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Design of a New Capsule Controlling Neutron Flux and Fluence and Temperature of Test Specimen

Kee Nam Choo and Young Hwan Kang
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yusong-gu, Taejon 305-353, Korea

Taiji Hoshiya, Motoji Niimi, and Takashi Saito
Japan Atomic Energy Research Institute
3607 Narita-cho, Oarai-machi, Higashi Ibaraki-gun, Ibaraki-ken, Japan

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Abstract

A new capsule that has a unique structure in which the test environments including neutron flux and fluence, and irradiation temperature can be controlled precisely during irradiation, was conceptually designed. The capsule structure and instrumentation were successfully designed according to the JMTR's standard procedures of capsule design. Based on the target irradiation, the details of the irradiation such as neutron fluence and irradiation temperature were calculated and the related capsule safety was evaluated. In addition, the effects of design parameters including the changes in inner-capsule configuration, heater capacity, and Helium gas pressure on the specimen temperature were analyzed with a computer program. Through these thermal and strength evaluations, this capsule was proved to be safe during the irradiation in the JMTR.

1. Introduction

The Japan Material Testing Reactor (JMTR) provides a wide variety of irradiation facilities such as the shroud irradiation facilities, the loop facilities, and the capsule irradiation facilities for the irradiation tests of nuclear materials, fuels, and radioisotope products. Among these test facilities, the capsule is the most useful system to cope with the various test requirements. In the JMTR, about 60 capsules can be loaded in the irradiation holes of the reactor core, 20 of which can be instrumented. For various purposes such as new alloy and fuel developments and life time estimation of nuclear power plants, various types of capsules having high performances are under development in JMTR [1].

As for a conventional irradiation test, it was difficult to maintain constant temperature and neutron flux during the reactor start-up and shut-down operation. So the test results might be often misinterpreted contrary to the desired test purpose [2]. Thus, an improved capsule, which could control the irradiation temperature and neutron fluence change corresponding to the reactor operation, was developed and irradiated in JMTR successfully [3]. However, the capsule could not control neutron flux as an important irradiation factor, and the parametric tests of those factors could not be performed in that capsule. Therefore, a new capsule in which the neutron flux, in addition to the irradiation temperature and neutron fluence, can be controlled simultaneously were conceptually designed and evaluated in this report.

The irradiation specimens in this capsule don't receive any thermal and neutron hysteresis during reactor start-up or shut-down operation. Thus, control of neutron flux and fluence of the test specimens becomes possible, irrespective of the reactor operation mode. In addition, parametric irradiation tests of irradiation temperature, neutron flux and fluence can be performed within one capsule.

Finally, this research on capsule design and safety evaluation in JMTR can be effectively applied to the HANARO (High flux Advanced Neutron Application ReactOr) capsule design and evaluation.

2. Conceptual Capsule Design

Generally, capsule design is proceeded in a sequence by conceptual design, detail design, and capsule control system design. In conceptual design stage, the selection of materials including specimens, determination of irradiation condition, design of basic capsule structure, thermal and strength designs are carried out.

2.1. Selection of Materials

The main structural parts of this capsule are an outer tube, inner-capsules including specimens, guide tubes, and a protection tube. Full and half size tensile specimens of stainless steel 316 and Inconel-625 were inserted in the inner-capsules. The details of the specimens are described in the Table 1. Basically, the other specimens such as impact, creep, and TEM (Transmission Electron Microscopy) specimens can be inserted in this capsule.

Table 1. Irradiation Test Specimens in New Capsule

Type	Materials	Number	Dimension
Tensile specimen (Standard)	Stainless steel 316	3	W11×t1×L70
	Inconel-625	3	(gauge;3×1×23)
Tensile specimen (Half Size)	Stainless steel 316	48	W11×t1×L35
	Inconel-625	48	

W: width t: thickness L: length

Stainless steels were used as materials of outer, inner, and protection tubes considering their strength and their compatibility with the reactor coolant. But the selection of the specimen holder is more dependent on the thermal design than the capsule structure. Aluminum was selected as a holder material by thermal calculation.

