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Station blackout analysis: Typical PWR response and investigation on possible operator actions

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STATION BLACKOUT ANALYSIS: TYPICAL PWR RESPONSE AND INVESTIGATION ON POSSIBLE OPERATOR ACTIONS

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List of Content

List of Figures

List of Tables

List of Abbreviations

CL	Cold Leg
ESF	Engineering Safety Feature
FW	Feed water
HL	Hot Leg
LOCA	Loss Of Coolant Accident
MCP	Main Coolant Pump
MSIV	Main Steam Isolation Valve
NPP	Nuclear Power Plant
PCT	Peak Cladding Temperature
PRZ	Pressurizer
PS	Primary Side
RPV	Reactor Pressure Vessel
RPV	Reactor Pressure Wessel
RV	Relief Valve
SBLOCA	Small Break LOCA
SBO	Station Black Out
SG	Steam Generator
UNIPI	University of Pisa

Summary

After Fukushima accident, a rising attention is posed on the strategy to cope with a station black out event. This report illustrates a preliminary study of a possible countermeasures applicable to a PWR.

Since the course of the accident is strongly influenced by the amount of water available in the steam generators the proposed strategy aims at maximizing the use of available water reservoir connected to the SG. Namely specific operator actions are tested to made usable mass of water stored inside the FW tank as to passively feed the SG guaranteeing their capabilities of cool down the reactor.

Two calculations are performed: the base case without any operator action and a second one with an Accident Management strategy in order to recover time to implement possible long term and continuative solutions.

1 Introduction

After Fukushima accident, a rising attention is posed on the strategy to cope with a station black out event. This report illustrates a preliminary study of a possible countermeasures applicable to a PWR.

Since the course of the accident is strongly influenced by the amount of water available in the steam generators the proposed strategy aims at maximizing the use of available water reservoir connected to the SG. Namely specific operator actions are tested to made usable mass of water stored inside the FW tank as to passively feed the SG guaranteeing their capabilities of cool down the reactor.

Two calculations are performed: the base case without any operator action and a second one with an Accident Management strategy in order to recover time to implement possible long term and continuative solutions.

1.1 Structure of the report

The report has four main chapters. Chapter three describes the nodalization used for the calculations, chapter four reports the obtained Steady State values. Chapter five reports and analyze the results of the calculations and chapter six fixes the conclusion and ideas for possible further investigation on the topic.

2 Adopted code description: RELAP5-3D

The selected code adopted to perform the analyses included in the present report is RELAP5-3D.

The RELAP5 series of codes has been developed at the Idaho National Laboratory (INL) under sponsorship of the U.S. Department of Energy, the U.S. Nuclear Regulatory Commission, members of the International Code Assessment and Applications Program (ICAP), members of the Code Applications and Maintenance Program (CAMP), and members of the International RELAP5 Users Group (IRUG). Specific applications of the code have included simulations of transients in light water reactor (LWR) systems such as loss of coolant, anticipated transients without scram (ATWS), and operational transients such as loss of feedwater, loss of offsite power, station blackout, and turbine trip. RELAP5-3D©, the latest in the series of RELAP5 codes, is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of vapor, liquid, non-condensable gases, and nonvolatile solute.

The RELAP5-3D© code is based on a non-homogeneous and non-equilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. The objective of the RELAP5-3D© development effort from the outset was to produce a code that included important first-order effects necessary for accurate prediction of system transients but that was sufficiently simple and cost effective so that parametric or sensitivity studies were possible.

The code includes many generic component models from which general systems can be simulated. The component models include pumps, valves, pipes, heat releasing or absorbing structures, reactor kinetics, electric heaters, jet pumps, turbines, separators, annuli, pressurizers, feedwater heaters, ECC mixers, accumulators, and control system components. In addition, special process models are included for effects such as form loss, flow at an abrupt area change, branching, choked flow, boron tracking, and non-condensable gas transport.

The system mathematical models are coupled into an efficient code structure. The code includes extensive input checking capability to help the user discover input errors and inconsistencies. Also included are free-format input, restart, renodalization, and variable output edit features. These user conveniences were developed in recognition that generally the major cost associated with the use of a system transient code is in the engineering labor and time involved in accumulating system data and developing system models, while the computer cost associated with generation of the final result is usually low (ref. [1]).

3 Description of the RELAP5-3D nodalization of the plant

The analysis was performed adopting Relap5-3D code using as a base input the sample case “typwr3d1.i” in order to avoid proprietary data issue. The selected input describes a typical four loop PWR with 3 loops collapsed, developed for SBLOCA calculation. For this reason the secondary side was roughly modelled and some details were completely missing (e.g. FW lines, FW tank, SG relief valves, etc.).

Many modifications both on TH and logical input deck sections have been implemented to make the nodalization suitable for the purpose of the present evaluation. Moreover a more accurate (i.e. closer to typical PWR data) and numerically stable steady state conditions were reached.

3.1 Improvement in primary side and secondary side modeling

To correctly implement the proposed strategy all the 4 loop have been modeled in order to simulate the behavior of all four SG independently. The steam lines were modeled by a PIPE component and to which the SG relief valves, modeled via TRIP VALVES with hysteresis, were connected. Two relief valves were modeled in each SG, where one valve was equivalent to three valves.

The SG play a crucial role in the SBO scenario, hence a correct prediction of their behavior is of a major importance. Following good nodalization practices (ref. [1] and ref. [4]) a sliced approach between SG down comer and SG riser was recovered splitting the DC in four volumes. Namely SG DC and riser are modeled by two parallel PIPE whose internal subdivision is equal for both components.

The turbine was modeled by four TIME DEPENDENT VOLUME in which the same TH conditions were set.

The FW system is not detailed represented however related piping and tanks are included in the model.

Due to the long lasting transient, the nodalization has been optimized to achieve fast computational response. Namely real time simulation can be performed running the code on a PC.

The following table reports the ESF expected to intervene in this transient together with their set points.

	Opening set point	Closure set point
	(MPa)	(MPa)
PRZ SRV	17.20	16.00
SG relife valves	8.37	7.96
Accumulator	4.14	Based on low level signal

Table 1 - ESF set points

The following set of figures (from Figure 1 to Figure 8) shows the sketch of the nodalization.

