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Investigation on the RPV structural behaviors caused by various cooling water levels under severe accident

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ABSTRACT

In the severe accident (SA) event of core meltdown, the 'In-vessel retention (IVR)' mitigation has been certified as an effective strategy for accident management in most advanced nuclear power plants. The traditional concept of IVR was based on the idea that the reactor pressure vessel (RPV) was fully submerged into the cooling water. However, the Fukushima accident showed that the cooling water was insufficient due to the malfunction of water supply system, so the RPV structural behavior had not been appropriately assessed. Therefore, the paper tries to address the structure-related issue on determining whether RPV safety can be maintained or not with the effect of various water levels created by the SA condition. In achieving this goal, the structural behaviors were numerically investigated in terms of several field parameters, such as temperature, deformation, stress (strain) and damage. Due to the melting pool on the inside and water cooling on the outside, the high temperature gradient was formed across the wall thickness, so RPV failure was found to be the consequence of creep, plasticity and thermal expansion. According to the requirement on RPV safety during the prescribed time, it must be ensured that the water cooling takes effect in preventing the structural failure under SA condition. Through vigorous investigation, it is found that the RPV safety is secured within the 100 creep h. Furthermore, the structural failure site, time and mode are predicted with consideration of the effect of various water levels. Most importantly, the failure is found to take place at the site aside around the water level.

1. Introduction

In the severe accident (SA) of core meltdown, a famous strategy called 'In-vessel (IVR) mitigation' is widely used by most advanced nuclear power plant (NPP) to maintain the safety of the reactor pressure vessel (RPV) [1]. In fact, the IVR mitigation has been certified by nuclear regulatory commission (NRC) as a standard measure in USA for SA management since 1996 [2]. On most occasions, the IVR mitigation is to provide long-term water cooling on the outside wall of the RPV, so the decay heat is removed without the need for any active actions and assistance measurement during the SA [3]. Accordingly, it can be known that the external water cooling is the most important characteristic for accident management, as shown in Fig. 1. In traditional concept of IVR, the lower head (LH) of the RPV is assumed to be fully submerged into the water flooding, prior to the arrival of core debris on the inside [4]. Therefore, the melting pool is formed within the RPV with the temperature of approximate 1327 °C, while the temperature on the outer vessel wall is close to the water saturation temperature of around 150 °C [5]. With the basic assumption of critical heat flux

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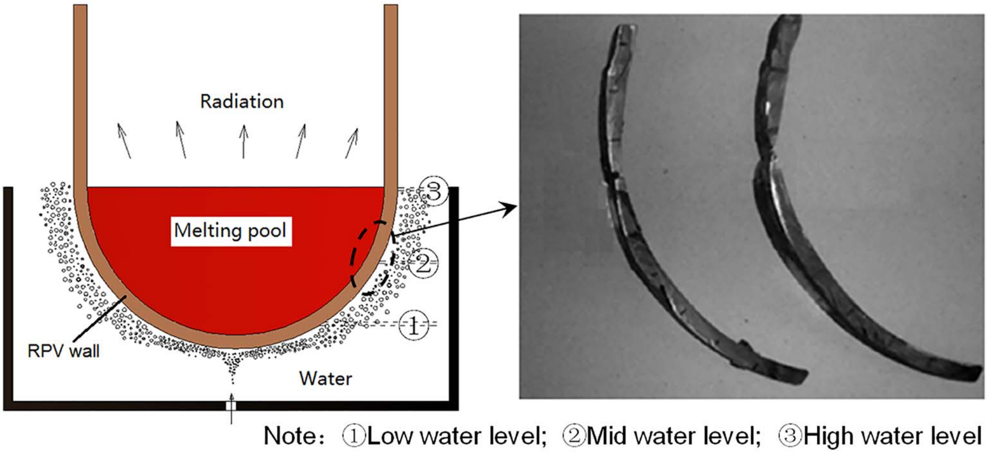

Fig. 1. The scheme of RPV with various water levels in severe accident and its typical failure segments [6,22].

