Design of the Capsule (13M-01K) for Irradiation of Fuel Cladding Materials in HANARO

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1. Introduction

ZIRLO is one of zirconium alloy, which is abbreviation of Zirconium Low Oxidation. Recent trend toward high fuel burn-ups, extended cycles, and higher primary coolant temperatures with higher lithium demands an advanced material for use in fuel assemblies. Nuclear-grade zirconium alloys contain more than 95% Zr, and therefore most of their properties are similar to those of pure zirconium [1]. ZIRLO material, used in fuel rod cladding, structural and flow mixing grids, instrumentation tubes, and guide thimbles, increases margin-to-fuel-rod-corrosion limits and enhances fuel assembly structural stability. The demonstrated corrosion resistance and enhanced structural stability of ZIRLO cladding enable longer cycle lengths at higher temperatures without reducing operating margins.

An instrumented capsule (13M-01K) was designed and fabricated for evaluation of the neutron irradiation properties of Zirlo material, which is commonly used for cladding of nuclear fuel. This capsule is now being irradiated for 2 cycles at CT test hole of HANARO, which was started at Jan 27 and will be ended at Mar 31, 2014. The structure of the capsule was based on the previous capsule (11M-22K capsule) which was successfully irradiated at the same hole of HANARO [2]. In the capsule, 182 specimens such as tensile specimens of plate type and ring type specimens were placed. Most of them are made of Zirlo, but a few are HANA material that is developed in KAERI. The irradiation test was requested by 4 universities including Dong-Kook and Han-Yang etc.

The capsule is composed of 5 layers, each of which has Al holder containing several specimens and an independent electric heater, thermocouples etc. During the irradiation test, temperatures of the specimens and fast neutron fluence were measured by 14 thermocouples and 5 sets of Ni-Ti-Fe neutron fluence monitors installed in the capsule. The capsule is irradiated for 2 cycles (28 days) at the CT test hole of HANARO of a 30MW thermal output at 350-390℃ up to a fast neutron fluence of 9.6×10^{20} (n/cm^2) (E>1.0 MeV).

2. Design of Capsule

2.1 Design requirements

1) Materials, type of specimens and irradiation temperatures

In Table 1, type and numbers of specimens are listed. Specimens are partially corroded and hydrogenated according to requirements with users. Irradiation temperatures of specimens were decided by a professor K. T. Kim of Dong-Kook University. The configurations of specimens are shown in Figure 1 to 3.

Table 1. Materials, types and irradiation temperatures

User	Material	Type	No.	Irradiation temp. (℃)
Dong-Kook Univ.	Zirlo	Ring	63	370-380
		Plate tensile	27	350-380
	HANA	Ring	60	370-380
Han-Yang Univ.	Zirlo	Plate tensile	32	350-380
	Zry-4			
Total numbers		Ring	123	
		Plate tensile	59	

