# Management of the SBLOCA sequences with HPIS failure in VVER-1000/V320 reactors; comparison with Westinghouse PWR strategies

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A B S T R A C T

In small break LOCA sequences with failure of the high-pressure safety injection system, the reactor coolant system pressure can stagnate at a high value making the medium and low-pressure safety injection systems unable to inject water into the core before its peak cladding temperature exceeds the safety limit. In this work, a review and comparison of different strategies presented in the Emergency Operating Procedures for managing these sequences in VVER-1000/V320 and Westinghouse PWR has been carried out. For this purpose, the Integrated Safety Assessment methodology, developed by the Spanish Nuclear Safety Council has been applied. The results show that the strategy related to the controlled SGs depressurization at a primary side cooling rate of 60 K/h in VVER-1000/V320 reactors and 55 K/h in Westinghouse PWR provides a wide safety margin. In cases where the Inadequate Core Cooling temperature is reached, the fast SGs depressurization strategy is also effective to avoid the core damage.

Acronyms

| | |
|---|---|
| Accumulators | (ACC) |
| Auxiliary Feedwater | (AFW) |
| Beyond Design Accident Management Guidance | (BDBAMG) |
| Steam Dump Valves to the Atmosphere | (BRU-A) |
| Steam Dump Valves to the Condenser | (BRU-K) |
| Core Damage | (CD) |
| Core Exit Thermocouples | (CET) |
| Critical Safety Functions | (CSF) |
| Nuclear Safety Council | (CSN) |
| Control Volume and Chemical System | (CVCS) |
| Degraded Core Cooling | (DCC) |
| Damage Domain | (DD) |
| Emergency Boron Injection System | (EBIS) |
| Emergency Core Cooling System | (ECCS) |
| Emergency Gas Removal System | (EGRS) |
| Emergency Feed Water | (EFW) |
| Emergency Operating Procedures | (EOPs) |
| Event Tree | (ET) |
| Hydro-Accumulator | (HA) |
| High Head Safety Injection | (HHSI) |
| Hot Leg | (HL) |
| High Pressure Injection System | (HPIS) |
| High Pressure Safety Injection | (HPSI) |
| Inadequate Core Cooling | (ICC) |
| Integrated Safety Assessment | (ISA) |
| Large Break Loss-of-Coolant Accident | (LBLOCA) |
| Low Pressure Injection System | (LPIS) |
| Low Pressure Safety Injection | (LPSI) |
| Medium Break Loss-of-Coolant Accident | (MBLOCA) |
| Main Control Room | (MCR) |
| Main Feed Water | (MFW) |
| Main Steam Isolation Valve | (MSIV/BZOK) |
| Nuclear Power Plant | (NPP) |
| Peak Cladding Temperature | (PCT) |
| Previous Damage | (PD) |
| PROBABILISTIC SAFETY ANALYSIS | (PSA) |
| Pressurized Water Reactor | (PWR) |
| Pressurized Water Reactor Westinghouse | (PWR-W) |
| Pressurizer | (PZR) |
| Reactor Coolant Pump | (RCP) |
| Reactor Coolant System | (RCS) |

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| | |
|---|---|
| Reactor Pressure Vessel | (RPV) |
| Reactor Vessel Level Indicator System | (RVLIS) |
| Refueling Water Storage Tank | (RWST) |
| Small Break Loss-of-Coolant Accident | (SBLOCA) |
| Steam Generator | (SG) |
| Thermal-hydraulic | (TH) |
| Total Loss of Feed Water | (TLFW) |

## 1. Introduction

In a VVER-1000/V320 reactor, if a Medium Break Loss-of-Coolant Accident (MBLOCA) sequence occurs with High Pressure Injection System (HPIS) failure, the Reactor Coolant System (RCS) depressurization is fast enough to allow first the Hydro-Accumulators (HAs) and then the Low-Pressure Injection System (LPIS) to act in time preventing Core Damage (CD). However, in Small Break Loss-of-Coolant Accident (SBLOCA) sequences with HPIS failure, the RCS pressure may stagnate above the HAs pressure, preventing the HAs and LPIS from replenishing the RCS inventory before reaching CD. This behavior can be also observed in Western Pressurized Water Reactor (PWR) designs, such as the Pressurizer Water Reactor-Westinghouse (PWR-W), but the range of break sizes in which it appears depends on several factors. Among the most important are: the thermal power of the core, the total RCS water inventory and the Emergency Core Cooling System (ECCS) designs. These types of sequences are some of the most risk-important design extension condition sequences and it is highly desirable that they be mapped in detail.

Therefore, in SBLOCA sequences with HPIS failure the operators must perform manual actions, following the appropriate Emergency Operating Procedures (EOPs), to cool and depressurize the RCS allowing the injection of the HAs and the LPIS. The EOPs provide guidance to the operator to bring the plant to a safe and stable condition in the event of this accidental sequence.

The UPM group has developed experience in reviewing and improving EOPs, determining available times for Main Control Room (MCR) crew management actions and verifying the Event Tree (ET) for different accidental sequences. The Integrated Safety Assessment (ISA) methodology, developed by the Spanish Nuclear Safety Council (CSN), has been extensively applied to these approaches at PWR-W and AP-1000 PWR, see (González-Cadelo et al., 2014, 2013, 2012; Ibánez et al., 2016; Mendizábal et al., 2024; Javier Montero-Mayorga et al., 2014; J. Montero-Mayorga et al., 2014; Queral et al., 2010; 2018, 2017, 2011). In addition, the ISA methodology has recently been applied to the analysis of the success criteria in MBLOCA and LBLOCA sequences in VVER-1000/V320 reactors with the aim of providing a new proposal for the ETs included in the Probabilistic Safety Analysis (PSA) level 1, see (Elena Redondo-Valero et al., 2023).

In the present paper, the ISA methodology has been applied to study different operator actions for managing SBLOCA sequences with HPIS failure in VVER-1000/V320 and 3 loops PWR-W. The Previous Damage (PD) curve and the different Damage Domains (DD) of the possible manual actions or strategies have been obtained by using the ISA methodology.

The paper is structured as follows: Section 2 reviews the management strategies related to the SBLOCA sequence in VVER-1000/V320 and PWR-W 3 loops. Section 3 describes the VVER-1000/V320 TH model used in this analysis. Subsequently, the SBLOCA sequences with HPIS failure without human actions and considering three different strategies in VVER-1000/V320 reactors are analyzed in Sections 4 to 7. This is followed by a comparison of the previously discussed manual actions in Section 8. Afterwards, in Section 9, the SBLOCA with HPIS failure in 3 loops PWR-W is analyzed and the results are compared with those of the VVER-1000/V320 reactors in Section 10. Finally, conclusions are drawn in Section 11.

## 2. Strategies related to SBLOCA sequences with HPIS failure in VVER-1000/V320 and Westinghouse PWR

This section discusses the different strategies for managing SBLOCA with HPIS failure sequences in VVER-1000/V320 and 3 loops PWR-W. A review of the literature on EOPs, ET related to SBLOCA sequences, and experimental tests has been performed to provide a global overview.

It is important to note that, although both reactor designs have similar thermal power, ~3000 $MW_{th}$, there are differences in the liquid volumes in both the RCS and Steam Generators (SG), see Table 1, and also in their ECCSs characteristics, see Table 2. The ECCSs are labelled differently in the VVER-1000/V320 and in the 3 loops PWR-W; the high-pressure system is named HPIS in the VVER-1000/V320 and High-Pressure Safety Injection (HPSI) or High-Head Safety Injection (HHSI) in the 3 loops PWR-W. The low-pressure system is named LPIS in the VVER-1000/V320 and Low-Pressure Safety Injection (LPSI) in the 3 loops PWR-W. The Hydro-Accumulators are named HA in the VVER-1000/V320 and Accumulators (ACC) in the PWR-W.

### *2.1. Management of Westinghouse PWR SBLOCA sequences with HPIS failure*

In the PWR-W, the EOPs aim to provide symptom-based recovery strategies to guide the MCR crew in the management of accident scenarios (Westinghouse owners group, 1983). They are divided into two different groups: The Optimal Recovery Guidelines (ORGs) and the Function Restoration Guidelines (FRGs), see Fig. 1. In an SBLOCA with HPSI failure sequence, the EOPs involved are as follows:

- When a reactor SCRAM occurs, the MCR crew begins to follow the ORG, specifically the EOP E 0 "reactor trip or safety injection". In EOP E 0, the RCS integrity is checked. If it is not preserved, there is a transition to EOP E 1 "loss of reactor or secondary coolant". Following the EOP E 1, the operator checks the RCS pressure. If it is higher than 1.5 MPa, there is a transition to the EOP ES-1.2 "post LOCA cooling and depressurization". The action indicated in EOP ES-1.2 to depressurize and cool the RCS is the controlled depressurization of the SGs at a cooling rate of 55 K/h through the SGs (TECNATOM, 1999), see Fig. 2.
- From the EOP E 0, the Critical Safety Functions (CSF) start to be monitored. There are six CSF status trees: F.0.1 "subcriticality", F.0.2 "core cooling", F.0.3 "heat sink", F.0.4 "RCS integrity", F.0.5 "containment integrity", F.0.6 "RCS coolant inventory", see (EPRI, 2011). The following criteria are used to determine the degree of threat for the CSF status tree: satisfied (green), not satisfied (yellow), severe challenge (orange) and extreme challenge (red). In those cases, where the status of the CSF status tree becomes severe challenge or extreme challenge, there is a transfer from the ORGs to the corresponding FRGs. In SBLOCA with HPSI failure sequences, the F.0.2 status tree plays an important role. Three FRGs can be distinguished in the F.0.2 status tree (EPRI, 2011), see Fig. 3:
  - o The EOP FR-C.3: Response to saturated core cooling (yellow).
  - o The EOP FR-C.2: Response to Degraded Core Cooling (DCC) (orange).
  - o The EOP FR-C.1: Response to Inadequate Core Cooling (ICC) (red).

The DCC condition is reached when the temperature of the Core Exit Thermocouples (CET) exceeds 376 °C (649 K), see (Eisenhut, 1982; IEEE, 2002; Lutz, 2004; NRC, 2006, 1983). If this occurs, the FR-C.2

**Table 1**
VVER-1000/V320 and Westinghouse PWR approximate liquid volumes.

| Reactor | VVER-1000/V320 | 3 loops PWR-W |
|---|---|---|
| RCS ($m^3$) | 340 | 260 |
| SGs ($m^3$) | 220 | 160 |

**Table 2**
VVER-1000/V320 and Westinghouse PWR medium and low pressure ECCS parameters.

| Parameters | | VVER-1000/ V320 | 3 loops PWR-W |
|---|---|---|---|
| HA/ACC | Nº of trains | 4 | 3 |
| | Volume ($m^3$) | 60 (x4) | 41 (x3) |
| | Liquid Volume ($m^3$) | 50 (x4) | 36 (x3) |
| | Discharge pressure (MPa) | 6 | 4.4 |
| LPIS/ LPSI | Nº of trains | 3 | 2 |
| | Shutoff head (MPa) | 2.5 | 1.5 |
| | Max mass flow rate per pump (kg/s) | 210 | 410 |

indicates that the SGs have to be depressurized at an RCS cooling rate of 55 K/h, similar to EOP ES-1.2. However, if the ICC condition is reached, i.e., the CET exceeds 650 °C (923 K), the EOP FR-C.1 indicates that the RCS shall be cooled through the SGs at the maximum RCS cooling rate (full opening of secondary side relief valves). It should be noted that there are F.0.2 status trees that consider the Reactor Vessel Level Indicator System (RVLIS) and the number of Reactor Coolant Pumps (RCP) running in addition to the CET temperature, to indicate which FRG must be followed FR-C.1, FR-C.2 or FR-C.3, see (EPRI, 2011; Javier Montero-Mayorga et al., 2014).

To understand the management of the SBLOCA sequence in the 3 loops PWR-W in case of HPSI failure, it is also useful to study the SBLOCA ET in addition to the EOPs, see Fig. 4. The SBLOCA ET indicates that in case of HPSI failure, to reach a successful end state, the success of the following headers is required, see red path (sequence 10) in Fig. 4:

- [S] SCRAM
- [AF] Auxiliary Feedwater (AFW).
- [D] RCS cooling and depressurization via the SGs.
- [A] Effective injection of the ACCs.
- [A-IS] Manual ACCs isolation or venting in order to avoid $N_2$ injection in the RCS.
- [L] LPSI, in its two actuation modes, first the injection from the Refueling Water Storage Tank (RWST) and
- [LR] the recirculation from the containment sump.

In most of the PSA of the PWR-W, the ETs header "RCS cooling via the SGs" considers the controlled SGs depressurization (ES-1.2 or FR C.2). However, some of them consider the fast SGs depressurization at the maximum RCS cooling rate (FR C.1). In summary, the main management strategies of SBLOCA with HPSI failure sequences in the PWR-W are:

- Controlled SGs depressurization through the relief valves in the steam lines at an RCS cooling rate of 55 K/h (in ES-1.2 or FR-C.2).
- Fast SGs depressurization through full opening of the relief valves in the steam lines when the ICC condition is reached, i.e., when CET temperature exceeds 650 °C (923 K) (in FR C.1).

### 2.2. Management of VVER-1000/V320 SBLOCA sequences with HPIS failure

In the late 1990s, a significant number of VVER Nuclear Power Plants (NPP) decided to change their accident management approach, see (Bánáti and Ézsol, 1997; Cherubini et al., 2008; Groudev and Hadjiev, 2001; Pavlova et al., 2007, 2008). Most of the VVER-1000/V320 NPP adopted the Westinghouse EOPs-like approach, see (Bica, 1999; IAEA, 2000; Linn et al., 2002; United States General Accounting Office, 1996) and Fig. 1. In some VVER-1000/V320 NPP, the equivalent of the PWR-W ORGs was referred to as the Accident Termination Guidelines (ATG), while the equivalent of the PWR-W FRGs were referred to as the Beyond Design Accident Management Guidance (BDBAMG), see (European commission EuropeAid Co-operation Office, 2006; Mullner, 2010). Besides, it is important to note that there is almost no public information on the EOPs of the VVER-1000/V320 reactors.

