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Corium Configuration and Penetration Tube Failure for Fukushima Daiichi Nuclear Power Plant

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1. Introduction

For the LWRs (light water reactors), the penetration tubes at the reactor vessel lower head are regarded as the most vulnerable structures along with a global vessel failure during a severe accident because they can be seriously damaged by a corium melt or debris relocated into the lower plenum of the vessel [1-5]. In particular, the BWRs (boiling water reactors) have more penetration tubes than the PWRs (pressurized water reactors) at the reactor vessel lower head due to the structural complexities at the reactor vessel upper head. Thus, the research on the penetration tube failure is of higher importance in the BWRs, as it could lead to melt discharge into the containment and subsequent release of radioactive materials to the environment due to the containment failure.

There are more than one hundred of penetration tubes in the Fukushima Daiichi NPPs (nuclear power plants), such as ICM-GTs (in-core monitoring guide tubes), CRGTs (control rod guide tubes) and drain tubes. The ICM-GTs include SRMs (source range monitors), IRMs (intermediate range monitors), LPRMs (local power range monitors) and TIPs (traversing in-core probes), which are much thinner than other tubes. In addition, the SRM/IRM guide tubes are dry tubes and their bottom ends are open to the drywell, whereas the others are wet tubes and plugged at the bottom ends [6]. Therefore, SRM/IRM guide tube failure is of high interest because they would be easy to buckle due to high tube temperature and melted by the corium melt or debris, both of which could lead to melt discharge out of the reactor vessel lower head through the failed portions of the tubes. In the accident of Fukushima Daiichi NPPs, it is estimated that the fuel and structural materials in the core had been melted for unit 1, 2 and 3 [6-9] and the molten corium fell onto the pedestal floor in some units through the damaged SRM/IRM guide tubes [6, 7].

Since 2012, KAERI have carried out the penetration failure experiments for the APR1400 ICI (in-core instrumentation) penetration tubes [2-5]. Based on the expertise of the corium generation in a cold crucible using induction heating technology and the experiences of penetration tube failure experiments by the corium melt, we have launched the research program entitled ‘Melting tests of the penetrating tubes through the BWR-RPV wall’ in 2014 in cooperation with IAE (The Institute of Applied Energy). The research objectives are to clarify the corium configuration (i.e., physical properties of solidified ingot) in the Fukushima accident and investigate experimentally the failure phenomena of the ICM-GTs (SRM/IRM and LPRM guide tubes) and CRGTs. The molten core configuration in the reactor vessel lower plenum provides the initial conditions for the penetration tube failure and insights for the decommissioning activities during the removal of core debris.

This paper describes a brief summary of new findings obtained in the experiments of corium configuration and SRM/IRM guide tube failure. The configuration of molten corium pool for a typical Fukushima Daiichi NPP unit 1 composition was investigated by a melting and solidification experiment in a small-scale VESTA-S facility. Then, the SRM/IRM guide tube failure experiment has been performed in a large-scale VESTA facility.

2. Experiments

2.1 Configuration of molten corium

To investigate the corium configuration relocated into the reactor vessel lower head, a melting and solidification experiment was performed for a typical Fukushima Daiichi NPP unit 1 composition of UO_2 /ZrO_2/ Zr/ STS/ B_4C mixture. The corium generation was conducted in a VESTA-S facility, which employs an induction heating technique with a cold crucible. The details of the experimental results can be found in the reference [10].

Figure 1 shows the material charging pattern, whose composition is UO_2 : Zr : ZrO_2 : STS304 : B_4C = 53 : 9 : 25 : 12 : 1 (wt.%). The total charging mass was 5.3 kg. The melt was generated by induction heating for 85 minutes, and the maximum supplied power was 85 kW.

