U.P.B. Sci. Bull., Series C, Vol. 81, Iss. 1, 2019 ISSN 2286-3540

UNCERTAINTY ANALYSIS CONSIDERING THE IMPLEMENTATION OF EARLY ACCIDENT MANAGEMENT MEASURES FOR CANDU REACTORS

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This paper is been focused on the uncertainty analysis of the early phase of a Station BlackOut accident considering the implementation of the early accident management measures such as SGs depressurization and water injection short and long after the depressurization moment. The objectives of the BEPU approach are: using a best-estimate code for the simulated accident scenario, the selection of the input parameters based on their impact on the failure criterion for the fuel channel, the determination of their associated uncertainty in terms of PDFs (Probabilistic Distribution Functions), the random sampling of the parameters based on the defined uncertainty, the code executions using the random samples, and the application of order statistic theory to determine the uncertainty regions for the limiting output quantities.

Keywords: Uncertainty, Best estimate, CANDU, Station BlackOut

1. Introduction

The worst nuclear accident after Cernobil (in august 1986), the Fukushima Daichii accident from March 11th, 2011 has increased nuclear experts' interest, all over the world, on the implementation of severe accident management measures. The Fukushima Daichii NPP, comprised of 6 BWR (Boiling Water Reactor) units, has gone through an earthquake causing damage to the electric power supply lines to the site, followed by a tsunami which caused substantial damage of the operational and safety infrastructure on the site. The combination of these two events led to a total loss of off-site and on-site electrical power, known as Station BlackOut accident. Due to unavailability of any source of cooling, Units 1-3 fuel melted, and the pressure vessel failed releasing hydrogen to the containment, which has eventually led to explosions damaging the reactor building and releasing radioactivity into atmosphere.

Even though CANDU reactors are different from BWRs, the effect of an unmitigated SBO accident could turn into a real challenge for the plant's components and systems, but also for the environment and population. A SBO

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accident in CANDU reactors is initiated by a total loss of off-site AC power concomitant with the turbine trip and the unavailability of the Class IV and the backup power (loss of all on-site standby and electric power supplies, the diesel generators). The present analysis includes a BEPU (Best Estimate Plus Uncertainty) approach using RELAP/SCDAPSIM best estimate tool with the integrated uncertainty package implemented in the code of a SBO scenario considering early severe accident management measures being implemented, which will be described in the next sections.

Even though RELAP/SCDAPSIM was initially designed for LWR thermal-hydraulic and safety analysis, UPB experts in nuclear engineering have started to analyze the applicability of the code to CANDU 6 reactors. In 2004 UPB and Nuclear Research Institute joint efforts to develop a generic CANDU 6 plant model which was used to analyze such a reactor behaviour during normal and accident conditions, such as: breaks in the pipes of the primary heat transport system: LOCA/LOECC accident [1], [2], a channel blockage transient [3] etc. An overview of the analyses performed at UPB with the RELAP5/SCDAPSIM code was included in [4]. RELAP/SCDAPSIM code has been used previously to analyze an unmitigated SBO accident in CANDU 6 reactors [5], [6], [7], and also with the accident mitigation measures [8], [9]. The studies performed have shown the capability of the RELAP/SCDAPSIM code for analyzing severe accident in CANDU reactors, and also the effectiveness of the management measures in limiting the accident progression. The management measures consisted in depressurizing and water injection in the secondary side of the SGs (Steam Generators), acting as a heat sink in severe accident scenarios; by recovering these boilers and showing that the fuel cladding temperature remains under the failure criterion.

This paper presents the effects of the uncertain parameters during the mitigated SBO accident in a CANDU 6 reactor, based on the reference case - considered being the unmitigated SBO accident, the study being performed in order to compare the evolution and effects of the resulted essential parameters (output parameters) from a severe accident scenario with the reference case where no management measures have been implemented. The reference case uncertainty analysis has been performed before by the authors in order to determine the moment of the SGs secondary side dryout time interval, becoming the reference case for the management measure implementation (depressurization of the SGs and water addition before and right after the evaluated dryout time interval, considered as early depressurization of the SGs). The uncertainty analysis of the SBO accident in a CANDU 6 reactor with severe accident management measures implemented has not been performed before this moment. A previous study on the uncertainties in CANDU 6 was performed for a LOCA (Loss of Cooling Accident) for a 35% break in the reactor inlet header [10].

