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Original Article

STRUCTURAL ASSESSMENT OF REACTOR PRESSURE VESSEL UNDER MULTI-LAYERED CORIUM FORMATION CONDITIONS

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ABSTRACT

External reactor vessel cooling (ERVC) for in-vessel retention (IVR) has been considered one of the most useful strategies to mitigate severe accidents. However, reliability of this common idea is weakened because many studies were focused on critical heat flux whereas there were diverse uncertainties in structural behaviors as well as thermal–hydraulic phenomena. In the present study, several key factors related to molten corium behaviors and thermal characteristics were examined under multi-layered corium formation conditions. Thereafter, systematic finite element analyses and subsequent damage evaluation with varying parameters were performed on a representative reactor pressure vessel (RPV) to figure out the possibility of high temperature induced failures. From the sensitivity analyses, it was proven that the reactor cavity should be flooded up to the top of the metal layer at least for successful accomplishment of the IVR-ERVC strategy. The thermal flux due to corium formation and the relocation time were also identified as crucial parameters. Moreover, three-layered corium formation conditions led to higher maximum von Mises stress values and consequently shorter creep rupture times as well as higher damage factors of the RPV than those obtained from two-layered conditions.

1. Introduction

As recent nuclear power plants (NPPs) are generating more electric power than before, the probability of accidents is also increased. When an accident involving loss of coolant leads to severe thermal loads, the reactor core, without any available cooling system, undergoes high temperature induced damage continuously; and the molten core may go down into the reactor pressure vessel (RPV) lower plenum. As the most important thing under these situations is to retain the molten substances inside the RPV, diverse strategies have been suggested to mitigate the accident progression, and the external reactor vessel cooling (ERVC) was selected as one of the effective ways. The concept of ERVC can be attained by supplying cooling water into the reactor cavity to take the heat from the external surface of the RPV. Hence, the overall understanding of complex phenomena during a severe accident is crucial, including the reactor vessel failure under ERVC

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conditions as well as corium behaviors in the lower plenum and thermal loads from the corium [1].

Although both thermal–hydraulic and structural assessment are necessary in order to establish effective ERVC strategies, lots of previous studies have focused on determining critical heat flux (CHF) of the RPV outer wall because it has been known as a promising criterion. For instance, the coolability limits of the RPV lower head were correlated with the CHF by considering two configurations of the ULPU experimental facility [2], and CHFs measured from the SUpreLeiter Test ANlage (SULTAN) test facility which showed possible coolability of large surfaces under natural convection [3]. Nine organizations also participated in a comprehensive project for assessment of reactor vessels by using EC-FOREVER (Experimental program on vessel creep, vessel failure and gap cooling), COPO (Experiments for heat flux distribution from a volumetrically heated corium pool), and ULPU (A IVR-related full-scale boiling heat transfer facility at USCB). Although the conclusion on failure criteria was only related to the thermal margin, the methodology and data of this project were applied to design an in-vessel retention (IVR) management scheme of Vodo-Vodyanoi Energetichesky Reactor in Russian (VVER) plants [4]. Accident Source Term Evaluation Code (ASTEC) code [5] and In Vessel Retention Analysis in Severe Accident (IVRASA) code [6] were adopted for the IVR simulation related to the CHF on the outer wall of the reactor vessel. Enhancement of the CHF estimation for additional thermal margin in the IVR-ERVC strategy was carried out through two-dimensional curved test section experiments [7] and the thermal load was compared with the maximum heat removal rate on the outer wall [8].

Structural assessment under diverse IVR-ERVC conditions is necessary because high temperature induced damage and/or creep rupture of the RPV are immediate threats under severe accidents. Although strain- and stress-based assessment for simple corium models [9], and damage evaluation based on finite element (FE) analyses [10–12] were conducted, there have been relatively few studies on structural assessment. In the present study, key factors related to molten corium behaviors and thermal characteristics are examined in order to derive a reasonable structural assessment method. Systematic heat transfer and thermal stress analyses are carried out for a domestic RPV under 10 postulated ERVC conditions with varying parameters, such as thermal flux due to multi-layered corium formation, and relocation time of the molten corium and water level of the ERVC. Subsequently, damage evaluation is performed employing two Larson–Miller parameter (LMP) models to predict creep damage factors and failure times, or wall penetration of the representative reactor vessel.

2. Brief review of corium formation processes

2.1. *Molten corium behaviors*

For the sake of mitigation of severe accident progression, appropriate cooling is important in a core melting situation. Provided heat is not removed effectively, the molten corium will be continually piled up and relocated in the RPV lower plenum. After completing this relocation process, the molten corium may form layered structures due to the different densities between metallic materials composed of stainless steels and zirconium alloys, and uranium–zirconium oxidic materials. When the molten corium with a very high temperature interacts with the metallic materials, oxide crusts are created and play the role of thermal barrier during heat transfer to the RPV wall.

In this study, two kinds of multi-layered configurations were assumed based on a recent piece of research [1]. Fig. 1A shows a schematic of typical two-layered molten corium formation. Here, the upper layer consists of metallic materials without any heat sources, and the lower layer consists of oxide materials releasing the decay heat. The thickness of each layer can be defined via the quantity and distribution ratio of the entire molten corium. Meanwhile, a schematic of three-layered molten corium formation by layer inversion is shown in Fig. 1B. If there is sufficient zirconium in the molten corium, uranium metal is able to be extracted from the oxidic pool to the metal layer [1]. Thereafter, dense materials in the metal layer successively go down to the bottom of the RPV, which make the heavy metal layer. This is known as the layer inversion phenomenon.

2.2. *Thermal characteristics upon ERVC conditions*

The severe accident management strategy isolates the radioactive materials inside the NPP site according to a set of procedures and guidelines. For achievement of this goal, among several strategies that have been suggested worldwide, the ERVC was judged in Korea as being one of the effective candidates. Whereas the reactor cavity should be flooded appropriately to reduce the thermal loads on the RPV wall, caused by high-temperature molten corium, it is not easy to predict overall phenomena in an ERVC situation due to complex heat transfer and material behaviors.

Fig. 1 also illustrates thermal characteristics inside and outside of the RPV due to the molten corium for two-layered (metallic layer and oxide pool) and three-layered (light metal layer, oxide pool, and heavy metal layer) corium formation cases; heat convection by external air and coolant; radiation heat transfer on the upper layer; and heat conduction in the RPV lower plenum by the molten corium. Focusing effects during the corium relocation processes can be explained as the heat concentrating phenomenon caused by conduction through a thin metal layer. As the focusing effect may lead to fatal damage at the sides of an RPV, contact with the upper layer is more than with other locations. This is a particular concern which should be noted during the structural assessment.

The internal radiation heat transfer as well as external heat convection conditions, depicted in Fig. 1, comply with the well-known relationships.

Heat convection from air:

$$q_a = h_a(T - T_a) \quad (1)$$

Heat convection from water: