Safety margins improvement by means of the passive second stage hydroaccumulators in a VVER-1000/V320 reactor

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ABSTRACT

Since the Fukushima accident, there has been a new surge in interest in passive safety systems that ensure the core integrity in accidental sequences involving a total loss of AC power. In this sense, the majority of the GEN-III reactors incorporate advanced passive safety systems. One such system is the Second Stage Hydroaccumulators (HA-2) system, which is a passive safety injection system included in some advanced VVER reactors. The goal of this paper is to analyse the impact of the HA-2 on the events of a LOCA sequence, with and without SBO. For this purpose, a VVER-1000/V320 thermal hydraulic model for TRACEV5P5 code has been modified to include the HA-2 system. By analysing the results, it is found that the single performance of this passive safety system along with the accumulators, without considering any other management action, is enough to avoid the core damage in medium/large LOCA along with SBO during 24 h, moreover this system allows also to relax the success criteria of the active High and Low Pressure Safety Injection Systems in medium/large LOCA sequences without SBO conditions.

1. Introduction

The International Atomic Energy Agency (IAEA) defines a Passive Safety Systems (PSS) as “a System which is composed entirely of passive components and structures or a System which uses active components in a very limited way to initiate subsequent passive operation”, (IAEA, 1994, 1991). Based on this definition, the IAEA establishes a classification to determine the passiveness level of a system based on whether it moves fluids or mechanical parts and whether it requires external power or signal inputs, see Table 1 and (Burgazzi, 2012; Fil et al., 1999; IAEA, 2009). In fact, PSSs cannot be classified exclusively as “passive” or “active”, as both passive and active means can be found in the single safety system, e.g. a system could be driven by natural forces, such as gravity, but need a valve opening to initiate the operation.

Furthermore, a PSS can also be classified according to the safety function they perform into three groups usually found into the literature (Bryk et al., 2019; Buchholz et al., 2015; Heung Chang et al., 2013; IAEA, 2019, 2016; Kaliatka, 2017; Yamada and Tuniz, 2011): Emergency Core Cooling Systems (ECCS), Passive Heat Removal Systems (PHRS) and Containment Cooling and Control Pressure (CCCP), see Table 2.

There are several European projects and NEA/CSNI/WGAMA activities, see (NEA, 2020), that have studied the behaviour of the PSSs: McSafer (Sanchez-Espinoza et al., 2021), PASTELS (Montotut, 2021), sCO2-4-NPP (Cagnac, 2022), PIACE (De Grandis et al., 2019), PERSEO Benchmark (Mascari et al., 2023), ISP-51 experiment in ACME (in progress), OECD/NEA ATLAS projects (NEA, 2022), or the OECD/NEA ETHARINUS project (PKL facility) (NEA, 2004).

The present work has been developed within the project “Integrated Safety Analysis of Modular and Evolutive Reactors” (ISASMORE). It is being carried out by the Universidad Politécnica de Madrid (UPM) in collaboration with the Karlsruhe Institute of Technology (KIT). Among the project goals, it can be mentioned:

- A review and comparison of the PSSs in PWR/VVER reactors,
- The analysis of the passive ECCS included in the VVER reactors.

The first motivation for the present research lies in the limited public information available on the HA-2 PSS, which is included in advanced VVER reactors and not present in any western design. Only a few severe accident analyses related with HA-2 PSS have been found in the literature, see (Lityshev et al., 2013) (IAEA, 2017) (Thi Hoa and Chi Thanh, 2015), which consider its performance during a Large Break Loss of

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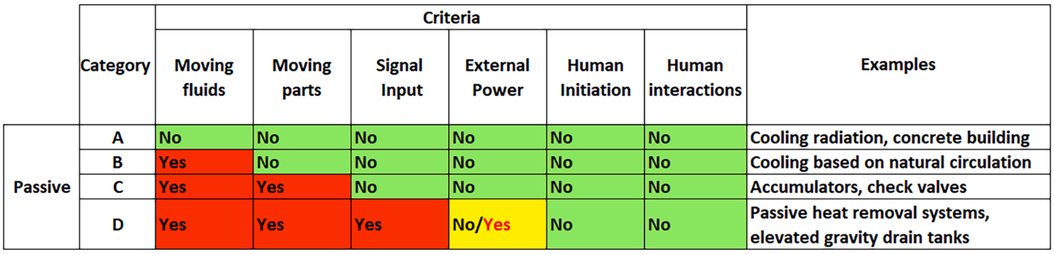
Nomenclature

ACC	Accumulators
ASVAD	Automatic Safety Valve for Accumulator Depressurization
ATLAS	Advanced Thermal-Hydraulic Test Loop for Accident Simulation
BRU-A	Steam Dump Valves to the Containment
BRU-K	Steam Dump Valves to the Condenser
BRU-SN	Steam Dump Valves to the Atmosphere
B&W	Babcock & Wilcox
BZOK	Main Isolation Vales
CCCP	Containment Cooling and Control Pressure
CD	Core Damage
CE	Combustion Engineering
CL	Cold Leg
CMT	Core Make-up Tank
CVCS	Control Volume and Chemical System
DBA	Design Basis Accident
DC	Downcomer
DEGB	Double Ended Guillotine Break
DVI	Direct Vessel Injection
EBIS	Emergency Boron Injection System
ECCS	Emergency Core Cooling System
EFW	Emergency Feed Water
EMT	Emergency Makeup Tank
ETHARINUS	Experimental Thermal Hydraulics for Analysis, Research and Innovations in Nuclear Safety
HA-1	First Stage Hydroaccumulator
HA-2	Second Stage Hydroaccumulator
HA-3	Third Stage Hydroaccumulator
HL	Hot Leg
HPIS	High Pressure Injection System
IAEA	International Atomic Energy Agency
IRWST	In-containment Refuelling Water Storage Tank
LBLOCA	Large Break Loss of Coolant Accident
LPIS	Low Pressure Injection System
LW-SMR	Light Water Small Modular Reactor
MBLOCA	Medium Break Loss of Coolant Accident
MFW	Main Feed Water
NPP	Nuclear Power Plant
PCT	Peak Cladding Temperature
PERSEO	In-Pool Energy Removal System for Emergency Operation
PHRS	Passive Heat Removal System
PKL	Primary Coolant Loop Test Facility
PRZ	Pressurizer
PSS	Passive Safety System
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RPV	Reactor Pressure Vessel
SBLOCA	Small Break Loss of Coolant Accident
SBO	Station Blackout
SC	Success Criteria
SG	Steam Generator
SL	Steam Line
SV	Safety Valves
TH	Thermal-hydraulic
TT	Turbine Trip
UP	Upper Plenum

Table 1
Passive safety systems IAEA categories.



	Category	Criteria						Examples
		Moving fluids	Moving parts	Signal Input	External Power	Human Initiation	Human interactions	
Passive	A	No	No	No	No	No	No	Cooling radiation, concrete building
	B	Yes	No	No	No	No	No	Cooling based on natural circulation
	C	Yes	Yes	No	No	No	No	Accumulators, check valves
	D	Yes	Yes	Yes	No/Yes	No	No	Passive heat removal systems, elevated gravity drain tanks

Table 2
Passive Safety Systems classified by safety functions.

Emergency Core Cooling Systems	Accumulators Make-up Tanks Elevated Gravity Drain Tanks (inside/outside containment) Long Term Core Cooling	
Passive Heat Removal Systems	Through the Steam Generators	Cooled by a water pool Cooled by air flow
	Through the Reactor Coolant System	Cooled by a water pool Cooled by a closed extra loop
Containment Cooling and Control Pressure	Suppression Pool Containment Condenser (cooled by water or air) Condensation on Containment inner wall	

Coolant Accident (LBLOCA) along with Station Blackout (SBO), but no detailed Thermal-Hydraulic (TH) analyses have been performed with system codes. The second main motivation of this research is to evaluate the impact on Medium Break Loss of Coolant Accident (MBLOCA) and LBLOCA success criteria (SC) of the HA-2 PSS implementation and look for possible "relaxations" of the number of trains required to adequately cope with the transient.

This research is complementary to the previous UPM experience in analysing the behaviour of other PSSs in the AP1000 reactor (Fernández-Cosials et al., 2017; Montero-Mayorga et al., 2015; Queral et al., 2017; Queral et al., 2016; Queral et al., 2015), the ACME experimental facility (participation in ISP-51), which is a scaled facility of the CAP1400 reactor, the NuScale LW-SMR (Campos-Muñoz et al., 2023; Redondo-Valero et al., 2022) and the CAREM-like LW-SMR. Moreover, UPM has also been involved in the McSafer (Sanchez-Espinoza et al., 2021) and the PIACE H2020 projects (Larriba del Apio et al., 2022).

In addition to this introduction section, the paper is organized as follows: Section 2 describes and compares the passive ECCS that can be found in the PWR and VVER reactors, the Section 3 outlines the TH

Table 3
Accumulator designs comparison.

Reactor design	Number of ACCs	Total capacity (m^3)	Pressure (MPa)	Injection connection
Westinghouse (3/4 loop)	3/4	41 (x3) /34 (x4)	4.4 / 4.5	CL
Siemens (Konvoi)	8	34 (x4)	2.5	4 to CL and 4 to HL
Framatome (P4)	4	47 (x4)	4.0	CL
B&W	2	51 (x2)	4.13	DVI to DC
CE	4	46.5 (x4)	4.11	CL
CPR1000	3	33.2 (water)(x 3)	4.93	CL
VVER-1000 and VVER-1200	4	60 (x4)	6.0	2 UP and 2 DC
VVER-1000/V446	4 HA-1 + 8 KWU ACCs	60 (x4) +45 (x8)	6.0 2.5	HA-1: 2 UP and 2 DC KWU ACCs: 4CL and 4 HL
EPR	4	150 (x4)	5.5	CL
AP1000 and CAP1400	2	56.6 (x2) /65 (x2)	4.9	DVI to DC
APR1400	4	68 (x4)	4.2	DVI to DC
Hualong	3	50 (x 3)	5.5	CL

Table 4
Make-up tanks designs comparison.

Reactor design	Number of trains	Total capacity (m^3)	Pressure Set Point (MPa)	Injection connection	Stages
VVER-1200/V392M & VVER-TOI	4	120 × 2 (x4)	1.5	Accumulator Injection Line UP/DC	4
VVER-1000/V412	4	120 × 2 (x4)	1.5	Accumulator Injection Line UP/DC	6
AP1000 / CAP1400	2	70.8 (x2) / 85 (x2)	11.7	DVI	1
ACP100	2	18 (x2)	N/A	DVI	1
SMART	4	N/A	∼11	DVI	1
SMR-160	2	N/A	N/A	DVI	1

model of the VVER-1000/V320 reactor in which the HA-2 has been modelled, Section 4 analyses the impact of the HA-2 on LOCA along with SBO sequences and Section 5 discusses how the implementation of the HA-2 can relax the ECCS SC in MBLOCA/LBLOCA sequences without SBO. Finally, the conclusions drawn from this research are set out in Section 6.

