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Development and verification of molten corium–concrete interaction code

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ABSTRACT

During a severe accident of Pressurized Water Reactor(PWR), the core materials was heated, melt located on the lower head of Reactor Pressure Vessel(RPV). With the temperature rise, the corium will melt through the lower head and discharge into the reactor cavity. Those corium will interact with the concrete and damage the integrity of the containment, so some coolability method should used to quench the corium. In order to investigate the progress of MCCI, a MCCI analysis code, that is MOCO, was developed. The MOCO includes the heat transfer behavior in axial and radial directions from the molten corium to the basemat and sidewall concrete, crust generation and growth, and coolability mechanisms reveal the concrete erosion and gas release, which are important for the interaction process. Cavity ablation depth, melt temperature, and gas release are the key parameters in the interaction research. The physical-chemistry reaction is also involved in MOCO code. In the present paper, the related MCCI experiment data were used to verify the models of the MOCO and the calculation results of MOCO were also compared with other MCCI analysis codes.

1. Introduction

In a severe accident event in a Light Water Reactor, corium, a mixture of molten materials issued from the fuel, cladding and structural elements, appears in the reactor core. In some series of severe accidents, corium is assumed to penetrate through the reactor pressure vessel and spread over the concrete basemat. Molten Corium Concrete Interaction (MCCI) then occurs, characterized by concrete ablation. During the interaction between molten corium and concrete, the molten materials are maintained at high temperature by decay heat from fission products retained in the melt and the chemical heat from the exothermal reaction. The temperature and heat fluxes involved are sufficient to decompose and ablate concrete (Alarcon-Ruizet et al., 2005; Khoury, 2000). The containment failure would occur if the basemat concrete is penetrated. Besides, a large amount of water vapor and carbon dioxide produced with the decomposition of concrete, which can react with metals and produce hydrogen and carbon monoxide, can lead to the overpressurization of containment. Hydrogen and carbon monoxide are also combustible gases, giving an additional risk of sudden overpressurization if they are ignited. Radioactive aerosols that evolve during core debris interactions can enhance radiological consequences of containment failure. Therefore a study on MCCI, which considers heat transfer mechanisms between molten corium and concrete determining the concrete ablation rate, and melt pool temperature, cooling from top flooding that determining the heat removal from the coolant (Fig. 1.), and chemical reactions that determining the noncondensible/combustible gas generation and aerosol release rate, is needed for safety assessment under severe accidents.

Various experimental and theoretical investigations have been conducted to understand the phenomena about MCCI. Large-scale or small-scale experiments were performed in many laboratories, and detailed computer codes were developed to simulate the MCCI phenomena. Many experiments were conducted in 1970–1990 at Sandia Nat. Lab.-SS, SWISS, SURC, HOT SOLID. (Powers and Arellano, 1981; Cronager et al., 1986) These tests mainly analyzed the behavior of concrete during the ablation process, the release of fission products, and also the ablation kinetics. Recent experiments on MCCI mainly address two subjects: the 2D aspects of the ablation and crust formation and melt segregation. Such as CCI (Farmer et al., 2005, 2006), VULCANO (Journeau et al., 2007), COMET-L (Alsmeyer et al., 2005). Several numerical methods have been

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Nomenclature

C	specific heat (J/kg)
m	mass (kg)
j	velocity (m/s)
r	reaction energy (kJ/mole)
x	distance (m)
h	heat transfer coefficient (W/m^2 K)
e	specific enthalpy (J/kg)
k	thermal conductivity (W/(m K))
d	thickness (cm)
g	gravity constant (m/s^2)
E	energy (J)
L_λ	Laplace constant
P	system pressure (Pa)
Q	heat energy (J)
T	temperature (K)
q	heat flux (J/m^2 s)
k_{ent}	melt entrainment coefficient
G	weight (N)
F	mechanical strength (N)
N	hole site density
t	time (s)

