Evaluating SAM Strategies of In-Vessel Retention in a Typical PWR under Extended Station Blackout Conditions

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1. Introduction

Ensuring the safe and reliable operation of nuclear power plants is of paramount significance in safeguarding the well-being of the public and the environment. To achieve this goal, multiple safety systems that can adeptly manage abnormal operational situations have been designed. Nonetheless, the potential for multiple system failures triggered by rare external events may still challenge the plant, potentially causing core damage and the release of radioactive materials as evident by the Fukushima Daiichi nuclear power plant disaster which underscored the vulnerability of existing nuclear power plants under an extended period of a Station Blackout (SBO).

In this context, Emergency Operating Procedures (EOPs) have emerged to steer operators to promptly and effectively address abnormal or emergency situations. By adhering to these procedures, operators can stabilize the plant and prevent the escalation of incidents into severe accidents. However, in the case a severe accident cannot be prevented, severe accident management guidelines (SAMG) are developed to guide the decisions of the technical support team as they instruct the operators to mitigate the situation.

The objective of this paper is to assess and compare the efficacy of the In-Vessel Retention (IVR) severe accident management (SAM) strategy through candidate high level actions (CHLA) such as depressurization and injection into the primary side using FLEX portable equipment on the one hand or with the External Reactor Vessel Cooling (ERVC) strategy on the other hand to maintain the molten corium within the vessel and avoid the complex ex-vessel phenomena, i.e. molten corium concrete interactions. Similar to the FLEX strategy which has been developed in USA, Korea developed the Multi-barrier Accident Coping Strategy (MACST) to strengthen the coping capabilities of nuclear power plants in response to extreme natural events [13].

A number of studies focused on assessing the success window of IVR strategies given the high level of uncertainties associated with melt pool convection, vessel wall heat conduction, and external boiling heat transfer; external cooling enhancements and their applicability to reactor designs; and additional cool-ability enhancement strategies proposed especially for high power-density reactors [2]. For APR-1400, establishing a cooling flow path and alignment of FLEX portable pumps within two hours has been proven to be a successful EOP under the conditions of extended SBO [8]. As for the IVR strategy by the ERVC approach – which involves flooding the reactor cavity before the molten debris relocates and submerging the reactor pressure vessel (RPV)– has been debated for high power-density reactors like APR1400 [9]. The key concern is ensuring the RPV lower head's integrity under the attendant thermo-mechanical loads, primarily imposed by the heat flux ensuing from the high temperature molten pool [6]. It has therefore been proposed to rely on forced convection for ex-vessel cooling rather than cooling by natural circulation when the vessel is flooded. [4]

The determination of the initial conditions for ERVC involves specifying debris mass relocating to the lower plenum, debris composition, molten pool configuration in the lower plenum, decay power, and thermo-physical properties of the debris and vessel wall [5]. Cavity conditions (water temperature and pressure) are of secondary importance if the lower head remains submerged, as the outer vessel wall temperature should stay close to the water saturation temperature [5].

In this work, the response of APR-1400 to an extended SBO event is simulated along with the systematic implementation of EOPs and SAMG to gauge their effectiveness in mitigating the accident. This investigation aims to yield valuable insight into the effectiveness of the safety measures and verify the overall resilience of nuclear power plants against severe accidents.

2. Methodology

As mentioned earlier, this study aims to explore the potential and limitations of the cooling schemes for successful IVR strategy for a high power-density reactor such as APR-1400.

2.1 ASYST Model

To test the resilience of the APR-1400 system under extended Station Blackout (SBO) conditions a model of APR1400 is developed using the ASYST (Adaptive System Thermal-hydraulics) code developed by Innovative Systems Software (ISS) [3] to evaluate the success window of the implementation of SAM guidelines for IVR strategy. The ASYST package offers multidimensional, multi-fluid models to accurately capture the attendant phenomena (melting, relocation, melt spreading, core-concrete interactions as well as fission product release and transport) during the severe accident scenario [7].

2.2 Model Assumptions and Initial conditions

A crucial first step is to define the initial and boundary conditions, along with the geometric parameters of key components and structures that influence the behavior of the APR1400 system during the accident scenario. To validate the model, the initial conditions are chosen in accordance with the guidelines outlined in Design Control Document (DCD) Chapter 15 of APR1400 NPP [1].

2.3 System Nodalization

To conduct the severe accident simulation, a thermal-hydraulics model of the two-loop APR1400 reactor has been developed. **Figure 1** illustrates the plant system nodalization, which provides a clear depiction of the key systems and components.

The thermal-hydraulics model encompasses the entire Reactor Coolant System (RCS), including the Reactor Pressure Vessel (RPV) connected to the Steam Generators (SGs). Four Reactor Circulation Pumps (RCPs) are connected via the cold legs to the RPV to circulate the coolant flow. A Pressurizer (PZR) is connected via a surge line to one of the hot legs to maintain the design pressure and accommodate pressure and temperature fluctuations.

The core is represented using five channels, each with the appropriate axial and radial power distributions. Furthermore, the core intake and output nozzles, lower and upper plenum, core bypass channels and the detailed core structures are modeled. The down-comer is split into eight channels to smooth out the fluctuation resulting from the safety injection system (SIS).

