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7.3 An Experimental Study on Feasibility of Ex-vessel Cooling through the External Guide Vessel

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Abstract

This paper presents the results of a series of experiments for assessing the efficacy of ex-vessel cooling through the external guide vessel during a severe accident. Four tests were performed in the LAVA test facility at KAERI, varying the boundary conditions at the outer surface of the vessel. The first test was a dry condition test conducted without cooling the outside of the vessel. On the other hand, in the second test, the cooling of the vessel surface was produced by gravity-driven forced injection of water along the annular gap of 25 mm between the vessel and the external guide vessel. Water flow rate was about 0.85 kg/s and total mass of available water was 300 kg. For the evaluation of the water flow rate effect, the third test was performed with a pool type cooling in the annulus without any circulation of water. These two external cooling tests were performed under elevated pressure of about 1.6 MPa. Finally, the fourth test was conducted under atmospheric pressure to evaluate the effect of system pressure on boiling heat transfer characteristics. In the dry test and the pool type ex-vessel cooling test performed under atmospheric pressure, the vessel was failed by a melt penetration at about 40 degree upper position from the vessel bottom, which is coincident with the boundary of the Al_2O_3/Fe melt separated layers. On the other hand, in both of the ex-vessel cooling tests conducted under elevated pressure of about 1.6 MPa, the vessel didn't fail. Compared with the pool boiling test, the vessel experienced effective cooling due to the inlet flow in the forced flow test. Synthesized the results of the tests, it was shown that the heat removal with ex-vessel cooling through the guide vessel is feasible, but the additional evaluations should be performed to guarantee enough thermal margin.

Key words : Ex-vessel Cooling, External Guide Vessel, Melt Separation, Heat Removal

1. Introduction

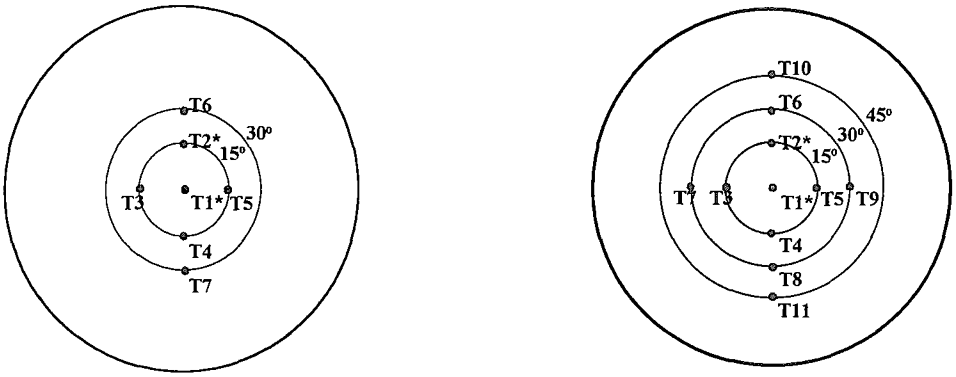
In-vessel Retention (IVR) is one of the severe accident management strategies that have been adopted by operating nuclear power plants and advanced designs. One viable means for IVR is the method of the external cooling of the reactor vessel by flooding the reactor cavity during a severe accident. The success of the external cooling concept depends on the effectiveness of the ex-vessel boiling process in dissipating the decay heat imposed by the molten core on the reactor vessel bottom. Also, for allowing the reactor cavity to flood, the availability of water to contact the outside of the lower head should be evaluated. For this reason, the studies performed so far were mainly designed to investigate downward-facing boiling phenomena in connection with the external cooling concept[1,2,3,4,7]. Despite many relevant studies have been performed so far, use of definite conclusion for any specific application is not up to the mark due to the uncertainties in the boiling heat transfer characteristics at the outer surface of the vessel. Also, an individual light water reactor differs in the power density, the materials in the core and the shape of the lower head, all of whose factors will influence the heat flux required to be removed with the external cooling. Therefore, the feasibility of that measure in the existing plants is highly plant-specific. Recently, I. S. Hwang et al. proposed an ex-vessel cooling measure using an artificial guide vessel named COASISO (Corium Attack Syndrome Immunization Structures Outside) to facilitate the rapid wetting of the lower head[5]. To concretize this methodology, however, the parametric evaluations on the dimension of the gap structure and the water mass flow rate for the effective cooling should be preceded.

