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THINNED PIPE MANAGEMENT PROGRAM OF KOREAN NUCLEAR POWER PLANTS

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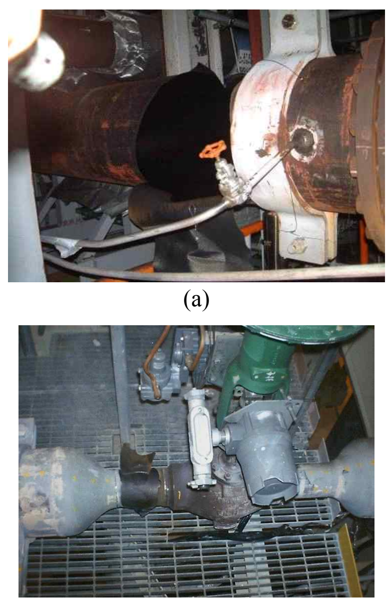
Local wall thinning and integrity degradation caused by several mechanisms, such as flow accelerated corrosion (FAC), cavitation, flashing and/or liquid drop impingements, are a main concern in carbon steel piping systems of nuclear power plant in terms of safety and operability. Thinned pipe management program (TPMP) had been developed and optimized to reduce the possibility of unplanned shutdown and/or power reduction due to pipe failure caused by wall thinning in the secondary side piping system. This program also consists of several technical elements such as prediction of wear rate for each component, prioritization of components for inspection, thickness measurement, calculation of actual wear and wear rate for each component. Decision making is associated with replacement or continuous service for thinned pipe components. Establishment of long-term strategy based on diagnosis of plant condition regarding overall wall thinning is also essential part of the program. Prediction models of wall thinning caused by FAC had been established for 24 operating nuclear plants. Long term strategies to manage the thinned pipe component were prepared and applied to each unit, which was reflecting plant specific design, operation, and inspection history, so that the structural integrity of piping system can be maintained. An alternative integrity assessment criterion and a computer program for thinned piping items were developed for the first time in the world, which was directly applicable to the secondary piping system of nuclear power plant. The thinned pipe management program is applied to all domestic nuclear power plants as a standard procedure form so that it contributes to preventing an accident caused by FAC.

Keywords : *flow accelerated corrosion, wall thinning, prediction model, integrity assessment*

1. Introduction

Wall thinning of carbon steel pipe components due to flow accelerated corrosion, cavitation, flashing, and/or droplet impingement is one of the most serious threats to the integrity of steam cycle piping systems in nuclear power plant.[1)] If the thickness of a pipe component were reduced below a critical level, it cannot sustain the operating pressure and consequently leads to leakage or rupture. As shown in Fig. 1(a) for Mihama Unit 3 and Fig. 1(b) for Hanbit Unit 3, even a single event of a high-energy pipe rupture can be a serious accident resulting in casualties and economical loss. Since mid of 1990s, KHNP has conducted a series of studies to develop and optimize the thinned pipe management program which is applicable to all domestic nuclear power plants.

This paper focuses on introduction of the thinned pipe management program and the research activities which were conducted during the latest study to optimize thinned



(a)

(b)

Fig. 1. Consequences of excessive wall thinning : (a) fatal and unplanned shutdown (b) power reduction.

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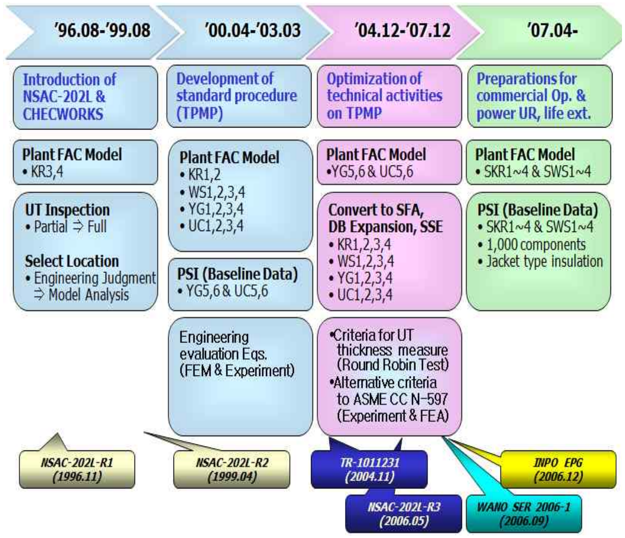


Fig. 2. History of Korean thinned pipe management program.

pipe management program.

2. THINNED PIPE MANAGEMENT PROGRAM

Korean TPMP consists of several technical items, such as performing FAC model analyses, prioritizing pipe components for inspection, obtaining reliable thickness data, calculating the wear and wear rate, and making decisions regarding replacement necessity or continuous service acceptability based on the remaining life of the component. To make a diagnosis of plant wear level and to set up a long-term monitoring plan is also included. NSAC-202L guideline [2] was used as reference for TPMP and EPRI CHECWORKS™ computer program as a tool. [3]

2.1 History of thinned pipe management program

Fig. 2 briefly shows the history of thinned pipe management program in Korea.

Through the first study on Kori Unit 3&4, the effectiveness of the management methodology based on NSAC-202L guideline and the usage of CHECWORKS™ program was verified. In the second project for other 14 Units, the thinned pipe management program was developed as a standard procedure. After fatal accident of Mihama Unit 3, KHNP had conducted the third study to optimize the current thinned pipe management program by reflecting the recently presented management guidelines from EPRI,[2] WANO,[4] and INPO.[5] The lessons learned from existing plants have been feed-backed to the units which are under design and construction through material upgrade, schedule change to thicker pipe, establishment of plant FAC model, obtaining of baseline thickness data, and so on.

