RBMK-1500 ACCIDENT MANAGEMENT FOR LOSS OF LONG-TERM CORE COOLING

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Results of the Level 1 probabilistic safety assessment of the Ignalina NPP has shown that in topography of the risk, transients dominate above the accidents with LOCAs and failure of the core long-term cooling are the main factors to frequency of the core damage. Previous analyses have shown, that after initial event, as a rule, the reactivity control, as well as short-term and intermediate cooling are provided. However, the acceptance criteria of the long-term cooling are not always carried out. It means that from this point of view the most dangerous accident scenarios are the scenarios related to loss of the core long-term cooling. On the other hand, the transition to the core condition due to loss of the long-term cooling specifies potential opportunities for the management of the accident consequences. Hence, accident management for the mitigation of the accident consequences should be considered and developed.

The most likely initiating event, which probably leads to the loss of long term cooling accident, is station blackout. The station blackout is the loss of normal electrical power supply for local needs with an additional failure on start-up of all diesel generators. In the case of loss of electrical power supply MCPs, the circulating pumps of the service water system and MFWPs are switched-off. At the same time, TCV of both turbines are closed. Failure of diesel generators leads to the non-operability of the ECCS long-term cooling subsystem. It means the impossibility to feed MCC by water. The analysis of the station blackout for Ignalina NPP was performed using RELAP5 code. The analysis results showed that in case of station blackout the depressurisation of the reactor coolant system should be initiated if any other action of core cooling restoration does not success. The depressurisation creates the conditions for water supply from ECCS hidroaccumulators and deaerators. Later the non-regular means (fire machine) for supply of firewater to the MCC should be employed.

Introduction

The station blackout analysis showed that approximately half an hour after beginning of the accident, drum separators become empty. One hour later, the dry-out in the core starts. It causes the heating-up of fuel elements and FC tubes. Acceptance criterion for FC tube walls will be reached approximately three hours after beginning of the accident. Since the pressure in the MCC is close to the nominal value, the possibility several fuel channels rupture is not excluded. However, these results also showed that there is a considerable time interval for the operator's actions directed forwards the restoration of the core cooling.

Three ways of potential accident management for loss of the long-term core cooling are discussed:

- de-pressurisation of the reactor coolant system and water supply using non-regular means for core re-flooding,
- decay heat removal from the core by ventilation of DS compartments,
- decay heat removal from the core by direct water supply into the reactor cavity.

The analysis of the Ignalina NPP RBMK-1500 reactors was performed using RELAP5 code. The results showed that the last two ways are inexpedient. The ventilation of drum separator compartments and direct water supply into the reactor cavity are not sufficient to remove the decay heat from the core. However, the de-pressurisation of MCC enables to mitigate the consequences of the loss of long-term core cooling. Therefore, such way of mitigation of accident consequences is recommended to be included in the RBMK-1500 accident management programme.

IGNALINA NPP RELAP5 MODEL

The RELAP5/MOD3.2 model of the Ignalina NPP was used for analyses of plant thermal-hydraulic response to various transients. The RELAP5 computer code has been developed by Idaho National Engineering Laboratory [1]. This is one-dimensional non-equilibrium two-phase thermal-hydraulic system code. The RELAP5 code has been successfully applied to PWR and BWR reactors. Because of the unique RBMK thermal-hydraulic system design, the assessment study is required to adapt the RELAP5 code to RBMK reactors. A brief description of the MCC and plant safety systems, as well as general description of the Ignalina NPP RELAP5 model, are given in [2]. Key features of the RELAP5 model of the Ignalina plant are as follows:

- The MCC is represented by three equivalent fuel channels (maximal, average and minimal power). The equivalent fuel channels model the heat generation in a group of real channels, as well as hydraulic properties of this group. The equivalent fuel channels are modelled by multiple axial and radial control volumes.

- Heat transfer among the equivalent fuel channels is approximated by means of heat exchange through the graphite moderator gaps to the reactor cavity gas circuit.

- Steam paths that remove the vapour from drum separators are represented explicitly, including steam lines, steam discharge valves, etc.

- Circuit of the CPS rods cooling and radial reflector cooling is modelled explicitly.

- Reactor cavity formed on a metal structure of the reactor shell together with bottom and top metal plates is modelled.