This paper presents the results of a feasibility experiment for assessing the efficacy of ex-vessel cooling through the external guide vessel proposed by the concept of COASISO. Experiments have been conducted in the LAVA test facility at KAERI, using a 1/8 linear scale mockup of a lower plenum[6]. The molten corium in the lower plenum was simulated using Al_2O_3/Fe thermite melt. In this study, four tests were performed varying the boundary conditions at the outer surface of the vessel.

2. Descriptions of Experiments

The experiments were performed in which the reactor vessel lower head was simulated with a 1/8 linear scale mock-up. This hemispherical test vessel made of commercial carbon steel (SA516-Gr.70) had a 50 cm diameter with a 2.5 cm wall thickness. To create the necessary high heat fluxes, up to 40 kg of molten Al_2O_3/Fe thermite was simulated as molten core. The Al_2O_3/Fe thermite melt achieves temperatures of about 2400 K. For disrupting the potential of the jet impingement effect of the high-temperature melt, the thermite melt reaction is initially generated in the lower head vessel.

Four tests were performed varying boundary conditions at the outer surface of the vessel. The first dry test was conducted without cooling the outside of the vessel. On the other hand, in the second test, the cooling of the vessel surface was produced by gravity-driven forced circulation of water along the annular gap of 25 mm between the vessel and the external guide vessel. Water flow rate was about 0.85 kg/s and total mass of available water was 300 kg. For the evaluation of the water flow rate effect, the third test was performed with water pool in the annulus without any circulation of water. The dry test was performed in open space at ambient pressure condition for visual observations on the sequences of the reaction. The other external cooling tests, however, were conducted inside the pressure vessel (LAVA facility) under elevated pressure of about 1.6 MPa. The initial water subcooling was similar in both tests by 180 K. In this study, another pool type ex-vessel cooling test was conducted under atmospheric pressure condition to evaluate the effect of system pressure on boiling heat transfer characteristics.



(a) Dry Test

(b) Ex-vessel Cooling Test

Figure 1. Thermocouples Locations

The occurrence of vessel failure and the thermal behavior of the vessel have been measured by K-type thermocouples embedded in the 3 mm depth of the vessel outer surface, as shown in Figure 1. The additional K-type thermocouples were embedded in the 20 mm depth of the vessel outer surface in the dry test and 13 mm depth of the vessel outer surface in the other ex-vessel cooling tests, respectively at marking points to calculate the conduction heat flux through the vessel wall.

3. Experimental Results

In the dry test, after about twenty-eight seconds from the thermite ignition, the vessel was heated to cause a complete melt penetration at about 40 degree from the apex of the vessel bottom. Figure 2 shows the configuration of the vessel failure and the calculated heat flux variations at T1, T2 thermocouple locations. According to the Figure 2 the imposed heat flux through the vessel exceeds 1.5 MW/m^2, which indicates that the heat flux generated from thermite melt in this study is quite conservative compared with the TMI-2 case even though decay heat effect isn't considered right now.

The Al_2O_3/Fe thermite melt is mixture of alumina (Al_2O_3) and iron (Fe). And since the iron is denser than the alumina, the separation of melt components occurred during the thermite reaction and so the first material to contact with the inner surface of the vessel was molten iron. The melt separation process occurred at about 40 degree from the apex of the vessel bottom, which is coincident with the location of the vessel failure. This result shows that the natural convection flow inside the melt pool and the melt separation process cause the formation of the hot spot and successive melt penetration.