2. Overview of passive emergency core cooling systems

An overview of the passive ECCS implemented in different reactor designs is convenient, as it provides an insight into the functions performed by each of them during an accidental sequence. Furthermore, the comparison of these passive ECCS allows the identification of possible improvements that might otherwise have been missed. The following is a summary of the passive ECCS included in Table 2:

- Accumulators (ACC): Tanks containing borated water and pressurized with non-condensable gases. All GEN-II and GEN-III PWR include this PSS, see Table 3 and (AREVA, 2007; Bajorek, 2007; Ebrahimgol et al., 2021; Gavrilas et al., 1995; Hosseini et al., 2020; Queral et al., 2021; Redondo-Valero et al., 2023; Shoushtari et al., 2016; USNRC HRTD, 2011). Moreover, ACCs can also be found in almost all the LW-SMR. The name given to the ACCs can be different depending on the design, so that for Babcock & Wilcox (B&W) reactors they are known as Core Flood Tanks, for Combustion Engineering (CE) reactors as Safety Injection Tanks and for the VVER reactors as First Stage Hydroaccumulators (HA-1). The main characteristics of ACCs are:
    i. ACCs are isolated from the Reactor Coolant System (RCS) by implementing check valves that open when the pressure in the RCS drops below the pressure of the non-condensable gases. It is noteworthy that the ACC pressure in VVER reactors are higher than in the other PWR reactors, see fourth column in Table 3.
    ii. According to the reactor design, different connections to the RCS can be found, see fifth column of Table 3. Some ACC designs are connected to the vessel and not to the Cold Legs (CL) or Hot Legs (HL), ensuring that in the event of a CL/HL LOCA the ACC inventory is not lost through the break instead of reaching the core.
    iii. Some reactors designs are equipped with valve downstream of the ACCs, which isolates them automatically when the borated water level dropped below a certain level, thus preventing non-condensable gases from entering the RCS and being deposit on the Steam Generators (SG) tubes, deteriorating the heat exchange in them (Cacuci, 2010; Fennovioma, 2015). In VVER-1000 reactors, these valves are AC motorised, but they are powered by first category of secured power supply, which implies that there is a DC/AC inverter at the battery output capable of powering the isolation valves for at least 12 h, so that in the event of an SBO sequence, isolation of the HA-1 is guaranteed (ČEZ, 2012). Previous VVER-440 reactors are equipped with floating valves inside the ACCs that have a similar function (Kral et al., 2011; Queral et al., 2021). Other PWR designs, e.g. Westinghouse, include in the Emergency Operating Procedures a manual action of isolating the ACCs or venting the nitrogen valves. In addition, new venting valves have been proposed, e.g. the Automatic Safety Valve for Accumulator Depressurization (ASVAD), which have been developed to passively vent ACCs when they reach 1.5 MPa (Freixa et al., 2021).
    iv. Finally, it can be highlighted that the design incorporated in the APR1400/APR + reactors includes a Fluidic Device that allows for the injection of the borated water in two stages. This enables a more efficient use of ACCs inventory during the refill phase of the LOCA and therefore extends injection to the end of the reflood phase, so that the LPIS (Low Pressure Injection System) can be excluded from the reactor design (Korea Hydro & Nuclear Power Co., 2012). An application to a VVER-1000/V446, Bushehr Nuclear Power Plant (NPP), has shown they improve the safety margins in LBLOCA sequences (Pouresgandar et al., 2022).
- Make-up Tanks: Tanks that are completely full of borated water. In VVER reactors this system is usually referred to as HA-2, while for the other reactors is usually known as Core Make-up Tank (CMT). A comparison of the make-up tanks included in different designs can be seen in Table 4 and (Deng et al., 2020; Kim et al., 2020; Shi et al., 2021). Some proposals have been made to include also this system in the secondary side of the CPR1000 and Hualong reactors, where it is known as the Emergency Makeup Tank (EMT) (Li et al., 2021; Sun et al., 2018; Zhang et al., 2011). The main characteristics of the make-up tanks are the following:
    i. They are connected upstream by a line to the RCS, either to the CL in the large reactors or to the pressure vessel in the LW-SMR (Kim et al., 2020; Qiu et al., 2023). In the AP1000, CAP1400, ACP100 and SMART reactors this upper line is open, i.e. in stand-by mode the CMTs are at the RCS pressure, however in the VVER reactors this line is initially closed, but contains a special dual check valve that opens when the pressure in the RCS is below 1.5 MPa (IAEA, 2017).
    ii. On the bottom, both the CMTs and the HA-2 are usually connected to the ACCs and HA-1 injection lines to the vessel. Under normal operation this line is isolated from the RCS with check or

Table 5
Reactor designs with passive ECCS.

ECCS	Category	Reactors Designs
Accumulator	C	ACP100, SMART, CAREM, SMR-160, NUWARD, RITM-200, VVER-1200, EPR, AP1000/CAP1400, APR1400, Hualong and GEN-II PWR
Make-up Tank	D	ACP100, SMART, AP1000/CAP1400, VVER-1200/V-392 M, VVER-1000/V-412
Elevated Gravity Tanks	D	ACP100, SMR-160, AP1000/CAP1400
Long Term core cooling with sump/cavity or from top of the RPV	D	ACP100, CAREM, RITM-200, SMART, SMR-160, NuScale, NUWARD, AP1000/CAP1400

isolation valves which open when the system is required to fulfil its safety function allowing the inventory flows into the RCS by the effect of the hydrostatic pressure (Veselov and Tishin, 2017). It is remarkable that in the VVER reactors HA-2 discharge in several stages, either 4 or 6 (only in Kudankulam NPP), which is achieved by means of 4 or 6 discharge pipes located inside the HA-2 at different heights (Agrawal et al., 2006; Maltsev, 2015; Queral et al., 2021).

iii. It should be noted that in the case of the VVER reactors, the pressure set-point of the HA-2 (1.5 MPa) is lower than that of the ACCs (labelled HA-1 in VVER reactors), so they actuate as a low pressure injection system, while in other designs the pressure set-point of the CMT (11.7 MPa) is higher than that of the ACCs, and then actuate like a high pressure injection system, see fourth column in Table 4.

iv. In addition, the VVER-1200/V-509 and the VVER-TOI reactors are equipped with a second make-up tank PSS named Third Stage Hydroaccumulators (HA-3), with four trains and total volume of 720 m^3, which come into operation following the emptying of the HA-2, after 24 h, ensuring core cooling for an additional 48 h. Unlike HA-2, HA-3 are placed outside the containment, are manually activated and have a single discharge stage (Maltsev, 2015; Queral et al., 2021; ROSATOM, 2022).

- Elevated Gravity Tanks: Tanks with large volumes of borated water, that can be placed outside or inside the containment at atmospheric conditions. They are located at high elevation and have the capability of supply water to the RCS by gravity during several days at low pressure conditions (Buchholz et al., 2015; IAEA, 2019; Yamada and Tuniz, 2011). An example is the In-containment Refuelling Water Storage Tank (IRWST) of the AP1000 reactors, which is connected to the DVI lines and has a total volume of 2070 m^3 (Queral et al., 2015). Furthermore, there are GEN-II reactors that have tanks at a higher level than their injection point to the Reactor Pressure Vessel (RPV), so that it is possible to inject borated water to the RCS from this tank passively, (Gavrilas et al., 1995), mainly at reduced inventory or mid-loop conditions.
- Long Term Core Cooling: this PSS consist of the sump or cavity located around the RPV and connected to it through a recirculation valve or a Direct Vessel Injection (DVI) line, e.g. AP1000. Its function is to passively return to the RCS the inventory lost during a LOCA sequence, that has condensed in the containment and accumulated in the RPV sump or cavity (Buchholz et al., 2015).

All the PSSs described in this section are designed to inject water into the RCS in the event of a LOCA sequence. In this sense, it can be highlighted how the ACCs and the make-up tanks are mostly intended to replenish the RCS inventory during the initial stages of the accidental sequence. However, in order to ensure core cooling for several hours or days, the Elevated Gravity Tanks and the Long Term Core Cooling PSSs have been mainly conceived, as they are able to passively recirculate water back to the reactor (Buchholz et al., 2020). An overview of the large GEN-III PWR and LW-SMR that includes the passive ECCS can be found in Table 5 and (Buchholz et al., 2020, 2015; ROSATOM, 2019; Zeliang et al., 2020).

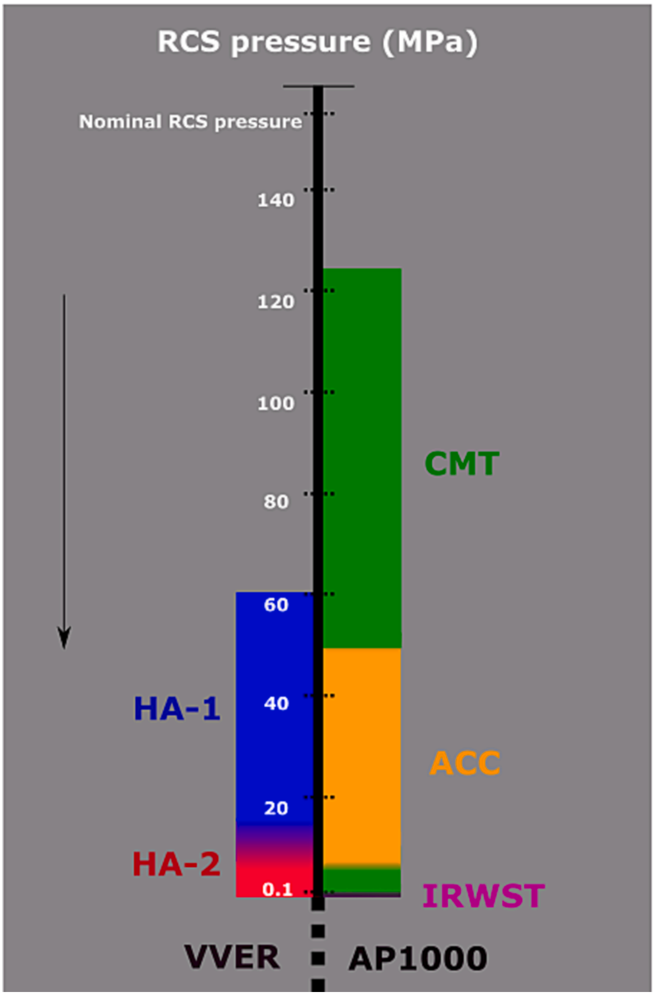


Fig. 1. VVER vs AP1000 Passive ECCS.

Following this review and based on the experience gained at the UPM, a clear distinction can be made between the passive ECCS at the AP1000/CAP1400 and the VVER reactors in which the HA-1 and the HA-2 PSSs are incorporated, see Fig. 1. Both designs are the only large nuclear reactors to include both high/medium and low passive ECCS:

- On the one hand, the AP1000/CAP1400 incorporates the CMTs as a passive high pressure ECCS, the ACCs and the IRWST, which is able to replenish water into the RCS at low pressure.
- On the other hand, there is no passive high pressure ECCS for VVER reactors whose function is equivalent to that of the CMTs in the AP1000/CAP1400 reactors, however, their ACCs have a higher pressure than that of the AP1000/CAP1400 ACCs, which allows them to act in time in MBLOCA and LBLOCA sequences, without the need for the operation of any other system. The HA-2 of the VVER are make-up tanks, however its function is not similar to that of the CMTs, since HA-2 are designed to replenish water in the RCS at low pressure during 24 h, which justifies that its total volume is greater than that of the CMTs.

