**Original Article**

# Development of Wall-Thinning Evaluation Procedure for Nuclear Power Plant Piping—Part 1: Quantification of Thickness Measurement Deviation

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A R T I C L E  I N F O

A B S T R A C T

Pipe wall thinning by flow-accelerated corrosion and various types of erosion is a significant and costly damage phenomenon in secondary piping systems of nuclear power plants (NPPs). Most NPPs have management programs to ensure pipe integrity due to wall thinning that includes periodic measurements for pipe wall thicknesses using nondestructive evaluation techniques. Numerous measurements using ultrasonic tests (UTs; one of the nondestructive evaluation technologies) have been performed during scheduled outages in NPPs. Using the thickness measurement data, wall thinning rates of each component are determined conservatively according to several evaluation methods developed by the United States Electric Power Research Institute. However, little is known about the conservativeness or reliability of the evaluation methods because of a lack of understanding of the measurement error. In this study, quantitative models for UT thickness measurement deviations of nuclear pipes and fittings were developed as the first step for establishing an optimized thinning evaluation procedure considering measurement error. In order to understand the characteristics of UT thickness measurement errors of nuclear pipes and fittings, round robin test results, which were obtained by previous researchers under laboratory conditions, were analyzed. Then, based on a large dataset of actual plant data from four NPPs, a quantitative model for UT thickness measurement deviation is proposed for plant conditions.

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# 1. Introduction

## 1.1. Pipe wall thinning management in nuclear power plants

The wall thinning of piping and vessels in a pressure boundary induced by flow-accelerated corrosion (FAC) or erosion–corrosion damage has caused many significant plant events over the past three decades [1]. An elbow rupture occurred in the condensate system at the Surry nuclear power plant (NPP) in 1986, and FAC was found to be the cause of its failure [2]. Since then, similar events related to FAC have been reported in the industry. Subsequent to these catastrophic failures, a number of studies were conducted in attempts to mitigate FAC, and several predictive models were developed. Nevertheless, severe wall thinning, leaks, and ruptures still occurred at Pleasant Prairie Power Plant in 1995, Mihama NPP in 2004, and the Iatan fossil power plant in 2007 [3]. In addition to these tragic events, a considerable number of wall thinning events have been reported.

Utilities implemented programs to protect piping against FAC degradations. The Electric Power Research Institute (EPRI) in the United States has issued many documents to help utilities maintain effective wall thinning management programs. NSAC-202L [4] suggested six interrelated key factors for establishing an effective wall thinning management program, and explained the importance of inspection and engineering judgment. Even though their analysis fails to prioritize the occurrences of wall thinning, sudden ruptures and catastrophic accidents can be prevented if adequate inspection and engineering judgment are applied in due process.

Generally, pipes and fittings (tees, elbows, reducers, expanders, etc.) with a nominal size of 2 inches (50.8 mm) or larger are inspected by measuring the wall thickness using the ultrasonic technique (UT) at predefined grids in NPPs. The hundreds of inspections of pipes and fittings are performed during refueling outages, and sometimes they are performed while the plant is running. The measurements are repeated at the same fixed locations after a few outages, if necessary. The acquired data allow the thinning rate to be estimated using several simple engineering formulae. Fig. 1 shows an example of a thickness measurement at the predefined grid, and data evaluation for managing pipe wall thinning.

## 1.2. Difficulties of interpretation of wall thinning using UT measurement data

All measurements are inaccurate to some degree. The application of UT for wall thickness measurement consists of a transducer sending pulses of ultrasonic energy into piping and then measuring the time delay of the returning echo pulse. In the process of inspection, the data can be read inaccurately owing to uncertainty caused by rough surfaces and complex curvature along with the distorted reading caused by nonparallel surfaces.



|  |  | A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U/S EX | 1 | 0,847 | 0,844 | 0,844 | 0,848 | 0,836 | 0,838 | 0,839 | 0,836 | 0,822 | 0,843 | 0,845 | 0,843 |
| | 2 | 0,845 | 0,843 | 0,840 | 0,846 | 0,832 | 0,836 | 0,837 | 0,832 | 0,832 | 0,852 | 0,843 | 0,841 |
| | 3 | 0,831 | 0,829 | 0,824 | 0,842 | 0,833 | 0,843 | 0,843 | 0,820 | 0,825 | 0,840 | 0,824 | 0,823 |
| U/S MAIN | 1 | 0,952 | 0,962 | 0,953 | 0,940 | 0,869 | 0,880 | 0,904 | 0,900 | 0,884 | 0,936 | 0,941 | 0,900 |
| | 2 | 0,976 | 0,962 | 0,961 | 0,946 | 0,882 | 0,891 | 0,914 | 0,905 | 0,888 | 0,947 | 0,977 | 0,977 |
| | 3 | 0,970 | 0,969 | 0,958 | 0,945 | 0,882 | 0,895 | 0,919 | 0,908 | 0,891 | 0,946 | 0,978 | 0,978 |
| | 4 | 0,968 | 0,970 | 0,967 | 0,952 | 0,889 | 0,896 | 0,921 | 0,902 | 0,892 | 0,952 | 0,980 | 0,985 |
| | 5 | 0,966 | 0,952 | 0,971 | 0,950 | 0,889 | 0,898 | 0,928 | 0,904 | 0,898 | 0,959 | 0,983 | 0,990 |
| | 6 | 0,966 | 0,948 | 0,954 | 0,952 | 0,883 | 0,897 | 0,925 | 0,907 | 0,899 | 0,960 | 0,982 | 0,987 |
| | 7 | 0,961 | 0,949 | 0,957 | 0,945 | 0,886 | 0,897 | 0,926 | 0,912 | 0,900 | 0,961 | 0,976 | 0,971 |
| | 8 | 0,952 | 0,948 | 0,953 | 0,949 | 0,886 | 0,895 | 0,927 | 0,905 | 0,895 | 0,956 | 0,971 | 0,970 |
| | 9 | 0,939 | 0,942 | 0,951 | 0,936 | 0,885 | 0,892 | 0,924 | 0,909 | 0,898 | 0,958 | 0,975 | 0,971 |
| | 10 | 0,939 | 0,934 | 0,948 | 0,903 | 0,878 | 0,886 | 0,929 | 0,911 | 0,903 | 0,957 | 0,973 | 0,966 |
| | 11 | 0,930 | 0,928 | 0,953 | 0,935 | 0,877 | 0,895 | 0,933 | 0,918 | 0,908 | 0,961 | 0,975 | 0,958 |
| | 12 | 0,939 | 0,931 | 0,952 | 0,945 | 0,878 | 0,894 | 0,938 | 0,922 | 0,909 | 0,961 | 0,975 | 0,951 |

Fig. 1 – Wall thickness measurement and evaluation examples for managing secondary system pipe wall thinning at nuclear power plants.

