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Long-Term Behavior by Beam Tube Break (BTLOCA) Accident at HANARO

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1. Introduction

HANARO is the 30 MW pool-type research reactor with finned fuel rods made of Uranium Silicide (U_3Si) inserted in Aluminum alloy. The reactor utilizes a neutron source rather than a thermal energy, therefore, it is operated in atmospheric pressure under the saturation temperature. Even the primary cooling pumps stop, the fuel is cooled in the reactor pool by natural convection with no external power. No fuel damage is expected in most of postulated initiating events (PIEs).

The pool water is the ultimate heat sink of the reactor system, which is contained in the concrete pool with the leak-tight steel liner. The devices such as the pipes and the pumps outside of the pool are located much higher than the reactor structure assembly(RSA), preventing the excessive loss of the pool water.

Beam tube break (BTLOCA), however, is the multiple failure of the seals of the beam tube, causing the excessive coolant loss when occurs. The beam tube is the penetration through the pool wall to extract the neutron source from the core, and has multiple seals to prevent the coolant loss through it. Although the simultaneous failures of multiple seals are not probable, the BTLOCA is the only scenario which causes the pool water level decrease to a dangerous level.

In this paper, the long-term behavior by BTLOCA accident was analyzed using MELCOR code, to examine the fuel degradation and corresponding fission product release. The results are expected to provide the insights for the emergency preparation for the reactor under an extreme situation.

2. Modeling for Analysis

The analysis was performed with the MELCOR code, the systematic analysis code for the severe accidents of nuclear reactors [1]. The code has capability of coping with various physics related to the nuclear reactor, including the fuel degradation and the fission product behavior. However, most of the models are developed for the nuclear power plants operated with UO_2 fuels. Many of research reactor including HANARO uses Uranium Silicide fuel with Aluminum alloy, which is incompatible with the MELCOR material library.

To overcome the limitation of fuel material library, the property of the fuel such as the thermal conductivity, the specific heat and the enthalpy were included in the input, and the fuel and cladding was substituted with the Uranium Silicide and the Aluminum alloy. Also, the release rate of the fission product from Uranium Silicide fuel was modeled using the sensitivity coefficients of MELCOR [2].

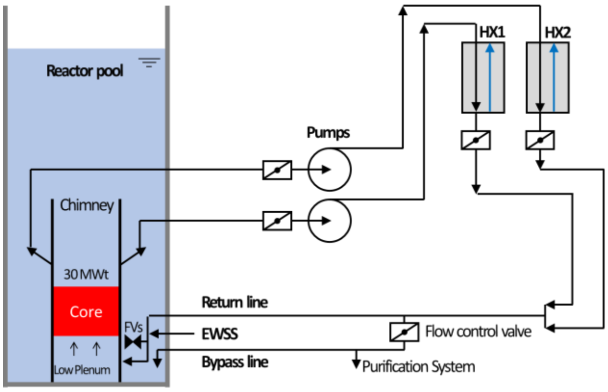

Fig. 1 Primary Cooling System (PCS) of HANARO

Figure 1 shows the schematic of primary cooling system (PCS) of HANARO, including the reactor structure assembly (RSA) and the reactor pool. The system is composed of two primary cooling trains, and each train equips a reactor cooling pump (RCP) and a heat exchanger. The heat from the core is delivered by the coolant and dumped to the secondary system at the heat exchangers. The two cooling trains are then merged into the common return line before connected to the lower plenum (LP) of the RSA. A bypass line is branched from the main cooling line for the purification of the primary coolant, and then discharges the clean coolant into the pool.

The flap valves are the engineering safety feature of the reactor, providing the path for the natural convection when the primary pumps stop. The flap valves are closed during normal operation, and opened passively when the differential pressure across the valves decreases lower than 100 Pa by the trip of the primary cooling pumps. The emergency water supply system (EWSS) supplies coolant when the pool water level becomes very low, however, was not considered in the analyses for the conservative analyses.