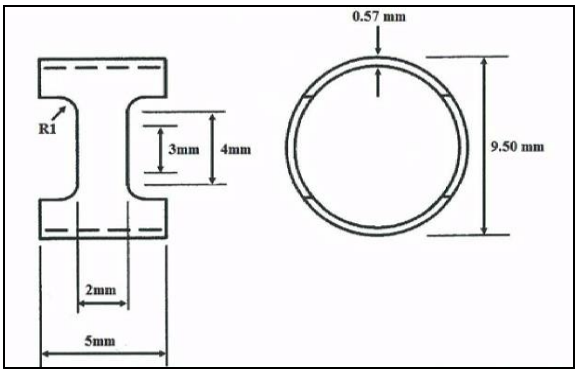

Figure 1. Geometry of ring specimen

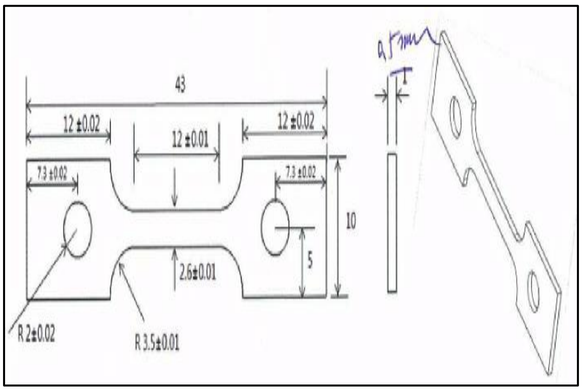

Figure 2. Plate tensile specimen of Dong-Kook University

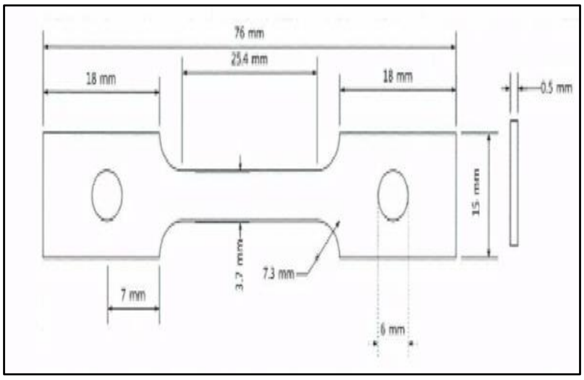

Figure 3. Plate tensile specimen of Han-Yang University

2) Fabrication of specimens

If specimens were corroded and hydrogenated after shaping the geometry, the sizes and shapes of specimens would be changed. These changes in specimens make it difficult to put specimens in capsule. Accordingly, shapes of specimens were processed after corroding and hydrogenating the parent materials. The specimens were handed over at the beginning of July from Dong-Kook University, which is a representative of 4 universities in charge of irradiation work.

2.2 Arrangement of specimens

There are lots of specimens consisting of 123 ring type and 59 plate type, and so it was not so easy to put all of them into 2 layers of capsule. Specimens were inserted into an Al holder as a square bar shape with spacers of same material as shown in Figure 4. Al holder plays a role of thermal media to release heat of specimen rapidly during irradiation because its thermal conductivity is relatively high. And the square bar shape of specimens makes handling simplify and thermal calculation of the capsule more exactly.

Figure 4. Al holder (thermal media) and ring/plate tensile specimen

Specimens are put in the 4th and 5th layers of the capsule as shown in Figure 5 and 6. In 4th layer of capsule, the plate tensile specimens of Dong-Kook University are inserted into the hole #4, and 5 ring specimens are inserted at the rest space of the #4. At the hole #1 and #3, 16 plate tensile specimens of Han-Yang University are put in with 7 ring specimens, and at the hole #2 only 22 ring specimens are put in.

