Concept Design, Application and Risk Assessment of New Forced Safety Injection Tank for Station Blackout Accident Scenario

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Abstract: In the current fleet of nuclear power plants, engineered safety systems are designed to perform fundamental safety functions. These fundamental safety functions are crucial, and failure of any one of these may lead to devastating accidents like the Fukushima Daiichi accident. The lesson learned from the Fukushima accident led to the development of advanced passive safety systems for all the new reactor designs and safety enhancements to the current nuclear fleet, such as accident tolerant fuel and US diverse and flexible coping strategies (FLEX). Safety injection tanks are an essential part of the engineered safety features. They are designed to refill the core in the event of medium-large or large break LOCA accidents. The amount of coolant inventory inside the safety injection tanks can provide extended time to core damage if utilized in other accidents such as Station Blackout. This research presents the conceptual design of the new forced safety injection tanks (FSIT). FSIT is designed by introducing a piston-based assembly on the top of the existing safety injection tank. The principle of operation is that when this system is activated, the pressure of the FSIT is increased above the discharge pressure using the backpressure from the pressurizer or steam generator (SG) to drive inventory into the system to gain additional time to core damage. This time can be imperative in deploying FLEX to recover the lost safety system. FSIT can be driven by various sources but the focus of this paper is limited to operation through the steam from the main steam line header. In this research, an SBO case study is performed to demonstrate the applicability and operating principles of FSIT. A simple PRA model was utilized to perform the risk assessment and FSIT is found to reduce the risk of early failure of turbine-driven auxiliary feedwater pumps.

1. INTRODUCTION

The engineered safety systems are designed to perform the fundamental safety functions including reactivity control, reactivity confinement, and decay heat removal and failure of any one of those could lead to the devastating accidents like Three-mile Island, Chernobyl, and Fukushima. In the Fukushima accident, the extended loss of all AC power (ELAP) or commonly known as station blackout (SBO) lead to the loss of decay heat removal function resulting in a severe accident and core damage. Since the Fukushima accident was caused by the loss of the ultimate heat sink resulting from the ELAP. The use of passive systems has been suggested as no external power is required to drive those [1]. Passive systems have proved to be the better options to improve the safety of the nuclear power plants and these are being implemented in all the new and upcoming nuclear power plants. For the existing nuclear fleet, US diverse and flexible coping strategies (FLEX) has been recommended by the Nuclear Energy Institute (NEI) [2] that can provide additional barrier up to 72 hrs. of the accident initiation. FLEX strategies consist of portable equipment such as portable pumps and generators located onsite in a secured building that can withstand external hazards. This equipment can be used to recover the lost safety functions such as removal of decay heat by injecting coolant directly into the steam generator or primary side, providing additional backup power to the turbine-driven pump controller and relief valves, maintaining containment integrity by providing a backup source for containment spray and, cooling a spent fuel pool [2]. FLEX has three different deployment methods [3] and in each method, the initial deployment time for FLEX is estimated to be 2 hrs. In an accident such as ELAP with turbine-driven auxiliary feedwater (TDAFW) pumps failing to start, it is highly unlikely that FLEX can be deployed because of early core failure. The target plant considered in this research is a generic PWR-based 1000 MWe nuclear power plant (NPP) that has four safety injection tanks (SITs) each attached to one of the four cold legs, containing 55000 kg of borated coolant inventory. Therefore, in this research, a modification to the existing safety injection tanks (SITs) are suggested to utilize the stored inventory to gain the additional margin to core damage and increase the likelihood of the recovery of the existing engineered safety system or deployment of the FLEX strategies.

Recently, the concept of hybrid safety injection tanks (HSIT)s [4] has been introduced by Korea Atomic Energy Research Institute (KAERI). This system uses the back pressure from the pressurizer to inject the inventory of the HSITs into the primary circuit in the event of an accident where the system's pressure is above the HSITs' pressure. The primary function of HSIT was to extend the time to core damage to increase the recovery probabilities of the lost safety functions [5,6]. The research was further to check the applicability of HSITs to other accidents. One of its benefits was using it for feed and bleed operations under low-pressure accidents [6]. The core can be saved by depressurizing the primary system up to the shutdown cooling system injection pressure. However, some issues can be improved. At first, the cooling capacity of the HSITs decreases due to the hot-water/steam injection from the pressurizer [5]. The bleed operation using a pressurizer relief valve caused the inventory of the HSITs to flow through the equalizing lines; therefore, the reactor coolant gas vent system (RCGVS) was used for the bleed operation [6]. The problem is that the RCGVS has a limited capacity and is not qualified for bleed operation. Therefore, the possible failure of the RCGVS stuck open at the reactor vessel head can lead to a more severe event. These issues can be resolved by modifying the design of HSITs to Forced Safety Injection Tanks (FSITs).

