VI Minsk International Heat and Mass Transfer Forum
MIF 2008, Minsk, May 19-23, 2008

UDC 621.039.534

EVALUATION OF HEAT TRANSFER BETWEEN PARALLEL FUEL CHANNELS DURING THE ANALYSIS OF BDBA IN RBMK REACTORS

A. Kaliatka, E. Uspuras, M. Vaisnoras

Laboratory of Nuclear Installation Safety, Lithuanian Energy Institute, Breslaujos str. 3, LT-44403, Kaunas, Lithuania
algis@mail.lei.lt uspuras@mail.lei.lt minde@mail.lei.lt

ABSTRACT

The Ignalina Nuclear Power Plant is a twin-unit with two RBMK-1500, graphite moderated, boiling water, multichannel reactors. After the decision was made to decommission the Ignalina NPP, Unit 1 was shut down on December 31, 2004, and Unit 2 is to be operated until the end of 2009. Despite of this fact, severe accident management guidelines for RBMK-1500 reactor at Ignalina NPP are prepared. In case of Beyond Design Basis Accidents it can occur that no water sources are available at the moment for heat removal from fuel channels. Specificity of RBMK reactor is such, that the channels with control rods are cooled with water supplied by the system totally independent from the reactor cooling system. Therefore the heat removal from RBMK-1500 reactor core using control and protection system cooling system can be used as non-regular mean for reactor cooldown in case of BDBA. The heat from fuel channels, where heat is generated, through graphite bricks is transferred in radial direction to cooled CPS channels.

This article presents the analysis of possibility to remove heat from reactor core in case of large LOCA by employing CPS channels cooling circuit. The analysis was performed for Ignalina NPP with RBMK-1500 reactor using RELAP5-3D and RELAP5 codes. Results of the analysis have shown, that in spite of high thermal inertia of graphite, this heat removal from CPS channels allows to slowdown the core heat-up process.

KEYWORDS: RBMK-1500, Beyond Design Basis Accident, RELAP5-3D code, Heat removal, Control and protection system cooling channels

1. INTRODUCTION

RBMK-1500 reactor, which is located at the Ignalina NPP site, is a multichannel boiling water and graphite moderated nuclear reactor. Reactor core consists of 2488 graphite columns with the vertical bore openings [1]. These openings are used for positioning of the fuel channels, which in turn are used for placing fuel assemblies, reactivity regulating control rods and several types of instruments into the core. Approximately 95% of energy is generated in fuel assemblies, while 5% – in graphite columns. Specificity of RBMK reactor is such, that the control rods are placed in the individual channels that are independent from the channels with fuel bundles. The channels with control rods are cooled with water supplied by the system totally independent from the reactor cooling system. The pressure in channels with control rods is always close to atmospheric. The geometry of the graphite columns and availability of FC and the channels of control and protection system located near by results in non-uniformity of heat fluxes and temperature distributions around the graphite columns periphery. Thus, in order to model the thermal hydraulic behaviour in the RBMK core it is necessary to represent heat conduction between the graphite columns. On the other hand, the heat removal from reactor core using CPS cooling system can be used as non-regular mean for reactor cooldown in case of Beyond Design Basis Accidents. In BDBA it can occur that no water sources are available at the moment for heat removal from FC [2]. But the removal of heat from reactor core by CPS cooling circuit is possible, since 211 CPS channels are distributed evenly in the reactor core (see Figure 1). These channels are filled with water supplied by the low pressure system totally independent from the Reactor Cooling

System (RCS). Thus, the large break in reactor cooling system does not disturb usage of the CPS cooling circuit. The proportion between channels with fuel assemblies and channels with control rods is 1661/211 = 7.87. Thus, we can assume that one CPS channel is environed by 8 FCs. The heat from fuel channels, where heat is generated, through graphite bricks is transferred in radial direction to cooled CPS channels (see Figure 2).

Thus, this article presents the analysis of heat removal by employing CPS channels cooling circuit. The analysis was performed for Ignalina NPP with RBMK-1500 reactor.

