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ANALYSIS OF BORON DILUTION SEQUENCE IN A NUSCALE POWER MODULE USING TRACE

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Within the framework of the "High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic Small Modular Reactors" (MCSAFER) H2020 European project, the Universidad Politécnica de Madrid (UPM) research group is developing, among other tasks, a TRACE-1D model of a NuScale Power Module (NPM) to simulate the Boron Dilution and the Steam Line Break transients. Particularly, the simulation of a Boron Dilution transient in a NPM accounting for the impact of the reactivity feedbacks on the core power has been carried out and the results are presented in this work. To do so, it was necessary to implement a high-order numerical method in the model to avoid numerical diffusion. The results shows that an important increase in the core power is produced due to the injection of unborated water within the primary coolant system and, consequently, the pressure in the primary side is also increased. For that reason, the reactor is tripped by the Reactor Protection System, and the Decay Heat Removal System actuation is also demanded to achieve a proper core-cooling during the whole transient.

INTRODUCTION

Small Modular Reactors (SMRs) will play an important role in the future of the nuclear industry because of its inherent safety features, operation flexibility and reduced costs. In that sense, NuScale is one the most disruptive SMR design and it is worth noticing that a NuScale nuclear power plant could be formed from 1 to 12 NuScale Power Modules (NPM). Each NPM consists of an integral PWR design which relies on natural circulation to establish the flow rate within the Reactor Coolant System (RCS) and only passive safety systems are implemented to deal with accidental situations. In addition, each NPM is provided with an independent secondary side and dedicated Chemical and Volume Control System (CVCS) and passive safety systems, see (NuScale Power, LLC, September 2013) and (NuScale Power, LLC, July 2020).

Regarding SMRs safety assessment, several international research projects have been launched recently. In fact, this study has been performed within the framework of the "High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic Small Modular Reactors" (McSAFER) Horizon 2020 Project. Among other tasks, it is expected that UPM research group will develop a TRACE-1D and 3D models of the NuScale SMR concept to perform the analysis of the Boron Dilution and Steam Line Break sequences.

This work is a part of a wider analysis of the NuScale response to a Boron Dilution sequence generated by a malfunction of the CVCS. Specifically, this analysis is focused on simulating a best estimate case of the Boron Dilution sequence in a NPM by means of the TRACE 1D model. The data and the assumptions implemented in the model are presented in the Design Standard Application (DCA) report of NuScale. Furthermore, the reactivity feedbacks are considered by means of the activation of the point kinetics model available in TRACE and it is assumed that the safety systems will perform as expected.

Finally, this paper is divided into four main sections. Firstly, an introduction to the NuScale concept is included in which a brief description of the NPM design is made and the generic Boron Dilution sequence in NuScale is also found. Secondly, the TRACE-1D model developed by UPM is presented as well as the steady-state calculation results at the next section. Then, a summarizing section of the Boron Dilution transient simulation with the results obtained by means of the application of the TRACE-1D model is provided. Finally, the main conclusions extracted from this work are presented in the last section.

NUSCALE CONCEPT INTRODUCTION

NuScale design description

The NPM consists of an integral concept of Small Modular Pressurized Water Reactor which relies on natural circulation to provide the primary coolant flow, which means that not only the core but also other components such as the helical Steam Generators (SGs) and the Pressurizer (PZR) are located within the cylindrical Reactor Pressure Vessel (RPV), see Figure 1.

The RPV is located within the Containment Vessel (CNV) which internal pressure remains at vacuum during normal operation to minimize heat losses. The CNV is made in steel, and it provides an enhanced safety feature against overpressure transients and, as it is partially immersed in the reactor pool (90 % of the CNV height), a RPV cooling capacity from the outside under accident conditions, Figure 2 and (NuScale Power, LLC, July 2020).