2.2. Determination of Irradiation Condition

This capsule will be inserted in the G-11 hole of JMTR as shown in Fig. 1 and is supposed to be irradiated during 121-125 cycles (5 cycles). The typical irradiation condition of the specimen in the G-11 test hole is as follows:

Thermal neutron	$13.9\times10^{13}\ cm^{-2}\cdot sec^{-1}$
Fast neutron (E>1 MeV)	$5.34\times10^{13} cm^{-2}\cdot sec^{-1}$
Heat generation	10w/g(for stainless steel)

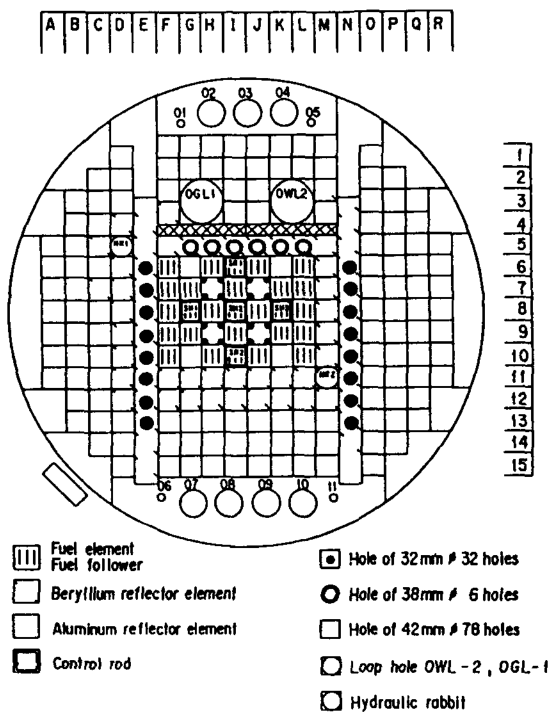

Fig. 1. JMTR Core Configuration

Specimen temperature 290℃
Environment He gas (1 atm)
Total length of specimen part
210 mm

However, the irradiation test condition of the specimens in this capsule can be changed into eight different modes as shown in Table 2. The final test conditions of the specimens will be determined in the detail design stage. The amount of neutron irradiation needed for the capsule safety evaluation, is calculated by the following equation.

Amount of irradiation (n/cm^2)
=Neutron Flux×30 days (50 MW)×24×3600 (sec)×Number of Irradiation Cycles×Peaking Coefficient×Safety Factor (1)

In the G-11 irradiation hole, the maximum thermal and fast neutron (E>1 MeV) fluxes are 13.9×10^{13} $cm^{-2}\cdot sec^{-1}$ and 5.34×10^{13} $cm^{-2}\cdot sec^{-1}$, respectively. Because JMTR uses the peaking coefficient of 1.32 and a safety factor of 1.5, the amounts of thermal and fast neutron irradiation of this capsule for safety analysis are calculated as 3.6×10^{21} (n/cm^2) and 1.4×10^{21} (n/cm^2), respectively.

2.3. Design of Capsule Structure

2.3.1. Capsule Structure Design

Six inner-capsules were successfully designed in a capsule of 60 mm diameter as shown in Fig. 2. The

Table 2. Irradiation Test Modes Controlling Multiple Environments

Temperature	Fluence	Flux	Mode
constant	constant	constant	mode 1
		variable	mode 2
	variable	constant	mode 3
		variable	mode 4
variable	constant	constant	mode 5
		variable	mode 6
	variable	constant	mode 7
		variable	mode 8

major structural parts of this capsule are composed of an outer tube, inner-capsules including specimens, guide tubes, and spacers. As a first step of capsule structure design, the dimensions of the major parts and the number and size of inner-capsule and guide tube should be determined. Fig. 2 shows the basic structure of the capsule and Fig. 3 shows the details of the inner-capsule and specimen. One inner-capsule of 6.7 mm diameter contains 18 half size tensile specimens of 1 mm thickness. These inner-capsules can be independently elevated and lowered between the outside and inside of the reactor core by inserting Helium gas in the bottom and top of the guide tube, respectively. The gas flow is controlled by the solenoid type gas valve system that is installed in the upside of capsule. The position of the inner-capsule is detected by electric detectors that are installed at the top and bottom sites of the guide tube. Thus, it is possible to insert specimens into the reactor core reflector region after the full operation of the reactor (50 MW), and to withdraw specimens to the outside of core region before reactor shut-down as shown in Fig. 4.