Since the driving force of the SITs is nitrogen blanket at about 4 MPa. These SITs cannot inject the complete inventory into the system even if the system pressure is around 4 MPa. To utilize the entire inventory of SITs, we need to force the inventory into the primary system. Therefore, a new design, "Forced Safety Injection Tank," is introduced. The operating principle of the FSIT is the fundamental Pascal's law that states that "when there is an increase in pressure at any point in a contained fluid, there is an equal increase at every other point in the container" [7]. The pressure from the primary system, steam generator (SG), or from an external pump source can be 2-4 MPa can increase the pressure of the SITs above the primary pressure and inject the SITs inventory into the system. But in this paper, the pressure from the SG is considered for the demonstration purpose. The mathematical equations refelecting the thermal hydraulic behavior were developed and integrated into the RELAP5 [8] input for generic 1000 MWe NPP and were solved using a semi-implicit finite difference scheme. A case study for ELAP/SBO with TDAFW pumps failing to start was performed to demonstrate the applicability of the suggested system. The use of the FSITs extended the time to core damage to an extent that timely deployment of FLEX strategies recovers the core. The risk assessment for the SBO scenario to quantify the risk reduction margin in recovering the engineered safety features and FLEX deployment was also performed.

This paper is organized as follows; Section 2 presents the basic design and operating principles of the new FSIT system. Section 3 and Section 4 provide the mathematical modeling and design basis of FSIT, respectively. Section 5 presents a simple case study of SBO/ELAP with early failure of TDAFW pumps to demonstrate the applicability of the suggested system. Section 6 summarizes the finding and conclusion of the study.

2. DESIGN OF FORCED SAFETY INJECTION TANKS

As discussed earlier, to utilize the inventory of SITs to increase the time to core damage, the pressure inside the SITs should be increased passively above the system pressure. The simple principle is demonstrated in Figure 1. There are two regions: Region A and Region B. The existing SITs (Region B) are modified to add the second region with movable piston and cylinder configuration on the top of SITs. The piston assembly is consisting of two pistons of different areas, the area of the piston in Region A is greater than that of the area of the piston in Region B. The size of the area is decided based on the design requirement. In this study, the ratio of the area, that is A_{sec}: A_{TK}, is calculated to be 3:1 based on the required head to drive the inventory into the primary circuit using the pressure from the SG. Once the system is activated, the pressure on region A can be increased up to 2-6 MPa from one of the pressure sources, which develops a back pressure in region B of about 6-18 MPa. The pressure sources for Region A in the NPP may include, but are not limited to, the exhausted steam from the secondary or primary, the pressure pumps such as FLEX or injection pumps with 3MPa head or more. Once the pressure inside Region A starts to build up to a point that it is more than the pressure force in Region B, the piston starts to move down with acceleration as given by Equations 1-3.

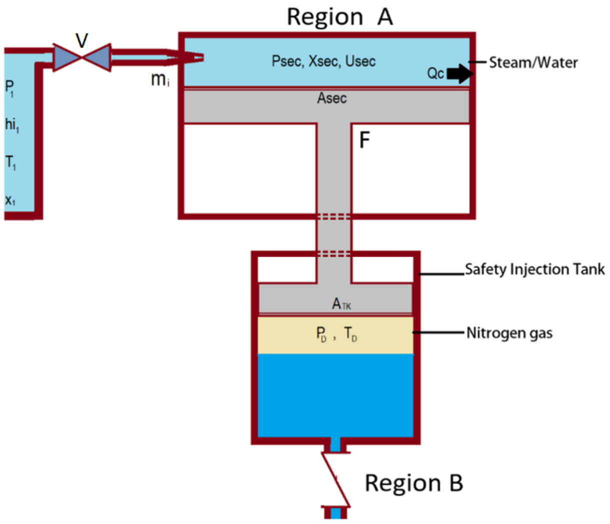
$$M_p a = P_{sec} A_{sec} - P_D A_{TK} + (M_p + m_t) g \quad (1)$$

$$a = \frac{1}{M_p}\left(P_{sec} A_{sec} - P_D A_{TK} + (M_p + m_t) g\right) \quad (2)$$

$$a = \frac{du}{dt} \quad (3)$$

where, M_p = mass of the piston assembly; m_t = mass of the steam and accumulated liquid in region A; P_{sec}= Pressure in Region A; A_{sec} = Area of the piston in Region A; A_{TK} = Area of the piston in Region B; u = piston velocity; a = acceleration of the piston due to net force.

Figure 1: Design of forced safety injection tank



As discussed earlier, the FSITs can be operated by internal or external sources, but in this research, the design parameters are selected in the vain of its operation from the SG. The stored steam at the SGs is sufficient to drive the pistons and inject the SITs inventories into the primary system. The selected design parameters are listed in Table 1. The length of the Region B was considered to be the length of SITs while the length of the Region A was considered to be the length of the calculated piston stroke. The piston stroke was calculated to bring the piston down enough that most of the SIT inventory is injected into the system at the maximum pressure that can be built inside the SIT.