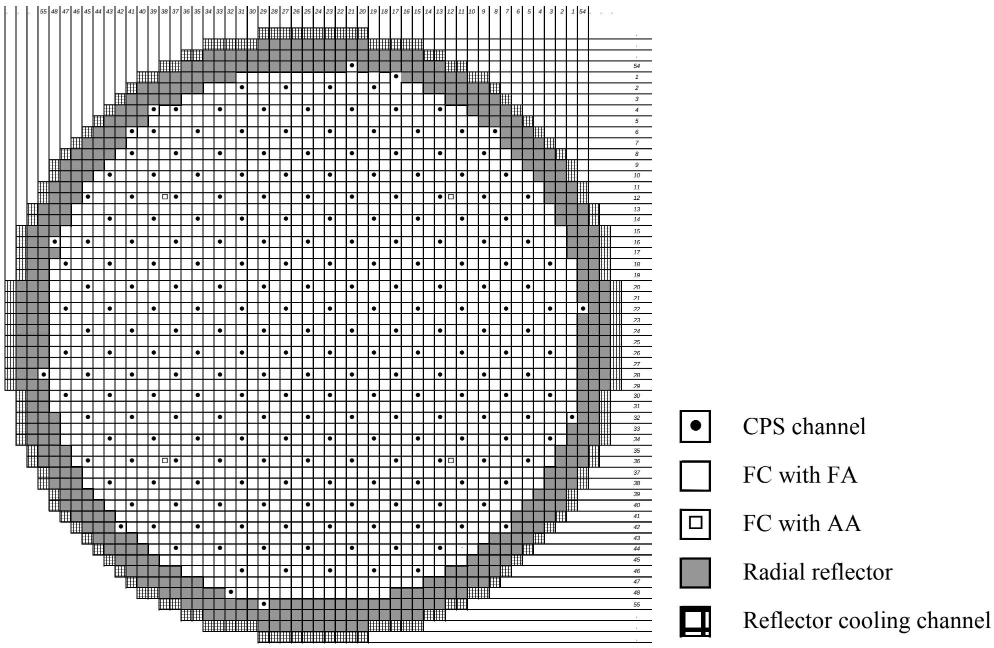

Figure 1. Distribution of fuel channels, CPS channels and graphite reflector cooling channels in the reactor core

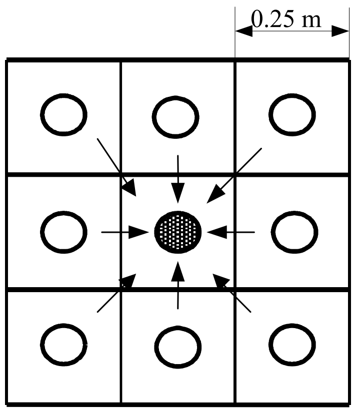

Figure 2. Heat transfer from FCs to cooled CPS channel

2. ASSESSMENT OF HEAT TRANSFER TRANSFERRED IN RADIAL DIRECTION BETWEEN ADJACENT GRAPHITE COLUMNS

2.1 Simulation of heat transfer transferred in radial direction by employing the inter-structure heat conduction model

For the simulation of heat transfer between fuel channels and CPS channels the RELAP5-3D code [3] was used. RELAP5-3D code has the inter-structure heat conduction model. This heat conduction enclosure model gives RELAP5-3D a general multidimensional heat conduction capability. As it was demonstrated by S. Paik [4], this model is applied to calculation of heat transfer through the gas gap between the RBMK reactor core graphite blocks.

The nodalization scheme of the developed model is presented in Figure 3. The one single CPS channel (2) with surrounding graphite column is modelled by "pipe" element with heat structure. The cold water in this channel is supplied from top distribution header (1) of CPS cooling circuit. The hot water from the CPS channel is removed in to bottom distribution header (3) of CPS cooling circuit. The pressure in the CPS cooling circuit is close to atmospheric.

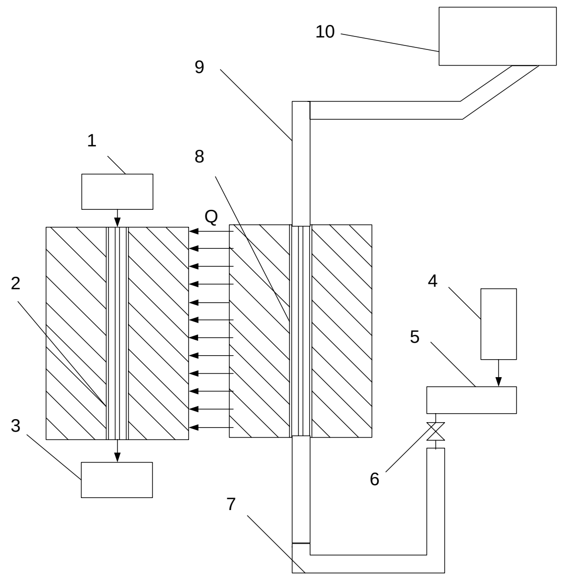

Figure 3. Simplified model of Ignalina NPP for thermal-hydraulic analysis of processes in RCS (for RELAP5-3D code): 1 – top distribution header of CPS, 2 – CPS channel, 3 – bottom distribution header of CPS, 4 – water supply from MCP pressure header, 5 – GDH, 6 – individual control valve, 7 – bottom water pipeline, 8 – eight equivalent fuel channels, 9 – steam – water pipeline, 10 – model of DS and steam lines

Eight FCs (8), placed in the graphite columns, surrounding this single CPS channel. These channels are fed by water from volume (4), which models water supply from MCP pressure header. Water from GDH, which is modelled by "branch" element (5), is supplied into bottom water pipeline (7) and later into fuel channels (8). The water flow through FC is regulated using individual control valve (6). The steam – water mixture is directed to the DS and steam line model (10), through steam – water pipeline (9). The volumes (1, 3, 4 and 10) are modelled by "time depended" elements with specified boundary conditions.

2.2 Gas gap conductance between adjacent graphite blocks

The graphite columns in RBMK-type reactors are separated by a small (~ 1 mm) gap. The gas gaps between graphite columns are filled with a gas mixture (40% of He and 60% of N2 by volume fraction) [1]. For establishing of the gas gap conductance between adjacent graphite blocks the additional calculation was performed. The problem consists of two graphite blocks separated by a gap (see Figure 4).

