# Effectiveness of In-Vessel Retention Strategies and Minimum Safety Injection Flow over Postulated Severe Accidents of OPR1000

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## 1. Introduction

In this study, several MELCOR simulations are conducted in search for effective in-vessel retention strategies over postulated severe accidents of SBLOCA, SBO, and TLOFW of OPR1000. Detailed accident sequences are presented and indicative parameters diagnosing the reactor thermal-hydraulic state are interrogated to provide useful information to the operator actions. To properly assist operator's action during the severe accident, the thermal-hydraulic parameters should be virtual, intuitive, and reliable. In addition, the parameters should be collected through the instrumentations close to the reactor core. In this regard, Core Exit Temperature (CET) and collapsed core water level are deemed as the commensurate parameters.

The objective of this study is first to evaluate various serious severe accident scenarios of OPR1000 with and without in-vessel retention strategies using MELCOR code. Second is to develop a mechanistic model of minimum safety injection flow using the thermal-hydraulic parameters of CET and collapsed water level obtained from the MELCOR simulation results.

## 2. Modeling Descriptions

### *2.1 MELCOR Input Model of OPR1000*

The reference nuclear power plant at current interest is Korean OPR1000, which consists of 2 loops of NSSS. Nominal electrical output is 1000 MWe. Detailed nodalization of the OPR1000 is available in recent Lee et al.'s study [1].

### *2.2 Employed Severe Accident Management Strategy*

The shift point from EOP to SAMG states is when CET reaches 650 $^oC$. Total 7 mitigation strategies are suggested for severe accident management. In this study, RCS depressurization strategies are introduced using different means for different accident scenarios. For SBLOCA, ADV opening has been adopted and for SBO and TLOFW, SDS operation has been considered. Sensitivity of operation timing following SAMG entrance is evaluated as compared to the base case, which includes no operator action under accident situation. Table I summarizes the simulation cases.

Table I: Problem Description

| Event | In-vessel retention | Timing | SAMG entrance | ECCS |
|---|---|---|---|---|
| SBLOCA | ADV | 0, 5, 10, 30, 40, 60 min | CET=650 $^oC$ | n/a |
| SBO | SDS | 0, 5, 10, 30, 40, 60 min | CET=650 $^oC$ | n/a |
| TLOFW | SDS | 0, 5, 10, 30, 40, 60 min | CET=650 $^oC$ | n/a |

## 3. Results and Discussion

### *3.1 Effectiveness of In-Vessel Retention Strategies*

MELCOR simulation was conducted for base cases of SBLOCA, SBO, and TLOFW. All cases result in RPV failure following core dryout, clad melt, $UO_2$ melt, and relocation. ECCS has not been considered for all cases. Fig. 1 shows the result of SBLOCA without HPSI with ADV opening. Timely ADV opening results in the best accident mitigation in terms of delayed clad melt, UO2 melt, relocation, and RPV failure. Fig. 2 shows the result of SBO without HPSI but with SDS opening. In all cases, SDS opening significantly delays the RPV failure by reducing the RCS pressure and thereby SIT becomes actuated. Overall, the TLOFW accident progression is expected to be similar to the SBO. The results are similar to Park et al.'s work [2, 3].

