E-Journal of Advanced Maintenance Vol.5 (2014) 228-237
Japan Society of Maintenology

Reliability Assessment for Thickness Inspection of Pipe Wall using Probability of Detection

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ABSTRACT

This paper proposes a reliability assessment method for pipe-wall thickness inspection using probability of detection (POD). Pipe-wall thicknesses are measured by certified inspectors with an ultrasonic thickness gauge. Since the inspectors have the different experiences and the frequency of inspections, the measured values are affected by the human factors of the inspectors and include some errors. In order to assess the reliability of inspection, first, the POD functions are determined based on the measured values of the pipe-wall thickness inspection. We verify that the results have the differences depending on five inspectors including two certified inspectors. Second, two human factors that affect the POD are indicated. Finally, it is confirmed that the POD can identify the human factors and assess the reliability for the pipe-wall thickness inspection.

KEYWORDS

pipe-wall thickness inspection, reliability assessment, probability of detection, human factor

ARTICLE INFORMATION

Article history:
Received 11 October 2013
Accepted 27January 2014

1. Introduction

In pipe-wall thinning managements in fire and nuclear power plants, in order to prevent accidents caused by defects and thinning, such as a burst of pipe and a leakage of water, pipe-wall thickness inspections are conducted. The Japan Society of Mechanical Engineers defined the pipe-wall thinning management standard. The inspections are periodically conducted by the inspectors that are certified based on the Japanese Society for Non-Destructive Inspection or the Japanese Industrial Standards [1]. However, even the certified inspectors, the differences of the inspection skills remain. The differences of the skills are based on human factors, and affect the results of the pipe-wall thickness inspection. The results also have the errors based on the human factors. It is impossible to reduce the errors to zero as long as the inspection is conducted by the inspectors. Since the power plants have been aging and the pipes which should be measured are increasing, the efficient inspections are required. Therefore, it is necessary to assess the reliability of the inspection skills.

In this paper, regarding the pipe-wall thickness inspections by an ultrasonic thickness gauge, the probability of detection (POD) which is used for a reliability assessment of inspection techniques is applied to assess the effects of the human factors. The POD, which has been applied to crack inspections of airplanes in the United States [2] and defect inspections of nuclear waste canisters in Sweden [3], is decided by the signal response model based on the inspection results. These studies fundamentally evaluated the reliability of the inspections using the POD, and do not discuss an assessment of inspection skills, especially a quantification of human factors. This paper verifies the possibility of the quantitative assessments of the inspection reliability by extracting the human factors using the POD. First, the conditions for the POD application are indicated, and a method to determine a signal response model from inspection results is described. Second, five inspectors that include two certified inspectors conduct simulated inspections of pipe-wall thicknesses with an ultrasonic thickness gauge, the results show there are the differences between the PODs of the inspectors. The two human factors which affect the PODs are discussed. Finally, we verify that the POD can specify the human factors such as the skills' problems of the inspectors. Therefore, the effectiveness of the reliability assessment using the POD is confirmed.

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2. Reliability Assessment using Probability of Detection

2.1. Conditions of reliability assessment

Reliability assessments of non-destructive inspections using the POD require inspection results that are acquired under three conditions indicated in Fig. 1 [4]. One of them is the condition of the specimen variation. It is necessary to define the shapes and the inspection positions of the specimens. The second is the condition of the apparatus variation. The condition defines the inspection apparatuses, and includes their settings, specifications, rules of apparatuses that indicate the calibration intervals, and so on. The third condition is the human factors. The human factors include the inspection procedures, the skills, and the experiences of the inspectors. When these conditions are constant, the inspection results are ensured repeatable, and can determine POD(a) functions.

