Use of Main Loop Isolating Valves Investigation in Case of SGTR

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During the development of Symptom Based Emergency Operating Procedures for VVER 440 units at Kozloduy NPP a number of analyses have been performed using the RELAP5/MOD3.2 computer code. Some of them discuss advantages and disadvantages of Main Loop Isolation Valves (GZZs) use in case of Steam Generator Tube Rupture (SGTR) accident. Use of the GZZs as a part of EOP mitigation strategies for Steam Generator Tube Rupture (SGTR) accidents is analyzed in this paper to identify the behavior of important VVER parameters. A double-ended single pipe break in SG #6 was chosen as representative. The results of these analyses presented in this report demonstrate that sometimes GZZs - installed on the hot and cold legs of the primary loops - could provide safety function but sometimes their closing and re-opening could make the situation worse. RELAP5/MOD3.2 computer code has been used to simulate the SGTR accident in VVER 440 NPP model. This model was developed at Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (INRNE-BAS), Sofia, for analyses of operational occurrences, abnormal events, and design bases scenarios. The model provides a significant analytical capability for the specialists working in the field of NPP safety.

This report was possible through the participation of the leading specialists from Kozloduy NPP and with the support of PNNL, under the International Nuclear Safety Program (INSP) of the United States Department of Energy.

I. Introduction

The reference power plant for this analysis is Unit 4 at Kozloduy NPP. This plant is a VVER 440/V230 pressurized water reactor that produced 1375 MW thermal power and generates 440 MW electric power. The VVER440/V230 design includes six coolant loops, each one including one main coolant pump and one horizontal steam generator. The behavior of the horizontal SGs is very different compared to the western type vertical SGs. For example, the secondary side of the horizontal steam generators contains much more water than the western type vertical SGs. The Russian type horizontal SGs are designed so that the internal steam generator natural circulation is organized. The internal steam generator natural circulation contributes water mixing and avoiding liquid temperature stratification in the SGs. During the SGTR accident temperature stratification could be anticipated in the upper volumes of the SG where the vapor fraction is formed. Changes in the water level due to filling of the ruptured SG make this problem insignificant and promote SG cooling down. Steam generators play very important role in the safe and reliable operation of VVER power plants. They determine the thermal-hydraulic responses of the primary coolant system during operational and accident transients.

II. Purpose of the analysis of GZZs use in case of SGTR and definition of the acceptance criterion

The main reason for these analyses is investigation of GZZs use in case of SGTR in supporting of SB EOPs. The calculations are designed to give an opportunity for wide estimation of GZZs use in case of primary to secondary loss of coolant accident (SGTR). The transient scenarios and acceptance failures are designed with the participation of leading specialist from Kozloduy NPP.

The following acceptance criteria are used to analyze SGTR for VVER–440/V230 :

1.Fuel cladding temperature – not more than 1200 ^{o}C.

2.Safe and steady end state.

In this analysis has been also investigated ability for fast depressurization using different systems – Spray in the pressurizer or PORV opening.

III. Event Description

This section contains a description of the expected plan response to a postulated Steam Generator Tube Rupture accident, where use of Main Loop Isolating Valves (GZZs) during the plant recovery is postulated, too.

The initiating event of the analyses is a double-ended one-pipe rupture in the middle layer of the tube bundle in SG #6 close to the cold collector. Since the primary system pressure is initially much greater than the steam generator pressure, reactor coolant flows from the primary into the secondary side of the affected steam generator. In response of this loss of reactor coolant, the pressurizer level and RCS pressure decrease. For the expected case, pressurizer water level decreasing leads to an automatic reactor trip signal.

As the contaminated coolant leaks from primary into the secondary side it will increase the secondary coolant reactivity resulting in high radiation indications. As primary coolant accumulates in the affected steam generator, normal feed water flow is automatically reduced to compensate high steam generator level.

The automatic systems alone will not terminate the primary to secondary leakage. When a tube failure has been identified, recovery actions begin by isolating feedwater flow to the affected steam generator (automatically), closing of GZZs and switching off MCP of the affected loop after reaching level 2.27 m in the ruptured SG #6. After GZZs closing it is necessary isolation of the affected SG #6 from its steam line by closing Main Steam Isolating Valve or Fast Acting Steam Isolating Valve (BZOK). SG #6 letdown system opening could normalize water level in it. In this way the break is completely isolated and this gives an opportunity for primary temperature and pressure reducing to stable and safe conditions. The accepted strategy for post cooling down of the damaged SG #6 is GZZs re-opening after primary side depressurization. In order to avoid secondary radiological releases the operator have to reduce primary pressure under the set point for SG #6 safety valves opening before GZZs re-opening.

There is possibility the both GZZs fail to close or fail to re-open after primary depressurization. There is also possibility that one of the both GZZs fail to re-open.

In this paper it has been investigated two Base case calculations and three Fail case calculations.

<u>Base Case calculations</u>:

- **Base Case, Variant A –** Isolation the damaged SG #6 by closing Main Loop Isolation Valves (GZZs), Depressurization by Spray in the pressurizer and consequent GZZs re-opening.
- **Base Case, Variant B**– RCS cooling to reaching 14 ^{0}C under the temperature of saturation in SG #6, Depressurization by pressurizer PORV opening, GZZs re-opening, SG #6 cooling down to 155 ^{0}C

<u>Fail Case calculations</u>:

- **Fail Case, Variant C** – GZZ #1 on the hot leg fail to re-open, supporting of 60 ^{0}C primary subcooling margin
- **Fail Case, Variant D** - GZZ #1 on the hot leg fail to re-open, supporting of 40-45 ^{0}C primary subcooling margin
- **Fail Case, Variant E** - GZZ #1 on the hot leg fail to re-open plus Loss of AC power simultaneous with the reactor SCRAM

IV. Assumptions

The broken tube is located in the middle layer of the tube bundle in SG #6 close to the cold collector.

