The pressure tube inspection and integrity evaluation in Fugen

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Two hundred and twenty four pressure tubes are installed vertically in the reactor of the Fugen. Each pressure tube accommodates a fuel assembly and forms the pressure boundary of the primary cooling system. The operating pressure is 6.8 MPa and temperature 280°C. The pressure tube, made of Heat Treated Zr-2.5%Nb, is approximately five meter long, with 117.8 mm inner diameter and 4.3 mm wall thickness. The pressure tube is connected to upper and lower extension tubes of stainless steel with the rolled-joint technique. The soundness of the pressure tube, rolled joints, and upper/lower extension tubes must be checked in an appropriate and systematic manner. To satisfy the requirements, in-service inspections (ISIs) and post irradiation examinations (PIEs) of the pressure tubes have been carried out during the 24 year operation of the Fugen.

Development of pressure tube inspection equipment started in 1971 for the ISIs. The first model of the equipment was developed and applied to the pre-service inspection of the pressure tubes in 1977. The measurement accuracy of the equipment was sufficient but the weight and size were too large to be set and handled in an irradiated environment. Thus, the design was modified to smaller the equipment in size, lighten to approx. 1/100 in weight, and realize to be handled with the refueling machine.

The improved equipment was used in the 4th annual inspection in March 1984. Ultrasonic flaw detections, inner diameter measurements and inner surface visual inspection of pressure tubes were conducted. Up to the 17th annual inspection in 2002, 146 inspections in total were executed. The ultrasonic inspection detected no defect on the pressure tubes. The measured strain due to the irradiation creep of pressure tubes corresponded with the design values.

To conduct the PIEs of the pressure tube materials, surveillance specimens were set in the special fuel assemblies and irradiated from the beginning of the reactor operation. Five PIEs have been carried out by 2002. The PIEs include tensile test, bending test, corrosion test, and measurement of hydrogen pick-up of the pressure tube material. All results of the tests satisfied the design values.

Based on the results of ISIs and PIEs, we have confirmed the integrity of the pressure tubes through the 24 year operation of Fugen.

KEYWORDS: pressure tube, Zr-2.5%Nb alloy, Fugen, in service inspection, creep

I. Introduction

Japan Nuclear Cycle Development Institute (JNC) 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.

The ATR Fugen has 224 pressure tubes made of Heat Treated Zr-2.5wt%Nb alloys.

The pressure tube components of the primary system of the Fugen reactor are inspected annually. Since the pressure tube assemblies of the Fugen are important components, they are subjected to in-service inspection (ISI) during the annual inspection to confirm their integrity from the viewpoint of structural strength.

Each pressure tube assembly consists of a pressure tube made of zirconium-niobium alloy (Zr-2.5wt%Nb), and upper and lower extension tubes made of stainless steel. The length is about 9m total. The pressure tube itself is approximately 5m long, with a 117.8mm inside diameter and a 4.3mm wall thickness. In the Fugen reactor, the 224 pressure tube assemblies are arranged vertically, each of them being of identical shape, size and material.

Therefore, ISI of the pressure tube assemblies is made using ‘sampling inspection’ criteria.

This application is the first time that the Zr-2.5wt%Nb alloy has been used as the structural material of pressure tubes in Japan.

Accordingly several selected pressure tubes are monitored in a follow-up inspection to measure the changes in the inside diameter that have occurred because of fast neutron irradiation creep.

Manual inspection of the pressure tubes is impossible because they are long, narrow tubes and they are highly radioactive. Higher availability factors of the reactor require shorter-term inspection. In addition, a highly precise inspection is needed because the pressure tubes are the most important component forming the pressure boundary of fast reactor core. For these reasons, pressure tube inspection equipment enabling remote handling, high-precision inspection to be performed in a short period was developed and put into practical use.
Zirconium alloy is widely used as material for the pressure tubes as this material possesses high strength and low absorption rate of neutron.

Zr-2.5wt%Nb alloy that has been heat treated in order to enhance its high temperature strength is adopted for Fugen.

Fuel assembly is stored inside the pressure tubes, and consequently pressure tubes are exposed to a high rate of neutron irradiation. Therefore evaluating the characteristic change of the material under irradiation is important. For this purpose, pressure tube surveillance specimens were assembled in the inside of the special fuel assemblies of Fugen from the initial stage of operation and were exposed to irradiation. The first surveillance specimens were taken out in February 1984 for post irradiation examinations. These specimens were transported from Fugen to the Material Monitoring Facility in O-arai Engineering Center in September 1984, and post irradiation examination which included tensile test, bending test, burst test, corrosion test, hydrogen analysis and metallographical test were carried out.