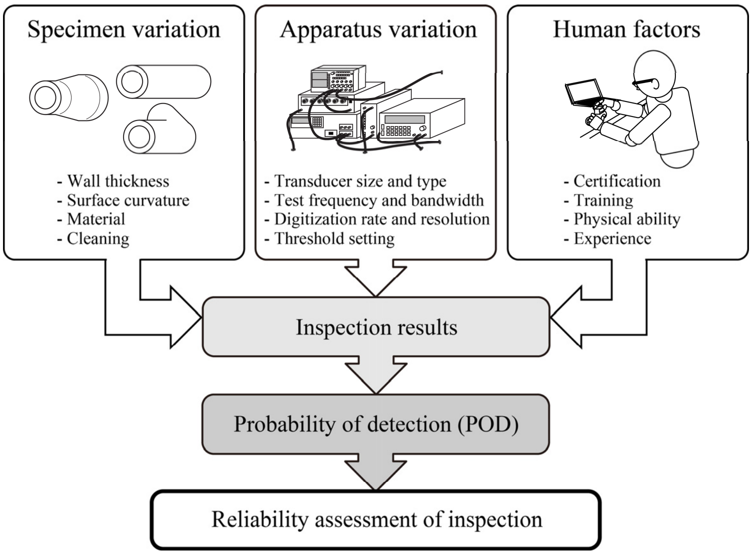


Fig. 1. Reliability assessment using POD.

The POD(a) functions are determined based on the inspection results and their true values. There are two analysis methods based on the format of the inspection results, namely, Hit/Miss or $\hat{a}$ analysis [4]. Hit/Miss method is used in the case of results which output 1 (hit) or 0 (miss), and requires much Hit/Miss data and their true values in order to estimate the parameters of the POD(a) function. This method was studied in the cases of crack detection which occurred on airplanes in the U.S. air force [2]. On the other hand, $\hat{a}$ analysis estimates the parameters of the POD(a) function from the measured values and their true values. The reliability assessments of inspection using electromagnetic acoustic transducers which were one of non-destructive inspections were conducted [5, 6]. In this study, $\hat{a}$ analysis assesses the reliability of pipe-wall thickness inspections using an ultrasonic thickness gauge.

2.2. Derivation of POD(a) function using $\hat{a}$ analysis

In this study, $\hat{a}$ analysis determines the POD(a) function based on the data set that has the measured value $\hat{a}$ and the pipe-wall thickness a as the true value. First, the measured value $\hat{a}$ is acquired via pipe-wall thickness inspections using specimens. Second, a signal response model is decided using logarithmic linear regression. If $g_a(\hat{a})$ represents the probability density of the measured value $\hat{a}$ for the pipe-wall thickness a, then:

$$\mathrm{POD}(a) = \int_{-\infty}^{\hat{a}_{\mathrm{dec}}} g_a(\hat{a}) d\hat{a} \tag{1}$$

$\hat{a}_{\mathrm{dec}}$ is the decision threshold defined in terms of the thickness that is required to be measured. Eq. (1) is illustrated in Fig. 2, in which the shaded area under the density functions represents the POD. In general, the relationship between the pipe-wall thickness *a* and the measured value $\hat{a}$ can be defined as follows:

$$\hat{a} = w(a) + \delta_{ga} \tag{2}$$

where $w(a)$ is the mean of $g_a(\hat{a})$ and δ_{ga} represents measurement noises. The distributional properties of δ_{ga} determine the probability density $g_a(\hat{a})$. The linear relationship between $\ln(\hat{a})$ and $\ln(a)$ is assumed to have normally distributed deviations. This model is expressed by:

$$\ln(\hat{a}) = \beta_0 + \beta_1 \ln(a) + \delta \tag{3}$$

where δ is normally distributed with zero mean and a constant standard deviation of σ_δ. $\hat{\beta}_0$, $\hat{\beta}_1$, and $\hat{\sigma}_\delta$ are estimates of β_0, β_1, and σ_δ, respectively. These values are obtained via maximum likelihood methods. The POD(*a*) function is calculated as:

$$\mathrm{POD}(a) = 1 - \Phi\left[\frac{\ln(a) - \hat{\mu}}{\hat{\sigma}}\right] \tag{4}$$

$$\hat{\mu} = \frac{\ln(\hat{a}_{dec}) - \hat{\beta}_0}{\hat{\beta}_1}, \quad \hat{\sigma} = \frac{\hat{\sigma}_\delta}{\hat{\beta}_1} \tag{5}$$

where Φ is the standard cumulative normal distribution function. $\hat{\mu}$ and $\hat{\sigma}$ are the mean and standard deviation of the pipe-wall thickness, respectively. An example of the POD(*a*) function is shown in Fig. 3. The lower one-sided confidence bound of the POD(*a*) function is given by

