VESTA Test Facility for Severe Accident Researches at KAERI

Hwan Yeol Kim*, Sang Mo An, Jaehoon Jung, Kwang Soon Ha, and Jin Ho Song
Korea Atomic Energy Research Institute
989-111 Daedeok-daero, Yuseong-gu, Daejeon 305-353, Republic of Korea
*hykim1@kaeri.re.kr; sangmoan@kaeri.re.kr; jhjung@kaeri.re.kr; tomo@kaeri.re.kr;
dosa@kaeri.re.kr

ABSTRACT

VESTA (Verification of Ex-vessel corium STAbilization) test facility constructed at KAERI in 2010 is used to perform various corium melt experiments. Since 2010, several tests have been performed for the verification of an ex-vessel core catcher design for the EU-APR1400. Jet impingement tests were performed to investigate the ablation characteristics of the sacrificial material by ZrO_2 melt. ZrO_2 melt of 65 to 70kg was discharged on the sacrificial material through a well-designed nozzle and the ablation depths were measured. Interaction tests between metallic melt and sacrificial material were performed to investigate the interaction kinetics of the sacrificial material. Two types of melt were used; one is the metallic corium melt with Fe 46%, U 31%, Zr 16%, and Cr 7% and the other is stainless steel (SUS304) melt. Metallic melt of 1.5 to 2.0kg was delivered to the sacrificial material, and the ablation depths were measured.
In addition, penetration tube failure tests were also performed for the APR1400 equipped with 61 in-core-instrumentation penetration nozzles and extended tubes at the reactor lower vessel. ZrO_2 melt was generated in a melting crucible and delivered down into an interaction crucible where the test specimen is installed. Sustained heat was supplied to the interaction crucible by an induction heater after the delivery of the melt from the melting crucible. Temperature distributions of the reactor bottom head and in-core-instrumentation penetration were measured by a series of thermocouples embedded along the specimen to evaluate the tube ejection mechanism. It is noted that the VESTA test facility has been used for various severe accident researches with corium and simulant melts at KAERI.

KEYWORDS
VESTA test facility, cold crucible melting, interaction test between melt and sacrificial concrete,
jet impingement test, penetration tube failure test

1. INTRODUCTION

An ex-vessel corium cooling system, such as an external core catcher, should be required for retaining and cooling the molten corium outside the reactor vessel, if retention of the molten core debris inside the reactor vessel is not assured during a postulated severe accident. In the year of 2010, the VESTA (Verification of Ex-vessel corium STAbilization) test facility was designed and constructed at KAERI to perform verification tests for the development of a core catcher. The test facility was originally designed to have the capability of passively injecting coolant and gas from below the corium melt. Not only simulants but also reactor materials are accommodated in the test facility. Afterwards, the test facility can be used for performing various tests using melts to resolve severe accident issues with some modifications.
During one year after the construction of the facility, shake-down tests and pre-melting tests were performed and a good performance was shown. Since 2011, several tests have been performed for the verification of an ex-vessel core catcher design for the EU-APR1400, i.e., a jet impingement test on

sacrificial material by ZrO_2 melt and an interaction test between corium melt and sacrificial material. In addition, in-core-instrumentation penetration tube failure tests were performed for APR1400, where 61 penetration nozzles and extended tubes are installed at the reactor lower vessel. Penetration tube failure mechanisms can be divided into two categories; tube ejection out of the vessel lower head and tube rupture outside the vessel. The experiments were focused on the penetration tube ejection, because it was relatively easy to simulate the sustained heating for the tube ejection test. Tube ejection begins with degrading the penetration tube weld strength to zero as the weld is exposed to temperatures as high as the weld melting point, which is called a weld failure, and then overcoming any binding force in the hole of the vessel wall that results from differential thermal expansion of the tube and vessel materials.
This paper deals with the introduction of the VESTA facility and research results with corium and simulant melts at the VESTA facility.