In an SBLOCA with HPIS failure sequence, before reaching ICC conditions, the management strategy carried out in VVER-1000/V320 reactors is to depressurize the SGs at a controlled RCS cooling rate. References were found indicating that the depressurization of the SGs is performed at an RCS cooling rate of 30 K/h or 60 K/h, see (Iegan et al., 2018; Mullner, 2010; Skalozubov et al., 2010). When the ICC condition

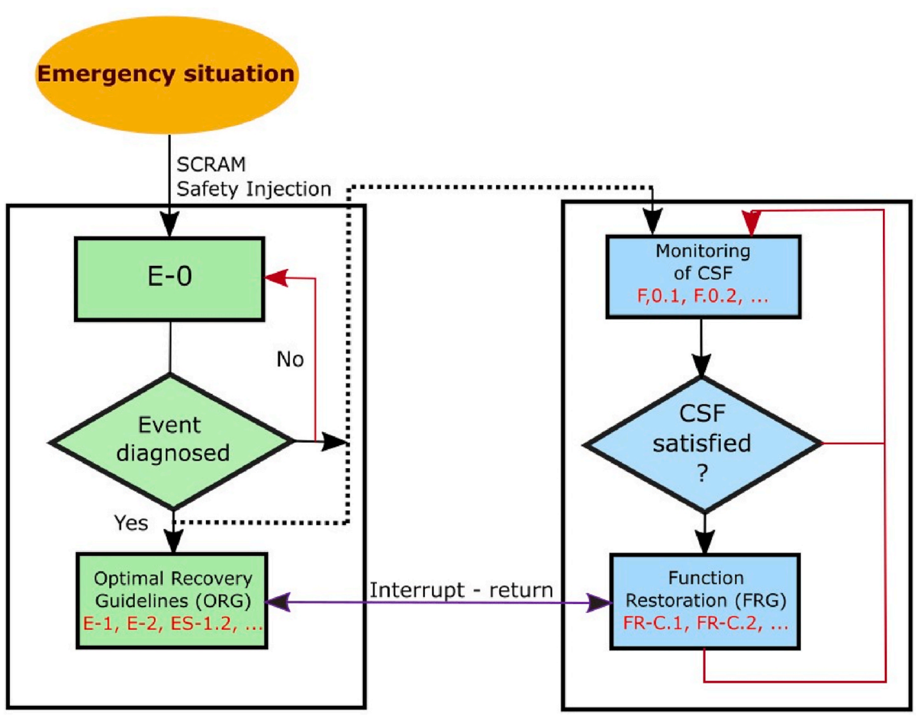


**Fig. 1.** Emergency Operating Procedures scheme.

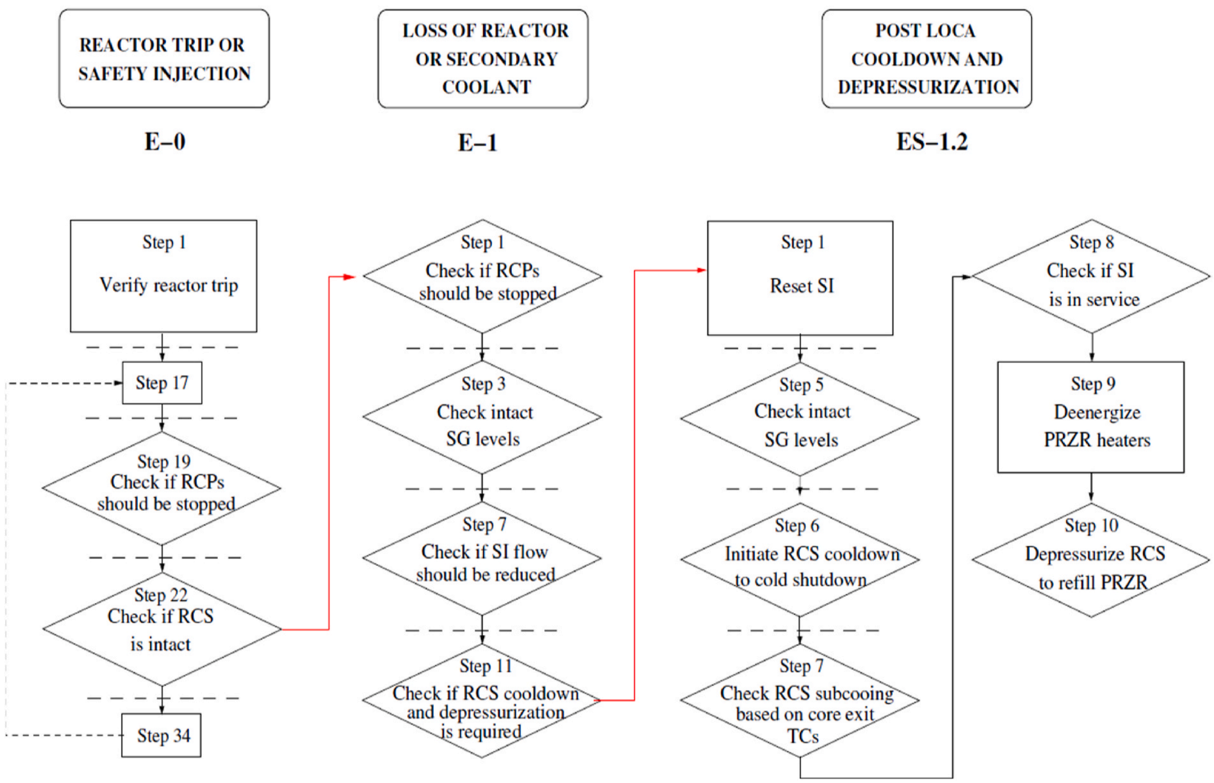


**Fig. 2.** Westinghouse PWR EOPs related with SBLOCA sequences (E−0, E−1, ES-1.2).

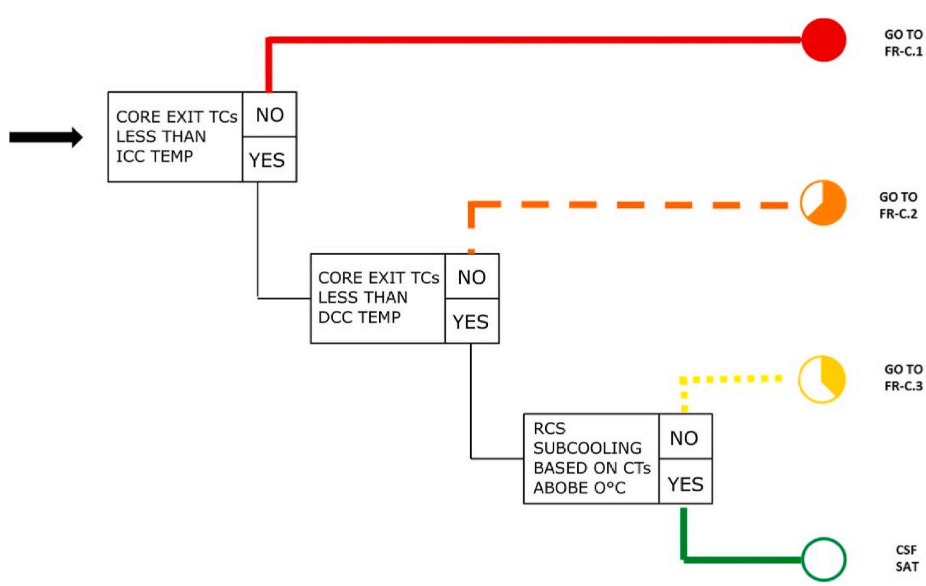


**Fig. 3.** Westinghouse PWR FRG core cooling status tree (i.e., F.0.2).

is reached, the EOPs specify that it is necessary to initiate SGs depressurization at the maximum RCS cooling rate, i.e., full opening of the Steam Dump Valves to the Condenser (BRU-K) or the Steam Dump Valves to the Atmosphere (BRU-A). References have been found indicating that the ICC condition is considered when the CET temperature exceeds between 350 °C (623 K) and 400 °C (673 K) (Groudev, 1998; Groudev and Georgieva, 2010; Mullner, 2010).

In order to develop and qualify the new EOPs for the VVER-1000 reactors, part A of project R2.03 of the TACE-97 program "Development of software for VVER and RBMK reactor accident analysis" was launched (Del Nevo and D'Auria, 2007; European commission EuropeAid Co-operation Office, 2006; Parisi et al., 1997.). Within this project, experiments were performed at the PSB-VVER experimental facility (Araneo, 2008; Del Nevo et al., 2007). Among the experiments carried out in the PSB-VVER facility, four can be highlighted in which SBLOCA sequences were reproduced: tests 11 and 12, where the management action consisted in the controlled SGs depressurization at an RCS cooling rate of 30 K/h; and tests 4 and 16, where the management action consisted in the SGs depressurization at the maximum RCS cooling rate.

On the other hand, the SBLOCA ET for VVER-1000/V320 reactors (Skalozubov et al., 2010) shows that in case of HPIS failure, the

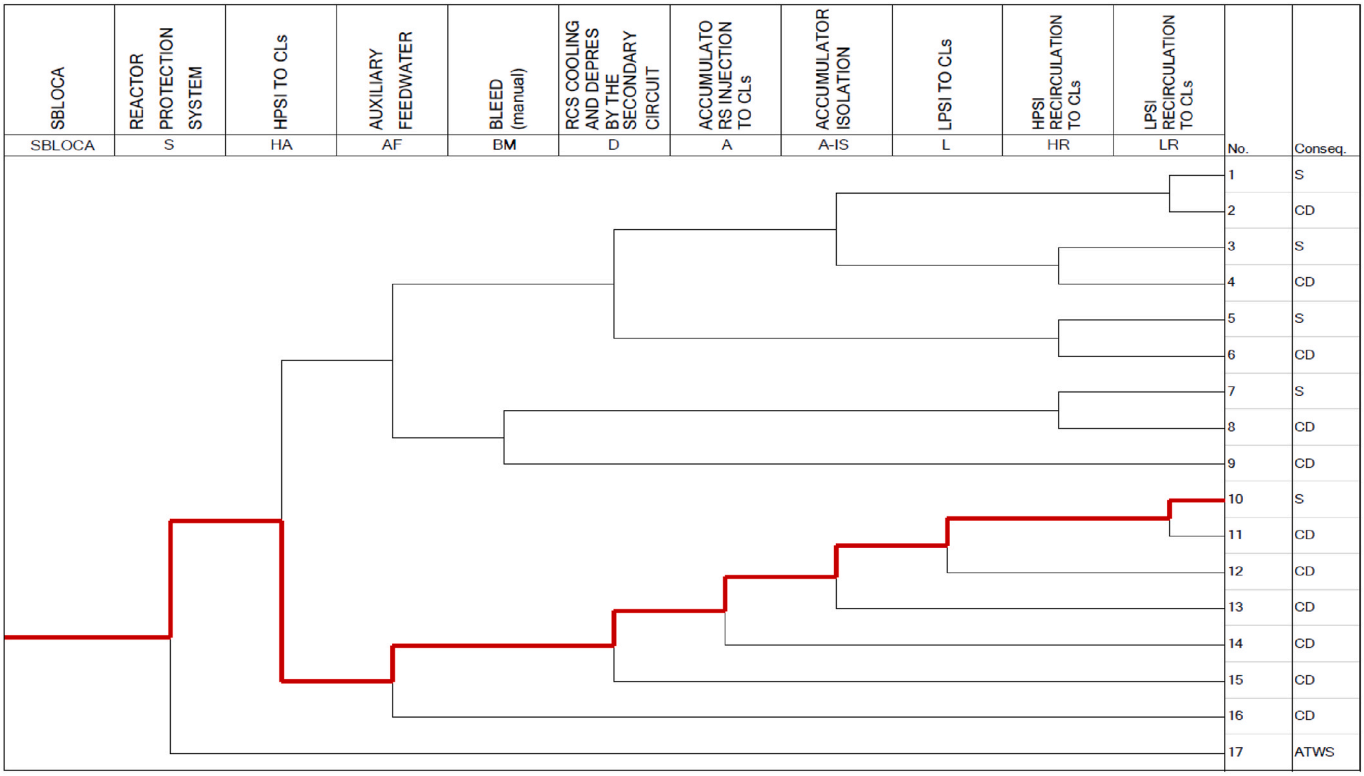


**Fig. 4.** Westinghouse PWR SBLOCA event tree.

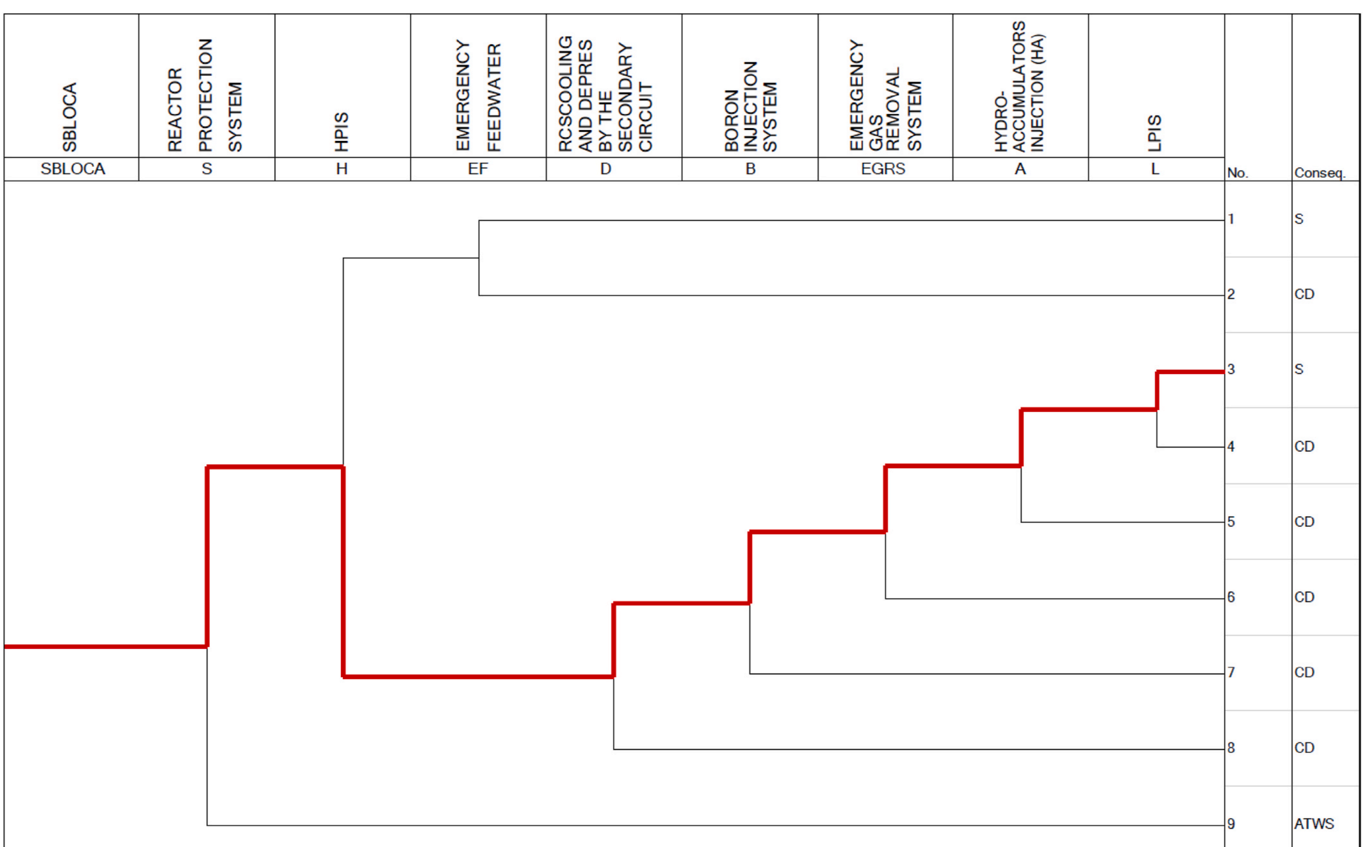


**Fig. 5.** VVER-1000/V320 SBLOCA event tree (Skalozubov et al., 2010).

remaining ET headers have to be fulfilled for the sequence to be successful, see Fig. 5 (sequence 3). These headers are the following:

- [S] SCRAM
- [D] RCS cooling by a controlled SGs depressurization along with operation of the Emergency Feed Water (EFW) or the AFW pumps.
- [B] Boron injection.
- [EGRS] Opening of the Emergency Gas Removal System (EGRS) valve.
- [A] Effective injection of the HAs.
- [L] Injection of the LPIS from containment sump tanks.

Therefore, the ET indicates that, in addition to the RCS cooling through the controlled SG depressurization, the EGRS actuation is also required. On the other hand, it should be noted that in the VVER-1000/V320 reactors, the RCS cooling by the SGs depressurization is performed through the BRU-K or through the BRU-A if the condenser is not available. In summary, the main strategies found in the VVER-1000/V320 reactors in the event of an SBLOCA with HPIS failure sequence are as follow:

- Controlled SGs depressurization at a RCS cooling rate of 30 K/h or 60 K/h.
- Controlled SGs depressurization along with EGRS actuation.
- Fast SGs depressurization at maximum RCS cooling rate when ICC condition is reached.

## 3. VVER-1000/V320 thermal-hydraulic plant model

The TRACEV5P5 code (NRC, 2017) model developed for the VVER-1000/V320 reactor for this analysis is shown in Figs. 6 and 7. 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 (Elena Redondo-Valero et al., 2023; E Redondo-Valero et al., 2023).

The TRACE model includes 255 Thermal-hydraulic (TH) components, 300 SIGNAL VARIABLES, 680 CONTROL BLOCKS and 46 TRIPS. The resulting integral plant model consists of following elements: primary loops, pressurizer (PZR), Reactor Pressure Vessel (RPV), core, SGs, steam lines and main steam header. The VVER-1000/V320 TH model also includes the ECCS, Fig. 8 (Queral et al., 2021), the Emergency Boron Injection System (EBIS), the Control Volume and Chemical System (CVCS) (comprising the Make-up and the Let-down), the Main Feed Water (MFW) and the EFW.

The actuation signals are included for the following safety systems: LPIS, HPIS, EBIS, BRU-A valves, steam lines safety valves, Main Steam Isolation valves (MSIV/BZOK), BRU-K valves, PZR safety valves and HA 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. Furthermore, the model contains the following control systems: 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, (Elena Redondo-Valero et al., 2023; E Redondo-Valero et al., 2023). The values obtained with the TRACEV5P5 model are very close to the reference plant data, see Table 3.

