Deformation Behavior of APR1400 Instrumentation Nozzle in Severe Accident Condition

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1.0 Introduction

Various Engineered Safety Features (ESFs) are incorporated in nuclear power plants to prevent postulated accidents and hence enhance both economic benefits and public acceptance.

Severe accidents for NPPs involve overheating of reactor core materials to their molten states, and subsequent relocation of molten materials to lower plenum of the RV as shown in Fig. 1.

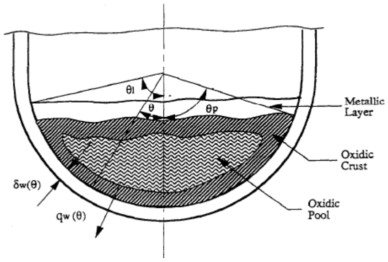

Fig. 1 In-vessel retention of corium [1]

During such accidents, there is possibility to compromise integrity of both the RV lower-head and instrument nozzles [2].

The purpose of the study is to undertake 2D thermo-mechanical and creep analysis of the APR1400 RV bottom-head, inclusive of the center BMI nozzle. The analysis was done using ANSYS 2019 VR1 software.

2.0 Methods and Results

2.0 Finite Element Analysis (FEA)

2.1 Meshing

Linear meshes with 10mm element sizes were used for static structural and transient thermal analysis. Contact edges and other areas of interest were modeled with finer elements to achieve convergence and improve accuracy of results during analysis. Mesh statistics included 18,516 nodes and 17,348 elements.

2.2 ANSYS Design Parameters

From previous research, corium deposited in lower plenum of RV during Total-Loss-of-Feed-Water (TLFW) was established to have weight of 194.5tons, implying about 80%-90% meltdown of core materials [1]. The weight was used as input load to RV lower-head.

2.3 Flow diagram

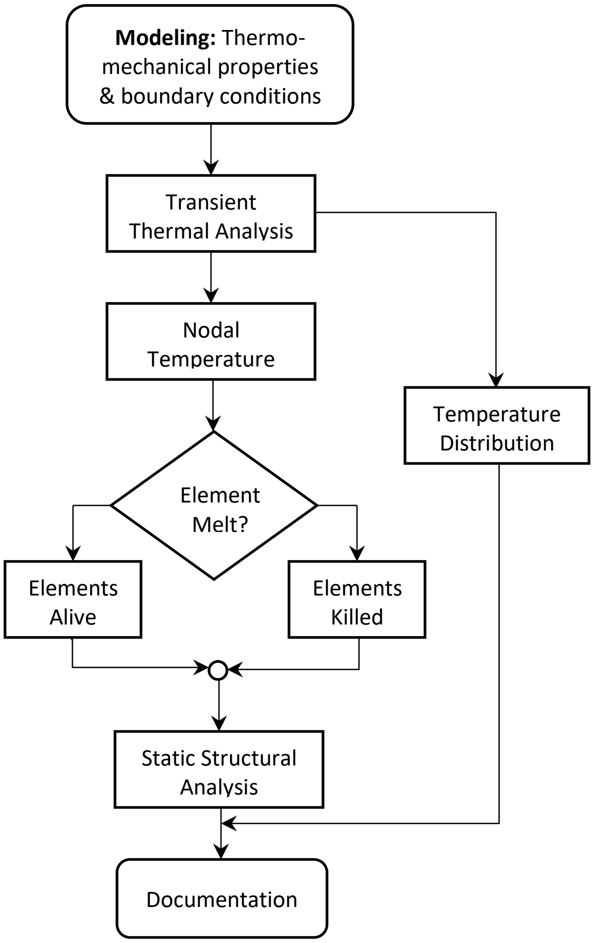

Fig. 2 Flow chart for methodology

2.4 Boundary Conditions

For structural analysis, bottom sections of the BMI nozzles were given fixed support condition. The top edge of the RV model was given frictionless support condition.

Thermo-mechanical analysis was performed taking into consideration internal pressure, standard earth gravity, corium weight, convection, heat fluxes, and imported thermal loads.

