Development of an Integrated RPV Lower Head Failure Assessment Module and Its Application to a Domestic 900 MWe-class PWR Station Blackout Scenario

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1. Introduction

Under severe accident conditions, the reactor pressure vessel (RPV) lower head is subjected to significant thermal and mechanical loads due to the relocation of molten core materials, which may eventually lead to vessel failure and the release of molten materials into the reactor cavity [1]. Therefore, reliable assessment of RPV lower head failure is important for evaluating the progression and consequences of severe accidents. This study presents an integrated RPV lower head failure assessment module developed over the past six years in collaboration with KINS as part of a regulatory research program [2-4]. The module incorporates several models for both global and local failure assessment.

The developed module is applied to a station blackout (SBO) scenario of a domestic 900 MWe-class pressurized water reactor, and the predicted failure behavior is analyzed and discussed. During an SBO, the loss of AC power limits active safety functions, and insufficient decay heat removal eventually leads to core degradation and relocation of molten core material to the RPV lower head.

2. Failure Assessment Module

The integrated failure assessment module incorporates four global failure models and two local penetration weld failure models, which are summarized in Table 1 and 2, respectively. The module evaluates lower head failure based on the thermomechanical loads acting on the vessel. Specifically, the input parameters include the time histories of vessel pressure and the inner- and outer-wall temperatures.

For the global failure assessment, the TH0 model evaluates the failure based on the mean temperature across the vessel wall. Failure is predicted when the mean temperature exceeds the melting temperature of the vessel material. The PV0 and PV1 models evaluate damage based on the Larson-Miller parameter, with the stress calculated using the pressurized vessel theory. The thermal load is represented by either the mean temperature across the vessel wall (PV0) or a linear distribution through the wall (PV1) [2]. The SH0 evaluates the stress based on the shell theory, with the mean temperature used as the thermal load [3]. The material behavior is described using the Norton creep law. In the PV0, PV1, and SH0 models, failure is predicted based on either by yield or strain criteria.

For the local failure assessment, the TH0 model predicts the failure when the in-vessel temperature exceeds the melting temperature of the penetration weld. The CR0 model evaluates the stress using the fracture-mechanics-based crack model, while the strain is calculated using the Norton creep law [4]. In the CR0 model, failure is predicted based on a strain criterion.

Table 1. Global failure assessment models.

Model	Thermal Load Profile	Mechanical Model	Material Behavior
TH0	Mean	-	-
PV0	Mean	Pressure Vessel	LMP
PV1	Linear	Pressure Vessel	LMP
SH0	Mean	Shell	Creep

Table 2. Local failure assessment models.

Model	Thermal Load Profile	Mechanical Model	Material Behavior
PTH0	Mean	-	-
CR0	Mean	Crack	Creep

3. Station Blackout Scenario

A station blackout (SBO) severe accident scenario is considered for a domestic 900 MWe-class nuclear power plant. The input parameters for the lower head failure assessment, including the time histories of vessel pressure and inner- and outer-wall temperatures, are obtained from MELCOR system code analysis. The vessel pressure and inner-wall temperature histories are shown in Figs. 1 and 2, respectively. The lower head failure assessment results obtained using MELCOR are also presented for comparison with those predicted by the present module. In this paper, only the global failure assessment results are presented, while the local failure assessment results will be presented at the conference.

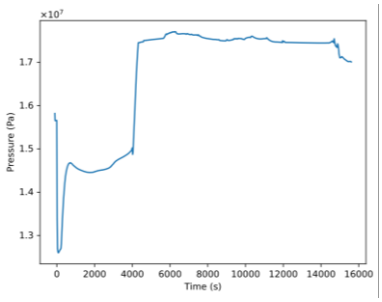


Figure 1. Vessel pressure history predicted by MELCOR.

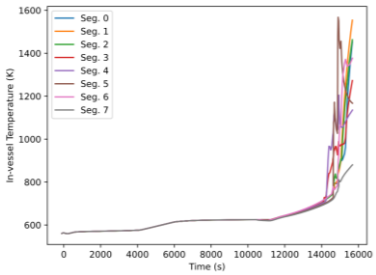


Figure 2. In-vessel temperature histories predicted by MELCOR. The segment numbers represent locations along the lower head, ranging from the bottom (Seg. 0) to the equator (Seg. 7).

4. Results and Discussion

Table 3 compares the global failure assessment results predicted by MELCOR and the different models. The failure location is given either by the segment number or angle measured downward from the lower-head equator (0˚) to the bottom (90˚). The predicted failure locations and modes are generally consistent among the models. In most cases, failure is predicted to initiate by yielding of the vessel material. This is attributed to the localized thermal loading, which reduces the yield stress of the vessel material at the failure location. In particular, the SH0 model predicts an earlier failure than the other models. This is attributed to the additional stress components considered in the shell theory, which lead to earlier yielding of the material under the same thermomechanical loading conditions.

