Proceedings of SCOPE
13-15 Nov. 2023 – KFUPM
Paper 23220

TRACE investigation on the performance of passive safety condenser as ultimate heat sink

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Abstract – *Passive safety systems are integrated into the latest generation of Light Water Reactors (LWRs), including small modular reactors. This paper employs the US-NRC TRACE thermal hydraulic code to examine the performance of a passive safety condenser known as SACO, designed to serve as the ultimate heat sink for dissipating decay heat during accident scenarios. The TRACE model is constructed with reference to the PKL/SACO test facility, which is an integral testing facility replicating a four-loop Western-type KWU pressurized water reactor (PWR). The PKL facility maintains a 1:1 height scaling and a 1:145 power and volume scaling. The safety condenser (SACO) is interconnected with the PKL facility via the secondary side of steam generator 1, effectively serving as a third natural circulation cooling loop during accident scenarios. The modeling of the PKL/SACO facility involves the use of both 1D and 3D TRACE components. Specifically, the SACO water pool is represented as a 3D TRACE VESSEL component, while all other facility components are represented as 1D TRACE components, including PIPE, VALVE, FILL, BREAK, and single junction. Previously, a series of parametric investigations had been conducted aimed at validating the PKL/SACO TRACE model. In the present research, the thermal-hydraulic behavior of the PKL facility is investigated in the presence of the SACO passive safety system during a Station Black Out (SBO) with Extended Loss of AC Power (LEAP) accident scenario. The SBO scenario entails an extended and prolonged transient process, which can be categorized into three distinct phases depending on the activation of the SACO system and the refilling process of the SACO pool. The findings indicate that the SACO system effectively manages to dissipate all decay heat, even though there is temporary evaporation of the SACO water pool.*

Keywords: TRACE, Passive system, SACO, PKL, Safety condenser

I. Introduction

Currently, most modern Light Water Reactors (LWRs) incorporate multiple natural circulation loops in their fundamental designs to serve as passive safety mechanisms [1]. One highly effective heat dissipation system is the passive safety condenser (SACO) [2, 3]. SACO serves as a durable system for removing decay heat over an extended period, primarily designed to replace the active Emergency Feedwater System (EFWS) with a passive secondary-side residual heat removal system. The essence of incorporating passive heat removal systems in a Pressurized Water Reactor (PWR) lies in their capacity to dissipate residual heat without requiring a constant supply of AC power and their autonomy from operator intervention [4]. SACO system is consisting of a straight-tube heat exchanges (HX) inserted into large water pool. SACO HX tubes are connected to the secondary side of SG1, as illustrated in Fig.1 [4]. SACO pool filled with water and operated under atmospheric pressure conditions. During accidents, SACO valves activated. As steam enters the SACO from top, it undergoes condensation within the straight tubes of the SACO. Simultaneously, the water on the pool side of the SACO is heated, eventually reaching a boiling point. Once boiling initiates within the pool, heat dissipation occurs through the evaporation of pool water, resulting in the release of pool inventory into the atmosphere during this process. This pool serves as the ultimate heat sink, facilitating the removal of decay heat from the secondary side. The duration of SACO operation is constrained by the quantity of water within the pool. After the pool water has evaporated, the SACO begins to transfer heat to the surrounding air, resulting in a significant reduction in the amount of heat removed from the secondary side. Thus, it is very important to ensure the refilling of the SACO water pool.

Numerous experimental and computational investigations have been conducted to assess the performance of passive cooling systems and their impact on the behavior of Nuclear Power Plants (NPPs) [5-7]. Several numerical research efforts have been undertaken to investigate the natural circulation behavior in various conceptual designs of passive safety systems. A comprehensive analysis of this behavior is achievable through the utilization of 3D Computational Fluid Dynamics (CFD) simulations. However, it should be noted that the LWRs fluid system is computationally expensive and involves multiple interact components, which makes it difficult to be modeled using CFD methods. Papini et al. [8] used GOTHIC and TRACE codes to model passive containment cooling system (PCCS) of PANDA facility. Their model included a vertical tube condenser immersed in a subcooled water pool, which is very similar concept in compare with SACO.