In addition, this capsule was designed to control the neutron flux of the specimens by adjusting the vertical position of the bottom detector and lower stopper in the guide tube (JMTR has a vertical neutron flux distribution [3]). Because the inner-capsules of the 93M-38J (serial number of JMTR capsule) capsule were designed to be positioned at maximum neutron flux region, the control of neutron flux of the specimens was not possible. The irradiation temperature of the specimens is crucially determined by the gamma heating and can be finally adjusted to the desired value by the gas control system and electric heater. Therefore, parametric irradiation tests of irradiation temperature, neutron flux and fluence can be precisely performed with this capsule.

2.3.2. Capsule Instrumentation Design

Five thermocouples, three sets of temperature

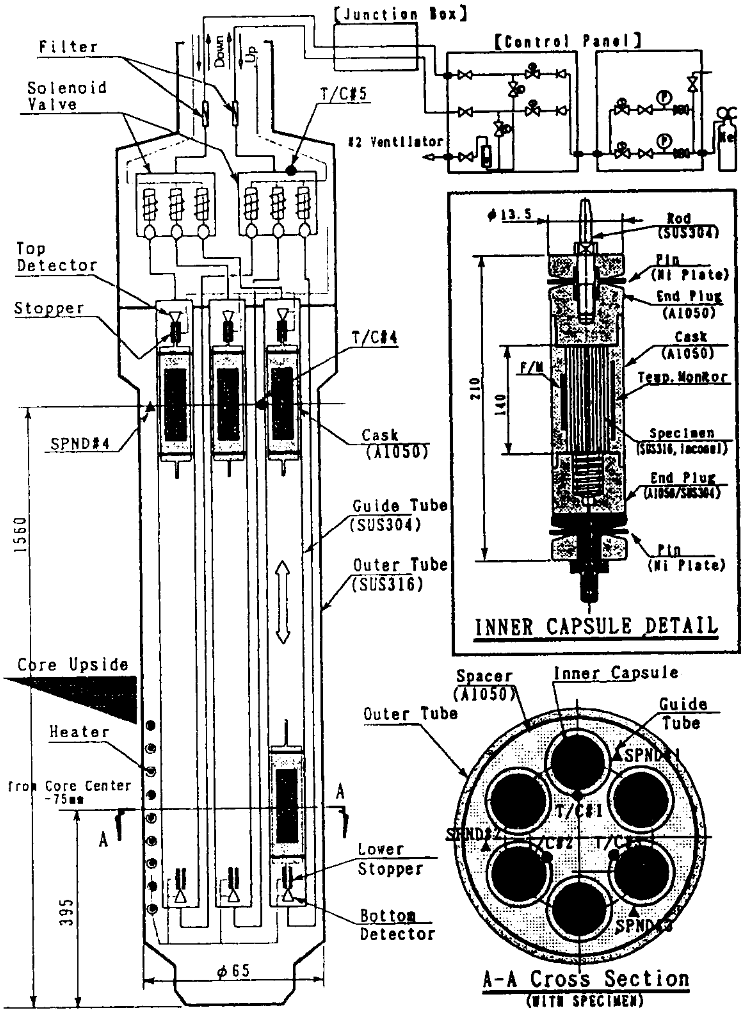

Fig. 2. Perspective View of New Capsule

monitors, four sets of SPNDs (Self-Powered Neutron Detectors), three sets of fluence monitors (F/M), and one heater are installed in this capsule. Three sets of the thermocouples and SPNDs are located at the reactor core center region. One thermocouple is installed at the upper part of the guide tube and another thermocouple is attached on the surface of solenoid valve. The locations of these instrumentations are shown in Fig. 3 and the specifications of the thermocouple, SPND, and F/M are as follows :

(1) Thermocouple : K-type (Chromel-Alumel), 5 sets
sheath diameter, 1.0 mm
(2) SPND : Rh emitter, 3 sets
sheath diameter, 2.0 mm
(3) F/M : A-V type (Φth, Φf), 3 sets
$\Phi 2\times 40$ mm (Aluminium container)

Due to the structural limit, the specimen temperature can not be directly measured during irradiation. Thus, three sets of the temperature monitors are inserted in the inner-capsules as shown in Fig. 4. The temperature monitor consists of seven different alloys having different melting points from 95℃ to 338℃ [4].