II. The pressure tube inspection and integrity evaluation

1. Design of the pressure tube

In undertaking design of the pressure tube, safety against ductile fracture was evaluated. In regards to the evaluation against unstable fracture, particular attention was paid to the characteristics of fracture toughness degradation due to the pressure tube material absorbing hydrogen under operating conditions. Also, as the pressure tube material will creep due to high neutron irradiation, creep strain was therefore evaluated and the limiting value was established.

(1) Tensile strength
The lower value of 1/3 of the ultimate tensile strength, of 2/3 of yield stress at room temperature and at 300℃.
(Allowable stress intensity : 18.3 kg/mm²)

(2) Fracture toughness value
Critical value against unstable fracture as established with consideration to propagation of hypothetical defect during operation.
(During operation : More than 40.6 kg-mm³/2)
(During hydrostatic pressure test : More than 35.0 kg-mm³/2)

(3) Limitation against creep strain
Value established with consideration for tolerance to prevent generation of accelerating creep.
(Creep strain limitation value : 2.5%(tentative value))

2. Purpose of surveillance examination

It is stated in “Minister Ordinance Establishing the Technical Standard Regarding Nuclear Installation for Power Generation” (Ordinance No.62 of Ministry of Economy Trade and Industry) that “The internals of vessel pertaining to nuclear reactor facility which will be the exposed to neutron irradiation of more than 1 MeV and its material has the possibility of considerable degradation must be provided with surveillance specimens as it is separately notified”, and therefore the pressure tube surveillance examination has its purpose the requirement to confirm the safety of the vessels (pressure tubes) by comprehending the degree of degradation by tracking the specimens that are exposed to irradiation under conditions similar to which vessels (pressure tubes) can possibility become materially degraded by irradiation. The surveillance examination conditions, and the specimens are taken out successively to be examined.

The special fuel assembly mentioned here is a fuel assembly for loading the surveillance examination specimens that has been reviewed to satisfy the condition that “the surveillance examination specimens must be arranged so that specimens will be exposed an equivalent neutron spectrum, neutron fluence and temperature history as the material of the vessel located is the neutron irradiation zone will be exposed to ” as prescribed in “Technical Standard of Structures Regarding Nuclear Power Facilities for Power Generation” (Notification No.501 of Ministry of Economy Trade and Industry).

3. Design of the pressure tube inspection

The pressure-tube inspection equipment (Fig.1) consists of the inspection devices, control board, signal transmission system, cable manipulator etc.. It can be used for ultrasonic flaw detection, measurement of the inside diameter and the form of the cross section and the visual inspection of the internal surfaces of the pressure tubes for the Fugen. It can also be used for visual inspection of the pressure tube lower extension tube welds, upper and lower rolled joints and inlet pipe welds. The detailed inspection ranges are shown in Fig.2.

The detectors, drive mechanisms, electronic circuits, seal plug etc. are small sized and built in the inspection devices to meet the size of the fuel assembly. Special attention was paid to the arrangement of parts, and almost all of them were so designed as to be smaller to make the resultant inspection devices small.

As shown in Fig.1. The inspection devices are remotely installed inside the pressure tube by using the refueling machine, and inspection is then carried out remotely through the control board. The connection and disconnection of the cable are also performed remotely by using the cable manipulator. The inspection devices are an ultrasonic flaw detection-inside diameter/form measuring device (UT/ID) and an internal surface visual inspection device(TV). The
ultrasonic flaw detection-inside diameter/form measuring device (shown in Fig.3, Fig.4) is composed of an ultrasonic flaw detector, an inside diameter measuring device, drive mechanisms, a seal plug, a guide mechanism, etc.. The internal surface visual inspection device (Fig.3) is composed of TV cameras and an optical system in detection section. They are then set up in cylindrical form with an outside diameter of 114mm × height 3.1m(UT/ID)/3.9m(TV). Each device is in a double-walled structure; the inner tube containing detectors moves vertically within the outer tube.

Further, in order to inspect the pressure tubes without draining the reactor coolant (light water), the inspection devices were so designed as to be used underwater; accordingly, the inner tubes are filled with several-hundred kPa of gas to prevent water leakage through the inner tubes. The seal plugs play roles of fixing the inspection devices to the pressure tube assembly and sealing the coolant, and their centers are provided with cable connection terminals.