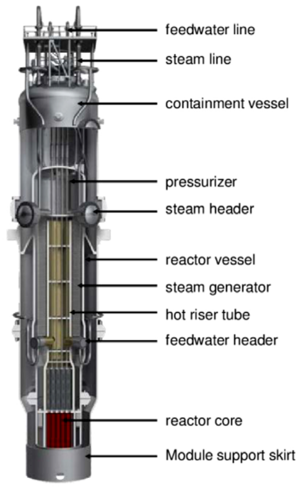

Figure 1. General arrangement of an NPM (Printed with permission of NuScale Power, LLC).

Parameter	Value	SI Units
Core thermal power	160	MW
NPM electrical capacity	50	MW
RCS operating pressure	12.755	MPa
Steam generator type	Vertical helical tube	2
Number of fuel assemblies	37	-
Fuel assembly lattice	17x17	Square
Refueling intervals	24	months

Table 1. Overall characteristics of an NPM.

A NPM relies on a small-sized core to generate 160 MW of thermal power with 37 PWR 17x17 fuel assemblies, and on two independent and intertwined helically coiled steam generators (SGs) surrounding the upper region of the riser to remove the heat generated by the core during normal operation, for further information see Table 1. It is worth noticing that the power control is achieved by the insertion or extraction of the control rods and by controlling the Boron concentration in the coolant.

Regarding the flow path within NuScale RPV, the coolant is heated within the core region flowing upwards through the central hot riser. Then, the flow reaches the top of the riser where it is redirected into the annular region between the riser and the RPV inner wall and forced to flow downwards directly through the region of the SG tube bundles. At that region, the heat in the coolant is transferred to the inventory in the secondary side of the SGs, so liquid water becomes denser and flows downwards by natural circulation. Finally, the primary coolant returns to the lower plenum through the downcomer reaching the core inlet again closing the primary loop, see Figure 2.

Each NPM is built with an independent steam supply system (including the turbine), a dedicated Chemical and Volume Control System (CVCS) and the passive safety systems.

The CVCS is responsible for controlling the Boron concentration in the RCS, the RCS water inventory, the PZR spray for controlling RCS pressure and the extraction of the non-condensable gases accumulated in the PZR steam bubble during normal operation, see (NuScale Power, LLC, July 2020).

Regarding the safety systems, the ECCS has been specially designed to deal with accident scenarios in which the normal core cooling by means of the SGs is not achievable (such as LOCA accidents) or low temperature overpressure transients, see (NuScale Power, LLC, July 2020). It is formed by three Reactor Vent Valves (RVVs) and the two Reactor Recirculation Valves (RRVs) mounted at the RPV top head and around 1.8 m above the top of the core, respectively.

On the other hand, the DHRS is devoted to remove the decay heat generated within the core when the reactor is tripped (under non-LOCA conditions and when the normal secondary cooling system is unavailable), see (NuScale Power, LLC, July 2020). That system consists of two trains

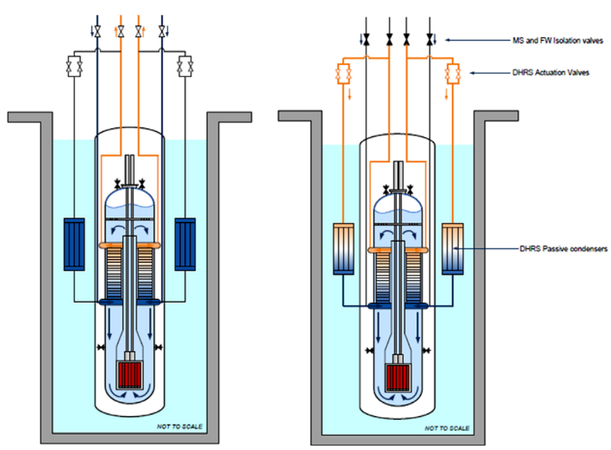

Figure 2. NPM performance under normal (left) and DHRS operation (right) scenarios (NuScale Power, LLC, September 2013).

of heat exchangers submerged in the reactor pool and connected to each main steam line, at a point before the Main Steam Isolation Valves (MSIVs), and to each feedwater line, see Figure 2. In that sense, when the NPM isolation is produced, a natural circulation flow rate is established between the SG and the DHRS heat exchanger. Therefore, the steam generation is driven by the decay heat generated in the core and the steam condensation by the cooling of the steam by the reactor pool closing the cycle, see Figure 2.

