ANALYSIS AND DEVELOPMENT OF THE AUTOMATED EMERGENCY ALGORITHM TO CONTROL PRIMARY TO SECONDARY LOCA FOR SUNPP SAFETY UPGRAADING

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ABSTRACT

The paper presents the results of the study conducted to support planned modernization of the South Ukraine nuclear power plant. The objective of the analysis has been to develop the automated emergency control algorithm for primary to secondary LOCA accident for SUNPP VVER-1000 safety upgrading.

According to the analyses performed in the framework of SAR, given accident is the most complex for control and has the largest contribution into the CDF value. This is because of IE diagnostics is difficult, emergency control is complicated for personnel, time available for decision making and actions performing is limited with coolant inventory for make-up, probability of SDVs on affected SG non-closing after opening is high, and as a consequence containment bypass, irretrievable loss of coolant and radioactive materials release into the environment are possible.

Unit design modifications are directed on expansion of safety systems capabilities to overcome given accident and to facilitate the personnel actions on emergency control. Safety systems modification according to developed algorithm will allow to simplify accident control by personnel and enable to control the ECCS discharge limiting pressure below the affected SG SDV opening pressure, and decrease the probability of the containment bypass sequences.
The analysis of the primary-to-secondary LOCA thermal-hydraulics has been conducted with RELAP5/Mod 3.2, and involved development of the dedicated analytical model, calculations of various plant response accident scenarios, conducting of plant personnel intervention analyses using full-scale simulator, development and justification of the emergency control algorithm aimed on the minimization of negative consequences of the primary-to-secondary LOCA.

Keywords: VVER-1000, thermal–hydraulic analysis, primary-to-secondary LOCA, automated algorithm, RELAP calculations.

1. PROBLEM DESCRIPTION

The primary to secondary leak accident is one of the most complex and specific accidents for the VVER type Reactor Unit. For this initiating event design operation of Unit automatics and systems does not allow to reach a safe stable condition without actions of the plant personnel on management of emergency process. Design progression of emergency process is accompanied with a leakage outside the containment that causes a radioactivity release to the environment. Such accident is accompanied by irrevocable loss of primary coolant as well as of ECCS tanks inventory. After exhaustion of ECCS tanks the opportunity of core decay heat removal is lost. For overcoming this accident complex operator actions are needed. These actions become complicated due to high dynamics of initial phase of emergency process, necessity to interfere into design operation of automation systems, and because of limited time before exhaustion of ECCS coolant inventory.

According to results of the safety analyses under the Level 1 PRA [1] for SU NPP Unit 1, contribution of "small" leaks with break of one tube into total core damage frequency (CDF) equals to 6%, and "large" breaks with SG collector cover lifting contribute about 11% of CDF. Such high contributions to CDF are caused by absence of systems of accident operative diagnostics, and, also, a necessity of operator interference into process of design automatic operation of safety systems to provide conditions for “emergency” SG (ESG) localization and a stable heat removal from the core without loss of coolant through ESG steam dump valves (SDV) to the environment.

Time from the moment of occurrence of a leak up to its identification, decision-making and start of operator actions essentially increases because of lack of operative diagnostics of the size of "small" leaks. Besides, there is no possibility for operative monitoring of leak development before and after the reactor scram.

Thermal hydraulic analyses of primary to secondary leaks, executed for the Level 1 PRA [1], DBA analysis [2] and for optimization of accident control algorithms [3], and also special analysis of operator actions on a Unit full-scope simulator (FSS) [4] show that the time interval for critical actions (switchings) during an active phase of the leakage in the most adverse case of collector cover lifting is limited to less than 5 minutes. Emergency process control during an initial phase of accident is complex and quite difficult as the prompt performance of a series of consecutive switchings for the ESG localization, the beginning of an emergency cooldown and timely deactivating of HPI pumps are required. It is necessary to consider that many of these actions are interdependent, i.e. performance of the subsequent actions depends on successful or unsuccessful performance of the previous one. Time for
decision-making and actions performing is limited by the coolant inventory available for primary feeding. Besides, there is a high probability of opening and not closing ESG SDV that can cause an irrevocable loss of primary coolant and uncontrollable release of radioactive materials to the environment. The results of simulation of such an accident with FSS show [4], that even at presence of optimum and precise instructions on accident control and with knowledge of initiating event of accident, an operator quite often makes critical errors or controls the accident not optimally.