The nodalization scheme of Ignalina NPP RELAP5 model is presented in Figure 1. MCC is modelled by one loop. Such model simplification is possible due to the fact that both real loops in the MCC in the case of station blackout are at the same conditions in reality. This loop model consists of three equivalent core pass with FC (12) of three power levels (11 channels of maximum power, 1637 channels of average power and 13 channels of minimum power). For the core power of 4200 MW_{th}, the channel average power is assumed to be 2.53 MW_{th}, the maximum channel power is 3.75 MW_{th} and minimum channel power is 0.88 MW_{th} [5]. Fuel channels are connected on one end to the GDH (9) by the lower water communication lines (10) via its flow control valve. The other end of the equivalent channels is connected to the DS by the steam-water communication line (14). Four real DSs are modelled as one volume (1). All downcomers are represented by a single equivalent pipe (2), further subdivided into a number of control volumes. MCP suction (3) and pressure (8) headers are represented as branch objects. Six operating MCPs are represented by one equivalent element (5) with check and throttling-regulating valves. Stand-by MCPs are not modelled. Bypass line (7) between the MCP suction and pressure headers is modelled with manual valves closed. This is in agreement with a modification recently implemented at the Ignalina NPP. Steam from the separators is directed to turbines via steam lines (15). Two "servo valve" [1] model the supplying of the steam to the turbines. The control of these valves was modelled on the algorithm of steam pressure regulators used at Ignalina NPP, when one turbine operates at the power maintenance regime, and other – at pressure maintenance in DS regime. In the case of station blackout TCV of both turbines are closed within 0.4 seconds. The closure of TCV leads to the imbalance between steam removal and steam generation in the core. The pressure in the DS starts to increase. There are eight SDV-C, which serves on bypasses to the condensers of turbines. However in the case of station blackout, operation of SDV-C is prohibited by Ignalina technological scheme because of condensers are not in operation. Steam pressure is controlled and peaks of pressure are eliminated by two SDV-A and twelve MSV by steam dump to pressure suppression pool of the ACS. The model also considers steam mass flow rate through the SDV-D to the deaerators. The ACS compartments were represented by time dependent volume with constant pressure of 100 kPa in the RELAP5 model. The SDV-A and MSV were modelled by motor valve elements with corresponding algorithm of their's opening and closure.

ECCS in the Ignalina NPP is divided into two subsystems: a system which provides emergency coolant water immediately after the initiation of the break (the short-term system) and a long-term system served by auxiliary feed water pumps and ECCS pumps. The short-term system consists of MFWP and 16 ECCS accumulators. In the case of station blackout all pumps are unavailable due to loss of normal electrical power supply for local needs. However, the water of about 170 m^3 from accumulators can be used for MCC feeding. The nodalization scheme of an ECCS train from accumulators is shown in Figure 2. The accumulator means a pressurised tank with volume of 25 m^3, which is just over half-full with water with temperature of 30 ^{0}C. The remaining part of the volume is filled with nitrogen gas at 9.8 MPa pressure. 16 accumulators are modelled by one element (1), which is described by special RELAP5 accumulator model. Water supply starts after opening of fast-acting valves (4). In the analysed cases, the manual opening of this valve was considered. The water from the accumulators is supplied to the GDH (7) of both loops of MCC through pipelines, check valves (5) and flow limiter (6). In order to prevent pressurised gas entering to the reactor, fast-acting shut-off valve (2) automatically closes when the water level falls down to a certain set point. The fast-acting valves were represented by motor valve elements in the RELAP5 model.

There are four deaerators, which contain 480 m^3 of water in the one unit of RBMK-1500. Initial pressure in the deaerators is 1.2 MPa, water temperature - 190 ^{0}C. The relative pipe (9), which connects the deaerators and GDH (this pipe does not exist in the reality) were assumed in this analysis.

All 235 CPS rods cooling channels are modelled by one equivalent channel (16). The elements (18) simulate 156 radial reflector cooling channels having a design “Field's pipe”. Water in to these channels is supplied from top distribution header and removed into bottom distribution header. Reactor cavity is formed by a metal structure of the reactor shell (19) together with bottom (20) and top (17) metal plates. The fuel channels and CPS channels are allocated inside the holes of graphite columns. There are 2488 graphite columns, which construct the reactor graphite stack. The graphite stack was modelled as thermal structure in the presented RELAP5 model.