Boron Dilution sequence in NuScale

According to (NuScale Power, LLC, July 2020), the Boron Dilution sequence in a NPM could be produced by two sources:

- The malfunction of the CVCS
- Human action failure to control the Boron concentration during normal operation.

The main CVCS features regarding the simulation of the Boron Dilution sequence are listed below:

- Two CVCS makeup pumps are responsible for controlling the Boron concentration by injecting borated or demineralized water into the RCS.
- The CVCS injection point is located immediately above the transition riser region and the discharge point, immediately below the SGs region.
- Automatic CVCS isolation when a SCRAM signal occurs.

Once the unborated water injection into the RCS begins, the unborated mass flow will reach the core by following the RCS flow path, going through the whole primary coolant loop, and eventually spreading the reduction in the Boron concentration to all regions in the RCS, so it can be said that the unborated water generates a dilution front which will be turning around the RCS, see Figure 3.

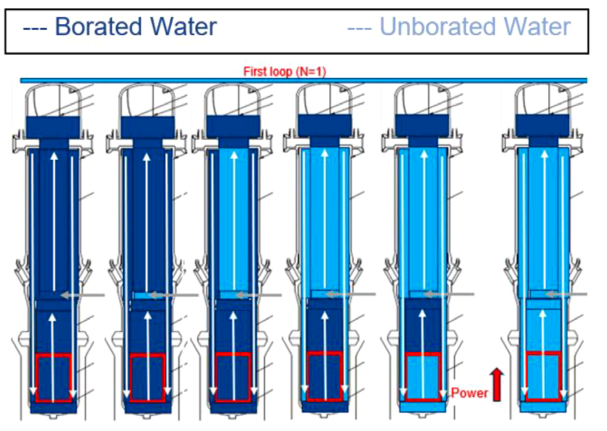

Figure 3. Boron Dilution Front evolution within the RCS.

As in conventional PWRs, the main consequence of the Boron Dilution sequence is the introduction of positive reactivity within the core increasing the current power up to the actuation of a SCRAM signal. As a result, the reactor is tripped, the CVCS isolation system is activated, and the injection of the demineralized water to the RCS is terminated. The MSIVs and FWIVS closure is also demanded and the DHRS starts to operate by means of the DHRS isolation valves opening using the reactor pool as the ultimate heat sink, see Figure 2.

MODELLING OF A NUSCALE POWER MODULE USING TRACE

TRACE-1D model of a NPM developed by UPM

The process to develop the TRACE-1D model of a NPM is divided into the following steps:

1. Creation of a database in which all public information retrieved from the available literature related to NuScale geometrical data, SCRAM signals, safety systems actuation signals and boundary conditions was collected, see (NuScale Power, LLC, July 2020), (NuScale Power, LLC, April 2019) and (NuScale Power, LLC, December 2016). Special attention is paid to the location of the sensors implemented in a NPM to measure the input variables of the different safety signals, see (NuScale Power, LLC, May 2020).
2. Nodalization scheme of the NPM, see Figure 4.
   a. The RCS is divided into the following regions: core and bypass, central hot riser (lower riser, transition riser, and upper riser), SG-tubes, downcomer, and lower plenum.
   b. The integrated pressurizer (PZR) is modeled by means of a dedicated PIPE component internal option implemented in TRACE and the heaters and PZR spray system effects are also included in the PZR model.
   c. Each NPM has two SGs, and each SG has two independent bundles of tubes. In the TRACE model, each bundle of tubes has been explicitly model.
   d. Each DHRS heat exchanger (one per DHRS train) has 80 vertical tubes. The DHRS heat exchangers has been modeled by eight PIPEs components for the tubes and two additional PIPEs for the collectors.