The analysis of radiation consequences of the given accident, executed within the framework of the SUNPP-1 DBA analysis [2] shows, that in case of opening ESG SDV or impossibility to deactivate a design operation of the HPI pumps, an onsite radioactive release may reach up to $\sim 10^4$ KU. The analysis of release and subsequent distribution of radioactive products shows, that near the border of a sanitary-protective zone the equivalent doze on a child thyroid depending on height of release, basically due to iodine, makes 1.32 - 3.44 Rem.

The listed negative features of emergency process and restricted time for successful actions of the operator require means for the operative control of a leak of coolant and necessity of automation of minimal-necessary scope of switchings for an accident localization and stabilization of process during the most active phase of the coolant release. The methods of computation modeling of various scenarios of emergency processes with application of computer code RELAP5/Mod3.2 have been used for the purposes of revealing the specific features of the primary-to-secondary leak accident, development of optimum algorithm for emergency processes control and assessment of required scope of automation. Besides, FSS have been used for simulation of emergency scenarios and analyses of operator actions on emergency processes control with application of FSS.

2. ACCIDENT PROGRESSION UNDER DESIGN AUTOMATICS OPERATION WITHOUT OPERATOR ACTIONS

Under primary-to-secondary leaks the primary coolant is released to the volume of an "emergency" steam generator. Primary pressure decreases. The behaviour of the plant key parameters and the equipment operation will depend on size of equivalent diameter of a leak.

Results of calculations related to influence of equivalent diameter of a leak on the time and the reason of reactor scram, the initial and steady mass flow rate through a leak and plant end state are presented below in table 1.

As results of the analysis have shown, a 15 mm leak through collector cover or break of SG tube (2x13 mm) makes the lower boundary of compensated primary-to-secondary leaks. Actuation of reactor scram signal for leaks with smaller diameters occurs due to decreasing in PRZ level down to 4.6 m. For leaks of 30 mm diameter and above a scram signal actuation occurs due to primary pressure decrease (see table 1).
Table 1 – The characteristics of an accident under design operation of automatics without operator actions

<table>
<thead>
<tr>
<th>Leak diameter, mm</th>
<th>Time of scram, s</th>
<th>Reason of scram</th>
<th>Coolant mass through leak before scram, t</th>
<th>Leak mass flow rate, kg/s</th>
<th>Mass release into atmosphere during 1 hour after scram, t</th>
<th>End state</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>6</td>
<td>P₁ ≤ 150 bar and N &gt; 75%Nₗ₀</td>
<td>4,9</td>
<td>870</td>
<td>140</td>
<td>402</td>
</tr>
<tr>
<td>80</td>
<td>15</td>
<td>Same</td>
<td>6,0</td>
<td>430</td>
<td>130</td>
<td>408</td>
</tr>
<tr>
<td>60</td>
<td>37</td>
<td>Same</td>
<td>8,3</td>
<td>260</td>
<td>123</td>
<td>382</td>
</tr>
<tr>
<td>40</td>
<td>85</td>
<td>Same</td>
<td>8,6</td>
<td>124</td>
<td>108</td>
<td>276</td>
</tr>
<tr>
<td>30</td>
<td>190</td>
<td>Same</td>
<td>11</td>
<td>61</td>
<td>55</td>
<td>136</td>
</tr>
<tr>
<td>4×13</td>
<td>749</td>
<td>PRZ level ≤ 4.6 m</td>
<td>26,7</td>
<td>41</td>
<td>16</td>
<td>19,6</td>
</tr>
<tr>
<td>20</td>
<td>1280</td>
<td>Same</td>
<td>20,2</td>
<td>27</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td>2×13</td>
<td>2703</td>
<td>Same</td>
<td>49,5</td>
<td>19</td>
<td>8</td>
<td>24,5</td>
</tr>
<tr>
<td>13</td>
<td>4227</td>
<td>Same</td>
<td>49,2</td>
<td>12</td>
<td>11</td>
<td>21,4</td>
</tr>
</tbody>
</table>