This paper presents an initial investigation into the performance of the passive safety condenser system under SBO, utilizing the US-NRC TRACE code with reference to the PKL/SACO test facility. For over a decade, the TRACE code has served as the primary system behavior code within the Laboratory for Reactor Physics and Thermal-Hydraulics (LRT) code system. This research aims to evaluate TRACE's capabilities in simulating natural circulation as a passive cooling method. TRACE has been specifically designed to conduct best-estimate analyses of accident scenarios in Light Water Reactors (LWRs), utilizing both 1D components and 3D VESSEL components [9]. The findings of this study contribute to a deeper understanding of natural circulation and flow instability within heat removal passive cooling systems.

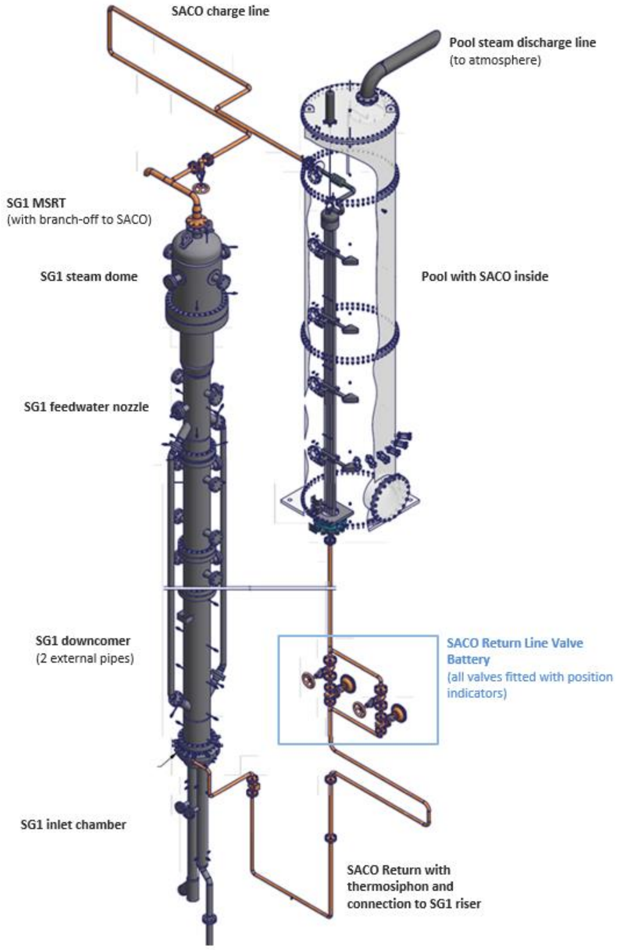

Fig. 1. Overview of SACO system connected to PKL-SG1.

II. Overview of PKL facility and test condition

PKL represents an integral testing facility that replicates a four-loop Western-type KWU PWR. This facility maintains a 1:1 height scale and a 1:145 scale in terms of volume and power. Its maximum power capacity reaches 2.5 MW, equivalent to 10% of the scaled full power, and it can operate under pressures of up to 46 bar in the primary loop and 60 bar in the secondary loop. The core power is supplied through 314 heating rods, each with three distinct power levels (inner zone, intermediate zone, and outer zone). The PKL facility comprehensively models the entire primary cooling system, encompassing components such as the reactor pressure vessel (RPV), reactor coolant pumps (RCP), steam generator U-tubes, pressurizer, hot legs, and cold legs. Additionally, it replicates all pertinent safety and auxiliary systems, including accumulator tanks, high-pressure safety injection, low-pressure safety injection, and the emergency feedwater system. Furthermore, crucial portions of the secondary system, such as steam generators, main steam lines, and feedwater lines, are also part of the PKL setup [10]. Fig. 2 provides a schematic representation of the layout of the PKL facility.