In the initial state of the transient it is assumed:

- Reactor power to be nominal.
- Burn up status – corresponding to the end of life.
- Primary pressure and temperature to be nominal.
- Initial secondary pressure is assumed to be nominal too.
- Pressurizer level is assumed as nominal - 5.2 m.
- Steam Generator water level is assumed to be nominal – 2.12 m

V. Single SGTR in VVER 440 – Base Case, Variant A - Isolation the damaged SG #6 by closing Main Loop Isolation Valves (GZZs), Depressurization by Spray in the pressurizer and consequent GZZs opening.

This calculation presents an effective strategy for preventing any secondary radiological releases to the environment.

The main operator action is break identification and isolation the damaged SG #6 from the RCS by GZZs closing. After that the operator have to isolate the affected SG #6 from feedwater and emergency feedwater supplying. The next operator action is isolation from its steam line by BZOK. In this way the break is completely isolated and this gives an opportunity for primary temperature and pressure reducing to stable and safe conditions.

The problem is that the affected SG #6 remains in hot condition. The accepted strategy for its cooling down is GZZs re-opening after RCS cooling down followed by primary depressurization using the Spray in pressurizer.

The operator starts to cool down RCS by BRU-Ks using the intact SGs. When the RCS temperature became with 10 ^{0}C less than the temperature of saturation corresponding to the pressure in the damaged SG #6 the operator starts primary depressurization. Depressurization has to continue until primary side pressure became equal to pressure in the damaged SG #6. The main purpose is avoiding SG safety valves opening and secondary side contamination after GZZs re-opening, which is the next operator action. The operator stops depressurization after reaching 10 ^{0}C subcooling margin in primary side.

It is accepted GZZs re-opening to be performed so that the pressure difference to be -0.1 kg/cm^2 (10^4 Pa).

The horizontal SG #6 is designed so that the internal neutral circulation is organized. It promotes liquid temperature unification in the damaged SG #6 and its successful cooling down.

List of events

1. The double ended break of one pipeline in SG #6 close to the cold collector.
2. The operator starts one Makeup pump (6 m^3/hr) to inject in primary loop.
3. Switching on pressurizer heaters due to primary pressure decreasing down to 120 kgf/cm^2.
4. Actuation of Emergency Protection–I (AZ-1) according to the set point “Pressurizer water level < 2.6 m”.
5. Switching off all Pressurizer heaters due to Pressurizer water level became less than 2.0 m.
6. Actuation of only one system for automatic step by step loading (AASSL) according to the set point “Pressurizer water level < 2 m”. Only HPP #1 starts to inject borated water with concentration of boric acid 39 g/kg.
7. Closing of Turbine Stop Valves (TSVs) of the both turbines 10 seconds after Emergency Protection-I actuation.
8. BRU-Ks opening due to pressure in the Main Steam Header reaches level 50 kgf/cm^2 (4.9 MPa)

9. The operator disconnects SG #6 from the feedwater and emergency feedwater lines after reaching 2.22 m.

10. Water level in the damaged SG #6 increases up to 2.27 m. This is the reason for the following operator actions:

- The operator switches off MCP #6;
- The automatic closes GZZs to 99.5% of their flow area. The other 0.5% the operator tightens manually. Closing of GZZs takes approximately 980 sec.

11. After Loop #6 isolation by GZZs closing:

- The operator isolates ruptured SG #6 from the steam line (by BZOK closing or Main Steam Isolating Valve P-1 on its steam line);
- The operator opens the Letdown system on the damaged SG #6.

12. The operator stops HPP #1 when the following conditions are executed:

- Core exit subcooling margin is higher than 10 kgf/cm^2;
- Primary side pressure is stable or increase;
- Pressurizer water level is higher than 3.5 m.

13. The operator starts to cooldown the RCS by BRU-Ks with speed 60 $^0C/hr$.

14. RCS cooling stops after reaching core exit temperature with 10 ^0C less than the saturated temperature corresponding to the pressure in the damaged SG #6. The operator starts to support this temperature.

15. The operator starts depressurization of primary side by using the Spray in the pressurizer.

16. The operator stops depressurization by Spray.

17. The operator disconnects the damaged SG #6 from its Letdown system when the pressure level in it became less than 46 kgf/cm^2.

18. GZZs opening after primary side depressurization so that the pressure differences to be - 0.1 kg/cm^2 (10^4 Pa).

19. After depressurization the operator starts to cooldown the RCS by BRU-Ks with speed 15 $^0C/hr$.

The most important parameters behavior is shown in the Figures from A.1. trough A.4. The calculation was performed up to 8000 sec into the transient time.

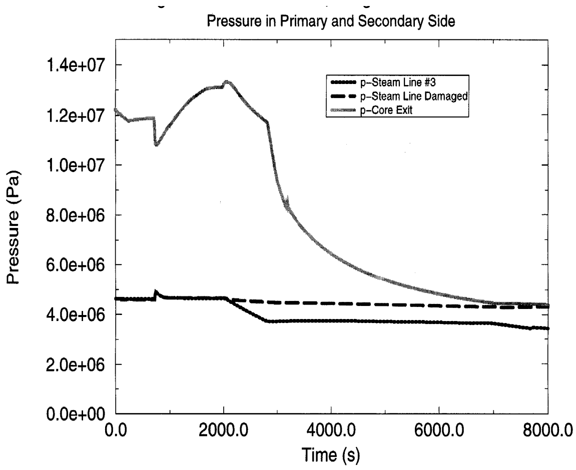

Fig. A.1.

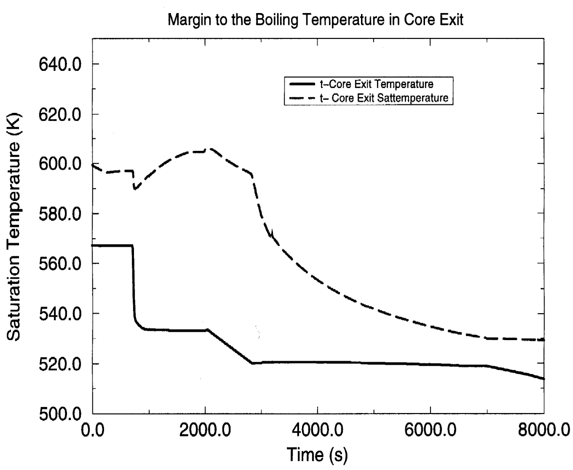

Fig. A.2.