During initial stage of accident before reactor scram actuation, any noticeable increasing of secondary pressure in emergency SG has not been noted for all range of non-compensated primary-to-secondary leaks, including the maximal considered size of a leak. Increase of pressure in emergency SG is limited due to turbine control valve (TCV) operation. For example, in case of 80 mm leak under the SG collector cover a TCV stem position increases about 10%. Increasing of a SG level during given stage is marked as the extremely insignificant. After reactor scram and turbine stop valve (TSV) closing any appreciable growth of pressure in ESG does not happen as well (with the condition that BRU-K is in operation). Thus, increasing of the ESG level begins. Intensity of this increase is in proportional dependence on the size of a leak. In case of a prohibition of BRU-K operation after reactor scram there is an increase of pressure in ESG up to setpoints of BRU-A operation. Time from the moment of TSV closing up to the BRU-A opening depends on the size of a leak and makes about four minutes for the greatest diameter of a leak (Figure 1).

Secondary pressure decrease (near main steam valve (MSV)) down to 56 kgf/cm² (after scram) or increase of an emergency SG level (up to 900 mm, with 2 minutes time delay) leads to TSV closing and, as consequence of main steam header (MSH) pressure increasing, to start of BRU-K operation. Further stabilization of Unit parameters is reached under operation of safety systems.

After completion of an initial "active" phase, an emergency process transform to so-called "pseudo-stabilized" condition with compensation of coolant loss by HPIS operation. The leak mass flow rate for "small" leaks of a considered range of breaks is established proportionally to leak diameter, for the top part of a leak range the mass flow rate does not
depend on the size of break and is corresponds to HPIS flow rate. Break size of about 50 mm is the boundary between these “small” and “large” leak “subranges”.

Such state is characterized by irreplaceable loss of coolant and release of activity out of containment, and remains practically stable until a full emptying of HPIS tanks and the termination of primary make-up. Loss of coolant occurs under conditions as follows:

a) under BRU-K operation accident passes with filling of the steam lines and the turbine condenser, thus radioactivity extends within the secondary systems outside containment, including a condensate-feeding piping;

b) in case of prohibition of BRU-K operation accident involves direct coolant and radiation release to the environment through BRU-A or SG SV.

![Graph](image)

**Figure 1** - Time interval before BRU-A opening after TSV closing (with prohibition of BRU-K operation) depending on primary-to-secondary leak equivalent diameter

However it is necessary to consider, that BRU-K are not qualified for operation with a steam-and-water mix. Therefore, realization of first of specified above modes may lead to BRU-K failure and, accordingly, after a while, emergency process with dump of coolant through BRU-K will be transformed to a mode with release through ESG BRU-A into the environment. In spite of the fact that it is stipulated to replace of BRU-A with ones qualified for operation with a steam-and-water mix, however their long operation and increase in amount of operation cycles during emergency process would increase probability of their failure.

Thus, actions of automatics are insufficient to stabilize emergency process and to exclude developments of additional “dependent” failures of BRU-K and BRU-A, to prevent irreplaceable loss of the coolant and loss of means to provide core cooling. All stages of emergency process will be accompanied by radioactivity release outside containment. Especially large release will begin after core heat up and damage of fuel. According to result
of modeling an accident with SG collector cover lifting, reactor core uncovering and permanent increase of cladding temperature begins approximately after 13000 seconds of emergency process. The maximal cladding temperature of 1200°C is reached after 15000 seconds.

For prevention of severe consequences of considered accident operator actions on the emergency control should be directed on isolation of emergency SG, prevention of irreversible loss of HPIS coolant, and also on primary pressure control to prevent SDV opening.

