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Technical Note

PARAMETER DEPENDENCE OF STEAM EXPLOSION LOADS AND PROPOSAL OF A SIMPLE EVALUATION METHOD

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ABSTRACT

The energetic steam explosion caused by contact between the high temperature molten core and water is one of the phenomena that may threaten the integrity of the containment vessel during severe accidents of light water reactors (LWRs). We examined the dependence of steam explosion loads in a typical reactor cavity geometry on selected model parameters and initial/boundary conditions by using a steam explosion simulation code, JASMINE, developed at Japan Atomic Energy Agency (JAEA). Among the parameters, we put an emphasis on the water pool depth that has significance in terms of accident mitigation strategies including cavity flooding. The results showed a strong correlation between the load and the premixed mass, defined as the mass of the molten material in low void zones (void fraction < 0.75). The jet diameter and velocity that comprise the flow rate were the primary factors to determine the premixed mass and the load. The water pool depth also showed a significant impact. The energy conversion ratio based on the enthalpy in the premixed mass was in a narrow range ~4%. Based on this observation, we proposed a simplified method for evaluation of the steam explosion load. The results showed fair agreement with JASMINE.

1. Introduction

The fuel coolant interaction (FCI), including energetic steam explosions, is one of the phenomena that may threaten the integrity of the containment vessel during severe accidents of light water reactors (LWRs). Presently the focus is on the ex-vessel (outside the reactor vessel) cases due to the high possibility of having a deep subcooled water pool that is a condition favorable for a strong steam explosion [1]. One of the difficulties of handling this phenomenon in terms of risk assessment is that the scaling of its load between the laboratory (10^{-3}–10^{2} kg, simulant materials) and plant scales (10^{2}–10^{5} kg, UO_2 base oxides) is not straightforward, due to the complexity of the phenomenon. Therefore, knowledge and fundamental models of the mechanisms obtained through experiments have been integrated into computer codes that can be applied to plant scale analysis [2,3].

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JASMINE is a steam explosion simulation code developed at Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan [4] and presently available from the Organization for Economic Cooperation and Development, Nuclear Energy Agency (OECD/NEA) Databank. A steam explosion is simulated in two steps: the premixing and explosion stages. The triggering is assumed at a certain time by the user. A validation and application strategy for steam explosion codes in risk assessment was proposed by Moriyama and Nakamura [5]. Their method proposes: (1) tuning of the explosion model parameters so that it simulates steam explosion experiments with alumina well; (2) consideration of possible differences between alumina and UO_2-ZrO_2 based prototypic material (corium) in solidification and void generation behavior during the premixing phase; and (3) assuming that triggering happens at the time the "premixed mass" becomes the maximum. The "premixed mass" was defined as the mass of the molten corium in zones where the void fraction is < 0.75. They showed dependence of the steam explosion loads on the jet breakup model parameters, jet inlet diameter, and triggering time.

In this work, we used the JASMINE code and extended the work of Moriyama and Nakamura [5] by including more parameters in the initial condition with an emphasis on the water pool depth that is important from the view point of accident management with a flooded cavity. We followed the definition of premixed mass by Moriyama and Nakamura [5] as a representative index of the premixing condition. The calculations in this work used model parameter settings validated on FARO and KROTOS experimental data [3,4]. The validity of plant scale application of JASMINE was, to some extent, demonstrated by showing results consistent with many other codes in the OECD/SERENA program [3], a cooperative analytical study on steam explosions including both experimental and plant scale simulations.

We also proposed a simple method for evaluation of the steam explosion load based on the results of this parameter study and a simple evaluation method for premixing by Moriyama et al. [6].

2. Brief description of JASMINE modeling concept

The JASMINE [4] code has a three component melt model and a two-phase flow solver coupled explicitly. The code simulates the premixing and explosion stages of the steam explosion in a cylindrical two-dimensional domain. The melt model of JASMINE for the premixing stage consists of the following three parts. Modeling concepts and assumptions are briefly described for each: (1) melt jet: a coherent downward stream of melt along the central axis modeled by vertical one-dimensional Eulerian formulation; the heat transfer is neglected; thus, it is assumed always molten; (2) melt particles: molten droplets or solid particles generated by breakup of the jet modeled by Lagrangian grouped-particle concept; the breakup primarily occurs under water; it is the primary heat transfer bearer due to large surface area; and (3) melt pool: a continuous pool or solid body on the floor modeled by radial one-dimensional Eulerian formulation; it is produced by direct arrival of the jet or re-agglomeration of particles.

In the explosion simulation, the jet is converted into equivalent particles and the melt pool on the floor is neglected. Once an explosion is triggered by an assumed pressure pulse, the hydrodynamically induced fine fragmentation of molten droplets provides the rapid heat source that supports the shock wave propagation. Thus, the mass of the molten material (not solidified) in good contact with water, that is ready to be fragmented, is the primary factor to determine the magnitude of the explosion. The mass, available for the energy conversion in the explosion phase, was named "premixed mass" and defined as the mass of molten particles and jet located in low void fraction (< 0.75) zones. For clarity, the three categories of melt mass are defined as: (1) total mass: all the melt mass in the system; (2) molten (jet and particles) mass: mass of the melt material at temperatures above the melting point (average of the liquidus and solidus point; the melt pool is eliminated); and (3) premixed mass: the molten mass staying in low void fraction zones (void fraction < 0.75). Important constitutive models include the melt jet breakup model based on empirical correlations for the breakup length, film boiling and radiation heat transfer for the melt particles, and fine fragmentation and rapid heat release models in the explosion. A description of the modeling details is available elsewhere [4].

3. Analysis condition assuming a typical pressurized water reactor (PWR) geometry

A typical reactor cavity geometry for pressurized water reactors (PWRs) used in OECD/SERENA Phase-I Task-4 [3] was referred to and modeled as shown in Fig. 1. The conditions for the analyses are summarized in Table 1. The melt material

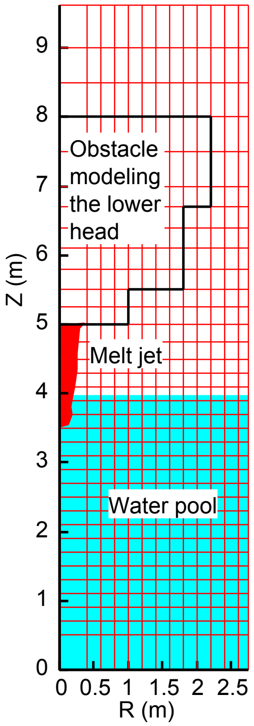

Fig. 1 – JASMINE analysis grid based on a typical PWR cavity geometry used in SERENA Phase I program [3]. PWR, pressurized water reactor.