Three ways of potential accident management for loss of the long-term core cooling are indicated in the model:

- water supply from ECCS accumulators, deaerators or using non-regular means to the GDH for core re-flooding (21),
- water supply from non-regular means in to spray system (22) for air humidification in the DS compartments (for decay heat removal from the reactor core by ventilation of DS compartments),
- water supply from non-regular means direct in to the reactor cavity (23).

In order to provide confidence in the ability of the models correctly represent the plant response to the upset conditions, the models have been benchmarked for several operational events, such as trip of all MCPs and spurious opening of three MSVs, inadvertent actuation of ECCS, etc. Calculation results obtained using Ignalina NPP RELAP5 model agree well with the plant data when similar boundary conditions are imposed [2], [3], [4].

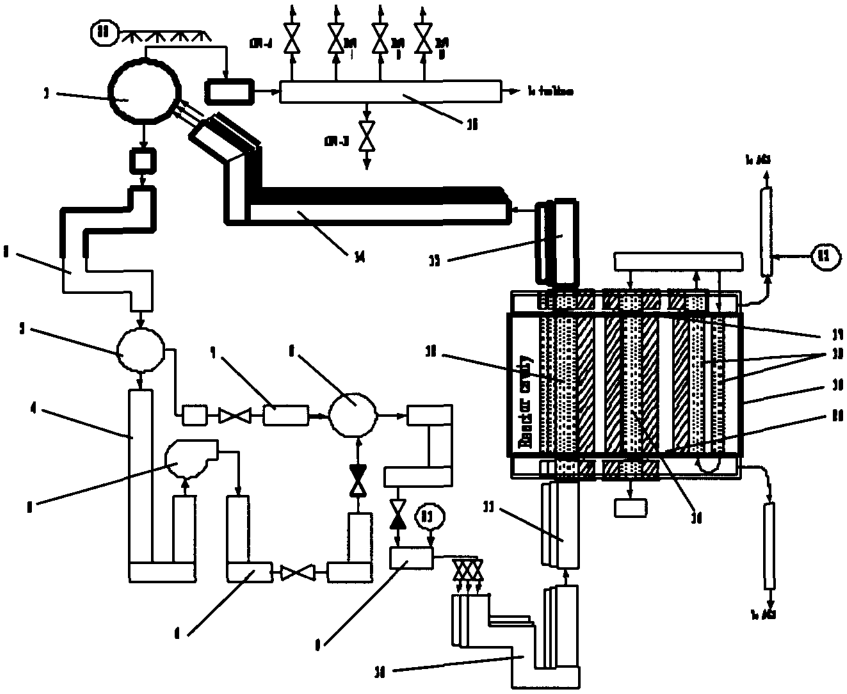

Figure 1. RELAP5 Ignalina NPP model nodalization scheme: 1 - DS, 2 - downcomers, 3 - MCP suction header, 4 - MCP suction piping, 5 - MCPs, 6 - MCP discharge piping, 7 - bypass line, 8 - MCP pressure header, 9 - GDHs, 10 - lower water communication line, 11 - reactor core inlet piping, 12 - FC, 13 - reactor core outlet piping, 14 - steam-water communication line, 15 - steam line, 16 - CPS rods cooling channel, 17 - top metal plate, 18 - radial reflector cooling channel, 19 – reactor shell, 20 - bottom metal plate, 21 - water supply in to GDH, 22 - water supply in to spry system for air humidification in the DS compartments, 23 - water supply direct in to the reactor cavity

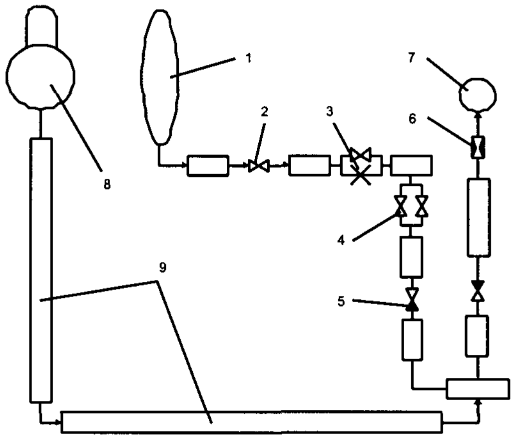

Figure 2. Nodalization scheme of deaerators and ECCS accumulators connection with GDH: 1 – accumulators, 2 - fast-acting shut-off valves, 3 – intermediate throttling, 4 - fast-acting valves, 5 – check valve, 6 – ECCS flow limiter, 7 – GDH, 8 – deaerators, 9 – assumed (relative) pipe for direct water supply from deaerators to GDH