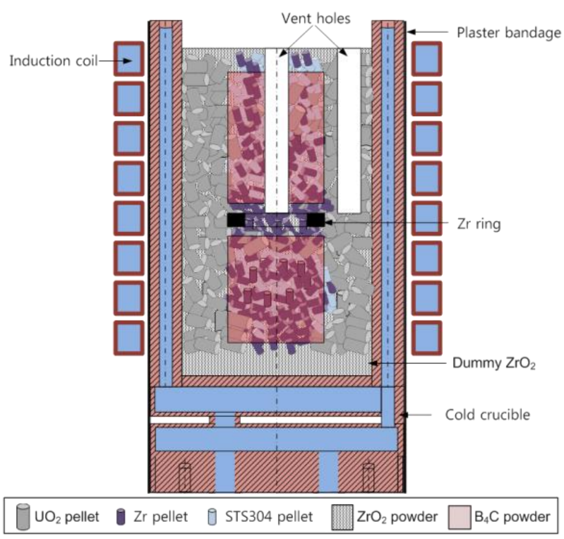

Fig. 1. Charging pattern of the melting materials.

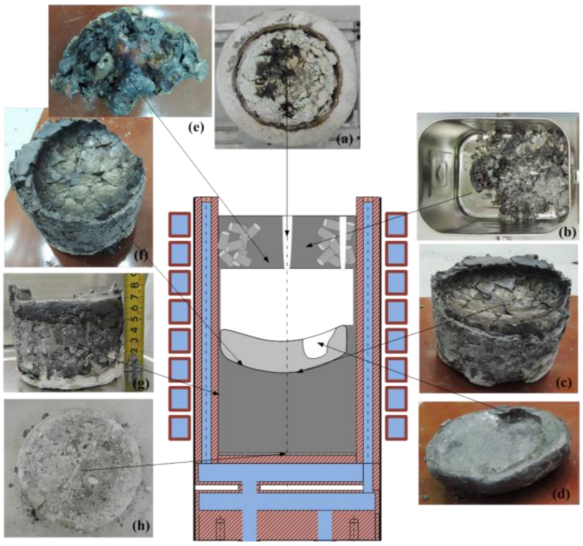

Fig. 2. Configuration of the corium ingot.

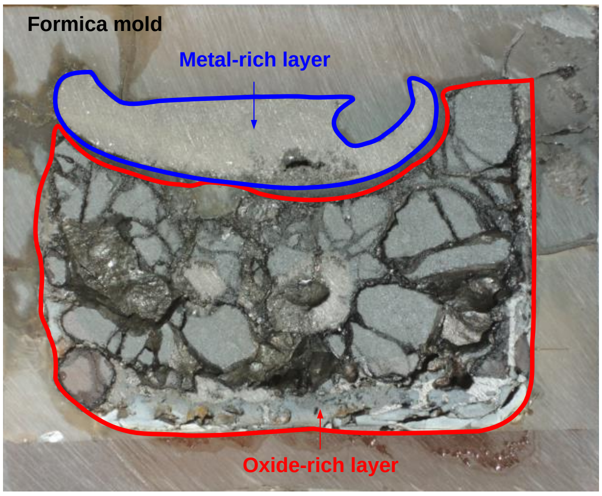

Fig. 3. Cross-sectional image of the corium ingot.

The configuration of the solidified corium ingot is represented in Figs. 2 and 3. It was found that a lump of corium ingot at the bottom of the crucible consists of two separative layers. The corium ingot was molded in Formica (thermosetting resin), and its cross-sectional image is shown in Fig. 3. Several samples were taken at the cross-section, and they were analyzed by ICP-AES (inductively coupled plasma atomic-emission spectrometry), EA (elemental analyzer), XRD (X-ray diffraction) and SEM-EDS (scanning electron microscopy-energy dispersive X-ray spectroscopy). It turned out that the upper (shinny gray) layer is metal-rich while the lower (dark gray) one is oxide-rich and has almost the same composition with the initial charging composition.

This two-layered configuration is very important in the aspect of understating the core melt progression and post-accident recovery actions for the Fukushima Daiichi NPPs. It would mean that the heat flux to the reactor vessel wall could be focused on the metal-rich region, because the decay heat generated in the UO_2-rich oxide region would be transmitted to the upper metal-rich region. Then heat flux to reactor vessel wall would be focused in the upper metal-rich region [11, 12]. In addition, if the metal layer is on the top of the core melt, there will be more chance of hydrogen generation during the flooding of the reactor for the recovery action.

