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POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION

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Irradiation Creep and Growth of Pressure Tubes in HWR Fugen*

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Abstract

The 165MWe prototype HWR Fugen has been in commercial operation since March 1979. The material of the pressure tube is heat treated Zr-2.5 wt%Nb alloy and the pressure tubes in the Fugen have been irradiated with the maximum fast neutron flux of about 3×10^{17} n/m²·sec. The pressure tubes have been inspected periodically according to the pressure tube monitoring program. In March 1984, inside diameter measurements on a small number of the pressure tubes were performed by using the pressure tube monitoring device adopting an ultrasonic wave method, and the diametrical

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irradiation creep and growth strain has been assessed. In February 1987, tube length measurements were performed and these data are to be used as the standard value for the estimation of the axial irradiation creep and growth strain. Besides, small diameter specimens pressurized by helium gas have begun being irradiated in the Fugen since April 1987.

1. Introduction

Power Reactor and Nuclear Fuel Development Corporation (PNC) in Japan has developed the ATR-Fugen, a 165MWe prototype boiling-light-water-cooled heavy-water-moderated pressure-tube-type reactor of Japan, which has operated satisfactorily since the start of commercial operation in March 1979. It achieved the total electrical generation of 7.2×10^{9} KW·h in January 1987. A 600MWe ATR Demonstration Plant has been designed on the basis of the experience of the Fugen and is scheduled to begin commercial operation at the end of 1990's. The ATR is a unique reactor designed mainly to use plutonium-uranium mixed oxide (Mox) fuels.

The ATR Fugen has 224 pressure tubes made of Heat Treated Zr-2.5 wt%Nb alloys which changes its size slightly by irradiation creep and growth. The pressure tubes in Heavy Water Reactor Fugen have been irradiated with the maximum fast neutron flux of about 3×10^{17} n/m²·sec. The pressure tubes have been inspected periodically according to the pressure tube monitoring program. This prograim includes the measurement of irradiation creep and growth of pressure tubes, as well as ultrasonic flaw detection and visual inspection of the internal surface of the pressure tubes.

Remote-controlled in-service inspection devices have been developed for this purpose [1]. To reduce the radiation exposure of inspectors, detectors with their associated electronics and drive mechanisms for vertical and rotating movements are housed in the inspection tool assembly, which can be mounted on or removed from the pressure tubes by remote control using a refuelling machine.

In March 1984, inside diameter measurements on a small number of the pressure tubes were performed by using the pressure tube monitoring device adopting an ultrasonic wave method. These measured data have been compared with the values which were obtained at the construction stage of the Fugen, and the diametrical irradiation-induced creep and growth strain of the pressure tubes has been assessed. In February 1987, tube length measurements were performed with the use of a newly developed pressure tube monitoring device and the standard value for the axial irradiation creep and growth strains were obtained. From the next measurements, the axial irradiation creep and growth strains can be obtained by the comparison of the measured value with this standard one. Hereafter, according to the pressure tube monitoring program, these measurements will be performed every 2-4 years at the anual inspection period of the Fugen.

Small diameter specimens pressurized by helium gas have been irradiated in the Fugen since April 1987 for the measurement of strains of irradiation creep and growth. These specimens are to be taken from the reactor every 2 years, and their dimension changes and microstructures are to be examined.

2. Implementations of pressure tube monitoring on irradiation creep and growth

For the measurement and assessment of irradiation creep and growth of pressure tubes of the Fugen, we have test items as follows.

(1) Measurements of diametrical irradiation creep and growth strain of pressure tubes are performed by the equipment PTM(I), using an ultrasonic wave method.

(2) Measurements of axial irradiation creep and growth strain of pressure tubes are performed by the equipment PTM(II) , using contact probes method.

(3) Measurements of dimension changes of small diameter specimens irradiated in the Fugen core are performed using an ultrasonic measuring device as post irradiation examinations.

Fig.1 shows the manufacturing process of pressure tubes of the Fugen. The billet of Zr-2.5 wt%Nb is extruded at high temperature by the use of horizontal extrusion press, cold-drawn and the then solution-heat-treated by guenching the material in the heating furnace into water from the temperature of 887°C. By the performance of this solution heat treatment our pressure tubes are called Heat Treated pressure tubes. After the solution heat treatment the material is cold-drawn up to the cold working rate of 5~15%. Then the material is aged in a vacuum furnace at 500°C for 24 hours, and by the final forming the pressure tube is made as inner diameter of 117.8 mm, thickness 4.3 mm and the length about 5500 mm. The chemical compsition of H.T.Zr-2.5 wt%Nb pressure tube is as follows: Nb=2.40~2.80 wt.%, O_2=900~1300 ppm, H_2=max.25 ppm and the balance is Zr. As for the manufacturing specification of mechanical properties of the pressure tube, the ultimate tensile strength is ≧537 MPa at 300°C and ≧763 MPa at R.T., the 0.2% proof stress is ≧392 MPa at 300°C and ≧529 MPa at R.T., the elongation is ≧10% at 300 ℃ and R.T., the hardness is ≧HV235, and the primary α phase is >5%.

HWR Fugen operating history is shown in Fig.2. The Fugen has started the commercial operation in March 1979. Before the commercial operation 23 pressure tubes were inspected as the pre-service inspection (PSI) in September 1977 by the use of PSI monitoring equipment developed by PNC. In this PSI monitoring, inside diameter measurements of 23 pressure tubes were performed by the linear variable differential transformer (LVDT) method, as well as the internal surface flaw detection by an ultrasonic method and the internal surface visual inspection by a TV method. In March 1984, 10 pressure tubes were inspected as the in-service inspection (ISI) by the use of pressure tube monitoring equipment, PTM(I) which was newly developed considering the high radiation field in the pressure tubes of about 2×10^5R/h by gamma rays. In the course of ISI monitoring, inside diameter measurements of 10 pressure tubes were performed by the ultrasonic method, as well as the internal surface flaw detection by ultrasonic method and the internal surface visual inspection by TV method. By the comparison of the values of the inside diameter between PSI data and ISI data, the increase of the inside diameter was obtained as the irradiation creep and growth strain.

And, in February 1987 the pressure tube length measurements were conducted for the first time in order to estimate the axial irradiation creep and growth by the use of newly developed pressure tube monitoring equipment, PTM(II). In this monitoring, 3 pressure tubes were inspected on the axial length measurement as well as on the flaw detection at the part of rolled joint. As the measurements of the axial length of pressure tubes were conducted for the first time in the Fugen, the data obtained in this monitoring are to be used as the standard value for the estimation of the axial irradiation creep and growth of the pressure tubes in the Fugen.

Development of the remote-controlled inspection equipment, PTM(I) was started in 1977. The method of inspection was first studied in the design. Extensive trial tests and evaluation of the test data were repeated until the final design was determined. The structure of the remote-controlled inspection equipment was completely changed from that of PSI equipment which was produced without the consideration of radiation exposure. In the equipments of PTM(I) and PTM(II), the detectors, electronic components and drive mechanisms are integrated in the inspection tool assembly, which can be inserted into the pressure tube using the refuelling machine. The radiation exposure can thus be small and the time of inspection is rather short.

Table 1 shows the irradiation conditions of pressure tubes in the Fugen. The pressure tubes are irradiated at 280°C and 7 MPa of inner pressure under the fast neutron flux of about 3×10^{17} $n/m^2\cdot sec$ with the fast neutron energy of more than 1 MeV. The hoop stress applied to the pressure tubes is 96 MPa.

The implementation of pressure tube monitoring is shown in Fig.3 in which the abscissa is the year and the ordinate is the fast neutron fluence with the unit of n/m^2. The implementation of inside diameter measurements performed in September 1977 as the PSI and in March 1984 as the ISI are indicated in the figure as well as that of the axial length measurement performed in February 1987. Also in the figure are indicated the scheduled ISI monitoring in the future which will be performed every 2 ~ 4 years.

Fig.4 shows the general view of the application of the pressure tube monitoring equipment. From the channel to be inspected the fuel assembly is taken out, and the pressure tube monitoring equipment PTM(I) or PTM(II) is inserted into the pressure tube by using the refuelling machine. At the bottom of the channel a seal plug is connected and in the primary coolant the pressure tube monitoring is perfomed on the measurements of the inside diameter and so on with the remote-controlled system.

As for the tests of the irradiation creep and growth with the use of small diameter specimens pressurized by helium gas, the irradiation has started at the Fugen in April 1987, which is indicated in Fig.3. These specimens are to be taken from the reactor every 2 years, and their dimension changes and microstructures are to be examined.

3. Inside diameter measurements of pressure tubes

3.1 Development of the monitoring equipments

The pressure components of the primary system of the Fugen reactor are inspected during the annual inspection. Inspection of the pressure tube assemblies is essential in order to confirm their in-service integrity for the safety of the pressure tube type reactor. In this pressure tube monitoring, the inside diameter measurements of pressure tubes are performed as well as another inspections.

For the above purposes of ISI and monitoring, development of a trial pressure tube inspection device was initiated in 1970. After a mock-up test of the equipment for one year, pre-service insepction (PSI) was conducted in 1977 for 23 pressure tube assemblies of the Fugen. In this PSI, the inside diameter measurements of 23 pressure tubes were also conducted by the LVDT method.

This pressure tube inspection equipment for PSI, however, has to be assembled or disassembled manually underneath the reactor core; in addition, the equipment itself is fairly massive. Its handling thus requires a great deal of manpower and time. Considerable radiation exposure of the personnel could result from the inspection after the operation of the Fugen if we use this pressure tube inspection equipment.

