# Measurement of the Shape in the Radioactive Area by Ultrasonic Wave Sensor

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The HANARO (High-flux Advanced Neutron Application Reactor) has been operated since 1995. The Cold Neutron (CN) hole was implanted in the reflector tank from the design stage. Before a vacuum chamber and a moderator cell for the cold neutron source are installed into the CN hole, it is necessary to measure exactly the size of the inside diameter and thickness of the CN hole to prevent the interference problem. Due to inaccessibility and high radiation field in the CN hole, a mechanical measurement method is not permitted. The immersed ultrasonic technique is considered as the best way to measure the thickness and the diameter of the CN hole. The 4-Axis manipulator was designed and fabricated for locating the ultrasonic sensors. The transducer of an ultrasonic sensor having 10 MHz frequency leads to high resolution as much as 0.03mm. The inside diameter and thickness of 550 points of the CN hole were measured using 2 channel ultrasonic sensors. The results show that the thickness and inside diameter of the CN hole is in the range of 3.3~6.7mm and ∅ 156~165mm, respectively. This data will be a good reference for the design of the cold neutron source facility.

**Key Words :** Cold Neutron Vertical Hole, Ultrasonic Immersion Method, 4-Axis Manipulator, Miniature Underwater TV Camera for Nuclear

## Nomenclature

a : Decrement ratio
d : Measurement resolution
D : Diameter of ultrasonic sensor (m)
MP : Deam metal path (mm)
R : Reflected amplitude/produced amplitude
S : Time of flight (sec)
T : Transmitted amplitude/produced amplitude
t : Specimen thickness (mm)
V : Sound velocity (m/s)
$V_L$ : Longitudinal wave velocity in solid (m/s)
$V_s$ : Shear wave velocity in solid (m/s)
$V_w$ : Lncident wave velocity in liquid (m/s)
$Z_w$ : The acoustic impedance of the material on the incident side of the interface
$Z_s$ : The acoustic impedance of the material on the exit side of the interface

*Greek Symbol*

$\alpha$ : Refracted angle of longitudinal wave
$\beta$ : Shear angle of transverse wave
$\theta$ : Incident angle
$\rho$ : Medium density (kg/m$^3$)
$\lambda$ : Ultrasonic wave length (m)

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## 1. Introduction

The HANARO (High-flux Advanced Neutron Application Reactor), a 30MW multi-purpose research reactor, is a large national research facility for producing radioactive isotope and for using neutron beams. Among neutron beams, the cold neutron has a long wavelength and lower energy than X-ray and the thermal neutron. It has been thus used for R&D of a new material and composite material as an essential research method for huge molecule like the protein and virus, inside investigation of material, and material surface (Choi, C. O., et al, 1999).

Passing the thermal neutron through the moderator like the liquid hydrogen in the HANARO reactor can produce the cold neutron. The system consists of the moderator, moderator vessel, and vacuum vessel named the Cold Neutron Source (CNS). Several CNS design studies have been carried out such as calculation of the heat load on the HANARO CNS moderator, design of heat removal system(Park, K. N., et al, 1999), measurement and analysis of heat load at vertical hole of CNS(Cho, et al., 1999).