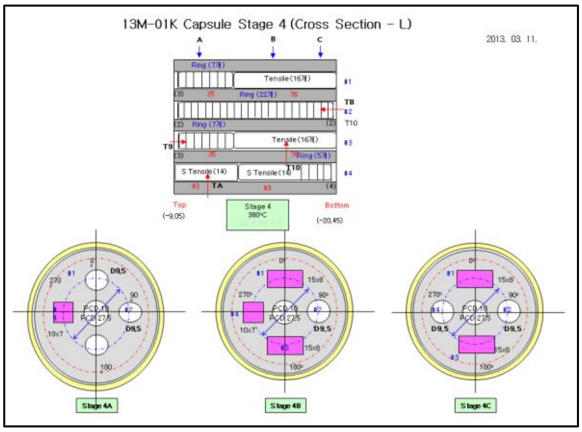

Figure 5. Arrangement of specimen at 4th layer

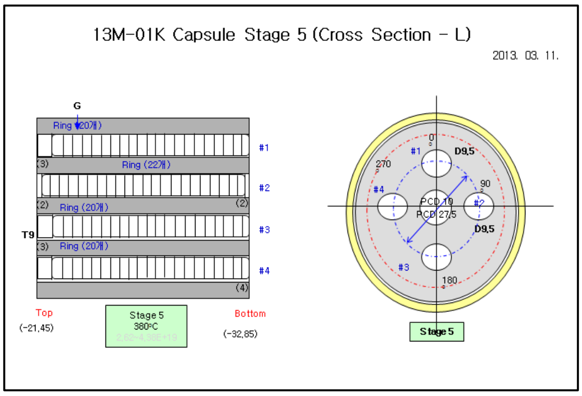

Figure 6. Arrangement of specimen at 5th layer

3) Ring specimens

The ring specimens of Dong-Kook University have shapes as shown in Figure 1. Several ring specimens are inserted in the center rod as in Figure 7, which takes the inner space of ring. The outer/inner diameters of the ring specimen are 9.5/8.36 respectively. The diameter of the center rod is 7.96mm, and the gap of 0.2 mm exists between specimen and center rod. The diameter of specimen hole is 9.7 mm, and so the gap is 0.1mm between specimen and specimen hole. The center rod is made of Zr, which is same material as specimen and makes the estimation and real of specimen temperature more exact.

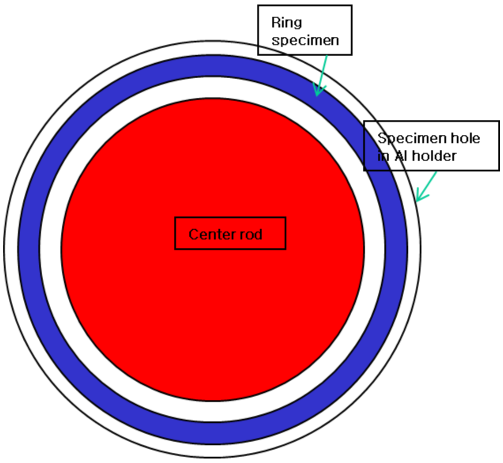

Figure 7. Ring specimen and center rod

4) Plate tensile specimens

The gap is 0.1mm between the plate tensile specimen and the hole.

2.3 Irradiation capsule

The irradiation capsule of 13M-01K was aimed for evaluation of irradiation properties of Zirlo and HANA materials at rather higher neutron fluence. The capsule was fabricated as same shape as the previous one (11M-22K), which was irradiated on July 2012 to irradiate some plate tensile and ring specimens of Zr material at the same CT hole. The irradiation conditions like temperatures are same as the first capsule according to a user's requirements. Temperatures of specimens rise by gamma heat during irradiation. Irradiation temperatures of the specimens were estimated using ANSYS codes [3] in the design stage. The irradiation temperatures can be adjusted by variation of the internal He pressure, power of micro-heater and width of gap in capsule. The capsule is composed of 5 layers, each of which has Al holders containing several specimens and an independent electric heater wound around Al holder, insulators placed on top and bottom and thermocouples etc. Besides, neutron fluence monitors of Ni-Ti-Fe material are installed on each layer. A friction welded tube between STS304 and Al1050 alloys was also introduced in the capsule to prevent a coolant leakage into a capsule during the capsule cutting process in HANARO. The configuration of specimen, Al holder and capsule is shown in Figure 8.

Figure 8. Specimen, Al holder and capsule

2.4 Irradiation test in HANARO

The capsule is currently being irradiated in the CT test hole of the HANARO of a 30MW reactor output power for 2 cycles (one cycle 28 days) as shown in Figure 9. The temperature of the specimens during an irradiation is initially increased by the gamma heating and then roughly adjusted to an optimum condition by the He gas control system. It is then finally adjusted to a desired value by micro-electric heaters. During an irradiation test, the temperatures of the specimens were measured and monitored with thermocouples installed in the capsule. The irradiation temperature of the specimens is being maintained in a range of 370±20℃ according to user requirements.

A fast neutron fluence of the specimens will be obtained up to 9.6×10^{20} (n/cm^2) (E>1.0MeV) [4]. The amount of neutron fluence of the specimens was calculated by the MCNP code and will be compared to the obtained value from the irradiated fluence monitors after irradiation. The irradiated capsule will be maintained in the reactor water pool for cooling of radioactivity. After cooling, the main body of the capsule will be cut off at bottom of the protection tube with a cutting device and it will be transported to the IMEF (Irradiated Materials Examination Facility). The irradiated specimens will be tested to evaluate the irradiation performance of the Zirlo and HANA material in the IMEF hot cell.