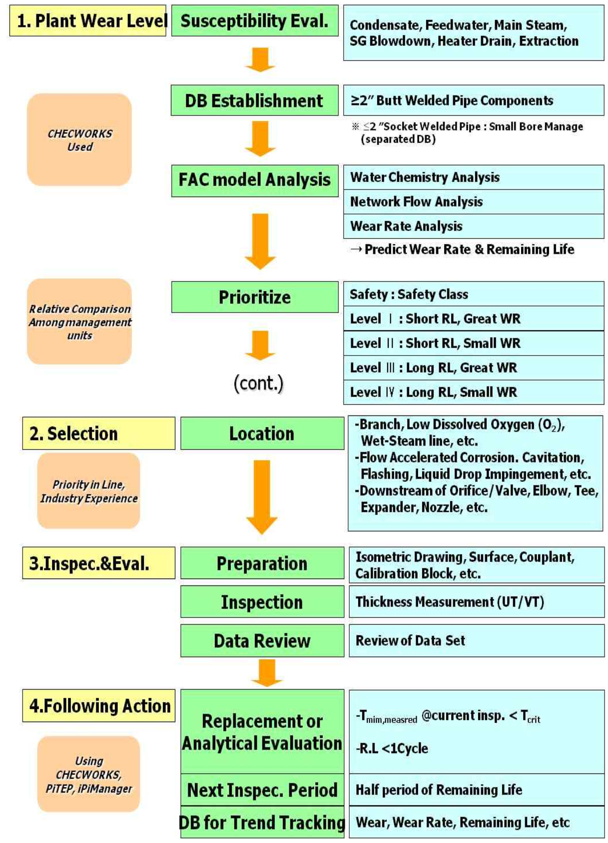


Fig. 3. Scheme of Korean thinned pipe management program.

As illustrated in Fig. 3, thinned pipe management program consists of several technical items, such as performing FAC model analyses, prioritizing pipe components for inspection, obtaining reliable thickness data, calculating the wear and wear rate, and making decisions regarding replacement necessity or continuous service acceptability based on the remaining life of the component.

2.2 Flow Accelerated Corrosion prediction model

The general formula of Chexal-Horowitz FAC model used in CHECWORKS™ is as follows [3] :

$$WR = F_1(T) \times F_2(AC) \times F_3(MT) \times F_4(O_2) \times F_5(pH) \times F_6(G) \times F_7(\alpha) \times F_8(N_2H_4) \quad (1)$$

Where: WR = wear rate
F_1 (T) = factor for temperature effect
F_2 (AC) = factor for alloy content effect
F_3 (MT) = factor for mass transfer effect
F_4 (O_2) = factor for dissolved oxygen effect
F_5 (pH) = factor for pH effect
F_6 (G) = factor for geometry effect

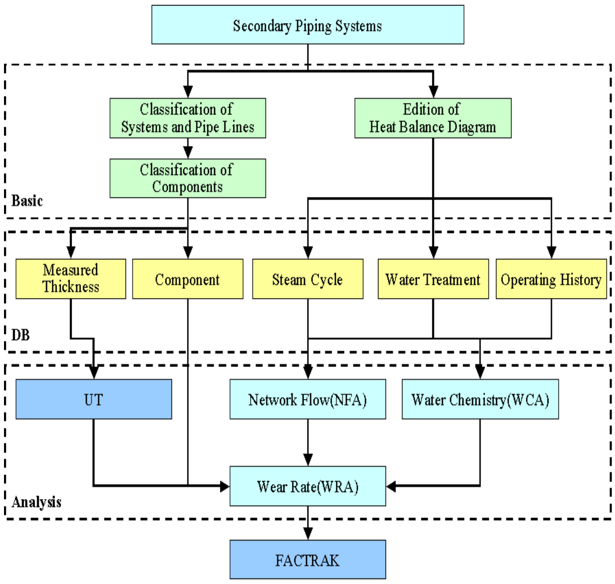


Fig. 4. Utilization of CHECWORKS™ program in TPMP.

F_7 (α) = factor for void fraction effect
F_8 (N_2H_4) = factor for hydrazine effect

2.3 Utilization of CHECWORKSTM

CHECWORKS™ program is used to predict the rate of wall thinning and remaining service life on a component-by-component basis and to evaluate the wall thickness data taken during inspections. Its function consists of several analysis and support tasks. The analysis tasks comprised of water chemistry analysis, network flow analysis, wear rate analysis, and UT analysis. The support tasks are composed of plant data management, isometric viewer, heat balance editor, and FACTRAK, etc. FAC analyses using CHECWORKS™ are performed in three stages. These are systematic piping system classification, database creation and wear rate analysis as illustrated in Fig. 4.