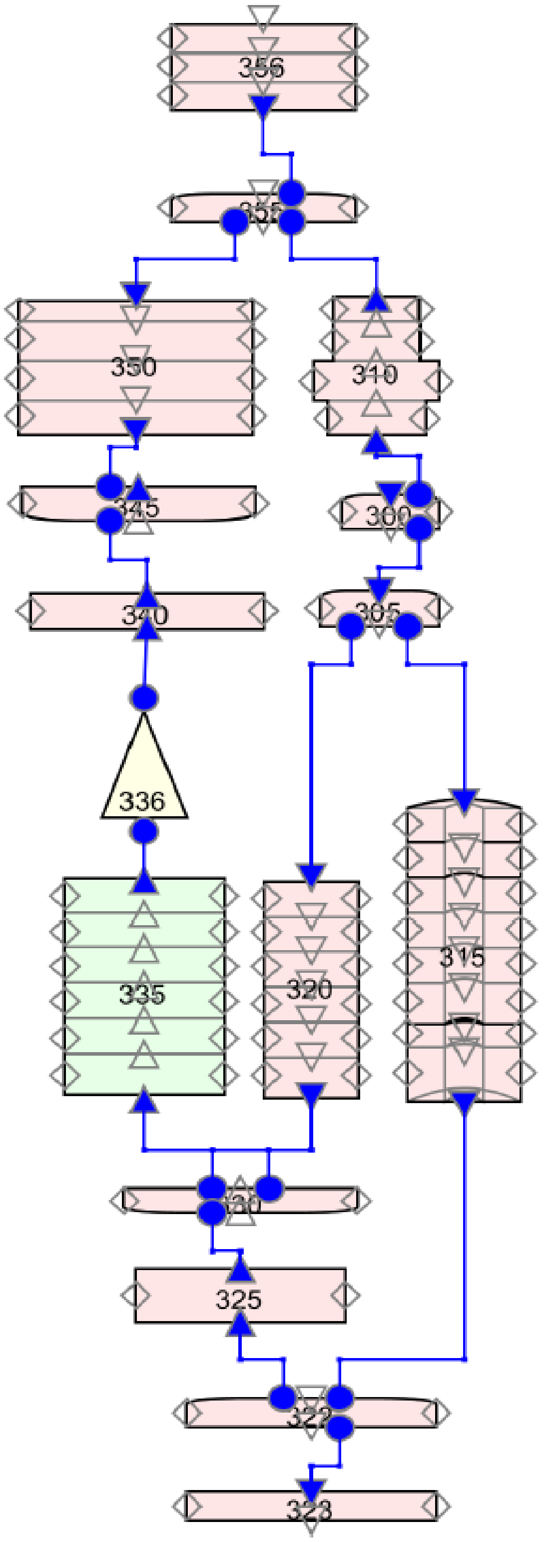

Figure 1 – RPV nodalization

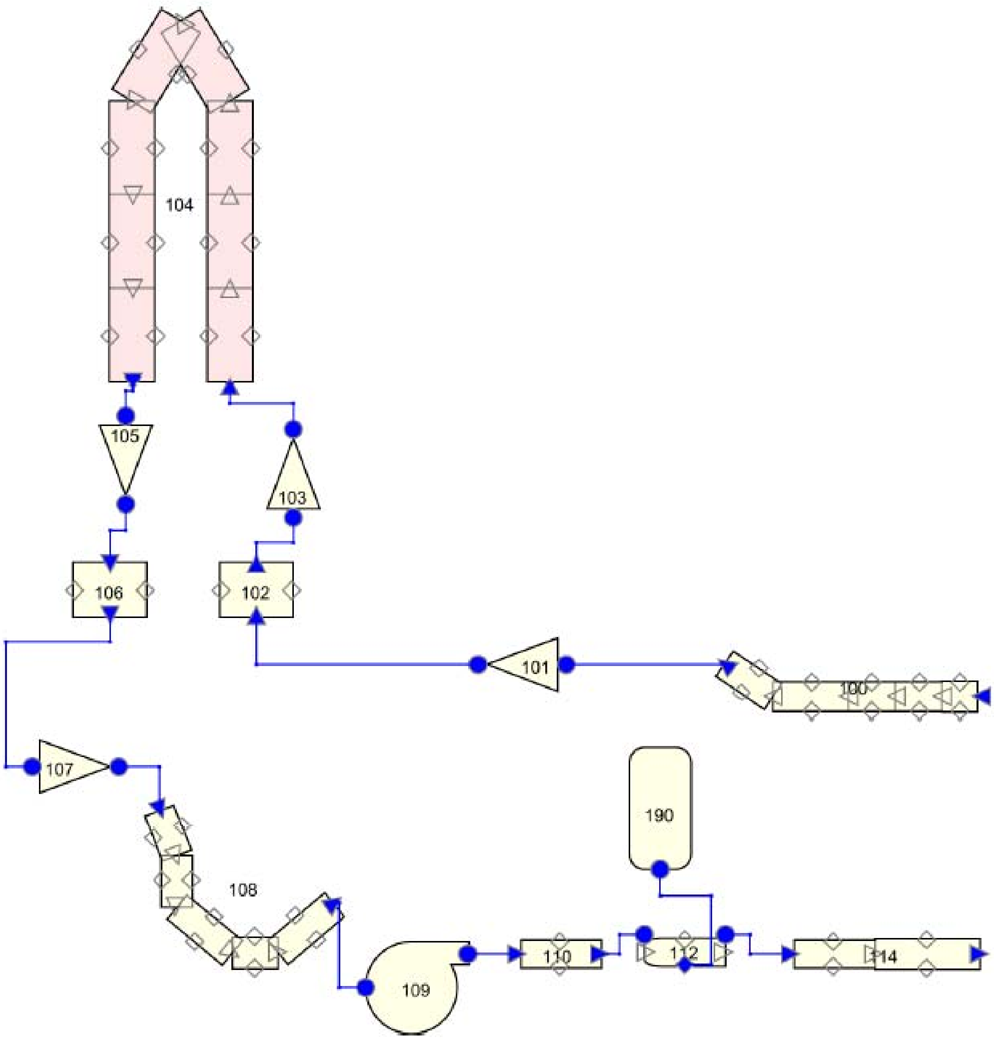

Figure 2 – Loop 1 nodalization, PS

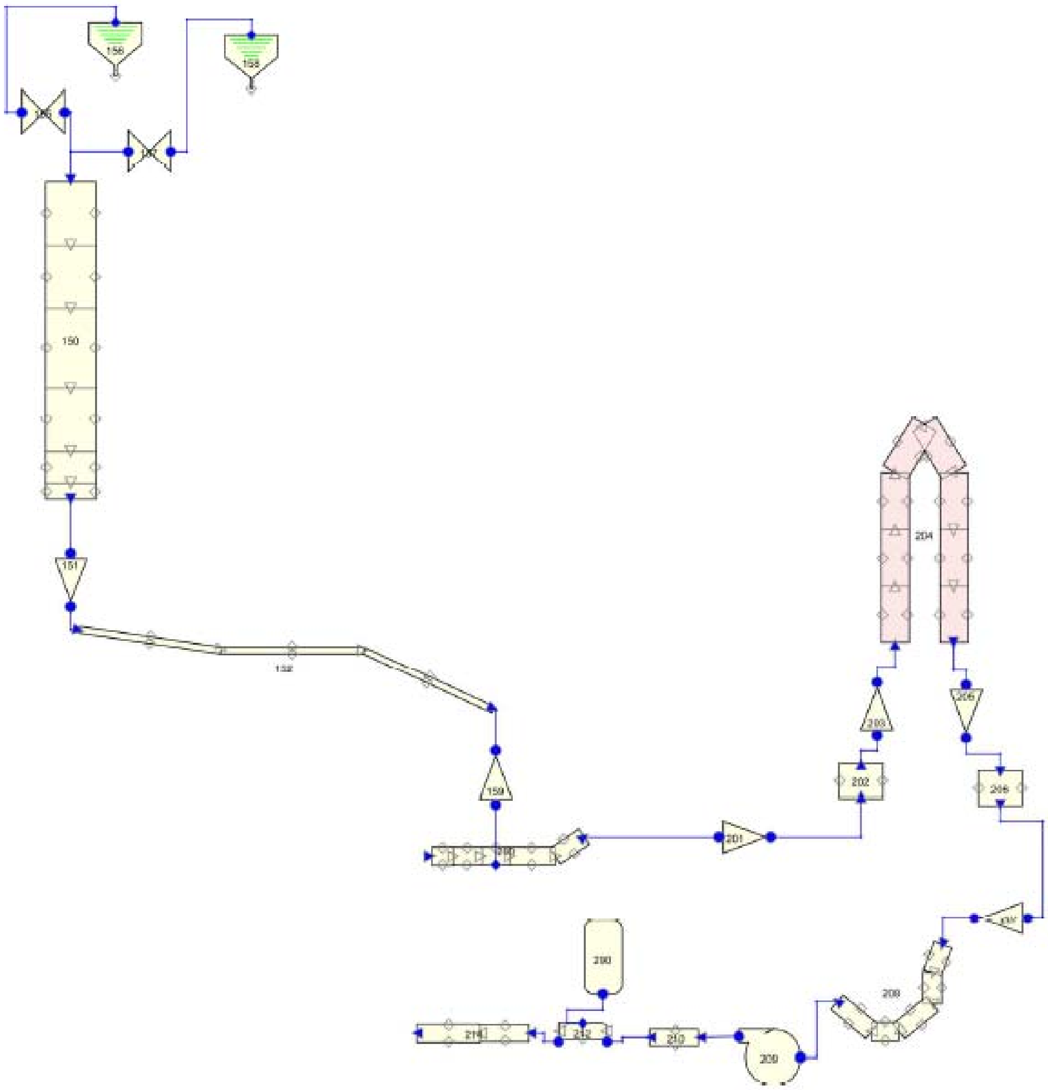

Figure 3 – Loop 2 nodalization, PS

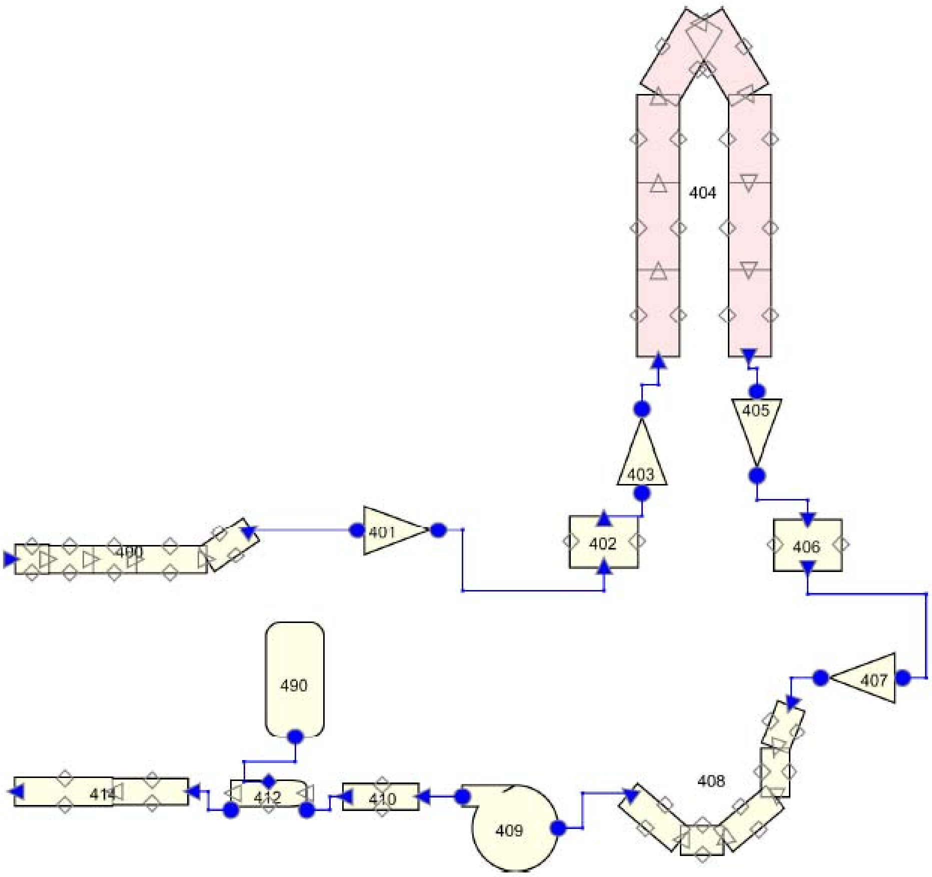

Figure 4 – Loop 3 nodalization, PS

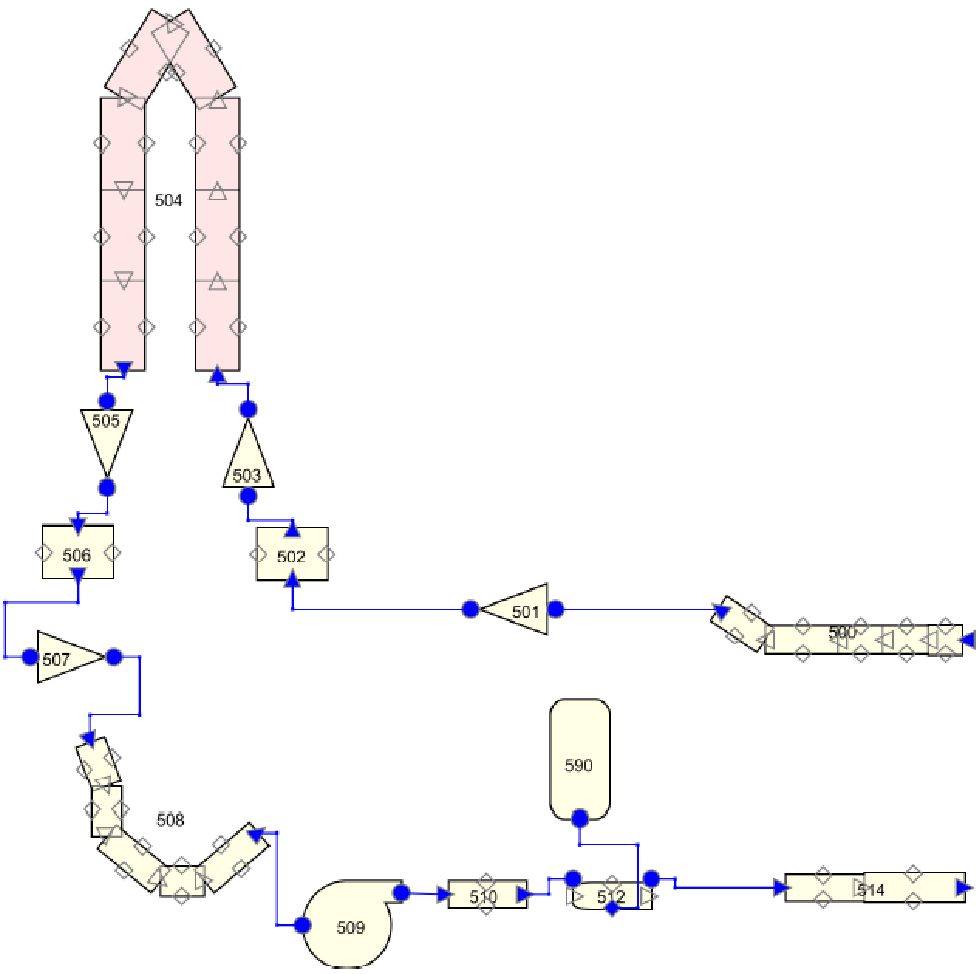

Figure 5 – Loop 4 nodalization, PS