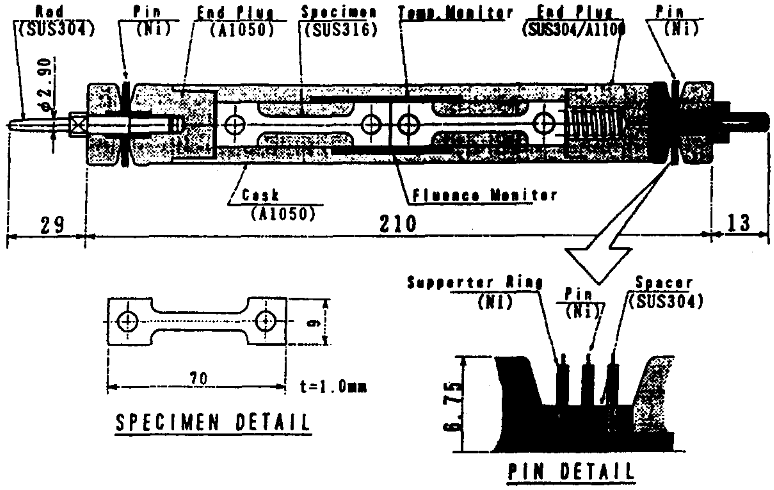

Fig. 3. Details of Inner Capsule in New Capsule

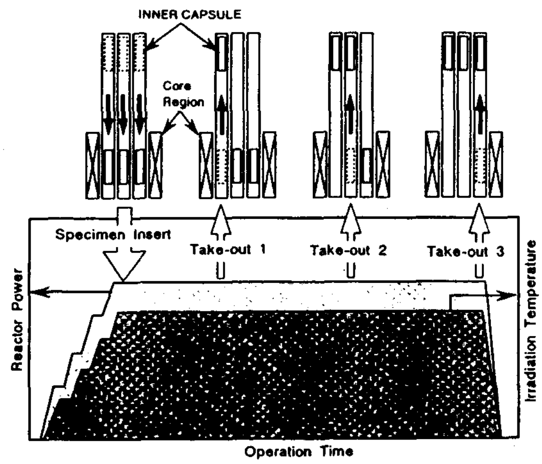

Fig. 4. Example of Parametric Irradiation Test

2.4. Capsule Thermal Design

The test holes of JMTR have different thermal and fast neutron flux according to its reactor position. In the irradiation test of material, the fast neutron and gamma spectra of test hole are very important. The former is necessary for the calculation of neutron fluence, and the latter is needed for the evaluation of gamma heating rate. The positions and gamma heatings (peak axial values for iron) of the test holes in the reactor core of JMTR are shown in Fig. 1. The peak axial value of gamma heating for iron in the G-11 hole is 4.0 (w/gm) and the material dependence ratio can be obtained in the reference book [3]. By gamma heating, heat is generated in the material inserted into test hole. Based on heat transfer theory, the temperatures of the capsule parts can be calculated. The detailed heat transfer theory for the capsule is well described in a previous report [5]. Two computer programs such as GENGTC [6] and TAC-2D codes have been developed to calculate the temperatures of the irradiation facilities in JMTR. GENGTC is a computer program for the heat transfer calculation of a 1-dimensional round body and TAC-2D program calculates the temperature distribution of a 2-dimensional round body.

This kind of capsule needs very precise temperature calculation and the temperature of the capsule is complicated by many factors including gap size, conductivity, and thermal expansion of the capsule structure. Thus, the computer program GENGTC is usually used to calculate the temperature distribution of the capsule. In this thermal calculation, the surface temperature of the outer tube of the capsule in contact with coolant must not cause the coolant to boil. The following coolant specifications is used in the temperature calculation.

