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Rapporto di analisi delle prestazioni dei sistemi computerizzati di supervisione, controllo e protezione

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RAPPORTO DI ANALISI DELLE PRESTAZIONI DEI SISTEMI COMPUTERIZZATI DI SUPERVISIONE, CONTROLLO E PROTEZIONE

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Argomenti trattati: Controllo dei Reattori Nucleari, Reattori Nucleari ad Acqua, Termoidraulica dei Reattori

Sommario

Questo documento illustra l'attività svolta nell'ambito della Task C-2 del PAR2010 "Analisi e Simulazione di Strumentazione di Supervisione, Controllo e Protezione". Tale attività è da inquadrarsi nelle attività svolte ai fini della reintroduzione di un simulatore ingegneristico di un reattore PWR nel laboratorio SIMING del Centro Ricerche ENEA Casaccia di Roma. Basandosi anche in parte sulle ricerche condotte nell'ambito del PAR2008-09, viene investigata la capacità simulativa del codice di sistema termoidraulico RELAP5-3D, mettendo in luce le problematiche relative alla modellazione realistica del sistema di supervisione, controllo e protezione. Le analisi sono effettuate prendendo a riferimento il reattore di Generazione III EPR ed eseguendo una serie di transitori operazionali.

Note

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Analisi delle Prestazioni dei Sistemi Computerizzati di Supervisione, Controllo e Protezione

Una delle peculiarità di un simulatore ingegneristico di un impianto nucleare è la capacità di simulazione dettagliata della strumentazione di supervisione, controllo e protezione. Generalmente, quando si effettuano simulazioni per le analisi di sicurezza, l'insieme di questi sistemi viene opportunamente semplificato, tenendo conto del solo sistema di protezione. Gli effetti degli altri sistemi (limitazione e controllo) vengono trascurati o considerati solo nel caso in cui la loro attuazione renda il risultato della simulazione più conservativo.

Chiaramente, tale approccio non può essere seguito quando, come nel caso di un simulatore ingegneristico, si vuole effettuare una simulazione di impianto realistica ed utile ai fini della verifica delle soluzioni progettuali adottate.

Mediante lo studio effettuato dal Gruppo San Piero a Grado (GRNSPG) dell'Università di Pisa-CIRTEN, si è voluto investigare in dettaglio alcune delle problematiche derivanti dalle simulazioni realistiche dei sistemi di controllo, limitazione e supervisione. Il codice di sistema utilizzato per tale studio è il codice RELAP5-3D, sviluppato dall'Idaho National Laboratory (USA) ed utilizzato da due delle più importanti aziende di simulatori nucleari americane (GSE Systems e WSC).

Lo studio eseguito è focalizzato sul sistema di controllo della pressione e del livello del pressurizzatore e sulla sua interconnessione con lo Steam Dump System. Utilizzando una nodalizzazione semplificata di un reattore PWR a 4 loop e le logiche di controllo del reattore di Generazione III EPR, si è effettuata una simulazione di due transitori operazionali, il Turbine Trip ed il Pressurizer Insurge.

Tali transitori sono stati analizzati utilizzando due approcci: l'approccio conservativo e quello realistico. Nel primo caso si è tenuto conto degli effetti del solo sistema di protezione e la simulazione è stata eseguita utilizzando il codice di sistema RELAP5-3D.

Nel secondo caso si sono implementate tutte le logiche del sistema di controllo, limitazione e protezione. A tale scopo si è reso necessario l'accoppiamento del codice di sistema RELAP5-3D con una routine in linguaggio FORTRAN simulante l'aspetto controllistico del problema. Al RELAP5-3D è stato quindi demandato esclusivamente il compito di eseguire la simulazione termoidraulica. Questo tipo di accoppiamento si rende necessario e viene impiegato in tutti i simulatori ingegneristici in quanto generalmente un codice termoidraulico di sistema non è dotato della complessità necessaria per la corretta simulazione dei sistemi di controllo.

I risultati dello studio effettuato dimostrano il ruolo fondamentale svolto dai sistemi di supervisione, controllo e protezione nel determinare la dinamica dell'impianto nucleare anche in occorrenza dei semplici transitori operazionali presi in considerazione.

Lo strumento software realizzato nell'ambito di questa task, benché limitato al solo controllo del pressurizzatore e dello Steam Dump System, consente di creare quella piattaforma simulativa di base su cui lavorare nei programmi futuri ai fini di realizzare un simulatore ingegneristico nel Centro Ricerche Casaccia.

Titolo

Implementazione della logica di regolazione e protezione della pressione e livello del pressurizzatore e dello Steam Dump System per un reattore PWR

Ente emittente

PAGINA DI GUARDIA

Descrittori

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Sommario

Il comportamento di un impianto nucleare durante i transitori operazionali ed incidentali è fortemente influenzato dalla risposta del sistema di controllo. Un analista che ha il compito di simulare tale sistema, utilizza, in genere, modelli conservativi, soprattutto nel caso in cui debba eseguire una simulazione per il "licensing" dell'impianto. Per applicazioni come i simulatori "full scope" o ingegneristici, invece, la scelta dei modelli ricade su quelli cosiddetti di "best-estimate". Il presente documento descrive un'applicazione dei due possibili approcci. L'approccio conservativo viene mostrato attraverso la modellazione del sistema di controllo e protezione del pressurizzatore e dello steam-dump di un PWR utilizzando il codice di calcolo Relap5-3D. L'approccio "best-estimate" viene invece perseguito accoppiando al Relap5-3D una routine Fortran descrivente fedelmente le controreazioni del sistema di controllo e protezione. Il Relap5-3D viene impiegato, in questo caso, per il solo calcolo del feedback termoidraulico. Entrambi gli approcci di simulazione del sistema di controllo e protezione vengono poi mostrati effettuando una simulazione di due transitori operazionali.

Note

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UNIVERSITY OF PISA

San Piero a Grado Nuclear Research Group

ANALISI E SIMULAZIONE DI STRUMENTAZIONE DI SUPERVISIONE, CONTROLLO E PROTEZIONE: Implementazione della logica di regolazione e protezione della pressione e livello del pressurizzatore e dello Steam Dump System per un reattore PWR

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Summary

The behavior of a NPP during transients and accidents is strongly influenced by the response of the NPP control system. An analyst which has the task to model the control system will usually choose a very conservative, simplified bounding approach when running a simulation for licensing applications, and a very precise best estimate approach for applications such as full scope simulators or engineering simulators.

In the present report provides a taste of both approaches. On the one hand, modeling of controls using the Relap5 “on board” control features is provided. On the other hand, a coupled code system, where Relap5 provides the thermal hydraulic feedback of the plant, while an external control module (written in FORTRAN) takes care of the control feedback. Both methods of simulation of controls are shown at work for three examples.

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1 Introduction

The behavior of a NPP during transients and accidents is strongly influenced by the response of the NPP control system. An analyst which has the task to model the control system will usually choose a very conservative, simplified bounding approach when running a simulation for licensing applications, and a very precise best estimate approach for applications such as full scope simulators or engineering simulators.

In the present report provides a taste of both approaches. On the one hand, modeling of controls using the Relap5 "on board" control features is provided. On the other hand, a coupled code system, where Relap5 provides the thermal hydraulic feedback of the plant, while an external control module (written in FORTRAN) takes care of the control feedback. Both methods of simulation of controls are shown at work for four examples.

Focus is given on modeling the controls of two systems of the NPP: the pressurizer, and the turbine bypass station. The cases that have been run have been chosen to demonstrate the controls of the PRZ, and the interaction of PRZ controls with other plant systems, such as the turbine bypass station. The Table below gives and overview of the examples that have been run, and the designation of the cases. At the current stage both modeling approaches, and the Relap5-3D/Relap5-3D sample cases are presented in this report.

	Thermal Hydraulics	**Controls**	**Thermal Hydraulics**	**Controls**
	Relap5-3D	Relap5-3D	Relap5-3D	Fortran Control Module
Turbine Trip with realistic assumptions on availability of plant systems	TBR5-BE		TBR5F-BE	
Turbine Trip with pessimistic assumptions on availability of plant systems	TBR5-CO		TBR5F-CO	
PRZ Insurge (artificial case)	INSR5-BE		INSR5F-BE	
PRZ Insurge (artificial case) variant – failure of spray	INSR5-CO		INSR5F-CO	

An implementation of a Pressurizer (PRZ) with Relap5-3D (R5) and FORTRAN is presented. The pressurizer is an important component of every Pressurized Water Reactors (PWR). Its aim is to maintain the Primary System (PS) pressure into a prescribed range, with the actuation of heaters and sprays. It is connected through the surge line to the Hot Leg (HL) of one of the PS loop (there are generally two, three or four loops, according to the total power of the reactor).

A latest generation Nuclear Power Plant (NPP), such as the European Pressurized Reactor (EPR), adopts a significantly bigger PRZ, compared to previous NPP designs, in order to smooth the response of operational transient and to increase the lifetime of this vital equipment. ***Table 1.1*** summarizes the main characteristics of an EPR pressurizer, taken in this contest as a PRZ reference model to be implemented (***Figure 1.1***).

1.1 Functions of PRZ and related controls

The pressurizer and related control systems have two main functions:

- **Pressure control**

During normal operation the pressurizer is the only component of the primary system that contains vapour. The compressible vapour volume shall prevent pressure spikes in case of increase or decrease of the medium PS temperature. The pressurizer is usually a stagnant volume connected to the HL by the surge line. During normal operation, the pressurizer is in saturated conditions. Two third of the PRZ are filled with saturated liquid, one third with saturated vapour. To keep the PRZ saturated, heaters, which are located in the liquid part, are constantly kept on – to compensate for heat losses by the PRZ wall. In addition, a small amount of vapour is produced. This additional vapor is condensed by a continuous flow of the PRZ sprays. To control the pressure, heaters and spray can be regulated. To limit excessive pressure increases, safety valves on PRZ top can open.

- **Mass control**

During normal operation the PRZ liquid level is an indication for the amount of PS fluid mass. So, the make-up and let-down system (to control the PS mass, chemistry and fluid purification) constantly exchanges a part of primary system liquid, regulates its outflow and inflow according to the PRZ level. The level set point keeps track of the average liquid temperature (sliding set point). If the fluid is colder than nominal, the set point for the PRZ level is lower than nominal, and the other way around. Goal of the system is to keep the liquid mass constant (instead of the liquid volume).

1.2 Three tier control system

In many NPP a three tier approach (protection system, limitation system and control system) is adopted. This type of approach will be followed also for this task. Here is a short description:

- **Protection system**

The protection system constitutes the highest level of controls. In case a signal from the protection system is triggered, it has precedence over signals from the control or the limitation systems. In some NPP the components used to build the protection system are analog, which makes the system highly reliable.

- **Limitation system**

The limitation system does not exist in all NPP designs. Typically German NPPs use this level, but also the EPR. The limitation system is a layer between the control system and the protection system. It uses more complex functions than the protection system, its set points are such that it interventions come before the protection system. The limitation system has precedence over the controls, but not over the protection system. Often an intervention of the protection system can be avoided by the limitation system.

- **Control system**

The control system has the lowest priority, but the most complex functions. It is responsible to control the unit during normal operations. Functions, which lead the reactor from safe to operating conditions, are fulfilled exclusively by the control system (e.g. the control is the only system that increases the reactor power).

1.3 Key design values and data for a typical PRZ

Please refer to Table 1.1 and Figure 1.1 for example design values of a PRZ.

CHARACTERISTICS	DATA (in red: British Units)
Design lifetime	60 years
Design pressure	176 bar (2,550 psia)
Design temperature	362 °C (684° F)
Total volume	75 m^3 (2,649 ft^3)
Water volume at full load	40 m^3 (1,410 ft^3)

Steam volume at full load	35 m^3 (1,240 ft^3)
Total length	14.4 m (47.2 ft)
Base material	18 MND 5, low alloy ferritic steel (SA-508 Gr. 3 Cl. 2)
Cladding	308L / 309L SS
Cylindrical shell thickness	140 mm (5.5 in)
Operating temperature	345 °C (653° F)
Operating pressure	154 bar (2,250 psia)
Number of heaters	108 + 8 spare
Installed heater power (approx.)	2600 kW
Heater sleeve material	Type 316 LN, austenitic stainless steel (S31653)
Total weight, empty	150 t (165 tons)
Total weight, filled with water	225 t (248 tons)
Number of operational spray lines	2 from RCPs
Number of auxiliary spray lines	1 from CVCS
Number and capacity of safety valve trains	3 x 300 t/h (660,000 lb/hr)
Number and capacity of depressurization valves	2 x 900 t/h (1,980,000 lb/hr)

Table 1.1 - EPR pressurizer characteristics (Source: AREVA, [Ref. 1])

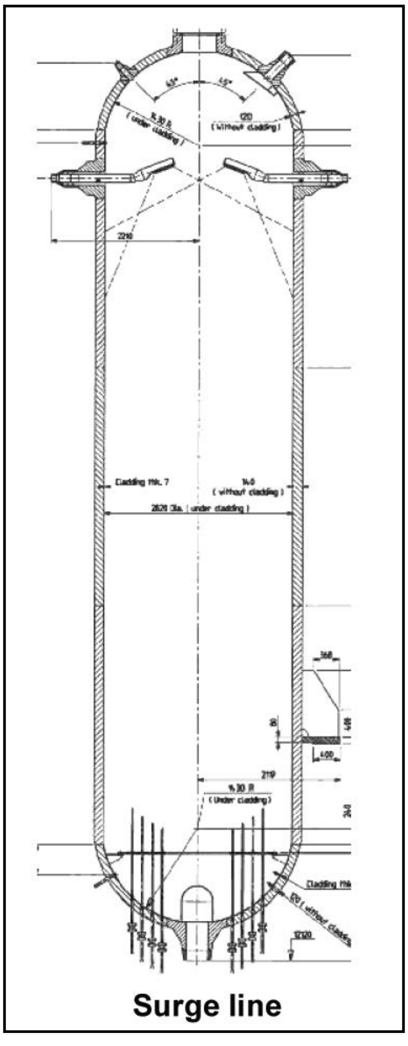

Figure 1.1 - PRZ, typical geometry (Source: AREVA, [Ref. 1])

1.4 Engineering Simulator and Plant Analyzer modeling differences

The approach of modeling a PRZ as described in the present document is suitable for simulators or engineering simulators. Compared to the modeling of a typical plant analyzer (as for example NPA which are distributed by IAEA) the following differences can be expected:

Thermohyraulics - Relap5-3D is a robust thermal hydraulic system code, using a six equation model. Vapor and steam phase do not have to be in equilibrium. A wide range of transient and accident conditions can be realistically represented.

The same is not necessarily true for plant analyzers. Plant analyzers aim to model the plant close to nominal values, putting emphasis on fast calculation algorithms, while neglecting physics. A more realistic behavior can be expected most of all for LOCA transients (such as PORV stuck open).

The I&C modeling of NPA tends to represent the complexity of the system (since an impression on the operation of the plant should be given). A relap5 only approach might miss features that a NPA might have. However, the Relap5-3D and Control module coupled code system can model the instrumentation and controls with arbitrary complexity.

2 Implementation and model development

The Relap5-3D package comes with a number of sample cases. One of them (filename typpwr3d2.i) describes a typical generic pressurized water reactor, and has been chosen as sample nodalisation.

A nodalization provided with the R5 documentation was chosen for modelling the PRZ behaviour, but many modifications both on Thermal Hydraulic (TH) and logical level were necessary.

2.1 Description of nodalization

The basic nodalization of a 3.6 GW_{th} Westinghouse PWR was copied by one of the examples of the R5-3D code, developed for a simple simulation of a LOCA. For that purpose, the secondary side and the pressurizer were roughly modelled (i.e. there was no spray line and the PRZ level control system was missing), and for simplification's sake the four-loop PWR was divided into two parts, the broken loop and the other three intact loops, coalesced into one.

2.2 Description of modifications

The former nodalization was essentially designed for LOCAs, where fast transients occur, and a detailed model of the secondary side as well as other PS components are not necessary. For the task of PRZ behaviour characterization, several components both in primary and secondary side needed to be implemented. We focused our attention mainly on the pressurizer and its connections. Though these modifications and improvements, the TH model is still very simplified, but enough reliable for our purpose. The modified components, both in the TH and logics aspects, are presented in the following paragraphs. A PS scheme of the nodalization is depicted in ***Figure 2.1***; from ***Figure 2.2*** to ***Figure 2.7*** detailed views of the nodalization are provided.

2.2.1 General improvement of the secondary side nodalization

An improvement of the secondary side nodalization was necessary because the Feed Water (FW) mass flow rate was set as constant, not sufficient to compensate the steam generated. In order to reach a steady-state, avoiding the empting of the Steam Generator (SG), a simple FW control system was set up. The FW mass flow rate is constantly equal to the steam flow through the Main Steam Isolation Valve (MSIV), therefore, if a scram occurs due to a turbine trip, the MSIV closes and the FW mass flow rate stops (station black-out, so no pumps).

2.2.2 Pressurizer

A bigger pressurizer was implemented, because the original one was suited for a 3.6 GW_{th} PWR. Therefore, the PRZ volume was raised from 50 m^3 to 85 m^3, increasing the area not the height. Then, the PRZ head was modelled with a branch, in order to connect all the spray valves and the relief valves.

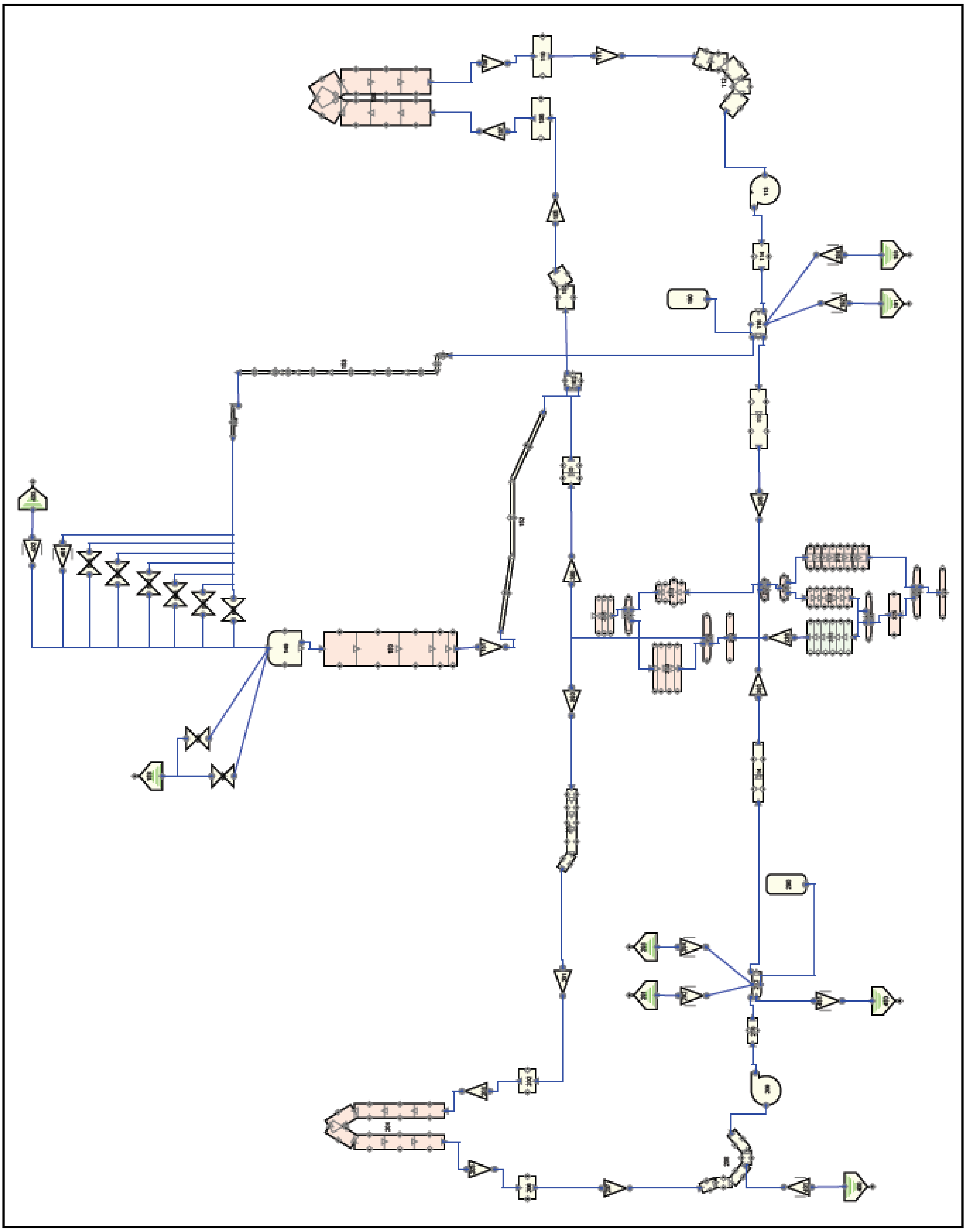

Figure 2.1 - PS scheme (details on the following Figures)