The classic concept of measurement error (i.e., bias plus random noise) can have a significant impact on the estimated results. According to an EPRI report [15], the uncertainty in a UT thickness measurement may be in the range of 5% of the thickness. Ultrasonic probes are highly dependent on the specimen's geometry and surface conditions, resulting in a loss of signal in certain areas. The UT signal may be refracted away from the sensor by an irregular surface. For the pre-defined fixed grid approach, the coverage error is always present and is directly dependent on the grid resolution [14].

The EPRI suggests several methods, such as the blanket method, band method, and Point to Point method, for determining wall thinning rates using measured data [5−13]. These methods are based on conservatism because of difficulties in interpretation of wall thinning. If sufficient reliability of the measured data is ensured, it is possible to determine the reliable wall thinning rate in a very simple way. However, the amount of degradation being measured is often relatively small compared to that of measurement error. The error can result in a substantial overstatement of the wall thinning, and it can possibly lead to mistakes in interpretation of proper wall thinning. Because the interpretation methods always yield conservative results, large unnecessary costs are incurred. Therefore, more accurate evaluation procedures are required in order to rule out the effect of measurement error.

### 1.3. Scope of the study

We plan to develop an optimized wall thinning evaluation procedure considering the thickness measurement errors. Although the EPRI has developed a variety of evaluation methods to determine wall thinning rates and presence of wall thinning using thickness measurement data, the reliability or conservativeness of their evaluation methods has not been estimated quantitatively. Also, the thickness measurement error is expected to vary depending on the type of components, measurement position, pipe diameter, wall thickness, etc. At present, such characteristics are not well known. In order to develop more reliable evaluation methods for wall thinning, evaluation must be improved considering the difficulties of interpretation.

First, a quantitative error model is developed for the thickness measurement data of pipes and fittings in an NPP. Round robin test results under laboratory conditions conducted in previous research are analyzed, and measurement error characteristics are quantified depending on the pipe diameter. However, the measurement error under plant conditions can be larger than that under laboratory conditions. In this paper, a methodology for quantifying measurement errors under actual plant conditions is developed, and then the methodology is applied to thickness measurement data from four NPPs in Korea. Based on the analysis results of measurement data under both laboratory and plant conditions, a best-estimated and an upper bound curve for the thickness measurement error of elbows are developed. These results will subsequently be used for the improvement and optimization of wall thinning evaluation method for NPPs.

## 2. Thickness measurement deviation under laboratory conditions

As a part of a comprehensive study of pipe wall thinning conducted by the Korea Electric Power Research Institute, Yi et al [16,17] and Kim et al [18] performed a round robin study to understand the UT measurement error for carbon steel pipes and fittings. In this section, we describe a developed

| Table 1 − Information on specimens for round robin thickness measurement tests. | | | | | | |
|---|---|---|---|---|---|---|
| Specimen origin | Outside diameter | Nominal wall thickness | Type | No. of specimens | No. of flaws | No. of grids |
| Machined flaws from laboratory | 2.4 inch (60.3 mm) | 0.154 inch (3.91 mm) | Straight | 1 | 7 | 96 |
| | | | Elbow | 1 | 2 | 42 |
| | | | Tee | 1 | 3 | 33 |
| | | | Reducer | 1 | 2 | 18 |
| | 4.5 inch (114.3 mm) | 0.237 inch (6.02 mm) | Straight | 1 | 7 | 144 |
| | | | Elbow | 1 | 2 | 110 |
| | | | Tee | 1 | 3 | 77 |
| | | | Reducer | 1 | 2 | 30 |
| | 6.6 inch (168.3 mm) | 0.280 inch (7.11 mm) | Straight | 1 | 7 | 120 |
| | | | Elbow | 1 | 2 | 110 |
| | | | Tee | 1 | 3 | 77 |
| | | | Reducer | 1 | 2 | 30 |
| | 8.6 inch (219.1 mm) | 0.322 inch (8.18 mm) | Straight | 1 | 7 | 144 |
| | | | Elbow | 1 | 2 | 110 |
| | | | Tee | 1 | 3 | 77 |
| | | | Reducer | 1 | 2 | 30 |
| | 12.8 inch (323.9 mm) | 0.375 inch (9.52 mm) | Straight | 1 | 7 | 132 |
| | | | Elbow | 1 | 2 | 110 |
| | | | Tee | 1 | 3 | 77 |
| Thinned at plant | 4.0 inch (101.6 mm) | 0.216 inch (5.49 mm) | Elbow | 1 | Natural | 216 |
| | | | Tee | 1 | Natural | 156 |
| | 16 inch (406.4 mm) | 0.500 inch (12.7 mm) | Elbow | 1 | Natural | 144 |
| | | 1.219 inch (30.96 mm) | Reducer | 1 | Natural | 48 |
| Total | | | | 23 | | 2,131 |

quantified model for the UT thickness measurement error of pipes and fittings based on the results of a previous round robin study. Table 1 shows the specimen data used in the round robin study.

### 2.1. Characteristics of round robin data

In the round robin study, 19 specimens (5 pipes and 14 fittings) were fabricated using the materials of ASTM (American Society for Testing and Materials) A106 Gr. B and A234 Gr. WPB for pipes and fittings, respectively, which included an artificially fabricated thinned area at their inner surfaces. Four additional specimens obtained from NPPs were used in the round robin. During the round robin study, a total of 2,131 measurements were conducted under laboratory conditions. Tests were performed according to the standard work procedure for Korean NPPs, which was based on a related EPRI report [4]. The tests were conducted by the inspectors currently implementing UT measurements with the equipment currently used in NPPs. The 12 inspectors participating in this round robin test held American Society for Nondestructive Testing UT level I or II qualifications from three different organizations.

It was expected that the thickness measurement error increases as the pipe outside diameter decreases, because the increase in surface curvature makes the contact with the UT measuring probe rather unstable. Also, an increase in surface curvature can increase the uncertainty of the contact angle of the probe. In Fig. 2A, the standard deviation of thickness measurement determined by the round robin test is plotted with respect to the outside diameters of pipes and fittings. Although the deviation for fittings is greater than that for pipes, only a slight trend is shown between the standard deviation of the thickness measurement and the outside diameter. In particular, one data point (the arrow mark in Fig. 2A) is far away from other data: the thickness/diameter ratio is much higher than that of the other data.

