MANAGEMENT OF THE SBLOCA SEQUENCES WITH HPIS FAILURE IN VVER-1000/V320 AND WESTINGHOUSE PWR

Authors

Elena Redondo-Valero[1], César Queral*[1], Kevin Fernandez-Cosials[1], Víctor Hugo Sanchez-Espinoza[2], Miguel Sánchez-Perea[3], Pavlin Groudev[4]

[1] Universidad Politécnica de Madrid (UPM), Ramiro de Maeztu 7, 28040 Madrid, Spain
[2] Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[3] Consejo de Seguridad Nuclear (CSN), Pedro Justo Dorado Dellmans, 11, 28040, Madrid, Spain
[4] Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Science, Tzarigradsko shaussee, 72, Sofia, Bulgaria

* Corresponding author: cesar.queral@upm.es

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

MANAGEMENT OF THE SBLOCA SEQUENCES WITH HPIS FAILURE IN VVER-1000/V320 AND WESTINGHOUSE PWR

Elena Redondo-Valero, Cesar Queral, Kevin Fernandez-Cosials, Victor Hugo Sanchez-Espinoza, Miguel Sanchez-Perea, Pavlin Groudev

Abstract

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 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 effective to avoid the core damage.

Acronyms

Accumulators (ACC)
Auxiliary Feedwater (AFW)
Beyond Design Basis Accident (BDBA)
Core Damage (CD)
Core Exit Thermocouples (CET)
Control Volume and Chemical System (CVCS)
Critical Safety Functions (CSF)
Damage Domain (DD)
Degraded Core Cooling (DCC)
Emergency Boron Injection System (EBIS)
Degraded Core Cooling (DCC)
Emergency Core Cooling System (ECCS)
Emergency Gas Removal System (EGRS)
Emergency Feed Water (EFW)
Emergency Operating Procedures (EOPs)
Event Tree (ET)
High Head Safety Injection (HHSI)
High Pressure Injection System (HPIS)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

High Pressure Safety Injection (HPSI)
Hot Leg (HL)
Hydro-Accumulator (HA)
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)
Main Feed Water (MFW)
Medium Break Loss-of-Coolant Accident (MBLOCA)
Nuclear Power Plant (NPP)
Nuclear Safety Council (CSN)
Peak Cladding Temperature (PCT)
Pressurizer (PZR)
Pressurized Water Reactor (PWR)
Pressurized Water Reactor Westinghouse (PWR-W)
Previous Damage (PD)
Probabilistic Safety Analysis (PSA)
Reactor Coolant Pump (RCP)
Reactor Coolant System (RCS)
Reactor Pressure Vessel (RPV)
Reactor Vessel Level Indicator System (RVLIS)
Refueling Water Storage Tank (RWST)
Small Break Loss-of-Coolant Accident (SBLOCA)
Steam Dump Valves to the Atmosphere (BRU-A)
Steam Dump Valves to the Condenser (BRU-K)
Steam Generator (SG)
Thermal-hydraulic (TH)
Total Loss of Feed Water (TLFW)

Highlights

- Management strategies for SBLOCA sequences with high-pressure injection system failure in VVER-1000/V320 and Westinghouse PWR.
- Reactor Coolant System cooling via the controlled or fast depressurization of the Steam Generators.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

Keywords

VVER-1000/V320, Westinghouse PWR, SBLOCA, Emergency Operating Procedures, Damage Domains.

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), which is assumed to occur when the Peak Cladding Temperature (PCT) exceeds 1477 K. However, in Small Break Loss-of-Coolant Accident (SBLOCA) sequences with HPIS failure, the RCS pressure may stagnate above the HA pressure, preventing the HA from replenishing the RCS inventory before exceeding the CD. This behavior can be observed in any Pressurized Water Reactor (PWR) design, 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 RCS water inventory and the Emergency Core Cooling System (ECCS) conditions.

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

The UPM group has developed experience in reviewing/improving EOPs, determining available times for control room 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 3 loops 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., 2023, 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 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 strategies related to the SBLOCA sequence management in VVER-1000/V320 and 3 loops PWR-W. 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, respectively. 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 given in Section 11.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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

This section discusses the different strategies for managing SBLOCA with HPIS failure sequence 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, there are differences in the liquid volumes in both the RCS and Steam Generators (SG), see Table 1, and in their ECCSs, 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) system in the 3 loops PWR-W. The accumulators are named HA in the VVER-1000/V320 and Accumulators (ACC) in the 3 loops PWR-W.

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

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

Parameters		VVER-1000/V320	3 loops PWR-W
Thermal Power (MW)		3000	3000
HA/ACC	Nº of trains	4	3
	Total 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)	1.5	2.5
	Max mass flow rate per pump (kg/s)	406.8	207.2

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

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 operator 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). In an SBLOCA with HPIS failure sequence, the EOPs involved are as follows:

- When a reactor SCRAM occurs, the control room crew begins to follow the ORG, specifically the EOP E-0 "reactor trip or safety injection". In EOP E-0 step 22, 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 in step 11, the operator checks the RCS pressure. If it is higher than 150 bar, 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

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

cool the RCS is the controlled depressurization of the SGs at a cooling rate of 55 K/h through the SGs (TECNATOM, 1999), see Figure 1.

- From the EOP E-0 step 24, 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". 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 (orange) or extreme challenge (red), 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 Figure 2:

    - The EOP FR-C.3: Response to saturated core cooling (yellow).
    - The EOP FR-C.2: Response to Degraded Core Cooling (DCC) (orange).
    - 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 ^{o}C (649 K), see (Eisenhut, 1982; IEEE, 2002; Lutz, 2004; NRC, 2006, 1983). If this occurs, the FR-C.2 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 ^{o}C (923 K), the EOP FR-C.1 indicates that the RCS shall be cooled through the SGs at the maximum RCS cooling rate. It should be noted that there are F.0.2 that consider the Reactor Vessel Level Indicator System (RVLIS) and the number of RCPs 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 (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 Figure 3. The SBLOCA ET indicates that in case of HPSI failure, to reach a successful end state, the success of the following headers is required: the Auxiliary Feedwater (AFW), the RCS cooling and depressurization via the SGs, the injection of the ACCs and the LPSI, in its two actuation modes, first the injection from the Refueling Water Storage Tank (RWST) and then the recirculation from the containment sump, see red path (sequence 10) in Figure 3.

In most of the PSA of the 3 loops PWR-W, the ETs header “RCS cooling via the SGs” considers the controlled SGs depressurization (ES-1.2 and 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 in the 3 loops PWR-W of SBLOCA with HPIS failure sequences 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 and 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 ^{o}C (923 K) (in FR C.1).

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

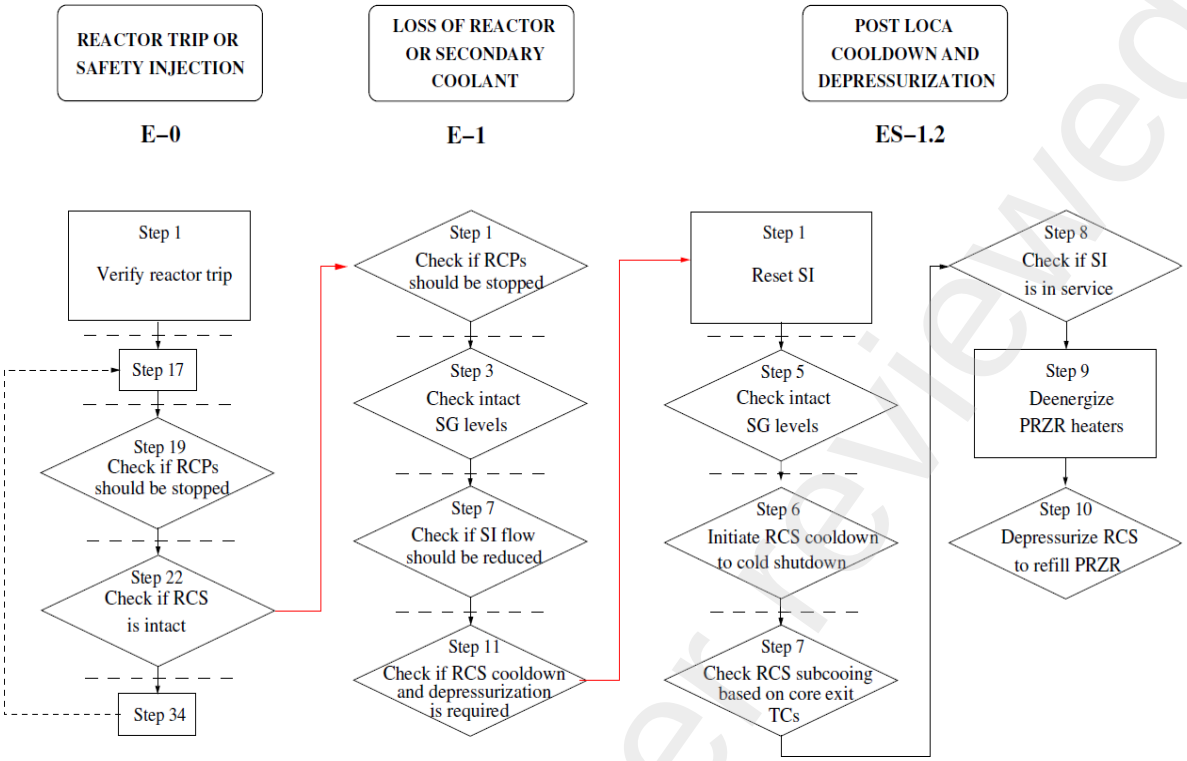

Figure 1 Westinghouse PWR EOP related with SBLOCA sequences (E-0, E-1, ES-1.2)

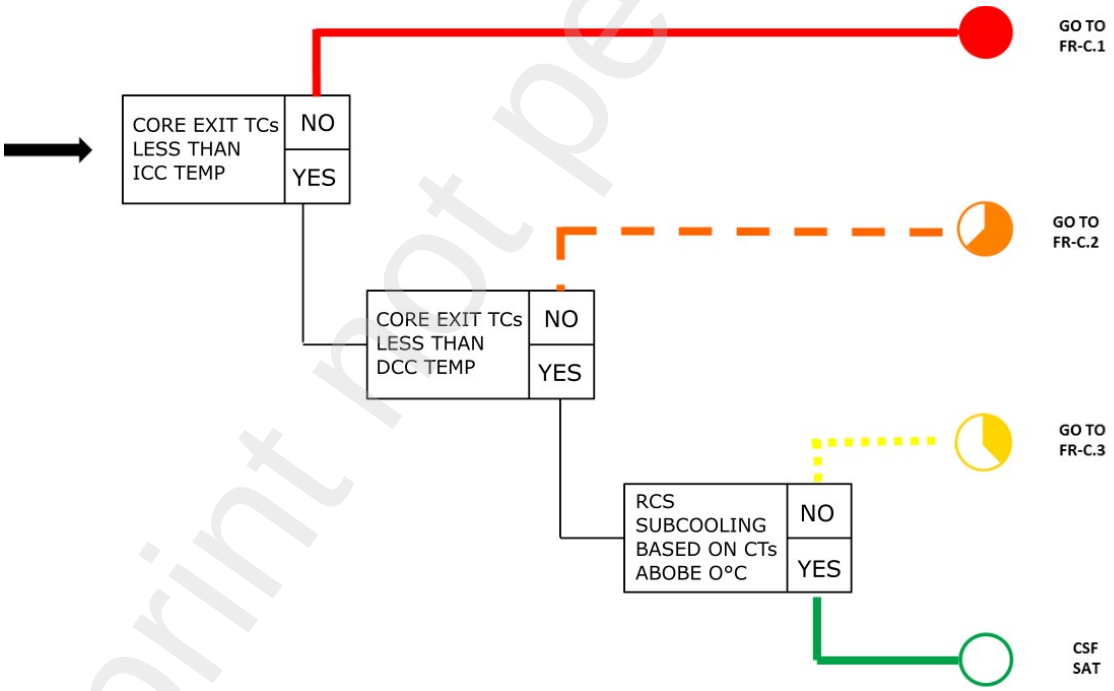

Figure 2 Westinghouse PWR FRG Core Cooling Status Tree (i.e., F.0.2)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

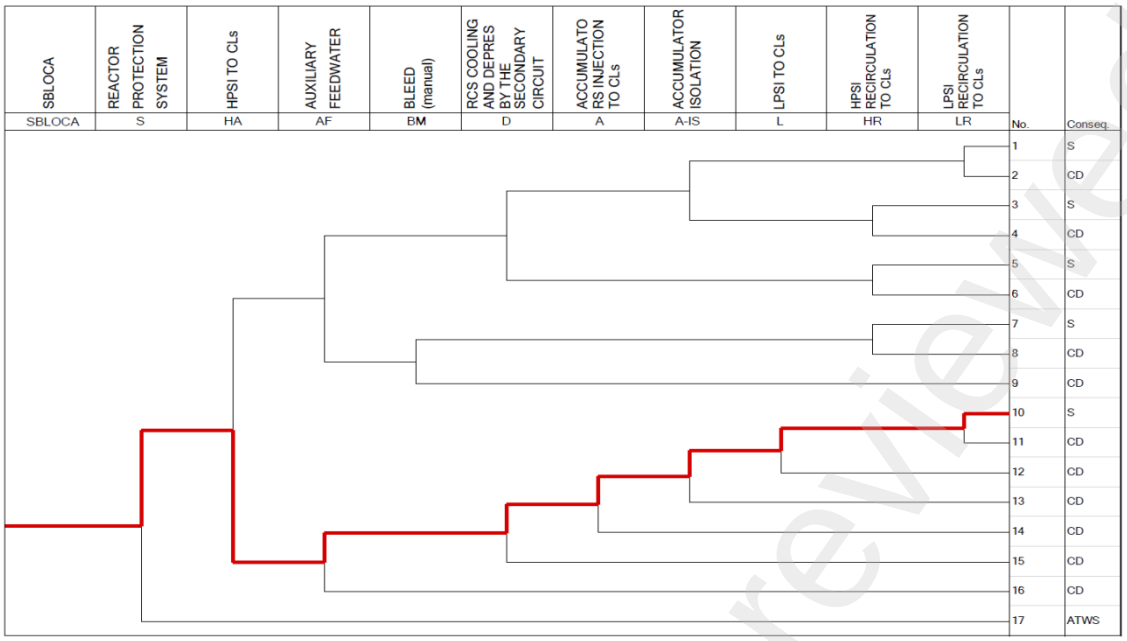

Figure 3 Westinghouse PWR SBLOCA Event Tree

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

In the late 1990s, a significant number of VVER NPPs decided to change their accident management approach, see (Bánáti and Ézsol, 1997; Cherubini et al., 2008; Groudev and Hadjiev, 2001; Pavlova et al., 2008, 2007). 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). 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). 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 is reached, the EOPs specify that it is necessary to initiate SGs depressurization at the maximum RCS cooling rate. References have been found indicating that the ICC condition is considered when the CET temperature exceeds 350 ^{o}C (623 K) to 400 ^{o}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., n.d.). Within this project, experiments were performed at the PSB-VVER experimental facility (Araneo, 2008; Del Nevo et al., 2007). A total of six PSB-VVER experiments reproduce SBLOCA sequences. In tests 11 and 12, a controlled SGs depressurization is performed at an RCS cooling rate of 30 K/h, while in tests 4 and 16, the depressurization is carried out at the maximum RCS cooling rate.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

On the other hand, the SBLOCA ET for VVER-1000/V320 reactors (Skalozubov et al., 2010) shows that in case of HPIS failure, the remaining ET headers have to be fulfilled for the sequence to be successful, see Figure 4 (sequence 3). These headers are the RCS cooling by the controlled SGs depressurization, the boron injection, the opening of the Emergency Gas Removal System (EGRS) valves in the RCS, the injection of the HA and finally the injection of the LPIS. Therefore, the ET indicates that in addition to the RCS cooling through the controlled SG depressurization, the EGRS actuation is also required. It should be noted that both LPIS actuation modes (injection and recirculation from the containment sump) are included in one header instead of two headers as in the 3 loops PWR-W ET.