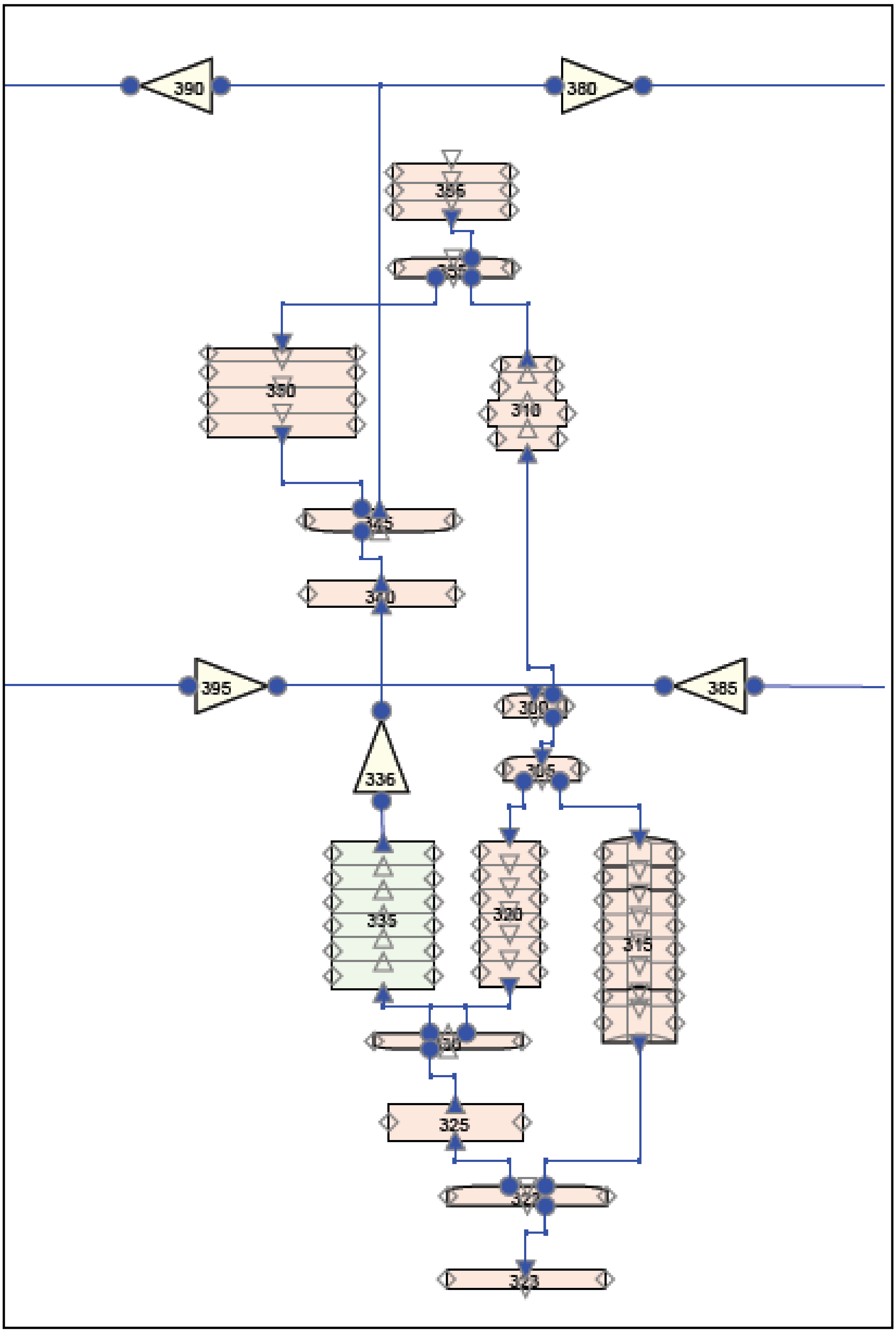

Figure 2.2 – Reactor pressure vessel and core region

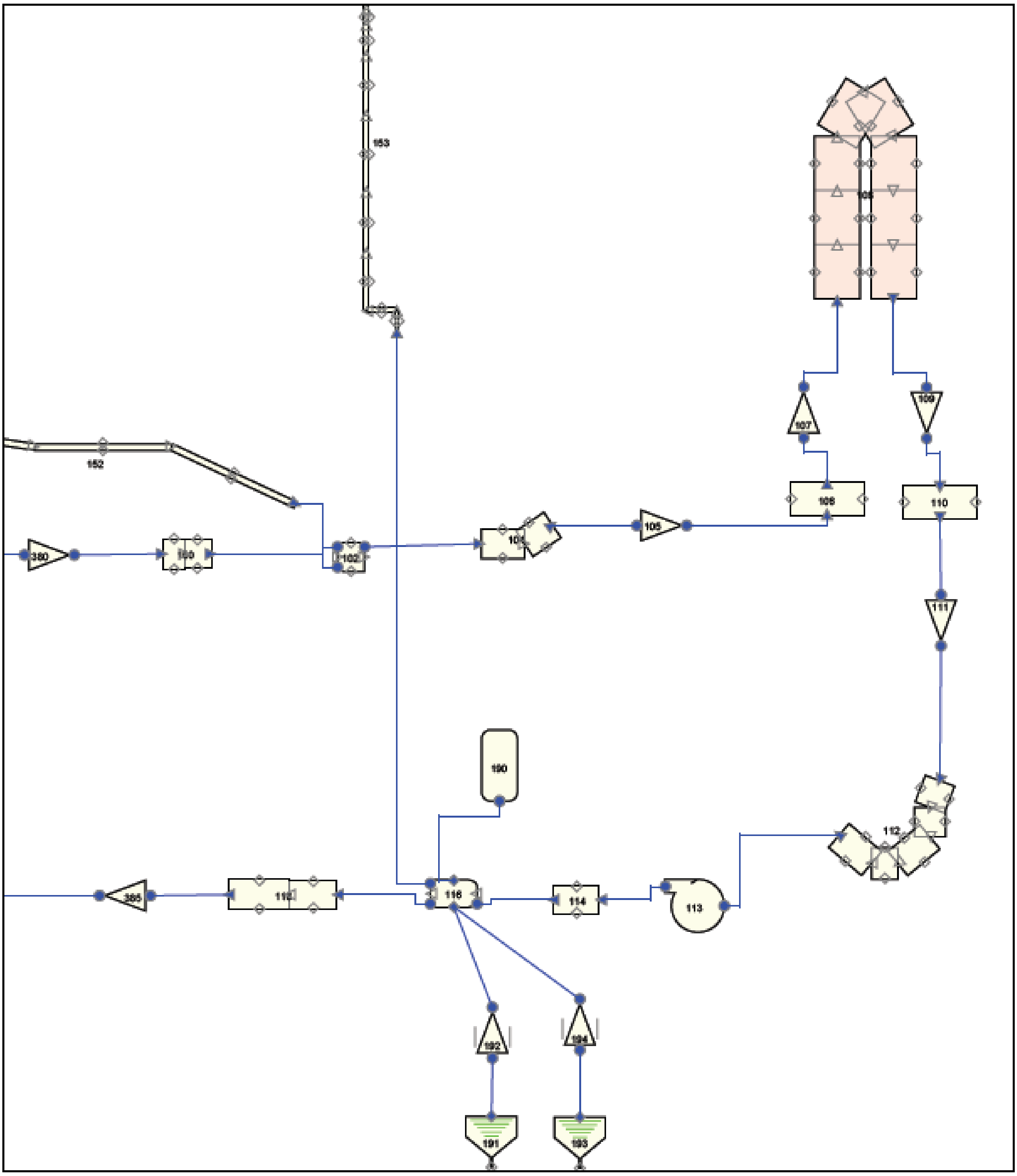

Figure 2.3 - Loop 1 (three coalesced loops) with surge line and spray line

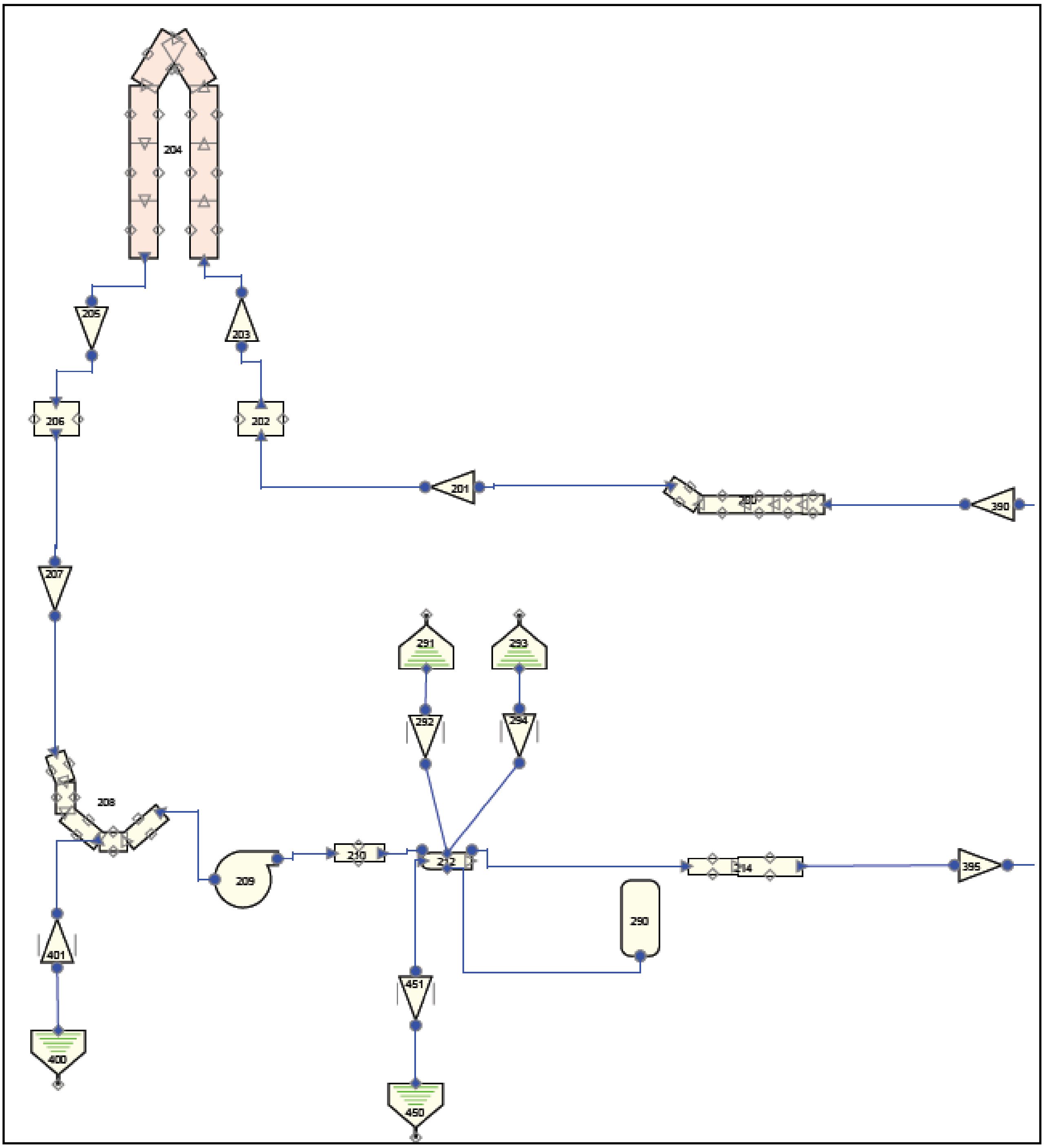

Figure 2.4 - Loop 2

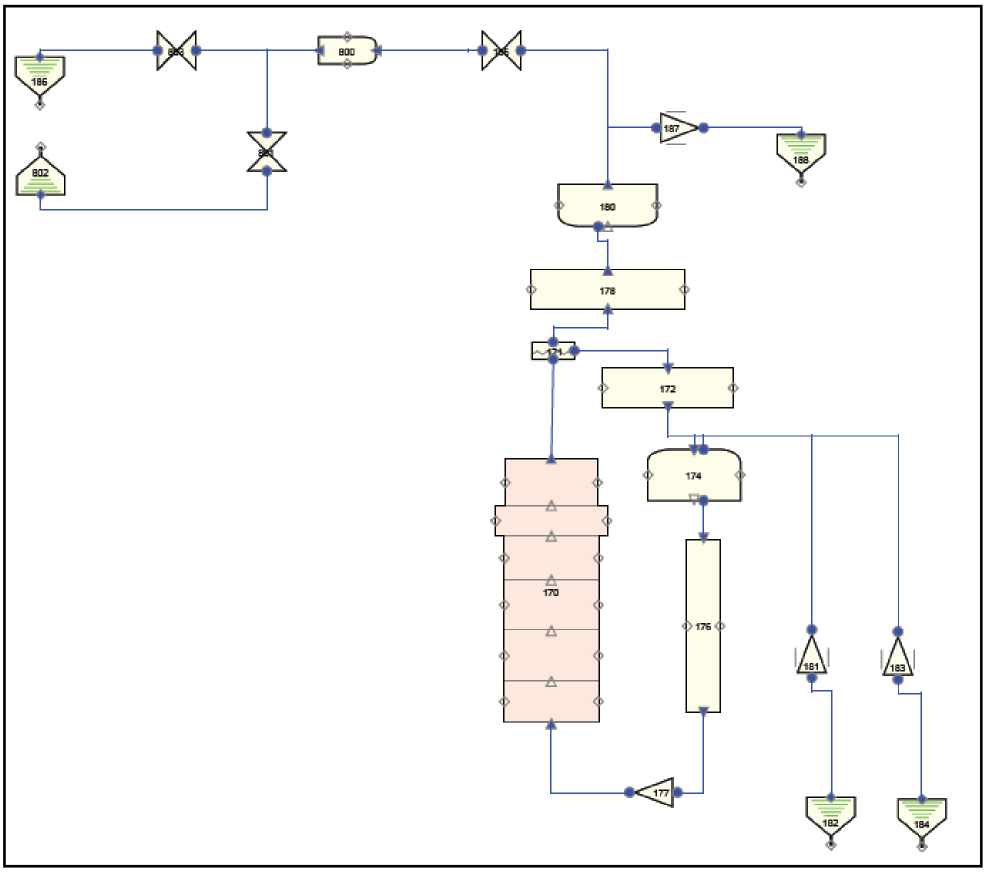

Figure 2.5 - Secondary side, SG1 (three SGs coalesced into one)

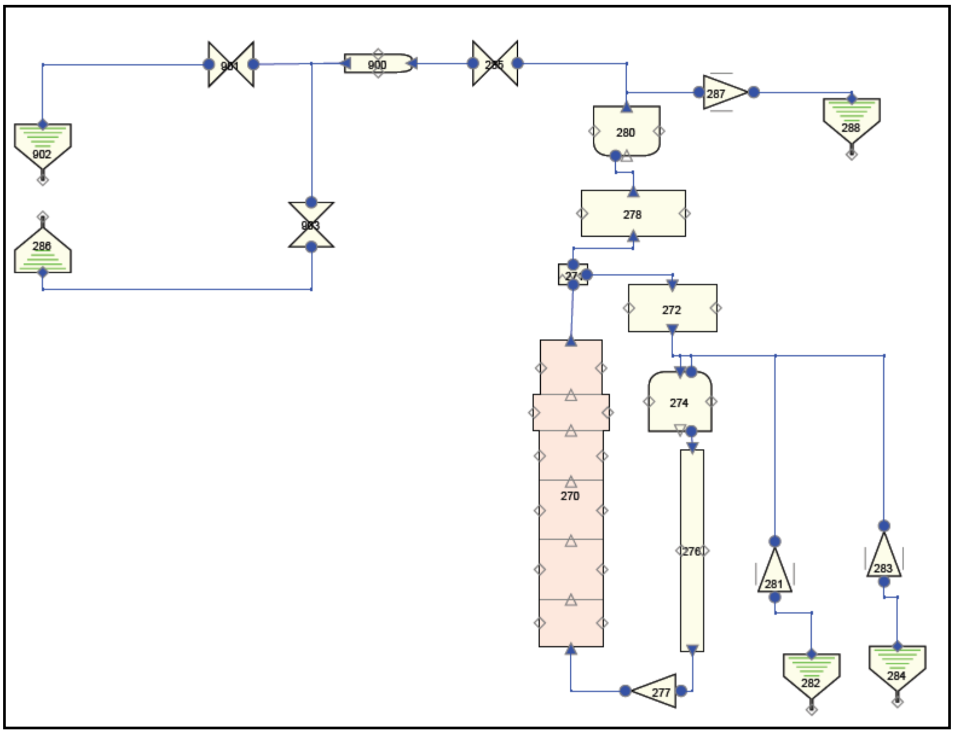

Figure 2.6- Secondary side, SG2

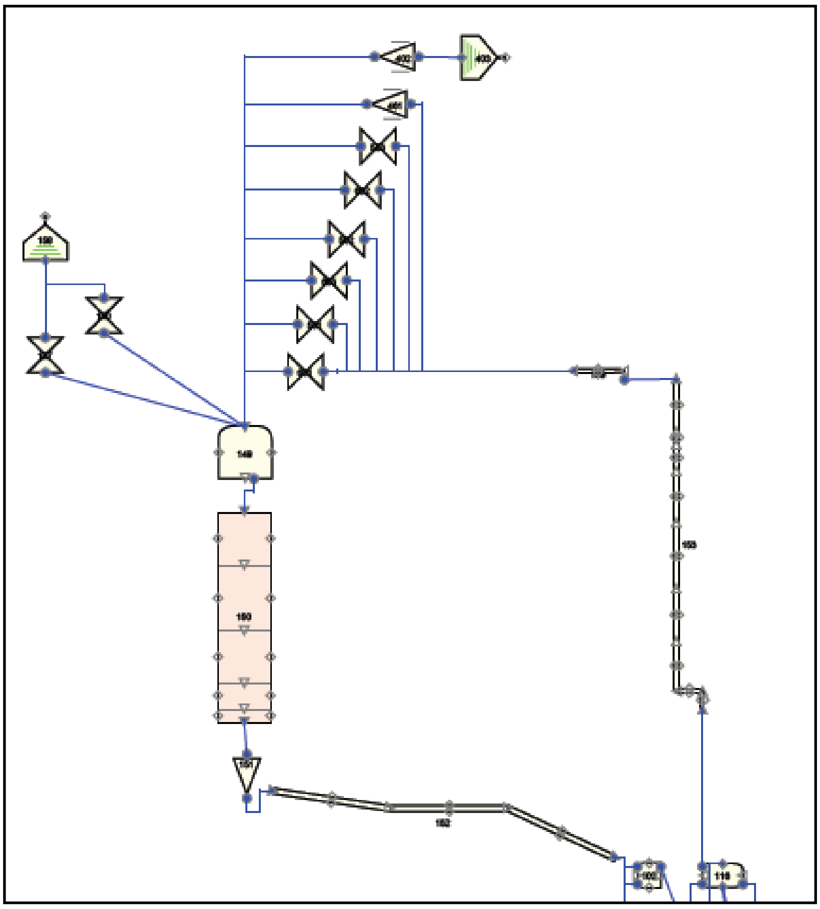

Figure 2.7 - Pressurizer with surge line and sprays

2.2.3 Spray from loop

Two spray lines, coalesced into one, were added and connected to the coalesced loops; the last component of the spray line is a branch in order to connect all spray valves. The spray line nodalization follows the sliced approach with the surge line and the pressurizer itself. Normal operation sprays are modelled with a time dependent junction; during normal operation, these sprays inject 0.5 kg s^{-1}, but in case of scram (so station black-out) the flow rate decreases to zero in ten seconds. Valves are designed in a simplified way, to allow a mass flow rate of 15 kg s^{-1}. See ***Table 2.1*** and ***Table 2.2*** for further details.

Component	R5-type	Design mass flow rate (kg/s)	Opening pressure (MPa)	Closure pressure (MPa)
Spray valve 1	Trip valve	15	15.2	15.1
Spray valve 2	Trip valve	15	15.28	15.272
Spray valve 3	Trip valve	15	15.36	15.352
Spray valve 4	Trip valve	15	15.44	15.432

Table 2.1 PRZ spray from logic level of control

Component	R5-type	Design mass flow rate (kg/s)	Opening pressure (MPa)	Closure pressure (MPa)	PRZ level (m)
Spray valve 1&2	Trip valve	15	15.6	15.2	< 13.9

Table 2.2 Spray from logic level of limitation

The valve hysteresis was implemented with a formula comprising two variable trips and three logical trips (example given in ***Figure 2.8***). The sprays from logic level of limitation are modelled with a further condition on the PRZ level with another variable trip (***Figure 2.9***).

```
* valve 1
513  p     149010000   ge   null   0     152.0e5     n  } variable trips
514  p     149010000   ge   null   0     151.0e5     n
609  611  and  514  n                                 } logical trips
610  609  or   513  n
611  610  and  514  n
```

Figure 2.8 - Excerpt of the input deck, illustrating the valves logic

```
* valve spray limitation loop 1 and 2
523  p     149010000   ge   null   0     156.0e5     n  } variable trips
524  p     149010000   ge   null   0     152.00e5    n
624  626  and  524  n                                 } logical trips
625  624  or   523  n
626  625  and  524  n
525  cntrlvar 23 le null 0 13.9 n * PRZ level condition  } further conditions on the PRZ
627  626  and  525  n
```

Figure 2.9 - Excerpt of the input deck, illustrating the spray valves logic

2.2.4 Make-up spray

The make-up spray belongs to the logic level of limitation. It is modelled as a time dependent junction and a time dependent volume, regulated by a trip. Maximum flow rate is 10 kg s^{-1}. Simplified assumptions were taken into account to perform a conservative approach: the highest make-up temperature was chosen in order to consider the minimum condensation potential. The auxiliary make-up spray mass flow rate is set to a constant value. See ***Table 2.3*** for details.

Component	R5-type	Design mass flow rate (kg/s)	Opening pressure (MPa)	Closure pressure (MPa)	PRZ level (m)	Spray injection temperature
Make-up spray	Time dependent junction	10	15.7	15.4	< 11.5	constantly equal to the extraction point of the level control (*tempf 212-01*)

Table 2.3 - Make-up spray

2.2.5 Heaters

Heaters are simulated like an active heat structure connected to the lowest PRZ volume. The permissive signals based on the PRZ level are not considered, because in the transient we are going to analyze the level will always increase. In case of station black-out, heaters power is set to zero, because heat losses are not modelled. The following logic illustrates the heaters power regulation:

- A control variable calculates the pressure difference in the PRZ upper head, between the reference and actual value ($\Delta p = p_{actual} - p_{reference}$) for the heaters actuation.
- A control variable (type function) sets the heaters power according to a given function described in a general table (see **Figure 2.10**).
- Taking into in account the heaters switch-off in case of scram and the following station black-out, heaters power is multiplied by a *"trip unit"* control variable, i.e. it is 0 in case of scram, and 1 in normal operation.

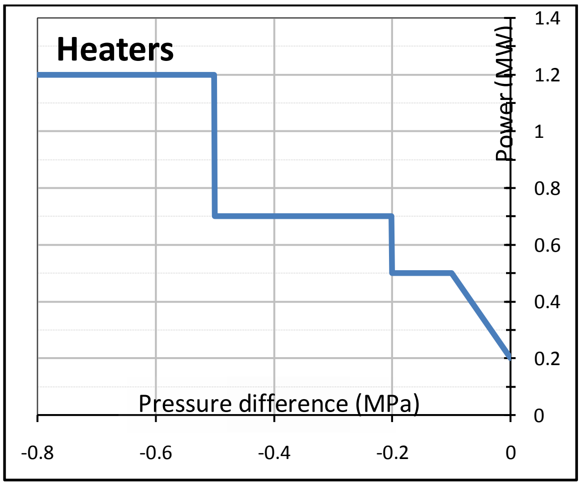

Figure 2.10 - Heaters power vs. PRZ pressure difference

2.2.6 PRZ relief valves

Two PRZ relief valves are modelled with trip valve components, ***Table 2.4***. Check valve are simulated with a high reverse flow losses coefficient.

Component	R5-type	Design mass flow rate (kg/s)	Opening pressure (MPa)	Closure pressure (MPa)
Relief valve 1	Trip valve	80	17.2	15
Relief valve 2	Trip valve	80	18.2	16

Table 2.4 PRZ relief valves

2.2.7 PRZ level control

PRZ collapsed water level is determined by a control variable, which sums the void fraction of each PRZ volume multiplied by the height of same volume. The injection and extraction mass flow rate are regulated by the difference of measured level and reference level ($\Delta L = L_{measured} - L_{reference}$). As a simplified assumption, this level is fixed to 9.1 m, not depending on the average reactor temperature (no sliding set point).

The injection system is modelled with a time dependent junction and a time dependent volume, connected to the coolant loop before the Main Coolant Pump (MCP). In order to simulate the recuperative heat exchange, the temperature in the time dependent volume of the injection system follows the temperature of the volume connected to the extraction time dependent junction. Control system doesn't apply in this case, and the injection system is regulated by the limitation system. The logic is as follows (see also ***Figure 2.11***):

- If the level difference (ΔL) is higher than the set point (0.5 m), the limitation system switches off any injection.
- If the level difference is lower than 0.5 m, the limitation system switches on another pump.

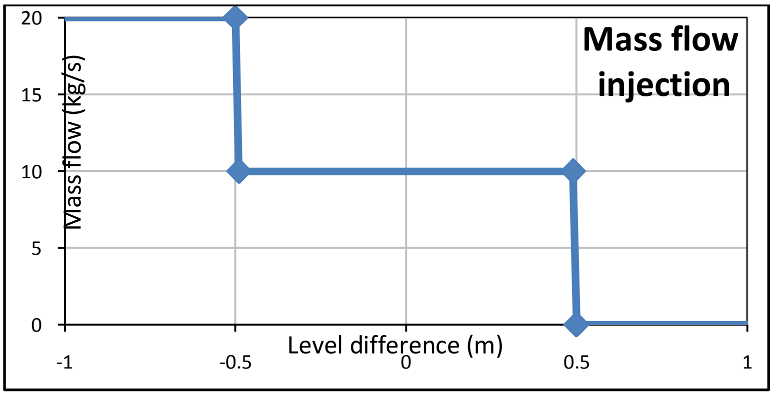

Figure 2.11 - Mass flow injection vs. PRZ level difference

Also the extraction system is modelled with a time dependent junction and a time dependent volume, connected after the MCP. Both control system and limitation system act on the regulation of the extraction system. The logic is as follows (see also ***Figure 2.12***):

- As a simplified as-sumption, the con-trol system act to regulate the level, if the ΔL is greater or less than 2 cm, without hysteresis.
- If the ΔL is between 0.02 m and 0.5 m, control valve opens to increase the mass flow rate extraction.
- If the ΔL > 0.5 m, another extraction valve fully opens.
- If the level difference is between -0.5 m and -0.02, than the control valve closes in order to decrease the extraction mass flow rate.
- If the level difference is less than -0.5 m, a minimum extraction of mass flow rate (2.3 kg s^{-1}) is assured

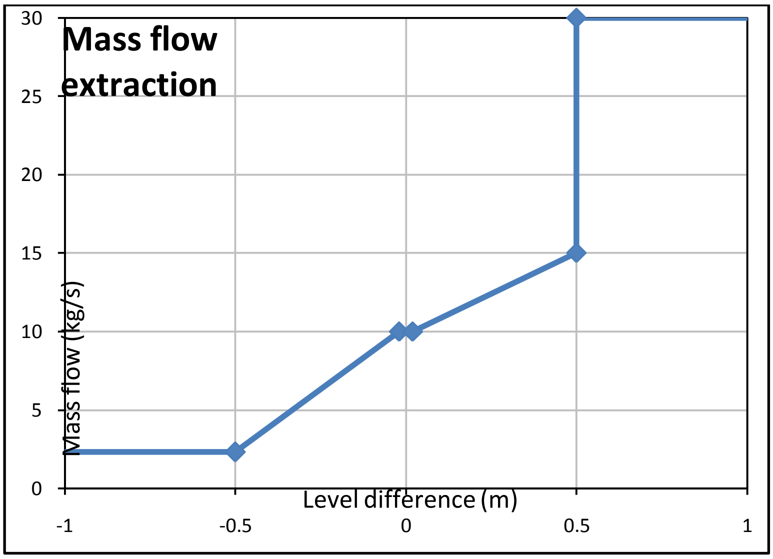

Figure 2.12 - Mass flow extraction vs. PRZ level difference

Generally, a common hysteresis is ± 20 cm; but in this modelling a simplified assumption was taken into account, and a smaller plateau (± 2 cm) was implemented.

2.2.8 Secondary side

The secondary side was modified in order to simulate a turbine trip. In the previous input deck, the MSIV was connected directly to the turbine (see ***Figure 2.13***, on the left there is the previous nodalization). In the new one (on the right), the MSIV is linked to a branch, that is connected to the turbine and the condenser through the turbine control valve and by-pass valve, respectively.

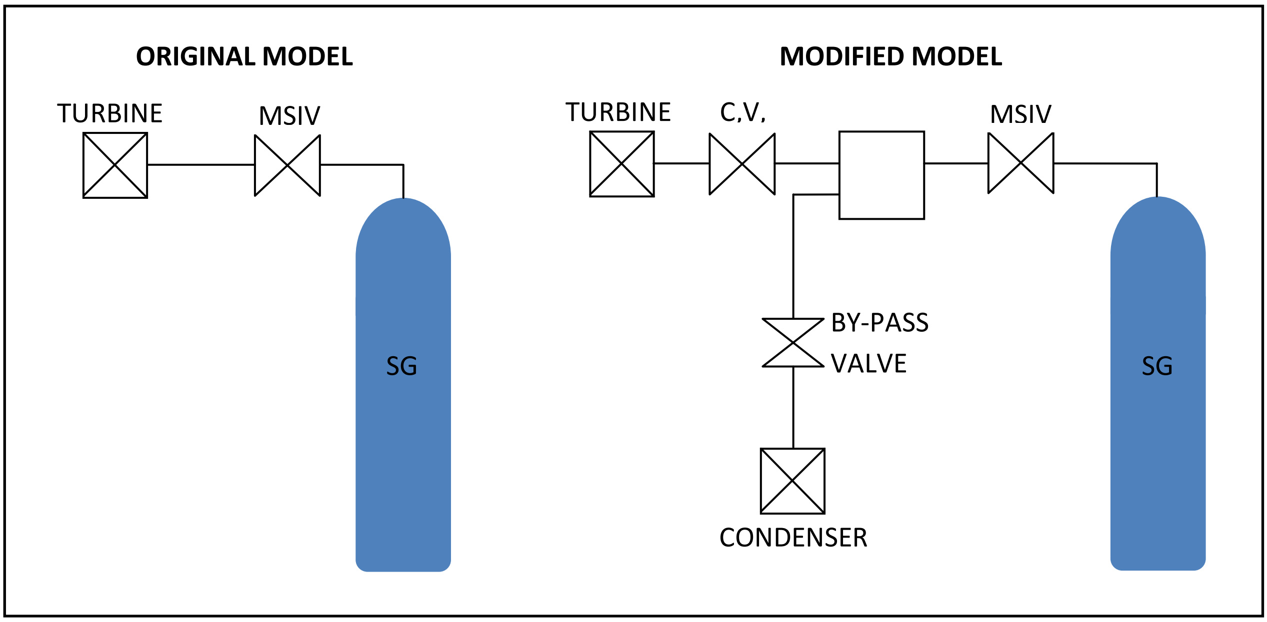

Figure 2.13 Sketches of secondary side, original and modified models

Other components were added to the secondary side:

- Condenser: a time dependent volume, pressure 0.05 MPa, temperature 315°K.

- By-pass valve: a ser-vo valve, activated when pressure in SGs is greater than 4.8 MPa; design mass flow rate is 80% of full power mass flow rate; the normalized area versus the nor-malized stem posi-tion is given by the NORMAREA general table (***Figure 2.14***).
- Turbine valve: a trip valve, designed like the MSIV (in this context a detailed modelling is not required).

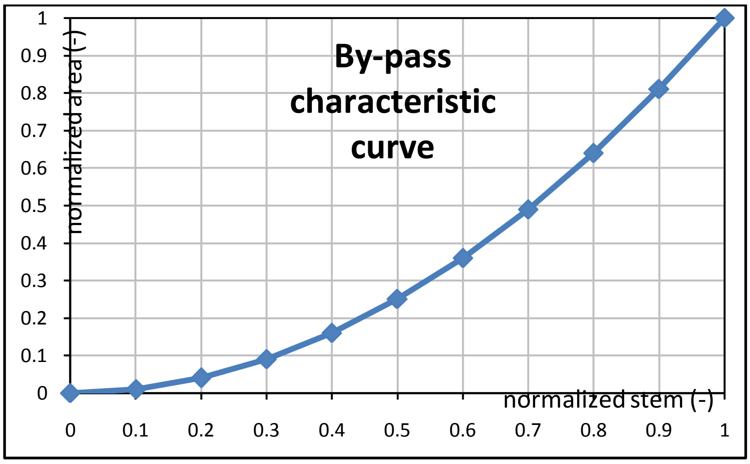

Figure 2.14 - By-pass normalized flow area vs. normalized stem position

2.2.9 Scram signals

For the purpose of this simulation, only the scram signals related to the pressurizer are implemented. Scram occurs if pressure or level values are outside the range given in ***Table 2.5***. Other simplified assumption: scram signal due to PRZ level are fixed and not sliding.