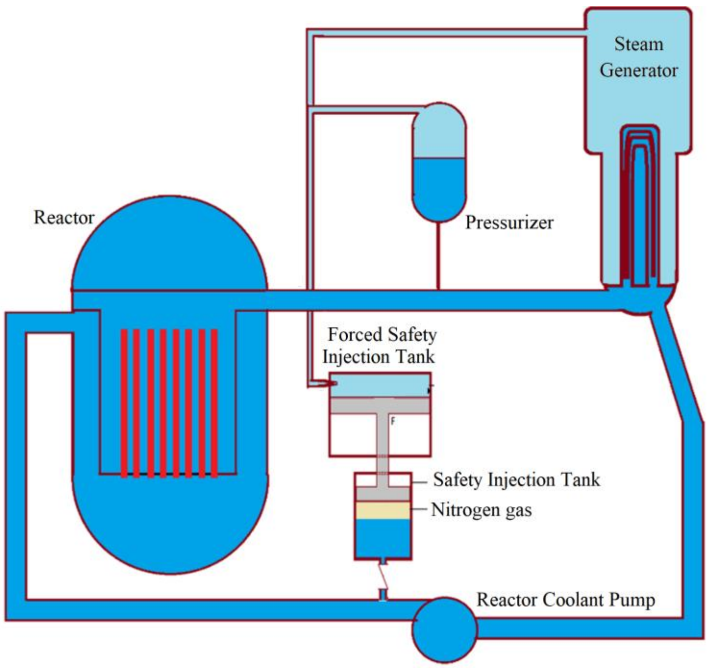
Table 1: Design parameters for FSITs

Parameters	Values(Units)	Reference/Remarks
Region A:		
Diameter of the piston	4.75 m	Calculated to increase the pressure of SITs to 3 folds
Length of the tank	8 m	Calculated piston stroke
Mass of the piston assembly	500 tons	Estimated by Grashoff's formula [9]
Region B:		
Diameter of the piston	2.6 m	Same as the diameter of SITs
Length of the tank	11 m	Length of SITs

3. FSIT MODELING

There are three configurations of the FSIT: Configuration A, B, and C which corresponds to the FSIT system where it is operated via pressurizer pressure, a SG pressure, and external pumps, respectively. The first two configurations are shown in Figure 2. For this paper, we have limited our scope to configuration B. The system is initiated by actuating the inlet valve V as shown in Figure 1. The high-energy steam enters a low-pressure region. The pressure is built up in region A, and the piston starts to move down, increasing the pressure of the SIT. Once the pressure reaches the pressure of the primary system, the coolant flows from the SITs into the primary system. So the modeling of the FSIT is done in three parts: the first, the mass and energy entering the region A; the second the mathematical modeling of region A and the work done by the steam in moving the piston assembly downwards; and the third, the modeling of FSIT tank to determine the pressure and outlet flow after the compression through the piston assembly. The following subsections delineate the mathematical models for each part.

Figure 2: Configurations A and B of the FSIT in the NPPs



3.1 Inlet Nozzle Flow Modeling

As shown in Figure 1, once the system is actuated, the high-pressure steam from SG will flow into the low-pressure region A which was initially assumed to be at atmospheric pressure. The inlet flow will depend on the downstream pressure and area of the valve opening. Since we assumed that the inlet nozzle area is constant, the main governing parameter will be the downstream pressure. If the downstream pressure is below the critical pressure value as given in Equation 4, the flow will be constant and defined as choked flow [10]. This flow is provided by Equation 5. If the downstream pressure is above the critical pressure, the flow is governed by the non-choked flow phenomenon and is calculated by Equation 6 [10].

$$\left(\frac{P_{crit}}{P_1}\right) = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \tag{4}$$

$$m_i = C_d A_i \sqrt{\gamma P_1 rho_1 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{5}$$

$$m_i = C_d A_i \sqrt{2P_1 rho_1 \left(\frac{\gamma}{\gamma-1}\right)\left[\left(\frac{P_{sec}}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_{sec}}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]} \tag{6}$$

where, P_{crit} is the critical value of downstream pressure for choked flow, P_1 is the upstream pressure, m_i is the inlet mass flow, C_d is the discharge coefficient, rho_1 is the density of the steam at the inlet, A_i is the Nozzle area and γ is the specific heat ratio.