Greek letters

σ	surface tension (kg/m^2)
μ	viscosity (kg/m s)
φ	enhancement factor
η	ablation depth (cm)
ρ	density (kg/m^3)
ν	gas velocity (cm/s)
ε	crust permeability

developed to simulate molten core concrete interaction and are used in safety studies to calculate the reactor cavity behavior during severe accident: CORCON (Bradley et al., 1993), COSACO (Nie et al., 2002), WECHSL (Reimann, 1987),TOLBIAC-ICB (Spindler et al., 2006) and ASTEC/MEDICIS (Cranga et al., 2005). It is well known that the calculation results of one-dimensional concrete ablation model predict well with the experimental results of SWISS (Blose et al.) and SURC (Copus et al., 1992) although the model cannot calculate the local ablation differences. And melt temperature history with time has been predicted exactly. But it is observed that large differences exist among the various experimental data and computer code calculations. Many efforts have attempted to increase the basic understanding of the unique heat and mass transfer processes that occur at the interface between corium and water when a corium–concrete interaction is flooded. A simple parametric core-concrete interaction code was developed for direct comparison with experimental results to provide a framework for assessing the ability of these models to adequately capture the corium cooling behavior.

The purpose of this work is to develop an analysis code, MOCO, to understand the physical phenomena of MCCI during severe accidents. Compared with experimental data, the calculation results showed a reasonable agreement with the melt temperature, concrete ablation depth, and gas generation rate.

The MOCO code considers the heat transfer behavior in axial and radial directions from the molten pool to the basemat and sidewall concrete, crust generation and growth, thermal stresses built-in the crust, disintegration of crust into debris by brittle fracture, natural convection heat transfer in debris, water ingression into the debris bed, and the gas release from the decomposed concrete. Calculation results are compared with corresponding experimental reports of MACE and CCI test series.

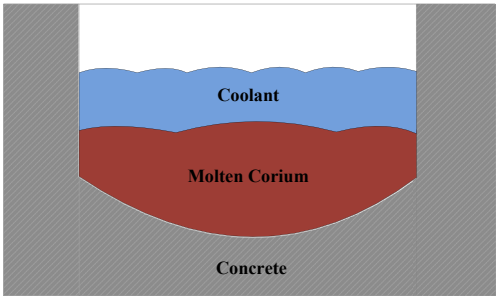

Fig. 1. Top flooding for achieving coolability.

2. Physical and chemical models

2.1. Conservation equations

The basic mass and energy conservation equations are solved to calculate the Molten Corium Concrete Interaction process. The mass conservation equation in the molten corium area can be written as:

$$\frac{\partial m}{\partial t} = \frac{\partial m_{side}}{\partial t} + \frac{\partial m_{basemat}}{\partial t} + \frac{\partial m_{core}}{\partial t} + m_{add} \tag{1}$$

where m_{side} and $m_{basemat}$ denote the mass from sidewall and basemat concrete to the corium area, respectively. m_{core} is the mass discharged from the lower head. m_{add} is the mass as the volume change for the concrete ablation.

Six heat source/sinks are considered in the energy conservation equation would consider in the code. The main heat source is the decay heat from the fission products. The others are heat from melt discharged from the failure RPV, chemical reactions between metallic melt constituents and concrete decomposition gases H_2O, CO_2, condensed phase chemical reactions between Zr and SiO_2, heat transfer to concrete, including slag heat sink, and heat transfer to overlying atmosphere. The energy conservation equation in the molten corium area can be written as:

$$\frac{\partial \mathrm{E}}{\partial t} = -Q_m + Q_{dec} + Q_{ht} + E_{ox} + E_{de} - Q_c - Q_{ent} + Q_{rpv} + Q_{add} \tag{2}$$

Where Q_m is the energy due to the change of corium mass, Q_{dec} is the decay heat, Q_{ht} is the heat transfer between corium and other parts.,E_{ox} is the oxidation heat in the corium, E_{de} is the decomposition heat from the concrete, Q_c is the heat transferred to the crust.,Q_{ent} is the entrainment heat from the corium to the upper crust, Q_{rpv} is the heat from the mass from RPV, Q_{add} is the additional energy due to error from the mass calculation.

In real reactor conditions, the melt composition can range from fully metallic to fully oxidic while those two phases are assumed to be well mixed in this code.

The mass conservation considers most core, concrete metals and their corresponding oxides. Besides, the conservation of mass equations for the crusts and the particle bed are solved in separate ways, and then the material properties can be evaluated on the basis of the actual compositions in different layers.