Modeling the In-Vessel Retention (IVR) strategy using depressurization and injection involves the incorporation of the pilot-operated safety relief valves (POSRVs) and FLEX pumps for injection as can be seen in Figure 1. These relief valves are connected to the pressurizer head and are to be deliberately opened for the primary side depressurization as a mitigation strategy for SBO. Additionally, three sets of main steam safety valves (MSSVs) are added to each steam line to avoid over pressurization on the secondary side and assist in the heat removal during the accident as they oscillate between their operational set points.

Further, the Safety Injection Tanks (SITs) are modeled as accumulators to accurately represent the safety injection flow rate through the fluidic device. To simulate the high and low flow rates, two valves are attached to each line connecting the SITs to the Reactor Pressure Vessel (RPV) down-comer.

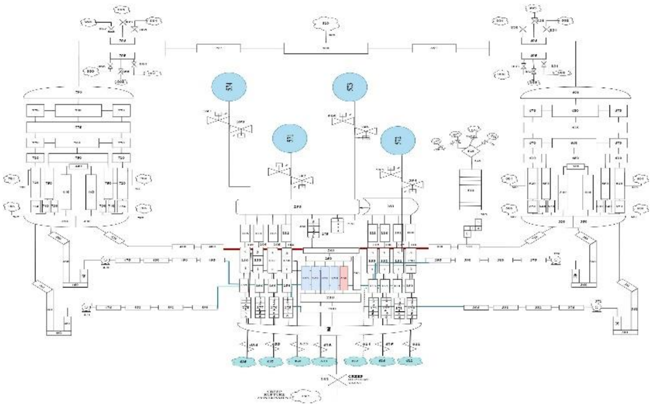

Figure 1: APR1400 Nodalization

In addition to the above systems, the model also includes the primary circuit injection using portable FLEX pumps. Each pump is modeled using a time-dependent volume and a time-dependent junction admitting the design flow rate when the pressure falls below a set threshold value. Further, a RPV creep rupture valve was added to the lower head to simulate the vessel failure by opening a flow path once the yield stress is reached.

One of the CHLAs within SAMG entails flooding the reactor cavity with water before any molten core debris reaches the lower plenum. Careful design of a streamlined pathway facilitates a natural circulation process on the reactor pressure vessel's (RPV) exterior [9]. To simulate ex-vessel cooling and assess the effectiveness of ERVC, a channel was coupled to the exterior of the RPV as shown in **Figure 2**. This allows the evaluation of the efficacy of the cavity flooding as a standalone strategy, excluding other EOPs, or SAM strategies during a Station Blackout (SBO).

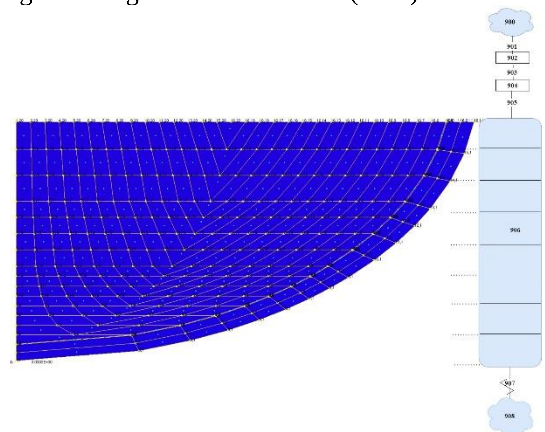

Figure 2: Couple Nodalization with ERVC

3. Results and Discussion

3.1 Model Validation

To validate the model is initialized in accordance with the guidelines outlined in APR1400 DCD. Comparing the steady state conditions, the model matches with reasonable accuracy those reported in DCD within less than 5% deviation as listed in Table 1.

Table 1 : Steady State Conditions

Thermal-Hydraulic Parameters	DCD	Model
Total core heat output MWt	3983	3983
primary system pressure (kg/cm^2 .A)	158.2	158.2
Reactor inlet coolant temperature (°C)	290.6	293.66
Re-exit average coolant temperature (°C)	325	325.60
No of active fuel rods	56876	56876
Pumps speed, rpm	1190	11900.13
flow rate (m^3/h)	21000	20940.63
SG pressure (kg/cm^2.A)	70.2	70.29
Feedwater temperature (°C)	232.2	232.2
Total steam flow per gen 10^6 (kg/h)	4.07	4.07
Steam quality (%)	99.75	96.0

3.2 Unmitigated SBO (Dry vs. Wet Cavity)

As a result of the accident, the Reactor Coolant Pumps (RCP) coast down, the Main Steam Isolation Valves (MSIV) are initiated, the main feed water is lost,

and both the reactor and turbine trip. An abrupt reduction in the reactor power to the decay heat level can be observed as illustrated in **Figure 3** due to the negative reactivity insertion by the shutdown control rods.

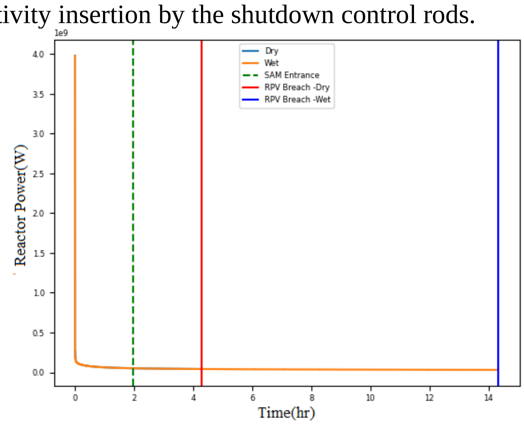

Figure 3: APR-1400 Reactor Power

When the RCPs coast down, the core flow rate drops significantly, prompting a temperature increase and expansion of the primary coolant. In response, the pressure in the Pressurizer (PZR) starts to increase until it reaches the activation threshold of the pressurizer POSRVs which triggers the swift cycling of the POSRVs until the PZR water level is depleted as illustrated in **Figure 4**, and PZR pressure is maintained on the same level as shown in **Figure 5**.