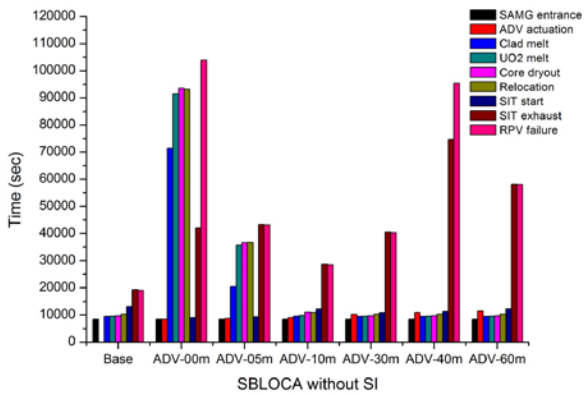


Fig. 1. MELCOR simulation result for SBLOCA

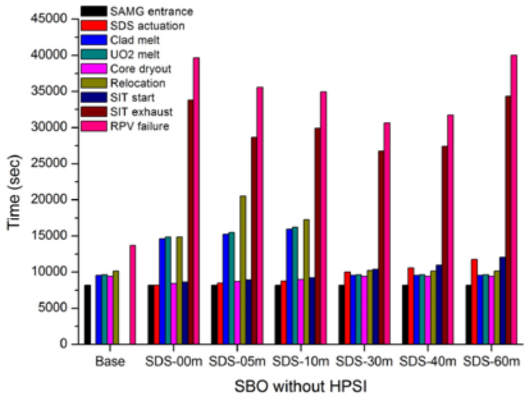


Fig. 2. MELCOR simulation result for SBO without HPSI

### *3.2 Safety Injection Flow Model for In-Vessel Retention*

Using the CET increase rate and water level decrease rate obtained from the MELCOR simulation, safety injection flow rate to maintain the core refilled with water under saturation condition is calculated. It is assumed that total heat generation consists of decay heat and oxidation heat as shown in Eq. (1). Since the decrease water level accelerates the oxidation, the water level data is utilized in calculating the oxidation heat. L is the core length uncovered and $L_o$ is the total core length.

$$\dot{Q}_{total} = \dot{Q}_{decay} + \dot{Q}_{ox}\frac{L}{L_o} \qquad (1)$$

The total heat which should be removed consists of steam generation and steam heatup, which are incorporated in Eq. (2).

$$\dot{Q}_{total} = \left(\rho_f A \frac{dL}{dt}\right) h_{fg} + \dot{m}_g c_p \Delta T_{CET} = \left(\rho_f A \frac{dL}{dt}\right) h_{fg} + M_g c_p \frac{dT_{CET}}{dt} \qquad (2)$$

where, $M_g$ is the steam mass and calculated by Ideal Gas' law as shown in Eq. (3). $V_o$ is the core volume $A$ is the cross-sectional core area. $T_{CET}$ is CET, $c_p$ is specific heat, $h_{fg}$ is heat of vaporization, $\rho_f$ is density of injection water, $dL/dt$ is water level decrease rate, and, $dT_{CET}/dt$ is CET increase rate.

$$M_g = \frac{P_{@CET}\left(\left(V_o + AL\right) M_{H_2O}\right)}{RT_{CET}} \qquad (3)$$

where, $P_{@CET}$ is the saturation pressure at CET and $R$ is gas constant. Then the flow injection supplied at subcooled condition is calculated by following Eq. (4)

$$\dot{m}_{inj} = \frac{\dot{Q}_{total}}{h_g - h_{f,inj}} = \frac{\left(\rho_f A \frac{dL}{dt}\right) h_{fg} + M_g c_p \frac{dT_{CET}}{dt}}{h_g - h_{f,inj}} \qquad (4)$$

Finally, the minimum flow injection is sum of subcooled flow injection plus the refilling flow injection as shown in Eq. (5).

$$\dot{m}_{\min} = \dot{m}_{inj} + \frac{\rho_f AL}{t_{refill}} \qquad (5)$$

where, $t_{fill}$ is the typical time for refilling the core with liquid water. For the SBLOCA case, the minimum safety injection flow was calculated and the result is shown in Fig. 4. The curve in red indicates the boundary of minimum flow injection and two possible safety injection flow rates at different RCS pressures through the HPSI are also given for comparison. Provided the HPSI is available and the RCS pressure is less than 120 bars, then the safety injection is expected to be much larger than the minimum safety injection.

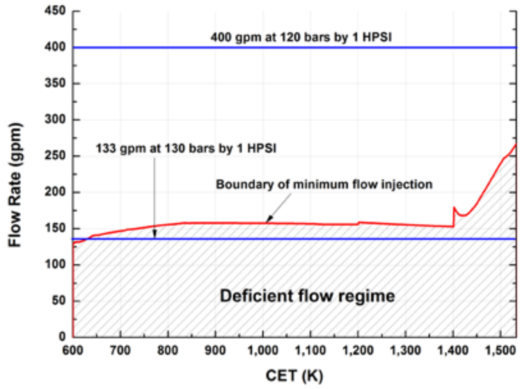


Fig. 4. Minimum safety injection flow with CET for SBLOCA case.

## 4. Conclusion

Effectiveness of RCS depressurization of OPR1000 is investigated for postulated severe accidents of SBLOCA, SBO, and TLOF. It is seen that timely operator action is important to achieve the best mitigation. Also The MELCOR simulation results of SBLOCA, SBO, and TLOFW are utilized to develop a model for minimum safety injection flow. The model suggests that if HPSI is available with RCS pressure lower than 120 bars, the core coolability can be guaranteed.

## Acknowledgement

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