RELAP/SCDAP SENSITIVITY STUDY ON THE EFFICIENCY IN SEVERE CORE DEGRADATION PREVENTION OF DEPRESSURIZATION AND WATER INJECTION INTO STEAM GENERATORS FOLLOWING SBO AT A CANDU-6 NPP

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Abstract

The paper takes into consideration the issue of severe accidents prevention that became a serious and continuous concernment of the nuclear stakeholders, mainly after Fukushima Daiichi nuclear accident. The efficiency of the preventive measures considered to be applied needs to be verified, including by analytical calculations. One of the most challenging events for all nuclear power reactors is Station Blackout (SBO) that can conduct in some conditions to the loss of safety functions and as a consequence to a severe accident. Therefore, prevention of severe accident in this case has been sustained with different measures to avoid loss of reactor decay heat removal. The paper considers a CANDU-6 NPP in a SBO event and simulates the application of the main preventive actions at different moments after reactor shutdown in order to determine by this sensitivity study how long these measures are still efficient in removing reactor decay heat. The considered actions in a SBO case at CANDU-6 consists in maintaining the Steam Generators (SGs) as an efficient heat sink, by SGs depressurization and their subsequent gravitationally feeding with cooling water from the dousing tank, a passive large source of water present in CANDU-6 project. Simulations to verify by calculation this heat sink efficiency have been performed using RELAP/SCDAP/MOD3.6(a) computer code and CANDU-6 NPP specific models. Calculations performed for this sensitivity study showed that SGs can be in this case an efficient heat sink for a long period of time, till three hours since the SBO event initiation, so even after the SGs drying-out.

1. INTRODUCTION

After Fukushima Daiichi nuclear accident, all European countries operating nuclear power reactors passed through a “stress-test” their Nuclear Power Plants, a re-assessment of nuclear safety in conditions of extreme external events and severe accidents. A number of general recommendations and country and plant specific recommendations resulted from this safety re-assessments, including measures for severe accident prevention and mitigation for existing reactors. These recommendations resulted in National Action Plans, containing actions, both for regulatory bodies and NPPs with the aim to increase the plants robustness and a better preparedness for severe accident management. Cernavoda NPP, from Romania, having two operating units equipped with CANDU-6 reactors has also taken measures for severe accident prevention, including for those resulted from the most challenging accident sequences, as SBO is, and also for verification and validation of the accident management measures considered in Emergency Operating Procedures (EOPs) and Severe Accident Management Guides (SAMGs).

In case of a Station Black-Out event at a CANDU-6 NPP, when all alternative power sources are lost, the reactor cooling can be lost too, if accident management measures are not considered in due time, and the damage of the reactor core is foreseen. The SBO event without any accident management measures was analysed many times, including by the authors of this paper (as in [7], [8], [9]) and the CANDU-6 plant systems behaviour is known. The sensitivity analysis presented in this paper has the aim to verify by calculation if the application of the management measures provided as in the SBO’ EOP or much later have success in ensuring an efficient heat sink for decay heat removal for a long time period. The analysis determines also the time limits for the application of these measures, consisting in SGs depressurization and addition of water from the dousing tank by opening the Boiler Make-up Water system isolation valves.
The Romanian regulatory body, National Commission for Nuclear Activities Control (CNCAN), together with “Politehnica” University of Bucharest, performed calculations independent (by the designer and utility) and alternative (to the calculations performed using CANDU specific codes) in order to verify the efficiency of SGs heat sink in removing the decay and avoiding severe accident in case of a SBO. SGs depressurization followed by water addition from the dousing tank into SGs were considered in this sensitivity study to be credited at different moments after SBO initiation, starting with 35 minutes - as it is stated into EOP for SBO, and till 3 h from the event initiation (about 1 h after SGs dry-out). The judgement of the efficiency of SGs in case of SBO was based on the behaviour of the primary circuit and reactor core, as a response to SGs make-up at different moments.

To perform this analysis, the best-estimate computer code RELAP/SCDAP/MOD3.6(a) was used together with CANDU-6 specific models. Different cases were considered in the analysis, with simulations performed for 20,000 s to 45,000 s, depending on the analysed case.

