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SAFETY ANALYSIS OF IGNALINA NPP DURING SHUTDOWN CONDITIONS

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ABSTRACT

The accident analysis for the Ignalina NPP with RBMK-1500 reactors at normal operating conditions and at minimum controlled power level (during startup of the reactor) has been performed in the frame of the project "In-Depth Safety Assessment of the Ignalina NPP", which was completed in 1996. However, the plant conditions during the reactor shutdown differ from conditions during reactor operation at full power (equipment status in protection systems, set points for actuation of safety and protection systems, etc.). Results of RELAP5 simulation of two worst initiating events during reactor shutdown - Pressure Header rupture in case of steam reactor cooldown as well as Pressure Header rupture in case of water reactor cooldown are discussed in the paper.

Results of analysis shown that reactor are reliably cooled in both cases. Further analysis for all range of initial events during reactor shutdown and at shutdown conditions is recommended.

1 INTRODUCTION

The accident analysis for the Ignalina NPP with RBMK-1500 reactors at normal operating conditions and at minimum controlled power level (during startup of the reactor) has been performed in the frame of the project "In-Depth Safety Assessment of the Ignalina NPP" [1], which was completed in 1996. However, the plant conditions during the reactor shutdown and at shutdown conditions differ from conditions during reactor operation at full power (equipment status in protection systems, set points for actuation of safety and protection systems, etc.). Therefore, safety analysis review team has recommended to perform analysis of accidents during reactor shutdown and at shutdown conditions. The main goal of these analyses are to demonstrate that Ignalina NPP status during low power operation and reactor shutdown bounded by plant status for similar transients during full power operation and/or lead to safe reactor conditions.

Results of RELAP5 simulation of two worst initiating events during reactor shutdown - Pressure Header rupture in case of steam reactor cooldown as well as Pressure Header rupture in case of water reactor cooldown are discussed in the paper.

2 IGNALINA NPP RELAP5 MODEL

The RELAP5/MOD3.2 model of the Ignalina NPP was used for analyses of thermal-hydraulic response of plant to various transients. The RELAP5 computer code has been developed by Idaho National Engineering Laboratory [2]. 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 main circulation circuit and plant safety systems, as well as general description of the RELAP5 model of Ignalina NPP, are given in [3]. Key features of the RELAP5/MOD3.2 model of the Ignalina plant are as follows:

- Both loops of the MCC are represented. Flow paths within a loop are modelled by one or more passes. In turn, a core pass model uses one or more equivalent fuel channels. 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 steam separators are represented explicitly, including steam lines, steam discharge valves, etc.
- Feed water system and ECCS are represented explicitly.

The nodalization scheme of RELAP5/MOD3.2 model is presented the Figure 1. The model consists of two loops. The left loop model consists of one equivalent core pass. All fuel channels of this core pass are represented by an equivalent channel (11-13) operating at average power and coolant flow rate. This channel is connected on one end to the Group Distribution Header (9) by the lower water communication line (10) via its flow control valve. The other end of the equivalent channel is connected to the Drum Separator by the steam-water communication line (14). The two DSs in the left loop are modeled as one volume (1). All downcomers are represented by a single equivalent pipe (2), further subdivided into a number of control volumes. The Main Circulation Pumps suction (3) and pressure (8) headers are represented as branch objects. Three operating MCPs are represented by one equivalent element (5) with check and throttling-regulating valves. The stand-by MCP is not modeled. The bypass line (7) between the MCP suction and the PH is modelled with the manual valves closed. This is in agreement with a modification recently performed at the Ignalina NPP. In comparison to the model for the left loop, the MCP system of right loop's is modeled with three equivalent pumps. The right loop's section between the PH and the DS is represented in a more detailed manner also. The right loop model consists of two equivalent core passes. One core pass represents one GDH. FCs from this GDH are represented by three equivalent channels with three power levels (single channel of maximum power, single channel of minimum power and 41 channel of an average power). The other core pass represents the other 19 GDHs. The FCs of this pass are simulated by an equivalent channel of average 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 $MW_{(th)}$. The guillotine rupture of MCP pressure header (17) is modeled by valve (18). The flow area of this valve is double of PH flow area. The valve (18) is connected to the volume

(19), which represents the MCC compartments. The steam from the separators is directed to turbines via steam lines (15). There are four SDV-C in the each loop of the MCC, which serves on bypasses to the condensers of the turbines. The pressure of the steam is also controlled and peaks of pressure are eliminated by two SDV-A and twelve MSV to pressure suppression pool of the Accident confinement system. The model also considers steam mass flow rate through the SDV-D to the deaerators.