Reactor coolant : pure water
Coolant temperature : 50℃
Coolant pressure : 0.18 kg/mm^2
Boiling point of coolant : 194℃
Heat transfer coefficient
at outer tube surface : 2.33W/cm · ℃

2.4.1. Model Simulation

GENGTC program calculates the temperature distribution of a 1-dimensional round body which has axis symmetry. Therefore, modelling works are necessary for the complicated capsule structure. Two modelling methods for thermal calculation have been suggested [6]. One is to change to a circle having the same length of boundary and the other is to change to a circle having the same cross section.

Because this capsule has a relatively large gap between the inner-capsule and the guide tube, the heat transfer through this gap crucially determines the temperature of the test specimens. Thus, the thermal calculation was carried out in two stages. At first, the simple modelling of the capsule was carried out as

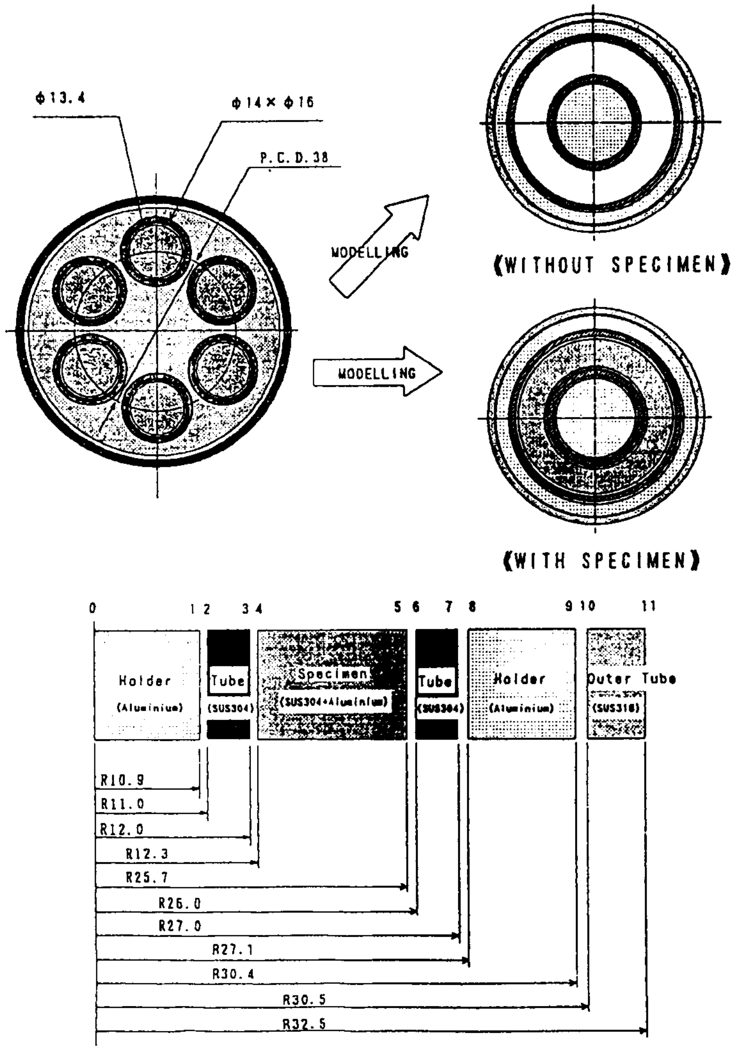

Fig. 5. Model Simulation (I) of Capsule for GENGTC

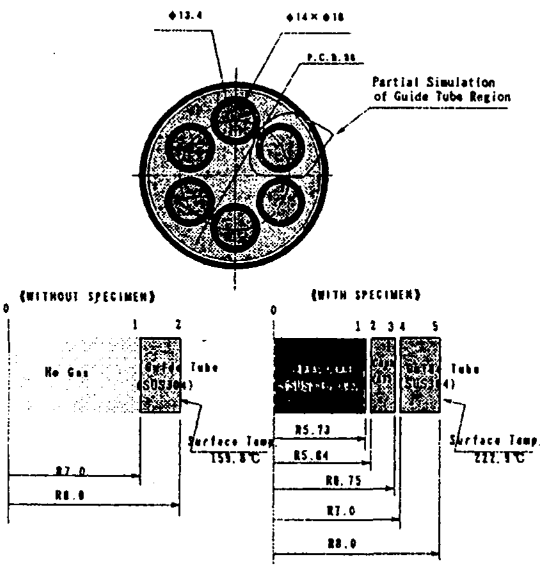

Fig. 6. Model Simulation (Ⅱ) of Guide Tube Region for GENGTC

shown in Fig. 5. In this modelling, the inner-capsule, guide tube, and spacer were just assumed as circles. The Al spacer and guide tube were each divided into two separate circles. By this modelling, the areas of those parts were changed. Thus, the density of each part was corrected according to its area change and used in thermal calculation. The other dimensions of the capsule were taken as actual figures.

Based on the outside temperature of guide tube obtained by the above thermal calculation, the second thermal modelling on the inner-capsule region was carried out as shown in Fig. 6. In this modelling, the specimens were modelled as a circle with diameter 5.73 mm based on the same boundary area. Due to the area changes of specimens and spacer, the input densities of these parts for thermal calculation were revised.

2.4.2. Temperature Evaluation