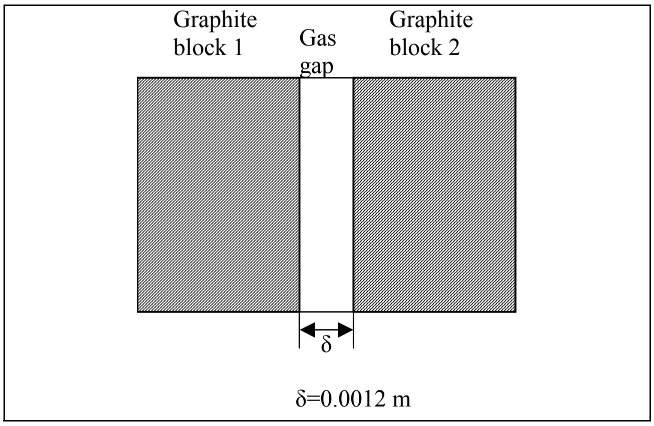

Figure 4. Schematic of two adjacent graphite blocks.

Heat transfer coefficient of the gas gap (gap conductance) can be expressed [6]:

$$\alpha = \frac{\lambda_e}{\delta}, \qquad (1)$$

where:

$$\lambda_e = \lambda_{gas} \cdot \varepsilon_k, \qquad (2)$$

In Eq. (2) λgas is the thermal conductivity coefficient of gas, ε_k is the convection coefficient.
Convection coefficient is equal to:

$$\varepsilon_k = c \cdot (Gr_\delta \cdot Pr_\delta)^n, \qquad (3)$$

where coefficient c and exponent n depend from Grashof number (Gr_δ) and Prandtl number (Pr_δ) for the gap product. If $Gr_\delta \cdot Pr_\delta$ < 1·103, then c=1.0, n=0.0. If 1·103 ≤ $Gr_\delta \cdot Pr_\delta$ < 1·106, then c=0.105, n=0.3. If 1·106 ≤ $Gr_\delta \cdot Pr_\delta$ ≤ 1·1010, then c=0.4, n=0.2.
Since for He and N_2 gas $Gr_\delta \cdot Pr_\delta$ < 1·103, then $\varepsilon_k = 1$ and $\lambda_e = \lambda_{gas}$.
According to RBMK designers [6], thermal conductivity coefficient can be expressed as follows:

$$\lambda_{gas} = (a + b \cdot T_{av}) \cdot 10^{-3}, \qquad (4)$$

where coefficients a and b depend on the He concentration (for the gas mixture 40 % of He and 60 % of N_2 a=58 and b=0.09), T_{av} – average gas temperature in the gap (it is assumed that the gas temperature is equal to the average temperature of the graphite surface 750 K). Using Eq. (4) we obtain that λ_{gas}=0.1255 W/m K. Then heat transfer coefficient of the gas gap (according to Eq. (1)) α=104.6 W/m^2•K.

2.3 Validation of the gas gap conductance model

The values of the determined heat transfer coefficient of the gas gap between adjacent graphite blocks was used in the "Heat Conductance" model [3] of the RELAP5-3D input, set for the simulation of the problem. Using the RELAP5-3D code, the steady-state condition of RBMK-1500 reactor, including the reactor cooling system operating conditions during the reactor operation on 4000 MW thermal power, were simulated. As could be seen from Figure 4, the calculated values of the graphite blocks outer surface temperature for the maximum and minimum power fuel channels are in reasonable agreement with the measured plant data [8].

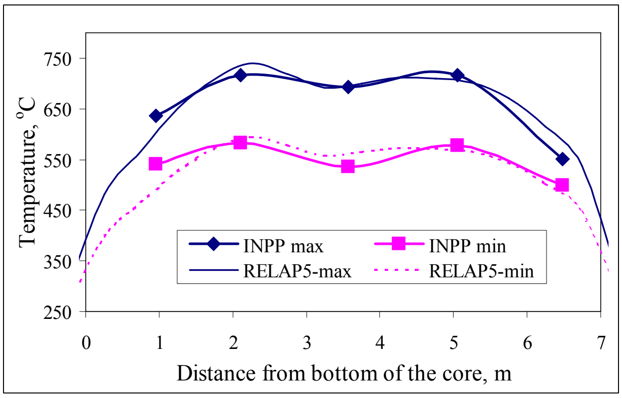

Figure 5. The calculated values of the graphite blocks outer surface temperature for the maximum and minimum power fuel channels (reactor power 4000 MW)

Such achieved correspondence of the measured data and the calculation results obtained using the RELAP5-3D code allows to conclude, that the selected methodology for the modelling of the heat transfer in RBMK reactor core is suitable.

3. EVALUATION OF AMOUNT OF HEAT, WHICH CAN BE REMOVED BY EMPLOYING COOLING OF CPS CHANNELS

For illustration of possibility to remove heat from reactor core using CPS cooling system the case of large break LOCA (guillotine break of the MCP pressure header) with failure of ECCS, when CPS channels cooling system remains in operation, is presented in this paper. In this BDBA case only two means for reactor cooldown are assumed: injection of ~180 m^3 of water from ECCS hydro-accumulators and availability of CPS channels cooling circuit with capacity of heat removal 28.5 MW. The structure of coolant flows in case of this event is presented in
Figure 6. It is assumed in the modelling, that before the accident the reactor operates at maximum allowed power level 4200 MW. The heat transfer in radial direction through fuel channels and CPS channels is shown in figure by arrows.