Figure 6 and **Figure 7** illustrate the significant role played by the Main Steam Safety Valves (MSSVs) in maintaining the Steam Generator (SG) pressure and preventing over pressurization due to heat buildup. It is worth noting that until the cycling set points of the POSRVs are reached, the primary method of cooling the Reactor Coolant System (RCS) relies on secondary heat removal via natural circulation.

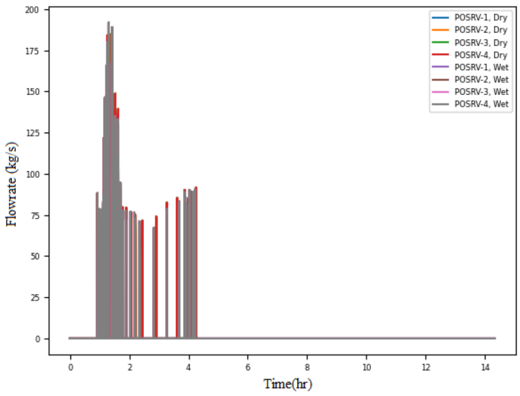

Figure 4 : POSRVs Flowrate

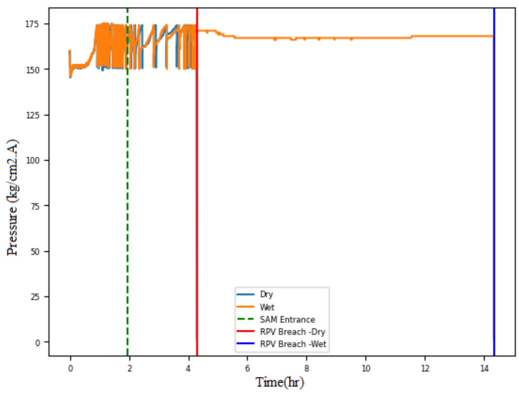

Figure 5: Pressurizer Pressure

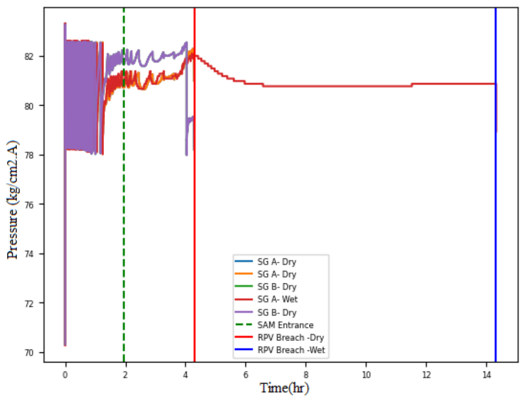

Figure 6: Steam Generators Pressure

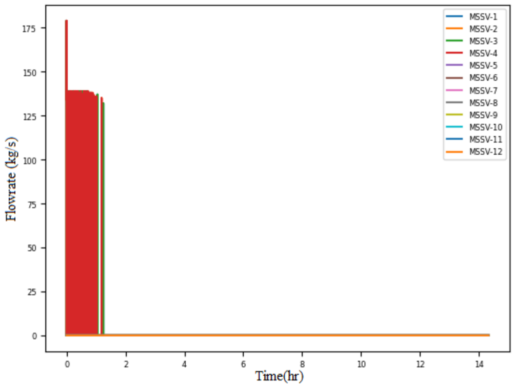

Figure 7: MSSVs Flowrate

However, natural circulation is only viable for a brief period given the loss of feed water and the assumed loss of auxiliary feed water supply. Consequently, safety valves cycle continuously to release the generated steam until the steam generators are depleted. The loss of cooling during the accident prompts a notable temperature rise within the APR1400 reactor system; ultimately the Peak Cladding Temperature (PCT) limit is violated which causes the core to start melting and relocating.

The Core Exit Temperature (CET) increase due to the heat transfer from the hot fuel eventually reaching 922K which marks the Severe Accident Management Guidelines (SAMGs) entrance condition at approximately 2.0 hours after the onset of SBO as evident in **Figure 8**.

