A STUDY ON THE ULTRASONIC THICKNESS MEASUREMENT OF WALL THINNED PIPE IN NUCLEAR POWER PLANTS

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Abstract

One of the most serious problems on the maintenance of piping system in nuclear power plant is the reduction of pipe-thickness induced by flow accelerated corrosion (FAC). In the design of nuclear power plants, it assumes that the thickness of the pipe used in the piping system is constant. In-service, piping components may experience wall thinning due to cavitations, general corrosion, microbiologically influenced corrosion, pitting, or FAC. The objective of this research is the experimental evaluation of the performance of examination procedures and techniques available for pipe inspection in nuclear power plants. Round robin (RR) test was circulated to the 3 participating organizations. Four kinds of pipe samples were circulated pipe, elbow, tee and reducer. A total of 68 flaws (some of which were combinations of flaws) were introduced into the pipes representing a wide range of types and locations. The major flaws introduced fell into two principle categories: 1) machined flaws simulating typical flaws such as wastage and pitting and 2) naturally introduced flaws due to FAC. The inspection procedures were based on ultrasonic procedures only. For procedures based on ultrasonic testing only, detection was very good for wall thinning flaw. In several cases of teams demonstrated their ability to identify the wall thinning flaw. Conclusions of the exercise indicate that this capability is necessary to qualify in overhaul inspection procedures for piping systems. The analysis proposed in this paper can be widely applied to the secondary piping system in nuclear power plants.

1. Introduction

Local wall thinning of the pipe used in nuclear power plants (NPPs) is the major cause of accidents in the nuclear power plant. Therefore, reliable non-destructive inspection methods to prevent these accidents in NPPs have been needed. The conventional inspection of wall thinning in the pipeline of NPPs was carried out by ultrasonic testing [1]. In overhaul, ultrasonic thickness measurement is performed selectively for the pipelines of NPPs in terms of their temperature, pressure, enthalpy, power level, water chemistry, component geometry, etc. Subsequently, these selective data for each component of the pipeline is stored and analyzed in computer S/W of CHECWORKS for the maintenance and conservation. CHECWORKS code used as a tool for making a diagnosis of plant wear level enable to predict the degree of wall thinning and the remaining service life on components [2]. CHECWORKS program use the result of ultrasonic thickness measurement as one of the important factors in the process of analysis to predict the remaining service life of NPPs. Therefore, if thickness of the pipe measured by inspector is much different from real thickness, the results can cause serious problems in the integrity of NPPs. To solve this problem, inspector's expertness is needed to be verified. In this study, round robin (RR) test was performed to evaluate the reliability of the data obtained from ultrasonic thickness measurement.

2. Reliability analysis model

The accuracy of ultrasonic thickness measurement is dependent on the factors such as expertness, calibration, surface condition and etc. These factors influence in the repeatability and reproducibility of the measured result. Repeatability is the variability of the measurements obtained by one person while measuring the same item repeatedly. This is also known as the inherent precision of the measurement equipment. In addition, reproducibility is the variability of the measurement system caused by differences in operator behavior. Mathematically, it is the variability of the average values obtained by several operators while measuring the same element [3]. Therefore, identification and quantification of sources of variation in a measurement process is needed. Usually, gage repeatability & reproducibility (R&R) analysis are conducted so that repeatability and reproducibility can be estimated from experiments. This strategy helps in finding those factors that contribute most to the total variation. Bias means the amount of difference between reference and measurement data [4].

2.1 Gage R&R analysis

Measurement system errors consist of repeatability and reproducibility. Repeatability error means measurement variation by one inspector with the same gage. Repeatability error includes measurement direction, position variations and etc. Reproducibility error consists of variation depending on each inspector's expertness, measurement methods, etc. The sum of the repeatability and reproducibility is called the Gage R&R value [5]. The ultrasonic thickness measurement system can be expressed by using Eq. (1).

$$Y_{ijk} = \mu + p_i + o_j + (op)_{ij} + e_{ijk} \qquad (1)$$

Where: μ = average of measured values at all points

p_i = influence of i^th point

o_j = influence of j^th inspector

$(op)_{ij}$ = interaction of p_i and o_j

e_{ijk} = errors from repeatability

p_i, o_j, $(op)_{ij}$, e_{ijk} represent standard distribution as shown in Eq. (2) and are independent on each other.