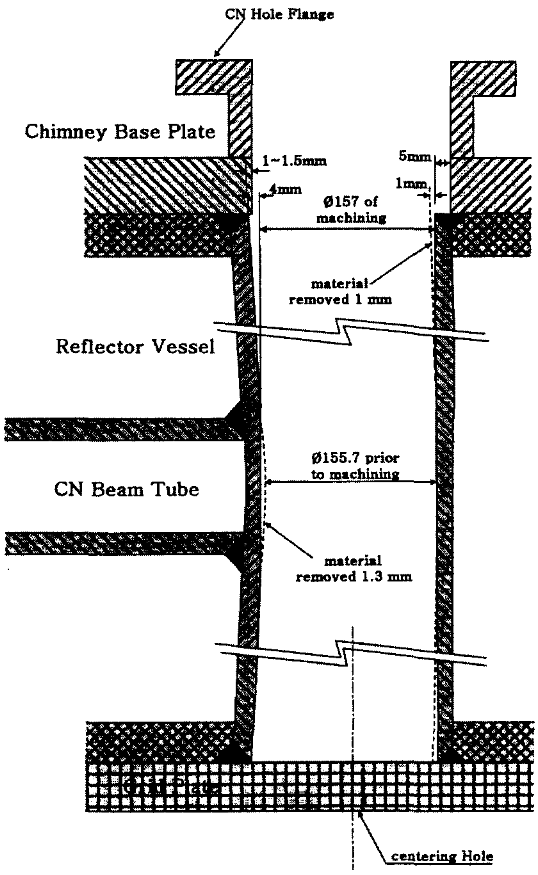


**Fig. 1** The vertical hole of CNS before initial criticality of HANARO

To maximize the gain of the passed cold neutron through the cold neutron source and to make easy maintenance of the cold neutron source as shown in Fig. 1, which includes vacuum tank, the water film between the CN hole and vacuum tank is minimized. In this study, the ultrasonic measurement technique was adopted to measure wall thickness and inside diameter of the CN hole for establishing the design criterion of the vacuum tank.

## 2. Surface Inspection in Radioactive Area

Surface inspection using a miniature underwater TV camera for a nuclear reactor was preceded to confirm the shape measuring experiment. This camera is designed to have radioactive durability. RAVA(Rotating Right-Angle Viewing Attachment) guide was employed to prevent RAVA camera's from trembling as shown in Fig. 2. The plane crossing chimney flange and RAVA guide were referred to as a reference point. Inspection begins with bringing down the camera 105mm from the reference point. A 2m ruler was stuck to the cable which connects camera to video cassette recorder(VCR), to know the location of the inspection.

At first, rough inspection was conducted from a reference point to the upper region of grid plate, and then detailed inspection was done. The in-

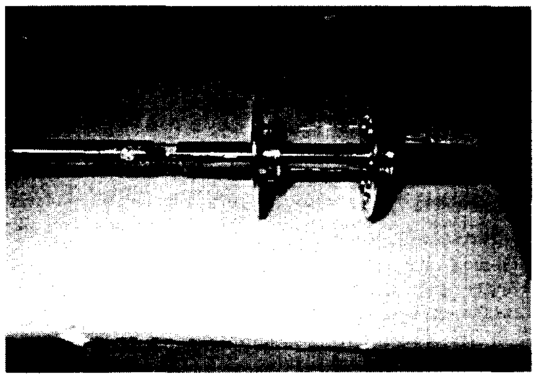

**Fig. 2** RAVA guide assembled in RAVA

**Fig. 3** Welding surface in the horizontal beam tube

spection camera was taken down with 2cm per 1 revolution. Some doubtable regions were inspected in more detail by adjusting the focus of the camera. The horizontal beam tube welded to the CN vertical hole is shown in Fig. 3. There is no trouble in the region according to inspection.

## 3. Ultrasonic Measurement Method

### 3.1 Measuring method selection

Essentially, two conditions have to be satisfied to measure the CN hole shape. First, it has to be possible to measure hole shape in the water because the CN hole is located at 12m depths underwater. Second, measurement has to be possible in a radioactive environment.

The measurement methods considered for length measurement are listed in Table 1; using the linear gage, three-point internal micrometer, ultrasonic sensor, and mock containment method that several mock vacuum tanks are manufactured with high accuracy and inserted with the CN hole. Among them, the ultrasonic method is considered to be most suitable in aspect of cost-effectiveness, precision and workability in a radioactive environment.

**Table 1** Comparison of measuring method

| Measuring Method | Consideration | | | |
|---|---|---|---|---|
| | Availability | Precision | Cost benefit | Accessibility in the Radiation zone |
| Linear gage | ○ | ○ | × | × |
| Three-point inside micrometer | ○ | ○ | × | × |
| Mock containment | ○ | ○ | ○ | × |
| Ultrasonic sensor | ○ | ○ | ○ | ○ |

The ultrasonic method is used widely for inspection of the structure defect, measurement of temperature and length, and cleaning, welding, power machinery. Especially, the immersed ultrasonic method is adopted for precise examinations like semiconductor manufacturing.

