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ANALYSIS OF CANDU6 REACTOR EARLY PHASE STATION BLACKOUT EVENT USING SCDAPSIM/RELAP5 CODE

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The paper presents the analysis of the early phase of a CANDU 6 station blackout using the SCDAPSIM/RELAP5 mod 3.6 code. Analyses of different assumption made which possibly have impact during this phase were performed.

Keywords: CANDU, station blackout, SCDAPSIM/RELAP5

1. Introduction

The loss of all alternative electrical power sources in a CANDU-6 plant as a result of a Station Black-Out (SBO) event will lead progressively to the degradation of the fuel element cooling.

During the early phase of SBO, as the Heat Transport System (HTS) loss his inventory, the fuel and the pressure tubes (PT) will heats up. The temperatures profile of PT, most probably, will be non-uniform due to the stratified flow condition within the fuel channels. As HTS pressure is still high at this moment, this non-uniform circumferential temperature distributions lead to pressure tube rupture. The present fuel channel rupture criteria assume that the pressure tube fails when it reaches a temperature at which it starts to deform (balloon). Therefore, the value of 1000 K at pressure tube inner surface is used for the present analyses [1].

Once the rupture of pressure tube occurs, the high pressure primary coolant will be discharged into calandria vessel (CV). Consequently, the pressure inside the calandria vessel increases rapidly and reaches the set point of the rupture disk. When the rupture disks open, a sudden decrease in the CV water level occurs due to initial rapid moderator expulsion into the containment. For CANDU plants, this point makes the transition from emergency operating procedures (EOP) to severe accident management guidance (SAMG) as clear and present threat of progression to a severe accident occurs [2].

The paper presents the analysis of the early phase of SBO which begins with the initiation of Station Black Out and ends with the blow of the calandria rupture disk. Analyses of different assumption made which possibly have impact

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on the timing of the pressure tube rupture were performed. The SCDAPSIM/RELAP5 mod 3.6 code [3] was used to perform this severe accident analysis.

2. CANDU6 plant model

Details of the SCDAPSIM/RELAP5 model of CANDU 6 plant, analysis methodology, assumptions and failure criteria used can be found in ref. [1], [4] and [5]. In practically all previously CANDU SBO analysis, the LVR are considered that discharge heavy water directly to the containment. In the present study, the overpressure protection of HTS in ensured by liquid relief valves (LRVs) that discharge heavy water from HTS into degasser-condenser (DGC). DGC overpressure protection is ensured by the discharge of steam and water into containment through the two spring relief valves, DGC-RVs. The model used for degasser-condenser is shown in Fig. 1.

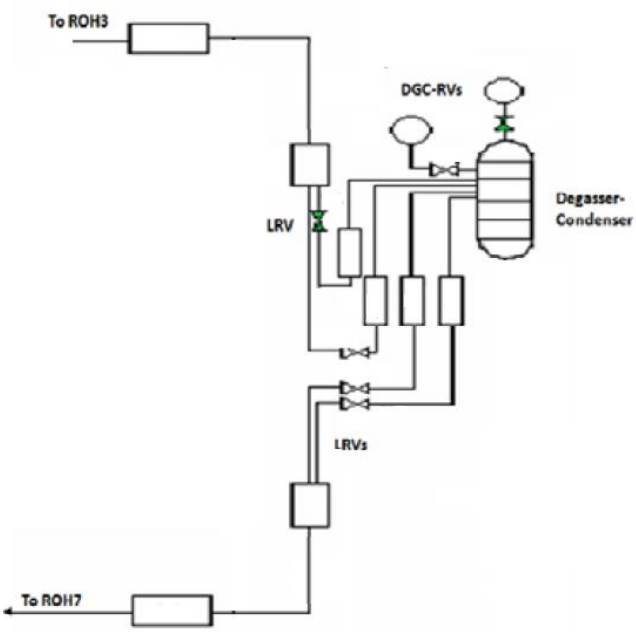

Fig. 1. Degasser-condenser model

For this study, nine sensitivity cases are performed to quantify the impact for the timing of rupture of pressure tube for different assumptions made during the early phase of the SBO scenario. These are:

– Impact of reactor power: (SC 1) to account for bulk reactor power uncertainties, the initial reactor power was assumed to be at 103% Full Power (FP). This is a common assumption made in design basis accident analysis for CANDU reactors to account for bulk reactor power uncertainties;

- Impact of steam generators secondary side leakages: there are two potential causes for SG mass inventory depletion during SBO: the SG blow down, normally 1%, and the check valve leakage [6]. To consider the impact of these possible secondary side leakages five cases were considered: 2.5 kg/s for each of all four SGs (SC 2), 1.5 kg/s for each of all four SGs (SC 3), 0.5 kg/s for each of all four SGs (SC 4), 2.5 kg/s for only one SG (SC 5), 2.5 kg/s for two SGs, one per loop, (SC 6).
- Impact of steam generators depressurization: injection of water into SGs is a main accident mitigation measure in case of a SBO event. However, in order to inject water from dousing tank or by Emergency Water System, the steam generators must be depressurized. Three cases were considerate: SGs depressurization at 15 minutes after loss of power followed by failure of water injection, (SC 7), SGs depressurization after 15 minutes followed by 30 l/s make-up water injection for all SGs (SC8) and SGs depressurization after 15 minutes followed by an amount of 30 l/s make-up water injection for all SGs concomitant with 2.5 kg/s secondary side leakage per SG (SC 9).

3. SCDAPSIM/RELAP5 analysis results

The accident phenomenology and timing of the main events during the early phase of CANDU 6 SBO event is well described in ref. [1]. First, the SBO scenario was run using the base case (BC) model. After SBO initiation, the pressure in both loops decreases rapidly with time, as the heat extracted initially from the coolant at SGs location is greater than the heat input to the coolant due to the loss of fission power from the reactor core, Fig. 2. During this phase of the SBO event, there are four heat sinks for the primary coolant: SGs, the main heat sink, the calandria vessel water, heat loss to environment and the end shield water. Pressure stabilized at about 8 MPa when heat extracted by the heat sinks match the decay heat generated in the core. Since feed water cannot be provided to SGs secondary side, the SGs mass inventories and therefore the water level in the steam generators continuously decrease as a result of boil-off, Fig. 3.

After the SGs secondary side inventories are depleted, at 7800 s, the SGs are no longer a heat sink to remove heat from HTS and the pressure in the HTS start to increase, as the remaining heat sinks are not sufficient to remove the decay heat. The pressure increases until it reaches the HTS liquid relief valve set point and then it oscillates at the relief valve set point as the coolant is discharged into the degasser-condenser. As DGC pressurize and fill with the coolant discharged from HTS, the pressure in HTS starts to increase again. This will cause the DGC-RV to open and the pressure drops, Fig. 2.

Although the amount of heat transferred to the moderator from the fuel channels and heat loss to the environment increases after SG dry-out, the loss of SGs as heat sink together with the continuous loss of inventory through the LRVs result in a rapid increase of average HTS void fraction and decrease of loops inventory. The cessation of the natural circulation flow in HTS would cause the coolant to boil off and to gives a rapid rise of the fuel channel temperatures. When pressure tube wall reaches 1000 K, the fuel channel ruptures. This occurs at 13 561 s (3.77 h).