In the first stage, piping lines and components in steam cycle systems are classified to facilitate database creation and site application. Because hundreds of lines and thousands of pipe components have to be established in a unit database, line and component names should not be duplicated. A heat balance diagram is also generated to perform water chemistry analysis and to serve as a gateway into the database. In the second stage, design and operating data such as temperature, pressure, enthalpy, power level, water chemistry, component geometry, etc., are inputted into the plant database. Finally, the wear rate analysis based on a generated database is performed to obtain the wear rate and remaining service life for each component. The FAC analyses are performed according to the processes of water chemistry analysis, network flow analysis, and wear rate analysis. To accurately predict the FAC wear rate, it is essential that the pH and dissolved oxygen levels are precisely determined at the desired location. This is the purpose of the water chemistry analysis. The various elements involved in water chemistry analysis are heat balance diagram, steam cycle data, power level data, and water treatment data. The network flow analysis is performed to calculate the thermal-hydraulic conditions affecting wall thinning. Network flow analysis results for a run definition include pressure drop due to friction, flow acceleration due to both density and area change, and pressure changes due to variation in elevation. The heat loss from the piping system to the environment is also calculated in this analysis. The network flow analysis is mainly performed for pipe runs that contain initially sub-cooled liquid but finally flash and become two-phase mixtures on the way to the designated equipment or to the condenser. The wear rate analysis is performed to calculate the wear rate of components in single-phase water and two-phase wet steam piping lines. The wear rate analysis is on a component-by-component basis. A component is a specific element within a piping line like an elbow, a tee, or a reducer, etc. The parameters such as total lifetime wear, residual thickness, and remaining service life, etc., are predicted from this wear rate analysis.

2.4 Creation of global database

The global plant database has an effect on all components data stored in the FAC database. The global plant data contains heat balance diagram, power level, plant period, steam cycle, and water treatment data. The heat balance diagram enables the simulation and analysis of the secondary water treatment for subsequent FAC analyses. The heat balance diagram is generated using the heat balance diagram editor task. Most of NPPs in Korea are operated at full power to cover base loads so that the power level is defined as 100% power level. The plant periods are used to specify the plant's operating history. The duration of the time when the plant was operating is classified as an operating period. The duration of time when the plant was not operating due to refueling is classified as a maintenance period. For example, KORI unit 1 has 19 operating cycles, to date. The steam cycle data is used to view and edit the thermodynamic data associated with a plant's heat balance. The operating thermal hydraulic data based on the Final Safety Analysis Report (FSAR) for a given plant is inputted as steam cycle data. The corrosiveness of water used in power plants depends on the pH and the concentration of dissolved oxygen levels. The primary factors responsible for the variation in pH level

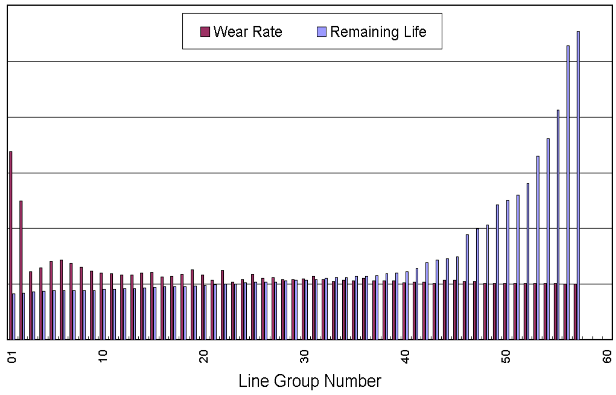


Fig. 5. Comparison of FAC susceptibility for KORI unit 1 (line group basis).

are the additives used for pH control, the operating temperature, and the volatility of the additives where steam and water separation occurs. The water chemistry data is inputted in the FAC database with average values sampled at the locations of the final feed-water, steam generator blow down, and condensate. In the water chemistry analysis, the parametric evaluation methods are selected in order to determine the impact of water chemistry on the local piping line within the secondary system.

2.5 Creation of component database

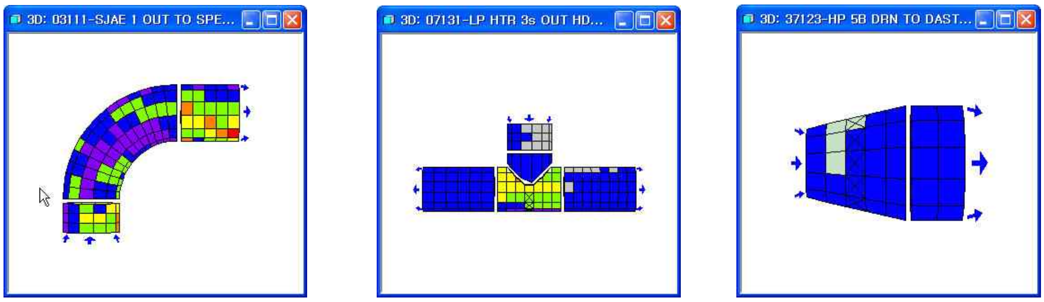
The component data stored in the FAC database contains pipeline information such as line identification, class, phase, etc., design information such as geometry, size, material, design temperature and pressure, etc., and operating information such as operating pressure, temperature, enthalpy, steam quality, etc. The component data is used as the basic information for the network flow and wear rate analysis. To facilitate the site application, the pipelines of each plant are classified systematically based on isometric drawings and P&IDs. Component names are also determined in accordance with isometric drawings and placing locations in the plants.

2.6 Flow Accelerated Corrosion model analysis

To reflect the water chemistry and thermal-hydraulic conditions of individual components, water chemistry and network flow analysis are performed prior to wear rate analysis. In case of KORI unit 1, water chemistry analysis was performed twice because of the water treatment changing from ammonia to ethanolamine at the 17th refueling outage. Network flow analysis was performed for 71 runs and wear rate analysis was performed for 174 pipelines and 3,736 pipe components. For WOLSUNG unit 1, the water chemistry analysis for morpholine treatment was performed, and the network flow analysis was performed for 65 runs. In addition, wear rate analysis was performed for 235 pipelines and 5,076 pipe components.