2.5 Creep Model

Creep failure criteria can either be strain based (otherwise called strain instability) or stressed-based (time damage), both of which require structural analysis of the RV and BMI nozzles to generate stresses and strains. Typical creep curve is as shown in Fig. 3 below:

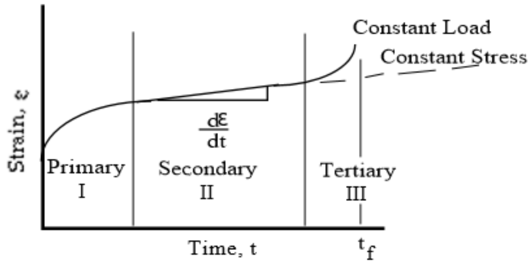

Fig. 3 Typical creep curve

The primary region denotes transient creep zone ($^{d\varepsilon}/_{dt} = 0$), secondary region is steady state creep ($\dot{\varepsilon}_{min} = \varepsilon^{\cdot}_{ss}$), while for tertiary zone the creep strain rate increases and necking occurs under consolidated failure mechanisms or constant load before the test item fails.

2.6 Element Death

All elements whose nodes had temperature values above the material melting point were deactivated using *'ekill'* command in APDL. Deactivation zeros out load vectors such as strain, specific heat, damping and mass for associated elements.

2.7 Setup for Transient Thermal Analysis

The RV bottom hemispherical section was subdivided into segments which were assigned different heat flux values. Heat fluxes were obtained from study on RV lower-head tube failure analysis data [2].

The exterior side of the vessel was subjected to cooling with ambient temperature of 150^{0}C due to nucleate boiling condition, and film coefficient of 0.022975 W/mm^2. Various mechanical and thermal properties of the model materials were obtained from various sources and incorporated in the model [2, 3, 4, 5]

2.8 Analysis Results

Transient Thermal Analysis

The temperature for the RV hemispherical section is as shown in Fig. 4 below.

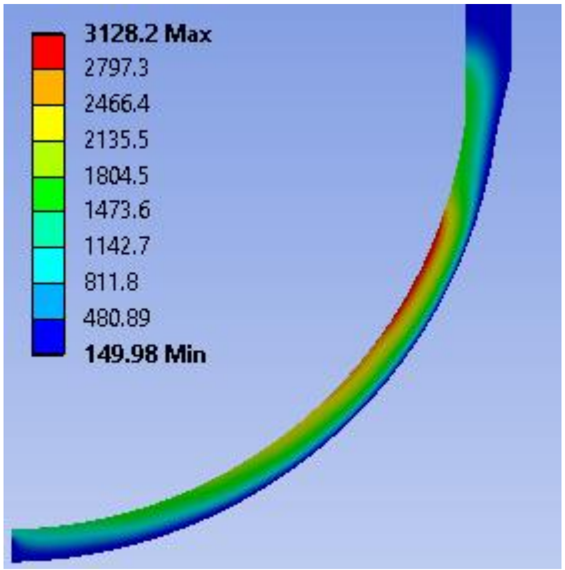

Fig. 4 Temperature distribution for RV bottom-head

Relatively high temperatures are observed at top side of the RV hemispherical region. The temperatures in most points in this section are above the melting points for SA-508 steel material for the RV. The exterior side of RV lower-head relatively maintains at coolant ambient temperature throughout the analysis.

Nozzle Temperature

The temperature of the centermost instrument nozzle is as shown in Fig. 5 below:

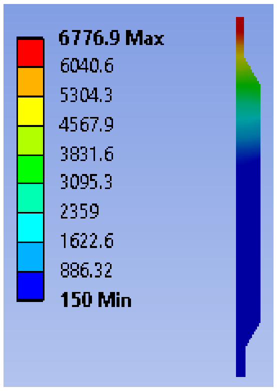

Fig. 5 Nozzle temperature distribution

The center BMI nozzle experiences temperatures up to 6776.9^{0}C over 15000 seconds period. This temperature is way above the melting temperatures of nozzle material. As a result, the nozzle partially melts at top region, while its bottom regions remain intact.

Static Structural Analysis

The study undertook structural analysis to assess integrity of the RV in case of severe accident, given the SAMS of In-Vessel Retention Eternal Reactor Vessel Cooling (IVR-ERVC).

To achieve this, the study incorporated standard earth gravity (9806.6 mm/s^2), internal pressure of 1MPa, and corium weight of 194.5tons [6]. Body temperature from thermal analysis was also imported as input for the analysis. The equivalent von-Mises stress in the RV lower-head is shown in Fig. 6 below.