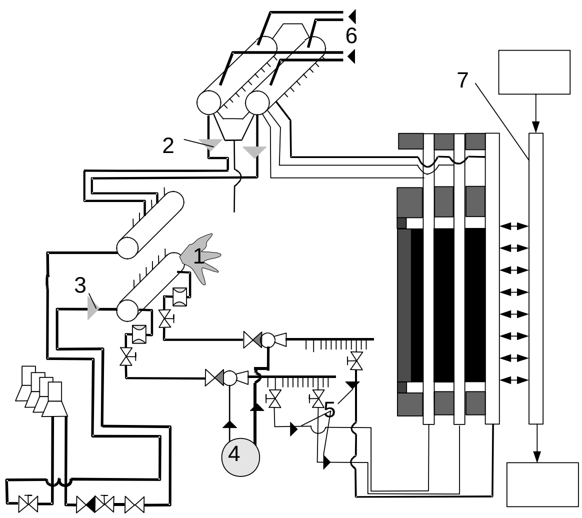

Figure 6. MCP pressure header break with failure of ECCS (except ECCS hydro accumulators):
1 – pressure header break; 2 – discharge of coolant from drum separators in the affected loop;
3 – discharge of coolant from lower part of reactor cooling circuit in the affected loop; 4, 5 – supply of water from ECCS hydro accumulators; 6 – supply of steam from DSs in in the intact loop; 7 – circuit for cooling of rods in reactor control and protection system

3.1 Preliminary analysis of amount removed heat by CPS channels

At first the preliminary analysis of amount removed heat by CPS channels was performed using simplified RELAP5-3D model, presented in Figure 3. It was assumed during the modelling that the water at constant temperature 40 °C is supplied in to top distribution header of CPS cooling circuit (position 1 in Figure 3). The water flows from top to bottom and is removed into bottom distribution header of CPS (position 3 in Figure 3). The behaviour of pressure in the reactor cooling system was assumed from previous calculation. Assumed behavior of pressure in the GDH and DS, coolant flow rate through fuel channels in the affected RCS loop are presented in Figure 7 and Figure 8.

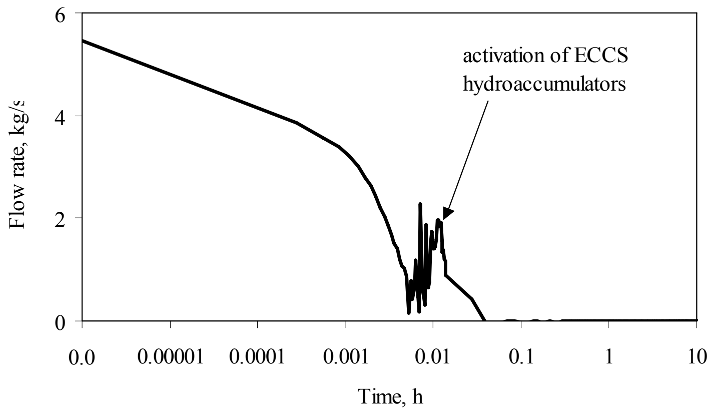

Figure 7. MCP pressure header break with failure of ECCS. Preliminary estimation of coolant flow rate through the single FC

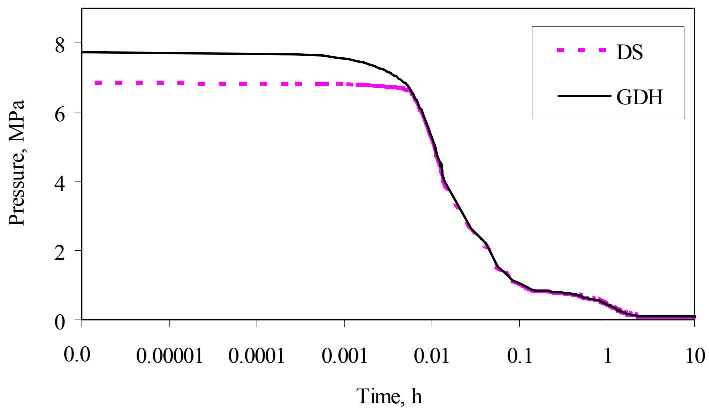

Figure 8. MCP pressure header break with failure of ECCS. Preliminary estimation of pressure behaviour in DS and GDH

The calculated behaviour of peak temperatures of fuel, cladding, FC wall, graphite columns and CPS channel wall in this case within first 16 hours is presented in Figure 9. As it is shown in this Figure, after temperature in graphite columns with FC starts increasing, the temperature of graphite column with CPS starts to increase too but with some delay. This indicates that heat from overheated fuel channels is transferred in radial direction through the graphite bricks and gas gaps between these graphite bricks into cooled CPS channels, as shown schematically in Figure 2. The heat transfer coefficient in the gas gap was assumed α=100 W/m^2•K, according calculations in subsection 2.2. The temperature of graphite with CPS channels is always lower than temperature of graphite with FC.

