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DESIGN, FABRICATION AND INSPECTION OF RABBIT CAPSULE

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Design, Fabrication and Inspection of Rabbit Capsule

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Many capsules designed by Irradiation Div. 1 have been irradiated in the JMTR reactor in past years. The Irradiation Div. 1 has been developing and studying the irradiation and design techniques.

This report contains the description of the design and inspection standard, fabrication and the basic design of small capsule called "Rabbit".

Therefore, this report is very useful for proposer who want to irradiate small specimen by irradiation facility in the JMTR reactor.

Keywords: Rabbit Irradiation Facility, Capsule.Design Hand Book, Desugn Standard, Inspection Standard, JMTR

ラビットキャプセルの設計・製作・検査

日本原子力研究所大洗研究所材料試験炉部
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（1986年10月13日受理）

照射第1課では，長年，多くの照射キャプセルの設計を担当し，照射技術及び設計技術の開発を続けて来た。

本レポートは，ラビットの設計及び検査基準，製作，基本設計とその方法を述べたものである。したがってJMTRを利用する者にとっては，非常に参考となる報告書である。

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1. Foreword

Japan Material Testing Reactor (JMTR) has many irradiation facilities called OGL-1 (Oarai-Gas Loop No. 1), OWL-2 (Oarai Water Loop No. 2), No. 1 and No. 2 hydraulic rabbit and capsules.

Especially, the hydraulic rabbit irradiation facility is very easy to use the small irradiation specimen. The hydraulic rabbit facility enables to insert or remove the small rabbit capsules to reactor core by hydraulic power in anytime.

Therefore, this paper contains the description of the design standard, inspection standard, fabrication and basic design of rabbit for proposer who want to use the rabbit facility for irradiation in the JMTR reactor.

2. Design Standard for Hydraulic Rabbit[1]

2.1 General

(Scope)

Article 1:

This standard specifies the design of rabbit aiming to perform the irradiation test at JMTR Hydraulic Rabbit Irradiation Facilities (hereinafter called "hydraulic rabbit facility").

(Definition)

Article 2:

In this standard, the meanings of terms mentioned below shall be defined conforming to the specified contents of each section.

(1) "Rabbit" including thermal bond, spacer, and buffer material, as needed by irradiation sample in the rabbit holder shall mean a capsule that is to be used for irradiation test on hydraulic rabbit facility.

(2) "Buffer material" shall mean a material to be used to soften shock in answer to need.

(3) "Rabbit holer" shall mean a vessel to contain sample as well as thermal bond, spacer, and buffer material as needed.

1. Foreword

Japan Material Testing Reactor (JMTR) has many irradiation facilities called OGL-1 (Oarai-Gas Loop No. 1), OWL-2 (Oarai Water Loop No. 2), No. 1 and No. 2 hydraulic rabbit and capsules.

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(3) "Rabbit holer" shall mean a vessel to contain sample as well as thermal bond, spacer, and buffer material as needed.

(Structure and Shape)

Article 3:

Structure and shape of the rabbit holder shall conform to the following each section:

(1) Rabbit holder

Rabbit holder shall be made in three types, closed type, leaky type, and open type, all of which are consisting of upper and lower caps and cylinder provided that the open type shall be of structure that sample is used as cylinder of rabbit holder.

a. Closed type — To be of structure so that rabbit holder is a closed vessel and only outer surface of the holder is in contact with coolant.

b. Leaky type — To be of structure that rabbit holder has holes enabling to pass the coolant inside of the holder which total area of coolant holes shall not exceed 40% of the pressurized area.

c. Open type — To be of structure that sample is used as a cylinder of rabbit holder, attaching upper and lower caps to the sample.

(2) Sample

Sample shall be classified into one containing and the other not containing nuclear fuel material where the former shall be called "fuel sample" and the latter "material sample".

a. Fuel sample — Shall be coated without fail.

b. Material sample — Shall be of liquid, powder, or solid. Sample of liquid, powder, or that generating gas during irradiation shall, in principle, be kept in a closed vessel.

1. Outer dimensions of rabbit shall be as follows:

   Max. diameter 32 mm

   Max. length 150 mm

   Shapes of both ends Hemisphere

2. Specific gravity of rabbit shall exceed 1.0, and the total weight be less than 2.2 kg in the air.

2.2 Designing

(Material Used)

Article 4:

1. Material used for rabbit (excluding sample) shall not cause radiation damage, quality change and deterioration by high temperature, trouble in operation of reactor and hydraulic rabbit irradiation facilities during irradiation test.
2. Structural components of rabbit directly in contact with rabbit coolant shall not hinder the operation of reactor and hydraulic rabbit irradiation facilities according to corrosion, separation, and solution. In particular, silver, copper, lead, cadmnium, and carbon steel shall not be used.
3. Structural components directly in contact with rabbit coolant shall, in principle, be of the following materials:

   Stainless steel
   Aluminum and aluminum alloys (copper content: less than 0.5%)
   Inconel
   17-4 PH
4. As thermal bond, liquid metal (Na, NaK) shall not be employed.
5. Buffer material shall, in principle, be aluminum foil, stainless steel wool, spring steel, stainless steel wire, or quartz wool.

(Thermal Design)

Article 5:

1. Exothermic limit of rabbit shall not exceed 20 kW for rabbit facility No. 1 and 9 kW for rabbit facility No. 2.
2. Main parts of rabbit shall be examined thermally, and temperature on each construction part shall be satisfied as following constructions:
   (1) Heat flux on outer surface of rabbit in contact with coolant shall not exceed 1.5×10^5 kcal/m^2 hr.
   (2) Central temperature of fuel sample shall not exceed the melting point temperature.
   (3) Temperature shall not cause harmful quality change or deterioration among structural components of rabbit and components in contact or apt to contact with the others.

(4) Harmful stress or deformation by the thermal expansion shall not be caused among structural components of rabbit.

(Strength Design)

Article 6:

1. Strength on each main part of rabbit shall be examined. Each part shall be strong enough for coolant pressure, inner pressure of thermal stress, and shock in insertion to the hydraulic rabbit facility. The shock in insertion shall be 300G.
2. Enough strength in design shall mean that satisfies the following conditions:
   (1) Mechanical stress shall not exceed the allowable stress.
   (2) The sum of thermal stress and mechanical stress shall not exceed three times of the allowable stress.
   (3) Fatigue fracture or thermal ratchet by repeat thermal stress shall not be caused.
   (4) Fracture by creep phenomenon or large change in the stress distribution shall not be caused.
3. The allowable stress of material used shall be the lowest in the following conditions, and the allowable stresses of main materials shall conform to the design manual specified separately.
   (1) 1/3 of the lowest prescribed value (standard value) of tensile strength.
   (2) 1/3 of tensile strength at the working temperature.
   (3) 2/3 of the lowest prescribed value of yield value.
   (4) 9/10 of the yield point at the working temperature, but not exceeding 2/3 of the lowest prescribed value of the yield point.

2.3 Manufacture

(Manufacture)

Article 7:

1. In manufacture, rabbit shall be tested and passed according to the stipulations of Rabbit Test Standard of Chapter II in the JMTR Capsule Test Standard.

2. In manufacture of rabbit, cleanliness shall be regarded satisfactorily, not to hinder the operation of reactor and irradiation test.
3. Welding of structural components of rabbit, particularly components requiring pressure resistance, air-tightness or water-tightness, shall be given the special consideration such as the welding inspection.
4. In manufacture of rabbit, silver soldering shall, in principle, not be employed. If, however, silver soldering is required, safety shall be confirmed satisfactorily so that the highest working temperature on the soldered part shall be confirmed by calculation, or the soldered part be coated if needed.
5. Structural components of rabbit shall not be loosened nor dropped off by the flowing force and vibration of rabbit coolant as well as shock in insertion to or removal from the facility.
6. Structural components of rabbit shall be marked. Mark on outer surface of rabbit shall be readable at 6 m below water surface.

3. Inspection Standard for Hydraulic Rabbit(2)

3.1 General

(Scope)

Article 1:

This standard is applied to the inspection of rabbit irradiated in the hydraulic rabbit irradiation facilities (hereinafter called "hydraulic rabbit facility") but not applied to the inspection aiming to produce at production of radioisotopes.

(Definition)

Article 2:

Definition of the terms below shall conform to the explanations in each section:

(1) "Un-irradiated nuclear fuel" means uranium, thorium, plutonium, and their compounds and their mixtures, which are irradiated in the JMTR.

2. In manufacture of rabbit, cleanliness shall be regarded satisfactorily, not to hinder the operation of reactor and irradiation test.
3. Welding of structural components of rabbit, particularly components requiring pressure resistance, air-tightness or water-tightness, shall be given the special consideration such as the welding inspection.
4. In manufacture of rabbit, silver soldering shall, in principle, not be employed. If, however, silver soldering is required, safety shall be confirmed satisfactorily so that the highest working temperature on the soldered part shall be confirmed by calculation, or the soldered part be coated if needed.
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(Definition)

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Definition of the terms below shall conform to the explanations in each section:

(1) "Un-irradiated nuclear fuel" means uranium, thorium, plutonium, and their compounds and their mixtures, which are irradiated in the JMTR.

(2) "Un-irradiated material which are irradiated in the JMTR" means a substance other than un-irradiated nuclear fuel.

(3) "Clad" means that covers directly un-irradiated nuclear fuel and un-irradiated material.