In order to understand the characteristics of the measurement deviation, a normalized deviation (the deviation divided by its nominal thickness) is plotted with the outside diameters of pipes and fittings in Fig. 2B. In this case, the normalized deviation increases consistently as the outside diameter decreases. In particular, one data point, which is far away from other data, goes along the overall trend as depicted by the arrow mark in Fig. 2B. Considering the characteristics of the round robin data shown in Fig. 2, we conclude that the thickness measurement error can be expressed as the normalized deviation in order to quantify the thickness measurement error of pipes and fittings in NPPs.

### 2.2. Quantification of UT thickness measurement deviation

As discussed in Section 2.1, the thickness measurement deviation can be expressed with respect to the relationship between the normalized deviation and the outside diameter of pipes or fittings. A power and an exponential function were considered as a representative functional equation for the
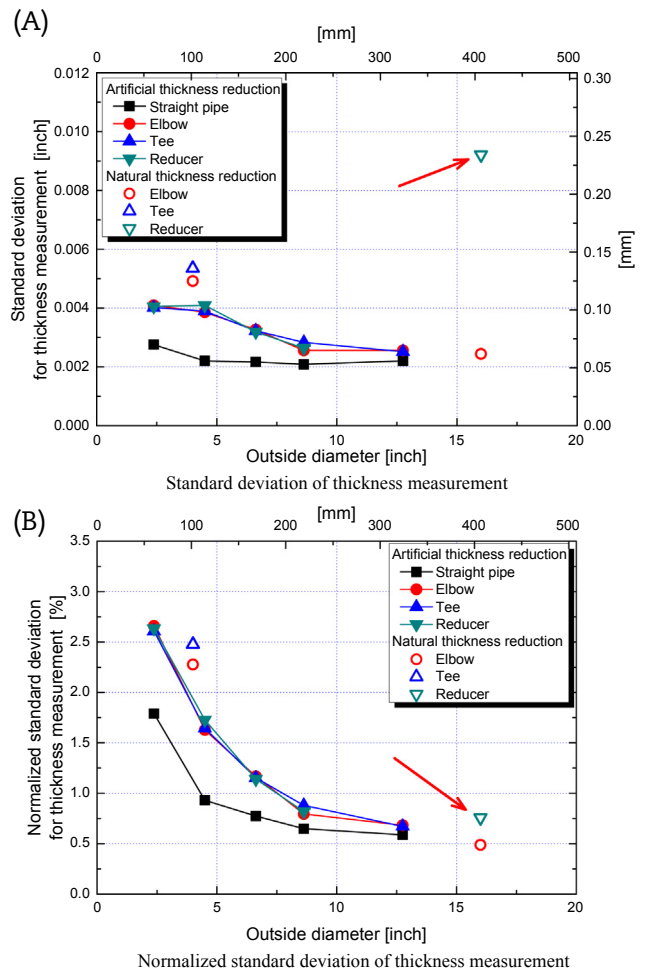


Fig. 2 − Thickness measurement deviation characteristics from the results of UT measurement round robin tests under laboratory conditions. UT, ultrasonic test.
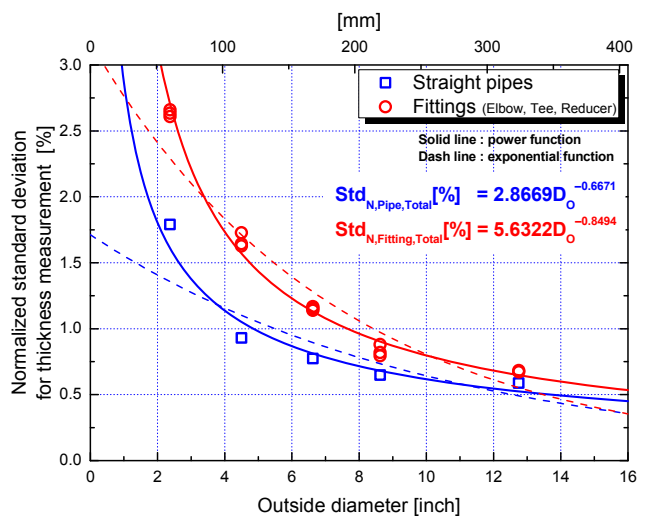


Fig. 3 − Curve fitting results for quantitative measurement deviation including both thinned and not-thinned location data under laboratory conditions.

characteristics shown in Fig. 2B. The curve fitting results of each function are shown in Fig. 3, in which the goodness of fit for the power function is better than the exponential function. Therefore, the thickness measurement deviation can be expressed as follows:

$$\begin{aligned}\frac{\text{Std}_{\text{Pipe,Total}}}{t_{\text{n}}} &= 0.02867 D_{\text{o}}^{-0.6671}, \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= 0.24808 D_{\text{o}}^{-0.6671}, \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{\text{Std}_{\text{Fitting,Total}}}{t_{\text{n}}} &= 0.05632 D_{\text{o}}^{-0.8494}, \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= 0.87888 D_{\text{o}}^{-0.8494}, \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned}$$

where $\text{Std}_{\text{Pipe,Total}}$ and $\text{Std}_{\text{Fitting,Total}}$ are the standard deviation for the thickness measurements of pipes and fittings, respectively, including both thinned and not-thinned locations. $t_{\text{n}}$ and $D_{\text{o}}$ are the nominal thickness and outside diameter of pipes and fittings, respectively.

The standard deviations shown in Figs. 2 and 3 and Eq. (1) are averaged values at both thinned and not-thinned locations of pipes and fittings. However, the round robin study results show that the thickness measurement deviations at thinned locations are higher than those at not-thinned locations. In consideration of these characteristics, the deviations have to be divided into groups of the thinned and not-thinned locations.

In order to find any kind of consistency in the measurement's deviation at thinned and not-thinned locations, various formulations were explored. However, no clear consistency was found. Among the explored results, the best formulation result is shown in Fig. 4. The curve fitting was conducted using a linear and an exponential function, and the goodness of fit for the exponential function is better than that of the linear function. The thickness measurement deviation at thinned and not-thinned locations can be expressed, respectively, as follows:
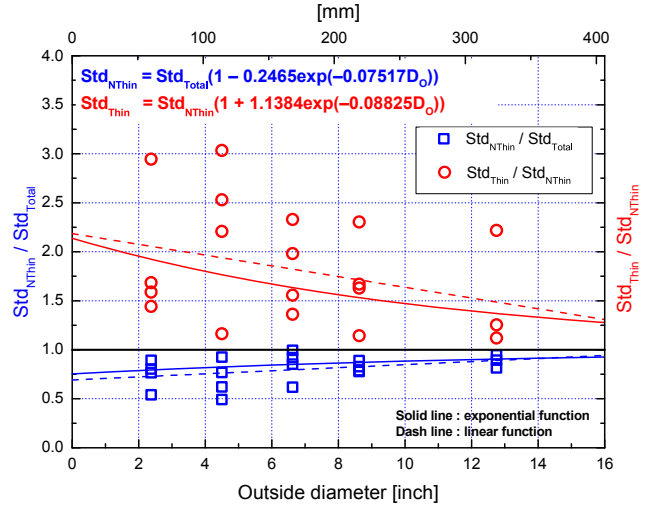