In order to provide confidence in the ability of the models to correctly represent the plant response to upset conditions, the models have been benchmarked for several operational events, such as trip of all the main circulation pumps and spurious opening of three main safety valves, inadvertent actuation of ECCS, etc. The calculation results obtained using the RELAP5 model agree well with the plant data when similar boundary conditions are imposed [3-6].

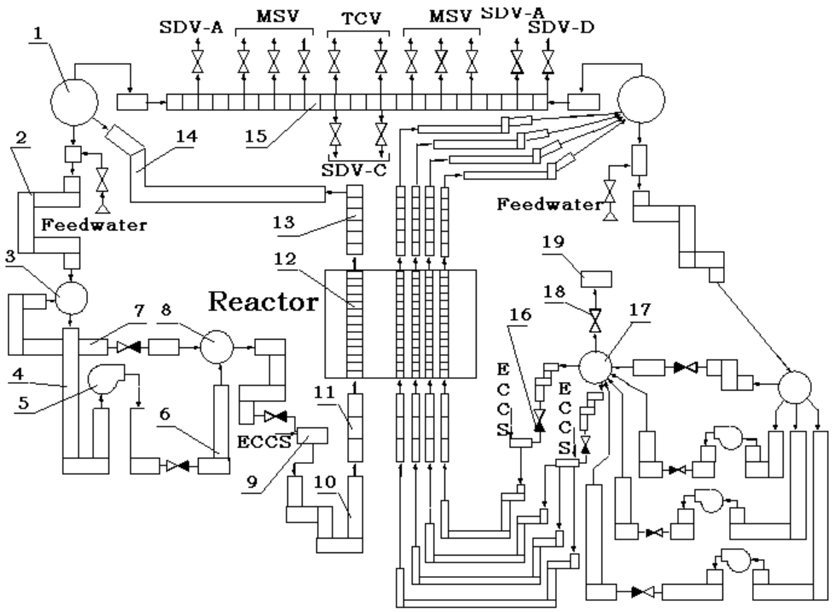

Figure 1 RELAP5 Ignalina NPP model nodalization scheme:

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 - check valve, 17 - ruptured PH, 18 - valve for rupture modelling, 19 - volume which represents MCC compartments

3 ANALYSIS OF PLANT RESPOSE TO PRESSUR HEADERS RUPTURES DURING REACTOR SHUTDOWN

Full breaks produce maximum coolant discharges from their respective pipelines, and thus the most stringent requirement for coolant makeup. The fastest coolant loss from the heat transport system is achieved by postulating a guillotine rupture of largest diameter pipe. A guillotine rupture of the pressure header is chosen as the worst full break in the Ignalina NPP circulation circuit. Furthermore, if a coincident failure of a check valve is postulated in one of the group distribution header, a group of channels connected to this header may not be adequately cooled.

This section evaluates the consequences of guillotine ruptures of Pressure Header with failure of GDH check valve to close during reactor shutdown in cases of steam as well as water reactor cooldown whose are selected as the most severe events to be examined in accident analysis.

3.1 Pressure Header Rupture During Steam Reactor Cooldown

According to the technological regulation [7], before reactor shutdown, it is necessary smoothly to reduce the reactor power and to unload turbines. With achievement of a level of the reactor power equal 1000 $MW_{(th)}$ (the pressure in DS is equal 6.86 MPa), the reactor shut down starts by the pushing AZ-1 button. Cooling down of the reactor and MCC after turbines switching-off can be started by smooth reduction of pressure in DS with nominal levels of water at the expense of regulating steam discharge through SDV-C and SDV-D. Such cooling down of the reactor refers to as steam cooldown and continue before decrease of water temperature in the MCC up to 180 ^{o}C (pressure in DS is equal 1 MPa) [7].