(4) "End cap" shall mean a cap that is attached to both ends of clad by welding, to cover un-irradiated nuclear fuel and un-irradiated material.

(5) "Fuel sample" means un-irradiated nuclear fuel covered with clad and end caps.

(6) "Material sample" means un-irradiated material covered with clad and end caps.

(7) "Structural component" means parts and materials consisting of rabbit, which are spring, pressure plate, insulation material, spacer, thermal bond and flux monitor.

(8) "Rabbit holder" means a vessel containing fuel and material samples, which is classified into leaky type and closed type. A mother type is provided that a sample can be used as a cylinder of rabbit holder (called "open type").

3.2 Fuel Sample

(Inspection of Clad)

Article 3:

Clad of fuel sample irradiated by the hydraulic rabbit (hereinafter called "clad") shall pass the inspections mentioned below provided that for fuel sample in size smaller than 10mmϕ×10mmℓ, (3) through (5) (a part of material tests) can be omitted upon approval of the Director of JMTR Project.

(1) Visual inspection

(2) Dimensional inspection

(3) Straightness inspection

(4) Flaw test

(5) Material composition and material tests

(Visual Inspection of Clad)

Article 4:

Inspection (1) mentioned above shall pass when it is adapted to the items mentioned in the following:

(1) Surface roughness shall be conformed to that in the specifications.

(2) Harmful flows shall not be found visually.

(3) Surface shall be fully clean, not containing rust, oil and fat, and paint.

(Dimensional Inspection of Clad)

Article 5:

1. Inspection (2) of Article 3 shall be performed on the items in the following provided that (1) can be omitted upon approval of the director of JMTR project when a fuel sample is smaller than 10mmϕ × 10mm.
   (1) Measurement of inner diameter
   (2) Measurement of outer diameter
   (3) Measurement of wall thickness
   (4) Measurement of length

2. Measurements mentioned above shall be performed according to the measuring accuracy mentioned in the following:
   (1) Inner diameter shall be measured by means of an air micrometer or a micrometer for inner diameter measurement. By means of the former, measurement shall be performed twice in two perpendicular directions on the entire length, and by means of the latter in two perpendicular directions on the ends, both with the measuring accuracy not exceeding 1/100 mm.
   (2) Outer diameter shall be measured by means of a micrometer where measurement shall be performed in two perpendicular directions on the both ends and in the center in necessary directions on the padded part. Measuring accuracy shall be less than 1/100 mm.
   (3) Wall thickness shall be measured by means of a micrometer for wall thickness on four points on each end with the measuring accuracy of less than 1/100 mm.
   (4) Length shall be measured with the measuring accuracy of less than 1/10 mm by means of a vernier calipers or a Go - No Go gauge.

3. The measure value obtained according to each item of paragraph 1

shall be passed when the value is conformed to that in the specifications or the approval drawing.

(Straightness Inspection of Clad)

Article 6:

1. Inspection (3) of Article 3 shall be passed when the measured value is a strightness strictly same as in the specifications or the approval drawing.
2. Straightness shall be measured with the measuring accuracy of 1/100 mm using the surface plate.

(Flaw Test on Clad)

Article 7:

1. Inspection (4) of Article 3 shall be performed according to the ultrasonic flaw test or the eddy current test.
2. When a flaw on pipe is recognized less than 10% of wall thickness comparing to that of a defected standard pipe in the ultrasonic flaw test or the eddy current test, the pipe shall be passed.

(Material Composition and Material Tests of Clad)

Article 8:

1. Test (5) of Article 3 shall conform to JIS.
2. In the test mentioned above, material strength shall be coincident with the value described in the specifications. If, however, the value is not described in the specifications, the value shall conform to that described in JIS or ASTM.
3. Materials not described in JIS shall be determined by the Director of JMTR project from case to case.

(Inspection of Un-irradiated Nuclear Fuel)

Article 9:

Un-irradiated nuclear fuel shall be inspected and passed by the inspections mentioned below provided that the sampling inspection may be performed for coated particle fuel.

(1) Visual inspection

(2) Dimensional inspection

(3) Weight inspection

(4) Composition test

(Visual Inspection of Un-irradiated Nuclear Fuel)

Article 10:

Inspection (1) mentioned above shall be passed when it is coincident with the items mentioned in the following:

(1) No harmful crack nor flaw shall be found on surface.

(2) No harmful adhered such as oil or paint shall be found on surface.

(Dimension Inspection of Un-irradiated Nuclear Fuel)

Article 11:

1. Inspection (2) of Article 9 shall be passed when the measured value is same to that in the specifications or the approval drawing.
2. In the inspection mentioned above, measurement shall be performed according to the following measuring accuracies:

   (1) For pellet type nuclear fuel, dimensions shall be measured by a micrometer with the measuring accuracy of finer than 1/100 mm on diameter and length.

   (2) Length of stack of the pellet type nuclear fuel shall be measured by a vernier calipers with the measuring accuracy finer than 1/10 mm.

   (3) Dimensions of nuclear fuel other than the pellet type nuclear fuel shall, in principle, be measured by a micrometer provided that a vernier calipers or a Go - No Go gauge shall be employed with the measuring accuracy finer than 1/10 mm if the micrometer is unable to be employed.

   (4) Powder or coated particle fuel which it is difficult to be measured directly shall conform to the inspection manual determined for each capsule provided that average particle size and particle size distribution shall be mentioned on request of the general manager of irradiation division III.

(Weight Inspection of Un-irradiated Nuclear Fuel)

Article 12:

1. Inspection (3) of Article 9 shall be passed when the measured value is same to that in the specifications.
2. In the inspection mentioned above, measurement shall be performed according to the measuring accuracies in the following:
   (1) Weight shall be measured with a balance of measuring accuracy finer than 1/10 gr for natural uranium, depleted uranium, and thorium as well as 1/100 gr for enriched uranium, plutonium, and uranium 233.

(Composition Test of Un-irradiated Nuclear Fuel)

Article 13:

Test (4) of Article 9 shall be conformed to the table of test results mentioned in each item in the following:

(1) Ceramic fuel shall be conformed to Table 1.
(2) Uranium and uranium alloy fuels shall conform to Table 2.
(3) Coated particle fuel shall conform to Table 3 provided that the items in Table 3 may be omitted partly upon approval of the Director of JMTR Project.

(Inspection of End Caps for Unirradiated Nuclear Fuel)

Article 14:

1. End cap for un-irradiated nuclear fuel (hereinafter called "end cap for fuel") shall pass the inspection in each item below provided that inspection may be omitted upon approval of the director of JMTR project when the size of fuel sample is smaller than 10mm$\phi \times 10$ mm.
   (1) Visual inspection
   (2) Dimension inspection
   (3) Material composition and material tests
2. Inspections (1), (2) and (3) of 1. shall conform to the provisions of Article 4, 5 and 8.

(Inspection of Fuel Sample)

Article 15:

Fuel sample shall pass the inspection of each item in the following provided that the inspections (3) and (8) may be omitted upon approval of the Director of JMTR Project when the size of fuel sample is smaller than 10mmϕ × 10mm.

(1) Appearance inspection
(2) Dimension inspection
(3) Straightness inspection
(4) Welded part inspection
(5) Helium leak test
(6) Surface contamination inspection
(7) Photographs
(8) Entire radiograph

(Visual Inspection of Fuel Sample)

Article 16:

Inspection (1) of Article 15 shall be conformed to the provisions of Article 4.

(Dimensioned Inspection of Fuel Sample)

Article 17:

Inspection (2) of Article 15 shall be conformed to the provisions of Article 5.

(Straightness Inspection of Fuel Sample)

Article 18:

Inspection (3) of Article 15 shall conform to the provisions of Article 6.

(Welded Part Inspection of Fuel Sample)

Article 19:

1. Inspection (4) of Article 15 shall be performed on the items below provided that the inspections (2) through (4) as well as 2., 3., and 5. may be omitted upon approval of the Director of JMTR Project

if the size of fuel sample is smaller than 10mmϕ × 10mm.

(1) Visual inspection

(2) Inspection of bead width of welded part

(3) Inspection of bead height of welded part

(4) Radiographic test of welded part

2. Inspection (1) of 1. shall pass the following items:

   (1) Harmful defect such as crack or flaw shall not be found on welded part.

   (2) Irregular coloring shall not be found on welded part.

   (3) Width and height of bead on welded part shall be even.

   (4) Harmful defect such as undercut shall not be found on welded part.

3. Inspections (2) and (3) in 1. shall pass when the measured values are same as those in the specifications or the approval drawings.

4. Inspections of 3., measurement shall be performed with the following measuring accuracies:

   (1) Width of bead of welded part shall be measured on the maximum and minimum values by a vernier calipers.

   (2) In measuring height of bead on welded part, the maximum and minimum values on four points of diameter including bead shall be measured by a micrometer.

5. Test (4) of 1. shall be performed conforming to JIS Z 3104 "Method of Radiographic Test and Classification of Radiographs for Steel Welds" and JIS Z 3105 "Method of Radiographic Test and Classification of Aluminum Welds" and shall pass when defects of welded part are less than 10% of wall thickness.

6. If, radiographic test is difficult to be applied, the test may be replaced with the dye penetrant test upon approval of the General manager of irradiation division III. Passing standard in this case shall be based on ASME Section III.

