Deterministic analysis of emergency water injection strategy during SBO

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Abstract

In the steam generator tube rupture (SGTR) accident due to reactor coolant system (RCS) integrity failure and bypassing the containment is particular importance accident that lead to releasing radioactive material into the atmosphere during the station black-out (SBO) severe accident. One of the measures taken to prevent the occurrence of SGTR is to install injection flow paths to supply emergency cooling water to external sources using fire engines to the SG secondary. In this study, after complete modeling of the primary and secondary circuits and the containment space of the power plant using the MELCOR severe accident analysis code, the effectiveness of the external cooling water injection strategy has been investigated. Based on this model, the effectiveness of the injection strategy using fire trucks during a potentially long SBO incident in the two-loops Westinghouse typical PWR has been investigated. The modeling results show that the external cooling water injection strategy using fire engines reduces temperature and damage function Larson Miller of steam generator tubes and prevent SGTR accident occurring after an SBO accident.

Keywords: Severe Accident Management , MELCOR Code, SGTR

Introduction

Among the severe accident, steam generator tubes rupture (SGTR) has the possibility that radioactive fission products of the primary system can be directly released into the atmosphere by bypassing the containment through the steam generator tubes and main steam safety valves(MSSVs) [1]. Thus severe accident mitigation function is strongly required for SGTR. One of the measures to increase the mitigation capability during a prolonged station blackout (SBO) accident and SGTR occurrence is installing injection flow paths to provide emergency cooling water of external sources using fire engines to the SGs secondary side[2].

In this study, we implemented this idea in order to evaluate the effectiveness of this accident management plan in case of SBO severe accidents (The TMLB sequence: T "transient event, M "failure of the secondary system steam relief valves and the power conversion system", L "failure of the auxiliary feed-water system", B "failure of the electric power to ESFs"[3]) for the 360 MW reactor being designed, using the MELCOR code [4]. One of the strengthening SBO mitigation capability for design basis and beyond design basis external events [5] is the establishment of preplan and pre-stage offsite resources to support uninterrupted core and spend fuel pool (SFP) cooling. Also, one of the action items related to mitigation measures against SBO sequences is installation of external water injection provision and equipment to SG. Effectiveness of external injection into SG of two-loop PWR needs to be examined. Therefore, in this research, the overall extended SBO coping capability of PWR NPP is analyzed to examine the effectiveness of the external water injection strategy and assume one hr after SBO, SG secondary side injection occurs properly. In the following, modeling and analyzes results using the MELCOR severe accident analysis code are provided in this article, and a summary of this strategy effectiveness is discussed a concluded in final.

SGTR accident & prevention Strategy

The NPP type of this research is a two-loop PWR [6]. The SBO accident is modeled, and its details are implemented in the MELCOR code structure, with a precise definition of the TMLB accident scenario in the model. According to this scenario, the main feed water system fails and the emergency feed water system is isolated, and it is assumed that the one of main steam line safety valves (MSSVs) will be locked in the open state with the first drainage operation [7]. The base case was set up for MELCOR to simulate the TMLB severe accident. Modeling including the following assumptions [8]:

- The power-operated relief valves on the secondary side of the SG on the pressurizer loop become stuck in an open position upon first challenge.
- The primary system does not depressurize following creep-rupture failure of any component in order to examine the failure sequence of the RCPB components.

In this article, after introducing the phenomenon of natural circulation during TMLB and heat removal by water injection strategy, the MELCOR model of SGTR and emergency injection strategy are described. Finally, various parameters such as pressure and temperature and other parameters in different SGs have been evaluated.

When a SBO occurs, a reactor and turbine trip is initiated. All active systems including emergency core cooling system, shutdown cooling system, and motor driven auxiliary feed water system become inoperable. Then, the SG pressure rapidly increases to the MSSV opening set point and releases steam to the environment periodically to maintain secondary pressure boundary integrity. RCS single phase natural circulation is established through the SG heat removal. However, the SG water source is not provided; the SG level is continuously decreased.