3. RESULTS OF EMERGENCY TRAINING ON FSS

To facilitate analysis of plant personnel actions on control of primary-to-secondary leak accident resulting from SG collector cover lifting, emergency scenarios have been simulated at the SUNPP FSS at the plant personnel trainings. Actual (real) working shifts of units 1 and 2, involved in training, have operated according to emergency operating instructions.

Some results of actions of plant personnel [4] on performance of «Emergency SG isolation and prevention of loss of coolant outside containment» task are presented below. This complex action involves isolation of an emergency steam generator, organization of intact SG cooldown, HPIS operation and primary pressure control to exclude ESG SDV opening. Success criterion for completion of such complex action is termination of coolant loss by FASIV without opening of SDVs.

The results of training for 11 various SU NPP working shifts obtained with taking into account actual characteristics of plant systems and automatics:

- Emergency SG FASIV closing.
  - In all 11 trainings the plant personnel fulfilled the actions intended for ESG steam isolation. During 8 trainings actions have been completed in due time (3-5 minutes of emergency process). In three trainings this action has been executed with a delay of 10-15 minutes, which has led to filling of steam lines with significant mass of water and has caused threat of dependent failure of BRU-K. At the moment of FASIV closing, primary pressure equaled to 61-70 kgf/cm².

- Organization of secondary cooldown.
  - This action was carried out in all 11 trainings. At the same time, at 1 training the cooldown rate at the initial stage of emergency process has been insufficient.
  - Time for completion of the action has varied in a wide range (2-44 minutes from the moment of IE occurrence).
  - During one training, the personnel has not controlled cooldown rate, that has led to operation of protection system, closing of FASIV and termination of feeding of all intact SG, in fact, to degradation of SF «Heat removal by the secondary side». The personnel have identified such lack of cooldown and resumed SG feeding, however, this has led to some delay in accident control.

- HPIS pumps switching-off.
Personnel actions on HPIS pumps switching-off were carried out in all 11 trainings. Time for completion of this action varied in a wide range (7-41 minutes from the moment of IE occurrence).

In 6 out of 11 cases the time interval between FASIV closing and HPIS switching-off has exceeded admissible, that has led to operation of ESG SDV.

Three trainings have involved repeated HPIS pump switching-on at 18, 20 and 25 minutes (after switching-off), that has led to primary pressure increase that in one case has caused SDV opening.

Primary pressure control (using EGES line from PRZ to the quench tank).

Personnel actions on using EGES line from PRZ to the quench tank were carried out in all 11 trainings.

Time for completion of this action varied in a wide range (4—81 minutes from the moment of IE occurrence).

In some cases EGES opening was uncoordinated with ESG isolation or was not effective enough, that led to ESG SDV opening.

Thus, under performance of accident control actions, the majority of working shifts made some errors which caused unsuccess of leak localization and radioactive release outside the containment and into the environment. Total statistics of action performance demonstrates 7 malfunctions for 11 demands.

It should be noted, that practically similar results have been obtained in analysis of ZNPP personnel actions [5]. There 12 «primary-to-secondary Ieak» trainings has been performed at ZNPP FSS. The basic and most widespread operator error has been non-performance of some vital actions directed on leak localization and parameters control to avoid ESG SDV opening (opening EGE line, HPIS pumps control, etc.). Untimely performance of such actions has led to opening and sticking in open position of ESG SDV in 7 trainings of 12.

Large differences in start time of distinct actions of accident control strategy as well as generally unsatisfactory results demonstrate real difficulties for plant personnel in case of necessity to carry out complex actions and outline the necessity of automation of such actions.

4. DESCRIPTION AND CRITERIA OF ALGORITHM OPERATION

To provide a transition of Unit to the safe end state, the proposed strategy and algorithm of accident control envisage the following:

- reduction of pressure difference between primary side and ESG, that is a necessary condition for the termination of loss of coolant through a leak and minimization of mass of radioactive coolant being released from the primary side. This is reached through the primary pressure decrease by means of injection in PRZ and/or operation of EGES system from PRZ to the quench tank during initial phase of emergency process;
- ESG pressure control below setpoints of SDV operation to prevent radioactive release outside containment and into the environment. This is reached during initial phase of emergency process by (a) delay of closing FASIV and (b) prohibition of ESG BRU-A opening, and further on (c) by means of operation of PRZ injection or EGES in the
pressure restriction mode and (d) restriction of HPIS and primary make-up operation depending on primary pressure.

