

Specific features of the RBMK-1500 reactor and BDBA management

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The processes that might occur during beyond-design-basis accidents (BDBA) in vessel-type light water reactors are rather well known, but many questions and uncertainties still remain. Experimental and analytical research is performed around the world to decrease the remaining uncertainties and develop reliable computer codes for simulation of the processes that could occur in the reactor core and containment in case of beyond-design-basis accidents. Understanding these phenomena would help developing strategies for the management of related accidents. This paper discusses the differences of RBMK-1500 from vessel-type reactors (BWR and PWR), identifies the possible BDBA scenarios and presents an approach to accident management that could be further developed at the Ignalina NPP to prevent accident developing into a severe accident.

Key words: accident management, RBMK-1500, Ignalina NPP

1. INTRODUCTION

The Ignalina NPP is the only nuclear power plant in Lithuania. The plant consists of two units commissioned in December 1983 and August 1987. Unit 1 of the Ignalina NPP was shut down for decommissioning at the end of 2004. Both units are equipped with channel-type graphite-moderated RBMK-1500 reactors.

In order to ensure the safe operation of the nuclear power plant, the defence-in-depth concept is applied, which includes five layers of defence: 1) prevention of abnormal operation and failures; 2) control of abnormal operation and detection of failures; 3) control of accidents within the design basis; 4) control of severe plant conditions including prevention of accident progression and mitigation of the consequences of severe accidents; 5) mitigation of radiological consequences of significant releases of radioactive materials [1]. The fourth layer of defence-in-depth relates to the management of beyond-design-basis accidents, which could be grouped in two categories: 1) beyond-design-basis accidents without significant core degradation, and 2) severe accidents [2]. Until now, at the Ignalina NPP a number of analyses were performed to investigate its safety [3-7], but those analyses mostly related to first three layers of defence-in-depth, *i.e.* the beyond-design-basis accidents and especially severe accidents were out of scope of these analyses. Regardless of

the low probability of their occurrence, severe accident phenomena are investigated for all types of the reactors in the world, because the consequences of such accidents could be catastrophic. Most of the research is performed for the prevailing vessel-type light water reactors PWR and BWR. Less research is performed for the channel-type reactors CANDU and RBMK as they are operated just in a few countries. Up to now, the phenomena that could occur in case of a severe accident in RBMK reactors have been not analysed in detail and very little literature is available on the issue. A general qualitative assessment of severe accident phenomena in RBMK reactors is presented in [8].

The RBMK is a boiling light water reactor, therefore it could be expected that the processes identified for BWR would be similar. Nevertheless, the presence of channels and graphite as a moderator could influence the accident processes, or other processes not identified for vessel-type reactors might occur.

This paper discusses the differences of RBMK-1500 from vessel-type reactors (BWR and PWR), identifies the possible BDBA scenarios and presents an approach to accident management that could be further developed at the Ignalina NPP to prevent an accident developing into a severe accident.

2. SPECIFICS OF RBMK-1500 AS COMPARED WITH VESSEL-TYPE REACTORS

In this paper, the differences between the RBMK and vessel-type reactors are discussed in the view of

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safety barriers and safety analysis. The consequences of any accident at the NPP (radioactive material release to the environment) depend on what safety barriers have been violated. As for any light water reactor (LWR), for RBMK-1500 there could be distinguished four safety barriers (Table).

Table. Safety barriers of RBMK-1500 and vessel-type reactors

RBMK-1500 Fuel pellet Fuel cladding Fuel channel and reactor cooling system Reactor cavity, ALS and reactor building (confinement)	Vessel-type reactors Fuel pellet ¹ Fuel cladding Reactor vessel and reactor cooling system Containment
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The RBMK is a boiling light water reactor with a nominal power of 4800 MW_{th} (1500 MW_{el}). After the Chernobyl accident the maximal allowed power is set to 4200 MW_{th}, *i.e.* the Ignalina NPP is operating at the power below its nominal. The moderator in the RBMK reactor is graphite. The fuel to the RBMK reactor could be loaded on-line, *i.e.* without shutting down the reactor. This online fuel reload puts specifics to the accidents during the fuel reloading, but the integral reactor core characteristic remains almost constant during the reactor operation. Thus, the effect of integral reactivity dependence on fuel burn-up is minimised in RBMK-type reactors.