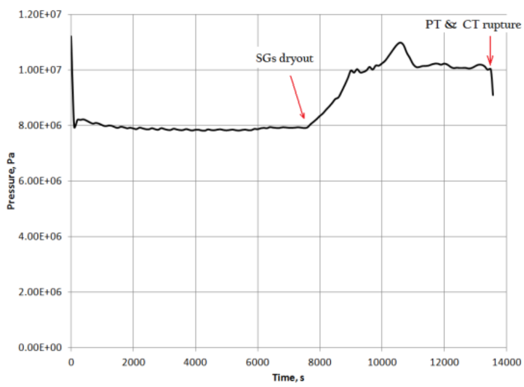

Fig. 2. HTS pressure

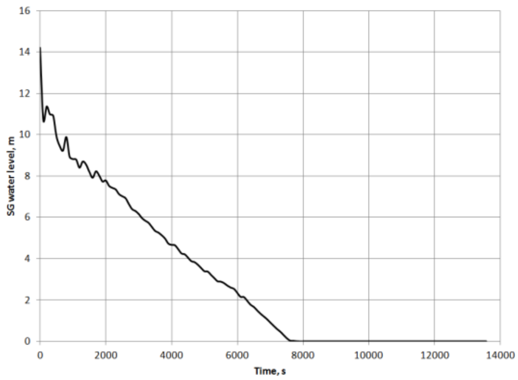

Fig. 3. SG water level

Two significant timing of events was considered to quantify the impact of different assumption made during the early phase of Station Blackout Scenario: the SGs secondary side dry-out and the opening of the calandria vessel rupture disks (which happen almost simultaneous with the pressure and calandria tubes rupture). Table 1 presents the results obtained for the base case and for the nine sensitivity study cases.

As can be seen from Table 1, for all analyzed cases, the 103% initial reactor power has the lowest impact on SGs dray-out and pressure tube rupture timing. However, for this case, not only the initial heat load to the steam generator and the energy stored in the fuel and HTC is greater than in the base case, but also the decay heat input is 3 % greater than in base case.

Steam generators secondary side leakages were modelled using a valve component connected to the lowest downcommer volume. During the entire period of SBO analyzed, the SGs pressure oscillates around main steam safety valves (MSSV) set point as the MSSVs opens and closes. This change in SGs pressure influences the leakage flow rate which in turn will oscillate, Fig. 4. Hence, the average leakages flow until the steam generators become dry, were: 2.24 kg/s for SC 2, 1.12 kg/s for SC 3 and 0.29 kg/s for SC 4.

Table 1

List of Significant significant timing of events for early phase of Station Blackout Scenario

Case	SG secondary sides are dry		Calandria vessel rupture disks #1-4 open	
	[s]	[h]	[s]	[h]
BC	7,800	2.17	13,561	3.77
SC 1	7,500	2.08	12,688	3.52
SC 2	4,500	1.25	8,991	2.49
SC 3	5,500	1.53	10,137	2.82
SC 4	6,800	1.89	11,784	3.27
SC 5	6,900/7,300	1.92/2.03	12,468	3.46
SC 6	6,900/7,300	1.92/2.03	12,337	3.43
SC 7	3,100	0.86	10,518	2.92
SC 8	13,600	3.78	-	-
SC 9	2,700	0.75	-	-

The SGs secondary side leakages have an important impact on SGs dray-out and pressure tube rupture timing. Even a low leakage flow rate, 0.29 kg/s on average, reduce the timing of SGs dray-out with about 17 min and the pressure tube rupture with about 30 min whereas a large leakage flow rate, 2.24 kg/s on average, reduce the timing of SGs dray-out with 55 min and the pressure tube rupture with about 1h and 16 min, Figs. 5 and 6. However, the effect of leakages, even for a large leakage flow rate, is greatly reduced when only one SG or one SG per loop is affected (Table 1).