3. VVER-1000/V320 thermal–hydraulic model

VVER-1000/V320 is a PWR 4-loops reactor with a thermal power of around 3000 MW$_{th}$ and an electric output of 1000 MW$_e$. The RCS volume

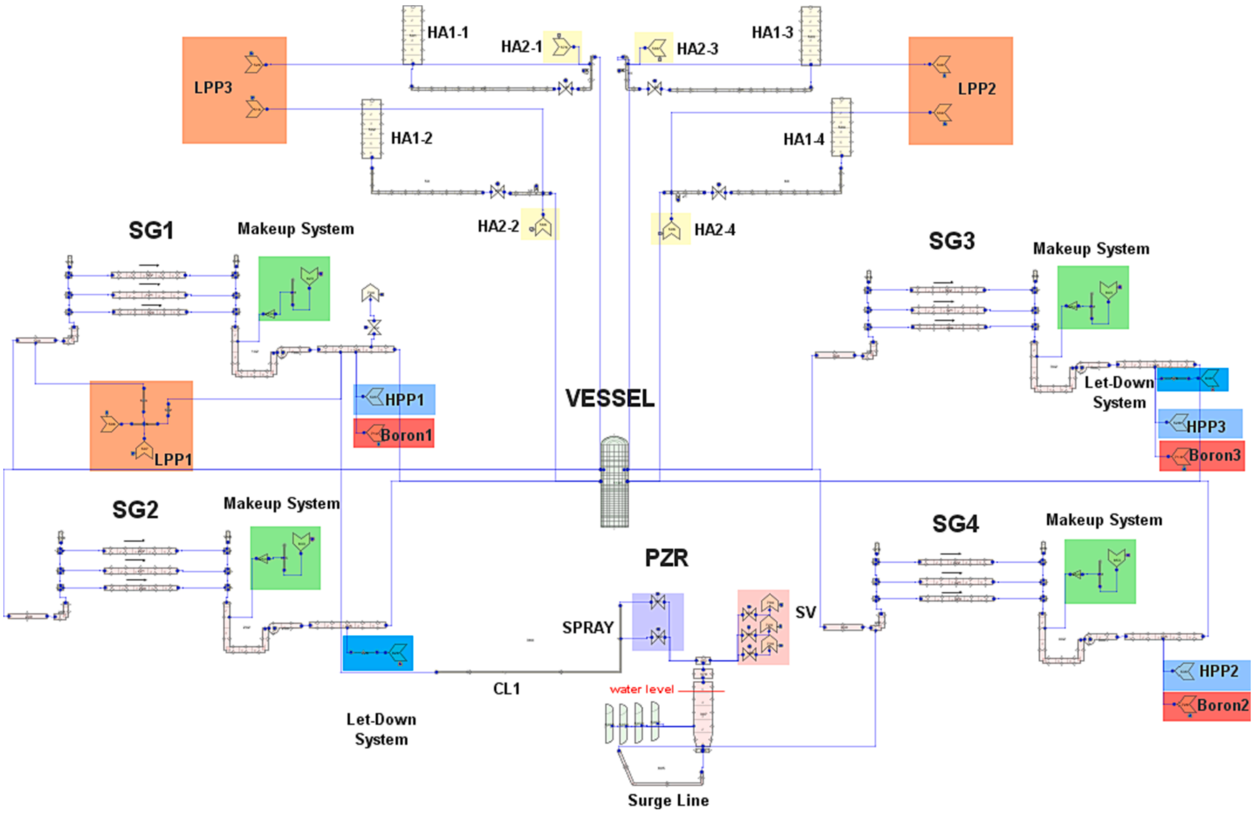


Fig. 2. Primary Side view of the VVER-1000/V320 TRACEV5P5 model.

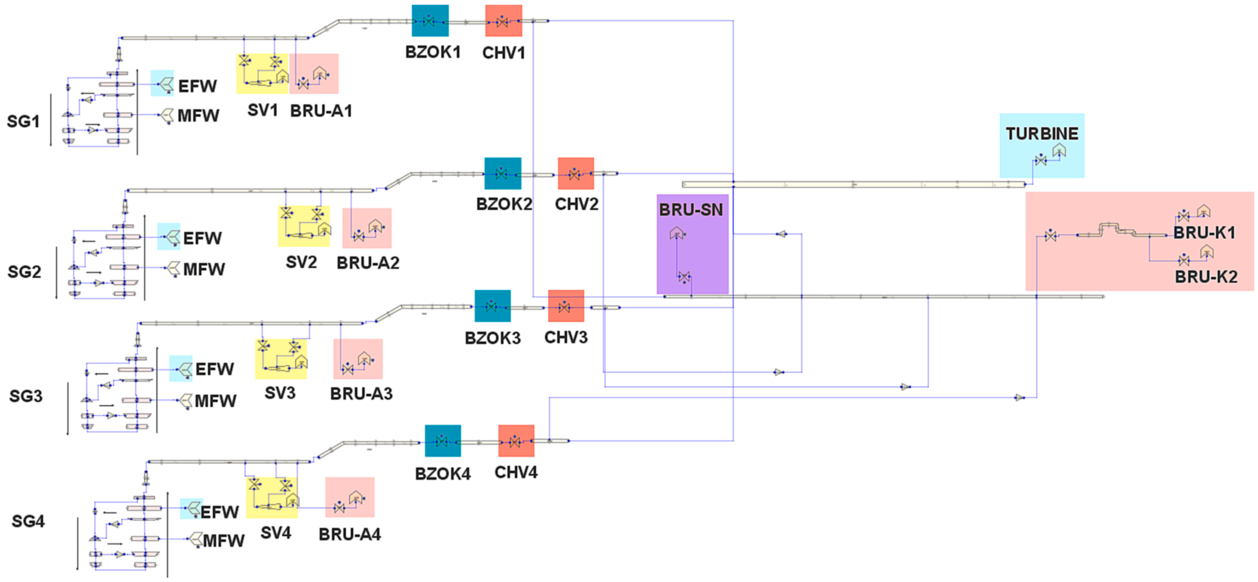


Fig. 3. Secondary Side view of the VVER-1000/V320 TRACEV5P5 model.

is 337 m^3, more than conventional western PWR. The connections of the four loops to the RPV are not symmetrical in the azimuthal direction but loops 1 and 4 are separated at an azimuthal angle of 55° to each other, with the hot legs being above the cold legs in the same angular position.

The TH model for the TRACEV5P5 code (NRC, 2017) to model a VVER-1000/V320 reactor used in this analysis is shown in Figs. 2 and 3. The nodalization has been built based on a VVER-1000/V320 RELAP5 model, (Sanchez-Espinoza and Bottcher, 2006), and has been applied for MB/LBLOCA analyses in previous studies, see (Redondo-Valero et al., 2023). The conversion of the TH model from the RELAP5 to the TRACEV5P5 code was performed component by component, adjusting the pressure drops for the RCS, secondary side of the SGs and steam lines. In this approach, the Cell Elevation Change (DELEV) option was selected to specify the elevation and orientation of the TH components because of its equivalence to RELAP5.

To solve the two-phase flow equations in the TH components, the SETS numerical method was selected. With regard to the friction factor correlation option, the homogeneous wall flow friction factor was

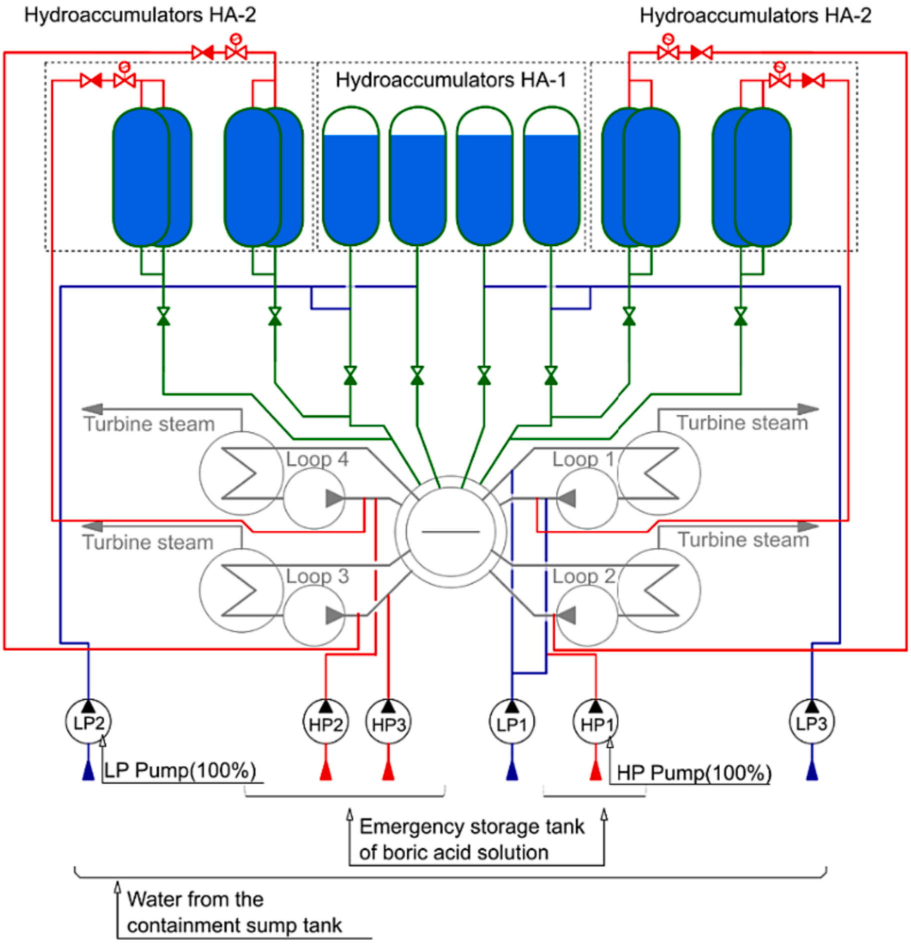


Fig. 4. ECCS configuration including HA-2 in VVER-1000/V320.

selected, except for the abrupt area changes which were adjusted to reproduce the RELAP5 model pressure drops.

The TH model includes 16 BREAKs, 29 FILLs, 164 PIPEs, 4 PUMPs, 4 SEPARATORs, 37 VALVEs, 1 VESSEL, 432 hydraulic connections, 300 SIGNAL VARIABLEs, 680 CONTROL BLOCKs and 46 TRIPs. The resulting integral plant model consists of following elements:

- Primary loops: The CLs and HL have been modelled with the 1D PIPEs, and the reactor coolant pumps (RCPs) have been modelled with the specific PUMPs component.
- Pressurizer (PZR): Connected to the HL 4 by the Surge Line. The PZR model also contains the spray line, connected to the CL1, the safety valves (SV) and four heaters groups.