In VVER-1000/V320 reactors, the RCS cooling by the SGs depressurization is performed through the Steam Dump Valves to the Condenser (BRU-K) or through the Steam Dump Valves to the Atmosphere (BRU-A) if the condenser is not available. In summary, the main strategies found in the VVER-1000/V320 reactors in the event of a SBLOCA with HPIS failure sequence are:

- Controlled SGs depressurization at an 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.

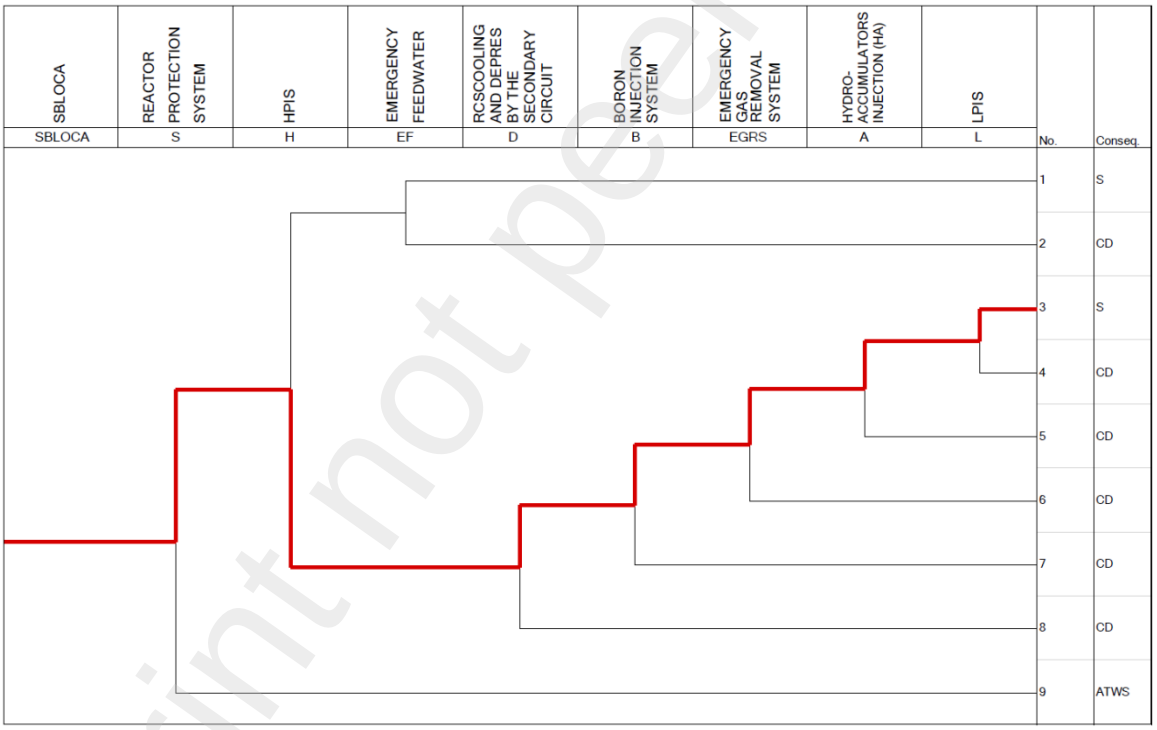

Figure 4 VVER-1000/V320 SBLOCA Event Tree (Skalozubov et al., 2010)

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 Figure 5 and Figure 6. 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).

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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), RPV, core, SGs, steam lines and steam headers. The VVER-1000/V320 TH model also includes the ECCS, Figure 7 (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 Emergency Feed Water (EFW).

The actuation signals are included for the following safety systems: the LPIS, the HPIS, the EBIS, the BRU-A valves, the safety valves and the BZOK main isolation valves of the steam lines, the BRU-K steam discharge valves to the condenser, the PZR spray and safety valves, and the 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.

In this study, the unavailability of the BRU-K valves is considered, therefore the SGs depressurization is performed by the BRU-A valves. The control implemented for the controlled SGs depressurization through the BRU-A valves model calculates the cooling function at 30 K/h or 60 K/h from the average temperature of the RCS at the moment the manual action is started. On the other hand, it measures the average temperature of the four RCS loops and calculates the difference with the value of the cooling curve at 30 K/h or 60 K/h at each time step. This deviation between the average RCS temperature and the cooling curve is then used as input in the control model to give the corresponding opening for the four BRU-A valves at any given time.

In this section it has been decided not to include the description of the TH model for the 3 loops PWR-W in this analysis, because it is extensively explained in other 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., 2023, 2018).

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

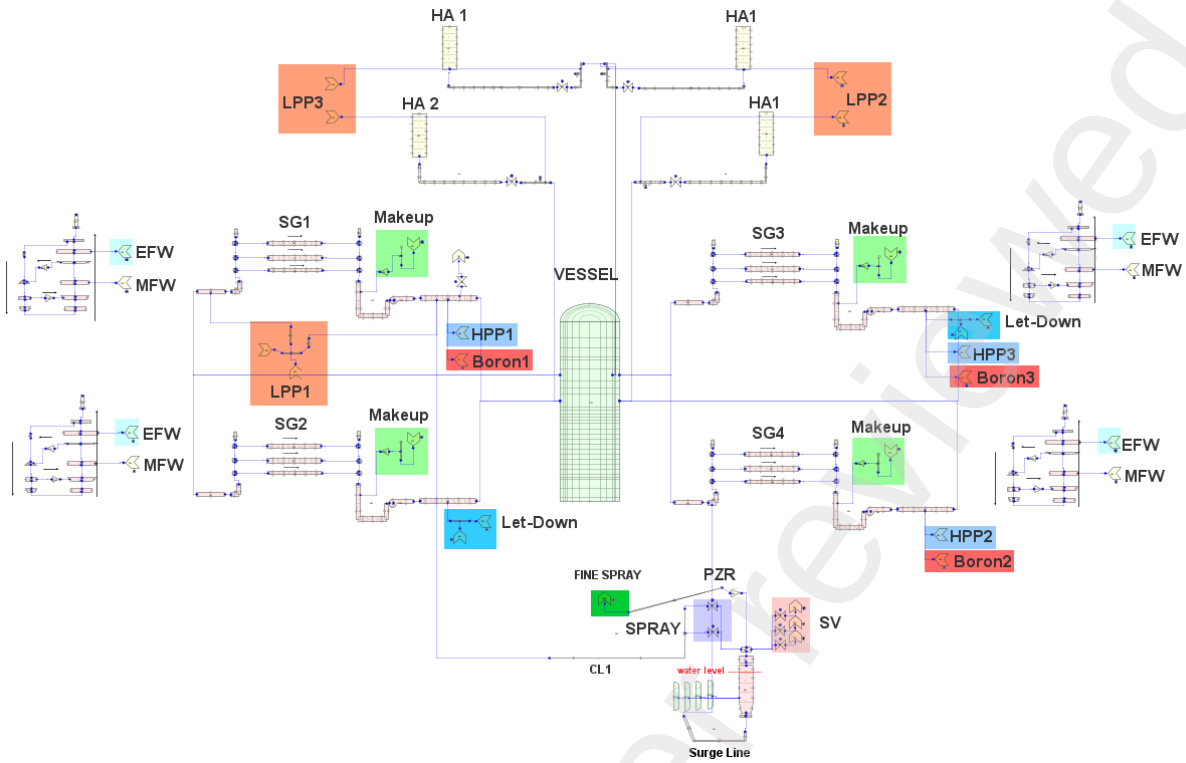

Figure 5 VVER-1000/V320 RCS TRACE TH model

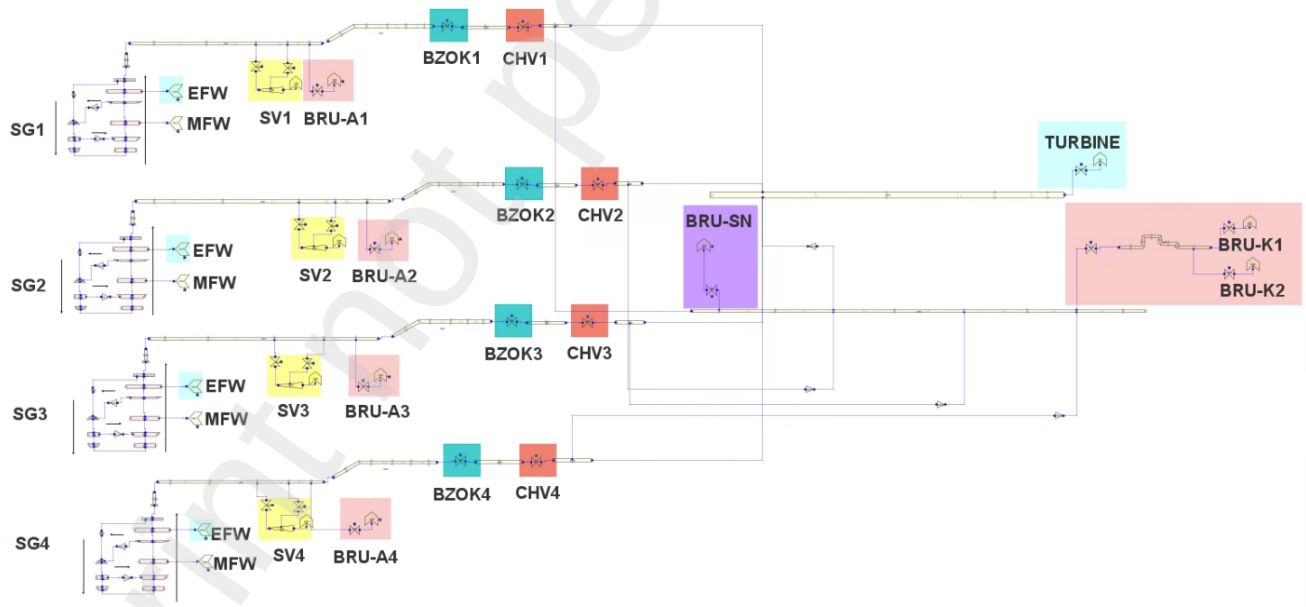

Figure 6 VVER-1000/V320 secondary side TRACE TH model

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

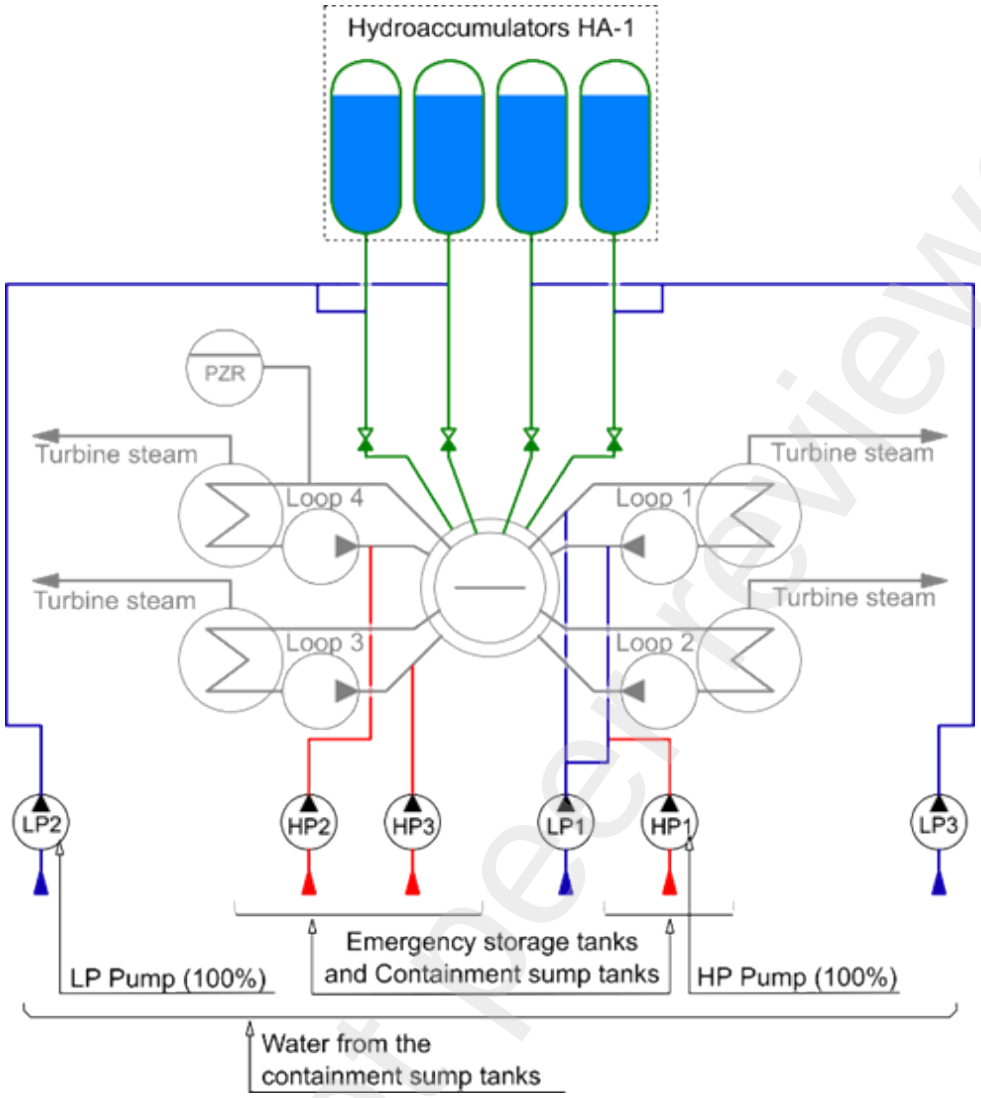

Figure 7 ECCS configuration in VVER-1000/V320

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

Table 3 Steady State Parameters of VVER-1000/V320

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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 control room crew are not considered. The 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

The break size of 1.5 in locate 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 begging of the transient: 100%.
- The LPIS and HA availability is limited to the success criteria: 2 out of 4 HA trains available and 1 out of 3 LPIS trains available (Skalozubov et al., 2010).