$$p_i \sim N(0, \sigma_p^2)$$
$$o_j \sim N(0, \sigma_o^2)$$
$$(op)_{ij} \sim N(0, \sigma_{op}^2)$$
$$e_{ijk} \sim N(0, \sigma_e^2)$$
(2)

Equation 3 shows the sum of squares (SS) of the value mentioned in Eq. (2).

$$SS_p = \sum_i \sum_j \sum_k (\bar{y}_{i\cdot\cdot} - \bar{\bar{y}})^2$$
$$SS_o = \sum_i \sum_j \sum_k (\bar{y}_{\cdot j\cdot} - \bar{\bar{y}})^2$$
$$SS_{op} = \sum_i \sum_j \sum_k (\bar{y}_{ij\cdot} - \bar{y}_{i\cdot\cdot} - \bar{y}_{\cdot j\cdot} + \bar{\bar{y}})^2 \qquad (3)$$
$$SS_T = \sum_i \sum_j \sum_k (\bar{y}_{ijk} - \bar{\bar{y}})^2$$
$$SS_e = SS_T - SS_o - SS_p - SS_{op}$$

Each SS is divided by degree of freedom(DF) to obtain the shown mean square(MS) in Eq. (4).

$$MS_p = ar\hat{\sigma}_p^2 + r\hat{\sigma}_{op}^2 + \hat{\sigma}_e^2$$
$$MS_o = pr\hat{\sigma}_o^2 + r\hat{\sigma}_{op}^2 + \hat{\sigma}_e^2$$
$$MS_{op} = r\hat{\sigma}_{op}^2 + \hat{\sigma}_e^2 \qquad (4)$$
$$MS_e = \hat{\sigma}_e^2$$

As shown in Eq. (5), the unbiased estimator of analysis of variance (ANOVA) is obtained from the solutions of equations in Eq. (4).

$$\hat{\sigma}_p^2 = \frac{MS_p - MS_{op}}{ar}$$
$$\hat{\sigma}_o^2 = \frac{MS_o - MS_{op}}{pr}$$
$$\hat{\sigma}_{op}^2 = \frac{MS_{op} - MS_e}{r} \qquad (5)$$
$$\hat{\sigma}_e^2 = MS_e$$

Table 1 shows the formula to calculate standard deviation components using the result obtained from Eq. (5). In these formulas, $\hat{\sigma}_e$ represents standard deviation from repeatability and sum of $\hat{\sigma}_o$ and $\hat{\sigma}_{op}$ from reproducibility. Consequently, standard deviation of the $\hat{\sigma}_{R\&R}$ is obtained from the sum of standard deviation of repeatability and reproducibility. $6\hat{\sigma}_{R\&R}$ means the total variation of overall measurement system. Here the number 6 represents the width of the confidence interval under a normal distribution that captures 99.73% of the process measurements.

Table 1: Standard deviation and gage R&R

Source	Standard deviation
Total Gage R&R	$\hat{\sigma}_{R\&R} = \sqrt{\hat{\sigma}_{Rpt}^2 + \hat{\sigma}_{Rpd}^2}$
Repeatability	$\hat{\sigma}_{Rpt} = \hat{\sigma}_e$

Reproducibility	$\hat{s}_{Rpd} = \sqrt{\hat{s}_o^2 + \hat{s}_{op}^2}$
Operator	$\hat{s}_o$
Operator*Part	$\hat{s}_{op}$
Part to Part	$\hat{s}_p$
Total variation	$\hat{s}_{total} = \sqrt{\hat{s}_{R\&R}^2 + \hat{s}_p^2}$

2.2 Bias analysis

Every point has reference value obtained by using precise measurement system and inspectors measured the thickness for all those points. $\overline{X}_i$ in Eq. (6) is the average value measured by each inspector for one point. Therefore, bias is the difference between reference and $\overline{X}_i$.

Every point has their own bias value, the average value of all of the bias is used for the accuracy analysis. The smaller bias, the greater accuracy is obtained.

$$Bias(y_i) = \overline{X}_i - reference$$

$$Ave.(Bias) = \frac{\sum y_i}{n} \quad (6)$$

3. Round Robin Test

The objective of this test is to verify the reliability of thickness measurement through the evaluation of critical factors that may influence in the result. For this aim, standard practice in NPPs is used in RR test and each process of RR test is established in consideration of the above factors.

