase of fuel temperatures are not related to the moment when the supply of water starts. The supplied water only removes the heat from the hot fuel channels. The fuel assemblies “12221” are located in a higher position comparing to other assemblies, thus the cooldown of these assemblies appears later (Figure 9).

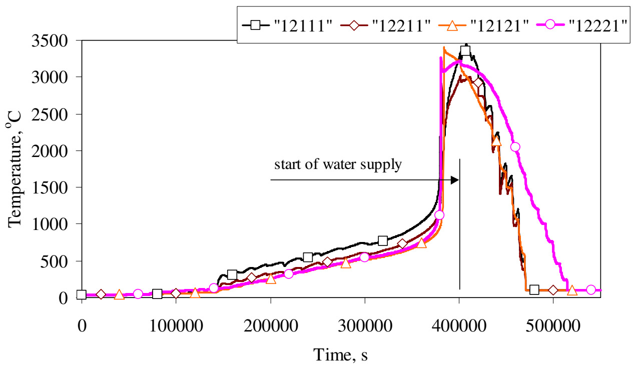

Figure 9 The calculated peak fuel temperatures in SFP when the steam-zirconium reaction is evaluated

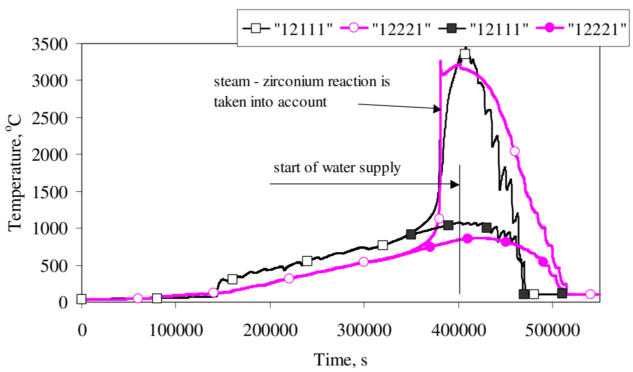

Figure 10 Comparison of maximal fuel temperatures calculated without evaluation of steam–zirconium reaction and when this exothermic reaction was taken into account

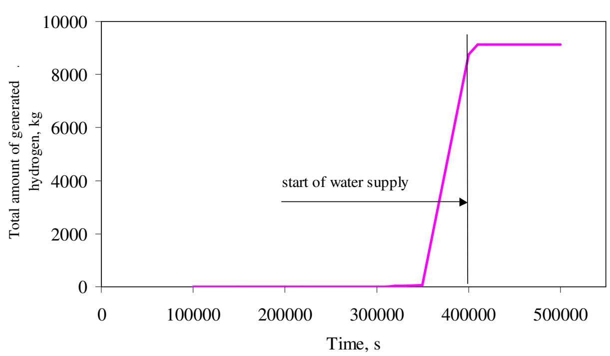

Figure 11 Total amount of generated hydrogen

ANALYSIS OF SPENT FUEL POOL DRYOUT AND REFLOODING USING ASTEC CODE

To understand the real behaviour of overheating the fuel rods after reflooding, the analysis was repeated using a computer code designed for the analyses of severe accidents in NPPs. ASTEC code is developed for the analysis of reactor accidents with core degradation and includes modules for the simulation of core degradation, melting and relocation, release and transport of fission product and aerosol, and behaviour of debris bed. ASTEC code is a source term code with modular structure [8]. A model developed using DIVA module of ASTEC V1.3R2 code is used in this paper. DIVA module simulates the in-vessel core degradation: the behaviour of in-vessel structures, the formation and the evolution of liquid and solid mixtures, thermal hydraulics, and chemical reactions between materials.

In the ASTEC code analysis, the simplified single pool model was created using DIVA module (Figure 12). DIVA module allows to model fuel assemblies in detail. So in the model, zirconium and stainless steel grids were taken into account. The initial volume of water, water level and initial water temperature in the ASTEC model of SFPs were assumed the same as in the above-described RELAP5 model. The fuel rod models “ROD1”, “ROD2”, “ROD3” and “ROD4” represent the same groups of SFAs as heat structures “12111”, “12211”, “12121” and “12211” in RELAP5 model (see Table 1). In the ASTEC calculations it was assumed that the leakage rate from the SFP is constant (21.1 kg/s). At the time moment t = 215,000 s, the SFP is completely empty and the leakage is terminated. The injection of water starts at the time t = 300,000 s, when the maximal fuel temperature exceeds 1000 °C (Figure 13).