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 in 595 s, see Figure 8. No HPIS pumps are working. 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 Figure 9. The core starts to uncover at about 6000s, see Figure 10. 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 x 10^5 kg, see Figure 11. It is worth noting that CD occurs when the RCS pressure is well above the LPIS setpoint.

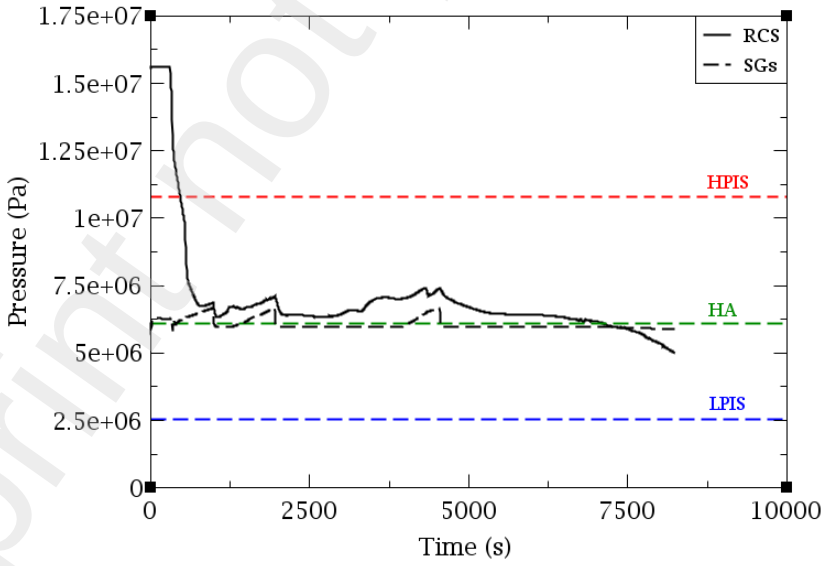

Figure 8 RCS and SGs pressure (1.5 in. SBLOCA with HPIS failure without human action)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

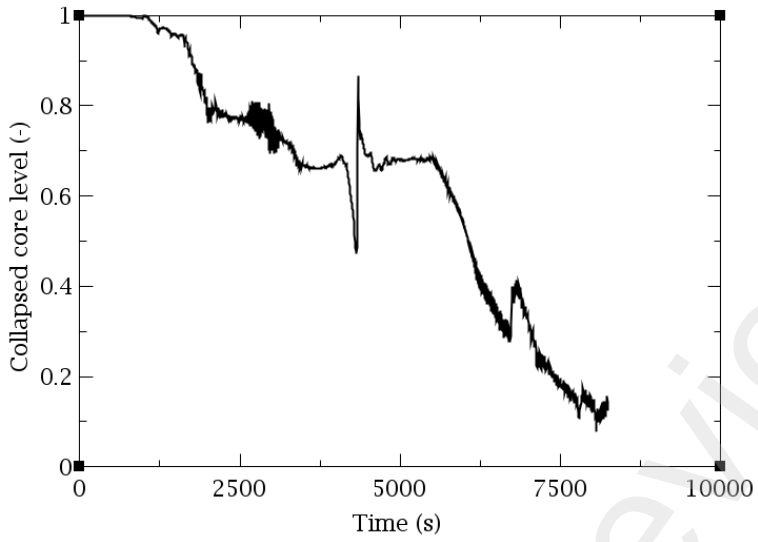

Figure 9 Collapsed Core Level (1.5 in. SBLOCA with HPIS failure without human action)

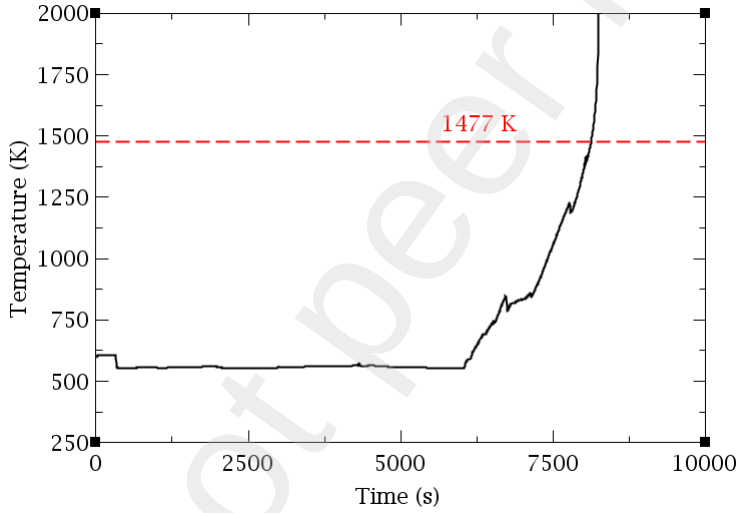

Figure 10 PCT (1.5 in. SBLOCA with HPIS failure without human action)

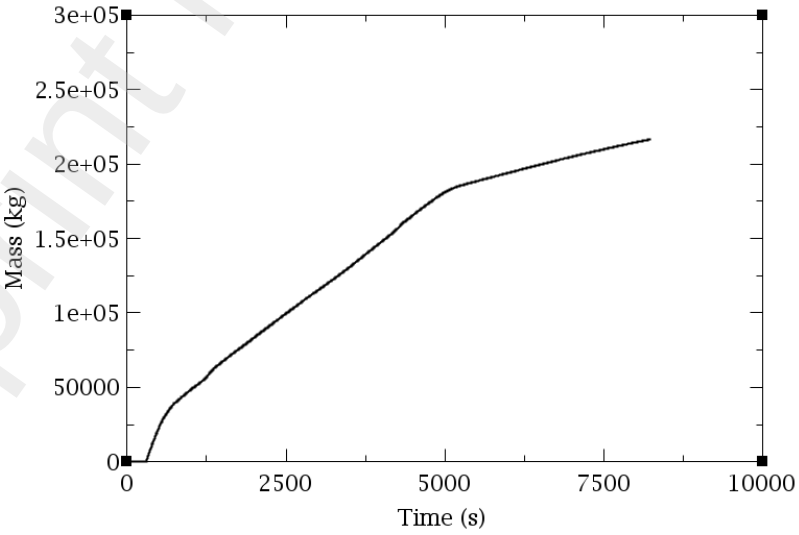

Figure 11 Integral of the mass flow through the break (1.5 in. SBLOCA with HPIS failure without human action)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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 action. This information is provided by the denominated Previous Damage (PD).

To obtain the PD, SBLOCA with HPIS failure sequences have been simulated for different break sizes without any management action. The range for the break size considered is from 1 to 6 in. with a sweep of 0.25 in. 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 Figure 12.

For the cases that CD is reached, CD times are plotted against the break sizes, see Figure 14. 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. The curve made up of all the red markers is called the PD curve. A detailed analysis of the PD obtained shows:

- From 2.5 in. 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 in., for smaller breaks sizes, CD takes a long time to occur, and as the break sizes get larger, CD occurs earlier.

Along with the PD curve, the core uncovering curve, the HA injection curve and the LPIS injection curves have also been plotted, see Figure 14. For this task, the time at which the core is uncovered and the time at which the HA and the LPIS begin to inject water into the RCS, if this occurred, have been determined from the simulations of the SBLOCA with HPIS sequences previously simulated to obtain the PD curve, see Figure 12 and Figure 13. The following conclusions can be drawn from these curves:

- The HA inject into the RCS at every break size analyzed, but at smaller break sizes, between 1 and 2.25 in., it is too late to stop the PCT from rising.
- The LPIS pumps start for break sizes from 2.25 in. 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).
- Except for the 2.25 in., the SBLOCA with HPIS failure sequences are successful when the LPIS inject water into the RCS.
- Although CD occurs up to 2.25 in., the core is uncovered up to 3 in.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

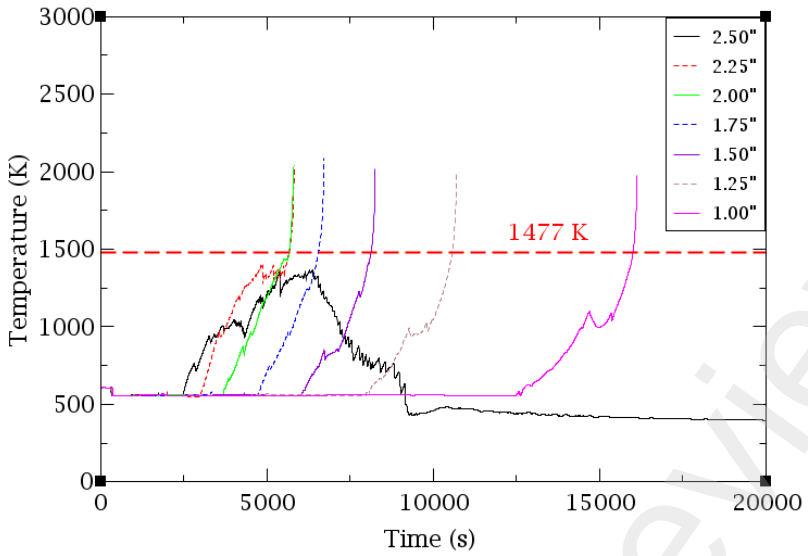

Figure 12 PCT in 1 to 2.5 in. SBLOCA with HPIS failure without human action

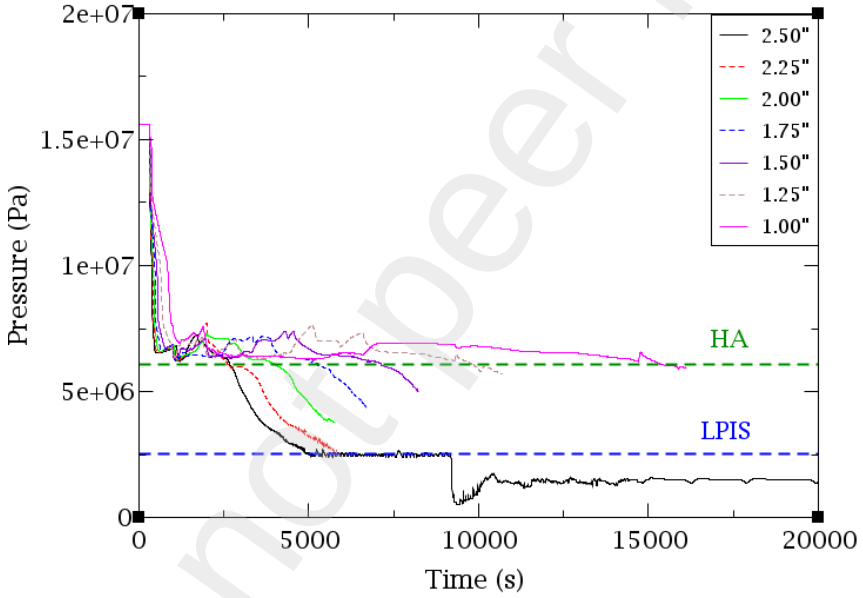

Figure 13 RCS pressure in 1 to 2.5 in. SBLOCA with HPIS failure without human action

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

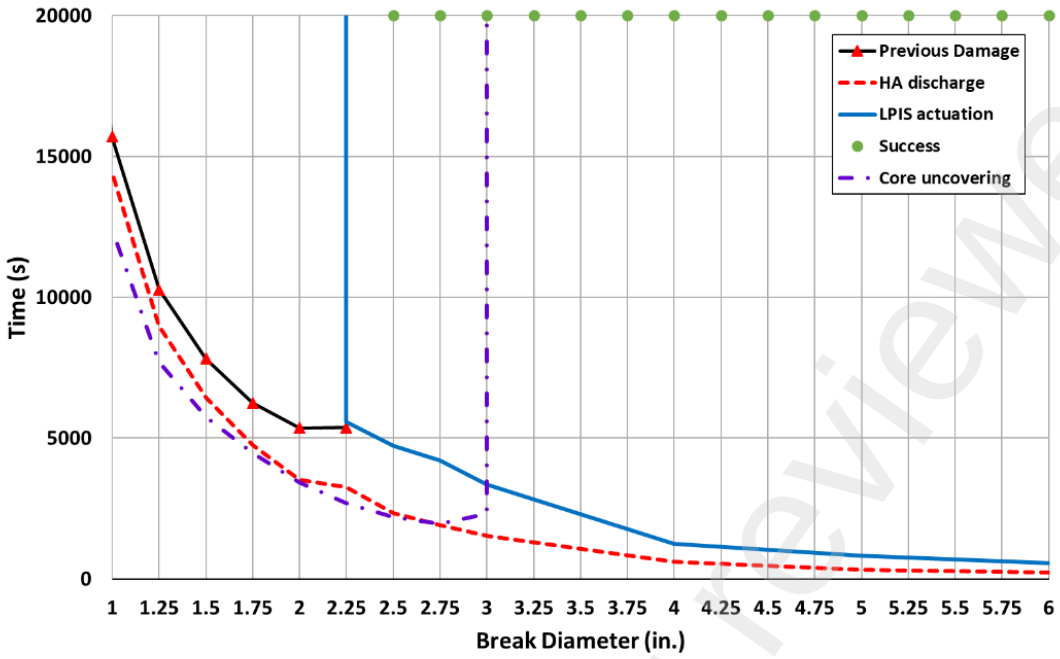

Figure 14 Previous Damage curve for SBLOCA with HPIS failure (VVER-1000/V320)

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

By obtaining the PD curve of the SBLOCA sequence with HPIS failure, it has been found that there is a range of break sizes that reach CD if no human actions are credited. Therefore, in these sequences, it is necessary that the control room 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 SBLOCA sequence with HPIS failure, 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 parameter. The break size chosen has been the 1.5 in. located in the cold leg 1 with the hypotheses considered in the base case of the SBLOCA sequence with HPIS failure without human actions.

The controlled SGs depressurization is performed by the BRU-A atmospheric valves located in the four steam lines, upstream of the safety valves. This human action is simulated with the TH model for the TRACE code by means of an implemented controller, see section 3.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

5.1.1. Depressurization with 30 K/h RCS cooling rate

The start time, from the beginning of the SBLOCA sequence, selected for the SGs depressurization at a 30 K/h rate have been 7000 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 sequence evolves in a different way, depending on the start of the SGs depressurization:

- 7000 s: In this case the operator action starts too late, Figure 15, since in the PD curve shows that the previous CD occurs at 7500 s.
- 6200 s and 5400 s: In this cases, the SGs pressure starts to reduce the RCS pressure as soon as the manual action is initiated, see Figure 16. The RCS pressure reaches the HA pressure and continues to fall, but before it reaches the LPIS cut-off pressure, CD occurs, see Figure 15. This is because the collapsed core level is already low when the operator action is initiated, see Figure 17.
- 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 Figure 16. 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 Figure 18. When this point is reached, the core is reflooded, see Figure 17.