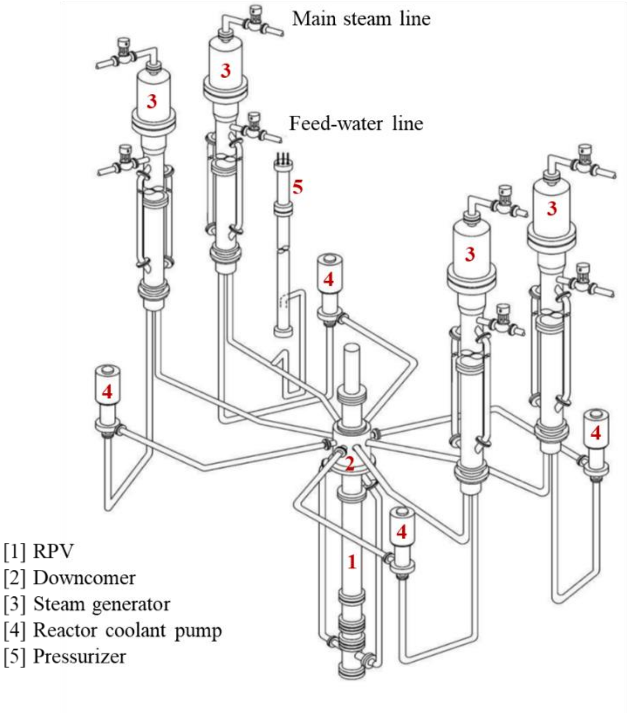

Fig. 2. General view of PKL test facility[11].

Recently, within the framework of EU-PASTELS project [12], PKL/SACO was utilized to perform several experimental studies on safety condenser aiming to enhance the current understanding of the system behavior driven by passive condenser, and thus to improve the modeling capabilities of thermal hydraulic system analysis codes. In this study, the SBO test specifications are described in Reference [13]. The main objective of this test is to characterize the thermal hydraulic parameters associated with the cooling-down process during SBO when SACO serves as the ultimate heat sink. The initial and boundary conditions of the TRACE model in comparison to the reference data are presented in Table I.

Table I PKL/SACO SBO Test Conditions

Primary side	TRACE	Reference
Core power (kW)	1671	1671
CET (oC)	244.3	245.1
CIT (oC)	242.5	242.0
Temperature after SG (oC)	219	218
Primary pressure (Bar)	44	45
Loop flow rate (kg/s)	39.4	39.6
Secondary side		
Main steam pressure (Bar)	33	33
SG1 water level (m)	8	8
SACO system		
Pool level (%)	100	100
Pool temperature (oC)	20	19.5
SACO tube level (%)	100	100

III. TRACE Model Assessment

TRACE code has been designed to perform best-estimate analyses of accident scenarios in LWRs, and can utilize 1D components and 3D VESSEL components [14]. PKL TRACE model has been developed with the reference to a RELAP model of PKL facility that was obtained from the Technical University of Catalonia [15]. The PKL model is a combination of 119 hydraulic volumes, 106 heat structures, 10 power components, and more than 780 control system components. Most of the PKL facility is represented using the 1D PIPE components such as; reactor pressure vessel (RPV), the four primary loops piping, pressurizer, accumulators (ACCs), and the SG U-tube bundle. TRACE separator components are used to model the secondary side of SGs. The core region is divided into 7 axial nodes. Four PUMP components are used to model PKL centrifugal pumps. FILL components are representing the feed water system, HPSI, and LPSI. 20 VALVE components are used to model the four SG isolation valves, four butterfly valves, four SG MSRCV, ACCs valves, pressurizer safety relief valve, and test break line. The POWER components are used to model the PKL core that is consisting of 314 heated rods, the bypass heaters of pressurizer, and SGs. On the other hand, heat structure components (HSTRs) are used to simulate heat loss from PKL facility outer surfaces. More detailed about PKL TRACE model can be found in [1, 16]. SACO TRACE model had been developed and integrated into PKL TRACE model with refereeing

[4]. As shown in Fig. 3, PIPE, VALVE, Single-Junction, Break, and Fill components have been used to model the SACO heat exchanger, charge line, return line, valves, and the pool. To simulate the natural circulation, the SACO pool has been modeled using two PIPE components with Single-Junction connections. The heat structure component is used to simulate the heat transfer between secondary side_SG1 and SACO pool through SACO heat exchanger. to the technical description report for SACO system.

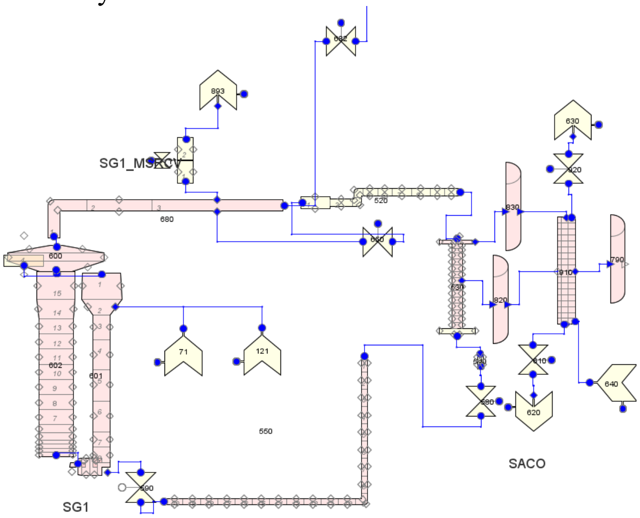

Fig. 3. TRACE nodalization of SACO system.