The control developed for the management strategy consisting of controlled SGs depressurization is implemented in the BRU-A valves. When the SGs depressurization is required, the control model calculates a reference RCS temperature corresponding to a cooling rate at 30 K/h or 60 K/h. It then takes the average temperature of the four RCS loops and determines the difference from the reference RCS temperature. This

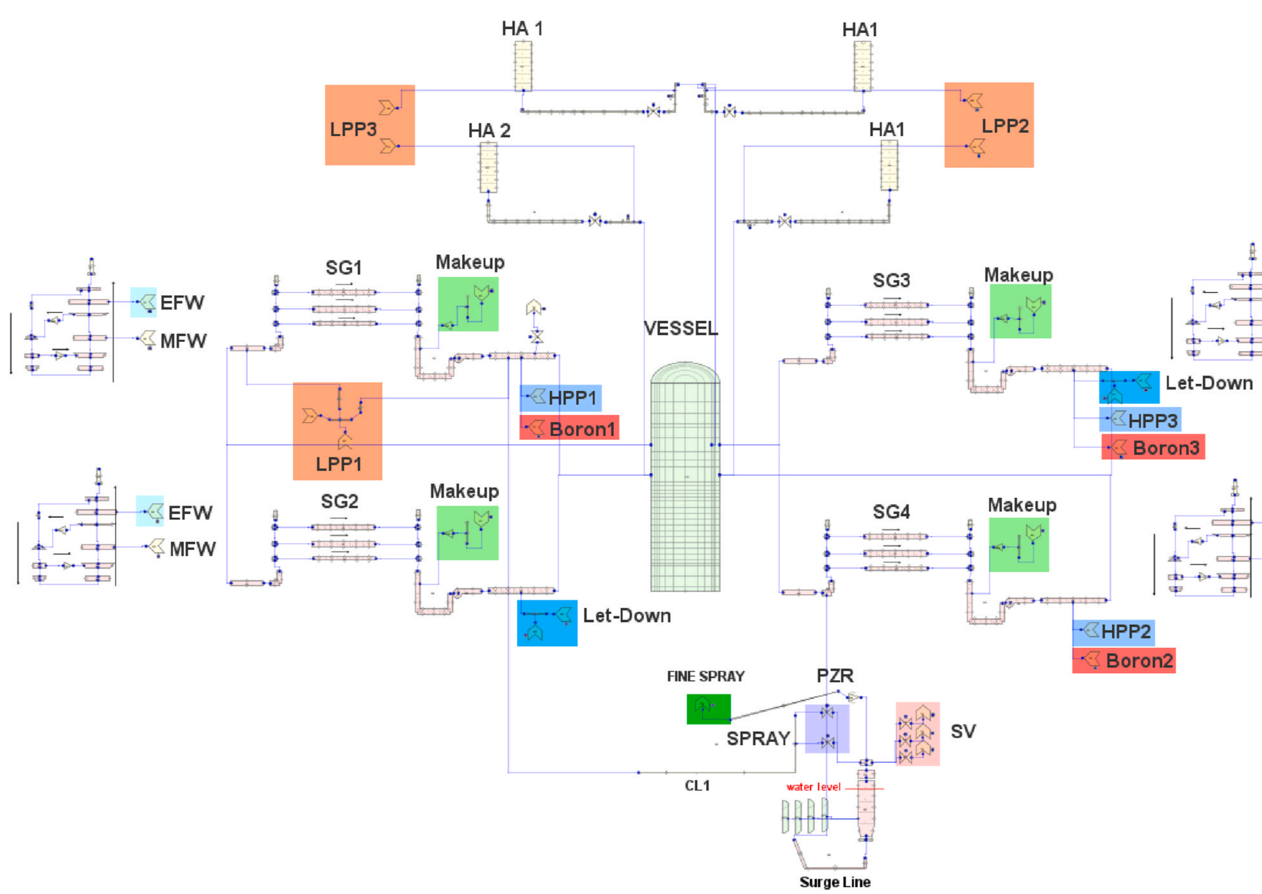


**Fig. 6.** VVER-1000/V320 RCS TRACE TH model.

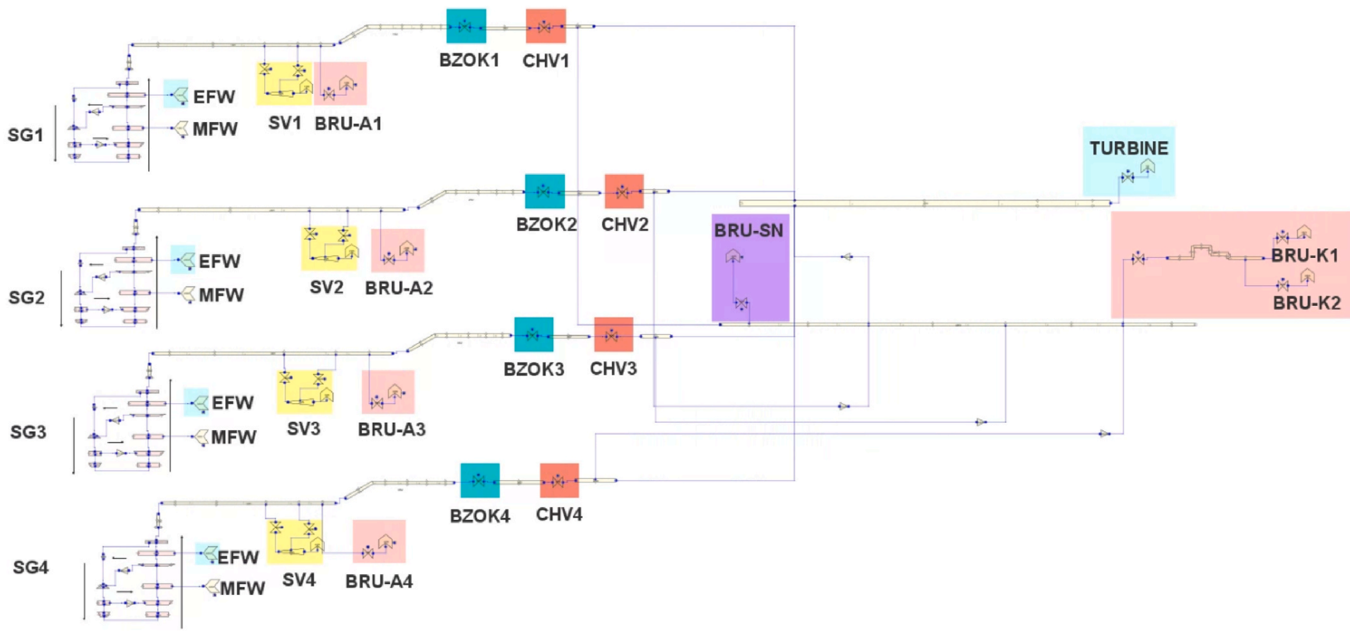


**Fig. 7.** VVER-1000/V320 secondary side TRACE TH model.

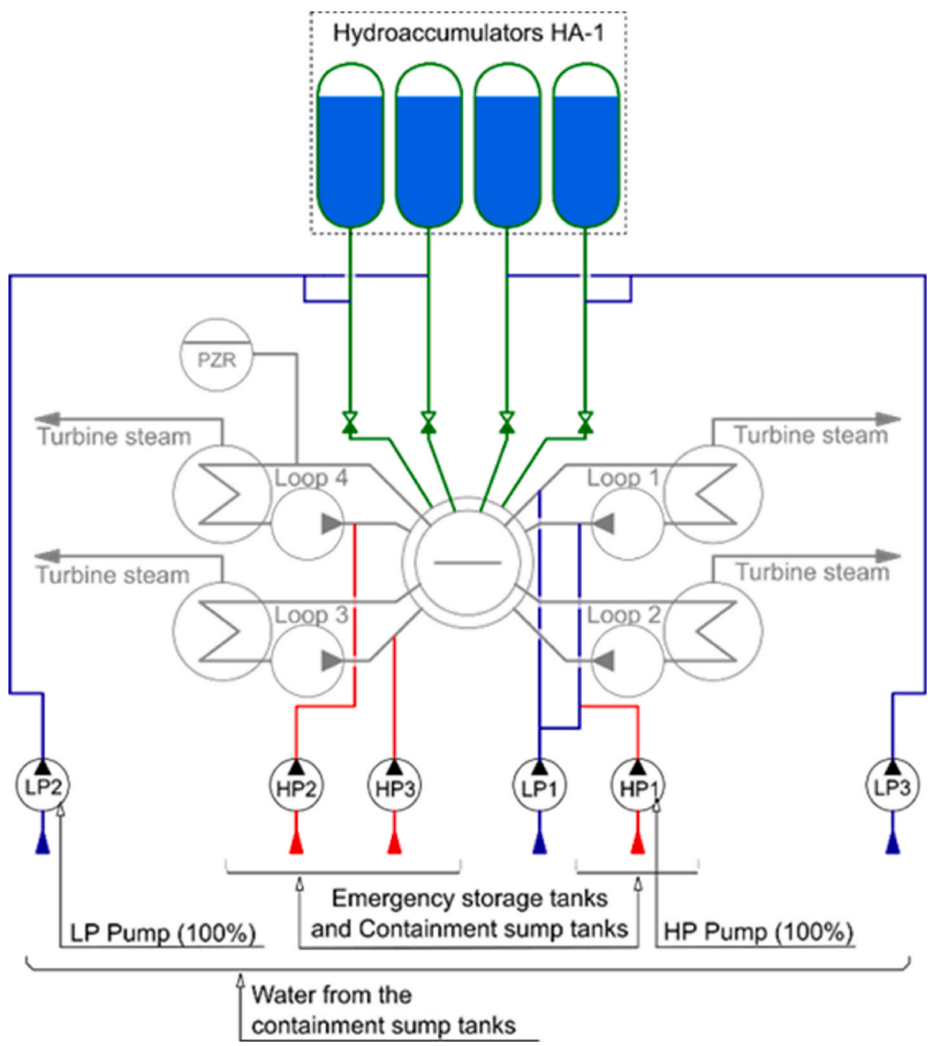


**Fig. 8.** ECCS configuration in VVER-1000/V320.

Table 3
Steady state parameters of VVER-1000/V320.

| Parameter | Reference NPP | TRACEV5P5 |
|---|---|---|
| Core power [MW] | 3010 | 3010 |
| Lower plenum pressure [MPa] | 15.84 | 15.86 |
| Core outlet pressure [MPa] | 15.70 | 15.74 |
| PZR level [m] | 8.70 | 8.71 |
| CLs temperature [K] | 560.85 | 560.96 |
| HLs temperature [K] | 591.55 | 591.13 |
| Average loop mass flowrate [kg/s] | 4456.00 | 4457.21 |
| SG outlet pressure [MPa] | 6.27 | 6.27 |
| MFW mass flowrate [kg/s] | 409.00 | 408.09 |
| MFW temperature [K] | 493 | 493 |
| SG level [m] | 2.50 | 2.50 |

temperature deviation serves as an input for the control model, which then adjusts the opening of the four BRU-A valves accordingly.

In this section it has been decided not to include the description of the TH model for the 3 loops PWR-W used in this analysis, because it is extensively explained in previous papers previously published by the UPM group, see (González-Cadelo et al., 2014; Javier Montero-Mayorga et al., 2014; J. Montero-Mayorga et al., 2014; Queral et al., 2010; 2018).

## 4. VVER-1000/V320 SBLOCA sequence with HPIS failure without human actions

In this section, the SBLOCA sequence with HPIS failure is analyzed with the VVER-1000/V320 TH model previously described in Section 3. The actions taken by the MCR crew are not considered in this section, but in the other following sections. The present section is structured as follows: first, SBLOCA with HPIS failure and no human intervention is analyzed as a base case. Then, the impact of the break size on the sequence is analyzed and the so-called Previous Damage (PD) curve is constructed.

### *4.1. SBLOCA sequence with HPIS failure: base case*

A break size of 1.5 inches located in the cold leg 1 was chosen for the SBLOCA sequence with HPIS failure without human action. In addition, the following hypotheses were made:

- Core power at the beginning of the transient: 100%.
- The LPIS and HA availability correspond to the SBLOCA success criteria ET: 2 out of 4 HA trains available and 1 out of 3 LPIS trains available (Skalozubov et al., 2010).
- The HPIS is unavailable.

The accidental sequence begins 300 s after the start of the simulation. During the first few seconds of the transient, the RCS pressure drops and reaches the HPIS setpoint, see Fig. 9, however the HPIS pumps do not inject during the sequence. The RCS pressure continues to fall, but remains just above the HA pressure, preventing the HA injection into the RPV. Therefore, the collapsed core water level does not recover as no safety system is refilling it, see Fig. 10. The core starts to uncover at about 6000 s, see Fig. 11. At 7081s, the RCS pressure becomes equal to that of the HA, allowing injection, but too late as the core water collapsed level is low. Finally, CD is reached when the PCT exceeds 1477 K at 8126 s. At this point, the total inventory lost due to the break is approximately 2.1 × $10^5$ kg, see Fig. 12. Besides, it is worth noting that CD occurs when the RCS pressure is well above the LPIS setpoint.

### *4.2. Previous Damage Curve. Impact of break size in SBLOCA evolution*

In order to assess the effectiveness of a management strategy in an accidental sequence, it is essential to know first when CD would occur without human actions. This information is provided by the denominated PD curve.

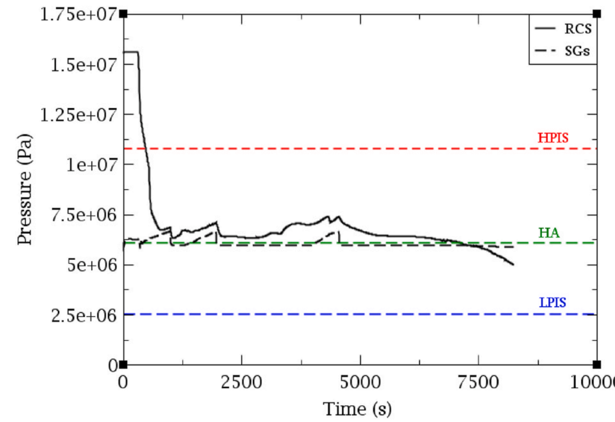


**Fig. 9.** RCS and SGs pressure (1.5 inches SBLOCA with HPIS failure without human actions).

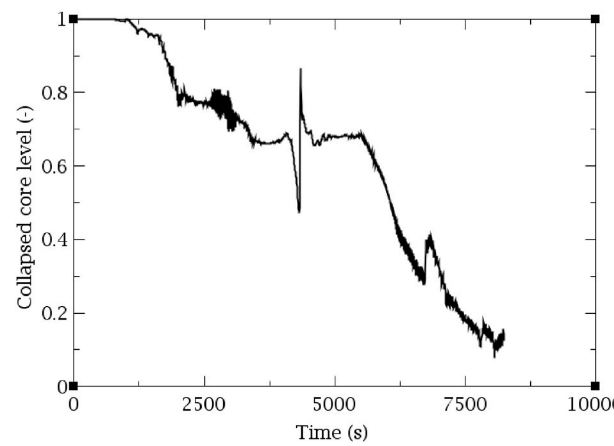


**Fig. 10.** Collapsed Core Level (1.5 inches SBLOCA with HPIS failure without human actions).

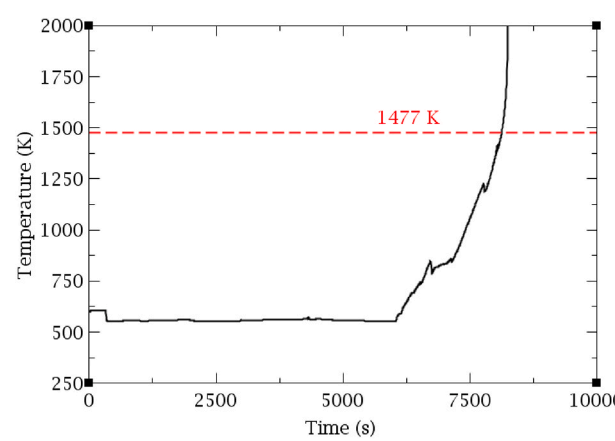


**Fig. 11.** PCT (1.5 inches SBLOCA with HPIS failure without human actions).

To obtain the PD curve, SBLOCA with HPIS failure sequences have been simulated for different break sizes without any management action. The range for the break sizes considered is between 1 and 6 inches with a step of 0.25 inches. Each simulated case can reach two conditions: damage, if the PCT exceeds 1477 K, or success if the PCT does not exceed this temperature, see Fig. 13. Besides, the RCS depressurization is also analyzed, see Fig. 14.

