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Analysis of an Innovative Passive Heat Removal System for Station Blackout Scenario

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ABSTRACT

Passive safety systems have the potential to either replace or complement active systems as part of an overall strategy to prevent and/or mitigate nuclear accidents. These systems form the basis of both advanced nuclear power plants and small modular reactors, which currently occupy a significant position in the nuclear market. The strength of these systems is derived from simple physical principles, such as natural circulation. Consequently, unlike the active systems, which rely on external power sources and human intervention to function correctly, the passive safety systems are considered more reliable and resilient.

This paper investigates an innovative passive safety system integrated into the SCOR (Simple COmpact Reactor) design with a specific focus on its role in a Station Blackout (SBO) scenario using a generic data set. The calculations were performed using an extended version of the thermal-hydraulic system code, which was customized with friction loss coefficients specific to bayonet tubes. In the reactor design, residual heat on the primary circuit is removed by RRP (Residual Heat Removal on Primary circuit) loops that contain bayonet heat exchangers. The results of the ATHLET calculations were investigated for both steady-state condition and transient behaviour during the SBO scenario. The SBO scenario simulations were performed under five unique conditions: four cases with different numbers of active RRP cycles and one case with no safety systems except safety valves. The use of four RRP cycles was found to maintain the plant in a safe condition for a minimum of 72 hours, even in the absence of AC power or operator intervention.

1 INTRODUCTION

The potential occurrence of an SBO accident plays a crucial role in the design considerations of nuclear power plants. Inadequate preparation for SBO scenarios has the potential to trigger a reactor core meltdown with potentially catastrophic consequences. Global awareness of the importance of this event has increased, especially after the Fukushima accidents caused by an earthquake followed by a tsunami that struck the east coast of Japan on 11 March 2011. As described in the IAEA Safety Guide SSG 34 [1], an SBO refers to a situation within a nuclear power plant (NPP) where there is a complete loss of AC power from external sources, the main generator and standby AC power sources.

Extensive research has been conducted to address safety concerns related to the SBO in both conventional and advanced NPPs. In order to effectively address such scenarios, NPP designers have emphasised the implementation of innovative passive safety systems that operate based on natural circulation principles. Passive safety systems are indeed considered a crucial technology for enhancing the safety of the NPPs in a range of potential accidents, not only in the case of the SBO events. A key characteristic of the passive systems is their ability to operate solely on the basis of fundamental physical principles. They are designed to operate autonomously for long periods of time without the need for human intervention to perform their intended tasks.

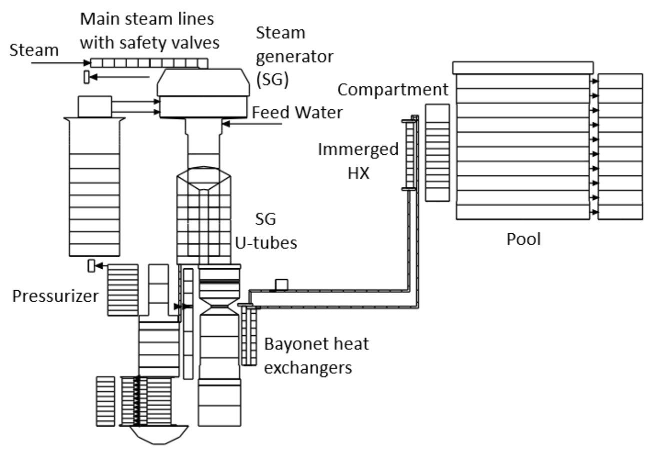
This paper evaluates the performance of the innovative passive decay heat removal system using bayonet heat exchangers integrated into the SCOR design. SCOR [2] is an integral design pressurized water reactor (iPWR) with a compact primary circuit. It is designed to operate at a thermal power level of 2000 MW^{th}, resulting in an electrical power output capacity of 630 MW. In the design, the primary circuit components such as the primary coolant pumps, control rod drive mechanism, pressurizer, heat exchangers of the passive decay heat removal systems etc. are all located within a compact layout. Only the steam generator is positioned on top of the reactor vessel. The downcomer houses sixteen modules. Each module contains a primary coolant pump, a venturi system and a bayonet heat exchanger. Residual heat removal on the primary circuit is performed by sixteen RRP loops. While twelve RRP loops are cooled by heat exchangers in air towers, other four RRP loops are cooled by immerged heat exchangers in pools. In this study, the focus was on the investigation of RRP loops cooled by immerged heat exchangers in the pools.