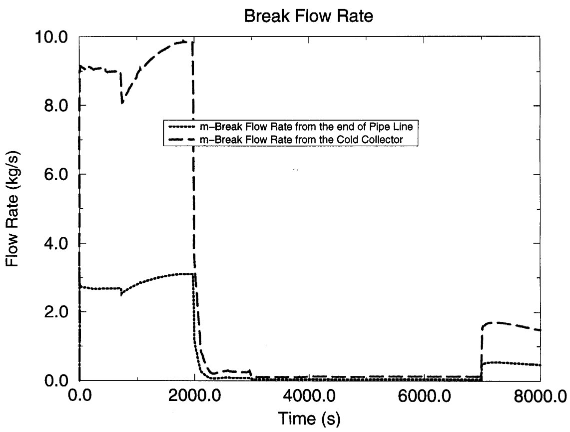

Fig. A.3.

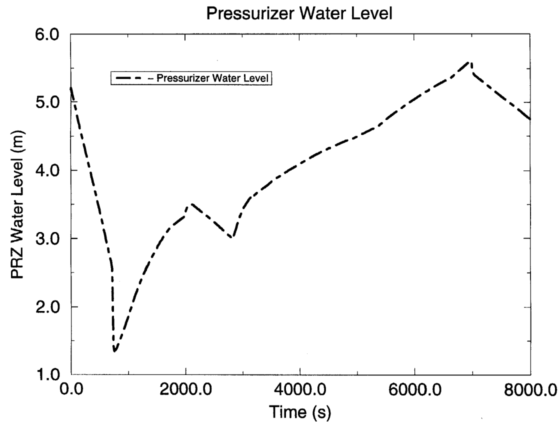

Fig. A.4.

The initial phase of double-ended single SG tube rupture initiates the following sequence of events:

- It causes decreasing of primary side pressure and respectively Pressurizer water level decreasing. Because of the break secondary side pressure in the damaged SG increases slowly.
- Initially SG #6 water level doesn't increase. Feedwater control system automatically compensates the changes in SG water level due to primary to secondary leakage by reducing the feedwater flow rate. At 805 sec water level in the damaged SG #6 increases with 100 mm over the nominal (2.12 m) and reaches 2.22 m. Because of that SG #6 is disconnected from feedwater and emergency feedwater lines.
- The operator could indicate sharp increasing of radioactivity in the damaged SG #6

At approximately 50 sec. during the transient time the operator starts one Makeup pump (6 m^3/hr) to inject in primary loop but it can't support the primary side pressure. After reaching the set point "Primary pressure less than 120 kgf/cm^2"at 250.0 sec all Pressurizer heaters switch on in attempt to maintain the primary side pressure (Figure A.1.). In spite of that primary side pressure continues to decrease.

Pressurizer Water Level (PWL) also decreases. At 711.0 sec it reaches 2.6 m, which is the set point for actuation of Emergency Protection-I (AZ-1).

Following the reactor trip, reactor power rapidly decreases to decay heat levels. Turbine trip initiates 10 seconds after the AZ-1 actuation. TSVs of the both turbines close at 721.0 sec. Steam flow to the turbine is terminated and the pressure in Main Steam Header starts to increases. At 731 sec it reaches 50 kgf/cm^2 and all four BRU-Ks open. Since the intact and ruptured steam generators are connected via the main steam header, no significant difference in pressures will be evident (see Figure A.1.).

At 716.0 sec after reaching the set point 2.0 m water level in the pressurizer HPP #1 starts to inject borated water with concentration of boric acid - 39 g/kg. This causes primary side pressure and Pressurizer water level increasing. There is significant core exit subcooling margin after the 716.0 sec (see Figure 2.). Due to reaching the set point 2.0 m pressurizer water level all Pressurizer heaters switch off.

After reaching 2.27 m SG water level at 990.0 sec the operator starts to close GZZs on Loop #6. The automatic closes 99.5% from GZZs flow area. The other 0.5% the operator tightens manually. It takes him 15 min (900 sec) and at the end of this period at 1968.0 sec the both GZZs on the damaged Loop #6 are completely closed. In this way the operator stops coolant blowdown from the reactor coolant system to SG #6 (see Figure A.3). Also at 1968.0 sec the break flow rate reaches its maximum of approximately 9.86 kg/s from the cold collector and 3.09 kg/s from the end of pipe line.

After GZZs closing the operator opens the SG #6 Letdown system and starts to close Main Steam Isolating Valve on the SG #6 steam line. It takes him 145 sec and at 2113.0 sec the ruptured SG #6 is completely disconnected from its steam line.

At 2117.0 sec the operator stops HPP #1 due to PWL increasing up to 3.5 m (see Figure A.4.).

The operator starts cooling down RCS with speed 60 ^{0}C/hr by BRU-Ks at 2117.0 sec (this is happened after HPP #1 switching off by the operator). At 2817.0 sec the core exit temperature became with 10 ^{0}C less than the saturated temperature corresponding to the pressure in the damaged SG #6. After that moment the operator stops RCS cooling down and starts to support primary coolant temperature. Pressure in the intact SGs decreases slowly due to coolant shrinkage in result of BRU-Ks work. The core exit temperature trend is shown in Figure A.2. There is a significant subcooling margin of approximately 75 ^{0}C at 2817.0 sec. This is the end of RCS cooling down and the beginning of primary depressurization.

At 2817 .0 sec the operator starts to depressurize primary side by Spray in the pressurizer (Figure A.1.). The purpose is primary side pressure to become equal to the secondary side pressure in the damaged SG #6 so that after GZZs opening the break flow rate to be minimal and to be avoided SG #6 safety valves opening.

Due to low Spray efficiency the operator stops primary side depressurization before pressure equilibrium conditions to be established. Although the primary pressure is not completely equalized to the secondary pressure into the damaged SG #6, primary pressure reducing is sufficient for averting SG #6 safety valves opening.

Steam Generator Water Level (SGWL) in the ruptured SG #6 increases and reaches its maximum value at 1968.0 sec. After that moment it starts to decrease due to opening of its letdown system. The operator disconnects SG #6 from its letdown system after reaching 46 kgf/cm^2 at 2980.0 sec.