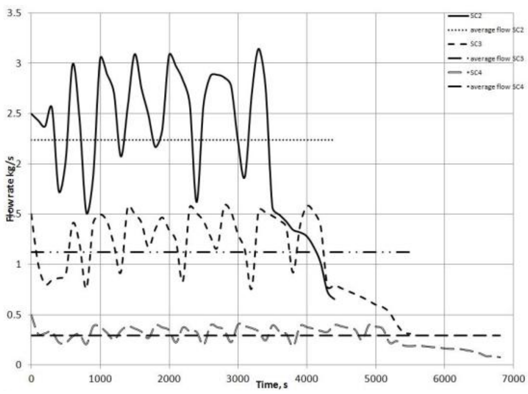

Fig. 4. SGs leakage flow rate

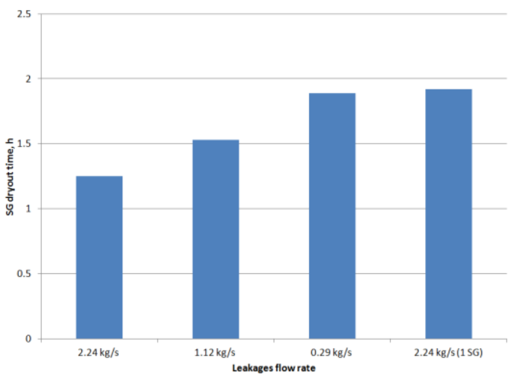

Fig. 5. SG dry-out time

Following the SGs depressurization the water level on secondary side drop considerably due to rapid vaporization of secondary side water (flashing), Fig. 7. The steam generators depressurization followed by failure of water injection has the most significant impact on SGs dray-out. In this case, SC7, SGs dry-out occurs after about 52 minutes. However, as depressurization of SGs lead also to the HTS depressurization, the increase of HTS pressure to the LRV opening set point is slower, Fig. 8, and the pressure tube rupture happens after 2h and 55 min, later than in SC2 and SC 3 cases.

If the SGs depressurization is followed by make-up water injection, even if the SGs dry-out occurs temporarily, the SGs level start to slowly increase as the make-up water is injected and the level of the decay heat generated into the core decrease in time, Fig. 7. Consequently, the PT temperature after initial growth begins to decrease without reaching the PT rupture temperature threshold, Fig. 9. The SGs secondary side leakages have impact only for the first 15 min of transient as the SGs depressurization practically stops leakages, Fig. 10.