2 ANALYSIS OF THE SBO

2.1 ATHLET Code Modelling of SCOR

A generic ATHLET model was created to represent the SCOR design. Figure 1 depicts the nodalization scheme of the model.

a)



b)

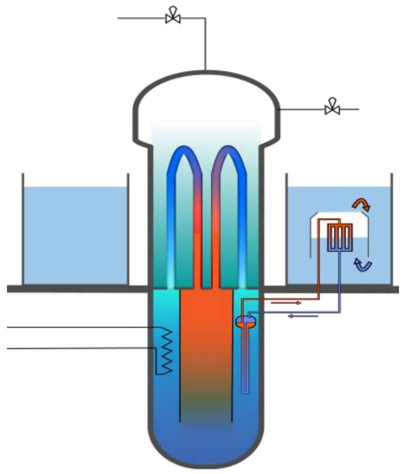


Figure 1 Nodalization of SCOR (a) and schematic representation (b)

In the primary circuit, the coolant flows upwards through the reactor core and absorbs heat from the core and increases its temperature. Then, it flows upwards through the riser and the centre of the pressurizer. The heated coolant flows upward and downward in the U- tubes of the SG and transfers the heat to feedwater in the secondary side of the SG through the U-tubes. After it leaves the SG, the coolant is collected in an annular plenum. From there it is distributed to flow to the sixteen modules in the downcomer. At each module, the coolant is pumped downwards by the primary coolant pumps, then flows downwards through the venturi and around the bayonet tubes, and at the lower side of the downcomer, the coolant from the sixteen modules is mixed and then reaches the lower plenum and flows back to the core, thus forming the closed primary circuit.

Pressurizer design of SCOR is quite different from any conventional type of PWR. It is designed as an annular shape with a closed upper side and an open lower side. The opening at the bottom allows water to flow in and out of the pressuriser. It is located on the upper part of the riser. The pressurizer with the primary safety valve is attached to the primary loop. Set point of primary safety valve is set to 97 bars, it is controlled by a General Control Simulation Module (GCSM) signal.

In the secondary circuit, the heat transferred from the primary side is absorbed by the feedwater, causing it to form a vapor-liquid mixture. Subsequently, this mixture is directed to the separator, where it undergoes a separation process. After separation, the liquid phase returns to the downcomer of the SG, while the vapor phase proceeds into the main steam lines. The U-tube SG is modelled in ATHLET using the control word STEAMGEN and includes a section of the main steam lines with the secondary safety valves. Since the focus of the study is on the transient thermal hydraulic characteristics of the primary circuit and on the passive safety system in case of the SBO accident, the model used in this study disregards the turbines and auxiliary equipment of the secondary circuit. The feedwater supply and main steam lines are modelled by FILL objects and GCSM control signals. During the SBO, the steam generator is isolated. This is achieved by reducing the mass flow rates in both the feedwater and main steam lines to zero using GCSM signals.

The tertiary circuits, called RRP loops, are used to remove the decay heat from the primary side to final heat sinks. Sixteen bayonet heat exchangers located in the reactor downcomer were modelled based on experience gained from [3], [4], [5], [6]. For this study, four RRP loops cooled by immerged heat exchangers in the pools are activated. The RRP loop consists of the bayonet heat exchanger, hot and cold legs and the heat exchanger in the pool. Each immerged heat exchanger in the pools is located in a compartment. The compartment is modelled with a thermo fluid dynamic object (TFO), and has a valve positioned at the top, while the bottom remains open to the pool. This TFO is modelled as steam-filled, because during normal operation of the reactor, the water in the compartment starts to boil and the generated steam is trapped under the compartment due to the closed valve. With the SCRAM signal, the valves of the compartments are automatically opened. This action releases the generated steam from the upper part of the compartment and allows water to enter from the bottom. This allows passive decay heat removal by creating natural circulation in both the pools and the RRP loops. Figure 2, obtained from ATLAS, which is the post-processing tool of ATHLET, depicts the events taking place inside the compartment before and immediately after the SBO.