(Helium Leak Test of Fuel Sample)

Article 20:

1. Test (5) of Article 15 shall be passed when leaking speed of helium is less than 1×10^{-7} atm-cc/sec.

2. To perform the inspection mentioned above, measurement shall be performed according to the following of 1.

(1) Helium leak test shall be performed according to the Bergier Method or equivalent by means of a helium leak detector of mass-spectrometric type.

(Inspection of Surface Contamination of Fuel Sample)

Article 21:

1. Inspection (6) of Article 15 shall be passed when the counting value of the alpha rays is less than 20 dpm/100 cm^2 provided that the inspection for fuel sample in the size less than 10mmϕ × 10mm may be omitted upon approval of the Director of JMTR Project.
2. To perform the inspection mentioned above, the following shall be required:
   (1) Inspection of surface contamination shall be performed according to the smear test using filter paper for inspection of surface contamination.
   (2) Radioactivity shall be measured by means of an alpha ray counter.

(Photographs of Fuel Sample)

Article 22:

Fuel sample shall be taken photograph meeting the following items:

(1) Two photographs at least shall be taken by arranging the members such as nuclear fuel, clad and end caps prior to assembling in relevant positions so that -he entire positional relation and sizes of those members are distinguished.
(2) Two photographs of appearance of the assembled fuel sample at least shall be taken so that the distinguishing mark is clearly visible. If, however, the distinguishing mark is not easily visible, a divisional photograph shall be taken.
(3) Photograph shall, in principle, be in a cabinet size, 120mm × 165mm.

(Entire Radiograph of Fuel Sample)

Article 23:

As for fuel sample, an entire radiograph shall be taken, enabling to distinguish clearly the inner structure of fuel sample.

3.3 Material Sample

(Inspection of Clad for Material Sample)

Article 24:

1. Clad for material sample shall pass the following inspections if the Director of JMTR Project considers necessary.
   (1) Visual inspection
   (2) Dimensional inspection
   (3) Straightness inspection
   (4) Defect inspection
   (5) Material composition and material test
2. Inspections (1) through (5) in the above shall be conformed to the provisions of Articles 4 through 8.

(Inspection of Un-irradiated Material)

Article 25:

1. Un-irradiated material shall pass the following inspections:
   (1) Visual inspection
   (2) Dimensional inspection
   (3) Weight inspection
   (4) Material composition and material test
2. Inspections (1) in 1. shall be passed when harmful adhered such as oil and tat, and paint are not found on surface of un-irradiated material.
3. Inspection (2) in 1. shall be passed when the measured values are same to those in the specifications or the approval drawing.
4. In the inspections in 3., measurement shall be performed with the following accuracies:
   (1) Dimensions shall, in principle, be measured with the measuring accuracy finer than 1/100 mm by a micrometer provided that measurement shall be performed with the measuring accuracy finer than 1/10 mm by a vernier calipers or an exclusive gauge if the micrometer is not applicable.
5. Inspection (3) of 1. shall be passed when the measured values are same to those in the specifications.
6. Test (4) of 1. shall be conformed to the provisions of Article 8

provided that material test may be omitted upon approval of the General manager of irradiation division III.

(Inspection of End Cap for Un-irradiated Material)

Article 26:

Inspection of end cap for un-irradiated material shall be conformed to the provisions of Article 14.

(Inspection of Material Sample)

Article 27:

1. Material sample shall pass the following inspections provided that the helium leak test (5) shall be performed if it is specified in the specifications. (3), (4) and (6) may be omitted upon approval of the Director of JMTR Project when the size of material sample is smaller than 10mmϕ × 10mm.
   (1) Visual inspection
   (2) Dimensional inspection
   (3) Straightness inspection
   (4) Welded part inspection
   (5) Helium leak test
   (6) Surface contamination inspection
2. Inspections (1) through (4) and (6) of 1. shall be conformed to the provisions of Articles 4 through 6, 19 and 21 provided that surface contamination inspection may be omitted upon approval of the General manager of irradiation division III.
3. Test (5) of 1. shall pass when the helium leaking speed is slower than 1×10^{-5} atm cc/sec provided that the test may be omitted upon approval of the General manager of irradiation division III.

(Photograph of Material Sample)

Article 28:

1. Photographing of material sample shall be conformed to the provisions of Article 22.

3.4 Unit Inspection

(Inspection of Structural Components)

Article 29:

Inspection of structural components shall be passed when the inspected values are same to those in the specifications or the approval drawing.

(Inspection of Rabbit Holder)

Article 30:

1. Rabbit holder shall pass the following inspections:
   (1) Visual inspection
   (2) Dimensional inspection
2. Inspections (1) and (2) of 1. shall be conformed to the provisions of Articles 4 and 5.

3.5 Completion Inspection

(Completion Inspection of Rabbit)

Article 31:

1. The following inspections are completion of rabbit shall be passed provided that rabbit of the leaky type or the open type shall not employ the inspections (4) through (6).
   (1) Visual inspection
   (2) Dimensional inspection
   (3) Weight inspection
   (4) Straightness inspection
   (5) Welded part inspection
   (6) Leak test
   (7) Entire radiography
2. Inspections (1), (2), (4), (5) and (7) of 1. shall be conformed to the provisions of Articles 4, 5, 18, 19 and 23.
3. Inspection (3) of 1. shall be passed when the total weight a piece is less than 2.2 kg.
4. Test (6) of 1. shall be performed according to the ethylene glycol method or the helium leak method. When leakage from rabbit is invisible in the former method, the test shall be passed, and when

the leaking speed is slower than 1×10^{-5} atm cc/sec in the latter method, the test shall be passed.

3.6 Acceptance Inspection

(Acceptance Inspection)

Article 32:

1. Acceptance of rabbit shall pass the following inspections:
   (1) Visual inspection
   (2) Dimensional inspection
   (3) Welded part appearance inspection
   (4) Passage inspection
   (5) Entire photographing
   (6) Mark inspection
2. Inspections (1), (2) and (3) of 1. shall be conformed to the provisions of Articles 4 and 5 and 2. of Article 19.
3. Inspection (4) of 1. shall use a test pipe having inner diameter same to that of rabbit transporting pipe of hydraulic rabbit. The inspection shall be passed if the rabbit can be fed through.
4. Inspection (5) of 1. shall be passed when photographs meeting the following items are taken:
   (1) At least two photographs of rabbit entirely showing the distinguishing mark item number shall be taken.
   (2) If the distinguishing mark is unclear on the photograph, a divisional photograph shall be taken.
   (3) Photograph shall, in principle, be in the cabinet size, 120mm × 165mm.
5. Inspection (6) of 1. shall be passed when the mark is clear and size and place are conformed to the specifications or the approval drawing.

Table 1

Item	Particular
Manufacturing method	
Chemical composition	
Density	(g/cm^3)
Enrichment of U^{235}	(%)
O/U ratio or equivalent	
U amount in 1 gr of fuel substance	(gr)
Impurity and additive concentration	
Amount of evaporative gas	(μℓ/gr)

Table 2

Item	Particular
Manufacturing method	
Density	(g/cm^3)
Enrichment of U^{235}	(%)
Particle size of chrystal	
U amount in 1 gr of fuel substance	(gr)
Impurity concentration	
Components of alloy element	

Table 3

	Item	Particular
Fuel Kernel	Manufacturing method	
	Density	(%T.D)
	Enrichment	(%)
	O/U ratio or equivalent	
	Impurity and additive concentration	
	Amount of evaporative gas	(μℓ/g)
Coated Fuel Particle	Manufacturing method	
	Density	(g/cm^3)
	Uranium amount	(%)
	Acid percolation rate	
	Breaking strength	
Compact	Manufacturing method	
	Relative uranium amount	(gr)
	Percolation rate of electric cracking acid	

4. Basic Design of Hydraulic Rabbit[3]

Design of Standard Rabbit at JMTE

4.1 Preface

JMTR has the irradiation facilities of hydraulic rabbit, which enable to irradiate sample at an optional time and an in an optional period by inserting and removing an irradiated sample in operation of nuclear reactor. There are two facilities of hydraulic rabbit in the JMTR, called HR-1 and HR-2[Note], having the performances as indicated in Table 1. (Note: JMTR employs the code HR for the hydraulic rabbit irradiation facilities, HR-1 as the first facilities and HR-2 as the second facilities.) Reactor core arrangement of facilities at JMTR is shown in Fig. 1. As HR-1 is in the second position of reflector and HR-2 in the first position of reflector, the strengths of neutron and gamma rays are different in each position. On HR-2 closer to the core fuel, both neutron flux and gamma ray strength are stronger than those on HR-1.

Rabbits for HR-1 and HR-2 are, as shown in Fig. 2, dimensions 32mmϕ × 150mm, being spherical on both ends. Accordingly, a rabbit is interchangable to both irradiation facilities. Every facility can be irradiated three units at the same time.

Exothermic limit of each rabbit is less than 20 kW on HR-1 and less than 9 kW on HR-2. These values are obtained at the point of reversal of water flow in feeding back rabbit from the reactor core when irradiation is finished, that is, in an experiment where the cooling condition is severest. Design shall be performed assuming that heat flux on outer surface of rabbit in contact with coolant is less than 1.5×10^5 kcal/m^{2}hr.

As rabbit is sent into the reactor core by water from through double tube in the rabbit facility. Strength calculation shall be performed where the inserting impact is 300 G. Strength of outer cylinder of rabbit shall be examined assuming that the outer pressure of coolant is 20 kg/cm^{2}G. Equivalent reactivity in inserting or removing three rabbits at the same time from reactor core shall be less than 0.1%ΔK/K.

