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THERMO-MECHANICAL ANALYSIS OF RVLH FOR APR1400 DURING A SEVERE ACCIDENT

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ABSTRACT

After Fukushima accident, it becomes very important issue to investigate BDBAs (Beyond Design Basis Accidents) more accurately in NPP (Nuclear Power Plant) design and operation. In such a severe accident condition, the molten core material forms an internally heated debris bed and eventually becomes a melted pool of corium, which will cause or induce thermal and mechanical loads to the reactor vessel wall and then can make penetrations leading to the failure. A good understanding on the mechanical behaviour of RVLH (Reactor Vessel Lower Head) under the condition is essential for verification of the integrity and improvement of accident mitigation strategies.

Coupled thermo-mechanical analysis was performed to investigate possibility and timescale of the failure. 2D axisymmetric finite element model was adopted based on APR1400 design data with relevant material properties such as heat convection coefficient of water, elastic-plastic strain data, and experimental data for creep. The thermal analysis model was iteratively refined to make thermal gradient contour line and element mesh boundary coincide so that bands of element mesh can be assigned to proper material properties for thermal stress analysis according to the result of thermal transient analysis. The objective of this paper is to develop the analysis method of the RVLH for APR1400 with thermo-mechanical analysis using FEM (Finite Elements Method) tools in case of core-melted severe accident condition, and investigate the creep behaviour in such case. The timescale of the creep failure can provide delay margin of emergency measures to mitigate the severe accident.

INTRODUCTION

During a severe accident causing core meltdown in the PWR (Pressurized Water Reactor), the RPV (Reactor Pressure Vessel) integrity is threatened by the relocation of molten core material into the lower head and the formation of a molten pool. In such a scenario, heat exchange between the pool and the vessel is provoke localized overheating and causes partial melting. For the stabilization of the RPV, the IVR-ERVC (In-Vessel Retention with External Reactor Vessel Cooling) strategy was employed in the LWR (Light Water Reactor) design such as AP-600, AP-1000, VVER-440, and APR1400.

Rempe et al. (1993) suggested 4-failure modes of PWR in case of severe accidents, namely, penetration tube heat-up and rupture, penetration tube ejection, localized failure by jet thermal loads, and lower head global failure. The failure by the penetration tube heat-up and rupture and penetration tube ejection was found to be very low conditional probability Kim et al. (2013). The jet thermal loads were also found to be insufficient to make failure in the vessel or to fail a penetration Sehgal (2012). To prevent or mitigate global failure of the lower head the APR1400 adopted IVR-ERVC strategy as a SAMS (Severe Accident Management Strategy). Under the IVR-ERVC strategy in severe accident condition, a good understanding of the mechanical behaviour of the RVLH is essential both for verification of structural integrity and for improving the SAMS.

For the prevention of the further progression of the accident it is important to know whether or not RPV will fail. If it fails, the location and the time of failure have to be evaluated. In this paper, the numerical simulations using ANSYS v.15 were performed to investigate the lower head failure of the APR1400.

