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Effect of Molten Steel on CDA Energetics

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1. Introduction

Containment of severe accidents in the primary system boundary is a design goal in most of the SFR design in the context of risk minimization. The reactor vessel and primary system boundary is designed, therefore, to resist certain amount of the energy load generated during the core disruptive accidents (CDAs). It would be necessary first to estimate the CDA energetics to assess the integrity of the reactor vessel and its internal structures.

In this study, equation of state(EOS) for the vapor pressure of the fuel-steel mixture was developed to investigate the effect of the molten steel structure on the energetics of severe accidents. A set of core disassembly analyses was then performed for the sodium-voided core of the KALIMER-150 design [1] using the VENUS-II code [2] for the various reactivity insertion rate up to 100 $/s.

2. Vapor Pressure of Fuel-Steel Mixture

It is known that a eutectic reaction begins to occur between molten uranium and steel at around 1,000 K and becomes significant at 1,400 K or so [3,4] In the core disruptive accidents, such as driven by the loss of flow accidents, molten fuel may liquefy the solid steel clad or structure. The behavior of the molten mixture of the fuel and steel will be different with that of the molten fuel during the accidents. The equation of state of vapor pressure is developed for the mixture of molten fuel and steel in this study to get an initial idea on the impact of the steel on the CDA energetics.

Regarding the U-Pu-Zr alloy, no experimental data is currently available but an EOS was developed based on general theoretical models. Using the principle of corresponding states (PCS) method, Joseph *et al.* [5] developed the following expression of vapor pressure for the metallic alloy (70% U, 20 % Pu and 10 % Zr, by wt.%),

$$\log P = 8.58 - 22{,}379/T - 0.946 \log T \quad (1)$$

where pressure is in MPa and temperature is in K.

The vapor pressure of the molten steel (SS316) is given by [6],

$$\log P = 11.1183 - 18{,}868/T \quad (2)$$

where pressure is in MPa and temperature in Kelvin, respectively. As was done for the fuel alloy, the vapor pressure of SS316 was calculated using the data of the elements of iron, chrome and nickel listed in Reference 7 to cross-check Equation (2). It was assumed for simplicity that the SS316 steel is composed of 80 % of iron, 18 % chrome and 12 % nickel by weight fraction. The result was that Equation (2) predicted pressure in fair agreement with the values calculated from elemental data.

The vapor pressure of the molten mixture of U-Pu-Zr alloy and steel was subsequently developed using Eq.(1) and Eq.(2) in accordance with their mole fractions. Figure 1 shows vapor pressure of the mixture of 80 wt %-fuel and 20 wt %-steel, which is the characteristic value of the driver fuel pins of the KALIMER-150 design. The curves of the fuel alloy and SS316 are also shown in the figure, for the purpose of comparison.

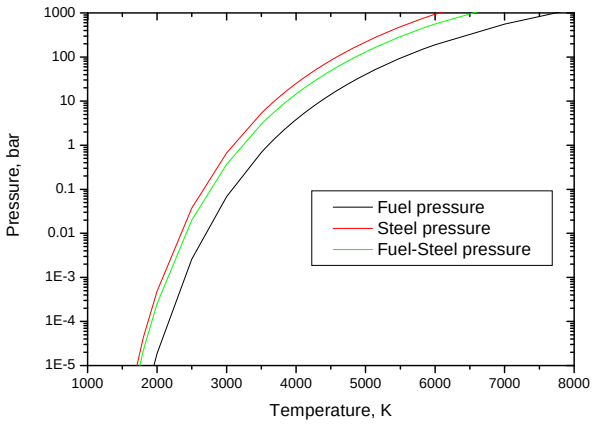

Fig.1. Vapor Pressure vs. Temperature of Fuel-Steel Mixture

3. Analysis Results

Figure 2 shows the reactivity changes above prompt critical during the power excursions induced by the

reactivity insertion at the rate of 100/s (, indicated by green line in the figure). Solid lines represent the reactivities resulting from the use of Equation (1), that is, the equation of state of the U-Pu-Zr fuel. Meanwhile, the dotted lines are the results obtained using the relationship of pressure and temperature for the fuel-steel mixture, as described in Section 2.

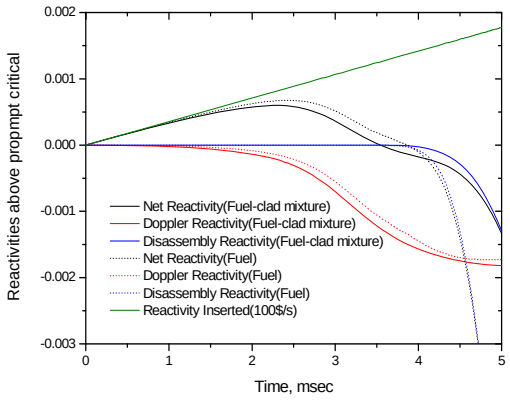

Fig.2. Reactivity changes during power excursions induced by reactivity insertion at the rate of 100/s

We can see in Figure 2 that the Doppler reactivity feedback effect of the fuel-steel mixture is smaller so that the net reactivity is pushed up higher than that of fuel alloy. This is due to the difference in the heat capacities between the fuel and the mixture. Given the change in internal energy, temperature change is inversely proportional to the heat capacity of a material. The heat capacity of the fuel-steel mixture is estimated to be 1.7 times larger than that of the fuel alloy, so that the change in temperature is that much less than that of the fuel alloy. The Doppler effect is in general inversely proportional the square root of the temperature of the metal fuel. Consequently, the Doppler effect in the mixture is smaller than that in the fuel alloy.

Given the temperature of the fuel or the mixture, in the mean time, pressure rises faster in the mixture than in the fuel, as shown in Figure 2. This makes the disassembly reactivity feedback in the mixture larger than that in the fuel, particularly at the later phase of the power excursion. As a result, the power excursion is terminated earlier. For the mixture, core power reaches its maximum at 6,660 Gw and energy released amounts to 10,300 MJ, which are about two times larger than those for the fuel.

4. Conclusion

The equation of state of vapor pressure is developed for the mixture of molten fuel and steel in this study to investigate the impact of the steel on the CDA energetics. Using the EOS of the mixture in the VENUS calculations resulted in more rapid power rise and larger energy release than the case for the fuel alloy. This is due mainly to the specific heat of the steel larger than that of the fuel alloy. For a change of the internal energy, the temperature change of the mixture is less than that of the fuel alloy, reducing the Doppler reactivity feedback. Consequently, the power rise is greater in the mixture than in the fuel alloy.

Acknowledgements

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