IV. Results and Discussion

This section presents the simulation results obtained using the TRACE code of the PKL/SACO SBO test. Figures 4 through 8 display these simulation results. Initially, the simulation ran for 1000 seconds to establish initial conditions consistent with the reference data summarized in Table I. At the start of the test (SoT), the primary set-point was fixed at 46 bar, and the secondary pressure set-point was raised from 33.0 bar to 38.4 bar. Simultaneously, all reactor coolant pumps (RCPs) were turned off, initiating their coast-down, and all feedwater supply to the steam generators (SGs) was terminated. Following SoT, secondary pressure increased, primary and secondary water inventory reduced, core temperatures increased, and water levels on both the primary and secondary sides decreased. This period is referred to as phase-A.

Once the water level in SG1 reduced to 2.9 m, the SACO system was activated (the beginning of phase-B), which occurred approximately 3400 seconds after SoT. As a result, there was a sudden drop in the secondary-side pressure of SG1, along with an increase in its water level, as illustrated in Fig. 5. Consequently, the primary pressure and the secondary pressure of SG2-4 decreased. Simultaneously, the peak cladding temperature (PCT), core exit temperature (CET), and core inlet temperature (CIT) decreased. Meanwhile, natural circulation was established in primary loop 1 and through the SACO heat exchanger (HX) tubes, as shown in Fig. 6. It's worth noting that all fluid entered the SACO HX as 100% steam and left as 100% liquid.

The natural circulation process facilitated the removal of decay heat from the core to the SACO pool. Consequently, the SACO pool temperature increased, and once it reached the saturation point, the SACO pool began to evaporate, resulting in a reduction in pool level, as shown in Fig. 7. When the SACO pool level decreased, the overall heat transfer decreased, leading to an increase in SG1 pressure. This, in turn, caused an increase in primary pressure, SG2-4 pressure, and primary temperatures. By the end of phase-B, the SACO pool was almost empty, and primary pressure had significantly increased. Once the primary pressure reached 41 bar, the SACO pool was refilled, marking the beginning of phase-C. During this stage, all system pressures and temperatures decreased.

In Fig. 8, the core power is compared with SACO removal power. After 78 seconds from SoT, core power decreased to 35% of its nominal value. During phase-A and before SACO activation, core decay heat was transferred to the secondary side and removed through the steam released from SGs. During this phase-A, SACO removal power remained at zero. However, after SACO activation in phase-B, core power continued to decrease, with most of the heat being transferred from the primary side to the SACO pool through SG1. As the SACO pool depleted during phase-B, SACO performance deteriorated, and heat losses became dominant in removing the core decay heat. Once the SACO pool was refilled during phase-C, core power remained stable, and SACO performance was reestablished. At this stage, all decay heat was removed by SACO. This study demonstrates the ability of the SACO passive safety condenser to remove decay heat for approximately 72 hours during the extended SBO transient.

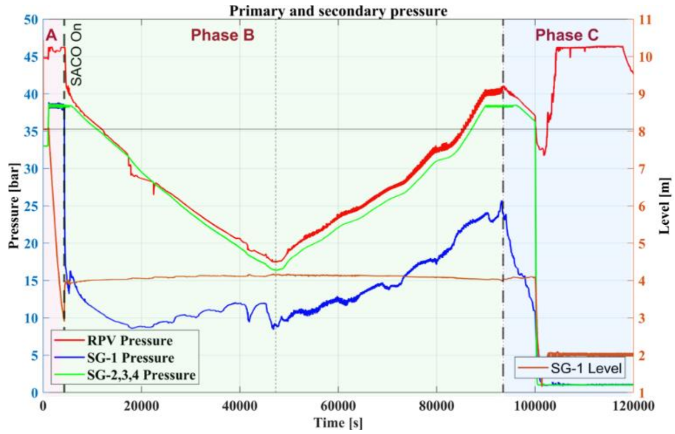

Fig. 4. Evolution of primary and secondary pressures of PKL/SACO during SBO test.