3.2 Region A Modeling

Once the system is actuated, the mass calculated in Section 3.1 flows into region A, as shown in Figure 1. The total mass at time t in region A 'm_t' is given by Equation 7.

$$\frac{dm_t}{dt} = m_i \tag{7}$$

The energy balance for region A is given by Equation 8 as below.

$$\frac{dU_{sec}}{dt} = m_i\left(\frac{{V_{ei}}^2}{2} + h_i\right) - P_{sec}A_{sec}u - Q_c{}' \tag{8}$$

Where V_{ei} is the inlet velocity of the steam/mixture which is given by Equation 9. As the inlet flow accumulates, the pressure is built inside the region A that pushes the piston downwards with a velocity 'u' (Equation 3), the change in volume of region A can be calculated by Equation 10. The other unknown in this is the heat loss to the wall of the container and that can be estimated by solving Equation 11.

$$V_{ei} = \frac{m_i}{A_i \rho_1} \tag{9}$$

$$\frac{dV_{sec}}{dt} = A_{sec}u \tag{10}$$

$$Q_c{}' = \alpha_w (A_{wall})(T_{sec} - T_{wall}) \tag{11}$$

where T_{wall} can be calculated by solving Equation 11 and Equation 12.

$$Q_c{}' = m_{steel}c_{steel}\left(\frac{dT_{wall}}{dt}\right) \tag{12}$$

The specific internal energy and fluid density in region A can be calculated by Equations 13 and 14. Once we have at least two thermodynamic properties, the other properties such as pressure, temperature, and quality can be calculated with the help of steam tables.

$$u_{sec} = \frac{U_{sec}}{m_t} \tag{13}$$

$$\rho_{sec} = \frac{m_t}{V_{sec}} \tag{14}$$

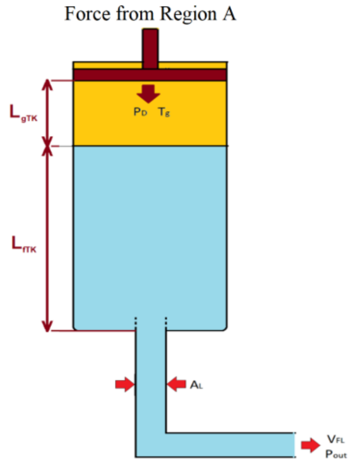
where,

m_t = total mass in region A
U_{sec} = Total internal energy of region A
V_{ei} = Inlet velocity of steam
h_i = Inlet specific enthalpy of the mixture
T_{sec} = Temperature of the bulk in region A
Q_c' = Heat transfer to the container A
α_w = Heat transfer coefficient to the wall inner surface
c_{steel}= Specific heat capacity of the steel
u_{sec} = specific
ρ_{sec} = Density of the fluid in region A
V_{sec} = Volume of the region A

3.3 Region B Modeling

As discussed earlier, region B is the existing safety injection tank system except for the piston assembly that has been introduced at the top of the region, the model described in Zhao et al., [11] was adopted and benchmarked with the existing model in RELAP5 as shown in Figure 3. The overall design is shown in. The equations for the SITs were rewritten to consider the effect of piston motion by introducing the piston velocity in the model. The mass and momentum balance model is the same as described by Zhao et al.,[11] and given by Equations 15 and 16.

Figure 3: Forced safety injection tank region B modeling



$$M_n - \rho_n(P_D, T_g)V_g = 0 \tag{15}$$

$$\rho_f L_{fTK}\frac{du_i}{dt} + \frac{1}{2}\rho_f\left({V_{FL}}^2 - {u_i}^2\right) + (P_{out} - P_D) - \rho_L g_x L_{fTK} + \frac{1}{2}K\rho_L {V_{FL}}^2 = 0 \tag{16}$$

While u_i is the interface velocity and is calculated by Equation 17 and 18.

$$u_i - \frac{dL_{fTK}}{dt} = 0 \tag{1}$$

$$A_{TK}\frac{dL_{fTK}}{dt} - A_L V_{FL} = 0 \quad (18)$$

The governing equation of the gas energy conservation at T_g is given by Equation 19.

$$M_n C_{vn}\frac{dT_g}{dt} + P_D\frac{dV_g}{dt} - Q_D = 0 \quad (19)$$

where Q_D is the total energy transfer rate into the gas volume and is neglected for the calculations, where V_g term can be replaced by Equation 20.

$$\frac{dV_g}{dt} - A_L V_{FL} + A_{TK} u = 0 \quad (20)$$

The pressure change in time t was updated using the simplified ideal gas equation as given by Equation 21. The additional Equations 22 and 23 are also required to model the tank overall length and volume.