### 3.2 Experiment theory and mock-up test

In the cylindrical shape structure, the immersion method can measure not only internal defects like pores or inclusion of cylinder but also diame-

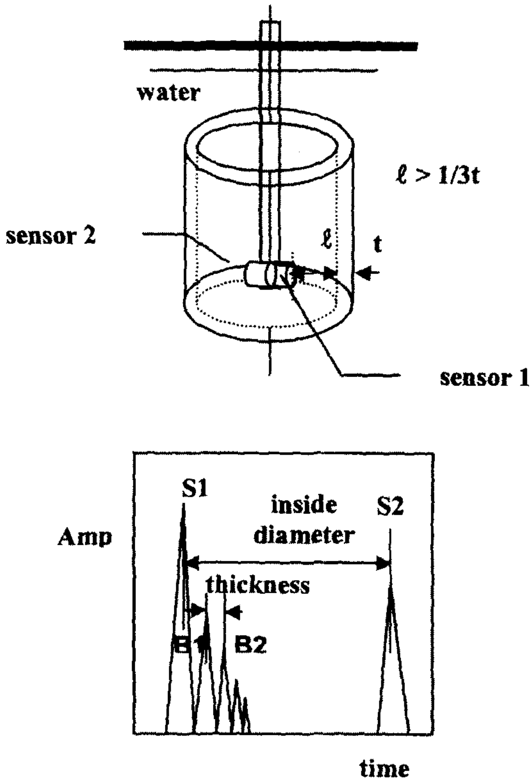


**Fig. 4** The concept of measurement by the ultrasonic sensor (upper) and the characteristic of ultrasonic signals for measurement (lower)

ter expansion or reduction due to a structure deformation, and thickness change by corrosion on the surface.

Ultrasonic signals by the immersion method are shown in Fig. 4. S1 and S2 are reflected signals from the inner surface of the CN hole to sensor, and the time interval between the signals is used for measuring the inner diameter. B1 and B2 are the reflected signals from the outer surface, and are used for measuring the CN hole thickness. Sensor 1 and sensor 2 are located at the center of the CN hole to measure inner and outer diameters accurately.

Amplitude of S1 signal from inside the surface of the CN hole is expressed in Eq. (1) with the acoustic impedances of the water and material of the cylindrical shape structure. The acoustic impedance Z is defined by density($\rho$) times acoustic velocity(V) in Eq. (3). Eq. (4) is a transmit amplitude of the ultrasonic wave into the cylindrical structure.

$$R=\frac{Z_W-Z_S}{Z_W+Z_S} \quad (1)$$

$$T=1-R \quad (2)$$

$$Z=\rho\cdot V \quad (3)$$

$$T=\frac{2Z_W}{Z_W+Z_S} \quad (4)$$

where :

- $Z_W$ : the acoustic impedance of the material on the incident side of the interface
- $Z_S$ : the acoustic impedance of the material on the exit side of the interface
- R : reflected amplitude/produced amplitude
- T : transmitted amplitude/produced amplitude
- $\rho$ : medium density(kg/m$^3$)
- V : sound velocity(m/s)

Therefore, the ratio of the reflected signals between the front and back surfaces of the plate of thickness t is expressed as Eq. (5).

$$\frac{Amplitude\ of\ S1}{Amplitude\ of\ B1}=(1-R^2)\cdot e^{2at} =\left(1-\frac{(Z_W-Z_S)^2}{(Z_W+Z_S)^2}\right)\cdot e^{2at} =\left(\frac{(4Z_WZ_S)}{(Z_W+Z_S)^2}\right)\cdot e^{2at} \quad (5)$$

where :

- a : decrement ratio
- t : specimen thickness

The calculated amplitude ratio of S1 and B1 is 0.94 : 0.12 from the Eq. (1) and Eq. (5). The acoustic impedances are $1.5\times10^6$kg/m$^2$ · s in the water and $45.4\times10^6$kg/m$^2$ · s in the material.

The amplitude difference of S1, S2 and B1, B2 allow to measure the inside diameter and thickness of the CN hole simultaneously. The beam divergence of the incident wave is considered for the precision measurement of the diameter and thickness. The ultrasonic sensors have to be equipped over one-third as much as the thickness from the wall to avoid the inner diameter signal which runs ahead of the thickness signal.