Analysis of plant blackout with water supply from ECCS accumulators and deaerators to the GDH

Analysis of decay heat removal from core due to station blackout without operator intervention shows that approximately 2000 s (~ 0.5 hours) after beginning of the accident, DS are completely empty. Heating-up of fuel element cladding and fuel channel tube walls starts approximately 6000 s (~1.6 hours) after beginning of the accident. Acceptance criterion for fuel element claddings (700 ^{0}C) in the channels with maximum power is reached approximately 7200 s (2 hours) after beginning of the accident. Approximately 12000 s (more as 3 hours) after beginning of the accident safety criterion for FC tube walls (650 ^{0}C) is reached. Since the pressure in the MCC is close to the nominal value, the possibility of several fuel channels rupture is not excluded.

Water supply from the ECCS accumulators enables considerably to postpone beginning of the water evaporation from the core. As the additional water reservoir the deaerators could be seen. In case of valves closure on steam supply piping from steam lines to the deaerators and guaranteeing connection from deaerators to the GDH, deaerators can serve as water reservoir. Water supply from the deaerators starts when pressure decreases in the GDH below the pressure in deaerators.

In the first hour after beginning of the accident MCC thermal hydraulic parameters changes similarly as in case of without operator intervention. In the modelling it was assumed that within one hour after beginning of the accident operator opens fast acting valves on the water supply piping from accumulators to the GDH (Figure 3).

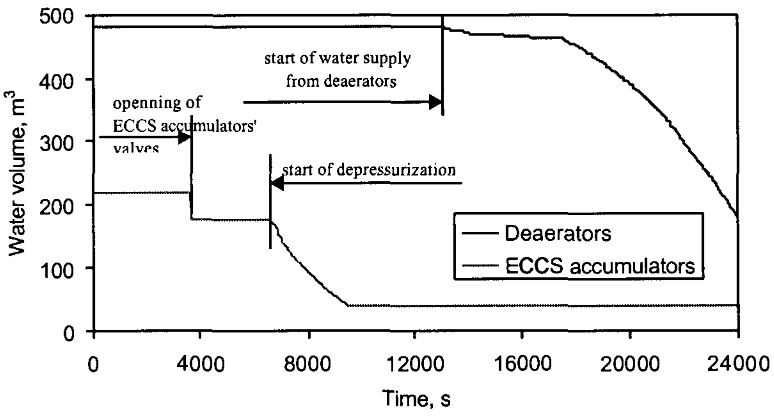

Figure 3. Water volume in the accumulators and in the deaerators

However, soon pressure in the accumulators and GDH becomes equal and cold water supply is stopped. Approximately 6100 s after beginning of the accident fuel cladding temperature in average loaded channels starts to increase. In the modelling it was assumed that temperature increase is a signal for operator to initiate depressurisation. MCC depressurisation is executed via opening one SDV-A (Figure 4). After beginning of MCC depressurisation, water supply to the GDH from accumulators is restored. Closure of fast acting valves at the accumulators' outlet prevents them from compete emptying and gas passage to the core (Figure 3).