2.7 Selection of components for inspection

From the FAC analyses results, components needed for inspection are selected based on the ranking of predicted remaining service life, as well as the wear rate. All systems on each plant are subdivided into several line groups that have the same function, and/or the same thermal hydraulic and water chemistry conditions. After considering the remaining service life as a primary and the wear rate as secondary, the representative component in each line groups is determined for comparison on a group-by-group basis. Line groups are re-arranged according to inspection necessity ranking.[4] In case of KORI unit 1, as illustrated in Fig. 5, 57 line groups are re-arranged and categorized into 4 levels. Level-1 (1~14) is for most severe line groups because of short remaining life and high wear rate, Level-2 (15~27) is for severe line groups because of short remaining life but low wear rate, Level-3 (28~45) is for moderate line groups because of long remaining life but high wear rate, and Level-4 (46~57) is for mild line groups because of long remaining life and low wear rate. The purpose of categorization is to determine the amount of components for each line group in proportion to the total amount of inspectable components during a given outage



(a) (b) (c)

Fig. 6. Full and extended grid layout for fittings; (a) Elbow (b) Tee (c) Reducer or Expander.

time schedule and manpower. For all Korean NPPs, 200~300 components are generally selected and inspected for each outages.

2.8 Thickness measurement

Components can be inspected for wall thinning using ultrasonic techniques (UT), radiography techniques (RT), or by visual observation. Because UT method can provide more complete data for measuring the remaining wall thickness, Korean NPPs use the UT thickness gage with electronic data loggers. Experience has shown that it is difficult to predict where the maximum wear will occur in a given component. To ensure that the maximum FAC wear can be detected, the UT grid fully covers the component being inspected. Because FAC can extend into the piping downstream and upstream, as illustrated Fig. 6, inspection grid is being extended from the toe of the upstream weld to three grid lines and from toe of the downstream weld to 2 pipe diameters (2D). To ensure that the thinned region can be identified, the grid size should not be greater than π D/12, where D is the nominal outside diameter, and should not be larger than 6 inches.

2.9 Evaluating inspection data and following action

The evaluation procedure consists of reviewing the inspection data for accuracy, determining the amount of wear, and determining the wear rate for each inspected component. This process is complicated by several factors, including the following;

- Unknown initial wall thickness (if baseline data was not taken)
- Variation of as-built thickness along the axis and around the circumference of the component
- Inaccuracies in NDE measurements
- The possibility of pipe to component misalignment, backing rings, or the use of counter-bore to match two surfaces
- Data recording errors or data transfer errors
- Obstructions that prevent complete girding (e.g., a welded attachment)

The challenge is to minimize the effect of these problems by applying uniform evaluation methods and utilizing engineering judgment. The inspection data should be carefully reviewed to identify any data that is judged to be in error. Erroneous data should preferably be re-inspected, or if necessary, eliminated to obtain valid reading. Once the data set is acceptable, any wear region on the component should be identified. The location of the potential wear region should be compared with the component orientation, flow direction, and attached piping. The variation in thickness within this region should be compared to the adjacent region to confirm the existence of wear. If data from previous inspections are available, they should be compared with the current measurements, and wear trends/patterns should be identified. There are four methods commonly used for determining the wear of piping components from UT inspection data. These methods are band method, area method, moving blanket method, and point-to-point method. Three of the methods, which are the band, area and blanket methods, estimate the components initial thickness and can be used for evaluation of components with single inspection data. These three methods are predicated on theory that the wear caused by FAC is typically found in a localized area or region. The point-to-point method can be used when data taken at the same grid locations exists from two or more outages (or baseline data plus data from one or more outages). In such cases, it is possible to obtain a difference in thickness readings for each grid inspection. The wear at each grid location is the thickness taken at the earlier inspection minus the thickness taken at the later inspection. The largest of the grid wear values is the component maximum wear between the two outages. The point-to-point method does not estimate the initial component thickness. Because most of Korean NPPs have no baseline data, moving blanket method is selected for an elbow's main section while band method is selected for the other type of fittings and sections. To evaluate the initially measured inspection data, the following 4 equations are used.

$$\text{Wear} = T_{ref}\,(T_{max} \text{ or } T_{nom}) - T_{min} \tag{2}$$

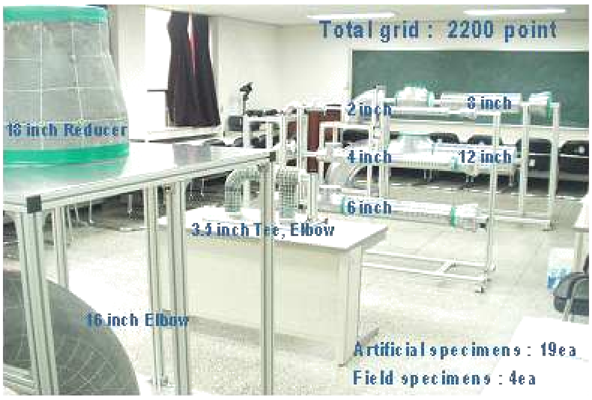
$$\text{Wear Rate} = \frac{T_{ref} - T_{min}}{\text{Operating Time}} \tag{3}$$

$$T_{crit} = \frac{P \cdot D}{2(S + y \cdot P)} + A \tag{4}$$

Where: T_{crit} = required wall thickness
P = design pressure
D = outside diameter
S = allowable stress
y = joint efficiency
A = additional thickness

$$\text{Remaining Service Life} = \frac{T_{min} - T_{crit}}{\text{Wear Rate}} \tag{5}$$