3.1 Experimental methods

The RR test was performed by 4 teams from 3 inspection companies, and each team consisted of 3 members as shown in Table 2. All mock-up specimens with artificial or natural wall thinned defect were measured by each inspector using a thickness gage and probe. In this test, the inspection performance of the condition was determined as follows in shown Eq. (7).

$$4team \times 3inspectors \times 2{,}200grids \times 3times = 79{,}200(Total) \quad (7)$$

The data obtained from RR test were analyzed by the method of gage R&R. For the analysis of the contribution of each error factor in the RR test results, the gage R&R method was used. Additionally the accuracy analysis was carried out with several types of probes in terms of diameter and frequency of 2 or 8 inch pipe which consists of straight, elbow, tee, and reducer. The detail information of four types of probes used in this experiment described in Table 3. In the process of this analysis, thickness measurement of each specimen with 2 or 8 inch diameter is performed with different type of probes by each inspector in a team and this process is the same for other 3 team. Subsequently, the bias of the above measured thickness data was analyzed. Throughout the above process, the reliability of each measurement system and inspectors can be evaluated and results from this test can improve the method of measuring thickness.

Table 2: 12 inspectors for RR Test

Group	Company	Experience (year)	ASNT Level	No.
1	A	5~10	Ⅱ	1
	A	5~10	Ⅱ	2
	A	5~10	Ⅱ	3
2	B	10~15	Ⅱ	4
	B	10~15	Ⅲ	5
	B	10~15	Ⅱ	6
3	B	1~5	Ⅰ	7
	B	1~5	Ⅰ	8
	B	1~5	Ⅰ	9
4	C	5~10	Ⅲ	10
	C	5~10	Ⅱ	11
	C	5~10	Ⅱ	12

Table 3: Information of four types of probes

Type	D790	D794	D798	D792
Diameter (mm)	11	7.2	7.2	7.2
Frequency (MHz)	5	5	7.5	10

3.2 Materials and specimens

Artificial corrosion flaw of varying depths 20, 40, 60 or 80% of nominal thickness were machined on the specimen with 2, 4, 6, 8 or 12 inch nominal diameter for all types of pipe, elbow, tee, and reducer as shown in Figure 1 and Table 4. In addition, to compare with artificial mock-up specimen 4 types of field specimens used in NPPs were prepared as shown in Figure 2 and Table 5. The full grid of the mock-up specimens were marked according to the standard practice as shown in Table 4 and elliptical FAC flaws were fabricated on the inner side of mock-up specimen by the criteria in Equation (8).

$$L = 4\sqrt{Rt}$$
$$W = pR \acute{} \, 0.25$$
(8)

Figure 1: *The Mock-up specimens of RR test*

Figure 2: *The field specimens of RR test*

Table 4: RR test specimens

Type		Nominal thickness (mm)	Flaw
2”	Pipe	3.91	7
	Elbow	3.91	2
	Tee	3.91	3
	Reduce	3.91	2
4”	Pipe	6.02	7
	Elbow	6.02	2
	Tee	6.02	3
	Reduce	6.02	2
6”	Pipe	7.11	7
	Elbow	7.11	2
	Tee	7.11	3
	Reduce	7.11	2
8”	Pipe	8.18	7
	Elbow	8.18	2
	Tee	8.18	3
	Reduce	8.18	2
12”	Pipe	9.52	7
	Elbow	9.52	2
	Tee	9.52	3
	Reduce	-	-
16” Elbow		12.7	Natural
3.5” Elbow		5.49	Natural
3.5” Tee		5.49	Natural
16” Expander		30.96	Natural

Table 5: Grid marking criteria in pipelines

Nominal diameter (inch)	Grid size (inch)	Main Grid No.	
		Longitudinal	Circumferential
2	1.000	7	7
4	1.178	12	12
6	1.734	12	12
8	2.258	12	12
12	3.338	12	12

4. Experimental Results

In this study, the data measured from the RR test was analyzed using the gage R&R and bias methods. The gage R&R method was applied to the analysis of the repeatability and reproducibility error in terms of shape and diameter of the mock-up specimen as well as expertness of inspectors. In addition, the bias method was utilized to evaluate the accuracy of probe used in the thickness measurement of 2 or 8 inch thick pipe according to diameter and frequency.