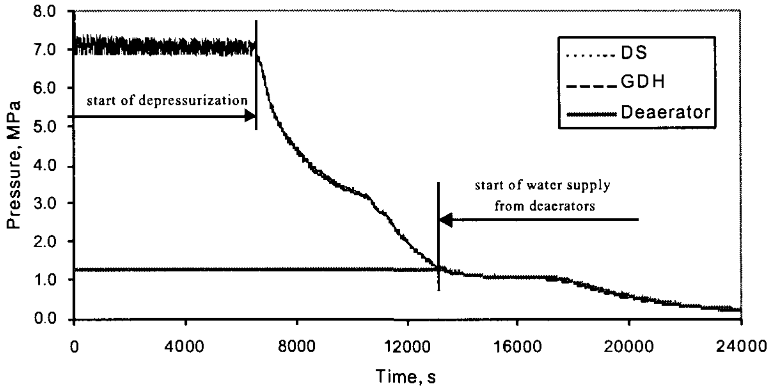

Figure 4. Pressure in the MCC and in the deaerators

Water supply from deaerators becomes possible only after pressure decrease in the GDH approximately down to 1.2 MPa (i.e. down to pressure in the deaerators). Water from deaerators reaches the core, heats-up there, boils-up and, thus, maintains the MCC pressure. Such pressure maintaining process lasts approximately one hour (Figure 4). Further due-to decrease of water amount in the deaerators, water supply to the GDH reduces and pressure in the MCC starts to decrease. The use of non-regular means with low-pressure water source is possible from this moment because the pressure in the MCC is low.

As it is shown in Figures 5 and 6, repeated increase of fuel cladding and fuel channel wall temperatures starts more than three hours after beginning of the accident. Water supply from the deaerators suppresses process of temperatures' increase. However, approximately five hours after beginning of the accident temperatures starts to increase once again. It means that it is necessary to resume water supply to the GDH via non-regular means. Acceptance criterion for fuel cladding (700 ^{0}C) in the average loaded channels is reached within approximately 310 minutes (more than within five hours) after beginning of the accident. In this case of modelling, heat transfer by radiation from fuel cladding to the fuel channel wall was not taken into account. Acceptance criterion for fuel channel walls (650 ^{0}C) in the average loaded channels was not reached during the analysed time period.

The CPS rods cooling and radial reflector cooling circuit remove the part of heat distributed in graphite. However, after plant blackout the pump of the CPS cooling circuit are switched-off. From this moment the water in the channels flows from the top storage tank. This tank becomes empty more than after 10 minutes and delivery of water stops. It leads to dry out of the CPS rods cooling and radial reflector cooling channels. From this moment, heat generated in these channels through graphite bricks and reactor gas circuit is transferred to FC.

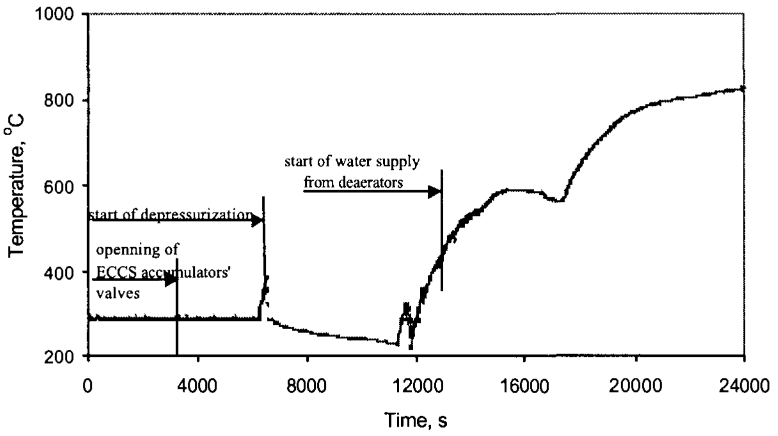

Figure 5. Peak cladding temperature in the average loaded channel

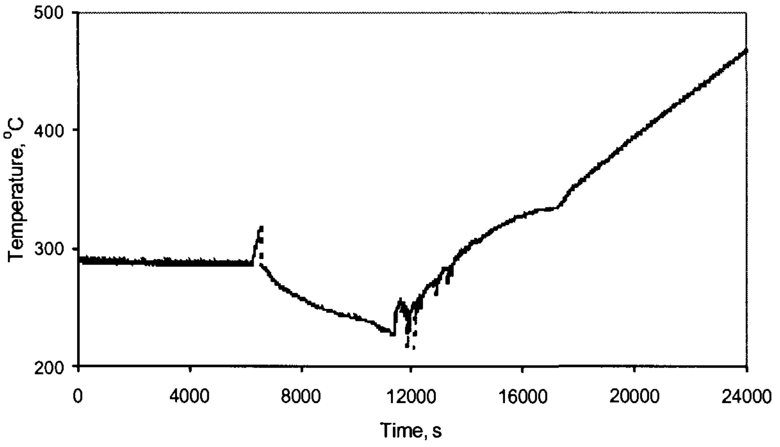

Figure 6. Peak FC tube wall temperature in the average loaded channel

Analysis results of plant blackout with water supply ECCS accumulator and deaerators showed that water supply to the GDH via non-regular means (fire machine) is necessary to start approximately 5 - 6 hours after beginning of the accident. Prior to that core could be cooled by water resources from accumulators and deaerators. If no operator action will be taken, this station blackout accident can transform into severe accident during this time span.