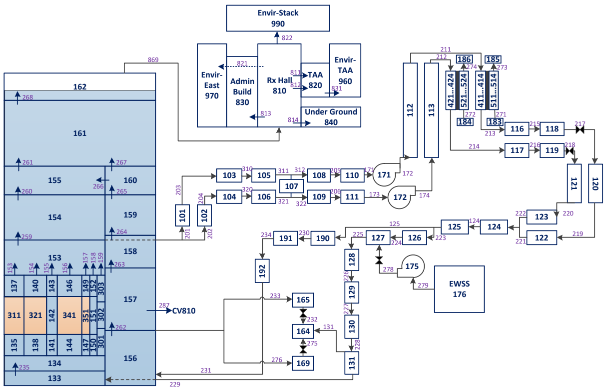

Fig. 2 Nodalization for MELCOR analysis

Table 1 Steady-State Condition of Analyses

Variable	Design	Analysis
Core Power (MW)	30	31.5
Core flow (kg/s)	703	685
Pool Level (m)	12.2	12.1
Coolant Temp (°C)	35	35.9

Figure 2 shows the nodalization of the reactor system for the MELCOR analyses. The detailed data for the modeling were referenced from the accident analyses report using RELAP/KMRR, which is the modified version of RELAP5/MOD2 developed for HANARO analyses [3].

Table 1 shows the major initial conditions used for the analyses. The conditions were determined considering the conservatism from the nominal design values, and the additional assumptions were also made for the conservative analyses as below

1. Only one flap valve works properly (single failure criterion).
2. The EWSS fails to supply coolant into the core.
3. The PCS pumps and the heat exchangers stop the operation with the reactor trip.

All the assumptions above are conservative in terms of fuel cooling, and results in the fastest transient during the accidents. For example, if the EWSS works properly, the fuel is not expected to be degraded until the EWSS coolant is depleted completely.

Figure 3 shows the cross sectional view of a standard beam tube. The beam tube casing is penetrating the concrete wall of the pool and connected to the pool liner, and multiple seals are preventing the coolant leak through the beam tube. The pool water can leak when the seal plate of the collimator and the diaphragm of the outer case ruptures simultaneously. The gap between collimator and the first grouting is only 2mm, and the opening area of the gap is 1.546e-3m^2. There is another gap between rear shielding plug and the first grouting, however, was not considered because the gap between the collimator and the first grouting was considered to be a bottle neck. The hydraulic diameter was 4 mm, and the length was about 500 mm.

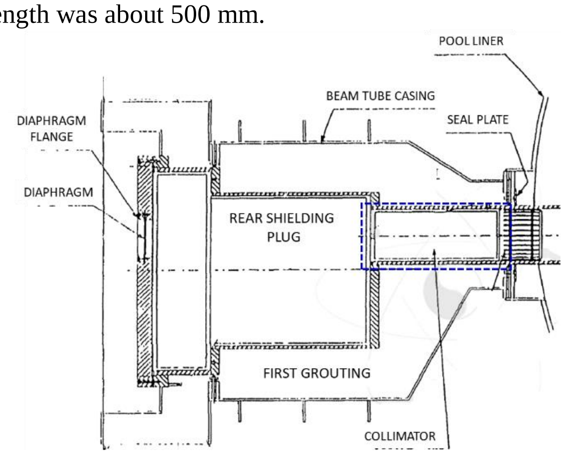

Fig. 3 Cross section of standard beam tube

Table 2 Event Sequences of BTLOCA

Events	Time (s(hr))
Beam tube seals break (BTLOCA)	0
Reactor trip by low-low pool level RCPs trip, HXs trip	3844(1.1)
Flap valve open passively	4169(1.2)
Level reaches chimney top	36800(10.2)
Fuel cooled by natural circulation	~

3. Analysis Results

3.1 Thermal-Hydraulic Behavior

Table 2 shows the major event sequences by BTLOCA scenario. When the beam tube seals break, the pool water flows out through the small gap of the beam tube, and the pool level decreases. When the pool level reaches the low-low set point, the reactor trips by the reactor protection system. The pumps were assumed to be tripped with the reactor trip, and the HXs also lose the function of heat removal. The RCPs start coast-down, and soon the flap valves open when the RCPs completely stop. Then, the core is cooled by natural convection.