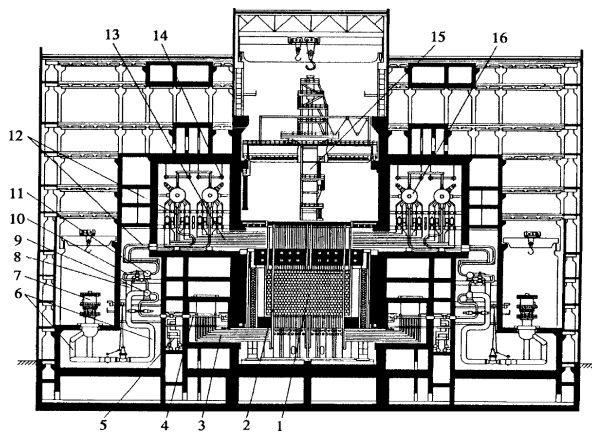


Fig. 1. General view of NPP with RBMK reactor.

1 – graphite stack, 2 – fuel channel, 3 – lower water piping, 4 – group distribution header, 5 – emergency core cooling pipes, 6 – MCP pressure pipes, 7 – main circulation pump, 8 – MCP suction pipes, 9 – pressure header, 10 – bypass pipes, 11 – suction header, 12 – downcomers, 13 – steam and water pipes, 14 – steamlines, 15 – refuelling machine, 16 – drum separator

¹ Some countries (*e.g.*, France) do not consider the fuel pellet as a safety barrier.

The location of the reactor core and its main components is shown in Fig. 1. A comparison of the RBMK with the vessel-type (BWR) reactors shows that these reactor types are quite similar in power per fuel quantity or fuel element length, but large differences appear when comparing reactor power per core volume [9]. The power of the RBMK reactor is somewhat less in that respect, and consequently its heat capacity is larger. These parameters have a certain impact on the operation of the reactor during an emergency.

2.1. Fuel

Initially RBMK-1500 reactors at the Ignalina NPP were loaded with UO₂ fuel of 2% enrichment. Currently at the Ignalina NPP the fuel of 2.4% and 2.6% enrichment with burnable erbium absorber is used. The fuel cladding is made of a zirconium and niobium alloy. The length of each fuel element is 3.5 m. This design of the RBMK reactor fuel differs very little from the fuel elements manufactured for standard BWR-type reactors [9]. More significant design differences are present in the manner in which the fuel elements are mounted into a fuel assembly. The shape of the assembly is determined by the geometric characteristics of the fuel channel in the core. In the case of a BWR this results in a square-shaped (usually 8 × 8) fuel cluster which fits into the square core spaces between the control rod blades. For an RBMK reactor, the fuel assembly is fit into a circular fuel channel (FC) having an inside diameter of 80 mm and an active core height of 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 assembly includes 18 fuel elements placed in two circles around the carrying rod. In spite that the RBMK fuel is similar to the fuel of any LWR, the probability of fuel damage in RBMK type reactors due to reactivity-initiated accidents is lower, because the typical time of reactivity insertion in RBMKs is measured in seconds rather than in microseconds as for other LWR [10].

2.2. Control rods

In the RBMK-1500, the reactor cooling system (RCS) is fully independent of the cooling channels of the reactor control & protection system (CPS). The control rods, which are placed in these individual channels, are made of boron carbide B₄C and aluminium. In total, there are 211 channels with control rods. These channels are filled with water supplied by the system totally independent of the reactor cooling system. The control rods control the core reactivity during normal operation and perform reactor scrambling in the case of emergency. One of the RBMK specifics is the positive void reactivity coefficient and the reactivity effect in case of FC and CPS channels dryout [11]. It leads to the lack of inherent safety

features in the RBMK design. In the case of voiding of the FC or CPS channels the power is not reduced by means of inherent physical processes such as steam generation. The reactivity loss due to fuel temperature increase (Doppler effect) is not effective enough. In order to increase the reliability of the reactor scram, a different shutdown system was installed at the Ignalina NPP in 2004.

2.3. Reactor cooling system

The reactor cooling system of RBMK-1500 has two loops which are interconnected via the steamlines and do not have a connection on the water part. Water is supplied to 1661 FC where it is heated to saturation and partially evaporates. The steam and water mixture then flows to the steam separators (usually they are called drum separators) of both loops, where the steam is separated from water and directed to the turbines. The water from the drum separators flows via downcomers to the MCP suction header and then by the pumps is supplied to the MCP pressure header, which is connected to 40 group distribution headers (20 headers in each RCS loop). Each group distribution header provides water to 41–43 fuel channels. The fuel channels are made of a zirconium and niobium alloy similar to that used for fuel cladding. The steam after passing turbines is directed to the condensers where it is condensed. The condensate is supplied to the deaerators from which it is directed back to the RCS by the main feedwater pipes.