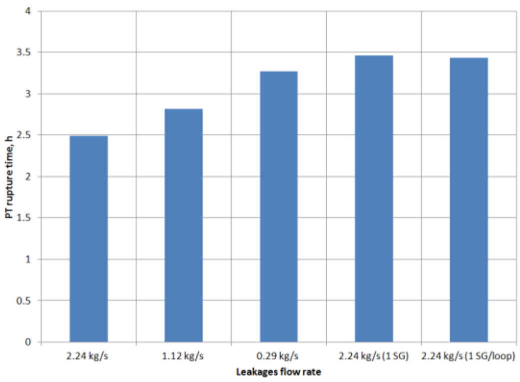

Fig. 6. PT rupture time

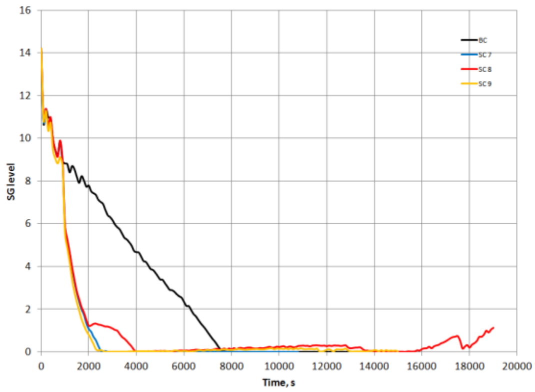

Fig. 7. SG water level

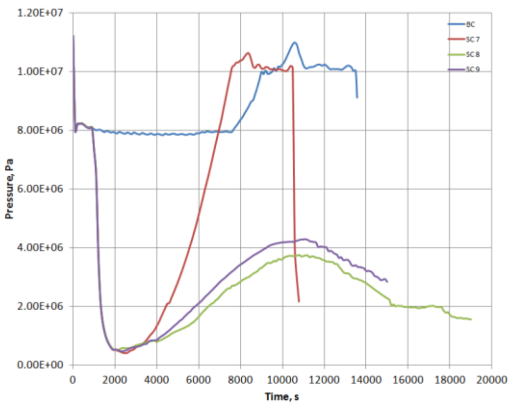

Fig. 8. HTS pressure

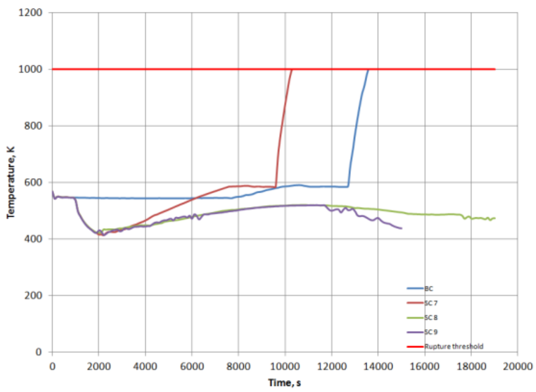

Fig. 9. PT temperature

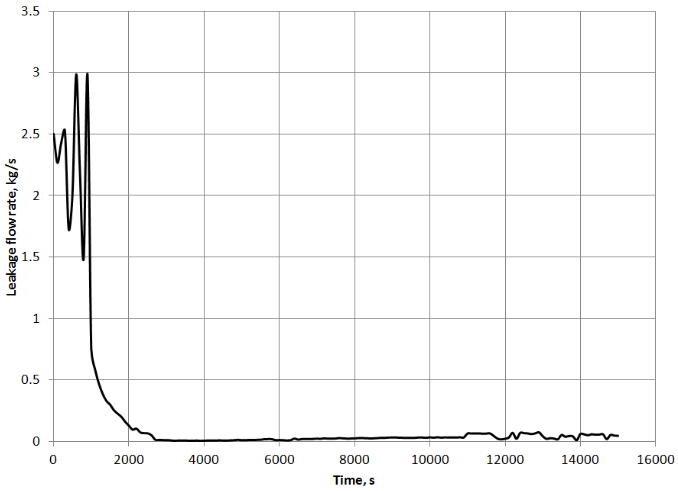

Fig. 10. SGs leakage flow rate case SC 9

4. Conclusions

The SCDAPSIM/RELAP5 mod 3.6 code was used to perform the sensitivity analyses to quantify the impact for the timing of the rupture of pressure tube for different assumptions made during a SBO scenario. The main results of this study can be summarized as it follows:

- Assumption of 103% initial reactor power lead to practically the same SG dry-out time, 5 min earlier, and a earlier pressure tube rupture event with about 15 minutes.
- Large SGs secondary side leakages have significant impact both for SG dry-out and for pressure tube rupture time. The effect is considerably reduced if only one SG per loop is affected by leakages or if the leakages are small.
- A leakage flow rate of 2.24 kg/s per SG for all steam generators give the fastest time for pressure tube rupture: 2.49 h.
- An earlier SGs depressurization, after 15 minutes, followed by 30 l/s make-up water injection for all SGs is an effective method to avoid pressure tube rupture even the SGs are affected by large secondary side leakages.

R E F E R E N C E S

[1]. "Benchmarking Severe Accident Computer Codes for Heavy Water Reactor", IAEA-TECDOC-1727, Vienna, 2013

[2]. *Nguyen, T., et al.*, Development of severe accident management guidance (SAMG) for the Canadian CANDU6 nuclear power plants, Nucl Eng Des (2007), doi:10.1016/j.nucengdes.2007.08.005

[3]. *C. M. Allison, J. K Hohorst.* Role of RELAP/SCDAPSIM in Nuclear Safety, TOPSAFE, Dubrovnik, Croatia. September 30-October 3, 2008 [4]. Benchmarking Severe Accident Computer Codes for Heavy Water Reactor Applications -IAEA TECDOC SERIES, TECDOC No. 1727, International Atomic Energy Agency, Vienna, 2013

[4]. *E. Dinca, D. Dupleac, I. Prisecaru*, "Analysis of the CANDU-6 plant behavior in case of very late steam generators depressurization and water injection following a station black-out accident", U.P.B. Sci. Bull., Series C, Vol. 78, Iss. 4, 2016

[5]. *E. Dinca, D. Dupleac, I. Prisecaru*, "RELAP/SCDAP simulation results for CANDU 6 accident management measure: primary heat transportsystem voluntary depressurization following a station blackout", U.P.B. Sci.Bull., Series C, Vol. 78, Iss. 3, 2016

[6]. *Sunil Nijhawan*, "Revised Submission to the CNSC Public Hearing on Ontario Power Generation Application to Renew the Reactor Operating Licence for Darlington Nuclear Reactors Hearing Number Ref. 2015-H-04", November 2-5, 2015, https://durhamnuclearawareness.com/wp-content/uploads/2015/11/Sunil-Nijhawan.pdf