Irradiation samples at HR-1 or HR-2 are roughly classified into three. The first is for production of RI, which produces ^{60}Co of long half-life. The second is a sample relating to the research by universities, which is versatile, namely, material or fuel as mentioned in 2. below. The third is a sample other than those mentioned above, which aims at short-time irradiation. Examples so far obtained indicate that for fuel sample, irradiation to observe the time dependency of irradiation behavior of samples such as UO_2 and PuO_2-UO_2 is performed, and for material sample, irradiation to study the irradiation time dependency affecting the strength of hastelloy as high-temperature material.

As mentioned above, irradiation by rabbit is available to various substances from fuel sample to material sample, and in irradiation, sample can be inserted and removed irrespective of the operation of reactor as mentioned before.

Generally, however, in irradiation, there are many samples with less problems of safety. These rabbits shall possibly be standardized, aiming at convenience somewhat to save time of design, fabrication and product. In the case that the irradiated rabbits were transfered to R.I. Manufacture Section and other sections, it will be better to use aluminum than stainless steel for rabbit material in view of the induced radioactivity. Based on such concept, designing method of standard rabbit has been established and executed. For the universitys' rabbit, the friction welding is being applied to material rabbit and, at the same time, time of design is also saving by standardizing inner diameters of rabbit. The following mentioned the designing of rabbit and the examples.

4.2 Design of Standard Rabbit

4.2.1 Outline of Standard Rabbit

A standard rabbit means a sealed rabbit made of aluminum containing standard sample, which satisfies the limited condition of irradiation determined in anticipation (See 3.). Aluminum is used in consideration to reduce activated productions. For each standard rabbit, accordingly, thermal and strength examinations are omitted. However, for rabbit not satisfying the above conditions, the thermal and strength examinations are performed, and the rabbit is to be examined by the safety examination committee of capsule organized JMTR staff.

4.2.2 Concept of Design

(1) Holder Part of Standard Rabbit

A standard rabbit (hereinafter called 'rabbit' in this section) is outlined in Fig. 2. The rabbit is shaped having outer diameter of 32 mm and length of 150 mm by both the irradiation facilities HR-1 and HR-2. Outer cylinder is made of aluminum, which is of less activation and short half-life material, in consideration that the rabbit is not disassembled after irradiation, and disassembled at the customer's own facilities after transport from JMTR to the customer.

The connection of holder and end cap of aluminum is made by the friction welding method when the customer is university. On the other hand, holder and end cap required by our own institute are connected by means of the electron beam welding at the Mechanical Engineering Division at Tokai Research Establishment of JAERI. After He gases is filled in the rabbit, the hole is welded by TIG. Rabbits in our own institute are mainly for RI production.

(2) Sample Part

Rabbits required in our own institute are mostly of those for the periodical production of RI. Irradiation samples to be used for them are mainly Au, Co HgO and UO_2. The dimensions and shapes of these samples are fixed except UO_2.

Samples required for irradiation from university facilities are various, from samples of low melting point to those of high melting point. Material samples for irradiation requested by university are classified into three types to be standard. The classified samples are shown in Table 2. The first class sample has the melting temperature 1,000°C and the highest irradiation temperature less than 1,000°C and the highest irradiation temperature less than 600°C, the third class sample the melting temperature 400 - 600°C and the highest irradiation temperature less than 400°C.

(3) Thermal Bond

Usually, sample is directly put into the holder as sample is small and irradiation temperature is low. Thermal bond is, however, necessary according to the shape of sample. Aluminum thermal bond is applied to a standard rabbit in consideration of the heat protecting condition and induced radioactivity.

4.3 Limited Conditions of Standard Sample and Standard Rabbit

(1) Conditions of Standard Sample

Standard sample of irradiated samples for irradiation are (1) material sample expected to be irradiated frequently in future, (2) sample having the melting temperature exceeding 400°C, (3) sample not generating gas, (4) sample not water-soluble, (5) sample not affected by reaction, and (6) sample undissoluble. Samples generating gas as or sample being water-soluble can apply the double sealing structure. Speaking of the reactivity of JMTR reactor, there is not any problem concerning to the reactivity to be confirmed by irradiating rabbit coated with Cd in the HR-2 performance test. In consideration of the above conditions, samples are classified into the first class through the third class, and a gap between outer diameter of sample and inner diameter of outer cylinder (inner diameter of thermal bond when thermal bond is used) is determined from Table 3 or 4.

(2) Conditions of Standard Rabbit

The design conditions of standard rabbit, ① material of holder shall be aluminum of A1100 or equivalent, ② total weight of rabbit be over 130 g and below 400 g, ③ plate thickness of outer cylinder of rabbit be over 3 mm for material equivalent to A1100, and ④ gap between outer diameter of thermal bond and inner diameter of outer cylinder be less than 0.15 mm when thermal bond is used.

4.4 Detail Design of Rabbit

Irradiating conditions of the hydraulic rabbit irradiation facilities, Machine No. 1 (HR-1) and Machine No. 2 (HR-2) are shown in Table 1.

As shown therein, amount of sample and outer gap of sample are different on irradiation facilities owing to various γ-heat generation. Details design are also different for university rabbit and RI rabbit. The detail design of university rabbit and RI rabbit are described in the following.

4.4.1 Design of University Rabbit

(1) Shape of Rabbit

Outer shape is made 32 mm in diameter × 150 mm in length as mentioned above, and outer cylinder is made of processed material of aluminum (A1050).

Regulator inner diameter of holder is 15 mm, but boring can be applied up to 3 mm in plate thickness if sample is large. If, a gas gap between outer diameter of sample and inner diameter of holder is large when sample is inserted in holder, thermal bond is enclosed. In this case, however, a gas gap between outer diameter of thermal bond and inner diameter of holder shall not exceed 0.3 mm in diameter.

(2) Thermal Design

University rabbits are made of various materials, which are considered comparatively stable by the irradiation in reactor where heat generation is only by γ-rays (gamma heating). However, some samples such as B and Li generate heat of reaction, which are not standard. Assuming that γ-heating depends upon the density but material, and obtaining the relation of gap for weight of a unit length and irradiation temperature, each thermal calculation can be omitted.

Weight of a unit length of sample classified into three steps and sample classified into the first class through the third class according to the melting point of sample to obtain the rate of gas gap are shown in Tables 3 and 4. This gas gap varies with the enclosed gas in sealing rabbit (air or He) and the irradiation facilities.

(3) Strength Design

As the friction welding is applied for the university rabbit, plate thickness of holder is fixed according to the friction welding conditions. The best plate thickness of friction-welded part is 6.5 mm.[4] 6.5 mm in plate thickness of holder is found sufficient as the thinnest plate thickness requires 3 mm enough by examination of outer pressure stress, inner pressure stress, and thermal stress at irradiation, assuming rabbit as a sealed vessel. The following completeness confirmation tests were performed to confirm the completeness of friction-welded part.

a) Burst test
b) Tensile test
c) Leak test
d) Inspection of friction-welded part by X-rays and ethylene glycol test
e) Metallographic test on friction-welded part.

These tests were performed by using a same shape as that of actual operation and letting the friction welding conditions be the parameters. According to the test results, plate thickness shall be over 6 mm and the reinforcement of friction welding be over 9 mm for A1100 (A1050).

(4) Sealing Conditions of Sample

University sample is enclosed in a holder of 15 mm in inner diameter, which cannot be large, and the gap between sample and inner diameter of holder is small where thermal bond is scarcely used.

As rabbit is driven into the reactor by hydraulic force, sample shall be protected from the damage by impact in driving. Impact acceleration of rabbit in driving is about 250 G, and the speed before collision is about 5 m/s. To simulate this impact, an impact test was performed by dropping a rabbit from 2 m high by free fall (the free fall height corresponding to 250 G is 1.3 m).

Internal structure was a sample enclosed in quartz pipe, which is not breakable. The shape of quartz pipe was 13 mm in diameter × 70 mm in length and in the remaining space, buffer material such as aluminum foil, quartz wool or stainless steel wool was stuffed. The result shows that no damage was found in fall from 2 m high with any buffer material. In any irradiations so far performed, no damage on quartz is found on sample enclosed in quartz. Standard rabbit without thermal bond contains quartz wool, SUS wool or aluminum foil in holder.

4.4.2 Irradiation Examples of University Rabbit

With regard to an example of irradiation of university rabbit, various samples such as pure metals, alloys, oxides and stones are bing irradiated as mentioned before. Standard samples of them are pure metals and alloys. Of standard samples, one is irradiated in every cycle and the other irradiated continuously during severaly cycles.

Irradiation sample Cu is irradiated most repeatedly. This type of sample is irradiated in every cycle. Sample Cu is of a thin plate or a thin round plate, which is cut into several sheets, wrapped in aluminum foil and inserted in rabbit holder. To protect the sample from damage by impact, buffer material (aluminum foil) is stuffed and spacers are inserted to hold the sample. Thereafter, end caps and outer cylinder are friction-welded and processed on outer periphery. In this case, air is enclosed.

Figure 3 show the situation of rabbit after welding and Fig. 4 shows an example of Cu sample rabbit.