The pool is modelled with two TFOs by having 90% and 10% of total volume with a Cross Connection Object (CCO) to enable the natural circulation of water inside the pool. A Time-Dependent Volume (TDV) is linked at the top of the pool and the boundary conditions were assigned at here.

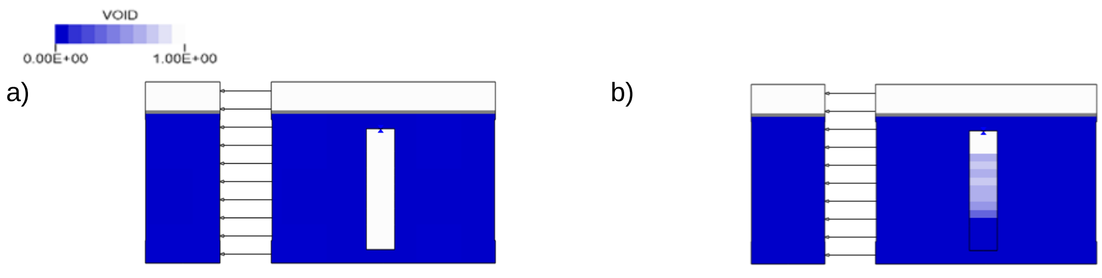


Figure 2 Illustration of the events taking place inside the compartment (a) before and (b) immediately after the SBO

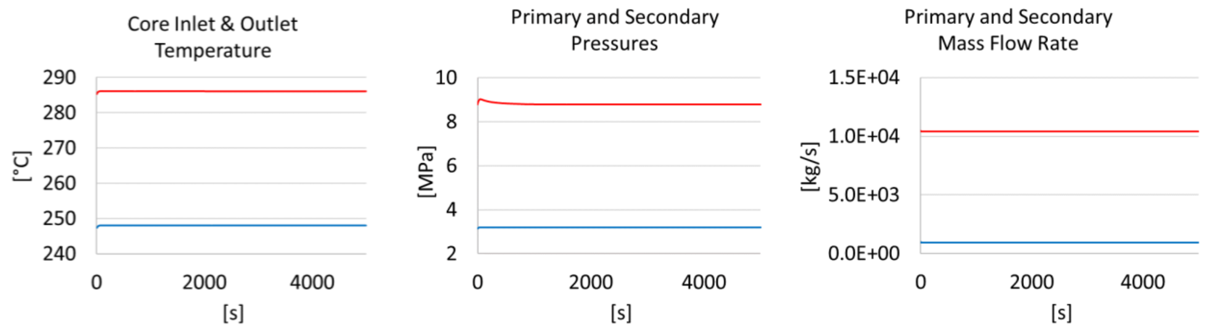
2.2 Steady State Analysis

Conducting a steady state analysis is an essential process to obtain meaningful results from the transient analyses. Reasonable steady state results can prove the accuracy of the developed model. Therefore, to verify the generic input deck, a steady-state analysis was performed at 100% core power and the results were compared with published design data.

2.2.1 Results of the Steady State Analysis

In this study, the steady-state analysis was conducted for a period of 5000 seconds, and the final state of the steady-state analysis is assumed to be the initial state for the subsequent transient analyses. Figure 1a shows the variation of the core inlet and outlet temperature. Figure 1b displays the variation of primary side and secondary side pressure at the steady state condition. The primary circuit pressure remains constant at 8.8 MPa after about 1000 s, and the SG secondary side pressure remains constant at 3.2 MPa, as shown in the figure. Figure 1c presents the variation of the mass flow rate of primary coolant and steam.

Table 1 presents the comparison of the results of the ATHLET steady state analysis with the published design values. Based on the data presented in Table 1, it is obvious that the results obtained from the steady state analysis are reasonable. It is therefore appropriate to proceed with the transient analyses.



(a) *(b)* *(c)*

Figure 3 Variation of main parameters during steady state analysis

Table 1: Steady calculation results comparison with design value.