It was also found that B_4C was concentrated in the upper metal-rich layer. This result is consistent with the findings in the EPICOR tests [13], where the B_4C content (about 1.4 wt%) was similar to the present condition (1 wt%) and all boron was found in the metallic ingot in the form of ZrB_2. In the previous MASCA tests [14], the low content of B_4C (<0.5 wt%) in PWR-type core melt turned out to have insignificant effect on the density of the metallic melt. However, they [13] demonstrated that high content of B_4C in BWR-type core melt plays a significant role in reducing the density of the metallic melt, which results in preventing the formation of a dense metallic phase at the bottom of the oxidic melt in a reactor lower head. Consequently, this result implies that if un-borated water is injected during the recovery actions, there is little material for neutron absorption, and consequently there is a possibility of recriticality [15]. As for the Fukushima Daiichi NPP, borated water has been injected into the reactor vessel during the accident progression, even when the possibility of recriticallity was so low [8]. This point has to be carefully looked at during the recovery actions and decommissioning activities such as the handling process during the removal of core debris, since there will be little control rod material of B_4C in the UO_2-rich region.

2.2 SRM/IRM guide tube failure

Figure 4 shows the VESTA experimental facility to perform the BWR penetration tube failure experiments. There are two cold crucibles for melt generation and reheating: a melt crucible in the upper vessel and an interaction crucible in the lower vessel. They are surrounded by the induction coil to which an electrical power from a high frequency power generator is supplied for induction heating. When a melt is generated in the melt crucible and reaches a desired temperature, an electrical power supply is stopped first for safety. Then, a plug at the bottom of the crucible is removed and a puncher is actuated to perforate the sintered layer at the bottom for the melt delivery. An intermediate melt catcher is mounted under the melt crucible to collect the melt temporarily and deliver the melt down into the interaction crucible through the melt delivery channel. A penetration test specimen, for example SRM/IRM guide tube, is installed at the bottom of the interaction crucible, and thus it is suddenly heated and eroded by the delivered melt. Then, an electrical power is supplied again towards the interaction crucible for melt reheating, which is for the simulation of sustained heating by decay heat.

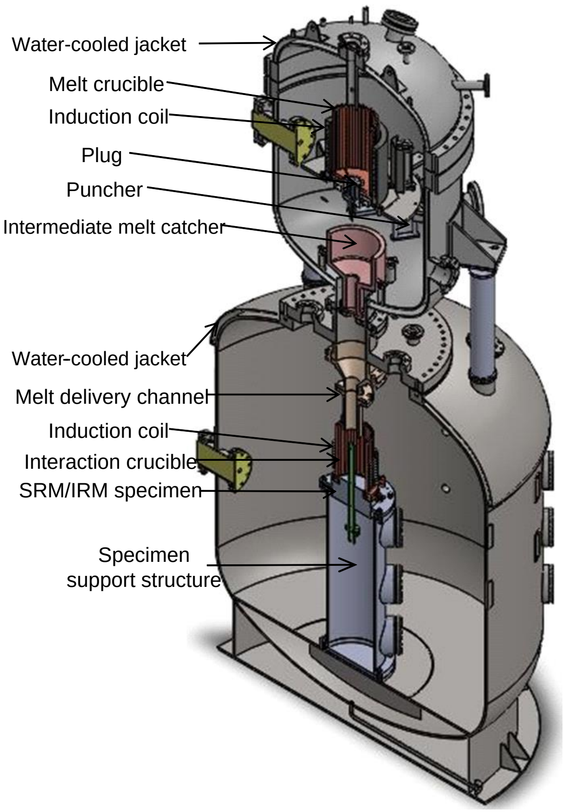

Fig. 4. Schematic of the VESTA facility.