It was assumed in the modelling, that after achievement of a level of the reactor power equal 1000 $MW_{(th)}$, operator shut down the reactor by pushing AZ-1 button. Simultaneously operator switches off all operating MFWP because of decrease of feedwater consumption. Because the reactor decay heat has the greatest influence on accident consequences, conservatively was accepted that the rupture occurs at the moment of a beginning of reactor power decrease. Decay heat in the reactor begins to decrease because of the CPS rods insertion into the zone and 20 seconds later after pushing AZ-1 button makes only approximately 6 % from initial power. The guillotine rupture of PH was accepted in the modelling, thus, the coolant discharges from the MCC without any interference from the MCP side and from the reactor core side through failed to close check valve on one of GDH both. Due pressure difference decrease between PH and DS in the affected loop and increase of pressure in MCC compartments, the signal on ECCS activation is generated almost at once after rupture occurs. The supplying of water from ECCS accumulators into the GDH of the MCC affected loop and from three ready to operate EFWP and four ECCS pumps into GDH of both loops of the MCC begins. The power supply for the three operating MCP in the affected loop of the MCC is disconnected by protection because of the coolant flow rate decrease on hydrostatic bearings in early beginning of the accident. MCPs of the intact loop are switched off by protection approximately in 50 seconds after rupture occurs.

The check valves of the MCC affected loop are closed after PH rupture at once. FCs of this loop are cooled by ECCS water in further. The operating MCP supplied coolant in the beginning of the accident cools the channels of the intact loop of the MCC. After switching-off MCP the GDH check valves in the intact loop of the MCC are closed and FC are cooled only by ECCS water. As it is visible from Figure 2, in fuel channels connected to GDH with fail to close check valve, the coolant flow reverse appears (the coolant gets from DS and discharged through the rupture). In the beginning of the accident these FC are cooled by steam-water mixture. However, after approximately 50 seconds after the beginning of accident, the DS gets empty and these FCs are cooled by saturated steam only. By change of cooling conditions is possible to explain behaviour of fuel cladding temperatures (Figure 2). During the first minute after beginning of the accident the temperatures decreases on approximately 50 ^{o}C, but further slowly increases. The behaviour of FC walls temperatures is very similar.

In modelling is taken into account, that after 10 minutes from beginning of the accident the operator takes actions directed on reduction of loss of the coolant through the break (following to the recommendations IAEA [8], in modelling is accepted non-intervention of the operator during the first 10 minutes). Is accepted, that following the instruction [9], the operator closes valves on pressure and suction pipelines of MCP of affected loop. For preparation of valves for their closing is required not less than four minutes. Therefore, it was accepted in the modelling, that the specified valves are closed approximately in 14 minutes after beginning of the accident (i.e. at the moment of time t = 840 seconds). Thus the discharge of the coolant through the rupture from the MCP side stops. Only coolant flowing by the reverse flow from DS through GDH with fail to close check valve is discharged through the rupture.

As four ECCS pumps and three EFWP continuously supplying water to both loops of the MCC, after operator actions the pressure in DS and in the failed GDH begins slowly increase. The change of pressure is resulted in insignificant increase of the saturated steam flow rate through FC, connected to GDH with failed to close check valve (Figure 2). However is enough even of insignificant increase of flow rate for improvement of conditions of these FC cooling. The temperature of fuel cladding in the channels connected to failed GDH begin to decrease slowly after actions of the operator. Specified temperatures remain much below than safety criteria all investigated period of time.