	Parameter	Ref. Value	ATHLET Calc.	% Diff.
Reactor Param	Mass flow rate [kg/s]	10465	10400	0.6
	Primary Pressure [MPa]	8.8	8.79	0.1
	Inlet core temperature [°C]	246.4	248.0	-0.7
	Outlet core temperature [°C]	285.4	286.1	-0.3
SG Param	Steam Flow [kg/s]	987	987	0.0
	Steam Pressure [MPa]	3.2	3.20	-0.1

2.3 Transient Analysis

The SBO accident was assumed to initiate at 0 seconds. Immediately following the SBO event, several actions take place: the primary pumps trip, the feedwater supply to the SG is lost, and the main steam isolation valves start to close. Two seconds later, SCRAM occurs, and the reactor power drops to the decay heat level. The SCRAM signal triggers the opening of the valves located at the top of the compartments. Once the valves are opened, the passive heat removal system is activated and the RRP loops start to remove the decay heat from the primary side to the pools. For this study, it is considered that the accident occurred directly at the end of three operation periods with an operation time of 720 days and a 60-day maintenance period in between. The decay heat curve that used in the simulations are calculated by applying DIN 25463 [7]. Two standard deviations σ for the fission products and an uncertainty of 0.4% for the thermal power of the reactor were included in the calculation for a conservative approach [8].

The transient analyses begin with the state defined at the 5000th s of the steady state analysis. The simulations of the SBO scenario were conducted for five different cases: Case 1 with one active RRP loop, case 2 with two active RRP loops, case 3 with three active RRP loops, case 4 with four active RRP loops, and the reference case without any safety system except the safety valves. All the simulations start from the same initial state, except for minimal numerical differences that result from the different number of active RRP loops.

2.3.1 Results of the Transient Analyses

In this section, firstly, the sequence of events that took place in the reference case is outlined for a better understanding of the subsequent results, and then a code-to-code comparison is performed with the available CATHARE results in the literature for the reference case. After that, the results of the simulations, which were performed by activating various numbers of the RRP loops in the model, are analysed.

In the reference case, power is initially removed by natural circulation on the primary side and by the evaporation of water on the secondary side of the SG during the initial phase of the transient. The combination of water evaporation and the unavailability of an emergency feed water supply leads to the depletion of water on the secondary side of the SG (refer to Figure 4a). Within the first few seconds of the event, the primary pressure decreases suddenly due to the reduction of the core power to the level of decay heat. This is followed by a rapid increase, and subsequent decrease to a specific level due to the buffering effect of the SG (refer to Figure 4b). In the meantime, power of the SG also decreases as the water level in the SG continue to decrease. When the SG can no longer effectively remove adequate energy, the primary pressure increases to the set point of the primary valves (refer to Figure 4b), and subsequently, the primary safety valve opens. After that, the primary mass inventory decreases due to increasing primary coolant loss through the primary safety valve (refer to Figure 4c). After a certain duration, the core becomes uncovered.

The ATHLET results of the reference case were compared with the results of the CATHARE code [9]. Both CATHARE and ATHLET calculations begin at 100% of the reactor power. However, specific details regarding the boundary conditions of the CATHARE calculation is unknown. Additionally, differences might exist between the geometries employed in these simulations, as the ATHLET input data was created based on available literature. Despite these uncertainties, this comparison can offer insights into the reliability of the generic ATHLET input deck, taking into account that the CATHARE calculation was performed by the designer of SCOR reactor. The comparison was conducted for the primary coolant pressure, and the water masses of primary and secondary side. As can be observed in Figure 4, all results are reasonable in a qualitative comparison. However, there are quantitative variations, which are expected due to the non-identical boundary conditions.