The amount of heat, which is transferred from fuel channels to CPS channels, was calculated using the presented RELAP5-3D model. The total amount of heat removed by 211 CPS channels is presented in Figure 9. As it is seen from this Figure, during normal operation, approximately 7 – 8 MW of heat is removed from reactor core by CPS channel cooling system. In case of accident, when graphite temperature increases, the amount of removed heat also increases up to 40 MW. The amount of removed heat is proportional to the temperature difference between graphite column with overheated FC and graphite column with cooled CPS channels. As it is seen from Figure 9, during normal operation of reactor, the temperatures of graphite columns with fuel channels and with CPS channels are similar – only insignificant amount of heat is removed from reactor core by system of CPS channels cooling. In case of accident, after dry-out and overheating of fuel channels (the cooling of CPS channels remains available), the temperature difference between CPS and FC graphite columns starts to increase (see Figure 9). This leads to increasing of amount of removed heat from hot FCs (see Figure 9). Based on the simulation performed using RELAP5-3D code, the dependency of capacity of removed heat from temperature of FCs graphite column was established. As it is presented in Figure 10, if graphite temperature is increasing, the capacity of removed heat is increasing as well. At graphite temperature 700°C the maximal constant value of heat removal from fuel channels (28.5 MW) is reached.

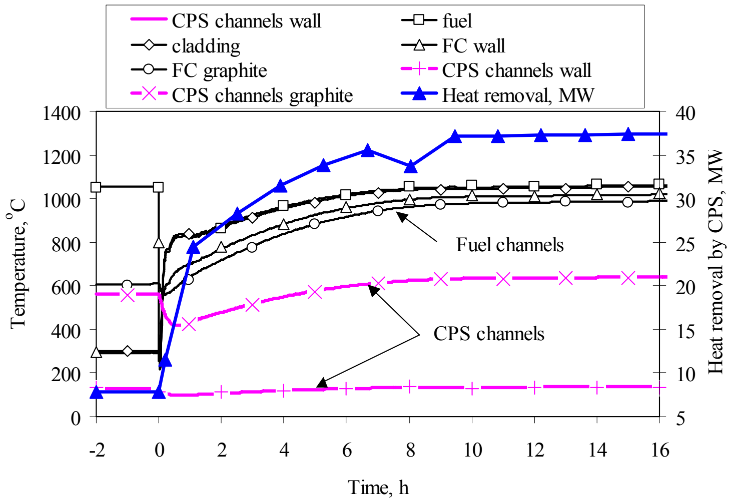

Figure 9. MCP pressure header break with failure of ECCS. The heat transfer from FC channels to CPS cooling channels is taken into account. Behaviour of peak temperatures of fuel, cladding, FC wall, graphite columns and CPS channel wall. Amount of heat transferred from fuel channels to 211 CPS channels

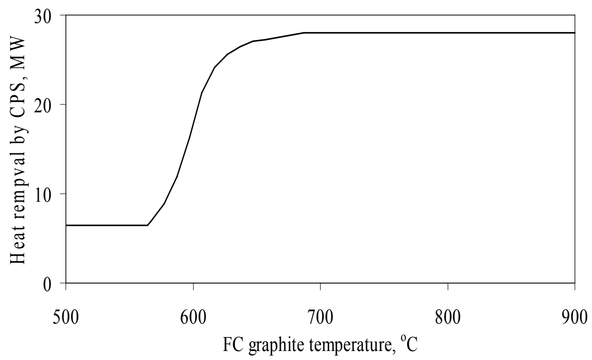

Figure 10. Dependency of removed heat capacity on the temperature of FCs graphite column, when regular CPS cooling circuit is available

3.2 Consequences of large break LOCA accident, evaluating the removal of part generated in core heat by CPS channels cooling circuit

The modelling of processes in reactor fuel channels in case of mentioned BDBA, when part of decay heat is removed by employing cooling of CPS channels, was performed using RELAP5 model. Nodalisation scheme of this model is presented in Figure 11. As it is shown in figure, the model of RCS consists of two loops, each of which corresponds to one loop of the actual circuit. Two steam DS in each RCS loop are modelled by generalized "separator" element (1). All downcomers are represented by a single equivalent pipe (2), further subdivided into a number of control volumes. The pump suction header (3) and the pump pressure header (8) are represented as RELAP5 "branch" [5] elements. Three operating Main Circulation Pumps are represented by one equivalent "pump" element (5) with check and throttling-regulating valves. The throttling-regulating valves are used for coolant flowrate regulation through the core. These valves are modelled by employing "servo valve" elements.