Analysis of plant blackout with DS compartment ventilation

Another possible way of accident consequences mitigation in case of station blackout is ventilation of DS compartments. There are two DS compartments (one for each reactor side) at Ignalina NPP. Equipment and piping in the DS compartments have considerable area of cooling: DS, steam header, part of the steam lines, part of the downcomers, steam-water piping and part of the channels, which are above the core. In Figure 1 above discussed equipment and pipes are marked by thick lines. DS compartments are connected by SWP piping corridor (Figure 7). Both compartments at the top have five rupture panels, which open at the excessive pressure in the compartments of 2 kPa. These panels are of 20 m^2 in each DS compartment and open to the accident steam release shaft. In the ceilings of the each steam relief shaft there are one or two pipes for air release in case of accident. There are nine such 1800 mm diameter pipes for each DS compartment. Each pipe is covered with a lid, which opens at the excessive pressure of 1.5 kPa [5]. Each DS compartment has four doorways of 1.2 m^2. Two doorways in each compartment are located at the bottom and other two - approximately eight meter higher (Figure 7). DS compartments are connected via SWP compartments, where there is a connection to the reactor hall through the gaps between the biological defence blocks - biological shielding. According to the design, effective area of gaps is 5 m^2 [5].

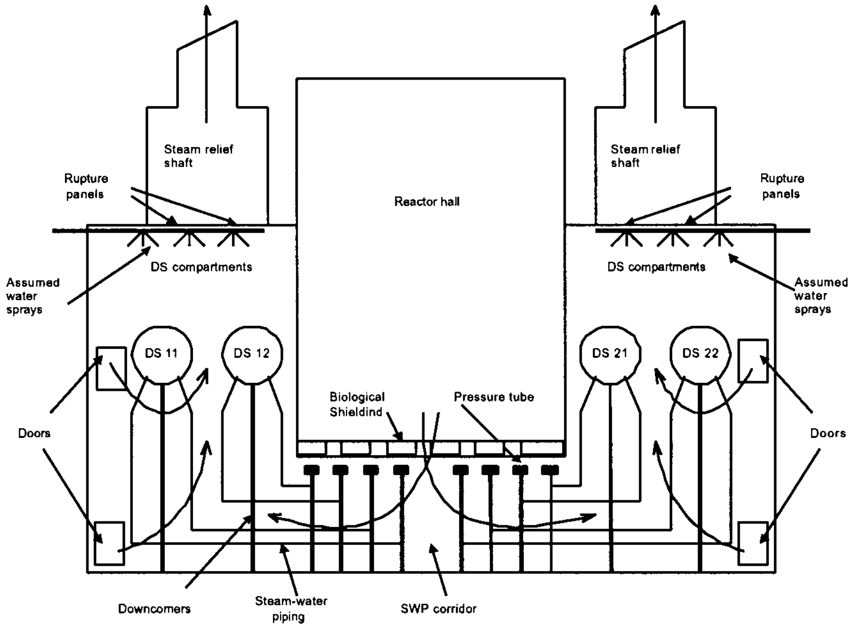

Figure 7. Schematic view of the DS compartments

During normal reactor operation the maximal air temperature in the DS compartments can reach 270 °C. If mentioned doors, rupture panels and lids of pipe are open, natural circulation of the air will be created in the DS compartments (it is marked by arrows in Figure 7). This natural circulation will be capable to remove a part of decay heat, generated in the core. The effect will be higher if the spray system for humidification of air will be installed. The DS compartments ventilation analysis was performed using CONTAIN code. The results of calculations shown that the total heat removal capacity, with 68.6 kg/s water with temperature of 30 ^{0}C through the spray to one DS compartment is about 10.5 MW.