The next applicable samples to be irradiated are pure metals and alloys. These samples are usually of thin plates, which are inserted in rabbit holder by wrapping scores of sheets in aluminum foil. Such kind of rabbit contains He gas usually. Figure 5 shows an example of Ti-sample.

As mentioned above, solid sample is wrapped in aluminum foil while powder sample employs a sample vessel. This vessel is made of quartz pipe. However quartz pipe is not considered sealed vessel in view of safety, sample generating gas or sample being water-soluble is sealed in a coated SUS pipe. There is no example of standard sample coated in a stainless steel pipe but an example of sample other than standard sample is a rabbit of stone irradiation. Samples are of muscovite, basalt or feldspar in flake or particle, which are wrapped in aluminum foil and inserted in a quartz pipe where the sample is fixed and sealed in a stainless steel pipe. This manipulation is made considering that sample can generate gas during irradiation. An example of stone sample is shown in Fig. 6.

4.4.3 Design of RI Rabbit

RI rabbit sample is that for production of RI, which is now Au for production ^{198}Au, Co for ^{60}Co, HgO for ^{197}Hg or ^{203}Hg and UO_2 as fuel sample for ^{99}Mo. UO_2 sample is fuel excluded from standard rabbit. These samples are nearly constant in the conditions required by users such as shape and amount. RI rabbit is, therefore, made standard by calculating heat and strength in the conditions (shape and amount), enabling to omit the thermal and strength examinations unless otherwise the conditions of sample are changed.

Rabbits of the samples Au, Co and HgO are all irradiated by HR-1.

Outer cylinder and end cap are of New A Type or New B Type. Plate thickness of outer cylinder shall exceed 3 mm for a material equivalent to A1100 according to the strength calculation.

(1) Au Irradiation Rabbit

This rabbit is that for Au irradiation aiming to produce ^{198}Au, which has been used to be irradiated from the trial period of JMTR.

Structure of Au irradiation rabbit is illustrated in Fig. 7. Irradiation sample is linear being enclosed in a sample vessel called 'rat' (See Fig. 7). This vessel is, however, not sealed. Sample is wrapped in aluminum foil and fixed in a thermal bond. Outer cylinder and end cap employ New B Type, and rabbit contains He gas. Sample Au is of the first class.

(2) Co Irradiation Rabbit

This rabbit is that for Co irradiation aiming to produce ^{60}Co., being irradiated from the trial period of JMTR same as Au irradiation. Structure of Co rabbit is illustrated in Fig. 8. Irradiation sample is linear, which is enclosed in a graphite block, wrapped in aluminum foil and built in a DL type inner capsule. Shape and amount of sample are varied with irradiation time, by which the graphite block containing sample is changed. Outer cylinder and end cap employs New A Type, and He gas is sealed in rabbit. Sample Co is of the first class.

(3) HgO Irradiation Rabbit

This rabbit is that for HgO irradiation aiming to produce ^{197}Hg and ^{203}Hg. For mercury a particular safety is required as it is volatile and easily sublimed, eroding materials of the reactor by producing amalgam in contact with various materials. Accordingly, examining the physical and chemical properties, irradiation behavior and irradiation data of HgO, the design conditions for HgO rabbit were determined. Structure of HgO rabbit is illustrated in Fig. 9.

The sample is HgO powder, which is enclosed in a quartz pipe, wrapped in aluminum foil, fixed in a thermal bond and built in a DL type inner capsule. As the sample HgO is dissolved here at 380°C or higher into oxygen and hydrogen[1)], sample temperature by irradiation shall not exceed 380°C. Some limiting conditions are, therefore, necessary.

The conditions are assumed as follows:

I) Sample (HgO powder) shall be less than 1 g.

II) Sample shall be enclosed in a quartz pipe under reduced pressure and kept in a DL type inner capsule.

III) Gas gap shall be conformed to the values in Fig. 9.

IV) Outer capsule of rabbit shall be of New A Type.

V) Rabbit shall contain He gas.

Prior to make rabbit standard, it is confirmed according to irradiation and disassembly after irradiation that there is no abnormal increase of inner pressure in a quartz pipe by dissolution of HgO nor fault on other structural components. Standard rabbit has been used from the JMTR reactor 27th operation cycle of JMTR.

Table 1 Performances of Irradiation Facilities for Hydraulic Rabbit

Item		HR-1	HR-2
Position of core		D-5	M-11
Thermal neutron flux	Max.	1.1×10^{14} n/cm^2·s	1.3×10^{14} n/cm^2·s
	Average	8.1×10^{13} n/cm^2·s	9.9×10^{13} n/cm^2·s
Fast neutron flux	Max.	8.8×10^{12} n/cm^2·s	2.1×10^{13} n/cm^2·s
	Average	6.7×10^{12} n/cm^2·s	1.6×10^{13} n/cm^2·s
γ-heating rate		1.1 W/g	2.2 W/g
Coolant		Light water	Light water
Flow rate of coolant		11 m^3/h	8.4 m^3/h
Temperature of coolant		Abt. 40°C	Abt. 40°C
Pressure of coolant		20 kg/cm^{2}G (Max.)	20 kg/cm^{2}G (Max)
Outer dimensions of Rabbit		$\phi32\times150\ell$	$\phi32\times150\ell$
Material of Rabbit		Aluminum or stainless steel	Aluminum or stainless steel
Max. dimensions of sample		$\phi26\times120\ell$	$\phi26\times120\ell$
Calorific power of sample		20 kW	9 kW
Max. insertion units of Rabbit		3	3
Irradiation time		1 min. or more	1 min. or more

Table 2 Sample for Aluminum Standard Rabbit of Closed Type

Sample element	Classification	Remarks
Ag	First class	
Au	1	
Au-Cu	1	
Al-B	2	
Al-Cu(0∿20% Al)	1	
Al-Cu(20∿45% Al)	2	
Al-Cu-B(0∿10%B)	3	
Al-Li(0∿35% Li)	2	
Al	2	Excl. powder
Be	1	
BeO	1	
CaF_2	1	
CaF_2-Nd	1	
CaF_2-NdF_3	1	
Co	1	
Cu	1	
Cu-Au(0∿15% Au)	1	
Cu-Bi(0∿23% Bi)	1	
Cu-Bi(23∿96% Bi)	2	
Cu-Fe	1	
Cu-Ge(0∿100% Ge)	2	
Cu-Ni(0∿100% Ni)	1	
Cu-Si(0∿4% Si)	1	
Cu-Si(4∿30% Si)	2	
Cu-Si(30∿90% Si)	1	
Cu-Sn(0∿65% Sn)	2	
Cu-Sn(65∿90% Sn)	3	
Cr	1	
Cu-Zn(0∿20% Zn)	1	
Cu-Pd(0∿100% Pd)	1	
Cu-Ag(0∿15% Ag)	1	
Fe	1	
Fe-B	1	
Fe-Cu(0∿1% Cu)	1	
Fe-Ti(0∿1% Ti)	1	

Gd_2O_3	1	
HgO	-	less than 1 g dissolvable at over 380°C
Hastelloy-X	1	
Ir	1	
KBr	2	Water-soluble
KCl	2	
$KCuF_3$	1	
LiF	2	
MgO	1	
MoO_3	1	
Mo	1	
Mn	1	
NaCl	2	
NbO	1	
NdF_3	1	
Ni	1	
Ni_3Al	1	
Nb-Zr(17.Zr)	1	
Nb	1	
Pt	1	
SUS	1	
SiC	1	
Si-Pd(0∿28% Pd)	1	
Ti	1	
Ti-Ce	2	
Ti-La	2	
Ti-Mn(0∿5% Mn)	1	
V	1	
Yb_2O_3	1	
Zn	3	

Table 3 r_g/r_s or HR-1 Standard Rabbit

Sample weight \ Gas / Sample	First class	Second class		Third class
	Air He	Air	He	
less than 10 g/cm	< 7.2 (%)	< 2.5 (%)	<14.0 (%)	< 9.5 (%)
5	<14.0	< 4.9	<34.1	<26.5
2	<41.4	< 9.5	<100	<73.2

r_g : Inner diameter of outer cylinder (or inner diameter of thermal bond)

r_s : Radius of sample

Table 4 r_g/r_s of HR-2 Standard Rabbit

Sample weight \ Gas / Sample	First class		Second class		Third class	
	He	Air	He	Air	He	Air
less than 10 g/cm	<19.2(%)	< 3.9(%)	< 9.3(%)	2.3(%)	< 4.6(%)	<1.4(%)
5	<44.2	< 7.9	<20.8	4.6	<10.6	<2.9
3	<85.5	<13.5	<38.4	7.2	<19.5	<4.9