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 collapse level is below 50 %, Figure 15 and Figure 17.

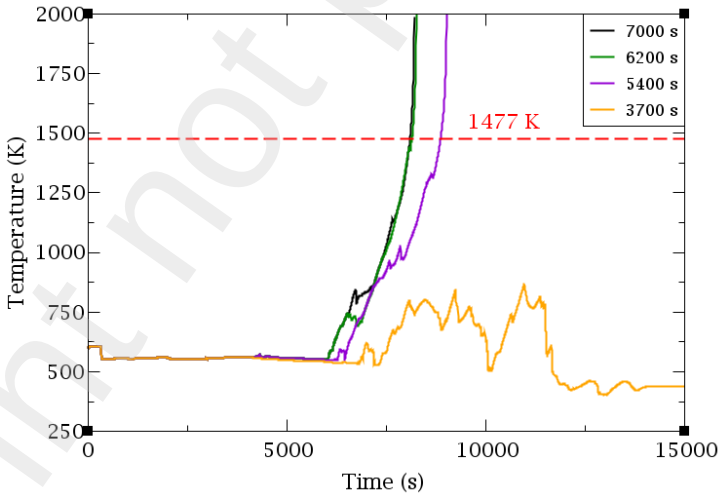

Figure 15 PCT (1.5 in. SBLOCA with HPIS failure and RCS cooling at 30 K/h)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

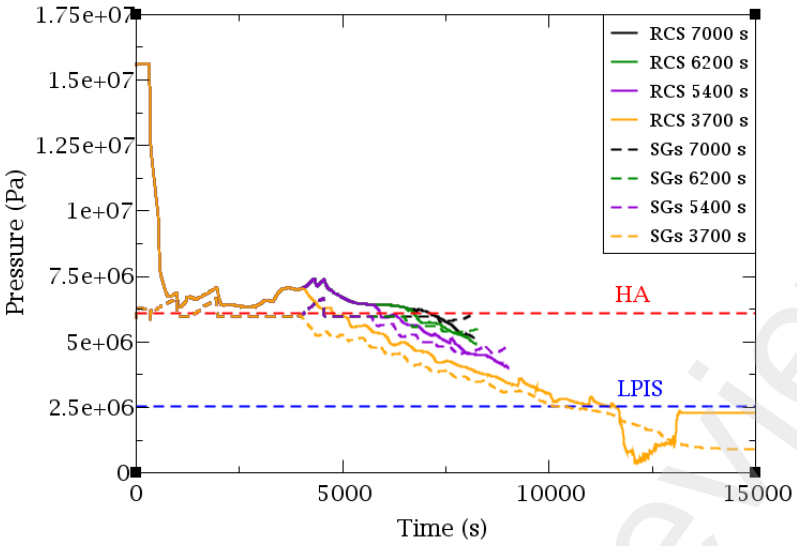

Figure 16 RCS and SGs pressure (1.5 in. SBLOCA with HPIS failure and RCS cooling at 30 K/h)

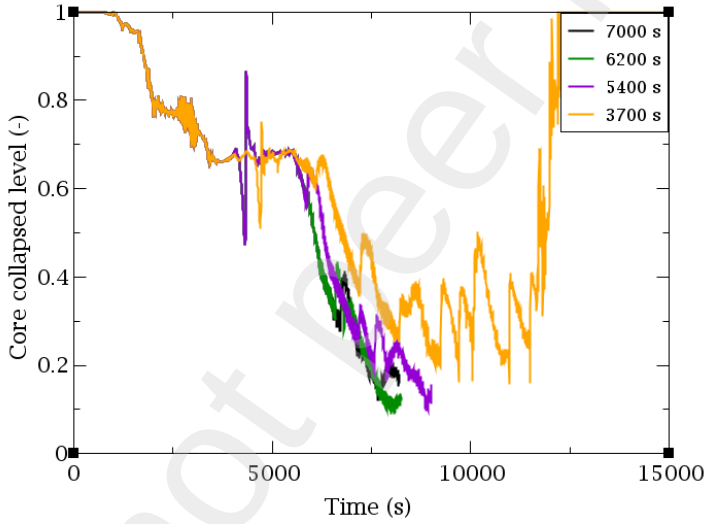

Figure 17 Core Collapsed Level (1.5 in. SBLOCA with HPIS failure and RCS cooling at 30 K/h)

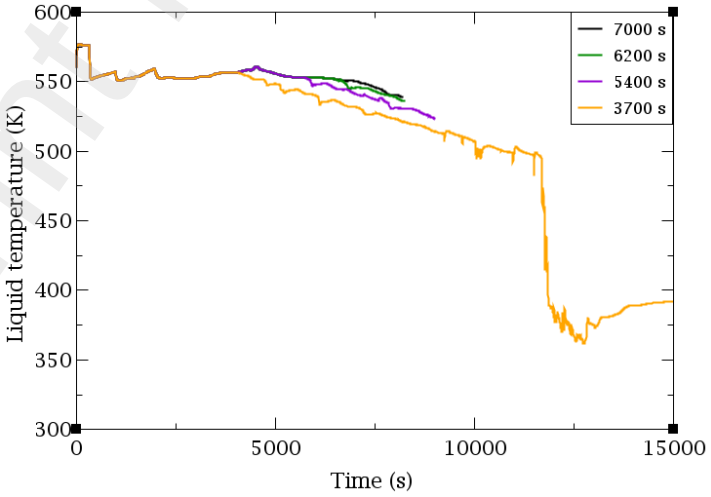

Figure 18 RCS average liquid temperature (1.5 in. SBLOCA with HPIS failure and RCS cooling at 30 K/h)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

5.1.2. Depressurization with 60 K/h RCS cooling rate

The start time, from the beginning of the SBLOCA sequence, selected for the SGs depressurization at a 60 K/h rate have been between 3700 and 7300 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 secondary side depressurization until the manual action is initiated, see Section 4.1. Thereafter, each of the four sequences has a different evolution:

- 7300 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 Figure 19.
- 6200 s: Although core uncovering occurs, see Figure 22, the RCS pressure successfully reaches the LPIS cut-off pressure in time to reflood the core, see Figure 21, before the PCT exceeds 1477 K, see Figure 20.
- 5400 s and 3700 s: The RCS pressure successfully reaches the LPIS cut-off pressure, see Figure 20.

As expected, the depressurization of the SGs at a RCS cooling rate of 60 K/h 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 collapse level is below 50 %, see Figure 19 and Figure 21.

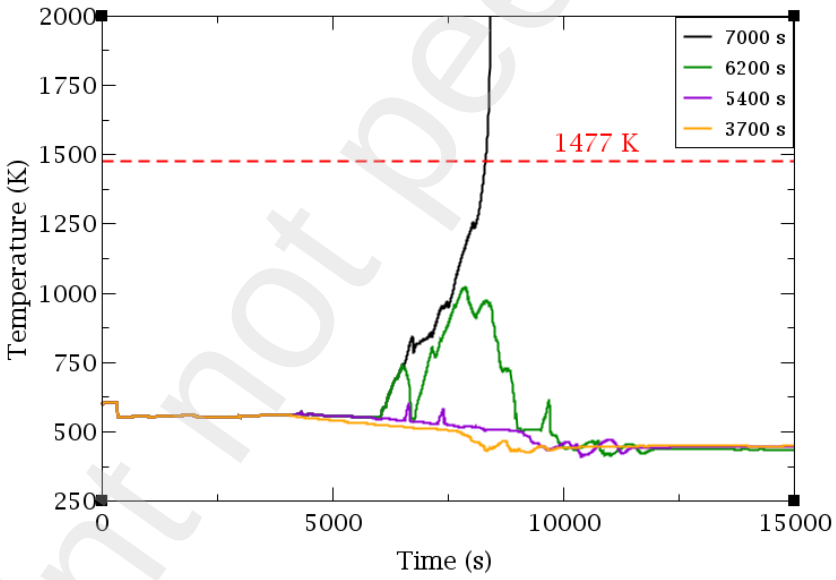

Figure 19 PCT (1.5 in. SBLOCA with HPIS failure and RCS cooling at 60 K/h)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

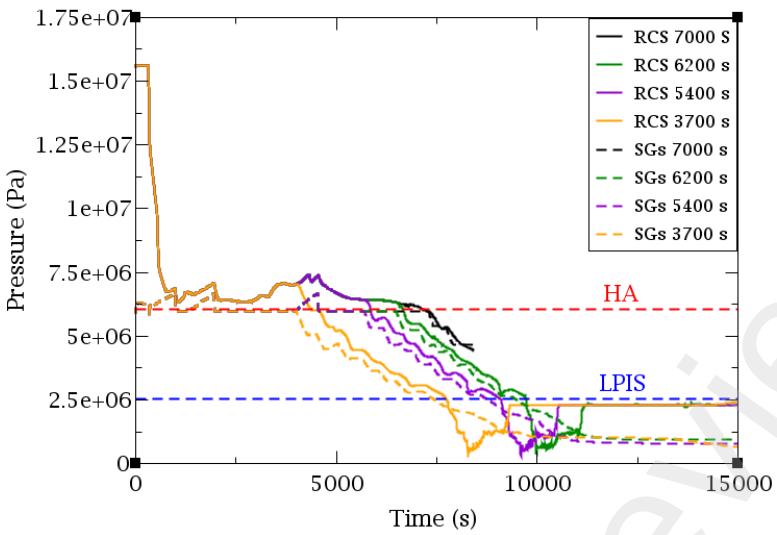

Figure 20 RCS and SGs pressure (1.5 in. SBLOCA with HPIS failure and RCS cooling at 60 K/h)

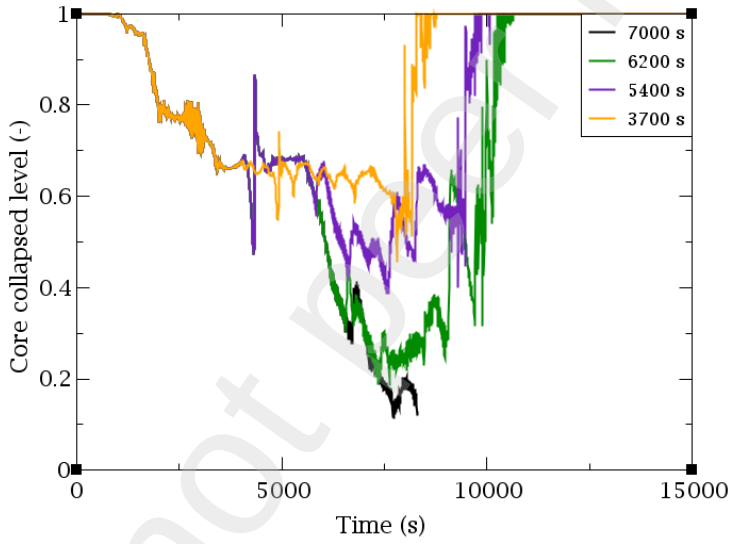

Figure 21 Core Collapsed Level (1.5 in. SBLOCA with HPIS failure and RCS cooling at 60 K/h)

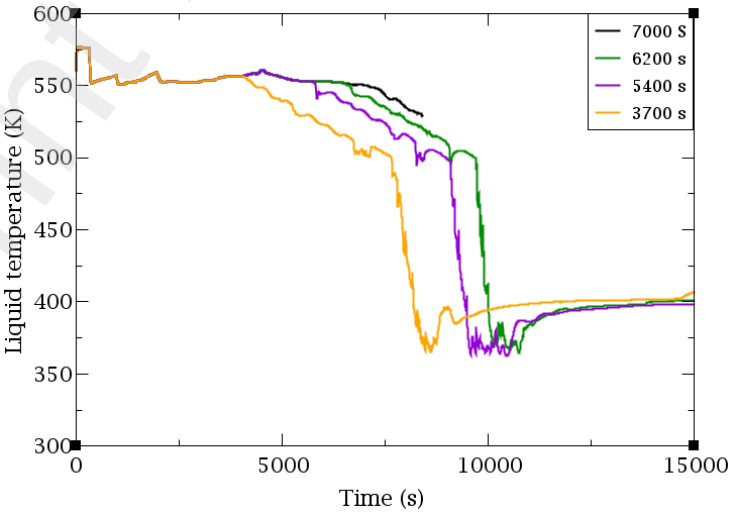

Figure 22 RCS average liquid temperature (1.5 in. SBLOCA with HPIS failure and RCS cooling at 60 K/h)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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, where CD is reached. The number of dimensions for this space region corresponds to the number of parameters involved in the analyzed sequence. The DD for the SBLOCA sequence with HPIS failure with controlled SGs depressurization has two dimensions as two parameters are varied, 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 value of the parameters considered. For that purpose, it is previously established which are the limits for 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 in.). 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. This is because if the manual action is initiated after the PCT exceeds 1477 K, it is not effective in preventing CD.

