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Model comparisons on molten core-concrete interactions

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Abstract Based on the plant model of 600-MW PWR, the molten core-concrete interactions (MCCI) under different models are studied. Station blackout (SBO) with steam-driven auxiliary feed water pump failure is selected as the case for the model comparisons analysis. The result shows that thermal resistance model between debris and concrete has much influence on the consequence of MCCI. The concrete erosion rate calculated with gas film model is much higher than that of slag film model. Some other model comparisons such as the chemical reaction heat and the configuration molten pool are also discussed.

Key words Severe accident, Molten core-concrete interactions, Concrete ablation rate, Thermal resistance

1 Introduction

In a postulated core melt accident of PWR, if the molten core is not retained in-vessel despite taking severe accident mitigation actions, the core debris will be relocated to the reactor cavity. Then the molten core will interact with the concrete basement, which would be molten by the heat transferred from hot corium, resulting in the containment failure through erosion[1]. The main problem having to be addressed is whether and when the corium will make its way through the basemat, since it would give rise to a failure of the containment. Although the molten core-concrete interactions (MCCI) have been investigated extensively, the uncertainties concerning for instance the lateral and axial ablation rates[2] remain to be resolved.

It is difficult to develop an accurate heat transfer model, because of the complexity of heat transfer problems associated with MCCI, the difficulties in conducting experiments with real reactor materials, and the lack of accurate material properties. However, a conservative estimation can be made by assuming that all the heat from the molten corium goes into the concrete. Measurements against such consequences can hardly be implemented in a nuclear power plant power plant. Therefore, reliable analyses on the erosion process are required.

In this paper, based on analysis of a severe accident sequence of station blackout (SBO) with steam-driven auxiliary feed water pump failure, the concrete ablation rate and hydrogen generation rate are achieved by a systematic code for severe accidents. Some effect elements such as thermal resistance model between debris and concrete, and the chemical reaction heat include or exclude the oxides as reactants, the configuration of debris layer take much effect on concrete ablation rate.

2 Model descriptions

2.1 Plant model

The plant model for a 600-MW PWR NPP is developed with a systematic code for severe accidents. Fig.1 is the nodalization diagram for a 600-MW PWR NPP. It contains two primary loops, the secondary system, safety injection system and auxiliary systems. The primary loops contain reactor pressure vessel, pressurizer, reactor coolant pumps and steam generators. The secondary system contains turbines and main steam pipes. The safety injection system contains two accumulators.

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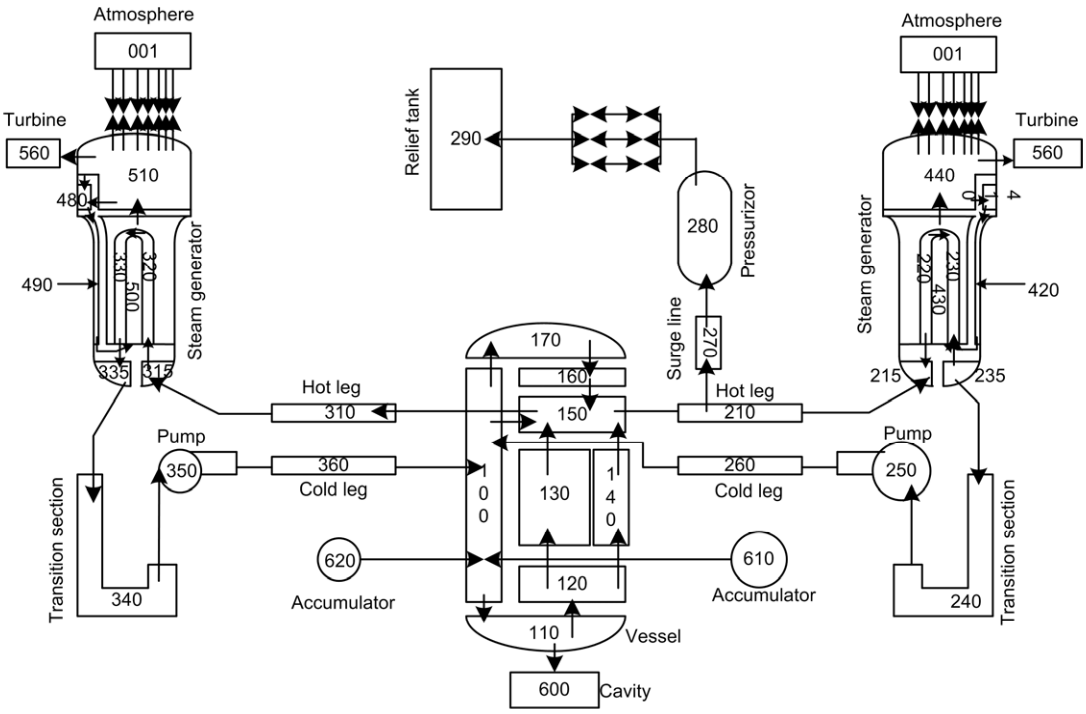