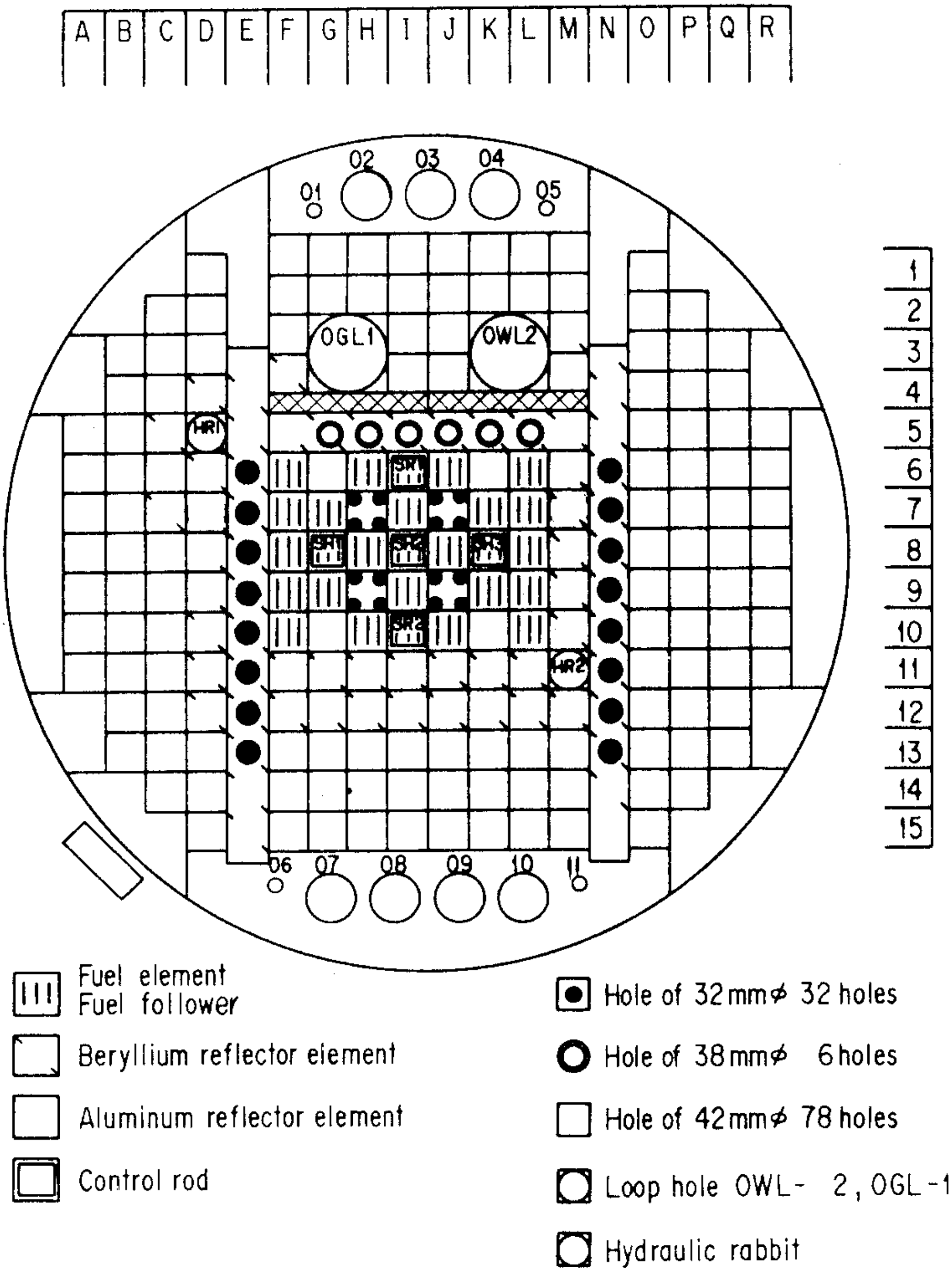
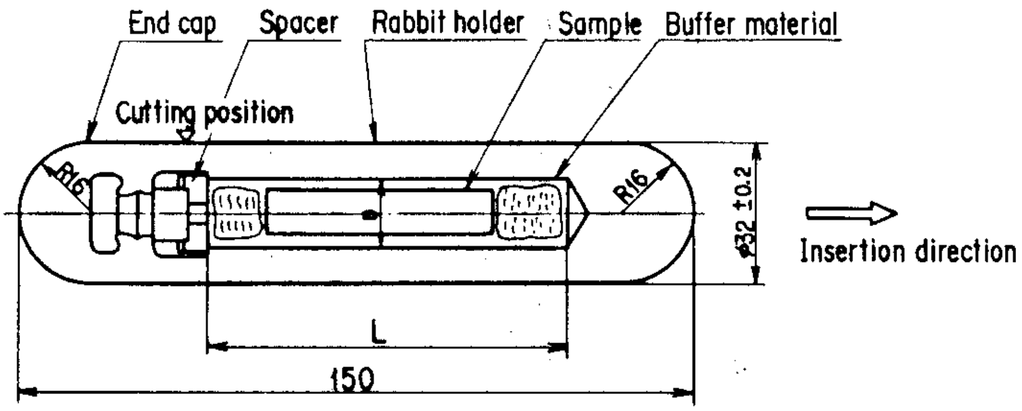


Fig. 1 Core Arrangement at JMTR



(Note) t : Over 6.0 mm
D : Outer diameter of sample hole (relative to sample)
L : Length of sample hole (relative to sample)
t,D,L shall be determined by designer

Fig.2 Outline of University Rabbit

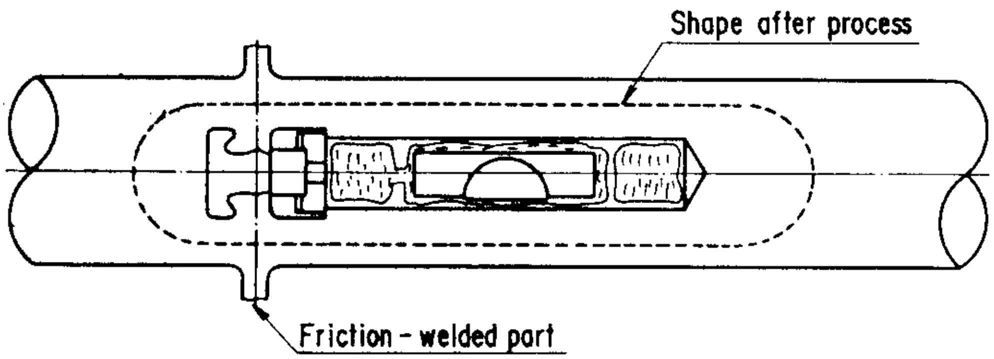
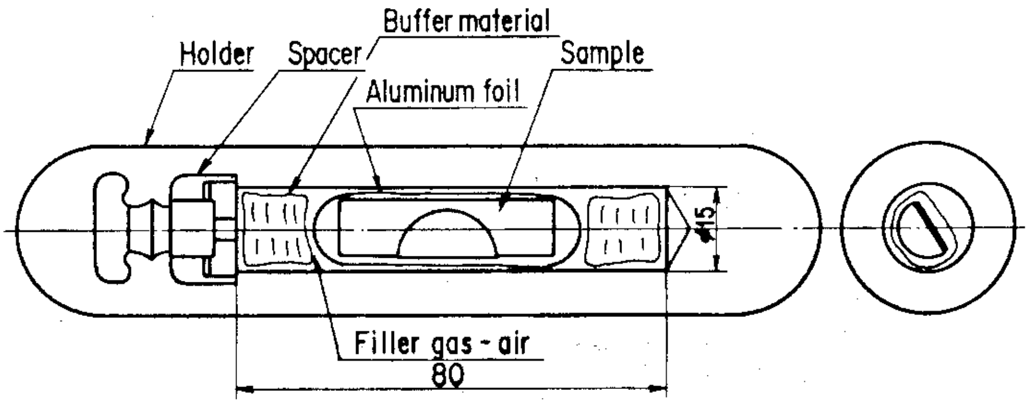
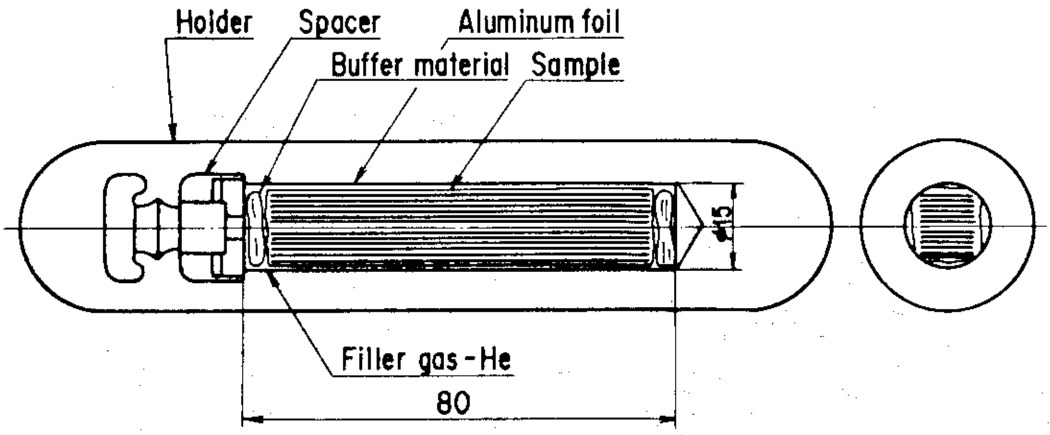


Fig.3 Shape of University Rabbit after Friction Welding



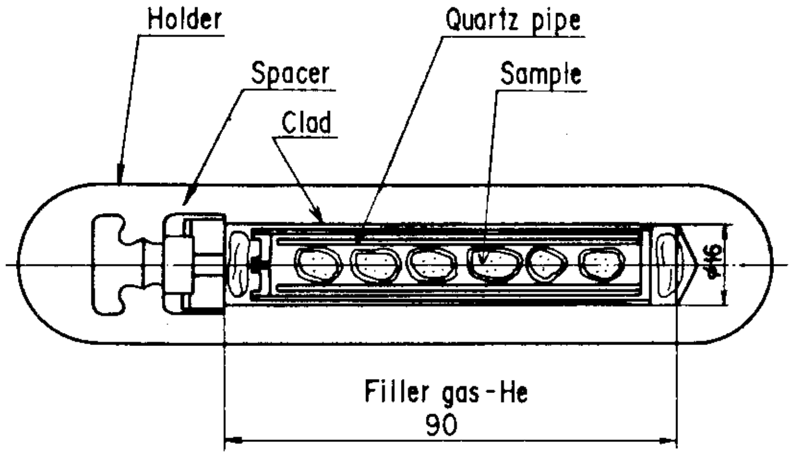
Sample	Shape	Pcs.	Weight
Cu	0.1 x 15 x 30	3	1 (g)
	18ϕ x 0.1	1	0.2

Fig.4 University Rabbit (Sample # 688 for irradiation of Cu.)