To greatly reduce radiation exposure at the time of pressure tube inspection and to shorten the time of inspection, a remote-controlled in-service inspection device was developed. The equipment consists of two types of inspection tool assemblies, a control panel, a signal transmission system and auxiliary equipment, and is capable of performing three kinds of inspection: measurement of the inside diameter, ultrasonic flaw detection and visual inspection of the internal surface.

The pressure tube inspection equipment for ISI, PTM(I), has the following features:

(1) The equipment is mounted on and removed from the pressure tube by remote manipulation, using a refuelling machine

(2) High-precision inspection is possible under high radiation field, about 2×10^5 R/h (gamma rays)

(3) Inside diameter measurement and ultrasonic flaw detection can be made at the same time, so the inspection period can be shortened

(4) In each detector, there is a built-in calibration mechanism; thus with the equipment inserted in the pressure tube, confirmation of its function and calibration are made readily.

3.2 Pressure tube monitoring equipment, PTM(I)

Fig.5 shows the pressure tube monitoring equipment, PTM(I). It is predicted that the inside diameter of the pressure tubes increases about 100 μm per year (in the middle of the reactor core) due to irradiation (fast neutron) creep and growth phenomena. To measure accurately such a small change in dimension, the accuracy in the inside diameter measuring device is designed to be ±20 μm. In PSI pressure tube inspection equipment, the differential transformer method was adpted. However, to reduce the size and to increase the inspection speed of the pressure tube inspection equipment, the ultrasonic wave method is employed for PTM(I). The inside diameter measurement method is illustrated in Fig.5(b).

In the inside diameter measuring device of PTM(I) there are two probes in a symmetrical arrangement at 180°. By measuring the elapse time from the instant when the ultrasonic wave is emitted from the probe to the instant when it returns to the probe after its reflection at the inner surface of the pressure tube, the distance the ultrasonic wave covers is obtained (distance = sound velocity × propagation time). With d_1 as the distance from probe 1 to the inner surface of the pressure tube, d_2 as the distance from probe 2 to the inner surface and d_0 as the distance between probe 1 and probe 2, the inside diameter (ID) of the pressure tube is given by

$$ID = d_1 + d_2 + d_0$$

As shown in Fig.5(b), inside diameter measurement is made over the whole region for the circumference from 0° to 360° and along the axial direction of the pressure tube in an upward spiral move with a pitch of 3 mm. Similar to ultrasonic flaw detection inspection, the inside diameter measuring device has a built-in easy calibration mechanism. The specifications of the pressure tube monitoring equipment, PTM(I) are shown in Table 2. For the measurements of the inside diameter of the pressure tubes, the ultrasonic wave method is adopted using 5 MHz ultrasonic probes. In the vertical drive mechanism, which is operated in water, the rack-and-pinion type is employed. The vertical position of the inspection device is detected by measuring the number of revolutions made by the pinion. For this purpose, the optical pulse encoder is suitable because of its small size and high resolution, but it is not resistant to radiation. Therefore, a magnetic pulse generator is employed. The rotary drive mechanism is of the gear type. For the inside diameter measurement and the flaw detection it takes about 60 minutes for one pressure tube.

3.3 Results of inside diameter measurements

Fig.6 shows the allocation of the pressure tube in the Fugen core for the inside diameter measurements. 23 solid circles mean the pressure tubes of which inside diameters were measured as the PSI in September 1977. 10 open circles mean the pressure tubes of which inside diameters were measured as the ISI by the PTM(I) in March 1984. 4 crosses mean the follow-up pressure tubes one of which inside diameters should be measured periodically as the obligation determined at the reactor construction stage because their fluences received throughout the life of reactor operation was estimated to be the highest.

By the comparison of the measured inside diameters between at PSI monitoring and at ISI monitoring, the diametrical irradiation creep and growth strains were obtained. The inside diameters were measured throughout the axial length of the pressure tubes and at each axial positions the inside diameters were measured around the tubes circumferencially from the angle 0° to 360°. The measured results were shown in Fig.7 at the angle 0° for example for the pressure tube No.2171, and Fig.8 shows the averaged values on the circumference from the angle 0° to 360°. In these figures the abscissa means the inside diameter of the pressure tube and the ordinate means the vertical position of the pressure tube measured from the bottom of the pressure tube assembly. In the figures the measured inside diamters were indicated for both the PSI monitoring in 1977 and the ISI monitoring in 1984. Also were plotted in these figures the diameter increment the PSI stage and the ISI stage, and the fast neutron flux. The abscissa values for the diameter increment by the irradiation creep growth were indicated at the top portion of the figures. During the period of about 6.5 years the diameter increment of the pressure tube is about 0.3 mm at maximum.

Fig.9 shows the summarized data of diametrical irradiation creep and growth strain for 8 pressure tubes in the Fugen. The abscissa means the fast neutron fluence and the ordinate means the diametrical irradiation creep and growth strain. Besides, in the figure the solid line almost straight means the calculated values with the use of the Ross-Ross equation [2] and the Ibrahim and Holt equation [3]. The value calculated by the Ross-Ross equation is almost identical to that calculated by the Ibrahim and Holt equation. In the figure one can understand that both of these equations can interpret the present diametrical data well because the present data are almost on the lines.

The equations we used are explained as follows.

(1) Design equation of the Fugen pressure tube by P.A. Ross-Ross

$$\dot{\varepsilon} = 3.18 \times 10^{-29} \Phi \sigma_t (T-160)$$

$\dot{\varepsilon}$: hr^{-1}

Φ : Flux ($n/m^2 \cdot s$)

σ_t : hoop stress (MPa)

T : temperature (℃)

(2) Creep and growth equation byE.F.Ibrahim and R.A.Holt

$$\dot{\varepsilon}_t = (E_{BT}\sigma_t - E_{TA}\sigma_{ac}) K_c \rho^{0.16} \Phi [\exp(-6500/T) + 5.5 \times 10^{-6}] + G_t K_g P^{0.82} \Phi \exp(-700/T)$$

$$\dot{\varepsilon}_a = (E_{BA}\sigma_t - E_{AA}\sigma_{ac}) K_c \rho^{0.16} \Phi [\exp(-6500/T) + 5.5 \times 10^{-6}] + G_a K_g \rho^{0.82} \Phi \exp(-700/T)$$

$\dot{\varepsilon}_t$, $\dot{\varepsilon}_a$:transverse and axial strain rates per hour

E_{BT}, E_{BA}, E_{TA},E_{AA}: anisotropy factors for creep

σ_t :transverse (hoop) stress from internal pressure (MPa)

G_t, G_a :anisotropy factros for irradiation growth in transverse and axial direction

σ_{ac} :compressive stress from the application of an end load on the tube (MPa)

Φ :fast neutron flux $n/m^2 \cdot s$ (>1MeV)

K_c :the rate constant for creep

K_g :the rate constant for growth

ρ :dislocation density

For the design of the pressure tubes in the Fugen the P.A.Ross-Ross equation (1) had been used for the estimation of the diametrical irradiation creep and growth, and this equation is very simple with the functions of flux, hoop stress and temperature.

As a reference, the calculation was performed with the use os the E.F. Ibrahim and R.A. Holt equation (2), which is very complicated. For this calculation the values such as anisotropy factors must be determined, and we adopted for them the values obtained in the Gentilly-1 Reactor. As one can see in Fig.9, the calculated values both by the Ross-Ross equation and by the Ibrahim and Holt equation are almost the same.

From the standpoint of the design of the Fugen, the designed value for the irradiation creep and growth strain was determined to be less than 2.5% throughout the reactor life of about 30 years.

4. Axial length measurements of pressure tubes

In February 1987, axial length measurements for 3 pressure tubes in the Fugen were conducted with the use of the pressure tube monitoring equipment, PTM(Ⅱ) , which is shown in Fig.10. The total length of this equipment is about 8 m. PTM(Ⅱ) was developed and manufactured so as to be loaded into the pressure tubes by the refuelling machine and to be treated by a remote-controlled system in order to reduce radiation exposure at the time of pressure tube inspection and to shorten the time of inspection. And under high radiation field of about 2×10^5R/h (gamma rays), high-precision inspection is possible by using PTM(Ⅱ) .

As shown in Fig.10, axial length of the pressure tube is measured from the lower rolled joint to the upper rolled joint. PTM(Ⅱ) has two contact probes which can move vertically and rotationally. At the lower rolled joint the probe can contact the upper part of the inner ring by moving rotationally and vertically, and the length C (in Fig.10) is to be measured by the pulse encorder method. Also, at the upper rolled joint another probe can contact the lower part of the inner ring and the length B is to be measured by the method. As for the length A which is the length between two probes, it is known beforehand because it is a fixed gauge. Furthermore, there are many thermocouples attached on the equipment and the temperature calibration on thermal expansion of materials is performed using them. Thus, the axial length (A + B + C) is to be measured as the length between the lower rolled joint and the upper rolled joint.

Table 3 shows the specification of the PTM(II). Although not indicated in the table, the PTM(II) has another function as to detect the flaw by ultrasonic wave method at the inner surface of the pressure tube near the rolled joints. The axial length of the pressure tube is measured with the fixed gauge and two contact probes of which length by the vertical movements can be transformed into rotations and signals by pulse encorders. The measuring accuracy is ±1.0 mm/4.8 m. The vertical drive mechanism is rack-and-pinion type and the rotary drive mechanism is of the gear type. For one pressure tube inspection it takes about 1.5 hours to measure the axial length and to inspect the flaw by ultrasonic wave method at the inner surface of the pressure tube near the rolled joints.

The axial length measurement was first performed in February 1987 and its data serve as the standard value for the estimation of the axial irradialtion creep and growth hereafter.