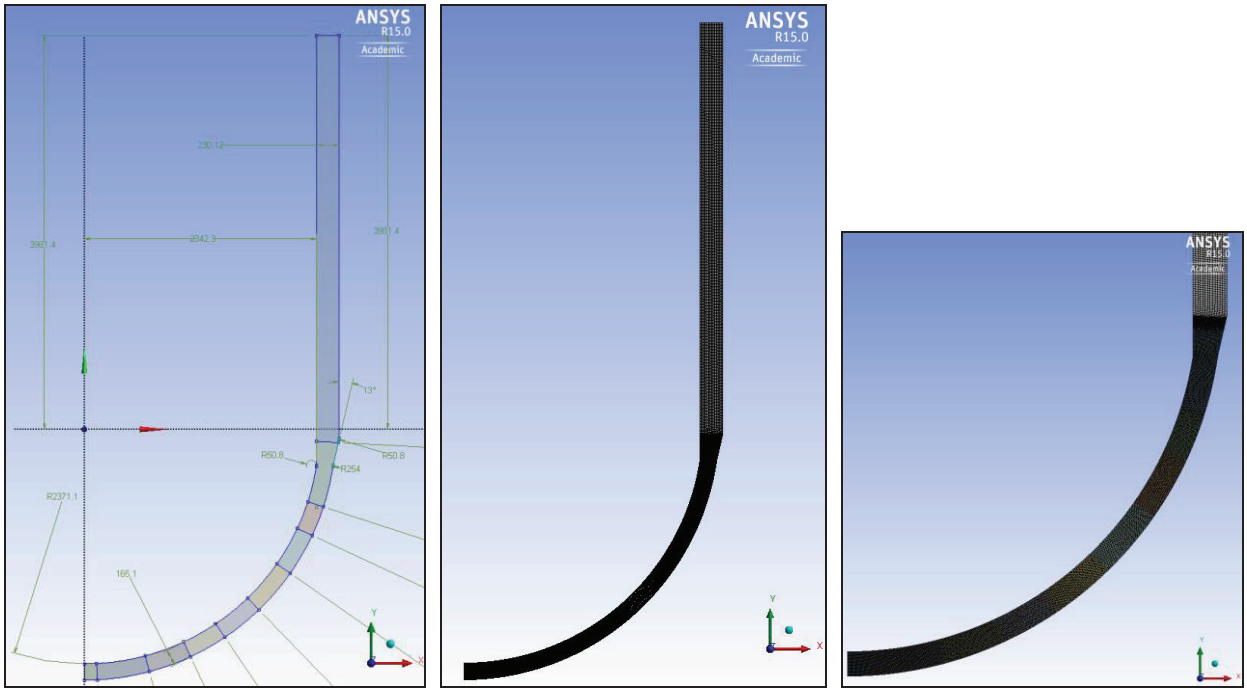
ANALYSIS METHOD

Coupled thermal and mechanical analysis was adopted to investigate realistic behaviour of RVLH using ANSYS v.15 workbench and mechanical APDL. The transient temperature field was calculated, and then the transient mechanical loads calculation was performed applying the appropriate temperature field. 2D axisymmetric finite element model was employed based on APR1400 design data of KHNP (2002) and relevant physical phenomena, for example, heat conduction, heat convection, thermal expansion, elastic-plastic strain relations, and creep behaviour.

Finite Element Modelling

The study is focused on the lower head of the vessel where the melted core is located. Therefore, the hot-legs and cold-legs, the hole for the ICI (In-Core Instrumentation) nozzle, and other detail parts were not included in the model. This has major advantage that an axis symmetric model could be established. The geometry of the modelling from RVLH up to bottom of hot-legs piping was made based on dimension data of APR1400 with actual scale as shown in figure 1 (a).

The reactor vessel was modelled with structural elements considering the material behaviour at high temperatures. The elements used for modelling the RPV are 4-node structural elements. Since the lower part of the vessel is in the focus, it was modelled with finer elements than the upper part of the RPV as shown in figure 1 (b) (c). Node numbers and element numbers are 19,838 and 19,021, respectively.



(a) (b) (c)

Figure 1. 2D axisymmetric geometry model (a), mesh model of RPV (b) and RVLH (c) for APR1400

Material Properties

The linear and non-linear, elastic and elastic-plastic, material properties at high temperatures are necessary for simulating the molten metal for the transient thermal analysis and structural analysis. The material property of the RPV was chosen from the material data of the APR1400 as steel SA-508 class 1 grade 3. The temperature dependent material properties such as melting temperature range, enthalpy, density, coefficient of thermal expansion, coefficient of thermal conductivity, and specific heat were obtained from Kim et al. (2013). The stress-strain curve such as non-linear material properties based on MISO (Multi-linear ISOtropic hardening) principles, elastic modulus, and poisson's ratio was obtained from Chintapalli and White (2009). The creep data from Alstadt and Moessner (2000) also should be applied to constitute the creep behaviour. All units were converted to SI unit and degree centigrade for engineering data input of ANSYS workbench.