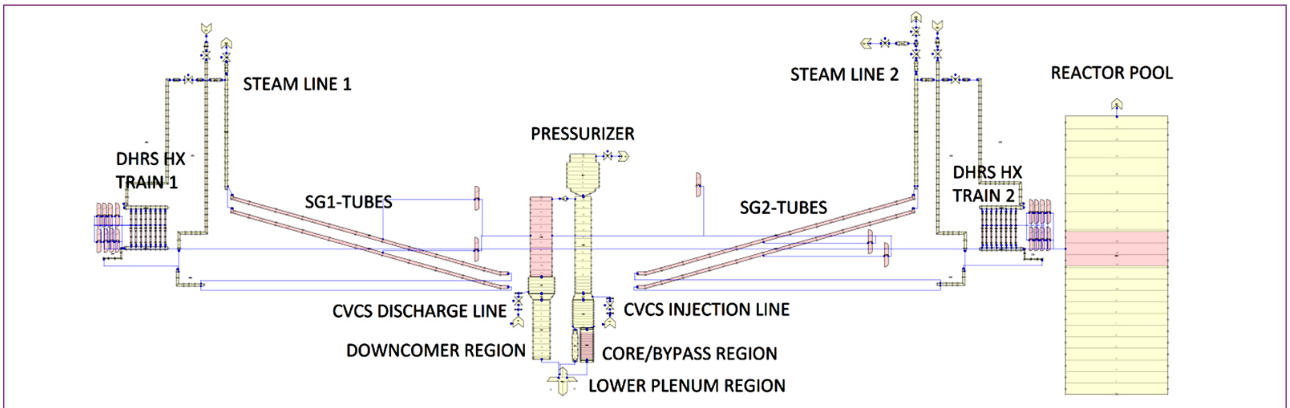

Figure 4. TRACE-1D model nodalization scheme.

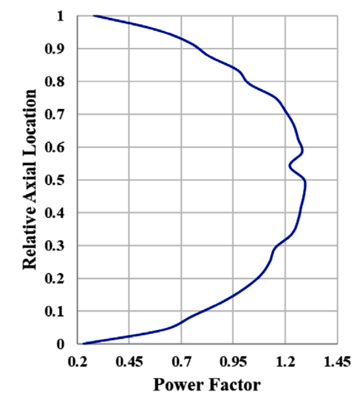

Figure 5. Axial Power Profile.

Parameter (SI Units)	DCA	TRACE-1D	Error (%)
RCS Pressure (MPa)	12.755	12.754	-0.01
RCS Mass-flow rate (kg/s)	535.24	535.32	0.01
Core Mass-flow rate (kg/s)	496.17	498.89	0.55
Core Inlet Temperature (K)	531.48	529.32	-0.4
PZR level (%)	60.00	59.99	-0.02
Steam Temperature (K)	580.04	568.28	-2.71
SG Outlet Pressure (MPa)	3.447	3.51	1.72

Table 2. Steady-State values comparison.

Parameter	Value
MTC (pcm/K)	0.0
DTC (pcm/K)	-2.52
Boron coefficient (pcm/ppm)	-10

Table 3. Reactivity Coefficients values.

e. The dedicated options available in TRACE to model regions with special geometries such as the 'Tube Bank Crossflow' PIPE for modeling the primary side of the SGs or the 'Curved Pipe' PIPE for modeling the SG-tubes, see (NRC, 2017), have been deployed in the TRACE model.

3. The numerical methods applied selected in the RCS model are the SEMI-IMPLICIT method to the time integration and the VAN LEER modified with FLUX LIMITERS method to the spatial difference in order to prevent numerical diffusion on the Boron Concentration results.
4. The CVCS makeup and letdown flow rates have been implemented within the TRACE-1D model as boundary conditions by means of the respective FILLs components.
5. A preliminary reactor pool model has been implemented in the model.