$$P_D V_g = M_n R_n T_g \quad (21)$$

$$u - \frac{dL_{TK}}{dt} = 0 \quad (22)$$

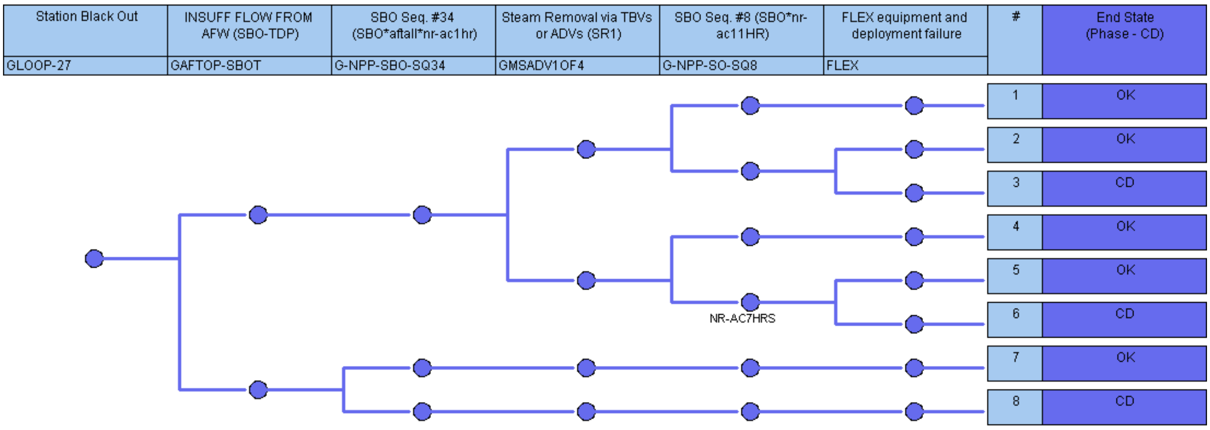
$$L_{TK} = L_{gTK} + L_{fTK} \quad (23)$$

where, P_D = Pressure in the SIT
L_{TK}= Length of the SIT
L_{gTK} = Length of the nitrogen blanket in SIT
L_{fTK}= Height of the liquid in SIT
V_g = Volume of Nitrogen
T_g = Temperature of Nitrogen
M_n = Mass of Nitrogen
R_n = Universal gas constant
A_L = Area of the pipe at the exit
A_{TK} = Area of SIT
C_{vn} = Heat capacity of nitrogen
u_i = Interface velocity
P_{out}= Downstream pressure at the exit
ρ_f = Density of the liquid inside SIT
ρ_L = Density of the liquid at the exit
V_{FL} = Velocity of the fluid at the exit
g_x = Gravitational acceleration

4. DESIGN BASIS FOR FSITS

The design bases for the FSIT were established on the findings from the author's previous study of medium break loss of coolant accident (MBLOCA) [12]. It was found in the case with SiC type accident tolerant fuel, the fuel core damage timings were extended up to 8000 s due to the intermittent injection of SITs. In another case study of station blackout (SBO) [13], it was concluded in the case study of SBO that a minimum of two hours is required to deploy/start the portable FLEX equipment by the local emergency team. If the existing SITs may be improved to FSITs, the injection of FSITs inventory at higher pressure may extend the coping time to provide the operator with enough room to deploy and start the FLEX. The design basis may be stated as “FSIT can provide the function of high-pressure safety injection pump up to limited time.” The simplified event tree (ET) for the SBO for existing NPP with FLEX is shown in Figure 4. In this figure, it can be seen that if the TDAFWs pump fails to actuate, then there is minimal time <1 hr. to recover the AC power before the core damage is inevitable. The minimum deployment timing for FLEX is estimated to be equal to or greater than two hours in previous studies [3,12] including diagnostics, giving directions to the local emergency team, and other associated actions. Even if the TDAFW pump works, the failure to remove the steam using ADVs may reduce the recovery timings to seven hours from 11 hr. Therefore, we hypothesize that if FSITs are available, the core damage can be prevented by the sequential operation of FSITs. FSITs may extend the coping time up to three hours, during which the FLEX may be made available by the local emergency team. In addition, even with the success of TDAFW pumps' operation, the AC power needs to be recovered in 7-11 hr., depending on the availability of aggressive cooldown. The FSIT may also be used to extend this time further to several additional hours.

Figure 4: Simplified event tree for ELAP/SBO with existing SITs



5. CASE STUDY: STATION BLACKOUT

To demonstrate the functionality of the FSITs in the SBO accident scenario, the mathematical model was implemented into the RELAP5 input using the control variable and trip logic option. In this case study, two cases with and without FSIT were performed and the results were compared. The initial conditions for both of the test cases are given in Table 2.