Before actual measuring, the mock-up was

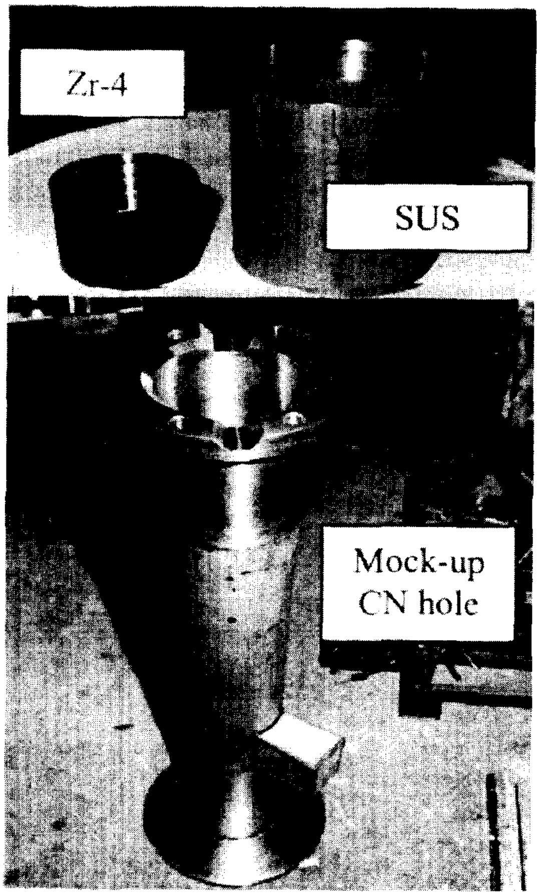


**Fig. 5** A Photo of mock-up

designed and manufactured to confirm whether the measuring was possible with an ultrasonic sensor. Among the three mock-ups in Fig. 5, ∅ 100mm made up of Zr-4 and ∅ 155mm made up of SUS were used for calibration of measuring signal from the CN hole. The mock-up CN hole was used for establishing the measurement process and operation test of the 4-axis manipulator.

The resolution of the measurement can be obtained up to half as much as the wavelength of the sensor frequency in accordance with Eq. (6), Bragg's law. In this case, precision of measurement is reached to 0.03mm by ultrasonic sensor having 10 MHz frequency.

$$\lambda=2d\sin\theta \qquad (6)$$

where :

$\lambda$ : ultrasonic wave length
d : measurement resolution
$\theta$ : incident angle

Table 2 shows the measurement errors that are verified by the digital vernier calipers.

Longitudinal wave transmits well in liquid and solid. The ultrasonic incident beam approaches and refracts to the inside surface of the CN hole, transforming to longitudinal and shear wave in accordance to the Eq. (7), Snell's law.

$$\frac{\sin\theta}{V_W}=\frac{\sin\alpha}{V_L}=\frac{\sin\beta}{V_S} \qquad (7)$$

where

$\theta$ : incident angle
$\alpha$ : refracted angle of longitudinal wave
$\beta$ : shear angle of transverse wave
$V_W$ : incident wave velocity in liquid (m/s)
$V_L$ : longitudinal wave velocity in solid (m/s)
$V_S$ : shear wave velocity in solid (m/s)

The divergence of the ultrasonic beam is obtained by Eq. (8). The divergence angle due to the curvature of the hole is considered to be the incident angle and a longitudinal, a shear and surface wave are transmitted and reflected on the cylindrical structure.

$$\sin\theta=0.51\frac{\lambda}{D} \qquad (8)$$

where :

$\lambda$ : ultrasonic wave length(m)
D : diameter of ultrasonic sensor(m)

The beam metal path (MP), meaning the inside diameter and thickness, is expressed by the Eq. (9).

$$MP=\frac{V\cdot S}{2} \qquad (9)$$

where :

MP : beam metal path(mm)
V : sound velocity(m/s)
S : time of flight

The beam divergence of 12mm diameter ultrasonic sensor is 4° in water on 10MHz transducer frequency in the experiment. The velocity of the longitudinal elastic wave is about 1490m/s in water and 4720m/s in Zr-4. In general, the velocity of the shear elastic wave is a half of longitudinal wave. Consequently, the reflected waves of 6° shear and 12° longitudinal are generated by Eq. (7).

### 3.3 Measurement instrument

The shape measurement apparatus was developed by considering working efficiency, safety, precision, cost-effectiveness in the radioactive working condition. Figure 6 shows the diagram of the measurement system. This system consists of the support, 4-axis manipulator and shape measurement system. In detail, the shape measurement system is composed of two USD15 ultrasonic instruments, two oscilloscopes (LeCroy 9400), a computer equipped with data acquisition system and a printer.