5. Irradiation creep and growth experiments using small diameter specimens

In the Fugen, irradiation creep and growth tests using small diameter specimens made of H.T. Zr-2.5 wt%Nb tubes have been carried out since April 1987 to obtain the creep and growth rate and the creep limit of this material. Creep specimens and growth specimens were made from small diameter tubes and now thes specimens have been irradiated in the Fugen. Creep specimens were internally pressurized with helium gas and growth specimens were small diameter pipes of which both ends were opened.

5.1 Specimen

The creep specimens shown in Fig.11 were produced from small diameter tubes to be irradiated in the special fuel assemblies of the Fugen. The inner diameter of the specimen is 35 mm and the thickness is 0.5 mm on the center region of 145 mm length. Both sides of the tube were TIG-welded with end blocks and the both end thicknesses of the tube are thickend to be 1.5 mm to decrease the applied stress at the weld points. The end blocks are also produced from H.T. Zr-2.5 wt%Nb alloy. Helium gas were put into the specimen from the small hole of an end block, and the hole were closed by TIG spot welding under the pressurized conditions. The growth specimens were made from the small diameter tube of H.T Zr-2.5 wt%Nb alloy.

The inner diameter of the specimen is 36 mm, the length is 30 mm and the thickness is 0.5 mm. The growth specimen is of the shape of an opened pipe.

5.2 Material properties of specimens

The small diameter test tubes were produced under the same manufacturing process as that for the Fugen pressure tubes as shown in Fig.1. Therefore, the material properties of the small diameter tubes are almost the same as those of the Fugen pressure tubes.

The cmparison of mechanical properties between the full size pressure tubes, the Fugen pressure tubes and the small diameter tubes is shown in Table 4. In this table, the ultimate tensile strength, the 0.2% proof stress and the percentage of the primary α phase are shown for both tubes, and this table shows that the mechanical properties for both tubes are almost the same.

For the crystallographic textures of the full size pressure tubes and the small diameter tubes, typical basal (0002) pole figures of H.T. Zr-2.5 wt%Nb tubes are shown in Fig.12. On the H.T. Zr-2.5 wt%Nb tubes, the basal plane normals were highly concentrated close to the longitudinal direction, at about 30 degrees tilted position from radial to longitudinal direction. As for the longitudinal direction, however, the integrated total intensity is not so large. Table 5 shows the resolved fractions of basal poles in the three principal directions.

The fraction of longitudinal direction is smaller than those of other two directions, but these differences are very small. From the texture analysis the hexagonal close packed crystals are considered to be distributed at random, and the texture of the small diameter tubes is similar to that of the full size pressure tubes.

5.3 Test conditions of creep and growth specimens

The creep specimens were put in capsule shown in Fig.13 together with growth specimens and corrosion specimens. The growth specimens which are not stressed are the same diameter as that of the creep specimens. The capsules were inserted into the special fuel assemblies in the Fugen. Fig.14 shows the schematic of the special fuel assembly. Capsules with these specimens were put into the cylindrical space at the middle of the special fuel assemblies with 36 fuel elements. Four special fuel assemblies were installed in the Fugen reactor with these specimens.

The creep specimens were pressurized up to three pressure levels. Hoop stresses of the specimens under irradiation are estimated to be 392 MPa, 294 MPa and 196 MPa, respectively which are higher than the operating hoop stress of the Fugen pressure tubes, 96 MPa. Thus the small diameter creep tests are performed with the accelerated test conditions on the hoop stress. Irradiation conditions of small diameter specimens are given in

Table 6. Average fast neutron flux (>1MeV) is 2×10^{17} n/m^2·sec and irradiation temperature is 280°C. Tweleve creep specimens as well as twenty-four growth specimens have been irradiated since April 1987 in the Fugen.

5.4 Measurements of creep and growth strain

Diameters of the creep and growth specimens will be measured every two years. Then, the capsules will be pulled out from the special fuel assemblies, and the outer diameter of the specimens will be measured by an ultrasonic measuring method through the outside of the capsule. These capsules will be reinstalled in the reactor after the measurement. Post irradiated specimens will be sent to the test facility with hot-cells in order to examine the detail dimension changes, hydrogen pick-up, microstructures and whether creep failures are occurred or not.

6. Conclusions

For the measurements and assessment of irradiation creep and growth of H.T. Zr-2.5 wt%Nb pressure tube of the Fugen, PNC developed the remote-controlled inspection equipments, namely, PTM(I) for the inside diameter measurement and PTM (II) for the axial length measurement. And small diameter specimens made of H.T.Zr-2.5 wt%Nb were pressurized by helium gas in it and the irradiation of these specimens were started at the Fugen in order to estimate its dimension changes hereafter. The summaries obtained are as follows.

(1) Diametrical irradiation creep and growth strain of the H.T. Zr-2.5 wt%Nb pressure tubes in the Fugen was obtained to be about 0.25% for the period of 6.5 years, the value being almost identical to that calculated by the Ross-Ross equation.

(2) The axial length of the H.T. Zr-2.5 wt%Nb pressure tubes in the Fugen were measured in February 1987 for the first time, and these values are to be used as the standard one for the estimation of the axial irradiation creep and growth hereafter. From the texture analysis of the pressure tubes of the Fugen, the hexagonal close packed crystals are considered to be distributed at random, so that, the axial irradiation creep and growth strain is considered to be less than that of the C.W. Zr-2.5 wt%Nb pressure tubes.

(3) By the irradiation in the Fugen of the H.T. Zr-2.5wt%Nb

small diameter specimens pressurized higher than those of the actual pressure tubes of the Fugen, and by measurements of their dimension changes every 2 years, we will obtain the irradiation creep and growth data under accelerated test conditions on the internal pressure.

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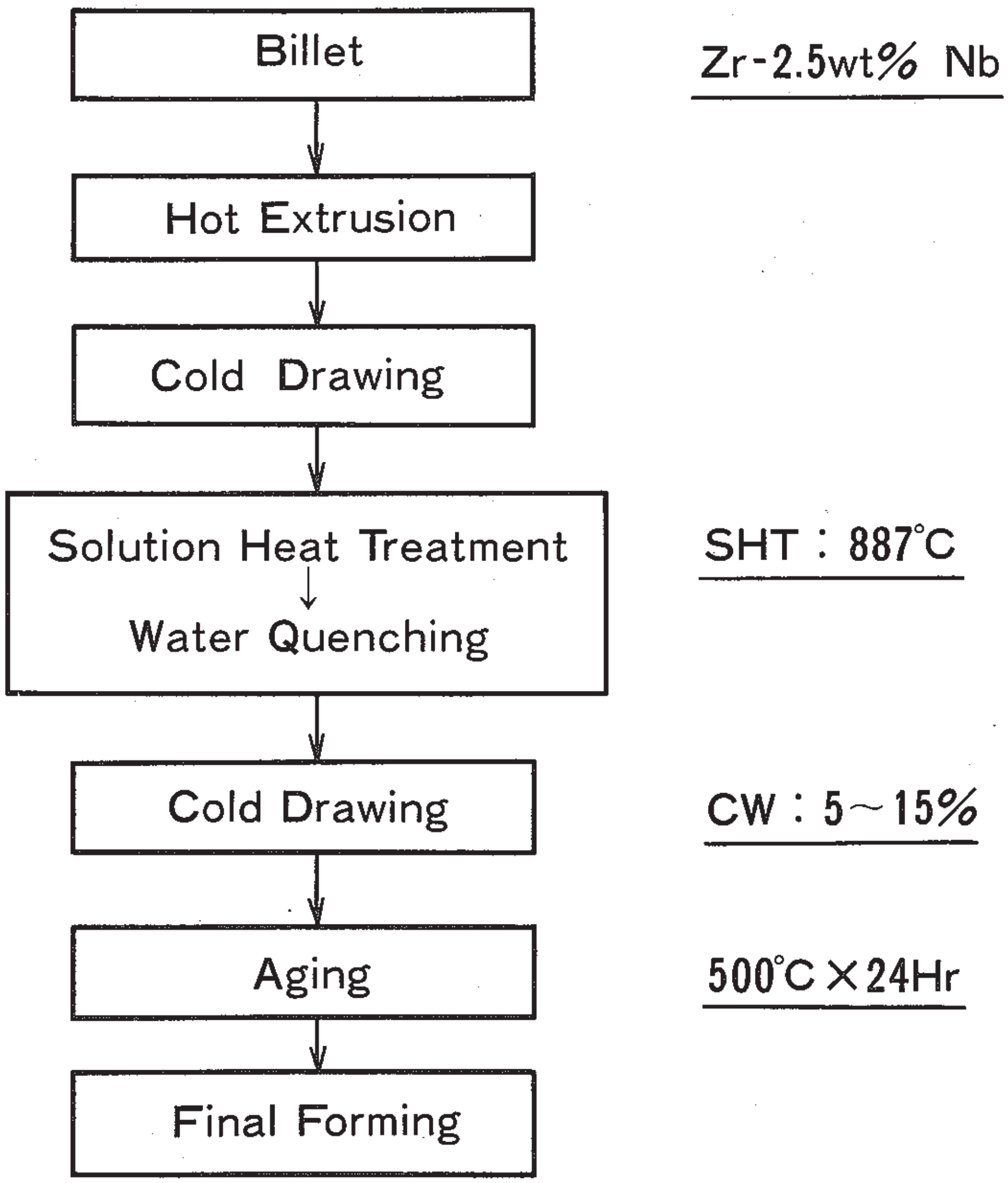


Fig. 1 Manufacturing process of H.T. Zr-2.5 wt%Nb pressure tubes.