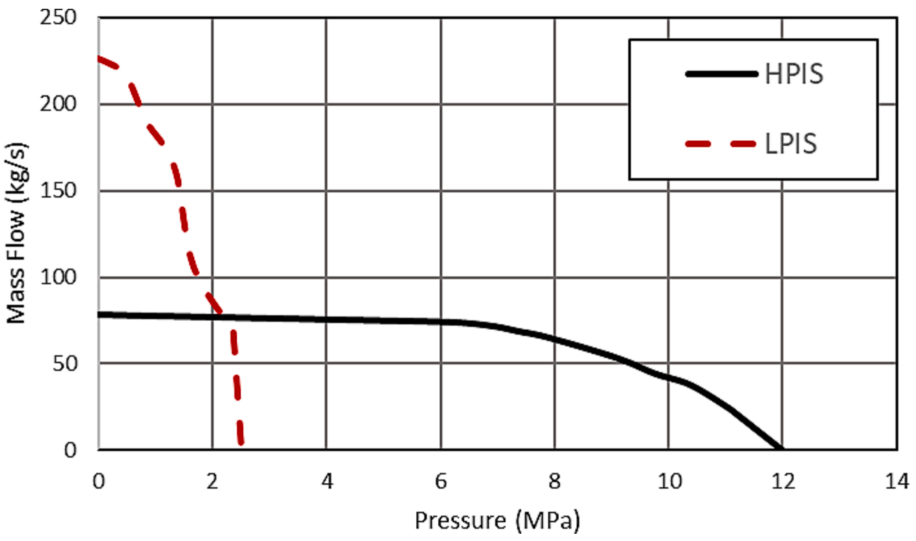


Fig. 5. HPIS and LPIS injection curves (per pump).

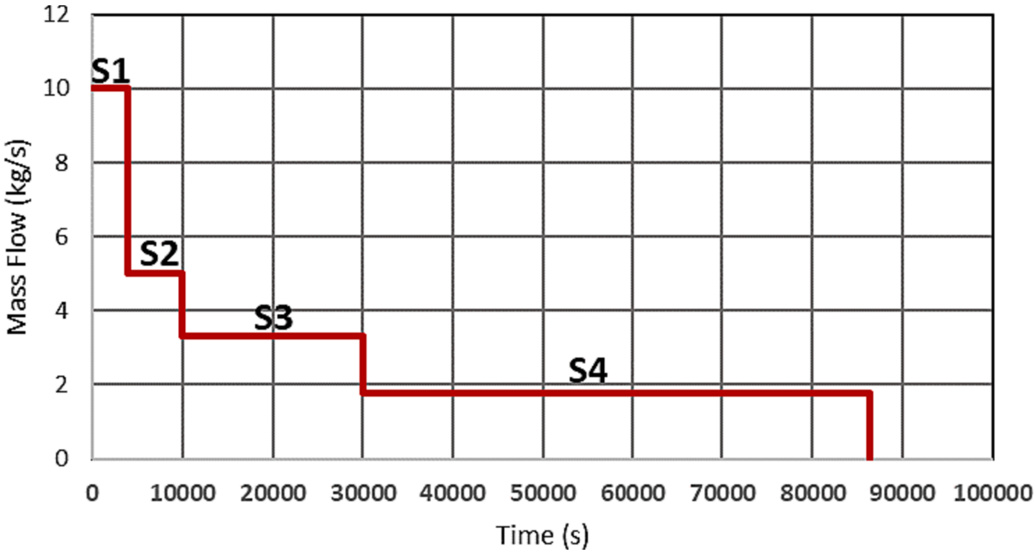


Fig. 6. Second Stage Hydroaccumulators (HA-2) mass flow rate (per HA-2 train).

- RPV: It has been modelled by a 3D VESSEL component which is divided into 50 axial levels, 6 azimuthal sectors and 6 radial sectors. The three inner rings are dedicated to the modelling of the core, the fourth ring to the modelling of the bypass, the fifth to the modelling of the core barrel and the sixth to the modelling of the downcomer.
- Core: A total of 18 HEAT STRUCTURE components are used to model the 50,856 fuel rods (163 hexagonal fuel assemblies, each with 312 fuel rods). Each HEAT STRUCTURE, has a height of 4 m and is divided into 12 axial levels (10 corresponding to the active part and 2 to the reflector part). A cosine axial power distribution is assumed and a hot fuel rod peaking factor of 1.74 (Iegan et al., 2016) has been included.
- SGs: In the primary side, the SG-tubes are modelled by three horizontal PIPEs. In the secondary side, the heat transfer zone is modelled on three horizontal levels. In the upper part is placed the liquid/steam SEPARATOR component.
- Steam lines (SL): including one steam dump valve to the containment (BRU-A), two safety valves, one main isolation valve (BZOK) and a check valve in each SL.

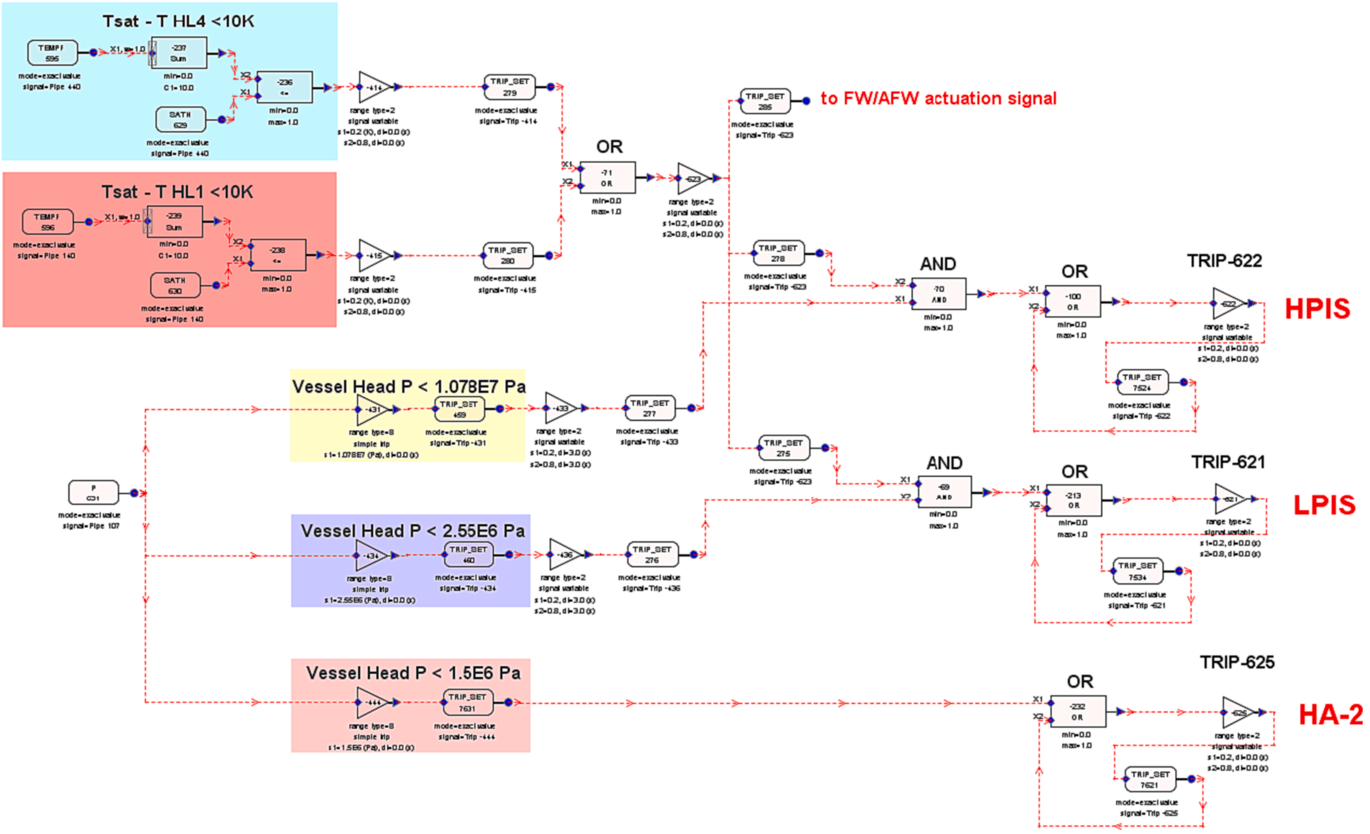


Fig. 7. HPIS, LPIS and HA-2 actuation signals in TRACEV5P5 model.

Table 6
System actuation signals I.

RCPs TRIP	
$\Delta SG_{\mathrm{level}} <\quad 0.5\ m$	**OR**
$\Delta SG_{\mathrm{level}} > 0.25$ m	**OR**
MSIV closing signal	**OR**
[$P_{SL} < 4.1$ MPa **AND** $T^{sat}_{core\_out} - T_{SL} > 75$ K **AND** $T_{HL} > 473.15$ K]	
SCRAM	
Power > 107 %	**OR**
SG level < 1.60 *m*	**OR**
User time-value	**OR**
$P_{RCS} > 17.65$ MPa	**OR**
PZR level < 4.6 *m*	**OR**
$P_{SG} > 7.84$ MPa	**OR**
[$P_{SL} < 4.1$ MPa **AND** $T^{sat}_{core\_out} - T_{SL} > 75$ K]	**OR**
$T^{sat}_{HL}\quad T_{HL} < 10$ K	**OR**
$\Delta P_{RCP} < 0.245$	**OR**
[$P_{core\ out} < 13.73$ MPa **AND** $T_{HL} > 533.15$ K]	**OR**
$T_{HL} > 597.15$ K	**OR**
[Power > 75 % MPa **AND** RCPs coast down]	**OR**
[Power > 75 % MPa **AND** $P_{core\ out} < 14.7$ MPa]	
PZR	
Heaters	
#1	On: Top Vessel P < 15.6 MPa **AND**
	PZR level > 4.2 *m*
	Off: Top Vessel P > 15.78 MPa **OR**
	PZR level > 4.2 *m*
#2	On: Top Vessel P < 15.6 MPa **AND**
	PZR level > 4.2 *m*
	Off: Top Vessel P > 15.6 MPa **OR**
	PZR level > 4.2 *m*
#3	On: Top Vessel P < 15.3 MPa **AND**
	PZR level > 4.2 *m*
	Off: Top Vessel P > 15.5 MPa **OR**
	PZR level > 4.2 *m*
#4	On: Top Vessel P < 15.3 MPa **AND**
	PZR level > 4.2 *m*
	Off: Top Vessel P > 15.5 MPa **OR**
	PZR level > 4.2 *m*
SPRAY	
#1	Open: TOP PZR > 16.27 MPa
	Close: TOP PZR < 15.97 MPa
#2	Open: TOP PZR > 16.46 MPa
	Close: TOP PZR < 16.17 MPa
SV	
#1 - #2	Open: TOP PZR > 18.62 MPa
	Close: TOP PZR < 17.84 MPa
#3	Open: TOP PZR > 18.13 MPa
	Close: TOP PZR < 17.25 MPa
ECCS	
LPIS	
$T^{sat}_{HL}\quad T_{HL} < 10$ K	**AND**
$P_{RCS} < 2.55$ MPa	
HPIS	
$T^{sat}_{HL}\quad T_{HL} < 10$ K	**AND**
$P_{RCS} < 10.7$ MPa	
HA-2	
$P_{RCS} < 1.5$ MPa	
EBIS	
User time-value	
CVCS	
$T^{sat}_{HL}\quad T_{HL} < 10$ K	

- Steam header: containing steam dump valves to the condenser (BRU-K), steam dump valves to the atmosphere (BRU-SN) and the turbine connection.
- The model also includes the Emergency Boron Injection System (EBIS), the Control Volume and Chemical System (CVCS) (comprising the Make-up and the Let-down with a mass flow rate of 8.19 kg/s), the Main Feed Water (MFW) and the Emergency Feed Water (EFW).

Table 7
System actuation signals II.