The 4-axis manipulator was designed and manufactured for positioning the ultrasonic sensor module, which was installed on the man-bridge of the reactor. The size of 4-axis manipulator is 120cm × 100cm × 150cm (length × wide × height).

**Table 2** measuring error of ultrasonic sensor(mm)

| Ultrasonic sensor | Vernier caliper | Measuring error |
|---|---|---|
| 1.132 | 1.17 | 0.038 |
| 2.360 | 2.34 | 0.02 |
| 3.228 | 3.20 | 0.028 |
| 4.230 | 4.21 | 0.02 |

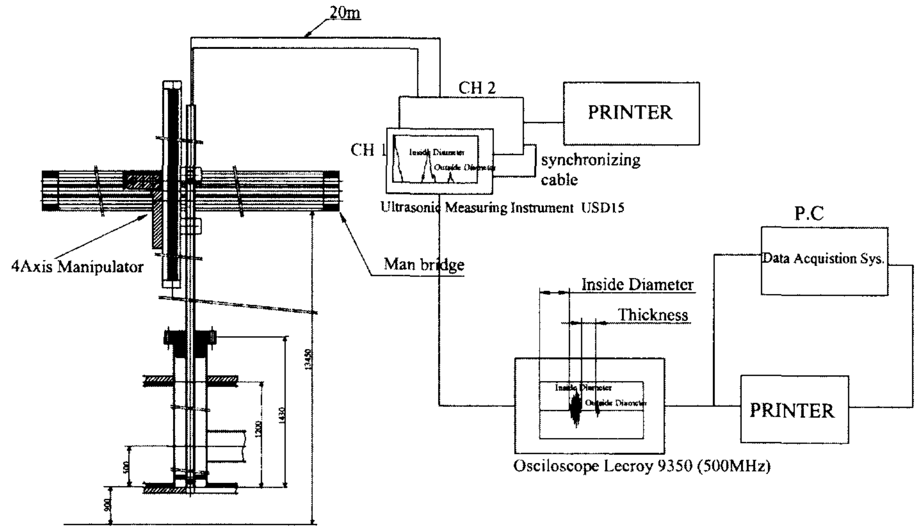


**Fig. 6** Diagram of ultrasonic measurement system

The 4-axis manipulator is designed to easily install and remove as well as rotate 360°. A steel ruler is attached in order to know the location of the measurement parts in the z-direction. An index is stuck for the precise operation of the rotating angle of the measuring channel.

Total length of the measurement probe is about 13m. That is assembled in the axial direction with five 3m-aluminum pipes by bolts.

## 4. Measurement Test and Results Analysis

### 4.1 Measurement test in the reactor

A 4-Axis manipulator was installed at the man-bridge and is controlled by hand, and two ultrasonic sensors are connected with two USD 15 ultrasonic measuring apparatus. The probe assembled ultrasonic sensor is located at the center of the CN hole by inserting the bottom limit plate into the center hole of the grid plate.

The location of the probe in the z-direction is settled as the zero position when the bottom limit plate is inserted completely at the grid plate. The South base of the HANARO was set 0° of the rotation axis as well as the reference zero point of the shear axis. The South of the measurement parts is determined to be 0° as a reference point.

The thickness of the CN hole is measured at

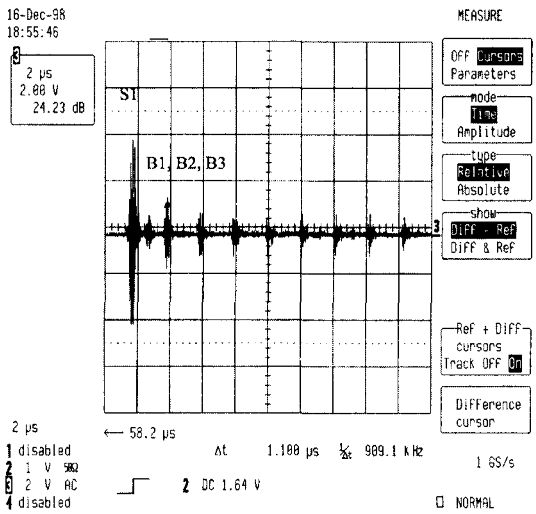


**Fig. 7** Ultrasonic signals pattern from CN-hole's regular surface

18 points from 0° to 160° with increasing 20°, because two ultrasonic sensors are assembled exactly in the opposite direction with an angle of 180°. After a revolution of 180°, the sensor assembled module is raised about 40mm to the next measurement location in z-direction. Therefore, 576 data are obtained from 18 points in rotation times of 32 points in z-axis direction.