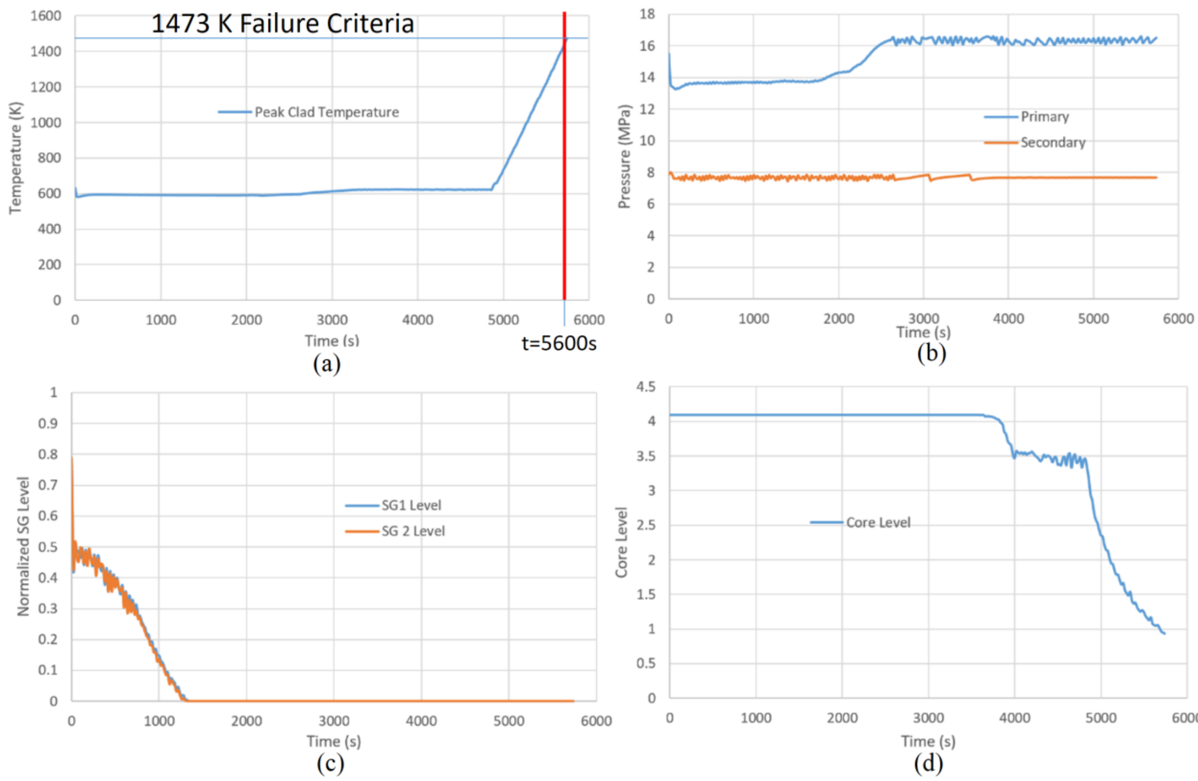
Table 2: Initial condition for SBO accident scenario

Parameters	Initial Values
Reactor power	2815 MWth
Primary pressure	15.51 MPa
Secondary side pressure	8.0 MPa
Hot-leg temperature	332 °C
Cold-leg temperature	302 °C
Feed water flow rate	807.63 kg/s per loop
Steam water flow rate	807.63 kg/s per loop
Feedwater temperature	232 °C
Reactor coolant pump flow rate	3759.1 kg/s

5.1 Case 1: SBO without FSIT

At first, the simulation corresponding to sequence 8, as shown in Figure 4, was performed and the results will be compared with the same sequence with the new FSIT. The reactor is assumed to be running at full power, at t=0 s there is a complete loss of all AC power. The reactor trips due to the deenergizing of the shutdown rods. TDAFW pumps should start to supply feedwater to the SG and were assumed to fail at t=0 s. The operator fails to recover the AC power within 1 hour as shown in Figure 4. Figure 5 (a) shows that if an operator fails to recover the AC power within 1 hour, the core can last up to 5600 s. Once the all AC power is lost, there is an inventory in the SG that provides the cooling up to about 1500 s, as shown in Figure 5 (c), there is some additional inventory inside the SG that cannot be measured as it is below the lowest measurement level in the SG. After the SG inventory depletes, the primary coolant heats up and the primary pressure starts to increase as shown in Figure 5 (b), it reaches the set point of the pressurizer relief valve at around t= 2600s, and this valve starts hunting until the primary inventory depletes to a point that core becomes uncover. This is shown in Figure 5 (d). It is worth noting that the minimum time required for FLEX injection was considered to be greater than 2 hrs. Therefore, FLEX was not able to inject inventory during the period of transient evolution.

Figure 5: Result for SBO without FSIT; (a) Peak cladding temperature; (b) Primary and secondary pressure; (c) Normalized SGs levels; (d) Collapsed core level

