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Evaluation of the Layer Inversion of Melt Pool during the Severe Accident in the APR1400

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1. Introduction

During the severe accidents, thermal load from the oxidic pool can be concentrated on the side wall of the RPV due to the thermal barrier effect in the thin metallic layer. The focusing effect of the metallic layer is mainly determined by the molten pool configuration in the lower head of the RPV. Therefore, for the precise evaluations on the coolability through the in-vessel retention of corium during the severe accident, the melt pool configuration should be accurately defined. The melt pool configurations inside the lower head of the reactor vessel affect the initial thermal load to the vessel and play a key role in determining the integrity of the reactor vessel.

In this study, thermodynamic analyses were performed to examine the final melt pool configuration during the severe accidents in the APR1400. As the representative accident scenarios, Large Break Loss of Coolant Accident (LBLOCA), Medium Break Loss of Coolant Accident (MBLOCA), Station Black Out (SBO), and Total Loss of Feed Water (TLFW) were considered. The initial melt pool conditions, such as melt mass and melt pool temperature etc., were calculated using the SCDAP/RELAP5/MOD3.3 code for each accident scenario of the APR1400. The thermodynamic analyses were performed using the GEMINI code [1]. Combined with the GEMINI code calculations and the peer review on the RASPLAV/ MASCA experimental results, the final melt pool configuration in case of MBLOCA sequence was determined as a first step. Based on the thermodynamic analyses for the melt pool compositions, the possibility of the layer inversion between the oxidic pool and the metallic layer was examined.

2. Layer Inversion Phenomena

In general, a two-layer melt pool with a light metallic layer of Fe-Zr on top of oxidic pool was assumed to be a bounding melt configuration in the analyses for the severe accidents. The experimental results of the OECD MASCA, however, have shown that when a sufficient amount of non-oxidized zirconium (Zr) is available, then metallic uranium (U) migrates to the metallic layer. The transfer of species between the U, O, Zr melt and the steel can result in a significant density increase of the metallic phase. The density increase of the metallic phase can lead to inverse stratification with an additional heavy metal layer below the oxidic pool. The presence of the metallic layer at the bottom of the lower head is likely to decrease the thickness of the top metallic layer and consequently to increase the risk of the focusing effect.

The density increase of the metallic phase is due to dissolution of uranium into the metallic phase. The thermo- dynamic calculations are aimed at determining the composition of a U-Zr-Fe-O mixture at thermodynamic equilibrium for a given temperature. The results of these calculations mainly depend on the U/Zr ratio, the Zr oxidation fraction, the mass of UO_2 and the mass of steel [3]. The less Zr is oxidized, the higher the mass of metal that can stratify below the oxidic pool. For a given mass of UO_2, when the mass of metallic Zr increases then it favors the dissolution of UO_2 and the transfer of metallic uranium in the steel layer. This leads to a significant increase of the mass of the steel. The temperature increase of corium contributes to the preferential dedensification of the metallic phase due to its strong thermal expansion. At higher temperatures above 3100 K, this phenomenon is partially balanced by the evaporation of iron and nickel. And B_4C leads to a slight dedensification of the metallic phase since it preferentially associates with metallic Zr, consequently reducing the Zr amount available for the UO_2 reduction. According to the previous finding, the temperature and additive B_4C material finally have a low impact on the steel mass that can stratify below the oxidic pool.

3. Thermodynamic Analysis using GEMINI Code

The thermodynamic analyses were performed using the GEMINI code. For a given temperature, the compositions of a U-Zr-Fe-O mixture were determined under the thermodynamic equilibrium conditions. Combined with the GEMINI code calculations and the peer review on the RASPLAV/MASCA experimental results, the final melt pool configurations were determined for the major accident scenarios of the APR1400.

The GEMINI code is a software which is capable of calculating the thermodynamic equilibrium states of a mixture for a given temperature using a thermodynamic database for the corium, NUCLEA07. Equilibrium of a mixture is established if the total Gibbs energy of the system for the selected conditions has reached the minimum. GEMINI calculates complex multiphase multi-component chemical equilibria (ideal gaseous phase, stoichiometric condensed substances and multi-component condensed solution phases) by minimizing of the total Gibbs energy of the system under either constant pressure or volume conditions. The minimization method is based on a general optimization technique, the “Direct Search method” of Hooke and Jeeves.

For the representative accident scenarios, GEMINI code analyses were performed to determine the final thermodynamic states of the melt compositions. Table 1 summarizes the GEMINI code analyses results for the mass distribution of the individual melt components. In this study, through the GEMINI code calculation, the mass fraction of the individual melt component which involved in the metallic phase and oxidic phase was determined as shown in the Table 1.