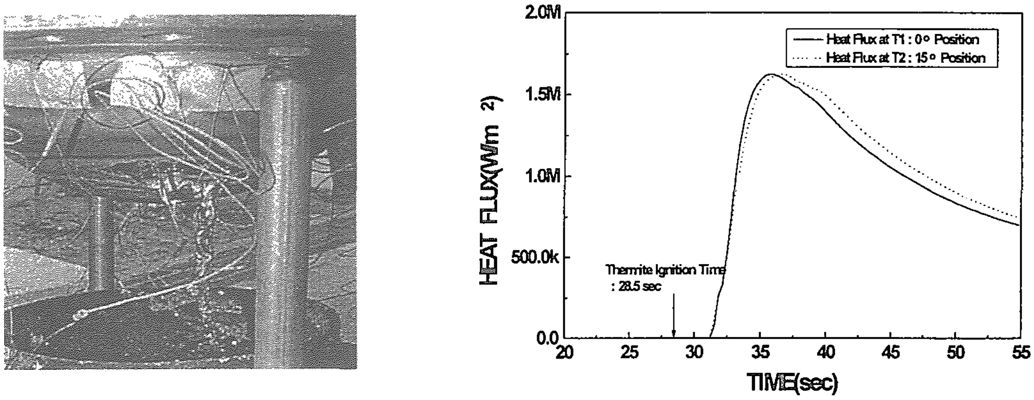
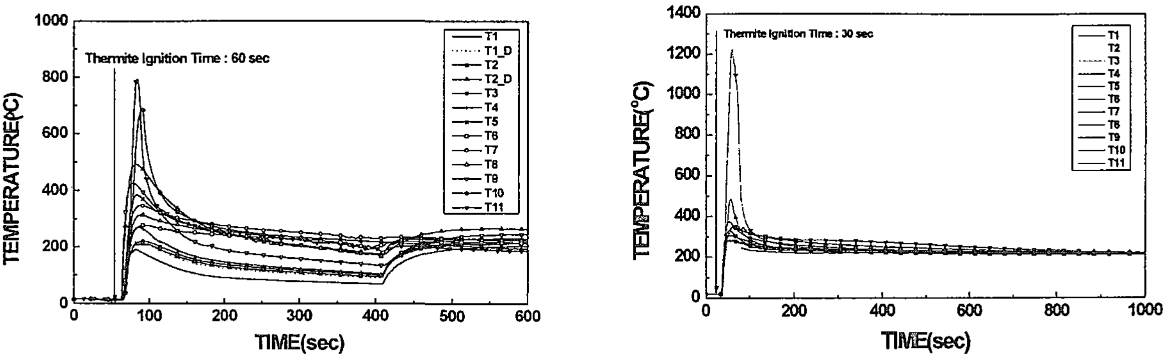


Figure 2. Configuration of the Vessel Failure and Calculated Heat Flux Variations in the Dry Test

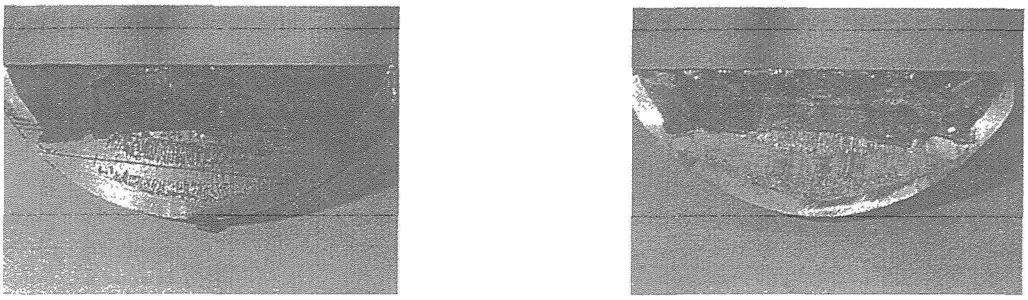
On the contrary to the results of the dry test, in both of the ex-vessel cooling tests performed under elevated pressure of 1.6 MPa, the vessel didn't fail. Figure 3 shows the temperature histories of the vessel in both of the tests. Compared with the pool type test, the vessel experienced effective cool down due to the inlet flow in the forced flow test. According to the cross-sectional view of the vessel in Figure 4, however, the iron welded to the inner surface of the vessel resulting in significant ablation at about 40 degree from the apex of the vessel bottom where the melt separation occurred. This result implies again the leading effect of the melt separation process on the thermal attack to the vessel. In the pool type ex-vessel cooling test conducted under atmospheric pressure, the vessel failed at similar timing and position to the case of the dry test. Figure 5 shows the configuration of the vessel failure.