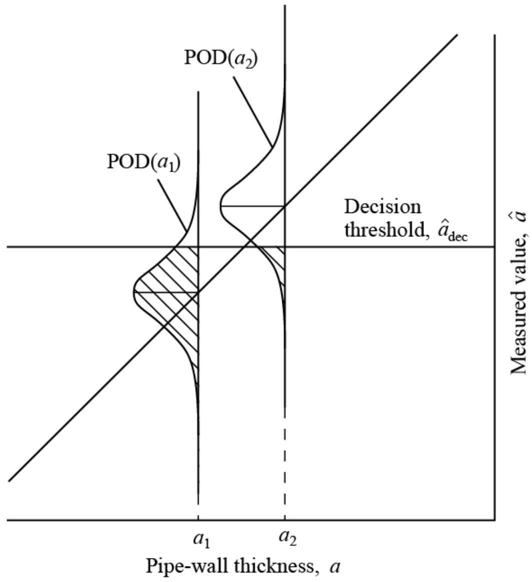
$$\mathrm{POD}_\alpha(a) = 1 - \Phi(\hat{z} - h) \tag{6}$$

where α is the confidence level, and

$$\hat{z} = \frac{\ln(a) - \hat{\mu}}{\hat{\sigma}} \tag{7}$$

$$h = \left\{\frac{\gamma}{nk_0}\left[1 + \frac{(k_0\hat{z} + k_1)^2}{k_0k_2 - k_1^2}\right]\right\}^{0.5} \tag{8}$$

where *n* is the number of measurements in the experiment. γ is the confidence coefficient and is obtained from the confidence level and the number of measurements in the experiment [7, 8]. k_0, k_1, k_2 are determined via the maximum likelihood analysis of $\theta = (\mu, \sigma)$ that are the parameters of the POD(*a*) function.



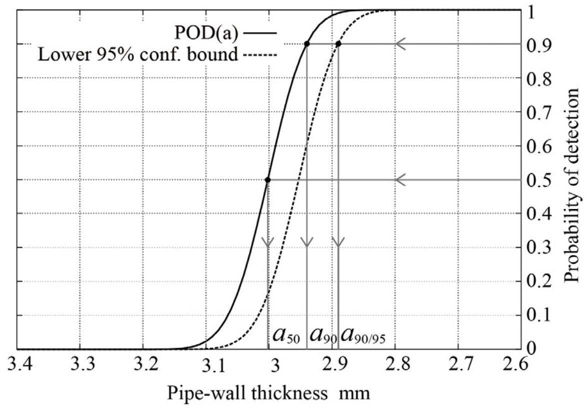


Fig. 2. Schematic of POD(*a*) calculation. (Modified from Beren 1989 [4])

Fig. 3. POD(*a*) function, lower 95% confidence bound and evaluation indicators.

2.3. Assessment indicators in POD(a) function

Figure 3 shows examples of a POD(a) function and its lower 95% confidence bound that were determined based on results of a preliminary experiment of a pipe-wall thickness inspection using an ultrasonic thickness gauge. The value of $\hat{a}_{dec}$ was 3.0. The line and the dashed line indicate the POD(a) function and the 95% confidence bound, respectively. $\hat{\mu}$ and $\hat{\sigma}$ are parameters which determine the position in the pipe-wall thickness direction and the slope of the POD(a) function. In addition, we focus on a_{50}, a_{90}, and $a_{90/95}$, which are defined by the inverses of the PODs. a_{50} is the pipe-wall thickness that the POD is 50%, and is the average of the POD(a) function on $\hat{a}_{dec}$. When a_{50} has a good agreement with $\hat{a}_{dec}$ and the slope is approximately vertical, the inspection was conducted with high reliability. a_{90} is the pipe-wall thickness that the POD is 90%. The inspection using $\hat{a}_{dec}$ as the threshold can detect a_{90} with the probability of 90%. $a_{90/95}$ is the pipe-wall thickness of 90% in the lower 95% confidence bound of the POD(a) function. $a_{90/95}$ is the more conservative value than a_{90}. The detectable pipe-wall thickness with the probability of 90% in the lower 95% confidence bound of the POD(a) function is assessed by $a_{90/95}$. The reliability assessment of the pipe-wall thicknesses that have regulation sizes or advanced thinning is enabled by the evaluation indicators of a_{50}, a_{90}, and $a_{90/95}$ that are determined based on the measured values including the specifications of the ultrasonic thickness gauge and the skills of the inspector.