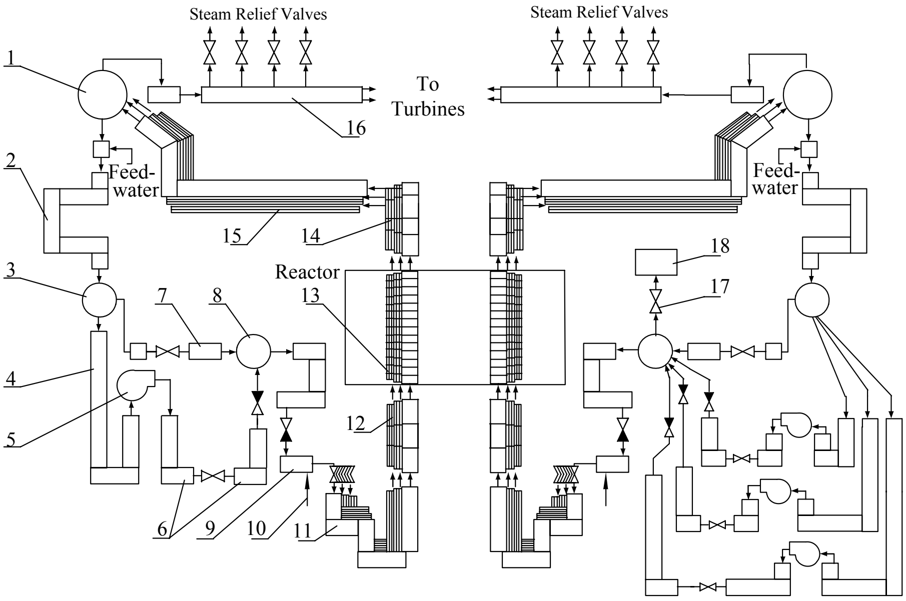

Figure 11. Ignalina NPP model nodalization diagram: 1 - DS, 2 - downcomers, 3 - MCP suction header, 4 - MCP suction piping, 5 - MCPs, 6 - MCP discharge piping, 7 - bypass line, 8 - MCP pressure header, 9 - GDHs, 10 - ECCS water injection, 11 - lower water communication line, 12 - reactor core inlet piping, 13 - reactor core piping, 14 - reactor core outlet piping, 15 - steam-water communication line, 16 - steam line, 17 - valve for break modelling, 18 – model of compartments, which surround the RCS pipelines

The normalized flow area versus normalized stem position is described in the RELAP5 model. The bypass line (7) between the pump suction header and the pump pressure header is modelled with the manual valves closed. This is in agreement with a modification performed at the Ignalina NPP. All fuel channels of the left core pass are represented by a few equivalent channels (13) operating at specific power and coolant flow. The group of 20 Group Distribution Headers (9) with connecting pipelines is modelled by RELAP5 "branch" component. The pipelines of the water communications (11) are connected to each FC. Each of these components represents the quantity of pipes appropriate to the number of elements in the corresponding FC in the core. The vertical parts of the FC (14) above the reactor core are represented by RELAP5 components "pipes". The pipelines of the steam-water communications (15) are connecting the fuel channels with DS. Compared to the model for the left loop, in the right loop, the MCP system is modelled with three equivalent pumps. The steam separated in the separators is directed to turbines via steam lines (16). Two turbine control valves organize steam supply to the turbines. The control of these valves was modelled by "servo valve" elements based on algorithm of steam pressure regulators used at Ignalina NPP. There are different steam relief valves in each loop of the RCS to direct the steam to the condensers of the turbines or to pressure suppression pools of Accident Localisation System. All models of steam relief valves are connected to the “time dependent” elements, which define boundary conditions in turbine condensers or ALS pressure suppression pools. The feedwater and ECCS water injection into the DS is simulated explicitly using RELAP5 “pipe”, “junction”, “volume” and “pump” elements (not presented in this paper). For the modelling of breaks in pipelines of reactor cooling system, the “valve” element (17) is used. This valve is connected to the volume (18), which represents the compartments covered reactor cooling system pipelines. A more detailed description of the model is presented in article [12].

It was assumed during the modelling that before the accident the reactor operated at maximum permissible thermal power level of 4200 MW. Through the broken header, the coolant in the first seconds after the break discharges, both from the fuel channels side and from the DS side. Sub-cooled water is discharged at the beginning; therefore the coolant flow rate through break is maximal and reaches approximately 47000 kg/s in the beginning of accident (see Figure 12). Later the discharge of coolant is decreased. Due to large discharge of the coolant through the break into the reinforced leak-tight compartments, the pressure sharply increases in these compartments and commands on reactor shutdown are generated. Reactor power decrease begins after 1.1 s from the beginning of accident. In the RELAP5 model, the heat generation in the core is modelled as heat source in the heat structures. Two heat structures are modelled: (1) fuel rod with 95 % heat generation in the fuel pellets; (2) FC and graphite column. The CPS channels are not modelled in the present RELAP5 model. In order to model the heat removal from FCs in radial direction by CPS channels, the amount of heat generated in the graphite was decreased. The capacity of removed heat was calculated, depending on temperature of graphite column (see dependency on Figure 10). Because some part of heat was subtracted from heat generated in the graphite, at some times heat generation in graphite becomes negative. This means that more heat is removed from graphite columns with FCs by CPS cooling system in comparison with heat generated due to decay heat (Figure 13).