Sample	Shape	Pcs.	Weight
Ti	35 x 10 x 0.3	30	14 (g)
	35 x 5 x 0.3	60	13

Fig.5 University Rabbit (Sample # 705 for irradiation of Ti)



Sample	Shape	Pcs.	Weight
Muscovite	flake	6	5.8(g)
Basalt	Particle		

Fig. 6 University Rabbit (Sample # 665 for irradiation of stone)

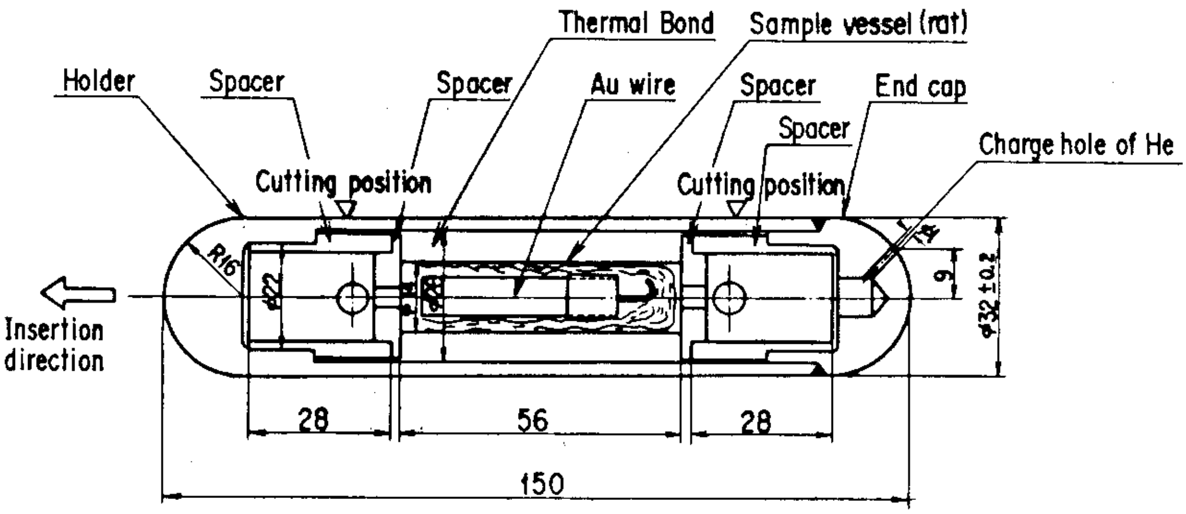


Fig. 7 RI Rabbit (Au)

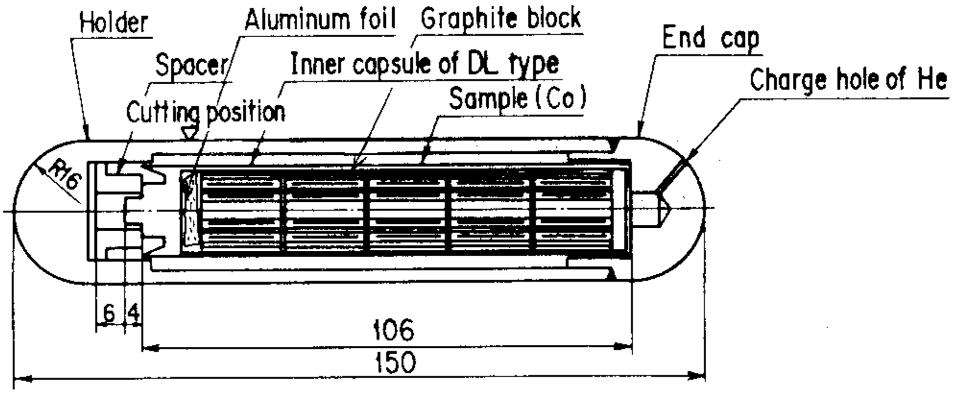


Fig. 8 RI Rabbit (Co)

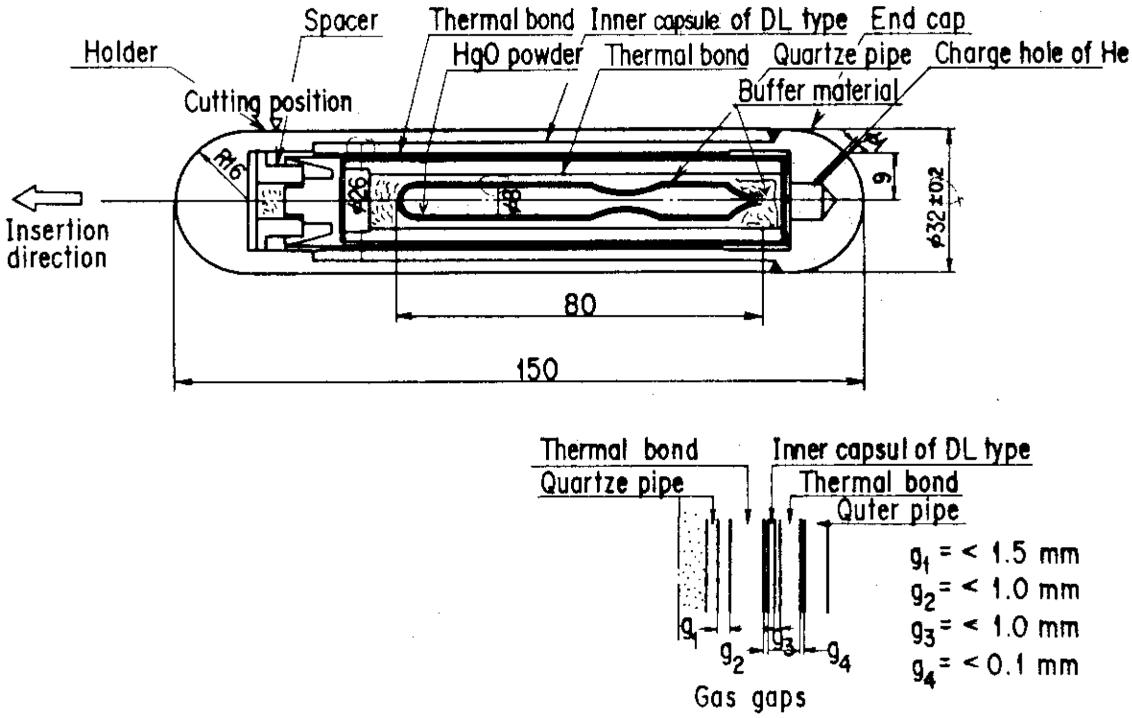


Fig. 9 RI Rabbit (HgO)

5. Design Manual of Rabbit(4)

Both the thermal design and the strength calculation on rabbit have to be described in this chapter.

These procedures, however, are as same one in the case of irradiation capsule which is other type irradiation facility than rabbit.

Therefore, the procedures mentioned in the following sections are able to be applied to the design of rabbit.

5.1 Thermal Design

5.1.1 View Points of Temperature Calculation

Temperature calculation is, according to test purpose, classified into (1) case that temperature of sample is controlled, (2) case that temperature is not controll-d but measured, and (3) case that both temperature contorl and temperature measurement are not performed. In any case it shall, in principle, be calculated to satisfy the conditions below provided that the thermal design is, in principle, to be one-dimensional.

(1) Primary coolant shall not be boiled on capsule surface.

(2) Fuel sample shall not be molten on any part.

(3) Harmful reaction shall not be caused among structural components in capsule during irradiation term. Compativility shall be satisfied.

Procedure of temperature calculation is:

(A) To calculate temperature distribution under the conditions of irradiation test (to meet test conditions and purposes), namely, in temperature increase and thermal expansion, according to the procedure 2.1 - 2.5 as mentioned below.

(B) To calculate strength under the conditions obtained in (A).

(C) After completion of manufacture of capsule, to calculate the final calculation for confirmation according to the values in the sample of dimension inspection.

5.1.2 Surface Temperature of Outer Cylinder of Capsule (T_1)

Surface temperature of an outer cylinder of capsule in contact with the primary coolant of reactor shall be calculated according to the following points so that the primary coolant shall not cause boiling.

The calculation shall be performed assuming that capsule inserted in inside of reactor inner tank is worked by the forced convection and capsule inserted in outside of reactor inner tank by the natural convection.