TURBINE TRIP	
Tsat T HLs < 10∘C	**OR**
HLs Liq. Temp > 599.15 K	**OR**
User time-value	**OR**
PZR level < 4 *m*	**OR**
Top vessel P > 17.65 MPa	**OR**
HL4 P < 14.71 MPa	**OR**
SG4 level > 2.65 *m*	**OR**
STEAM-HEADER P < 5.098 MPa	
MFW	
$T^{sat}_{HL}\quad T_{HL} < 10$ K	**OR**
$T_{HL} > 599.15$ K	**OR**
PZR level < 4 *m*	**OR**
$P_{top\_vessel} > 17.65$ MPa	**OR**
$P_{HL} < 14.71$ MPa	
EFW	
$\Delta SG_{\mathrm{level}} <\quad 0.75\ m$	
SL	
BRU-A	
Open: $P_{SL} > 7.25$ MPa	
Close: $P_{SL} < 6.27$ MPa	
SV-DUMP	
#1	Open: $P_{SL} > 8.23$ MPa
	Close: $P_{SL} < 6.86$ MPa
#2	Open: $P_{SL} > 8.43$ MPa
	Close: $P_{SL} < 6.86$ MPa
BZOK	
Open: User time-value	
Close: $P_{SL} < 4.69$ MPa	
Steam Header	
BRU-K	
Open: PSL > 6.667 MPa	
Close: PSL < 5.786 MPa	
BRU-SN	
Open: ΔT (HL4)/dt > -30 K/h **AND** BRU-SN Mass Flow < 37 kg/s	
Close: BRU-SN Mass Flow > 80 kg/s	

The ECCS consists of two active systems, the High Pressure Injection System (HPIS) and the LPIS, and two PSSs, the HA-1 and the HA-2, see Fig. 4. The following is a description of each of them.

- HPIS and LPIS: These active safety systems are modelled with boundary conditions, whose injection curves are shown in Fig. 5. The triggering of the actuation signal of both the LPIS and the HPIS requires two conditions to be met; the first is that the subcooling margin falls below 10 K and the second is that the RPV head pressure is less than 10.78 MPa for the HPIS and 2.55 MPa for the LPIS.
- HA-1: The HA-1 are modelled with special PIPEs divided into 6 cells of 10 m^3 each, of which 5 are full of water and 1 of nitrogen. They are isolated from the RCS with check valves. This system is also equipped with valves that close when the level in the HA-1 is below 1.2 m. They are connected to the RCS by means of the HA-1 injection lines, two of which are attached to the RPV UP and the other two to the RPV DC.
- HA-2: Each of the four HA-2 PSS trains, consisting in two 120 m^3 tanks with a boron concentration of 16 g/kg, have been modelled with boundary conditions. The four injection stages selected are that of (ROSATOM, 2022), see Fig. 6. The HA-2 actuation signal includes a 100 s delay after the RCS pressure is below 1.5 MPa.

In addition to the LPIS, the HPIS and the HA-2 PSS actuation signals, see Fig. 7, the TH model for the TRACEV5P5 code includes the actuation signals for the following safety systems: the BRU-A valves, the safety valves and the BZOK main isolation valves of the SL, the BRU-K steam discharge valves to the condenser and BRU-SN steam dump valves to the atmosphere, the PZR heaters, spray and safety valves, the EBIS and the

Table 8
Steady State parameters of the VVER-1000 TRACEV5P5 model.

Parameter	Reference NPP (Kolev et al., 2006)	TRACEV5P5	Error (%)
Core power (MW)	3010	3010	0.00
Lower plenum pressure (MPa)	15.84	15.86	0.12
Core outlet pressure (MPa)	15.70	15.74	0.25
PZR level (m)	8.70	8.71	0.11
CLs temperature (K)	560.85	560.96	0.01
HLs temperature (K)	591.55	591.13	0.07
Average loop mass flowrate (kg/s)	4456.00	4457.21	0.02
SG outlet pressure (MPa)	6.27	6.27	0.00
MFW mass flowrate (kg/s)	409.00	408.09	0.22
MFW temperature (K)	493	493	0.00
SG level (m)	2.50	2.50	0.00

Table 9
HA-2 inyection flow rates for different availability configurations.

	Stage 1	Stage 2	Stage 3	Stage 4
Period of time (s)	100 – 4000	4001 – 10,000	10,001 – 30,000	30,001 – 86,400
Total Mass Flow (kg/s) 4 out of 4 trains	40	20	13.2	7.12
Total Mass Flow (kg/s) 3 out of 4 trains	30	15	9.9	5.34
Total Mass Flow (kg/s) 2 out of 4 trains	20	10	6.6	3.56

HA-1 isolation valves. Moreover, the SCRAM, the RCP trip, the turbine trip, the MFW pump trip and the EFW pump start up signals have also been modelled. A summary of the actuation signal is included in Tables 6 and 7. Furthermore, the model contains the following system controls: the PZR level control, the PZR pressure control and the SGs level control.

This model has been validated in steady state conditions against data from a VVER-1000/V320 NPP. The values obtained with the TRACEV5P5 model are very close to the reference plant data, see Table 8.

4. Impact of the HA-2 system in LOCA along with SBO sequences

The Design Basis Accident (DBA) for which the HA-2 PSS has been mainly designed is the LOCA along with SBO (Asmolov et al., 2017; Turkish Atomic Energy Authority, 2018). According to (ROSATOM, 2022), the HA-2 PSS, with the availability of 3 out of 4 trains, and the operation of the PHRS are able to avoid the Core Damage (CD) during 24 h, furthermore reference, (Agrawal et al., 2006), reports that the HA-2 PSS has the capacity to remove all the decay heat with the availability of 3 out of 4 trains for 8 h without the PHRS operation.

Considering this information, this section focuses on the analysis concerning the impact of the HA-2 PSS in LOCA sequences along with SBO for a VVER-1000 reactor. First an analytical study, verified later by TH simulations, is carried out to evaluate the HA-2 PSS capability to remove the decay heat over 24 h. The HA-1 SC to ensure core cooling during the initial phase of the accidental sequence are then analysed.

4.1. Analysis of the HA-2 capacity to perform its safety function

In order to verify the ability of the HA-2 PSS to perform its long-term safety function, once the HA-1 inventory has discharged and it is the only ECCS available, the maximum theoretical energy that the system would be able to remove has been calculated for the Double Ended Guillotine Break (DEGB) LBLOCA along with SBO sequence, since it is the most limiting break size. The calculation has been performed considering the complete vaporization of the HA-2 mass flow rate, i.e.G, for 2 out of 4 trains, 3 out of 4 trains and 4 out of 4 trains available.

$$Q_{vap} = G(h_{out} - h_{in}) = G(h_{v,out}^{sat} - h_{l,in})$$

Since the objective is to know the maximum capacity of the system to remove heat, the enthalpy of the water in HA-2 ($h_{l,in} = 1.26\mathrm{E}+05$ J/kg) has been selected assuming that the tanks are at environmental temperature (303.15 K) while the steam coming out of the break has been considered to be saturated at atmospheric pressure ($h_{v,out}^{sat} = 2.68\mathrm{E}+06$ J/kg). The HA-2 mass flow rate for each of the four stages has been established according to the available trains, see Table 9. The analytical calculations, see Fig. 8, show that:

- If 2 out of 4 trains are considered, the HA-2 PSS alone cannot remove the decay heat from the last three stages.

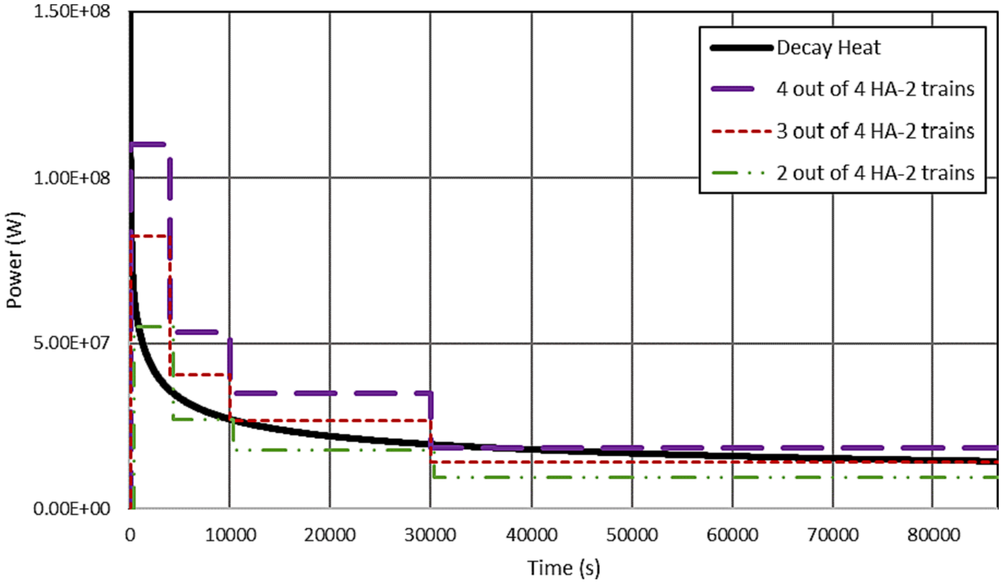


Fig. 8. Maximum heat removal capacity of the HA-2 system vs decay heat in a DEGB LOCA along with SBO sequence.

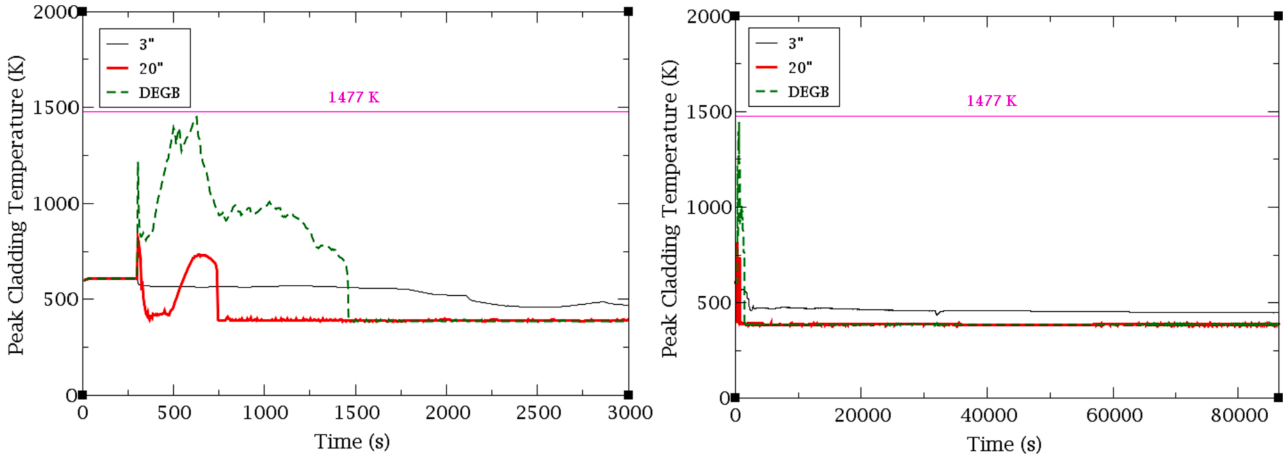


Fig. 9. PCT (short and long term) for different break sizes in LOCA + SBO scenario (4 out of 4 HA-2 trains).