2. SHORT DESCRIPTION OF THE CANDU-6 REACTOR AND SAFETY FEATURES

CANDU-6 reactors are somehow different comparing with PWR or BWR reactors, from more design considerations. CANDU reactor is located in a horizontal calandria vessel (CV), around 6 m long and 6 m in diameter, containing 380 fuel channels linked with inlet and outlet feeders, attached to the inlet and outlet large headers, which are part of the Primary Heat Transport System (PHTS). CANDU6 reactor uses natural uranium as nuclear fuel, heavy water as reactor coolant inside the fuel channels, and heavy water as moderator, outside of the fuel channels but inside the calandria vessel. Each fuel channel is composed by a 6 m long pressure tube (PT) contained in a calandria tube (CT), the two tubes being separated by CO2 for thermal isolation. PHTS is composed by 4 passes through the reactor, in 2 eight-shape independent loops, each having 180 fuel channels, 180 inlet feeders, 180 outlet feeders, 2 Reactor Inlet Headers (RIH), 2 Reactor Outlet Headers (ROH), 2 Steam Generator (SG), 2 primary pumps and large pipes for connection. Reactor inlet and outlet headers, SGs, pumps and large pipes are all located above calandria vessel with fuel channels inside. The two loops are interconnected and both are connected to the pressurizer, but in case of a LOCA they can be isolated, one by the other and also by the pressurizer. 4 Liquid Relief Valves (LRV) ensure the primary overpressure protection, discharging primary coolant into degasser condenser (DGC), when their pressure setpoint of 10.24 MPa(g) is reached. The ROHs normal operation pressure is 10 MPa (a). If the pressure increases in DGC over the setpoint of 10.16 MPa(g), two Relief Valves (RV), spring actuated, open and close to reduce the DGC tank internal pressure, discharging steam or heavy water into containment atmosphere.

The overpressure protection of the four SGs, vertical type with integrated preheater, is ensured by 16 Main Steam Safety Valves (MSSV), organized in 4 groups, both spring and pneumatic actuated. These MSSVs can also be used for a fast depressurization of SGs. This depressurization can be an automatic action, with opening of 8 MSSVs – when some specific conditions are met, or it can be performed by manual opening of MSSVs by the operator. In both cases there is a need only for power supplied by batteries, as the MSSVs are spring and pneumatic actuated and they have independent local tanks with compressed air for their opening. A field operator can block them in open position using a dedicated tool in order to create an open path for steam release from SGs to atmosphere. If it is necessary, the operator can open manually in the field MSSVs, pneumatically or using a dedicated tool.

A large amount of water, around 2,000 m³, is available in the dousing tank - located near the top of the containment, to ensure the cooling water for containment spray in a LOCA case and water for the Medium Pressure stage of the ECCS, can be also used in SBO event to recover the SGs inventory, pouring gravitationally through the BMW system piping and open valves.

CANDU-6 reactor shutdown is ensured by the two fast shutdown systems, provided by design, fail safe, acting in less than 2 seconds each on different trip parameters. Containment isolation, even at the loss of power (fail safe feature by design) as well as the dousing spray, local air coolers and Igniters, ensure the containment protection and prevent the radioactive releases into environment in case of an accident. The newer safety improvements after Fukushima Daiichi accident, including the hydrogen management using Passive Autocatalytic Recombiners (PARs) and the Emergency Filtered Containment Ventilation System (EFCVS), different AC power mobile generators and provisions for alternative heat sinks increased the capacity of the CANDU-6 plant to prevent the severe accidents and to mitigate their consequences.
3. DESCRIPTION OF SBO EVENT AT CANDU-6 REACTOR

In case of a SBO at a CANDU-6 NPP, the total loss of alternative power will determine the loss of nuclear fuel cooling, as the primary pumps, the main and auxiliary feedwater pumps, the feed pump and the shutdown cooling pumps. The batteries are still available to command the opening of some valves, as MSSV – for steam generators rapid depressurization, or LRVs for PHTS overpressure protection. Both sets of valves have also dedicated tanks with instrument air for valves actuation, so the loss of instrument air will not affect the opening of MSSVs and LWRs, at least for a while (longer than 2 hours).

Loss of nuclear fuel cooling, as a direct consequence of loss of all heat sinks, will conduct also to a possible loss of some barriers (cladding failure, discharge of a mix of fluids from PHTS to DC and the containment atmosphere, through the spring actuated Degasser Condenser Relief Valves (DCRV)). Reactor shutdown and containment isolation safety functions are not affected by the SBO event.

In case of a SBO, after reactor shutdown, the decay heat will be transferred by natural circulation from the reactor core to the SGs. The steam generated will be removed through the open MSSVs. The SGs initial inventory of about 40 t each will ensure the heat removal for about 2 h, when the boilers dry-out. Loss of heat sink after SGs boiling-off will determine primary circuit pressurization and LRWs opening to discharge heavy water into DGC. In turn, DGC tank pressurization will conduct to the spring opening of RVs, which will discharge steam and water into containment atmosphere. For a while, this path LRWs-DGC-RVs-containment atmosphere will ensure the reactor core heat removal but will also conduct to the primary inventory decreasing, which will lead to overheating of the nuclear fuel and to the fuel channel break, at around 13,000s since SBO initiation, according to [7, 8, 9]. Channels break determine a fast pressurization of the moderator and, after the calandria ducts rupture disks break, to the expulsion of a large amount of moderator into containment. The uncovering of some upper fuel channels will conduct to the overheating of the PT/CT and in not a long time to the channel disassembly and beginning of the core damage into severe accident. This scenario of SBO without any measure to protect the reactor core to fail, as it is briefly described above, has been analysed many times, using MAAP4-CANDU, ISAAC or even RELAP/SCDAP computer codes, as it can be seen in [1], too. This SBO scenario was analysed also by the authors of this paper, using the same version of RELAP/SCDAP computer code and the same models [7, 8, 9], in order to have a base for comparison with cases where different accident management measures are considered. It allows also to determine the time windows available to implement accident management measures considered to prevent the core degradation and avoid severe accident.