At 6950.0 sec the operator starts to cool down primary system by BRU-Ks with speed 15 ^{0}C/hr. SG #6 cooling down comes simultaneous with RCS cooling down.

The main conclusion for this calculation with GZZs closing, depressurization by Spray in the pressurizer and consequent GZZs re-opening is that the Spray system is not effective for deep depressurization of primary side, especially when the cold leg temperature is closed to the saturated temperature. To avoid this problem the operator have to cooldown primary side a little bit more but not more than 15 ^{0}C below the saturated temperature in the ruptured SG #6. According to the Technical Specification the isolating by GZZs loop could be joined to the other working loops if the temperature difference between them is less than 15 ^{0}C.

VI. <u>Single SGTR in VVER 440 – Base Case, Variant B</u> - Isolation the damaged SG #6 by GZZs, Depressurization by pressurizer PORV opening and consequent cooling of the RCS and the damaged SG #6 after GZZs opening

This transient was run to demonstrate ability for fast primary depressurization by pressurizer PORV opening and presents an effective strategy for preventing any secondary radiological release to the environment. As in the previous case the damaged SG #6 has been isolated from primary circuit by GZZs closing. Consequent RCS cooling is performed to reaching a primary temperature level, which is with 14 ^{0}C less than the temperature of saturation in the damaged SG #6. Depressurization is performed by pressurizer PORV opening and continues until primary pressure became equal to pressure in the damaged SG #6. In this way the operator prevents SG #6 safety valves opening and on the other hand eliminates break flow rate. The accepted strategy for SG #6 cooling down is GZZs re-opening so that the pump pressure difference to be -0.1 kg/cm^2 (10^4 Pa). After that the operator starts to cooldown the RCS by BRU-Ks with speed 15 ^{0}C/hr. As a result of this subcooling margin in the primary side starts to increase and when it reaches 40 ^{0}C the operator starts to support it by Spray activation in the pressurizer. The operator stops MCP #2 after reaching 200 ^{0}C coolant temperature. In this way he reduses the inserted heat due to work of MCPs.

The most important parameters behavior is shown in the Figures from B.1 through B.4. The calculation was performed up to 20000 sec. into the transient time.

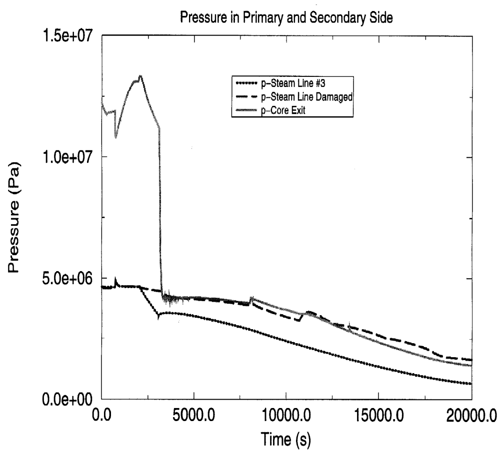

Fig. B.1.

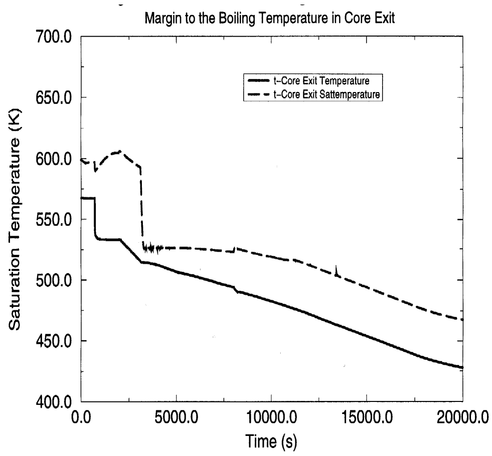

Fig. B.2.

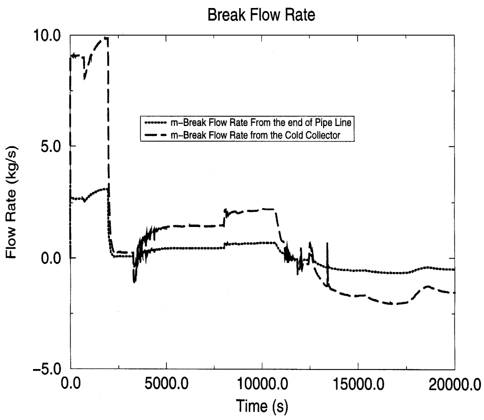

Fig. B.3.

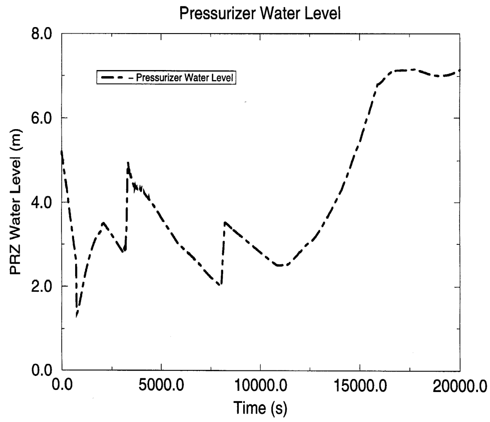

Fig. B.4.

The main conclusion for <u>Variant B</u> calculation is that the suggested strategy is effective for successful and safe plant recovery. It allows SG #6 cooling down simultaneous with RCS cooling. At the end of calculation temperature in the damaged SG #6 is approximately 155 ^{0}C and there is no problem to continue its cooldown.

VII. <u>Single SGTR in VVER 440 – Fail Case, Variant C</u> - Isolation of the damaged SG #6 by GZZs closing, Depressurization by pressurizer PORV opening, Failure of GZZ#1 on the Hot leg #6 to re-open, Supporting of 60 ^{0}C subcooling margin by Spray in the pressurizer

In the following scenario it has been investigated consequences of GZZs failure to re-open.