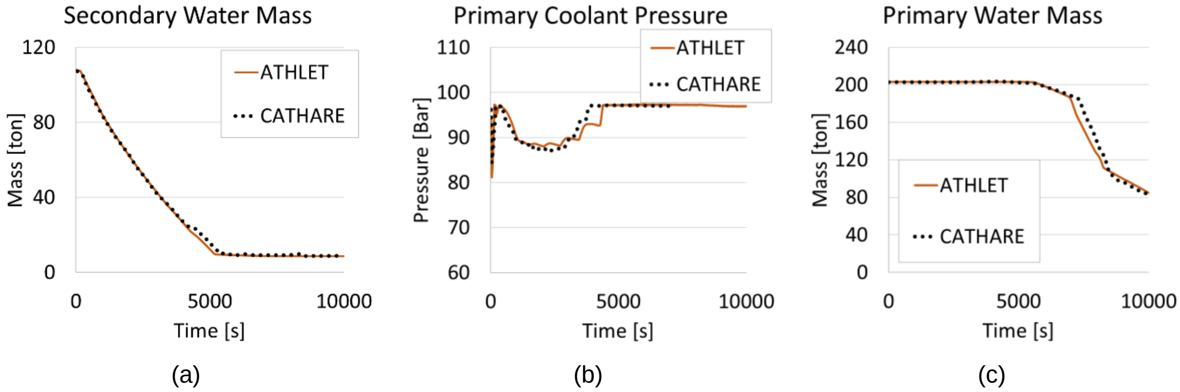


Figure 4 Results for Secondary Water Mass (a) Primary Coolant Pressure (b) Primary Water Mass* (c)
*Without pressurizer

By activating the RRP loops in the model, in addition to the buffering effect of the SG, the decay heat is removed by the RRP loops. As shown in Figure 5, the primary pressure decreases at a faster rate with increasing numbers of active RRP loops in the model. Similarly, the time taken for the primary pressure to reach the set point of the primary safety valve increases as the number of active RRP loops in the models increases.

Figure 6 illustrates the quantity of water present on the secondary side of the SG. As depicted in the figure, depletion of the liquid phase of water takes roughly one and a half hours in the reference case. After that only steam remains in the secondary side of the SG. The number of RRP loops affects the amount of water remaining on the secondary side of the SG; an increase in the number of RRP loops results in more water remaining in the SG.

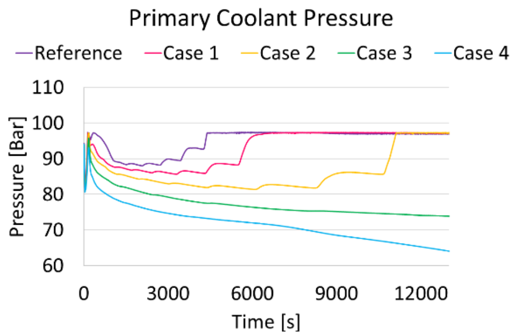


Figure 5 Primary coolant pressure vs time

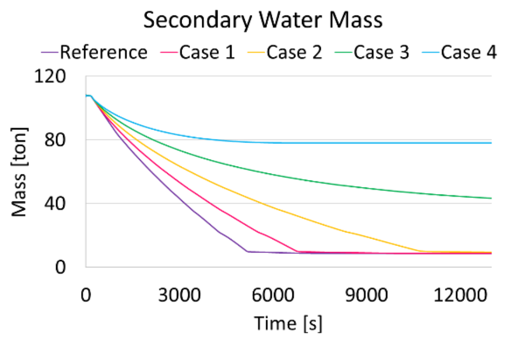


Figure 6 Secondary water mass vs time

Figure 7 depicts the variation of primary coolant mass over time. As the primary pressure reaches the set point of the safety valve, coolant is released to maintain the primary pressure at 97 bar. This phenomenon is clearly observable in the figure, particularly for the reference case and case 1. For case 3 and case 4, there is no change in mass because the safety valve remains closed during the reported time period depicted in the figure.

Figure 8 displays the core exit temperature over time. Following the SCRAM event, the temperature experiences a rapid initial increase, followed by a drop to certain levels due to both the buffering effect of the SG and the influence of the RRP loops. In the reference case, the temperature begins to rise as the buffering effect of SG diminishes. This takes place in less than an hour. The increase in the number of RRP loops extends this period. During the time period shown in the figure, it can be seen that case 4 and case 3 effectively remove enough heat from the primary side to prevent the temperature from rising again.