2. DESCRIPTION OF VESTA FACILITY AND PRE-MELTING TEST

A schematic diagram of the facility is shown in Figure 1. The facility is composed of a furnace vessel, a corium melting system including an intermediate melt catcher and a power supply for induction heating, a melt delivery system, a coolant supply system, an auxiliary system, and an instrumentation and control system. The furnace vessel protects the melting crucible in which simulant melt and corium melt are generated by a cold crucible induction heating technology. When the molten corium is sufficiently formed inside the crucible and the molten corium approaches a sufficiently high temperature above the melting point, a plug installed underneath the crucible is removed, and a puncher is remotely actuated to perforate the sintered bottom layer for the melt delivery. A cone-shaped intermediate melt catcher is mounted between the furnace vessel and the test section to collect the melt temporarily and deliver a melt jet into the test section. The power supply system was designed to supply electrical power for the generation of melt in the crucible. An induction heating method was used with an induction heater of 450 kW in power and 100 kHz in frequency. It is expected that up to 400 kg of corium melt can be generated with the power supply system. The coolant supply system is composed of an intermediate cooler and a cooling tower to remove the heat generated in the induction heater, the induction coil, the cold crucible, and the plug. MgO coating is provided at the lower part of the furnace vessel and the melt delivery piping. The water injection tank is provided to cool down the melt in the test section. The condensate tank is provided to condense the steam flowing from the test section.

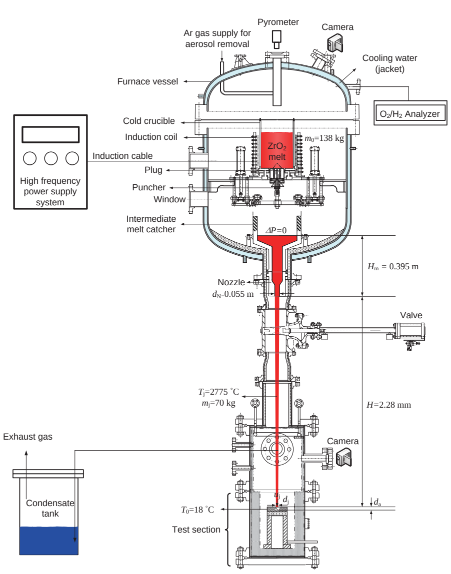

Figure 1. Schematic of VESTA facility.

VESTA experimental data include melt temperatures, coolant temperatures and flow rates, gas temperature, vessel pressures, and water levels in the tanks. The melt temperatures generated by the furnace vessel are measured by two infrared thermometers (3R-35C15-0000, MODLINE 3, IRCON). Each thermometer has two sensors with spectral ranges of 0.7-1.08 μm (wide range sensor) and 1.08 μm (narrow range sensor), a useful temperature range of 1773 – 3773 K, a response time of 0.01 to 60 sec., an accuracy of within 0.6%, and a controllable spectral e-slope range of 0.850 to 1.150. All measured data are collected and controlled by using a data acquisition system (DAS, PXI, National Instruments). The DAS system for the VESTA experiment is capable of 32-DC signal input channels with a 2 MS/s single-channel sampling rate (NI PXIe-6363), and 64-thermocouple signal channels with 80 S/s sampling rates and 24-bit resolution (NI PXIe-4353). The DAS is controlled by using a LabVIEW program on a personal computer.

Figure 2 shows the charging of ZrO_2 in the cold crucible for the pre-melting test. The total charged mass of ZrO_2 (crushed ingot and powdered ZrO_2) was 151 kg. An initiator made of a ZrO_2 ring was placed at one-third of the height from the bottom of the cold crucible. Three holes were provided inside the charged ZrO_2, two holes for the venting of the gases, and one hole for the temperature measurement by the pyrometer. Power was continuously supplied from the generator with a stepwise increment until the end of the melting process. The maximum power to the crucible was about 300 kW. It took about 160 min. for complete melting. If the water outlet temperature of the plug increases a lot during the melting process, it is judged that the melting is completed. Then, the plug is removed and the puncher is actuated. Figure 3 shows the surface of the melt. Figure 4 shows the surface temperature of the melt measured by the pyrometer installed at the upper furnace vessel. The maximum temperature was about 2860 °C. As time passed, the surface temperature dropped below 2000 °C, because the hole for the temperature measurement by the pyrometer collapsed and a surface crust was formed. However, the maximum temperature inside the melt is sure to be consistently maintained at about 2860 °C.