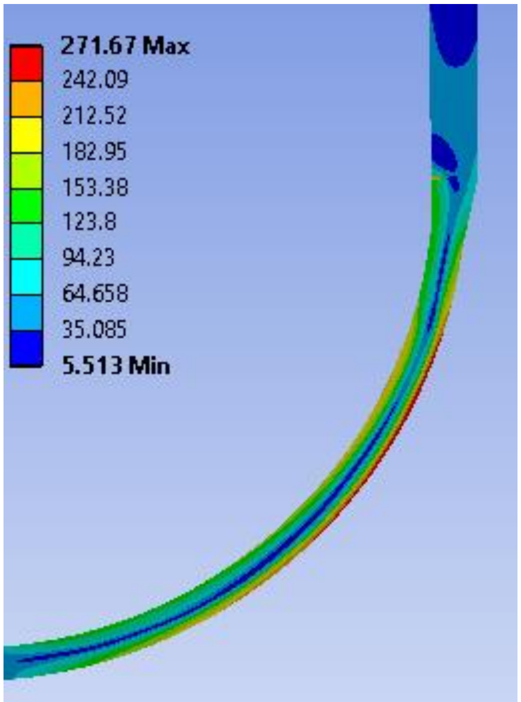

Fig. 6: Equivalent stress across geometries

Fig. 6 shows that the equivalent stress across geometries of RV hemispherical lowerhead reaches maximum of 271.67 MPa and with minimum value of 5.513 MPa.

With the weight loading for the 80-90% corium melt, failure of the vessel under the considered boundary conditions is noted at 13,318seconds which translates to about 3hrs 40minutes RV integrity maintainance, before failure.

Creep Deformation

The equivalent plastic and creep strains are shown in Fig. 7 and Fig. 8 below:

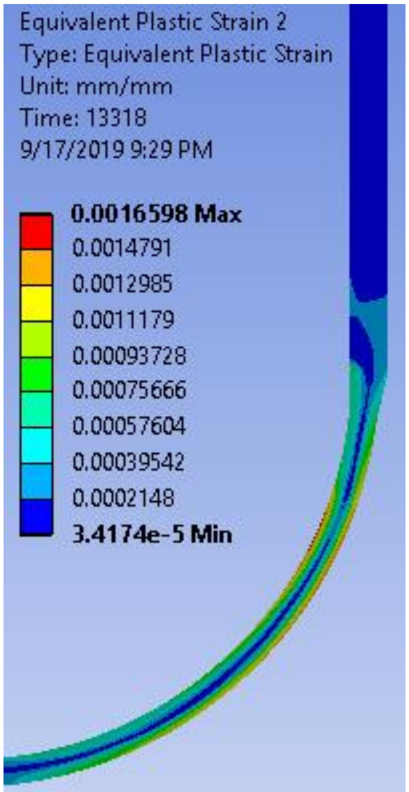

Fig. 7 Equivalent plastic strain of RV lowerhead

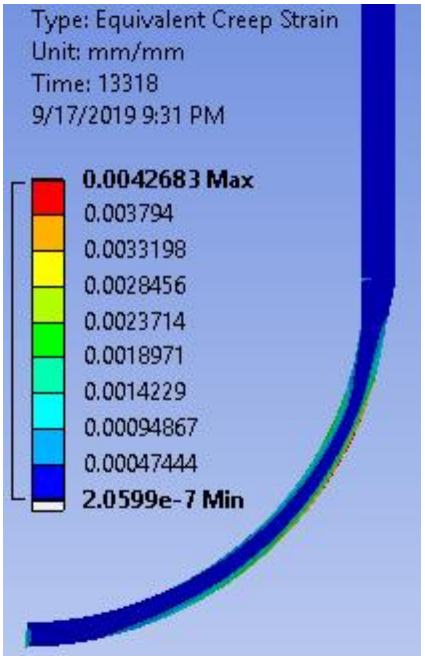

Fig. 8 Equivalent creep strain of RV lowerhead

3. Conclusions

2D thermo-mechanical analysis of the RV and center nozzle was undertaken in this study. For simplicity purposes and due to nucleate boiling, temperature of 150^0C was given as input for RV outer wall temperature. Across the outer vessel walls, effects of phase change is assumed to be negligible.

With the various boundary conditions, the top region of the center nozzle exhibit high temperatures up to $6{,}776.9^0$C. Also the inner temperature of the RV hemispherical sections reach $3{,}128^0$C. These temperatures are way above the melting point of the RV and nozzle materials, hence melting occurs for elements whose temperatures equal or surpluses melting points.

From the analysis, failure occurs at 13,318seconds which translates to about 3hrs 40 minutes after initiation of the TLFW severe accident scenario. The failure is governed by plasticity, thermal plasticity and creep effects.

ACKNOWLEDGEMENT
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