It was determined, and considered into dedicated EOP for SBO, that the most important measures in case of SBO are to ensure SGs as heat sink, preserving in the same time the primary coolant inventory. In order to keep SGs as a heat sink and remove the heat from the primary coolant, the SGs water inventory recovering has to be ensured. A large amount of water, around 2,000 m³, is available in the dousing tank - located near the top of the containment, to ensure the cooling water for containment spray in a LOCA case and water for the Medium Pressure stage of the ECCS. This water from the dousing tank can be also used in SBO event to recover the SGs inventory, pouring gravitationally through the BMW system. The SGs depressurization is mandatory to permit the gravitationally pouring of water, and also the opening of the Boiler Make-up Water system isolation valves to ensure the water path. Once the BMW valves are opened and SGs depressurized, the dousing tank water can ensure the SGs inventory for at least 27 hours, as it resulted from [6], with a maximum water flow of about 43 l/s, for all SGs, according to [6]. This prevents the reactor core conditions degradation and severe accident initiation, as the analysis demonstrated. As long the water is provided to SGs and steam is removed to atmosphere, the thermosyphoning ensures the decay heat removal. On long-term, the Emergency Power Supply system (EPS) or Mobile Diesel Generator (MDG) will supply the necessary electrical power and the EWS will provide water to SGs.

4. ANALYSIS METHODOLOGY, MODELS AND INPUT DATA

The analysis presented in this paper has been performed using RELAP/SCDAPSIM/MOD3.6(a) computer code, described in [3], [4], and [5], and also CANDU-6 NPP specific models. A detailed presentation of CANDU-6 NPP models for RELAP/SCDAP code (the PHTS model, the secondary side of SGs model, the CANDU-6 reactor core model - using RELAP5 and SCDAP components), the analysis methodology,
assumptions, initial conditions and failure criteria used in the SBO accident analysis are basically the same as those used in [1], section 3.6, where SBO event, without any accident management measure applied, was analysed. The CANDU-6 specific models for RELAP/SCDAP code were developed in time by different Romanian specialists, interested in the study of CANDU-6 reactor in severe accidents and design basis accidents, using a best estimate computer code, an alternative solution to the CANDU specific computer codes. These specialists worked mainly with “Politehnica” University of Bucharest during different studies, including for PhD theses preparation.

The analysis presented in this paper has used a newer version of the REPAL/SDDAP code comparing with [1], and some improvements to models, as a more detailed model for the reactor core and for the LRWs-DGC-RVs path, in order to increase the accuracy of simulation (as the primary inventory discharged into containment from the primary circuit and the reactor core behaviour). The input model is for a generic CANDU-6 NPP. For the simulation of the SGs depressurization and water addition time-dependent conditions were used.

This study considered that the SGs depressurization followed by water addition from the dousing tank, essential in the case of SBO at a CANDU-6 reactor, are applied at different moments from the SBO initiation, in order to determine the time window in which their application conduct to efficient results in removing the reactor decay heat and prevent the core damage. The analysis presented in this paper has used a constant flow of water of 40 l/s of water from the dousing tank to all SGs after SGs depressurization. This flow resulted as optimum (according to [8]), to extract the decay heat from the primary coolant, and it was also confirmed by the tests performed during the stress-tests of Cernavoda NPP, as it is presented in [6]. The following cases have been considered for the analysis presented in this paper:

(a) SGs depressurization by automatic or operator action, at about 35 minutes after SBO initiation, as it is considered in EOP for SBO. Simulation was performed for SGs depressurization at 2200s, and water injection into SGs 100s later;
(b) SGs depressurization by operator action at 7200 s, 2h from the event initiation when the boilers dry-out, and water addition from the dousing tank into SGs after 100s;
(c) SGs depressurization by operator action at 9000 s (2.5 h), when LRWs already opened and discharged some water into DGC and then into containment by RVs, and water addition into SGs after 100s;
(d) SGs depressurization by operator action at 10800 s (3h), when a large amount of water has been lost from the primary circuit by the cycling opening of LRWs and DGC-RVs and water addition into SGs after 100s.