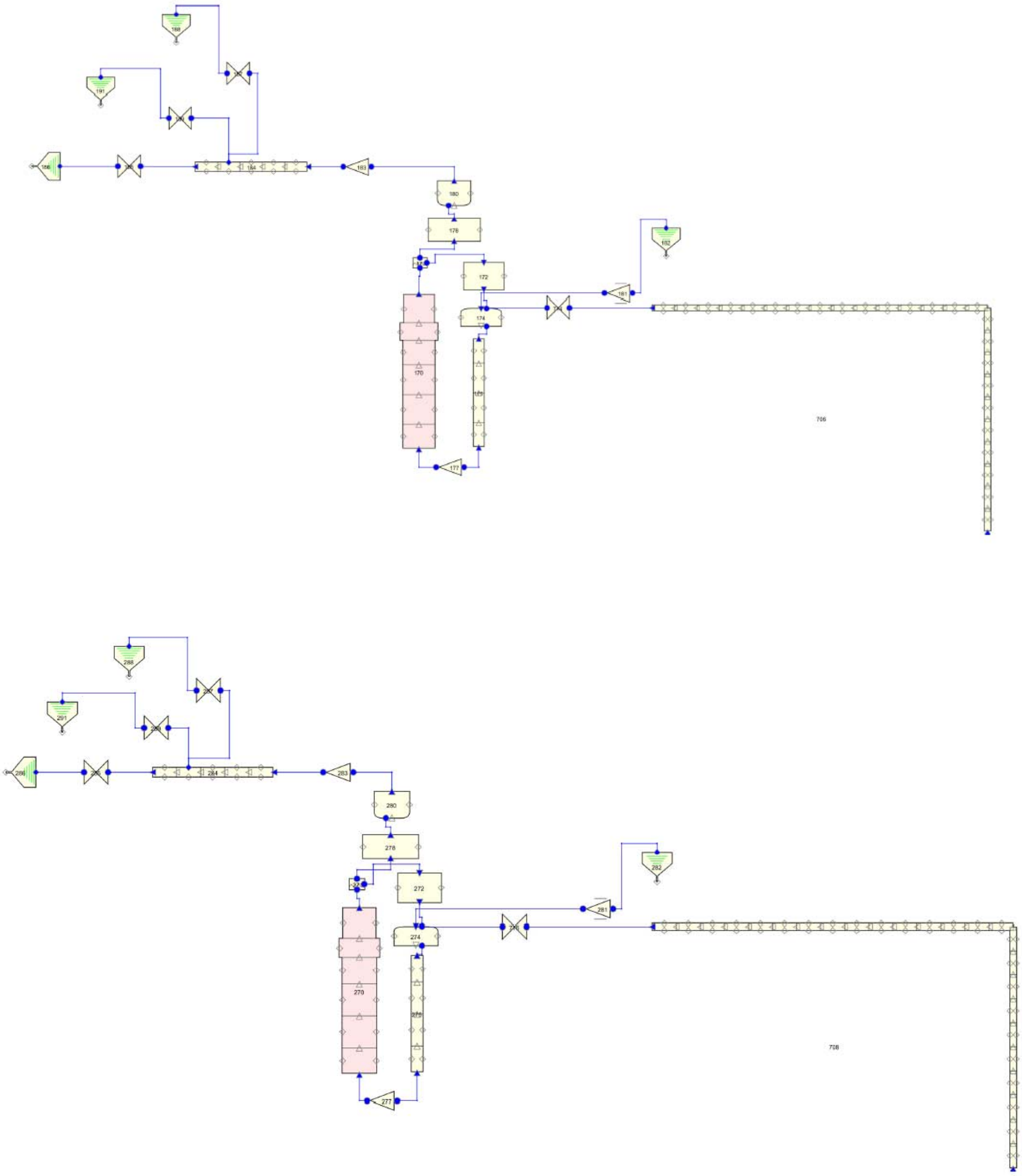

Figure 6 – Secondary Side 1 and 2 nodalization

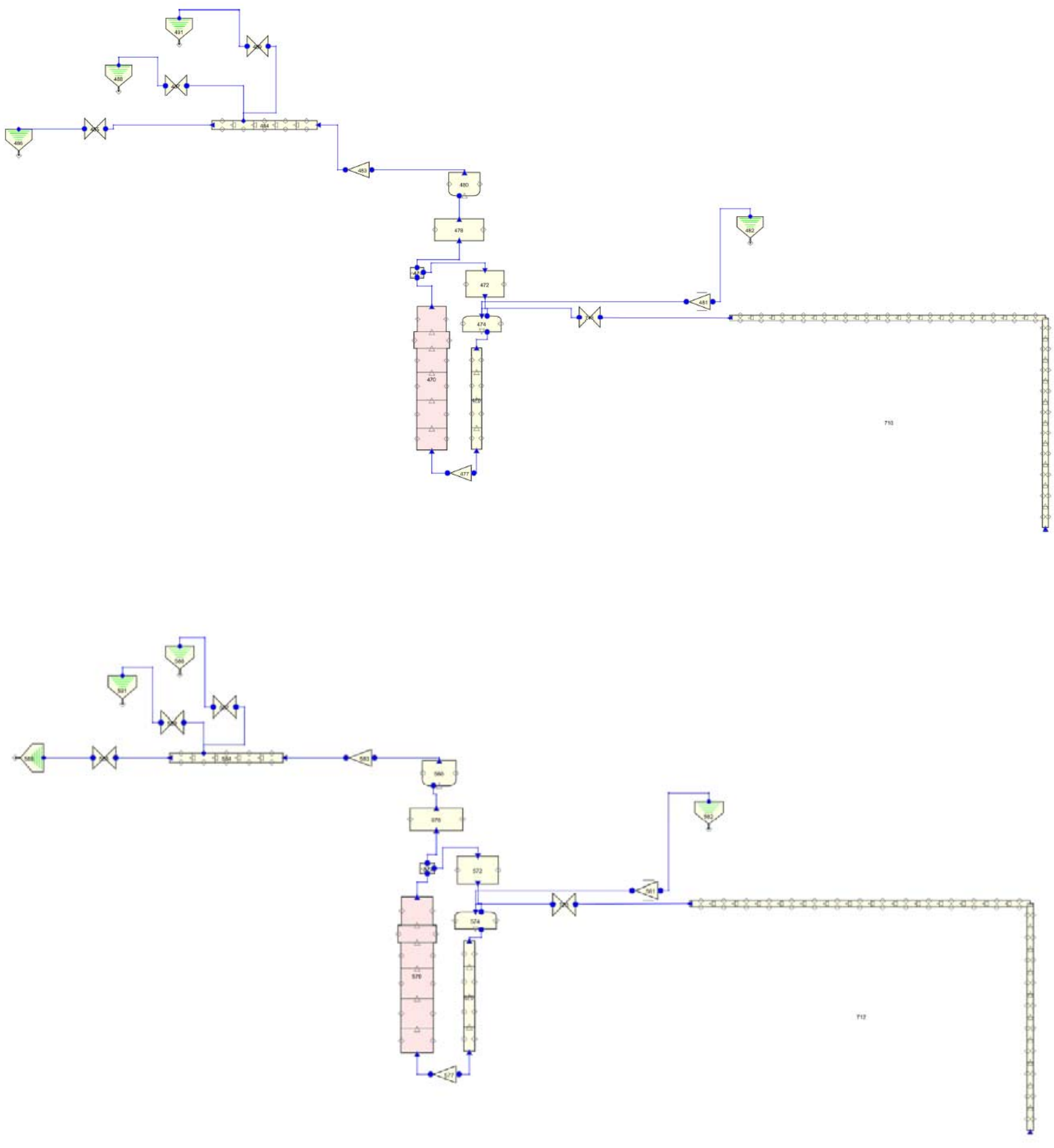

Figure 7 – Secondary Side 2 and 3 nodalization

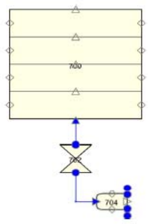

Figure 8 – FW Tank nodalization

4 Steady state achievement

During the SS phase the FW system is simplified with a TIME DEPENDENT JUNCTION and a TIME DEPENTENT VOLUME.