3. Simulated Inspection Experiment of Pipe-wall Thickness Measurement using Ultrasonic Thickness Gauge

In order to decide the POD(a) functions based on the pipe-wall thickness inspections, we conducted simulated inspection experiments using an ultrasonic thickness gauge. In these experiments, each inspector acquired the measured values individually. The other conditions of the specimen and the apparatus were maintained constant to verify the effects of the human factors. The conditions were as follows.

- Specimens

An example of the specimens is shown in Fig. 4. The specimens used are 17 carbon steel pipes with simulated corrosion; each specimen has seven inspection positions, as shown in Fig. 5. The diameter of the pipes is 60.5 mm, and the specimens are halved longitudinally. Each circular radius of the simulated corrosion in the specimen differs. The designed values of the pipe-wall thickness at the position 4 are 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 5.5 mm. The chord length of the simulated corrosions is 100 mm. All the pipe-wall thicknesses at the inspection positions were measured by a laser distance meter to determine the POD(a) functions as a described in Section 2.2.

- Inspection apparatus

The inspection apparatus is the ultrasonic thickness gauge shown in Fig. 6. The major specifications are as follows.

- Inspection device : DM-4 (Manufactured by GE Inspection Tech.)
- Transducer : DA-401 (Manufactured by GE Inspection Tech.)
- Mode : Pulse-echo method
- Number of measurement : 1

The transducer is 12.5 mm in diameter, and generates longitudinal waves. Their frequency is 5 MHz. The coupling medium is glycerin paste. The outputs of the ultrasonic thickness gauge are used as the measured values $\hat{a}$ described in Section 2.2.

- Inspectors

The inspectors are five who include two inspectors certified by the Japan Society for Non-Destructive Inspection and three non-certified inspectors. The two certified inspectors have the skills of Level 3 and 2 with regard to the ultrasonic inspection (UT3 and UT2), and are called as A and B in this paper, respectively. Each level represents the followings, provided that NDT indicates non-destructive inspection techniques.

- Level 3
  An inspector has a detailed knowledge of NDT, and can conduct and direct all of NDT operations.
- Level 2
  An inspector can conduct and direct NDT operations in accordance with confirmed NDT operation procedures.

In addition, the inspection conditions and procedures which were directed to the inspectors in the experiments are the followings. The procedures include a calibration operation because inspectors of non-destructive inspection in plants carry specimens for calibration all the time and calibrate their apparatus several times a day. The non-certified inspectors, before the experiments, trained enough the usages of the inspection apparatus and were directed to comply with the inspection procedures.

- Inspection conditions
  - To conduct at the temperature of from 10 to 30 degrees C
  - To obtain the calibration values at the center of the white-marked circles of the calibration specimens
  - To measure the pipe-wall thicknesses at the center of the white-marked circles of the specimens
  - To record the measured values to two places of decimals
- Inspection procedures

1) Conduct the two-point calibration with the two points (1.0 mm and 6.0 mm) of the calibration specimens, and proceed to 2).
2) Check the results of 1). If there is the difference more than 0.2 mm, return to 1), otherwise proceed to 3).
3) Measure the pipe-wall thicknesses of the seven white-marked circles of all specimens in order and repeat them 10 times. Then, proceed to 4). If it has been more than 4 hours after the last calibration by inspections or a rest, proceed to 4).
4) Check the measured values of the two points (1.0 mm and 6.0 mm) of the calibration specimens. If they have the difference more than 0.2 mm, delete the measured values of 3) and return to 1). Otherwise, proceed to 5).
5) Record the measured values. If all the specimens have been measured, finish the inspection. Otherwise, return to 3).

The number of the measured values of the procedures is 1190 per each inspector.

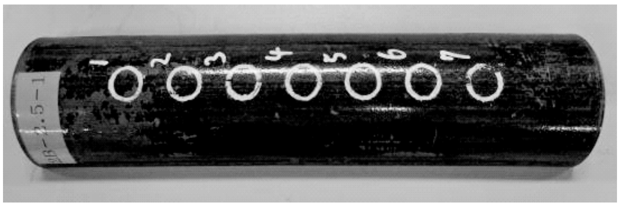


Fig. 4. Example of specimen.