During this postulated severe accident, counter-current flow in the hot legs and steam generators during high-pressure sequence is an important and uncertain phenomenon. Hot gases coming from the core flow along the top of the hot leg, enter the inlet plenum of the steam generators, and form a plume that rises toward the steam generator tube bundle. This natural circulation phenomenon affects the heat-up and eventual creep rupture of the hot leg and the steam generator tubes during high-pressure sequences [8].

RCS components under stress at high temperatures will undergo irreversible strain known as material creep. When the strain is large enough, the component can rupture. Rupture of the RCS components due to material creep may be predicted by the application of the Larson-Miller parameter method. The method may also be applied for cases of time-varying temperature by considering the fractional contribution to rupture during consecutive intervals. MELCOR has the ability to model and calculate the creep rupture due to high pressure and temperature of the surge line, hot leg, and the steam generator tubes.

According to ref.[9] the counter-current natural circulation phenomena in RCS during the TMLB scenario will lead to the occurrence of steam generator tubes rupture.

In this article, the effectiveness of the AFW by fire engine operation on SGTR prevention is analyzed. The emergency cooling water system consists of a fixed pipe connected from the steam generators to the outside of the containment. A standby valve is installed on the pipe. Following the occurrence of an TMLB, movable equipment (for example, a fire truck injection) can be connected to the pipe hole at the opening of the isolation valve. In many accidents with very hazardous work conditions, the inside of the containment cannot be made accessible or manageable. However, because the emergency cooling water system can be operated from outside the containment, it has the advantages of high accessibility and maintenance during an accident [10].

We assume an auxiliary charging pump is installed parallel to the existing charging pumps to provide seal injection water to the two RCPs to prevent the leakage of coolant through the RCP seals. The SG injection flow paths are also installed along the discharge line of the AFW pump. Water sources of fire trucks are available 1 hour after initiating SBO and will be pumped the water into secondary side of SGs. Detailed SG external injection flow paths are shown in Figure 1.

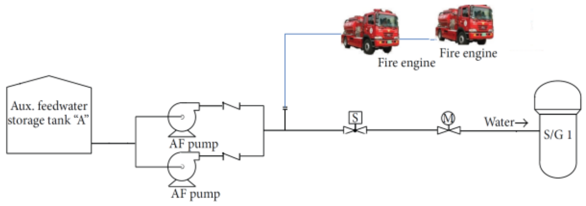

Figure 1. SG external injection flow paths by fire trucks

External secondary injection flow path is located at discharge line of AFW piping and injection flow rate is assumed to be constant rate.

Results and discussion

The results of two cases of this scenario. Once case is without any severe accident management and other is using of fire truck injection, 1 hour after initiating SBO. In this scenario, assumed PSV stuck open occurred in one loop only. Thus, the secondary side pressure decreased and primary to secondary differential pressure increased.

In the first case of this scenario, high temperature water-steam flow passes through u-tube and lead to increasing temperature of u-tube structures. So, there is circumferential temperature stratification in u-tube piping, and it could lead to creep rupture. This phenomenon is reflected based on Larson Miller creep rupture failure model in MELCOR. This concurrent natural circulation is maintained up to 3.328 hrs until liquid level is completely depleted (figure2). During this time, steam flows through the u-tubes, these phenomena is shown in figure3.

In these cases, core degradation and melting occur in the RCS. Eventually, the RCS fails due to the failure of the in core instrument tube caused by molten corium relocation to the lower head at 10.242 hrs. Because high pressure is maintained before RCS fails, a large amount of superheated steam and hydrogen is discharged into containment after RCS fails.

The external injection flows to SG secondary side using by fire-trucks with 3.3 kg/s constant mass flow rate (figure 4). When SG level is fully recovered by fire truck action, injection stop to prevent SG overfilling. Then evaporation of water lead to decreasing water level, thus the external injection flow rate is start again and maintain a stable condition as shown in Figure 5.

This flow rate is compatible to removal of decay heat generated in the core. The maximum core exit temperature decreases and the U-tubes integrity is maintained. Figure 6 shows the integrated water inventory required for 24 hrs of injection to SG. The total water inventories are 245 ton, that is required for AFW fire trucks. This inventory of water is supplied by 14 numbers of fire trucks.