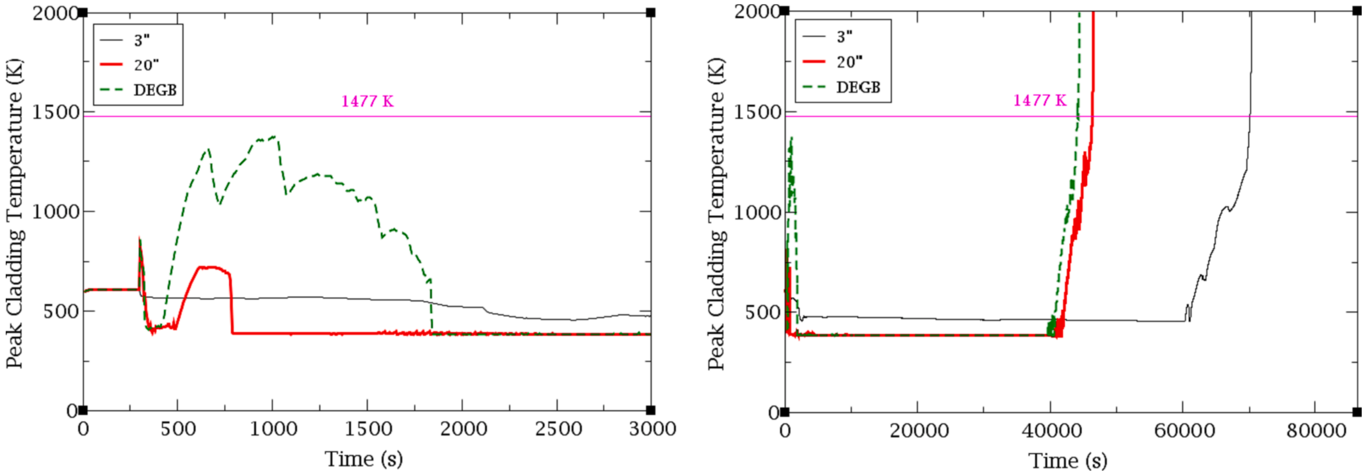


Fig. 10. PCT (short and long term) for different break sizes in LOCA + SBO scenario (3 out of 4 HA-2 trains).

- If 3 of the 4 trains are considered, the HA-2 PSS alone is only enough to cool the reactor during the first three injection stages, i.e. 8 h. Which agrees with (Agrawal et al., 2006).
- If 4 out of 4 trains are considered, it is enough to cool the core during the four stages (24 h) since the decay heat power is lower than the power removed by the four trains in all of them. Therefore, the actuation of the PHRS is not needed in this case.

It is important to notice that a positive energy balance, between the energy that the HA-2 is able to remove and the energy released in the core, is only a necessary condition but not a sufficient condition for the success of the sequence, since other phenomena such as RCS inventory distribution must be considered, and then TH simulations are needed in order to verify these conclusions. Therefore, a large number of LOCA diameters along with SBO sequences have been simulated with the VVER-1000/V320 TH model for TRACEV5P5 code. The simulations have been performed considering the full availability of the HA-1, for both cases assuming the operation of 3 out of 4 trains and 4 out of 4 trains of the HA-2 PSS.

The simulation results agree with those obtained analytically and with (Agrawal et al., 2006), showing that the performance of the HA-2 PSS with four trains is enough to maintain core cooling with the Peak Cladding Temperature (PCT) below 1477 K for 24 h, see Fig. 9, and that if 3 out of 4 trains are available, the core cooling is assured only for the first 8 h, see Fig. 10.

The evolution of the events for the DEGB and 3 in. LOCA along with

Table 10
DEGB and 3 in. LOCA along with SBO sequence evolution (3 out of 4 and 4 out of 4 HA-2 configuration).

Event	3 in. 3 out of 4 HA-2/ 4 out of 4 HA-2 (s)	DEGB 3 out of 4 HA-2/ 4 out of 4 HA-2 (s)
DEGB LBLOCA along with SBO (SCRAM, MFW pumps and RCPs trip, TT, loss of the condenser, CVCS off)	0	0
Control rods fully inserted	5	4
HA-1 injection begins	1470	10
HA-2 injection set-point (RCS Pressure < 1.5 MPa)	1935	25
First stage HA-2 injection (RCS Pressure < 1.5 MPa + delay)	2035	125
HA-1 injection ends	2250/ 2295	75
Second stage HA-2 injection begins	5935	4025
Third stage HA-2 injection begins	11,935	10,325
Fourth stage HA-2 injection begins	31,939	30,325
PCT > 1477 K	69803/ Not reached	43867/ Not reached
HA-2 injection ends (Time HA-2 starts to operate + 24 h)	CD before HA-2 injection ends / 88,335	CD before HA-2 injection ends/ 86,525

Table 11
Time HA-2 start operating, Time PCT 1477 K and Time margin (LOCA along with SBO sequences).

LOCA size (inches)	Time HA-2 can start injecting (s)	Time PCT = 1477 K (s)	Time margin (s)
2	8705	5361	Not available (<0)
3	5847	7088	1241
4	1375	5661	4286
6	650	2640	1990
8	405	2245	1840
12	230	1610	1380
20	150	705	555
25	135	245	210
30	126	196	70
DEGB (47)	120	190	70

SBO sequence is shown in Table 10 (for both 3 out of 4 HA-2 and 4 out of 4 HA-2 configurations). The onset of injection for both HA-1 and HA-2 PSS is earlier for the DEGB LOCA than for the 3 in. LOCA, because the depressurization of the RCS in 3 in. LOCA is slower. However, for both break sizes with the 4 out of 4 HA-2 PSS configuration, the PCT does not exceed 1477 K, while with 3 out of 4 HA-2 it does, being about 25000 s earlier for the DEGB LOCA. Finally, it can be observed that for the successful sequences, the HA-2 fourth injection stage ends 24 h after its start.

It is worth noting that in the simulations there are no effective interactions found between the HA-1 and the HA-2 systems, i.e. there is no mass flow rate HA-1 reduction because HA-2 injection. For medium break sizes (less than 6 in.) there is a short period when both systems are injecting simultaneously but there is no reduction in the HA-1 mass flow rate. For larger break sizes (more than 6 in.) the HA-1 are isolated before the HA-2 injection, see rows 6 and 7 in Table 10. The reason for this is that the HA-1 injects until its isolation valves close, when the HA-1 pressure reaches almost 0.8 MPa, and the HA-2 begins injection between 0.78 and 0.3 MPa (for 6 in. onwards), due to the delay in the HA-2 actuation signal. As a result, both systems do not overlap.

4.2. PSA level 1 HA-1 success criteria with HA-2 fully available

In the previous subsection, analytical calculations and TH simulations lead to the conclusion, that the full availability of the HA-2 PSS is necessary to ensure the core cooling for 24 h in LOCA along with SBO sequence, where the only available ECCS are the HA-1 and the HA-2 and there are no human actions. In the present subsection, the HA-1 SC in these sequences has been examined. This analysis has been done in two steps:

- The break size range for which the HA-2 performance is guaranteed prior to reaching CD has been searched.
- The minimum HA-1 configuration to prevent the second core peak temperature of the LOCA sequence from exceeding 1477 K has been found for the range of break sizes previously obtained.

As mentioned in the introduction, the HA-2 set point is 1.5 MPa, lower than the pressure set point of the LPIS (2.55 MPa), which means that to come into operation it will need that the pressure in the RCS dropped considerably. Therefore, HA-2 starts injecting straight away without the need of another safety system actuation in the case of MB/LBLOCAs, however in the case of a Small Break Loss of Coolant Accident (SBLOCA), a previous depressurization of the RCS is necessary since the pressure remains stagnant well above 1.5 MPa making it impossible for HA-2 PSS to start operating on time.

Therefore, a wide range (from 2 in. to DEGB) of the LOCA along with SBO sequences, without the actuation of the HA-2 PSS, has been simulated in order to know from what break size the RCS pressure would allow the injection of HA-2 before the CD has been reached, without considering any depressurization action. The results show that from 3 in. break onwards the HA-2 is able to inject water before the CD occurs, see Table 11.

Next, a sensitivity analysis has been performed, by simulating the LOCA along with SBO sequence with the HA-2 full availability from 3 in. to DEGB, to find out the HA-1 SC, see Figs. 11 and 12. The results show that the HA-1 SC to 3 in. is 2 out of 4 trains, for larger MBLOCA breaks it relaxes, becoming unnecessary the HA-1 injection from 6 to 8 in., however for LBLOCA the minimum HA-1 configuration increases again, becoming even 4 out of 4 from 30 in. onwards, see Fig. 13.

5. HA-2 impact in MB/LBLOCA success criteria

After the study of the impact of the HA-2 PSS in LOCA along with SBO sequences, the focus is now on the analyse how the ECCS SC in MB/

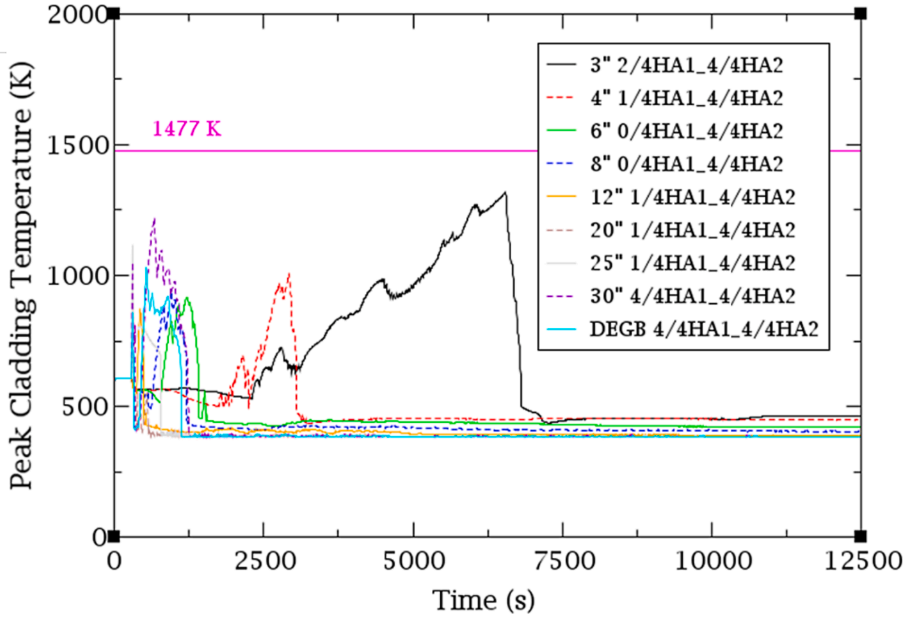


Fig. 11. MB/LBLOCA along with SBO PCT with the minimum HA-1 configuration required (HA-2 system fully available).