- Localization of radioactive primary coolant within the volume of emergency SG (as maximum, as possible). This is reached by prohibition of ESG BRU-K operation after increasing of SG level, and further on through closing of ESG FASIV and let-down of all SGs. Too early FASIV closing is inadmissible, as it leads to pressure increasing in ESG, opening of BRU-A or SG SV and radioactivity release into the environment.
- Primary inventory and pressurizer level control. This is reached by the timely termination of leak and by adequate coolant injection from HPIS and (or) primary make-up system. The mandatory condition for recovery of PRZ level is injection into PRZ or operation of EGES line into the quench tank.
- Maintaining natural circulation within intact loops and recovery of a margin to saturation. This is reached by primary inventory control and secondary cooldown through intact SG.
- Injection of boron to reach required concentration in primary coolant. This is reached through organization of water exchange in the primary side by means of make-up and let-down system operation in parallel to secondary cooldown.
- Cooling of emergency loop. This is reached by switching on at least one RCP of intact loop after recovery of a margin to saturation.

According to the above-stated, the following detailed criteria are used for estimating results of analyses and efficiency of accident control algorithm:

- Timely termination of loss of primary coolant through the leak.
- Values of parameters and trends of their change - primary inventory and reactor level.
- Sufficient secondary heat removal.
- Restoration of natural circulation within intact loops.
- Recovery of a PRZ level.
- Recovery of a margin to saturation.
- Keeping reactor subcritical.
- Minimization of radioactivity release (it is proportional to coolant release) from the primary circuit and outside the plant.
- No ESG SDV opening (or minimum number of actuations in case of impossibility to avoid opening).
- Minimization of mass of primary coolant dumped through EGES to the quench tank and, whenever possible, no rupture of the membrane and primary coolant release to the containment.

5. RESULT OF SIMULATIONS

Key events of transients under realization of the developed algorithm and the characteristic of the end state are specified in Table 2 [3]. As the beginning of action according to algorithm is adhered to reactor scram signal and «Primary-to-secondary leak» signal, then zero time point for each scenario corresponds to reactor scram actuation for convenience of the analysis results under various break diameters.
Table 2 – The characteristics of emergency processes under design operation of algorithm without operator actions

<table>
<thead>
<tr>
<th>Characteristics of process</th>
<th>Leak diameter, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Termination of loss of coolant to the environment, s</td>
<td>400</td>
</tr>
<tr>
<td>Termination of loss of coolant through leak, s</td>
<td>800</td>
</tr>
<tr>
<td>Coolant mass through leak after reactor scram, t</td>
<td>75</td>
</tr>
<tr>
<td>Coolant mass through ESG SDV, kg</td>
<td>0</td>
</tr>
<tr>
<td>Number of operation cycle of SDV ESG</td>
<td>0</td>
</tr>
<tr>
<td>Steady natural circulation in intact loops</td>
<td>Yes</td>
</tr>
<tr>
<td>Recovery of PRZ level, s</td>
<td>800</td>
</tr>
<tr>
<td>Recovery of margin to saturation, s</td>
<td>1910</td>
</tr>
<tr>
<td>Reactor level (minimum / on algorithm completion), m</td>
<td>11.2 / 12.0 /</td>
</tr>
</tbody>
</table>

Prohibition of ESG BRU-A operation (or increasing of opening/closing setpoints) allows to increase a threshold of admissible pressure in ESG as well as to decrease risk of SDV opening and radioactive release into the environment. Temporal prohibition for operator actions on ESG FASIV closing serves as «protection against the personnel error» and allows to exclude possible erroneous actions on premature closing of FASIV at initial stage of emergency process that could lead to opening of BRU-A (SG SV) of emergency SG.

To prevent an excess of pressure and opening of ESG SDVs, operator actions on primary pressure control are carried out. For these purposes PRZ heaters are switched off and injection into PRZ steam dome from primary make-up system is organized with operation in automatic mode to support PRZ level.