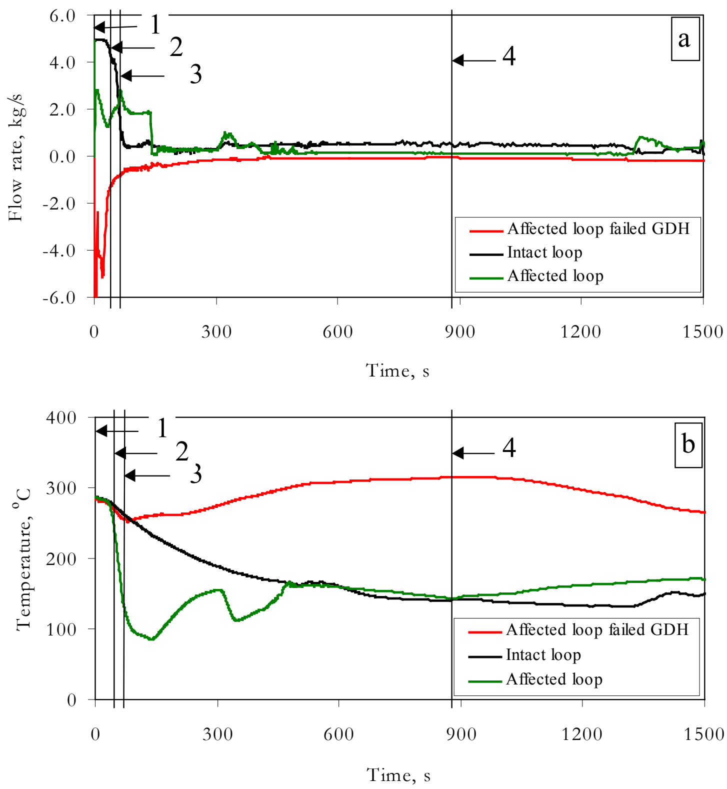

Figure 2 Pressure header rupture during steam reactor cooldown:

a - Coolant flow rate through fuel channels; b - Behaviour of the fuel cladding temperatures; 1 - Pressure header rupture, ECCS activation; 2 – Trip of MCP of intact loop; 3 – DS of affected loop get empty; 4 – Valves in the pressure and suction MCP pipelines are closed

3.2 Pressure Header Rupture During Water Reactor Cooldown

After water temperature in MCC decreases down to 180 °C and pressure in DS up to 1 MPa, further reactor cooldown in water regime with removal of the heat in additional coolers of the purification and cooling system can bee choose. Reactor cooldown according to [7] should be done not exceeding speed of the water temperature change in the MCC more than 10 ^{o}C/h. With the specified rate from the moment of AZ-1 operation prior to the beginning of water cooldown should pass not less than 10 hours. The reactor decay heat 10 hours after shutdown is 0.59 % of the initial power. If initial reactor power to accept equal 4200 MW, then in the PH guillotine rupture modelling, during water cooldown state the reactor power should be equal 24.8 $MW_{(th)}$.

In modelling is accepted that at the beginning of the water cooldown, the operator, following the [7] disconnects one MCP from one side of MCC and one MCP from other side. It is assumed that at the same time occurred guillotine rupture of PH. During the first seconds after beginning of the accident because of the coolant flow rate decrease on hydrostatic bearings the electric motor of single operating MCP in the affected loop is disconnected. MCP in the intact loop of the MCC is disconnected by protection approximately in 680 seconds later. Due pressure difference decrease between PH and DS in the affected loop and increase of pressure in MCC compartments, the signal on ECCS activation is generated almost at once after rupture occurs. MFWP are in the switched off condition during reactor water cooldown state. Because of too high difference of pressure on fast acting valves on lines of water supplying from ECCS accumulators into GDH, these valves can not open. EFWP can not operate because of fast drop of pressure in the MCC also. Thus, on a signal about ECCS activation, only four ECCS pumps are supplying water into GDH of both loops of the MCC.

The coolant supplied by operating MCP in the beginning of the accident cools the channels of intact loop of the MCC. After MCP switching-off, these FCs are cooled by ECCS water only. The channels of the affected loop of the MCC at once after pressure header rupture are cooled only by ECCS water (Figure 3). Fuel channels, connected to GDH with failed to close check valve is cooled by the reverse flow of the coolant from DS. Steam-water mixture flows through these channels in the beginning of the accident. However, after DS gets empty (after approximately 200 s from the beginning of the accident) these FCs are cooled by saturated steam only. While the channels are cooled by steam-water mixture, the temperatures of fuel cladding and FC walls drops, but after transition to cooling by saturated steam the temperatures begin slowly increase. After 500 seconds from the moment of the rupture, the temperatures of the fuel cladding are stabilised in the range of 200 ^{o}C (Figure 3).