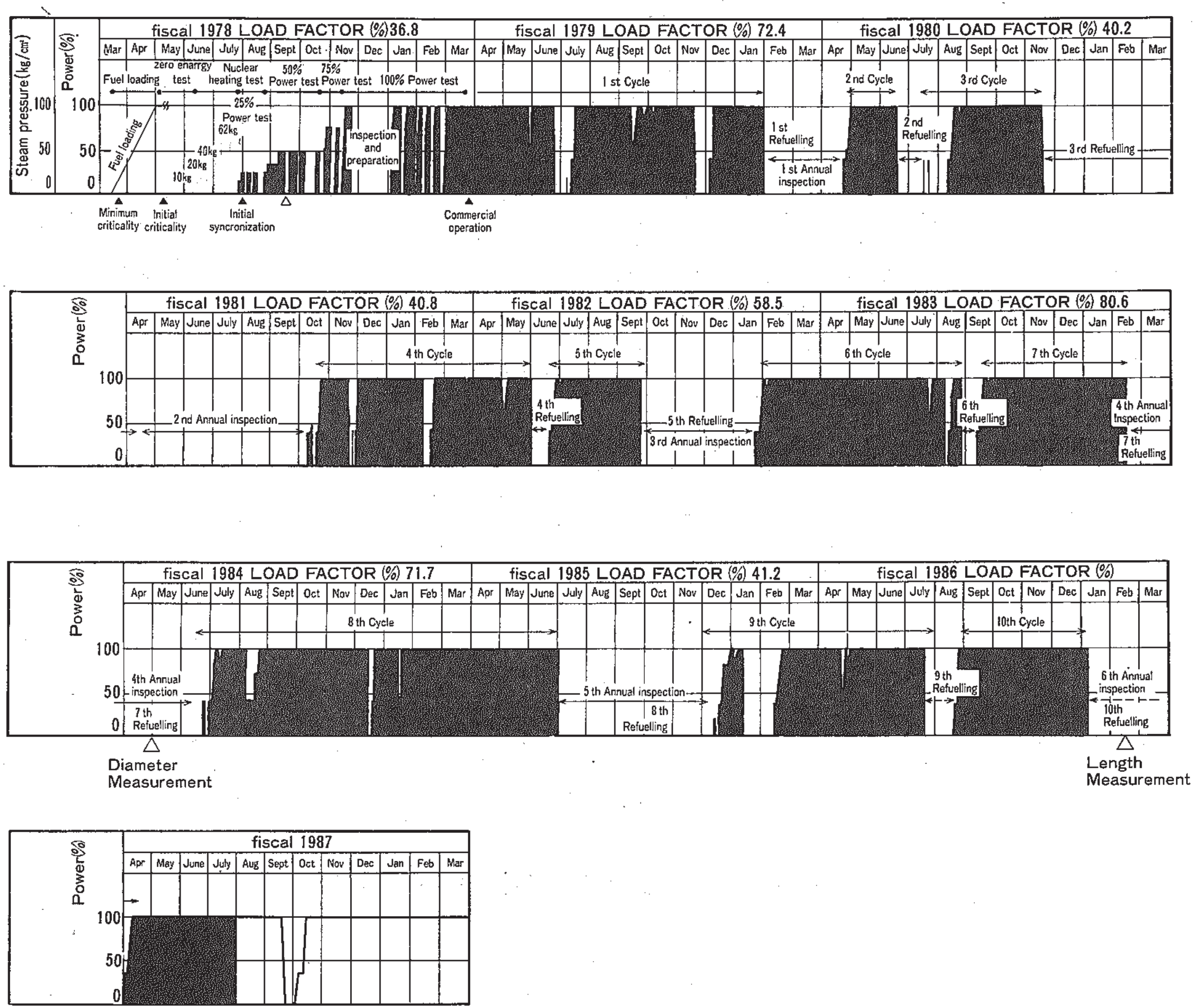


Fig. 2 The HWR Fugen operating history

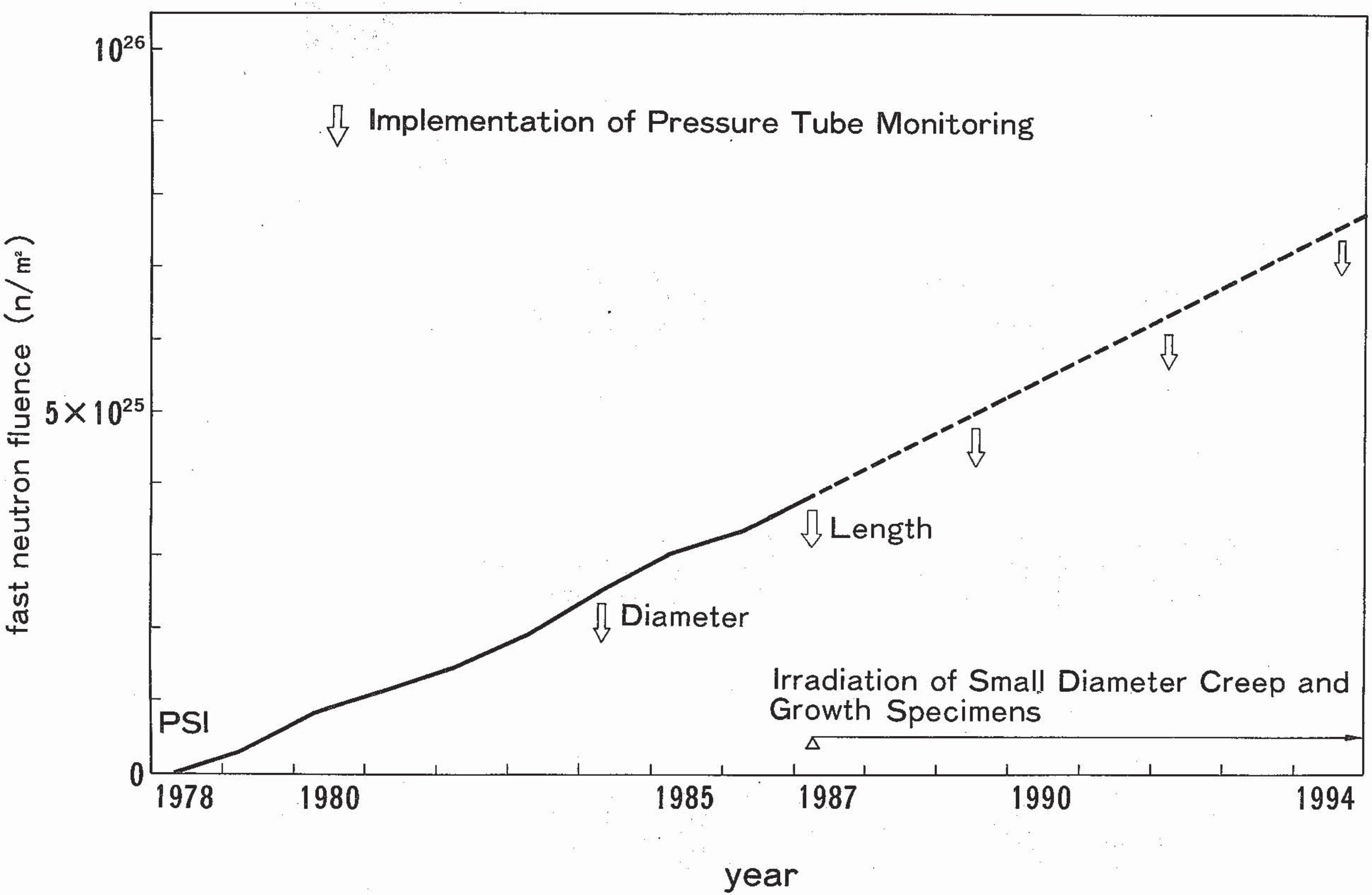


Fig. 3 Program for implementations of pressure tube monitoring in the Fugen

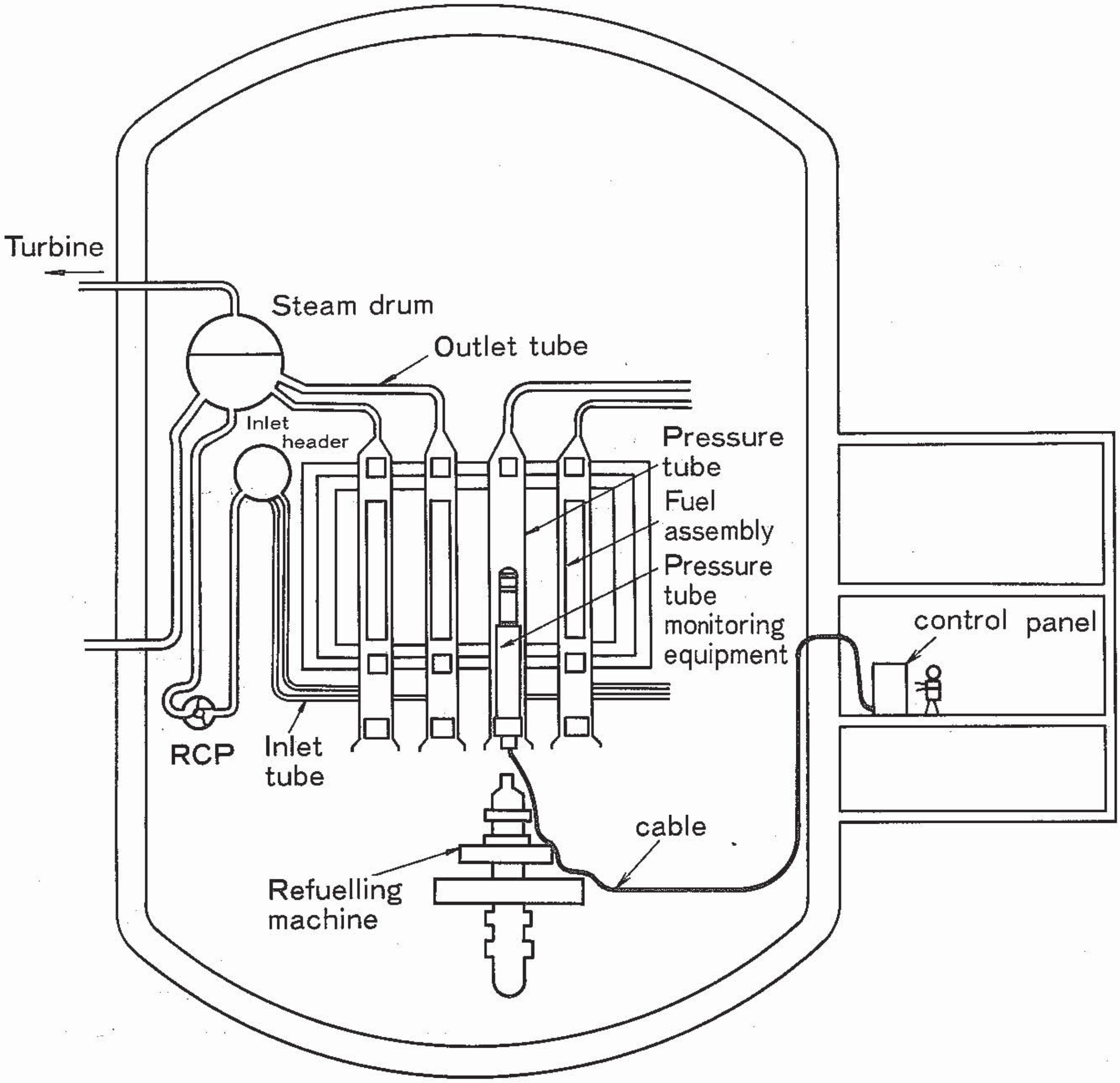
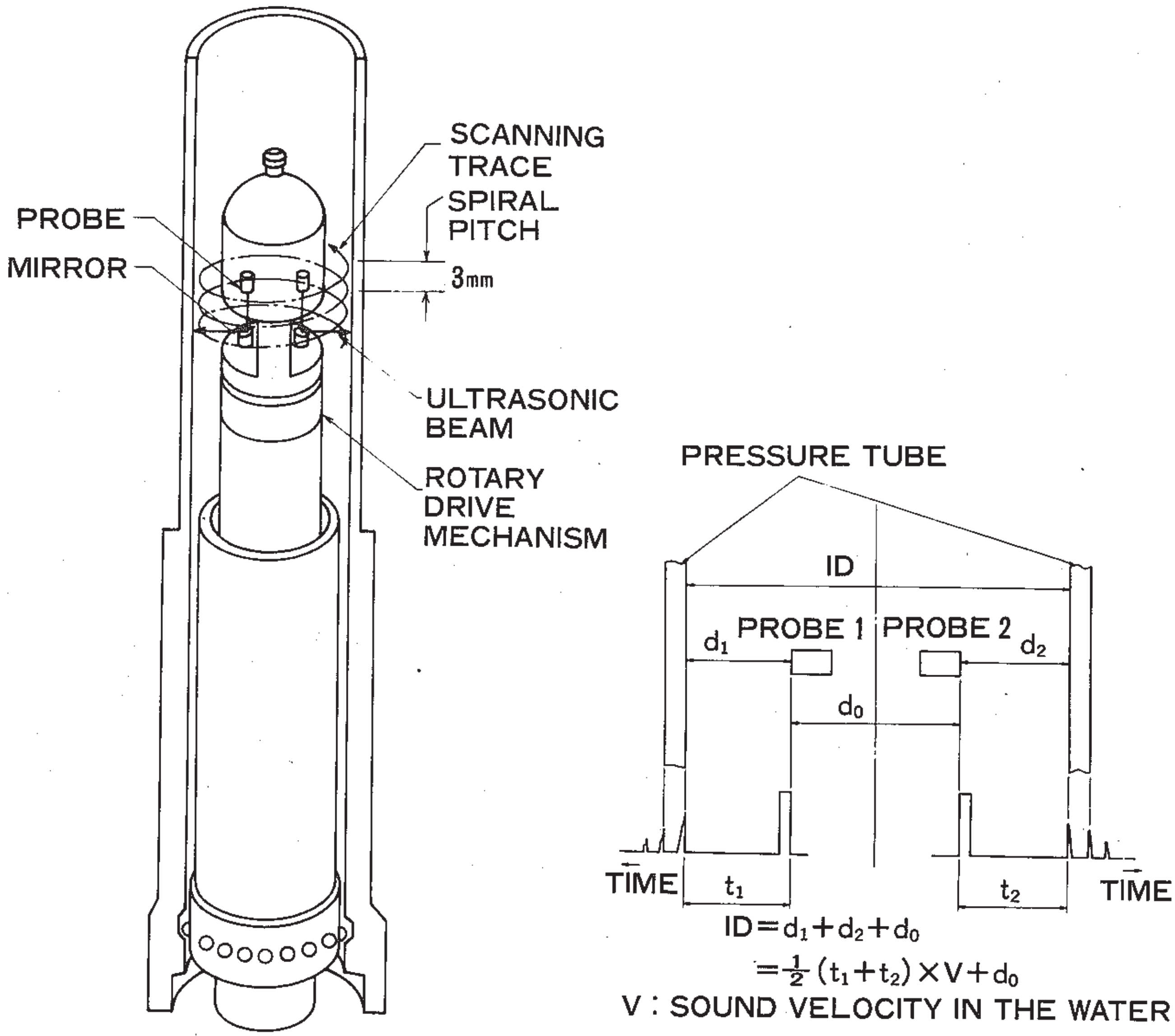


Fig. 4 General view of the application of pressure tube monitoring equipment