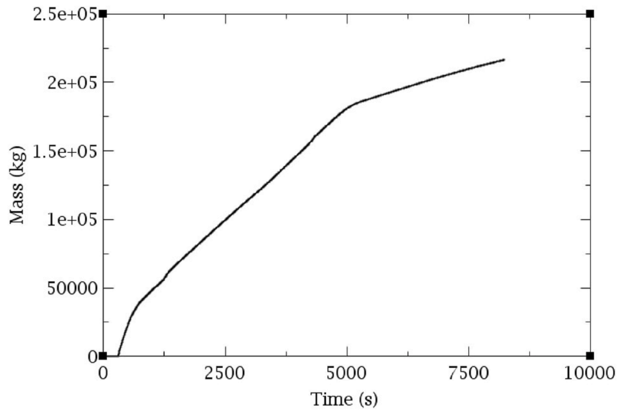


**Fig. 12.** Integral of the mass flow rate through the break (1.5 inches SBLOCA with HPIS failure without human actions).

For the cases that CD is reached, CD times are plotted against the break sizes, see Fig. 15. The "damage" sequences are represented by a red marker at the time CD is reached, while the "success" sequences are represented by a green marker (see electronic version). The curve that follows all the red markers is called the PD curve. A detailed analysis of the PD obtained shows:

- From 2.5 inches onwards the LOCA sequences with HPIS failure, are successful. This is because the RCS is depressurizing through the break fast enough allowing the injection of the HA and LPIS on time.
- Between 1 and 2.25 inches, all the sequences exceed the damage condition. For smaller breaks sizes, CD takes longer to occur, and as the break sizes get larger, CD occurs earlier.

Along with the PD curve, the core uncovering time curve, the HA time injection curve and the LPIS time injection curves have also been plotted, see Fig. 15. The following conclusions can be drawn from these curves:

- The HAs inject into the RCS at every break size analyzed, but at smaller break sizes, between 1 and 2.25 inches, it is too late to stop the PCT from rising.
- The LPIS pump injects before damage for break sizes from 2.25 inches onwards. This is because for smaller LOCA the RCS pressure remains around the HA pressure, preventing it from reaching the LPIS shutoff pressure (2.55 MPa).
- The SBLOCA with HPIS failure sequences are successful when the LPIS inject water into the RCS before CD.

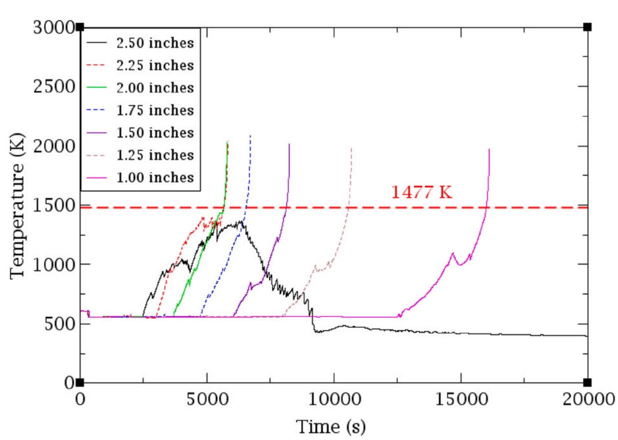


**Fig. 13.** PCT in 1–2.5 inches SBLOCA with HPIS failure without human actions.

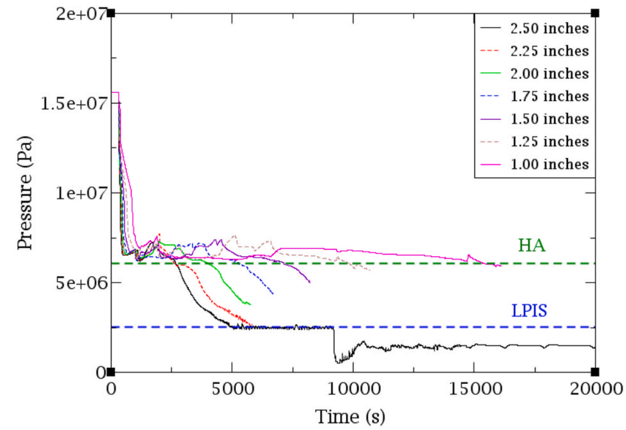


**Fig. 14.** RCS pressure in 1–2.5 inches. SBLOCA with HPIS failure without human actions.

- There is core uncovering from 1 to 3 inches but from 2.5 inches onwards LPIS injection avoid CD.

## 5. VVER-1000/V320 SBLOCA sequence with HPIS failure and controlled SGs depressurization

In CD reaching sequences, it is necessary that the MCR crew performs a management strategy to ensure core cooling. In this section, the effect of the controlled SGs depressurization action to cool the RCS is analyzed. The section is structured as follows:

- Section 5.1: A set of four cases of the SBLOCA with HPIS failure and controlled SGs depressurization is shown for each of the RCS cooling rates under study, 30 K/h and 60 K/h.
- Section 5.2: The DDs for 30 K/h and 60 K/h are obtained.
- Section 5.3: A sensitivity analysis of the DD on certain boundary conditions is presented.

### *5.1. SBLOCA sequence with HPIS failure and SGs controlled depressurization: base cases*

The sequences in which the operators have performed the action of depressurizing the SGs in a controlled manner, is analyzed in detail below for both RCS cooling rates, 30 K/h and 60 K/h. For both cooling rates, the SBLOCA sequence has been simulated with different start times of the manual action, to assess how sensitive the success of the sequence is to this time value. The break size chosen has been the 1.5 inches located in the cold leg 1 with the hypotheses considered in the base case of the SBLOCA sequence with HPIS failure without human actions, Section 4.1.

The controlled SGs depressurization is performed by the BRU-A valves located in the four steam lines, upstream of the safety valves. This human action is simulated within the TRACE model by means of an implemented control, see Section 3.

#### *5.1.1. Depressurization with 30 K/h RCS cooling rate*

The start time, from the beginning of the SBLOCA sequence (1.5 inches), selected for the SGs depressurization at a 30 K/h rate have been 7000 s, 6200 s, 5400 s and 3700 s. The SBLOCA sequence starts 300 s after the beginning of the simulation and the evolution of the events is that of the sequence without SGs depressurization until the manual action is initiated, see Section 4.1. From then on, each SBLOCA sequence evolves in a different way, depending on the start of the SGs depressurization:

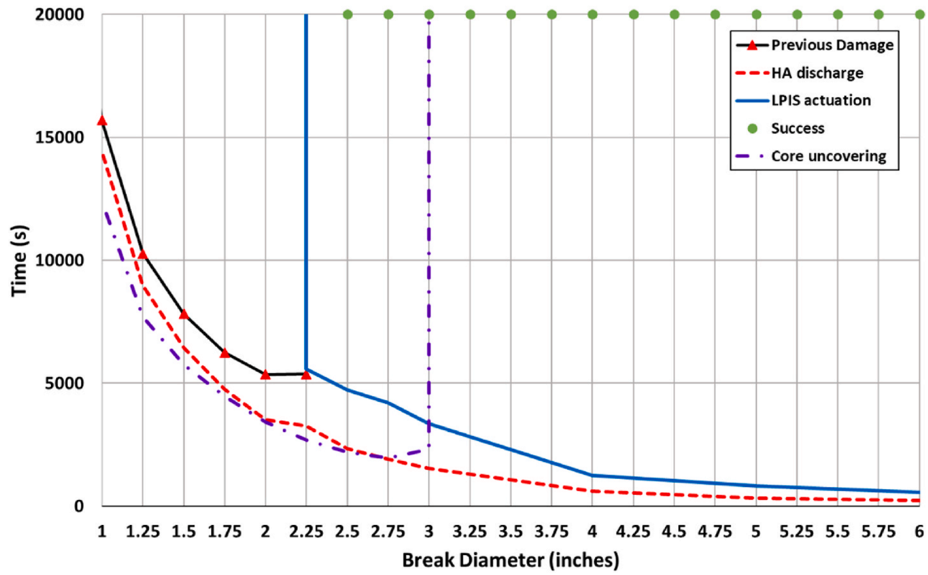


**Fig. 15.** Previous Damage curve for SBLOCA with HPIS failure (VVER-1000/V320).

- 7000 s: In this case the operator action starts too late, Fig. 16, since in the PD curve shows that the previous CD occurs at 7500 s.
- 6200 s and 5400 s: In these cases, the SGs pressure starts to reduce the RCS pressure as soon as the manual action is initiated, see Fig. 17. The RCS pressure reaches the HA pressure and continues to fall, but before it reaches the LPIS cut-off pressure, CD occurs, see Fig. 16. This is because the collapsed core level is already low when the operator action is initiated, see Fig. 18.
- 3700 s: In this case, since the manual action is initiated earlier, the RCS pressure reaches the LPIS cut-off pressure before CD occurs, see Fig. 17. It can be seen that the RCS cools at a rate of 30 K/h until it reaches the LPIS cut-off pressure at about 12000 s, see Fig. 19. When this point is reached, the core is reflooded, see Fig. 18.

For the four analyzed start times for the controlled SGs depressurization at an RCS rate of 30 K/h that have been analyzed, it can be observed that the core uncovering, which occurs once the PCT starts to increase, begins when the core collapsed level is below ≈50 %, Figs. 16 and 18.

*5.1.2. Depressurization with 60 K/h RCS cooling rate*

The start time, from the beginning of the SBLOCA sequence (1.5 inches), selected for the SGs depressurization at a 60 K/h rate have been between 3700 and 7000 s. The SBLOCA sequence starts 300 s after the

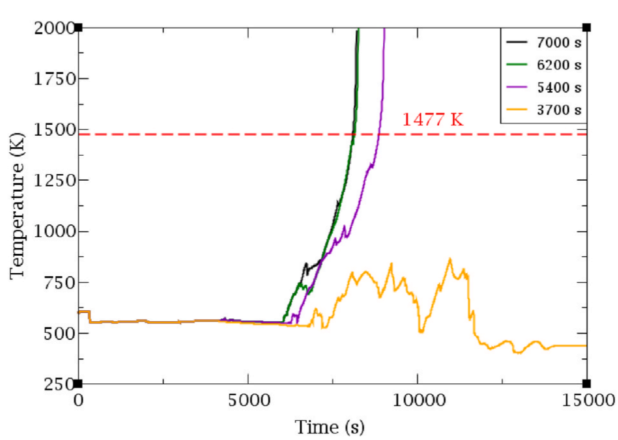


**Fig. 16.** PCT (1.5 inches SBLOCA with HPIS failure and RCS cooling at 30 K/h).

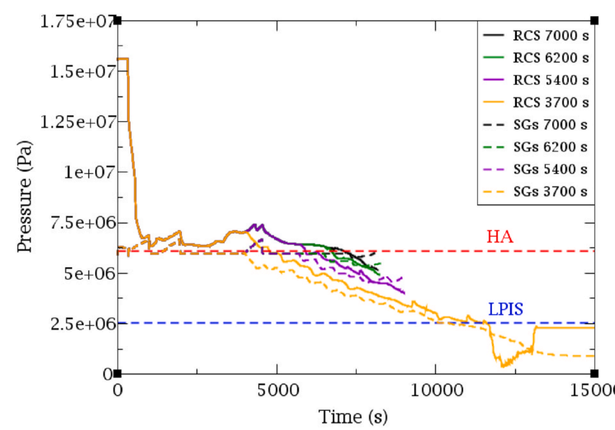


**Fig. 17.** RCS and SGs pressure (1.5 inches SBLOCA with HPIS failure and RCS cooling at 30 K/h).

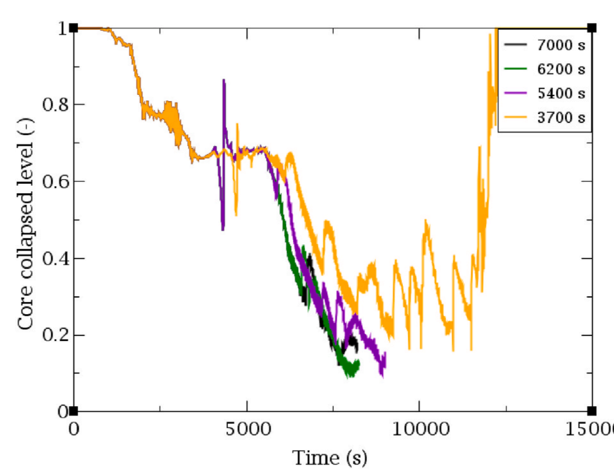


**Fig. 18.** Core Collapsed Level (1.5 inches SBLOCA with HPIS failure and RCS cooling at 30 K/h).

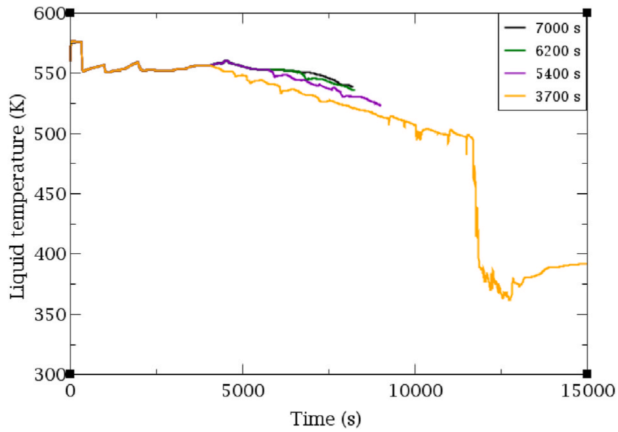


**Fig. 19.** RCS average liquid temperature (1.5 inches SBLOCA with HPIS failure and RCS cooling at 30 K/h).

beginning of the simulation and the evolution of the events is that of the sequence without secondary side depressurization until the manual action is initiated, see Section 4.1. Thereafter, each of the four SBLOCA sequences has a different evolution:

- 7000 s: It can be observed that as soon as the depressurization of the SGs starts, the RCS pressure starts to drop rapidly, however, the core level is too low when the HA discharge starts, so that finally CD cannot be avoided, see Fig. 20.
- 6200 s: Although core uncovering occurs, see Fig. 22, the RCS pressure successfully reaches the LPIS cut-off pressure in time to reflood the core, see Fig. 21, before the PCT exceeds 1477 K, see Fig. 20.
- 5400 s and 3700 s: The RCS pressure successfully reaches the LPIS cut-off pressure, see Fig. 21.

As expected, the depressurization of the SGs at an RCS cooling rate of 60 K/h, see Figs. 21 and 23, allows the RCS pressure to reach the LPIS cut-off pressure earlier than for a cooling rate of 30 K/h. This means that core reflooding starts much earlier, when the PCT is not yet high. For the four analyzed start time, it can be observed that the core uncovering, which occurs once the PCT starts to increase, begins when the core collapsed level is below 50 %, see Figs. 20 and 22.