The calculated temperatures of the guide tube surface and specimens of this new capsule are shown in Table 3, and compared with those of 93M-38J capsule having three inner-capsules [7]. Even though the surface temperatures of the guide tube of this capsule show a little higher values than the 93M-38J capsule, the specimen temperature shows a little lower value than the prior capsule in the case of six inner-capsules at maximum gamma flux position. Therefore, considering the structural similarity of this capsule to the 93M-38J capsule and the lower specimen temperature of the capsule by TAC-2D code calculation, this new capsule is judged to be good enough for irradiation tests of around 290℃.

Table 3. Comparison of Temperatures of Guide Tube Surface and Specimen for New Capsule and three Inner-Tube Capsule (93M-38J capsule)

Type of Capsule	New Capsule (six Inner-Capsules)		93M-38J Capsule (three Inner-Capsules)	
Inner-Capsule Number at Max. γ Position	0	6	0	3
Guide Tube Surface Temp. (℃)	159.8	222.9	148	208
Specimen Temperature by GENGTC, (℃)	160.8[1)]	345.4	150[1)]	377
Specimen Temperature by TAC-2D, (℃)	–	–	136	227

1) Center temperature of guide tube

2.4.3. Parameter Effect on Specimen Temperature

To see the parameter effect on the specimen temperature, the changes in inner-capsule configuration, Helium gas pressure, and heater capacity were analyzed with GENGTC code. The specimen temperature was basically changed from 275℃ to 345℃ by gamma heating according to the inner-capsule configuration (in the case of 1 atm Helium gas and zero heater power). When all the six inner-capsules were located in the maximum gamma flux region, the specimen temperature was the highest. As a inner-capsule was elevated, the temperature of the remaining specimens lowered by about 14℃. In addition, the specimen temperature could be raised by lowering the

Helium gas pressure in the capsule. The specimen temperature was raised by about 65℃ by the change of Helium gas from 1 atm to 0.4 atm (conventional mode in JMTR). And finally, the specimen temperature would be controlled to the desired test temperature by using heater system. The test temperature increased by about 28℃ with increasing the heater capacity up to 200W/cm. Through these factors' combination, the specimen temperature could be changed from 275℃ to 424℃ in this capsule. Thus, to obtain exact irradiation temperature of the specimen, more precise control of capsule parameters should be performed in the detail design stage of the capsule.