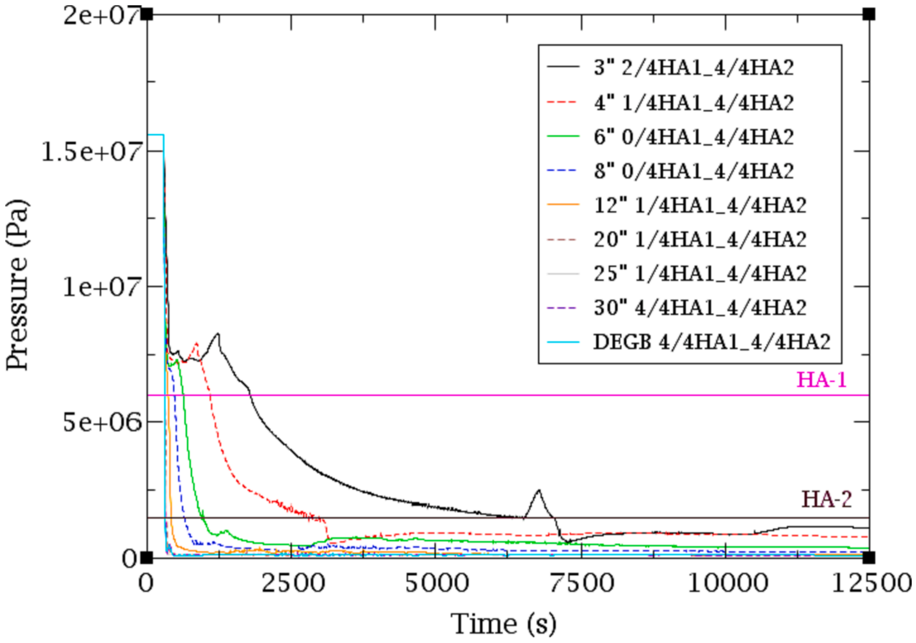


Fig. 12. MB/LBLOCA along with SBO RCS pressure with the minimum HA-1 configuration required (HA-2 system fully available).

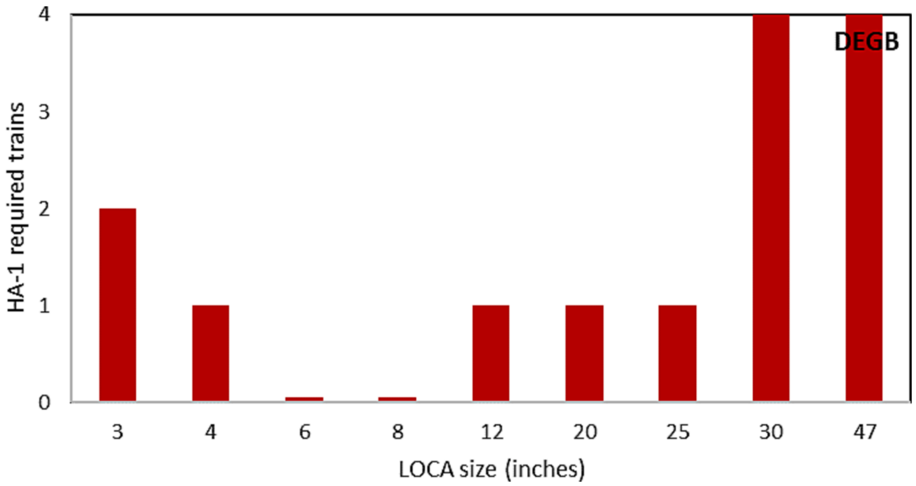


Fig. 13. Number of HA-1 trains required to avoid core damage in LOCA along with SBO sequences with the HA-2 system performance.

LBLOCA sequences, without SBO, can be relaxed if the performance of the HA-2 system is considered. The SC analysis is performed into two steps. First the SC without considering HA-2 are presented (section 5.1), then the new SC considering HA-2 actuation are obtained (section 5.2).

Above all, it should be mentioned that in this analysis, a sequence is defined by concatenating the letter that identifies its headers written in upper or lower case so, if it is uppercase it represents success while if it is in lower case it represents failure of the system. *A* or *a* represent the HA-1, *H* or *h* represent the HPIS and *L* or *l* represent the LPIS. In addition, the number of operating trains out of the total is written before the letter if the system is available. For instance, the sequence “1/3H-a-l” denotes a sequence in which one HPIS train is available and the HA-1 and the LPIS systems have failed.

5.1. *MB/LBLOCA success criteria without considering HA-2*

In a previous work, (Redondo-Valero et al., 2023), a verification of the SC of event trees for MB/LBLOCA sequences described in (Skalozubov et al., 2010) was carried out. A large number of simulations were then performed to analyse all possible ECCS configurations that allow avoiding CD for break sizes from 2 in. to DEGB, see Table 12.

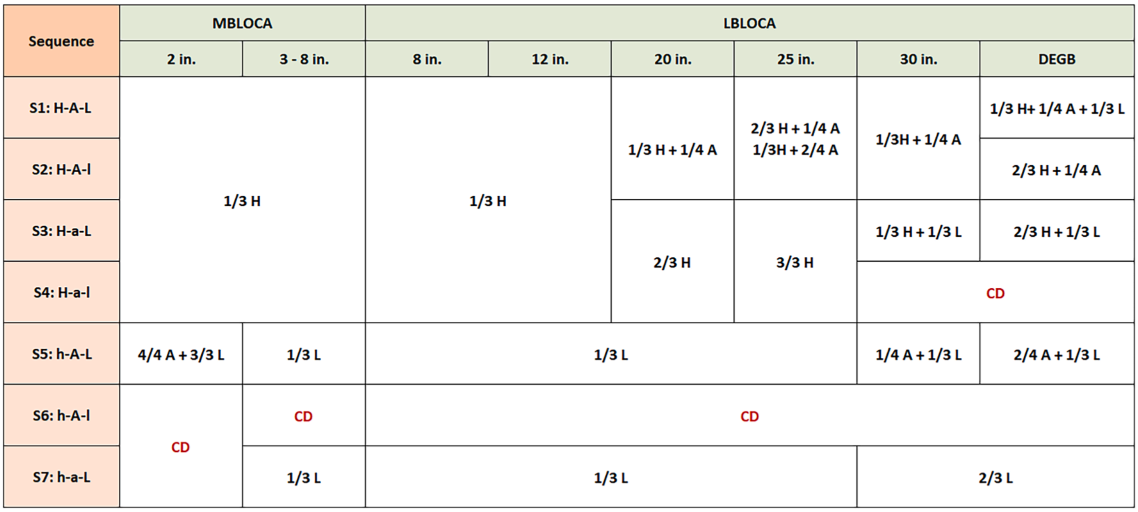
As shown in Table 12, 1 out of 3 HPIS trains is enough for success over the entire MBLOCA range. However, 1 out of 3 LPIS trains is enough to succeed only between 3 and 8 in., with all the HA-1 and the LPIS trains needed for 2 in.. In the LBLOCA range it is remarkable that from 8 to 12 in., the availability of 1 out of 3 HPIS or LPIS trains is enough for success. However, as the size of the break increases, the need for more than one ECCS trains or even the joint performance of trains from different ECCSs becomes necessary.

5.2. *MB/LBLOCA success criteria considering HA-2 actuation*

In order to simplify this analysis, it has been reviewed in which sequences the actuation of the HA-2 PSS allows to relax the SC for any of the other ECCSs. Therefore, only those sequences in Table 12 that require more than one train of the LPIS, HPIS or/and HA-1 have been selected, see second column of the Table 13.

Having identified the sequences that have the potential to relax some

Table 12
MBLOCA and LBLOCA success criteria with standard ECCS.



Sequence	MBLOCA		LBLOCA					
	2 in.	3 - 8 in.	8 in.	12 in.	20 in.	25 in.	30 in.	DEGB
S1: H-A-L	1/3 H		1/3 H		1/3 H + 1/4 A	2/3 H + 1/4 A 1/3H + 2/4 A	1/3H + 1/4 A	1/3 H+ 1/4 A + 1/3 L
S2: H-A-l								2/3 H + 1/4 A
S3: H-a-L					2/3 H	3/3 H	1/3 H + 1/3 L	2/3 H + 1/3 L
S4: H-a-l							CD	
S5: h-A-L	4/4 A + 3/3 L	1/3 L	1/3 L				1/4 A + 1/3 L	2/4 A + 1/3 L
S6: h-A-l	CD	CD	CD					
S7: h-a-L		1/3 L	1/3 L				2/3 L	

Table 13
Time HA-2 start operating, time PCT 1477 K and time margin (LOCA sequences).

LOCA size (inches)	Sequence	*Time HA-2 start operating (s)*	*Time PCT = 1477 K (s)*	*Time margin (s)*
2	h-4/4A-2/3L	~ 15,000	10,368	Not available (<0)
	h-3/4A-3/3L	~ 13,000	7176	Not available (<0)
20	1/3H-a-l	490	495	5
25	2/3H-a-l	435	430	Not available (<0)
	1/3H-1/4A-l	445	465	10
30	3/3H-a-l	426	405	Not available (<0)
	h-a-1/3L	426	427	1 (not enough time)
DEGB (47)	3/3H-a-l	421	389	Not available (<0)
	1/3H-1/4A-l	420	459	39
	1/3H-a-1/3L	421	403	Not available (<0)
	h-1/4A-1/3L	462	470	8
	h-a-1/3L	434	435	1 (not enough time)

SC, the time at which the HA-2 set point is reached, i.e. 100 s after the RCS pressure drops below 1.5 MPa, was obtained. The time margin to avoid CD was then calculated by subtracting the HA-2 start operating time from the time at which the PCT exceeded 1477 K, see Table 13.

Following this analysis, it has been obtained that the sequences in which HA-2 PSS can avoid CD are 20 in. LBLOCA (1/3H-a-l), 25 in. LBLOCA (1/3H-1/4A-l), DEGB LBLOCA (1/3H-1/4A-l) and DEGB LBLOCA (h-1/4A-1/3L). Two sequences have been identified where the HA-2 actuation begins only 1 second before CD is reached. Therefore, it is considered that in them the HA-2 PSS would not actuate in time to prevent the core temperature from exceeding 1477 K, these sequences are 30 in. LBLOCA (h-a-1/3L) and DEGB LBLOCA (h-a-1/3L), see fifth column of Table 13.

In order to verify that the four sequences, with the possibility of the HA-2 PSS having an impact on their SC, are successful, they have been simulated with the TH model. The results of the simulations show that three of the four sequences are indeed successful.

- In 25 in. LBLOCA (1/3H-1/4A-l) sequence, it can be observed as the HA-2 system is able to reduce the maximum PCT from 1787 K to 1074, see Fig. 14.
- In DEGB LBLOCA (1/3H-1/4A-l) sequence without the HA-2 actuation the PCT exceeds 1477 K, on the other hand the code stops the simulation when the PCT reaches 2018 K and then the long term evolution cannot be analysed. The actuation of the HA-2 PSS allows to reduce the PCT to a maximum value of 1350 K, see Fig. 15.
- In the DEGB LBLOCA (h-a-1/3L) sequence HA-2 system is able to reduce the PCT from 1594 K to 1149 K see Fig. 16.

As some of the cases have a low time margin of a few seconds, it would be possible to perform a BEPU analysis to confirm the probability of success. However, this quantification time is not a requirement for PSA; hence is not performed in this analysis. On the other hand, increasing the HA-2 PSS set point could potentially allow an earlier injection of the HA-2 PSS and prevent the CD in a few more LOCA sequences. Nevertheless, it appears that this modification could not have a significant impact on the CD frecuency. Consequently, no set point modification is proposed.

Finally, Table 14 shows the final MB/LBLOCA SC when the performace of the HA-2 PSS is considered. In white background are those sequences in which the SC has not been change, i.e. they are the ones in Table 12. In color background (see electronic version) are those in which the SC have changed, in green the new SC in sequences with an active ECCS, either HPIS or LPIS, and in yellow are the SC for the sequences without active ECCS.