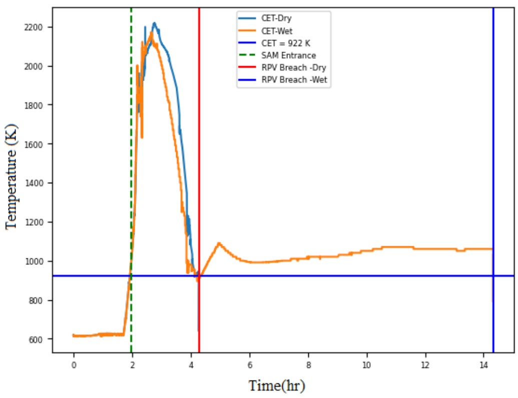

Figure 8: CET and SAMGs Entrance Condition

As the coolant undergoes a boiling process, CET approaches the saturation condition causing a drop in the collapsed water level within the RV and the core becomes exposed, as illustrated in **Figure 9**. The CET continues to increase until it reaches a peak value around 2200 K before candling ensues and molten material slowly drops when the molten corium relocates to the lower plenum as demonstrated by the core degradation map in **Figure 10.**

The prolonged exposure to high temperatures after core relocation can cause creep deformation ultimately leading to vessel breach at around 4.26 hours in case of a dry cavity. On the other hand, with a wet cavity the deformation can be sustained for a prolonged period before the integrity of the RPV is lost at approximately 14.3 hours. The RPV failure is manifested by the activation of a creep rupture valve attached to the lower head, suggesting a potential opening in the RPV due to the combination of high temperatures and creep deformation.

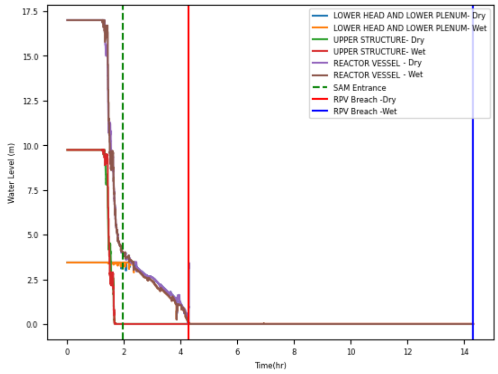

Figure 9 : Collapsed Water Level

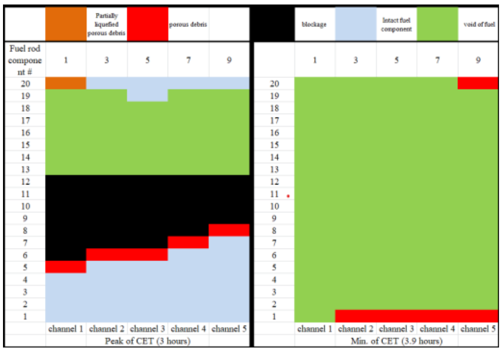

Figure 10 : Core Degradation Map

As the temperature approaches 2200 K, the conditions become favorable for the exothermic reaction oxidizing Zircaloy and producing hydrogen within the core, as depicted in **Figure 11**. This oxidation process results in an additional heat release which further stresses the system as visible in **Figure 12**. In the case of a wet cavity, some of this heat is transferred via the external vessel wall, which makes it possible to retard vessel breach till 14.3 hours.

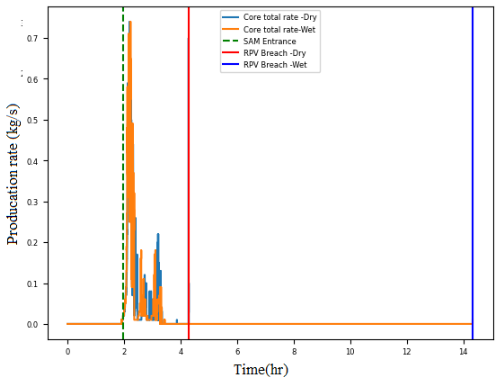

Figure 11: H_2 Generation rate

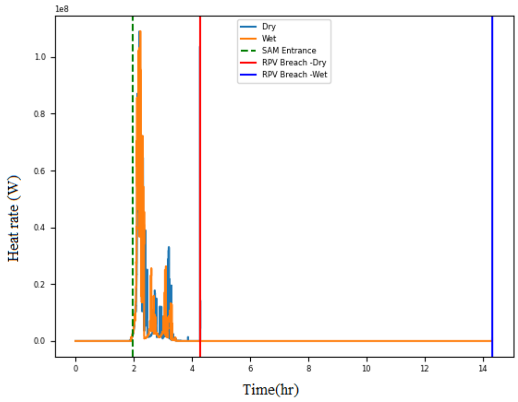

Figure 12: Oxidation Rate

Next, a molten pool of liquefied fuel and other materials forms and the coolable geometry is lost, hence limiting the direct contact between the fuel cladding and steam and thereby creating less favorable conditions for the chemical reaction which impedes the rapid and sustained hydrogen generation. The growth of this molten pool exerts stress on the oxide shell which may develop cracks allowing the molten material to relocate to the lower head and form a pool of molten corium. Eventually, the concentrated power density associated with the molten pool impose significant thermo-mechanical stresses leading to a vessel breach. In the case of a dry cavity, the thermal stress causes the vessel to breach almost instantaneously after relocation at 4.26 hours as illustrated in **Figure 13**. On the other hand, in the case of a wet cavity, the presence of a water pool outside the vessel allowed the dissipation of heat which in turn slowed the creep rupture to 14.3 hours.