5. ANALYSIS RESULTS

In order to determine the CANDU-6 NPP behaviour in case of a SBO event, when the two important preventive actions (of SGs depressurization and water addition from the dousing tank) were considered in analysis, the evolutions of the following main parameters have been monitored and extracted in graphs:

- PHTS pressure, considering the pressure in ROH (Pa);
- The SGs water level (m from the tube-sheet) (or water inventory in SGs, - kg);
- Maximum fuel surface temperature (MFST - conservatively the cladding temperature is considered at this value,) – K degrees; this is the most important parameter, showing if the nuclear fuel is adequately cooled or not;
- PHTS coolant inventory, in the two loops, important mainly after LRWs-DGC-RVs path opening (first time at around 9000s, according to [6, 8]) – considered only for the case (d).

The following results have been obtained, sustained by the graphs presented in TABLE 1:

(a) In the case (a), meaning the actions taken as in the EOP for SBO, the SGs depressurization followed by the water addition in the SGs at a flow rate of 40 l/s determines the PHTS depressurization, with a maximum of 2.4 MPa. SGs inventory starts to recover and arrives at around nominal value at approximately 7 h (25000 s); after this moment, the flow to the SGs can be reduced significantly, as the decay heat decreased, too. As LRVs do not open in this case, the PHTS inventory remains constant and the fuel well cooled (the maximum fuel surface temperature remains less than 500 K).

(b) In case (b), the SGs depressurization and water addition into SGs occur after 2 h since SBO initiation, at this moment SGs being almost empty (according to [7]). As the LRVs did not open yet, the PHTS inventory is still constant. The maximum fuel surface temperature does not increase over, the fuel
remaining well cooled on long term. This case being bounded by the case (c), the PHTS pressure and SGs' water level are not presented.

(c) In this case, the LRVs already opened but they didn’t reduce the PHTS inventory till the SGs depressurization. Even if water is added 100 s after SGs depressurization, it is not enough to stop the tendency of PHTS pressure increasing, and for a short period of time LRVs and DGC-RVs will open and discharge some heavy water into containment. The heat removed by the water added into SGs will succeed to decrease the PHTS pressure and cool adequately the nuclear fuel. The maximum fuel surface temperature does not increase over 600 K.

(d) The case (d) is the limiting case analysed, in which the SGs depressurization followed by water addition into SGs can be considered still a success from the point of view of the fuel temperature. This can be seen in the graph presenting the maximum fuel surface temperature which indicates that the fuel become still well cooled, as the value of this parameters does not increase over 750 K, meaning less than 500 C (cladding failure is not expected at this temperature). On long term, this temperature remains almost constant, at around 400K. The LRVs-DGC-RVs opening allowed a large amount of heavy water to be discharged from the PHTS, approximately half of each loop inventory being lost. This discharge will probably conduct to the containment pressurization, situation that needs to be analysed.

**TABLE 1. COMPARATIVE BEHAVIOUR OF CANDU-6 PHTS AND SGs IN CASE OF SBO WITH SG’s DEPRESSURIZATION AND WATER ADDITION INTO SG’s AT DIFFERENT TIMES**

<table>
<thead>
<tr>
<th>SGs water level (m) – over tube-sheet</th>
<th>ROH pressure (Pa)</th>
<th>Maximum fuel surface temperature (°K)</th>
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</thead>
<tbody>
<tr>
<td>(a) for SGs depressurization at 2200s, and water injection into SGs 100s later</td>
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<tr>
<td>(b) SGs depressurization at 7200s, and water injection into SGs 100s later</td>
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<tr>
<td>(c) SGs depressurization at 9000s, and water injection into SGs 100s later</td>
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6. CONCLUSIONS

This sensitivity study has indicated that SGs can become and remain an efficient heat sink following a SBO event at a CANDU-6 NPP, when the SGs depressurization is performed before 3 h following the SBO initiation and water is added in less than 100 s, with a minimum flow rate of 40 l/s.

SGs depressurization followed by water addition are able to maintain the efficient core cooling and integrity, preventing the severe core damage.

In case of a very late SGs depressurization followed by water addition (between 9000-10800 s), even if the fuel surface temperature indicates a success regarding the fuel cooling, a significant amount of heavy water can be discharged from the PHTS through LRVs – DGC-RVs open valves and can possible determine the containment pressurization over the containment spray setpoint. This situation needs to be analysed separately, as well as the configurations in which BMW isolation valves and MSSVs could be. Therefore, it is considered that SGs depressurization and water addition from the dousing tank through the BMW isolation valves after 2.5 hours from the SBO event initiation are risky and not recommended because a containment breach could eventually occur in this case.

7. REFERENCES