(a) Forced Flow Ex-vessel Cooling Test

(b) Pool Boiling Ex-vessel Cooling Test

Figure 3. Temperature Histories of the Vessel in the Ex-vessel Cooling Test



(a) Forced Flow Ex-vessel Cooling Test (b) Pool Type Ex-vessel Cooling Test

Figure 4. Cross-sectional View of the Vessel

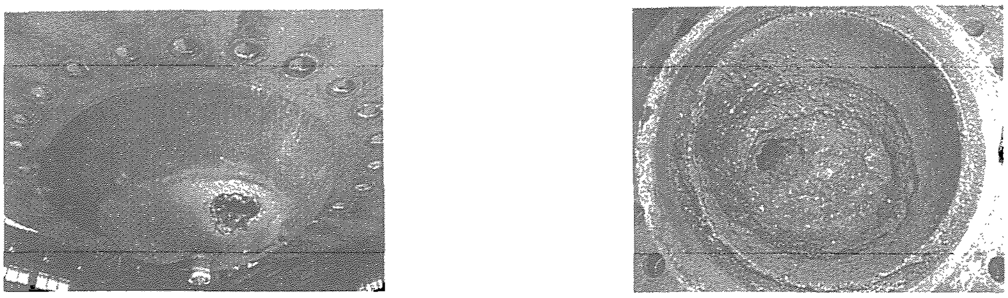


Figure 5. Configuration of the Vessel Failure in the Pool Boiling Ex-vessel Cooling Test Performed under ambient Pressure

Unlike to the result of the forced flow ex-vessel cooling test, in the pool type ex-vessel cooling test, the configuration of the vessel ablation was quite asymmetric, which could be found in the temperature histories of the vessel in Figure 3 also. This result implies that the heat transfer in the pool type ex-vessel cooling test could be asymmetric depending on the initial conditions such as melt generation process etc.. On the other hand, in the forced flow ex-vessel cooling test, the uniform cooling of the vessel along the same latitude could be achieved by means of forced inlet water flow at the bottom of the vessel.

Figure 6 shows the calculated heat flux and the heat transfer coefficients from the vessel outer surface to the adjacent water in the forced flow ex-vessel cooling test. According to the heat flux in Figure 6 it is shown that the upper position of the vessel experienced severer thermal attack but the heat flux decreased with time because of the increasing conduction length as the melt solidified inside the vessel. The averaged heat transfer coefficients at T1, T2 were 6000 W/m^2K, 8000 W/m^2K, respectively which indicate that the vessel effectively cooled down by nucleate boiling at the surface of the vessel.

Figure 7 shows the calculated heat flux and the heat transfer coefficients from the vessel outer surface to the adjacent water in the pool type ex-vessel cooling test performed under elevated pressure of 1.6 MPa. In this test, the heat flux at 15 degree from the apex of the vessel bottom is slightly less than that of the forced ex-vessel cooling test and the averaged heat transfer coefficients at T1, T2 were 3000 W/m^{2}K, 4000 W/m^{2}K, respectively. According to Figure 6 and 7, in the forced flow test, the heat removal capacity at the vessel surface is larger than the case of the pool boiling test due to the gravity-driven forced inlet water flow.

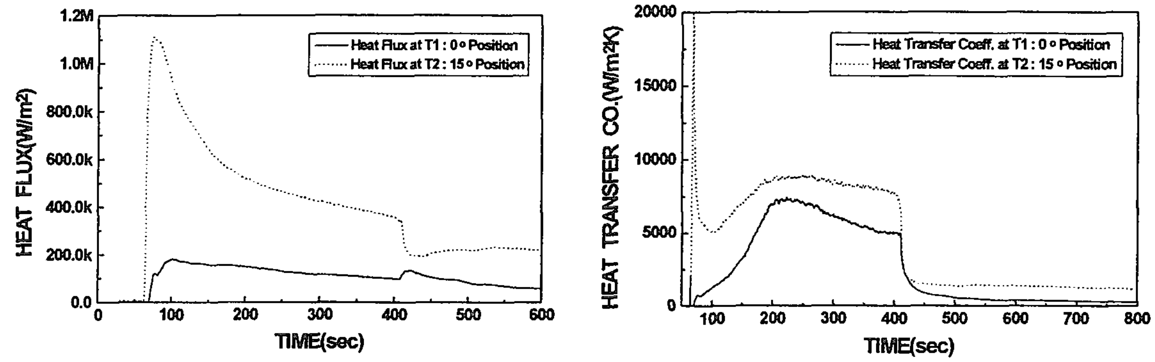


Figure 6. Calculated Heat Flux and Heat Transfer Coefficients in the Forced Flow Ex-vessel Cooling Test