The total mass of the water in the RCS is approximately 2000 tons. The amount of water and steam related to 1 MW power in RBMK-1500 (as well as energy accumulated there) is relatively large in comparison to any vessel-type reactor. This feature leads to a rather slow change of the steam pressure in LOCA type accidents in RBMK. The large amount of piping is also one of the RBMK reactor features. Both in the main cooling circuit and in the steam lines it is possible to find a horizontal piping segment connected to the vertical pipe and further connected to the horizontal piping at a different elevation, and *vice versa*, there are cases when vertical pipes are connected to the horizontal piping. In such a peculiar geometry at low coolant flow velocities, a complex steam separation, stratification and other similar phenomena are possible. Another specificity of RBMK is a possible flow instability in the parallel fuel channels in case of some accidents.

The comparison between safety barriers of vessel-type reactors and RBMK-1500 (see Table) has shown that each fuel channel corresponds to a reactor vessel. Therefore it is the most important part of RCS. In case of severe accidents with fuel melting, fuel debris is expected to remain in the fuel channels or lower water piping. Thus, a core–concrete interaction has a low probability to occur.

The fuel channels in the RBMK-1500 are placed in a graphite stack consisting of 2488 graphite columns with vertical bore openings. These openings are used for positioning the channels, which in turn are used for placing fuel assemblies, control rods and several types of instruments into the core. The graphite stack is located in a hermetically sealed cavity, which is filled with a helium and nitrogen mixture, to prevent the oxidation of the graphite [9]. The temperature conditions for the RBMK reactor graphite stack are determined by conditions of heat transfer to fuel channels and CPS channels. The geometry of the graphite columns and the availability of different power FC and the CPS channels located nearby result in non-uniform heat fluxes and temperature distributions around the periphery of the graphite columns. Thus, heat transfer takes place in the radial direction in the graphite stack. It is possible to remove the heat from the fuel channels to the graphite stack in the radial direction and further from the graphite to the adjacent cooled channels. Some part of the decay heat could be removed from the core to the massive biological shielding. Due to a high heat capacity of the graphite stack (there are 1700 tons of graphite in the reactor), fuel melt due to decay heat is hardly probable in case of BDBA in RBMK-type reactors.

As is already mentioned, the fuel channel of the RBMK reactor according to its function and location corresponds to a pressure vessel of vessel-type reactors. The failure of FC can occur due to impact of pressure and temperature on the channel walls which are made from zirconium and niobium alloy. If the FC heats up while the internal pressure in the RCS is elevated, it may expand until it contacts the surrounding graphite blocks [12]. In the RBMK reactor, the deformation of fuel channels is arrested at rather modest uniform strain values due to a contact of the deformed FC with the surrounding graphite block. Experiments show that the contacted channel fails only if and when the graphite block is disrupted by the pressure load transmitted to it by the deformed channel. At the nominal pressure in FC (7–8 MPa) the temperature of fuel channel failure is no less than 650 °C. Also, the oxidation of fuel channels due to steam–zirconium reaction (the same mechanism as for fuel element claddings) could lead to fuel channel failure. This exothermic reaction becomes very rapid at a temperature higher than 1200 °C.

2.4. Confinement

At the Ignalina NPP there is a system of leaktight compartments, which performs a function of confinement (see Table). A detailed description of this system is presented in [13]. This system consists of the accident localisation system (ALS) and reactor cavity (RC). The ALS covers the biggest part of RCS

equipment and piping, while the fuel channels together with the graphite stack are placed inside the RC. The leaktight RC is formed by a cylindrical metal structure together with bottom and top metal plates. If a FC ruptured, the steam–water mixture would be released to this cavity and come into contact with the hot surfaces of the graphite stack.