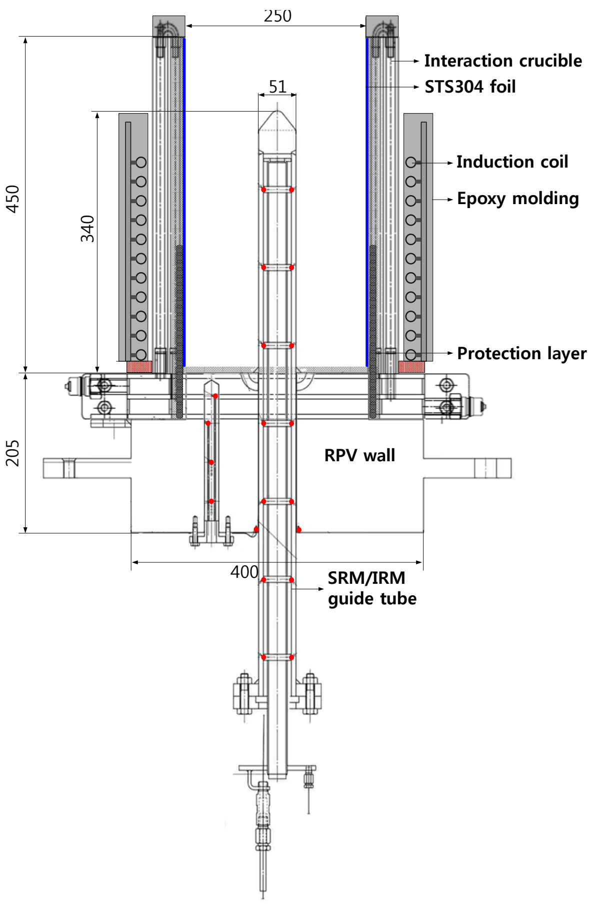

Fig. 5. Assembly of a SRM/IRM guide tube specimen and interaction crucible.

A test specimen of a SRM/IRM guide tube with a RPV (reactor pressure vessel) wall was manufactured by Hitachi-GE according to the real manufacturing process with the same materials and dimensions. The SRM/IRM guide tube is a double-pipe type and installed at the center of the RPV wall. Thus, there are two melt flow paths when the tube is damaged by the melt; one is the inside of the inner tube and the other is a gap between the inner and the outer tubes.

An assembly of the SRM/IRM guide tube specimen and interaction crucible is shown in Fig. 5. Several thermocouples are installed at the tube wall (red dots in Fig. 5) to monitor the tube temperature distribution and melt position during the interaction with the melt. To avoid damage of the interaction crucible during the melt delivery and reheating process, a protection layer was installed at the inner wall of the interaction crucible using a STS304 foil, ZrO_2 powder and UO_2 pellets.

The material composition charged in the melt crucible was UO_2 : ZrO_2 = 70 : 30 (wt.%), and the total charging mass was 150.3 kg. The melt was generated by induction heating for 70 minutes, and the maximum supplied power was 300 kW. The maximum melt temperature measured by an optical pyrometer was 2473℃. About 60 kg of melt was delivered into the interaction crucible, and it was reheated for 8.5 minutes.

Figure 6 shows the temperature readings at the 6 locations above the RPV wall (6 red dots above the RPV wall in Fig. 5) during the melt reheating process (8.5 minutes). As shown Fig. 6, the tube temperatures above the RPV wall increased rapidly in a few minutes to reach 1500℃, which is around the melting temperature of the penetration tube. That means the penetration tube above the RPV wall was melted in a few minutes by direct contact with the melt. It was visualized under the bottom of RPV wall that the melt was released first from the gap between the inner and the outer tubes, and some minutes later from the inside of the inner tube. The snap shots of the melt discharge from these flow paths are given in Fig. 7, where the configuration of the solidified ingot in the interaction crucible is also represented with the photographs.

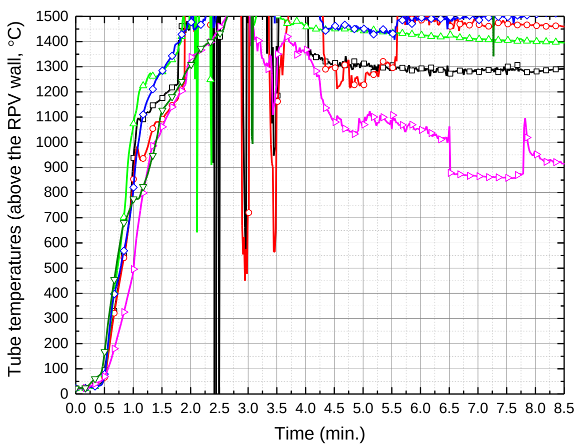

Fig. 6. Temperature distribution of the penetration tube above the RPV wall during the melt reheating process.