2. Uncertainty package in RELAP/SCDAPSIM

The uncertainty package implemented in RELAP/SCDAPSIM/MOD3.4 allows the automatic execution of an uncertainty analysis based on the probabilistic "input uncertainty propagation" approach of the BEPU methodology developed by CSN-UPC (see reference [11]). The characteristic steps of this approach are: the use of the RELAP/SCDAPSIM best-estimate tool to simulate the SBO scenario, the selection of a set of input parameters based on their impact to the failure criteria[4], their associated probabilistic distribution functions (PDF's), meaning their uncertainty, the random sampling of its based on the defined uncertainty, the code execution using the generated random samples, and the application of order statistics theory to determine the uncertainty regions for the restrictive output quantities, *i.e.* the failure criteria. In addition, the Wilks' formula determines the number of required code execution to estimate the i^{th} percentile of the output quantity given a certain confidence level, that being independent of the selected parameters to perturb.

A complete uncertainty analysis using RELAP/SCDAPSIM tool requires the execution of three related phases, as follows [11]:

- The "setup" phase, which generates the total number of sampled values (also called "weights") and information needed to build the tolerance bounds during the "post-processing" phase. The weights are used to associate uncertainty to code parameters by applying them as multipliers to the base values. During this phase the code also computes the required number of code runs by using the Wilks' formula, or simply uses the value supplied by the user. The informations need to be inclluded in the reference case input file along with the input parameters. The input parameter are two types: "input treatable parameters", referring to the ones from the regular input deck, and "source correlation parameters", being parameters treated from the source code correlations.
- The "simulation" phase, which consists of the reference case run in which the simulation is done as if there were no uncertainties associated to any of the parameters, and the set of uncertainty runs which have associated to the selected parameters the range of variation.
- The "post-processing" phase, consists in reading the restart-plot files written during the reference case and the uncertainty runs and generating the rank matrices for the output quantities defined in the "post-processing" input file. The rank matrices contain the values for the output parameters sorted according to its rank and are used to determine the tolerance intervals.

[4] According to [12], the severe accident scenario (such as the proposed Station BlackOut scenario) will refer to failure criteria, not to safety criteria, since the integrity of the core (the fuel channel, calandria vessel etc.) is assumed to be lost at some point of the analysis.

3. Analysis methodology and assumptions

For the purpose of this paper, the SBO scenario in a CANDU 6 reactor has been selected, and it will be carried up until the pressure tube failure (since the present model for CANDU 6 build in RELAP/SCDAPSIM code becomes uncertain for the following stages of the accident, and another reason is that the code does not include CANDU specific models).

For the proposed SBO scenario, the main assumptions made were as follows:

- Class IV power and all onsite standby and emergency electric power supplies are unavailable;
- The unavailability of the Emergency Core Cooling System;
- Primary Heat Transport System loop isolation is not credited;
- SGs safety valves are available (with the set point for opening and closing to relieve pressure);
- Crash cool-down system credited;
- Air-operated atmosphere steam discharge valves are fail-closed;
- Pressurizer steam bleed valves are fail-closed;
- Moderator cover gas system bleed valves is assumed available;
- Some of the operator interventions are not credited.

The early phase selected for this analysis will be limited to 17000 s (from which the first 400 s refers to the steady state conditions). A previous analysis of the SBO accident scenario with no uncertainty associated [13] showed that the pressure tube failure occurs at about 14795 s from the beginning of the analysis performed. A recent uncertainty analysis [14] of this phase of the accident showed that the first fuel channel failure occurs in the time interval of 13600-15800 s.

The present analyses were focused on the impact of the uncertain parameters on the selected output parameters (pressure and mass flow in the PHTS, water level in the SGs, channels temperatures) with the depressurization of the SGs secondary side (1h after the initiating event, at 4000 s from the beginning of the analysis for two of the analyzed cases) followed by cooling water injection from the dousing tank. The crash cooldown will start with the depressurization of the SGs through the operator action by manually open the MSSVs to relief pressure from the secondary side and locking the valves in open position. The water injected into SGs is assumed to have 30°C, and the minimum flow rate that could be injected from the dousing tank is 30 l/s. A smaller amount of cold water (a total flow of 26 l/s) has been selected to be injected from the dousing tank by gravity into SGs (6.5 l/s per each SG) until the end of the analysis. The proposed scenarios regarding the time depressurization and water addition are as follows:

- case 1: depressurization of the SGs 1h after the initiating event (4000 s from the beginning of the analysis), and a constant cold water flow of 6.5 l/s per each SG short after the depressurization moment (100s after the depressurization time) until the end of the analysis;

- case 2: depressurization of the SGs 1h after the initiating event (4000 s from the beginning of the analysis), and a constant cold-water flow of 6.5 l/s per each SG long time after the depressurization moment (3600 s after the depressurization time) until the end of the analysis;

4. Reference input model and uncertainties

Unlike the PWRs (Pressurized Water Reactors) CANDU 6 reactor is a heavy water cooled and moderated reactor, using natural uranium as a fuel, and it has some unique features, such as, horizontal geometry (using 380 individual pressurized fuel channels, each channel containing 12 fuel bundles), two completely independent systems: Primary Heat Transport System shown in Fig. 1 and Moderator System shown in Fig. 2.

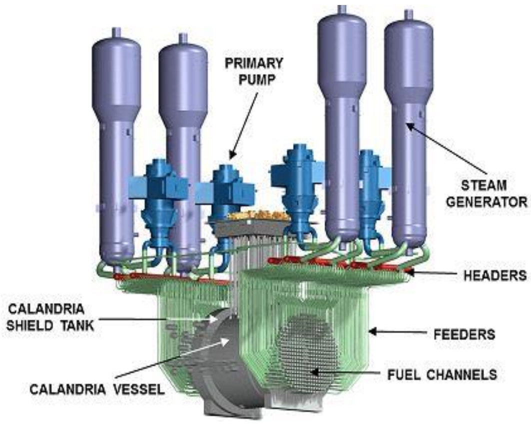

Fig. 1 Primary heat transport system [15]

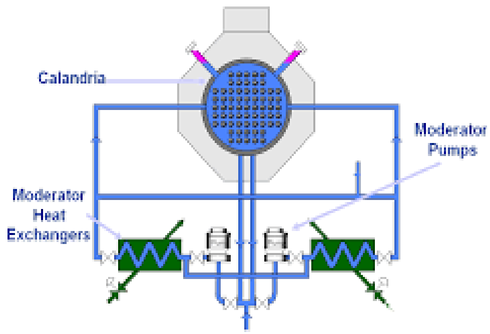

Fig. 2 Moderator System [15]

The primary heat transport system circulates heavy water (D_2O) through the horizontal fuel channels at high pressure and temperature (p=10 MPa and T_{in}=266°C, T_{out}=312°C) compared to the moderator system which contains heavy water at low pressure and temperature (p=1 MPa, T=70°C) in the horizontal cylindrical calandria vessel. The fuel channels are immersed in the moderator from the calandria vessel, this serving as an alternative source of cooling (removing approximately 5% of the heat produced in the core at normal operation) [15].