Condition	Value
PRZ pressure	> 15.7 MPa < 14.3 MPa
OR	
PRZ level	> 13.5 m < 3.4 m

Table 2.5 - PRZ scram signal

2.3 Relap5 to Fortran Control Module Coupling

While it is possible in principle to model every control system elements with the tools that Relap5 provides (physical and logical trip functions, and among the logical trip functions the logic and, or and not), the limited number of trip elements that the analyst can use poses a limit on the complexity of the control model. Several approaches are common practice to deal with this limitations:

Simplified control model: For most safety analysis applications in the field of licensing a conservative approach is adopted – which means, that only safety grade control systems are considered to be functional. This reduces greatly the complexity of the problem, since the most complex control systems are within the lower tiers.

Simplified/complex mix model: in case the focus is put on just a single element of the control system, the analyst can spend effort to model this aspect in detail, while neglecting other parts of the NPP controls. While this may be a viable approach for many applications, there is the disadvantage that one model can only be used for special cases.

External control system modeling: If great detail is required, and at the same time a general purpose model (like for example for a full scope- or engineering simulator) the Relap5 control elements are not sufficient, and the analyst has to resort to an external application. Relap5-3D provides a poorly documented direct interface to external applications (such as npa or rgui), however, a prerequisite to use this interface is the availability of the Relap5 source code. Since this prerequisite is not always fulfilled, University of Pisa developed a general method of coupling a Relap5-3D nodalisation to an external control module, which is presented in the following sections.

2.3.1 External coupling logic

The coupling approach that has been adopted consists of three submodules.

- Relap5 thermal hydraulic model
- Control module (Fortran program)
- Driver module (Perl script)

The thermal hydraulic model is as described in section 2.2, with the only difference that valve positions, heater power and reactor power are read by control variables, which are described as constants.

A Perl script takes care of the overall coordination of the process, and the data transfer from one module to the other.

The control module, which is written in Fortran and therefore allows to model controls with arbitrary complexity, reads pressures, temperatures (in general, variables that represent sensors at the plant), processes them (simulating the control of the plant), and provides position of control rods (reactor power), position of valves, state of pumps etc. The perl driver script again takes over, processes the output, and prepares a Relap5 input file, rewriting the constants mentioned above with the new values as calculated by the control module. Relap5 is then called as restart, and the problem is advanced from t to t+dt.

After the relap5 calcution the driver module tests if the problem time already reached the preset end time. If so, the calculation is terminated, otherwise the loop continues.

Figure 2.15 provides an overview on the process.

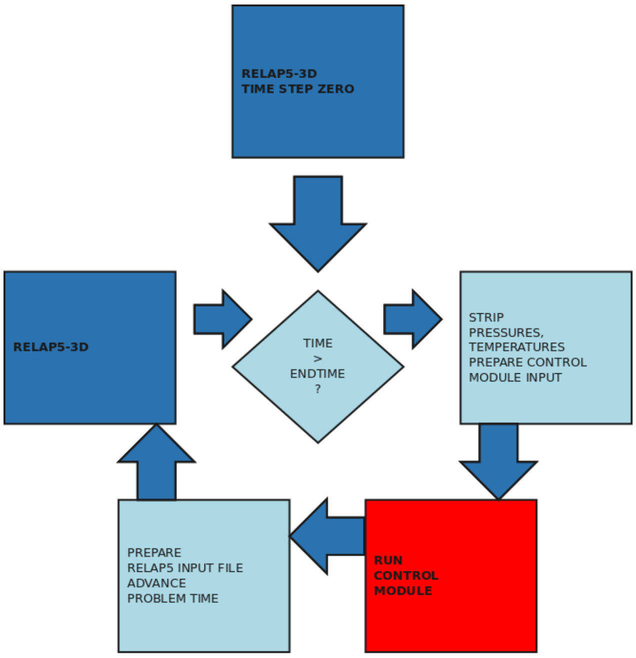

Figure 2.15 – Relap5 Fortran Coupled control logic.

2.3.2 Perl script main loop listing

The following section lists the main loop of the perl driver module. For simplicity, the subprograms are not listed.

```
################
#              #
# main program #
#              #
################

printf("Relap5 - Fortran CTRL coupling script\n");
printf("University of Pisa, GRNSPG, 30 Nov 2011\n");
printf("---------------------------------------\n\n");
printf("Reading configuration from $configfile ...\n ");
read_config();

printf("Creating folders $relapresults and $ctrlresults ...\n");
mkdir($relapresults);
mkdir($ctrlresults);
$time = 0;

# Run Relap for one ts to have initial values

printf("Running relap initial step ...\n");
create_relap_initial_file();
run_relap_save_result();

# start main loop
printf("Starting main loop - calculation until $endtime\n");
```

```
while( $time < $endtime) {

  printf("Time: %4.1f ",$time);

  printf("stripping ... ");
  pstrip_relap();

  printf("running ctrl ... ");
  prepare_cntrol_input();
  run_control();

  printf("running relap ... ");
  prepare_relap_input();
  run_relap_save_result();

  $time = $time + $couplingdt;
}


printf("\nFinished - exiting.\n");
```

2.3.3 Fortran control module

Relap 5 is not a suitable programme to implement the complex logical trips occurring during an operational transient, , and in the previous simulation many simplified assumptions were taken into account. However, a programme like FORTRAN is more suited for the logic implementation (for instance, sliding set points). Elements on how specific controls have been implemented in fortran are given below:

PKMAX=MAX(PKL(1),PKL(2))	*comments:*
PKMIN=MIN(PKL(1),PKL(2))	
EXPP=EXP(-DZEIT/TAUP)	
PKMAX(I)=PKL(I)-(PKL(I)-PKMAX(I))*EXPP	
*********SPRAY CONTROL	
IF(PKMAX.GT.SLOOP1) LSLOOP1=.TRUE.	*--> on*
IF(PKMAX.LT.SLOOP1+HSLOOP1) LSLOOP1=.FALSE.	*--> off*
IF(PKMAX.GT.SLOOP2) LSLOOP2=.TRUE.	*--> on*
IF(PKMAX.LT.SLOOP2+HSLOOP2) LSLOOP2=.FALSE.	*--> off*
IF(PKMAX.GT.SLOOP3) LSLOOP3=.TRUE.	*--> on*
IF(PKMAX.LT.SLOOP3+HSLOOP3) LSLOOP3=.FALSE.	*--> off*
IF(PKMAX.GT.SLOOP4) LSLOOP4=.TRUE.	*--> on*
IF(PKMAX.LT.SLOOP4+HSLOOP4) LSLOOP4=.FALSE.	*--> off*

*********SPRAY LOOP LIMITATION

```
IF(PKMAX.GT.SLOOPL)       LSLOOPL=.TRUE.                    --> on
IF(PKMAX.LT.SLOOPL+HSLOOPL) LSLOOPL=.FALSE.                 --> delay

LPRZLEV1 = .TRUE.
IF(PRZLEV.LT.PRZLEV1)     LPRZLEV1=.FALSE.                  --> permissive level
                                                            Heaters limitation on
```

*********SPRAY MAKE-UP LIMITATION

```
IF(PKMAX.GT.SMKUPL)       LSLOOPL=.TRUE.      --> ON
IF(PKMAX.LT.SMKUPL+HSMKUPL) LSLOOPL=.FALSE.       ---> DELAY

LPRZLEV2 = .TRUE.
IF(PRZLEV.LT.PRZLEV2)     LPRZLEV2=.FALSE.                  --> permissive level
                                                            Heaters limitation on
```

*********HEATERS CONTROL

```
IF(PKMIN.LT.PHEAT1)       LPHEAT1=.TRUE.
IF(PKMIN.GT.PHEAT1+HPHEAT1) LPHEAT1=.FALSE.
IF(PKMIN.LT.PHEAT2)       LPHEAT2=.TRUE.
IF(PKMIN.GT.PHEAT2+HPHEAT2) LPHEAT2=.FALSE.
IF(PKMIN.LT.PHEAT3)       LPHEAT3=.TRUE.
IF(PKMIN.GT.PHEAT3+HPHEAT3) LPHEAT3=.FALSE.

LPRZLEV3 = .TRUE.
```

```
IF(PRZLEV.LT.PRZLEV3)      LPRZLEV3=.FALSE.                         --> permissive level


*********HEATERS LIMITATION

* AC ON

 IF(PKMIN.LT.PHEAT4)      LPHEAT4=.TRUE.                            --> delay

 IF(PKMIN.LT.PHEAT5)      LPHEAT4=.FALSE.


************* SLIDING LEVEL SET POINT

   DIFF=HMESS-HDHGL

   V=VAUFGL

   IF(DIFF.LT.0.0) V=VABGL

   IF(ABS(DIFF).LE.ABS(V*DZEIT)) HDHGL=HDHGL+DIFF

   IF(ABS(DIFF).GT.ABS(V*DZEIT)) HDHGL=HDHGL+V*DZEIT

   IF(HDHGL+DHGLO.GT.HGLMAX) HDHGL=HGLMAX-DHGLO

   IF(HDHGL+DHGLU.LT.HGLMIN) HDHGL=HGLMIN-DHGLU


   HDHGLO=HDHGL+DHGLO

   HDHGLU=HDHGL+DHGLU
```

3 Transient Turbine Trip (with/without by-pass)

A steady-state calculation up to 3000 seconds was performed. The turbine trip is actuated by the closure of the turbine control valve at t = 3000 s. Two cases are considered:

a) Best estimate (control system, limitation system and protection system available)
b) Conservative (only protection system available)

In case a), one second after the turbine trip, the reactor power is lowered to 80% of nominal power, and the by-pass line is available. The reactor power is set by a general table, and the power reduction to 80% occurs linearly into 20 seconds.

In case b), there's no power reduction and no by-pass line. The reactor power is evaluated by the R5 neutron Point Kinetics (PK), and the reactivity insertion due to the scram signal is modelled by the REAC-T general table.

In the following paragraphs these two cases are discussed, and in the following chapter the insurge case is illustrated. In the related Figures, only the transient is displayed (30 minutes), and Figures are ordered and indexed in this way:

Figure **3.**1	Reactor power
Figure **3.**2	PRZ pressure
Figure **3.**3	PRZ collapsed level
Figure **3.**4	PRZ heaters power
Figure **3.**5	Level control (injection and extraction)
Figure **3.**6	Make-up spray
Figure **3.**7	Spray 1&2 from control system and spray 1 from the limitation system
Figure **3.**8	Spray 3&4 from control system and spray 2 from the limitation system
Figure **3.**9	Steam Line mass flow rate
Figure **3.**10	By-pass mass flow rate

3.1 Best Estimate Case (with by-pass)

As soon as the turbine trip occurs, the reactor power is reduced to 80% in few seconds (***Figure 3.1***). In this case the by-pass is available, so the steam from the Steam Line is decreased from almost 2000 kg s^{-1} to about 1500 kg s^{-1} , a 75% reduction (***Figure 3.10***), and it is delivered to the by-pass line (***Figure 3.9***).

After the turbine trip, PS pressure increases for a while (5 ÷ 15 s), but then the reactor power reduction will contribute to a sensitive reduction of the pressure (***Figure 3.2***) up to about 50 s, when heaters start to rebalance the pressure. As the transient goes on, two small peaks are experienced between 200 s and 400 s, corresponding to the sprays actuation; then pressure slowly declines. PRZ heaters will actuate as soon as the pressure is lower than the reference value, as explained in ***Figure 2.10***. In this transient, the PRZ pressure falls below the reference value (ca. 15 MPa) two times: between 20 s and 120 s, as mentioned above, and after 800 s, so in these ranges heaters will work (***Figure 3.4***).

PRZ level (***Figure 3.3***) follows the pressure trend in the first part of the transient (100 s): so the there is a small level increase, due to the pressure spike, and then the level decreases according to the pressure reduction. Injection and extraction will actuate in order to rebalance the level (***Figure 3.5***). So, when the level reaches its minimum at about 50 s, the injection doubles and the extraction falls to its minimum value, 2.3 kg s^{-1}, and eventually they will go back to the original settings. Notice, after 1000 s, the PRZ level is a little bit higher than the reference one ($\Delta L > 0$), so extraction mass flow rate increases according to the rules set in ***Figure 2.12***.

There is no make-up spray (Figure 3.6) because its actuation conditions are not met, i.e. pressure doesn't exceed 15.7 MPa (see Table 2.3). Among the other sprays (Figure 3.7 and Figure 3.8) only the spray No. 1 of the control system will activate to counterbalance the pressure peak, at about 235 s and 335 s. More precisely, according to Table 2.1, as soon as the pressure reaches 15.2 MPa (see again Figure 3.2), the spray valve 1 opens; and then it closes when the pressure falls below 15.1 MPa. That is not enough, and indeed the pressure starts to increases again, so the spray valve 1 will open for a second time. After this, pressure is more or less stabilized, and for the remainder of the transient, no more sprays are needed.

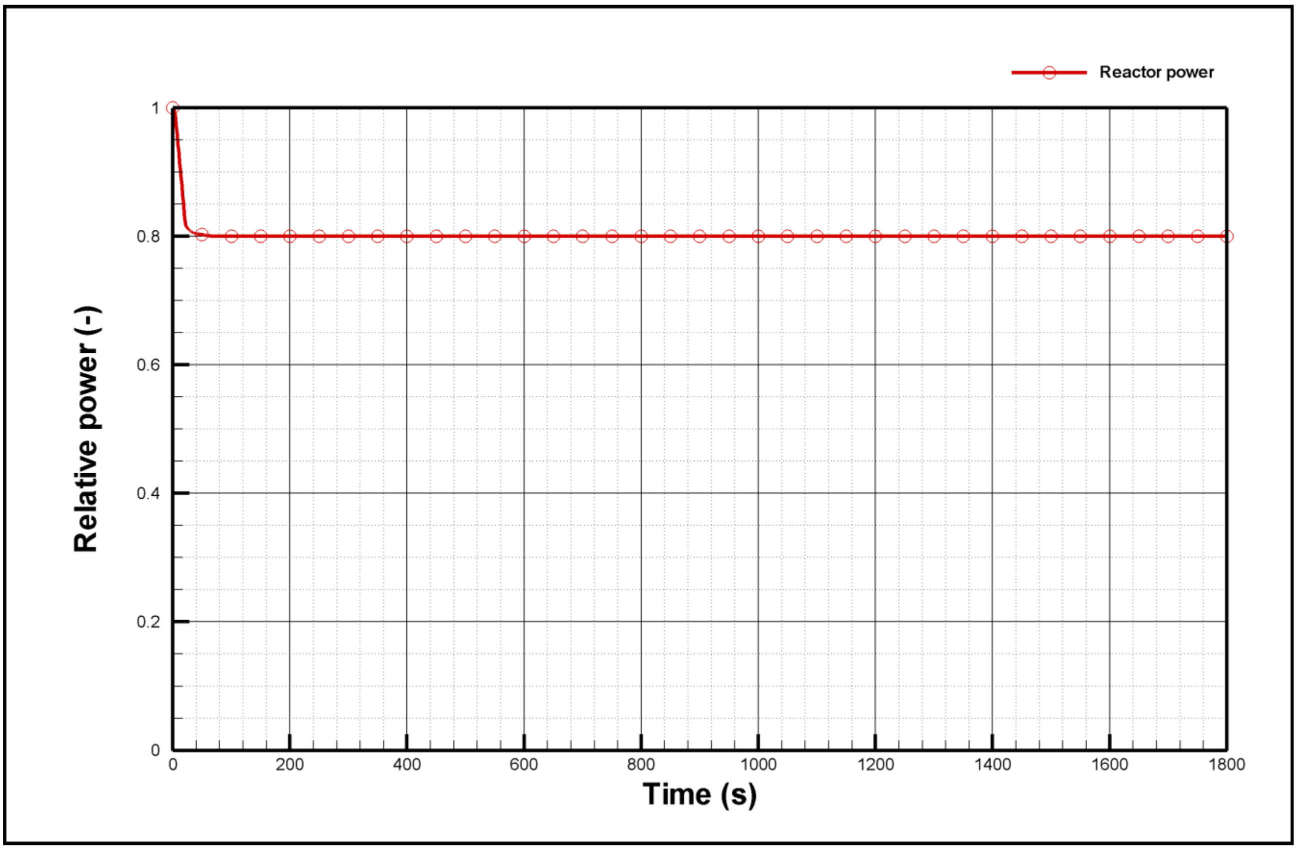

Figure 3.1 - Reactor power (best estimate case)

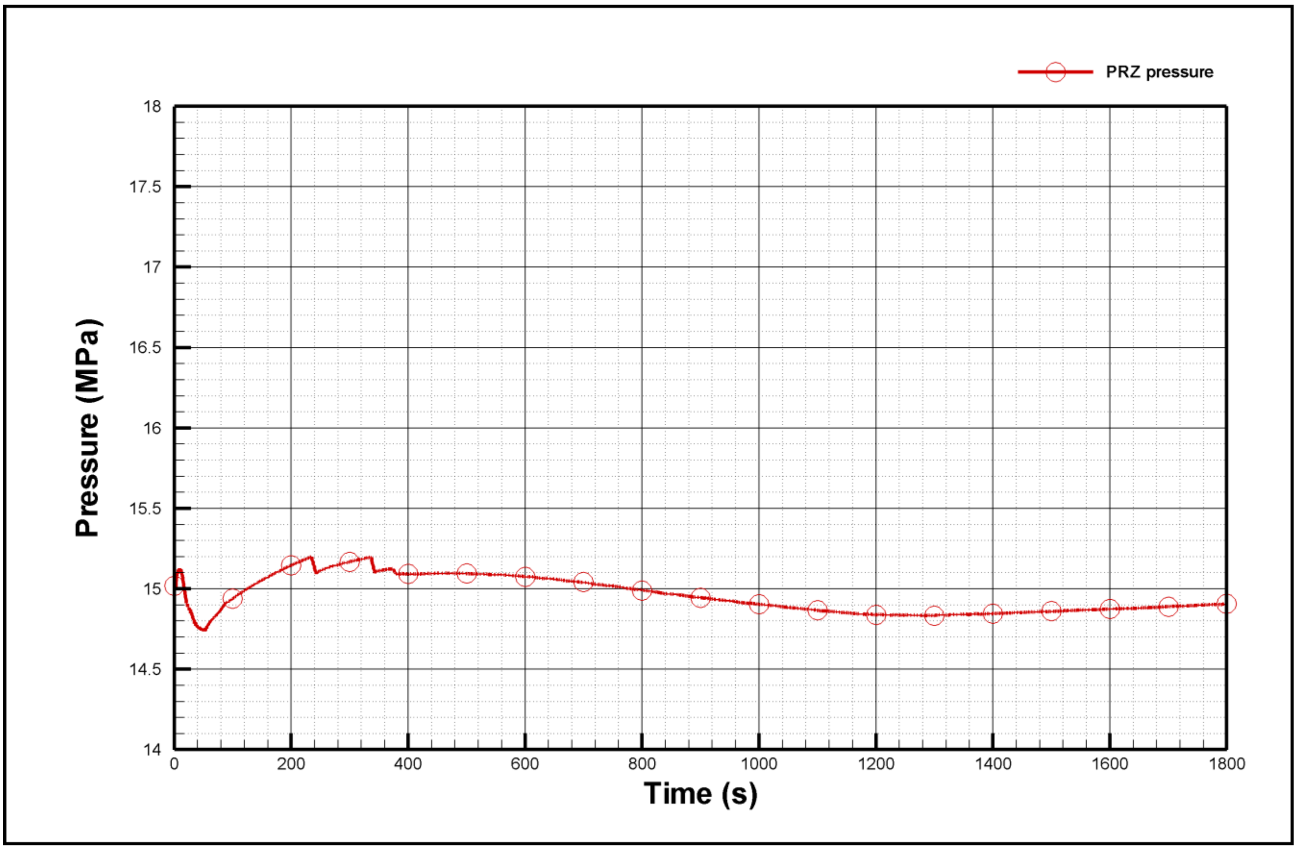

Figure 3.2 - PRZ pressure (best estimate case)

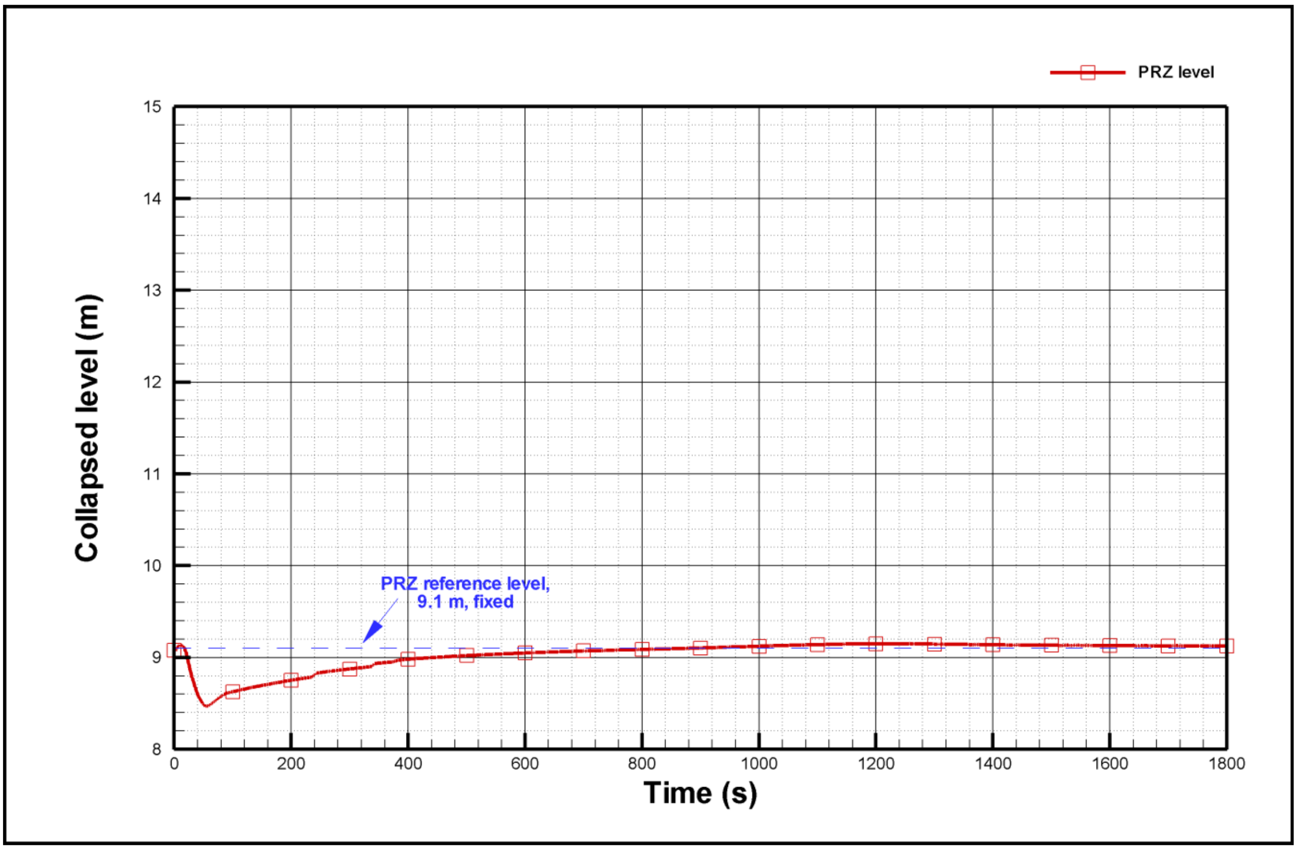

Figure 3.3 - PRZ collapsed level (best estimate case)

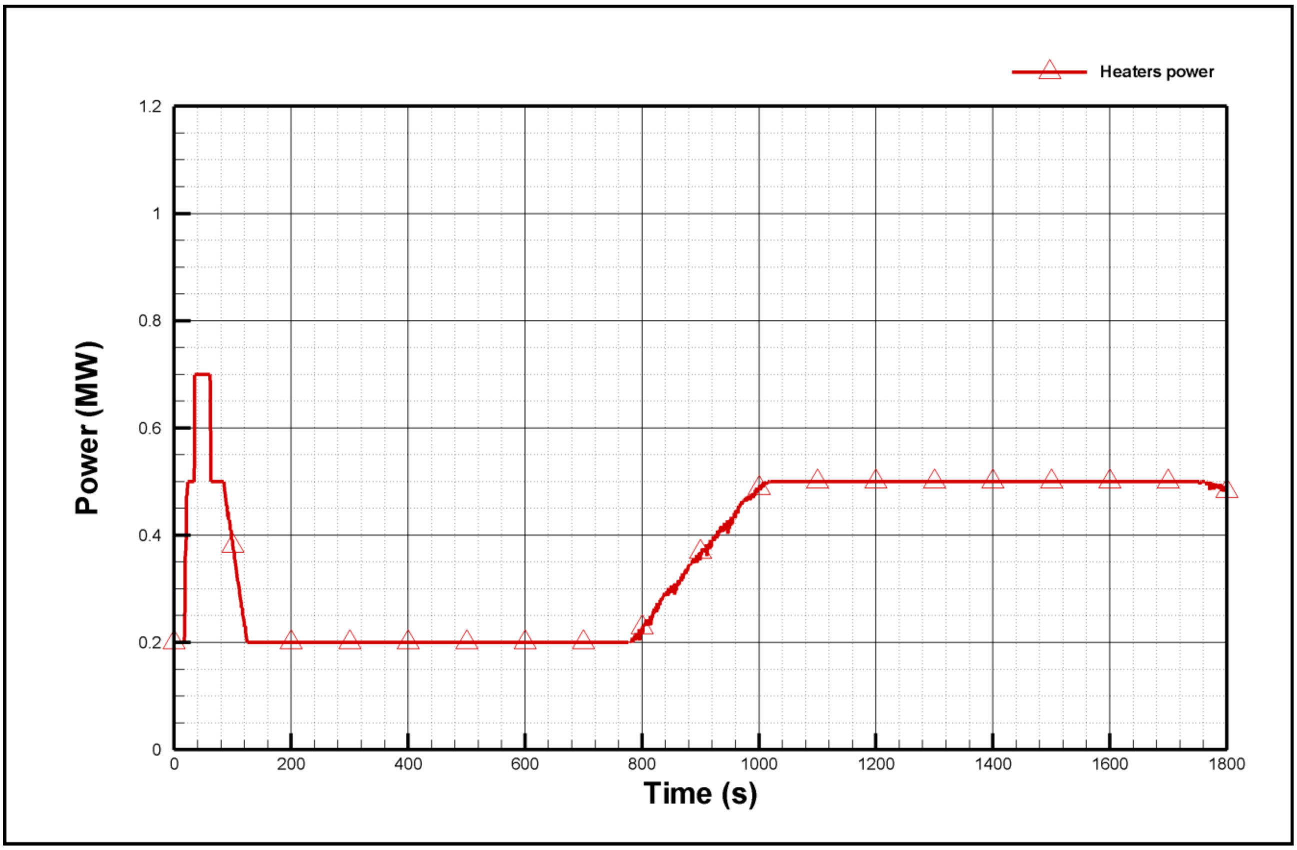

Figure 3.4 - PRZ heaters power (best estimate case)