For rupture time (t_R) evaluation, a function to relate t_R with the four parameters is required. In deterministic modeling of creep rupture events for severe accident analysis with MELCOR, the criterion for rate-dependent creep rupture (both pressure and temperature are time-dependent) is based on the so-called damage function (R) which is the time-fraction damage integral [11]. The criterion for the creep rupture is achieved when the damage function equals unity,

$$R = \int_0^{t_f} \frac{dt}{t_R(T, m_p, \sigma)} = 1, \quad (1)$$

Where, t_f is the creep rupture failure time (s), t_R is the time (s) to rupture, T is the temperature (K), σ is the stress; and m_p stands for intensity factor (unitless, usually assumed to be a unity). The denominator t_R is given by the Larsen- Miller correlation and is calculated by:

$$t_R = 10^{P_{LM}/T - C}, \quad (2)$$

Here P_{LM} is the Larson–Miller parameter; C identifies the property of structural material; and P_{LM} has dimensions of temperature and is fit as a function of the effective stress, σ_e [11]:

$$P_{LM} = \min[a_1 \log \sigma_e + b_1, a_2 \log \sigma_e + b_2], \quad (3)$$

Where, $\sigma_e = \rho \Delta P / z$ with ρ and z being the pipe radius and wall thickness, respectively, and ΔP being the difference between the inside and outside pressure.

Figure 7 shows the MELCOR prediction of the water-vapor temperatures in the SG average tube of both cases. Figure 8 shows that the SG U-tubes fails at the critical value R = 1 (for case one), due to the high pressure and temperature in the RCS, as a result of thermo mechanical creep rupture at 7.03 h. The damage function (R) equals to unity at this time for the hot-leg piping which represents the occurrence of U-tubes creep rupture under high pressure and temperature. Due to low surface area of SG tubes rupture, the RCS pressure trend doesn't decrease after the U-tubes rupture. In case 2, damage function value will be constant after the fire truck injection and prevent from SG tubes creep rupture.

These calculation results show that the external injection into the SG is an effective procedure to mitigate an extended SBO (TMLB) scenario when this is successfully performed within 1 hour after SAMG initiation.

