Implementation of Larson-Miller Creep Model to CINEMA code for Simulation of Steam Generator Tube Rupture Accident in APR1400

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1. Introduction

We are to use the CINEMA (Code for INtegrated severe accidEnt Management and Analysis) [1] to simulate the Steam Generator Tube Rupture (SGTR) caused by a Station Black Out (SBO) accident in the Advanced Power Reactor 1400 (APR1400) [2]. For prediction of the location and timing of creep failure at a pressure boundary structure, the code has a reasonable model for the creep failure. However, the CINEMA code has no creep model for this SGTR simulation, so the Larson-Miller creep model [3] used in the MELCOR code [4] is investigated and its implementation to the CINEMA code is followed by a verification process.

Finally, we performed the preliminary SGTR analysis of APR1400 by the CINEMA code with this creep model.

2. Larson-Miller (LM) Creep Model

2.1 Investigation of LM creep model in the MELCOR code

The MELCOR code can predict the creep failure of the cylindrical structure such as a steam generator u-tubes by the Larson-Miller (LM) model [3,4]. This model takes into account the hoop stress caused by the pressure difference between inner and outer wall surfaces of the pipe. The circumferential stress ($\boldsymbol{\sigma_\theta}$) is

$$\boldsymbol{\sigma_\theta} = \frac{r_i^2 P_i - r_o^2 P_o}{(r_o^2 - r_i^2)} + \frac{(P_i - P_o)\, r_i^2\, r_o^2}{(r_o^2 - r_i^2)\, r^2} \qquad (1)$$

where,
$\boldsymbol{r}$: radius of pipe (m),
$\boldsymbol{r_i}$: inner radius (m), $\boldsymbol{r_o}$: outer radius (m),
$\boldsymbol{P_i}$: inner pressure (Pa), $\boldsymbol{P_o}$: outer pressure (Pa),

as shown in Fig. 1.

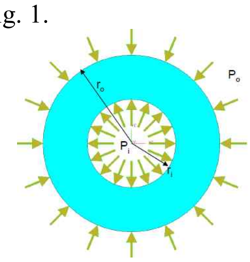


Fig. 1. Configuration of the stress acting on the cylindrical pipe.

The effective stress ($\boldsymbol{\sigma_{eff}}$) can be obtained by the maximum stress in Eq. (1) when $\boldsymbol{r = r_i}$.

Finally we can get $\boldsymbol{\sigma_{eff}}$ in the following equation as

$$\boldsymbol{\sigma_{eff}} = \frac{(r_o^2 + r_i^2)P_i - 2r_o^2 P_o}{(r_o^2 - r_i^2)} \ . \qquad (2)$$

In order to determine if the structure fails due to temperature and $\boldsymbol{\sigma_{eff}}$ a LM parameter $\boldsymbol{P_{LM}}$ is calculated as

$$\boldsymbol{P_{LM} = C_1 bg\ (\sigma_{eff}) + C_2} \qquad (3)$$

where, $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ are constants, which are defined by the material of the structure as shown in Table 1.

Table 1: Constants, $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ for $\boldsymbol{P_{LM}}$ calculation

Material	$\boldsymbol{C_1}$	$\boldsymbol{C_2}$
Carbon steel	-5335.0	62291.3
SUS 316	-7400.0	81088.4
Inconel 600	-6296.1	67130.0

Figure 1 shows the results of $\boldsymbol{P_{LM}}$ in Eq. (3) for different material properties in Table 1.

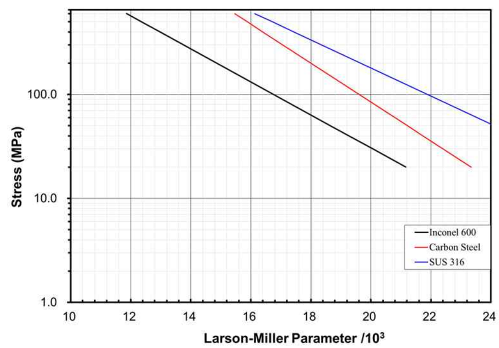


Fig. 2. Comparison of $\boldsymbol{P_{LM}}$ for different materials.