The FW mass flow rate is constantly equal to the steam mass flow rate flowing through the Main Steam Isolation Valve (MSIV), in order to ensure a correct balance of the SG inventory.

The PRZ pressure is controlled during the first part of the SS procedure and the initialization of the PRZ level was tuned to obtain typical PWR values.

A satisfactory steady state is reached in 200 seconds running a 'null' transient. The following table reports the obtained steady state parameters.

Parameter	Unit	SS Value
Reactor Power	MW	3600.00
SG exchanged power	MW	3599.01
Pressurizer pressure	bar	154.86
Pressurizer level	m	6.98
Hot leg temperature	K	607.55
Cold leg temperature	K	573.56
Hot leg 1 mass flow rate	Kg/s	4306.30
Hot leg 2 mass flow rate	Kg/s	4305.00
Hot leg 3 mass flow rate	Kg/s	4306.30
Hot leg 4 mass flow rate	Kg/s	4306.30
Core mass flow rate	Kg/s	17223.90
SG pressure	bar	65.54
SG level	m	12.17
FW temperature	K	493.43
Main steam SG 1	Kg/s	491.12
Main steam SG 2	Kg/s	490.14
Main steam SG 3	Kg/s	491.12
Main steam SG 4	Kg/s	491.12
Main steam mass flow rate	Kg/s	1963.50
SS reached in 200 s		

Table 2 – Typical PWR: obtained steady state values

5 Obtained results

In the next two paragraphs the result of the base case, SBO without any operator action, and a SBO with preliminary operator action are illustrated.

Peak Cladding Temperature is chosen as principal calculation figure of merit. Considering the RELAP5 code capability the simulation is not reliable if core damage is predicted. Onset of core damage is supposed to occur when PCT exceeds 1500 K.

5.1 Base case

In the first case (base case) no operator actions are assumed to observe the plant behaviour in order to individuate an optimized strategy to postpone as much as possible the core damage.

The SBO occurs at 0.0 s and automatically the reactor trip is initiated, from this moment any active system of the plant became unavailable in particular the MCP and the FW pumps run down and also the auxiliary FW is unavailable.

Primary side pressure falls from the nominal value down to 12 MPa as a consequence of the scram and it stabilizes at about 13 MPa (Figure 9). After roughly 3600 s from the start of the transient, PS pressure starts to increase reaching the PRZ SRV showing a cycling trend around valve set points till the end of the simulation.

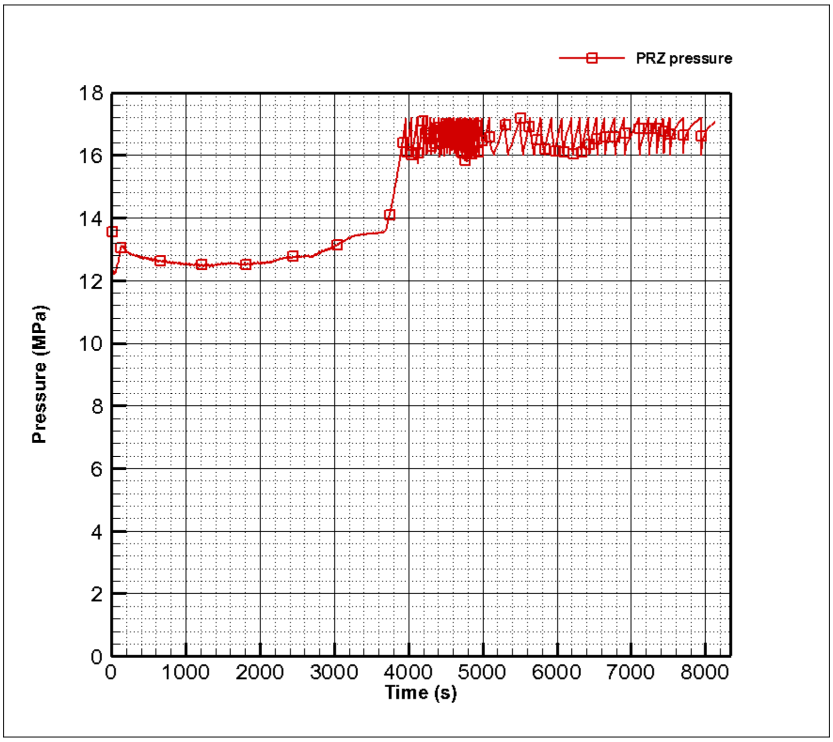

Figure 9 –PRZ Pressure, base case

After the scram PRZ level (Figure 10) falls down from 7 m to 5 m and remains stable until 3600 s when it starts to increase up to 15m for the increment of the temperature in the PS. Later on due to the multiple intervention of the PRZ SRV, the level decreases down. At 7400s from the start of the transient, the PRZ is empty.

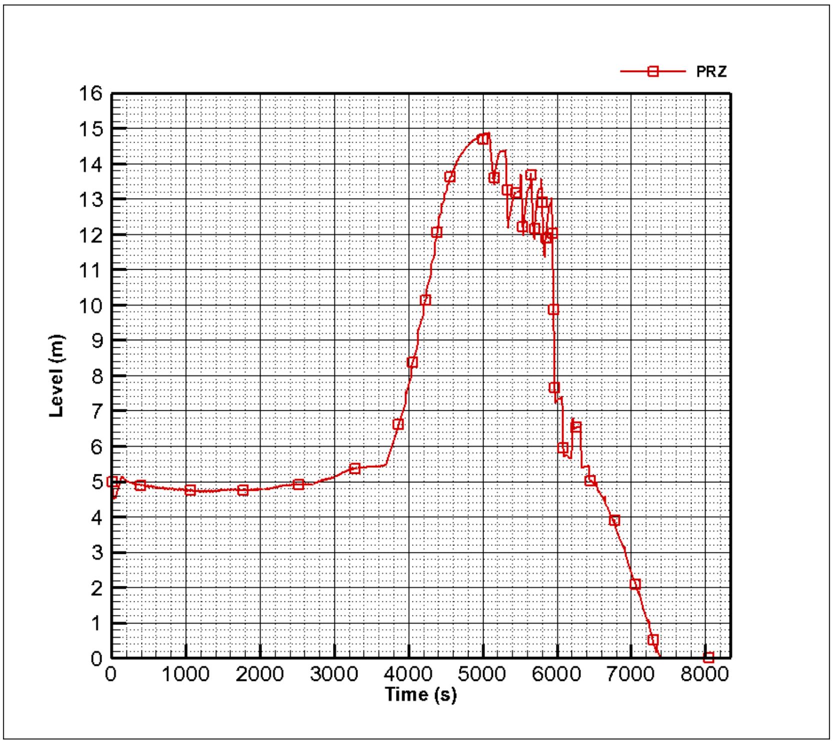

Figure 10 – PRZ Level, base case

Due to the high pressure evolution scenario, the accumulators cannot discharge their inventory in the CL, hence their contribution on cooling the reactor is not available (Figure 11).

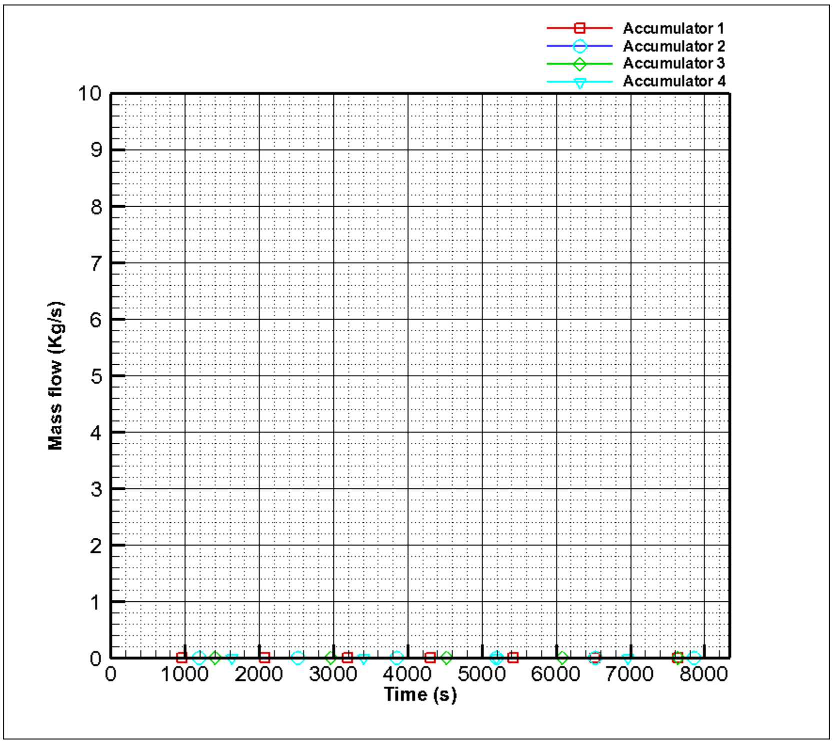

Figure 11 – Accumulators, base case

In the secondary side, after the SBO the MSIV closes so the SG pressure start to increase from 6.5 MPa and it is limited only by the SG SRV set point (Figure 12). SG SRV starts to cycle between 8.4 and 8 MPa (opening and closure set points respectively) driving the SG pressure trend.