4.1. Gage R&R Analysis Results

The shapes of the mock-up specimens were analyzed. The results of gage R&R analysis of the mock-up specimens according to its shape are presented in Table 6. As shown in Table 6, the most accurate results occurred in straight pipe. This result indicates that potential error is the least in the thickness measurement of straight pipe among 4 types of pipes shown in Table 6.

Table 6: Standard deviation and gage R&R results of mock-up specimens

Part	Standard deviation (± mm)	Gage R&R (± mm)
Pipe	0.058	0.174
Elbow	0.082	0.245
Tee	0.083	0.248
Reducer	0.089	0.267

Table 7 shows the percentage of repeatability and reproducibility of the mock-up specimens. The result represent that the ratio of repeatability to reproducibility is approximately 3:1. This fact means that there is the repeatability of thickness measurement should be improved due to the high ratio compared to the reproducibility.

Table 7: The repeatability and reproducibility in mock-up specimens

Part	Repeatability	Reproducibility
Pipe	70.16%	29.84%
Elbow	76.70%	23.30%
Tee	73.29%	26.71%
Reducer	74.33%	25.67%

Table 8 shows the gage R&R analysis of the field specimens. In this table, field specimen has the higher value of gage R&R than that of mock-up specimen. This result represent that the inspection condition of field specimens is poor due to the rough surface and the weld regions.

Table 8: Standard deviation and gage R&R results of field specimens

Part	Standard deviation (± mm)	Gage R&R (± mm)
3.5inch Tee	0.125	0.374
3.5inch Elbow	0.136	0.409
16inch Elbow	0.062	0.187
16inch Expander	0.234	0.702

Table 9 shows the percentage of repeatability and reproducibility of the field specimens in total error of measurement system. The results shown in Table 8 correspond to those of the mock-up specimens.

Table 9: The repeatability and reproducibility in field specimens

Part	Repeatability	Reproducibility
3.5inch Tee	71.36%	28.64%
3.5inch Elbow	88.54%	11.46%
16inch Elbow	77.49%	22.51%
16inch Expander	62.27%	37.73%

Gage R&R analysis of the mock-up specimens according to their shape and diameter is presented in Table 10. The straight pipes show the most accurate gage R&R value within 0.2mm except for the 2 inch pipe. In every type of specimen, high accuracy of measured data was obtained as the diameter increased.

Table 10: Gage R&R analysis of mock-up specimens shape types and diameters

Diameter (inch)	Pipe (± mm)	Elbow (± mm)	Tee (± mm)	Reducer (± mm)
2	0.211	0.312	0.306	0.308
4	0.169	0.293	0.279	0.312
6	0.164	0.249	0.246	0.244
8	0.159	0.195	0.217	0.202
12	0.167	0.194	0.191	-

Gage R&R analysis of the mock-up specimens according to group of inspectors and shape of specimens was presented in Table 10. Table 10 shows that the most accurate result of gage R&R is occurred 0.206mm in the group 2. On the other hand, the worst result of gage R&R is occurred 0.247m in the group 3. This result indicates that expertness is major factor to evaluate the thickness of wall-thinning.

Table 11: Gage R&R analysis in mock-up specimens according to groups and shapes

Diameter (inch)	1group (± mm)	2group (± mm)	3group (± mm)	4group (± mm)
Pipe	0.172	0.143	0.194	0.187
Elbow	0.244	0.241	0.254	0.256
Tee	0.266	0.206	0.256	0.262
Reducer	0.268	0.232	0.283	0.283
Average	0.238	0.206	0.247	0.245

4.2. Bias analysis results

Reference data from all the points of mock-up specimens were obtained by pulse-echo method using a 10MHz, 6mm diameter probe. Probe diameter and frequency are very important factors in ultrasonic thickness measurement systems. Therefore, the bias analysis was carried out with several types of probes in terms of diameters and frequencies. Therefore the adaptability of probes in 2 or 8 inch elements was evaluated by bias analysis. From this analysis the optimum probe in pipelines of various type and diameter can be determined. The bias analysis of the mock-up specimens is presented in Table 11 in terms of their diameter and type. The values in the bracket are percentage of nominal thickness. The most accurate result is shown in straight pipe. In fittings, tee shows the most accurate results and the 2 inch elbow and reducer show the worst results (over 5%) due to their bending shape. Therefore, it is needed to find a probe with appropriate diameter and frequency to reduce the bias.