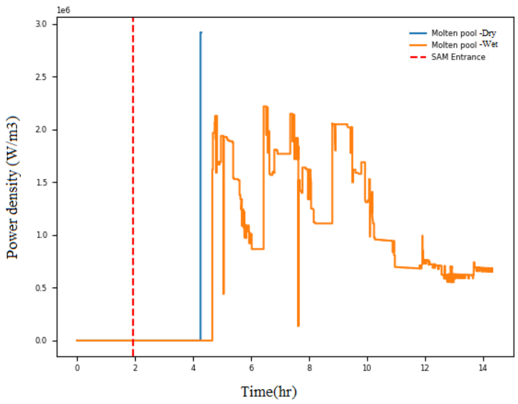

Figure 13: Molten Pool Power Density

3.3 In-Vessel Retention via FLEX Equipment

The In-Vessel Retention **(**IVR) process involves three steps performed by operators. Initially, depressurization is initiated by opening the POSRVs, which subsequently triggers the injection of water from the SITs as the RCS pressure drops below the design threshold value. Next, the FLEX portable pump, with an injection rate of 30 kg/s, is aligned within two hours to ensure complete core coverage. These actions were successful in maintaining the PCT well below the safety limit of 1477 K, as depicted in **Figure 14**.

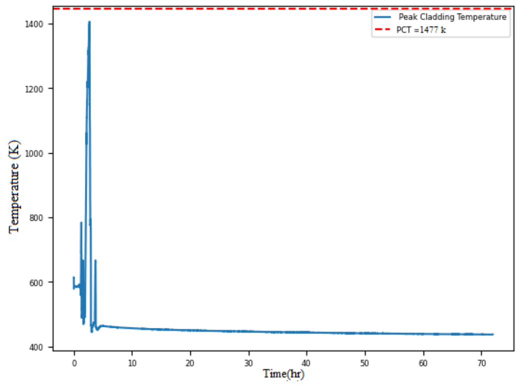

Figure 14: PCT with FLEX Strategy

It is worth noting that the CET was effectively controlled at about 400 K, as depicted in **Figure 15**, through the successful alignment of the FLEX equipment within two hours from the SAMGs entrance condition.

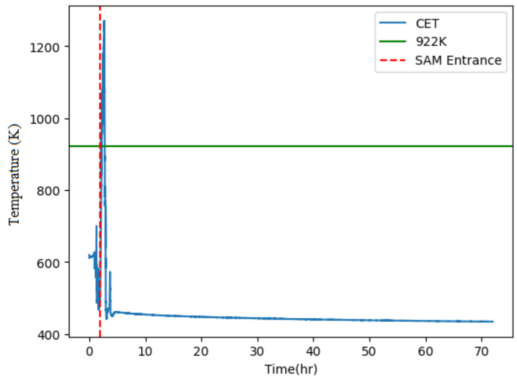

Figure 15: CET with FLEX Strategy

The FLEX pump was aligned at 2 hours with a flowrate set at 30 kg/s as indicated in **Figure 16.** It should be noted that it is intended to investigate different injection timing to assess the impact of injection timing on the window of success for the FLEX strategy as will be shown later.

This flow rate has been calculated to offset the decay heat using the following heat balance:

$$\dot{P}_D = \dot{m}\left(c_p \Delta T_{sub} + \Delta h_{fg}\right) \quad .... [1]$$

where

$\dot{P}_D$ = decay power (W)

$\dot{m}$ = injection flow rate (*kg/s*)

c_p= fluid specific heat (*J/kg K*)

ΔT_{sub}= degree of subcooling (K)

Δh_{fg}= latent heat (*J/kg*)

El-Wakil [14] proposed a correlation to estimate the rate of decay heat generation as follows:

$$\frac{\dot{P}_D}{\dot{P}_o} = 0.095\ t_s^{-0.26} \quad .... [2]$$

where
$\dot{P}_o$= operating power (W)
t_s = time after shutdown (s)

Using the heat balance in equation 1, alongside with the definition in equation 2, it is possible to estimate the injection flow rate. Two cases may be considered. One limit assumes that the injected water does not undergo phase change, hence only sensible heat is considered:

$$\dot{m}_{max} = \frac{\dot{P}_D}{c_p \Delta T_{sub}} = \frac{0.095 \dot{P}_o\ t_s^{-0.26}}{c_p \Delta T_{sub}} \quad [3]$$

The other case assumes that all injected water is transformed into vapor. In this case, the sensible heat may be neglected in comparison to the latent heat:

$$\dot{m}_{min} = \frac{\dot{P}_D}{\Delta h_{fg}} = \frac{0.095 \dot{P}_o\ t_s^{-0.26}}{\Delta h_{fg}} \quad ... [4]$$

Based on those two limiting cases, an average injection flow rate of 30 kg/s is calculated using equations 3 and 4 for the FLEX portable pump.

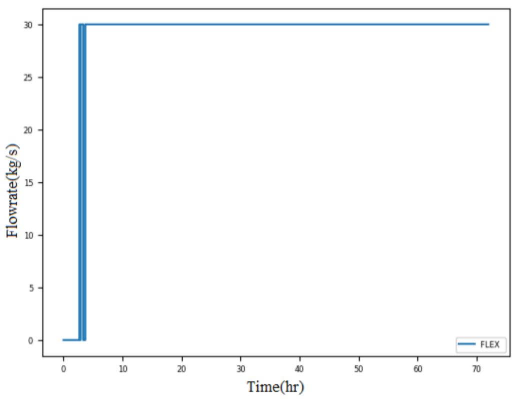

Figure 16: FLEX Flowrate

As indicated in **Figure 17**, the water level inside the RPV exhibited an initial decrease during the transient, but that was subsequently reversed with a slight increase in the collapsed water level as a result of the implementation of the FLEX strategy.