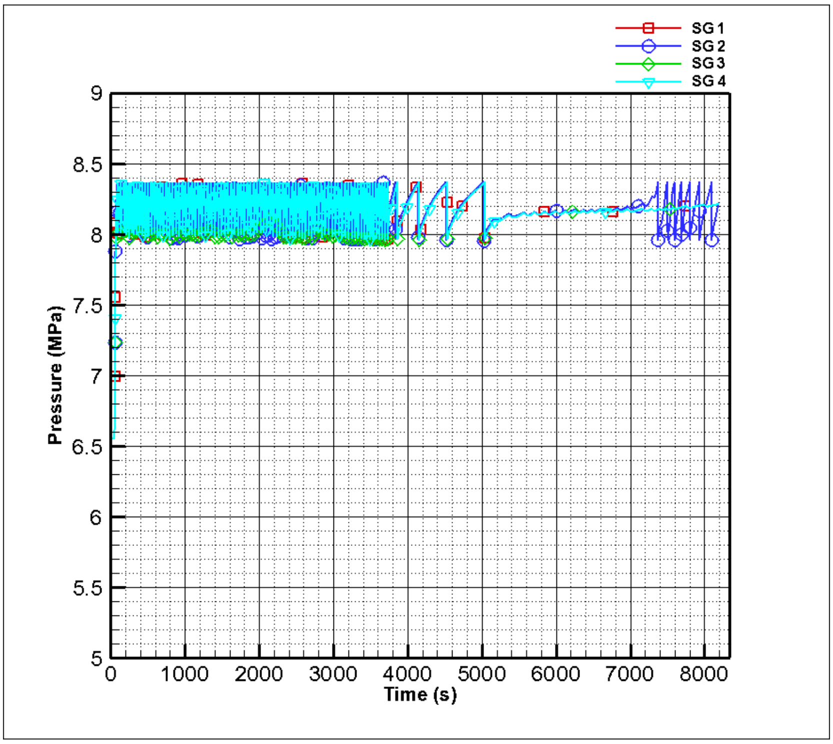

Figure 12 –SGs Pressure, base case

As a consequence of the SCRAM, SG level falls from 12m to 9.5m. Going on in the transient SG level linearly decreases. In 3600 s all SG secondary side inventory is lost, hence decay heat is not anymore extracted by the primary system.

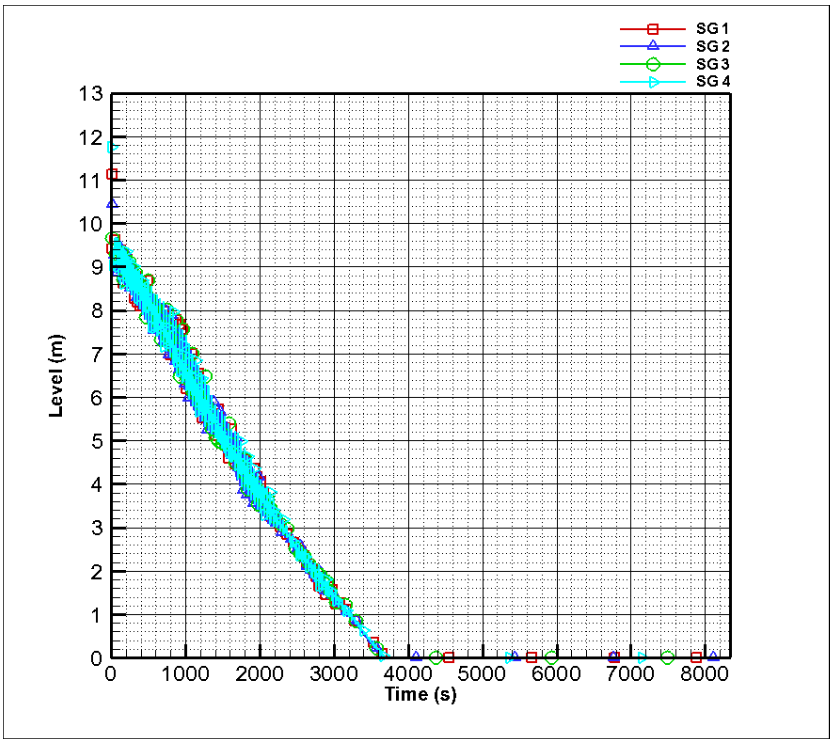

Figure 13 – SGs Collapsed Water Level, base case

Lack of primary side cooling is shown in Figure 14 which shows the unbalance between reactor and SG exchanged power.

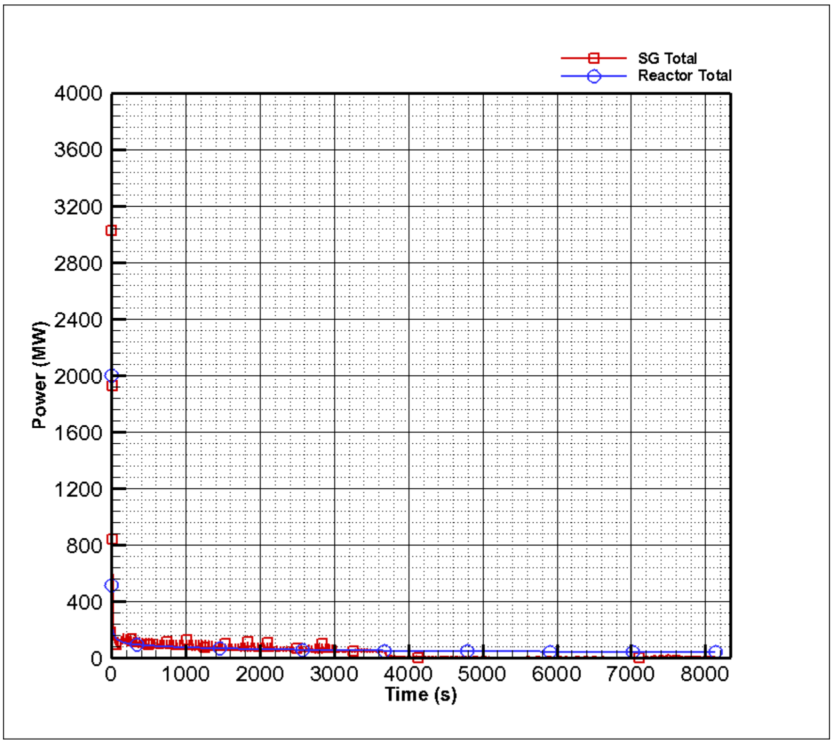

Figure 14 –Reactor and SG exchanged Power, base case

Since the high pressure in the SG and the unavailability of external power is not possible to feed the SG and to recover the heat transfer from the primary to secondary side. Figure 15 shows the lack of mass flow through the FW piping, while Figure 16 shows the FW tank level that is kept at its nominal value within the whole scenario.