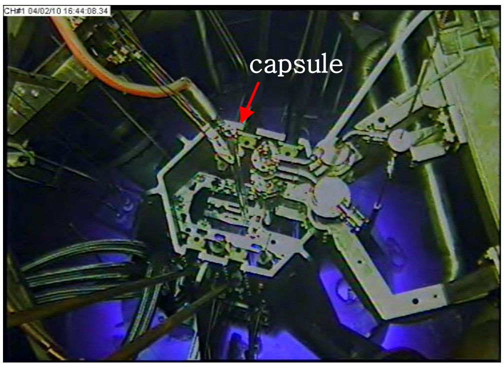

Figure 9. Reactor during the irradiation test

3. Calculation of temperatures

1) Properties and heat generation rate

The properties of materials used in the capsule are listed in Table 2 and 3. Heat generation rates are referred to the data calculated for safety analysis recently [4]. In this calculation, the values in 450mm height of the control rod are used. The heat generation rates are listed in Table 4 and 5.

Table 2. Properties of materials

	Density (g/c/㎤)	Melting temp.(℃)	Thermal expansion (/1℃)	Specific heat (cal/gr/℃)
Al	2.7	660	23 (x 10^{-6})	0.21
SS304	7.9	1,400~1,420	17 (x 10^{-6})	0.12
Zr-2	6.47			
He	0.1328 (100℃)			

Table 3. Thermal conductivities

	Thermal conductivity (W/m.℃) (℃)						
	0	50	100	200	300	400	600
Al	202		206	215	228	249	-
SS304	14.9		16.2	17.9	19.3	20.8	23.6
Zr-2		11.6	12.1	13.1	14.2	15.9	19.9
He	0.135		0.169	0.197	0.225	0.251	0.275

* ASME Sec.III App.A & Holman Book [6]

Table 4. Heat generation rate of 13M-01K capsule at 4th layer (CR 450mm)

Layers	y-coord. (cm)	Sec-tion	γ-Heating rate (W/g)			Heat generation density (W/m^3) (x 10^{6})		
			Specimen SS304	Al	SS316	Specimen (SS304)	Thermal media (Al)	Tube (SS316L),
1	-20.45 to -17.6	C	5.6	4.9	5.4	44.24	13.23	42.66
2	-17.6 to -14.75	B	5.8	5.2	5.8	45.82	14.04	45.82
3	-14.75 to -13.5	B	6.1	5.4	5.9	48.19	14.58	46.61
4	-13.5 to -11.9	A	6.2	5.5	6.1	48.98	14.85	48.19
5	-11.9 to -9.05	A	6.2	5.5	6.1	48.98	14.85	48.19

Table 5. Heat generation rate of 13M-01K capsule at 4th layer (CR 450mm)

Layer	y-coord. (cm)	Section	γ-Heating rate (W/g)			Heat generation density (W/m^3) (x 10^{6})		
			Specimen SS304	Al	SS316	Specimen (SS304)	Thermal media Al	Tube (SS316L)
1	-32.85 to -30	G	3.6	3.1	3.4	28.44	8.37	26.86
2	-30 to -27.15	G	4.2	3.6	4	33.18	9.72	31.6
3	-27.15 to -24.3	G	4.7	4.1	4.9	37.13	11.07	38.71
4	-24.3 to -21.45	G	5.1	4.4	5.2	40.29	11.88	41.08

2) Condition for calculation of temperatures

The ANSYS program was used for the thermal analysis. A two-dimensional model for the specimen section was generated. The temperature of the cooling water in the reactor in-core is about 33 ℃, and the heat transfer coefficient at the outer surface of the external tube is 30.3 x 10^3 W/m^2℃, which was determined experimentally [5]. The gap between specimen and specimen hole is assumed to be 0.1mm. And deformation of ring specimens due to corrosion and hydrogenation is not so small that the diameters are changed irregularly and not constant. Therefore, the gap between ring specimen and the center rod is assumed to be 0.2 mm in this calculation, which is almost average value.