**Fig. 4 – Curve fitting results for difference of measurement deviation between thinned and not-thinned location.**

$$\begin{aligned}\frac{\text{Std}_{\text{NThin}}}{\text{Std}_{\text{Total}}} &= 1 - 0.2465\exp(-0.07517 D_{\text{o}}), \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= 1 - 0.2465\exp(-0.002959 D_{\text{o}}), \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned}$$

$$\begin{aligned}\frac{\text{Std}_{\text{Thin}}}{\text{Std}_{\text{NThin}}} &= 1 + 1.1384\exp(-0.08825 D_{\text{o}}), \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= 1 + 1.1384\exp(-0.003474 D_{\text{o}}), \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned} \tag{2}$$

where $\text{Std}_{\text{Thin}}$ and $\text{Std}_{\text{NThin}}$ are standard deviations for the thickness measurement of pipes and fittings at thinned and not-thinned locations, respectively, and $\text{Std}_{\text{Total}}$ is the standard deviation for the thickness measurement of pipes and fittings including both thinned and not-thinned locations.

By combining Eqs. (1) and (2), the thickness measurement deviation at thinned and not-thinned locations can be expressed as follows:

$$\begin{aligned}\frac{\text{Std}_{\text{Pipe,NThin}}}{t_n} &= 0.02867 D_{\text{o}}^{-0.6671}(1 - 0.2465\exp(-0.07517 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= 0.24808 D_{\text{o}}^{-0.6671}(1 - 0.2465\exp(-0.002959 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned}$$

$$\begin{aligned}\frac{\text{Std}_{\text{Pipe,Thin}}}{t_n} &= \frac{\text{Std}_{\text{Pipe,NThin}}}{t_n}(1 + 1.1384\exp(-0.08825 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= \frac{\text{Std}_{\text{Pipe,NThin}}}{t_n}(1 + 1.1384\exp(-0.003474 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned}$$

$$\begin{aligned}\frac{\text{Std}_{\text{Fitting,NThin}}}{t_n} &= 0.05632 D_{\text{o}}^{-0.8494}(1 - 0.2465\exp(-0.07517 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= 0.87888 D_{\text{o}}^{-0.8494}(1 - 0.2465\exp(-0.002959 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned}$$

$$\begin{aligned}\frac{\text{Std}_{\text{Fitting,Thin}}}{t_n} &= \frac{\text{Std}_{\text{Fitting,NThin}}}{t_n}(1 + 1.1384\exp(-0.08825 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{inch}] \\ &= \frac{\text{Std}_{\text{Fitting,NThin}}}{t_n}(1 + 1.1384\exp(-0.003474 D_{\text{o}})), \quad \text{where } D_{\text{o}}[\text{mm}]\end{aligned} \tag{3}$$
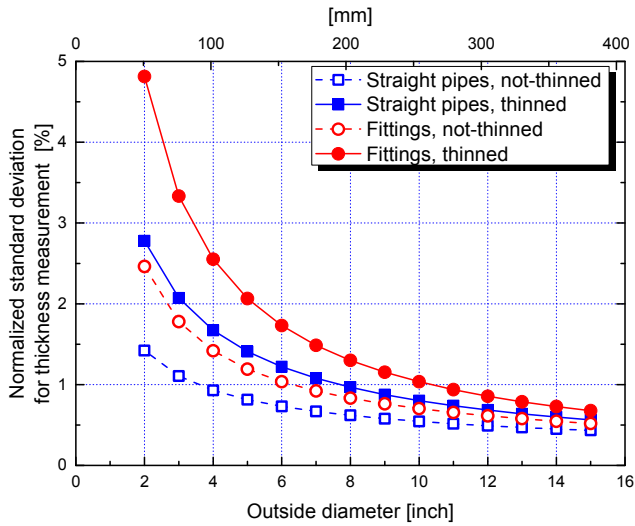
Fig. 5 – Developed quantification models for ultrasonic thickness measurement deviation of carbon steel pipes and fittings based on round robin test results under laboratory conditions.

where $Std_{Pipe,Thin}$ and $Std_{Pipe,NThin}$ are the standard deviations for the thickness measurements of pipes at thinned and not-thinned locations, respectively. $Std_{Fitting,Thin}$ and $Std_{Fitting,NThin}$ are the standard deviations for thickness measurements of fittings at thinned and not-thinned locations, respectively.

The thickness measurement deviation described by Eq. (3) is shown graphically in Fig. 5. The normalized standard deviations of 8-inch fittings are about 0.8% and 1.3% at the not-thinned locations and thinned locations, respectively. Even if a 95% upper bound value for the measurement deviation ($Z = 1.645$) is considered, the uncertainties for the measurement of 8-inch fitting are 1.3% and 2.0% at the not-thinned locations and thinned locations, respectively. These values are much lower than 5% of uncertainty, which is set forth by the EPRI report [15] based on field experiences. We expect that the difference between the estimated measurement deviation and the field experience (EPRI) is due to the difference between the round robin study under laboratory conditions and the field experience under plant conditions.

| Table 2 – Monte Carlo simulation input variables used to understand the characteristics of measurement deviation evaluation formula. | |
|---|---|
| Input variables | Values |
| True thickness ($t_{true}$) | 1 inch (25.4 mm) |
| Measurement standard deviation | 0.01 inch (0.254 mm) = 1% of $t_{true}$ |
| Thinning rate | 0.00 in/yr (0.00 mm/yr) 0.01 in/yr (0.254 mm/yr) |
| Number of measurements ($K$) | 3, 4, 5, and 6 times |
| Timing of measurements (time$_k$)*    Equal intervals | 0/1/2 yr, 0/2/4 yr |
|    Unequal intervals | 0/0.5/2 yr, 0/0.25/2 yr |
| * In the case of $K = 3$. | |

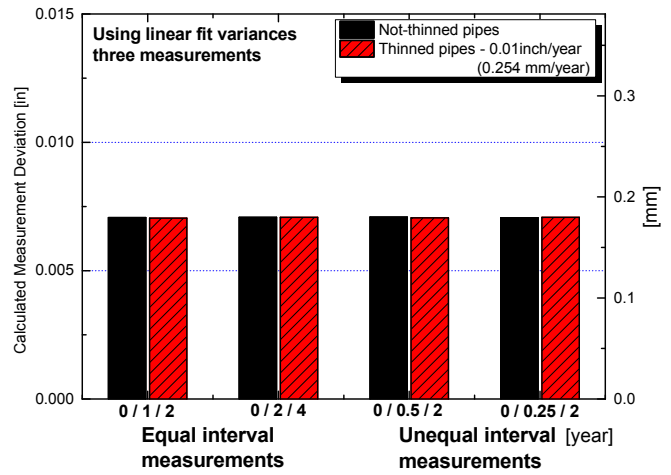

Fig. 6 – Effects of measurement intervals and thinning rates on the calculation of measurement deviation using linear fit variances.