In the BTLOCA scenario, the decreasing speed of the pool level determines the mission time for available mitigation measures for the event. The pool level decrease in the previous safety analysis report is calculated simply based on the Bernoulli equation as [3]

$$m_{break} = \rho_{water} C_d A_{break} \sqrt{2g\Delta z},$$

where the C_d is the discharge coefficient, conservatively assumed as 1. However, the break flow rate depends not only the break area, but also the hydraulic diameter and length of the break. Since the flow pass through the beam tube is narrow and long annular shape, the actual discharge coefficient is expected to be much higher than 1, delaying the pool level decrease.

Figure 4 shows the pool level during BTLOCA calculated from MELCOR and those calculated by Bernoulli equation. In about 10.2 hour from the beginning of the accident, the pool level reaches the top of the RSA chimney. In comparison, the previous safety analysis report claimed that the level reaches to the chimney top in 3 hr 52 min, which showed much faster transient because the calculation neglected the break.

After the pool level reaches the top of the RSA chimney, the EWSS starts operation which is not guaranteed in the analyses. The flow rate from EWSS is about 11.4kg/s when supplied passively by gravity. When the EWSS works, the pool level stops to decreases, and the accident progress is delayed until the EWSS coolant is depleted.

Figure 5 shows the coolant flow of the PCS and through the core and the flap valve. When the PCPs is tripped, the reactor core is cooled by natural convection not via the flap valve, but through the entire PCS loop. The natural convection through the PCS occurs by the density difference across the heat exchangers, and stops