Table 1. GEMINI code analyses results

	TLFW					SBO		MBLOCA (4.28 inch)		LBLOCA (9.6 inch)	
	w/o SDS		with SDS								
	Metallic	Oxidic	Metallic	Oxidic	FCC	Metallic	Oxidic	Metallic	Oxidic	Metallic	Oxidic
B	1.01	0.09	0.000	1.10		0.46	0.05	1.00	0.10	0.67	0.22
C	0.30	0.00	0.000	0.30		0.00	0.00	0.30	0.00	0.01	0.00
Cr	8.76	0.24	0.000	9.00		0.29	0.06	8.81	0.19	2.97	0.09
Fe	35.88	0.12	0.000	36.00	0.00	7.04	0.22	35.91	0.09	28.27	0.13
Ni	3.92	0.08	0.000	4.00		1.43	0.17	3.94	0.06	3.34	0.07
O	0.30	17.84	0.000	0.32	13.45	0.21	15.57	0.29	13.70	0.21	12.37
U	14.65	85.14	0.001	15.36	68.12	9.87	78.55	16.04	71.41	14.40	78.70
Zr	6.05	19.12	0.000	7.74	13.12	4.95	19.44	5.23	12.14	2.09	4.66

4. Evaluation of Layer Inversion

Layer inversion phenomena where a heavy metallic layer stratifies below the oxidic pool were evaluated using the GEMINI code analyses results. For the quantitative evaluation on the layer inversion phenomena, the density variation of oxidic and metallic phases under the thermodynamic equilibrium should be determined. In addition, the systematic effects of the U/Zr ratio, the Zr oxidation fraction, the mass of UO_2 and steel should be considered.

In this study, as a first step, the layer inversion of the heavy metallic phase was examined for the case of the MBLOCA listed in the table 1. Density variations of oxidic and metallic phases were evaluated using the density variation graph which was developed by CEA [2]. The Zr oxidation fraction, Cn was assumed to be 30 % although the actual Zr oxidation fraction of the MBLOCA case was 36.4 % in the SCDAP/RELAP5/ MOD3.3 code calculation result [3]. For a C30 Zr oxidation fraction, the metallic phase is heavier than the oxidic phase until an iron mass near 24 ton.

In addition to this iron mass relocated below the oxidic pool, the whole metallic uranium and the part of metallic zirconium listed in the table 1 can stratify below the oxidic pool for the MBLOCA case of the APR1400. The mass of metallic zirconium which stratify below the oxidic pool was calculated by assuming that the mass fraction of uranium is fixed at 0.4 among the total mass of heavy metallic phase below the oxidic pool. Therefore, the total mass of heavy metallic layer below the oxidic pool is 40.1 ton by summing the iron, the uranium, and the zirconium in the case of MBLOCA sequence of the APR1400.

Fig. 1 shows the final melt pool configuration in the case of MBLOCA sequence of the APR1400. In this study, two cases of two-layer melt pool and three-layer melt pool was compared as shown in Fig. 1. If the layer inversion of the heavy metallic phase is considered, the thickness of the top metallic layer decreases from 0.583 m to 0.305 m, which indicates the increase risk of the focusing effect in case of the layer inversion of the heavy metallic phase.

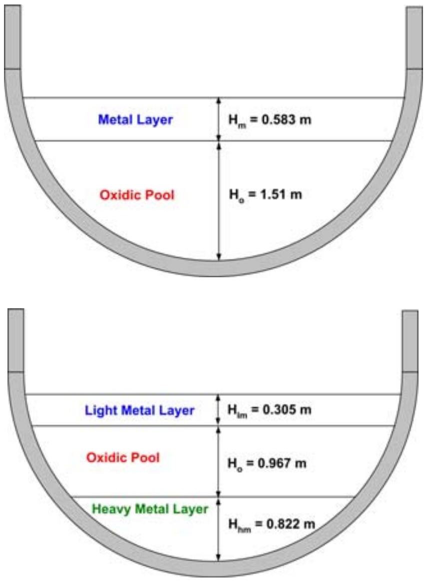

Fig. 1 Final melt pool configuration in the MBLOCA case

5. Conclusions

Layer inversion of the heavy metallic phase was examined for the case of the MBLOCA sequence of the APR1400. The thermodynamic analyses results address the possibility of the melt pool layer inversion in the MBLOCA sequence. The total mass of heavy metallic layer below the oxidic pool is 40.1 ton by summing the iron, the uranium, and the zirconium in the case of MBLOCA sequence of the APR1400. If the layer inversion of the heavy metallic phase is considered, the thickness of the top metallic layer decreases from 0.583 m to 0.305 m, which indicates an increased risk of the focusing effect in case of the layer inversion of the heavy metallic phase.

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