(A)

$$Var_{LinearFit} / Var_{true}$$

(B)

$$\frac{Var_{LinearFit}}{Var_{True}} = \frac{K-2}{K-1}$$

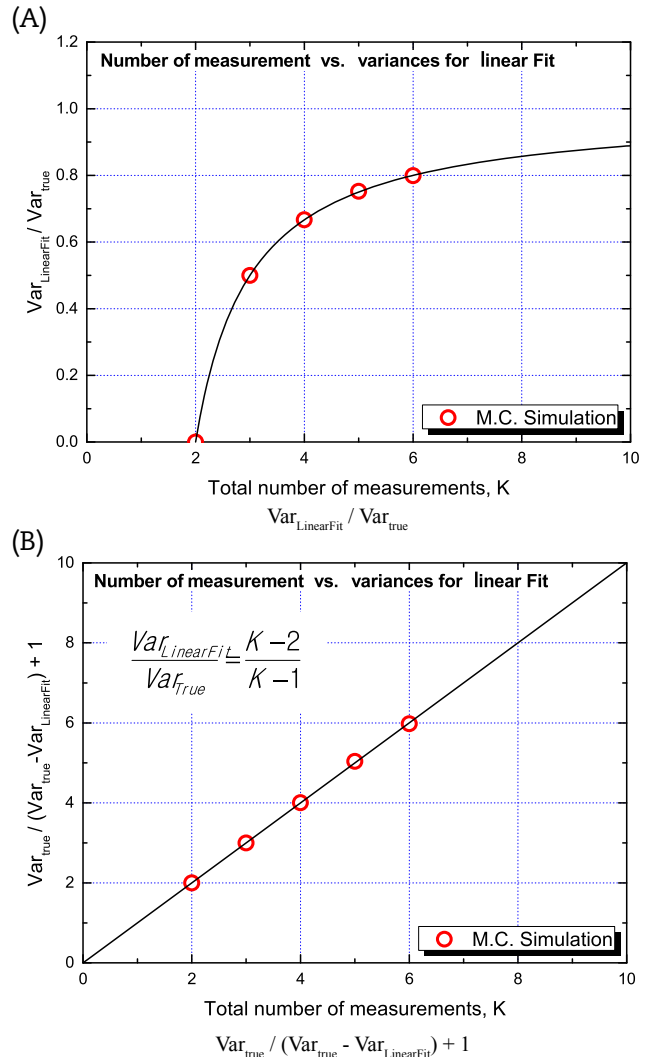$$Var_{true} / (Var_{true} - Var_{LinearFit}) + 1$$

Fig. 7 – Effect of total number of measurements ($K$) on calculating measurement deviations using linear fit variances.

**Table 3 – Thickness measurement data summary for measurement deviation quantification.**

| Elbow size | | | | Unit 1 | | Unit 2 | | Unit 3 | | Unit 4 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Outside Diameter | | Nominal Thickness | | No. of comp. | No. of meas. | No. of comp. | No. of meas. | No. of comp. | No. of meas. | No. of comp. | No. of meas. |
| (inch) | (mm) | (inch) | (mm) | | | | | | | | |
| 3.500 | 88.9 | 0.216 | 5.49 | – | – | – | – | 2 | 6 | – | – |
| | | 0.300 | 7.62 | 5 | 20 | – | – | – | – | – | – |
| 4.500 | 114.3 | 0.237 | 6.02 | 1 | 3 | 1 | 3 | 3 | 9 | 4 | 12 |
| 6.625 | 168.3 | 0.280 | 7.11 | – | – | – | – | 1 | 3 | – | – |
| | | 0.432 | 10.97 | – | – | 1 | 3 | – | – | 1 | 3 |
| | | 0.562 | 14.28 | – | – | – | – | 4 | 16 | 3 | 10 |
| 8.625 | 219.1 | 0.322 | 8.18 | 1 | 3 | 1 | 3 | – | – | 1 | 3 |
| 10.75 | 273.1 | 0.365 | 9.27 | – | – | – | – | 1 | 3 | – | – |
| | | 0.500 | 12.70 | – | – | – | – | 3 | 10 | 2 | 6 |
| | | 0.844 | 21.44 | 1 | 4 | 1 | 5 | – | – | – | – |
| 12.75 | 323.9 | 0.330 | 8.38 | – | – | – | – | – | – | 2 | 6 |
| | | 0.406 | 10.31 | 1 | 3 | 2 | 6 | – | – | – | – |
| | | 0.500 | 12.70 | – | – | – | – | 1 | 5 | – | – |
| | | 0.844 | 21.44 | 1 | 3 | 2 | 6 | – | – | – | – |
| 16 | 406.4 | 0.375 | 9.53 | – | – | 3 | 11 | 3 | 13 | 1 | 5 |
| | | 0.500 | 12.70 | 3 | 9 | 3 | 10 | 1 | 5 | 1 | 4 |
| | | 0.844 | 21.44 | 1 | 3 | – | – | 5 | 16 | – | – |
| | | 1.219 | 30.96 | – | – | – | – | 5 | 18 | 6 | 21 |
| 18 | 457.2 | 0.375 | 9.53 | – | – | 1 | 3 | – | – | – | – |
| | | 0.500 | 12.70 | 1 | 3 | 1 | 3 | – | – | – | – |
| | | 0.562 | 14.27 | 2 | 6 | 2 | 6 | – | – | – | – |
| | | 0.938 | 23.83 | 1 | 3 | 2 | 6 | – | – | – | – |
| | | 1.375 | 34.93 | 6 | 19 | 5 | 16 | – | – | – | – |
| 20 | 508.0 | 0.562 | 14.27 | – | – | – | – | – | – | 3 | 9 |
| | | 0.594 | 15.09 | 2 | 6 | 1 | 4 | – | – | – | – |
| | | 1.500 | 38.10 | 4 | 15 | 2 | 10 | – | – | – | – |
| 24 | 609.6 | 0.375 | 9.53 | – | – | – | – | 1 | 4 | 1 | 4 |
| | | 0.625 | 15.88 | – | – | – | – | 3 | 10 | – | – |
| | | 0.688 | 17.48 | 2 | 7 | 1 | 3 | – | – | – | – |
| | | 1.562 | 39.67 | – | – | – | – | 28 | 111 | 20 | 78 |
| 26 | 660.4 | 1.000 | 25.40 | – | – | 1 | 3 | 1 | 3 | – | – |
| 28 | 711.2 | 0.500 | 12.70 | 2 | 6 | 2 | 7 | – | – | – | – |
| 30 | 762.0 | 0.375 | 9.53 | 1 | 3 | – | – | – | – | – | – |
| | | 1.640 | 41.66 | 1 | 3 | 1 | 4 | – | – | – | – |
| 32 | 812.8 | 1.188 | 30.18 | – | – | – | – | 1 | 3 | – | – |
| | | 1.320 | 33.53 | – | – | 1 | 4 | – | – | – | – |
| | | 1.325 | 33.66 | – | – | 1 | 4 | – | – | – | – |
| | | 1.338 | 33.99 | – | – | – | – | 1 | 3 | 2 | 6 |
| | | 2.000 | 50.80 | – | – | – | – | 1 | 4 | – | – |
| Subtotal | | | | 36 | 119 | 35 | 120 | 65 | 242 | 47 | 167 |
| Total | | No. of comp. | | | | | | 183 | | | |
| | | No. of meas. | | | | | | 648 | | | |