(a) AUTOMATIC OPERATION MODE OF INSID DIAMETER AND ULTRASONIC MEASUREMENTS

(b) METHOD OF INSIDE DIAMETER MEASUREMENT.

Fig. 5 Schematic of the equipment, PTM(I) for inside diameter measurements of pressure tubes in the Fugen.

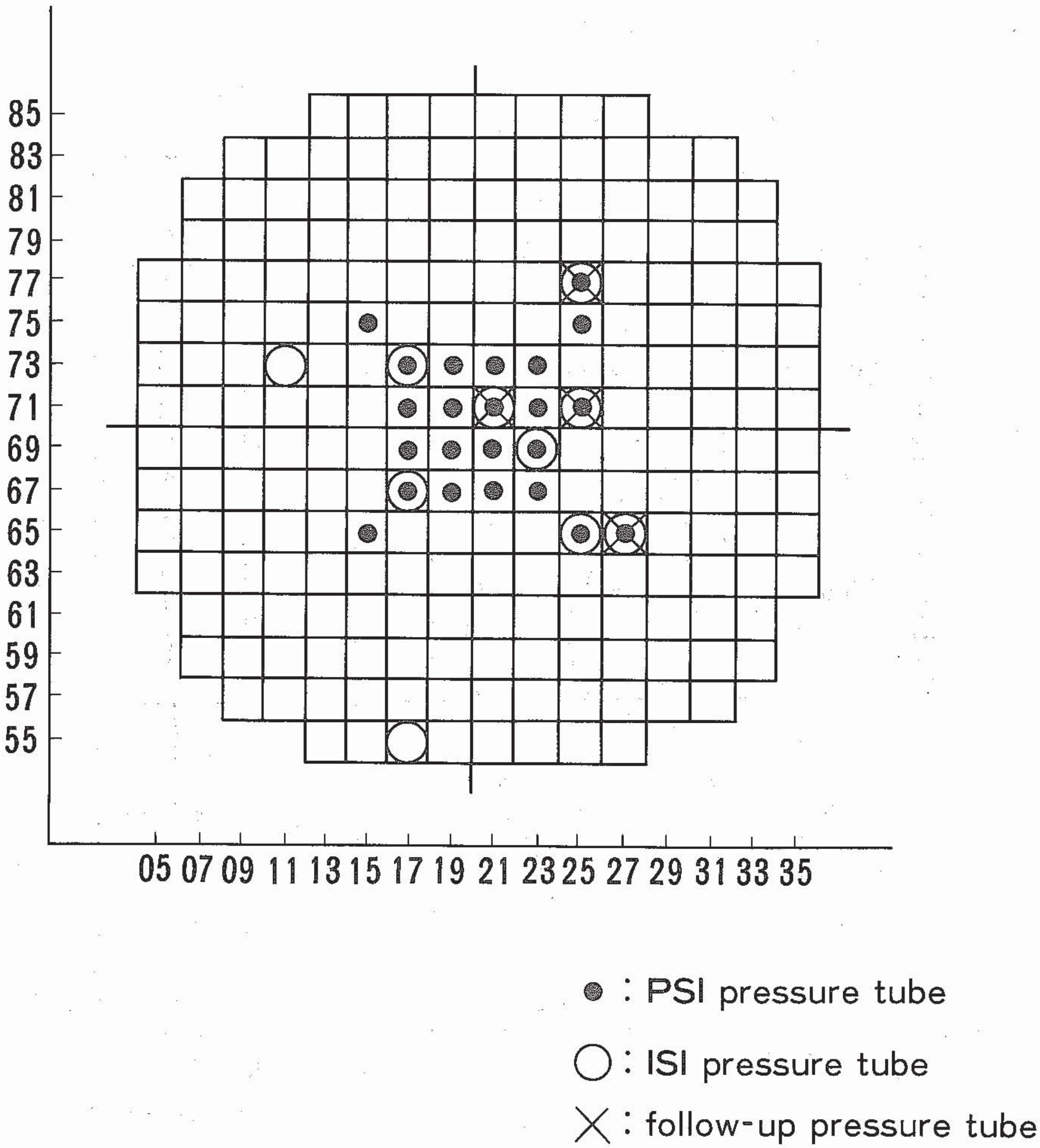


Fig. 6 Allocation of pressure tubes in the Fugen for inside diameter measurements