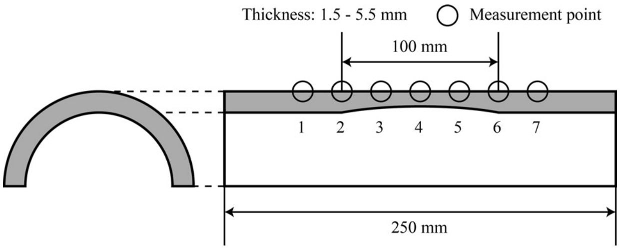


Fig. 5. Specimen structure.

Fig. 6. Ultrasonic thickness gauge.

4. Experimental results

The POD(a) functions were determined based on the pipe-wall thicknesses and the measured values of the simulated inspection experiments. First, the data set which includes the pipe-wall thickness a and the measured value $\hat{a}$ was created with regard to each inspector. The signal response model was determined from a linear relation between $\ln(a)$ and $\ln(\hat{a})$. Fig. 7 shows the relation of the inspector A. The logarithms of the pipe-wall thickness a and the measured value $\hat{a}$ have a linear relation in Fig. 7. The parameters of the signal response models of each inspector determined via the maximum likelihood estimation method are listed in Table 1. In the conditions of these signal response models and $\hat{a}_{\text{dec}} = 3.0$, the POD($a$) functions and the 95 % lower confidence bounds determined using Eq. (4) and Eq. (6) are shown in Fig. 8. Moreover, the estimated parameters and the assessment indicators of the POD(a) functions are listed in Table 2. The POD(a) functions of each inspector have the differences of the slopes in Fig. 8. At the lower values of $\hat{\sigma}$, the slopes of the POD(a) functions were steep and the variations of the POD were large. The magnitude relations of $\hat{\sigma}$ of each inspector were A < B < C < D < E. These relations show that those of the certified inspectors were smaller than those of the uncertified inspectors, and inspector A with the high-level certification had the smallest value. Since these results corresponding to the skills of the inspectors, $\hat{\sigma}$ can assess the precisions of the inspections. If a_{50} is equal to the decision threshold $\hat{a}_{\text{dec}} = 3.0$, the inspector can detect the pipe-wall thickness of 3.0 mm with the POD of 50%. Conversely, the large differences between a_{50} and $\hat{a}_{\text{dec}}$ indicate that the absolute errors of the inspection are large. In the five inspectors, the difference between a_{50} and $\hat{a}_{\text{dec}}$ of inspector A was the smallest value, and that of inspector E was the largest. This result shows that inspector E's absolute errors were large. In Fig. 8, the difference between the POD(a) function and the 95% lower confidence bound of inspector A was smaller than that of inspector E. Correspondingly, this result was also confirmed by $a_{90/95}$ in Table 2. The small difference between $a_{90/95}$ and a_{50} indicates the high-reliability inspection result.

As described above, $\hat{\sigma}$, a_{50}, $a_{90/95}$, and the POD(a) function determined based on the measured values of the simulated inspection experiments have quantified the reliability of the inspection. In the experiments, the factors affecting the reliability are the human factors. This paper discusses the specific factors of the human factors using the results in Section 5.

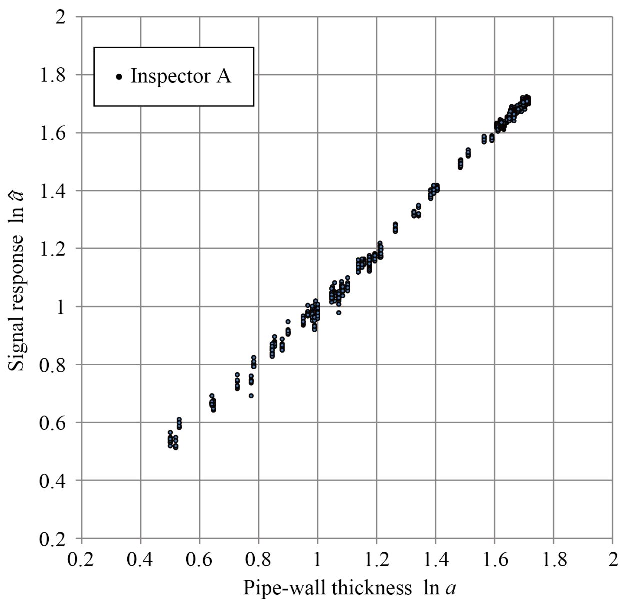


Fig. 7. ln $\hat{a}$ versus ln *a* relation of inspector A.