The greater value between nominal thickness and measured maximum thickness is determined as the reference/initial thickness. According to equation (2), the dif-



(a)

O.D. (inch)	Pipe (%)	Elbow (%)	Tee (%)	Reducer (%)	Average (%)
2	+2.53 −2.72	+2.82 −2.84	+3.04 −4.08	+2.21 −2.99	+2.65 −3.16
4	+1.64 −1.96	+1.27 −1.65	+1.98 −2.50	+2.32 −2.46	+1.80 −2.14
6	+1.28 −1.52	+2.31 −2.20	+1.89 −1.74	+3.00 −2.77	+2.12 −2.06
8	+1.54 −1.48	+2.13 −2.00	+1.58 −1.52	+2.16 −2.26	+1.85 −1.81
12	+1.52 −1.43	+1.42 −1.46	+1.10 −1.22	−	+1.35 −1.37
Average	+1.69 −1.84	+1.99 −2.03	+1.89 −2.24	+2.42 −2.62	−

(b)

Fig. 7. Round robin tests for ultrasonic thickness measurement system : (a) specimens for RRT (b) accuracy of well-trained NDE personnel.

ference between reference thickness and measured minimum thickness is determined as the amount of wear. According to equation (3), the amount of wear is divided by operating time so that the wear rate is determined. Required wall thickness can be determined by equation (4) presented in ASME Code. According to equation (5), the remaining thickness is divided by the wear rate to determine the remaining service life. Remaining thickness is the difference between measured minimum thickness and required thickness. If the calculated remaining service life of a component is shorter than the amount of time until the next outage, the detailed analysis is performed to obtain a more accurate value of the acceptable thickness. If necessary, it should be repaired or replaced before the plant startup. In cases where the remaining service life of a component is longer than one operating cycle time, the outage corresponding to the half of the remaining life is determined as the second inspection timing. The second inspection is conducted to confirm the results of the first inspection and to obtain data for trending of wear. Inspections following the second inspection are scheduled as necessary to monitor plant susceptibility and to inspect wearing components prior to the end of their service life.

2.10 Improvement of water chemistry to reduce FAC damage

Optimizing the inspection planning process is important, but reduction of FAC wear rates is needed to reduce the number of inspections and the probability of failure. Because of this, water chemistry for most of the Korean Pressurized Water Reactors (PWR) had been improved. In KORI units 1&2 and YONGGWANG units 1&2, the pH control amine had already changed from ammonia to ethanolamine while morpholine treatment in WOLSUNG units (Pressurized Heavy Water Reactor) is maintained from plant initial startup. It is anticipated that the wear rate of pipelines within the extraction system of PWRs can be reduced to a factor of ten.

3. RESEARCH ACTIVITIES

3.1 Accuracy improvement of ultrasonic thickness measurement

The reliability of thickness data from ultrasonic thickness measurement plays an important role in the thinned pipe management program. Round robin test, as illustrated in Fig. 7, was performed to quantify the inaccuracy of measured thickness data. For this test, the artificially and naturally thinned specimens were used. From this round robin test, well trained NDE personnel showed good accuracy as illustrated in Fig. 7(b). Even though for the smallest specimen, 2 inch OD, they measured thickness in good accuracy, plus 2.7 percent, minus 3.1 percent. In this process, the criteria for optimizing ultrasonic thickness measurement system, combination of personal-device-size, had been setup and included in standard procedure.

3.2 Development of alternative engineering evaluation

ASME Code Case N-597-2,[6)] as illustrated in Fig. 8, is used for integrity evaluation of thinned pipe component in the thinned pipe management program. Engineering evaluation methodology presented in this code case contains some limitations for application. Experimental and analytical efforts were tried out to develop alternative criteria which can be applied to the non-safety thinned pipe component.

3.2.1 Specimens for real scale failure test

The real scale failure tests were carried out using commercial carbon steel pipe components of 114.3mm in diameter (schedule 80), containing a simulated local wall

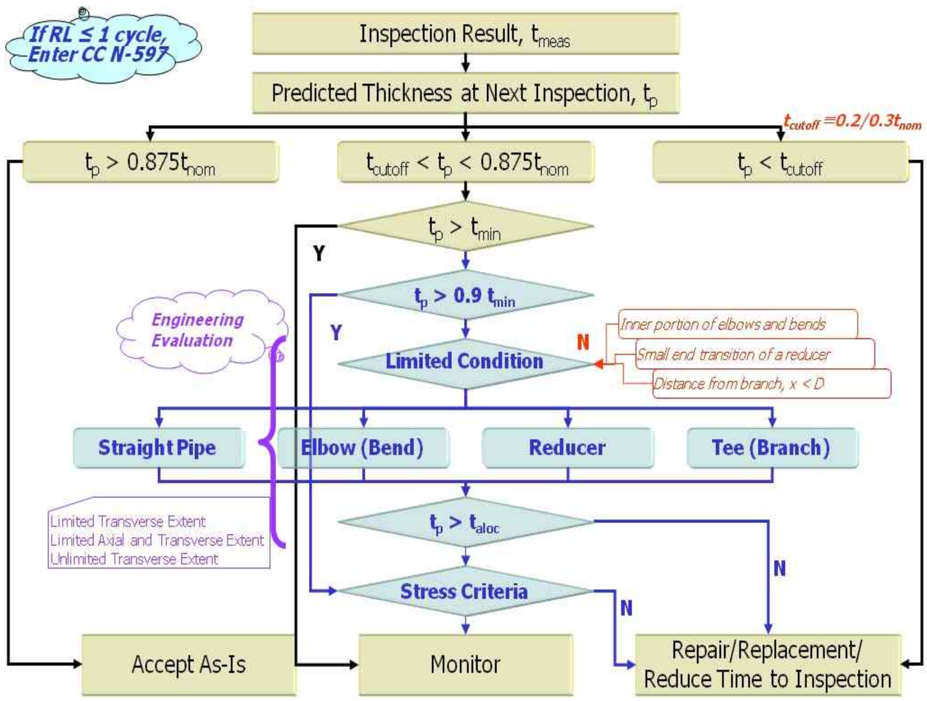


Fig. 8. Outline of ASME Code Case N-597-2.