Calculating conditions are as follows:

Primary coolant of reactor	:	Pure water
Bulk water temperature of reactor primary coolant, T_o	:	50°C
Pressure of reactor primary coolant	:	14 kg/cm^2
Boiling point of reactor primary coolant	:	194°C (14 kg/cm^2)
		190°C (13 kg/cm^2)
		187°C (12 kg/cm^2)

Equations to be used are:

$$T_1 = T_o + \frac{Q}{\pi Dh} \qquad Q = \pi Dh(T_1 - T_o)$$

$$h = \frac{\lambda_w \cdot N_u}{d_e}$$

λ_w : Thermal conductivity of water at average temperature of T_1 and T_o, W/cm°C

d_e : Corresponding diameter cm

T_1 : Temperature on outer surface of rabbit °C

T_o : Temperature of bulk water = 50°C

h : Thermal conductivity W/cm^2°C

For N_u, the equations mentioned below are used:

1) For Natural Convection

(a) For Laminar Boundary Layer ($P_r \cdot G_r < 10^4$)

$$N_u = \frac{4}{3} f(P_r) \cdot G_r{}^{0.25}$$

(Ostrach's equation)

Values of $f(P_r)$ are indicated in the following table.

P_r	0.01	0.72	1.00	2.00	10	100	1000
$f(P_r)$	0.0581	0.3568	0.4010	0.5066	0.8269	1.5492	2.8044

(b) For Turbulent Boundary Layer ($P_r \cdot G_r > 10^9$)

$$N_u = 0.129\ (G_r \cdot P_r)^{1/3}$$

(Jacob's equation)

P_r at average temperature of P_r ; T_1, T_o

For G_r

$G_r = g \cdot \beta \cdot \ell^3 (T_1 - T_o) / \nu^2$

- β : Coefficient of cubical exapnsion, 1/°C
- g : Gravitational acceleration = 9.8 m/s^2 = 980 cm/s^2
- l : Length m, cm
- ν : Coefficient of kinetic viscosity at average temperature of T_1 and T_o m^2/s, cm^2/s

Calculation shall be performed by uniting all units to m-s or cm-s. G_r and N_u will generate same results when calculating by any equations mentioned above.

2) Temperature on Inner Surface of Outer Cylinder of Capsule (T_2)
Temperature on inner surface of outer cylinder of capsule is obtained as follows:

$$T_2 = T_1 + \Delta T_1$$

T_1 : Outer temperature on outer cylinder

$$\Delta T_1 = \frac{Q}{2\pi\lambda_{os}} \log_e \frac{D_o}{D_I}$$ (Only thermal conductivity in radial direction is considered.)

- λ_{os} : Thermal conductivity at average temperature of T_1 and T_2 of outer cylinder material
- D_o : Outer diameter of outer cylinder
- D_I : Inner diameter of outer cylinder

3) Temperature on Outer Surface of Inner Cylinder of Capsule (In Use of Thermal Bond or Inner Capsule)
Temperature of the gas gap between inner and outer cylinder os capsule is obtained.

$$T_3 = T_2 + \Delta T_2$$

$$\Delta T_2 = \frac{Q}{2\pi\lambda_G} \log_e \frac{D'_O}{D'_I}$$ (Only thermal conductivity in radial direction is considered.)

λ_G : Thermal conductivity at average temperature of T_2 and T_3 of gas

D'_O : Outer diameter of gas gap

D'_I : Inner diameter of gas gap

4) Temperature on Inner Surface of Inner Cylinder of Capsule (In Use of Thermal Bond or Inner Capsule)

Inner surface temperature of inner cylinder of capsule is obtained as follows:

$$T_4 = T_3 + \Delta T_3$$

$$\Delta T_3 = \frac{Q}{2\pi\lambda_{IS}} \log_e \frac{D''_O}{D''_I}$$

λ_{IS} : Thermal conductivity at average temperature of T_3 and T_4 of inner cylinder material

D''_O : Outer diameter of inner cylinder

D''_I : Inner diameter of inner cylinder

5) Calculation of Central Temperature

Central temperature is calculated on UO_2 pellet according to (1) the average temperature method or (2) Lyon's equation. Otherwise, it is calculated on $(U, Pu)O_2$ pellet according to (3) Bally's equation. Calculation is available by selecting one of the above three methods.

(1) Average temperature method

$$T_s = T_c + \frac{Q}{4\pi K}$$

where, the thermal conductivity K shall employ the value at $T = \frac{T_s+T_c}{2}$.

T_s : Surface temperature,

T_c : Centerline temperature.

(2) Convergent calculation by Lyon's equation

$$\int KdT - \frac{Q}{4\pi} = 38.24 \log_e \left(\frac{T_c+402.55}{T_s+402.55}\right) \div 1.197 \times 10^{-13}$$

$$\times \{(T_c+273.15)^4 - (T_s+273.15)^4\} - \frac{Q}{4\pi} = 0$$

where, T_c & T_s : °C

From above Eq. T_c is obtained according to Neuton-Lapson's Method.

(3) Convergent calculation by Bally's equation

$$\int KdT - \frac{Q}{4\pi} = 0.0110(T_c-T_s) + \left(\frac{1}{0.4848-0.4465D}\right)\log_e \frac{T_c}{T_s}$$

$$- \frac{Q}{4\pi} = 0$$

where, D : the ratio of dencity to theoritical dencity of pellet. $(\% \times \frac{1}{100})$.

Center hall pellet shall be taken below equation.

$$Q = Q\cdot[1 - \frac{2\cdot R_q^2}{R(\ell)^2 - R_q^2} \cdot \log \frac{R(\ell)}{R_q}]$$

R_q : Outer diameter of pellet

$R(\ell)$: Inner diameter of pellet

5.2 Strength Calculation

5.2.1 Strength Calculation

Strength calculation shall, in principle, be performed by obtaining stress of each part of capsule, which shall satisfy each condition concerned.

(1) Stress shall be divided into mechanical stress and thermal stress.

(2) Mechanical stress (σ_p) shall contain the primary membrane stress, primary bending stress, and secondary stress by the inner and outer pressures and thermal stress by the temperature difference in irradiating direction, which shall not exceed the allowable stress.

(3) Thermal stress (σ_T) shall contain the thermal stress by the temperature difference in radial direction and local stress concentration,

and $\sigma_T + \sigma_p$ shall not exceed three times of the allowable stress.

(4) Fatigue fracture and thermal ratchet by the repeated thermal stress shall not be caused.

(5) Damage by the creep phenomenon or the large change in stress distribution shall not be caused. Especially connection box, connection unit, and so forth, conforming to ASME CODE SEC. VIII samely to pressure vessel provided that calculation shall be performed on the places where the primary coolant pressure is applied directly.

Procedure of the strength calculation is:

(1) To examine strength of cylinder according to 2.2.

(2) If strength is similar to the allowable limit according to the result of (1), to confirm the above conditions by performing a more detailed stress calculation at need.

5.2 Strength of Cylinder

1) Inner Pressure

(1) Inner pressure by He gas

$$P_{He} = \frac{273 + T_G}{273} \times \frac{1}{100} \qquad \text{kg/mm}^2$$

T_G : Gas temperature (average of temperature on sample surface and rabbit inside)

2) Strength of Cylinder

(1) Strength to inner pressure

Of the stress caused on cylinder to inner pressure, stress in circumferential direction is the highest, which shall be obtained:

$$\sigma = \frac{PD_I}{2t} \qquad \text{kg/mm}^2$$

P	:	Inner pressure	kg/mm^2
D_I	:	Inner diameter of cylinder	mm
t	:	Plate thickness of cylinder	mm

(2) Thermal Stress

On cylinder body, the absolute value of stress is same to those of inner and outer surfaces by the working compression and tensile stress (high inside temperature). Stress is same in axial and circumferential directions, which shall be obtained by the following equation:

$$\sigma_{max} = \frac{\alpha \cdot E(t_1 - t_2)}{2(1-\nu)} \qquad kg/mm^2$$

(To assume the temperature distirbution be linear)

α	:	Linear expansion rate	1/°C
ν	:	Poisson's ratio	
E	:	Young's modulus	kg/mm^2
t_1, t_2	:	Inside and outside temperature of cylinder	°C

(3) Strength to Outer Pressure

When pipes are employed outside capsule, the piping shell have outer pressure strength sufficient to JMTR primary coolant. When employing pipe other than those pipes, the following examination shall be performed:

(a) Stress in circumferential direction

$$\sigma_o = \frac{2 \cdot P_2 R_2^2}{P_2^2 - R_1^2}$$

R_1, R_2	:	Inner and outer radii of cylinder	mm
P_2	:	Outer pressure = 0.18	kg/mm^2

3) Evaluation of Stress

(1) Allowable Stress

As the allowable stress of the rabbit holder (outer cylinder A1050, σ_a of 1.3 kg/mm^2 (at 100°C) shall be taken up.

(2) Evaluation of Stress

For rabbit, stress shall be evaluated on only outer cylinder, satisfying the following equations:

$\sigma < \sigma_a$	σ	:	Stress to inner pressure
$\lvert\sigma_o\rvert < \sigma_a$	σ_o	:	Stress to outer pressure

$\sigma_{t\ max} + \sigma < 3\sigma_a$ σ_t : Thermal stress

$\sigma_{t\ max} + |\sigma_o| < 3\sigma_a$ σ_a : Allowable stress

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$\sigma_{t\ max} + \sigma < 3\sigma_a$ σ_t : Thermal stress

$\sigma_{t\ max} + |\sigma_o| < 3\sigma_a$ σ_a : Allowable stress

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