Figures 3 and 4 compare the normalized strain and equivalent stress histories at the failure location predicted by the different models. Rapid creep deformation begins at approximately 14,800 s, followed shortly by yielding of the vessel wall before the normalized strain reaches unity, corresponding to the rupture criterion. It is noteworthy that the SH0 model predicts the earliest failure, although the accumulated strain is less significant than those predicted by the other models.

The stress histories show similar behavior for the PV0 and SH0 models, although SH0 predicts slightly higher stresses due to the additional stress components considered in the shell theory. The PV1 and MELCOR results show good agreement, particularly with respect to the effect of the thermal gradient through the vessel wall.

Figure 5 shows the temperature, strain, and equivalent stress contours predicted by the PV1 model at the time of failure. A significant thermal load is concentrated near the failure location, resulting in rapid local creep deformation. The influence of the through-wall thermal gradient on the stress distribution is observed throughout the lower head wall.

5. Conclusions

This study presented an integrated RPV lower head failure assessment module and applied it to a station blackout scenario of a domestic 900 MWe-class nuclear power plant. The module incorporates multiple models for global and local failure assessment under thermomechanical loading conditions. The global failure assessment results showed generally consistent failure locations and modes among the different models and MELCOR. The vessel failure was predicted to initiate by yielding due to the localized thermal loading and the resulting reduction in material strength. Among the models, SH0 predicted an earlier failure due to the additional stress components considered in the shell theory, while PV1 showed good agreement with MELCOR, particularly in capturing the effect of the through-wall thermal gradient. These results demonstrate the applicability of the developed module for assessing RPV lower head failure under severe accident conditions.

Table 3. Global failure assessment results.

Model	Time (sec)	Location (Seg. No. or Downward angle)	Mode
MELCOR 0D	15,657	Seg. 5 (31~ 40˚)	Rupture
MELCOR 1D	15,631	Seg. 6 (15~ 30˚)	Through-wall yield
PV0	14,874	Seg. 5 (31~ 40˚)	Yield
	14,926	Seg. 5 (31~ 40˚)	Rupture
PV1	14,880	Seg. 5 (31~ 40˚)	Through-wall yield
SH0	14,870	40˚	Yield
	15,256	30˚	Rupture

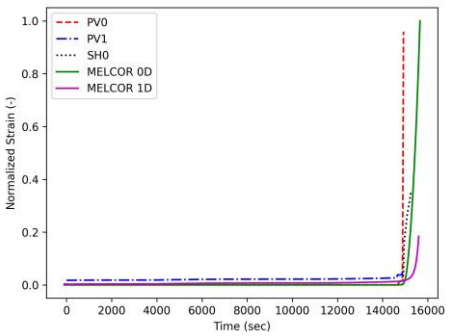


Figure 3. Normalized strain history at the failure location.

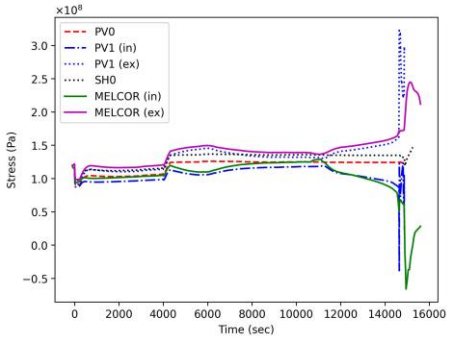
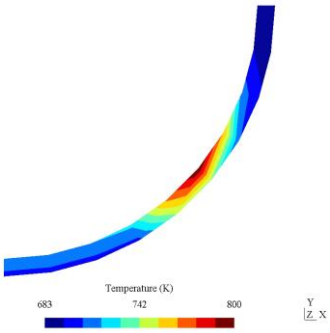
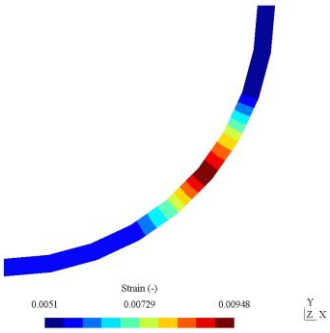


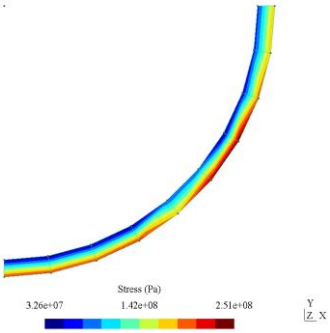
Figure 4. Equivalent stress history at the failure location.



(a)



(b)



(c)

Figure 5. (a) Temperature, (b) strain, and (c) equivalent stress distributions of the PV1 model at the failure time.

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