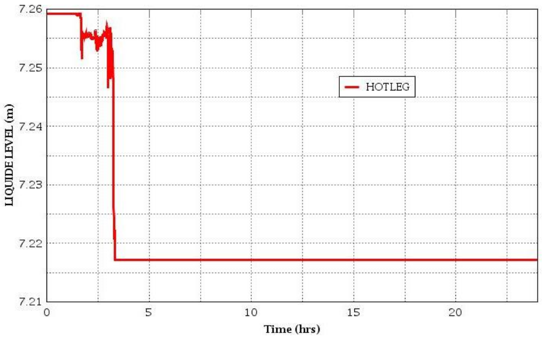

Figure 2. Hot leg liquid level

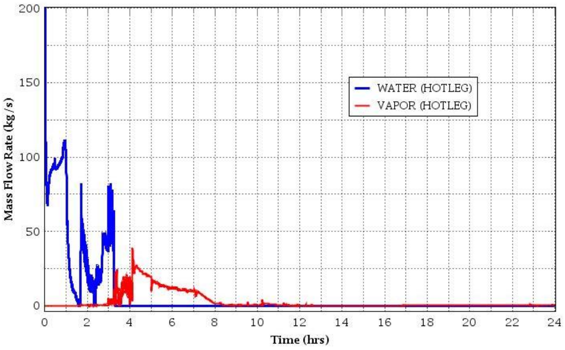

Figure 3. Water and steam mass flow rate in U-tubes

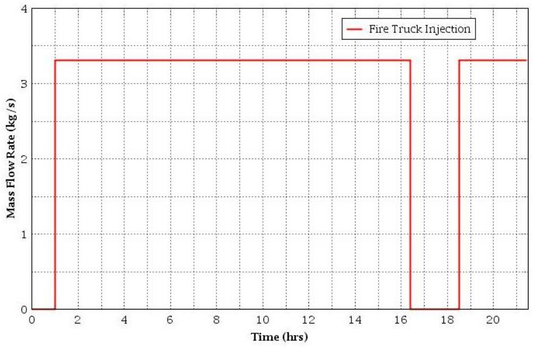

Figure 4. fire trucks mass flow rate injection

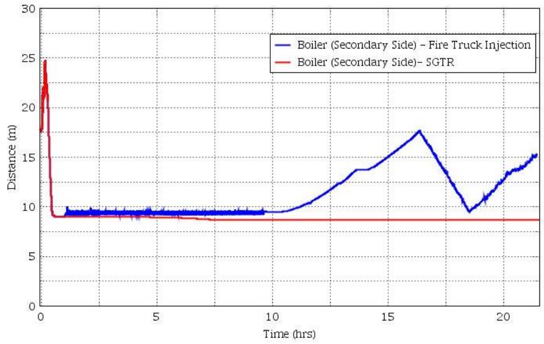

Figure 5. Liqid level in SG boiler of two cases

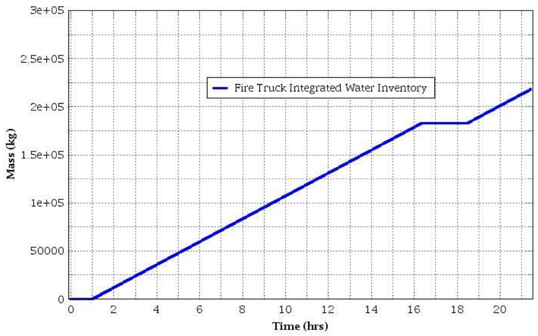

Figure 6. Total water required for SGTR preventation

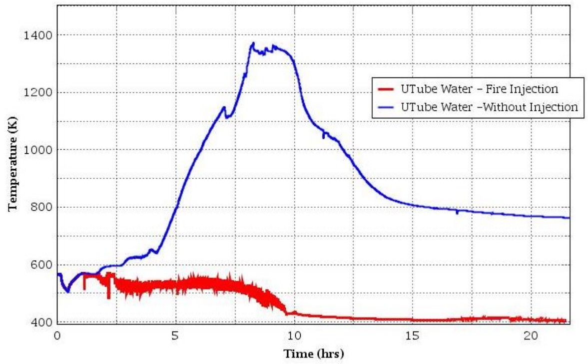

Figure 7. SG U-tubes water-vapor temperature of two cases

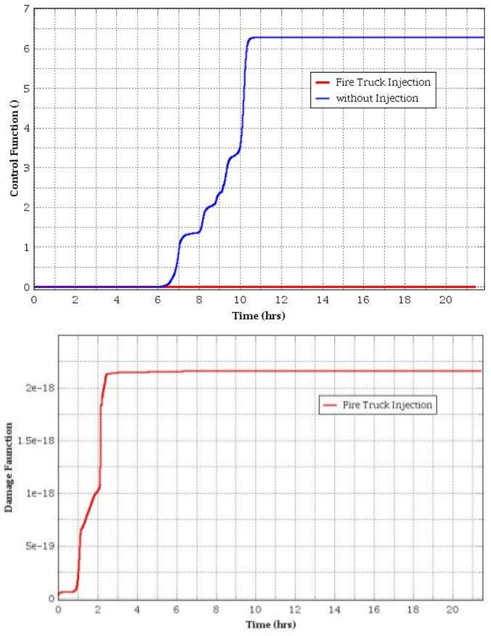

Figure 7. Damage function of two cases

Conclusions

After the Fukushima Daiichi nuclear power plant accident, mitigation measures against extended SBO sequences is an importance issue that should be investigated for PWR NPP. Therefore, the overall extended SBO coping capability of the 2-loops PWR NPP is examined to assess the effectiveness of an external water injection strategy.

In this article an external injection strategy into SG using 14 numbers of commercial fire trucks (with 18000 liters capacity) is evaluated to prevention of SG U–tubes creep rupture. According to results of MELCOR modeling of PWR NPP, fire trucks water injection strategy that operate 1 hour after TMLB accident occurrence can prevent SG U-tubes rupture that is a potential way to release of radionuclide from RCS to environment by containment bypass. Due to results, external injection strategy into SG using 14 numbers of commercial fire trucks (with 18000 liters capacity) is an effective strategy to mitigate an extended TMLB scenario.

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