Boundary Conditions and Loads

A molten corium pool including metallic materials such as stainless steel and zircaloy, and oxide materials such as UO_2 and ZrO_2 may form at the initial stage. The corium pool may be stratified into two layers such as an upper metallic layer without volumetric heat source and a lower oxide layer with volumetric decay heat source due to their density differences. This two-layer melt pool formation is assumed to be a bounding melt pool configuration for the thermal load analysis under the IVR-ERVC.

The internal heat flux distribution resulted by melt pool circulation is major input data for evaluating the reactor vessel. Normalized heat fluxes were obtained by average internal heat flux after the relocation of molten core material into the lower head and the formation of a molten pool. The heat flux distribution as a thermal load was applied in case of TLOFW (Total Loss of Feed Water) according to the safety analysis results of Kim et al. (2013) sketched in figure 2. The TLOFW is more severe case than SBO (Station Blackout) due to higher heat flux distribution. Bottom of RVLH is 0 degree, matching part of RVLH and RPV shell is 90 degree.

The description of the heat transfer from the RPV to the surrounding water is an important part of the model. The entire vessel is externally flooded up to cold leg level at severe accident as like IVR-ERVC. We assumed that outside wall temperature of RPV and ambient temperature are uniformly at 130 ˚C through effective nucleate boiling. The convection coefficient of water at 130 ˚C was applied to the outside of reactor vessel surface. The effects of phase change are assumed as negligible at the outside wall.

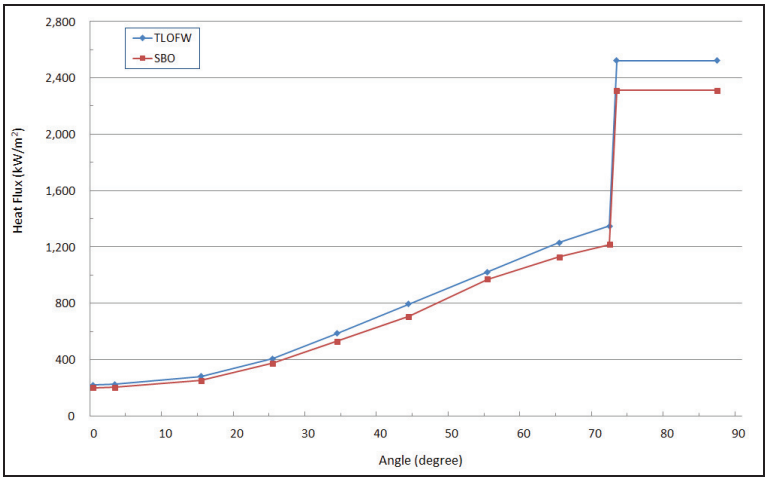
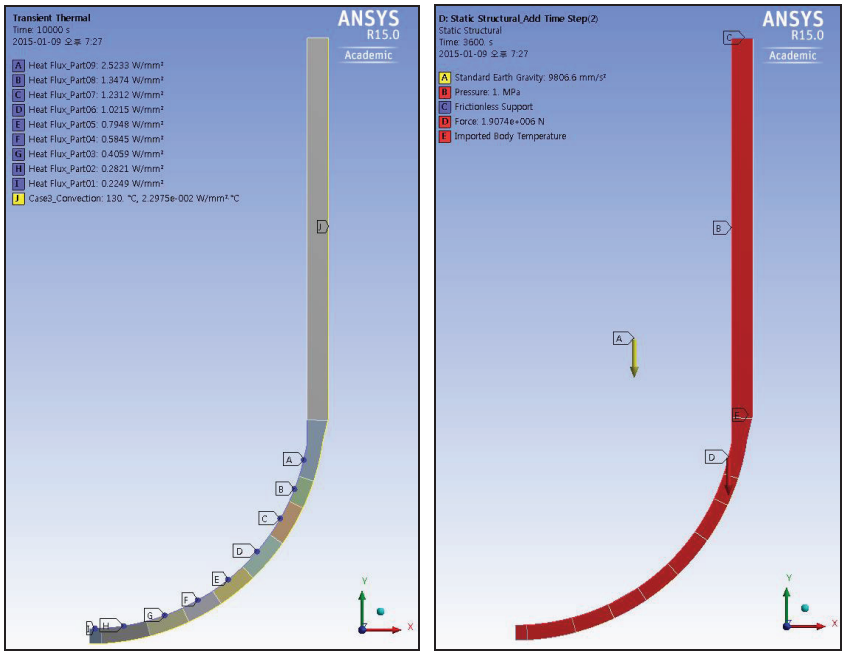