Each inspection device is almost completely remotely operable. Thus, the only work to be done manually is attachment of the inspection device to and detachment of it from a refueling machine, and cleaning of the device after inspection.

Signals detected at the respective detectors are transmitted to the control board through signal transmission systems. Ultrasonic flaw detection signals are displayed on a Braun tube and inside diameter/form measurement signals on a Braun tube and a digital device. The data are then fed to a minicomputer and graphically processed off-line. Internal surface visual inspection signals are displayed as an image on a monitoring TV; these are recorded with a video tape recorder.

4. Inside Diameter/Form Measuring Device

Since the pressure tube are exposed to neutron irradiation and high-temperature(280°C), high-pressure (7MPa) water during reactor operation, it is predicted that the inside diameter of the pressure tubes increases about 100 μ m per year (in the middle of the reactor core) due to irradiation creep.

To measure precisely such a small amount of change in dimensions, the target precision for development was placed at ± 20 μ m ( 1/5 of the annual amount of change ). Moreover, to confirm no deformation of the pressure tubes during their service life (30year), the function of measuring the cross-sectional forms of the pressure tubes was added to the inside diameter measuring device. A non-contact ultrasonic method was developed for high-speed inspection. The inside diameter measuring method is shown in Fig.4.

In addition to the probes for ultrasonic flaw detection, the inside diameter measuring device is provided with two probes in a symmetrical arrangement 180°, which face the inner surface of the pressure tube. The time required for the emitted ultrasonic wave to return to the probe after its reflection at the inner surface of the pressure tube is first measured, followed by the measurement of the time
required for the emitted ultrasonic wave to return to the probe after its reflection at the surface of the reflector.

The difference in time is then converted into the a length (length = sound velocity × time) to obtain inside diameter.

The reflectors are provided to eliminate measurement errors due to the thermal strain of the piezoelectric transducer of the probe. If the length between the reflectors (fixed), the length from the reflector 1 to the inner surface of the pressure tube and that from the reflector 2 to the inner surface of the pressure tube are L0, L1, and L2, respectively, then the inside diameter (ID) can be written as follows:

\[ ID = L1 + L2 + L0 \]

As shown in Fig.4, inside diameter measurement is carried out over the whole region (on1° basis) along with ultrasonic flaw detection in an upward spiral move with a pitch of 3mm. As the operation period of pressure tube tends to expand, so the guide mechanism (See Fig.4) are set up at 3 points with an interval of 120° and they are pushed forward simultaneously by springs so that the beams may be applied to the positions along the correct diameter at any height of the pressure tube.

As to form measurement, the radii are measured by using one of the probes for inside diameter measurement together with the angles of rotation, and the results are plotted on a two-dimensional coordinate by using the data processor to draw the cross-sectional form of the pressure tube. The method of radius measurement is the same as that of inside diameter measurement, whereas the angle of rotation is measured by the angle gauge attached to the rotary drive mechanism. The cross-sectional form is measured after inside diameter measurement; while the inner tube is lowered, it is stopped at given measuring point for a short time to measure the radii covering 360°.

In this method, the amount of axial deflection at the time of head rotation leads directly to measurement errors, so that amount of deflection is measured by using a completely round reference gauge prior to inspection, and the measurement errors are corrected after form measurement.

In the ultrasonic measurement method, the variation in water temperature (10℃~40℃) and form of ultrasonic beams greatly affect the measurement precision. To improve the precision, therefore, in-depth developmental tests were carried out to find out a suitable method for measuring the pressure tubes. The results can be summarized as follows:

1. A probe for water temperature calibration was newly provided separately. It was incorporated near the probe for inside diameter measurement to calibrate the water temperatures of the measuring points.
2. To focus the ultrasonic beams on one point of a to-be-measured section, a high-frequency (15MHz) point-focusing (about 0.3mm in diameter) type was employed for the probe, whereas a doughnut-like disk type was used for the reflector so as not to disturb the ultrasonic beams.
3. Since L0 varies with thermal expansion, it is calibrated by calculation.
4. The reference gauge to be used for calibration was specially made of quartz glass with an extremely small thermal expansion.