The accident localisation system, together with the reactor cavity venting system, is a pressure suppression type confinement. The pressure suppression principle usually is employed in the nuclear power plants with BWR and VVER reactors. At the Ignalina NPP there are 10 condensing pools (sometimes they are called suppression pools) located in two ALS towers. In each tower there are five shallow pools, with water depth of ~1 m, located one above another. Four lower condensing pools are employed in case of RCS piping ruptures in the ALS compartments where the major RCS components (MCP pressure header, suction header, group distribution header, etc.) are located. The fifth (uppermost) condensing pools in both towers are used to condense the steam released from the RCS via the steam relief valves. Additionally, the fifth condensing pool located in the left ALS tower is used to condense the steam which is released from MCC in the case of fuel channel rupture in the reactor cavity. In the case of multiple fuel channel rupture, the reactor cavity venting system opens another path to release the steam to the ALS compartments before the lower condensing pools, *i.e.* to employ the condensing capacity of the lower pools in both ALS towers.

During the normal operation the ALS compartments are filled with air, while the reactor cavity in order to prevent the graphite oxidation is filled with a helium and nitrogen mixture.

The design of pressures of the reactor cavity and ALS compartments in different locations is presented in Fig. 2. One can see that the design excess pressure of the ALS compartments ranges from 80 kPa to 300 kPa. The pressure suppression type containments of an NPP with a BWR reactor usually have a design pressure of ~500 kPa. Such difference in design pressures is caused by the fact that during the initial phase of the accident the clean air from the ALS wetwell (compartments behind the condensing pools) is released to the environment. Releasing noncondensable gases from the ALS prevents high pressure in the compartments.

The most critical part of the Ignalina NPP confinement is the reactor cavity, which confines the steam release in case of a rupture of the fuel channel. If in case of multiple rupture of fuel channels the integrity of the reactor cavity is lost by lifting up the upper plate, then the integrity of the rest fuel channels would be lost as well. Such event would lead to severe consequences similar to the Chernobyl accident.

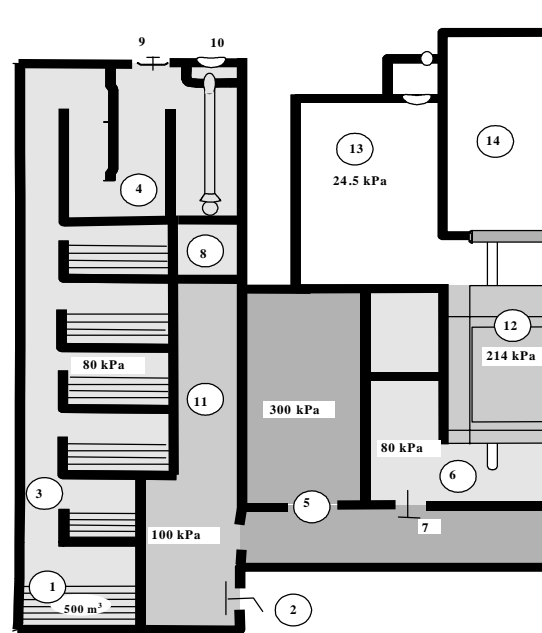


Fig. 2. Design pressures in RBMK-1500 confinement [14]: 1 – hot condensate chamber, 2 – vacuum breaker, 3 – air venting channel, 4 – gas delay chamber, 5 – reinforced leaktight compartments, 6 – lower water piping compartments, 7 – steam discharge valves, 8 – top steam reception chamber, 9 – blow-out hatches, 10 – tip-up hatches, 11 – steam distribution corridor, 12 – reactor cavity, 13 – Drum separator compartments, 14 – turbine hall

It should be noted that at the Ignalina NPP part of the RCS above the reactor core is located outside the leaktight compartments of the ALS, differently from typical PWR or BWR plants which have a full containment. The drum separators and part of downcomers are contained in the DS compartments, which are connected to the reactor hall. In the case of an accident these compartments have special valves or hatches that open to release the steam gas mixture to the environment.

2.5. Engineered safety features

The most important system to ensure the short-term and long-term core cooling is the emergency core cooling system (ECCS). This system consists of the ECCS hydro-accumulators, main feedwater pumps, auxiliary feedwater pumps and ECCS pumps. All these systems can inject water to the RCS at a high pressure. The ECCS hydro-accumulators are a passive subsystem of ECCS, and they inject water to the core during the initial phase of the accident when the ECCS pumps and auxiliary feedwater pumps are starting up. This approach is similar in other NPPs.