Figure 2. Charging of ZrO_2.

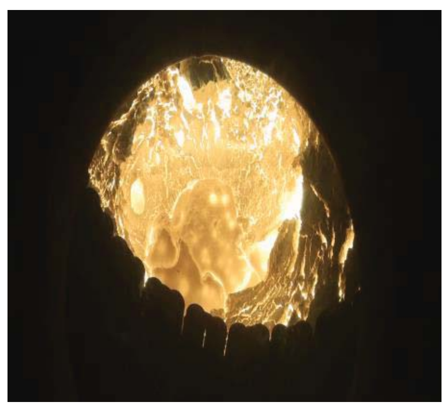

Figure 3. Surface of melt.

After the complete melting, the plug was removed from the bottom of the cold crucible and the puncher system was actuated. The melt was temporarily contained in the melt catcher and dropped into the test section through an orifice with an inner diameter of 50 mm. The melt delivery process was videotaped. The melt delivery duration was about 13 sec. An investigation of the cold crucible and the test section showed that the melting of the ZrO_2 was successful, and most of the melt was delivered to the test section. Figure 5 shows the surface crust in the crucible after the test.

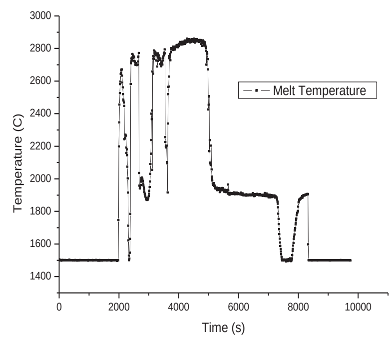

Figure 4. Melt temperature. **Figure 5. ZrO_2 crust.**

3. CORE CATCHER DESIGN VERIFICATION TEST for EU-APR1400

The ex-vessel core catcher (PECS: Passive Ex-vessel corium retaining and Cooling System) is installed to retain the corium in the reactor cavity of the EU-APR1400. The core catcher concept incorporates a number of engineering solutions used in the catcher designs of the European EPR and Russian VVER-1000 reactors, such as thin-layer corium spreading for better cooling, retention of the melt in a water-cooled steel vessel, and use of sacrificial material (SM) to control the melt properties. SM is one of the key elements of the catcher design and its performance is critical for melt retention efficiency. This SM consists of oxide components, but the core catcher also includes sacrificial steel which reacts with the metal melt of the molten corium to reduce its temperature. When the reactor vessel fails, the reactor cavity is flooded by the gravity driven flow from the IRWST (In-containment Refueling Water Storage Tank) after molten corium spreads on the core catcher body during a severe accident. Decay heat and sensible heat of the relocated and spread corium pool are removed by the natural circulation flow at the bottom and side wall of the core catcher and the top water cooling of the corium combined with the dedicated containment spray system. Figure 6 shows a core catcher system.

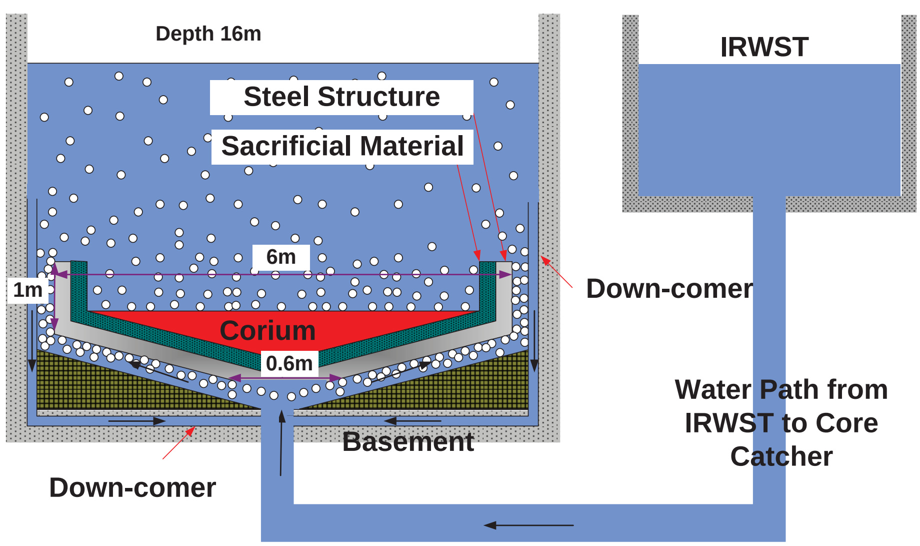

Figure 6. Core catcher system.