Figure 2. Internal heat fluxes in case of TLOFW and SBS scenario

Park et al. (2015) summarized the corium weight of final melt pool at the reactor vessel failure in the lower plenum of the APR1400 for five major selected sequences of severe accidents. In all sequences, approximately 80 ~ 90 % of the core material was melted and relocated to the lower plenum of the reactor vessel in the APR1400. By comparing with the hand calculation for the melted corium weight, the result could be appropriate to the corium weight for the input load of the analysis. Thus, the deadweight of melted corium was assumed as 194.5 tons.

The gravity acceleration, 9806.6 mm/s^2, was applied overall modelling for considering the deadweight of the RPV. The internal pressure was assumed 1 MPa considering depressurization by SDS (Safety Depressurization System). Even if the SDS will be properly activated in severe accident condition, the internal pressure cannot be same as atmospheric pressure (1 atm. ≒ 0.1 MPa) because the RPV would be full of evaporated steam comes from cooling water. Therefore, 10 bar (≒ 1 MPa) has been applied as internal pressure for the structural analysis under the severe accident condition.

The boundary condition data and loads for thermal transient analysis were inputted in Transient Thermal module of ANSYS workbench as shown in figure 3 (a), and the boundary condition data and loads for structural analysis for structural analysis were inputted in Static Structural module of ANSYS workbench as shown in figure 3 (b).



(a) (b)

Figure 3. Thermal (a) and structural (b) Boundary conditions and loads

Thermal Transient Analysis

A coupled thermal and mechanical analysis can be solved with design data of APR1400, material properties, boundary conditions, and loads. Since the structural elements do not allow for direct thermal mechanical coupling, a sequential coupled analysis method was adopted. At first, thermal transient analysis was carried out to calculate the temperature distribution of the RPV. The analysis was performed until 10,000 seconds since the temperature distribution became steady-state after 8,000 seconds

Post Processing

After finishing thermal transient analysis, post processing was carried to eliminate the elements over melting temperature (1461 ˚C) using ANSYS mechanical APDL commands. The method of eliminating the elements is element death processing in the ANSYS. To achieve the "element death" effect, the program does not actually remove "killed" elements. Instead, it deactivates them by multiplying their stiffness, conductivity, and other material properties by extremely reduction factor. This factor is set to 1.0×10^{-6} as default in ANSYS (2013). The result of post processing is shown in figure 4.