A 20m-cable is used to measure the shape of the CN hole locating under water in a depth of

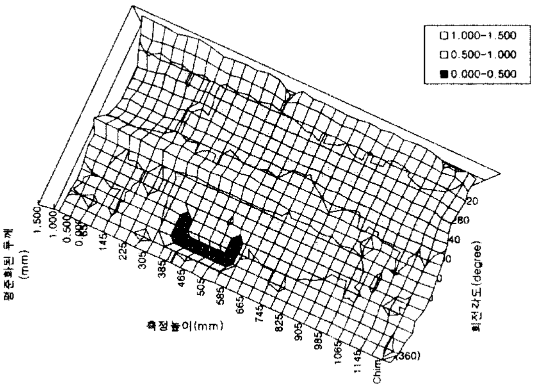


**Fig. 8** 3D-Image of CN hole's thickness

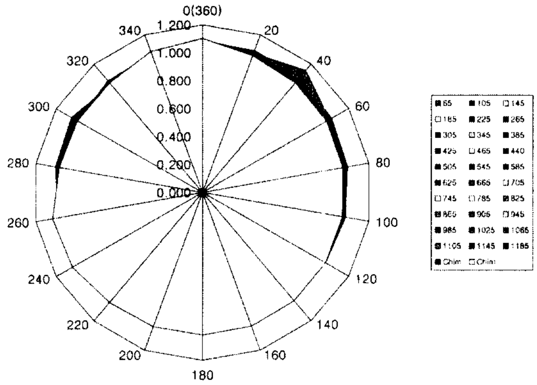


**Fig. 9** 2D-Image of CN hole's Inside radius

12m. There is no problem to obtain sensor signals without an amplifier. Normal result of the thickness signal is shown in Fig. 7.

### 4.2 Results and analysis

Detailed distribution of measurement data is shown in Fig. 8. Most signals are in 4-6mm. Less than 4mm thickness is found near 220°~280° of upper and lower CN hole, because CN hole was bored to make better welding deformation due to welding of horizontal beam tube. Thickness of 6mm or larger which can be seen near at 160° and 340° is not a machined part of the original CN hole. Moreover, the horizontal beam tube appears as 'ㄷ' shape, because one side was not measured and just passed by a different length: the thickness of the horizontal beam tube steel is 5mm while the measurement interval is 40mm. The minimum value of 3.3mm, satisfies the Safety Analysis Report, which demands a thickness of at least 3.1mm.

It is possible to measure the diameter and the thickness simultaneously using the ultrasonic sensor. As shown in Fig. 9, the measured values of radius are from 72.2mm to 87.0mm. This large eccentric error causes a problem in design and manufacturing. Since the 72.2mm radius can be seen in the range of 160°~180°, the diameter will not be over ∅ 144mm with the installing of the vacuum vessel.

When the reactor was built, the vertical CN hole size was changed to ∅ 155.7mm on the process of the horizontal beam tube welding. Since it causes trouble to install the cold neutron source at the CN hole, the inside diameter was machined to ∅ 157mm by boring.

The diameter of the CN hole was measured in the range of ∅ 155.8mm to ∅ 165mm. If it was preceded to measure precisely the position of the CN hole flange, the outside diameter of vacuum vessel could be ∅ 155mm.

## 5. Conclusions

The inside diameter and thickness of the Cold Neutron hole in the HANARO were measured considering two conditions; the measured object is located in 12m of water and in a radioactive area. Following are results of this study :

(1) Surface inspection using miniature underwater TV camera was effected the measuring stability and approach in the activity area.

(2) It is possible to assemble the vacuum vessel under the size of diameter ∅ 144mm. The vacuum vessel with diameter of ∅ 155mm can also be assembled, if it is preceded to measure the of the CN hole flange pin precisely.

(3) The measured minimum thickness of the CN hole is 3.3mm which satisfies the demand of the safety analysis report.

(4) The 4-axis shape measurement system was developed for measuring the thickness and diameter with an ultrasonic sensor, and the measurement technique was developed to measure the thickness and diameter simultaneously.

(5) The developed system will be used for the

inspection of the HANARO on working, which is performed in accordance with IAEA working ID35-G7.

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