To exclude a fluid flow through BRU-K, which are not qualified for operation with water, a prohibition for BRU-K operation is imposed.

As results of analysis have shown, ESG pressure increase up to SDV opening under initial stage of accident is possible only after TSV closure, moreover, the earlier TSV closing causes the higher secondary pressure, including pressure in the ESG. Early TSV closing is possible as a result of personnel error (premature TSV closing or ESG isolation) or as a result of coincident loss of offsite power.

Analysis results have demonstrated that automatic actions during the first stage of accident control allow excluding radioactivity release into the environment at the beginning of
accident after “primary-to-secondary leak” signal occurred, and create appropriate conditions for ESG isolation.

Second stage of accident control automatic algorithm starts with some delay (delay time has been evaluated by preliminary analysis). First of all, additional actions (extra to PRZ spray injection) for primary pressure limitation are undertaken. For this purpose automatic operation of the EGES line from PRZ to the quench tank is switched on (opening/closure within pressure range that excludes opening of ESG SDV). During second stage FASIVs at the intact SGs are closed, then these SGs are used for secondary cooldown with rate of 60°C/h down to primary temperature of 230°C. Also ESG needs to be isolated from feedwater.

With some delay after “primary-to-secondary leak” signal occurred, ESG FASIV is closed. Flow rates from high pressure systems (HPIS and primary make-up) are limited depending on the PRZ level. Such combined actions allow achieving leak isolation and loss of primary coolant (fig. 2 and 3).

The analysis has demonstrated that operation of the suggested algorithm without additional failure or IE of accident allows the following:

- terminating primary-to-secondary leak,
- minimizing coolant mass and radioactivity release from the primary side, and isolating them inside ESG,
- excluding ESG SDV opening and radioactivity release to the environment,
- reaching stable state with keeping all required SFs,
- creating conditions for further transition of reactor to safety end state.

Figure 2 - Integrated mass flow rate through PRISE leak (after scram) under algorithm operation: 1 - 80 mm leak; 2 - 15 mm leak
6. ANALYSIS OF INFLUENCE OF FAILURES OR ADDITIONAL INITIATING EVENTS ON REALIZATION OF ACCIDENT CONTROL ALGORITHM

To analyze efficiency of suggested accident control algorithm in case of failures or additional IEs the following BDBA have been modeled:

- accident control using algorithm in case of HPIS failure (failure of primary inventory control SF);
- accident control using algorithm in case of PRZ spray and EGES failure (failure of primary pressure decrease and restriction SF);
- accident control using algorithm in case of EGES valve failure to close after opening (failure of primary pressure control SF);
- accident control using algorithm in case of HPIS pump failure to turn into recirculation mode (failure of primary pressure restriction SF);
- accident control using algorithm in case of secondary cooldown failure (failure of heat removal from primary to secondary SF);
- accident control using algorithm in case of false signal “primary-to-secondary leak” occurrence;
- accident control using algorithm in case of additional IE “primary leak inside the containment from cold leg”; 
- accident control using algorithm in case of additional IE “primary leak inside the containment from pressurizer steam dome”; 
- accident control using algorithm in case of additional IE “loss of offsite power”;
- accident control using algorithm in case of additional IE “loss of offsite power” and ESG SDV failure to close after opening (failure of secondary pressure control SF);

Table 3 below denotes some key events and characteristics of accident with additional failures including peak values of key parameters and end state. The beginning of time scale for each scenario corresponds to reactor scram actuation for convenience of the analysis results under various failures.