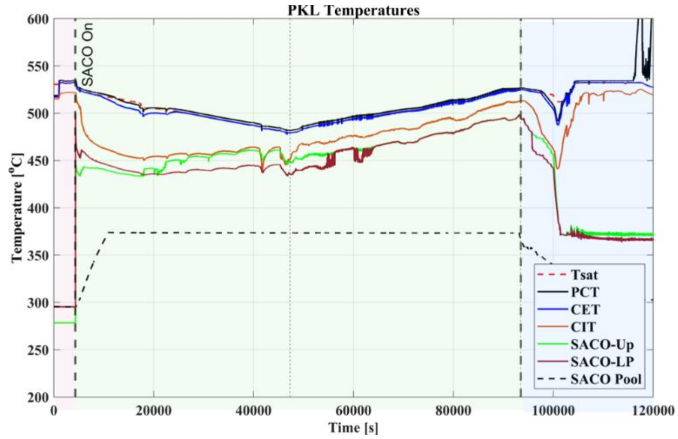

Fig. 5. Evolution of PKL/SACO temperatures during SBO test.

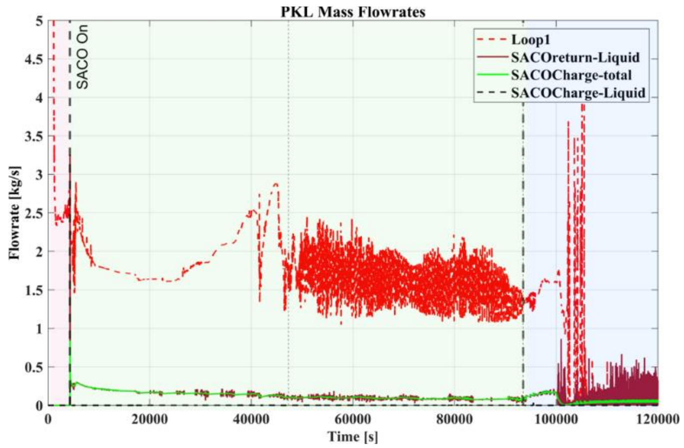

Fig. 6. Natural circulation flow rate through PKL and SACO system during SBO test

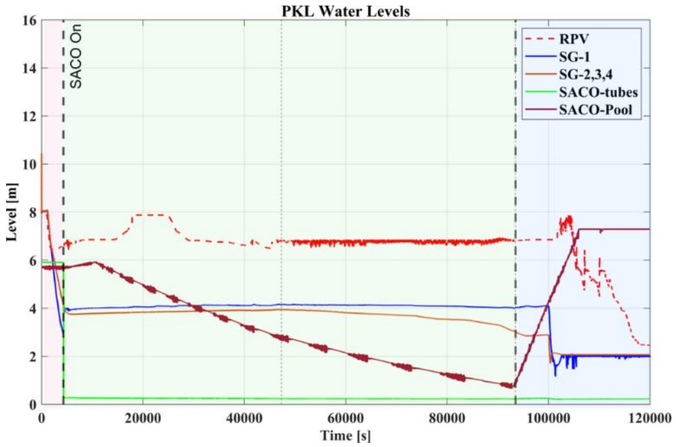

Fig. 7. Evolution of PKL/SACO temperatures during SBO test.

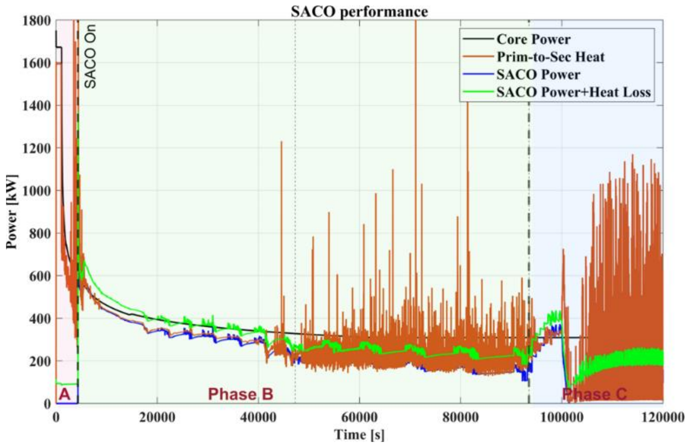

Fig. 8. SACO performance to remove the residual heat from the core during SBO test.