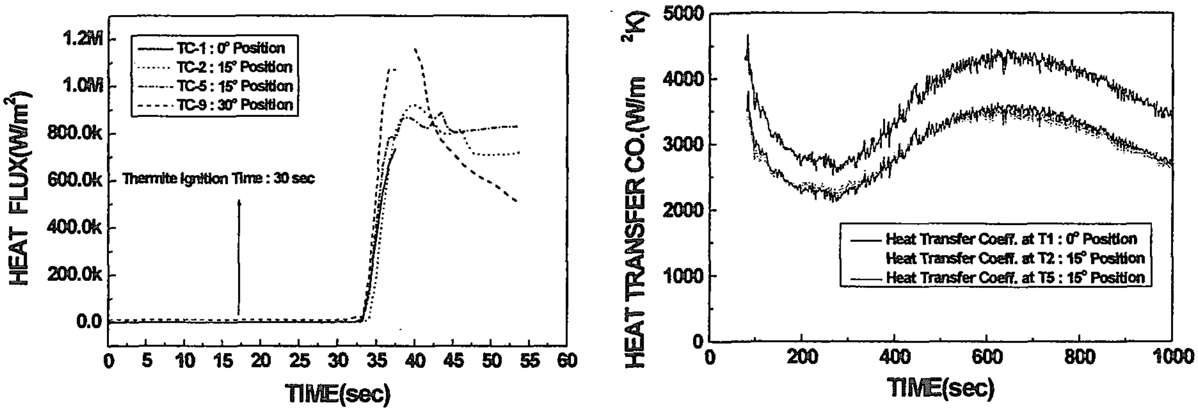


Figure 7. Calculated Heat Flux and Heat Transfer Coefficients in the Pool Boiling Ex-vessel Cooling Test performed under 1.6 MPa

4. Conclusions

A series of experiments for assessing the efficacy of ex-vessel cooling through the external guide vessel were performed in the LAVA test facility at KAERI, varying the boundary conditions at the outer surface of the vessel. In the dry test and the pool type ex-vessel cooling test performed under atmospheric pressure, the vessel failed by a melt penetration at about 40 degree upper position from the vessel bottom, which is coincident with the boundary of the Al_2O_3/Fe melt separated layers. On the other hand, in both of the ex-vessel cooling tests conducted under elevated pressure of about 1.6 MPa, the vessel didn't fail. Compared with the pool type test, the vessel experienced effective cooling due to the inlet flow in the forced flow test.

As the feasibility study of the ex-vessel cooling through the external guide vessel, the results of this study couldn't fully guarantee the applicability of the pool type ex-vessel cooling measure. However, if the forced flow ex-vessel cooling could be achieved at the outer surface of the vessel, even though the formation of hot spot at the upper portion of the vessel, the vessel could effectively cool down by heat removal with ex-vessel cooling. To concretize the feasibility of the ex-vessel cooling through the guide vessel in this study, the additional tests varying the flow rate of water and the gap size should be performed. Also, the thermal-hydraulic experiments to quantify the coolability limits of the reactor vessel lower head by external cooling measure will be conducted at KAERI in late 1999.

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REFERENCES

1. Robert E. Henry et al., "Cooling of Core Debris within the Reactor Vessel Lower Head," Nuclear Technology, Vol. 101, pp 385 - 399(1993).
2. T. Y. Chu et al., "Ex-vessel Boiling Experiments : Laboratory and Reactor Scale Testing of the Flooded Cavity Concept for In-vessel Core Retention," Nuclear Engineering and Design, Vol. 169, pp 77 - 88(1997).
3. F. B. Cheung et al., "Critical Heat Flux(CHF) Phenomenon on a Downward Facing Curved Surface : Effects of Thermal Insulation," NUREG/CR-5534(1998).
4. T. G. Theofanous et al., "In-vessel Coolability and Retention of a Core Melt," Nuclear Engineering and Design, Vol. 169, pp 1 - 48(1997).
5. I. S. Hwang, et al., "The COASISO Design(II) : Proof-of-principle Demonstration," The 14th KAIF/KNS Annual Conference, Seoul, Korea, April 7-9, 1999.
6. K. H. Kang, et al., "Experimental Investigation on In-vessel Debris Coolability through Inherent Cooling Mechanism, OECD/CSNI Workshop on In-Vessel Core Debris Retention and Coolability, Garching, Germany, March 3-6, 1998.
7. Yang, S. H., Baek, W. P. And Chang, S. H., " An Experimental Study of the Pool-boiling CHF on Downward Facing Plates ", Journal of the Korean Nuclear Society, V. 26(4), p493-501, 1994