Table 3 – Key characteristics of emergency processes under automated operation of accident control algorithm accompanied with failures or additional IE

<table>
<thead>
<tr>
<th>Emergency process</th>
<th>Termination of loss of coolant to the environment, s</th>
<th>Coolant mass through leak after reactor scram, t</th>
<th>Coolant mass through ESG SDV, t</th>
<th>Steady natural circulation in intact loops</th>
<th>Recovery of PRZ level, s</th>
<th>Recovery of margin to saturation, s</th>
<th>Primary inventory (minimum / at algorithm completion), t</th>
<th>End state</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Yes, 400</td>
<td>71</td>
<td>0</td>
<td>Yes</td>
<td>No</td>
<td>2290</td>
<td>196 / 275</td>
<td>OK-OK</td>
</tr>
<tr>
<td>F2</td>
<td>Yes, 650</td>
<td>83</td>
<td>2.1</td>
<td>Yes</td>
<td>No</td>
<td>1200</td>
<td>216 / 260</td>
<td>OK(RS)-OK</td>
</tr>
<tr>
<td>F3</td>
<td>Yes, 400</td>
<td>74</td>
<td>0</td>
<td>Yes</td>
<td>No</td>
<td>480</td>
<td>215 / 253</td>
<td>OK-L</td>
</tr>
<tr>
<td>F4</td>
<td>No due to term of scenario</td>
<td>155</td>
<td>63</td>
<td>HPIS operation</td>
<td>680</td>
<td>320</td>
<td>216 / 320</td>
<td>NO(RG)</td>
</tr>
<tr>
<td>F5</td>
<td>Yes, 400</td>
<td>81</td>
<td>0</td>
<td>No</td>
<td>750</td>
<td>No</td>
<td>217 / 273</td>
<td>OK-L</td>
</tr>
<tr>
<td>F6</td>
<td>No PRISE</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>500</td>
<td>1820</td>
<td>257 / 275</td>
<td>OK-OK</td>
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<tr>
<td>F7</td>
<td>Yes, 400</td>
<td>81</td>
<td>0</td>
<td>Yes</td>
<td>680</td>
<td>1800</td>
<td>215 / 273</td>
<td>OK-L</td>
</tr>
<tr>
<td>F8</td>
<td>Yes, 400</td>
<td>54</td>
<td>0</td>
<td>Yes</td>
<td>H/B</td>
<td>700</td>
<td>209 / 235</td>
<td>OK-L</td>
</tr>
<tr>
<td>F9</td>
<td>Yes, 400</td>
<td>5</td>
<td>0</td>
<td>Yes</td>
<td>250</td>
<td>No</td>
<td>230 / 242</td>
<td>OK-L</td>
</tr>
</tbody>
</table>
### Emergency process

<table>
<thead>
<tr>
<th>Emergency process</th>
<th>Termination of loss of coolant to the environment, s</th>
<th>Coolant mass through leak after reactor scram, t</th>
<th>Coolant mass through ESG SDV, t</th>
<th>Steady natural circulation in intact loops</th>
<th>Recovery of PRZ level, s</th>
<th>Recovery of margin to saturation, s</th>
<th>Primary inventory (minimum / at algorithm completion), t</th>
<th>End state</th>
</tr>
</thead>
<tbody>
<tr>
<td>F10 100 mm PRISE LOCA with IE «LOSP»</td>
<td>Yes, 400</td>
<td>71</td>
<td>10,2</td>
<td>450</td>
<td>380</td>
<td>2540</td>
<td>219 / 264</td>
<td>OK(RG) - OK</td>
</tr>
<tr>
<td>F11 100 mm PRISE LOCA with IE «LOSP» and failure of ESG SDV to close</td>
<td>No HPIS switch off after 1000 s</td>
<td>600 (1h)</td>
<td>530 (1h)</td>
<td>No</td>
<td>No</td>
<td>3100</td>
<td>133 / 220</td>
<td>NO(RG)</td>
</tr>
</tbody>
</table>

**Notes:**

Yes - no termination,
No - no restore,

OK-OK - Containment bypass eliminated, release outside containment stopped, SF restored, stable condition reached.
OK(RS)-OK - Containment bypass eliminated, release outside the containment is negligible, SF restored, stable condition reached.
OK(RG)-OK - Containment bypass eliminated, release outside the containment is considerable, SF restored, stable condition reached.
OK-L - Containment bypass eliminated, there is a leak inside the containment, operator actions to reach final safety conditions are needed.
NO(RG) - Containment bypass not eliminated, release outside the containment is considerable, operator actions to reach final safety conditions are needed.