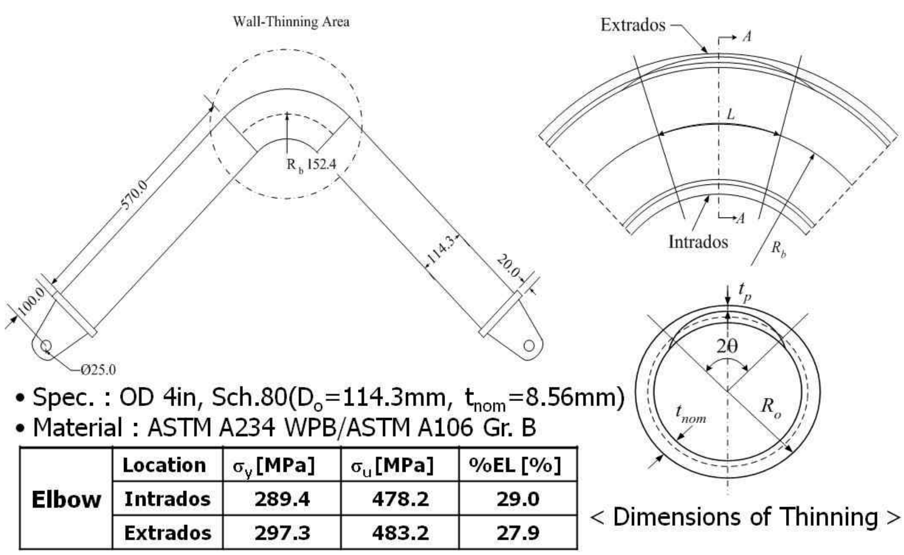


Fig. 9. Dimension of specimen for real scale failure tests.

thinning. As shown in Fig. 9, the specimens were prepared by welding of 3 pieces of segment (pipe-elbow-pipe) and those were end-capped to accommodate the internal pressure. The elbows were machined to obtain the uniform dimensions of outer diameter prior to wall thinning. Local wall thinning was made by machining at extrados or intrados of elbow segment located at the middle of specimen. In the experiment, various axial length (L), circumferential angles (2θ), and minimum wall thickness (t_p) were considered. The dimensions of wall thinning were specified by equivalent axial length (L/D_o), circumferential angle of area where the wall thickness is thinner than the minimum thickness (t_{min}=5.3mm, for pressure 10MPa and material A234 WPB) required by construction codes, ASME B&PV Sec. III or ASME B31.1. The axial and circumferential shapes of thinning area were assumed as circular. After the thinning defects at the target area of elbow were made, the dimensions of locally wall thinned