Six diesel generators per unit provide the emergency power supply to the Ignalina NPP. In the event of a loss of normal electric power supply they are started up automatically following a trip of all turbines or a loss of grid and can start supplying power

in ~35 seconds. The diesel generators provide power for the emergency feedwater supply pumps and ECCS pumps and other safety equipment. The number of diesel generators is related to the number of safety-related process system trains. Each diesel generator is connected to a specific safety-related process system train (ECCS pump). A typical PWR or BWR has three diesel generators in the electrical power supply system.

There are eight steam discharge valves with steam release to a turbine condenser (SDV-C), which serves on bypasses to the condensers of turbines. However, in the case of station blackout, the operation of SDV-C is prohibited by the Ignalina technological scheme because there is no vacuum in the condensers. Steam pressure is controlled and peaks of pressure are eliminated by two SDV-A and twelve main safety valves (MSV) by steam dump to the ALS condensing pool. The total capacity of all SDV-A and MSV is equal to approximately 60% of steam generation in the core.

3. THE RBMK-1500 REACTOR AND APPROACH TO ACCIDENT MANAGEMENT

As is mentioned, the channel-type graphite-moderated reactors of RBMK type use the same coolant and fuel as the vessel-type light water reactors. However, RBMK reactors have no full containment, therefore it is most important to develop an accident management approach that would prevent severe core degradation. All the measures that prevent development of accidents into severe accidents can be collected in two groups: 1) short-term, and 2) long-term. In the short-term (case within the first seconds of accident) the operators have no time for accident management, therefore an automatic activation of the safety systems (mainly CPS and ECCS) is required. Many modifications of these safety systems in order to increase their reliability have already been implemented at the Ignalina NPP. However, in some cases the long-term measures (intervention is necessary a few hours after the reactor shutdown) are sufficient. In such cases, to prevent the development of accidents into severe accidents, the emergency operation procedures and/or severe accident management guidelines should be developed and implemented.

3.1. Implemented modifications to prevent accident escalation (short-term measures)

The results of in-depth safety assessment of the Ignalina NPP [3] showed that in most accidents initiated by equipment failures (*e.g.*, anticipated operational occurrences) the acceptance criteria are not violated. However, in the case of group distribution header (GDH) flow blockage, the overheating and rupture of at least several fuel channels could occur.

Analysis of LOCA events concluded that the RBMK-1500 is quite well protected against the breaks that occur in the reinforced leak-tight compartments if they do not result in local flow degradation. However, the ECCS activation is not fast enough to prevent the dangerous early temperature excursion in the case of partial breaks of one GDH. A similar situation with a loss of natural circulation through the fuel channels could occur due to a sharp pressure drop in the RCS (large break of steam lines). This situation could lead to a disbalance between energy source and heat sink and to the core damage. Also, some ATWS scenarios can lead to unacceptable consequences. For example, in the case of a loss of the preferred electrical power, at a maximum permissible operational power level, the pressure in the RCS can exceed the safety limit within one minute. The reactor power is not reduced by the inherent physical processes such as steam generation. It demonstrates the lack of inherent safety features in the RBMK design.

A special Safety Improvement Programme was developed to implement modifications requested after finalizing results of the analysis presented in the report [3]. According to this programme, in the year 2000 the new algorithms for CPS and ECCS activation based on the coolant flow rate decrease through GDH was implemented at the Ignalina NPP. The new signal ensures the timely reactor shutdown and the ECCS actuation. This short-term measure prevents the coolant flow rate reduction in the group of fuel channels (in case of GDH blockage or partial GDH break). It allows to disturb the coolant flow stagnation and a dangerous fuel cladding, and fuel channel temperatures are not reached [15]. At present, the Ignalina NPP is adequately protected not only in the case of guillotine ruptures of the pipelines, but also in the case of partial breaks and other accidents that could result in a local flow degradation.

The situation related to the natural circulation destruction due to a sharp pressure drop in the RCS is possible in the case of steamline break. Part of steamlines is located in the turbine hall where the pressure gauges are not installed. Therefore there is no direct signal to indicate that a steamline break occurs in these compartments (as in other cases pressure increase in compartments indicates coolant discharge through the break). It means that the signals for reactor shutdown and ECCS activation will be generated with a delay on secondary parameters (*e.g.*, water level decrease in DS). On the other hand, a sharp pressure drop in the RCS is a characteristic feature in the case of RBMK steamline break. To improve the situation, in 1998–1999 a new reactor scram signal based on fast pressure decrease in DS was implemented at the Ignalina NPP. This modification allowed to avoid the overheating of the reactor core in steamline break cases.