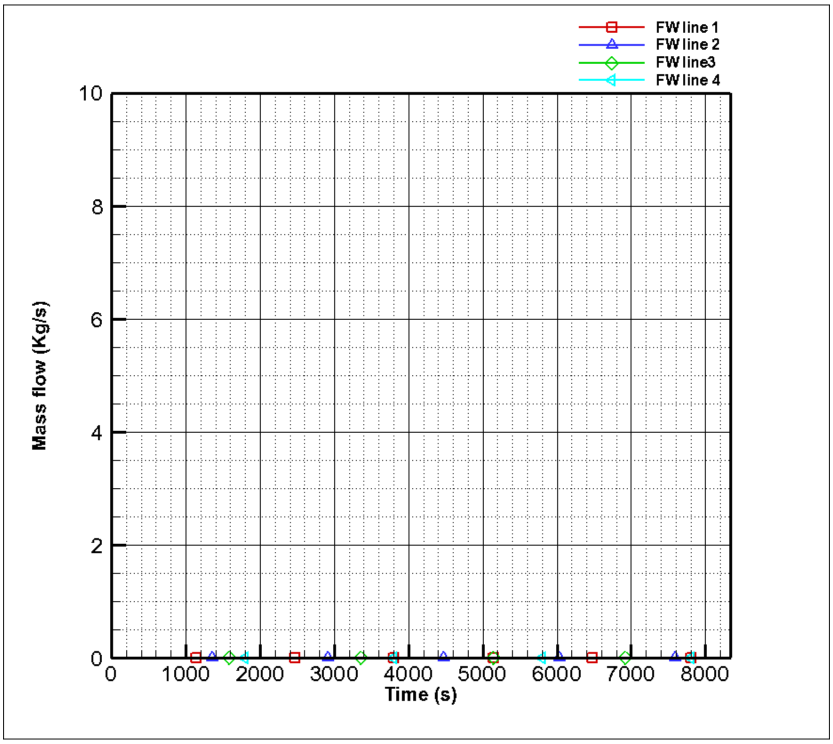

Figure 15 – FW lines mass flow, base case

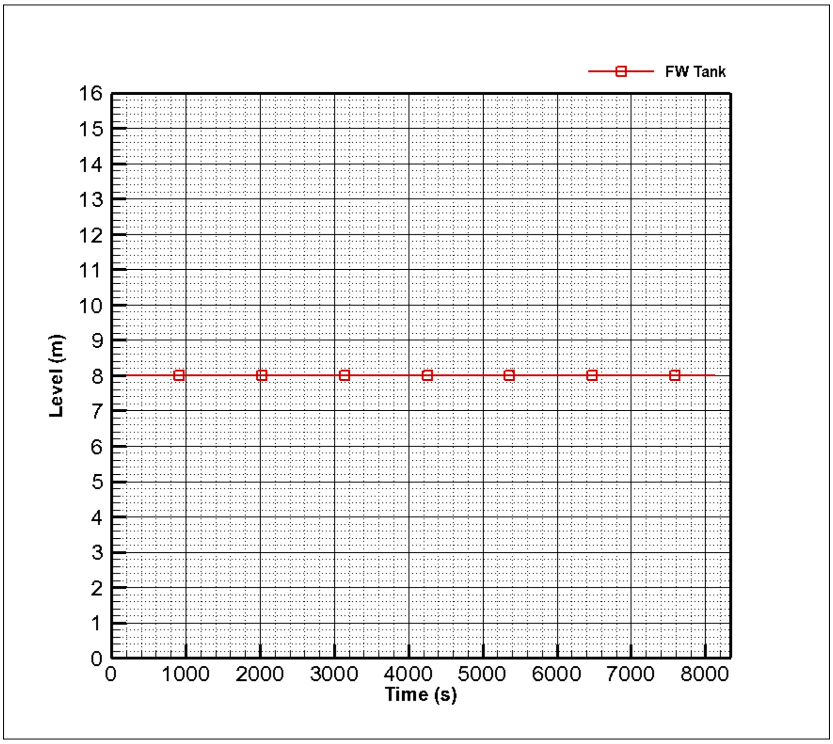

Figure 16 - FW Tank Level, base case

After 8340 s the PCT reaches 1500K, i.e. the assumed set point of core damage occurrence.

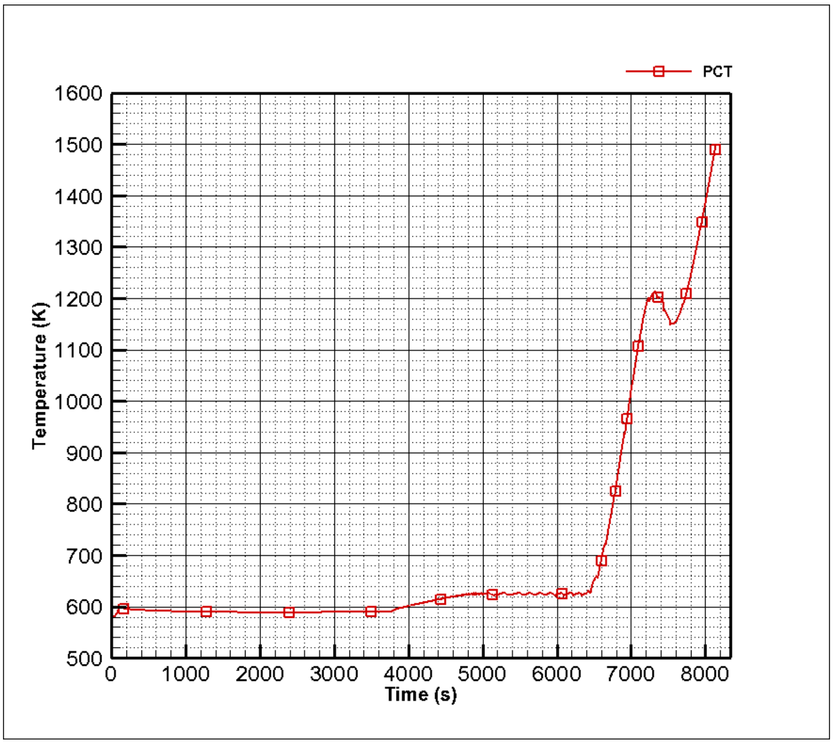

Figure 17 – PCT, base case

Table 3 lists the sequence of events related to the SBO scenario without operator action.

Time	Event	Note
0.0	SBO	Initiating event
	SCRAM	Consequence of SBO
	MSIV closure	Consequence of SBO
	Loss of FW pumps	Consequence of SBO
	Loss of MCP	Consequence of SBO
3600	PRZ SRV opening	First occurrence
	SGs empty (loss of heat sink)	
5000	Maximum PRZ level	
7400	PRZ empty	
8340	On set of core damage	Stop of simualtion

Table 3 – Sequence of Main Events, base case

5.2 *Preliminary study of an optimized operator actions*

In the second calculation a preliminary study of a possible operator action to delay the core damage is presented. Namely is assumed that after 1800s the operator opens one SG RV in one SG and every 500s opens the same valve in another SG in order to depressurize the SS. The aim of the proposed strategy is to passively feed the SG by the water stored in the FW line and in the FW tank, whose assumed inventory is about 50 tons.

Operator action	Time (s)
Opening of one SG 1 relief valve	1800
Opening of one SG 2 relief valve	2300
Opening of one SG 3 relief valve	2800
Opening of one SG 4 relief valve	3300

Table 4 – Operator Action Timing

Obstacle of passiv feeding is caused by presence of discontinuities and by check valves (i.e. the largest pressure drop), which strongly depend upon by the reactor design. A simple configuration of the check valves considered in the nodalization is shown in Figure 8 **Errore. L'origine riferimento non è stata trovata.** and **Errore. L'origine riferimento non è stata trovata.**.

The SBO occurs at 0.0 s and automatically the reactor trip is initiated, from this moment any active system of the plant became unavailable in particular the MCP and the FW pumps run down and also the auxiliary FW is unavailable.

Primary side pressure falls from the nominal value down to 12 MPa (Figure 18) as a consequence of the scram. From 1800s to 4000s the decrease rate is faster and at 12000s the accumulators could inject cold water until 21000 s (Figure 19). PS pressure remains almost stable at roughly 4 MPa until 24000. After this time it starts to increases and reaches the PRZ SRV set point at 29000 s starting cycling around its set points.

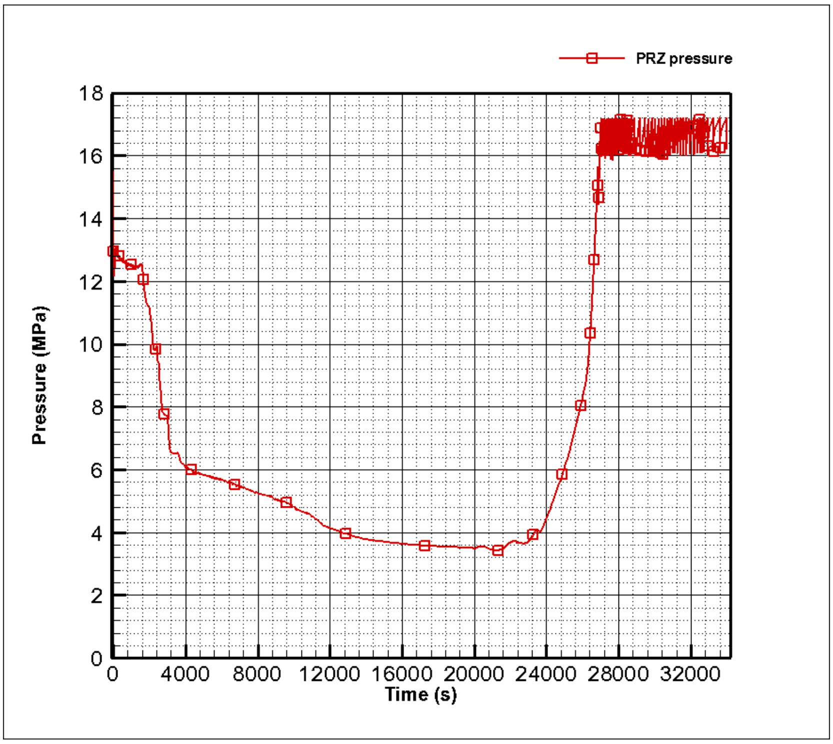

Figure 18 – PRZ Pressure, operator action

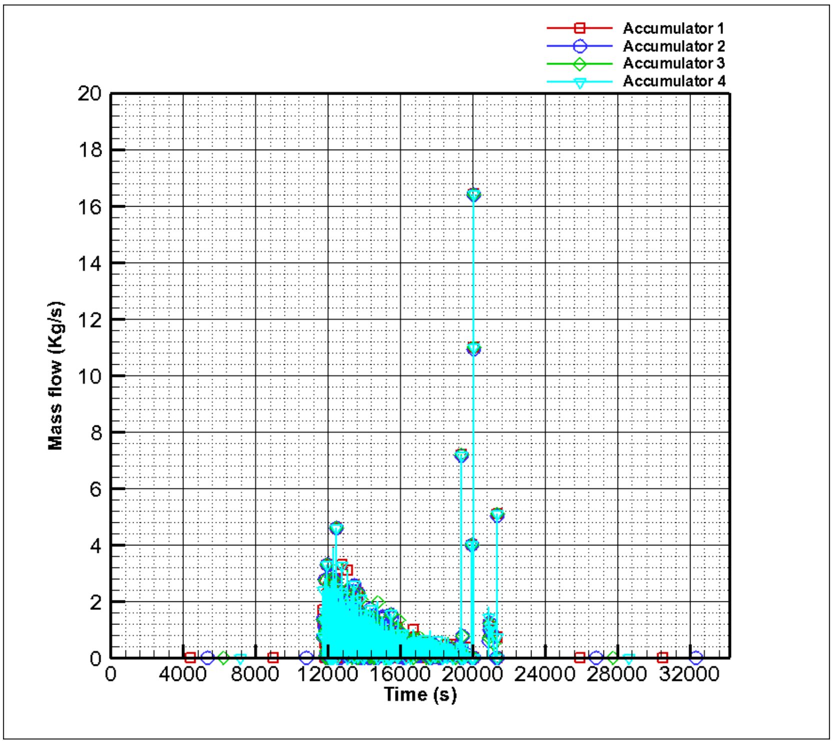

Figure 19 – Accumulator mass flow, operator action

After the scram PRZ level decrease from7m to 5 m (Figure 20). After 1800 s the PRZ level decrease very fast due to the secondary side cooling. At 2500 s the PRZ is empty. The level starts to increase after 20000 s reaching 15 m at 28000 s and the starts to decrease again because the mass discharged through the PRZ SRV. At 32000 s the PRZ is again empty.