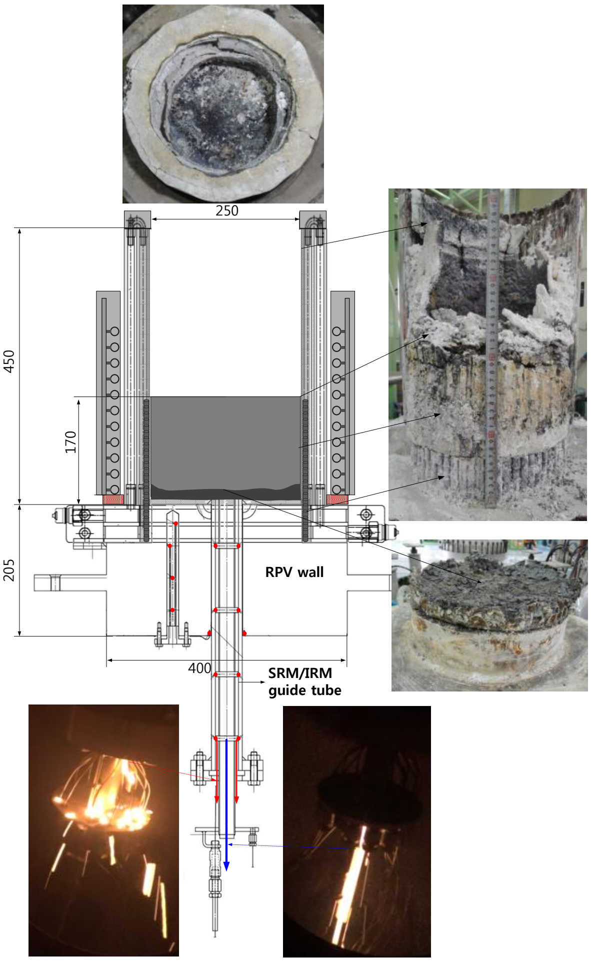

Fig. 7. Configuration of the solidified ingot in the interaction crucible and melt discharge snap shots.

In the SRM/IRM guide tube failure experiment, melt reheating for a long time was not possible because the interaction crucible was damaged early by the metallic melt produced from the tube melting. Even in the short melt reheating period, however, the penetration tube above the RPV wall was estimated to be completely melted in a few minutes, and consequently some amount of melt was discharged through the melted portions of the tube. This implies that the SRM/IRM guide tube might have been damaged more seriously in the Fukushima accident, which led to large amount of corium discharge into the pedestal floor as evaluated by the computational analysis [6, 7].

3. Conclusions

The experimental researches to investigate the corium configuration and the penetration tube failure for the Fukushima Daiichi NPPs were introduced and some meaningful results were summarized. It was shown that the corium ingot was separated into two layers, of which the upper layer was metal-rich while the lower one was oxide-rich. It seemed that B_4C would contribute to reducing the density of the metallic melt. The two-layered configuration will provide useful information to understand the core melt progression and post-recovery actions for the Fukushima Daiichi NPPs. In addition, we performed a large scale penetration tube failure experiment for the SRM/IRM guide tube, and showed high possibilities of large amount of corium discharge out of the reactor vessel lower head, which followed by the tube melting in a very short time.

We are planning to perform the penetration tube failure experiments for another dry tube of ICM-GT (LPRM guide tube), and later for the wet tube (CRGT). However, there are still technical problems to be solved such as early damage of the cold crucible by metallic melt, which preclude various melt generation including metal compositions and long melt reheating time after the tube melting as well. Therefore, we are trying to improve the crucible design and find better solutions to protect the cold crucible effectively from the metallic melt.

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