An analysis of ATWS with a loss of preferred electrical power shows that the fuel channels would be overheated and destroyed if the reactor is not shut down immediately [16]. In this case the steam supply to turbines would be terminated due to turbine trip, but the reactor power remains constant and the pressure relief devices are not able to discharge all the steam generated in the reactor. In 2004, at the Ignalina NPP the Diverse Shutdown System (DSS) was implemented, and the frequency of ATWS became negligible ($< 10^{-7}/\text{year}$). The analysis presented in [16] shows that after DSS implementation the reactor would be timely shut down without any damage of the reactor core.

3.2. Possibilities for accident management

The heat-up, damage and melting of the reactor core could occur due to a loss of long-term cooling. The results of the Level 1 probabilistic safety assessment of the Ignalina NPP has shown that in the topography of risk the transients dominate above the accidents with LOCAs, and failures of the core long-term cooling are the main factors of the frequency of the core damage. The most likely initiating event which probably leads to elimination of long-term cooling accidents is a blackout of the NPP.

The blackout of the NPP is the loss of normal electric power supply for local needs with an additional failure to start up all the diesel generators. In the case of a loss of electric power supply MCPs, the circulating pumps of the service water system and feedwater supply pumps are switched off. A failure of the diesel generators leads to a failure initiating the long-term subsystem of the ECCS. It means that it is impossible to inject water to the RCS. The analysis [17, 18] showed that ~ 1.5 hours (5400 s) after the beginning of the accident a dangerous heat-up of fuel elements and fuel channels begins (Fig. 3).

Three ways of potential accident management for the loss of the long-term core cooling were discussed in [18]:

- decay heat removal by ventilation of DS compartments,

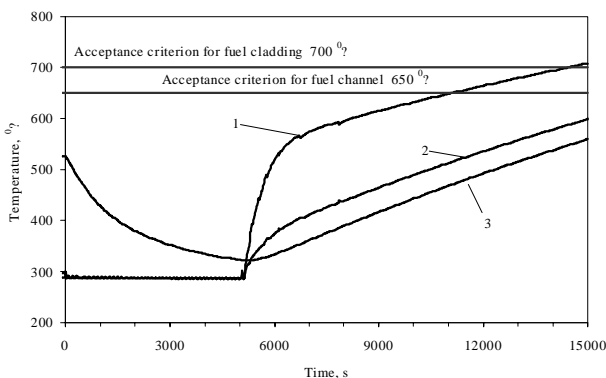


Fig. 3. Temperature of fuel cladding (1), fuel channel (2) and graphite block (3) in average loaded FC

- decay heat removal by direct water supply into the reactor cavity,

- de-pressurisation of the reactor coolant system and water supply from ECCS hydro-accumulators, deaerators or using non-regular means to the GDH.

The results have shown that the first two ways are inexpedient. The ventilation of DS compartments and the direct water supply into the RC are not sufficient to remove the decay heat from the core. However, the de-pressurisation of RCS and the following water supply from regular and non-regular means to the GDH in the case of a loss of long-term cooling gives considerably better results compared with the other two measures. In the analysis [18] it has been assumed that the depressurisation of RCS by opening two SDV-A starts when the fuel cladding temperature in the FC of maximum power reaches 700 °C (the further heating of fuel elements and fuel channels can lead to a failure of these safety barriers). The opening of the steam relief devices allows to decrease the RCS pressure and to use the available low-pressure water sources. This strategy is well known as the “bleed-and-feed” strategy for accident management in vessel-type reactors. The analysis [18] has shown that when the pressure in the GDH reduces down to the pressure in deaerators, boiling water from deaerators passes into the reactor cooling circuit. Boiling water evaporates in the reactor core and the generated steam is discharged through opened steam discharge devices. The water amount in deaerators decreases and later wa-

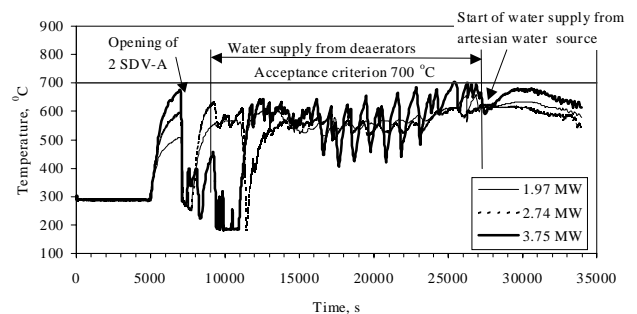


Fig. 4. RCS depressurisation and water supply from deaerators and artesian water source. Fuel cladding temperature in the FC of different power