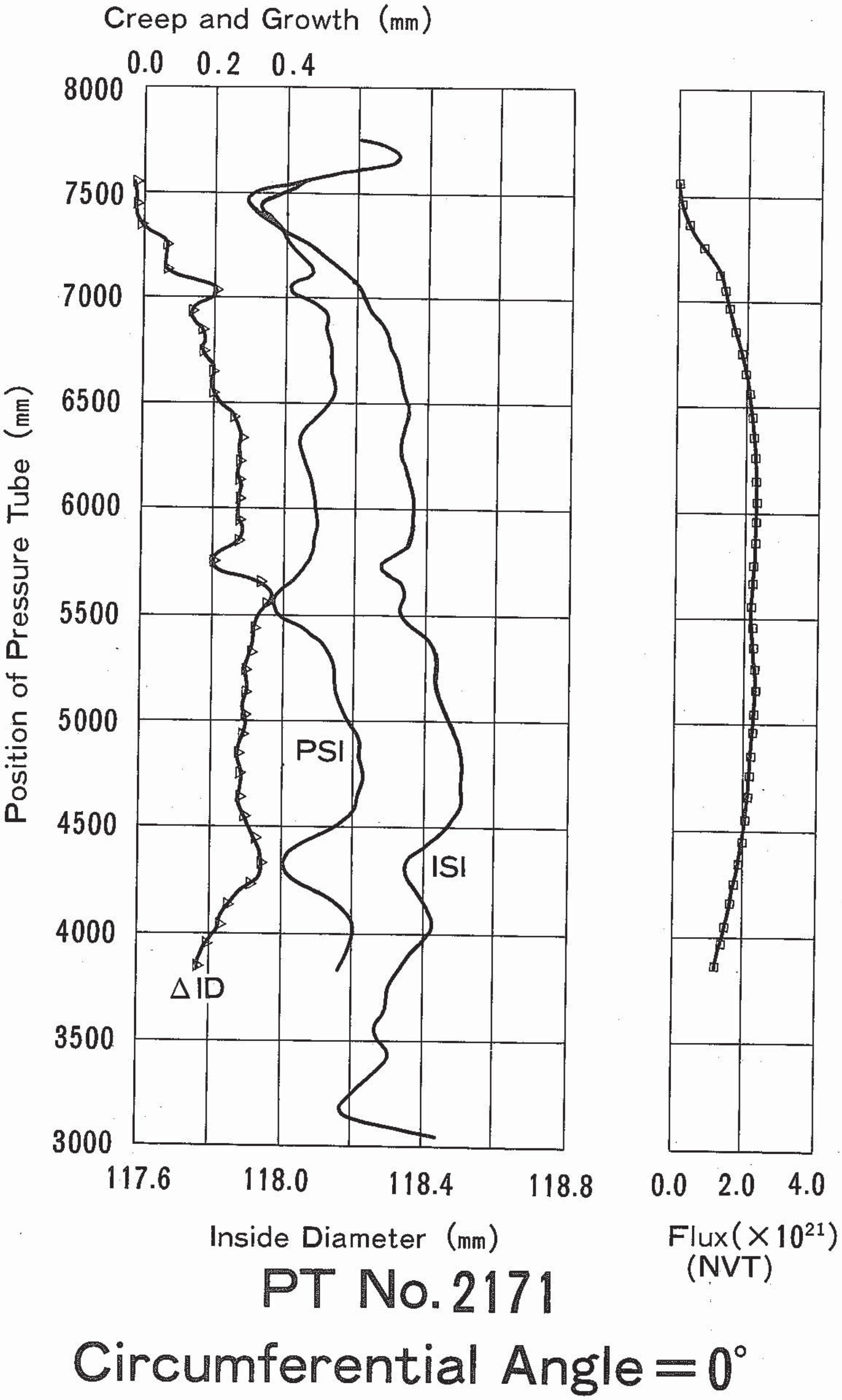
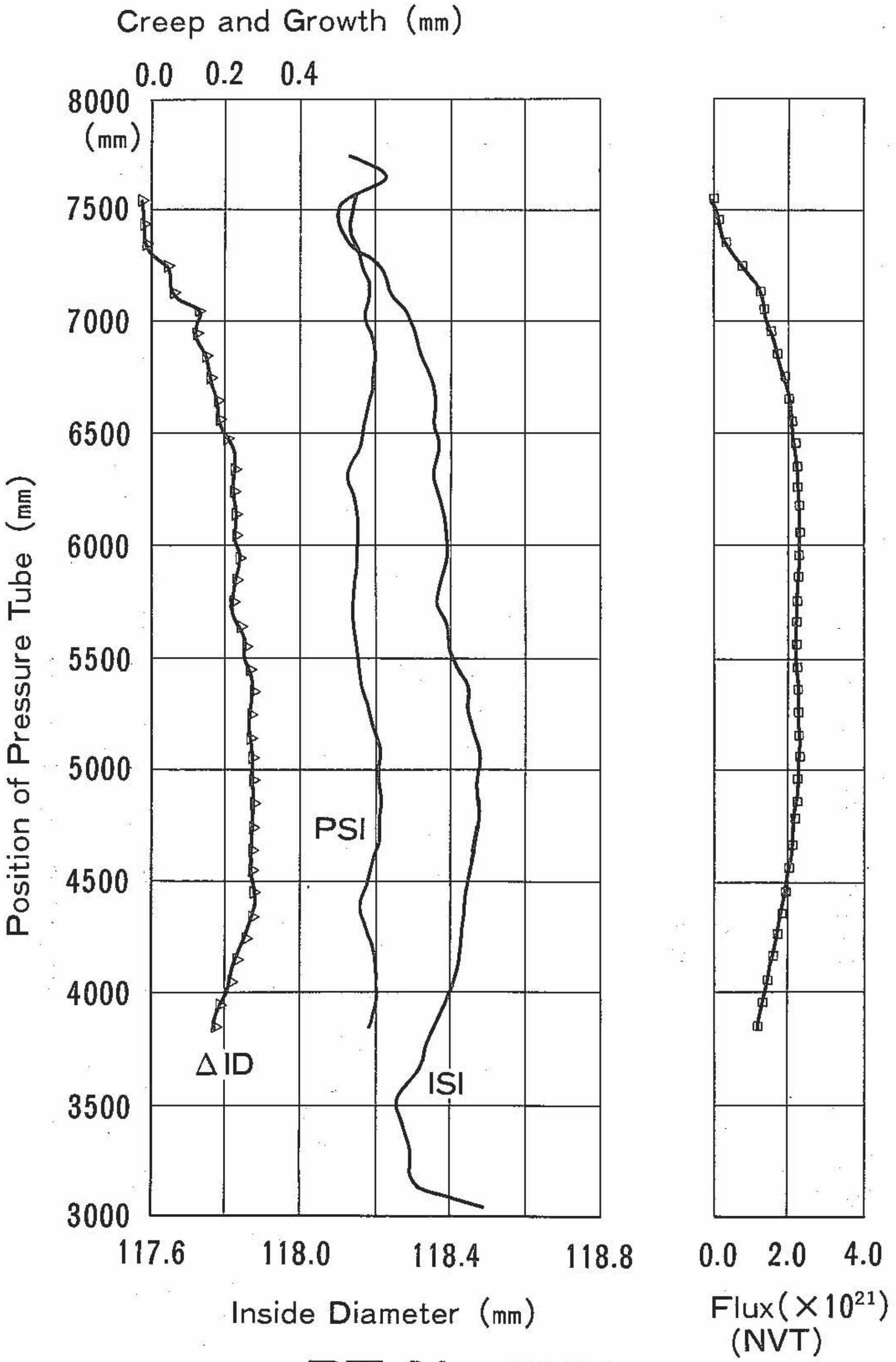


Fig. 7 Results of inside diameter measurements of the pressure tube No.2171 at circumferential angle of 0°



PT No. 2171

Average Values on Circumferential Angles 0°～360°

Fig. 8 Results of inside diameter measurements of the pressure tube No.2171 as the averaged values on circumferential angles 0°～360°

