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Ex-Vessel Steam Explosion Loads in Pressurized Water Reactors

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1. Introduction

In light water reactor core melt accidents, the molten fuel can be brought into contact with coolant water in the course of the melt relocation in-vessel and ex-vessel as well as in an accident mitigation action of water addition. The potential risk of explosive molten fuel coolant interactions (FCI, steam explosion) has drawn substantial attention in the safety analysis of reactor severe accidents. The steam explosion intensity is largely dependent upon the degree of volumetric fractions of melt droplets and steam in the fuel-coolant mixture. The rate of melt jet breakup and droplet sizes are, therefore, the key physical parameters in the analysis of FCIs.

In a recent OECD/NEA international program SERENA [1], FCI has been studied, in particular, on the status of code capabilities to predict FCI induced dynamic loading of the reactor structures, and identifying area where additional research may be needed to reduce the level of uncertainties in the code predictions. The first phase of SERENA project showed that the codes still cannot calculate all attributes with equal degree of precision. The predicted void fractions in the mixture are generally much higher than the data and are up to the level at which an energetic explosion is not likely, but the codes predict energetic explosion under such highly voided mixture. Currently the SERENA project is in the second phase with experimental as well as analytical work.

In this paper, ex-vessel steam explosion loads in PWRs calculated by the TRACER-II code, a four-field numerical model of fuel-coolant mixing and explosion propagation, are presented with an emphasis on the jet breakup modeling.

2. Computational Models and Results

2.1 TRACER-II Code

The TRACER-II code [2,3] has been developed for a comprehensive computational model for consistent simulation of the physical processes of mixing and propagation of vapor explosions. In developing the code, the experimental and analytical work in the past has been thoroughly reviewed with focus on the important constitutive relations representing the physics of vapor explosions. The mathematical model consists of the continuity, momentum, and energy conservation equations for multiphase flow that are coupled to the constitutive relations.

In the event that melt jet pours into coolant, it is postulated that the melt stream (jet) breaks up into droplets, and the droplets are dispersed into coolant liquid and the vapor film exists between the melt and the coolant liquid. When the triggering is applied, as a prescribed high pressure or high fragmentation rate in a cell in the present model, a shock wave propagates through the pre-mixture and the melt droplets are fragmented into fine debris and rapid heat transfer from melt to coolant occurs. The fragmented melt debris is assumed to become thermal and mechanical equilibrium with coolant liquid as soon as the fragments are generated.

For describing such physical events, the model includes five fluid fields; melt jet, melt droplets, liquid and vapor coolant, and fragmented melt debris. However, in the present model the combination of coolant liquid and melt debris are treated as one velocity field for simplicity.

In SERENA-I exercise, the melt jet and drops were treated as single fluid and this made it difficult to implement the unique feature of melt jet breakup. Also single melting point for melt solidification did not allow the melt status in the solidification interval bounded by liquidus and solidus temperatures. To improve these shortcomings, the following features were implemented in TRACER-II code.

(1) The melt jet fluid is separately modeled from melt drop.

(2) Melt jet breakup is modeled by Kelvin-Helmholtz instability for the jet surface [4,5] and by boundary layer stripping for the jet leading edge. The melt jet breakup rate and drop size are calculated based on the K-H model.

(3) Melt solidification is modeled by calculating melt temperature based on uniform distribution of the latent heat of fusion over the solidification interval between solidus temperature and liquidus temperature.

2.2 PWR Ex-Vessel Steam Explosion

The typical ex-vessel geometry for steam explosion analysis for PWRs is shown in Fig.1. The melt can be released at the bottom area of the reactor vessel lower head or at the side depending on the failure mode of the lower head. In this problem, it is assumed the melt is released at the center of lower head, which could be the case of ICI tube failure. The melt jet diameter is 0.3 m and the initial jet velocity is 4 m/s. The water pool is 3.6 m deep, 50 K subcooling in 2 bars of ambient pressure.