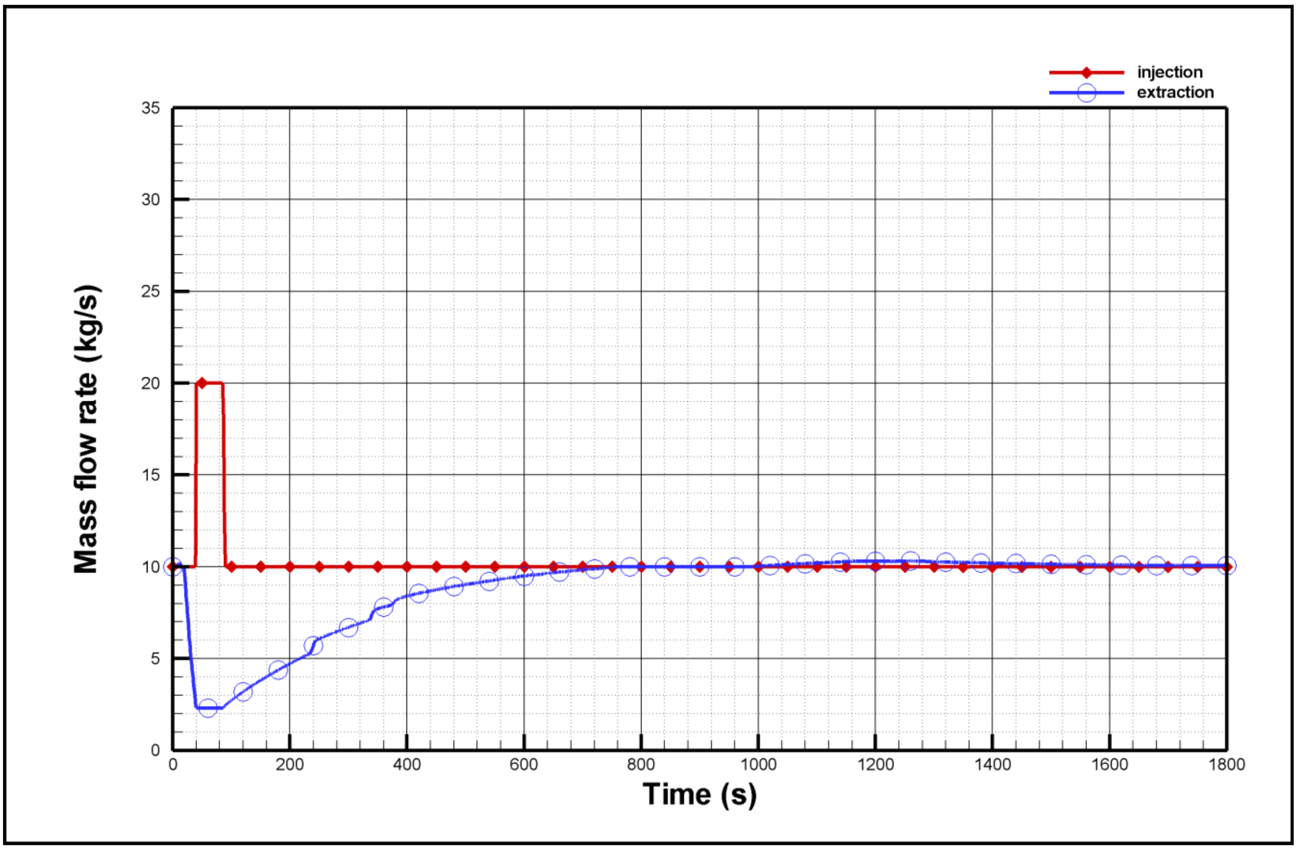

Figure 3.5 - Level control (best estimate case)

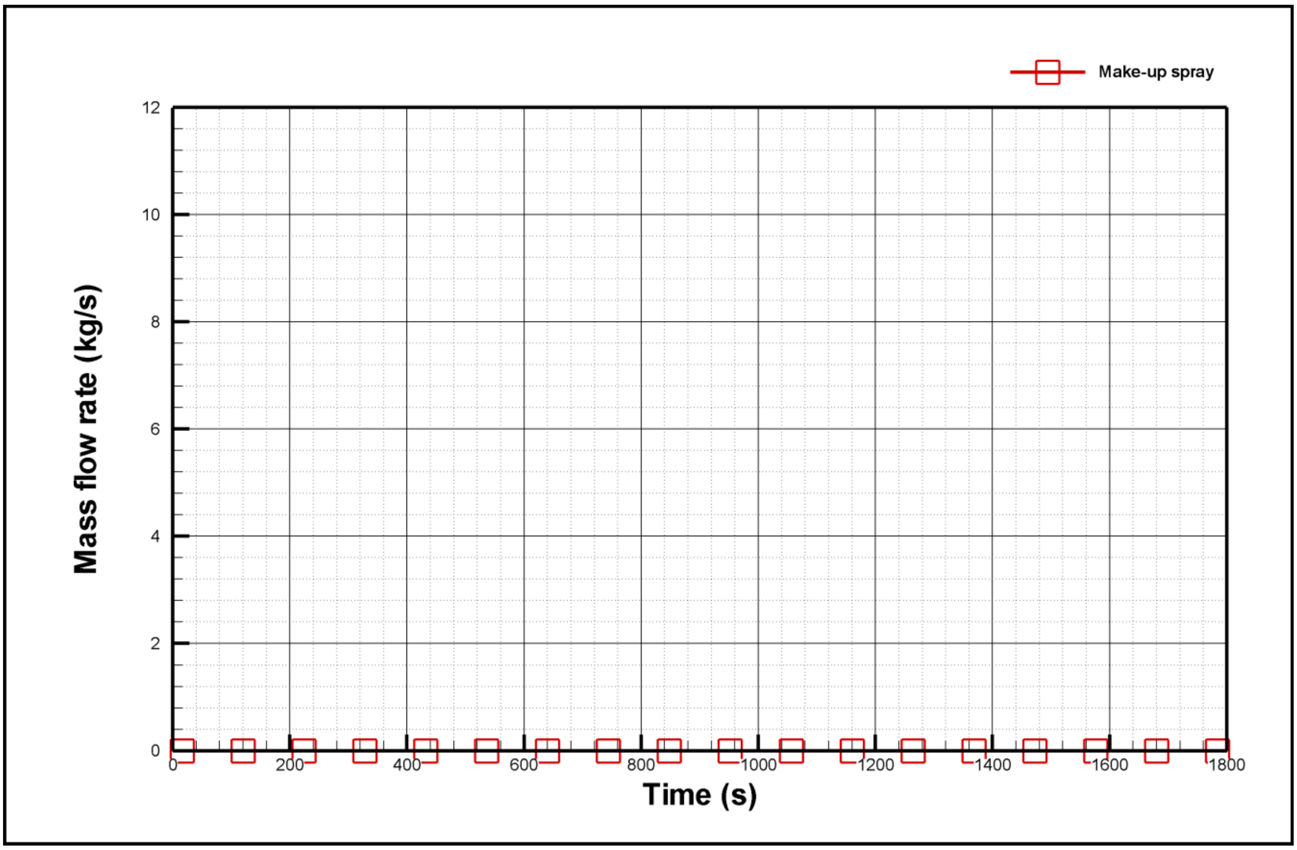

Figure 3.6 - Make-up spray (best estimate case)

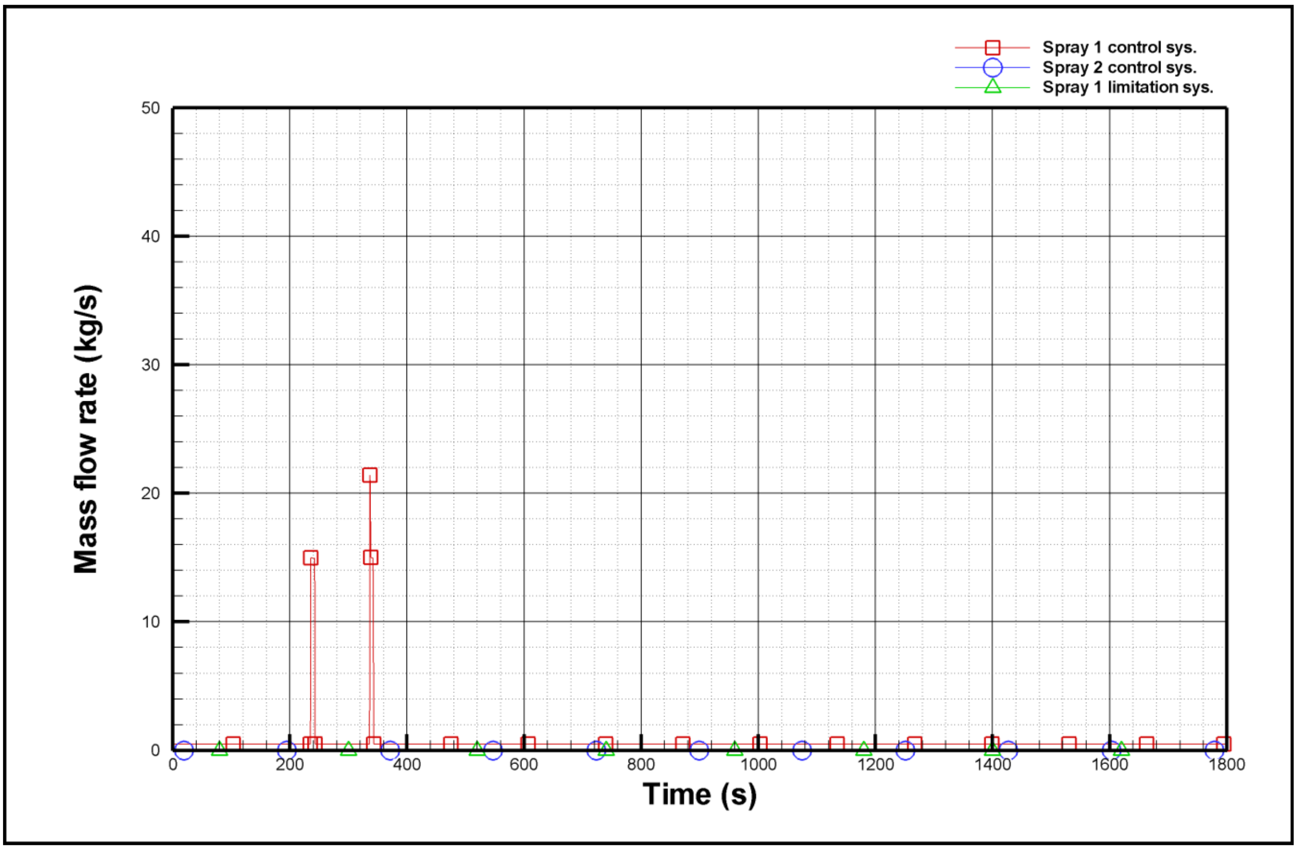

Figure 3.7 - Spray 1&2 from control system and spray 1 from the limitation system (best estimate case)

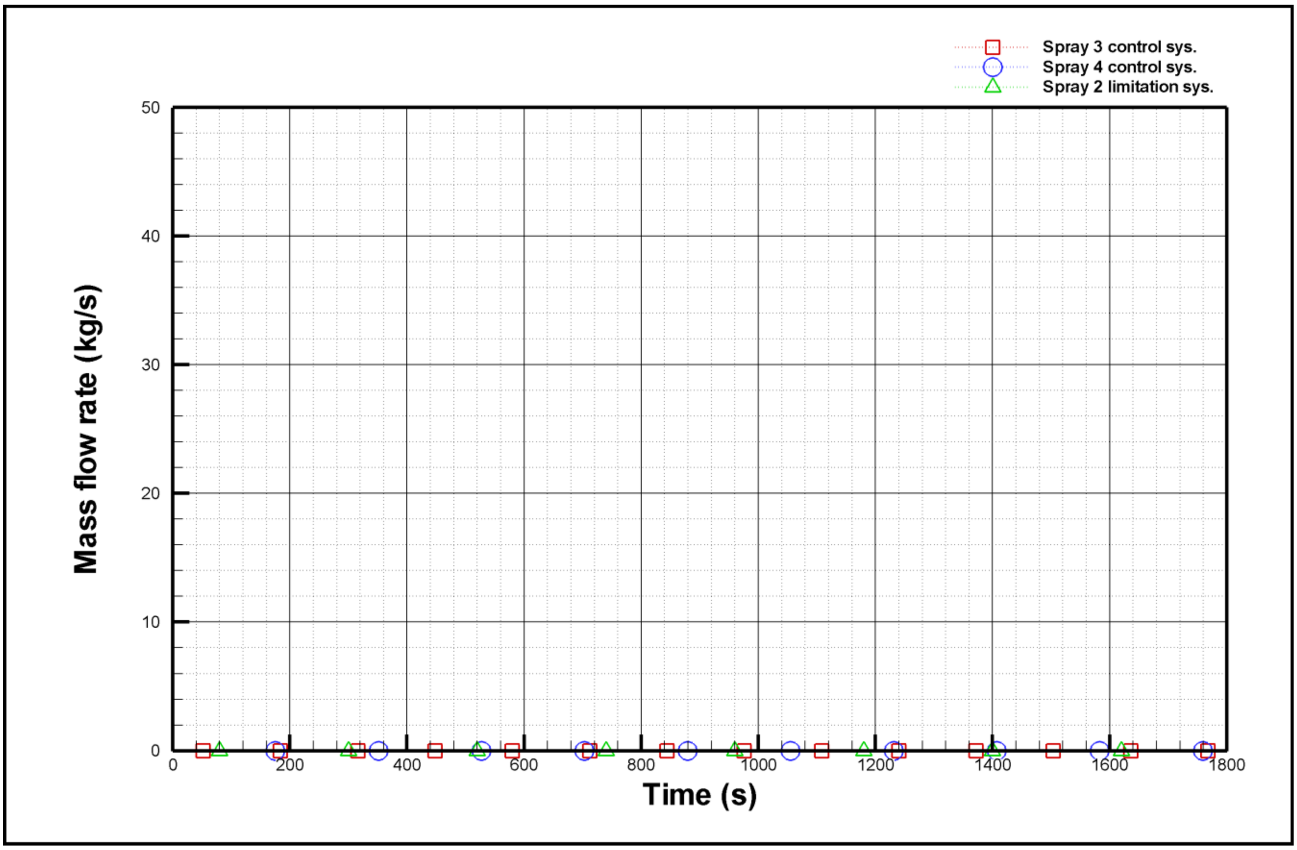

Figure 3.8 - Spray 3&4 from control system and spray 2 from the limitation system (best estimate case)

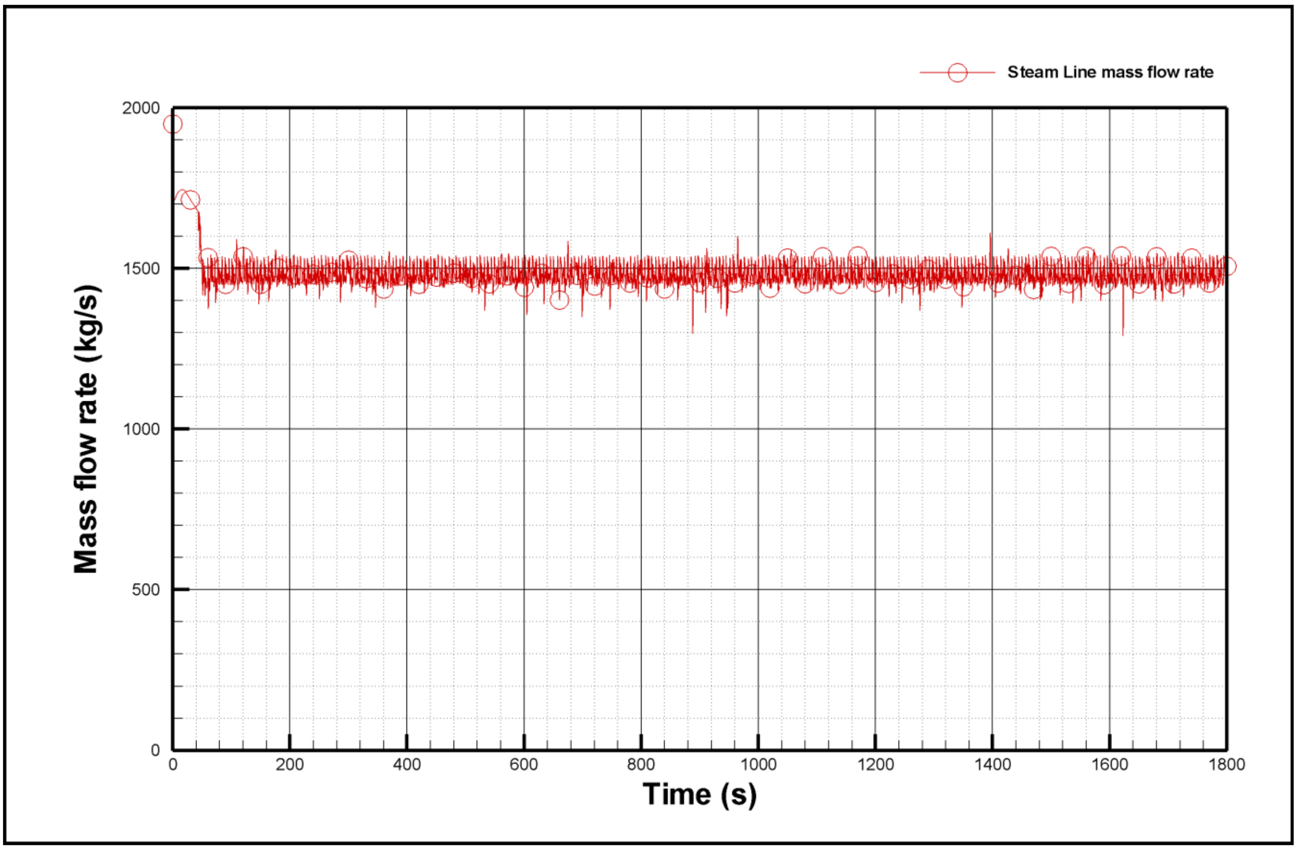

Figure 3.9 - Steam Line mass flow rate (best estimate case)

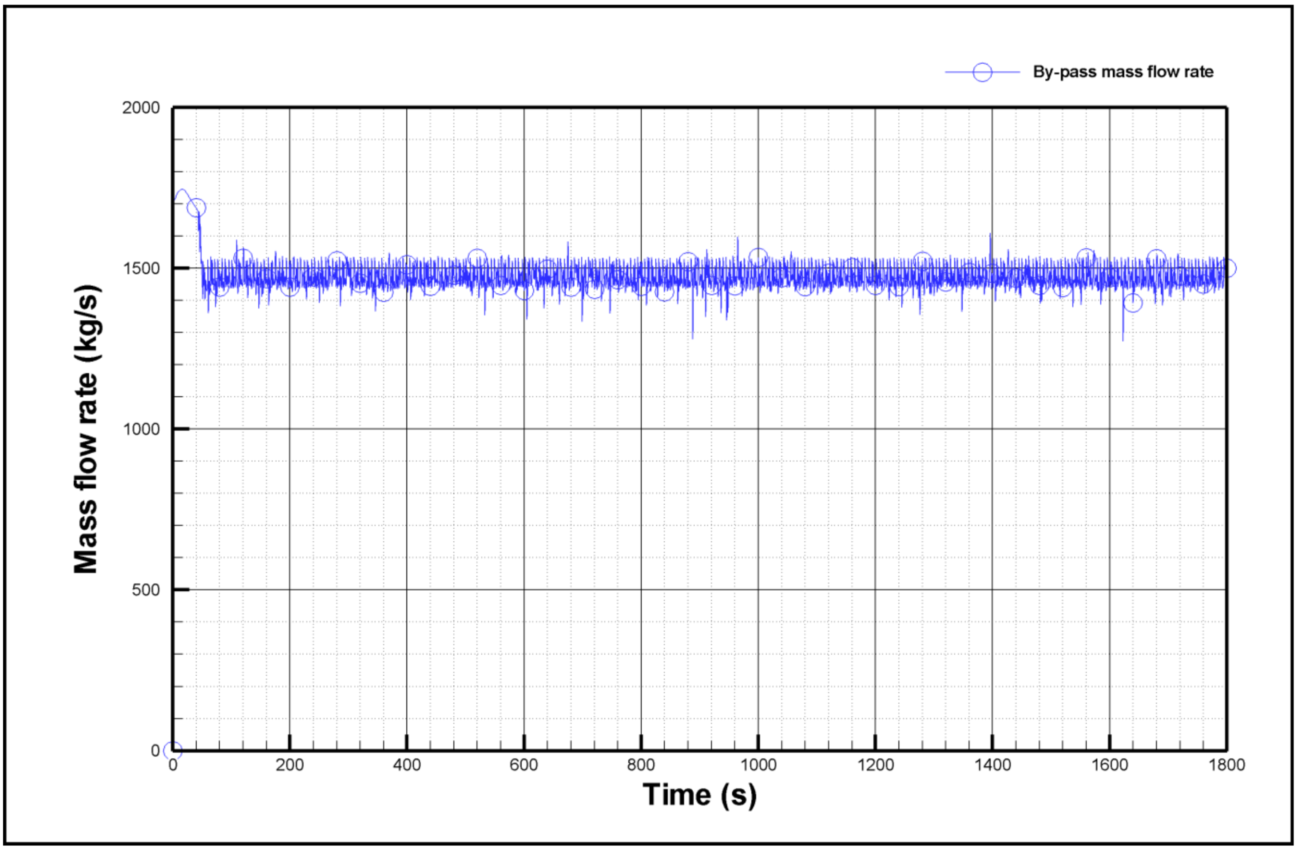

Figure 3.10 **-** By-pass mass flow rate (best estimate case)

3.2 Conservative case (without by-pass)

In the conservative case, the by-pass line is considered not available, and so, as soon as the turbine trip occurs, there is no mass flow rate through the steam line and the by-pass line (***Figure 3.19*** and ***Figure 3.20***). The scram signal is activated according to the conditions given in ***Table 2.5***, so, in this case, after about 5 seconds the scram occurs, because the PRZ pressure exceeds the limit (***Figure 3.11***). As a consequence of the scram, no power is available (station black-out).

Pressure (***Figure 3.12***) increases sharply as soon as the turbine trip occurs, because the there is no heat exchange with the secondary side, due to the limitations on the by-pass line. But, after the scram, pressure reduces for a while, and then increases again due to the lack of circulation in the PS, following the station black-out. After the second pressure peak, the PRZ pressure will slowly decrease.

The PRZ heaters operate normally at 200 kW until the scram (5 s), then they are not available due to the station black-out (***Figure 3.14***).

The PRZ level increases in the first seconds of the transient (***Figure 3.13***), according to the pressure raise, so there is a relative peak, corresponding to the first pressure peak; then the level will increase again, and it will be generally rather high (ΔL > 0.5 for most of the transient).

Injection and extraction (***Figure 3.15***) follow the PRZ level behaviour, so during the first level peak (ΔL > 0.5), the extraction augments to 30 kg s^{-1}, and the injection falls to 0 kg s^{-1}. After few seconds, after this small level peak, injection and extraction tend to return to their design values, but they don't succeed, because the level is still high, and so for the remainder of the transient extraction will operate at its maximum, and there is no injection.

The sprays from the control system and limitation system will activate in the first few seconds of the transient due to the pressure spike (**Figure 3.17** and **Figure 3.18**), but during the rest of the transient, only the make-up spray will operate, because in case of station black-out those spray are not available. The make-up spray (***Figure 3.16***) will activate two times, in order to lower the corresponding pressure peaks. By the way, the effect of the make-up spray can be clearly seen in the second pressure peak (***Figure 3.12***): during the raise, the pressure slope changes when pressure reaches 15.7 MPa, due to the actuation of the spray, as well as in the phase of the pressure reduction, at 15.4 MPa, there is an abrupt change in the slope, because the make-up spray stops, and the pressure decreases slower.

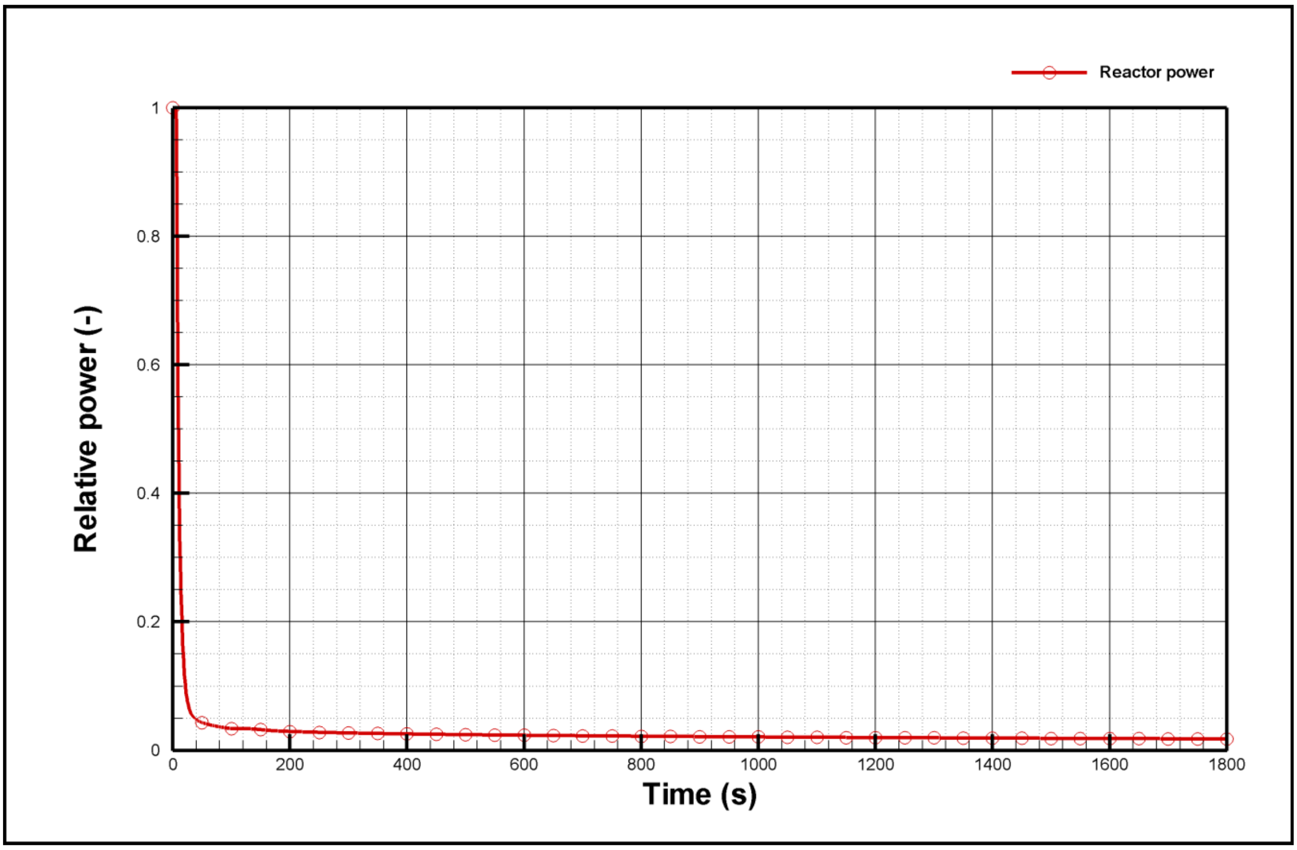

Figure 3.11 - Reactor power (conservative case)

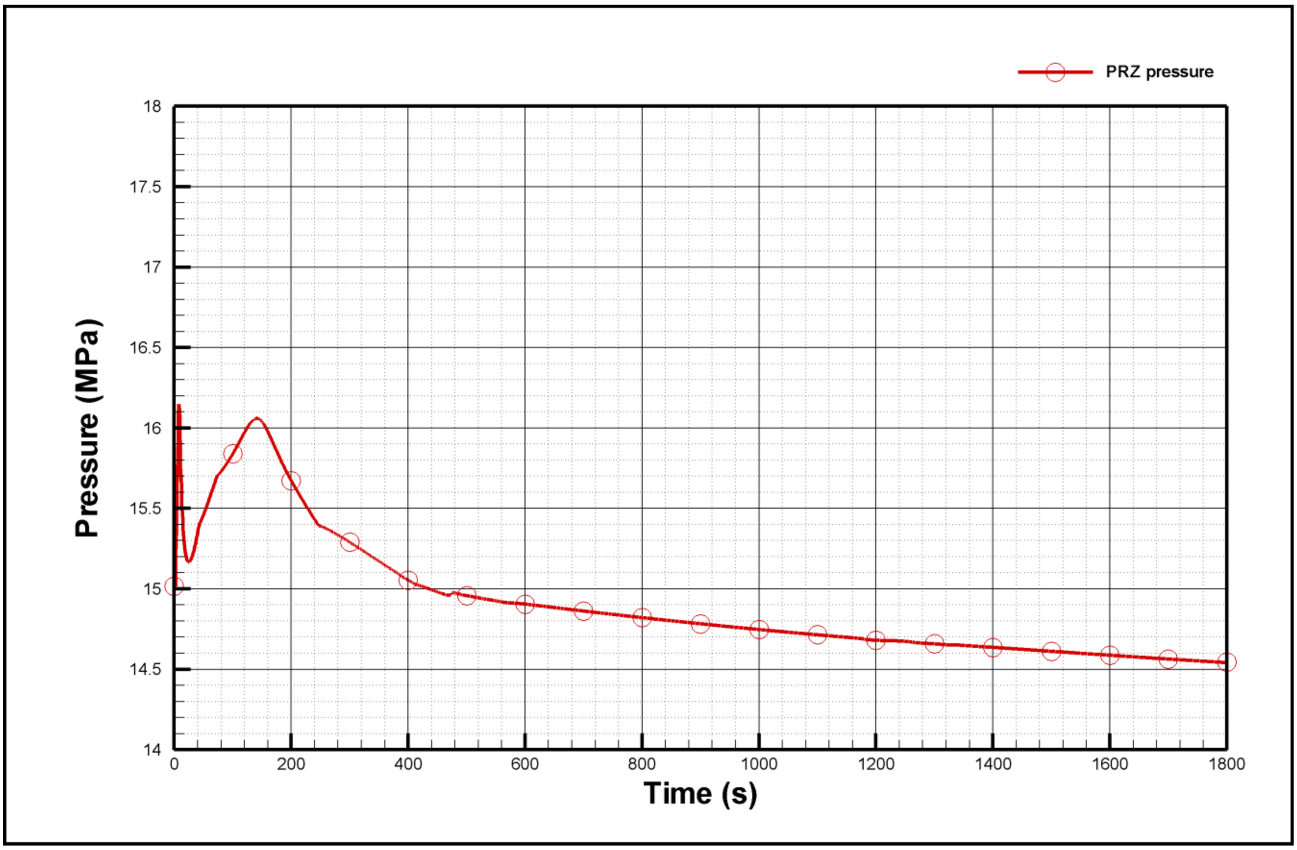

Figure 3.12 - PRZ pressure (conservative case)

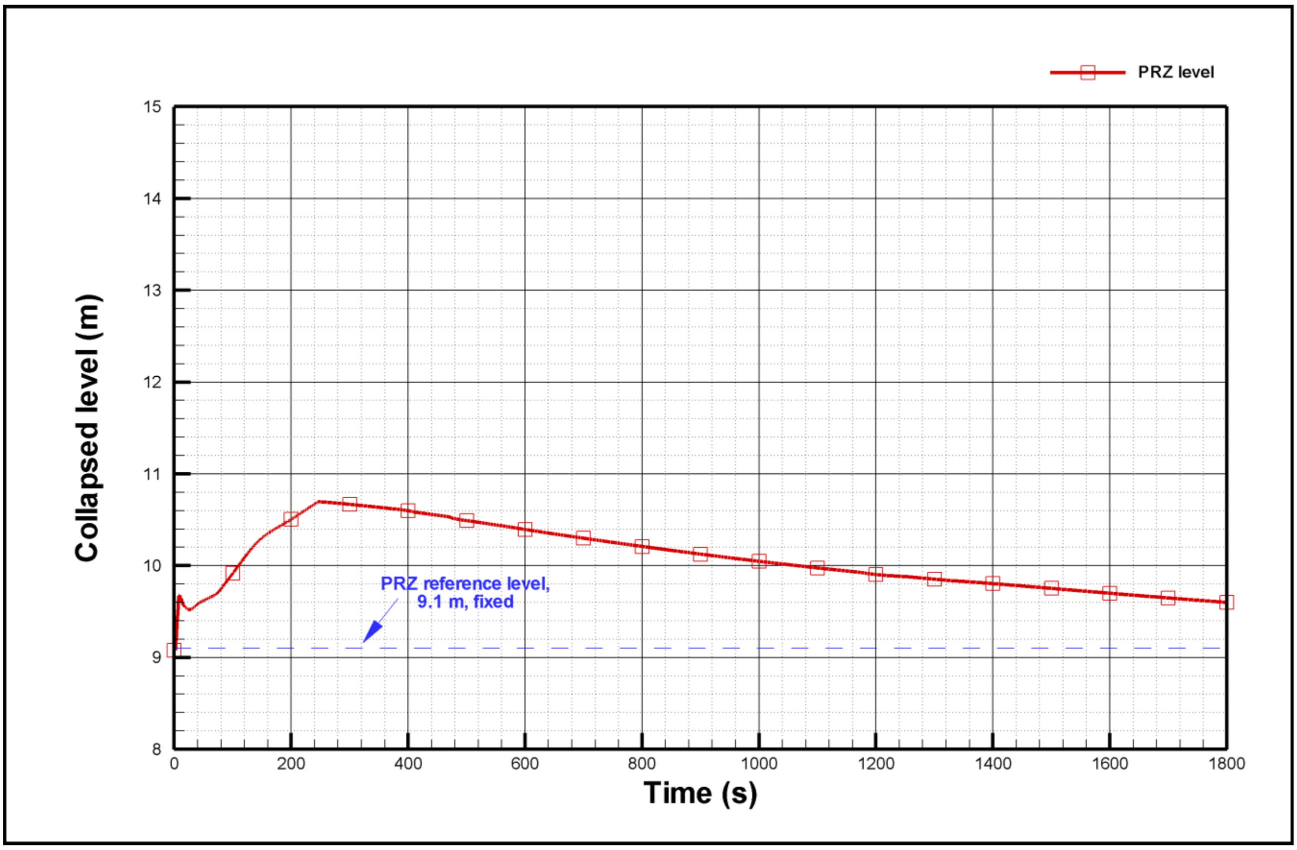

Figure 3.13 - PRZ collapsed level (conservative case)

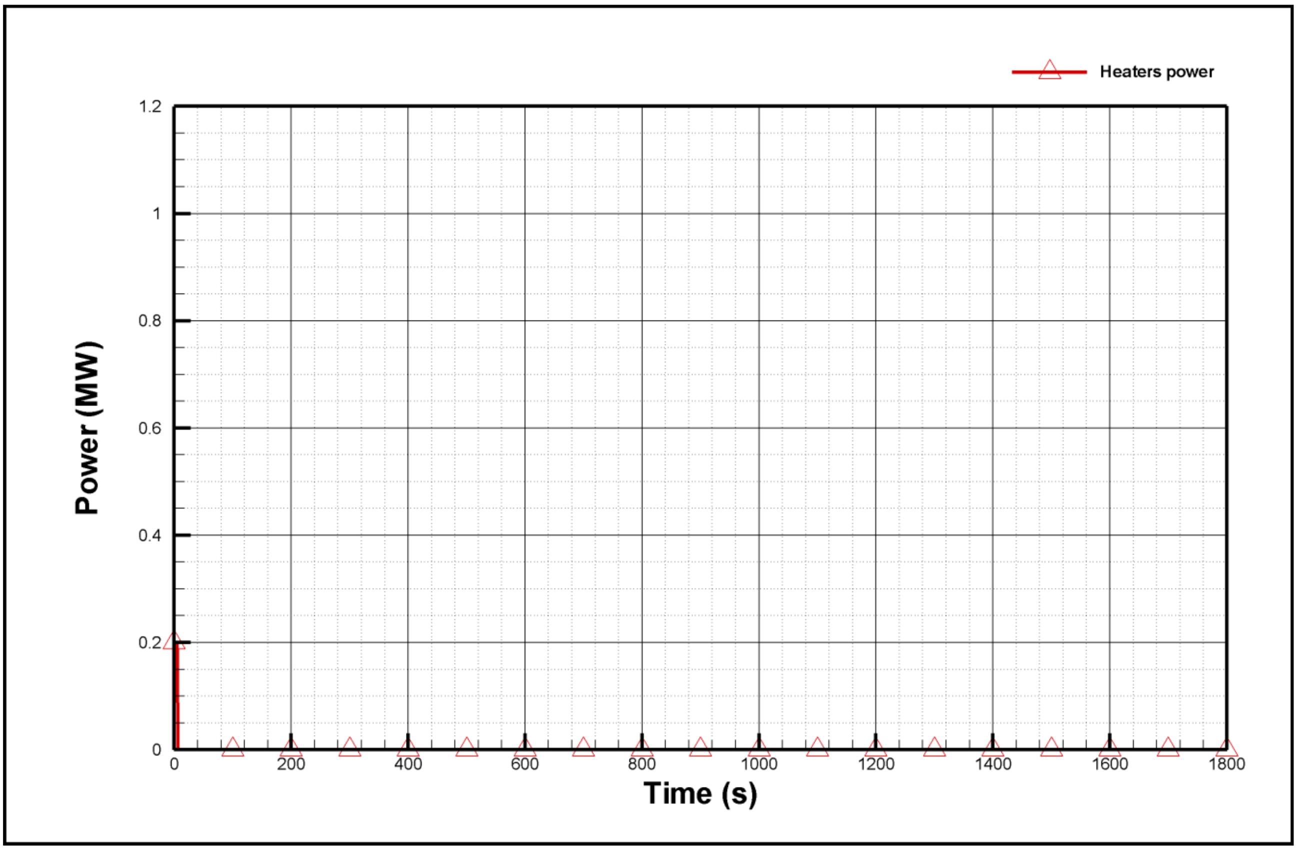

Figure 3.14 - PRZ heaters power (conservative case)

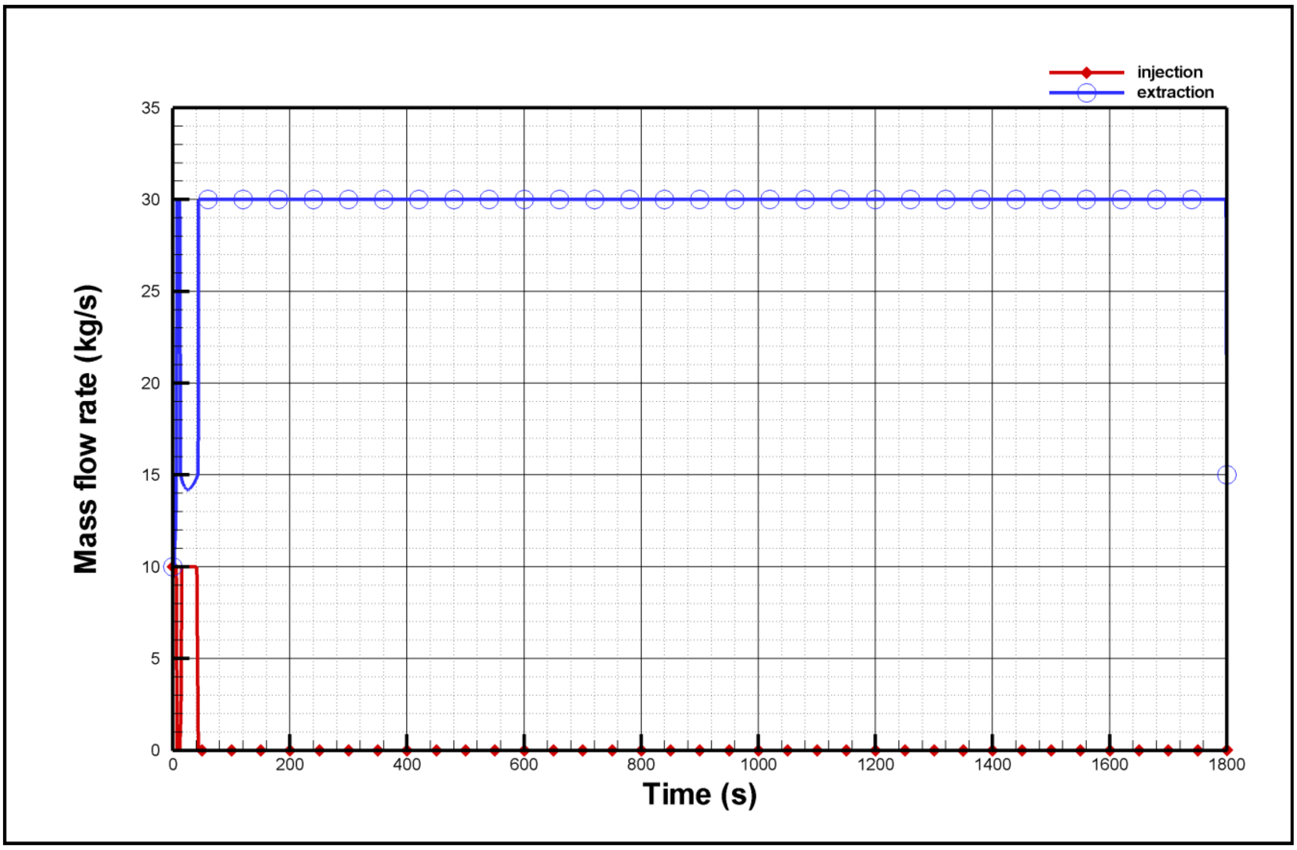

Figure 3.15 - Level control (conservative case)

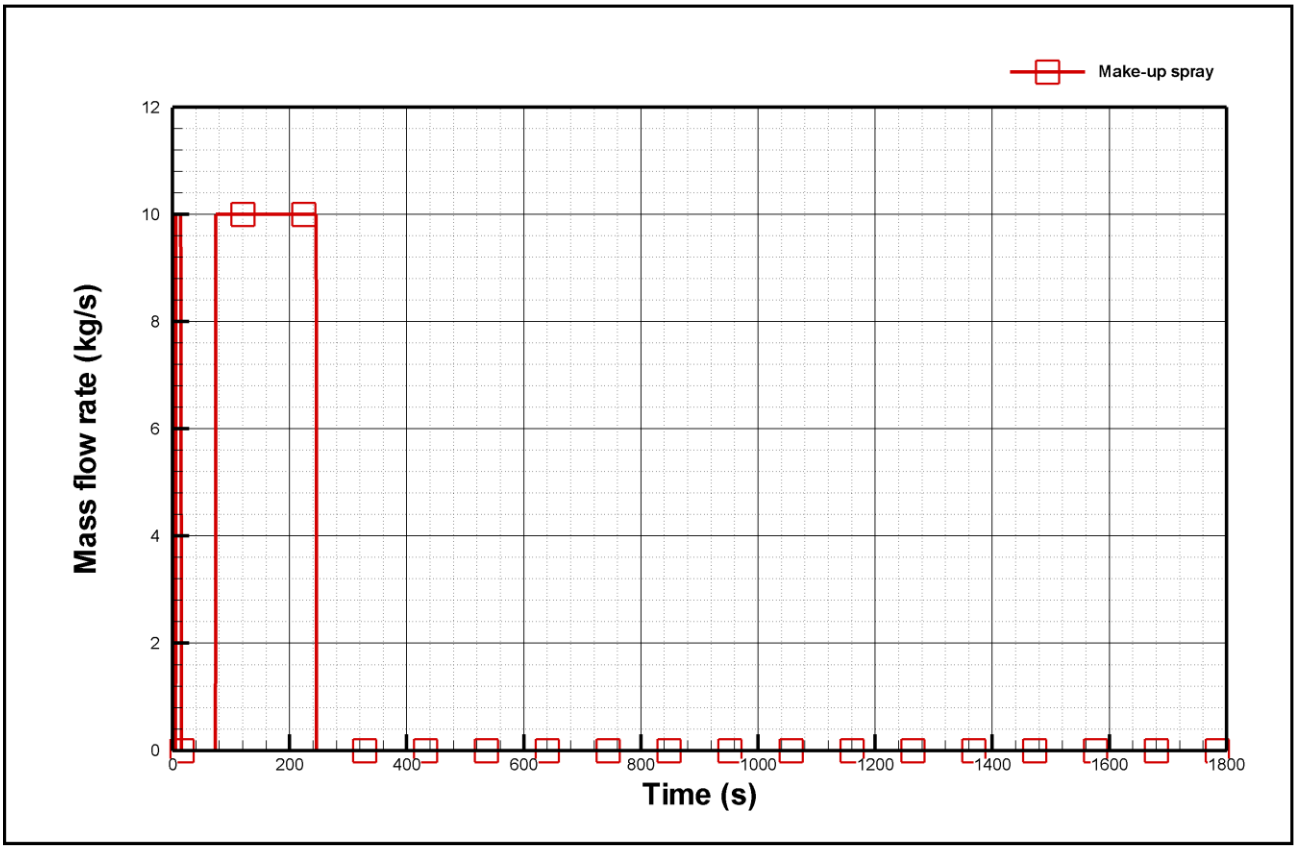

Figure 3.16 - Make-up spray (conservative case)

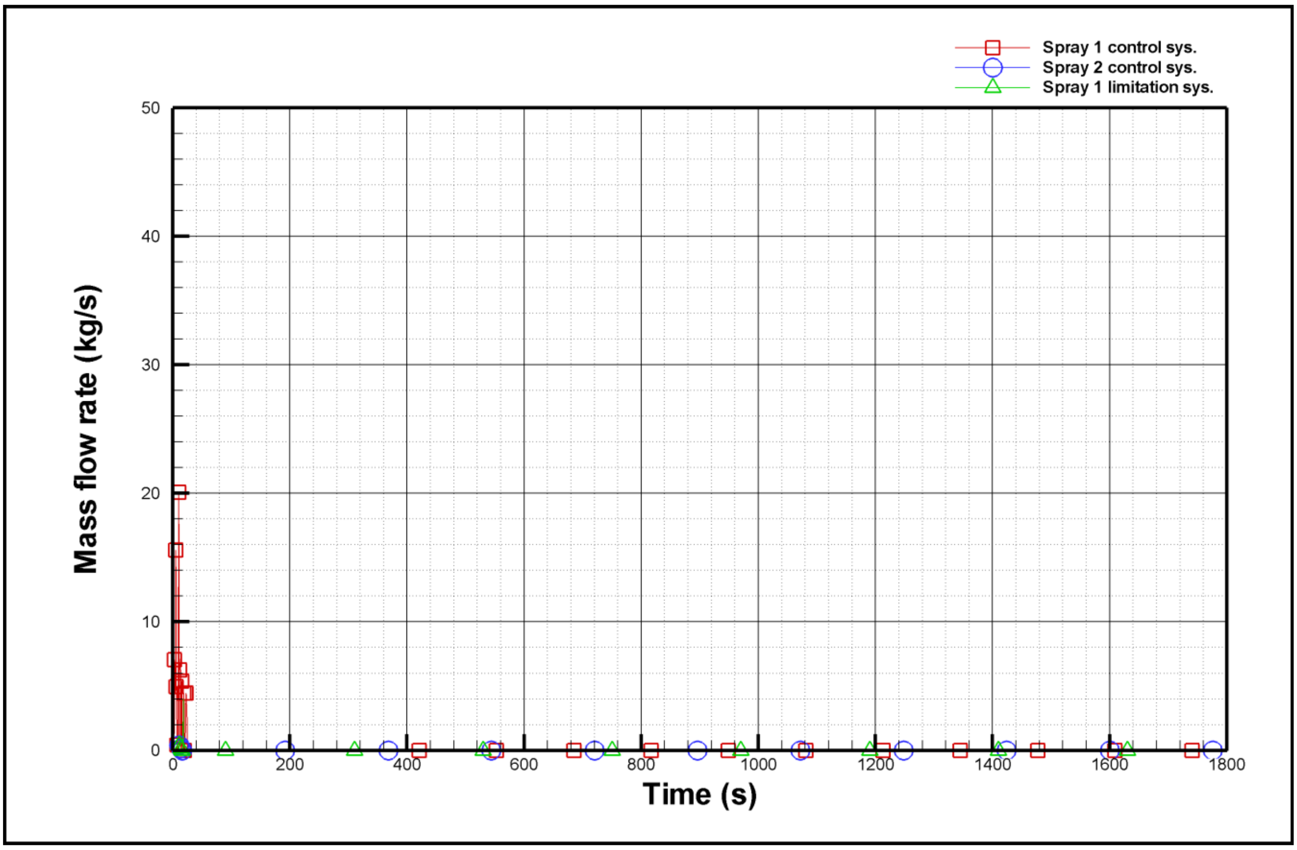

Figure 3.17 - Spray 1&2 from control system and spray 1 from the limitation system (conservative case)

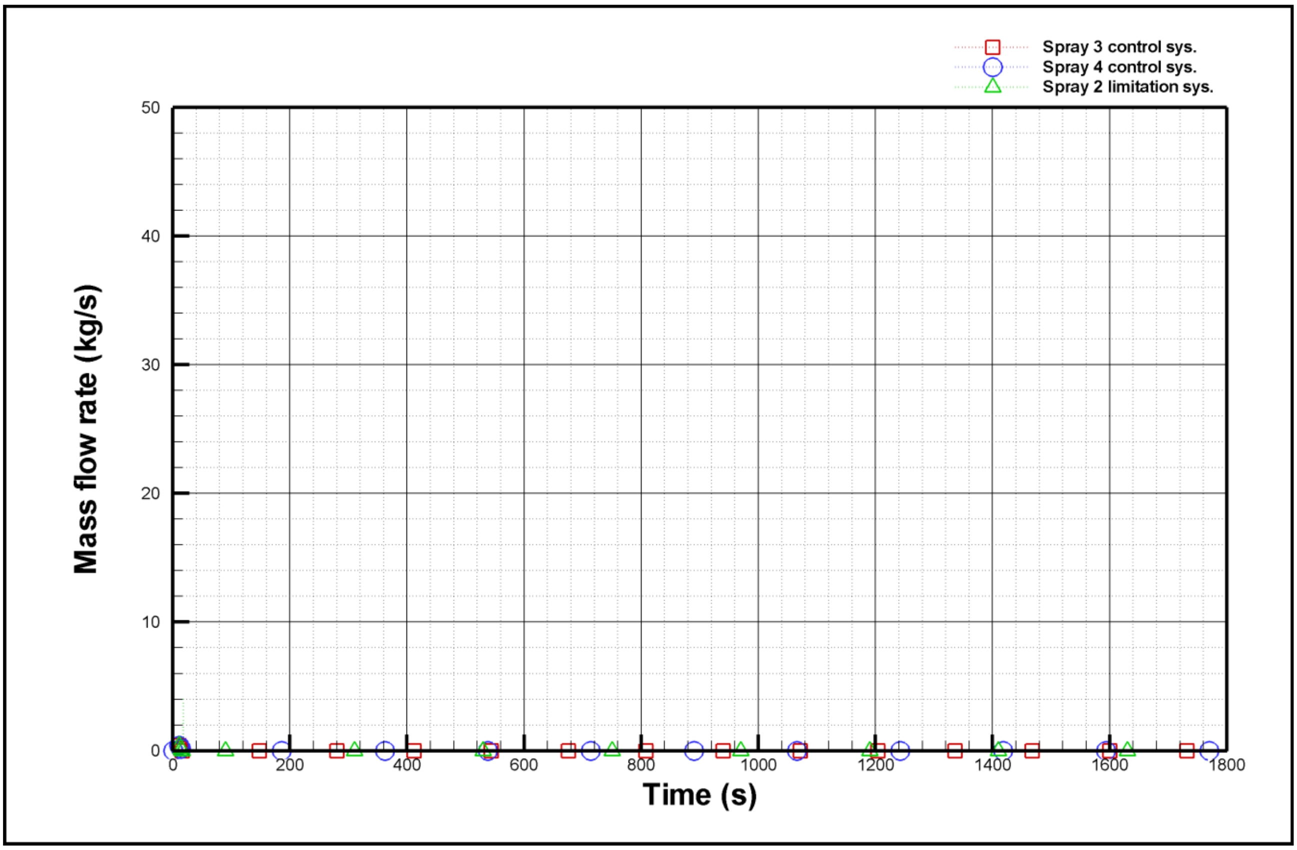

Figure 3.18 - Spray 3&4 from control system and spray 2 from the limitation system (conservative case)

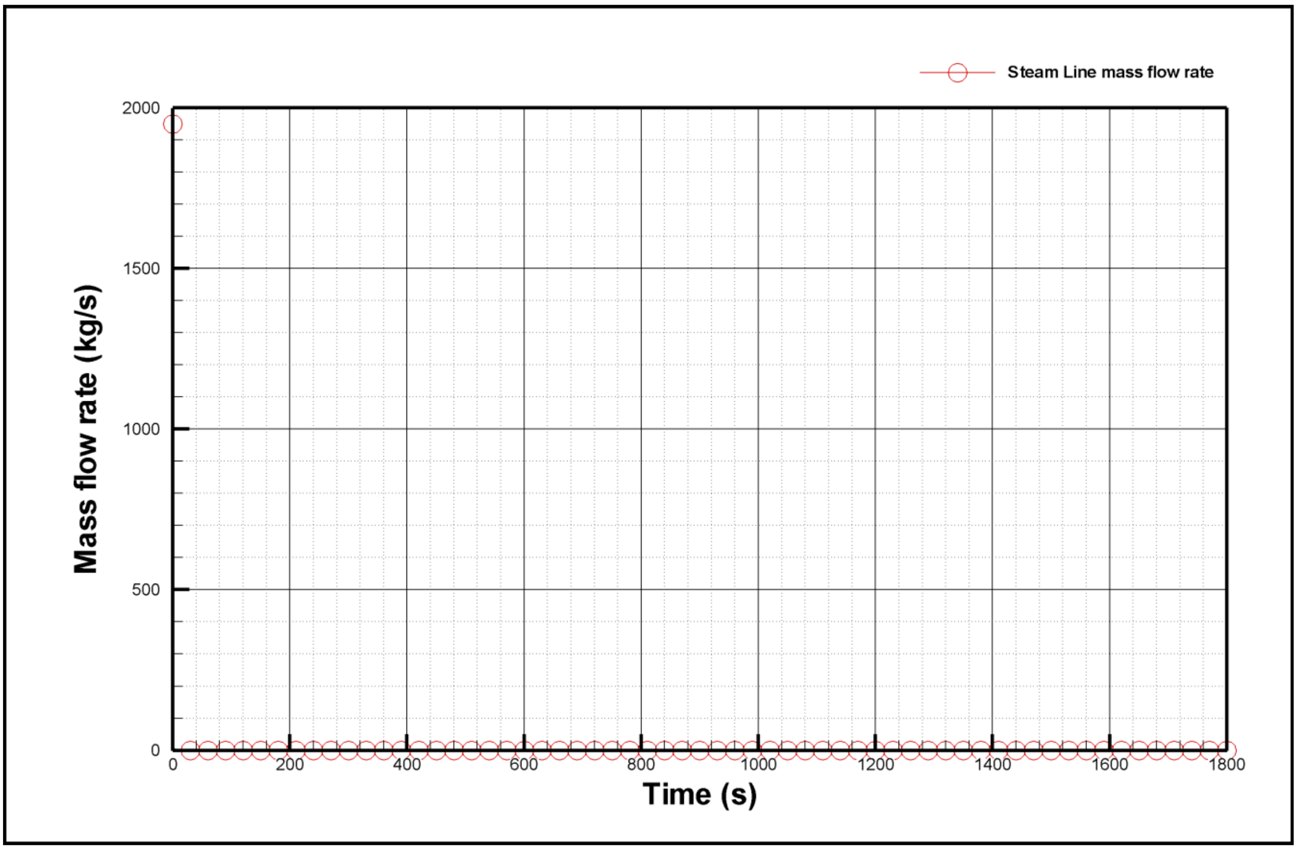

Figure 3.19 - Steam Line mass flow rate (conservative case)