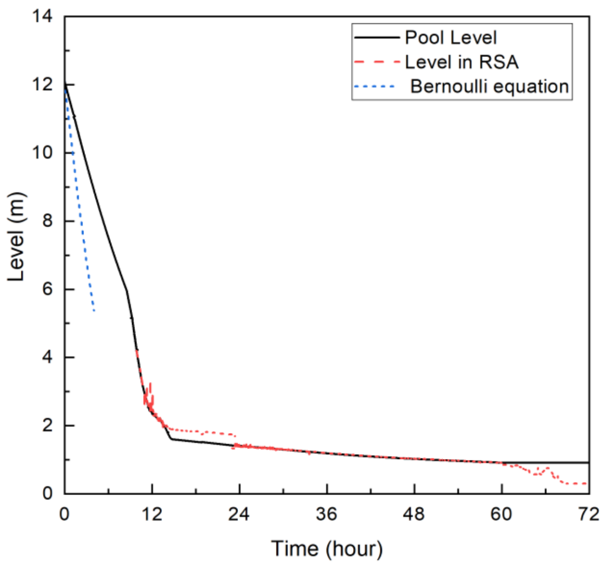

Fig. 4 Pool level decrease during BTLOCA

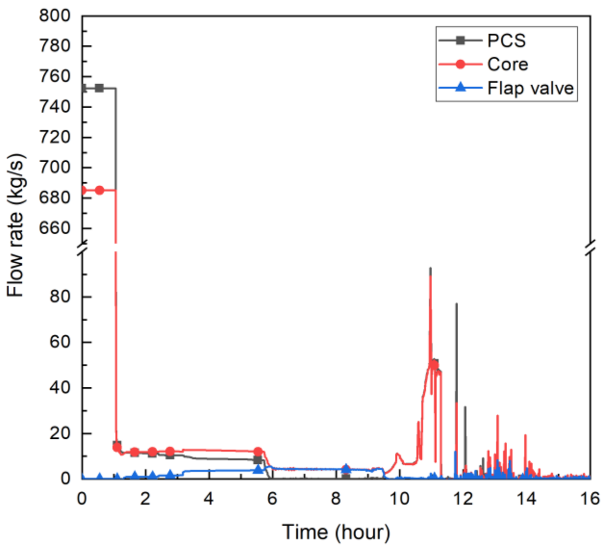

Fig. 5 Coolant flow during BTLOCA

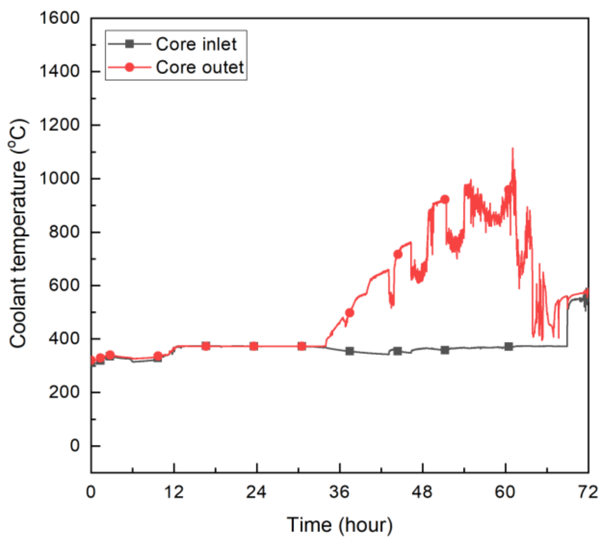

Fig. 6 Coolant temperatures during BTLOCA

when the temperature of the entire PCS become homogenized. Then, the natural convection occurs via the flap valve, until the water level in the RSA decreases by the evaporation due to the decay heat from the core.

Figure 6 shows the inlet and outlet temperature of the reactor core, which is maintained below the saturation temperature until about 33 hours from the event initiation by the natural convection and the latent heat of the coolant. When the coolant temperature reaches the saturation point, the core outlet temperature increases by the steam generation, and the fuel starts to degrades. The core inlet temperature keeps the saturation points until 70 hours, and then the temperature increases when the water is completely dry out.

3.2 Fuel Degradation

Figure 7 shows core nodalization of HANARO, with 16 axial nodes. The core and the grid plates are composed with 4 radial rings, and the lower plenum is with 6 rings.

Figure 8 shows the fuel temperature during the event, and the temperature becomes as high as 1100 K, and then melts down and drops to the lower plenum. Since the fuel rod is made of Uranium Silicide and Aluminum alloy, the melting temperature is much lower than the fuels in most of PWRs. Typically, the melting temperature of the Aluminum alloy is about 930 K. Also, negligible amount of hydrogen was generated due to the low temperature.

Figure 9 shows the relocation of the active fuel material, starts to drop to the grid plates and the lower plenum after about 60 hours from the event initiation. Most of the fuel materials dropped to the lower plenum but about 20 kg of the fuel material remains at the grid plates even after 72 hours. The grid plates material, Aluminum alloy, also shows similar behavior except for the initial position.