This scenario repeats the base case - <u>Variant C</u> through the end of primary side depressurization by pressurizer PORV opening. After depressurization by PORV the operator starts to re-open GZZs on the damaged loop #6 but one of them – the GZZ#1 on the hot leg – stuck in close position. As a result of this flow rate in the hot leg #6 is stagnant and there is no any opportunity for its cooling down. The operator could use break flow rate to cooldown cold leg #6 and ruptured SG #6. This method has low efficiency and will take much time.

SG #6 cooling down is organized by switching on Emergency Feedwater Pumps (EFWP) to inject in the ruptured SG #6 and opening letdown system of the damaged SG #6.

It is also accepted RCS cooling down with maximum speed of 60 ^{0}C/hr by BRU-Ks. As a result of this primary subcooling margin increase. According to the Technical Specification the operator has to support subcooling margin from 40 ^{0}C to 80 ^{0}C. In the fail case calculations the operator supports it by

Spray in the pressurizer. The earlier Spray actuation and supporting of small subcooling margin (40 ^{0}C) leads to reducing of Spray efficiency and pressurizer overfilling. On the other hand the later Spray actuation and supporting of big subcooling margin (60 ^{0}C) leads to pressurizer water level decreasing. It will cause actuation of HPP to support Pressurizer water level. For fail case calculations – <u>Variant C</u> it is accepted supporting of 60 ^{0}C primary side subcooling margin.

The most important parameter behavior is shown in the Figures from C.1 through C.4. The calculation was performed up to 18000.0 sec. into the transient time.

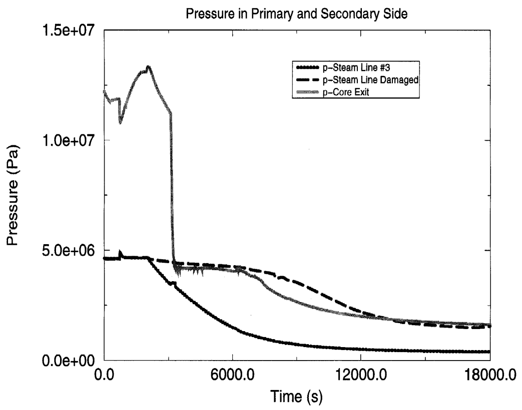

Fig. C.1.

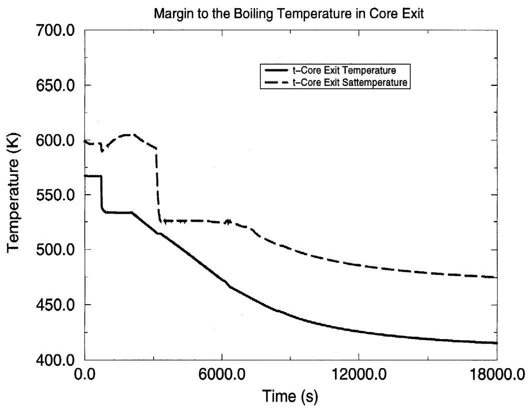

Fig. C.2.

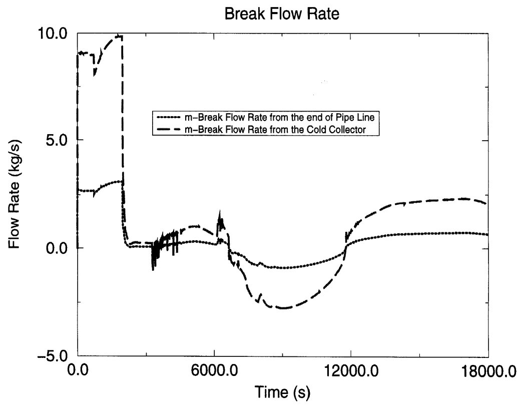

Fig. C.3.

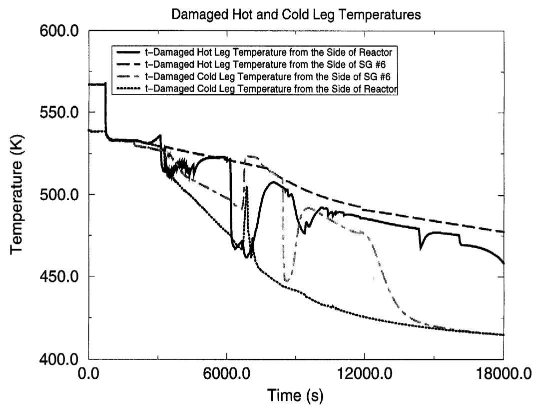

Fig.C.4.

The sequence of events through the moment when the operator starts to re-open GZZs is the same like in the base case <u>Variant B</u>. In the fail case calculations – <u>Variant C</u> it was assumed failure of GZZ#1 on the hot leg #6 to re- open.

At 3115.0 sec the operator starts to depressurize primary side by PORV opening due to reaching the set point 14 ^{0}C margin between the core exit temperature and the saturated temperature corresponding to the pressure (saturated) in the ruptured SG #6. As in the base case - <u>Variant B</u> depressurization continues to establishing of pressure equilibrium conditions between the primary side and the ruptured SG #6 at 3315.0 sec. At 3315.0 sec the operator starts to open GZZs but one of them – GZZ #1 on the hot leg #6 fail to re-open. The operator takes a decision to open GZZ #2 at 100%.

Primary and secondary pressure behavior is presented in the Figure C.1. As it seen from the figure at 6700.0 sec the operator actuates the Spray in the pressurizer and primary side pressure became significantly lower than the secondary side pressure. This is due to reaching 60 ^{0}C subcooling margin in primary side. As a consequence reverse break flow rate appears (Figure C.3).

The trend of Core Exit Temperature is presented in the Figure C.2. According to the scenario after GZZs closing the operator starts to cooldown primary side with maximum speed 60 ^{0}C/hr by BRU-Ks. At approximately 7800 sec Core Exit Temperature gets to plate due to secondary pressure decreasing.

In the initial stage of the transient water level in the damaged SG increase because of the break flow rate. During the whole transient time the operator supports it by EFWPs and the SG #6 letdown system.

As in the base case – Variant B in the fail case - Variant C the operator supports pressurizer water level during the transient time by HPP #1 and the both Makeup pumps.