III. Result

1. The pressure tube inspection

Inspection of pressure tube assemblies has periodically been executed in total 6times between the 4th periodical inspection in 1983 (when the pressure tube inspection equipment was installed in Fugen) and the 17th periodical inspection in 2002.

Pressure tube assemblies to be inspected are selected at each inspection time according to the 10 year in-service
inspection plan in consideration of fuel exchanging plan, pre-service inspection results (23 inspections in total were executed) and monitoring neutron influence increase pressure tubes (hard condition in middle core) results of dimensional change of tubes by creep phenomenon.

The pressure tube inspection equipment has excellent operating experience. Inspection period with the equipment is approximately 10 days so that there is no affect on the plant outage period. And exposure dose equivalent has been none at all although high radiation environment in directly on the core. As mentioned above, the practicality of the inspection equipment has already been confirmed enough.

(1) UT result
In the UT of the pressure tube with Unit-1 (UT-ID) and of the upper and lower rolled-joints with Unit-2, no indication has been defected. But we defected the echo that surface jammed attend rough.

Rough surface was position of spacer of fuel assembly, pressure tube was scratched when it touched the fuel assembly.

The integrity of those pressure tubes has been confirmed.

All the inspection results are stored in the magnetic tape or computer and figured by a data processor.

By the way, inspection result of Unit-2 was not regulation, so independent of inspection in Fugen.

(2) Inside diameter measurement result
All the inside diameter measurement results are also stored in the magnetic tape or computer and figured by a data processor.

Inside diameter measurement results are compared with the measurement results in the pre-service inspection(PSI) for obtaining the relation between dimensional change in circumferential direction by creep phenomenon and Fast neutron fluence.

From the results, it was confirmed that the measured value of dimensional change by creep phenomenon of the pressure tube material indicated straight line of graphic and gave good agreement with the forecast value by the design curve type. So these equipments were confirmed high accuracy.

The measured value maximum strain quantity (approximately 1%) of 17th periodical inspection were compared the limitation of durability pressure tube were appreciated 2.5% in bore. Then, these results were sufficiently afforded to life span.

An example of the inside diameter measurement results and the relations between dimensional change in circumferential direction by creep and neutron influence are shown in Fig.5, and Figure respectively.

(3) Inner surface visual inspection result
On account of the reflection, brightness of illumination lamps was adjustable, then, inner surface visual inspection was confirmed by automatic completely remotely operable. Its inspection of each pressure tube was taken within 30 minutes and drive pattern of the equipment was 5 times lap. TV monitor data during inspection are recorded with a video tape recorder. And some of the data is processed to photographs with a video printer.

From the results inner surfaces of pressure tubes were covered with crad generally and traces of fuel assembly guides were also found. But abnormal defect was not found.

Fig.6 Surveillance Specimen of pressure tube Material
2. Test specimens and evaluations

The post irradiation examination results of the first pressure tube material surveillance specimens removed from Fugen are reported here.

(1) Tensile test

Shown Fig. 7 are results of the tensile performed at room temperature and 300°C. The changes in the ultimate tensile strength, 0.2% proof stress and elongation resulting from irradiation can be seen. The ultimate tensile strength and the 0.2% proof stress of irradiated material show value of 20% to 30% increase in comparison to unirradiated material within the test temperature range of room temperature to 300°C. Elongation shows a tendency of limited decrease as the effect of irradiation. “Circumferential” and “axial” refer to specimens taken in the circumferential direction and axial direction respectively on the pressure tube. The circumferential specimen was taken after the pressure tube had been made into a flat plate.

The 0.2% proof stress and the ultimate tensile strength increased with irradiation, and therefore these values after the irradiation satisfied the allowable stress intensity of Sm=18.3 kg/mm².

(2) Bending test

Fracture toughness values obtained from the bending fracture test are shown in Figure 8. The value of fracture toughness by irradiation shows a tendency opposite the tensile strength and the fracture toughness decrease by irradiation. During the initial period of irradiation the decreasing tendency is high, but the rate of decrease as the neutron fluence became smaller over approximately $10^{21}$ n/cm². The hydrogen concentration of the irradiated material shown in Figure 9 is approximately 10 to 30 ppm.

With the increase in temperature the fracture toughness and at about 150°C the approximate maximum value is reached.
The reason for the fracture toughness value dropping a little over 150°C is considered to be the effect of the drop in the yield stress of the material. Fracture toughness value indicates a tendency of decreasing with the increase in the neutron fluence but the fracture toughness value decrease is limited at 300°C which is the approximate operating of the pressure tubes of Fugen. Fracture toughness value at high temperature exhibits breaking behavior closely similar to ductile fracture. From the post irradiation examination results that have been gained to date, it is considered that the decrease of fracture toughness value at operating temperature is limited.