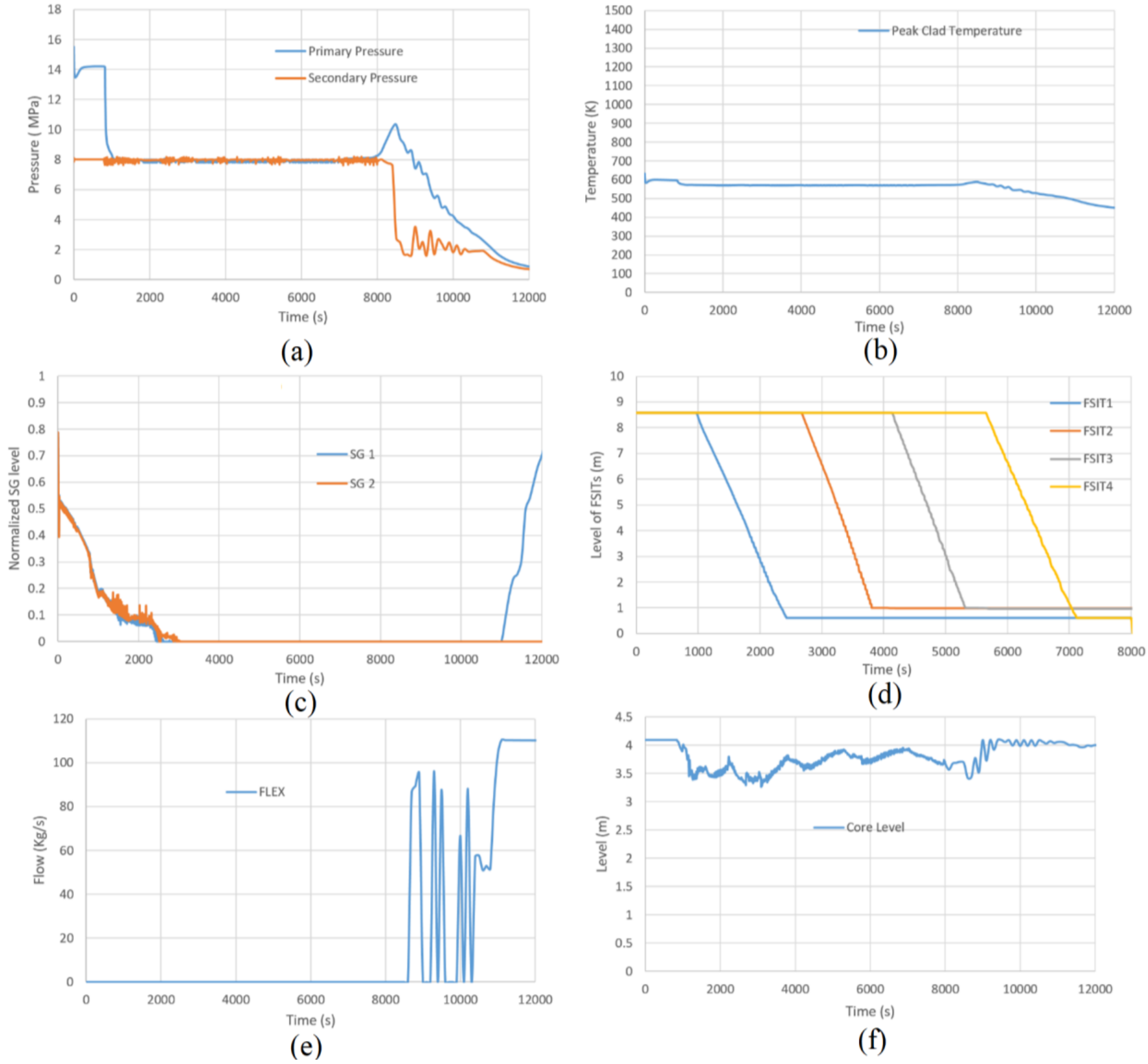


5.2 Case 2: SBO with FSIT

In this paper, the focus of the study is the operation through the stored steam in the SG (configuration B). When activated, SG steam at a high pressure fills into region A, as shown in Figure 2, and drives the FSIT inventory into the primary system. Each FSIT can provide the backup for up to 1000- 1200 s additional seconds. So the operation of all four in sequence may add up to 4000-4800 s. Since the volume of SGs is much larger than that of region A of FSITs, the stored steam in SG, even with low inventory, can be used to drive FSITs. Since FSITs can provide the inventory backup for the HPSI system for some time, the feed and bleed strategy can be initiated to provide additional time to core damage. In the feed and bleed operation using FSIT, we assume a set-point of 20% SG level.

After the accident initiation, the reactor trips due to loss of AC power, and due to EDG failing to start, the active motor-driven auxiliary feedwater pumps cannot provide the sufficient inventory to remove decay heat, and the TDAFW pumps were also assumed unavailable. The inventory inside the SGs will provide the decay heat removal to some extent as shown in Figure 6 (c) until both SGs are depleted. So to gain additional time for preventing the core damage, the operator actuates the feed and bleed strategy using FSITs on the actuation signal generated at 20% of SG level nominal value. This signal actuates the feed operation using FSITs. The bleed was performed by the operator using a pressurizer relief valve (PRV). Initially, the primary pressure plunges to the values of about 8 MPa and then the depressurization was limited by the steam-water mixture removal via PRV. As shown in Figure 6 (d) the FSIT started to inject its inventory, maintaining the core level as shown in Figure 6 (f). It is to remind us that Figure 6 (f) shows the collapsed core level that is, where it includes the voids generated due to boiling in the core. The inventory loss from PRV was compensated by injection through FSITs in a sequential manner. Each FSIT actuation begins on the low level of the preceding FSIT. The peak cladding temperature was maintained well below the failure criteria of 1473K, as shown in Figure 6 (b). Figure 6 (e) indicates that actuation of FLEX even after 2 hours and 20 minutes of accident recovered the core.