Using the LM parameter, the temperature of the structure ($\boldsymbol{T}$) and an additional material constant $\boldsymbol{C_3}$ (see Table 2), the remaining time until the failure of the structure ($\boldsymbol{t_R}$) can be calculated by

$$\boldsymbol{t_R} = \mathbf{10}^{\left(\frac{P_{LM}}{T} - C_3\right)} \ . \qquad (4)$$

Table 2: Constant, $\boldsymbol{C_3}$ of $\boldsymbol{t_R}$ for different materials

Material	$\boldsymbol{C_3}$
Carbon steel	16.44
SUS 316	16.44
Inconel 600	11.44

The time, t_R specifies the length of time that intact structure could withstand the constant stress of σ_{eff} and the temperature of T . This assumption is based on experimental investigations and is called the stationary creep rate. The steady creep rate is not valid at the start of the stress on the structure and close to its failure. However, in the MELCOR code, it is approximated that the steady creep rate is valid from the start of the stress until the failure of the structure. This approximation allows for the calculation of the life time progress, ε_{new} based on t_R according to the following equation:

$$\varepsilon_{new} = \varepsilon_{old} + \frac{\Delta t}{t_R} \ . \qquad (5)$$

The fraction of the current time step Δt from the time of t_R can be considered to be the fraction of damage caused in the structure by the current stress and temperature. ε_{old} is the life time progress calculated in the previous time step. If ε_{new} exceeds the value of 1, the structure fails.

2.2 Verification of the LM creep model implemented in the CINEMA code

For the implementation of the LM creep model to the CINEMA code, the equations (2), (3), and (4) should be calculated for each time step. This arithmetic processes are accomplished by the general control functions provided by the CINEMA code.

The actual fractional life time is obtained by time integration, but the code calculates it by summation in a recursive way for each *i* th time step (Δt_i):

$$\int \frac{dt}{t_R(t)} \approx \sum \frac{\Delta t_i}{t_R(t_i)} \ . \qquad (5)$$

If the value in Eq. (5) reaches 1.0, it is assumed that the creep failure starts. This creep failure results in the break opening for the flow path between the failed structure and the surrounding volume.

For the verification of LM creep model implemented in the CINEMA code the benchmarking problem is defined with general operation conditions of APR1400. We assumed the primary and secondary pressure of APR1400 for the inner and the outer pressures of the pipe structure. The geometric size such as the inner and the outer diameters are determined by the design data of APR1400. The creep properties of the materials (SUS316, Inconel 600) are obtained from those used in the MELCOR code.

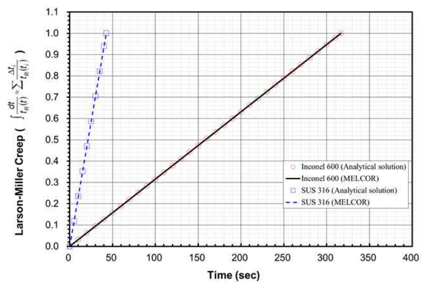
Table 3 shows the boundary conditions for LM creep calculations.

Table 3: Boundary conditions for benchmark problem

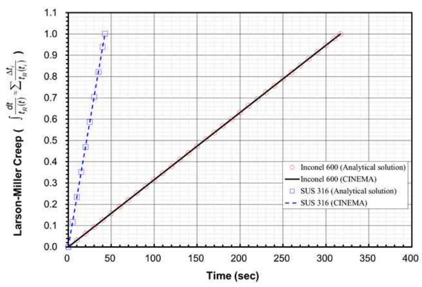
P_i	1.5×10^7 (Pa)
P_o	7.0×10^6 (Pa)
T	1300.0 (K)
r_i	8.4582×10^{-3} (m)
r_o	9.525×10^{-3} (m)

The analytical solution for cross checking of the CINEMA code prediction can be obtained by the Eq. (4). The constant boundary conditions in Table 3 result in the stationary creep rate, which gives the same life time, t_R for each time step during the CINEMA calculation.

Figure 3 shows the benchmark results comparing the code predictions with analytical solution. The CINEMA code predictions are in good agreement with the MELCOR predictions as well as the analytical solutions. The creep rate for the SUS 316 is relatively faster than that for Inconel 600. Although the LM parameter (P_{LM}) for SUS 316 case is higher than that for Inconel 600 as shown in Fig. 2, the additional material constant C_3 dominantly determines this difference of creep rate. The life times before creep failure, t_R are compared in Table 3.



(a) MELCOR vs. Analytical solution



(b) CINEMA vs. Analytical solution

Fig. 3. Benchmark test results for the LM creep model with different codes.

Table 3: Comparison of t_R from benchmark test results

Material	MELCOR	CINEMA	Analytical solution
SUS 316	42.7 sec	42.6 sec	42.57 sec
Inconel 600	316.9 sec	316.8 sec	316.72 sec

3. Preliminary Analysis of SGTR in APR1400 Plant

The implementation LM creep model to CINEMA code is tested in the simulation of SGTR in APR1400.

The initial event is SBO accident in the APR1400. The SBO accident results in the high pressure and high temperature conditions in the primary coolant system. When the core exit temperature reaches, it is assumed that the severe accident starts and the operator manually opens the ADS valves in the secondary coolant system.

Finally, the pressure difference between primary and secondary side becomes high and SG u-tubes are heated up, which can induce SGTR.

Besides the SG u-tubes, the creep failure can occur in the pressurizer surge line and hot leg. Therefore, the LM creep model is applied to 3 locations in SG u-tubes, the surge line, and hot leg.