In order to obtain the DD for both controlled depressurizations at an RCS cooling rate of 30 K/h or 60 K/h, it has been simulated the SBLOCA sequence with HPIS failure for each break size between 1 and 2.25 in., with an interval of 0.25 in., testing different start times of the manual action from the PD curve, see Figure 23 (left) and Figure 24 (left). The DD is then obtained by drawing the line separating the damage and success regions, see Figure 23 (right) and Figure 24 (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 operator to reach the EOP path where the action is indicated to be performed. The time required by the control room 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 operation, see Figure 25.

$$T_{available} = T_{damage\ domain} - T_{min}$$

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

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

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

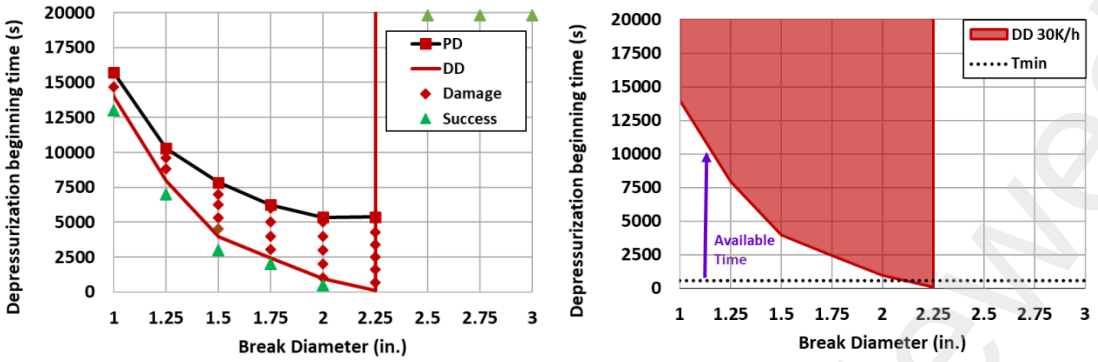

Figure 23 Damage Domain for SBLOCA with HPIS failure and 30 K/h RCS cooling (VVER-1000/V320)

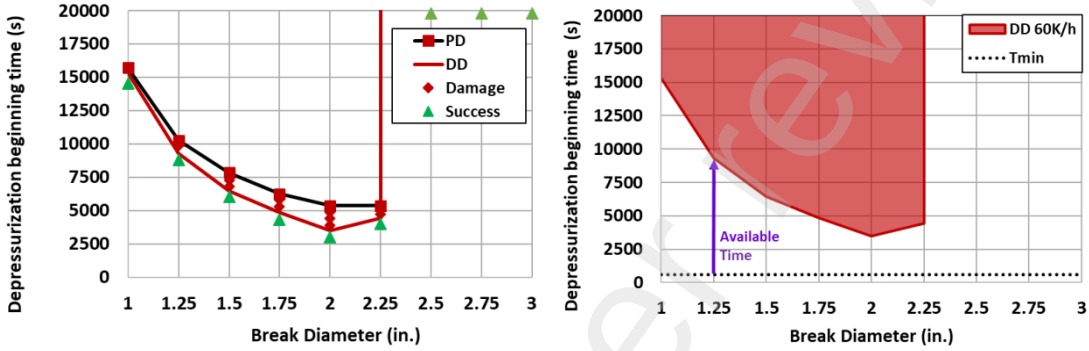

Figure 24 Damage Domain for SBLOCA with HPIS failure and 60 K/h RCS cooling (VVER-1000/V320)

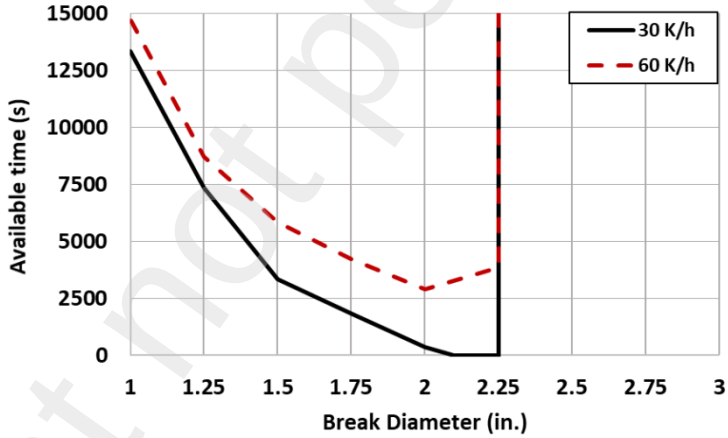

Figure 25 Available Times for SBLOCA with HPIS failure sequence with 30 K/h and 60 K/h RCS cooling (VVER-1000/V320)

5.3. SGs controlled depressurization. DD Sensitivity analysis

In the previous section, the DD has 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 HA and LPIS trains are those of the success criteria. In the present section, a sensitivity analysis of the DD to different boundary conditions for the core power and availability of the HA and LPIS trains has been carried out:

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

- Original case: The ECCS available trains are 2 out of 4 HA trains and 1 out of 3 LPIS trains. Core power at 100%.
- 2nd case (Power uprate): The ECCS available trains are 2 out of 4 HA trains and 1 out of 3 LPIS trains. Core power at 120%.
- 3rd case (ECCS fully available): The ECCS available trains are 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 available trains are 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 Figure 26 and Figure 27. 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 in. and it takes all the time between 2.25 and 2.75 in. For the third case (ECCS fully available) the DD extends to 1.75 in. where it reaches 4500 s, while, for the fourth case (power uprate and ECCS fully available) the DD extends to 2 in. 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 lower, 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 control room 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 reaches the same break size limits as the DDs for the 30 K/h RCS cooling rate, but it extends less in the time. The most limiting case is the second (power uprate) as it extends to 2.75 in. for which it reaches 850 s. For the third case (ECCS fully available) the DD reaches 7850 s for 1.75 in., while, for the fourth case (power uprate and ECCS fully available), the DD reaches 5400 s for 2 in.

  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.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

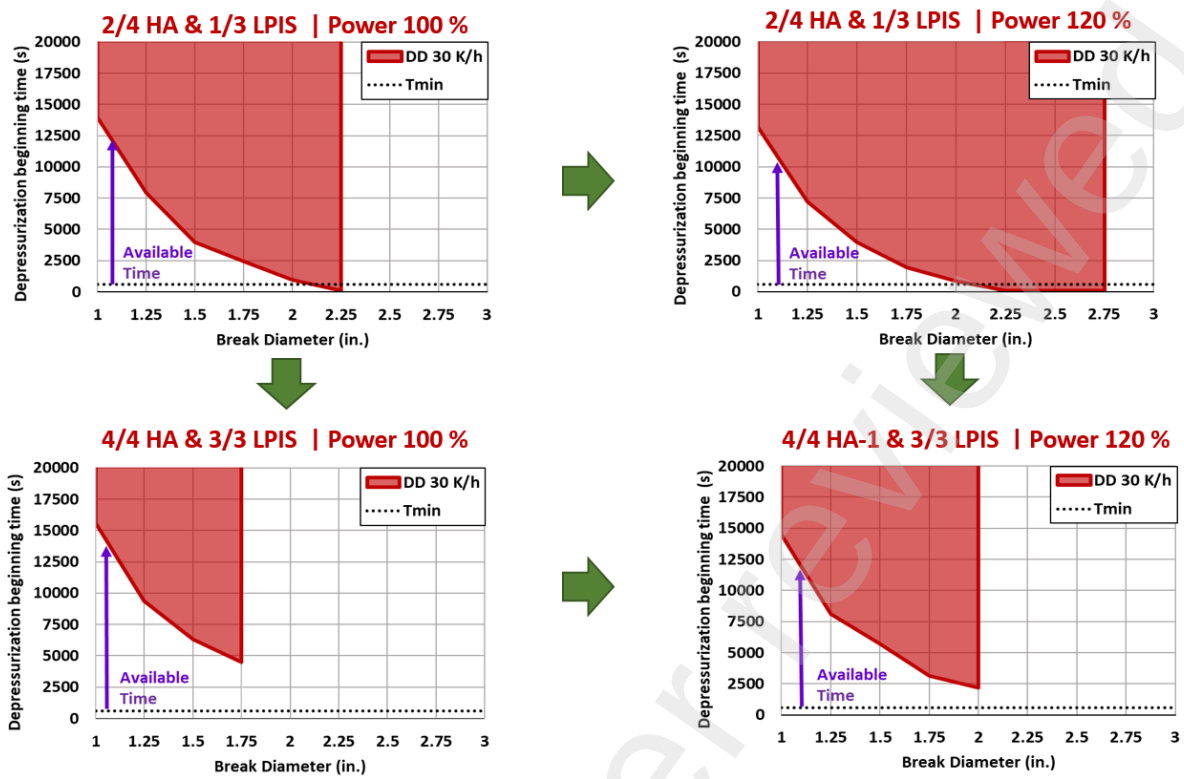

Figure 26 Damage Domain sensitivity analysis for SBLOCA with HPIS failure and 30 K/h RCS cooling (VVER-1000/V320)

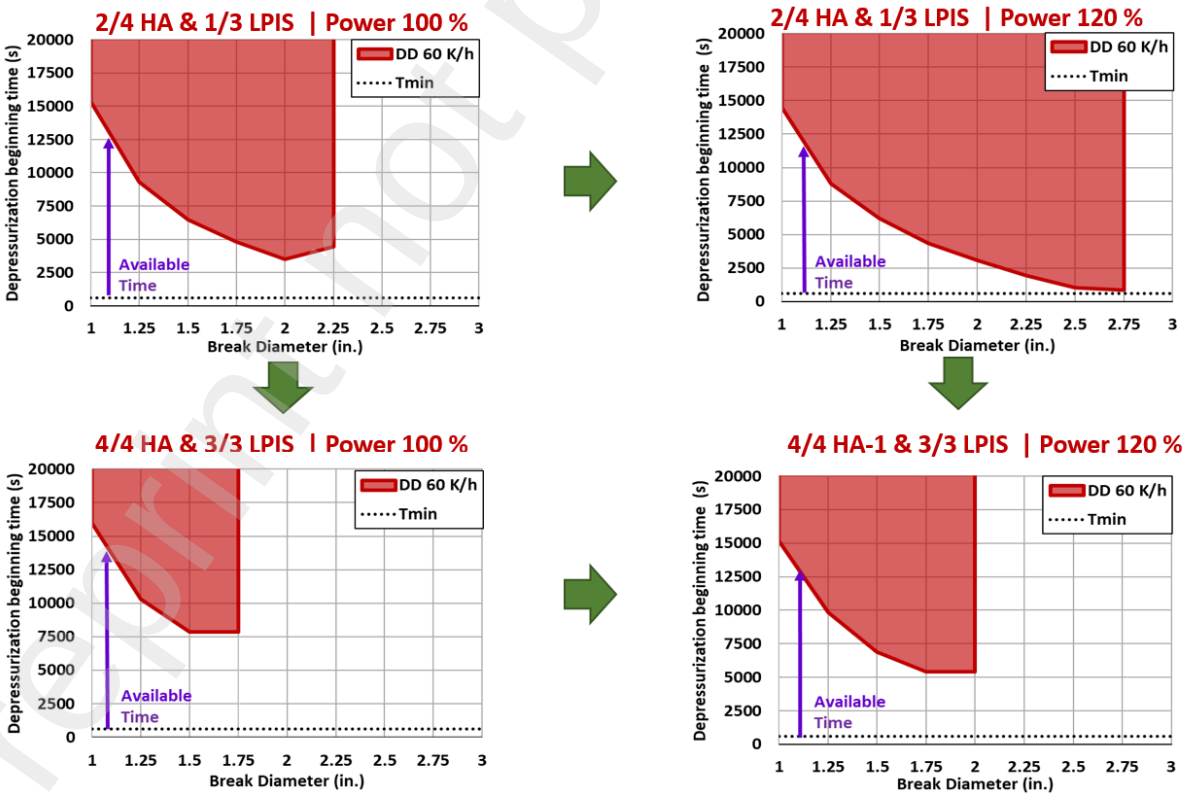

Figure 27 Damage Domain sensitivity analysis for SBLOCA with HPIS failure and 60 K/h RCS cooling (VVER-1000/V320)

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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

The EGRS is a safety system developed to remove steam-gas mixture from the upper RPV, the PZR and from the steam collector 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).

The SBLOCA ET for the VVER-1000/V320 reactor, Figure 4, 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 required. Based on the DDs obtained for the controlled SGs depressurization in Section 5, it was verified that the EGRS 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 Figure 28-A, the DD indicates that the opening of a EGRS valve would be necessary in order to avoid CD for the whole SBLOCA spectrum.

Therefore, Section 6 intends to analyse 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 of the same located in the PZR with a diameter of 1.25 in.

First, the DD of the EGRS actuation alone was obtained following the approaches used in Section 5, see Figure 28-B. It can be seen that the DD extends over the entire beginning depressurization time dimension from 1 to 1.75 in., 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 in., 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 in. If the areas of both openings in the RCS are summed, an area equivalent to the area of the LOCA break size plus approximately 0.5 in. is obtained, see Table 4. Therefore, despite the EGRS, sequences from 1 to 1.75 in. 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 Figure 28-C. It has been considered that the operator opens the EGRS valve 100 seconds after the beginning of the controlled SGs depressurization. The DD have 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 in. EGRS valve has been calculated. The available time obtained has been compared with that of the two strategies alone, see Figure 29. The following conclusions can be drawn:

- 1 to 1.75 in.: 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 curve values are lower. The

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

1.75 in. break size has no available time, it is medium for 1.5 in. and long from 1 to 1.25 in.

- 2 to 2.25 in: 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 hour.

Break diameter (in.)	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

Table 4 SBLOCA area along with the EGRS valve area

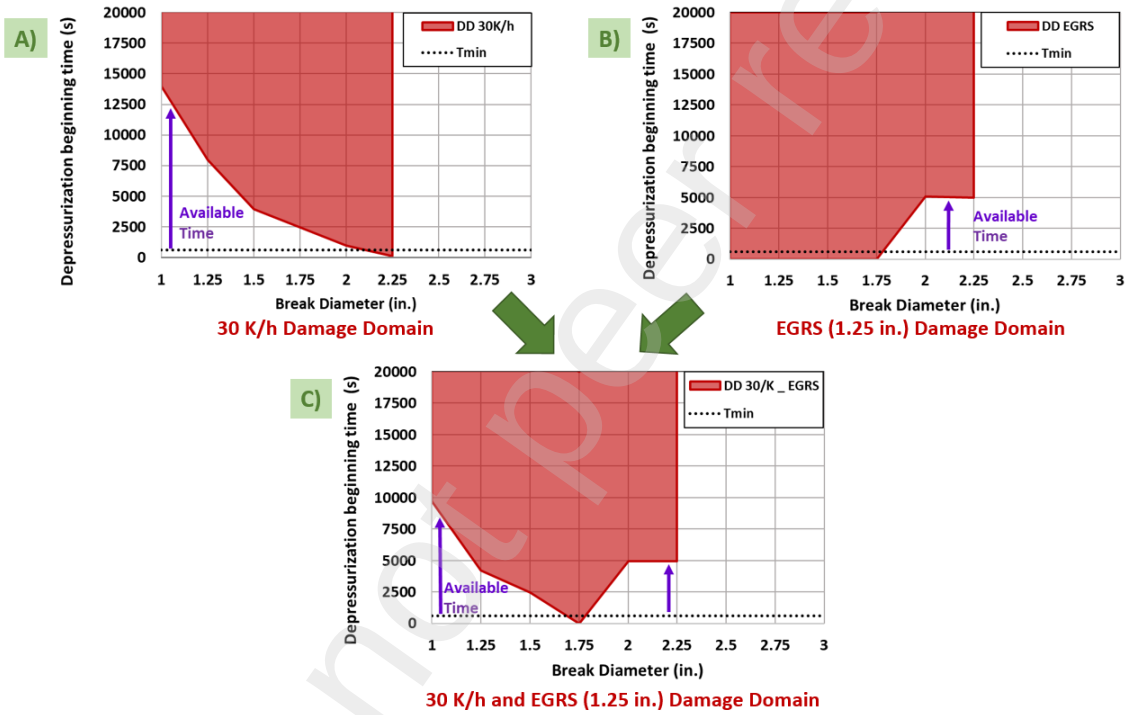

Figure 28 Damage Domain for SBLOCA with HPIS failure and 30 K/h RCS cooling along with EGRS actuation (VVER-1000/V320)

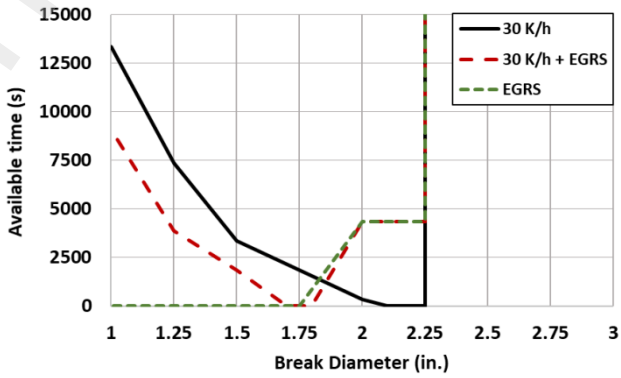

Figure 29 Available time for SBLOCA with HPIS failure and 30 K/h RCS cooling along with EGRS actuation (VVER-1000/V320)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

6.1. EGRS valves 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 with the opening of one of the EGRS valves, see Figure 30. 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 in.). 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 in.). 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 in., half the area of the 2.5 in. 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 in. causes high cooling rates, more than 60 K/h. In case of considering a valve with a diameter of 1.72 in., the DD limit is close to the PD curve from 1.75 to 2.25 in break sizes.