(CHF) on the RPV during the accident period, it can be learnt from previous studies that the RPV safety can be secured within a prescribed time [6]. The above conventional IVR concept isn't seriously challenged until the Fukushima accident on 2011 [7]. It showed that the malfunction took place in the cooling water supply system, resulting in insufficiency of water supply. Furthermore, the consequence of the disaster indicated that the structural behavior had not been appropriately assessed [8]. Therefore, the related key issue is that whether LH structural integrity can be maintained with various cooling water levels under severe accident.

As indicated before, the structural safety is in the top priority for the operation of nuclear power plants, especially for the event of severe accident, so the IVR mitigation should be robust and capable of relieving the accident consequence. In most cases, the RPV integrity should be ensured during the first 72 h, while the operator may have sufficient time to take some emergence measures [9]. However, due to the complexity of the thermal-mechanical loadings, some of the failure mechanisms are not fully understood due to the low possibility of the occurrence [10,11]. In dealing with the issue of structural safety under SA, numerous efforts have been made by researchers and engineers. For the past several years, many geometrical scaled tests had been performed to characterize the failure site, time and mode of the RPV structure under the programs [12–17] of FOREVER, USNRC/SNL, LIVE and CORVIS. Under the loading of severe accident, one of 1:10 scaled test specimens can be seen in Fig. 1, and the LH failed at the site around the high water level. Besides, a number of finite element (FE) computations had been carried out for investigating the structural failure behaviors under the simulated thermal-mechanical loadings [18], like the loadings of critical heat flux (CHF) and low internal pressure. As indicated in previous studies [19,20], both experimental and theoretical results showed that the predictability of the failure time, site and mode varied with the field parameters, such as temperature, stress, strain. Due to core meltdown on the inside and external water cooling, the high temperature gradient is formed across the wall thickness. Consequently, it is found that creep damage accumulates over a wide area on the inside wall, while the local plastic damage is concentrated on the outside wall [21]. With the increase of creep time, both creep and plastic damages are increasing very significantly and interacted with each other at the site of geometric discontinuity [22]. As pointed out in some literatures [23,24], the CHF loading may be considered as a limit thermal boundary on the inside wall before the occurrence of melt-through, the failure process was found to be very complex, including wall bulge, thinning and even necking at the failure site. Moreover, the plastic and viscoplastic straining was the major contributors to the global or local failure. So far, the complete assessment on Fukushima accident had been submitted to the IAEA by Japan government, one of the critical issues was to answer whether the IVR mitigation takes effect or not [25]. Actually, the water cooling was the essential measure for ensuring the RPV integrity, as given in the report of the accident event. However, this kind of research on the effect of various water levels is scarcely found in the previous studies [26], especially for the era before Fukushima accident. The typical example of water levels is depicted in Fig. 1, indicating that the cooling water can be maintained at low, mid and high level respectively. Accordingly, the assumption of neglecting the water level effect on structural failure in traditional IVR concept is seriously challenged nowadays. In dealing with the above issue, the in-depth understanding of the RPV structural behavior is urgently necessary with the consideration of the effect of various water levels.

Therefore, the main task of the paper is to numerically investigate the RPV structural behaviors with the effect of various water levels under the severe accident of core meltdown, which is seldom concerned in previous studies. Toward this end, the 2D FE-models of the RPV with various water levels were developed on the platform of ABAQUS. In order to make a comparison, three typical water levels were employed in the analysis, including low, mid and high water levels. Due to the high temperature gradient across the wall thickness, the time- and temperature-dependent material properties were considered in the FEM, which were also highly nonlinear relationships for creep and plasticity. In accounting for the most dangerous situation before the melt-through, the critical heat flux (CHF) was regarded as the limit thermal boundary condition on the FEM. In order to make sure whether the RPV safety was maintained or not, the 100 creep h was taken as a basis for the FE calculation. Through vigorous investigation, it was found that the RPV safety can be secured within the 100 h, and the RPV structural failure took place at the site aside around the water level. Finally, the structural behaviors of the RPV with various water levels were analyzed carefully by means of field parameters, such as temperature, deformation, stress (strain) and damage. Most importantly, the phenomenon of deformation incompatibility and stress