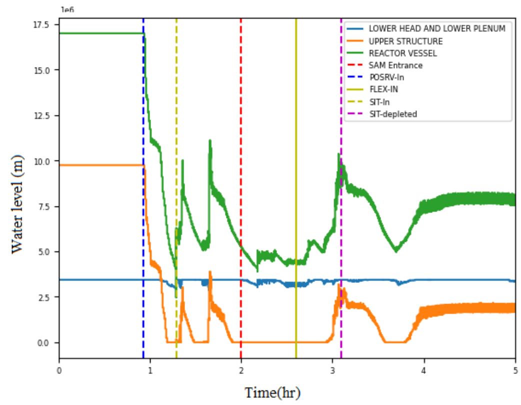

Figure 17: Water Level

Following the entrance of SAMG, there was a minor occurrence of hydrogen generation accompanied by a relatively low oxidation rate as depicted in **Figure 15** and **Figure 19**, respectively. This may be attributed to the preservation of the fuel intact with a limited extent of damage as illustrated in the core degradation map in **Figure 20**. A summary of the sequence of events is provided in **Table 2**.

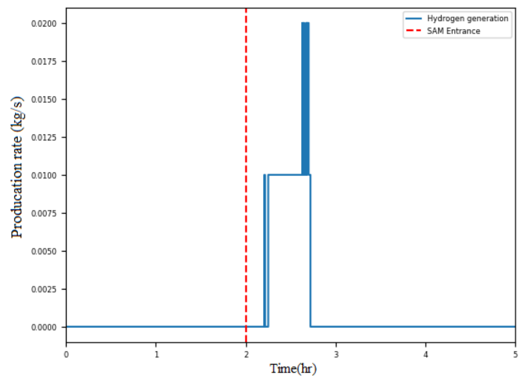

Figure 18: H_2 **Generation rate**

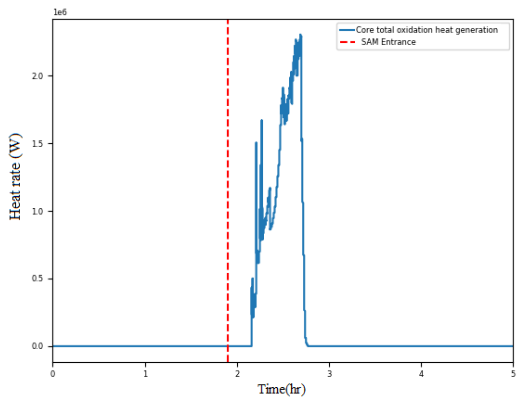

Figure 19: Oxidation Rate

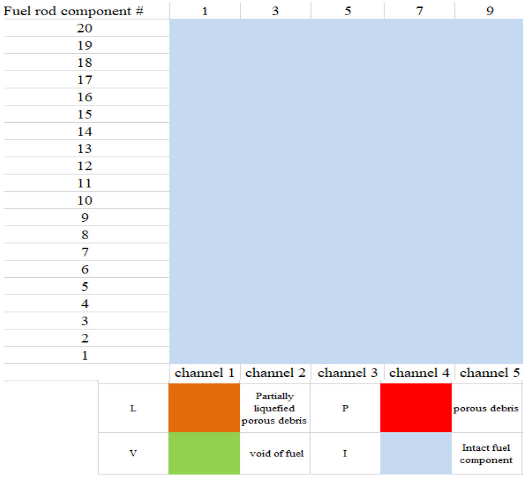

Figure 20: Core Degradation Map

3.4 Evaluating the Ex-Vessel Cooling Strategy

As previously mentioned, the concept of ex-vessel cooling was put forth to address the critical heat flux bottleneck associated with natural circulation when flooding the cavity of reactors with high power density. An alternative approach could involve creating a streamlined path for a high rate of forced coolant flow, which would effectively manage heat removal without being limited by critical heat flux.

Table 2: SBO Mitigation via FLEX Injection

Time (hr)	Sequence of Events
0.0	Initiating event (Loss of power)
0.0	MSSV actuation
0.93	POSRV set point
1.29	SIT actuation/ Depressurization via POSRV
1.9	SAMGs entrance
2.8	FLEX aligned
3.1	SIT Depleted
3.7	FLEX injection starts
72.0	No vessel Breach

The results presented in **Section 3.2**, aimed to evaluate the impact of a wet cavity in providing cooling based on natural circulation with an average flow rate of 875 kg/s established within the cavity which has been estimated based on other studies in the open literature [12]. As shown earlier, the success of this strategy is only limited to ~ 14.3 hours. To increase the success window, forced circulation using a high flowrate of 10000 kg/s was used as can be seen in **Figure 21**. At this time in the accident when the molten material has relocated to the lower head, significant decay energy of $4.4 \times 10^8\ J$ has accumulated within the debris pool and is transferred instantaneously to the vessel within 1 *s*. The mass flow rate required to offset this heat, can be calculated following the energy balance presented earlier and assuming a subcooling of 10°C.

The injection was initiated after the relocation of debris into the lower head which is around 3 hours from entrance of SAMGs.