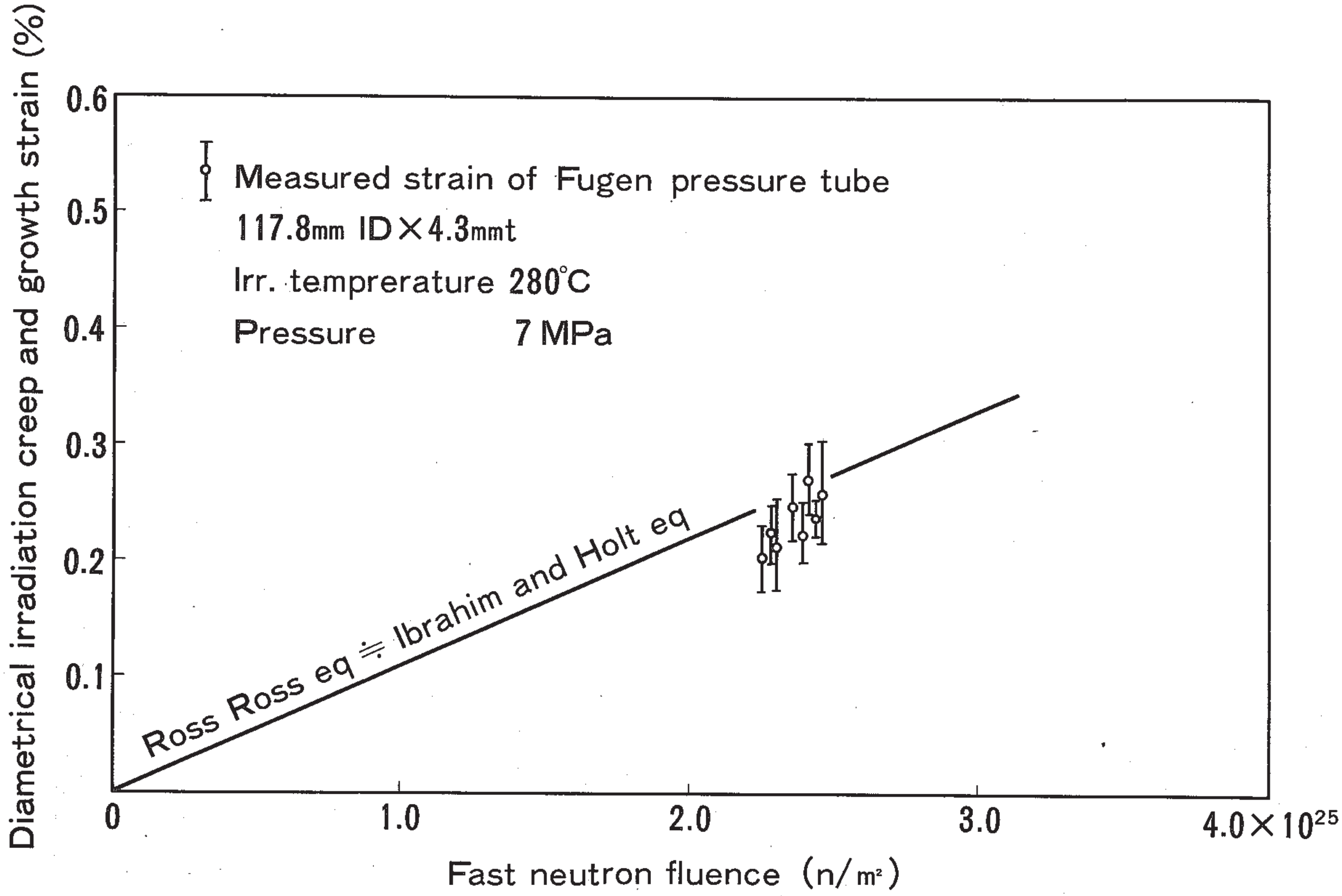
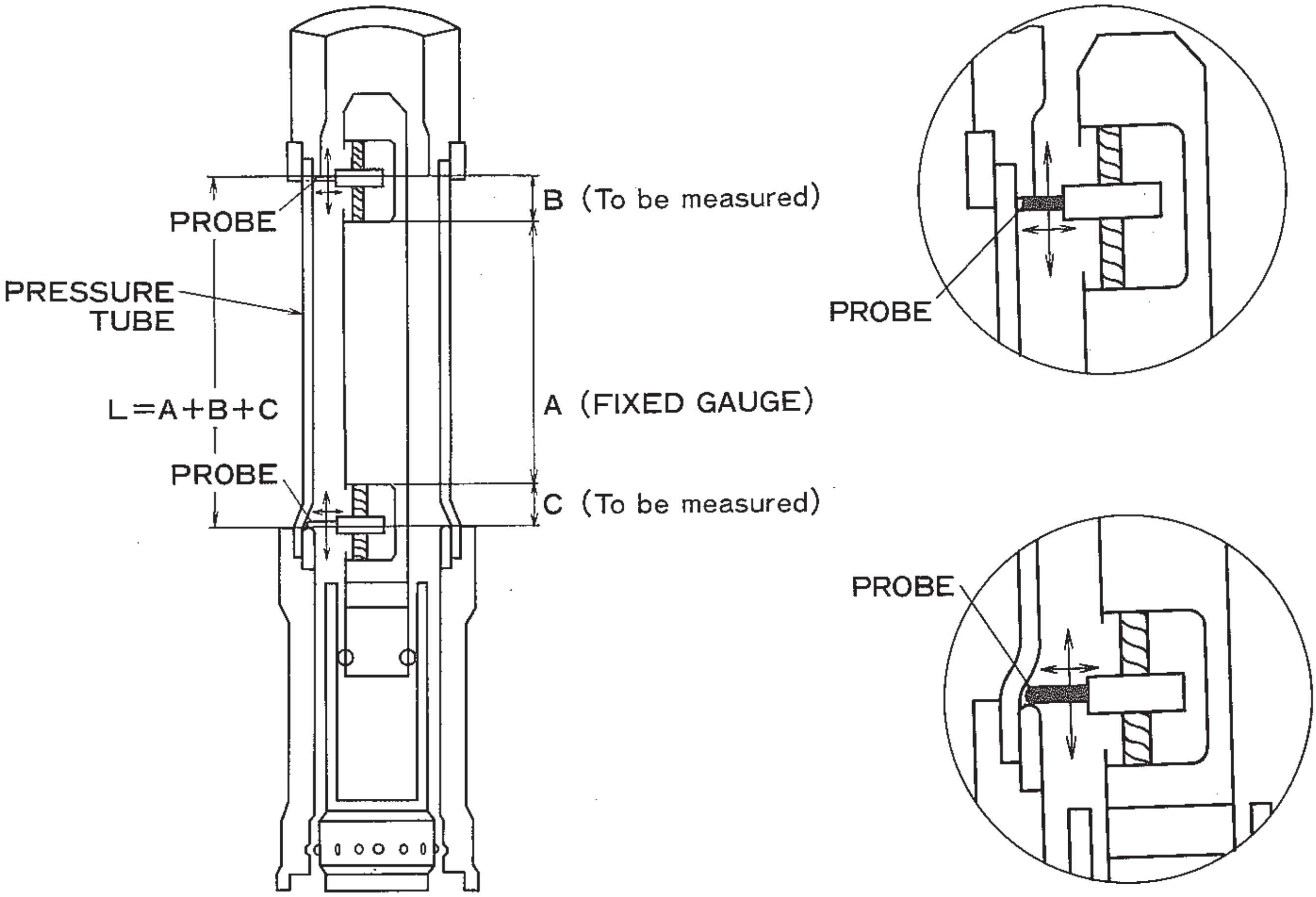


Fig. 9 Results of diametrical irradiation creep and growth strains of pressure tubes in the Fugen as a function of fast neutron fluence



Method of Axial Length Measurement

Pressure Tube Inspection Equipment, PTM [II]

Fig.10 Schematic and photograph of the equipment, PTM(II) for axial length measurements of pressure tubes in the Fugen

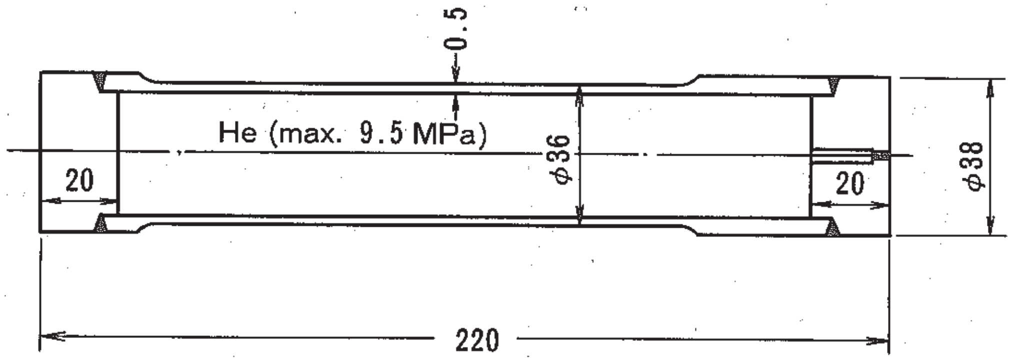
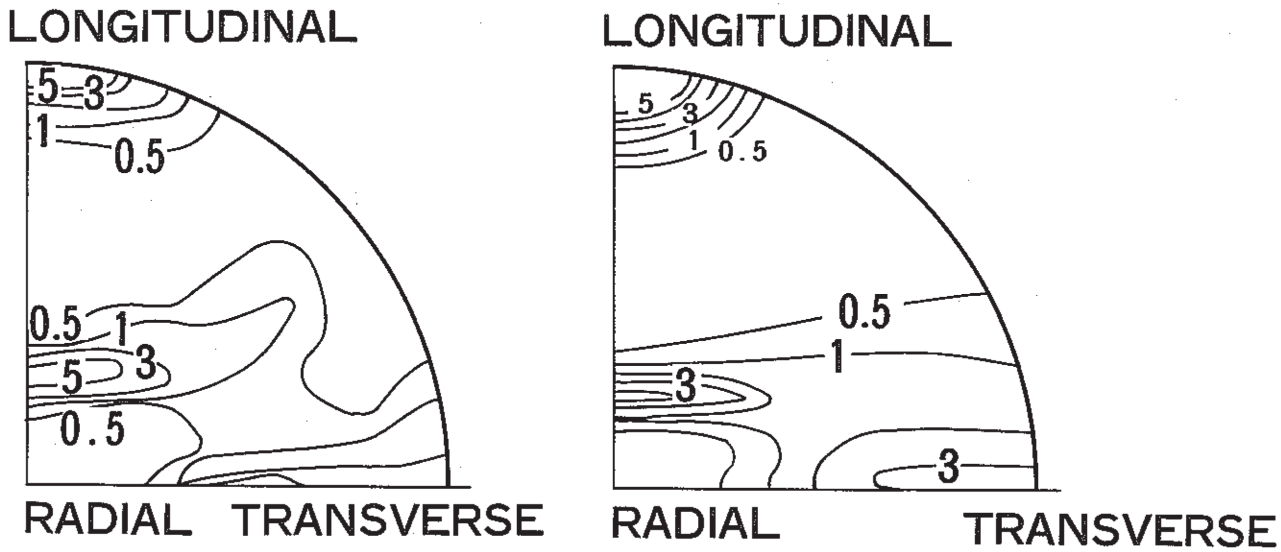
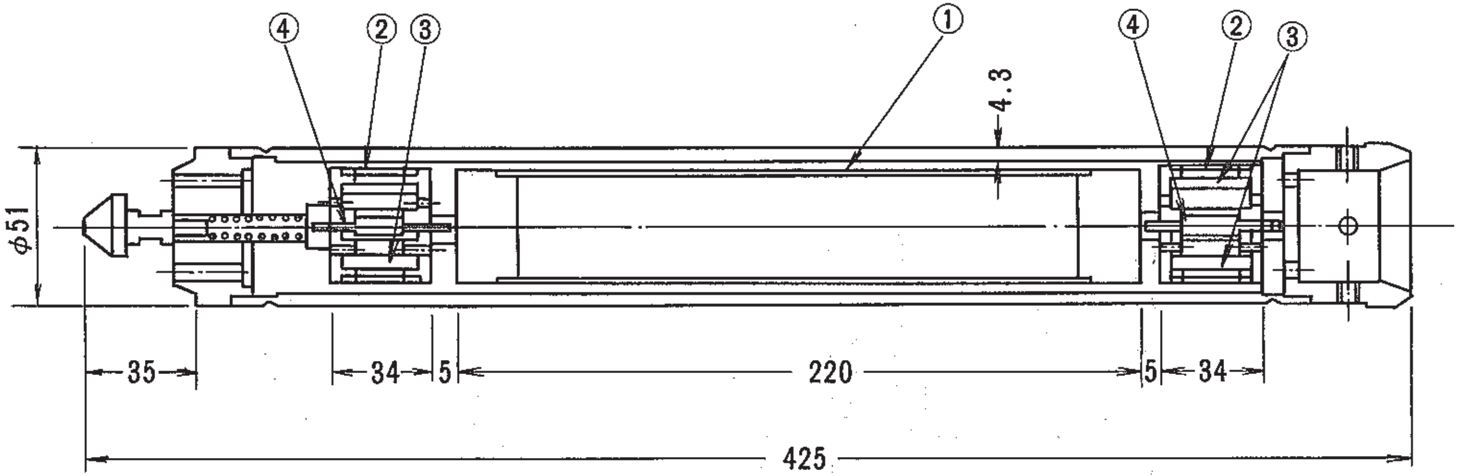