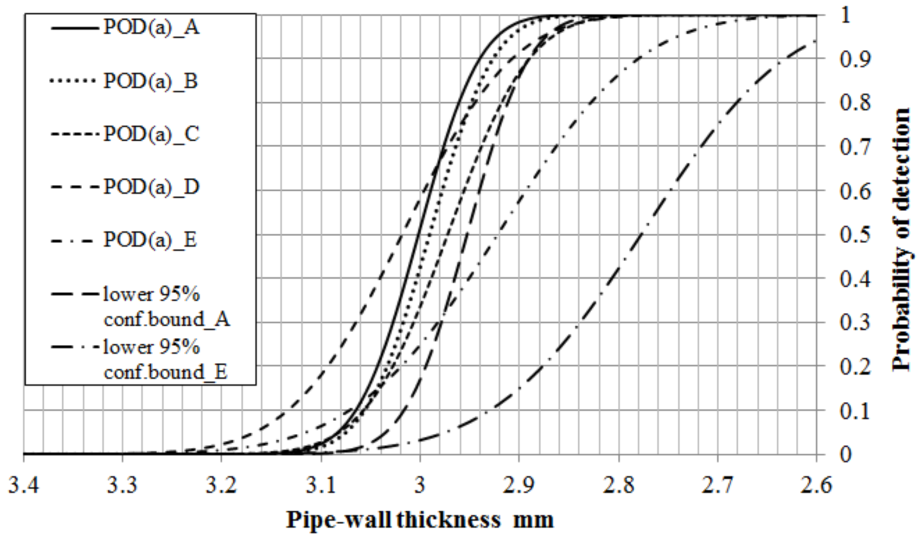


Fig. 8. POD(*a*) function and lower 95% confidence bound of each inspector.

Table 1 Estimated values of POD(*a*) function of each inspector.

	A	B	C	D	E
$\hat{\beta}_0$	-0.004	0.004	0.030	-0.01	0.048
$\hat{\beta}_1$	1.003	0.999	0.981	1.006	0.980
$\hat{\sigma}_\delta$	0.016	0.016	0.022	0.029	0.038

Table 2 Estimated values of POD(*a*) function parameters of each inspector.

	A	B	C	D	E
$\hat{\mu}$	1.099	1.095	1.088	1.105	1.072
$\hat{\sigma}$	0.0162	0.017	0.0219	0.029	0.039
a_{50}	3.00	2.99	2.97	3.02	2.92
a_{90}	2.94	2.93	2.89	2.91	2.78
$a_{90/95}$	2.89	2.88	2.82	2.81	2.63

5. Discussion on human factors affecting POD

Since the pipe-wall thickness inspections are conducted by the inspectors with the ultrasonic thickness gauge, the measured values have the errors between the center positions of the white-marked circles on the specimens and the center position of the transducer (hereafter, the errors are called the contact position errors). Moreover, it is possible that the calibration skills conducted several times a day give the errors to the measured values (hereafter, the errors are called the calibration errors). Next, on the supposition that the contact position errors and the calibration errors of the human factors affect the pipe-wall thickness inspections, the possibilities of the reliability assessment of the human factors using the POD(a) function are verified.

In order to verify the effects of the contact position errors for the POD(a) function, 5 of 10 pipe-wall thicknesses of each specimen measured by the laser distance meter were altered by adding or subtracting of 0.1, 0.25, 0.5 mm. The addition or the subtraction was randomly decided. In the condition of the decision threshold $\hat{a}_{\text{dec}} = 3.0$, the POD($a$) functions were determined based on the 10 pipe-wall thicknesses including the 5 altered values. The POD(a) function is shown in Fig. 9, and Table 3 lists $\hat{\sigma}$. Fig. 9 shows that the slopes of the POD(a) functions are gentle in the case of the large values of the addition or the subtraction. The precision of the contact positions decreases by the addition or the subtraction, and the effects on the POD(a) functions are shown as the slopes. Therefore, these results indicate that the slope of the POD(a) function can assess the degree of precision of the inspection.