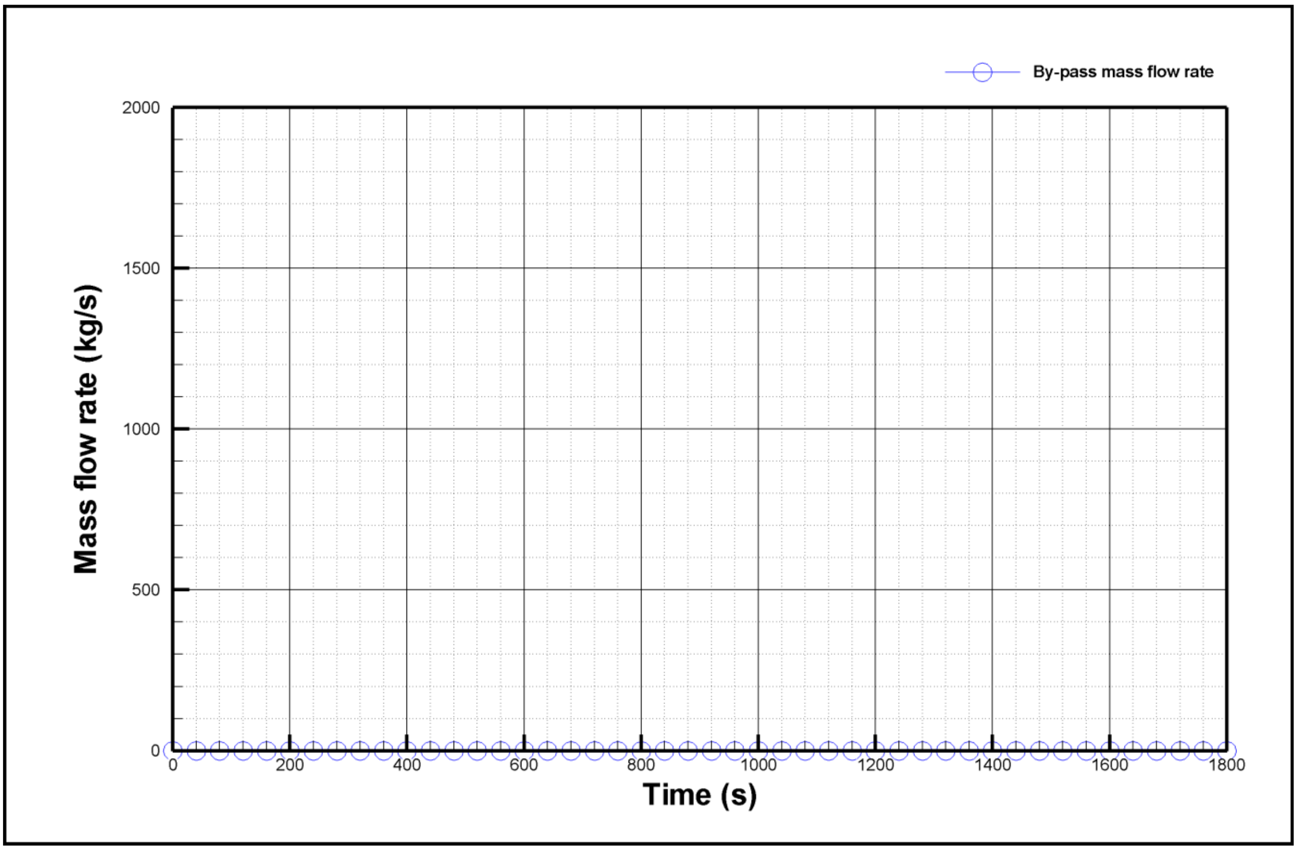

Figure 3.20 - By-pass mass flow rate (conservative case)

4 Artifical Case – Insurge

The following section presents analysis of an uncontrolled increase of reactor coolant mass (which leads to an increase of PRZ level and PRZ pressure). Two variants have been analyzed. Firstly, all PRZ related systems are assumed to be functional. Secondly, a failure of all spray systems has been assumed.

4.1 Insurge with all systems working

A steady-state calculation up to 3000 seconds was performed. At 3010 s (10 s in the following Figures), the charging system starts to inject cold water (at about 37 °C) with a mass flow rate of 80 kg s^{-1}. In this case, only the PRZ-related control system, limitation system and protection system are available.

The PRZ level (***Figure 4.3***) will rise sensitively until the scram signal is reached (13.5 m) at about 280 s, so the scram occurs (***Figure 4.1***). Then the level reduces for a while, but at about 300 s it increases again due to the pressure raise, eventually covering the whole height of the pressurizer. According to the high PRZ level, the injection falls to zero, and the extraction goes to its maximum (***Figure 4.5***).

The pressure increases as soon as the cold injection starts (***Figure 4.2***), but the sprays actuation try to stop the rise (***Figure 4.7*** and ***Figure 4.8***). The make-up spray (***Figure 4.6***) doesn't play any role because the PRZ pressure does not exceed 15.7 MPa while the PRZ level is below 11.5 m. Once the level is above 11.5 m, actuation of the spray (limitation system) is inhibited by the protection system to prevent overfilling of the PRZ. The sprays will eventually succeed to reduce the pressure after 200 s, and a further sharp pressure reduction occurs with the scram. But following the scram, there is no mass flow in the secondary side (***Figure 4.9***) and the by-pass line is not available (***Figure 4.10***), so the pressure rises quickly, up to 17.2 MPa, when the first relief valve opens (see ***Table 2.4***) at about 465 s. After the pressure relief valve opening, the slope of the rising level will decrease (see again **Figure 4.3**), but is not enough to avoid the filling of the pressurizer at about 535 s. So, the PZR pressure increases sharply until a second relief valve opening. The rest of the transient is dominated by these openings and closures of the relief valve (it opens at 17.2 MPa and closes at 15 MPa).

PRZ heaters (***Figure 4.4***) don't play a significant role in this transient. They activate at about 250 s, due to pressure reduction, but thet operate for a short time, because the scram occurs, and any power is not available to the heaters as the aftermath of the station black-out.

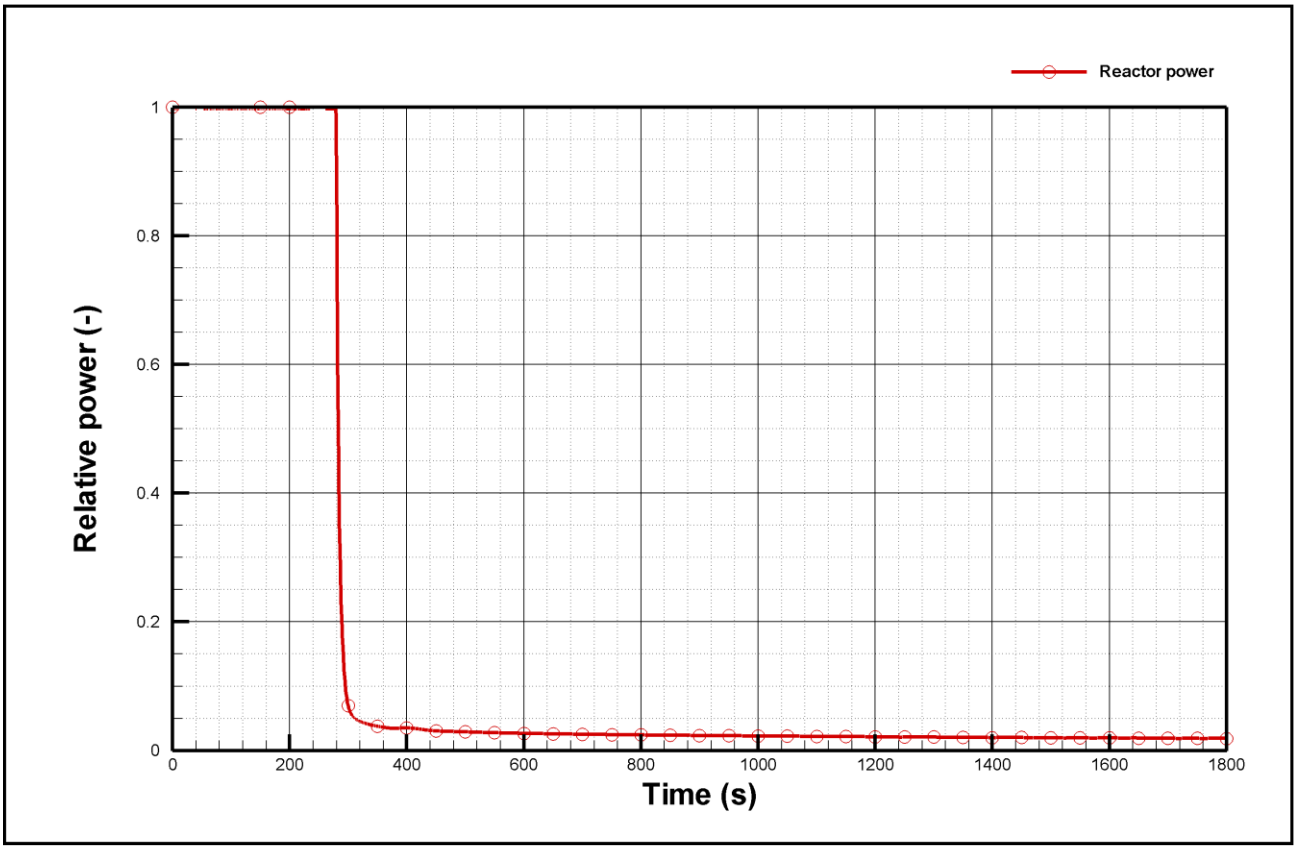

Figure 4.1 Reactor power (insurge case)

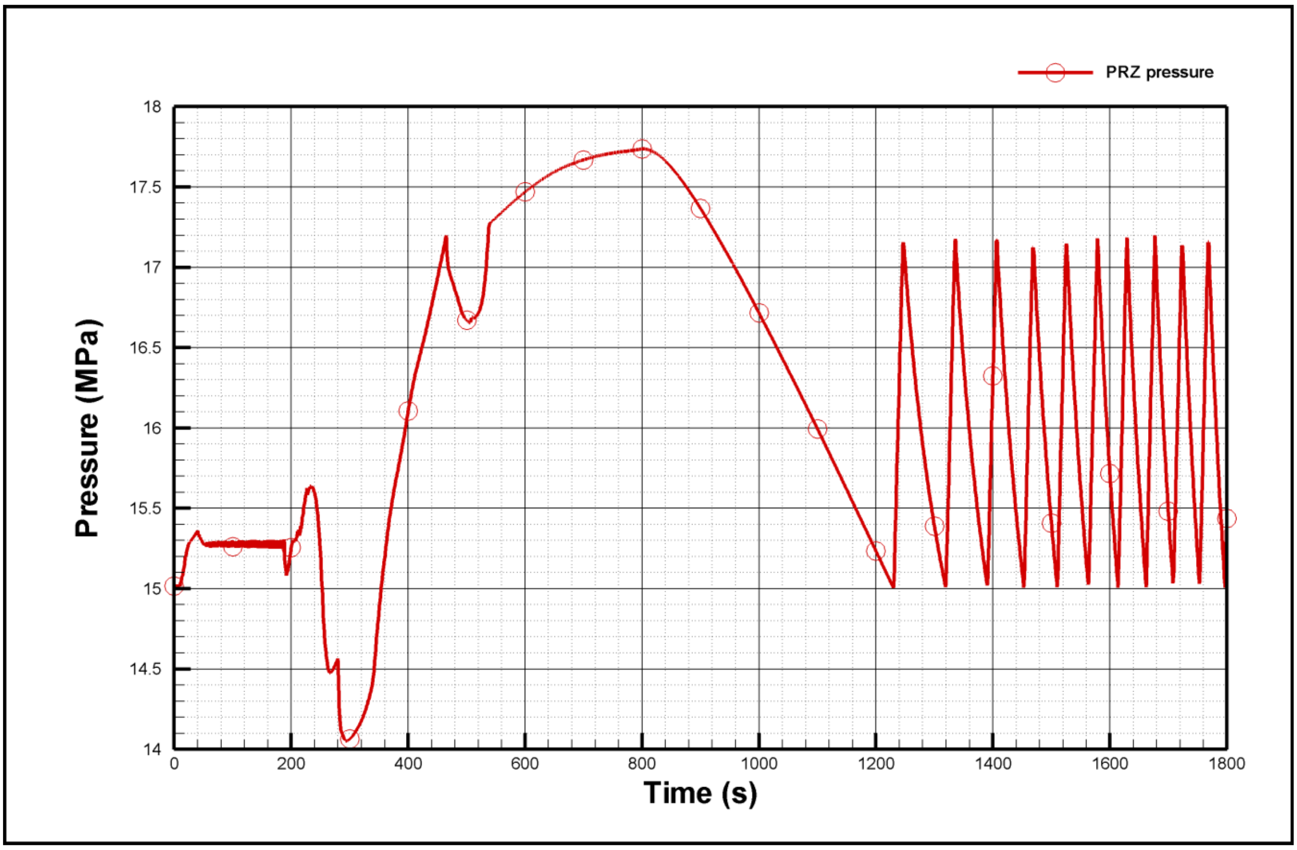

Figure 4.2 - PRZ pressure (insurge case)

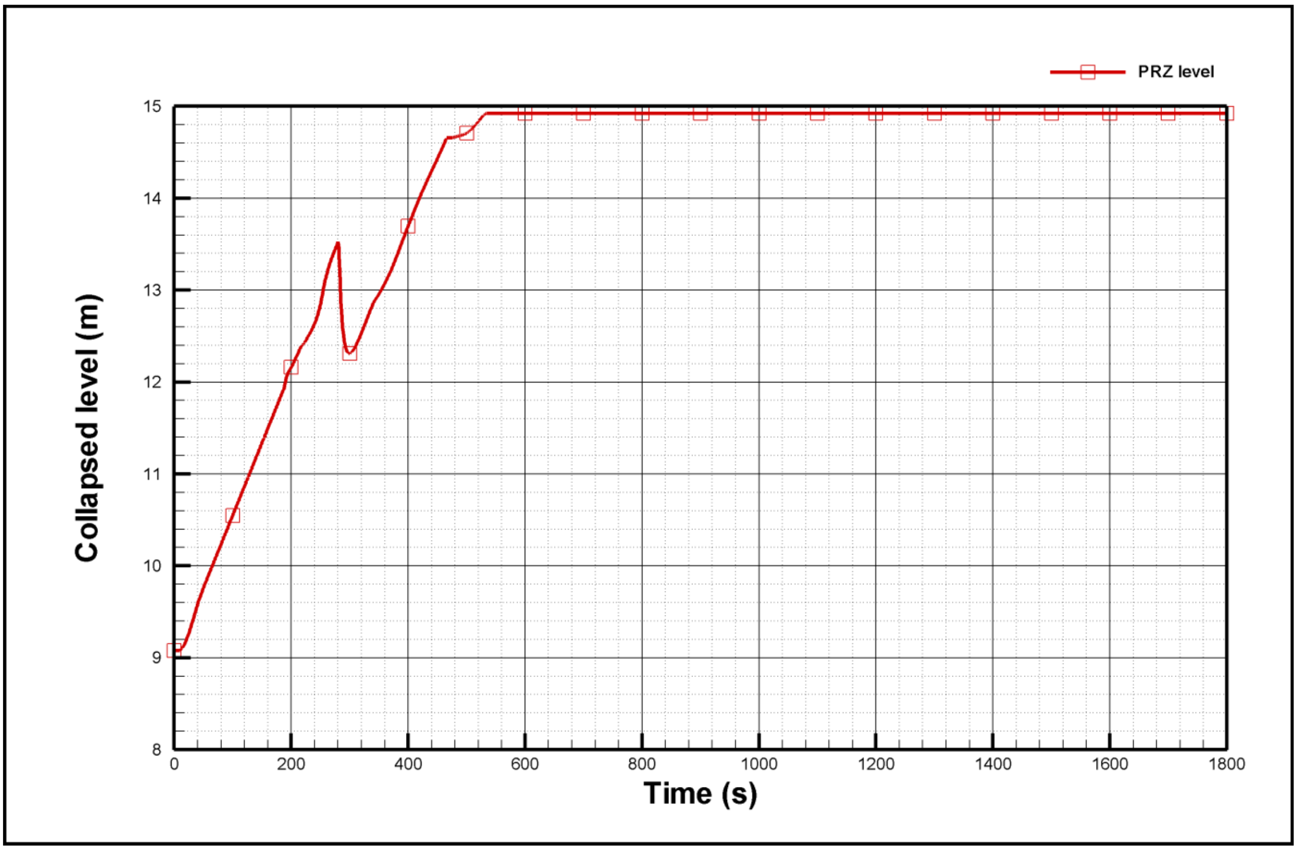

Figure 4.3 - PRZ collapsed level (insurge case)

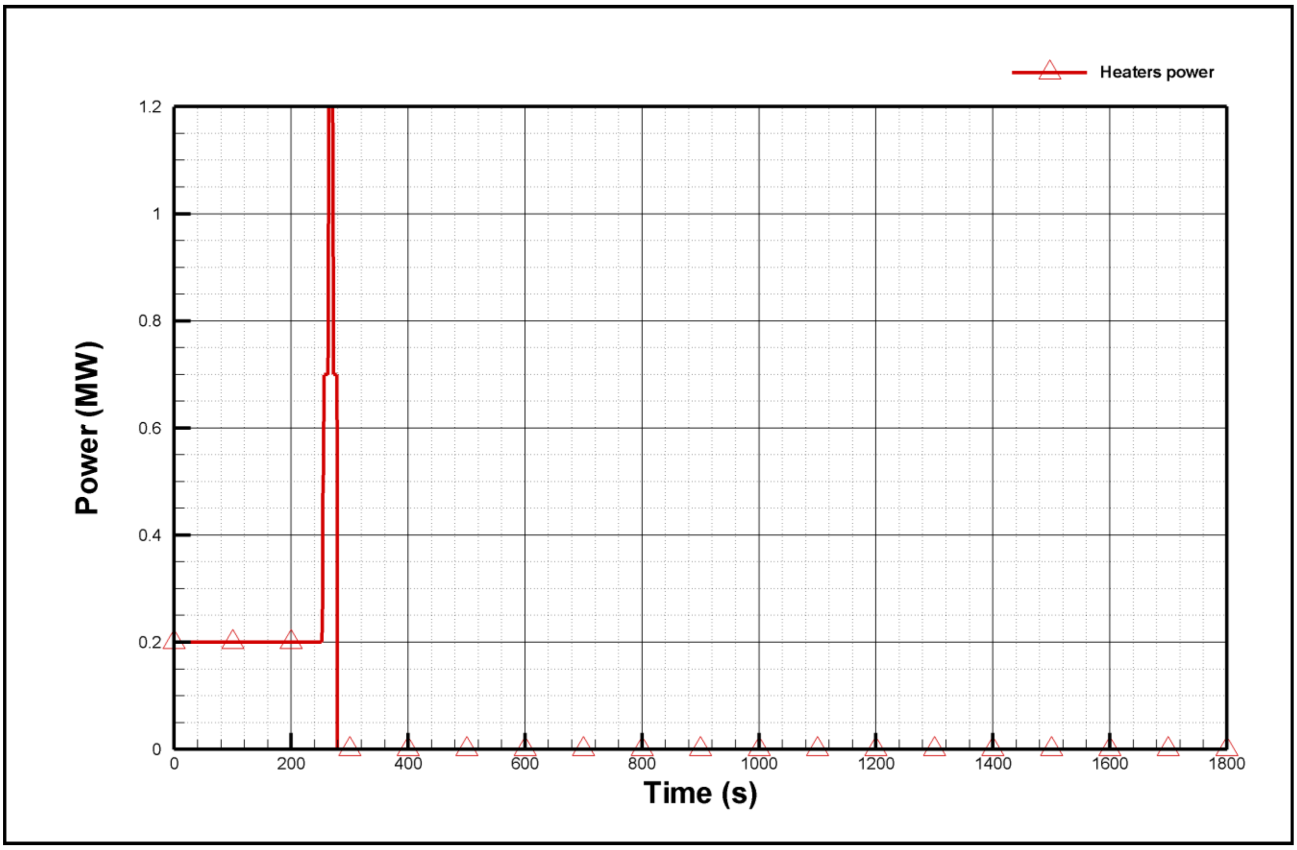

Figure 4.4 - PRZ heaters power (insurge case)

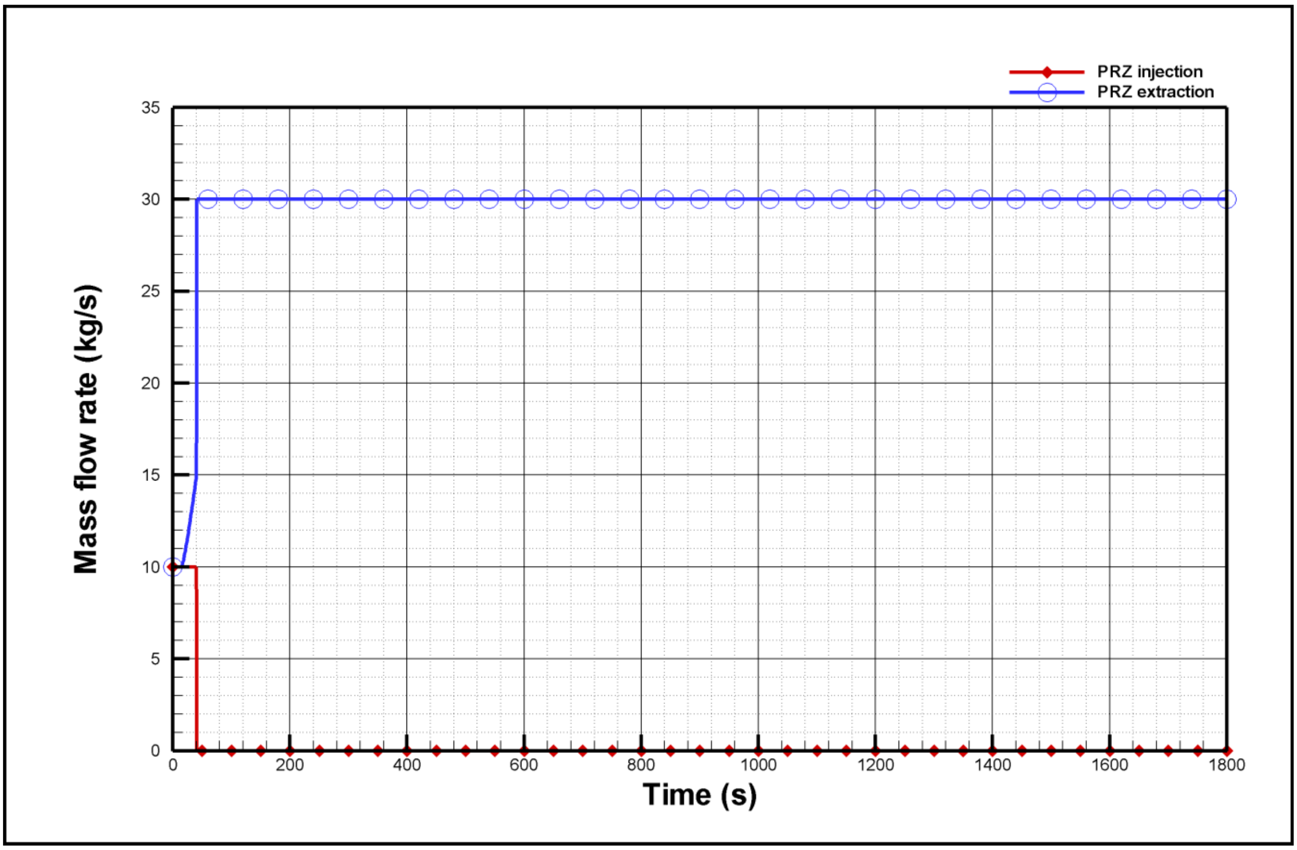

Figure 4.5 - Level control (insurge case)

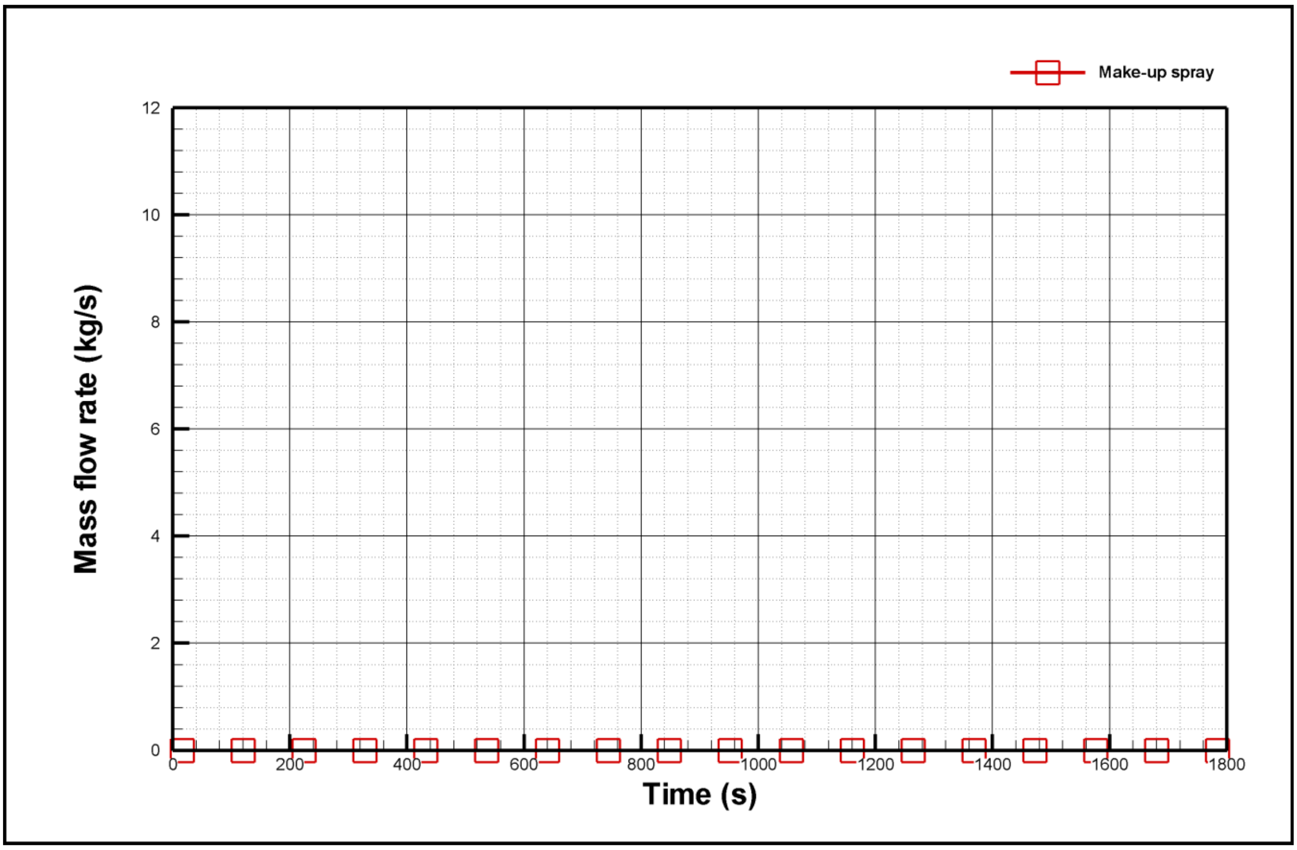

Figure 4.6 - Spray 1&2 from control system and spray 1 from the limitation system (insurge case)