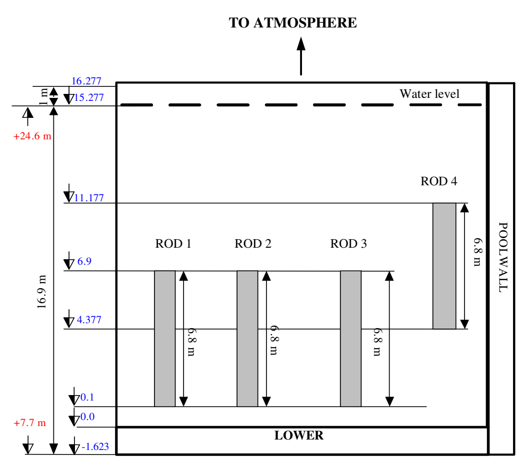

Figure 12 SFP and SFAs nodalization scheme in ASTEC model

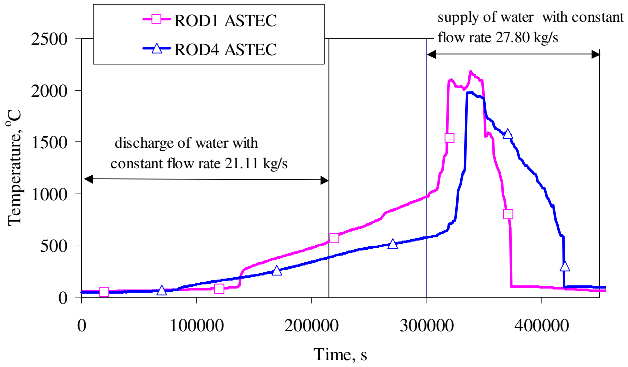

Figure 13 Maximal fuel temperatures calculated using ASTEC code

As it is presented in Figure 13, the injection of water in the SFP with the overheated SFAs leads to the exothermic steam-zirconium reaction and fast increase of temperatures of fuel claddings. Such reaction appears in all groups of SFAs ("ROD1" – "ROD4"). The maximal fuel temperatures exceed 2000 °C: in such case all fuel claddings will be damaged, oxidised from both sides and melting of claddings and stainless steel grids will appear. In the ASTEC calculations the total amount of hydrogen generated due to the steam-zirconium reaction is about 7200 kg (Figure 14). Such total amount of hydrogen is smaller, comparing to the RELAP5 calculation (Figure 11). This is because in the ASTEC calculation not all available zirconium is oxidised (after the water injection, the bottom parts of fuel rods are cooled-down) in contradiction to the RELAP5 calculation.

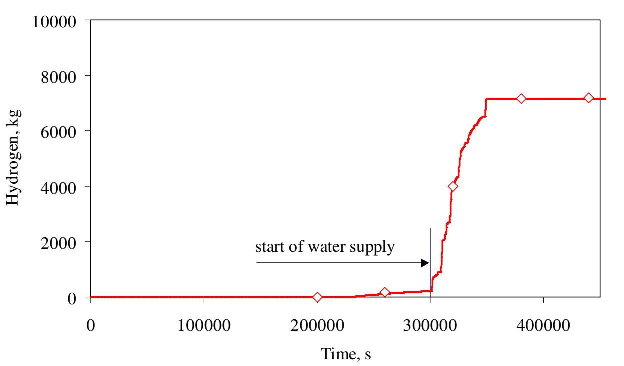

Figure 14 Hydrogen generation due to Zr oxidation in the ASTEC analysis

CONCLUSION

This paper presents the calculation results of the most probable severe accident in spent fuel pools, i.e. the loss of heat removal due to water leakage in SFP. The analysis of this event, which covers all possible phenomena in SFPs, was performed for SFP at Ignalina NPP Unit 2.

For the analysis of the accident, the model of spent fuel pools was developed using RELAP5 and ASTEC codes. The developed model allowed to model different phenomena: uncovering and heat-up of fuel rods, steam–zirconium reaction, quenching of hot fuel rods by water, etc. The results of the analysis showed, that the late operator actions: injection of water in to SFP with overheated fuel rods can lead to the generation of huge amount of hydrogen, failure of fuel claddings and release of radioactive isotopes to the environment.

Such analyses are useful for the evaluation of different accident mitigation measures. The perfection of SFP models and benchmarking of calculations with different models developed using other codes are planned in the future.

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