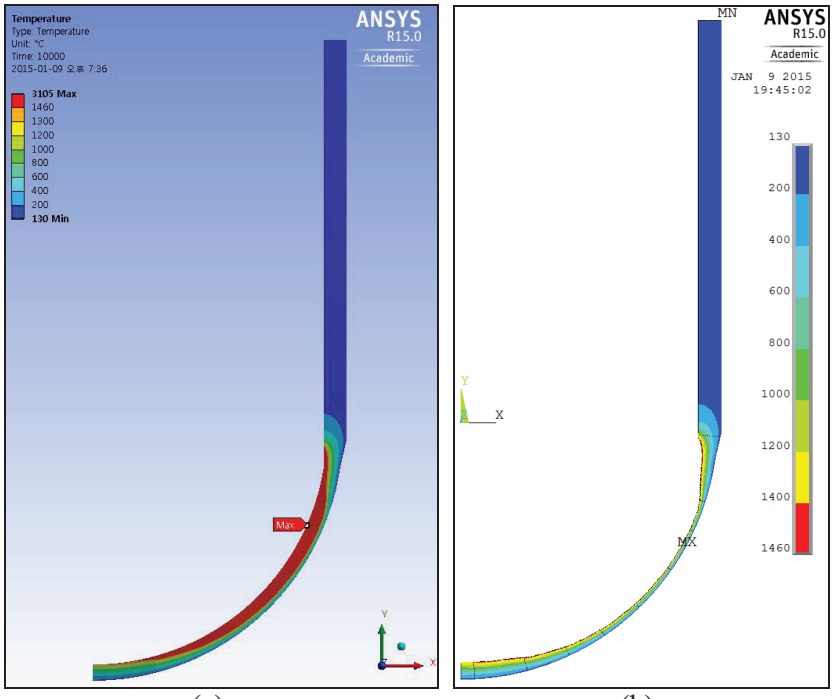


Figure 4. Temperature distribution of RPV (a) and post processing for eliminating melted elements (b)

Structural Analysis including Creep Behaviour

After the post processing, elastic-plastic FEM analysis including creep effect was carried out using the spatial temperature field as a body input loads. The lower head of the RPV is loaded by the deadweight of melted corium and the vessel, the internal pressure, and the temperature field which is the output of thermal transient analysis. The deadweight of melted corium, the internal pressure, and the gravity loads cause primary stresses, which are not relieved by the deformation of the vessel wall but are even increased due to wall thickness reduction. Unlike this, the temperature gradient causes secondary stresses which can be relieved by plastic deformation.

The main deformation mechanisms of the RPV wall are creep and plasticity according to recent studies of Sehgal (2012). Creep is a time-dependent process and connected to the failure at elevated temperatures (above 600 ˚C), whereas plasticity occurs promptly, that is, simultaneously with the loads. The analysis was performed until 1, 2, 5, 10, 20, and 40 hours to check trend of elastic, plastic, and creep strain, and then increased the time up to 350 hours to find minimum time to reach 15 % creep strain criteria.

FAILURE CRITERIA

The strain-based failure criteria have been used for the standard safety evaluation of structures in high temperature condition rather than stress-based failure criteria Chavez et al. (1995). Since the plasticity and the creep are known as main deformation mechanisms of the RVLH, the failure criteria for plasticity and creep were described in this section.

Plastic Strain Criteria

The plastic deformation is a prompt process occurring only above an yield strength. Failure criteria used by Bohl and Butler as well as Berman and others were phenomenologically based on continuum mechanics. Each criterion is based on failure by equivalent plastic strain (ε_p) which is defined in terms of the principal plastic strains (ε_1, ε_2, ε_3) as the following Equation 1.

$$\varepsilon_p = \frac{\sqrt{2}}{3}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2] \quad (1)$$

According to Bohl and Butler, the failure would be occurred at 12 % equivalent plastic strain. Berman and others placed 18 % Cho et al. (2013). The failure criteria will have to be evaluated conservatively. For this purpose, the mechanistic ideas of ductile failure based on void nucleation, growth, and with particular reference to the work of Shockey et al. (1980) were used. It was found that voids nucleate predominantly on included particles and that the threshold strain of 11 % is needed for nucleation Cho et al. (2013). Park et al. (2001) also applied 11 % strain as a structural failure criterion. Thus, 11 % criterion was adopted as the plastic failure criterion for the evaluation.