Fig.1 Nodalization of the 600-MW PWR NPP.

2.2 Cavity model

Nuclear reactor core consists of uranium dioxide rod with zirconium cladding and steel structures (carbon steel and stainless steel). At high temperatures zirconium is oxidized by water vapor, so the main constituents of corium are UO_2, ZrO_2, Zr, Fe, Cr and Ni. In an accident, the core melts would drop into the cavity, causing the reaction of molten core with concrete.

A layer of solid corium crust may exist at the core-concrete interface. There are two models of the thermal resistance which will be described in detail in Section 2.

The oxides in corium and concrete are miscible with each other, but the metallic species are immiscible with the oxides. Because the metals are lighter than the corium oxides, a metallic layer can be formed on the surface of oxide pool. When concrete oxides are added to the melt, its density eventually becomes smaller than the density of metals. Then, the metallic layer may be relocated to the pool bottom. On the other hand, intense stirring of the pool by rising gas bubbles may cause the metals and oxides to be mixed with each other.

The corium is continuously heated by the radioactive decay of the fission products in the melt. Another heat source is the chemical reaction heat. The most important chemical reaction in the pool is the oxidation of metals by the concrete decomposition gases.

2.3 Initial conditions

Major parameters of the 600-MW PWR are listed in Table 1. Typical composition of concrete is: SiO_2 65.65%, CaO 11.98%, Al_2O_3 7.82%, K_2O 2.71%, Na_2O 1.35%, Fe_2O_3 1.19% and H_2O 9.30%.

Table 1 Main parameters of a 600-MW PWR NPP

Parameters	Values
Core thermal power / MW	1,930
Average coolant temperature / K	583.15
Pressurizer pressure / MPa	15.5
Mass of UO_2 in the core region / kg	63,133
Mass of Zr cladding in the core region / kg	15,810
Containment free volume / m^3	~50,640
Containment pressure and temperature / $MPa \cdot K^{-1}$	0.1/300
Thickness of the basemat and the sidewall	4 m /2.17 m

2.4 Accident sequence selection

Because numerous severe accident sequences could lead to MCCI, it is unpractical and unnecessary to calculate all the postulated conditions, and typical accident sequences should be screened out. Given a reference to the sequence selection criteria in 10 CFR 50.54(f) of U.S. Nuclear Regulatory Commission, on the basis of the reference plant's level 1 probabilistic safety assessment (PSA), station blackout (SBO) is selected as the base case for the model comparisons.

3 Model comparison of MCCI

3.1 Thermal resistance between debris and concrete

The rate of concrete ablation is controlled by the heat transfer from the melt to concrete. A layer of solid corium crust may also exist at the molten core-concrete interface. There are two thermal resistance models. One is the gas film model, which assumed that gas released from the decomposing concrete was sufficient to form a stable gas film between the debris pool and the concrete. The other is the slag film model, which deemed intermittent debris-concrete contact occurs and results in periodic growth and removal of slag from the interface.