Finally, the CNV and the ECCS are not implemented in this TRACE model because their actuations are not expected for the Boron Dilution transient, so incorporating them to the model is considered out of the scope of the present work.

Steady-State calculation

A steady-state calculation of 20000 s including the following DCA: Chapter XV assumptions has been performed:

- The reactor is initially working at 100% Nominal Power and at the Beginning of Cycle (BOC) condition, see Figure 5.
- Nominal values are assumed for the RCS and the secondary side parameters except for the mass flow rate, which is restrained to its minimum DCA value (535.24 kg/s).
- The letdown mass flow rate is assumed to be equal to the makeup one which is restrained to its maximum value (3.15 kg/s).
- The makeup temperature is restrained to its minimum value (278 K).
- The initial Boron concentration is 1600 ppm.

A comparison of the steady-state results obtained with the TRACE model and the ones presented in the DCA report is depicted in Table 2.

BORON DILUTION TRANSIENT SIMULATION USING TRACE

In this study, an analysis of the Boron Dilution sequence in a NPM is performed using the described TRACE-1D model. The point kinetics model is activated, the reactivity coefficients values implemented, see Table 3, and the decay heat is explicitly model by means of the ANS-94 correlation. The SCRAM and DHRS actuation signals are also included in the model as well as the SCRAM worth due to the control rods insertion.

After 20000 s of steady-state calculation, the transient calculation begins and the CVCS makeup pumps start to inject unborated water ([B] = 0 ppm) within the RCS, see Figure 6. Core Average Boron Concentration. The reduction of the Boron concentration causes an important increase in the core power (Figure 7) due to the unbalanced reactivities, see Figure 8. Consequently, there is a large increase in the PZR pressure (Figure 9) which leads to the reactor trip (PZR pres-

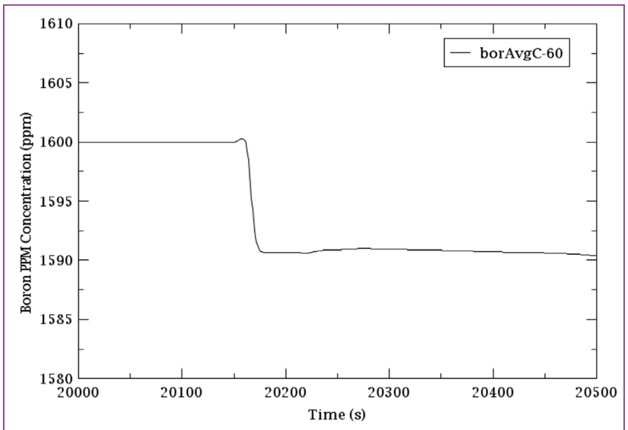

Figure 6. Core Average Boron Concentration.

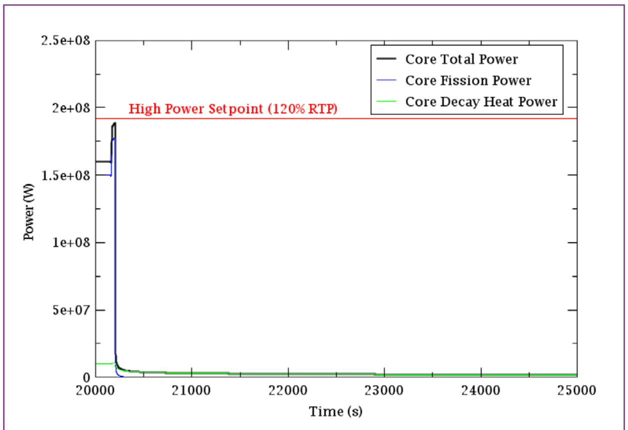

Figure 7. Power evolution.