Analysis of station blackout with DS compartments ventilation was performed using RELAP5 model. It was assumed in the modelling, that approximately 5500 s after beginning of the accident (then the fuel cladding temperature in average loaded channels start to increase) the 10.5 MW of heat starts to be removed from hot outside surface area of DS, steam header, part of the steam lines, part of the downcomers, steam-water piping and part of the channels, which are above the core. The amount of removed heat is approximately seven times smaller than heat generated in the core. The behaviour of fuel cladding temperatures in case of station blackout without operators intervention and in case with ventilation of DS compartments is compared in the Figure 8. As it is seen, the decrease of temperatures due to ventilation is negligible.

Analyses results show that implementation of this measure would not be expedient because:

- Heat removal by means of ventilation is not effective;
- Technically it is complicated (when even emergency diesel-generators are not operated) to equip sprays for air moistening and to open mentioned doors, rupture panels and lids for air release in case of accident.

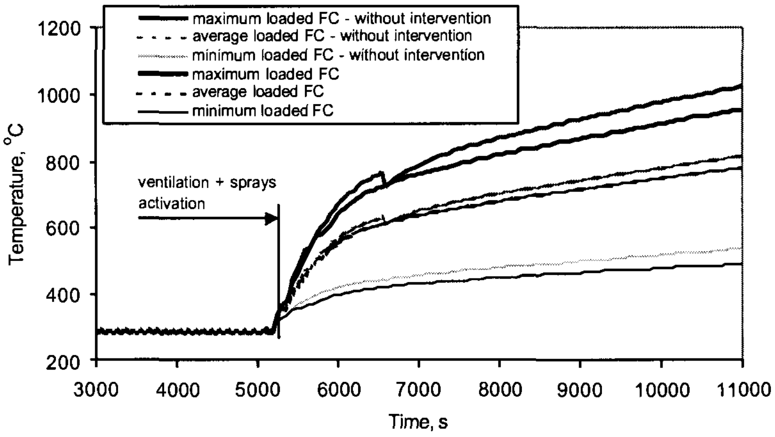

Figure 8. Peak fuel cladding temperature in the fuel channels of different power

Analysis of plant blackout with direct water supply into the reactor cavity

Sequence of the basic events and operating of the systems during first 5000 s in the below presented case is similar as in case with DS compartments ventilation or without operator intervention. It was assumed in the analysis, that at the moment of beginning of core heat-up (5800 s after beginning of the accident) the supplying of water into the top part of the reactor cavity starts. Flow rate of water was assumed equal 68.6 kg/s (the capacity of one ECCS pump) and temperature 30 °C. In the paper the interaction of cold water and hot graphite, which might lead to the degradation of the graphite stack, was not analysed. The aim of the performed analysis was to evaluate the expediency of such kind of core cooling in order to assess the possibility to escape the heat-up and melting of the fuel rods, when other measures do not provide required cooling. This kind of cooling is used only in the critical case. Advantage of such way of accident management is that pressure in the RC is close to atmospheric. It means that for water supply it is possible to use any non-regular sources at low pressure.

By getting in the top part of RC, water flows down along the outer surface of the graphite stack into ring space between a reactor shell and stack. Gaps between the graphite columns are very narrow (1.2 mm [5]), and temperature of the graphite blocks at center of the core is higher than 300 °C when water supply starts. Thus, a water flow downwards along these gaps is practically impossible. Coolant flow rate inside the graphite stack - through the gaps between the graphite columns is presented in Figure 9. In comparison with the flow rate of supplied water, flow rate through gaps is insignificant. Through area outside of the graphite stack the water flows into the bottom part of the reactor cavity and through the pipelines is removed in to the reinforced leak-tight compartments of ACS.