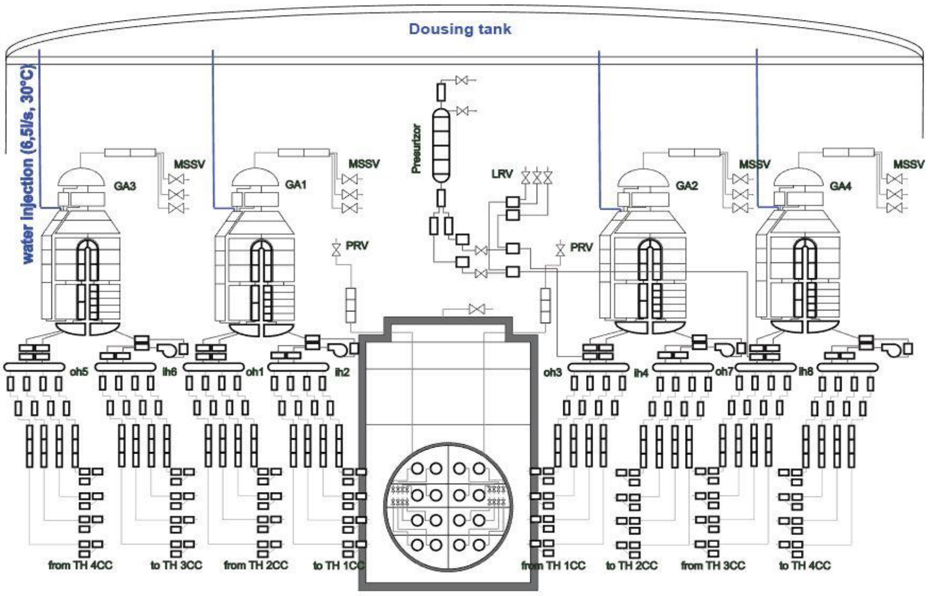

Fig. 3 CANDU 6 plant noding diagram in RELAP/SCDAPSIM[5]

The RELAP/SCDAPSIM nodalization of the CANDU 6 plant from the reference input deck is shown in Fig. 3. The PHTS contains 16 thermal hydraulic fuel channels (grouped based on the power distribution in the core and axial elevation, *i.e.* connection with the calandria vessel axial volumes) modeled as pipe components having 12 axial volumes corresponding to the 12 fuel bundles inside the channel, connected to the reactor inlet/outlet headers through 32 additional feeders. Calandria vessel has been modeled as two vertically oriented parallel pipe components having 4 axial nodes, one axial node being connected to each row of fuel channels (as depicted in Fig. 4) simulating the heat transfer from the fuel channel to the moderator.

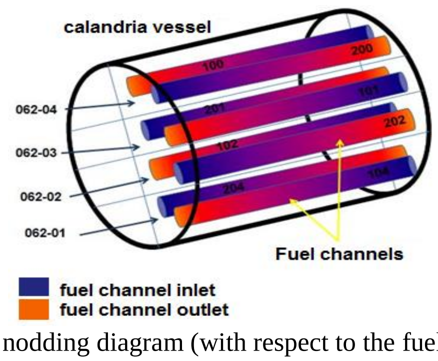

Fig. 4 Calandria vessel nodding diagram (with respect to the fuel channels arrangement)

[5] The noding diagram was developed by the author [16] for GRAPE (Graphical RELAP/SCDAPSIM Analysis Platform for Education and Engineering) based on the input deck for the CANDU 6 SBO developed at UPB.

For the uncertainty analysis a total number of 23 parameters were selected. The amount of parameters selected were organized into two groups depending upon the perturbation which could be applied directly in the regular input deck, the so-called input treatable parameters, or had to be implemented in the source files, the so-called source correlation parameters.

Regardless of the parameter's nature, the uncertainty package in RELAP5/SCDAPSIM allows the perturbation of the two groups of parameters in a similar way, without the need of neither modifying nor re-compiling the code; the required information is a list of the selected input parameters and their uncertainty information in the format of a multiplier factor. The selected parameters [13] are listed below in Table 1 and Table 2.

Table 1

Input treatable parameters

Input treatable parameters				
	Phenomena	Parameter	Distribution	Comments
1	Power	Initial core power	ND	Multiplier applied to the time power table for the initial power (±3%FP[6])
2		Power after scram	ND[7]	Multiplier applied to the time-power table for the power after scram.
3		Peaking factor	UD[8]	Multiplier applied to the central core nodes, which have the larger coefficients of the cosine power shape. The rest of the core nodes are multiplied by a normalization factor to keep the sum of the coefficients to 1.0.
4	Fuel channel behaviour	Thermal conductivity	ND	T≤1000K
5			ND	T>1000K
6		Specific heat	ND	T≤1800K
7			ND	T>1800K
8	Core	Form loss coefficients	UD	Multiplier applied to the junctions of the pipes modeling the core
9	Initial mass flow	Steady-state pump velocity	ND	Multiplier applied to the mas flow right after the pump stop (inertia moment)
10	SGs pressure	Local pressure loss coefficients in the secondary side of the SGs	LD[9]	Multiplier applied to the junctions of the volumes modeling the secondary side of the steam generators
		Initial pressure	ND	Multiplier applied to the initial pressure

[6] FP - full power
[7] ND - normal distribution
[8] UD - uniform distribution
[9] LD - log-normal distribution

Input treatable parameters				
11				of the secondary system (±3-5%P_{in})
12	Flow rate at LRVs	Discharge coefficient	ND	Multiplier applied to the pressure in the reactor inlet and outlet headers
13	Flow rate at MSSVs	Discharge coefficient	ND	Multiplier applied to the pressure in the steam dome of the SGs