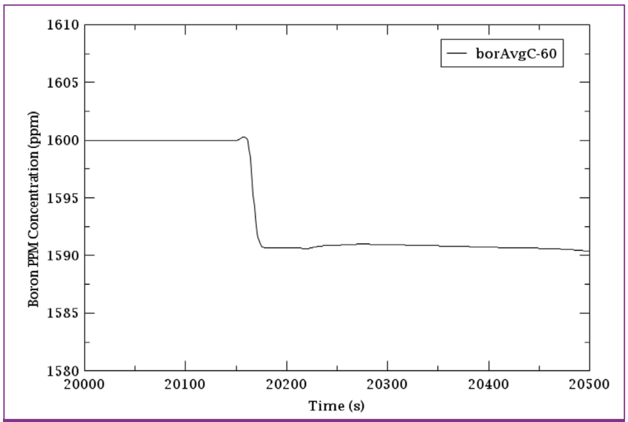

Figure 6. Core Average Boron Concentration.

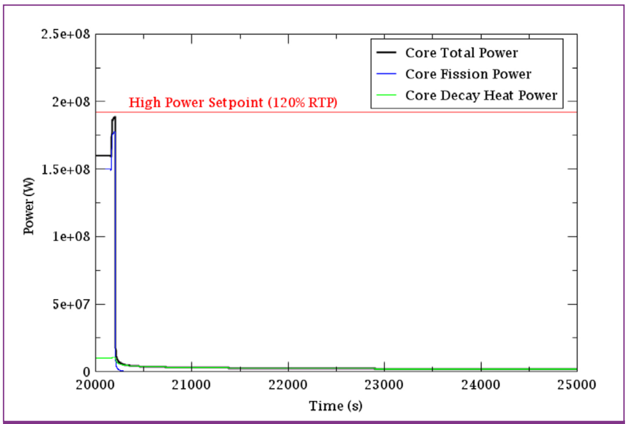

Figure 7. Power evolution.

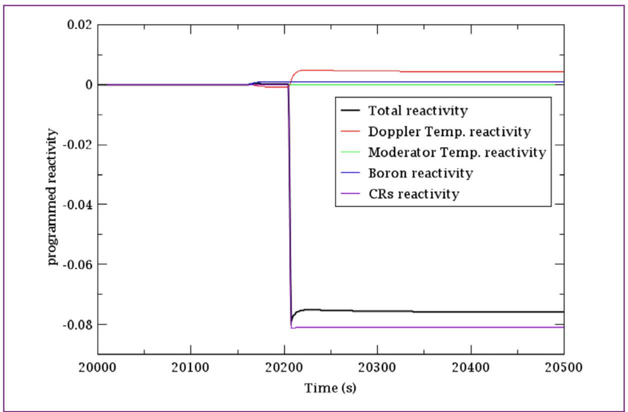

Figure 8. Reactivity contributors.

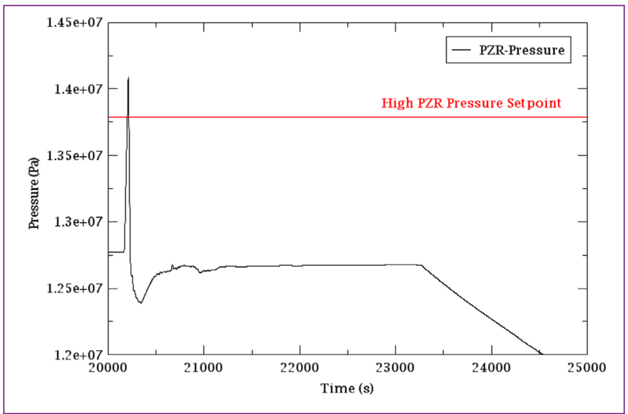

Figure 9. PZR Pressure.