Fig.11 A small diameter creep specimen irradiated in the Fugen



Pressure tube (117.8mm^{ID})   Small diameter tube (35mm^{ID})

Fig.12 Typical basal (0002) pole figures of H.T. Zr-2.5 wt%Nb pressure tubes (117.8 mmID) and H.T. Zr-2.5 wt%Nb small diameter tubes (35 mmID)



5	Holder	Zr-2.5% Nb
4	Flux monitor	Fe, Cu, Nb
3	Corrosion specimen	Zr-2.5% Nb
2	Growth specimen	Zr-2.5% Nb
1	Creep specimen	Zr-2.5% Nb
No.	Parts name	Material

Fig.13 A capsule with creep and growth specimens for irradiation

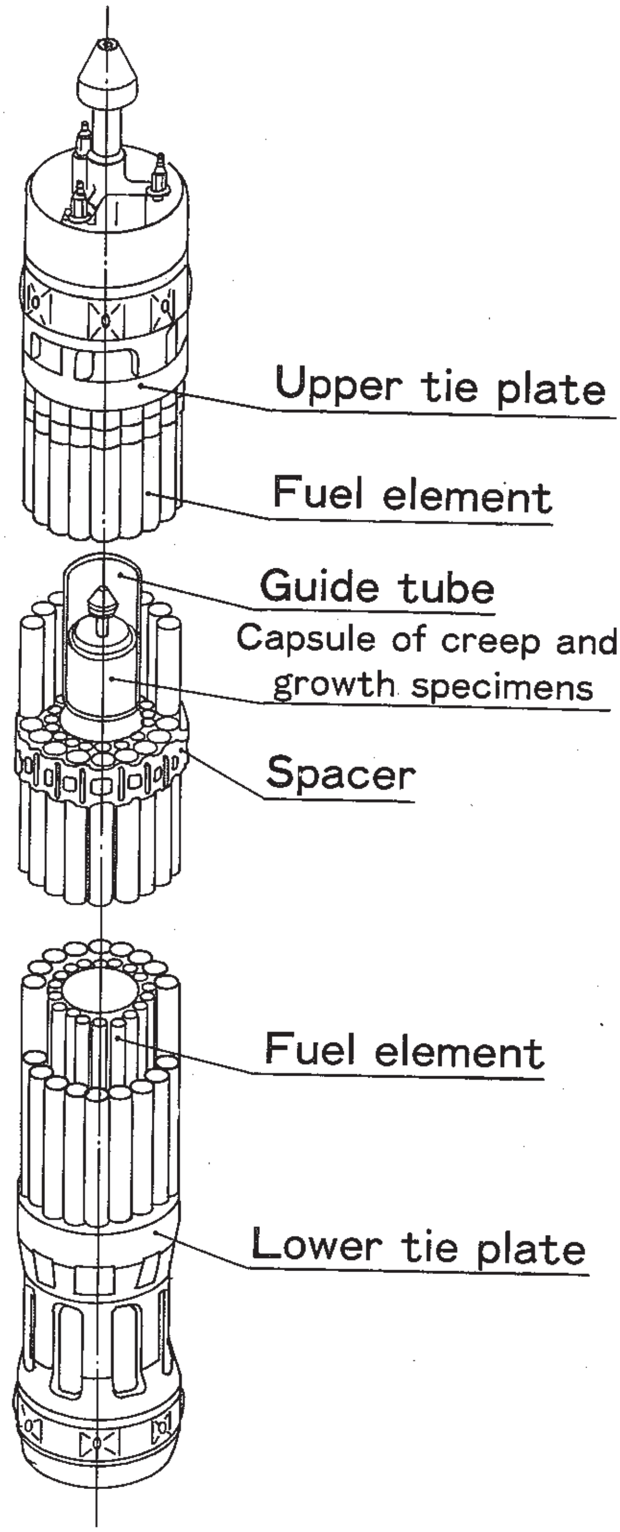


Fig.14 Schematic of a special fuel assembly with capsule for irradiation

Table 1
Irradiation condition of pressure tubes in the Fugen

Item	Value
Fast Neutron Flux	av. $3\times10^{17}n/m^2\cdot sec$ (> 1 MeV)
Irradiation Temperature	280℃
Inner Pressure	7 MPa
Hoop Stress	96MPa

Table 2
Specifications of the pressure tube monitoring equipment, PTM(I)

Inside diameter measuring device(ID)	Measurement type	Ultrasonic(5MHz)
	Measuring accuracy	±20μm
	Measuring range	117.5mm－119.5mm
Vertical drive mechanism	Type	Rack-and-pinion
	Speed	ID･UT:30mm/min－300mm/min
		VT:200mm/min－800mm/min
	Position detection accuracy	±4min
Rotary drive mechanism	Type	Gear
	Speed	ID･UT:0.1－1rev/s
		VT:1rev/min
	Angle detection accuracy	±2°
Equipment operating conditions	Environment	Reactor primary cooling water
	Temperature	10℃－40℃
	Pressure	Maximum 0.4MPa
	Radiation	Gamma rays 2×10^{5}R/h

Table 3
Specifications of the pressure tube monitoring equipment, PTM (II)

Axial Length measuring device	Measurement type	Contact probe
	Measuring accuracy	±1.0mm/4.8 m
	Measuring range	4790～4830mm(Pressure tube)
Vertical drive mechanism	Type	Rack-and-pinion
	Speed	3, 5mm/sec
	Stroke	930mm
	Position detection accuracy	±1mm
Rotary drive mechanism	Type	Gear
	Speed	12, 24degrees/sec
	Angle detection accuracy	±2°
Equipment operating conditions	Environment	Reactor primary cooling water
	Temperature	10℃−40℃
	Pressure	Maximum 0.4MPa
	Radiation	Gamma rays 3×10^5R/h

Table 4
Comparison of mechanical properties between full size pressure tubes and small diameter pressure tubes

Mechanical property		Full size pressure tubes (117.8mmI.D.×4.3mmt)	Small diameter pressure tubes (35.0mmI.D.×0.5mmt)
UTS (MPa)	R.T.	830	830
	300℃	600	590
0.2%PS (MPa)	R.T.	700	710
	300℃	480	490
Primary α (%)		13	13

Table 5
The resolved fractions of basal poles in the three principal directions of H.T. Zr-2.5wt%Nb tubes (sample)

Tube Size	Radial Direction	Transverse Direction	Longitudinal Direction
117.8mmdia.	0.345	0.360	0.308
35mmdia.	0.337	0.398	0.274

Table 6
Irradiation condition of small diameter creep specimens in the Fugen

Item	Value		
Fast Neutron Flux ($n/m^2 \cdot sec$)	av. 2×10^{17} (> 1 MeV)		
Irradiation Temperature (℃)	280		
Inner Pressure (at R.T.) (MPa)	9.5	8.0	6.6
Hoop Stress under Irradiation (MPa)	392	294	196
Inner gas	He		