Creep Strain Criteria

The creep can be supposed the main cause of failure of the RPV by the high temperature load as a result of melt pool formation. It is well known that stress and temperature can affect significantly the creep rate of structural materials. A typical creep curves for metals exhibit three characteristic behaviour regions, namely, primary stage, secondary stage, and tertiary stage before fracture. The instantaneous deformation occurs immediately upon applicant of the load and may contain both elastic and plastic deformation. The primary stage, transient creep, is changing at a decreasing rate as a result of strain hardening. The secondary stage, steady creep, is that the creep rate reaches a minimum and remains constants. The tertiary stage is that the creep rate continues to increase and is also accompanied by a reduction in cross-sectional area and the onset of necking, hence increase in acting stress ; thereby, resulting in fracture Harvey (1985).

The creep strain is a function of time, temperature, and stress. Since pressure components are subject to varying stresses, methods are required for using the constant stress creep response to predict their behaviour under variable conditions. This has given rise to a number of applicable creep theories of which many have been directed to fitting the experimental data of a specific material. In this analysis, a modified time hardening creep model was chosen in ANSYS module. See Equation 2 as follow :

$$\varepsilon_{cr} = \frac{c_1\, \sigma^{c_2}\, t^{c_3+1}\, e^{-c_4/T}}{c_3 + 1}, \qquad c_1 > 0 \quad (2)$$

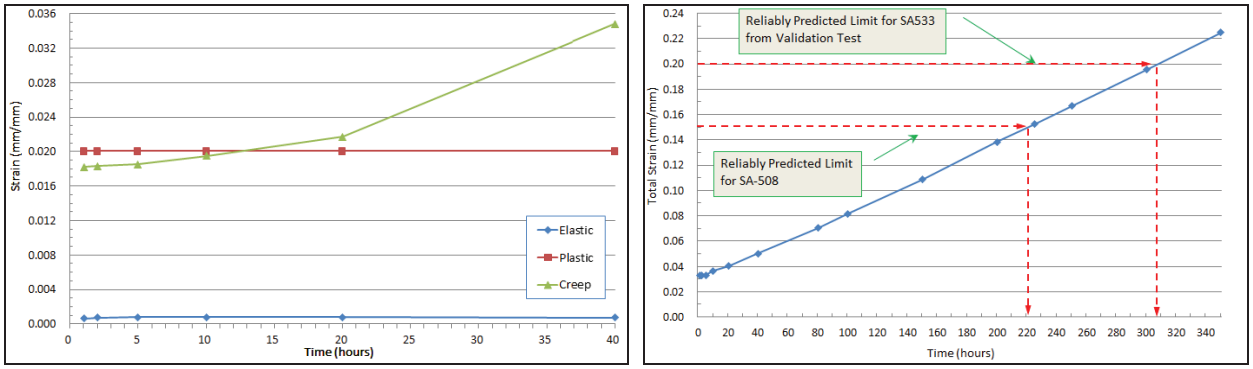
where ε_{cr} is the equivalent creep strain, σ is the equivalent stress, t is time, T is temperature, and $c_1 \sim c_4$ are constants to be determined by curve fitting with experimental data Villanueva et al. (2012). Because of insufficient experimental data of SA-508 in high temperature region, coefficients for the model were generated using the experimental creep data of SA-533 B1 taken from Alstadt and Moessner (2000).

Villanueva et al. (2012) had performed the validation test for the modified time-hardening model, Equation 2, with SA-533B1 material. The test identify a range of percentage strain that we consider as reliably predicted by the model and beyond this range the results are only considered that failure is expected to happen. The test found that the strains within 20 % can be considered as reliably predicted range. Alstadt and Willschutz (2000) also proposed that 20 % creep strain which was considered as very conservative creep rupture strain for all stresses and temperatures. However, Lim (1998) performed material tests of SA-508 for study on creep behaviour in cases of 600, 660, 700, and 750 ˚C. Even if the test data were not sufficient for this analysis due to no data in high temperature region, the test found out interesting results for SA-508 material ; The strain error under 15 % strain is very small and the errors increase as strain increase. In other words, the strains within 15 % can be considered as reliably predicted range. Cho et al. (2013) also proposed 15 % strain as an acceptable creep failure criterion. Thus, time to 15 % criterion was adopted as the minimum estimated vessel wall failure time considering factors as described above and uncertainties.