Table 2

Source correlation parameters

Source correlation parameters				
	Phenomena	Parameter	Distribution	Comments
1	Heat transfer (SGs, fuel channels, moderator, containment)	Single phase liquid	UD	Heat transfer coefficient
2		Subcooled nucleate boiling	UD	Heat transfer coefficient
3		Saturated nucleate boiling	TD[10]	Heat transfer coefficient
4		Subcooled transition boling	TD	Heat transfer coefficient
5		Saturated transition boiling	TD	Heat transfer coefficient
6		Subcooled film boiling	TD	Heat transfer coefficient
7		Saturated film boiling	TD	Heat transfer coefficient
8		Single phase vapor	UD	Heat transfer coefficient
9		Condensation when void is less than one	UD	Heat transfer coefficient
10	CHF	CHF multiplier	LD	Groenveld lookup table method

5. Analysis and results

The execution phase consisted in 93 code runs, according to Wilks' formula (2nd order of application). According to order statistics theory, the 95/95 unilateral tolerance limit is given by rank number 92, i.e. the second largest value, and covers the 95th percentile of the output quantity with a confidence level of 0.95. On the other hand, the 5/95 unilateral tolerance limit is given by rank number 2, i.e. the second smallest value, and covers the 5th percentile of the output quantity with a confidence level of 0.95.

[10] TD - trapezoidal distribution

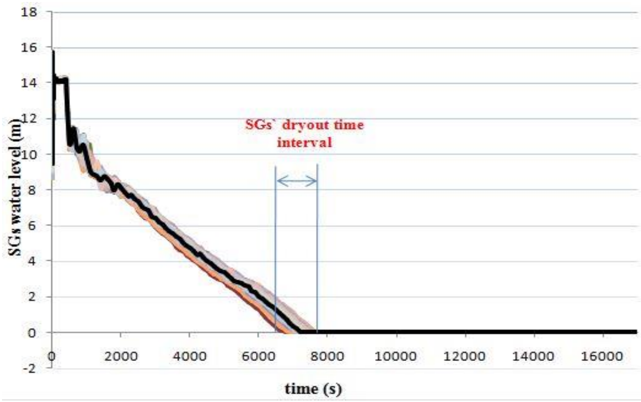

Fig. 5. SGs secondary side water level

Fig. 5 shows the SGs dryout moment when uncertainties are considered for the proposed SBO scenario, which is expected to occur in the time interval of 6700 - 7600 s.

- ***Case 1: SGs depressurizes 1h after the initiating event and water injected 100s after the depressurization moment (before SGs dryout)***