It was done investigation of Boric Acid concentration in primary side and the results show that there is a sufficient concentration of Boric Acid in primary side during the whole transient time.

The hot and cold leg temperatures in the damaged loop #6 measured from the side of the reactor (near to the outlet and inlet nozzles) and from the side of the damaged SG #6 are presented in Figure C.4. During the whole transient time the operator could not find an effective strategy to cooldown the hot leg #6 which remains almost in hot condition. Nevertheless a small temperature decreasing is observed.

Cooling of the hot leg #6 from the side of SG #6 follows the temperature trend in the damaged SG #6.

The hot leg coolant temperature from the side of the reactor vessel follows cooling down of the Pressurizer. Deviations of the temperature measured at this part of hot leg #6 are due to HPP #1 actuation at 6140.0 sec. As it seen from the Figure deviations reaches approximately 60 ^{0}C and this is the possible maximum. This effect appears because in the model the pressurizer is jointed to the non-isolating part of hot leg #6. Injection of HPP #1 organizes temporary flow from the reactor through the outlet nozzle of loop #6 towards the pressurizer.

More complicated is the situation in cold leg #6. In spite of GZZ #2 is completely open there is differences in the behavior of the temperatures measured in the different parts of cold leg #6. At 6700 sec due to Spray actuation and reverse break flow rate appearance a jump of the temperatures in the both sides of cold leg #6 is observed. More interesting is the gap of the cold leg temperature curve from the side of SG #6 that appeared at 8430.0 sec. It is happened due to bursting of a steam bubble generated at this part of the cold leg (from the side of the SG #6) and entering of a colder coolant from the side of the reactor, which fills the place of the bubble. The bubble is formatted next to the break because after Spray actuation the hot water from still non-cooled SG #6 enters into the primary side. The bubble in cold leg #6 is generated at 7200.0 sec is burst at approximately 8430.0 sec. After 11750.0 sec flow rate in the cold leg #6 changes its direction from primary to secondary side and the cold leg temperature from the side of SG #6 equalizes to the cold leg temperature from the side of the reactor (see Figure C.4.).

The main conclusion for fail case calculation – Variant C is that during the whole transient time the operator could not find successful way for hot leg #6 cooldown. Although of this temperatures calculated at the both sides of the damaged GZZ#1 indicates small decreasing. The later Spray actuation and supporting a big subcooling margin of 60 ^{0}C leads to pressurizer water level decreasing and consequent HPP#1 switching on. It creates temperature deviations of approximately 60 ^{0}C in the hot leg #6 from the side of the reactor.

VIII. Single SGTR in VVER 440 – Fail Case, Variant D - Isolation the damaged SG #6 by GZZs closing, Depressurization by PORV, Failure of GZZ#1 on the Hot leg #6 to re-open, Supporting 40 - 45 ^{0}C subcooling margin using the Spray in the pressurizer

The sequence of events is the same like in the fail case - Variant C but it is accepted supporting of 40 – 45 ^{0}C subcooling margin in primary side. The operator actuates Spray earlier than in Variant C. At this time there is sufficient pressurizer water level in the pressurizer so it is not necessary HPP switching on. Due to low subcooling margin after a while the Spray is inefficient. To increase Spray efficiency at 6000 sec the operator starts to support 45 ^{0}C subcooling margin in primary side.

The behavior of some important parameters is shown in the Figures from D.1 and D.2. The calculation was performed up to 18000.0 sec. into the transient time.

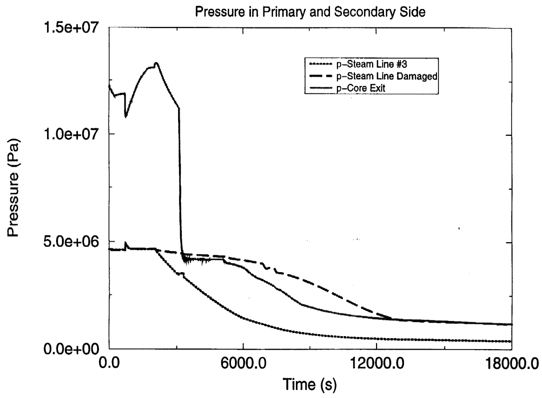

Fig. D.1.

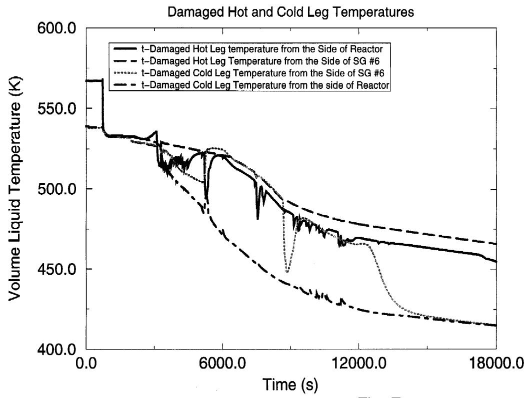

Fig. D.2.

The main conclusion for fail case calculations – <u>Variant D</u> is that at 40 ^{0}C primary subcooling margin Spray has low efficiency. That's why after 6000 sec it is necessary supporting of 45 ^{0}C subcooling margin in primary side. On the other hand earlier Spray actuation prevents pressurizer water level decreasing to the set point for HPP switching on. As a result of this the disturbances in the hot and cold leg temperatures from the side of the reactor are significantly lower in comparison with fail case calculations – <u>Variant C</u>.

IX. <u>Single SGTR in VVER 440 – Fail Case, Variant E</u> - Isolation the damaged SG #6 by GZZs closing, Loss of AC Power simultaneous with Reactor SCRAM, Failure of GZZ#1 on the Hot leg #6 to re-open, Supporting of 40 ^{0}C primary subcooling margin by PORV

For this fail case calculation there were assumed the following equipment failures**:**

- Loss of AC Power simultaneous with Reactor SCRAM
- Failure of GZZ#1 on the Hot leg #6 to re-open

The most important parameter behavior is presented in the Figures from E.1. trough E.4. The calculation was performed up to 15000.0 sec into the transient time.