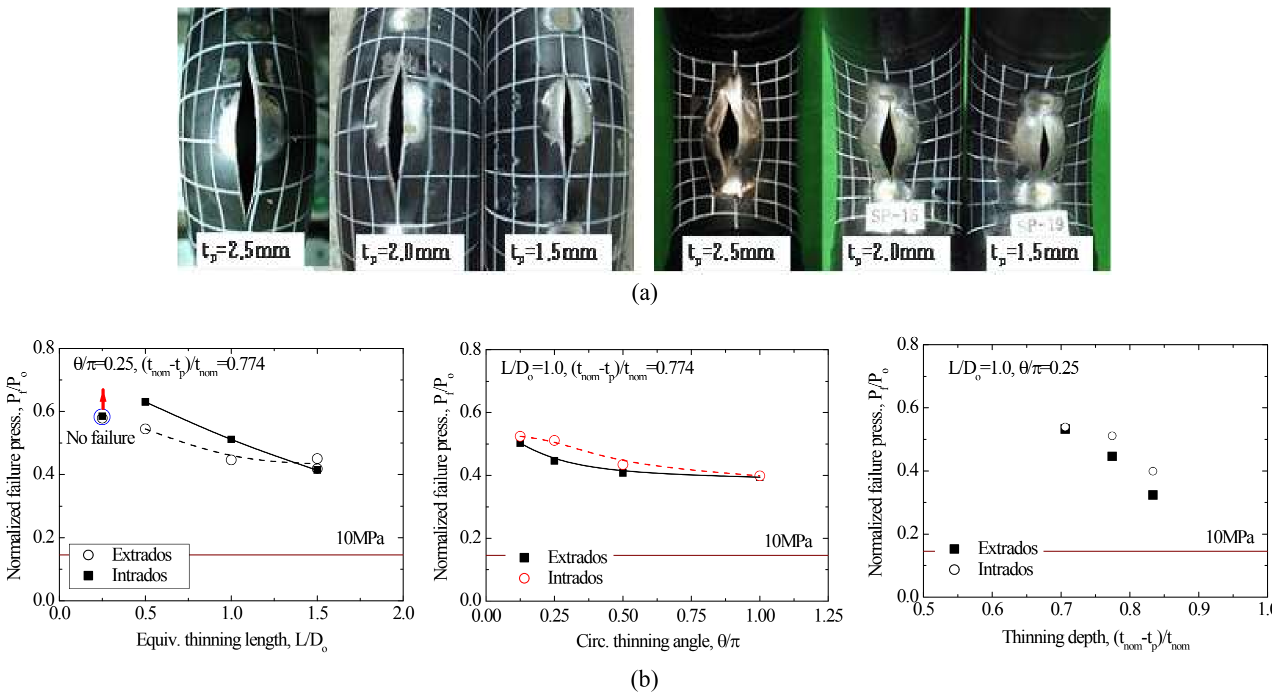


Fig. 10. Results of burst tests of wall thinned elbows : (a) burst modes according to the thinning location and the minimum thickness (b) comparison of burst pressure according to the thinning dimension.

area for all specimens were checked by ultrasonic thickness measurement technique.

3.2.2 Failure pressure test

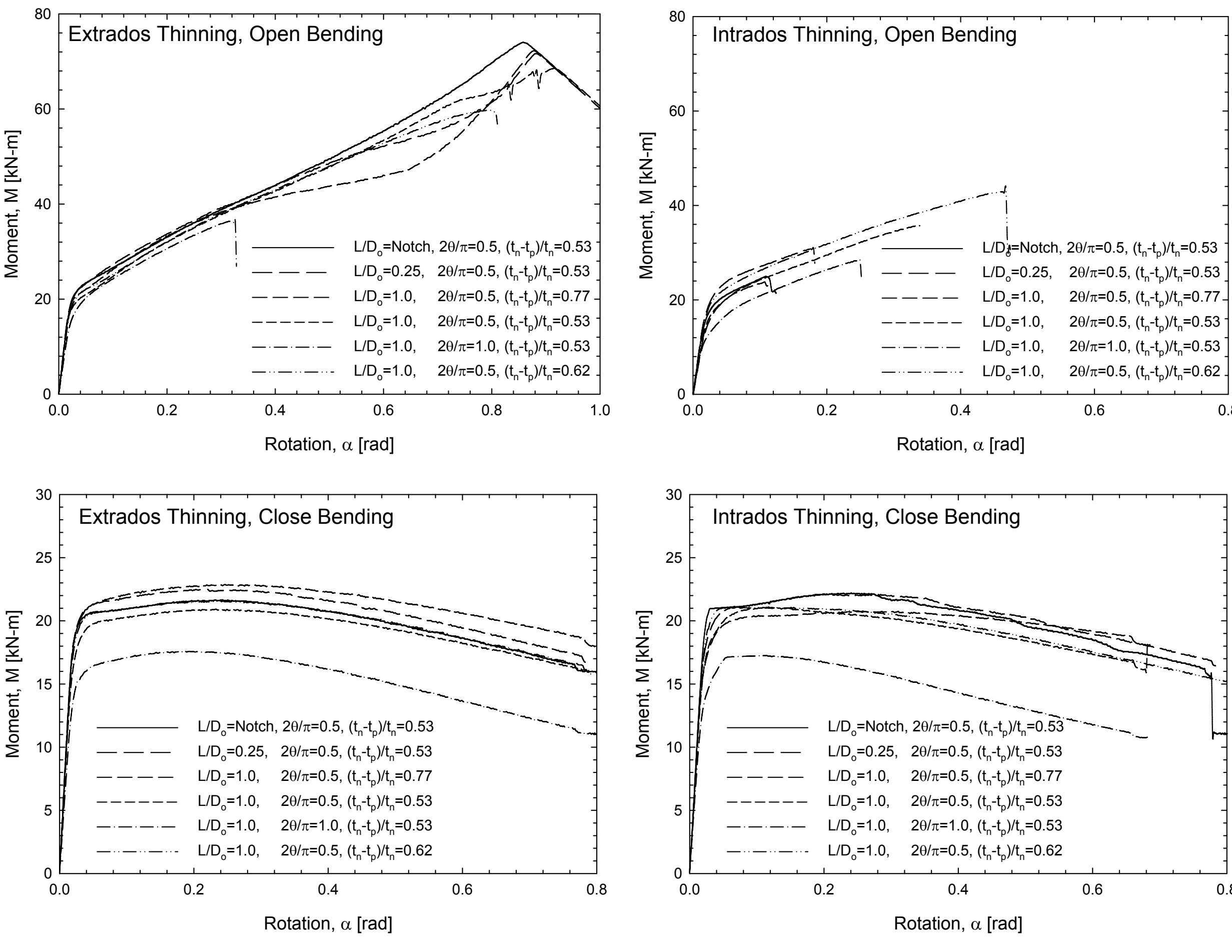
A series of burst tests using real scale pipe elbows containing simulated wall thinning defect were performed to evaluate the effects of local wall thinning on the failure pressure of elbows.[9] The tests were conducted under simple internal pressure at room temperature. Fig. 10 shows the results of burst tests of wall-thinned elbows. Fig. 10(a) shows the burst modes according to the thinning location and the minimum thickness while Fig. 10(b) shows comparison of burst pressure according to the thinning dimension.