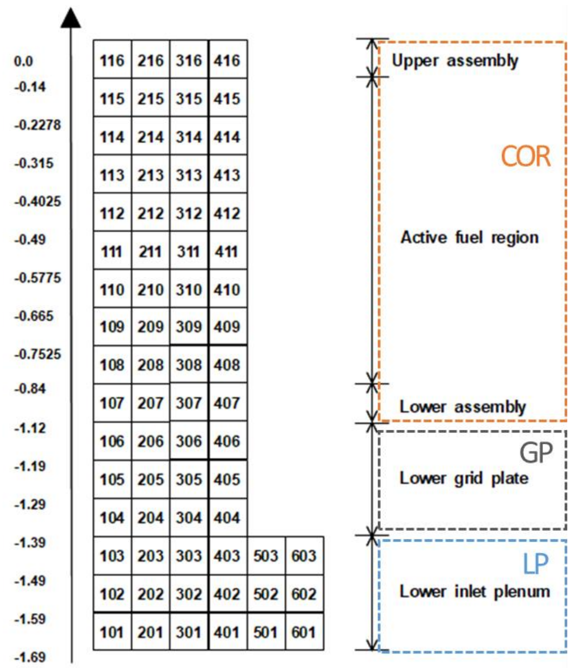

Fig. 7 Core nodalization of HANARO

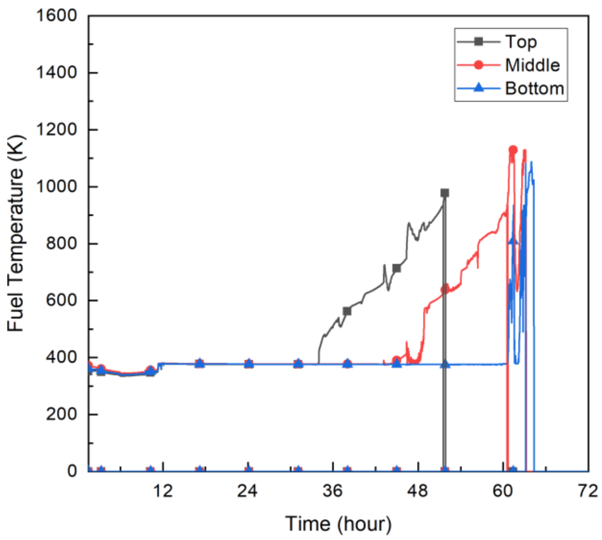

Fig. 8 Fuel temperatures during BTLOCA

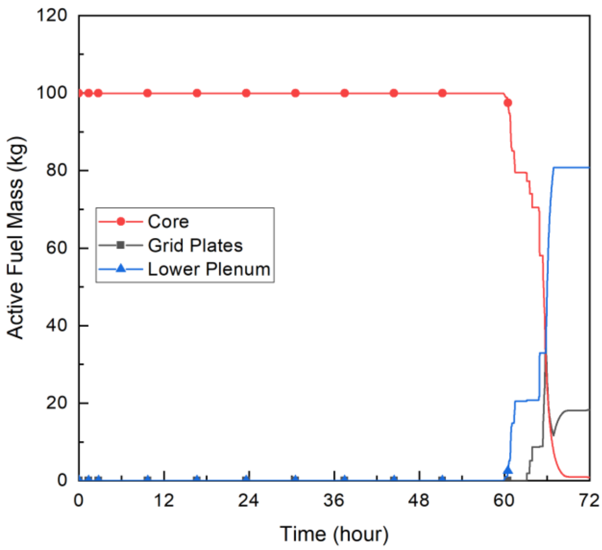

Fig. 9 Active fuel mass during BTLOCA

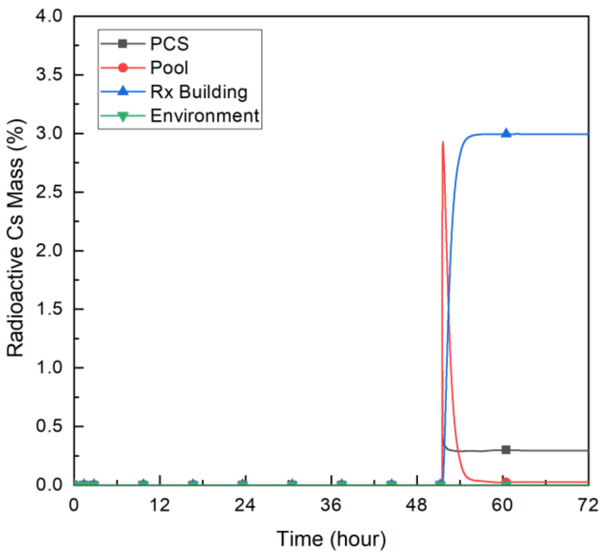

Fig. 10 Radioactive Cs mass during BTLOCA

3.3 Fission product release

Figure 10 shows the long-term Cs release by the BTLOCA, in a form of CsOH aerosol. It should be noted that only about 3% of total core inventory is released, due to the low temperature of degraded fuel. The Cs is initially released from the PCS to the reactor pool and then moves to the reactor building as the pool water evaporates. The aerosol is then released to the environment by the natural leakage from the reactor building, however, the leak is negligibly small. The reason of the small leakage is due to the low pressure in the reactor building. Even the pool water evaporates by the decay heat from the core, the reactor building does not pressurize because the evaporated steam condensates in the building due to the large volume of the building and the slow transient. Therefore, the leak from the reactor building to the environment occurs very slowly.

By the small release fraction and the small leakage from the reactor building, the environmental effect by the BTLOCA at HANARO seems negligibly smaller than conventional nuclear power plants, however, detailed radiological consequences need to be evaluated via Level 3 PSA.

5. Summary

The long-term behavior during BTLOCA in HANARO was analyzed using MELCOR code. The beam tube break was assumed by the simultaneous break of seals, and the reactor behaviors by the coolant loss was reported

The water level decreased much slower than that expected by Bernoulli equation in the previous safety analysis, and the fuel degradation started about 36 hours from the accident initiation. After that, the fuel started to heat up and then melted down finally after 60 hours. The fuel was then relocated from the core region to the lower plenum, and the fission products were released.

The total release of Cs aerosol from the fuel was only about 3% of the initial inventory, because of the low temperature of degraded fuel. At the same time, the release to the environment was negligibly small, due to the low pressure in the reactor building.

Acknowledgement

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