3) Calculation of temperatures

Table 6 shows the temperature analysis results of the 4th layer of the capsule by ANSYS code. An analysis was performed repeatedly until the calculated values converged on the target temperatures by adjusting the He gap between the outer tube and the thermal media. No matter how small the gap is in $0.4K_{He,\ 1atm}$ (the pressure that the conductivity of He becomes 0.4 times of the conductivity of He at 1 atm), the temperatures can't lower to the target ones. Here, $0.4K_{He,\ 1atm}$ means the pressure that the conductivity of He becomes 0.4 times of that at 1 atm. However, the temperatures get to target ones when the internal pressure of the capsule becomes $0.6K_{He,\ 1atm.}$ and the gap is reduced to be 0.1mm.

Table 6. Effect on temperatures of gap at the 4th layer of 13M-01K capsule (CR 450mm)

Layer	y-coord (cm)	Sec-tion	Target temp. (℃)	Gap (mm)		$0.4K_{He,\ 1atm}$ Temp (℃)		$0.6K_{He,\ 1atm}$ Temp (℃)	
				Al holder/outer tube	center rod/ring	center rod	ring	center rod	ring
						plate tensile		plate tensile	
4	-13.5 to -11.9	A	plate tensile 350~380 & ring 370~380	0.15	0.2	(750)	592	(575)	455
						591		453	
				0.12	0.2	(690)	529	(534)	411
						526		410	
				0.10	0.2	(653)	490	(506)	380
						485		375	

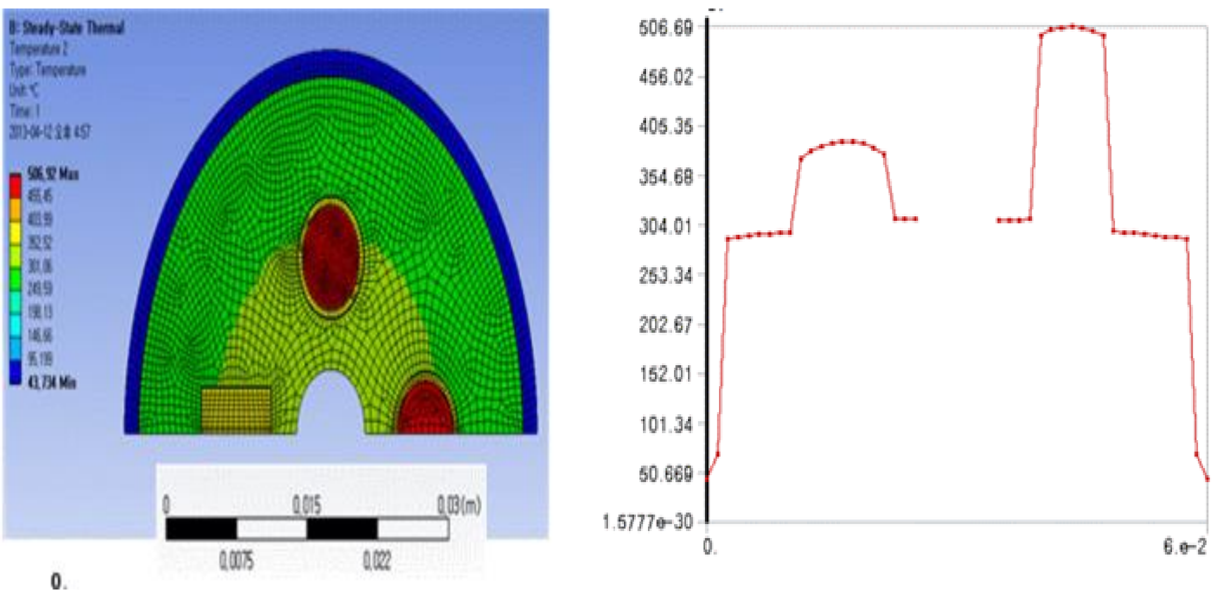

Figure 10. Temperature profile at section 4A of layer 4
(0.1mm outer gap/0.2mm gap between center rod and ring)

Table 7. Temperatures and gaps at the 4th layer of 13M-01K capsule (CR 450mm)