Next, in order to verify the effects of the calibration errors for the POD(a) function, the pipe-wall thicknesses of each specimen measured by the laser distance meter were altered by adding the calibration error of -0.25, -0.1, or +0.1 mm. The POD(a) functions which were determined based on the altered pipe-wall thicknesses and the decision threshold $\hat{a}_{\text{dec}} = 3.0$ are shown in Fig. 10. a_{50} is also listed in Table 4. In Fig. 10, a_{50} was low on the condition that the altered pipe-wall thicknesses are lower than the pipe-wall thickness of 3.0 mm. Conversely, a_{50} was large in the case of the large altered pipe-wall thicknesses. It was found that the calibration errors give effects to the amount of variation of the measured values. These results indicate the possibility of the assessment of the calibration errors by a_{50}.

Finally, based on the results shown in Section 4, the errors affected by human factors are discussed. Since the values of $\hat{\sigma}$ were the ranking of A < B < C < D < E, the certified inspector of the skill level 3 had the lowest contact position error. Moreover, with regard to the calibration errors, the differences between a_{50} and the decision threshold $\hat{a}_{\text{dec}} = 3.0$ are listed in Table 5. The certified inspector of the skill level 3 had the excellent result of the calibration errors as well as the result of the contact position error. Therefore, under the conditions described in Section 3, it was verified that $\hat{\sigma}$ and a_{50} of the POD(a) functions determined based on the simulated pipe-wall thickness inspections can assess the effects of the human factors.

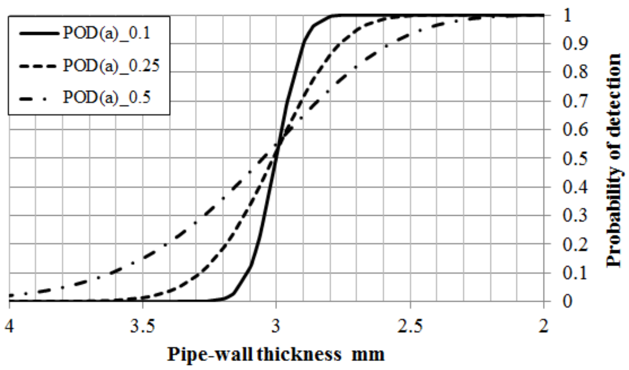


Fig. 9. POD(a) function including simulated inspection error.

Table 3 Simulated position error versus $\hat{\sigma}$.

Position error [mm]	0.1	0.25	0.5
$\hat{\sigma}$	0.027	0.068	0.133

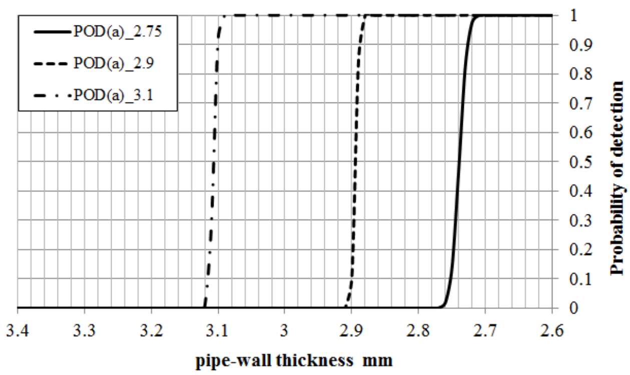


Fig. 10. POD(*a*) function including simulated calibration error.

Table 4 a_{50} versus simulated calibration error relation.

Calibration error [mm]	-0.25	-0.1	0.0	0.1
a_{50}	2.75	2.90	3.00	3.10

Table 5 Calibration error of each inspector.

Inspector	A	B	C	D	E
Calibration Error [mm]	0.0	0.01	0.03	-0.02	0.08

6. Conclusion

In order to determine the POD(*a*) functions of the pipe-wall thickness inspections using the ultrasonic thickness gauge, the experiments of the simulated pipe-wall thicknesses inspections were conducted under the arranged conditions of the specimens, the apparatus, and the human factors. The reliability of the certified inspectors was high inside the range of the experimental results. The POD(*a*) functions specified the human factors and the skills' problems of the inspectors. Since the experiments were the low number of the inspectors, in the future, the experiments of the simulated inspections by many inspectors are required. In addition, after the POD assess other inspections with regard to pipe-wall thickness, it is necessary to discuss a possibility of applications to selection methods of inspections. The final stage of this study would attempt to apply the results of reliability assessments to coordination of inspection schedules.

Acknowledgement

This work has been conducted as a part of the National Research Project for Enhancement of Measures against the Ageing of Nuclear Power Plants sponsored by the Nuclear Regulation Agency (NRA) in Japan.

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