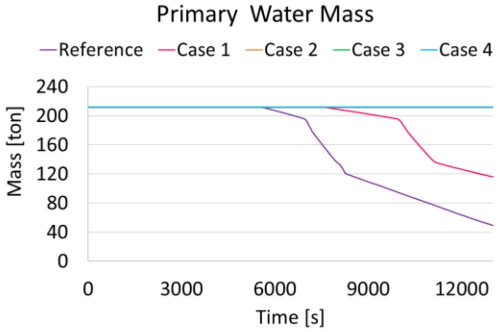


Figure 7 Primary water mass vs time

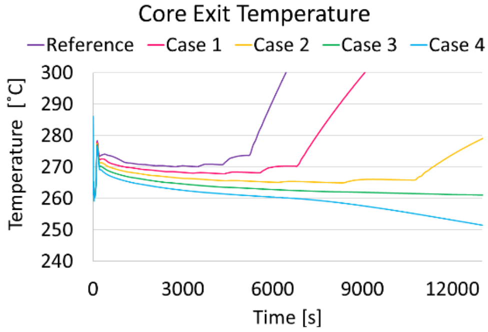


Figure 8 Core exit temperature vs time

However, it is important to keep in mind that the ultimate heat sinks are the pools, which have limited autonomy for a specific duration. The water in the pools evaporates and the heat removal capacity of the system decreases. Due to the inability to remove further heat by RRP loops and the persistence of decay heat, both the pressure and temperature rise again on the primary side.

Figure 9 shows the comparison between the decay heat and the power removed by both the RRP loops and the buffering effect of the SG. In the first few hours, a significant amount of heat is removed from the primary side due to the buffering effect of the SG. Thereafter, the RRP loops continue to remove energy from the primary side. As expected, the removed power falls below the decay heat curve first in case 1 and then in cases 2 and 3 respectively. Only Case 4 was found to be sufficient to ensure the safety of the plant for at least 72 hours. This indicates that the SBO scenario can be effectively managed passively (within the vessel, the RRP loops, and the heat sinks) using only 4 RRP loops. The cause of the oscillations observed in the curves is currently under investigation.

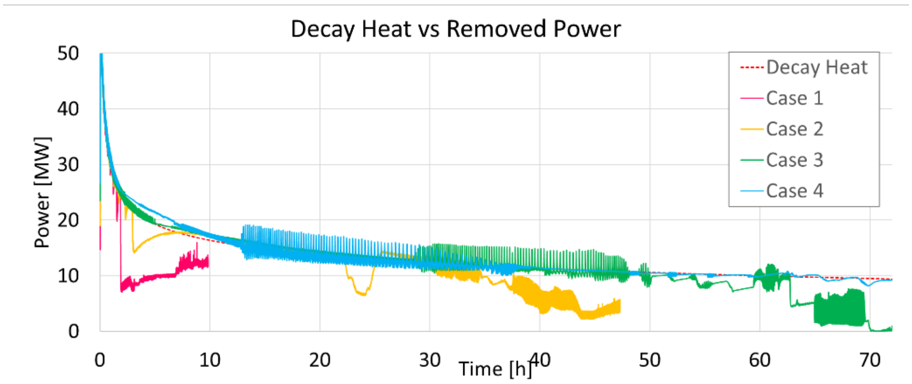


Figure 9 Decay Heat vs Removed Power

3 CONCLUSIONS

This paper investigates the passive heat removal system designed for the integral pressurised water reactor, which uses the bayonet heat exchangers. The effectiveness of the system is evaluated in the context of the SBO accident using the extended version of the thermohydraulic system code ATHLET. The study focuses specifically on the RRP loops connected to the pools as the final heat sinks. A generic input deck for SCOR design was created based on available data from the literature. Steady-state analysis was then conducted at 100% core power, and the results were compared with published design data to verify the input deck. The results of the ATHLET calculation and the published design data were found to be in good agreement. Following these steps, the transient analyses were carried out in five different scenarios. These analyses included the case with no safety system except the safety valves and the cases with one, two, three and four active RRP loops in the reactor. The results of the transient analyses have been studied in detail and indicate that maintaining four out of the sixteen RRP loops is sufficient to effectively control of the core decay heat, even during the SBO event that lasts for 72 hours. In addition, the comparisons were made between the ATHLET code results and the published CATHARE code results for the reference case.

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