comp., components; meas., measurements.

## 3. Thickness measurement deviation under plant conditions

In this section, we consider the thickness measurement deviation under plant conditions. As previously mentioned, the estimated measurement deviation is much lower than the value from EPRI field experience. Therefore, an estimation of deviations from the measured data under plant conditions is needed. When actual plant measurement data are used for determining measurement deviations, the true values of wall thickness must be determined at all grid locations. However, the true values are unknown for the actual plant data, and the number of repeated measurements at the same location is limited. Also, differences in the repeated measurement data are affected by wall thinning during the repeated measurement interval.

Accordingly, a methodology for quantifying the measurement deviation was developed using limited measurement data in NPPs. The thickness measurement deviations under plant conditions were quantified by applying the proposed method to four NPPs in Korea. In order to eliminate the added complexity of various kinds of fittings, only an elbow component was considered in this evaluation.
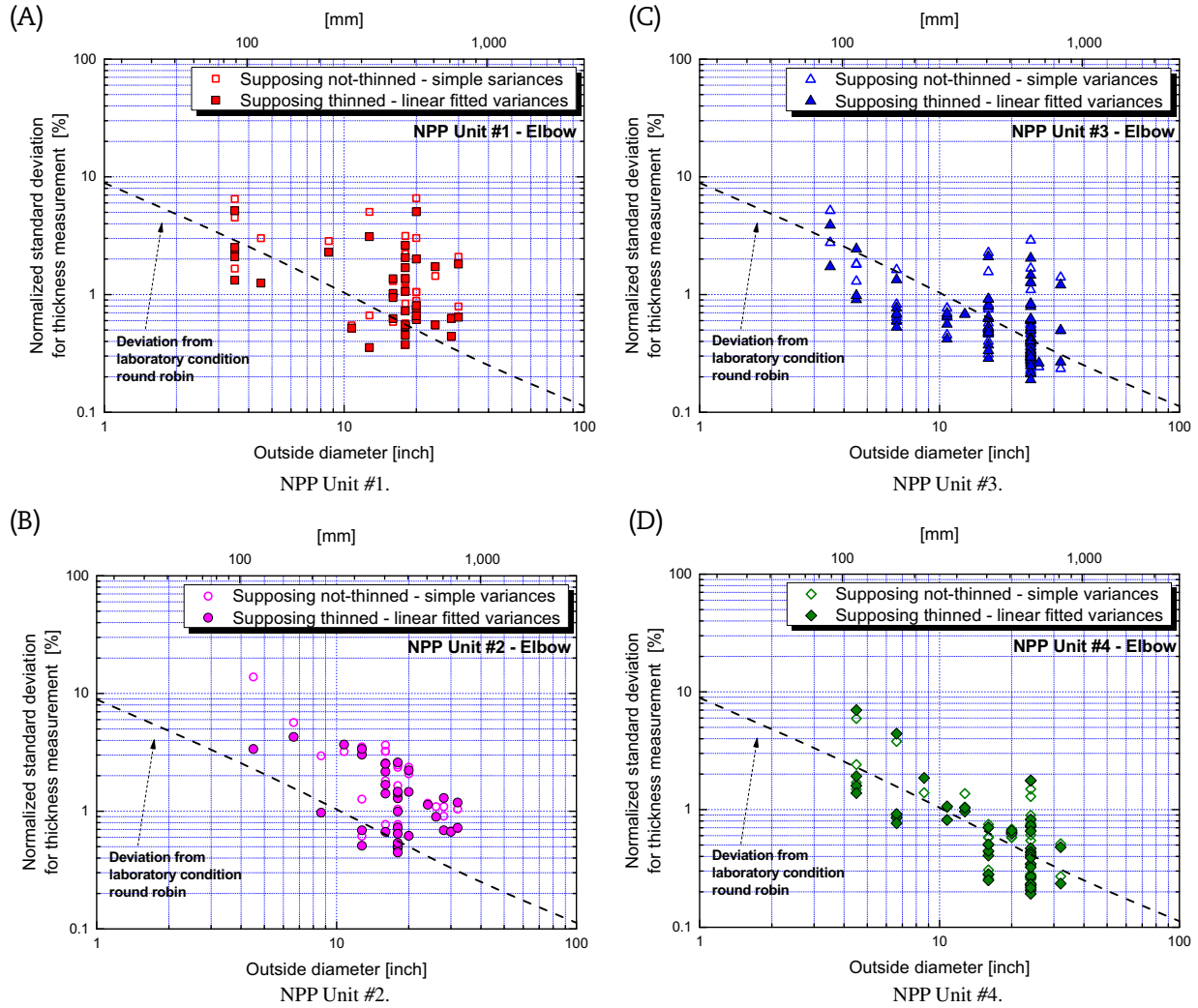
**Fig. 8 − Thickness measurement deviations from the data measured at four NPPs under plant conditions. NPPs, nuclear power plants.**

Considering the measurement deviation characteristics of the various fittings shown in Figs. 2 and 3, we expect that the measurement deviation of the elbow is similar to those of other kinds of fittings (tee, reducer, etc.).