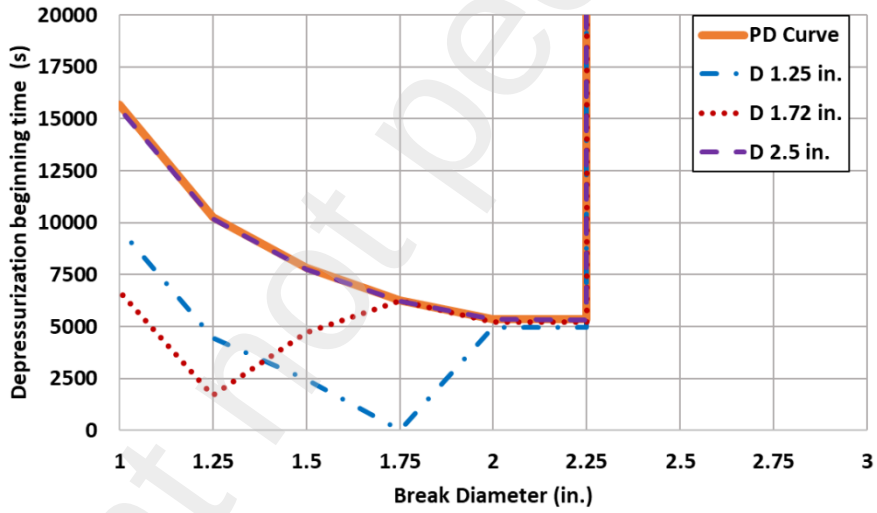

Figure 30 DD sensitivity analysis on the EGRS valve diameter

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 thermal shock in the structural material, making it brittle and causing its failure.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

References have been found where the SGs fast depressurization is performed when the CET temperature exceeds 350 ºC (Mullner, 2010). On 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 ºC (923 K) (FR C.1). Taking this information into account, it has been decided to analyze the fast SGs depressurization in VVER-100/V320 reactors considering two ICC temperature values, 350 ºC (623 K) and 650 ºC (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 ºC (623 K) and 650 ºC (923 K), see Figure 31.

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 control room crew to initiate the action from the PD curve values, obtained in section 4. The value considered for the time required by the control room crew is 60 s, as this is the time taken by the operators perform this action in simulator training. The following conclusions can be drawn from the time margin curves obtained:

$$T_{margin} = T_{previous\ damage} - T_{ICC} - T_{min}$$

- ICC = 350 ºC (623 K): the margin time obtained is quite similar for all the break sizes. The break with the largest margin being the 2.25 in. with 2296 s and the one with the smallest margin being the 1.75 in. with 1381 s, see Figure 32.
- ICC= 650 ºC (923 K): the margin time obtained is much smaller than the time margin obtained for ICC = 350 ºC (623 K). The break with the largest margin being the 2.25 in. with 1151 s and the one with the smallest margin being the 1 in. with 265 s, see Figure 33.

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 Figure 34. 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 starts 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 condition occurs, see Figure 35.

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 control room crew to initiate the action, see Figure 36.

$$T_{available} = T_{damage\ domain} - T_{ICC} - T_{min}$$

It has been considered that the available time can be classified into three categories: short, if it is less than 15 minutes, medium, if it is between 15 minutes and 1 hour, or long, if it is more than 1 hour. 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 ºC (623 K).

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

- 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 in. at 1352 s. The available time for all the break sizes is medium, ranging from 15 minutes to 1 hour.
- Considering that the ICC occurs when the CET temperature exceeds 650 °C (923 K), the break size with the shortest available time is 2 in. at 190 s. The available time for all break sizes, except for 2.25 in. is considered shot because it is less than 15 minutes.

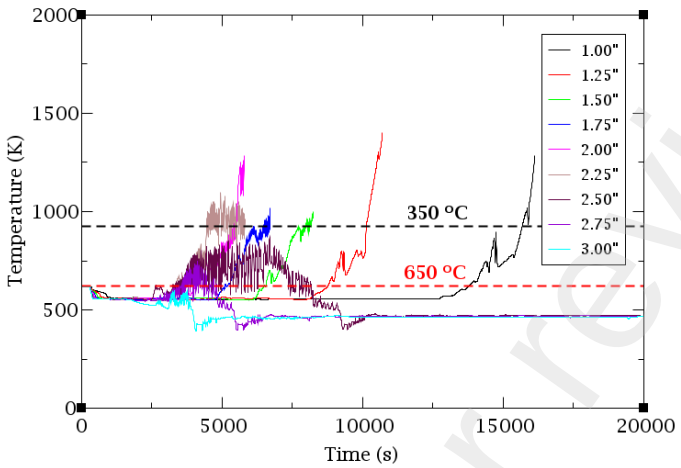

Figure 31 CET temperature in SBLOCA with HPIS failure without human actions (VVER-1000/V320)

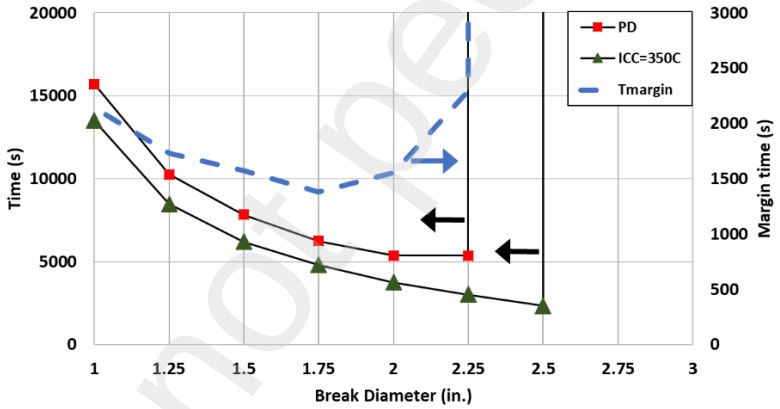

Figure 32 Time margin for RCS maximum cooling rate via the SGs at ICC = 350 ^{0}C (VVER-1000/V320)

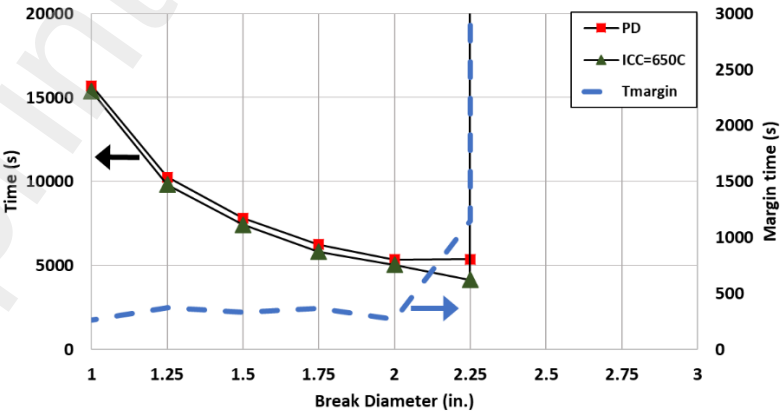

Figure 33 Time margin for RCS maximum cooling rate via the SGs at ICC = 650 ^{0}C (VVER-1000/V320)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

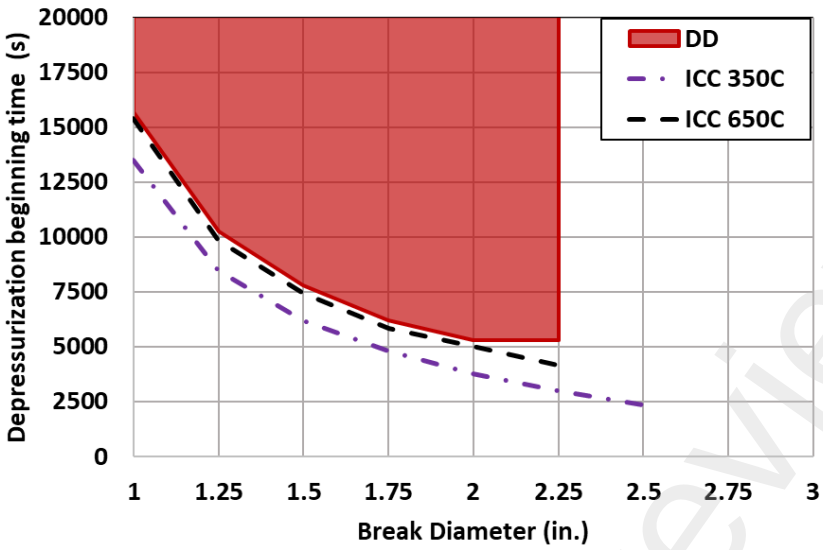

Figure 34 Damage Domain for SBLOCA with HPIS failure and RCS maximum cooling rate via the SGs (VVER-1000/V320)

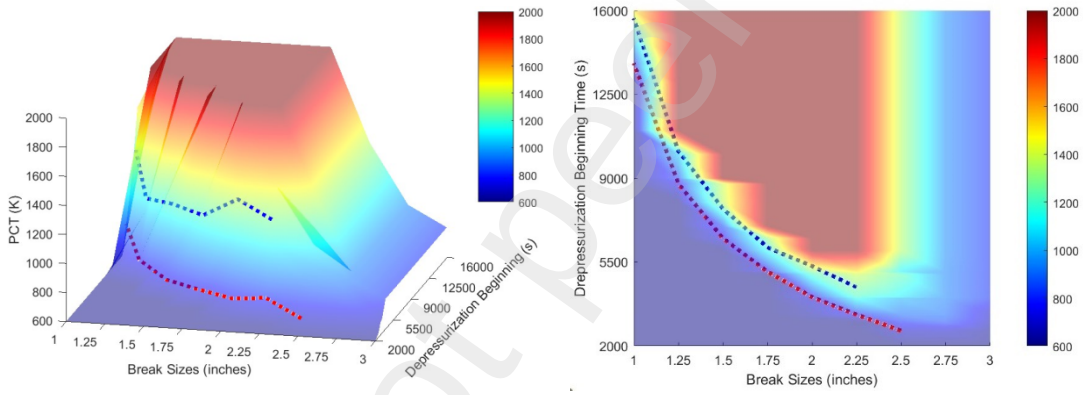

Figure 35 PCT in SBLOCA with HPIS failure and RCS maximum cooling rate via the SGs (VVER-1000/V320)

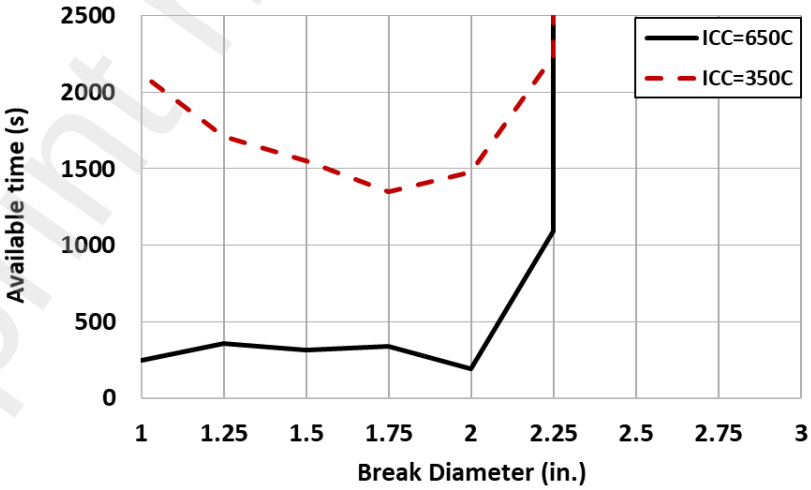

Figure 36 Available time for SBLOCA with HPIS failure sequence and RCS maximum cooling rate via the SGs at ICC = 350 ^{0}C and ICC = 650 ^{0}C (VVER-1000/V320)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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 analysed strategies have been compared by plotting the lines delimiting these DDs on the same graph, see Figure 37. Likewise, the available time curves obtained for the different strategies has been compared, see Figure 38 and Table 5. From this comparison, it can be concluded the following:

- The strategy with the highest available time between 1 to 2 in. is the controlled SGs depressurization at an RCS cooling rate of 60 K/h for all break sizes. The strategy with the highest available time between 2 and 2.25 in. is the controlled SGs depressurization along with the opening of a 1.25 in. EGRS valve.
- The strategy with the shortest available time up to 1.5 in. is the fast SGs depressurization, for 1.75 in. it is the controlled SGs depressurization along with the EGRS actuation, and for 2 and 2.25 in. it is the controlled SGs depressurization at an RCS cooling rate of 30 K/h.