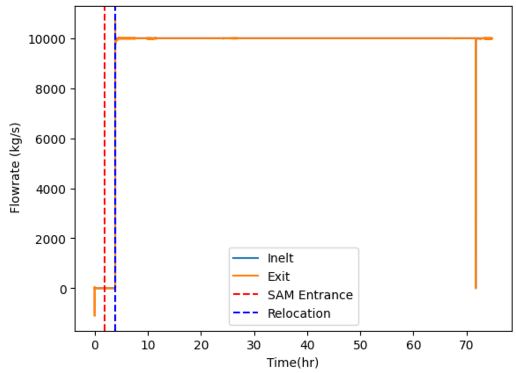

Figure 21: Flowrate in Ex-Vessel Channel

The fluctuation of water level within the channel varied due to the formation of voids within the channel. As illustrated in **Figure 22**, the water level within the channel began to decrease around the time of relocation. Nonetheless, the flow rate was adequate to uphold the structural integrity of the RPV until 72 hours.

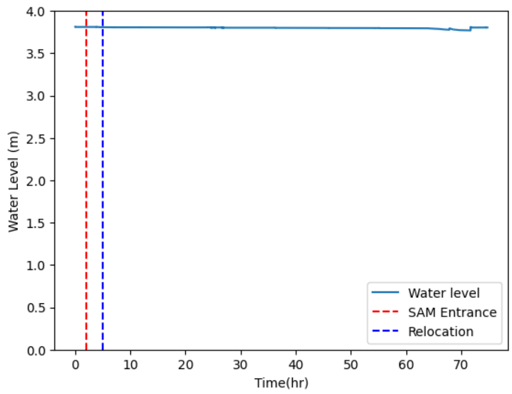

Figure 22: Water Level in Ex-Vessel Cooling Channel

The ex-vessel cooling strategy using forced circulation succeeded in maintaining the average temperature of the debris below 2200 K as shown in **Figure 23** and hence suppress the power density of the molten within 5 hours after the relocation as can be seen in **Figure 24**.

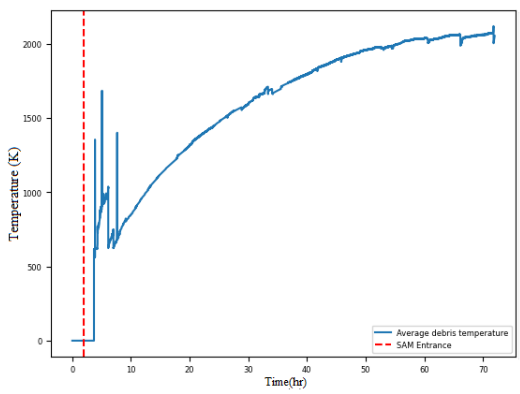

Figure 23: Debris Temperature

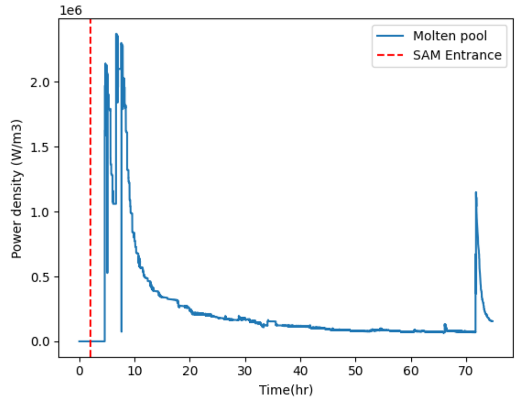

Figure 24: Power Density of Molten Pool

4.5 FLEX Injection with Ex-Vessel Cooling

As an alternative strategy, a combination of both FLEX injection and ERVC via cavity flooding may prove to be efficient especially for high power-density reactors considering the relatively low flowrate 875 kg/s by natural circulation which could independently ensure the RPV integrity for 14.3 hours.

In this section, the impact of the timing of cavity flooding on the system response was explored. An endeavor was made to initiate the injection through the FLEX component just before the core relocated to the lower head. A simulation was conducted with FLEX injection using a flowrate of 30 kg/s along with flooding the cavity by assuming a low flowrate of 875 kg/s for ERVC based on natural circulation. For this simulation, three different time frames for FLEX alignment were chosen: 2.8, 3.9, and 4.72 hours from the beginning of the SBO conditions, as depicted in **Figure 25**.

The aim was to determine whether maintaining a wet cavity would offer a wider range of operator actions to ensure the integrity of the RPV. During the evaluation of SAMGs entry, it was observed that the timing was approximately 2.7 hours, in contrast to a dry cavity situation which took about 2.0 hours in reference to **Figure 8** and **Figure 26**. Despite the delay in FLEX injection, the temperature was successfully brought back under control to the same level across all three scenarios as illustrated in **Figure 27**.