The superficial gas velocity is a key parameter that affects heat transfer of the interfacial of the melt/concrete. Under the gas film model, the bubble-enhanced heat transfer is the dominant heat transfer mode for the MCCI. The following equation is recommended by Greene for the bubbling heat transfer coefficient h ($\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$)[3]:

$$h = 0.28\ k^{2/3}\ g^{1/3}\ C_\mathrm{p}^{\ 1/3}\ \rho^{2/3}\ j_\mathrm{g}^{\ 0.22}\ \mu^{-1/3} \tag{1}$$

where j_g=volumetric gas flux/area=superficial gas velocity, and μ is dynamic viscosity, k is heat conductivity coefficient, C_p is specific heat capacity, ρ is molten pool density. The same correlation can be applied for both the horizontal and the vertical surfaces.

The free convection heat transfer coefficient to a vertical wall can be calculated from Eq.(2):

$$Nu = \left[0.825 + \frac{0.387\,Ra^{1/6}}{[1+(0.492/\mathrm{Pr})^{9/16}]^{8/27}}\right]^2 \tag{2}$$

where $\mathrm{Pr} = C_\mathrm{p}\mu/k$ for the molten pool.

While in the slag film model[4], a modified version of the Kutateladze correlation is used for bubbling heat transfer coefficient h ($\mathrm{W/m^2K}$):

$$h = \frac{1.6\times10^{-7}\sigma^2 h_1 + j_\mathrm{g}^{\ 2}\mu^2 h_2}{1.6\times10^{-7}\sigma^2 + j_\mathrm{g}^{\ 2}\mu^2} \tag{3}$$

$$h_1 = 1.5\times10^{-5}\frac{k^{1/3}}{g^{1/6}}(c_\mathrm{p}p)^{2/3}(\rho-\rho_\mathrm{g})^{1/2} j_\mathrm{g}^{\ 2/3} \tag{4}$$

$$h_2 = 3\times10^{-5}\frac{k^{1/3}}{g^{1/6}}(c_\mathrm{p}p)^{2/3}(\rho-\rho_\mathrm{g})^{1/2} j_\mathrm{g}^{\ 1/6}\mu^{-1/2} \tag{5}$$

where p is the pressure, ρ_g is the density of gas in the bubbles and σ is the surface tension. Eq.(3) is used for downwards heat transfer. Because of the high viscosities of the oxidic corium melts, h_2 usually has more weight in the weighted average of Eq.(2). For radial heat transfer, Eq.(4) is used.

The gas film model and slag film model can be selected for the melt/concrete interface at the bottom and radial surface of the debris. Comparing the axial and radial concrete ablation depth under different models (Figs.2 and 3), one sees that the radial ablation of the concrete is similar to the axial ablation. Under the gas + gas model, it ablates about 30% more than that of slag + slag model in 83.3 h. At the beginning 24 h of MCCI, the ablation rate is fast and the two different modes are similar. With different thermal resistance model, the heat flux transferred to the concrete is different which cause the ablation rate different. The trend of hydrogen production is similar to that shown in Fig.4.

The superficial gas velocity is a key parameter that effects heat transfer of the interfacial of the melt and concrete. Kutateladze and Malenkov suggests that only at relative high superficial gas velocity can it form a stable gas film[5]. And under the postulated severe accident sequence, superficial gas velocity is much lower and can't form a stable gas film. Therefore, the concrete ablation rate and hydrogen generation rate are over-evaluated with the gas film model.

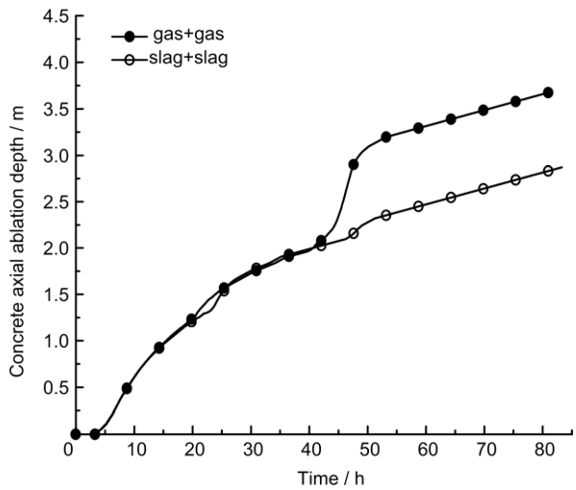

Fig.2 Axial ablation depth under different thermal resistance models.