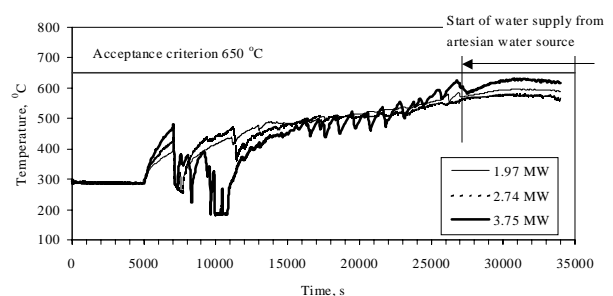


Fig. 5. RCS depressurisation and water supply from deaerators and artesian water source. Fuel channel temperature in the FC of different power

ter supply from deaerators is terminated. However, as is shown in Figs. 4 and 5, the reactor core cooling by RCS depressurisation and water supply from deaerators give additional 4 hours for the operator to restore water supply from the external water source with high-pressure or low-pressure pumps.

The provided examples show that still there are possibilities to improve the safety of RBMK reactors. The accident management possibilities by decreasing pressure and injecting water to the RCS should be further investigated and possibly could be implemented at the Ignalina NPP with a RBMK-1500 reactor.

3.3. Severe accident phenomena in RBMK

In the worst case, if no operator actions were undertaken, 12–44 fuel channels with the higher power level will be ruptured in the case of a loss of long-term core cooling. The steam–water mixture would be released to the reactor cavity and come into contact with the hot surfaces of the graphite stack. The rupture of fuel channels due to overheating in the case of a loss of long-term core cooling will occur when the biggest part of water will be already evaporated from the reactor cooling system. Thus, only the superheated steam will be discharged into the RC. This discharge does not lead to the reactor cavity failure, because the pressure increase in the RC will be not so drastic and the reactor cavity venting system will be able to remove the steam from reactor cavity maintaining its integrity. On the other hand, the discharge of the coolant from the rupture will lead to a depressurisation of the RCS. Therefore, later the processes would be continued at a low pressure in the RCS.

Figure 6 shows the behaviour of fuel claddings, fuel channels, and graphite stack temperatures calculated using the RELAP5/SCDAPSIM code in the case of RBMK-1500 reactor blackout, without any operator intervention. As is shown in the figure, the rupture of a group of fuel channels occurs after approximately 3 hours after the beginning of the accident. When the fuel cladding temperatures reach 800 °C and higher, a failure of the fuel claddings due to ballooning occurs. The ballooning occurs because the pressure in the RCS (outside fuel elements) is close to atmospheric at that time moment and the pressure inside fuel channels is high. The fuel cladding and fuel channel temperatures reach the level of 1000–1200 °C approximately 6.3–7.5 hours after the beginning of the accident. At this temperature the oxidation of claddings and fuel channels made from a zirconium–niobium alloy starts. However, this process is slow due to the absence of steam in the RCS. Within these first 6–7 hours, water supply into the fuel channels is an appropriate action for the reactor cooldown. The supply of water in later phases would lead to a fast steam–zirconium reaction and would accelerate the core damage process.