### 5.2. *Damage domains for the SGs controlled depressurization*

The Damage Domain (DD) for a given action in a given sequence can be defined as the region of the space of uncertain parameters where CD

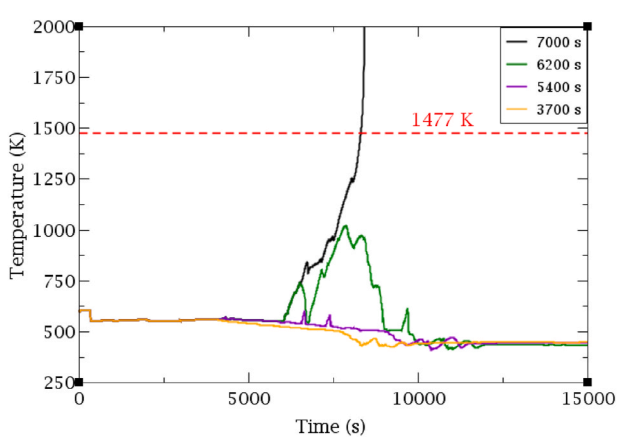


**Fig. 20.** PCT (1.5 inches SBLOCA with HPIS failure and RCS cooling at 60 K/h).

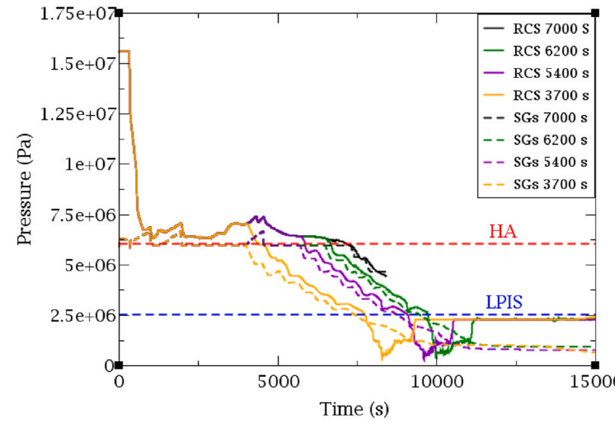


**Fig. 21.** RCS and SGs pressure (1.5 inches SBLOCA with HPIS failure and RCS cooling at 60 K/h).

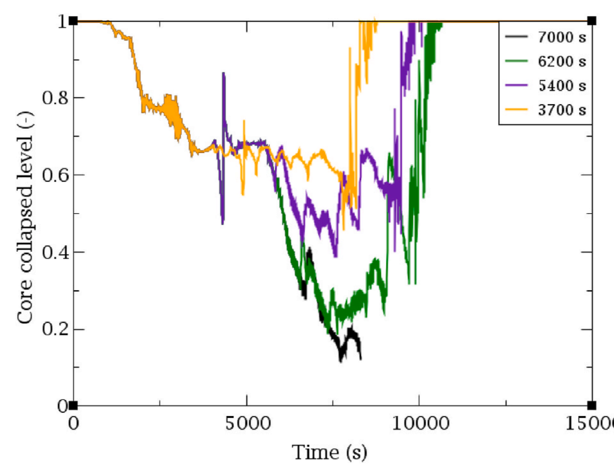


**Fig. 22.** Core Collapsed Level (1.5 inches SBLOCA with HPIS failure and RCS cooling at 60 K/h).

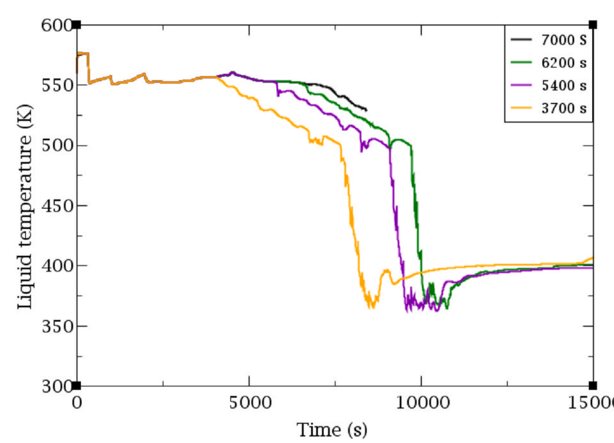


**Fig. 23.** RCS average liquid temperature (1.5 inches SBLOCA with HPIS failure and RCS cooling at 60 K/h).

(or any damage condition considered) is reached. The number of dimensions for this space region corresponds to the number of uncertain parameters involved in the analyzed sequence. The considered DD for the SBLOCA sequence with HPIS failure with controlled SGs depressurization has two dimensions, the break size and the start time of the manual action.

In order to obtain the DD, a series of TH simulations are performed by varying the parameters considered. For that purpose, it is previously established which are the limits for the seeking of the DD. The following considerations have been made in this analysis:

- Break Size: the DD in the break size dimension lies between the limits of the PD curve (1, 2.25 inches). This is because the sequences with larger break sizes that do not fall within the PD curve are successful without the need for any manual action.
- Depressurization start time: The DD enclosed the PD curve in the depressurization beginning time dimension.

In order to obtain the DD for both RCS cooling rates of 30 K/h or 60 K/h, the SBLOCA with HPIS failure sequence has been simulated for each break size between 1 and 2.25 inches, with an interval of 0.25 inches, testing different start times of the manual action from the PD curve, see Fig. 24 (left) and Fig. 25 (left). The DD is then obtained by drawing the line separating the damage and success regions, see Fig. 24 (right) and Fig. 25 (right).

The DD provides information on the time from which the manual action considered is no longer effective, but another factor has to be taken into account: the time it takes for the MCR crew to reach the EOP step where the action is indicated to be performed. The time required by the MCR crew to initiate the controlled depressurization of the SGs is around 600 s ($t_{min} = 600$ s). Subtracting this time from the DD lower limit gives the available time to accomplish the human action, see Fig. 26.

$$t_{available} = t_{DD} \qquad t_{min}$$

In this study, the available time is classified into three categories: short, if it is less than 15 min, medium, if it is between 15 min and 1 h, or long, if it is more than 1 h. The following conclusions can be drawn from these curves:

- 30 K/h RCS cooling rate: The break sizes around 2.25 inches have no available time to depressurize at an RCS cooling rate of 30 K/h. The available time is short for the 2 inches break size, medium between 1. 75 and 1.5 inches, and long below 1.5 inches.
- 60 K/h RCS cooling rate: The smallest available time is given for the 2 inches break size, but in this case the available time is medium, 2900 s. The available time is medium between 2.25 and 2 inches and long below 1.75 inches.

The available time obtained corresponds to a $t_{min} = 600$ s. It should be noted that there is some uncertainty in the time required by the MCR crew. Therefore, if a larger $t_{min}$ value is found, the available time for the 60 K/h RCS cooling rate would be lower and the range of break sizes without available time for the 30 K/h RCS cooling rate would be greater, see Fig. 26.

### 5.3. SGs controlled depressurization. DD sensitivity analysis

In the previous section, the DDs have been obtained for the SBLOCA sequence with HPIS failure and controlled SGs depressurization by considering the following hypotheses: the accidental transient occurs with the core power is at 100 % and the available HAs and LPIS trains are those of the success criteria. In the present section, a sensitivity analysis of the DDs to different boundary conditions for the core power and availability of the HA and LPIS trains has been carried out:

- Original case: The ECCS availability is 2 out of 4 HA trains and 1 out of 3 LPIS trains. Core power at 100%.
- 2nd case (Power uprate): The ECCS availability is 2 out of 4 HA trains and 1 out of 3 LPIS trains. Core power at 120%.
- 3rd case (ECCS fully available): The ECCS availability is 4 out of 4 HA trains and 3 out of 3 LPIS trains. Core power at 100%.
- 4th case (Power uprate and ECCS fully available): The ECCS availability is 4 out of 4 HA trains and 3 out of 3 LPIS trains. Core power at 120%.

The DDs have been obtained by following the steps described in the previous Section 5.2. Furthermore, the sensitivity analysis has been performed for both the 30 K/h and the 60 K/h RCS cooling rates, see Figs. 27 and 28. The overall outcome is that the DD is much more sensitive to the available HA and LPIS trains than to the core power. For each cooling rates the following can be highlighted:

- DDs for the 30 K/h cooling rate: The most limiting case is the second (power uprate), as it extends to 2.75 inches and there is no available time between 2.25 and 2.75 inches. For the third case (ECCS fully available) the DD is reduced to 1.75 inches where the border reaches 4500 s, while, for the fourth case (power uprate and ECCS fully available) the DD is also reduced to 2 inches where it reaches 2200 s.

  The sensitivity analysis on the DD associated with the 30 K/h cooling rate strategy shows that if the HA and the LPIS trains are fully available, the DD is smaller, both in the break size dimension and in the depressurization beginning time dimension. Therefore, the 30 K/h cooling rate could be enough to provide the MCR crew with a large available time in the case of 100% power with 4 out of 4 HA and 3 out of 3 LPIS trains are available.

- DDs for the 60 K/h cooling rate: it should be noted that the DDs for the 60 K/h RCS cooling rate reach the same break size limits as the DDs for the 30 K/h RCS cooling rate, but they extends less in the time. The most limiting case is the second (power uprate) as it extends to 2.75 inches for which it reaches 850 s. For the third case

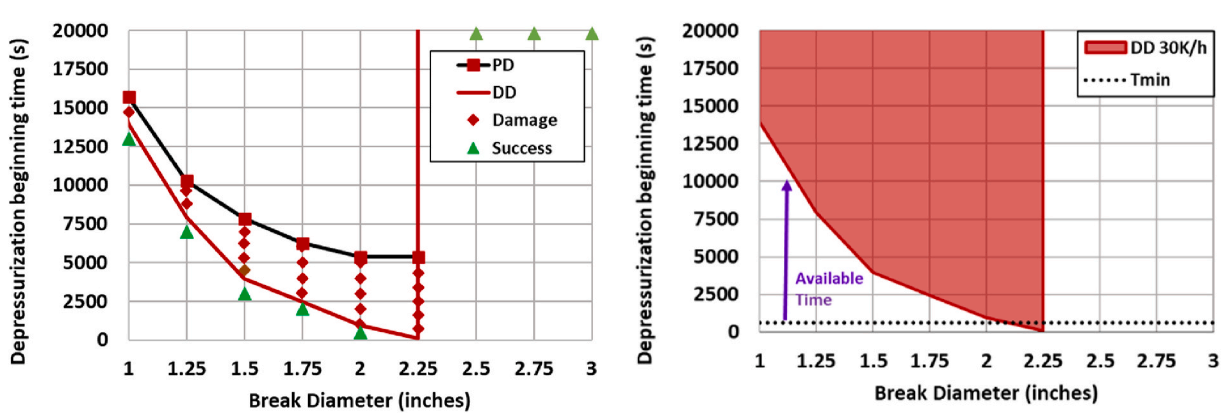


**Fig. 24.** Damage Domain for SBLOCA with HPIS failure and 30 K/h RCS cooling (VVER-1000/V320).

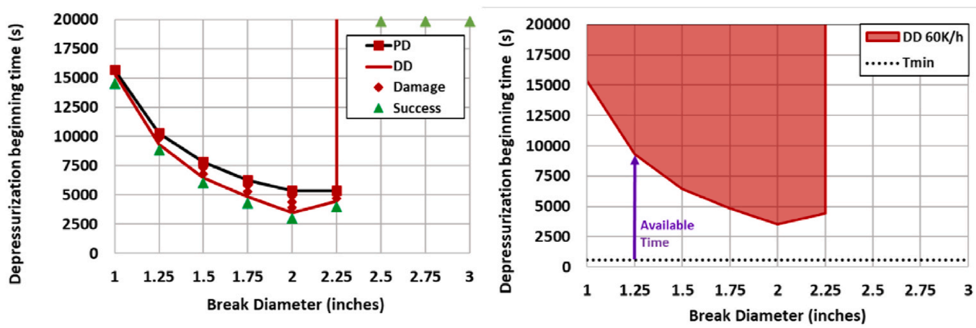


**Fig. 25.** Damage Domain for SBLOCA with HPIS failure and 60 K/h RCS cooling (VVER-1000/V320).

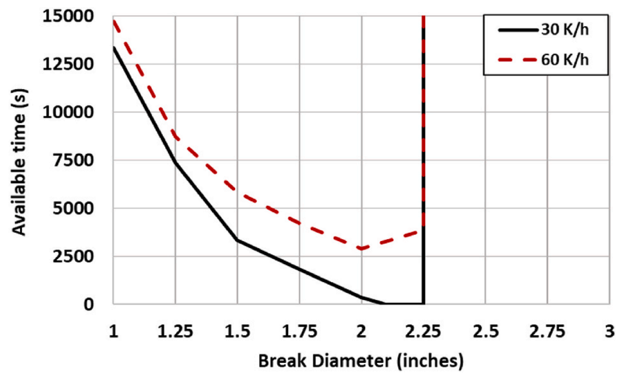


**Fig. 26.** Available Times for SBLOCA with HPIS failure sequence with 30 K/h and 60 K/h RCS cooling (VVER-1000/V320).

(ECCS fully available) the DD reaches 7850 s for 1.75 inches, while, for the fourth case (power uprate and ECCS fully available), the DD reaches 5400 s for 2 inches.

It should be noted that if a 20 % power uprate is performed in a VVER-1000/V320 reactor, the strategy associated with the controlled SGs depressurization at an RCS cooling rate of 60 K/h may not be enough to avoid CD, considering the time required by the operator to initiate the management action. Therefore, in this case, it would be necessary to study other strategies to complement the controlled SGs depressurization or to apply higher cooling rates.

## 6. VVER-1000/V320 SBLOCA sequences with HPIS failure, controlled SGs depressurization and EGRS actuation

The EGRS is a safety system developed to remove the steam-gas mixture from the upper RPV, the PZR and the primary side of the SGs, (Iegan et al., 2018). In the references, some cases have been found where the depressurization of the RCS through the EGRS is studied in SBLOCA sequences with HPIS failure (Groudev, 1998), or Total Loss of Feed Water (TLFW) sequences, (Gencheva et al., 2005). Besides, the SBLOCA ET for the VVER-1000/V320 reactor, Fig. 5 and (Skalozubov et al., 2010), shows that for the sequence in which the HPIS is not available, in addition to the RCS cooling by the controlled SGs depressurization, the EGRS opening valve is also required to avoid CD.

Based on the DDs obtained for the controlled SGs depressurization in Section 5, it was verified that the EGRS actuation is not necessary when the depressurization is performed at an RCS cooling rate of 60 K/h. However, when the SGs depressurization is performed at an RCS cooling rate of 30 K/h, see Fig. 24 (right), the DD indicates that the opening of an EGRS valve might be useful in order to avoid CD for the whole SBLOCA spectrum.

In order to analyze the impact that the EGRS could have in the SBLOCA without HPIS sequences in VVER-1000/V320 reactors, the DD for the EGRS actuation has been obtained in Section 6.1. Then, in Section 6.2, it has been performed a sensitivity analysis on the EGRS valves diameter.

### 6.1. Damage domains for the EGRS actuation

The aim is to analyze the impact of the EGRS performance in SBLOCA sequences with HPIS failure where the controlled SGs depressurization at a rate of 30 K/h is applied. It has been considered that the actuation of this safety system consists in the opening of a valve located in the PZR with a diameter of 1.25 inches.

First, the DD of the EGRS actuation alone was obtained following the approaches used in Section 5, see Fig. 29-B. It can be seen that the DD extends over the entire beginning depressurization time dimension from 1 to 1.75 inches, i.e., even if the EGRS valve were opened at the time the SBLOCA occurs the sequence would not be successful. However, for break sizes of 2 and 2.25 inches, the DD limit is similar to the PD curve values. This is because opening an EGRS valve is equivalent to inducing a second LOCA of 1.25 inches in the RCS. The sum of both areas, i.e. the EGRS valve are and the LOCA break, is shown in Table 4. Therefore, despite the EGRS, sequences from 1 to 1.75 inches are not successful, because the RCS opening areas (LOCA + EGRS valve) are still small enough to allow it to depressurize in time for the HA and LPIS injection before CD.

Subsequently, the DD of both combined strategies, SGs depressurization at 30 K/h and EGRS valve opening, has been obtained, see Fig. 29-C. It has been considered that the operator opens the EGRS valve 100 s after the beginning of the controlled SGs depressurization. The DD has been obtained following the same steps used in Section 5. It can be seen how the resulting DD is a combination of the DD for the controlled depressurization at 30 K/h and the DD of the EGRS performance.

Then, the available time for the strategy of controlled SGs depressurization combined with the opening of a 1.25 inches EGRS valve has been calculated. The available time obtained has been compared with that of the two strategies alone, see Fig. 30. The following conclusions can be drawn:

- 1–1.75 inches: The shape of the available time curve is similar to the available time curve for the controlled SGs depressurization at 30 K/h, but the time values are lower. The 1.75 inches break size has no available time, it is medium for 1.5 inches and long from 1 to 1.25 inches.
- 2–2.25 inches: The available time curve is very close to the available time curve for the EGRS strategy alone. A long available time is considered, because it is greater than 1 h.