2.5. Capsule Strength Design

During the reactor operation, the capsule should be safe against all possible stresses applied to the capsule parts. Thus, the pressure boundary such as the outer tube and guide tube is analyzed in view of strength safety. The stresses that happen on the capsule outer tube during reactor operation are thermal stresses due to the temperature gradient across its wall, inner gas pressure, and outer coolant pressure. The guide tube receives stress due to internal gas pressure and thermal stress due to the temperature gradient. Therefore, the safeties of the capsule outer tube and guide tube against these stresses should be proved. The stresses occurring on the capsule are calculated as follows :

(1) Stress due to Inner Gas Pressure

The gas in the gap exerts a pressure on the inner wall of the tube when it is heated. The internal pressure operating on tube by Helium gas is

$$P_{He} = \frac{273 + TG}{273} \times \frac{P1}{100} \tag{2}$$

where, TG is the highest temperature of Helium gas and P1 is initial gas pressure. This inner gas pressure causes circumferential stress on tube. The circumferential stress caused by internal pressure is

$$\sigma_i = \frac{P_{He} \times D_i}{2 \times t} \tag{3}$$

where, D_i is tube inner diameter and t is tube thickness.

(2) Stress due to Outer Coolant Pressure

The reactor coolant exerts a pressure on the outer wall of the tube. The circumferential stress due to coolant pressure is

$$\sigma_o = \frac{2 \times P \times (R2 \times R2)}{(R2 \times R2) - (R1 \times R1)} \tag{4}$$

where, P is the coolant pressure and R2 is the tube outer radius and R1 is the tube inner radius.

(3) Limit Yield Stress of the Outer Tube

The limit yield stress of the outer tube is

$$P_{cr} = \frac{E \times (t \times t \times t)}{4 \times \{1 - (\nu) \times (\nu)\} \times (R2 \times R2 \times R2)} \tag{5}$$

where, E is Young's coefficient, 19800 kg/mm^2 and ν is Poisson's ratio, 0.25.

(4) Maximum Thermal Stress

The tube with a temperature gradient across its wall will experience thermal stress on its inner and outer walls. The maximum circumferential thermal stress is

$$P_{tmax} = \frac{\alpha \times E \times (T1 - T2)}{2 \times (1 - \nu)} \tag{6}$$

where, α is the linear expansion coefficient, 16.5×10^{-6}/℃ and T1 and T2 are the inside and outside temperatures of the tube. P_{tmax} exerts as a compressive stress on the inner surface and as a tensile stress on the outer surface of tube.

(5) End Plug Strength

The end plug of the capsule should have enough strength. The strength of end plug is

$$\frac{(t_p \times t_p)}{(t \times t)} > \frac{3}{8} \times \frac{D_i}{t} \quad (7)$$

where, t_p is thickness of end plug of tube.

Finally, using these calculated values, the tubes are judged safe if they satisfy the following equations.

$$|\sigma_o| < \sigma_a \quad (8)$$

$$|\sigma_o| + \sigma_{tmax} < 3\sigma_a \quad (9)$$

where, σ_o : radial stress by outer pressure

σ_a : allowed stress

σ_{tmax} : maximum thermal stress.

The allowed stress of the material in use, σ_a is determined as the lowest of the following conditions:

a. 1/3 of the lowest prescribed value of tensile strength.
b. 1/3 of the tensile strength at working temperature.
c. 2/3 of the lowest prescribed value of yield stress.
d. 9/10 of the yield stress at working temperature, but not exceeding the above condition c.

2.5.1. Outer Tube Strength Evaluation

During the reactor operation, the capsule outer tube receives several stresses due to inner gas pressure, coolant pressure, and temperature gradient across the tube wall. The stresses occurring on the outer tube are calculated as follows by using the above equations.

The internal pressure operating on the outer tube by Helium gas, (P_{He}) is obtained at the highest temperature of Helium gas, 598℃ (in the case of the 200 W/cm heater) as 0.032 kg/mm^2. The initial gas pressure is 1 atm (1.03323 kgf/mm^2). Thus, the circumferential stress on the outer tube by the inner gas pressure is obtained as σ_i = 0.49 kg/mm^2. The circumferential stress due to coolant pressure is obtained as $\sigma_o = -3.02$ kg/mm^2, where, coolant pressure, P, is 0.18 kg/mm^2 and tube outer radius, R2, is 32.5 mm and tube inner radius, R1, is 30.5 mm. The limit yield stress of outer tube is obtained as P_{cr} = 1.23 kg/mm^2.