IV. Conclusions

In this paper, TRACE system analysis code was utilized to evaluate the performance of safety condenser SACO during SBO test. Three distinct phases were observed during the long transient of SBO. In Phase-A, the test initiated with the reactor trip and shutdown of reactor coolant pumps and feedwater supply to the steam generators. This led to an increase in secondary pressure, reduction in water inventory, higher core temperatures, and lower water levels in both primary and secondary systems. Phase-B began when the water level in SG1 reached a critical point, activating the SACO system. Throughout Phase-B, the SACO system effectively removed decay heat from the core to the SACO pool. The SACO pool temperature increased until it reached saturation, causing evaporation and a reduction in pool level. This reduction impacted heat transfer, leading to increased SG1 pressure, primary pressure, and SG2-4 pressure, along with primary temperature. At the end of Phase-B, the SACO pool was nearly empty, and primary pressure had significantly increased. Phase-C began with the refilling of the SACO pool, and during this stage, all system pressures and temperatures decreased. In summary, the study revealed the SACO passive safety condenser's ability to efficiently remove decay heat for approximately 72 hours during a prolonged SBO event, marking a significant contribution to nuclear safety.

Acknowledgments

This work was partly funded by the Swiss Nuclear Safety Inspectorate ENSI (CTR00604) within the framework of the STARS program (http://www.psi.ch/stars). It was also partly funded by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No. 945275 (PASTELS, Work Package 3 on "PKL/SACO safety condenser").

References

1. Al-Yahia, O.S., et al., *TRACE code simulation of the interaction between reactor coolant system and containment building with passive heat removal system.* Nuclear Engineering and Design, 2023. **406**: p. 112234.
2. Batheja, P., et al., *Secondary-side residual-heat removal system for pressurized-water nuclear reactors*. 1995, Google Patents.
3. Conrads, H.-J., et al., *Secondary-side residual-heat removal system for pressurized-water nuclear reactors*. 1995, Google Patents.
4. FRA-G, *PKL & SACO Technical Description & Design Review Report*. 2020: EU-PASTELS.
5. Chang, S.H., S.H. Kim, and J.Y. Choi, *Design of integrated passive safety system (IPSS) for ultimate passive safety of nuclear power plants.* Nuclear Engineering and Design, 2013. **260**: p. 104-120.
6. Bakhmetiev, A.M., et al., *Experimental study of a passive system for lowering damaging pressure levels in the protective shell of the KLT-40S reactor facility.* Atomic Energy, 2010. **108**(5): p. 343-348.
7. Montout, M., C. Herer, and J. Telkkä, *[ICAPP 2023] PASTELS project-overall progress of the project on experimental and numerical activities on passive safety systems.* Nuclear Engineering and Technology, 2023.
8. Papini, D., et al., *Assessment of GOTHIC and TRACE codes against selected PANDA experiments on a Passive Containment Condenser.* Nuclear Engineering and Design, 2014. **278**: p. 542-557.
9. Commission, U.S.N.R., *TRACE V5.0 Patch 7 Theory Manual*. 2022, Washington, DC: U.S. Nuclear Regulatory Commission: Office of Nuclear Regulatory Research.
10. Umminger, K., R. Mandl, and R. Wegner, *Restart of natural circulation in a PWR–PKL test results and s-relap5 calculations.* Nuclear Engineering and Design, 2002. **215**(1): p. 39-50.
11. Umminger, K. and A. Del Nevo, *Integral test facilities and thermal-hydraulic system codes in nuclear safety analysis*. 2012, Hindawi.
12. *PASTELS: passive systems simulating the thermal-hydrulic with experimental studies* 2020; Available from: https://www.pastels-h2020.eu/page/en/about-pastels/workpackages.php.
13. FRA-G, *P2.1 Boundary & Initial Conditions (BIC) as Conducted – Data Compilation*. 2023: EU-PASTELS.
14. US-NRC, *TRACE code V5.0*. 2017.
15. Terradas, J.F., *Sb-loca. With boron dilution in pressurized water reactors, impact to the operation and safety*. 2007, Universitat Politècnica de Catalunya (UPC).
16. Mukin, R., et al., *Modeling and analysis of selected organization for economic cooperation and development PKL-3 station blackout experiments using TRACE.* Nuclear Engineering and Technology, 2018. **50**(3): p. 356-367.