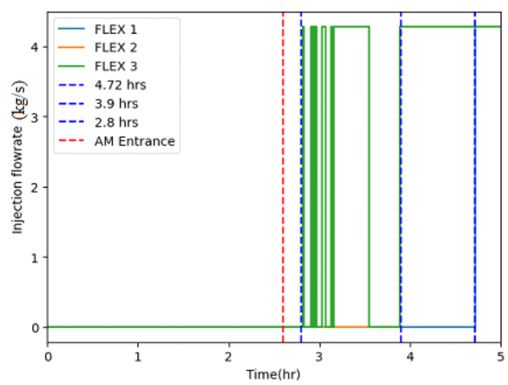

Figure 25: Primary-Side Injection by FLEX Pump

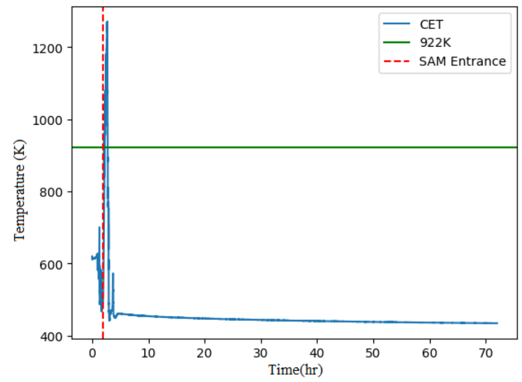

Figure 26: CET for Different FLEX Injection Timing

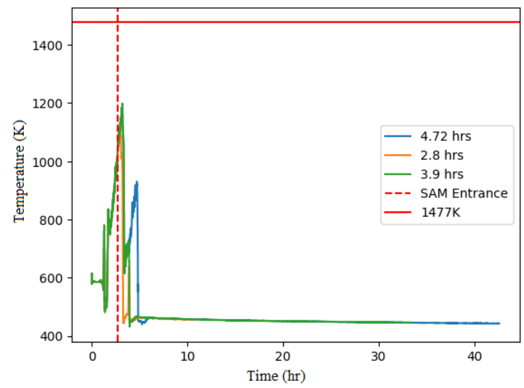

Figure 27: PCT for Different Injection Timing

A modest rate of hydrogen production was noted as illustrated in **Figure 28** as a result of the oxidation process as can be seen in **Figure 29**. It should be noted that the water level was successfully restored in the core for 48 hours, despite the delay of FLEX injection as presented in **Figure 30**. The core degradation map in **Figure 31** indicates the preservation of fuel integrity, hence providing confidence that the FLEX injection will effectively ensure the RPV integrity for duration of 72 hours in the three cases.

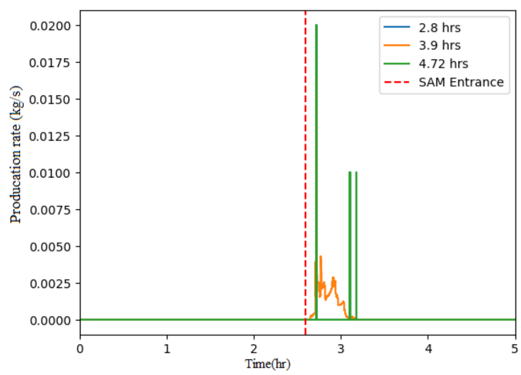

Figure 28: H_2 Generation for Different Injection Timing

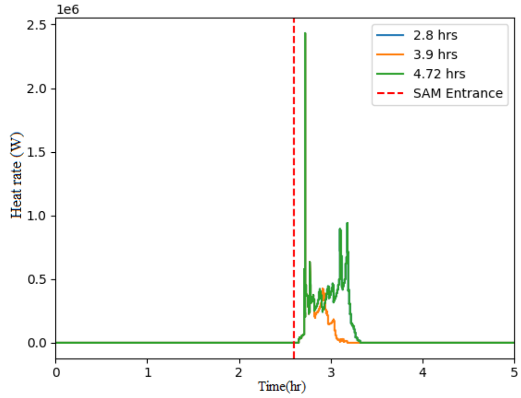

Figure 29: Oxidation rate at Different Injection Timing

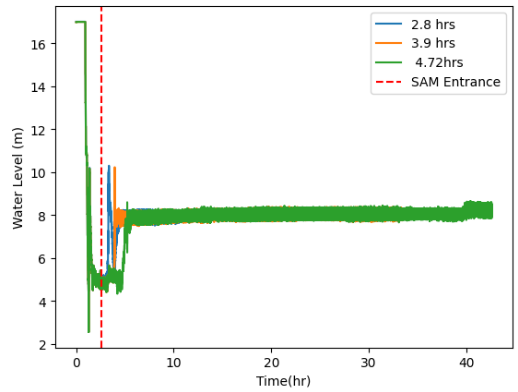

Figure 30: RPV Water Level at Different Injection Timing

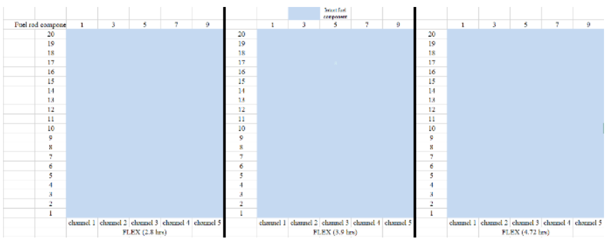

Figure 31: Core Degradation Map after 48 hours

Conclusions

This research explored the behavior of APR1400 under extended SBO and compared the implementation of depressurization and injection using FLEX pump to the Ex-Vessel Cooling by either natural or forced circulation for In-Vessel Retention (IVR). Implementing the IVR strategy within a dry cavity ensures the RPV integrity for 72 hours on condition the FLEX pump is aligned within 2 hours. Similarly, ERVC using forced circulation with high flowrates. However, opting for cavity flooding to externally cool the vessel via natural circulation can only conserve the vessel for 14.3 hours. The success window can however be extended to 48 hours when combined with FLEX injection even when the injection is delayed. To evaluate the success window under various uncertainties, it is planned to conduct an uncertainty analysis of this hybrid strategy.

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