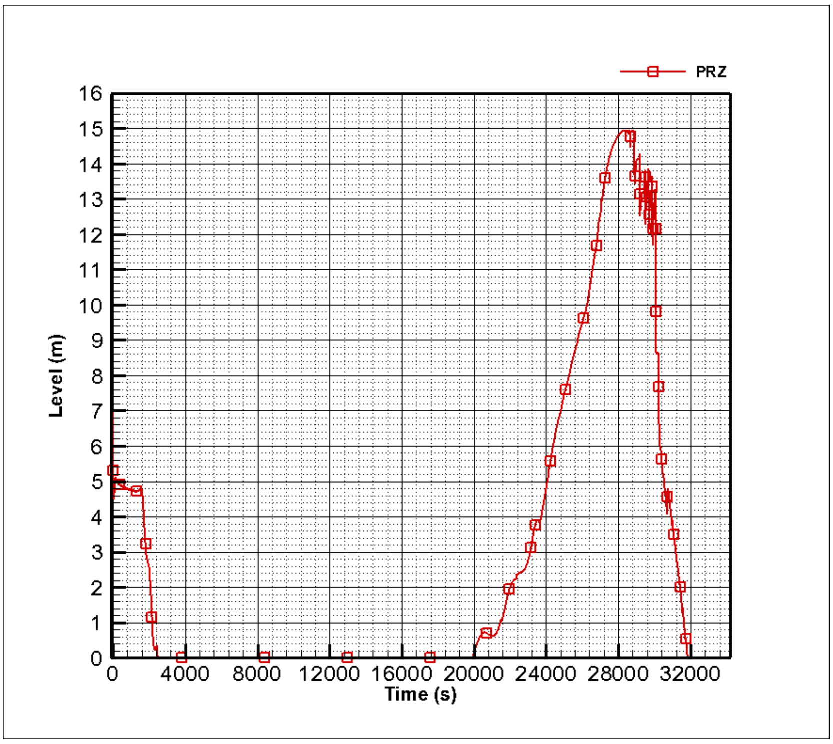

Figure 20 – PRZ Level, operator action

In the secondary side as a consequence of SBO event, the MSIV closes and pressure in SG increases up to SG RV setpoint which start to cycle until 1800 s (Figure 21). At this time the operator is supposed to open one SG RV per each SG with a delay of 500 s between two consecutive actions. When the valve is opened the pressure reaches about 0.5 MPa and after 20000 seconds atmospheric pressure is reached and kept.

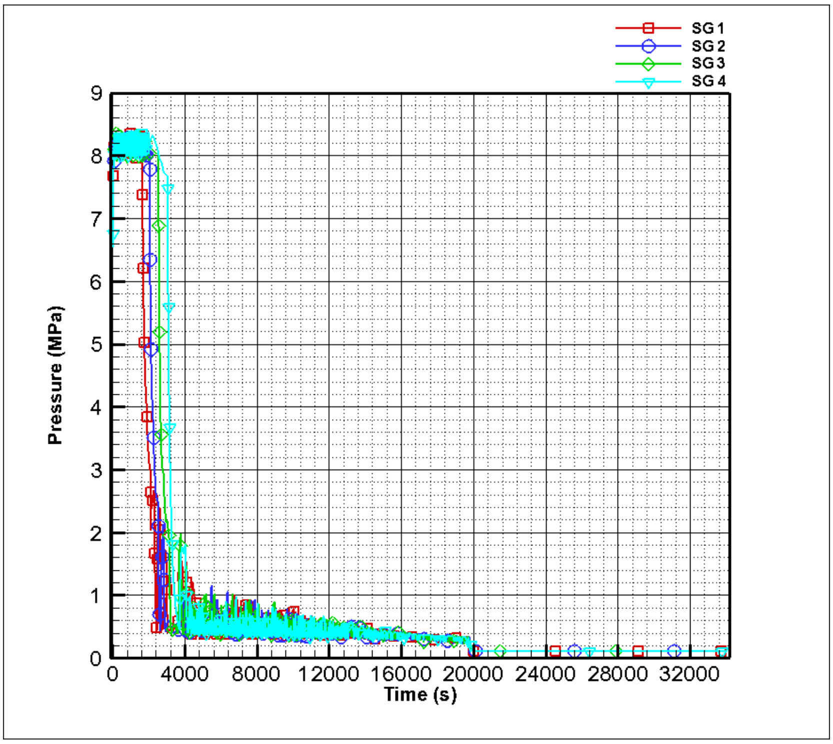

Figure 21 – SGs Pressure, operator action

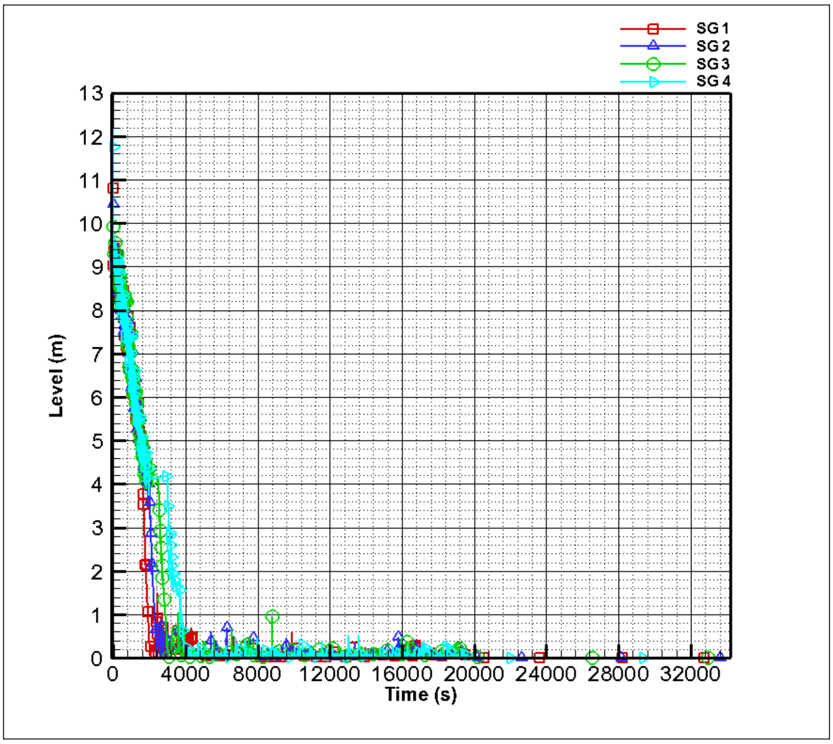

Figure 22 – SGs Level, operator action

When SG pressure follow above 2 MPa the water available in FW lines and in the FW tank passively flows into the SG. Benefit of passive feeding is reflected into the SG level (Figure 22), such an injection lasts up to about 20000 s (Figure 23). Behaviour of FW tank level is shown in Figure 24.