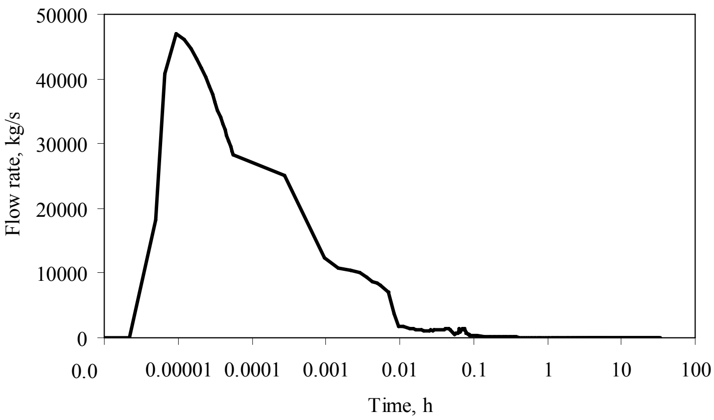

Figure 12. Coolant flow rate through the break

As it is seen from the coolant flow rate behaviour through fuel channels, the MCPs continue to operate in the intact loop of the RCS within first 50 seconds. In the affected loop the coolant flow rate is affected by water injection from hydro-accumulators. Approximately 20 – 40 minutes after beginning of the accident dry-out and overheating of core components starts (Figure 14) due to loss of coolant in both loops of RCS. The graphite stack, which is a moderator in RBMK-1500 reactor, is an efficient heat sink and slows down the heat-up of the core. As it is presented in Figure 14, due to the removal of heat from CPS channels, the peak fuel temperatures are below 1000°C. Failure of fuel claddings is possible in some fuel channels. The failures are possible due to ballooning of claddings at high cladding temperature and high pressure difference across the cladding (high pressure of gases inside fuel rods and low pressure outside – in RCS). The fuel channels remains intact, because pressure inside channels (in RCS) is close to the atmospheric. The failure of channel walls due to ballooning may appear only if pressure inside FC is higher than 4 MPa. Assuming heat removal, using CPS channels cooling circuit, approximately 16 hours after the beginning of the accident, a slow decrease of core components temperature begins. This is because decay heat, generated in the core, at this time moment decreases down to the level of heat, which is removed from CPS channels (Figure 13). The cool down process is very slow, because after the decrease of graphite temperature, the temperature gradient from fuel channels to control rods channels is decreasing as well. Thus, the amount of removed heat is decreasing (see the dependency on Figure 10).

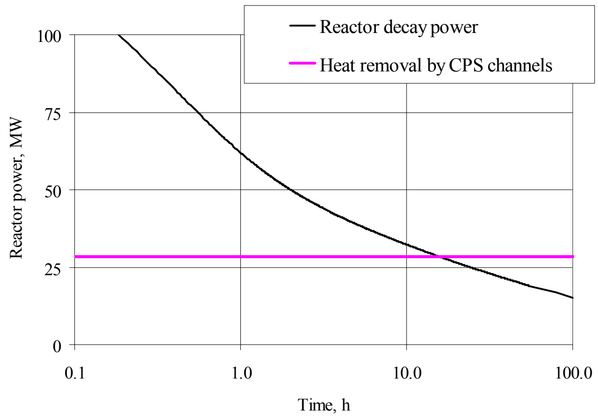

Figure 13. Comparison of reactor decay heat with capacity of heat removal from core by CPS cooling circuit (when regular CPS cooling system is available)

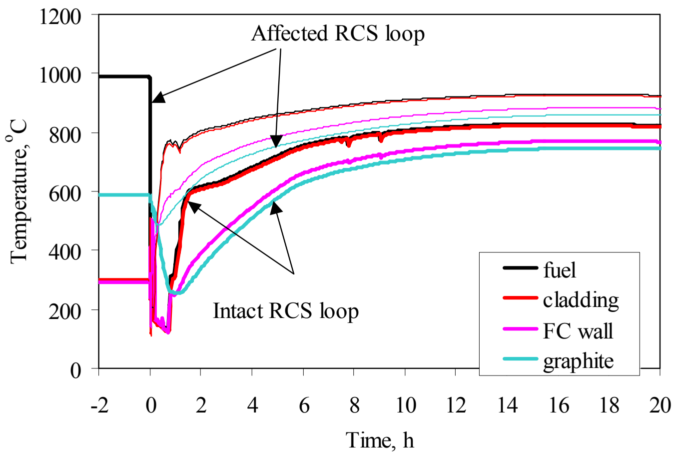

Figure 14. Behaviour of fuel, cladding, FC wall and graphite column temperatures for fuel channels with the average 2.53 MW power level

To evaluate the influence of the heat removal effect from the reactor core using a CPS cooling system, the case where the heat transfer to CPS channels is not taken into account is presented in Figure 15. In this case the temperatures of core components are increasing continuously, because all decay heat, generated in the reactor core, is used for heating of core components. In this case after ~10 hours, the 1450°C temperature is reached and the melting of stainless steel grids in fuel assemblies starts. Later, ~40 hours after the beginning of the accident the temperatures increase up to 2400-2600 °C and ceramic formation in fuel assemblies starts [13].

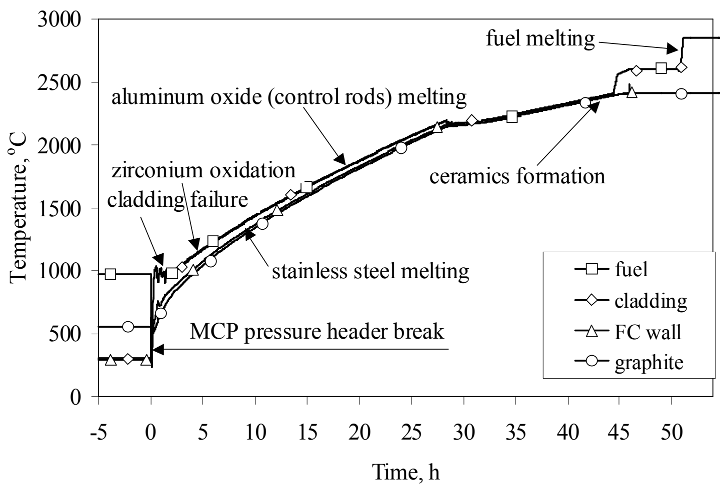

Figure 15. Behaviour of core components temperatures [13]

4. ACKNOWLEDGMENTS

This analysis was performed in the frames of the PHARE project No. 2003/5812.04.02 "Support for VATESI and its TSOs in assessment of beyond design basis accidents for RBMK-1500 reactors" and project "Development of Manual on Management of Beyond Design Basis Accidents at Ignalina NPP" coordinated by the consortium Jacobsen Engineering Ltd from UK and Scientec from USA and sponsored by the UK Department of Trading and Industry. The authors of the article would like to express their gratitude to the sponsors, coordinators and Ignalina NPP for support of the performed analysis.