In modelling is taken into account, that after a bit more than 10 minutes after beginning of the accident, the operator takes actions directed on reduction of loss of the coolant through the break. It is assumed, that following the instruction [9], the operator closes valves on pressure and suction pipelines of MCP of affected loop. Thus the discharge of the coolant through the rupture from the MCP side stops. Only coolant flowing by the reverse flow from DS through GDH with fail to close check valve is discharged through the rupture. As four ECCS pumps continuously supplying water to both loops of the MCC, after approximately 1000 seconds after valves closing, DS of the affected loop start be filled by water. When the level of water in these DS exceeds a level of connection of steam-water communication pipelines, the water begins to flow into FC of the failed GDH. It results in sharp increase of the reverse coolant flow rate through GDH with failed to close check valve (Figure 3) and to sharp decreasing of fuel cladding temperature. The temperatures of fuel cladding and FC walls remain much below than safety criteria all investigated period of time.

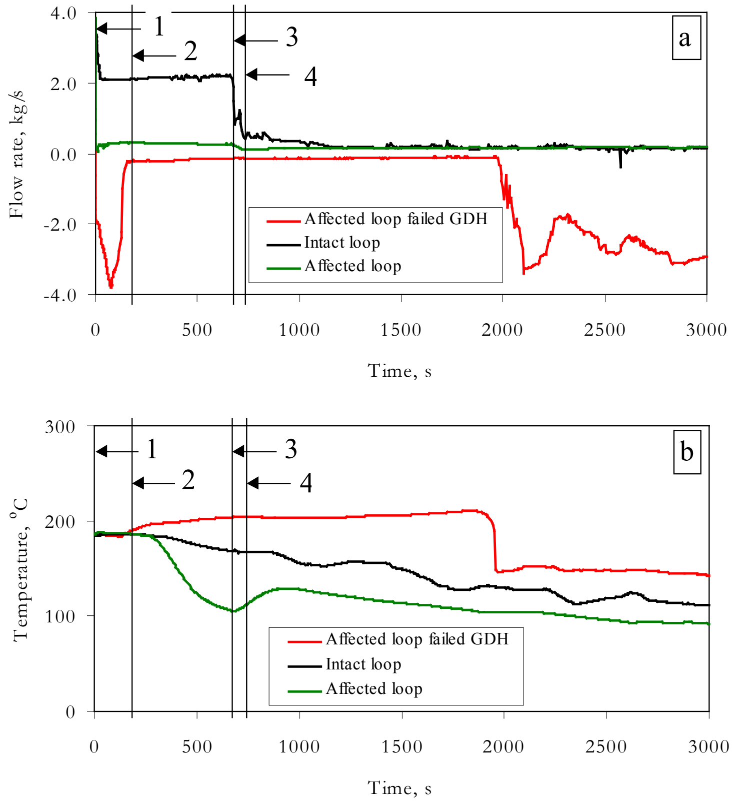

Figure 3 Pressure header rupture during water reactor cooldown:

a - Coolant flow rate through fuel channels; b - Behaviour of the fuel cladding temperatures; 1 - Pressure header rupture, ECCS activation; 2 – DS of affected loop get empty; 3 – Trip of MCP of intact loop; 4 – Valves in the pressure and suction MCP pipelines are closed

4 CONCLUSIONS

Pilot study of two worst initiating events during RBMK-1500 reactor shutdown – Pressure Header rupture in case of steam reactor cooldown as well as Pressure Header rupture in case of water reactor cooldown - are performed using the Ignalina NPP RELAP5 model. Results of analysis shown that reactor are reliably cooled in both cases. Further analysis for all range of initial events during reactor shutdown and at shutdown conditions is recommended.

5 ABREVIATIONS

AZ-1	Reactor Emergency Protection Mode (Reactor Scram)
DS	Drum Separator
ECCS	Emergency Core Cooling System
EFWP	Emergency Feed Water Pump
FC	Fuel Channel
GDH	Group Distribution Header
MCC	Main Circulation Circuit
MCP	Main Circulation Pump
MFWP	Main Feed Water Pump

MSV	Main Safety Valve
NPP	Nuclear Power Plant
PH	Pressure Header
RBMK	Large Channel Type Water-Cooled Graphite-Moderated Reactor
SDV-A	Steam Discharge Valve to Accident Localization System
SDV-C	Steam Discharge Valves to Condenser
SDV-D	Steam Discharge Valve to the Deaerator
TCV	Turbine Control Valve

5.1 Subscripts

th	thermal

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