Layer	y-coord (cm)	Sec-tion	Target temp. (℃)	Gap (mm)		$0.4K_{He, 1atm}$ temp.(℃)		$0.6K_{He, 1atm}$ temp.(℃)		He 1atm temp.(℃)	
				Al holder/outer tube	center rod/ring	c. rod	Ring	c. rod	ring	c. rod	Ring
						Han-plate	Dong-Plate	Han-plate	Dong-plate	Han-plate	Dong-plate
1	-20.45 to -17.6	C	Plate tensile 350~380 & Ring 370~380	0.1	0.2	624	475	484	369	358	276
						492	-	384	-	286	-
2	-17.6 to -14.75	B		0.09	0.2	625	469	485	367	360	275
						489	465	380	360	285	271
3	-14.75 to -13.5	B		0.08	0.2	625	461	486	361	361	272
						481	455	377	355	282	268
4	-13.5 to -11.9	A		0.1	0.2	653	490	506	380	372	284
						-	485	-	375	-	282
5	-11.9 to -9.05	A		0.1	0.2	653	490	506	380	372	284
						-	485	-	375	-	282

The temperature calculation at the 4^{th} layer was done at $0.6K_{He, 1atm}$, the same pressure for calculation of temperatures at the 5^{th} layer was used to find suitable gaps at which the temperatures of plate tensile specimens can reach the target ones. The temperatures at the 5^{th} layer are estimated as listed in Table 9.

Table 8. Temperatures and gaps at the 4th layer of 13M-01K capsule (CR 450mm)

Layer	y-coord (cm)	section	Target temp. (℃)	gap (mm)		$0.4K_{He, 1atm}$ temp.(℃)		$0.6K_{He, 1atm}$ temp.(℃)		He 1atm temp.(℃)	
				specimen holder/outer tube	center rod/ring	center	ring	center	ring	center	ring
1	-32.85 to -30	all	ring 370~380	0.24	0.2	602	506	461	386	333	278
2	-30 to -27.15	all		0.19	0.2	609	496	468	381	339	277
3	-27.15 to -24.3	all		0.16	0.2	622	497	497	382	349	279
4	-24.3 to -21.45	all		0.14	0.2	627	490	483	379	354	278

4. Results

The results of calculation of temperatures and gaps to adjust requirements by the universities collaboration are summarized as follows

1) The quantities of specimens are increased (60 of HANA ring specimens are added)
2) Specimens are put into two layers of the 4th and 5th of 13M-01K capsule
3) The irradiation test is performed at CT hole of HANARO to adjust the required fluence.
4) The target temperatures are 370-380℃ in ring specimen and 350-380℃ in plate tensile specimen
5) Temperatures calculated at $0.4K_{He, 1atm}$ are estimated higher than target ones. Accordingly, the design basis internal pressure of capsule is estimated to be $0.6K_{He, 1atm}$ in the irradiation test.
6) Temperatures can be reached target ones at the gaps shown in Table 7 and 8.

5. Conclusions

In this capsule, the two kinds of irradiation tests are performed at quite different temperatures. At upper 3 layers of the capsule, specimens for irradiation at high-temperature are inserted, and they would reach higher than 950℃ during irradiation. The high temperature irradiation test is necessary for development of materials to be used materials for VHTR among future reactor systems. At lower 2 layers of the capsule, Zirlo and HANA material are inserted for irradiation test at lower than 400℃. This test was requested by Dong-Kook and Han-Yang University to conduct in-core irradiation of fuel cladding material such as Zirlo and HANA. The results will be contributed to improve fuel cladding materials of currently operating NPP, and will be used to develop new types of dry fuel storage device

Acknowledgements

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REFERENCES

1. Wikipedia, the free encyclopedia, Zirconium Alloy
2. M.S. Cho, Design, Fabrication and Test Report on the Instrumented Capsule (11M-22K) Ti/graphite Thermal Media for High-temperature Irradiation Test, KAERI Report TR-4879, 2013
3. ANSYS IP Inc., ANSYS User's manual, Ver. 9.0, ANSYS IP Inc., USA, 2005.
4. S.T. Hong, Analysis of nuclear features of 13M-01K capsule, Internal memo HAN-SL-CR-13-01, 2013. 1
5. Y.S. Lee, M.H. Choi, Y.H. Kang, Nucl. Eng. Des. 205 (2001) 205.
6. J. P. Holman, Heat transfer, McGraw-Hill