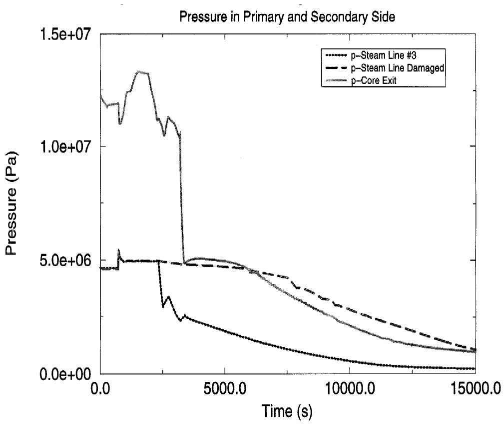

Fig. E.1.

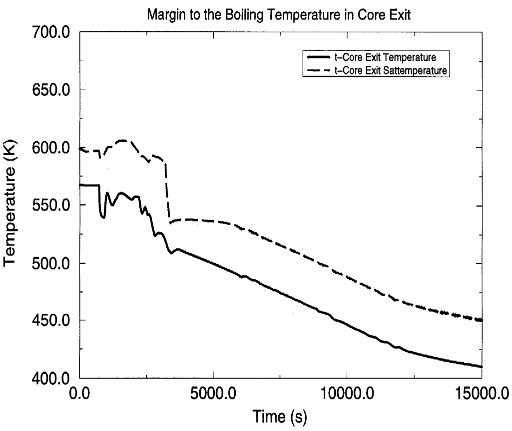

Fig. E.2.

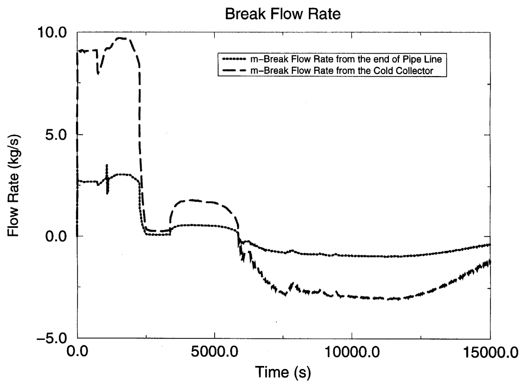

Fig. E.3.

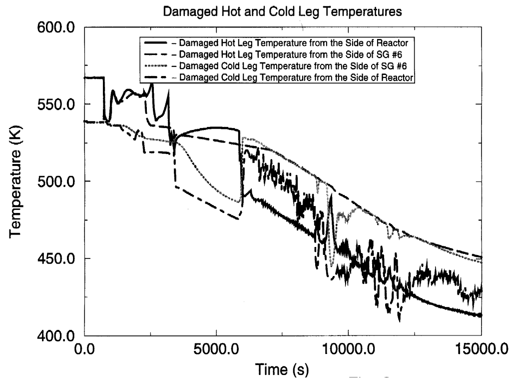

Fig. E.4.

According to the set point "Pressurizer water level < 2.6 m" at 711.0 sec there is actuation of Emergency Protection–I simultaneous with Loss of AC Power. Loss of AC Power initiates the following sequence of events at 711.0 sec:

- All pressurizer heaters switch off.
- The working Makeup pump stops.
- All feed water pumps (FWPs) stop.
- MCP #2 and MCP #5 stop mechanically.
- MCPs #1, #3, #4 and #6 stop on electromechanical run down (start to work with decreasing revolutions and after approximately 3 minutes stop).

Due to loss of all MCPs after 891.0 sec the core exit temperature starts to increase rapidly. The trend of core exit temperature is shown in the Figure E.2.

Turbine Stop Valves (TSVs) of the both turbines close at 721.0 sec approximately 10 sec after Loss of AC power. It causes secondary side pressure increasing. BRU-As open at the same time. As a reasult of this pressure in the Main Steam Header and in the ruptured SG #6 starts to decrease.

At 746.0 sec one HPP #1 starts to inject borated water in pimary side with concentration of boric acid 39 g/kg. It is happened approximately 35 seconds after "Loss of AC Power". The delay time for Turbo-Generator getting to full power is 30 seconds. The delay time for HPP #1 delivery is approximately 5 seconds. HPP #1 could not increase the primary pressure and respectively PRZ water level immediately. Pressurizer water level continues to decrease and at 830.0 reaches its minimum 1.65 m so the operator switches on one Makeup pump to support it (see Figure E.4.). After that moment primary pressure starts to increase rapidly (Figure E.1).

Because of the break water level in the damaged SG #6 increases and at 1290.0 sec reaches 2.27 m. As a result of this the operator isolates the damaged Loop #6 by automatic GZZs closing (see Figure E.3). At 2268.0 sec they are completely closed.

After GZZs closing the operator starts RCS cooling down by BRU-As. It is impossible without restoration of SGs supplying with feedwater. At 840.0 sec due to reaching the set point 2.02 m water level the operator starts to feed SGs #1, #3 and #4 by Emergency Feedwater Pumps. At 1700.0 sec due to reaching the set point 2.02 m water level the operator switches on Emergency Feedwater Pumps to inject in SGs #2 and #5. The earlier EFWPs injection in SGs #1, #3 and #4 is due to MCPs #1, #3, #4 stop on electromechanical run down. As a result of this the heat exchange in this SGs is more intensive than in the SGs #2 and #5 and water level in them drop faster.

Due to reaching the set point 3.5 m pressurizer water level and execution of all other required conditions for HPP switching off (primary pressure increasing and significant primary subcooling margin) at 1910.0 sec the operator switches off HPP#1. At 1910.0 sec pressure difference between primary and secondary sides is maximum, which provokes respectively maximum break flow rate of approximately 12.67 kg/s at the same time (Figure E.3).

After GZZs closing at 2268.0 sec the operator starts to close Main Steam Isolating Valves on the damaged SG #6 steam line. It takes him 145 sec according to the scenario. At 2413.0 sec SG #6 is completely isolated from its steam line and the operator starts to cool down RCS by BRU-As with speed 60 ^{0}C/hr. In attempt to support this speed at 2500.0 sec he closes BRU-As. The operator opens and closes them again at 2750.0 sec and 3200.0 sec. From 2413.0 sec to 3200.0 sec primary side temperature has been reduced with approximately 26 ^{0}C (see Figure E.2). Actually in this period of time cooldown rate is significantly higher than 60 ^{0}C/hr but if we get one hour as a base, average speed of RCS cooling for each one of the hours during the transient doesn't exceed 60 ^{0}C/hr.

