Evaluation of Thermal-Hydraulic Performance for HANARO Irradiation Test of High Density LEU Target

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) is developing a high density LEU target with higher density of uranium than before to produce fission ^{99}Mo[1]. The high density target can alleviate the reduction in the amount of ^{235}U due to the conversion of high enriched uranium (HEU) to low enriched uranium (LEU), reduce the radioactive waste and increase the production efficiency of fission ^{99}Mo. This is based on the centrifugal atomization technology developed by KAERI that it is more advantageous for manufacturing high density target than crushing-based manufacturing methods. Therefore, when the development is completed, the outstanding performance of high density LEU target manufactured by centrifugal atomization technology will be verified. In additional, many requests will be expected from domestic and foreign users.

In order to confirm the performance of high density LEU target manufactured by centrifugal atomization technology, it is necessary to conduct the in-reactor testing. HANARO irradiation test was planned for high density LEU targets with 3.2 gU/cc and 4.0 gU/cc that the uranium densities were increased up to 54% than conventional one. As the uranium density increases, the heat flux in the core also increases, so it is necessary to evaluate the thermal-hydraulic safety of the HANARO irradiation test. In this paper, we present the safety analysis results based on the out-of-core hydraulic test for in-reactor testing of high density LEU target at HANARO.

2. Out-of-reactor hydraulic test

2.1 Test rig design

The test rig for the irradiation test of the high density LEU targets was identically designed as the test of target for KJRR conducted in 2018[2]. Fig. 1 shows the assembly drawing of the rig. It can accommodate real size six targets. The targets are inserted into the upper and lower housing clusters. The spacing between the targets was referred from the design of the target holder of KJRR. The overall structure design of the rig was applied from the design of the instrumented capsule because it is verified in HANARO by various tests.

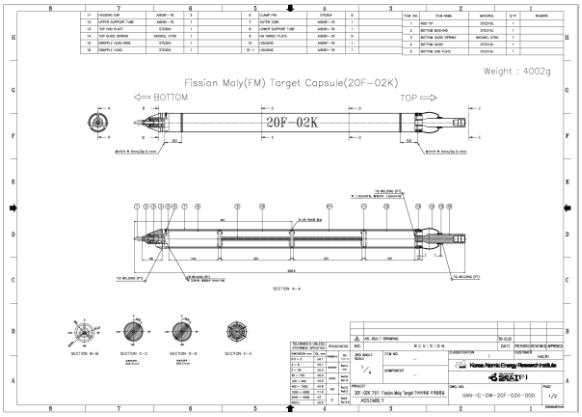

Fig. 1. Assembly drawing of test rig for high density target

2.2 Test facility

A single channel test loop was used to measure the hydraulic properties of test rig. The single channel test loop is a facility that can simulate hydraulic behavior in a single hexagonal or circular flow tube. It can measure the hydraulic characteristics according to the loading of the test rig under normal operating conditions, differential pressure between entrance and exit channel of 209 kPa. Representative hydraulic parameters are the channel flow rate and the differential pressure in the bypass flow path that does not contribute to the cooling of the target. Also, it is evaluated whether the rig can maintain the integrity in the HANARO irradiation hole by measuring flow induced vibration with Laser Doppler Vibrometer (LDV). Fig. 2 shows a picture of out-of-reactor hydraulic test in the single channel test loop for the test rig.

Fig. 2. Out-of-reactor hydraulic test of test rig

2.3 Test results

Since the design specifications of the rig and the targets for both KJRR and high density LEU target are same, the same hydraulic parameter measurement was expected, but the test results were different. In the case of KJRR target, the channel flow rate was 6.15 kg/s, whereas the high density LEU target was 8.3 kg/s. As the result of the test analysis, it was confirmed that the housing cluster cover was misassembled and blocked the cooling channel during the test for KJRR target. Therefore, it is necessary to check whether the assembly is properly performed when assembling for the irradiation test between the rig and targets.

Table 1 shows the measurement results of hydraulic parameters. The channel flow path consists of a flow path that flows into the rig to cool the target and a bypass flow path that flows out of the rig inside channel. As the result of measuring the differential pressure of the bypass flow path, it was 132 kPa. Considering the hydraulic characteristics and design specifications, the flow rate of bypass flow path can be evaluated. The Root Mean Square (RMS) vibration displacements were 9.65 μm in the north-south direction and 20 μm in the east-west direction, showing no significant difference from other test rigs. The frequency characteristics of the rig also showed similar with the previously tested rigs, so it was evaluated that there would be no resonance with the HANARO pump frequency (99Hz). Through this data, the inherent safety of the rig has been confirmed. This hydraulic test results will be also used as input data for thermal-hydraulic safety evaluation.

Table I: Measured results of hydraulic parameters

Variable	Measured value
Flow rate of channel (Fuel dummy)	12.7 kg/s
Flow rate of channel (Test rig for high density target)	8.3 kg/s
Flow rate of channel (Test rig for KJRR target)	6.15 kg/s
Differental pressure of bypass flow path	132 kPa
Vibration displacement (north-south direction)	9.65 μm
Vibration displacement (east-west direction)	20 μm

3. Thermal-Hydraulic Evaluations

3.1 Evaluation method

We conducted the safety evaluation under normal operation and accident condition. We established the acceptable criteria for the safety analysis of high density LEU target test at HANARO as follows:

(1) In order to maintain the cooling capacity of the target during normal operation, boiling should not occur on the target surface. Therefore, Onset of Nucleate Boling (ONB) temperature margin mare than 3℃ must be secured.
(2) The target should not be melt during normal operation or accident conditions. Therefore, the meat maximum temperature should not exceed 400℃ conservatively.
(3) In case of any accident condition, more than Critical Heat Flux Ratio (CHFR) of 1.5 must be maintained to ensure the integrity of the target.