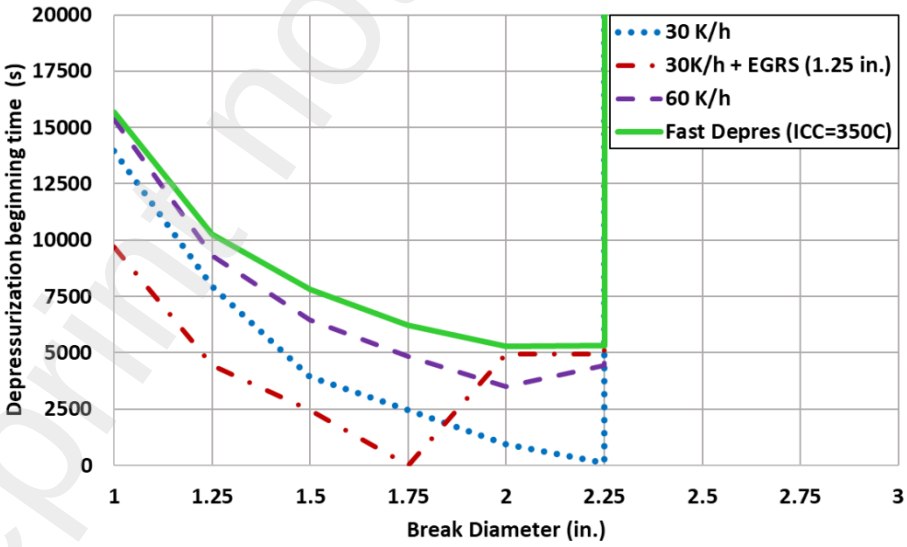

Figure 37 Damage Domains comparison for SBLOCA with HPIS failure management strategies (VVER-1000/V320)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

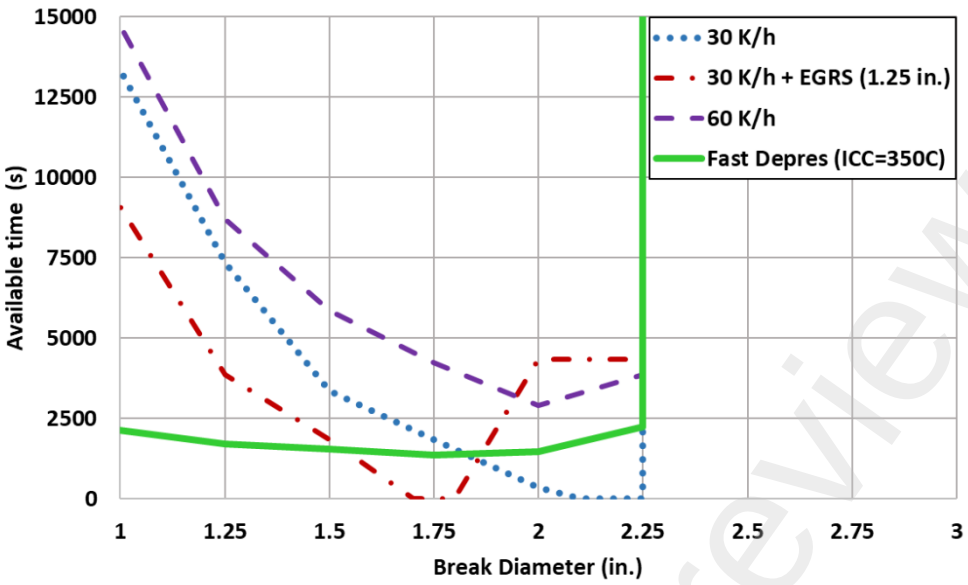

Figure 38 Available times comparison for SBLOCA with HPIS failure management strategies (VVER-1000/V320)

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 in.	0
	EGRS valve diameter = 1.72 in.	1100
	EGRS valve diameter = 2.5 in.	4705
Fast SG depressurization	ICC =350 ºC	1352
	ICC =650 ºC	190

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

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 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 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) is that of the success criterion. On the hand, it is noteworthy that the 3 loops PWR-W do not have automatic RCPs trip, unlike the VVER-1000/V320 reactors. Therefore, in order for the conditions considered in both models analysed 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.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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 Figure 39. As can be seen, the PD occurs up to 2 in. break sizes, and the break size where the PD occurs first is 1.5 in. at 7263 s. While the ACC inject prior to the PD for all sizes, only those break sizes where the LPIS injects are successful, except for the 2 in. 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 Figure 40, and for the SGs depressurization at the maximum RCS cooling rate, see Figure 41. 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 Figure 42. It has been considered that the available time can be classified into three categories, as in the VVER-1000/V320 strategies: short, if it is less than 15 minutes, medium, if it is between 15 minutes and 1 hour, or long, if it is more than 1 hour. The following can be drawn from the results obtained:

- 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 depressurization strategy is 900 s, for 1.75 in, which is considered medium as it is 15 minutes.
- The break size with the lowest available time in the fast 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 minutes. Although the minimum available time is short, it may be reasonable as the control room crew would be particularly attentive to the CET temperatures under these conditions.

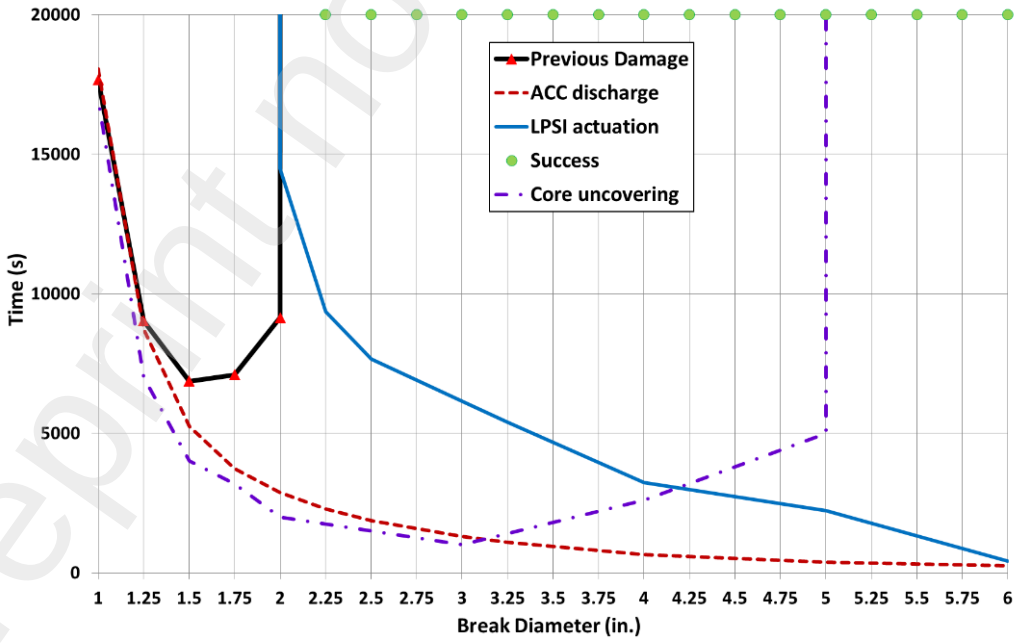

Figure 39 Previous Damage Curve for SBLOCA with HPIS failure (3 loops PWR-W)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

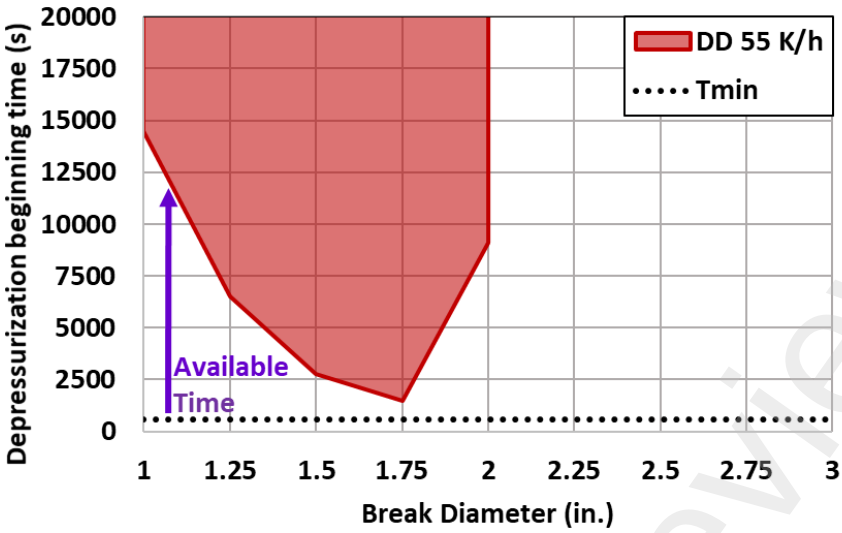

Figure 40 Damage Domains for SBLOCA with HPIS failure and 55 K/h RCS cooling (3 loops PWR-W)

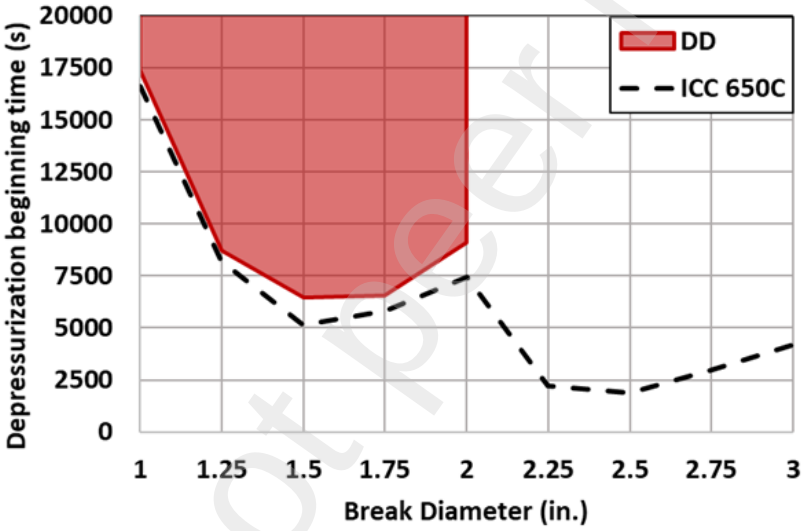

Figure 41 Damage Domain for SBLOCA with HPIS failure and maximum RCS cooling via the SGs (3 loops PWR-W)

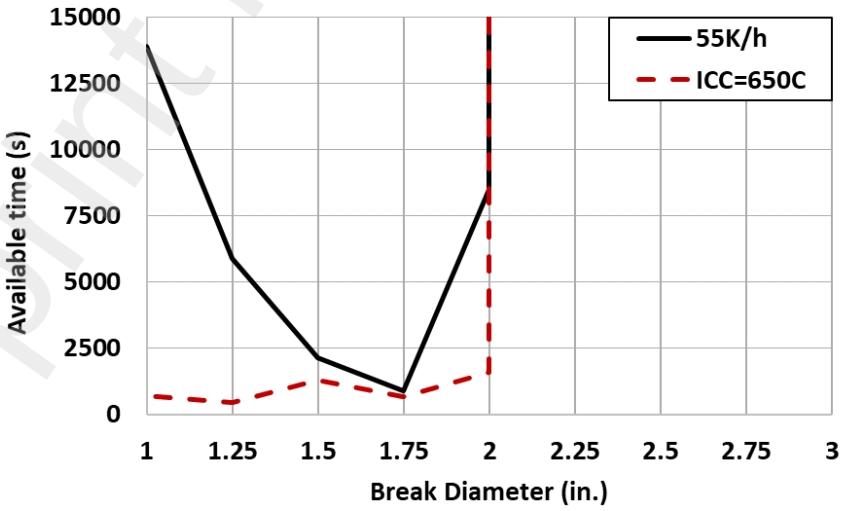

Figure 42 Available time for SBLOCA with HPIS failure and RCS cooling (3 loops PWR-W)

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

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 controlled SGs depressurization at 60 K/h RCS cooling rate in VVER-1000 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 in., for the VVER-1000/V320 reactor it reaches 2.25 in. However, the DD is higher in the 3 loops PWR-W up to 1.75 in., see Figure 43.
- SGs fast depressurization: While for the 3 loops PWR-W the DD reaches 2 in., for the VVER-1000/V320 reactor it reaches 2.25 in. For smaller break sizes and for those larger than 1.75 in. the DD is greater for the VVER-1000/V320 reactor, but for break sizes between 1.25 and 1.75 in. the DD is greater for the 3 loops PWR-W, see Figure 44.

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 Figure 45, and for the SGs depressurization at maximum RCS rate, see Figure 46. Moreover, the minimum available time for each strategy is shown in Table 6. The following conclusions can be drawn from the results obtained:

- In controlled SGs depressurization strategy, the available time for the VVER-1000/V320 is higher up to 1.75 in., while for 2 in. the 3 loops PWR-W has the higher available time.
- The biggest difference in the available time for the controlled SGs depressurization is at the 1.75 in. break size, where the difference is 5600 s.
- Up to 1.75 in. the available time curve for the 3 loops PWR-W is between the available time curve for the VVER-1000/V320 if the ICC condition is considered to occur when the CET temperature exceeds 350 ºC (623 K) and the available time curve for the VVER-1000/V320 if the ICC condition is considered to occur when the CET temperature exceeds 650 ºC (923 K). However, the available time for 2 in. in the 3 loops PWR-W exceeds the available time for the VVER-1000/V320 whatever its ICC condition.

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

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

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

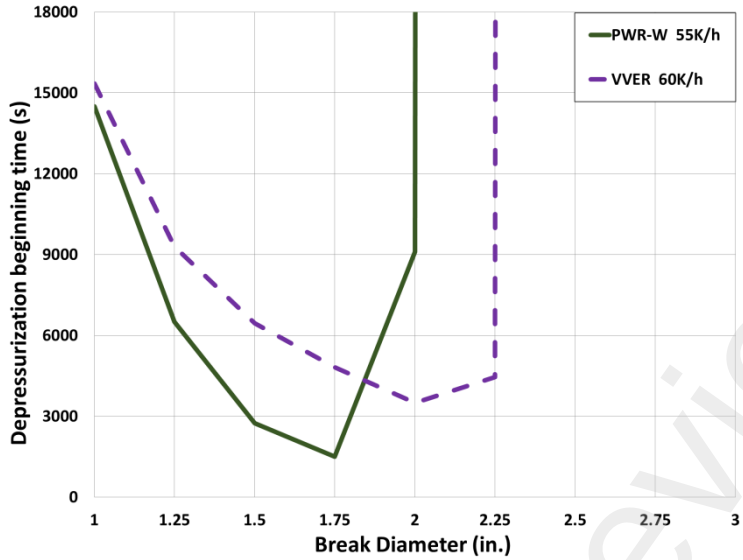

Figure 43 Damage Domain for SBLOCA with HPIS failure and controlled SGs depressurization in 3 loops PWR-W and VVER-1000/V320