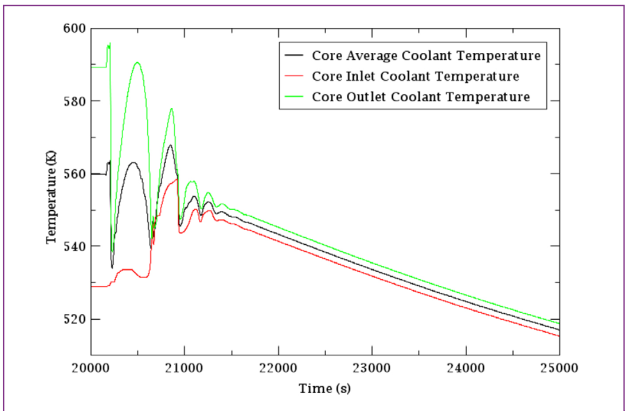

Figure 10. Core Temperature.

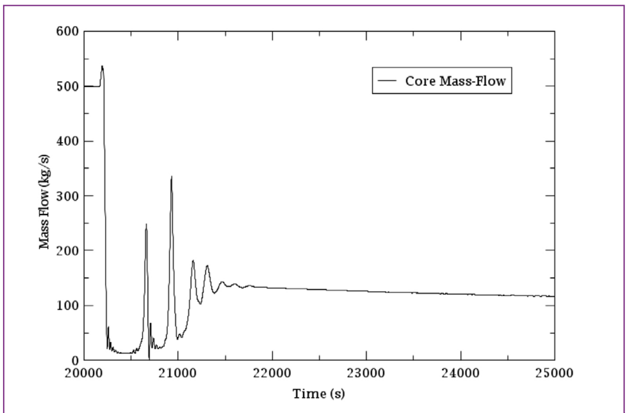

Figure 11. Core Mass Flow.

sure reaches 137.895 bar), see Figure 9, and to the isolation of the NPM (isolation of the main steam and feedwater lines and also the CVCS system). Furthermore, the DHRS actuation is also demanded, and the DHRS isolation valves full opening is achieved 30 seconds later. From here on out, the decay heat generated in the core is removed by the action of the SGs and the DHRS.

Due to the power transient produced by the Boron Dilution sequence, an RCS flow rate and temperature transient occurs as well, see Figure 10 and Figure 11. However, the reactor trip along with the DHRS actuation allows to establish a proper core-cooling condition of the core avoiding exceeding the DNBR safety limit during the whole transient.

Once the reactor is tripped and an adequate core cooling condition achieved, the water level within the PZR starts to decrease. However, the PZR pressure remains around 126 bar due to the action of the PZR heaters. Finally, as the water level within the PZR keeps on diminishing, the low-level condition is reached in the PZR after 3266 s of transient simulation and, as a result, the PZR heaters are tripped and the PZR pressure starts to decrease, see Figure 9.

CONCLUSIONS AND FUTURE WORKS

The main conclusions drawn from this study are listed below:

- The Boron Dilution transient produces an increase in the core power causing the reactor trip because of a high-pressure condition within the RCS. The NPM is isolated and the injection of unborated water into the RCS terminated.

- The DHRS is responsible for establishing an adequate core-cooling condition avoiding the core damage or exceeding any safety limit.
- So far, the TRACE-1D model of a NPM developed by UPM within the MCSAFER project framework has shown promising results. However, certain improvements will be implemented in the final version.
- The point kinetics model has been implemented in the TRACE-1D model successfully and it is working appropriately.
- TRACE code is able to capture the physics of the Boron dilution transient by means of the application of high-order numerical methods.

Regarding the ongoing works, the reactor pool modelling approach is under assessment and several improvements will be implemented in the TRACE 1-D model. In addition, the analysis of the Steam Line Break transient is also in progress. On the other hand, a TRACE-3D standalone model of the NPM and a TRACE-3D model of the RCS coupled with a SCF model of the NuScale core are also under development in order to assess the impact of possible asymmetrical phenomena within the RPV on the response of the NPM to the postulated transients.

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