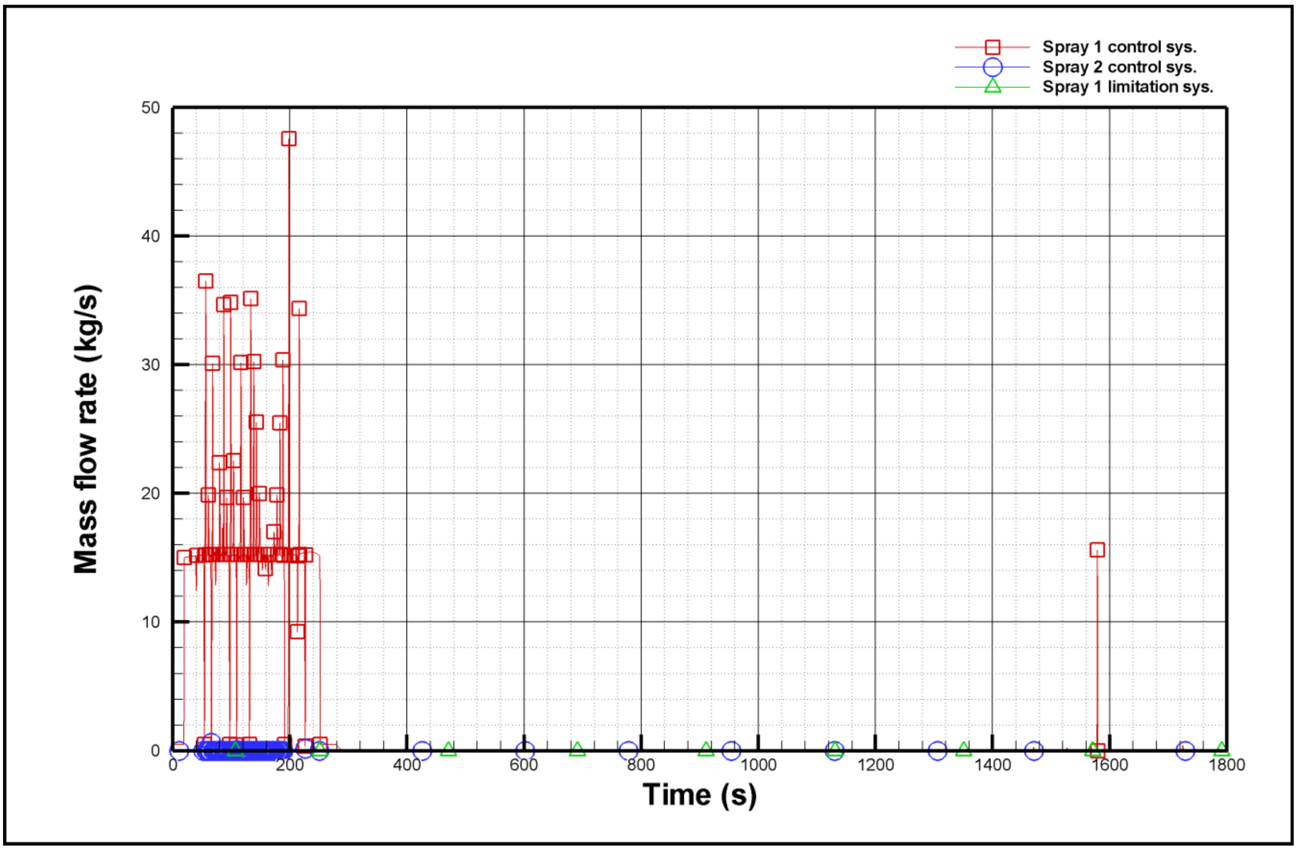

Figure 4.7 - Spray 3&4 from control system and spray 2 from the limitation system (insurge case)

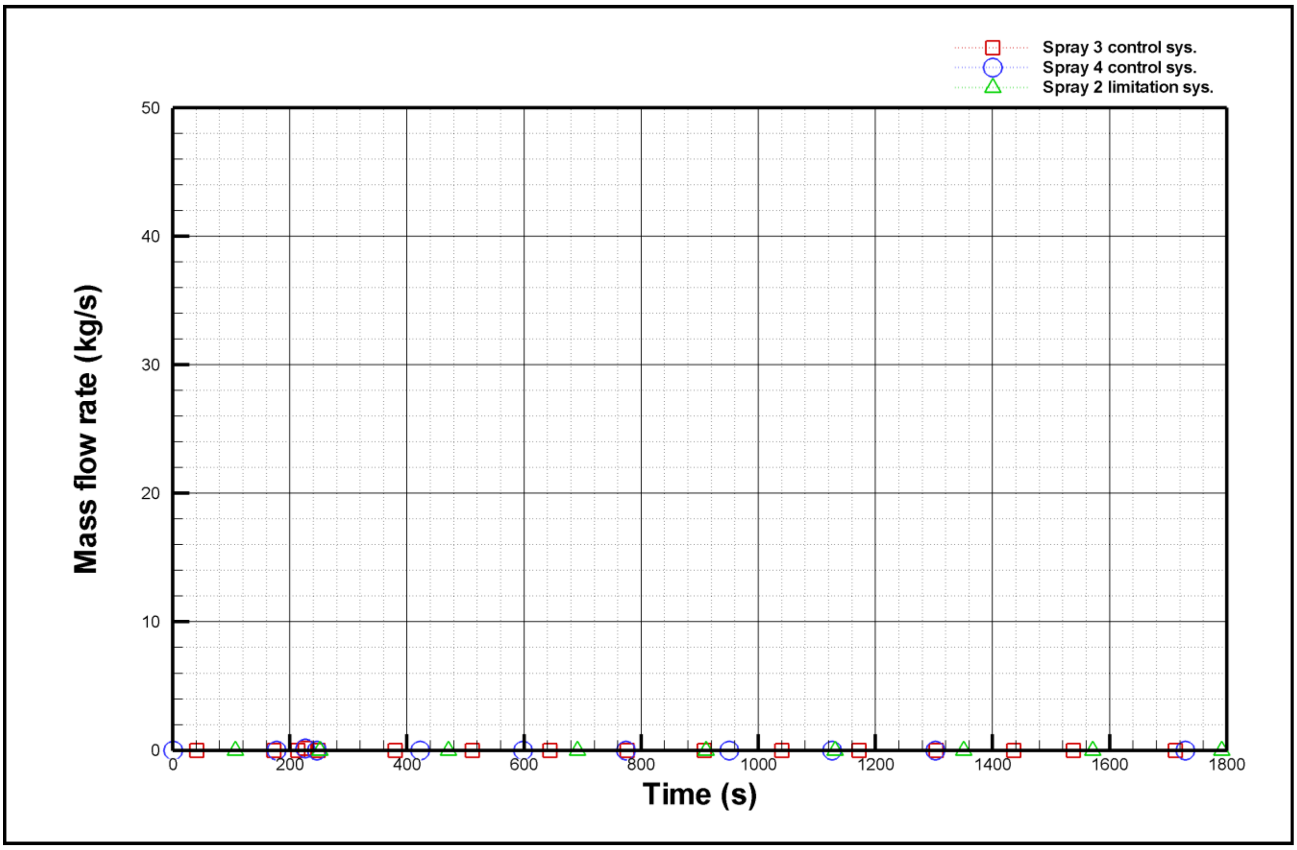

Figure 4.8 - Make-up spray (insurge case)

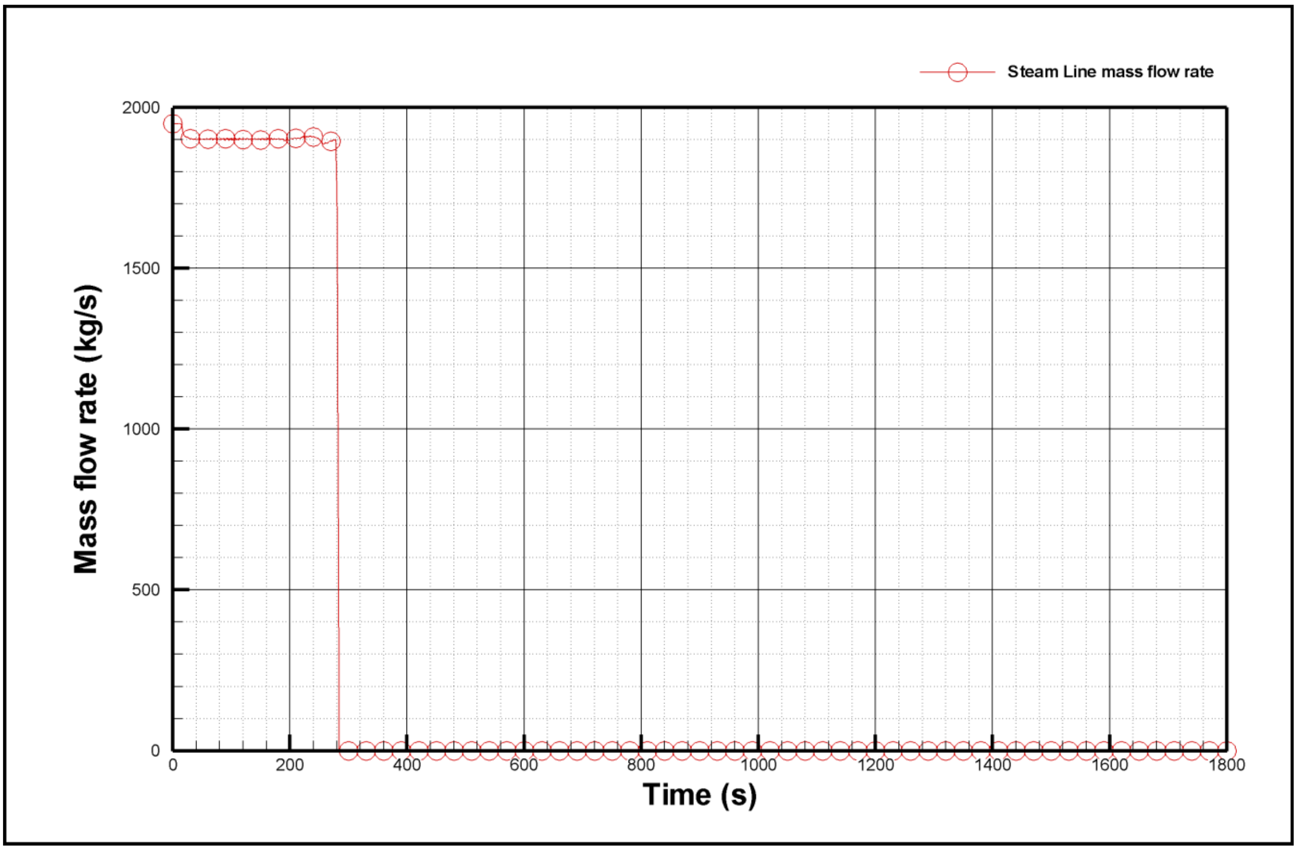

Figure 4.9 - Steam Line mass flow rate (insurge case)

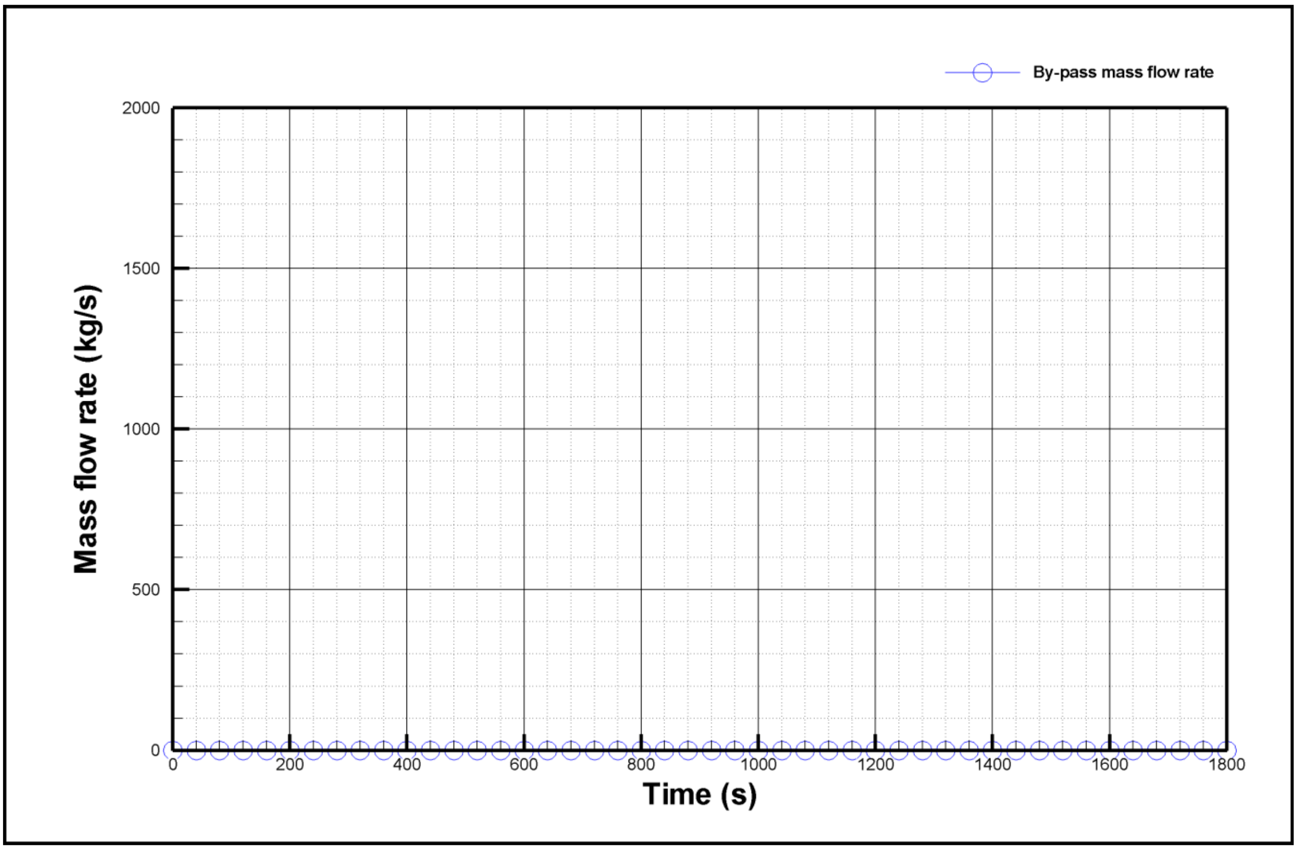

Figure 4.10 - By-pass mass flow rate (insurge case)

4.2 Insurge with failure of all spray systems

A steady-state calculation up to 3000 seconds was performed. At 3010 s (10 s in the following Figures), the charging system starts to inject cold water (at about 37 °C) with a mass flow rate of 80 kg s^{-1}. In this case, only the PRZ-related control system, limitation system and protection system are available. Failure of all spray systems is assumed.

The PRZ level (***Figure 4.13***) will rise sensitively, but this time, since no spray is available to limit the pressure increase, scram will occur for high primary pressure – earlier than in the best estimate case (***Figure 4.11***). Then the level reduces for a while due to contraction of coolant, but will start to increase once new steady state values are reached, and the injection dominates again the transient. Eventually the level will cover the whole height of the pressurizer. According to the high PRZ level, the injection falls to zero, and the extraction goes to its maximum (***Figure 4.15***).

The pressure increase is limited by the two safety valves. One valve is not sufficient to limit the pressure, so the pressure rises up to the set point of the second safety valves. The combination of the two valves is able to limit the pressure increase, and to bleed the mass that is injected from the system. The pressure trend shows cycling between the valve opening- and closing set points (***Figure 4.12***).

PRZ heaters (***Figure 4.14***) don’t play a significant role in this transient.

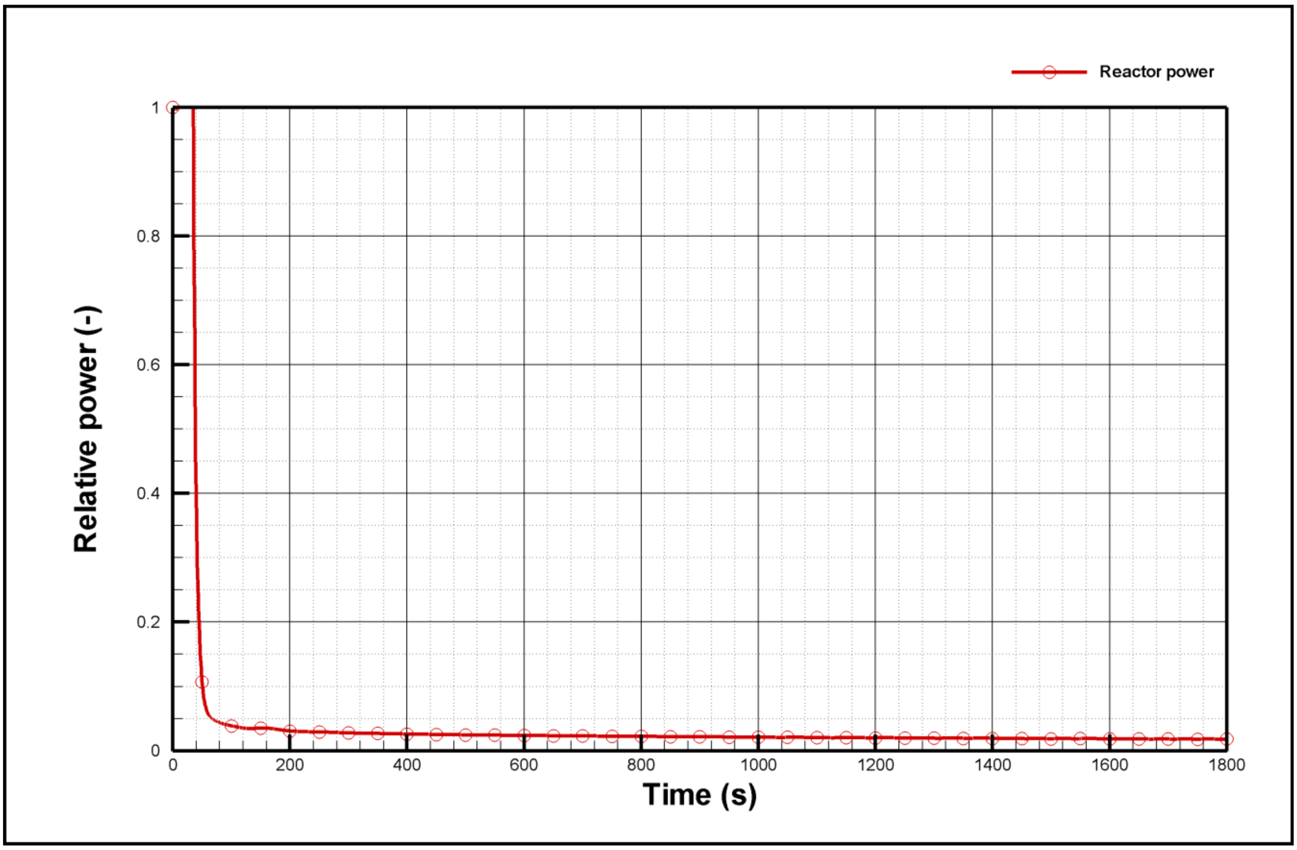

Figure 4.11 Reactor power (insurge – conservative case)

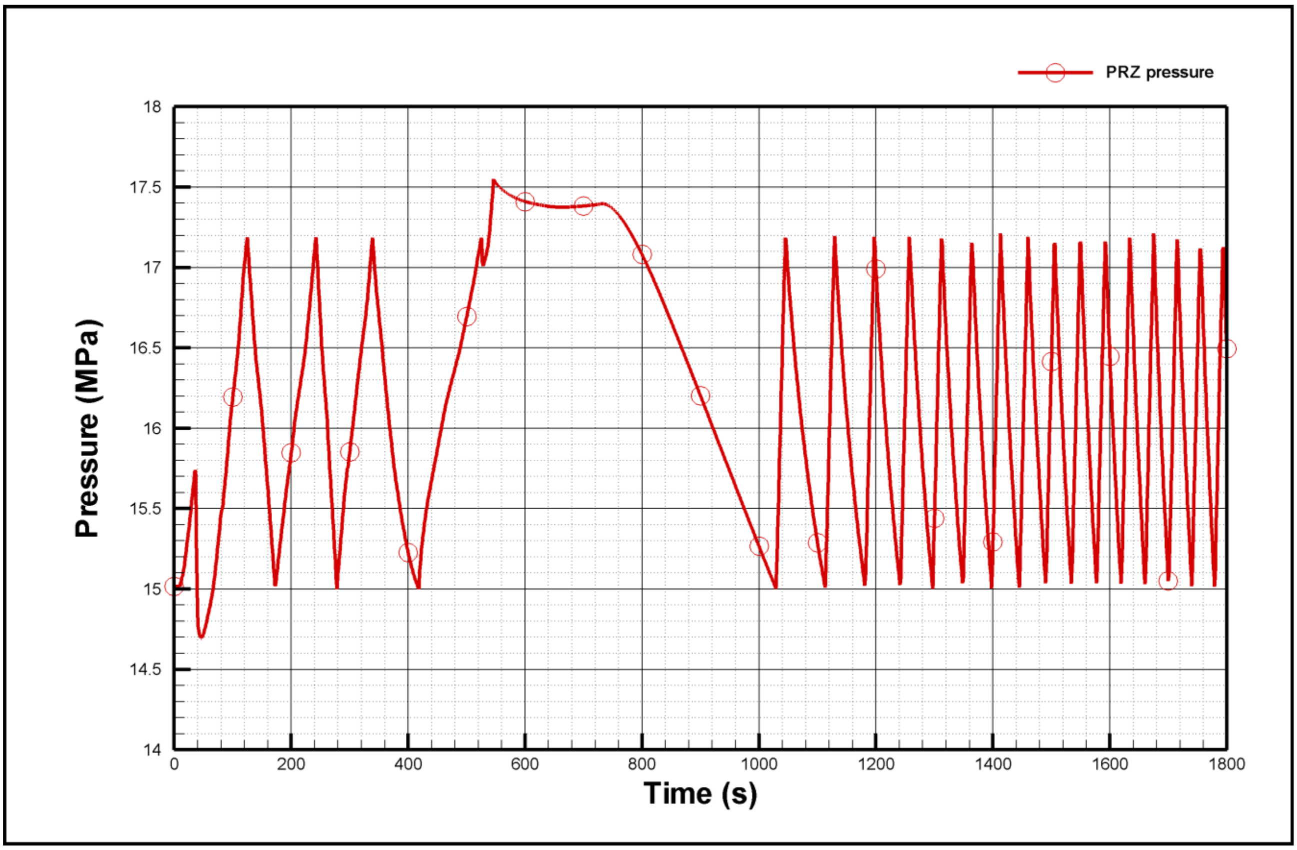

Figure 4.12 - PRZ pressure (insurge – conservative case)

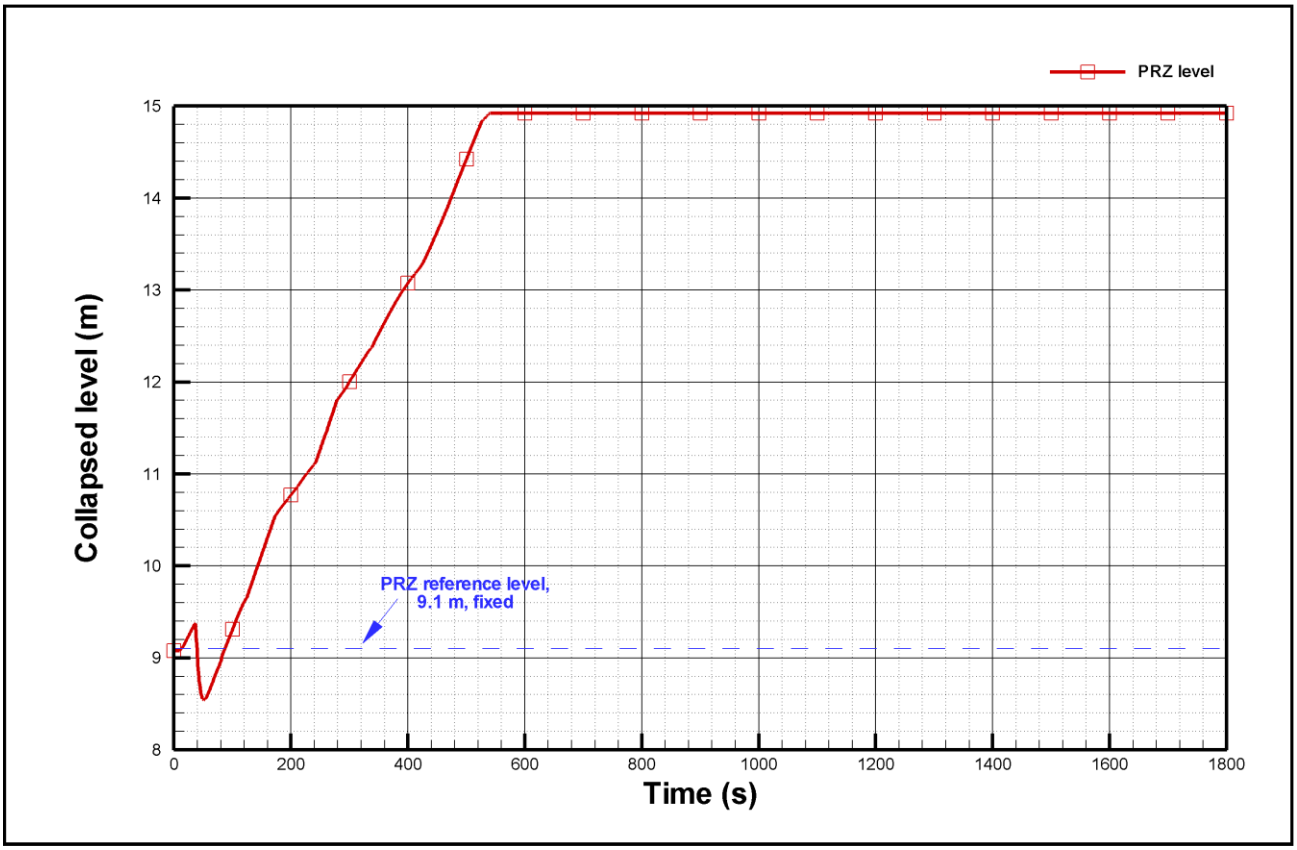

Figure 4.13 - PRZ collapsed level (insurge – conservative case)