### 6.2. EGRS valve diameter sensitivity analysis

A sensitivity analysis has been performed on the EGRS valve diameter to see its impact on the DD of the strategy consisting of controlled SGs depressurization at an RCS cooling rate of 30 K/h in combination

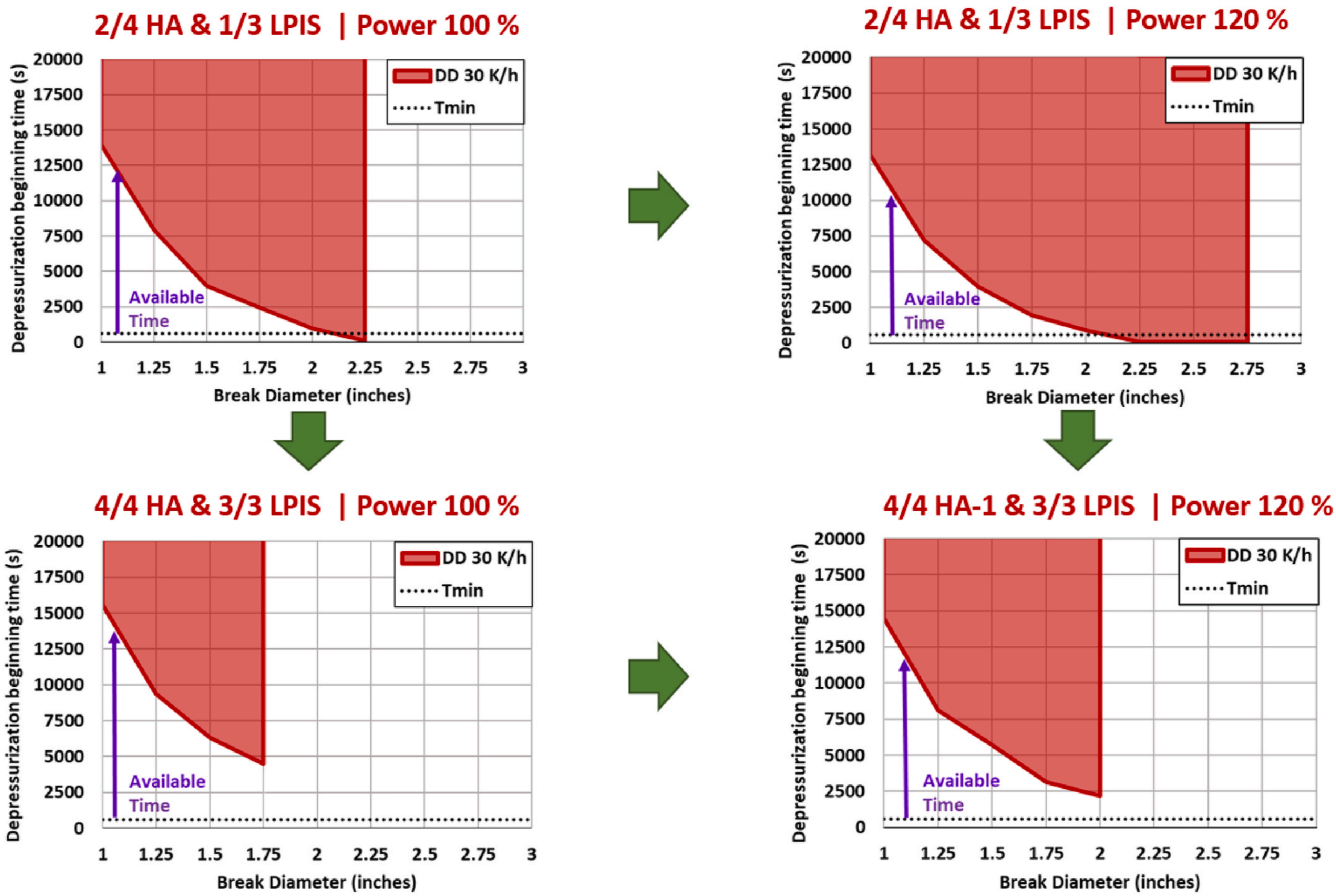


**Fig. 27.** Damage Domain sensitivity analysis for SBLOCA with HPIS failure and 30 K/h RCS cooling (VVER-1000/V320).

with the opening of one of the EGRS valves, see Fig. 31. It is important to note that the size of the EGRS valves can be different for NPPs of the same reactor design. Therefore, the DD has been obtained for the following cases:

- The opening valve has the diameter as one of the PZR safety valve (diameter = 2.5 inches). This option has been considered as the EOPs of some VVER-1000/V320 NPPs may consider opening the PZR safety valves instead of the EGRS valves.
- The opening valve had half the area of the PZR safety valve (diameter = 1.72 inches). This option has been considered as references (Mullner, 2010) indicated that the EGRS valves area can be half that of the PZR safety valves area.

The lowest value obtained for the DD limit is 2000 s (diameter = 1.72 inches, half the area of the 2.5 inches diameter valve), so despite considering the minimum time needed by the operator to execute the strategy, there would be enough available time. If the opening EGRS valve has the area of one of the PZR safety valves, the DD limit has values close to those of the PD curve. This is because the opening of a valve with diameter of 2.5 inches causes high cooling rates, more than 60 K/h. In case of considering a valve with a diameter of 1.72 inches, the DD limit is close to the PD curve from 1.75 to 2.25 inches break sizes.

## 7. VVER-1000/V320 SBLOCA sequences with HPIS failure and SGs depressurization at maximum RCS cooling rate

In the management of the SBLOCA sequences with HPIS, there is an alternative manual action for those cases where the core cooling CSF is not fulfilled, i.e., when the ICC condition is reached. This consists in performing a maximum RCS cooling by means of a fast SGs depressurization, which implies the full opening of the BRU-A valves. It should be noted that the fast SG depressurization causes high RCS cooling rates, exceeding 200 K/h, which can lead to hazardous thermal shock conditions.

References have been found where the SGs fast depressurization is performed when the CET temperature exceeds 350 °C, 623 K, (Mullner, 2010). On the other hand, in the PWR-W, whose EOPs were used as a reference for the actual EOPs of the VVER-1000/V320 reactors, the ICC condition is reached when the CET temperature exceeds 650 °C (923 K) (FR C.1). Taking this information into account, it has been decided to analyze the fast SGs depressurization in VVER-1000/V320 reactors considering both ICC temperature values, 350 °C (623 K) and 650 °C (923 K).

First it has been obtained when the ICC temperatures considered are reached. For this purpose, the SBLOCA with HPIS failure sequences without human action have been simulated and it has been found when the steam temperature at the core exit exceeded 350 °C (623 K) and 650 °C (923 K), see Fig. 32.

Subsequently, the margin time curve, which gives the time from the occurrence of the ICC to the occurrence of the PD has been then obtained. This was done by subtracting the ICC time and the time taken by the MCR crew to initiate the action from the PD curve values, obtained in Section 4. The value considered for the time required by the MCR crew is 60 s, as this is the time taken by the operators to perform this action in simulator training. The following conclusions can be drawn from the time margin curves obtained:

$$t_{margin} = t_{PD} \quad t_{ICC} \quad t_{min}$$

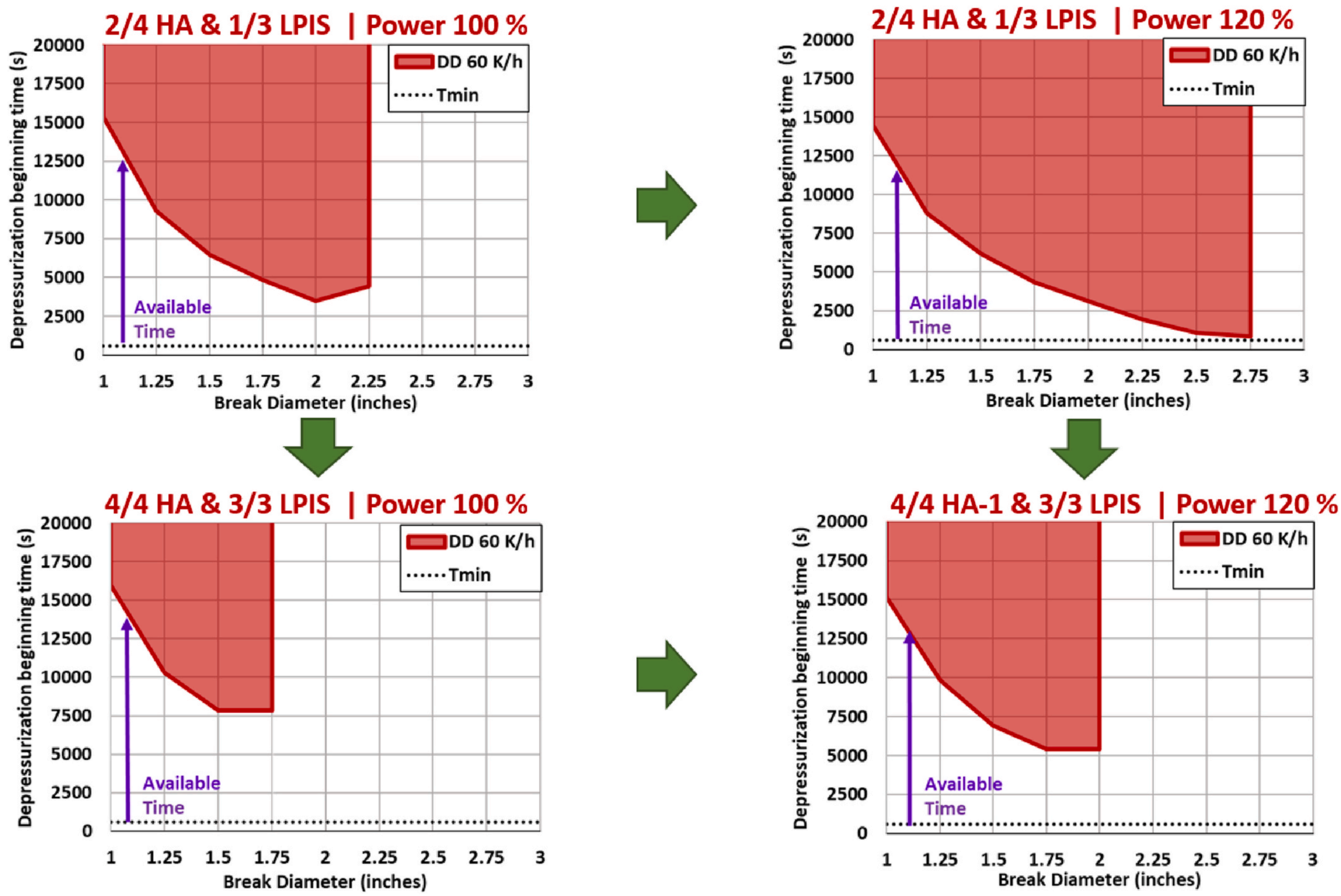


**Fig. 28.** Damage Domain sensitivity analysis for SBLOCA with HPIS failure and 60 K/h RCS cooling (VVER-1000/V320).

- ICC = 350 °C (623 K): the margin time obtained is similar for all the break sizes. The break size with the largest margin being the 2.25 inches with 2296 s and the one with the smallest margin being the 1.75 inches with 1381 s, see Fig. 33.
- ICC = 650 °C (923 K): the margin time obtained is much smaller than the time margin obtained for ICC = 350 °C (623 K). The break size with the largest margin being the 2.25 inches with 1151 s and the one with the smallest margin being the 1 inch with 265 s, see Fig. 34.

Afterwards, the DD for the fast SGs depressurization has been obtained. For this, the steps described in Section 5 for calculating the DD for the controlled SGs depressurizations have been followed. The DD obtained has been plotted together with the two ICC curves (350 °C and 650 °C) for those cases without depressurization, this allow to check how closed they are to the DD border, see Fig. 35. In addition, a surface has also been generated showing the PCT values as a function of the start time of the fast SGs depressurization action and of the break size. On this surface, two curves have been plotted showing the PCT values reached in the case where the manual action starts just when the ICC conditions occur, see Fig. 36.

Finally, the available time to perform the maximum RCS depressurization and cooling by a fast SGs depressurization has been calculated. This time is determined by subtracting the time in which the ICC condition occurs from the DD, minus the time required by the MCR crew to initiate the action, see Fig. 37.

$$t_{available} = t_{DD} \quad t_{ICC} \quad t_{min}$$

The following conclusions can be drawn from the obtained curves:

- The available time to perform the action is longer when considering that the ICC condition occurs when the CET temperature exceeds 350 °C (623 K).
- Considering that the ICC occurs when the CET temperature exceeds 350 °C (623 K), the break size with the shortest available time is 1.75 inches at 1352 s. The available time for all the break sizes is medium, ranging from 15 min to 1 h.
- Considering that the ICC occurs when the CET temperature exceeds 650 °C (923 K), the break size with the shortest available time is 2 inches at 190 s. The available time for all break sizes, except for 2.25 inches is considered shot because it is less than 15 min.

## 8. Comparison of management strategies for VVER-1000/V320 SBLOCA sequences with HPIS failure

The purpose of this section is to provide an overview of the different strategies that can be implemented in a VVER-1000/V320 reactor to manage an SBLOCA sequence with HPIS failure. The following have been analyzed in this work:

- The controlled SGs depressurization at an RCS cooling rates of 30 K/h and 60 K/h (Section 5).
- Controlled SGs depressurization at an RCS cooling rate of 30 K/h along with the EGRS actuation (Section 6).
- The SGs depressurization at maximum RCS cooling rate when ICC condition is reached (Section 7).

The DDs obtained for all analyzed strategies have been compared by plotting the lines delimiting these DDs on the same graph, see Fig. 38. Likewise, the available time curves obtained for the different strategies

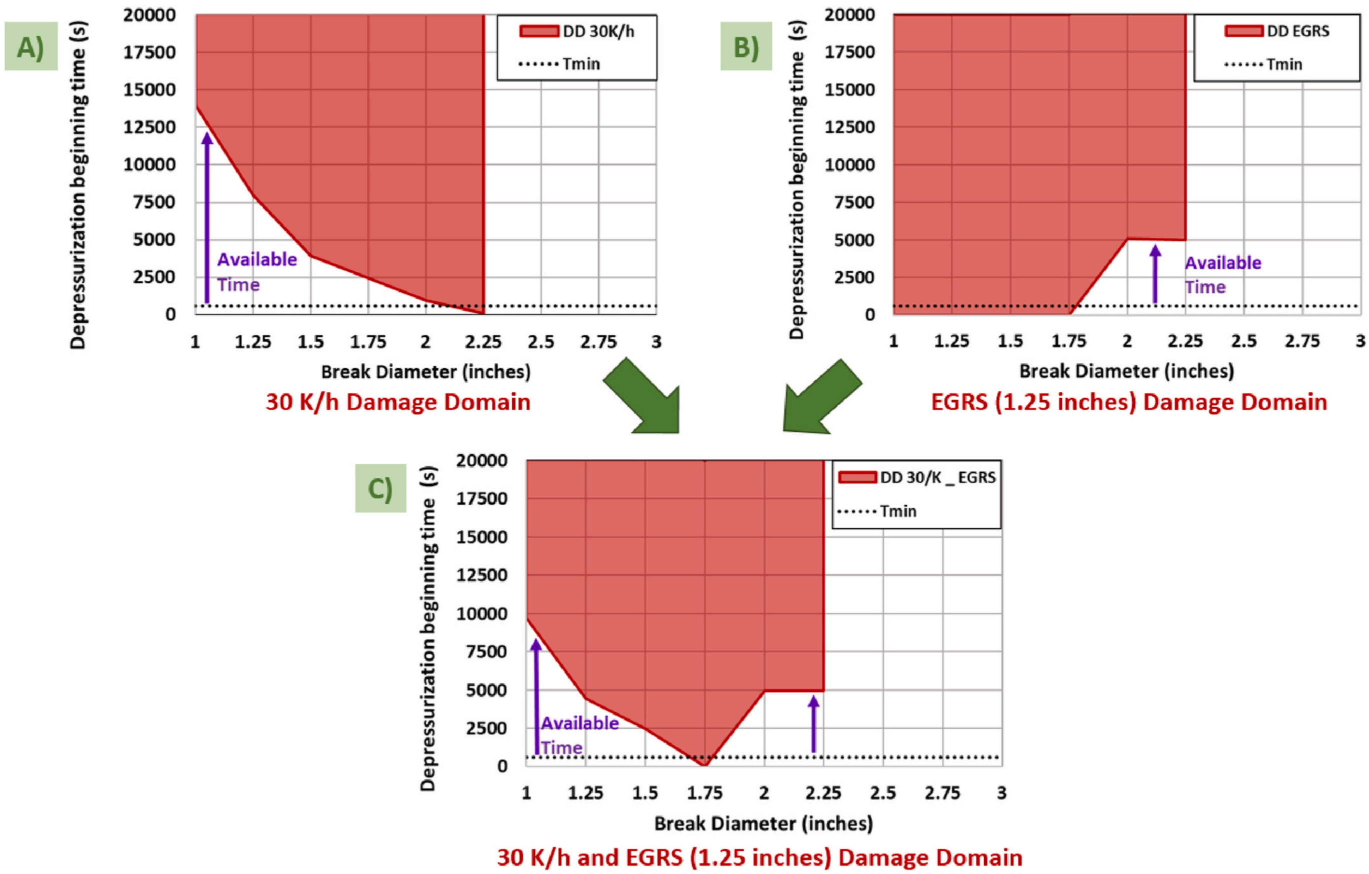


**Fig. 29.** Damage Domain for SBLOCA with HPIS failure and 30 K/h RCS cooling along with EGRS actuation (VVER-1000/V320).