ANALYSIS RESULTS AND DISCUSSIONS

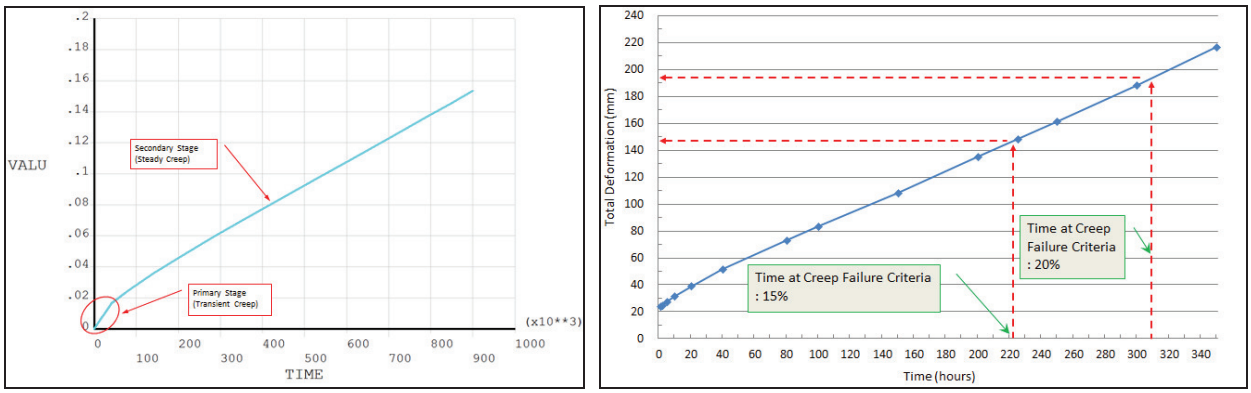
Analysis Results

Three parts in the deformation of the material, namely, elastic deformation, plasticity, and creep behaviour have to be taken into account. Figure 5 (a) shows that two strain results except creep strain have constant values. Equivalent elastic, plastic, creep, and total strain are shown in figure 7.



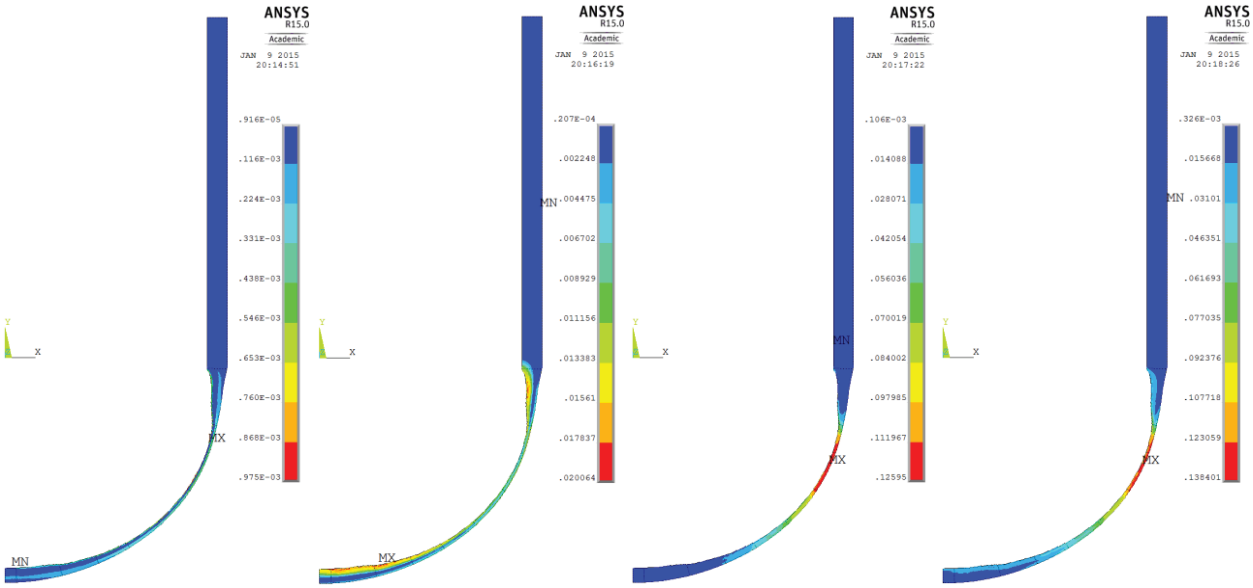
(a) (b)