Table 12: Bias analysis results of mock-up specimens

Diameter (inch)	Pipe (mm)	Elbow (mm)	Tee (mm)	Reducer (mm)
2	0.054 (1.4%)	0.251 (6.4%)	0.104 (2.7%)	0.207 (5.3%)
4	0.081 (1.3%)	0.135 (2.2%)	0.077 (1.3%)	0.093 (1.5%)
6	0.044 (0.6%)	0.115 (1.6%)	0.075 (1.1%)	0.083 (1.2%)
8	0.056 (0.7%)	0.070 (0.9%)	0.091 (1.1%)	0.074 (0.9%)
12	0.042 (0.4%)	0.048 (0.5%)	0.086 (0.9%)	-

The bias analysis of the components of 2 inch using probes is presented in Table 12. Four types of probes were used in this analysis. Probes with 5, 7.5 and 10 MHz were used in this experiment. The one of four probes has diameter of 11mm and the others have 7.1mm. In the analysis of component of 2 inch, the bias was influenced highly by probe. The probe of 7.1mm shows more accurate results especially in the elbow and reducer. The probe with 5MHz and 7.1mm shows the most accurate results in the 2 inch components among probes with same diameter.

Table 13: Bias analysis results in 2inches element of probes

Probe type	Pipe (mm)	Elbow (mm)	Tee (mm)	Reducer (mm)
5MHz (11mm)	0.054 (1.4%)	0.251 (6.4%)	0.104 (2.7%)	0.207 (5.3%)
5MHz (7.1mm)	0.017 (0.4%)	0.108 (2.8%)	0.073 (1.9%)	0.085 (2.2%)
7.5MHz (7.1mm)	0.024 (0.6%)	0.121 (3.1%)	0.068 (1.7%)	0.099 (2.5%)
10MHz (7.1mm)	0.035 (0.9%)	0.156 (4.0%)	0.074 (1.9%)	0.072 (1.8%)

In the analysis of components with 8inch diameter, the bias was influenced by probe diameter as shown in Table 13. From these results, as diameter of specimen increases, the importance of probe diameter decreased. Frequency has small influence on bias. The probe with 5MHz and 7.1mm shows the most accurate results in the 8 inch components among all of the probes.

Table 14: Bias analysis results in 8inches element of probes.

Probe type	Pipe (mm)	Elbow (mm)	Tee (mm)	Reducer (mm)
5MHz (11mm)	0.056 (0.7%)	0.070 (0.9%)	0.091 (1.1%)	0.074 (0.9%)
5MHz (7.1mm)	0.048 (0.6%)	0.052 (0.6%)	0.082 (1.0%)	0.081 (1.0%)
7.5MHz (7.1mm)	0.055 (0.7%)	0.056 (0.7%)	0.072 (0.9%)	0.082 (1.0%)
10MHz (7.1mm)	0.050 (0.6%)	0.053 (0.6%)	0.093 (1.1%)	0.089 (1.1%)

5. Conclusion

In this study, RR test was performed to verify expertness of inspectors for thickness measurement of piping system in NPPs. Mock-up and field specimens were prepared for RR test and the data of thickness measurement were obtained by 12 inspectors from 4 companies. Reliability was verified in terms of shape and diameter of pipe and inspectors team by using gage R&R from obtained data. The results were as follows:

(1) Repeatability and reproducibility take charge of 75% and 25% respectively in total variation of measurement system.

(2) The maximum deviation of gage R&R value depending on expertness of team of inspectors is 0.041mm.

(3) The accuracy becomes higher as diameter increases. The most accurate result is shown in straight pipe and result from elbow and reducer with 2inch is worst.

(4) Probe with 5MHz and 7.1mm diameter shows most accurate result in components of 2 and 8inch diameter of pipes.

The results of this study can be used to preparestandard practice for reliable thickness measurement in pipelines of NPPs.

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6. Reference

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