5. CONCLUSIONS

The analysis of possibility to remove heat from RBMK-1500 reactor core in case of large LOCA by employing cooling of CPS channels was performed using RELAP5-3D and RELAP5 codes. The part of heat, which can be removed by CPS in long-term accident becomes significant, when level of decay heat is decreased. In spite of high thermal inertia of graphite, this heat removal from CPS channels allows to slowdown effectively the core heat-up process.

If regular CPS cooling circuit with the pumps and heat exchangers are available, this circuit can remove up to 28.5 MW from reactor core. Decay heat, generated in the core, decreases down to this level of heat, which is removed from CPS channels, 16 hours after the beginning of the accident. Starting from this time moment the slow decrease of core components temperature begins. RELAP5 analysis shows that due to removal of heat from CPS channels, the peak fuel temperatures are below 1000 °C. Thus in this case use of this system allows to prevent zirconium oxidation and melting of stainless steel grids and fuel.

Nomenclature

a, b, c	Coefficients
α	Heat transfer coefficient of the gas gap, W/m^2 K
δ	Gap dimension, m
ε_k	Convection coefficient
n	Exponent
λ_{gas}	Gas thermal conductivity coefficient, W/m K
λ_e	Equivalent thermal conductivity coefficient, W/m K
T_{av}	Average gas temperature, K

Gr_δ	Grashof number
Pr_δ	Prandtl number
AA	Additional Absorber
CPS	Control and Protection System
BDBA	Beyond Design Basis Accidents
DS	Drum Separator
ECCS	Emergency Core Cooling System
FA	Fuel Assembly
FC	Fuel Channel
GDH	Group Distribution Header
LOCA	Loss of Coolant Accident
MCP	Main Circulation Pump
RCS	Reactor Cooling System
RBMK	Russian Acronym for "Water-Graphite Boiling Reactor"

References

1. Almenas K., Kaliatka A., Ušpuras E. Ignalina RBMK-1500. A Source Book. Extended and Updated Version, Lithuanian Energy Institute, Kaunas, Lithuania, 1998.
2. Kaliatka A., Ušpuras E. Accident and transient processes at NPPs with channel-type reactors: monography // Kaunas: Lithuanian Energy Institute, 2006. Thermophysics: 28. 298 p. ISBN 9986-492-87-4.
3. RELAP5-3D Code Manual, Appendix A, RELAP5-3D Input Data Requirements, INEEL-EXT-98-00834-V2, 1998.
4. Paik S. RELAP5-3D multidimensional heat conduction enclosure model for RBMK reactor application. Nuclear Technology. 1999. Vol. 128, pp. 87-102.
5. Fletcher C. D. et. al., 1992. RELAP5/MOD3 code manual user's guidelines, Idaho National Engineering Lab., NUREG/CR-5535.
6. Ušpuras E., Kaliatka A. Evaluation of Weak Heat Conduction Mechanism for Long-term LOCAs in RBMK-1500 // Nuclear Technology. 2007, Vol. 158, p. 18-25.
7. Expertise of the regular algorithm for the calculation of the graphite temperature and the analysis of the possibility for its modification. Russian Research Center "Kurchatov Institute" report No. 33-08/29, 1998.
8. Ignalina NPP ICS database (Ignalina NPP second reactor unit condition on 16.04.1998).
9. Ušpuras E., Urbonavičius E., Kaliatka A. Specific features of the RBMK-1500 reactor and BDBA management // Energetika. ISSN 0235-7208. 2005, Nr. 3, P. 1–9.
10. Ušpuras E., Kaliatka A., Augutis J., Rimkevičius S., Urbonavičius E., Kopustinskas V. Safety analysis of beyond design basis accidents in RBMK-1500 reactors // Annals of Nuclear Energy. ISSN 0306-4549. 2007, Vol. 34, p. 356-373.
11. Novoselsky O. YU., Filinov V. N. Computational Assessment of RBMK Pressure Tube Rupture at Accident Heating, Proc. International Exchange Forum on Analytical Methods and Computational Tools for NPP Safety Assessment, Obninsk, Russia (1996).
12. Kaliatka A., Ušpuras E. Thermal-hydraulic analysis of accidents leading to local coolant flow decrease in the main circulation circuit of RBMK-1500. Nuclear Engineering and Design. 2002. Vol. 217, No. 1-2, pp. 91-101.
13. Ušpuras E., Kaliatka A., Urbonas R. Evaluation of non-regular means for heat removal from RBMK reactor core in case of BDBA // Proc. of 12th Int. Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-12), Pittsburgh, Pennsylvania, U.S.A. September 30-October 4, 2007, CD p. 1-14.