Figure 5. Maximum equivalent strains, 40 hours, (a) and maximum equivalent total strain, 350 hours, (b)



(a) (b)

Figure 6. Maximum creep strain of maximum element (a) and maximum total deformation, 350 hours, (b)



(a) (b) (c) (d)

Figure 7. Equivalent elastic (a), plastic (b), creep (c), and total (d) strain distributions, 200 hours

Discussions

The maximum equivalent plastic strain at any time is 0.02006 (2.006 %) in figure 5 (a) which is significantly below than 11 % of the plastic failure criterion, and the maximum equivalent total strain after 1 hour was 0.03305 (3.305 %) in figure 5 (b) which is also much lower value than 15 % of the creep failure criterion. Thus, the probability of prompt RVLH failure may be very low in the severe accident condition.

However, the equivalent creep strain has trend to increase as time goes on in figure 5 (a). The minimum time to reach 15 % total strain can be found in figure 5 (b), it is around 220 hours. The timescale to reach 15 % strain can provide the timescale for delay of emergency measures to mitigate the severe accident with proper actions. The 220 hours is result when heat flux from the core melt assumes constant during analysis time under the assumed boundary conditions. Since the heat flux would be decreased as time passes by severe accident measures, the 220 hours is minimum value and conservative analysis result. Figure 6 (a) shows the equivalent creep strain of the element that has maximum equivalent creep strain among all elements. Primary and secondary stage of creep strain can be found in figure 6 (a).

CONCLUSIONS

First, the thermo-mechanical analysis method and procedure of the RPV for APR1400 using FEM tool, ANSYS workbench and mechanical APDL, under the core-melted severe accident condition was developed in this paper. This study can be applied to various commercial reactor types, for example, OPR 1000, APR+ under operating or designing nuclear power plants. Second, the possibility of plastic and creep failure of the RVLH for the APR1400 is considerably low in the severe accident under the assumed boundary conditions. However, the plastic failure can be the major cause of lower head failure on the reactor vessel at initial time, and the creep failure cannot be negligible as failure factor as time goes on without proper safety measures.

The SA533B1 data was substituted for creep data of SA-508 in the study. In addition, it was found that the steel ablation at the interface between corium and vessel steel is not only a thermal phenomenon in the METCOR experiments Bechta et al. (2006). Corrosion processes and the formation of eutectics lead to the erosion of the vessel steel at temperatures that are significantly lower than the melting temperature of steel. It called thermo-chemical attack of the corium (corrosion) Sehgal (2012). The reduced wall thickness due to the thermo-chemical effect increases the equivalent stress. As a result, the plastic strain will be increased, and the minimum time to reach 15 % creep strain will be decreased. It comes closer to failure criteria. Thus, further study is recommended to evaluate the structural integrity of the RPV under the severe accident conditions more exactly by considering thermo-chemical attack of the corium and creep properties of SA-508 in the analysis.

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