Figure 4 shows the nodalization of APR1400 for CIMEMA simulation. In this nodalization the upper and lower region of hot legs are separated to model the horizontally stratified flow with steam and water in the upper and lower region of hot legs, respectively.

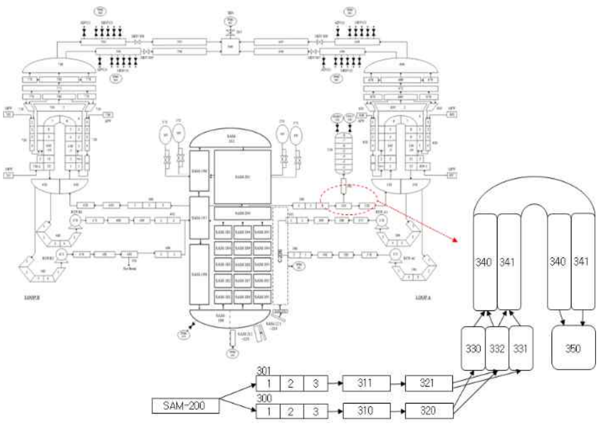


Fig. 4. CINEMA code nodalization for APR1400.

Figure 5 shows the behavior of the primary system pressure during the transient simulation. Initially the primary system pressure reaches the upper boundary conditions for opening PORSV. When the creep rupture occurs in the primary system, the pressure boundary is broken and the pressure rapidly decreases.

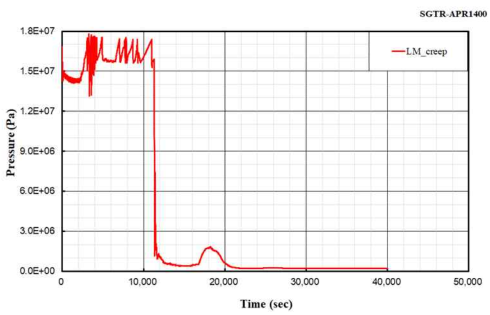


Fig. 5. Primary pressure for SGTR in APR1400.

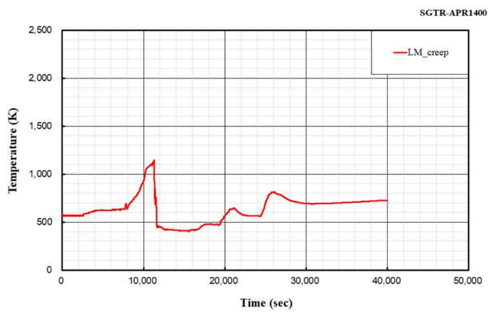


Fig. 6. Temperature of SG u-tube for SGTR in APR1400.

Figure 6 shows the temperature behavior of SG u-tubes. Since the melting temperature of SG u-tube is about 1,650 K, the creep failure by LM model occurs before reaching the melting temperature of the structure.

The variation of the fractional life time in Eq. (5) is plotted in Fig. 7. All these time variations for 3 different locations are initially around 0.0 and suddenly rise to 1.0 within 1,000 seconds. However, the failure times recognized by a value of 1.0 are different for each case.

Table 4 lists these failure times for 3 different cases, where the earliest creep failure time (11,319 seconds) is found in the case of SGTR.

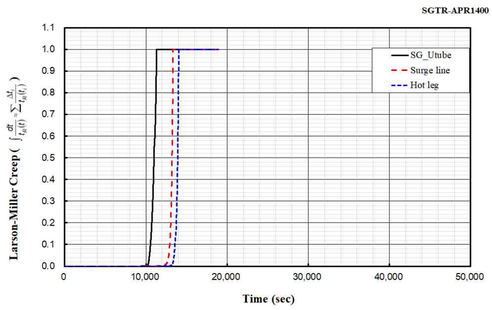


Fig. 7. Comparison of creep failure time for 3 different locations.

Table 4: Creep failure time for 3 different locations

Creep location	Structure material	Creep failure time
SG u-tubes	Inconel 600	11,319 sec
Surge line	SUS 316	13,333 sec
Hot leg	SUS 316	14,037 sec

4. Conclusions

A SGTR induced by a severe accident is simulated by the CINEMA code. For this purpose, the Larson-Miller creep model to initiate the rupture of SG u-tubes is implemented to the CINEMA code.

The benchmark problem to verify this creep model implementation in the CINEMA code is defined and the CINEMA predictions are shown to be in good agreement with the MELCOR code predictions as well as the analytical solutions.

The preliminary simulation of a SBO accident in APR1400 is performed to investigate how this new creep model works for predicting the creep failures in the structures composing of the primary pressure boundary.

A creep failure induced by a severe accident such as SBO was simulated successfully. It is also shown that a SBO accident can more likely induce the SGTR rather than the rupture at a pressurizer surge line or a hot leg.

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