3.1. Jet impingement test on sacrificial material by ZrO_2 melt

When a molten corium jet is discharged due to the reactor vessel failure during a severe accident, the core catcher body will be damaged seriously by corium jet impingement. Therefore, the surface of EU-APR1400 core catcher on which the corium jet impinges is protected by a sacrificial material (SM). The sacrificial material on the core catcher body structure is eroded by a corium jet impingement. The ablation of the sacrificial material by corium jet impingement is influenced by several factors such as the corium jet composition, degree of superheat, pouring time, impinging velocity, and thermophysical properties of the structural materials. The ablation rate is limited considerably by crust formation generated above the material surface. However, the ablation rate of the sacrificial material containing moisture like concrete can be lower than the model predictions because the thermal radiation heat transfer may be the dominant mechanism across the layer due to the suddenly generated steam layer above the surface. A jet impingement test was performed to investigate the ablation rate of the sacrificial material on the core catcher body and to verify the existing ablation models.

Figure 7 shows the test section. The SM specimen has dimensions of 216 mm in diameter and 50 mm in thickness, and is positioned at the center of the test section and supported by a MgO plate with a MgO-lined SUS tube structure. The test section is protected basically by a thick MgO wall, and an alumina blanket is attached to the inner wall for easy disassembly of the ZrO_2 ingot after the experiments. Once the melt jet impinges onto the SM specimen, the melt spreads out and then flows down into the annular space between the supporting structure and the MgO wall. In the first test, the cold crucible was filled with 138 kg of ZrO_2 powder and the electrical power was increased gradually up to 263 kW with 86 kHz for highly superheated melt generation. The melt temperature just before the melt delivery was measured to be 2775 °C by an optical pyrometer. Among the initial charged mass in the cold crucible, 70 kg of ZrO_2 melt was delivered into the test section and the jet impingement took place for only a few seconds. During the whole melt generation process (~ 2 hours), the pressure difference between the furnace vessel and the test section was negligibly small so that the gravitational force for the jet impingement onto the SM specimen can be regarded as the only driving force.

Figure 8 shows the specimen after the test. The ablation depths in the first and second tests were estimated as 3.23 mm and 4.33 mm, respectively. These values were between 1 mm and 6 mm, which was estimated by existing ablation models.

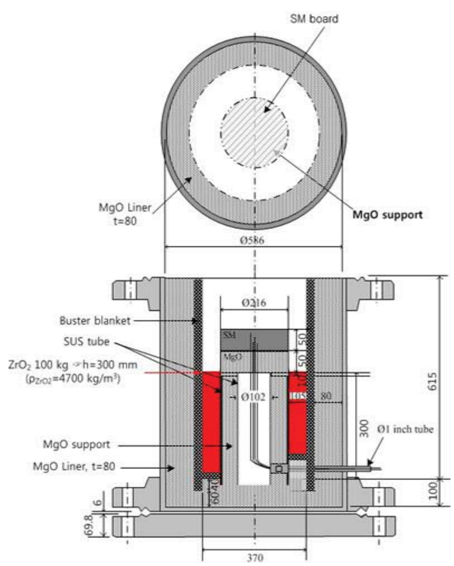

Figure 7. Jet impingement test section.

Figure 8. Test specimen after test.

3.2. Interaction test between corium melt and sacrificial material

An experimental facility of VESTA (Verification of Ex-vessel corium STAbilization) –S (Small) with a cold crucible melting technique was established to investigate the interaction mechanism between the corium and sacrificial materials. Figure 9 shows the VESTA-S test facility. This facility includes the generation of the metallic melt using an induction heating method, melt delivery, and measurement of the interaction process. A high-frequency generator, coolers, and auxiliary system are used in common with the VESTA facility. The metallic melt was generated in the upper melt crucible and delivered into the lower interaction crucible, where the sacrificial material specimen interacted with the metallic melt. This melt-delivery method was adopted for preventing the specimen from pre-heating and chemical change during the long melt generation process (2 to 3 hours).