From this burst tests, the following conclusions were derived. The dependences of failure pressure on thinning length and depth in the wall thinned elbow were similar to the results of wall thinned straight pipe. The failure pressure decreased with increasing circumferential thinning angle, which was different from that observed in the straight pipe. The existing failure pressure evaluation models for wall thinned elbow showed excessive conservatism. For intrados wall thinning case, the conservatism was significant and the variation in failure pressure with thinning dimensions could not be properly estimated. For extrados wall-thinning case, the existing models appropriately estimated the dependence of failure pressure on the thinning length and depth. All specimens tested were failed by bulging followed by axial cracking. For extrados and intrados wall-thinned elbows, the crack always occurred at the minimum wall thinned area. For entire circumferentially thinned elbow, however, the crack location was dependent on axial thinning length.

3.2.3 Failure load test

A series of combined load tests using real scale pipe elbows containing simulated wall thinning defect were performed to evaluate the effects of local wall thinning on the failure moment of elbows.[10, 11] Internal pressure and in-plane bending moment are considered as combined load. Fig. 11 shows the results of combined load tests of wall-thinned elbows. Fig. 11(a) shows the failure modes according to the thinning location and the bending direction while Fig. 11(b) does the moment behaviours for the thinning location and the bending direction. From this combined load tests, the following conclusions were derived. For both location of wall thinning and both type of bending, the plastic deformation of large arc thinned elbows was started at lower bending moment and smaller rotation than those of small arc thinned elbows. The plastic deformation of intrados thinned elbows was started at lower bending moment and smaller rotation than those of extrados elbows, especially in the open mode bending. The failure of local wall thinned elbow was classified into three modes, buckling, ovalization, and crack. For the open mode, buckling was occurred at the thinned region

(a)



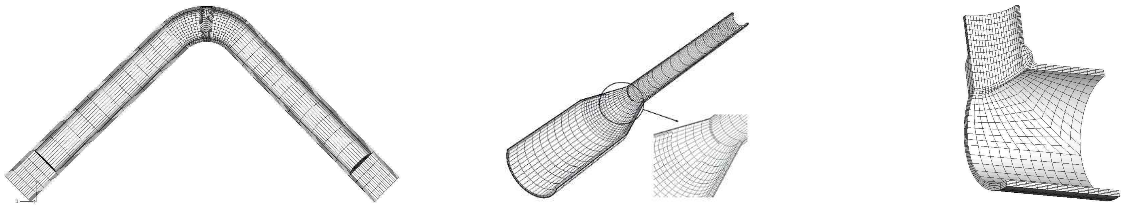
(b)

Fig. 11. Results of combined load tests of wall-thinned elbows : (a) failure modes according to the thinning location and the bending direction (b) moment behaviours according to the thinning location and the bending direction.

of the extrados circumferential angle. And, crack was occurred at the intrados region for the other three cases. Ovalization was occurred for all cases, and it was extended to the some region of straight pipe. For the close mode, buckling was occurred at the intrados for all cases. No crack was occurred for all cases. Ovalization was occurred for all cases, and it was extended to the some region of straight pipe. All test cases had at least three times physical safe margin of twice elastic slope moment compared with maximum allowable moment based on construction code.

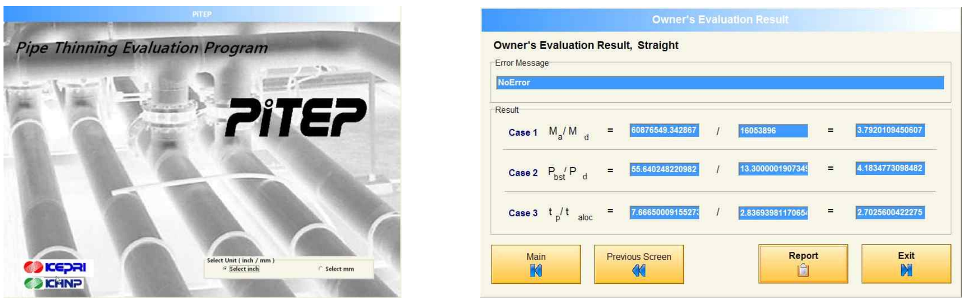
3.2.4 Finite element analysis

Detailed three-dimensional (3–D) finite element analyses for pipe bends, reducer, and tee under combined pressure and bending were performed based on elastic–perfectly plastic materials with the small geometry change option. A wide range of parameters related to the thinning dimension, thinning location, and the internal pressure. Fig. 12 shows the finite element analysis for thinned pipe components.[12, 13]



(a) (b) (c)

Fig. 12. Examples of finite element analysis model for thinned pipe components : (a) elbow (b) reducer (c) tee.



(a) (b)

Fig. 13. Pipe thickness evaluation program (PiTEP) : (a) start (b) result.

3.2.5 Pipe thickness evaluation program

Closed-from approximations of plastic limit loads for 4 types of pipe component (elbow, reducer, tee, straight pipe) under internal pressure and/or bending moment are presented based on the finite element analysis results.

These are coded to a computer program called PiTEP, as illustrated in Fig. 13. The result of this program includes the safe margin in moment, pressure, and thickness aspect of thinned component. These safe margins mean the ratio of endurable moment of thinned pipe component and allowed moment of not thinned pipe component by construction code, and that of burst pressure of thinned pipe component and design pressure.

4. CUNCLUSION

Even a single event of a high-energy pipe rupture can be a serious accident resulting in casualties and economical loss. Korean nuclear power plants have made important efforts developing the predictive plant models, the criteria for the thickness measurement, the alternative local wall thinning assessment criteria, and so on. The purpose of these efforts is to concentrate the resources to find out and measure the pipe components which are actually experiencing wall thinning, so as to improve the reliability of TPMP. These integrated approach related to the management of wall thinned piping system will be able to minimize the possibility of pipe failure, as it has been so far.

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