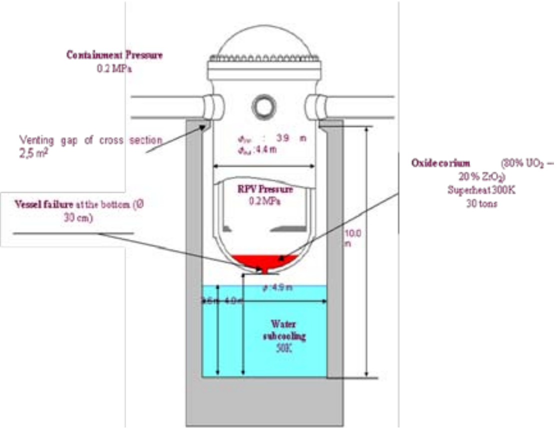

Fig. 1. Geometry of PWR Ex-Vessel Steam Explosion

The free fall height is 0.4 m, thus the distance from the lower head to the cavity floor is 4.0 m. The cavity is assumed to be circular cylinder with the diameter of 4.9 m. The geometry is axi-symmetrical in nature, thus axi-symmetry, two-dimensional (r, z) calculation has been carried out. The domain is divided into 8 radial meshes (Δr=0.3 m) and 40 axial meshes (Δz=0.1 m).

2.3 Mixing and Explosion Calculations

The 30 cm diameter corium jet was released from the reactor vessel, fell 0.4 m in the air and entered the 3.6 m deep water pool in the reactor cavity. The jet reached the cavity floor in 0.67 second.

The total jet mass entered during 0.67 second was 1335 kg and the mass of melt drops unsolidified, i.e., melt temperature was higher than the solidus temperature, was 69 kg. The melt mass changes are shown in Fig. 2.

It was assumed the explosion was triggered when the melt jet touched the floor. The triggering method was to set 15 MPa pressure in the first cell from the bottom. The explosion pressures in the center of melt mixture at various heights are shown in Fig. 3. The peak explosion pressure is around 20 MPa and ~2 MPa at the wall.

The impulses at the various locations of the cavity wall are shown in Fig. 4. The maximum impulse at 20 ms was about 30 kPa·s.

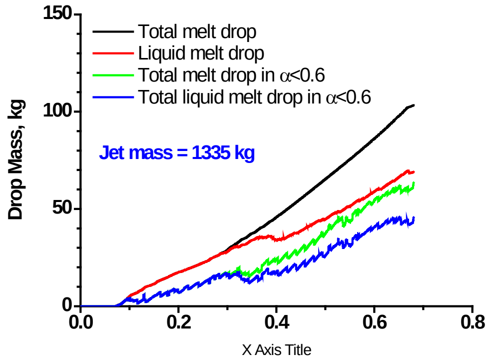

Fig. 2. Melt Leading Edge Positon

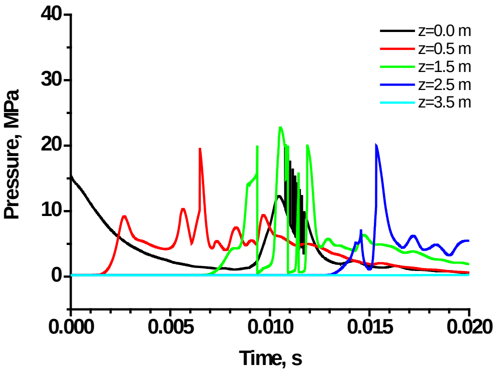

Fig. 3. Explosion Pressure Traces in the Mixture Center

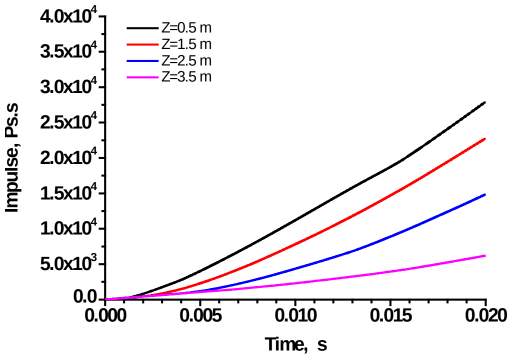

Fig. 4. Explosion Impulses at Cavity Wall

3. Conclusions

Ex-vessel steam explosion loads in PWRs were calculated using the TRACER-II code, a four-field numerical model of fuel-coolant mixing and explosion propagation. For 30 cm-diameter corium jet entering 0.4 m free fall and 3.6 m deep, 50 K subcooled water pool, the peak explosion pressure in the mixture was ~20 MPa and ~2 MPa at the wall. The maximum impulse at the cavity wall was ~30 kPa·s.

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