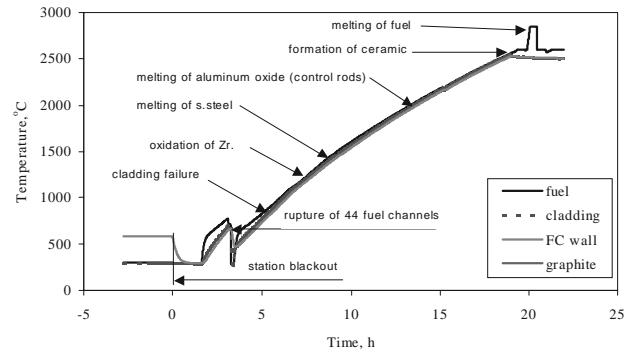


Fig. 6. Main consequences in case of station blackout

When the temperature of the fuel claddings and fuel channels reaches 1450 °C, melting of stainless steel grids and zirconium at 1760 °C starts (Fig. 6). Probably at the same time the fuel channels will fail. At a temperature of 1930–2050 °C and 2330 °C the melting of aluminium oxide (control rod claddings) and boron–carbide (control rod elements) starts. The formation of ceramic (U , Zr , ZrO_2) starts at a temperature of 2600 °C. An analysis performed using the RELAP5/SCDAPSIM code shows that fuel melting (melting of ZrO_2 and UO_2) starts at a low pressure approximately 20 hours after the beginning of the accident at 2690 °C and 2850 °C, respectively (Fig. 6). The core heat-up process is comparably slow due to two factors: 1) high inertia of the graphite stack, which performs the function of a heat sink, 2) the specific power per core volume of RBMK reactors is approximately 10 times lower as compared to PWR and BWR reactors. A high pressure melt ejection and direct containment heating, the phenomena related rather to PWR design, could not occur in the RBMK-1500 reactor due to a limited space inside the reactor cavity. The reactor cavity is surrounded by cylindrical water tanks, which play a role of biological shielding. In cases of a severe accident these tanks will accumulate heat from the core. Thus, despite the fuel melting process in the reactor core, the metal structures that form the reactor cavity will remain intact for a long time due to heat dissipation.

4. CONCLUSIONS

The paper presents an overview of the specific features of RBMK-1500 reactors. The modifications of the safety systems implemented at the Ignalina NPP prevent the reactor core degradation in the first seconds of the accident.

The large heat capacity of graphite provides an effective heat sink which slows down the accident progression and delays the time until a severe core damage occurs. Even in the case of blackout the operators at the NPP have ~6–7 hours to recover the power supply and restore the failed equipment. The melting of fuel at a low pressure in the reactor

cooling system starts approximately 20 hours after the beginning of the accident. Therefore there are good possibilities for accident management at the Ignalina NPP with an RBMK-1500 reactor.

The possibilities to decrease the pressure and inject water into the RCS in the case of an accident should be further investigated as the main approach to accident management.

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Nomenclature

ALS	Accident Localisation System
ATWS	Anticipated Transients Without Scram
BDBA	Beyond Design Basis Accident
BWR	Boiling Water Reactor
CPS	Control Protection System
DS	Drum Separator
DBA	Design Basis Accident
DSS	Diverse Shutdown System
ECCS	Emergency Core Cooling System
FC	Fuel Channel
GDH	Group Distribution Header
LOCA	Loss-of-Coolant Accident
LWP	Lower Water Piping
LWR	Light Water Reactor
MCP	Main Cooling Pump
NPP	Nuclear Power Plant
PWR	Pressurised Water Reactor
RBMK	Russian abbreviation for "Large-power channel-type reactor"
RDPIE	Research and Development Institute of Power Engineering
RC	Reactor Cavity
RCS	Reactor Cooling System

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**RBMK-1500 SPECIFIKA IR NEPROJEKTINIO
AVARIJŲ VALDYMAS**

S a n t r a u k a

Procesai, kurie gali vykti neprojektinio avarijų metu korpusiniuose lengvojo vandens reaktoriuose, yra gana įnominiai, tačiau

vis dar išlieka daug klausimų ir neapibrėžtumų. Pasaulyje atliekami eksperimentiniai ir analitiniai tyrimai, siekiant sumažinti likusius neapibrėžtumus ir sukurti patikimą programą paketą reaktoriaus aktyviojoje zonoje neprojektinio avarijos atveju vykstantiems procesams modeliuoti. Vykstančių reikšmingų supratimų padėtis sukurti tokios avarijos valdymo strategijas. Dėmesį straipsnyje aptariami RBMK-1500 ir korpusinio reaktoriaus (BWR ir PWR) skirtumai, identifikuojami galimi neprojektinio avarijos scenarijai ir pateikiami avarijos valdymo metodai, kurie ateityje gali būti pritaikyti Ignalinos AE. Avarijos valdymas neleistavariu atveju vykiamas peraugti sunkias avarijas.

Raktažodžiai: avarijos valdymas, RBMK-1500, Ignalinos AE

Yra aiškiai matoma, kad avarijos valdymas, RBMK-1500, Ignalinos AE

Nėra aiškiai matoma, kad avarijos valdymas, RBMK-1500, Ignalinos AE

Dažniau

Įdomu, kad avarijos valdymas, RBMK-1500, Ignalinos AE

dažniau matoma, kad avarijos valdymas, RBMK-1500, Ignalinos AE

Įdomu, kad avarijos valdymas, RBMK-1500, Ignalinos AE