Magnesium oxide (MgO) powder is sintered on the inside wall of the crucible to protect the crucible not only thermally but also electro-magnetically. A water-cooled induction coil is located outside of the crucible to supply electro-magnetic energy. Some thermocouples, which are shielded by tungsten or alumina tubes and an optical pyrometer, were used to measure the metallic melt temperature. In particular, an argon (Ar) gas purging tube between the top of the cold crucible and the optical pyrometer was installed to remove some aerosols generated from the molten corium and finally secure the optical path. A hollow rod was also installed in the melt to make rays emitted from the molten material into the blackbody radiation.

When the molten material temperature reached the expected condition, the melt was poured into the interaction crucible by the remote-controlled rotating system. The interaction crucible has a similar feature to the melt crucible, that is, a water-cooled and MgO-coated crucible. After the melt delivery process, the interaction crucible was instantaneously heated up through the water-cooled coil by switching the power generator from the melt crucible to the interaction crucible. A specimen was installed inside the interaction crucible; therefore, the interaction of the hot melt with the cold specimen occurred immediately after the melt delivery. Several thermocouples were embedded in the specimen with different radii and depths to measure the ablation rate. Six tests were performed, where two kinds of metallic melts were employed for the experiments; one is a metallic corium melt composed of Fe 46%, U 31%, Zr 16%, and Cr 7% of total mass and the other is stainless steel (SUS304) melt, which was used to separate the effects of U and Zr components in the melt. The compositions of SUS304 are known as Cr 18 to 20%, Ni 9 to 13%, $C<0.08\%$, $Si<0.1\%$, $Mn<2\%$, $P<0.045\%$, $S<0.03\%$. In the present experiments, the stainless steel melt was assumed to have average compositions, i.e., Fe 70%, Cr 19% and Ni 11%.

The ablation profile of the specimen might be assumed to be a spherical shape because the side wall of the specimen in the cold crucible maintained a constant coolant temperature. In addition, chemical analyses such as ICP-AES, SEM, EPMA, and XRD were also performed using samples from ingots after the experiments to analyze the compositions and microscopic features during the reaction process.

As shown in Figure 10, two typical ablation rates of the specimen were identified; this seems to be why the interaction mechanism might be changed from the thermal to chemical interaction. The VESTA-S test successfully simulated the interaction phenomena of the metallic melt with the sacrificial material on the core catcher body.

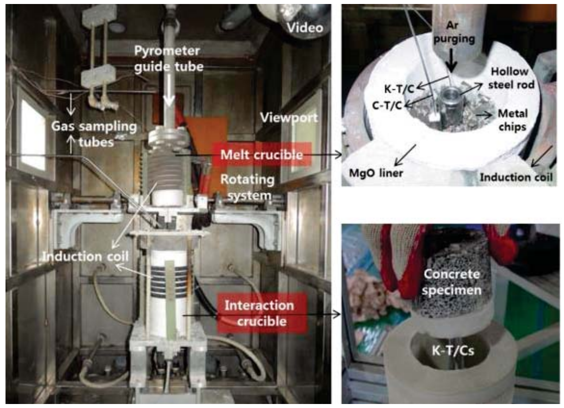

Figure 9. VESTA-S test facility.

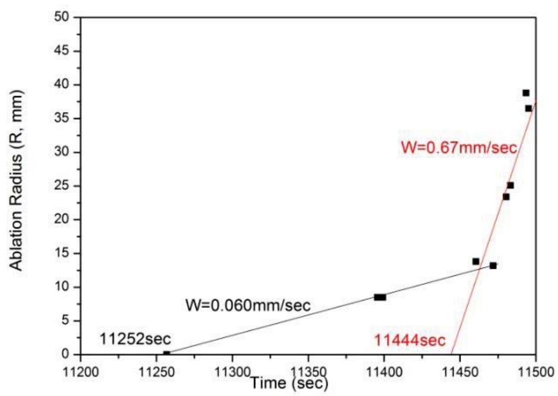

Figure 10. VESTA-S test results on the ablation rate.