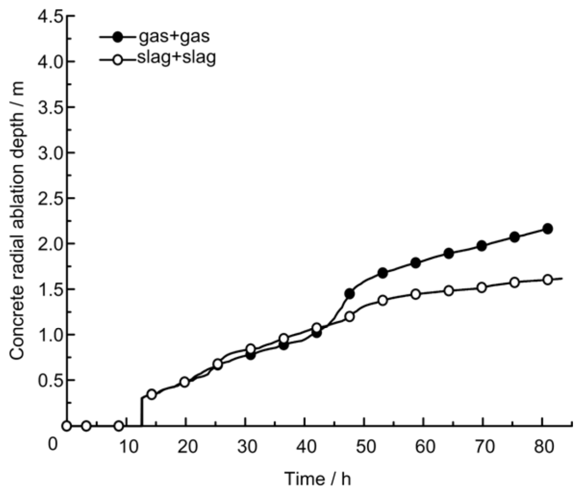

Fig.3 Radial ablation depths at different thermal resistances.

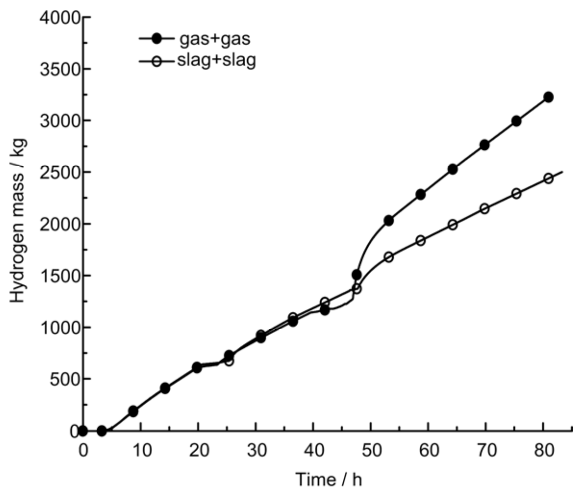

Fig.4 Hydrogen generation under different thermal resistance models.

3.2 Chemical reaction heat

The molten core-concrete interaction is driven primarily by decay heat power generated within the debris pool, with heat from oxidation reactions. The main chemical reactions should be considered as following:

(1) $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + 6.3\ MJ \cdot kg^{-1}$
(2) $Zr + 2CO_2 \rightarrow ZrO_2 + 2CO + 5.7\ MJ \cdot kg^{-1}$
(3) $2Cr + 3H_2O \rightarrow Cr_2O_3 + 3H2 + 3.6\ MJ \cdot kg^{-1}$
(4) $2Cr + 3CO_2 \rightarrow Cr_2O_3 + 3CO + 2.8\ MJ \cdot kg^{-1}$
(5) $Fe + H_2O + 3.0\ kJ \cdot kg^{-1} \rightarrow FeO + H_2$
(6) $Fe + CO_2 + 480\ kJ \cdot kg^{-1} \rightarrow FeO + CO$

Also the reduction of SiO_2 and Fe_2O_3 by zirconium plays an important role:

(1) $Zr+2SiO_2+4.7\ MJ \cdot kg^{-1}Zr \rightarrow ZrO_2+2SiO(g)$ (T > 1870℃)
(2) $Zr+SiO_2 \rightarrow ZrO_2+Si+1.6\ MJ \cdot kg^{-1}Zr$ (T < 1870℃)
(3) $3Zr + 2Fe_2O_3 \rightarrow 3ZrO_2 + 4Fe + 5.8\ MJ \cdot kg^{-1}Zr$

The comparisons of concrete ablation depth and hydrogen generation with and without oxides (SiO_2 and Fe_2O_3) from concrete decomposition as reactants are shown in Figs.5 and 6. The ablation depth and hydrogen production without oxides from concrete decomposition as reactants are about 15–30% and 50% less than that of including the reactions, because the chemical reaction heat from the reaction of oxides and zirconium is an important part of heat to ablate the concrete, which should be considered in accident analysis. In SURC-4 experiment[5], a vigorous interaction was observed between metallic zirconium and a siliceous concrete with low gas content.