### 3.1. Development of methodology for deviation prediction using plant data

In the case of measurement experiences in Korean NPPs, there are tens of elbow components that were measured three to six times repeatedly, and that have more than 50 measurement locations at their grids (consisting of $i$ columns and $j$ rows). Although three to six samples are insufficient to estimate reliable sample deviations, the average of more than 50 sample deviations of these can represent the characteristics of the population. Measurement deviations can be calculated at each measurement location of a component if the measurements are repeated twice or more during a few decades.

If it is assumed that the thickness has not decreased during repeated measurement interval, the measurement deviations at each location can be calculated by using Eq. (4):

$$\text{Std}_{\text{NThin},ij}^2 = \text{Var}_{\text{NThin},ij}(t_{ijk}) = \frac{\sum_{k=1}^{K}\left(t_{ijk} - t_{\text{Av},ij}\right)^2}{K-1},$$

$$t_{\text{Av},ij} = \frac{\sum_{k=1}^{K}\left(t_{ijk}\right)}{K}, \tag{4}$$

where $\text{Std}_{\text{NThin},ij}$ and $\text{Var}_{\text{NThin},ij}$ are the thickness measurement deviations and variances at the grid location $(i,j)$ (assuming that thinning does not occur), respectively. $i$ and $j$ are the column and row numbers of a grid. $k$ is the number of repeated measurements. $t_{ijk}$ and $t_{\text{Av},ij}$ are measured thickness values at the $k$th time and the time-averaged measured thickness at grid location $(i,j)$, respectively. $K$ represents the total number of repeated measurements.

As previously mentioned, the determined sample deviations from Eq. (4) using 3–5 data at one grid location cannot have enough reliability for the representative values for the population deviation. Therefore, a reliable value for thickness

measurement deviations can be determined by averaging values at all grid locations of a component. Because the average value for standard deviations must be calculated from averaging variances [19], the thickness measurement deviation of a component is calculated as follows:

$$\mathrm{Std}^2_{\mathrm{NThin}} = \mathrm{Var}_{\mathrm{NThin}} = \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} \left(\mathrm{Var}_{\mathrm{NThin},ij}\left(t_{ijk}\right)\right)}{IJ}, \quad (5)$$

where $\mathrm{Std}_{\mathrm{NThin}}$ and $\mathrm{Var}_{\mathrm{NThin}}$ are standard deviations and variances for thickness measurements of a component (assuming that thinning does not occur), respectively, and $I$ and $J$ denote the total number of grid columns and grid rows, respectively.

Eqs. (4) and (5) were derived by assuming that the wall thickness does not decrease during repeated measurements. If wall thinning occurs during that period, the standard deviation [using Eq. (4)] is larger than the true value of the standard deviation for the thickness measurement by the amount of wall thinning.

In order to consider wall thinning during measurement periods, thinning rates should be determined in each measurement location. If the thinning rate in each location is assumed to be a constant value during the period, the thinning rate can be estimated through a linear fitting of the measured data. Regarding the result of the linear fitting as the true value of thickness at that measurement time, Eq. (6) substitutes for Eq. (4) in calculating the standard deviation (or variance) for the thickness measurement at each measurement location:

$$\mathrm{Var}_{\mathrm{Thin},ij}\left(t_{ijk}\right) = \frac{\sum_{k=1}^{K} \left(t_{ijk} - t_{\mathrm{LF},ijk}\right)^2}{K - 1}, \quad t_{\mathrm{LF},ijk} = a_{ij}\mathrm{time}_k + b_{ij}, \quad (6)$$

where $\mathrm{Var}_{\mathrm{Thin},ij}$ are measurement variances at the grid location $(i,j)$, assuming a constant thinning rate; $t_{\mathrm{LF},ijk}$ is the determined thickness from a linear fitting of measured data at grid location $(i,j)$ at the $k$th measurement time; $a_{ij}$ and $b_{ij}$ are the linear fitting constants for the measured data at grid location $(i,j)$; and $\mathrm{time}_k$ is the $k$th measurement time.

Simple Monte Carlo simulations were performed in order to check the reliability of Eq. (6). In the simulations, true values of measurement deviations and wall thicknesses were assumed, and random values for measurement data were generated. The sample deviations were calculated using Eq. (6) and compared with the true value of measurement deviations assumed previously. Simulation cases are shown in Table 2. The effect of measurement time intervals on the calculation results based on Eq. (6) was evaluated. Calculated sample deviations for various kinds of time intervals are shown in Fig. 6. As shown in the figure, the time interval does not affect the sample deviation in the cases of equal and unequal intervals of repeated measurement times. However, the calculated sample deviation, 0.007 inch (0.178 mm), is much lower than the true value of the standard deviation, 0.01 inch (0.254 mm).

The effect of the number of repeated measurements on calculated sample deviations was estimated using Monte Carlo simulations. As shown in Fig. 7A, the sample deviation increases as the measurement time increases, even for the same true value of the measurement deviation. By

examining the characteristics of sample deviations, we confirmed that a degree of freedom $(K - 1)$ used in Eq. (6) must be replaced with $(K - 2)$. When the degree of freedom in Eq. (6) is changed to $(K - 2)$, the calculated sample deviations agree well with the true value, as shown in Fig. 7B. This means that the number of degrees of freedom was reduced by the linear fitting. Therefore, Eq. (6) must be modified as follows:

$$\mathrm{Var}_{\mathrm{Thin},ij}\left(t_{ijk}\right) = \frac{\sum_{k=1}^{K} \left(t_{ijk} - t_{\mathrm{LF},ijk}\right)^2}{K - 2}, \quad t_{\mathrm{LF},ijk} = a_{ij}\mathrm{time}_k + b_{ij}, \quad (7)$$