**Table 4**
SBLOCA area along with the EGRS valve area.

| Break diameter (inches) | Break area ($m^2$) | Break area + EGRS area ($m^2$) |
|---|---|---|
| 1 | 5.07E-4 | 1.31E-3 |
| 1.25 | 7.92E-4 | 1.60E-3 |
| 1.5 | 1.14E-3 | 1.94E-3 |
| 1.75 | 1.55E-3 | 2.35E-3 |
| 2 | 2.03E-3 | 2.83E-3 |
| 2.25 | 2.57E-3 | 3.36E-3 |

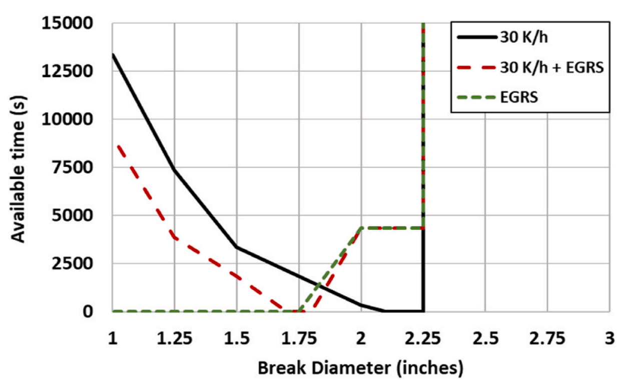


**Fig. 30.** Available time for SBLOCA with HPIS failure and 30 K/h RCS cooling along with EGRS actuation (VVER-1000/V320).

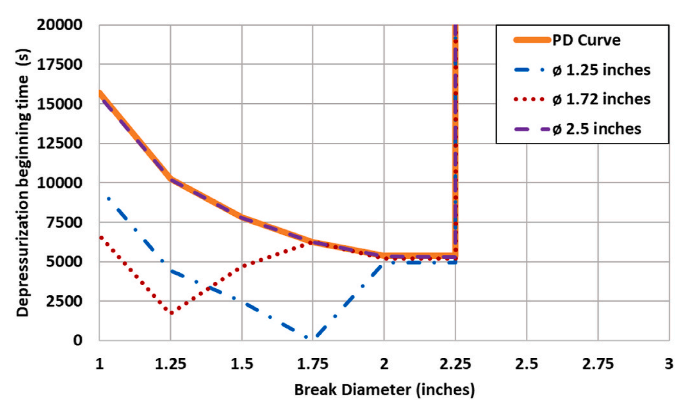


**Fig. 31.** DD sensitivity analysis on the EGRS valve diameter.

have been compared, see Fig. 39 and Table 5. From this comparison, it can be concluded the following:

- The strategy with the highest available time for the whole range of break sizes is the controlled SGs depressurization at an RCS cooling rate of 60 K/h. The second one is the corresponding to the fast SGs depressurization.
- The other strategies cannot avoid CD in the whole range of break sizes.

As mention in the previous sections, the available times obtained are highly dependent on the time required by the MCR crew to perform the corresponding management action, i.e., the $t_{min}$ selected. However, it should also be noted that the calculated available times are subject to

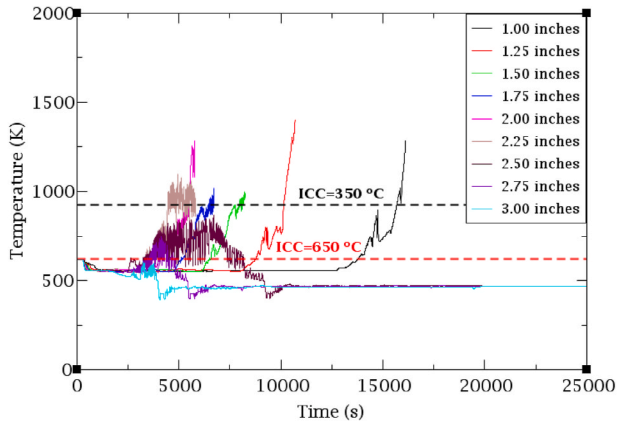


**Fig. 32.** CET temperature in SBLOCA with HPIS failure without human actions (VVER-1000/V320).

other uncertainties, mainly related to the options and hypotheses assumed in the TH model and the system code applied in the analysis.

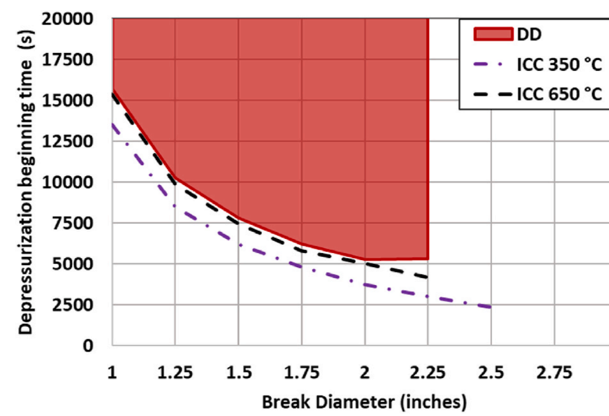


**Fig. 35.** Damage Domain for SBLOCA with HPIS failure and RCS maximum cooling rate via the SGs (VVER-1000/V320).

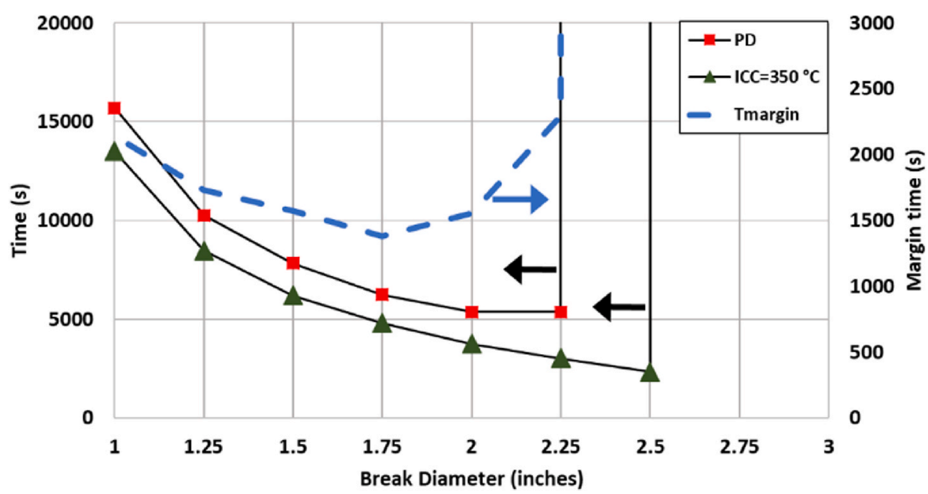


**Fig. 33.** Time margin for RCS maximum cooling rate via the SGs at ICC 350 °C (VVER-1000/V320).

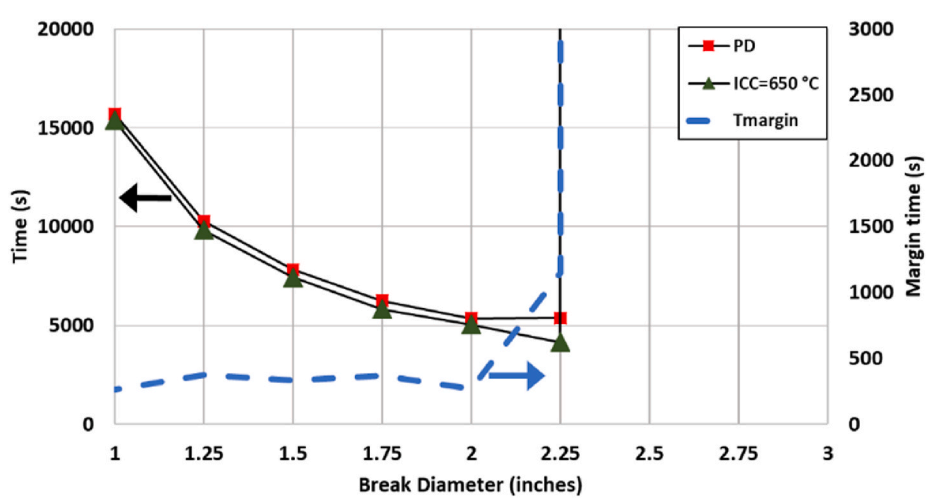


**Fig. 34.** Time margin for RCS maximum cooling rate via the SGs at ICC 650 °C (VVER-1000/V320).

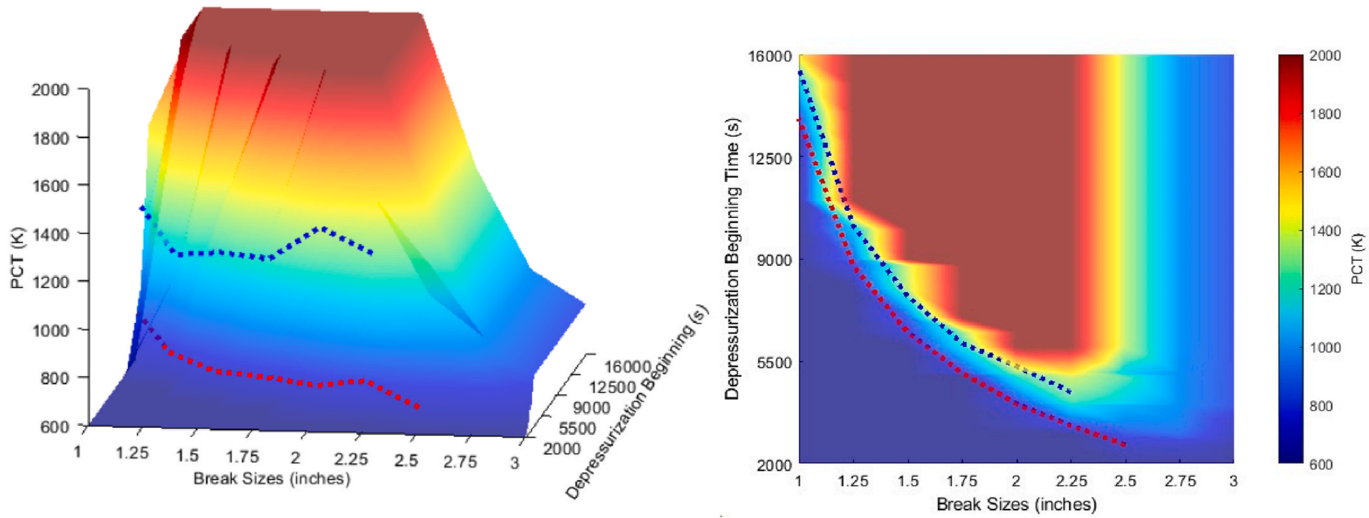


**Fig. 36.** PCT in SBLOCA with HPIS failure and RCS maximum cooling rate via the SGs (VVER-1000/V320).

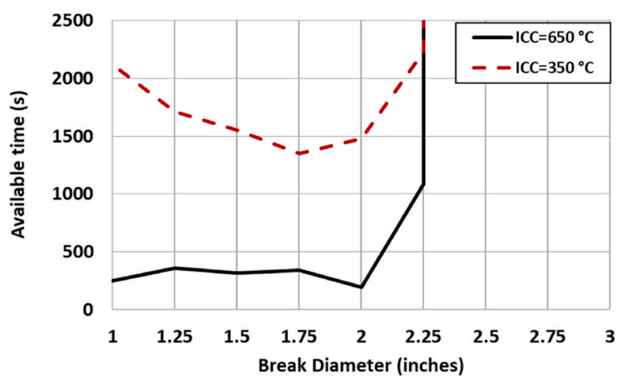


**Fig. 37.** Available time for SBLOCA with HPIS failure sequence and RCS maximum cooling rate via the SGs at ICC 350 °C and ICC 650 °C (VVER-1000/V320).

## 9. Verification of EOPs strategies in Westinghouse PWR for SBLOCA sequences with HPIS failure

This section is focused on the analysis of the different management strategies that can be found in a 3 loops PWR-W for the SBLOCA sequence with HPSI failure. As seen in Section 2, in 3 loops PWR-W two strategies can be distinguished depending on whether ICC condition has been reached:

- Controlled SGs depressurization: The PWR-W EOP ES-1.2 and EOP FR-C2 indicate that this action is performed at 55 K/h.
- Fast SGs depressurization: this strategy is adopted when the ICC condition has been reached, i.e., CETs exceed 650 °C (923 K).

The hypotheses considered in the 3 loops PWR-W TH model are similar to those considered for the VVER-1000/V320 TH model: the core power at the beginning of the accidental sequence is 100 % and the available trains of the ACC (2 out of 3 trains) and the LPSI (1 out of 2 trains) are those of the success criteria. On the other hand, it is noteworthy that the PWR-W do not have automatic RCPs trip, unlike the VVER-1000/V320 reactors. Therefore, in order for the conditions

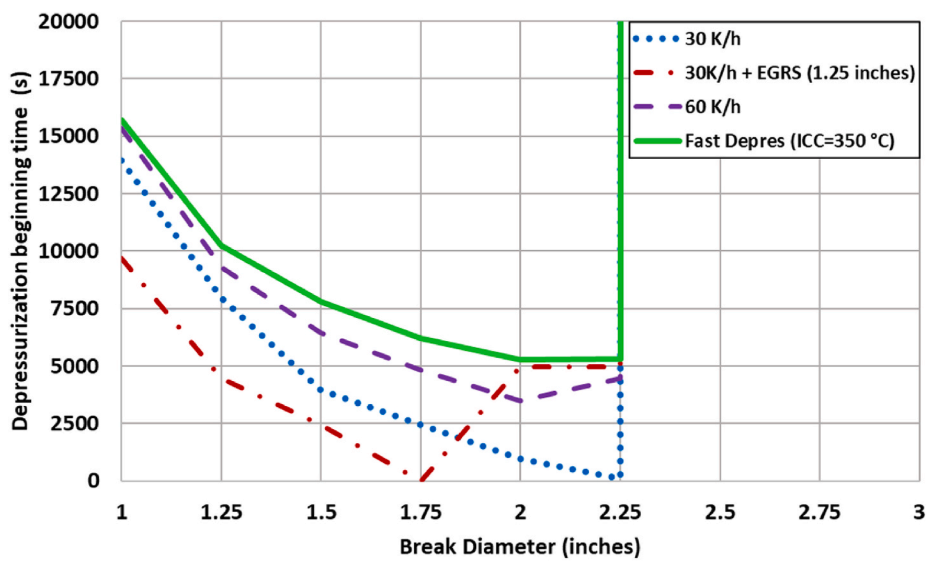


**Fig. 38.** Damage Domains comparison for SBLOCA with HPIS failure management strategies (VVER-1000/V320).

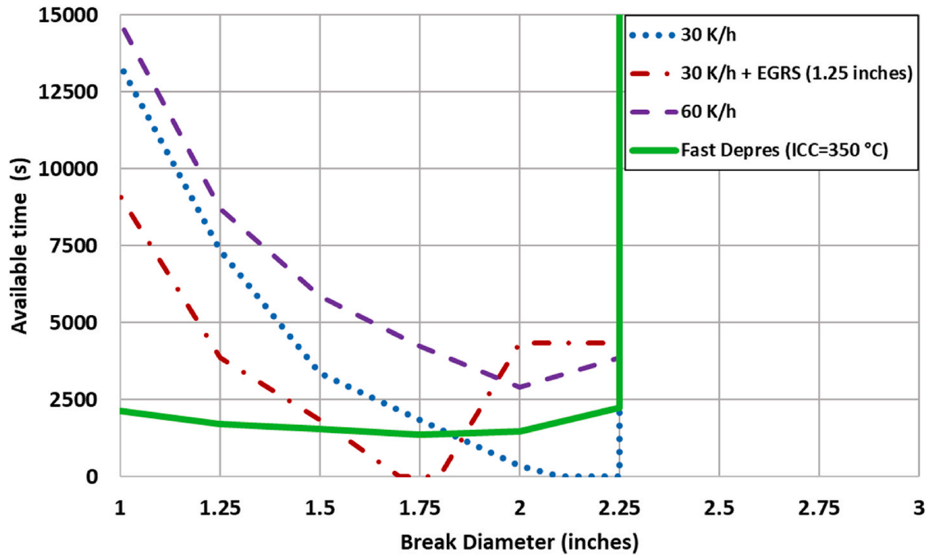


**Fig. 39.** Available times comparison for SBLOCA with HPIS failure management strategies (VVER-1000/V320).

**Table 5**
Minimum available time in VVER-1000/V320 for SBLOCA with HPIS failure sequence strategies.

| Strategy | | Minimum Available Time (s) |
|---|---|---|
| Controlled SG depressurization at 30 K/h | | 0 |
| Controlled SG depressurization at 60 K/h | | 2900 |
| Controlled SG depressurization at 30 K/h along with the opening of a EGRS valve | EGRS valve diameter = 1.25 inches | 0 |
| | EGRS valve diameter = 1.72 inches | 1100 |
| | EGRS valve diameter = 2.5 inches | 4705 |
| Fast SG depressurization | ICC = 350 °C | 1352 |
| | ICC = 650 °C | 190 |

considered in both models analyzed to be similar, it has been assumed that the RCSs in the 3 loops PWR-W are triggered at the beginning of the accidental sequence.