Achievement of more precise speed of RCS cooling in the beginning of the transient is complicated due to HPP actuation (PRZ water level drops to 2.0 m), actuation of Emergency Feedwater Pumps and inertness of the primary coolant system due to existing natural circulation in primary side.

At 3200.0 sec the operator starts depressurization of primary side by pressurizer PORV opening (see Figure E.1.). As a result of this Pressurizer Water Level (PWL) increases rapidly and reaches approximately 8.4 m at 3380.0 sec when the operator closes PORV and stops depressurization (see Figure E.4.). At 3380.0 sec primary side pressure became equal to secondary pressure in the damaged SG #6. In this way, after GZZs re-opening – which is the aim of operator - the operator avoids secondary pressure increasing to the set point for SG safety valves opening and stops the break flow rate.

In this transient it was assumed failure of GZZ #1 on the hot leg #6 to re-open. At 3380.0 sec the operator starts to open GZZs but GZZ #1 on the hot leg #6 fail to re-open. The operator opens only GZZ #2 at 100%.

Due to reaching the set point of 6.8 m pressurizer water level at 3300.0 sec working Makeup pump switches off automatically. Due to PORV closing at 3380.0 sec pressurizer water level starts to decrease (Figure E.4.). When it reaches the set point 5.0 m at 4720.0 sec the operator switches on one Makeup pump to inject in primary side.

At 6000.0 sec core exit subcooling margin reaches 40 ^{0}C and the operator starts to keep this value by pressurizer PORV opening (see Figure E.2). As a result of this after 6000.0 sec the reverse break flow rate is observed (see Figure E.3.).

At 7580.0 sec due to SG #6 water level decreasing to 2.02 m the operator switches on one Emergency Feedwater Pump to inject in it.

The hot and cold leg temperatures in the damaged loop #6 measured from the side of the reactor (near to the outlet and inlet nozzles) and from the side of the damaged SG #6 are presented in Figure E.6. During the whole transient time the operator could not find an effective strategy to cooldown the hot leg #6 which remains almost in hot condition. In spite of that a small temperature decreasing is observed.

After GZZs closing cooling of the hot leg #6 from the side of SG #6 follows the temperature trend in the damaged SG #6. At the end of the transient hot leg #6 temperature is with approximately 10 ^{0}C more than the temperature in the affected SG #6 (see Figures E.6.*)*.

The hot leg coolant temperature from the side of the reactor vessel follows cooling down of the Pressurizer. Deviations of the temperature measured at this part of hot leg #6 are due to PORV actuation at 3200.0 sec and at 6000.0 sec. PORV opening organizes flow rate from the reactor to the pressurizer.

Trends of the cold leg #6 temperatures are shown in the same Figure E.6. At 6000 sec due to PORV actuation and reverse break flow rate appearance a jump of the temperatures in the both sides of cold leg #6 is observed.

There is a sufficient concentration of Boric Acid in primary side during the whole transient time (see Figure E.5.). After PORV actuation at 6000.0 sec a reverse break flow rate of approximately 3.0 kg/s is appeared. From the beginning of transient to 6000.0 sec due to existing break flow rate from primary to secondary side concentration of boric acid in the damaged SG #6 increases. Even at the end of the transient time secondary boron concentration is higher then the required minimum for primary side in case of reactor shutting down. So, there is no possibility for generation of local areas with low boron concentration when the reverse break flow rate appearance after 6000.0 sec.

The main conclusion for this fail case calculation – <u>Variant E</u> is that the safety systems and operator actions are effective for plant recovery. Appearance of natural circulation in primary side and inertness of primary coolant system after Loss of AC power make difficult supporting of precise cooldown rate. There are periods of several minutes during the transient when the cooldown rate is higher than 60 ^{0}C. In spite of that, average speed of RCS cooling for an hour transient time doesn't exceed 60 ^{0}C/hr. The operator continues primary cooling up to reaching core exit subcooling margin 40 ^{0}C and starts to support it by PORV. In this way the operator supports PRZ water level higher than 2.0 m and avoids HPP actuation.

General conclusion:

Use of GZZs in case of primary to secondary leak accidents (SGTR) has some benefits and drawbacks. Actually benefits and drawbacks are also observed in case of non-use of GZZs for plant recovery. The thermal-hydraulic analysis of the calculations presented above shows that that practically use of GZZs is possible and the operator could bring the plant to stable and safety condition. Although of that sometimes GZZs use could make the situation worse. If after isolation the damaged SG is depressurized completely, the coolant in the isolated loop is cooled significantly. In case of inadvertent GZZs opening this cold water could get into the core. Also the arisen thermal stresses on the GZZs could create leakage, so the cold water could get in to the core even the inadvertent opening is not assumed. A considerable priority in case of non-use of GZZs is the possibility for cooling the damaged SG and the corresponding hot and cold legs simultaneous with RCS. This variant of cooling is the most optimum from the point of view of regular temperature distribution upstream of the damaged hot and cold legs and in the ruptured SG, and therefore this leads to reducing the thermal stresses in the damaged loop equipment (GZZs, MCP and ruptured SG).

In the presented above scenarios with isolation the damaged SG, primary depressurization and consequent GZZs re-opening in a certain degree the benefits of the both approaches are integrated. In case of GZZs failure to re-open areas with stagnant flow could be observed. These areas obstruct regular cooling of the affected hot and cold legs and the ruptured SG.

The bigger thermal stresses in case of GZZs use for isolation of the damaged loop determine the possibility for appearance of additional equipment failures.

X. References

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[4] Data Base for VVER 440, "Safety Analyses Capability Improvement of KNPP (SACI of KNPP) in the field of Thermal Hydraulic Analysis", BOA 278065-A-R4, INRNE-BAS, Sofia.

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