By averaging the sample variance of thickness measurements for all measurement locations of grids, the thickness measurement deviation of a component can be calculated as follows:

$$\mathrm{Std}^2_{\mathrm{Thin}} = \mathrm{Var}_{\mathrm{Thin}} = \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} \left(\mathrm{Var}_{\mathrm{Thin},ij}\left(t_{ijk}\right)\right)}{IJ} \quad (8)$$
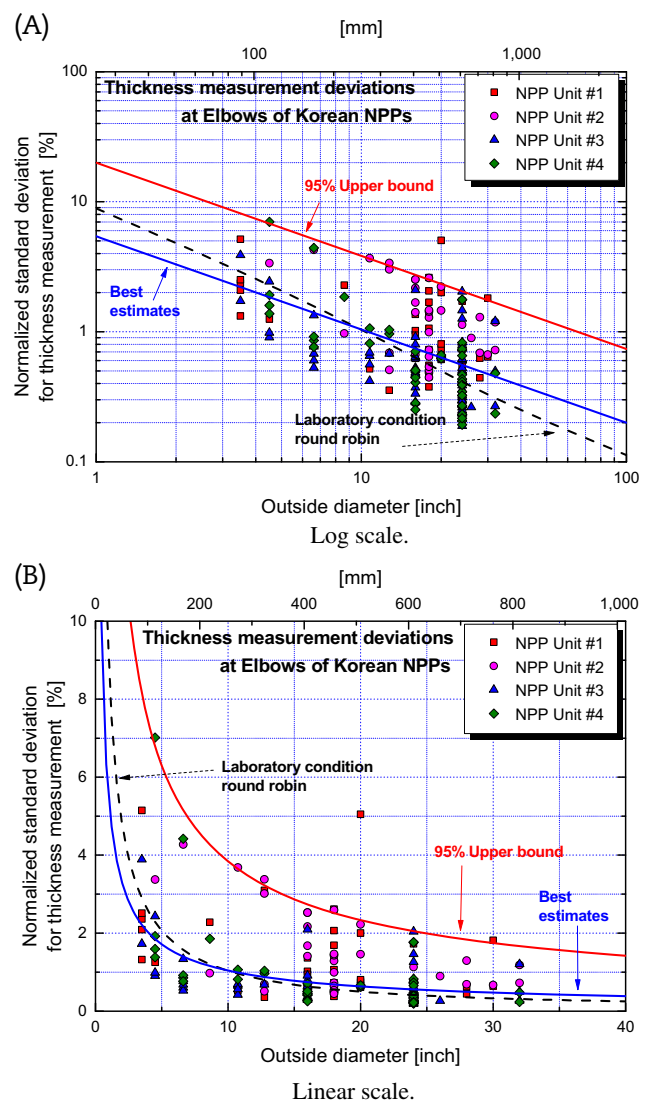


Fig. 9 – Developed quantification models for ultrasonic thickness measurement deviation of carbon steel fittings based on the data measured at four NPPs under plant conditions. NPPs, nuclear power plants.

In summary, an evaluation equation for thickness measurement deviation using three or more repeated measurement datasets was developed with an unknown true thickness and thinning rate during the measurement period. Using Eqs. (4) and (5), the upper bound of measurement deviations can be calculated when the thickness reduction during the measurement period is ignored. Using Eqs. (7) and (8), the best estimated value of measurement deviations can be calculated in which the thinning rate during the measurement period is supposed to be constant.

### 3.2.  Quantification of thickness measurement deviation in Korean NPPs

By applying thickness measurement data at four NPPs in Korea to Eqs. (4), (5), (7), and (8), the thickness measure-

ment deviations were quantified under plant conditions. As summarized in Table 3, measurement data from 183 elbow components were used. In many cases, the thickness measurement data at the counter bore region (both ends of an elbow) has more measurement deviations than those at the body region of an elbow because of additional fabrication for welding. In order to eliminate this effect, only data from the body region were used in this analysis.

The standard deviations for four NPPs are shown in Figs. 8A−8D, compared with the measurement deviation, $Std_{Fitting,Thin}$ in Eq. (3), which is the measurement deviation model under laboratory conditions. In Fig. 8, "simple variance" means the results of Eqs. (4) and (5), and "linear fitted variance" means the results of Eqs. (7) and (8). As shown in the figure, the thickness measurement deviation under plant conditions was increased as the elbow diameter was decreased, although there is a slight difference among them. Additionally, the deviation data under the plant conditions are distributed around the deviation line under laboratory conditions.

The best estimated values [Eqs. (7) and (8)] for standard deviations using measured data from four NPPs are shown in Fig. 9, and the curve fitting results for a power function is compared with the results from laboratory conditions [$Std_{Fitting,Thin}$ in Eq. (3)]. As shown in the figure, the best estimated deviations under plant conditions are in good agreement with those under laboratory conditions. However, the deviations under plant conditions at each component are widely distributed. This means that the average of the thickness measurement deviation under plant conditions is not significantly higher than that under

laboratory conditions, whereas there are several components having significantly higher deviations under plant conditions.

We expect that the variations in thickness measurement deviations shown in Fig. 9 are attributable to the variations in surface roughness, complex curvatures, nonparallel surfaces, etc., of components. Considering this kind of variation, an upper bound prediction line (a 95% reliability level) for thickness measurement deviation was constructed as shown in Fig. 9.

Eq. (9) is the expression for the best estimates of normalized standard deviation, and Eq. (10) is for an upper bound prediction line.

$$\frac{Std_{Elbow,Plant,Mean}}{t_n} = 0.05429 D_o^{-0.7172}, \quad \text{where } D_o[\text{inch}]$$
$$= 0.55242 D_o^{-0.7172}, \quad \text{where } D_o[\text{mm}] \tag{9}$$

$$\frac{Std_{Elbow,Plant,95\%UB}}{t_n} = \exp\left(-2.9135 + 1.301\sqrt{\frac{\ln D_o}{1{,}464} + 1.004}\right) D_o^{-0.7172}, \quad \text{where } D_o[\text{inch}]$$

$$= \exp\left(-0.68047 + 3.018\sqrt{\frac{\ln D_o - 3.2347}{1{,}464} + 1.004}\right) D_o^{-0.7172}, \quad \text{where } D_o[\text{mm}] \tag{10}$$

From a conservative point of view, the standard deviation of the thickness measurement is about 2% to 6% of the nominal thickness for 5- to 25-inch (127−635 mm) diameter elbows, which are consistent values with respect to the EPRI experience as presented in their report (1987). The thickness measurement deviation model described by Eqs. (9) and (10) and the methodology for determining measurement deviation using plant data are very helpful to study thinning assessment procedures and their statistical reliabilities.

## 4.  Conclusion

As the first step in understanding thinning assessment procedures and their reliabilities, quantitative models for UT thickness measurement deviations of NPP pipes and fittings were developed in this study. Our conclusions are as follows:

(1) By analyzing the results of round robin studies performed under laboratory conditions by previous researchers, we confirmed that the normalized deviation (the deviation divided by the nominal thickness) increased consistently as the outside diameter of pipes and fittings decreased.
(2) A methodology was developed to estimate thickness measurement deviations of pipes and fittings using measurement data at NPPs when the true value of the wall thickness was unknown.

(3) Through analyzing the thickness measurement data of elbows from four NPPs, quantitative models for thickness measurement deviations are developed as a function of a fitting outer diameter. The model includes both average values and 95% upper bound values for various elbow components in NPPs.

## Conflicts of interest

The authors declare no conflicts of interest.

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