The thermal-hydraulic safety evaluation for the test of the high density LEU target was conducted using TH_Calc Win[3] code. It is reliable for this evaluation because it was verified to have the same performance with TMAP, which is the licensing code for KJRR design.

3.2 Input data

The TH_Calc Win requires input data such as the thermal-hydraulic characteristics of test rig during the HANARO test and the design specifications of target and rig. Among them, the important information is the flow rate that contributes to cooling the target. We need to convert from the differential pressure measured by hydraulic test to the flow rate of the bypass flow path, which does not contribute to the cooling of the target. By subtracting the converted bypass flow rate from the channel flow rate, the flow rate contributing to cooling can be calculated. However, since the design of single channel test loop is slightly different with HANARO irradiation hole, we conservatively used 20% of uncertainty value. In addition, 5% uncertainty of the instrumentation and system was considered. Finally, the cooling flow rate for target of 4.18 kg/s was used for safety evaluation of high density LEU target test.

3.3 Evaluation results

The heat flux of high density LEU target during the test was evaluated by McCARD[4] from full core simulation at the beginning of the cycle (BOC), the middle of the cycle (MOC) and the end of the cycle (EOC) considering the operation of control absorber rod and HANARO driver fuel depletion. In the McCARD evaluation, only fresh target without considering depletion was conservatively considered. We representatively assumed the accident conditions such as the control rod absorber withdrawal and locked rotor of pump. According to the HANARO safety analysis report[5], it was evaluated that the heat flux is increased by 131% in case of the control rod absorber withdrawal accident and the flow rate is decreased by 56% in case of the locked rotor accident compared to the normal operation condition. The design and manufacturing information of the test rig and target was used for uncertainty calculation for safety evaluation.

Table 2 and 3 shows the safety evaluation results for the high density LEU target test at HANARO. The ONB temperature margin was exceeded at the upper target when assuming the EOC during normal operation at full power (30 MW_{th}) operation. At the reactor power of 27 MW_{th}, every evaluation was satisfied. As mentioned

above, the heat flux analysis result at the EOC is very conservative because target depletion was not considered. Nevertheless, to ensure test safety with enough thermal margins, the power of HANARO should be 27 MW_{th} or less. Since all results were satisfactory in the accident condition, it was concluded that the test could be carried out at HANARO if the power could be adjusted.

Table II: Safety evaluation results under normal operation

	Upper target (30 MW_{th})		**Upper target (27 MW_{th})**	
Mode	B.E.	C.E.	B.E.	C.E.
Average heat flux (W/cm^2)	178.4		160.56	
Power peaking factor	1.333		1.333	
Housing exit coolant temperature (℃)	44.52	46.08	43.72	45.12
Target surface temperature (℃)	104.87	152.24	98.15	140.87
Cladding temperature (℃)	122.12	176.89	113.68	163.06
Target meat temperature (℃)	214.95	309.52	197.22	282.42
ONB temperature margin (℃)	42.73	**-5.91**	49.45	5.46
CHFR	4.01	2.8	4.47	3.13

B.E. : Best Estimation, C.E. : Conservative Estimation

Table III: Safety evaluation results under accident condition (27 MW_{th})

	Lower target (3.2 gU/cc)		**Upper target (4.0 gU/cc)**	
Mode	RIA*	LOFA**	RIA	LOFA
Average heat flux (W/cm2)	177.66		160.56	
Power peaking factor	1.133		1.333	
Housing exit coolant temperature (℃)	40.9	42.69	47.8	51.9
Target surface temperature (℃)	102.93	116.98	172.48	200.59
Cladding temperature (℃)	116.59	127.42	201.54	222.78
Target meat temperature (℃)	**153.13**	**155.3**	**357.9**	**342.14**
ONB temperature margin (℃)	45.17	30.42	-26.15	-56.83
CHFR	**5.53**	**6.68**	**2.36**	**2.74**

* RIA : Control rod absorber withdrawal, **LOFA : locked rotor of pump

4. Conclusions

The out-of-reactor hydraulic testing and safety evaluation were performed for the in-reactor testing of high density LEU target and the followings could be concluded.

(1) The results of the hydraulic test showed a difference from the test results with KJRR target test despite same design. This was found to be due to misassembled housing cluster cover during the out-of-reactor hydraulic test. Therefore, there should be no mistake in the process of assembling the rig for the target test. It should be confirmed during the assembling between the rig and target.

(2) As the result of the safety analysis, it was confirmed that the ONB temperature margin at the full power (30 MW_{th}) operation exceeded the allowable criterion. It was satisfied at 27 MW_{th}, so HANARO should be operated with less than 27 MW_{th} for high density LEU target testing.

(3) When accident condition was assumed, all acceptable criteria were met from the safety evaluation.

High density LEU target testing is currently being conducted without any problems at HANARO. The results of this test are expected to be used as important data for the development of the target manufactured by centrifugal atomization technology of KAERI.

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