To analyze both strategies, the PD curve has first been obtained using the methodology applied to the VVER-1000/V320 reactor in Section 4. Along with the PD curve, the core uncovered curve, the ACC injection curve and the LPSI injection curves have also been plotted, see Fig. 40. As can be seen, the PD occurs up to 2 inches break sizes, and the break size where the PD occurs first is 1.5 inches at 7263 s. While the ACC inject prior to the PD for all sizes, only those break sizes where the LPSI injects are successful, except for the 2 inches break size, for which it does so after the PD has already occurred.

From the PD curve, the DD have been generated both for the controlled SGs depressurization at an RCS cooling rate of 55 K/h, see Fig. 41, and for the SGs depressurization at the maximum RCS cooling rate, see Fig. 42. The approach has been the one applied in the search for DDs in the VVER-1000/V320 reactor strategies.

Subsequently, the available time has been calculated for both strategies, see Fig. 43. The following can be drawn from the results obtained:

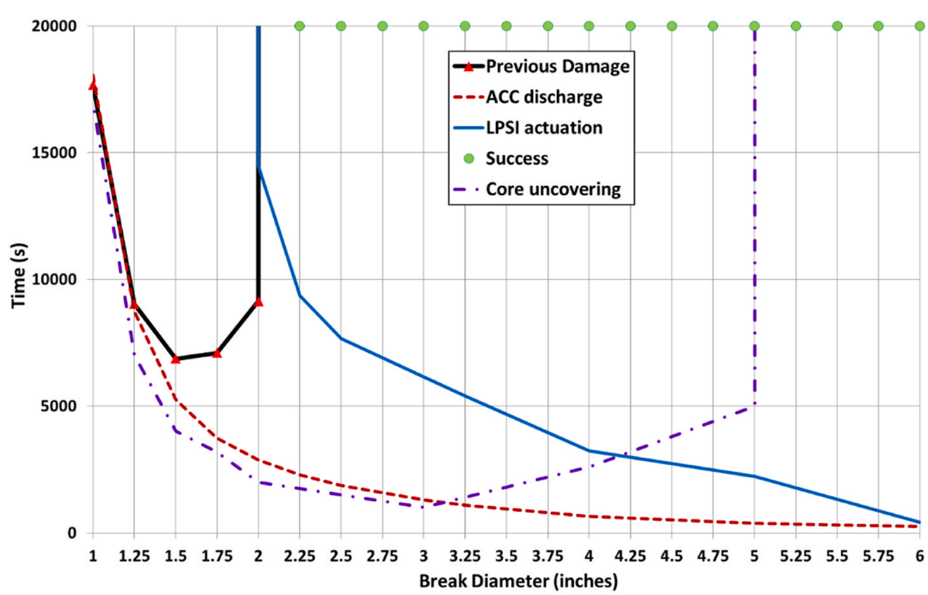


**Fig. 40.** Previous Damage Curve for SBLOCA with HPIS failure (3 loops PWR-W).

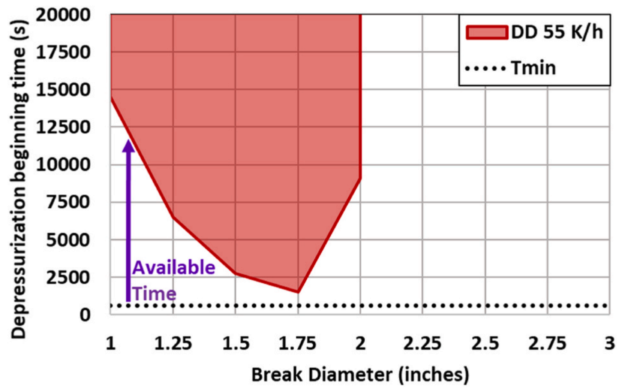


**Fig. 41.** Damage Domains for SBLOCA with HPIS failure and 55 K/h RCS cooling (3 loops PWR-W).

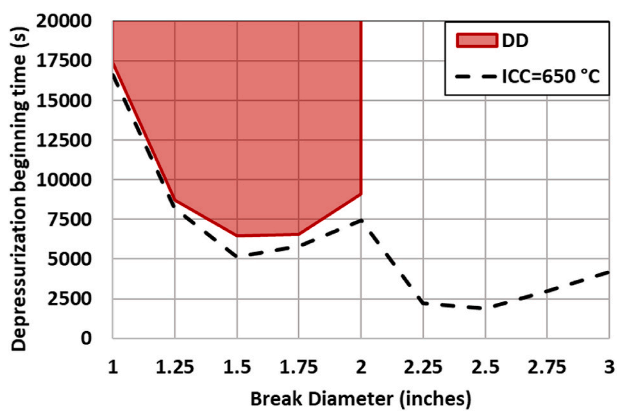


**Fig. 42.** Damage Domain for SBLOCA with HPIS failure and maximum RCS cooling via the SGs (3 loops PWR-W).

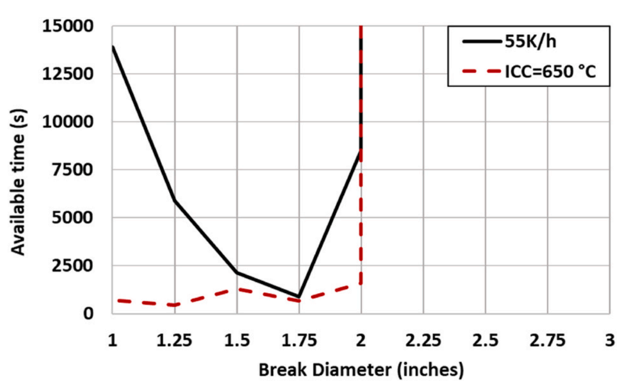


**Fig. 43.** Available time for SBLOCA with HPIS failure and RCS cooling (3 loops PWR-W).

- The available time for depressurization at maximum RCS cooling rate is much smaller than for controlled depressurization. This is because depressurization at maximum RCS cooling rate is initiated only if the ICC condition has been reached.
- The lowest available time in the controlled SGs depressurization strategy is 900 s, for 1.75 inches, which is considered medium as it is 15 min.
- The break size with the lowest available time in the fast SGs depressurization strategy is 1.25 in, which is 460 s. This is considered to be a short available time, as it is less than 15 min. Although the minimum available time is short, it may be reasonable as the MCR crew would be particularly attentive to the CET temperatures under these conditions.

## 10. Comparison of VVER-1000/V320 and Westinghouse PWR strategies in SBLOCA sequences with HPIS failure

The main aim in this section is to compare the results previously obtained with the TH model for the TRACE code of a VVER-1000/V320 reactor with those of a TH model of a 3 loops PWR-W. To be consistent, the DD for the controlled SGs depressurization at a 55 K/h RCS cooling rate in 3 loops PWR-W has been compared with the DD at 60 K/h RCS cooling rate in VVER-1000/V320 reactor. On the other hand, the DD for the SGs depressurization at maximum RCS cooling rate for the 3 loops PWR-W has been compared with that for the VVER-1000/V320 reactor. The following can be drawn:

- Controlled SGs depressurization: While for the 3 loops PWR-W the DD limit reaches 2 inches, for the VVER-1000/V320 reactor it reaches 2.25 inches. However, the DD is larger in the 3 loops PWR-W up to 1.75 inches, see Fig. 44.
- SGs fast depressurization: While for the 3 loops PWR-W the DD reaches 2 inches, for the VVER-1000/V320 reactor it reaches 2.25 inches. For smaller break sizes and for those larger than 1.75 inches the DD is greater for the VVER-1000/V320 reactor, but for break sizes between 1.25 and 1.75 inches the DD is greater for the 3 loops PWR-W, see Fig. 45.

In addition to the comparison of DDs, the available times for both PWR designs have also been compared, for the controlled SGs depressurization strategy, see Fig. 46, and for the SGs depressurization at maximum RCS rate, see Fig. 47. Moreover, the minimum available time for each strategy is shown in Table 6. The following main conclusions can be drawn from the results obtained:

- The strategy with the highest available time for the whole range of break sizes is the controlled SGs depressurization at an RCS cooling rate of 60/55 K/h for both designs.
- The second one is the corresponding to the fast SGs depressurization.

## 11. Conclusions

In this work, different management strategies to ensure core cooling in SBLOCA sequences with HPIS failure in both VVER-1000/V320 and Westinghouse PWR have been reviewed and analyzed. The main

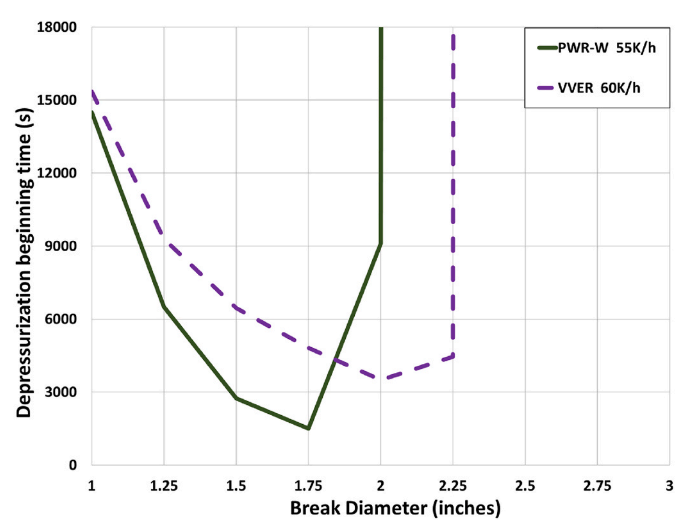


**Fig. 44.** Damage Domain for SBLOCA with HPIS failure and controlled SGs depressurization in 3 loops PWR-W and VVER-1000/V320.

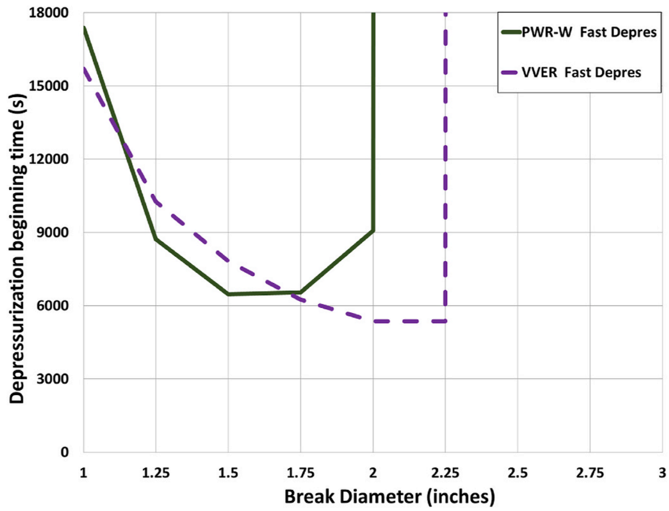


**Fig. 45.** Damage Domain for SBLOCA with HPIS failure and maximum RCS cooling rate in3 loops PWR-W and VVER-1000/V320.

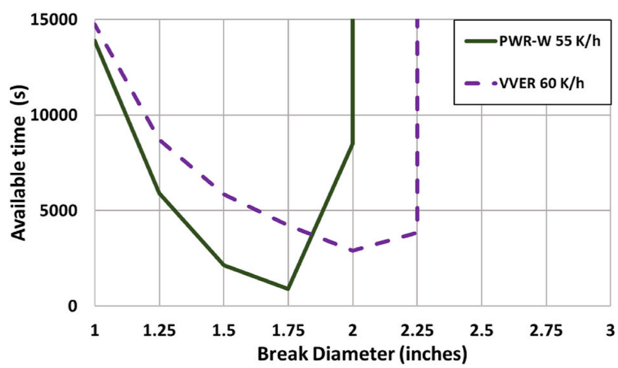


**Fig. 46.** Available times for SBLOCA with HPIS failure controlled SGs depressurization in 3 loops PWR-W and VVER-1000/V320.

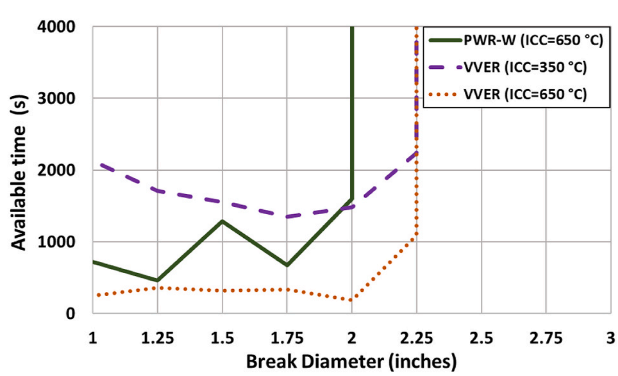


**Fig. 47.** Available times for SBLOCA with HPIS failure and fast cooling in 3 loops PWR-W and VVER-1000/V320.

conclusions obtained by means of the ISA methodology are as follows:

- In the VVER-1000/V320 reactor, if the success criteria are considered for the HA and LPIS trains, there are break sizes with no available time for the controlled SGs depressurization at an RCS cooling rate of 30 K/h. However, the controlled SGs depressurization at an RCS cooling rate of 60 K/h strategy provides a longer available time.

**Table 6**
Minimum available time in 3 loops PWR-W and VVER-1000/V320.

| PWR design | Strategy | Minimum Available Time (s) |
|---|---|---|
| VVER-1000/V320 | Controlled SG depressurization at 60 K/h | 2900 |
| | Fast SG depressurization (ICC = 350 °C) | 1352 |
| | Fast SG depressurization (ICC = 650 °C) | 190 |
| 3 loops PWR-W | Controlled SG depressurization at 55 K/h | 900 |
| | Fast SG depressurization (ICC = 650 °C) | 460 |

- The sensitivity analysis performed on the DD of the controlled SGs depressurization at 30 K/h strategy in VVER-1000/V320 has shown that if the HAs and the LPIS trains are fully available, the DD limits are smaller, so that there can be enough available time over the whole range of break sizes. However, if a 20% power uprate is performed, the DD limits are larger, so that the range of break sizes without available time increases.
- The sensitivity analysis performed on the DD of the controlled SGs depressurization at 60 K/h strategy has shown that if a 20 % power uprate is performed in a VVER-1000/V320 reactor, this management strategy may not be enough to avoid CD.
- In the VVER-1000/V320 reactor, the available time for the controlled SGs depressurization at an RCS cooling rate of 30 K/h is significantly modified if this is performed in combination with the opening of an EGRS valve. When the opening EGRS valve diameter is approximately 1.7 inches, there is enough available time for the entire range of break sizes, whereas for the smaller diameters, there is no available time for some break sizes. The success of this strategy then depends on the EGRS valve sizes of each NPP.
- The available time for controlled SGs depressurization at an RCS cooling rate of 55 K/h in the 3 loops PWR-W is large enough for the MCR crew.
- In the VVER-1000/V320 reactor, the fast SGs depressurization provides an adequate available time if it is considered that the ICC condition is reached when the CET temperature exceeds 350 °C (623 K) instead of 650 °C (923 K).
- In the PWR-W, when ICC conditions are reached, i.e., the CET temperature exceeds 650 °C (923 K), the maximum RCS cooling rate depressurization strategy allows to avoid core damage with enough available time.

It is emphasized that in the present work, a thorough review of Event Trees, EOPs and the public references related to SBLOCA with HPIS failure sequences, has been carried out, combined with the application of the ISA methodology. This comprehensive approach has allowed the identification of the available times for the MCR crew under different management strategies for both designs, VVER-1000/V320 and PWR-W.

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## CRediT authorship contribution statement

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

**Espinoza:** Writing – review & editing, Resources, Methodology, Conceptualization. **Miguel Sánchez-Perea:** Writing – review & editing, Resources, Methodology, Conceptualization. **Pavlin Groudev:** Writing – review & editing, Resources, Methodology, Conceptualization.

## 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 data that has been used is confidential.

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