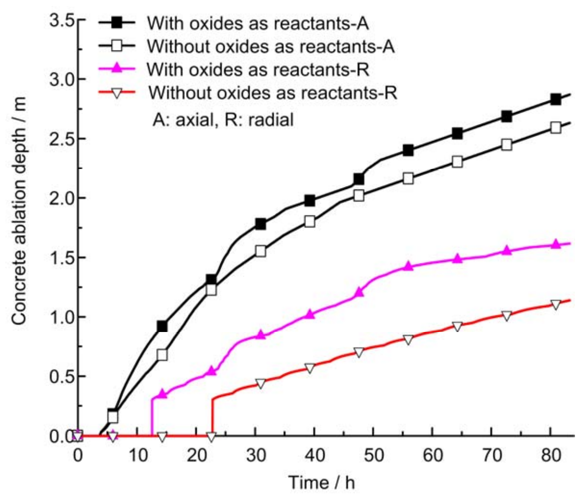

Fig.5 Concrete ablation depths with or without oxides as reactants.

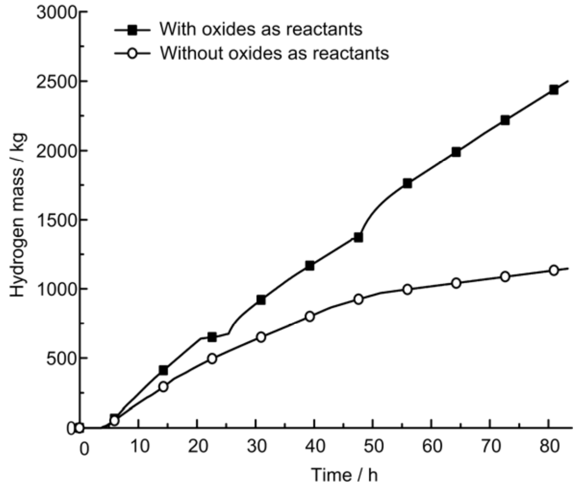

Fig.6 Hydrogen generation with and without oxides as reactants.

Fig.7 is the heat to the concrete with and without oxides from concrete decomposition as reactants. With the oxides as reactants, the decay heat is higher. When the temperature of molten pool is lower than 1870℃, the oxide-zirconium reaction releases quantity of heat, which has some fluctuations, causing the ablation more severe.

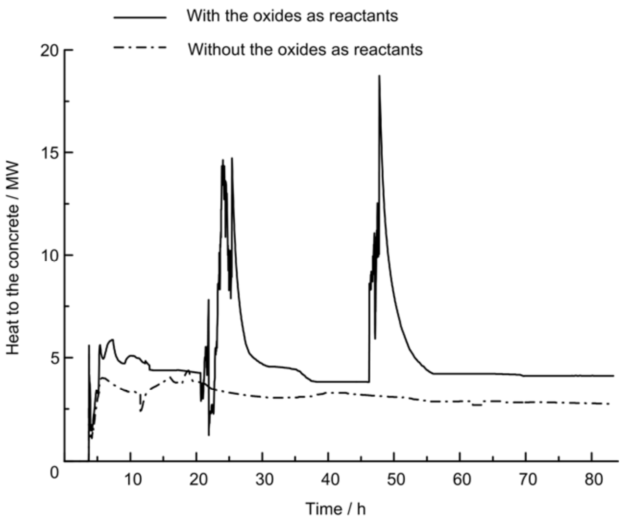

Fig.7 Heat to concrete with and without oxides as reactants in SBO sequence.