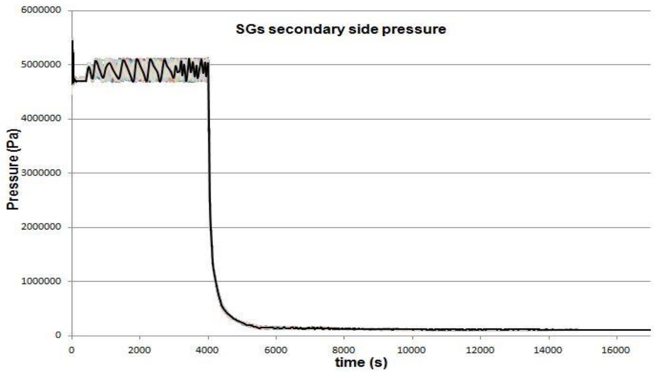

Fig. 6 SGs pressure in the steam dome

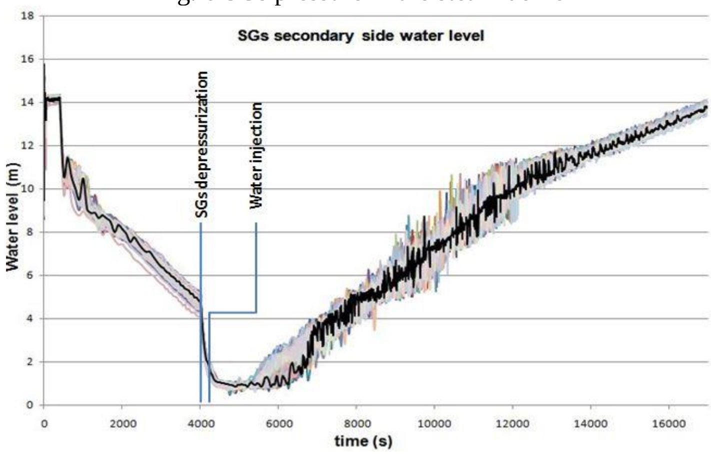

Fig. 7 SGs secondary side water level

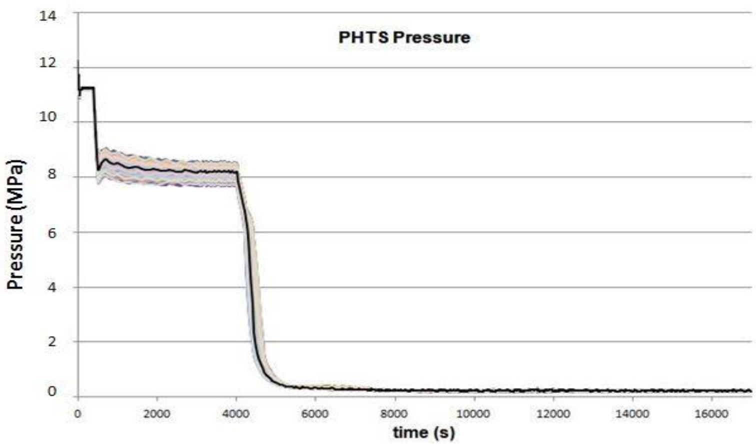

Fig. 8 PHTS pressure

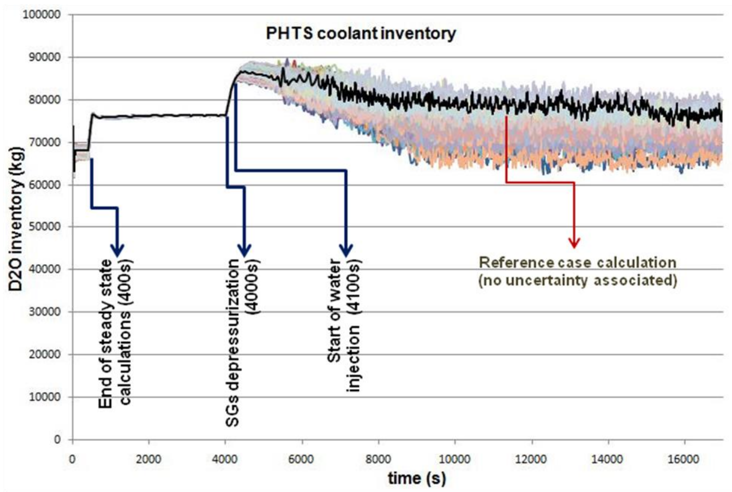

Fig. 9 PHTS D_2O inventory

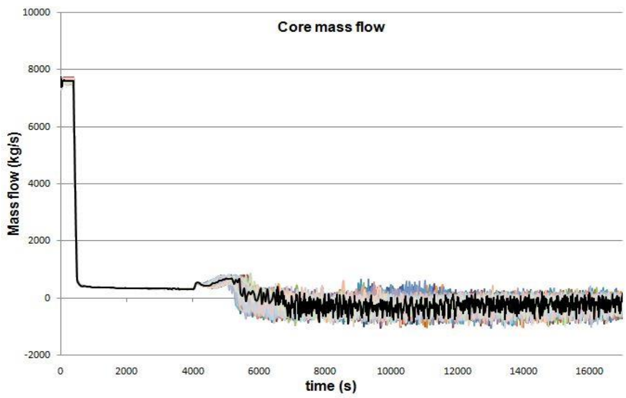

Fig. 10 Core coolant mass flow

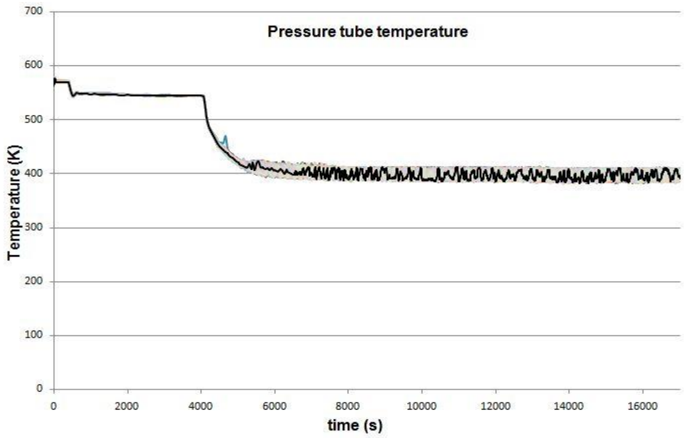

Fig. 11 Pressure tube inside surface temperature

- ***Case 2: SGs depressurizes 1h after the initiating event and water injected 1h after the depressurization moment (long after the SGs dryout)***