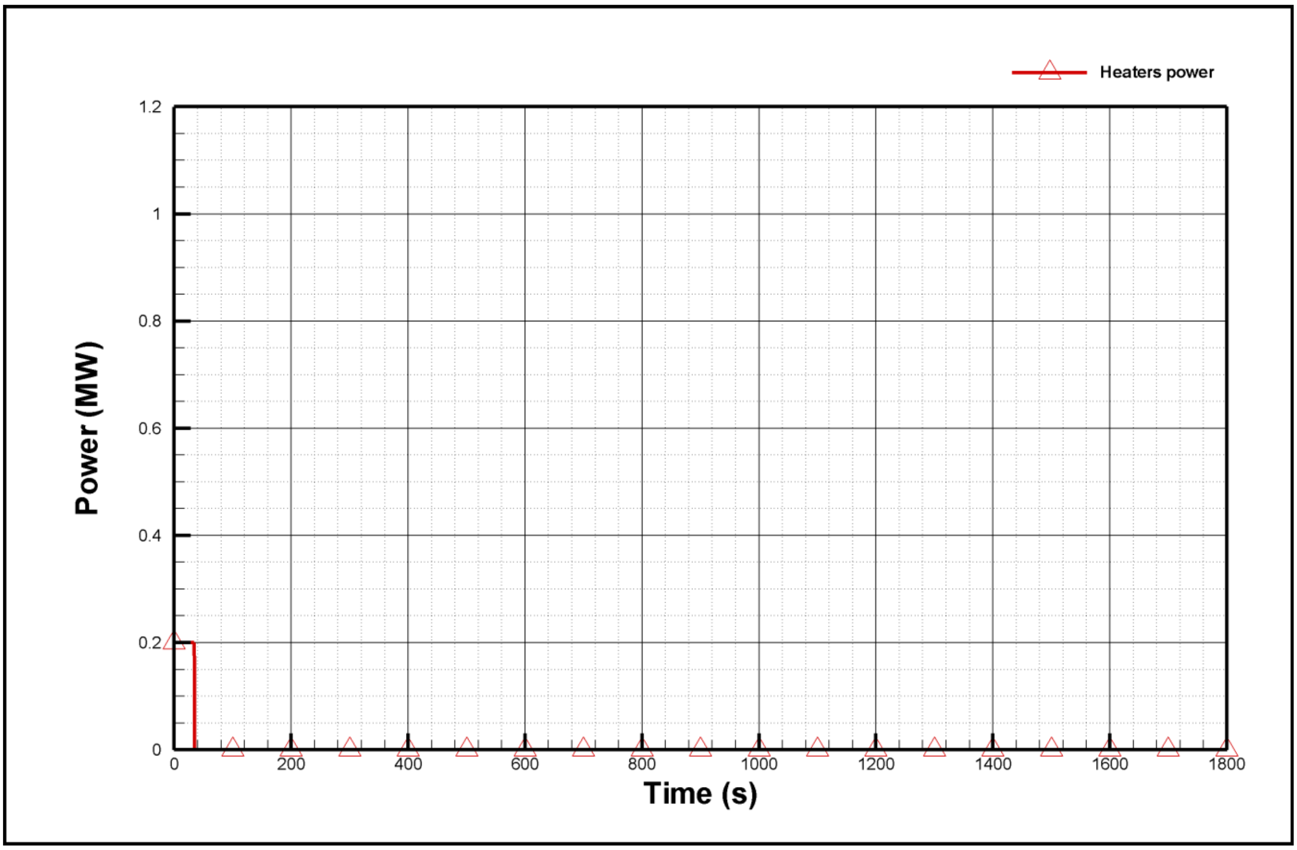

Figure 4.14 - PRZ heaters power (insurge – conservative case)

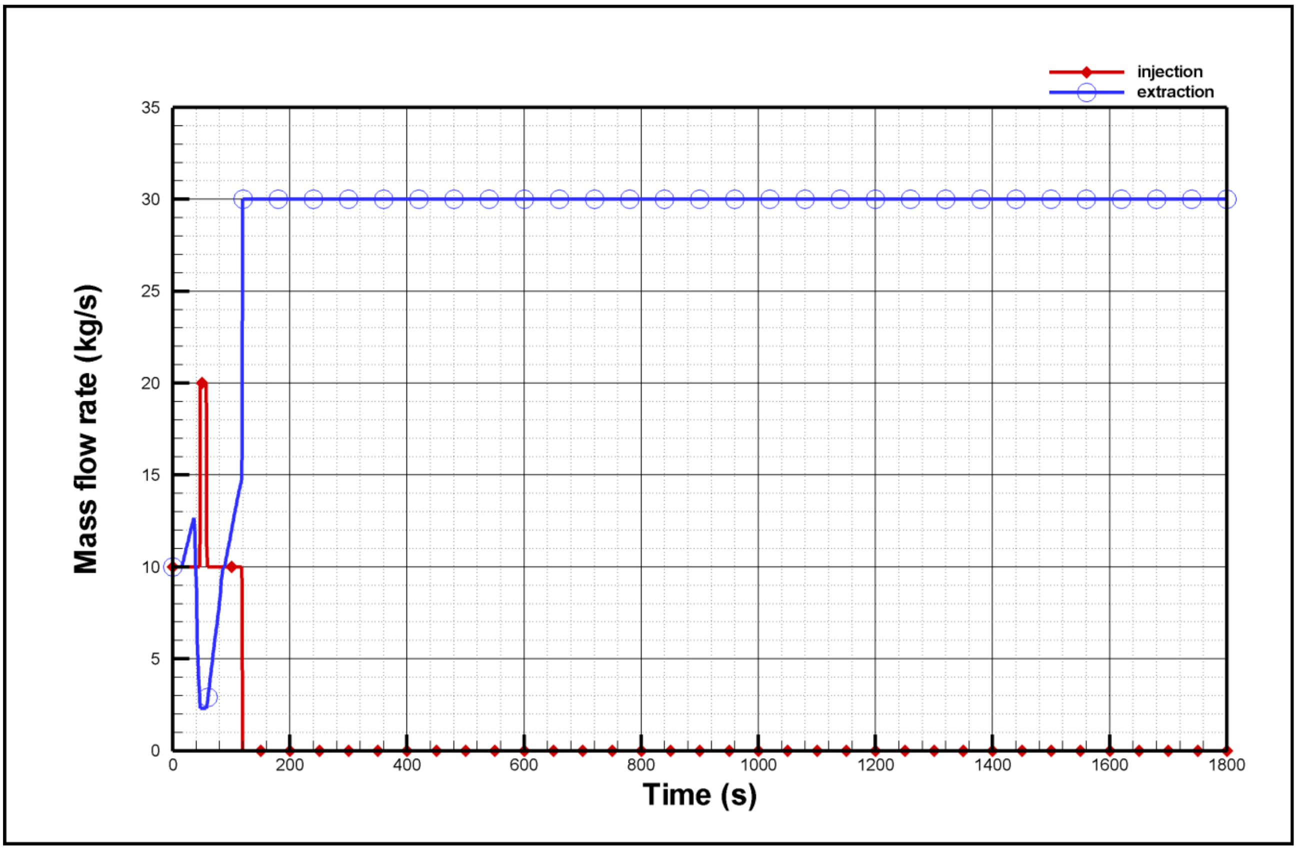

Figure 4.15 - Level control (insurge – conservative case)

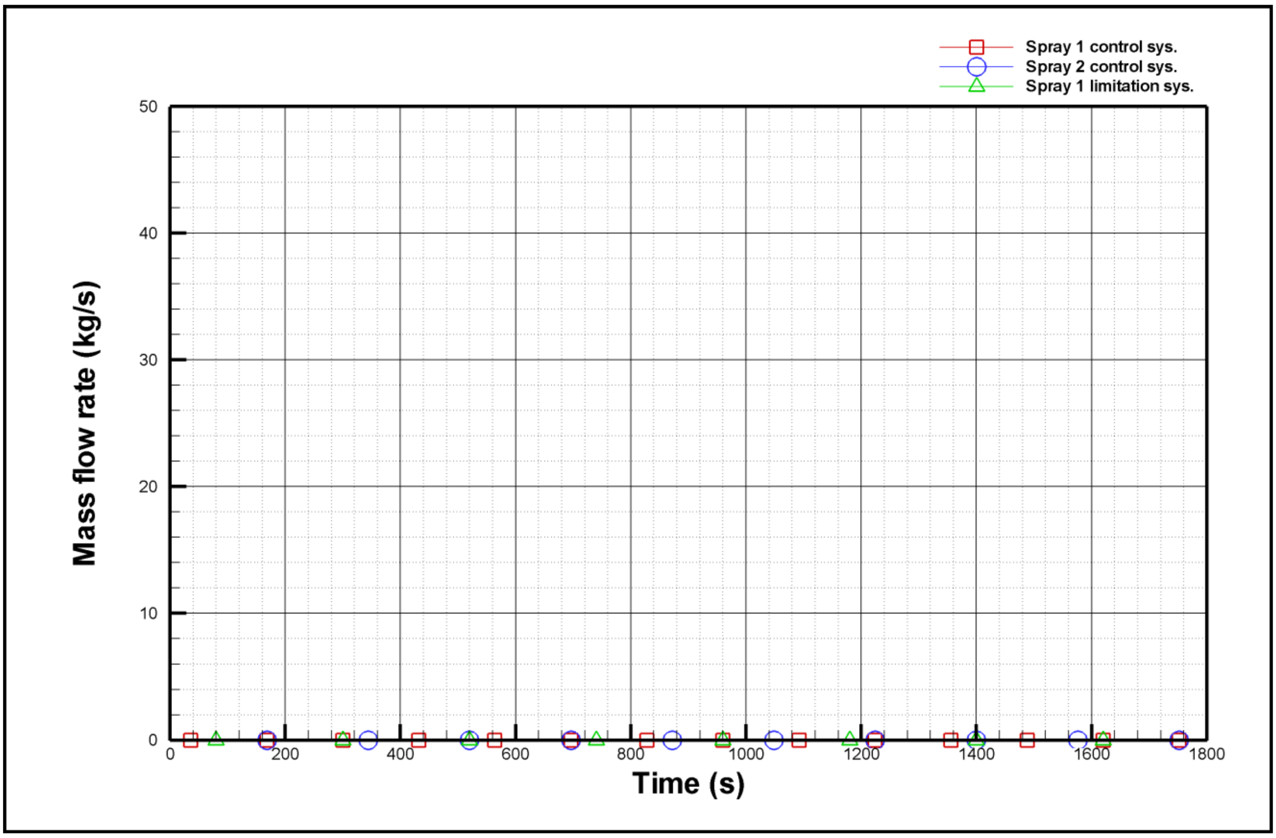

Figure 4.16 - Spray 1&2 from control system and spray 1 from the limitation system (insurge – conservative case)

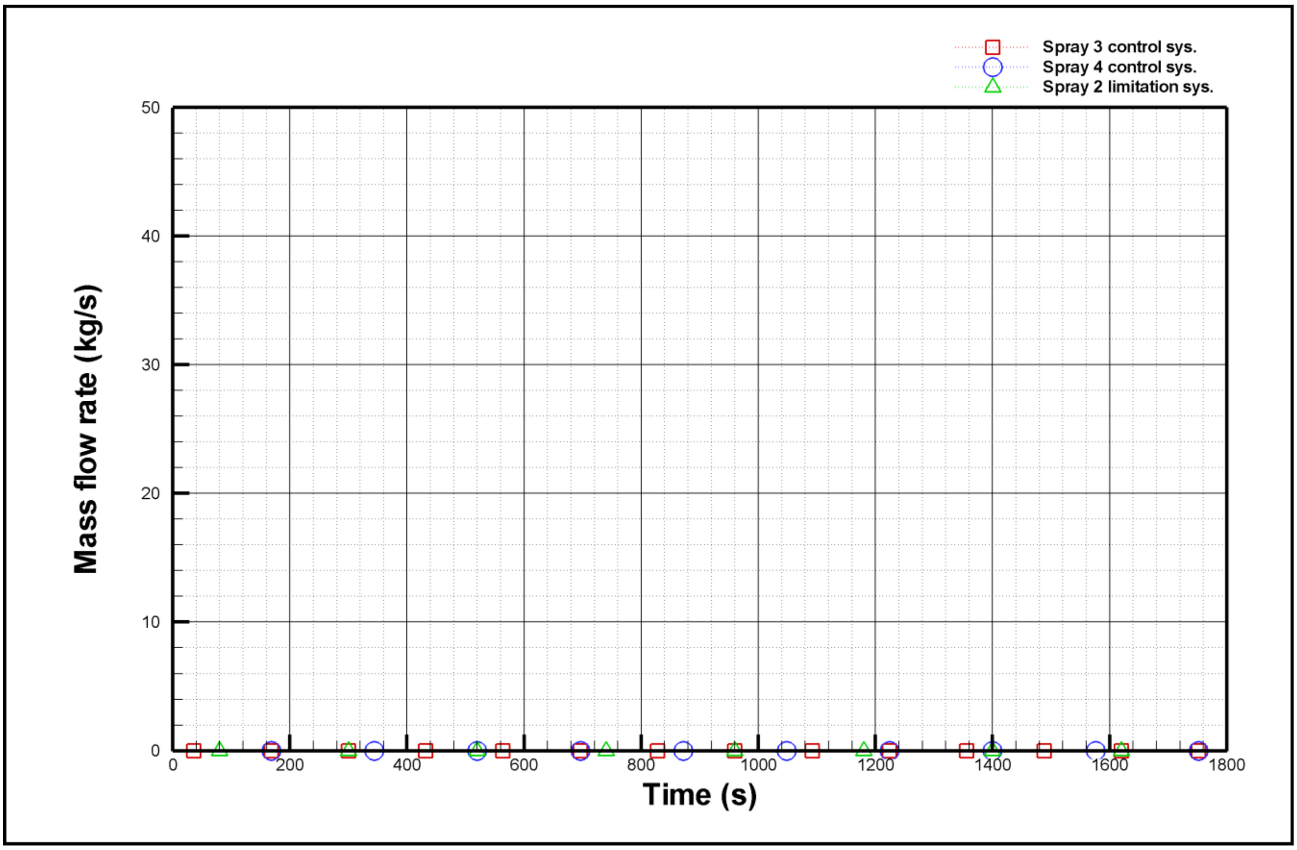

Figure 4.17 - Spray 3&4 from control system and spray 2 from the limitation system (insurge – conservative case)

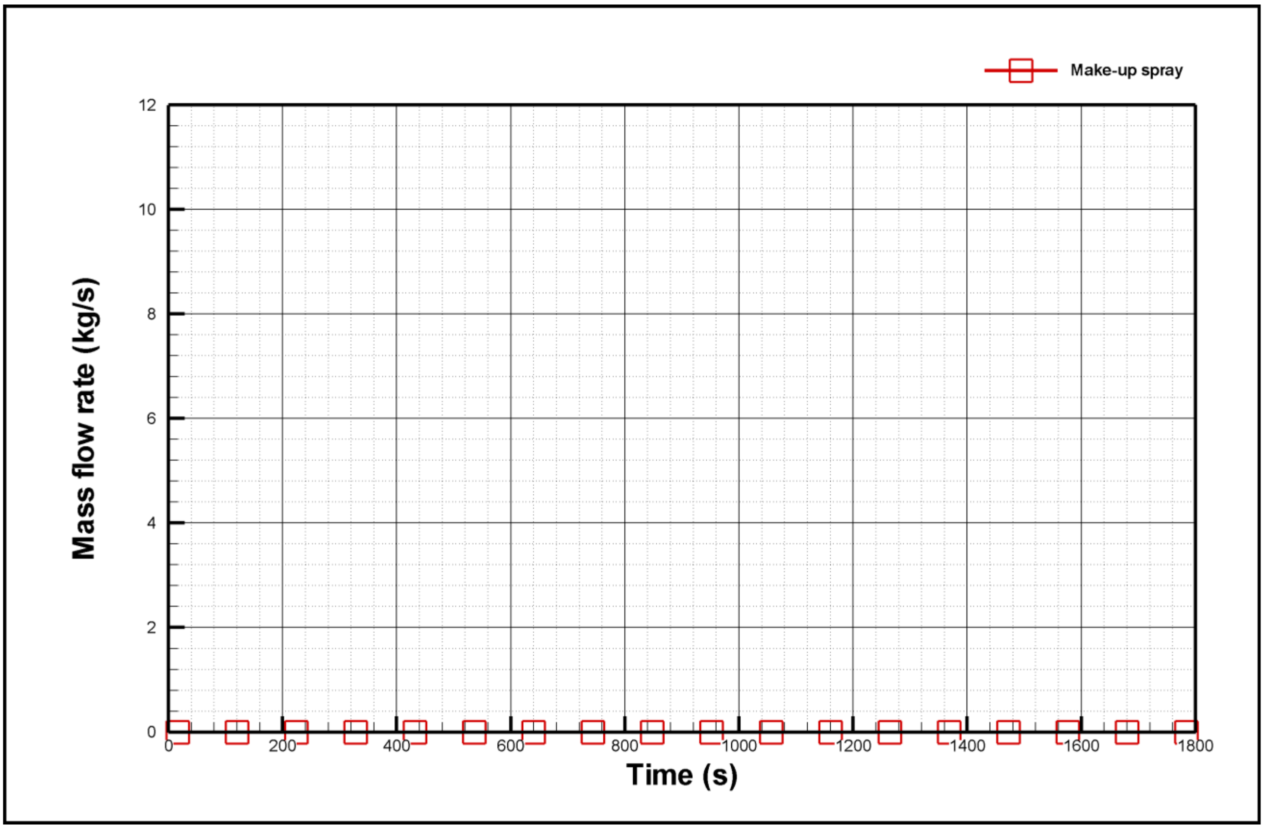

Figure 4.18 - Make-up spray (insurge – conservative case)

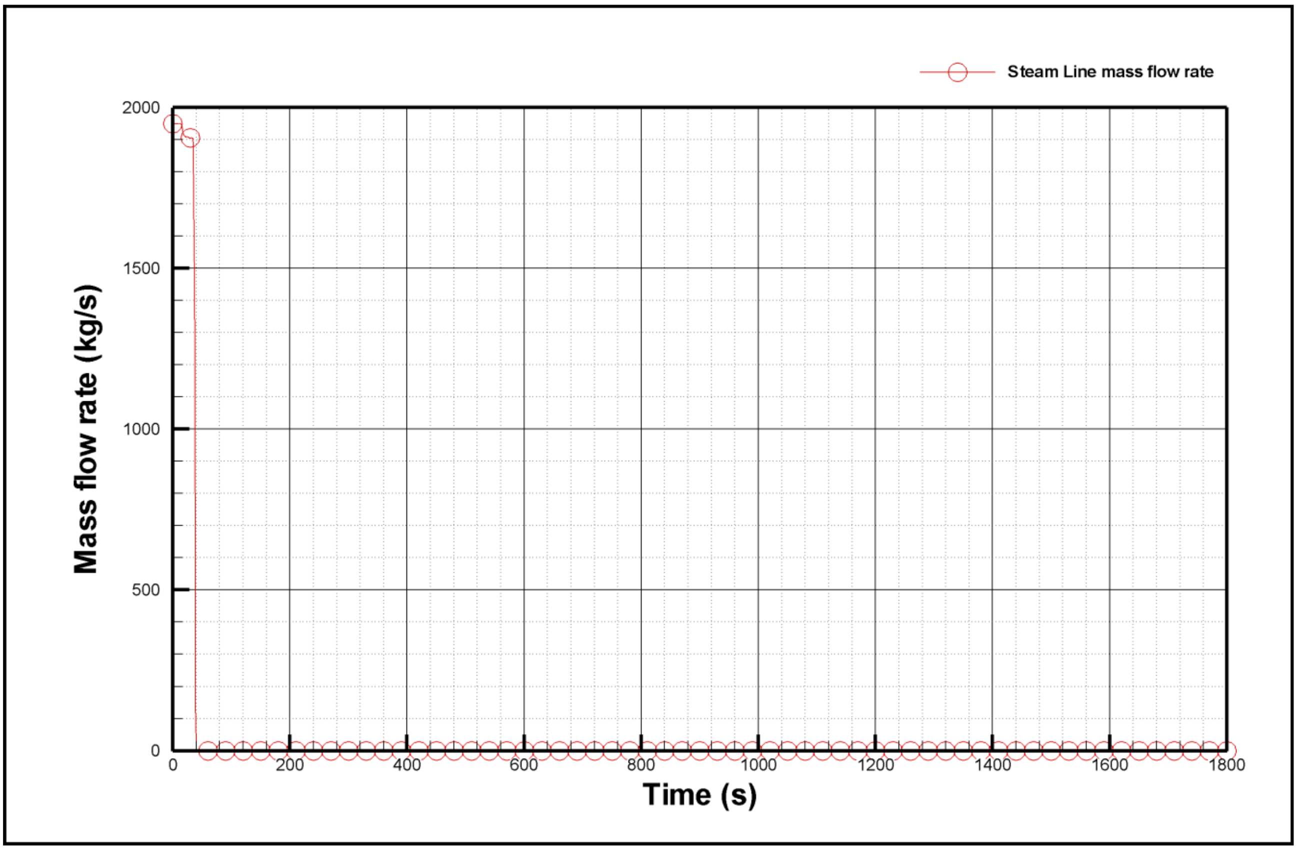

Figure 4.19 - Steam Line mass flow rate (insurge – conservative case)

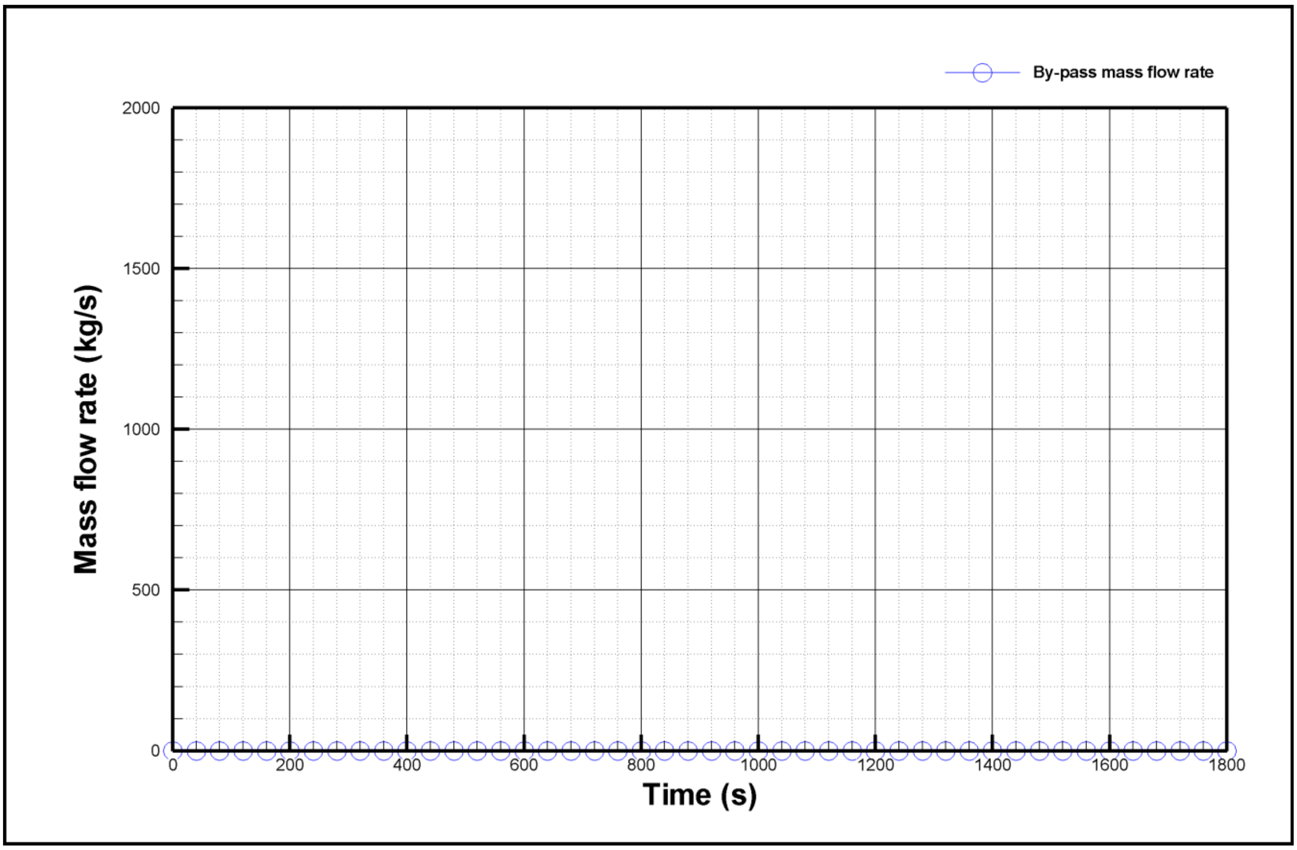

Figure 4.20 - By-pass mass flow rate (insurge – conservative case)

5 Conclusions

The present report gave an overview on two different modeling approaches of the control system of a NPP, using the controls related to a PRZ and turbine bypass station as example. Both approaches have been tested in case of a Turbine Trip with conservative assumptions, best estimate assumptions, and insurge into a PRZ with and without spray.

While in principle any control system can be modeled with and, or and not components (as provided by the Relap5 input deck description language), the finite number of elements puts a limit on the complexity of the control system that can be modeled.

While in the presented example the Relap5 cards are sufficient to model the controls of the PRZ in great detail, a general purpose nodalisation, which requires not only the pressurizer controls to be modeled, but the whole plant, will exceed the limit of the Relap5 capabilities.

It is therefore advisable to adopt a Relap5/Fortran control module coupled approach, if a NPP control module for realistic applications such as simulator are envisaged.

6 List of Abbreviations

CVCS	chemical and volume control system
ΔL	level difference
Δp	pressure difference
EPR	European pressurized reactor
FW	feed water
GW_{th}	giga Watt thermal
HL	hot leg
LOCA	loss of coolant accident
MCP	main coolant pump
MSIV	main steam isolation valve
NPP	nuclear power plant
PK	point kinetics
PRZ	pressurizer
PS	primary system
PWR	pressurized water reactor
RCP	reactor coolant pump
R5	Relap5©
SG	steam generator
TH	thermal hydraulic

7 References

[Ref. 1] Brochure for the U.S. EPR (Areva, 2007)