3.3 The configuration of debris layer

The configuration of the debris may be fully mixed or stratified. Enforced mixing is the simplest mode, with the debris always considered to form a single layer. The most general structure of the enforced stratification mode is a three-layer configuration, with light oxide layer (LOX), over a metallic layer (MET), over a heavy oxide layer (HOX) stayed at the bottom. The comparison of axial ablation depth of the two models is shown in Fig.8. It seems that the ablation of the concrete is quite different. Before 15 h, the ablation rate is about 6.0–12.0 cm/h under mixing mode, while under stratification mode, the ablation rate is about 3.4–6.8 cm/h, which is 40% less than that of mixing mode.

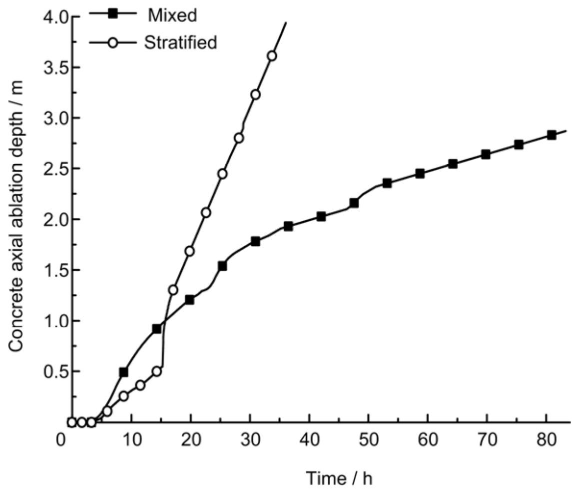

Fig.8 Axial ablation depth comparison under mixed or stratified molten pool.

But at 15 h, associating with acute chemical reaction heat, the configuration of the debris changed and the concrete ablates rapid. Because of oxides from the concrete decomposition ingression into the heavy oxide layer, the density of heavy oxide layer became light. The temperature of molten pool dropped from 2140 K to 1852 K (Fig.9). Because the reaction between oxides (such as SiO_2) and metals released a large mount of heat, the concrete ablates very fast. After that, the metallic layer falls to the bottom and the concrete ablates even faster than the mixed mode for its good thermal conductivity. The ablation rate is about 13.7 cm/h under stratification mode, much higher than that of the mixing mode.

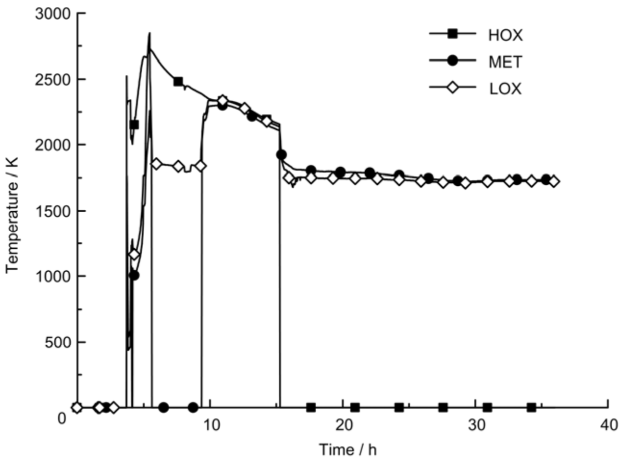

Fig.9 Temperatures of the layers in the stratified molten pool.

4 Conclusion

One severe accident sequence induced by station blackout (SBO) with the steam driven auxiliary feed water pump failure is analyzed for a 600-MW PWR NPP. The analysis is focused on the model comparison with the ablation rate and depth and the hydrogen production in MCCI scenario to illustrate which model is more suitable to the safety analysis.

Different thermal resistance model has much influence on the consequence of MCCI. The concrete erosion rate calculated with gas plus gas film model is much higher than that of slag plus slag film model, which means that gas film model enhances the heat transfer from molten core to the concrete, which has small thermal resistance. The oxides as reactants must be considered because amount of heat is generated. The configuration of molten pool has much influence, too, on the ablation rate and hydrogen production.

Therefore, from the view of safety analysis, these influence factors should be considered to gain conservative results.

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