(3) Burst test

In the test to obtain fracture toughness, burst test (at room temperature) was performed as the reference to the bend test. The fracture toughness value at room temperature obtained by the burst test was approximately equivalent to the value gained in the bending fracture test.

(4) Corrosion test

Fig.10 show corrosion test result. The vertical axis is the corrosion depth (reduction in wall thickness), and the horizontal axis represents fast neutron fluence irradiation time (days) respectively. The depth of corrosion is extremely limited in comparison to the design value. An estimation is made here of the safety degree in relation to reduction in wall thickness of the pressure tube. A review was made from the point of view of the fast neutron fluence and the irradiation time (converted at 100% electric power).

Design corrosion rate : 310 μm(at the end of 30 years life)

Fluence of 30 years : $22 \times 10^{21} \text{n/cm}^2$

Number of days of irradiation : 7,665days ($30 \times 365 \times 0.7$)

Load factor of Fugen was, however, set at 70%.

When the above values are applied, the design corrosion amount in this case will be as follows:
Fluence base : \((2.7 \times 10^{21}/22 \times 10^{21}) \times 310 = 38 \ \mu m\)

Irradiation time base : \((1,162/(30 \times 365 \times 0.7)) \times 310 = 47 \ \mu m\)

The design corrosion rate for fluence base and irradiation time base are of approximately equal values. The corrosion depth obtained from corrosion weight increment is from 1.9 to 3.6 \(\mu m\), and therefore there is an adequately large degree of safety in comparison to the 38 \(\mu m\) and 47 \(\mu m\) were estimated by design corrosion rate.

(5) Hydrogen analysis

The pressure tube material absorbs hydrogen from the reactor water during operation and becomes brittle, and it is therefore important to perform a hydrogen analysis of the specimen.

Fig.9 shows the results of fast neutron fluence and hydrogen pick-up of the pressure tube material. With the increase of fast neutron fluence, there is some increase in the hydrogen content although the amount of increase in the hydrogen content although the amount of increase is limited. The first pressure tube surveillance specimen removed from Fugen was taken out from the reactor 5 years after entering into commercial operation (the period of time in the reactor was 6 years), and during this period approximately 10 ppm of hydrogen has been absorbed from the reactor water.

In the design of Fugen it was estimated that maximum 211 ppm of hydrogen will be absorbed in 30 years. The date obtained at this time is lower than the design predicted value of 7 ppm/year, and the results can be assessed as being favorable.

Also hydrogen analysis values of the respective specimens showed approximately equal value.

IV. Conclusion

Pressure tube inspection equipment enabling the remote inspection of the pressure tubes of Fugen to be performed in a short time with high precision was developed and demonstrated. The following conclusions can be drawn:

Small-size inspection devices that can be accommodated inside the pressure tube permit the remote attachment and detachment of the devices from the pressure tube by using the refueling machine. Further, remote inspection through the control board became possible. Owing to these measures, a nearly completely remote handling method has been put in practical use and the exposure of inspection personnel be reduce to a minimum.

The diametrical creep strain of the pressure tube agrees well with the design value.

The result to the first post irradiation examination (equivalent to 3.2 year of operation when converted at full power, fast neutron influence \(2.7 \times 10^{21} \text{n/cm}^2(\text{e}<1\text{MeV})\)) of the pressure tube material surveillance specimens were as follows:

(1) Tensile strength increased approximately 20 to 30% by irradiation, and elongation decreased somewhat.

(2) Fracture toughness value showed a tendency contrary to tensile strength and decreased with irradiation. However, the rate of decrease was large at the initial period of irradiation, and the rate of decrease by irradiation became smaller at fast neutron influence of \(10^{21} \text{n/cm}^2\). Decrease of toughness due to irradiation at approximately 300°C which is Fugen approximate operation temperature is limited.

(3) Hydrogen pick-up after being deposited in the reactor for a 5 year period after the start of operation was approximately 10ppm which is lower than the design predicted value of maximum 7 ppm per year and was favorable.

The material characteristics of the pressure tube by neutron irradiation satisfied the design value of the pressure tubes as it has been compiled above.

References