The maximum circumferential thermal stress of the outer tube due to the temperature gradient across its wall is obtained as P_{tmax} = 9.79 kg/mm^2, where, the inside and outside temperatures of the outer tube are obtained as 110.7℃ and 65.6℃. These values, that are the largest temperature differences across its wall, are obtained for the six inner-capsules at maximum flux region with a 200 W/cm heater. P_{tmax} exerts as compressive stress on the inner surface and as tensile stress on the outer surface of tube. The strength of end plug is obtained as 25.0 kg/mm^2, where, the thickness of end plug of the outer tube, tp is 10.0 mm.

Using the above calculated values, the strength evaluation on the outer tube is carried out as follows :

i) Circumferential stress due to internal pressure ($\sigma_i < \sigma_a$)
0.49<14.1 ..................................O.K.

ii) Circumferential stress due to external pressure ($|\sigma_o| < \sigma_a$)
3.02<14.1 ..................................O.K.

iii) Limit yield stress due to external pressure ($P_{cr} > 3P$)
1.23>0.54 ..................................O.K.

iv) Sum of maximum mechanical and thermal stresses ($|\sigma_o| + \sigma_{tmax} < 3\sigma_a$)
3.02 + 9.79 = 12.80<42.3 ..................O.K.

The capsule outer tube satisfies all the above requirements. Thus, it is proved to have enough strength during irradiation tests.

2.5.2. Guide Tube Strength Evaluation

The guide tube receives stress due to inner gas pressure and thermal stress due to temperature gradient across the wall. The stresses occurred on the guide tube are calculated as follows.

The internal pressure operating on the guide tube (stainless steel 304) by Helium gas is calculated as

P_{He} = 0.023 kg/mm^2, where, TG is obtained as 353.2℃ from thermal calculation (in case of 200 W/cm heater) and the initial gas pressure is 1 atm (1.03323 kgf/mm^2). The circumferential stress by the internal pressure is calculated as σ_i = 0.16 kg/mm^2, where, the outer tube inner diameter, D_i, is 14 mm and tube thickness, t, is 1 mm. The limit yield stress of guide tube is obtained as P_{cr} = 1.23 kg/mm^2. Where Young's coefficient, E, is 18300 kg/mm^2 and Poisson's ratio, ν, is 0.30.

The maximum circumferential thermal stress due to a temperature gradient across the guide tube wall is obtained as P_{tmax} = 0.98 kg/mm^2, where, the inside and outside temperatures of guide tube are obtained as 110.7 ℃ and 65.6 ℃. The strength of the end plug is calculated as 25.0 kg/mm^2, where, the thickness of the guide tube's end plug, t_p is 5.00 mm.

Using the above calculated values, the strength evaluation on the guide tube is carried out as follows :

i) Circumferential stress due to internal pressure ($\sigma_i < \sigma_a$)
 0.16<12.5 ⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯O.K.

ii) Limit yield stress due to external pressure ($P_{cr} > 3P$)
 1.23>0.54 ⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯O.K.

iii) Sum of maximum mechanical and thermal stresses ($|\sigma_o| + \sigma_{tmax} < 3\sigma_a$)
 0.16+0.98 = 1.14<37.6 ⋯⋯⋯⋯⋯⋯⋯O.K.

The guide tube satisfies all the requirements. Thus, it is proved to have enough strength.

3. Conclusions

A new capsule in which the test environment can be controlled was conceptually designed and evaluated. With this capsule, control of the irradiation temperature, and the neutron flux and fluence of the test specimens becomes possible, irrespective of reactor operation mode. In addition, the parametric irradiation tests on the effects of irradiation temperature, neutron flux and fluence can be performed in a capsule. The main structural parts, irradiation condition, and capsule structure including instrumentation were designed. And the model simulations of the capsule for temperature evaluation were performed and the parameter effects of inner-capsule configuration, heater capacity, and Helium gas pressure were analyzed with GENGTC code. The capsule was proved to be safe during reactor operation through thermal and strength evaluations.

The test reactor HANARO has been constructed in KAERI, and is under test operation. These techniques and experiences obtained through the thermal and strength evaluations of this new capsule can be applied effectively to the design and safety evaluation of the HANARO capsule.

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