4. PENETRATION TUBE FAILURE TEST for APR1400

There are 61 in-core-instrumentation penetration tubes at the reactor lower vessel for APR1400. These penetrations are regarded as the most vulnerable parts during a severe accident because they can be damaged seriously by corium melt or debris relocated into the vessel lower plenum. Figure 11 shows a schematic of the APR1400 in-core-instrumentation penetration tube attached to the center of the vessel lower head and test specimen. The vessel material is SA508, Grade 3, Class 1, and has a thickness of 180.6 mm (175 mm vessel and 5.6 mm stainless steel cladding). The penetration tube is made of Inconel-690 and manufactured by boring a vertical hole into the vessel lower head, inserting a tube through the hole, and welding the tube to the vessel's inner surface.

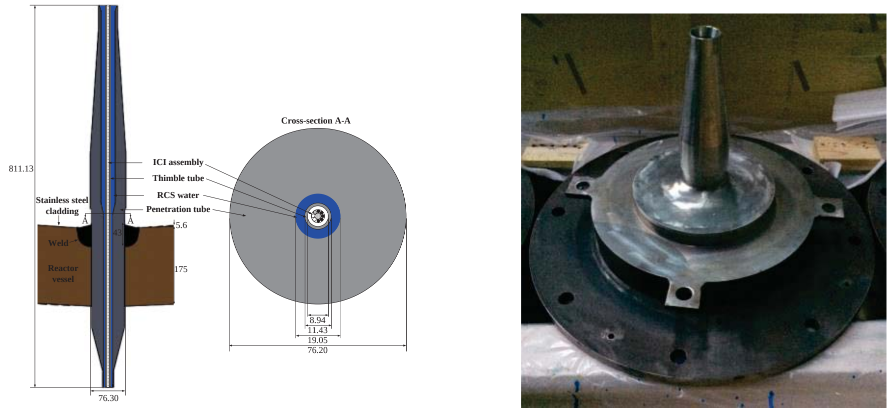

Figure 11. APR1400 in-core-instrumentation penetration tube and test specimen.

The experimental setup consists of three parts: a furnace vessel, a melt delivery channel, and an interaction vessel, as shown in Figure 12. In the generation of the melt, the furnace vessel of the VESTA facility was used. An interaction vessel was newly constructed to perform the penetration failure experiment and simulate the in-vessel and ex-vessel boundary conditions during a severe accident, i.e., high pressure and external reactor vessel cooling. The vessel jackets are cooled by water during the experiment. A melt delivery channel is connected between the furnace and interaction vessels, and the inner channel wall is coated with a MgO refractory layer. A penetration test specimen including an in-core-instrumentation tube of the APR1400 reactor vessel was manufactured based on the standard manufacturing process. The temperature distributions of the reactor vessel, reactor vessel hole, and penetration tube were measured by thermocouples embedded in the test specimen. The penetration weld was heated up as high as its melting temperature by the melt, and the test specimen was pressurized by air at nearly 1 bar.

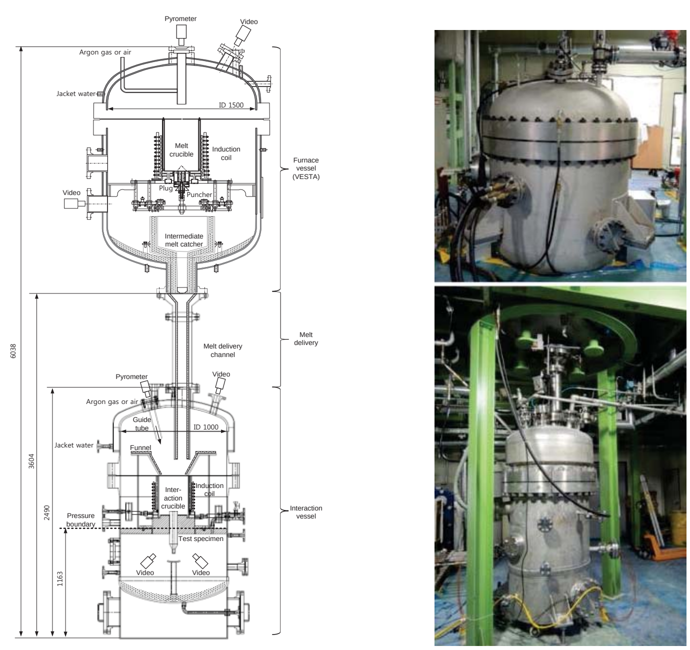

Figure 12. Experimental setup.