Table 3 illustrates that application of accident control algorithm allows terminating loss of primary coolant inventory in case of all considered emergency scenarios except F4 (HPIS pump failure to turn into recirculation). All scenarios have demonstrated sufficient primary coolant inventory during accident (except scenario F5 - failure secondary cooldown), and stable natural circulation in intact loops that provides for heat removal from the core.

The short time opening of ESG SDV happens in case of failure of primary pressure control and in case of loss of offsite power. Nevertheless, algorithm actions allow to minimize a number of SDV openings and to limit significantly mass of primary coolant dumped into the environment.

In case of secondary cooldown failure positive results of algorithm include limitation of ESG pressure and exclusion of radioactivity release into the environment through ESG SDV.
In case of SG SV failure to close after opening, the primary pressure decreases down to LPIS operation into primary side. For instance, under break of 100 mm the primary pressure and temperature within one hour decrease down to limits, which are appropriate for operation of the planned cooldown line. There is sufficient boric water inventory in LPIS tanks that ensures favorable conditions for transition of unit to stable safety condition.

Positive effect of applying the accident control algorithm in case of failure to switch HPIS to recirculation consists in significant decrease of primary coolant radioactivity release into the environment through ESG SDV. Also it leads to increase of time margins for performing required actions by the plant personnel.

Summarizing all above discussed, it should be noted that application of the algorithm for majority of considered BDBA scenarios allows to meet acceptance criteria and safety functions. For the rest scenarios it leads to increase of time margins for required operator actions.

7. CONCLUSIONS

Calculations of emergency scenarios of initiating events involving loss of coolant from primary to secondary side have been conducted for a range of breaks, non-compensated by primary make-up system, from the 15 mm minimal equivalent diameter up to maximal at SG collector cover lifting (including double-ended breaks of SG piping). The results of analyses allow to reveal and generalize characteristic features of the course of transient progression.

The algorithm of actions on accident control has been developed and the analyses confirming efficiency of application of algorithm at various scenarios of leaks from primary-to-secondary have been conducted. The analyses have shown that at design course of emergency process (without imposing additional failures or IEs), the proposed algorithm of accident control provides for fulfillment of required safety functions and acceptance criteria.

The analysis of influence of additional failures of the equipment and IE on realization of the proposed algorithm has shown, that application of algorithm for some of the beyond design scenarios also ensures fulfillment of safety functions and acceptance criteria, and for other part it, at least, facilitates course of emergency process and performance of required recovery actions by the plant personnel on the Unit transition to the safe end state.

As follows from the results of calculations, the size of primary-to-secondary leak causes certain influence on behaviour of Unit key parameters and the equipment operation. At the same time, realization of the suggested algorithm of emergency actions, possessing sufficient universality, allows to bring the power Unit in a safe stable condition for the entire range of leaks, considered in the analyses.
NOMENCLATURES

BDBA - beyond design basis accident
BRU-A - steam dump valve into atmosphere
BRU-K - steam dump valve into condenser
CDF - core damage frequency
DBA - design basis accident
EGES - gas evacuation system
ESG - steam generator (affected)
FASIV - fast acting steam isolation valve
FSS - full-scope simulator
HPI - high pressure injection
HPIS - high pressure injection system
IE - initial event
LPIS - low pressure injection system
LOCA - loss of coolant accident
MSV - main steam valve
PRA - probabilistic risk assessment
PRISE - primary-to-secondary leak
PRZ - pressurizer
RCP - reactor coolant pump
SUNPP - South-Ukraine nuclear power plant
SAR - safety assessment report
SDV - steam dump valve
SF - safety function
SG - steam generator
SV - safety valve
TCV - turbine control valve
TSV - turbine stop valve
VVER - pressurized water reactor

REFERENCES


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[3] Designing of optimum strategy of emergency procedures and design recommendations on updating the equipment of protection and blocking for recovery of safety functions on the basis of analytical researches on strategy and algorithms of emergency processes control in case of primary-to-secondary leak for VVER-1000 unit 1 of SU NPP. 2007.