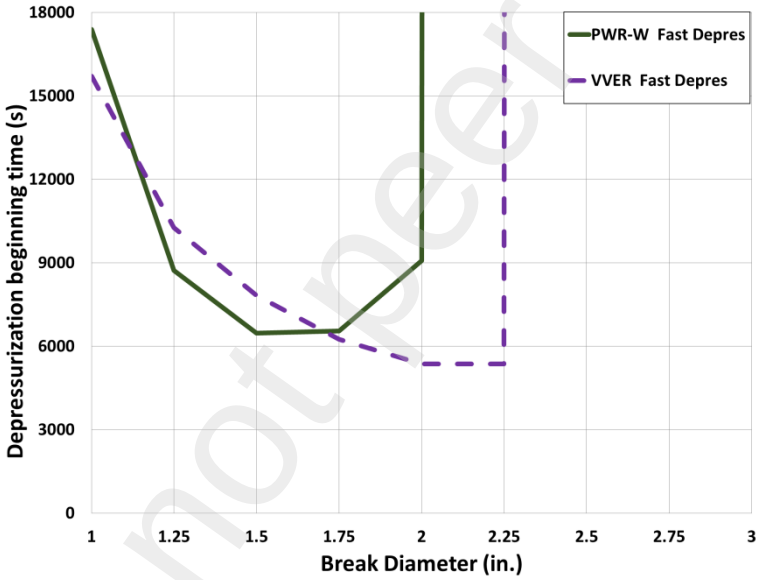

Figure 44 Damage Domain for SBLOCA with HPIS failure and maximum RCS cooling rate in3 loops PWR-W and VVER-1000/V320

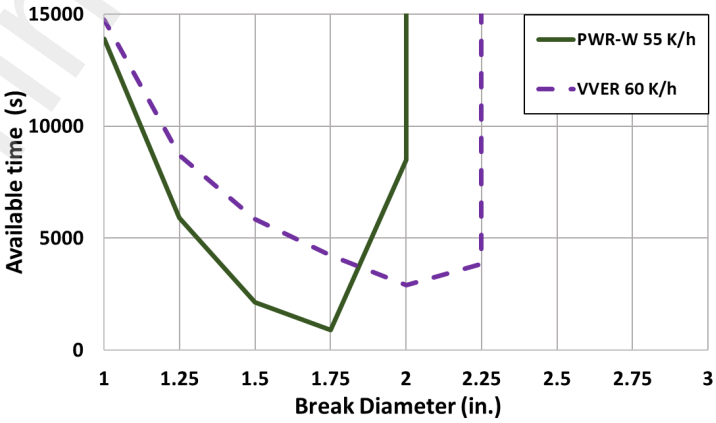

Figure 45 Available times for SBLOCA with HPIS failure controlled SGs depressurization in 3 loops PWR-W and VVER-1000/V320

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

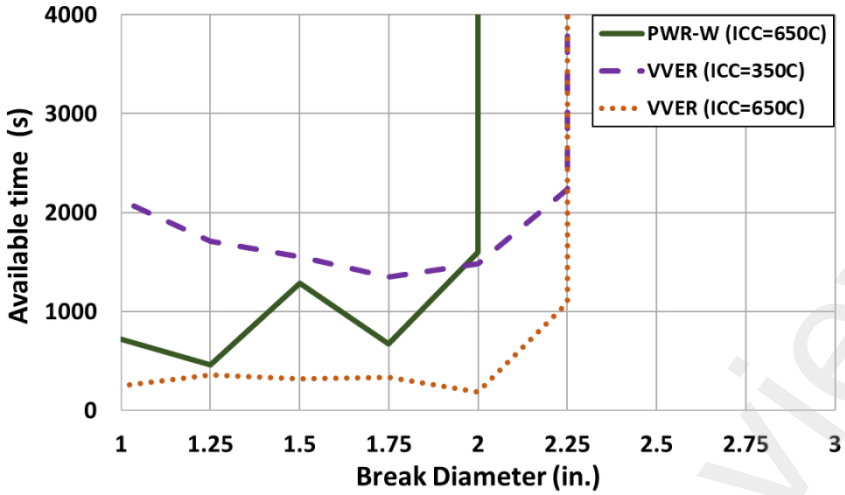

Figure 46 Available times for SBLOCA with HPIS failure and fast cooling in 3 loops PWR-W and VVER-1000/V320

11. Conclusions

In this work, different management strategies to ensure core cooling in SBLOCA sequences with HPIS failure in both in VVER-1000/V320 and Westinghouse PWR have been reviewed and analyzed. The main conclusions obtained by means of the ISA methodology are as follows:

- In VVER-1000/V320 reactor, if the success criteria are considered for the HA and LPIS trains, there are break sizes that have 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 long available time.
- 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 HA and the LPIS trains are fully available, instead of the success criteria number of trains, the DD limits are lower, so that there can be enough available time over the whole range of break sizes.
- 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 in., 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 time available for controlled SGs depressurization at an RCS cooling rate of 55 K/h in the 3 loops PWR-W indicates that the operator has a large margin of time.
- 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 ^{o}C (623 K) instead of 650 ^{o}C (923 K).
- In the PWR-W, when ICC conditions are reached, i.e., the CET temperature exceeds 650 ^{o}C (923 K), the maximum RCS cooling rate depressurization strategy allows to avoid core damage with enough available time.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

Acknowledgement

This work in the framework of the Grant PID2019-108755RB-I00 (ISASMORE) funded by MCIN/AEI/ 10.13039/501100011033.

The authors also wish to dedicate this work to the memory of José M. Izquierdo (1947–2023) who was the main developer of ISA methodology.

References

Araneo, D.A., 2008. Realization of a Methodology for the assessment of "Best Estimate" codes for the analysis of nuclear systems and application to Cathare2 V2.5 code. Università di Pisa PhD Thesis.

Bánáti, J., Ézsol, G., 1997. Simulation of some emergency operating procedures for VVER-440 reactors. Proccedings of the ASME Nuclear Engineering Division 21.

Bica, M., 1999. EOPs at NPP Temelin analytical support for EOPs verification, in: RER/9/046 Workshop on Development and Validation of EOP/AMG. Bratislava, Slovakia.

Cherubini, M., Muellner, N., D'auria, F., Petrangeli, G., 2008. Application of an optimized AM procedure following a SBO in a VVER-1000. Nuclear Engineering and Design 238, 74–80.

Del Nevo, A., D'Auria, F., 2007. Comparative study of the thermal-hydraulic system codes performaces in predicting experiments performed in VVER-1000 simulator, in: The 5th International Conference "Safety Assurance of NPP with WWER" FSUE OKB "GIDROPRESS." Podolsk, Russia.

Del Nevo, A., D'Auria, F., Mazzini, M., Bykov, M., Elkin, I. V, Suslov, A., 2007. The design of PSB-VVER experiments carried-out inside the TACIS contract N.30303., in: 15th International Conference on Nuclear Engineering (ICONE15). Nagoya, Japan.

Eisenhut, D.G., 1982. Inadequate Core Cooling Instrumentation System. Generic Letter 82-28. USNRC.

EPRI, 2011. Education of Risk Professionals Module 3: Initiating Events, Accident Sequences and Success Criteria. 1022996 Final Report.

European commission EuropeAid Co-operation Office, 2006. TACIS . Software development for accident analysis of VVER and RBMK reactors in Russia. Part A (VVER-1000). Final technical report.

Gencheva, R. V, Stefanova, A.E., Groudev, P.P., 2005. RELAP5/MOD3.2 investigation of reactor vessel YR line capabilities for primary side depressurization during the TLFW in VVER1000/V320. Ann Nucl Energy 32, 1407–1434.

González-Cadelo, J., Queral, C., Montero-Mayorga, J., 2014. Analysis of cold leg LOCA with failed HPSI by means of integrated safety assessment methodology. Ann Nucl Energy 69, 144–167.

González-Cadelo, J., Queral, C., Montero-Mayorga, J., 2013. Effects of break location and time uncertainties in small-break and medium-break LOCA sequences with unavailability of HPSI, in: 21st International Conference on Nuclear Engineering. Volume 3: Nuclear Safety and Security; Codes, Standards, Licensing and Regulatory Issues; Computational Fluid

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

Dynamics and Coupled Codes. V003T06A040. ASME. https://doi.org/ 10.1115/ICONE21-16348, Chengdu, China.

González-Cadelo, J., Queral, J., Montero-Mayorga, J., Martínez-Murillo, J.C., 2012. Accident management actions in a lower head SBLOCA with HPSI failed, in: 20th International Conference on Nuclear Engineering and the ASME 2012 Power Conference. https://doi.org/10.1115/ICONE20-POWER2012-54280, Anaheim, California, USA, pp. 165–172.

Groudev, P., Hadjiev, V., 2001. Analytical validation of EOPs for Kozloduy NPP VVER 1000, in: WANO-MC Workshop "Emergency Operating Instructions: Validation, Inculcation of EOI and Personnel Training." Paks NPP, Hungary.

Groudev, P.P., 1998. Analyzing SBLOCA in Support of EOP Development, in: Bulgarian Nuclear Society. Sofia, Bulgaria, pp. 18–19.

Groudev, P.P., Georgieva, E.L., 2010. Loss of 'Core cooling' at low power and cold condition of VVER-1000/V320. Progress in Nuclear Energy 52, 229–235.

IAEA, 2000. Performance of operating and advanced light water reactor designs. IAEA-TECDOC-1245, in: Technical Committee Meeting. Munich, Germany.

Ibánez, L., Hortal, J., Queral, C., Gómez-Magán, J., Sánchez-Perea, M., Fernández, I., Meléndez, E., Expósito, A., Izquierdo, J.M., Gil, J., Marrao, H., Villalba-Jabonero, E., 2016. Application of the Integrated Safety Assessment methodology to safety margins. Dynamic Event Trees, Damage Domains and Risk Assessment . Reliab Eng Syst Saf 147, 170–193.

IEEE, 2002. IEEE Standard Criteria for Accident Monitoring Instrumentation for Nuclear Power Generating Stations Std. 497-2002. Institute of Electrical andElectronics Engineers.

Iegan, S., Mazur, A., Vorobyov, Y., Zhabin, O., Yanovskiy, S., 2018. TRACE VVER-1000/V-320 Model Validation. NUREG/IA-0490.

Linn, P.A., Julian, H. V, Chapman, J.R., Trifanov, A., Zhabin, O., Fedorchenko, S., Rybchuk, A., 2002. Applying U.S. EOP analytical justification experience for VVER plants in the Ukraine, in: 10th International Conference on Nuclear Engineering, ICONE10-22640. Arlington, VA.

Lutz, R.J., 2004. Post-Accident Monitoring Instrumentation Re-Definition for Westinghouse NSSS Plants. Technical Report WCAP-15981-NP. WestinghouseElectric Company.

Mendizábal, R., Sánchez, M., Queral, C., Hortal, J., Martorell, S., Pelayo, F., Freixa, J., 2024. Activities in Spain on the integration of probabilistic and deterministic DEC-A scenarios safety analysis methods. Discussion on their applicability to. Nuclear Engineering and Design 419, 112944.

Montero-Mayorga, J., Queral, C., Gonzalez-Cadelo, J., 2014. Effects of delayed RCP trip during SBLOCA in PWR. Ann Nucl Energy 63, 107–125. https://doi.org/10.1016/J.ANUCENE.2013.06.030

Montero-Mayorga, Javier, Queral, C., Rivas-Lewicky, J., González-Cadelo, J., 2014. Effects of RCP trip when recovering HPSI during LOCA in a Westinghouse PWR. Nuclear Engineering and Design 280, 389–403. https://doi.org/10.1016/J.NUCENGDES.2014.09.005

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

Mullner, N., 2010. Simulation of Beyond Design Basis Accidents – a Contribution to Risk Analysis of Nuclear Power Plants. Universität Wien PhD thesis.

NRC, 2017. TRACE V5.840 User Manual: Input Specification. Input Specification, User's Manual.

NRC, 2006. Criteria for Accident Monitoring Instrumentation for Nuclear Power Plants. Regulatory Guide 1.97, Rev. 4.

NRC, 1983. Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident. RegulatoryGuide 1.97, Rev. 3.

Parisi, C., D'Auria, F., Mazzini, M., Jankowski, M., n.d. An overview of the TACIS project (R2.03/97) dealing with WWER-1000 and RBMK technologies. IAEA-CN-114/44p.

Pavlova, M.P., Andreeva, M., Groudev, P.P., 2007. RELAP5/MOD3.2 blackout investigation for validation of EOPs for KNPP VVER-1000/V320. Progress in Nuclear Energy 49, 409–427.

Pavlova, M.P., Groudev, P.P., Hadjiev, V., 2008. Systematic approach for the analytical validation of Kozloduy NPP, VVER-1000/V320 symptom based emergency operating procedures. Progress in Nuclear Energy 50, 27–32.

Queral, C., Gómez-Magán, J., París, C., Rivas-Lewicky, J., Sánchez-Perea, M., Gil, J., Mula, J., Meléndez, E., Hortal, J., Izquierdo, J.M., Fernández, I., 2018. Dynamic event trees without success criteria for full spectrum LOCA sequences applying the integrated safety assessment (ISA) methodology. Reliab Eng Syst Saf 171, 152–168. https://doi.org/10.1016/J.RESS.2017.11.004

Queral, C., González-Cadelo, J., Jimenez, G., Villalba, E., 2010. Accident management actions in an upper-head small-break loss-of-coolant accident with high pressure safety injection failed. Nuclear Technology 175, 572–593.

Queral, C., González-Cadelo, J., Prada, D., Montero, J., Martínez-Murillo, J.C., Pérez, J., 2011. Analysis of surge line MBLOCA sequences with HPSI failed, in: The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics (NURETH-14).

Queral, C., Montero-Mayorga, J., Rivas-Lewicky, J., Rebollo, M.J., 2017. Verification of AP1000 low-margin PRA sequences based on best-estimated calculations. Ann Nucl Energy 104, 9–27.

Queral, C., Sánchez-Espinoza, V., Egelkraut, D., Fernández-Cosials, K., Redondo-Valero, E., García-Morillo, A., 2021. Safety Systems of Gen-III/Gen-III+ VVER reactors. Nuclear España.

Redondo-Valero, E, Queral, C., Fernandez-Cosials, K., Sanchez-Espinoza, V., 2023. Analysis of MBLOCA and LBLOCA success criteria in VVER-1000/V320 reactors: New proposals for PSA Level 1. Nuclear engineering and technology 55, 623–639.

Redondo-Valero, Elena, Queral, C., Fernandez-Cosials, K., Sanchez-Espinoza, V., 2023. Safety margins improvement by means of the passive second stage hydroaccumulators in a VVER-1000/V320 reactor . Nuclear Engineering and Design 414.

Sanchez-Espinoza, V., Bottcher, M., 2006. Investigations of the VVER-1000 coolant transient benchmark phase with the coupled system code RELAP5/PARCS. Progress in Nuclear Energy, Progress in Nuclear Energy 48, 865–879.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220

Skalozubov, B., Klyuchnikov, A., Kolykhanov, B., 2010. Fundamentals of management of design accidents with loss of coolant at the power plant (in Russian).

TECNATOM, 1999. Introduction to Accident Analysis, TECNATOM Operating Practices Course, PF3T-LA-M12 (in Spanish).

United States General Accounting Office, 1996. Status of U.S. assistance to improve the safety of Soviet-Designed reactors. GAO/RCED-97-5.

Westinghouse owners group, 1983. Emergency response guidelines revision1. Validation program plant.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4781220