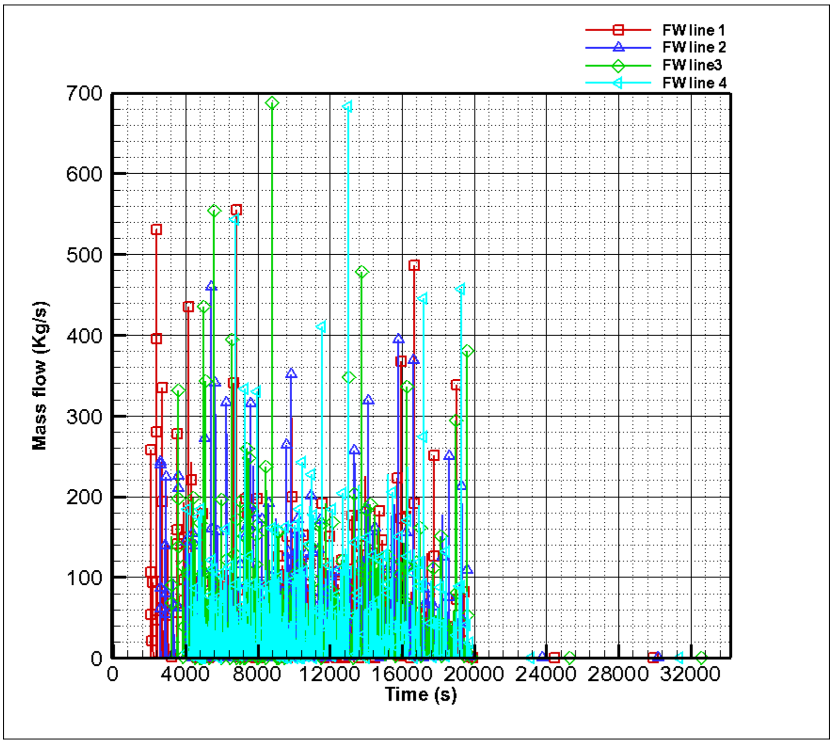

Figure 23 – FW mass flow rate, operator action

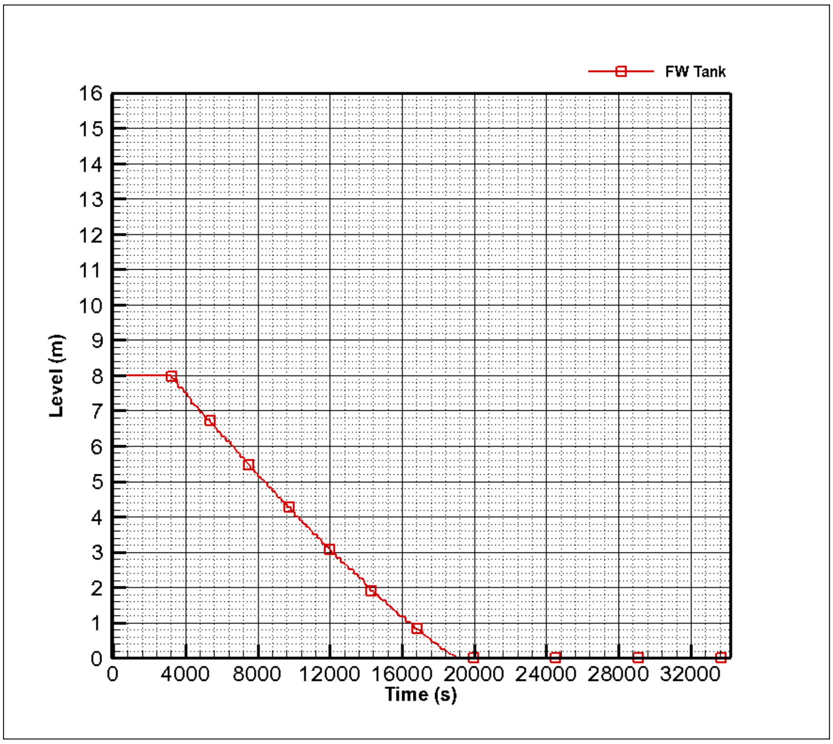

Figure 24- FW Tank Level, operator action

Until 20000 s a level of about 0.5 m can be observed in all SG and consequently from 50 MW to 100 MW can be effectively exchanged (Figure 25), within this period, from the primary to secondary side ensuring decay heat removal. After 20000s the reservoir of additional water ends, consequently heat exchange is degraded and clad temperature starts to rise till dangerous thresholds.

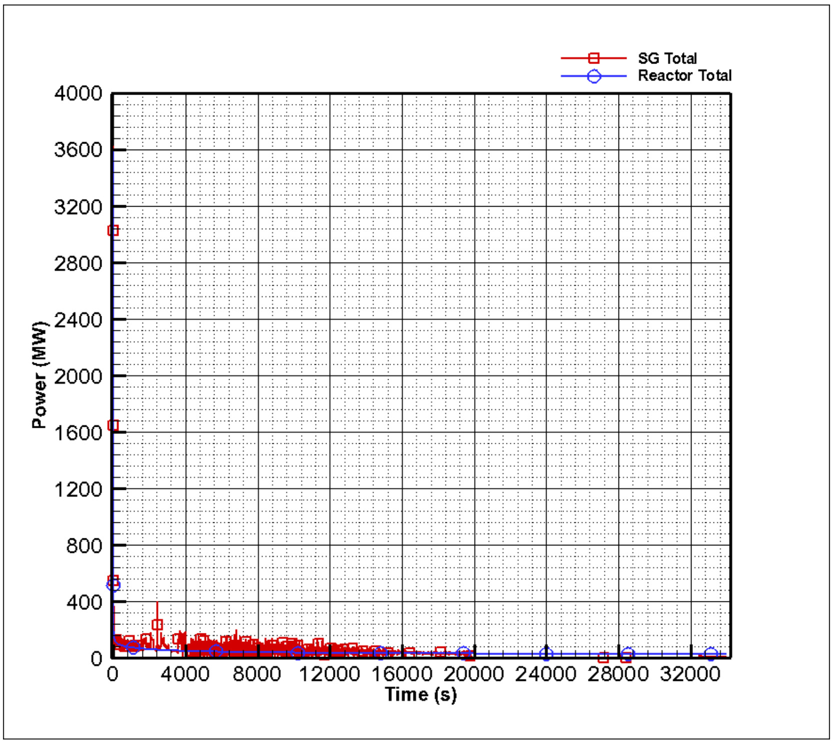

Figure 25 – Reactor and SG exchanged power, operator action

At 34200 s the PCT exceeded 1500 K reaching the onset of core damage.

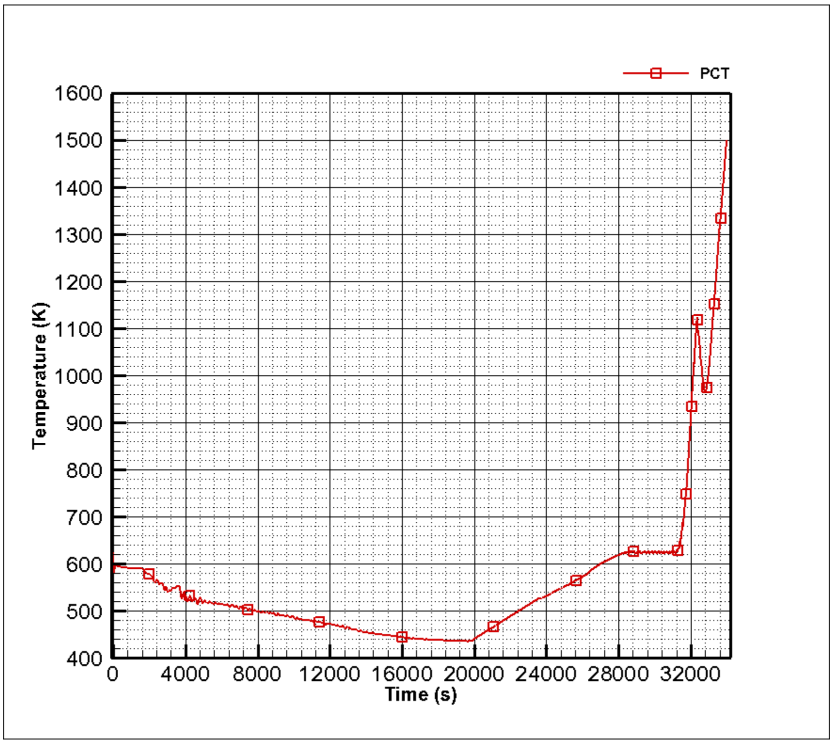

Figure 26 – PCT, operator action

Table 5 lists the sequence of main events of the case SBO with operator action based on voluntary secondary side depressurization.

Time	Event	Note
0.0	SBO	Initiating event
	SCRAM	Consequence of SBO
	MSIV closure	Consequence of SBO
	Loss of FW pumps	Consequence of SBO
	Loss of MCP	Consequence of SBO
1800	SG1 SRV fully open	First operator action
2300	SG2 SRV fully open	Second operator action
2800	SG3 SRV fully open	Third operator action
3300	SG4 SRV fully open	Fourth operator action
4000	PRZ empty	
12000	Accumulator injection	
20000	Passive SG feeding stop	
28000	Max level in PRZ	
29000	SG RV open cyclically	
32000	SG empty (loss of heat sink)	
34200	PCT = 1500 K, onset of core damage	Stop of the simulation

Table 5 – Sequence of main events, operator action

6 Conclusions and possible future activities

The present work describe the application of a possible accident management strategy to cope with a SBO scenario. The target reactor is a PWR design, 4 loops and nominal thermal power of 3000 MW_{th}.

The strategy is based on voluntary SG depressurization to make possible their passive feeding. In fact water is passively injected from the FW piping and FW tank due to the pressure difference created by the operator action.

Comparing the computed scenarios in which operator actions are not credited (case 1) and in which the operator intervenes (case 2), it can be seen that the proposed strategy is clearly effective, namely:

Passive SG feeding occurs if secondary side depressurization is performed (case 2).

The onset of core damage (assumed when PCT reaches 1500 K) occurs at 8400 s and at 34200 s for the case 1 and 2 respectively. The gained time is remarkable.

Both scenarios end with a primary side pressure greater than the nominal value, but the pressure evolution in the case of operator action performance, decreases down to accumulator set point.

Taking into consideration the benefits highlighted above, future activities can be envisaged exploring:

The higher level of details of FW systems (piping, fittings, valves, etc.) including eventual leakages of the FW tank.

The optimization of operator actions in terms of timing (i.e.time of first action and delay among the successive actions) and sequences (one by one SG depressurization has been postulated, other combinations are possible).

The introduction of primary side depressurization (via either RV or gas removal system) with the aim at limiting as much as possible the value at which the onset of core damage occurs.

The interaction between secondary and primary side depressurization, margin of optimization can be found in terms of sequence and timing.

The performed and planned scenario ahead of actual investigated time frame, suitable code should be adopted in case.

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[3] Cherubini M., Muellner M., D'Auria F., Petrangeli G. "Application of an optimized AM procedure following a SBO in a VVER-1000" J. Nuclear Engineering and Design, Vol. 238 (2008), pp. 74–80.

[4] Cherubini M., D'Auria F., Ferreri J.C., Mazzantini O. "Simulation of a Natural Circulation Test in the PSB-VVER Installation" Int. Topical Meet. on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon (F), October 2-6, 2005.

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