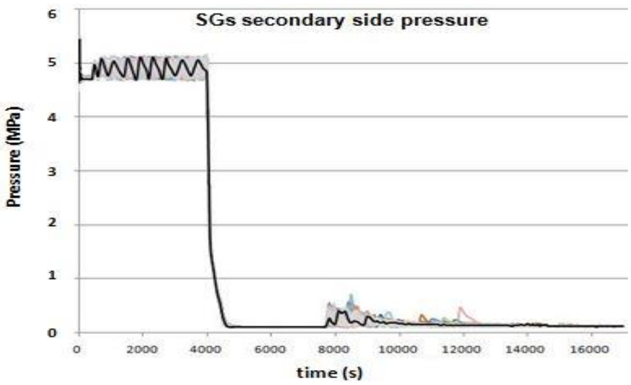

Fig. 12 SGs pressure in the steam dome

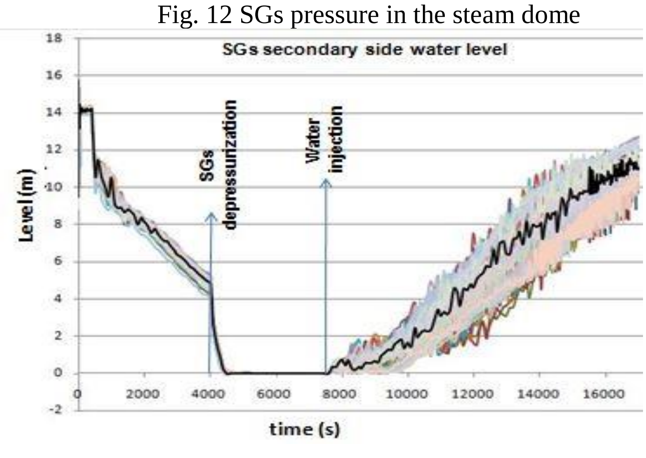

Fig. 13 SGs secondary side water level

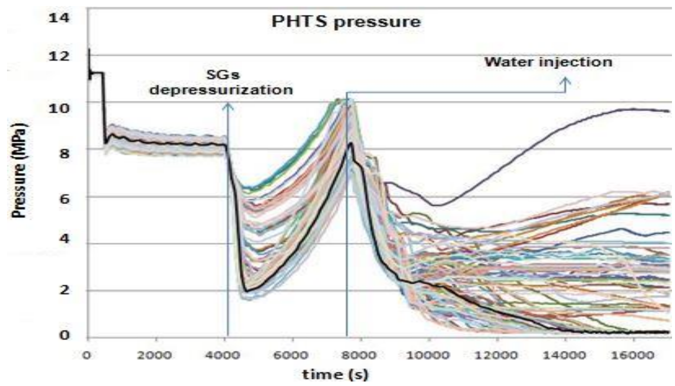

Fig. 14 PHTS pressure

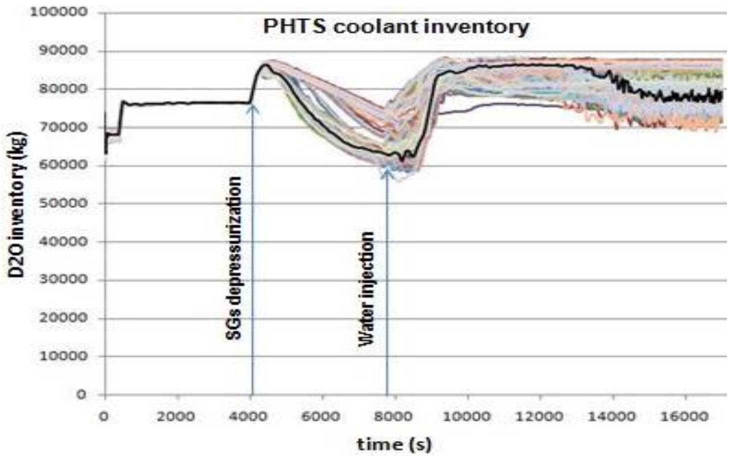

Fig. 15 PHTS D_2O inventory

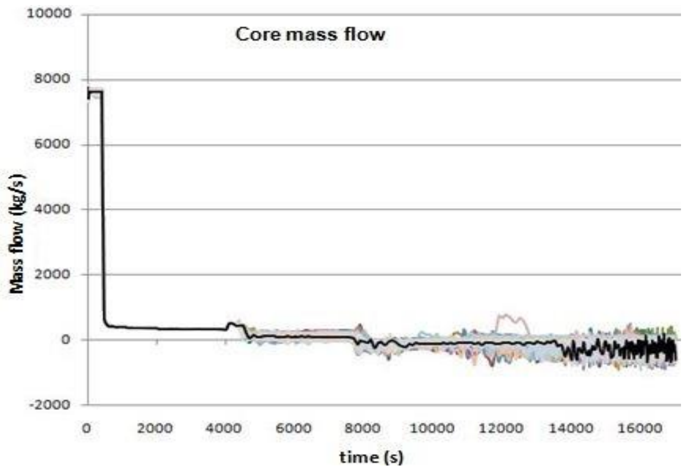

Fig. 16 Core coolant mass flow

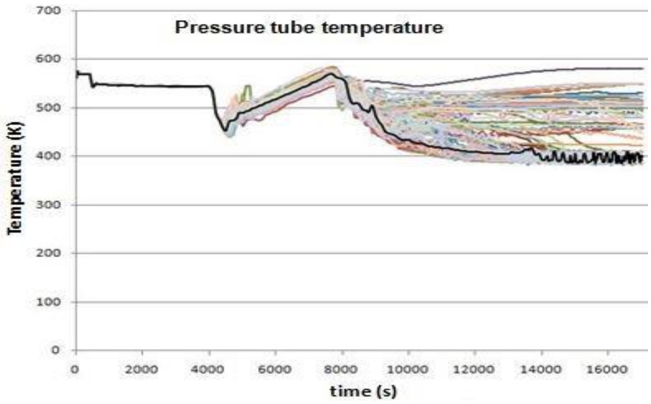

Fig. 17 Pressure tube inside surface temperature

5. Conclusions and discussions

The uncertainty package in RELAP/SCDAPSIM was successfully applied to the CANDU 6 SBO analysis. The lack of experimental data for a SBO accident in a commercial CANDU 6 reactor only allows a qualitative approach of this analysis. From the total amount of 23 parameters selected for the uncertainty analysis, only 10 of them are of source correlation type, and they are related to wall-to-fluid heat transfer (calandria tubes to moderator, fuel sheath to coolant, steam generators U tubes to secondary coolant, calandria walls and moderator etc.), critical heat flux, and fuel channel behavior. As for the input treatable parameters, the form of the uncertainty is defined through a multiplier defined by a PDF and its characteristic parameters.

Following the prescriptions for CANDU 6 under severe accident conditions, maintaining the integrity of the safety barriers (i.e. fuel pellet, fuel sheath, PHTS limits - pressure tubes and calandria tubes, calandria vessel) is the key aspect to look for. The SBO analysis with water injection in the secondary side of the SGs was performed to demonstrate the efficiency of the implemented measures when uncertainties are considered. Since the pressure tube inside surface temperature remains below 1000K (as prescribed in [12]), the accident management measures considered in the present analysis have proved to be efficient. It is noticeable that the water injection has a major impact on the uncertainty band, since the uncertainty band increases for most of the output quantities (water level in the secondary side of the steam generators, total core mass flow, PHTS coolant inventory, PHTS pressure - except for the case when water is injected right after the depressurization of the SGs, and pressure tube inside surface temperature). The analysis was limited to the early phase of the SBO accident due to the fact that beyond this point the present model for CANDU 6 reactors in RELAP/SCDAPSIM becomes uncertain.

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