ZrO_2 was used as a simulant for corium melt, and as a first try, it was charged above the penetration test specimen in the interaction crucible. That is, the melt generation and erosion of the penetration test specimen take place simultaneously in the interaction crucible. The ZrO_2 ingot from the previous experiments was used along with ZrO_2 power for the efficient melting process. This means that the melt can be generated more efficiently by using an ingot because of the high heat transfer characteristics. The total charging mass of ZrO_2 was 51.7 kg (power 25.5 kg and ingot 26.2 kg) and two metal Zirconium (Zr) rings (large ring 0.24 kg and small ring 0.08 kg) were used as an initiator.
Figure 13 shows the thermocouple readings of the reactor vessel hole (RVH), penetration weld (PW), and penetration tube (P). It was predicted that most of the penetration weld and the tube above the surface of the reactor vessel were eroded in the final stage. When the weld temperature began to increase rapidly (~ 9800 s), the penetration test specimen started to be pressurized at nearly 1 bar by increasing the air injection flow rate into the interaction vessel and decreasing the exhaust gas flow rate. However, the penetration tube ejection did not occur in the end, and thus the interaction vessel was depressurized and the experiment was terminated. The measurement data could be used for verification of the analysis model under development at KAERI.

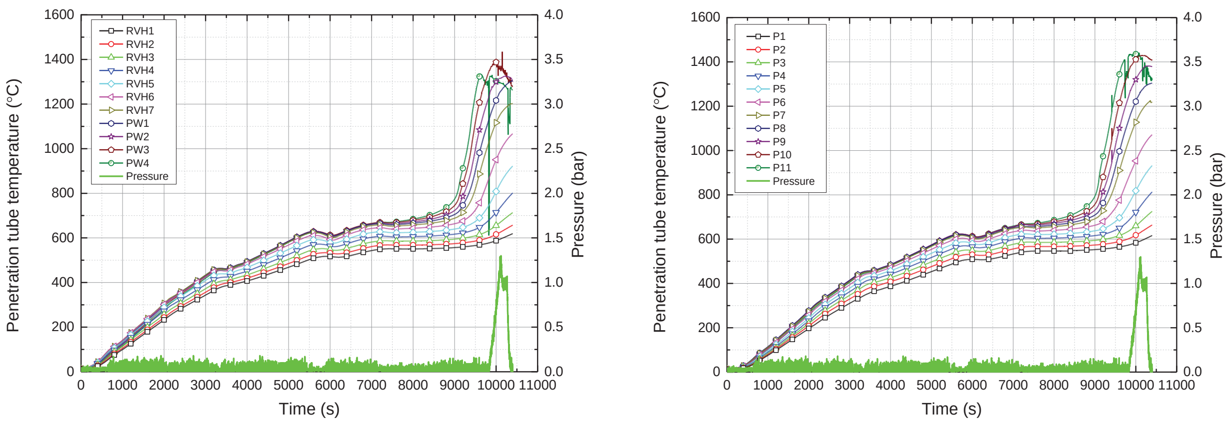

Figure 13. Experimental results.

5. CONCLUSIONS

VESTA test facility constructed at KAERI in 2010 was briefly described. It was originally designed to have the capability of passively injecting coolant and gas from below the corium melt for the development of a core catcher. Afterwards, it could be used to perform various severe accident researches with some modifications. Since 2011, several tests have been performed for a verification of an ex-vessel core catcher design for the EU-APR1400, i.e., a jet impingement test on a sacrificial material by ZrO_2 melt and an interaction test between the corium melt and sacrificial material. In addition, in-core-instrumentation penetration tube failure tests were performed for APR1400, where 61 penetration nozzles and extended tubes were installed at the lower reactor vessel. It was noted that the VESTA test facility has been used for various severe accident researches with corium and simulant melts at KAERI.

ACKNOWLEDGMENTS

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