Figure 6: Results for SBO with FSIT; (a) Primary and secondary pressure; (b) Peak cladding temperature;(c) Normalized SG level; (d) Level of FSITs;(e) FLEX injection flow;(f) Collapsed core level



5. RISK ASSESSMENT

The simplified event tree for SBO is shown in Figure 4. Case 1 study provides the simulated result for the sequence 8. If the TDAFW pumps fail to start in the event of SBO, early AC power recovery (~ 1 hr) is necessary to prevent the core damage. However, if FSITs are available, this time can be extended up to 3 hrs., increasing the recovery probabilities of AC power and other equipment including FLEX. The fault trees for the FSIT system with the nominal values of failure probabilities for motorized valves, tanks, piston seal, and bleed operation failure were developed. These fault trees were added to the event tree of SBO as given in Figure 7. The CDF for both the cases was calculated and compared and the results are summarized in Table 3. The addition of FSIT reduced the CDF for SBO by 84.7%.

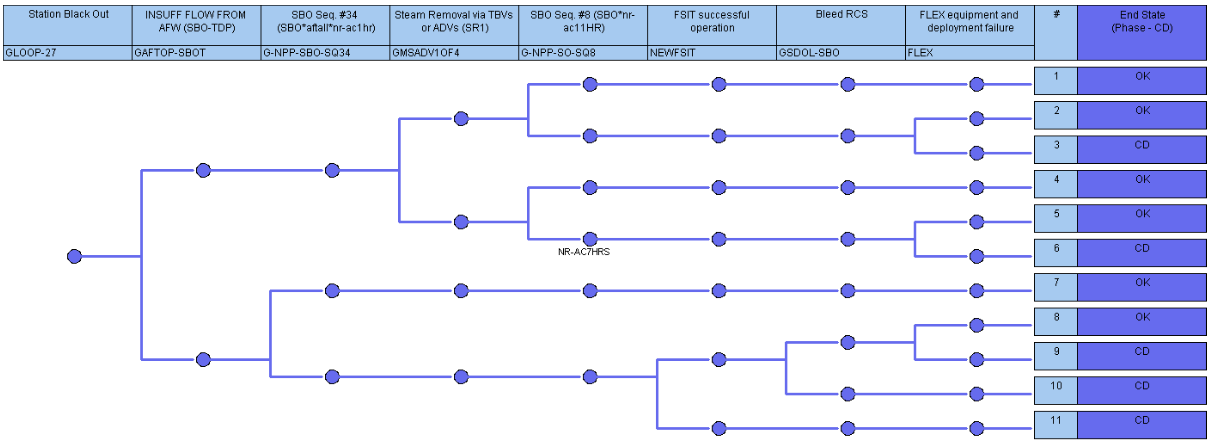


Figure 7: SBO event tree with FSIT operation

Table 3: CDF for SBO accident scenario

SBO events	CDF Values
Case 1: Simplified SBO without FSIT	2.88e-8
Case 2: Simplified SBO with FSIT	4.40e-9
CDF reduction	~84%

4. CONCLUSION

In this paper, a concept design of a new FSIT system has been suggested. This system utilizes the pressure from SGs (configuration B) inside the containment to increase the pressure inside the existing SITs above the primary pressure so that they can inject the inventory into the system. The basic principle is to scale up the pressure using a piston assembly in a ratio of the piston's heads at each end of the assembly. The complete mathematical model was presented and implemented in RELAP5 thermal-hydraulic code using control variable and trip logic options. In this way, this system can be implemented into the generic 1000MWe PWR-based nuclear power plant.

A case study was performed to assess the significance of this system to the SBO accident scenario with TDAFW pumps failing to start. If TDAFW pumps fail to start, there is very little time before the core is damaged. In those scenarios, the sequential operation of FSITs will increase the time to an extent that FLEX may become available. The additional time gain also increases the recovery probabilities for the recovery of AC power and other safety systems such as TDAFW pumps. A simple PRA model was developed and the CDF was quantified for the SBO accident sequence. It was found that adding FSITs operation with bleed operation reduces the CDF for SBO by 84%.

The design is conceptual and requires validation by experiments. As discussed earlier, this design may be extended in the future to operate in other two configurations: configuration A that is using the steam from pressurizer, and configuration C that is using water from some external source and can also be applied to other designs or beyond design base accidents such as small or medium break LOCA, Steam generator tube rupture, etc.

Acknowledgements

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