6. Conclusions

A large number of TRACE simulations of different LOCA sequences for the VVER-1000 reactor were carried out to study the impact on the accident progression of the Hydroaccumulators (HA-2) for different combination of the availability of the ECCS.

Based on the performed investigations, following conclusions can be drawn:

- The TRACE code is robust for a wide range of VVER LOCAs with various combinations of the availability of safety systems.
- Studies on the AP1000/CAP1400 reactor performed at UPM and the current analyses on the VVER reactors make possible to compare the

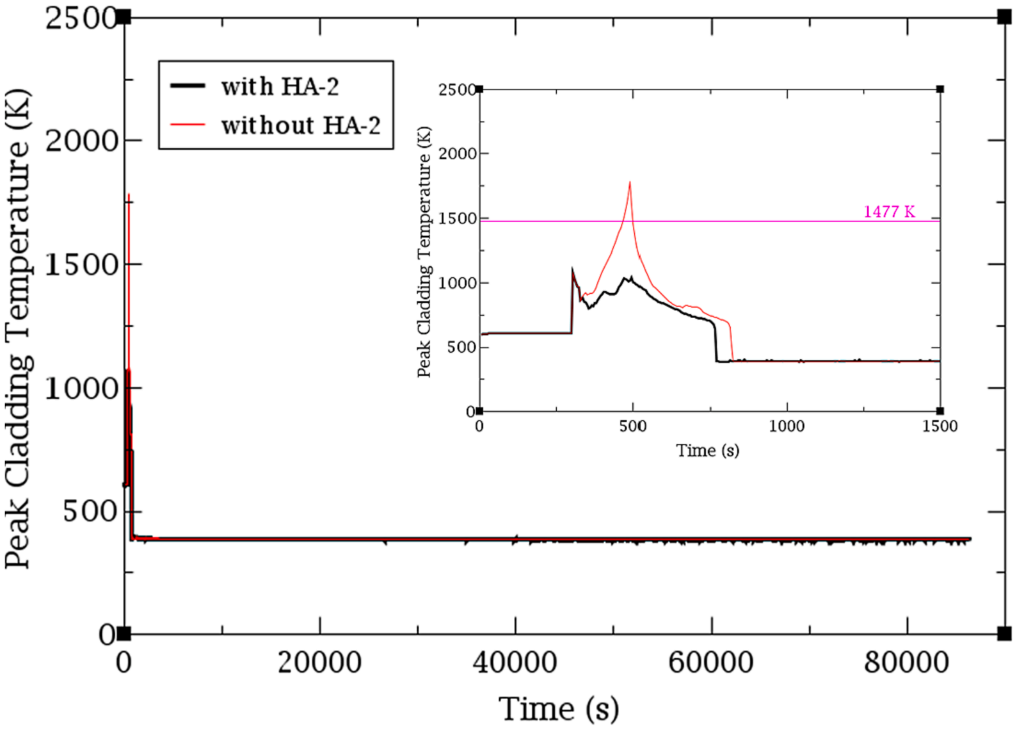


Fig. 14. PCT (25 in. 1/3H-1/4A-l).

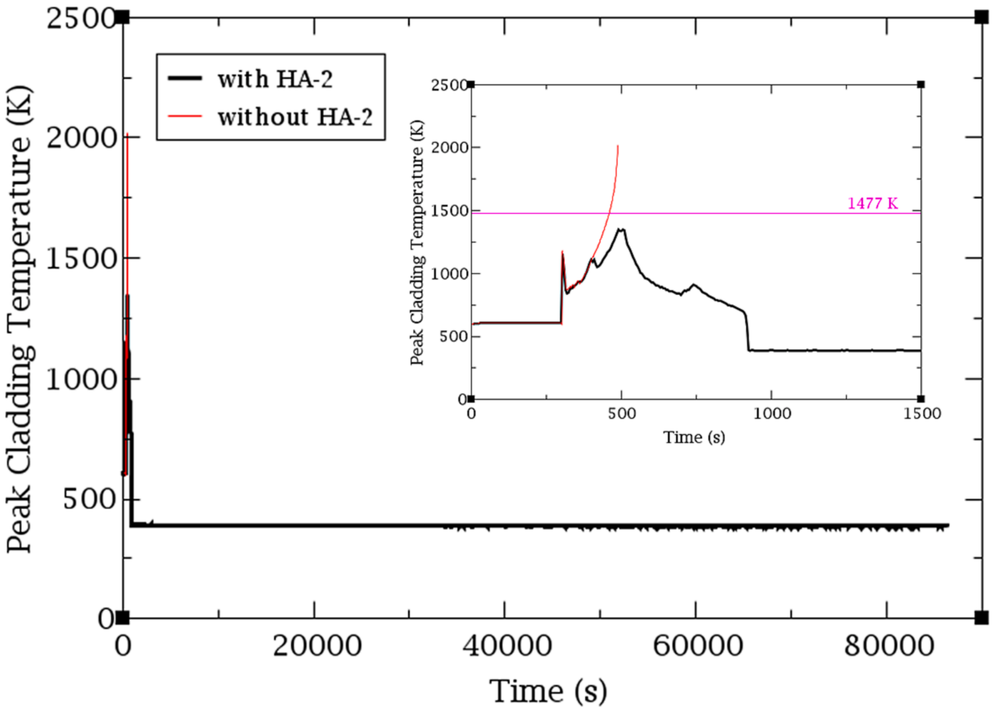


Fig. 15. PCT (DEGB 1/3H-1/4A-l).

impact of passive ECCS of the VVER, i.e. HA-1 and HA-2, and those of the AP1000/CAP1400, i.e. the CMT, ACC and IRWST. In LOCA along with SBO sequences, from 3 in. to DEGB, with the full availability of the HA-1 PSS, 4 out of 4 HA-2 trains are enough to avoid core damage for 24 h without the need for any other safety system.

- In LOCA along with SBO sequences, from 3 in. to DEGB, with the full availability of the HA-1 PSS, 3 out of 4 HA-2 trains are able to cool the core for 8 h, thereafter PHRS intervention or active ECCS recovery would be required.
- The HA-1 success criteria in case of LOCAs ranging from 3 in. to DEGB along with SBO sequences were identified thanks to the systematic studies performed with TRACE assuming full availability of the HA-2 PSS.

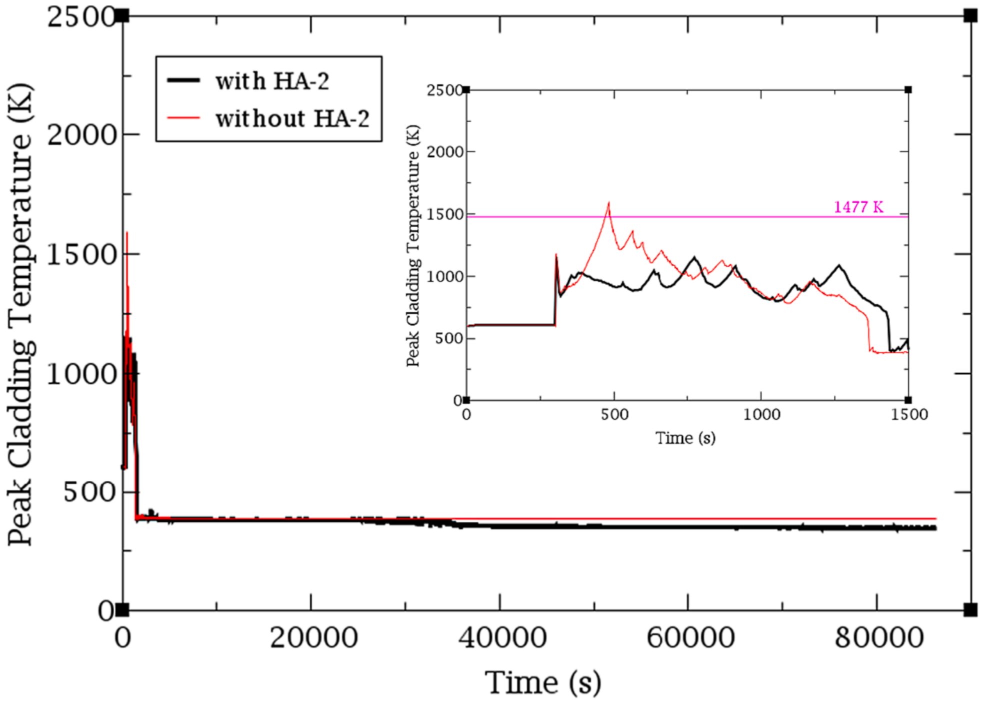


Fig. 16. PCT (DEGB h-1/4A-1/3L).

Table 14
New success criteria for MB/LBLOCA sequences considering the HA-2 system actuacion.

Sequence	MBLOCA					LBLOCA				
	2 in.	3 in.	4 in.	6 in.	8 in.	12 in.	20 in.	25 in.	30 in.	DEGB
S1: H-A-L	1/3 H (607 K)	1/3 H (607 K)	1/3 H (607 K)	1/3 H (607 K)	1/3 H (607 K)	1/3 H (723 K)	1/3 H + 1/4 A (849 K)	1/3 H + 1/4 A (1074 K)	1/3H + 1/4 A (1119 K)	1/3H + 1/4 A (1350 K)
S2: H-A-l										
S3: H-a-L							2/3 H (1266 K)	3/3 H (1309 K)	1/3 H + 1/3 L (1338 K)	2/3 H + 1/3 L (1349 K)
S4: H-a-l									CD (>1477 K)	CD (>1477 K)
S5: h-A-L	4/4 A + 3/3 L (1374 K)	1/3 L (1169 K)	1/3 L (923 K)	1/3 L (656 K)	1/3 L (655 K)	1/3 L (1067 K)	1/3 L (1314 K)	1/3 L (1392 K)	1/4 A + 1/3 L (1169 K)	1/4 A + 1/3 L (1149 K)
S6: h-A-l (24 hours)	CD (>1477 K)	2/4 A (1314 K)	1/4 A (1009 K)	0/4 A (916 K)	0/4 A (939 K)	1/4 A (872 K)	1/4 A (818 K)	1/4 A (1117 K)	4/4 A (1219 K)	4/4 A (1421 K)
S7: h-a-L		1/3 L (1169 K)	1/3 L (923 K)	1/3 L (656 K)	1/3 L (655 K)	1/3 L (1067 K)	1/3 L (1314 K)	1/3 L (1392 K)	2/3 L (1251 K)	2/3 L (1275 K)

- If the actuation of the HA-2 is considered, the TRACE analysis of some MB/LBLOCA sequences have shown that it is possible to relax the combined success criteria of the LPIS, HPIS and HA-1.
- In the sequences analysed, no negative interactions were found between HA-2 and the other injection systems.
- The main uncertainties in this kind of analysis are related to flow resistance and RCS liquid levels. BEPU analyses should be considered if they want to be taken into account.

CRediT authorship contribution statement

Elena Redondo-Valero: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Visualization. **César Queral:** Conceptualization, Methodology, Software, Investigation, Resources, Writing – review & editing, Supervision. **Kevin Fernandez-Cosials:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision. **Víctor Sanchez-Espinoza:** Conceptualization, Methodology, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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