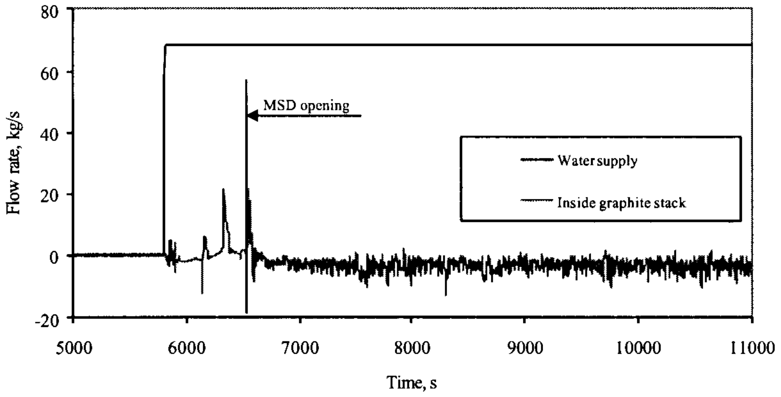

Figure 9. Water flow rate through gaps between graphite columns (inside graphite stack)

Injected water cools the metal structures of RC, bottom and top graphite moderator blocks and outer surface of radial graphite reflector. However, because the water does not reach a deep lines of the graphite blocks, the temperature of graphite at the center of the core increases. Changes of peak temperature of the fuel cladding without intervention of the operator are compared with attempt to cool down the reactor core by direct water supply in to RC. As it is shown from the Figure 10, the rate of the fuel cladding heat up decreases because of water supply. However, the reactor cool down does not begin. The stabilisation of the fuel cladding and FC tube walls temperature in the channels of average power 10000 - 11000 s after beginning of the accident is caused by features of modelling. In modelling was accepted, that the channels of average power are located near to radial reflector channels. As the channels of the reflector are cooled well by water, which is passing down along an outer surface of the graphite stack, these channels are capable to remove a part of the heat from the adjacent fuel channels. In reality, such approach will be correct only for peripheral channels.

Performed analysis results clearly indicates that proposed solution of heat removal by direct water supply in to RC is not feasible.

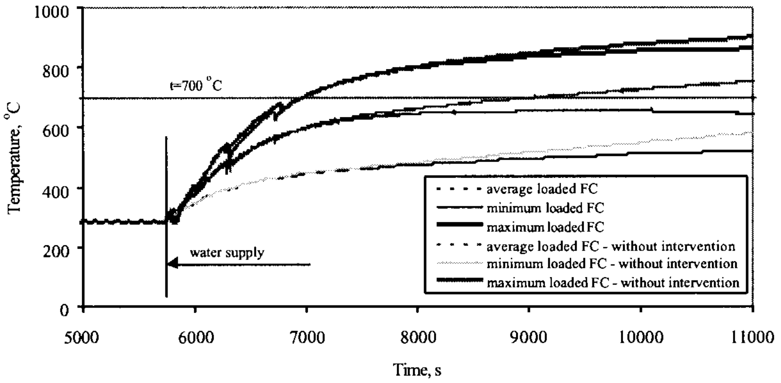

Figure 10. Peak fuel cladding temperature in the fuel channels of different power

CONCLUSIONS

The analysis of the station blackout for Ignalina NPP was performed using RELAP5 code. Three ways of potential accident management for loss of the long-term core cooling are discussed:

- de-pressurisation of the reactor coolant system and water supply from ECCS accumulators, deaerators or using non-regular means to the GDH for core re-flooding,
- decay heat removal from the core by ventilation of DS compartments,
- decay heat removal from the core by direct water supply into the reactor cavity.

The results showed that the last two ways are inexpedient. The ventilation of drum separator compartments and direct water supply into the reactor cavity are not sufficient to remove the decay heat from the core. However, the de-pressurisation of MCC enables to mitigate the consequences of the loss of long-term core cooling. Therefore, such way of mitigation of accident consequences is recommended to be included in the RBMK-1500 accident management programme.

Nomenclature

ACS	Accident Confinement System
CPS	Control and Protection System
DS	Drum Separator
ECCS	Emergency Core Cooling System
FC	Fuel Channel
GDH	Group Distribution Header
LOCA	Loss of Coolant Accidents
MCC	Main Circulation Circuit
MCP	Main Circulation Pump
MFWP	Main Feed Water Pump

MSV	Main Safety Valve
NPP	Nuclear Power Plant
RBMK	Russian Acronym for “Channeled Large Power Reactor”
RC	Reactor Cavity
SDV-A	Steam Discharge Valves to Accident Localization System
SDV-C	Steam Discharge Valves to Turbine Condensers
SDV-D	Steam Discharge Valves to Deaerators and to in-house needs
TCV	Turbine Control Valve

Subscripts

th	thermal

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