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Evaluation of Wall Thinning of the Steel Piping after Long Term Operation at Fugen Power Station

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ABSTRACT

Wall thinning of serviced carbon steel piping of the secondary cooling system after long term operation of Advanced Thermal prototype Reactor (ATR) Fugen power station has been investigated as a series of evaluation of validity and availability of utilization of serviced materials on research projects focused on aging management.
Reliability of wall thinning rates of the steel piping has been examined referring the previous inspection data.
Examinations also have been made on prediction of wall thinning rates, rationalization of management of pipe wall thinning and verification of countermeasures against wall thinning.

KEYWORDS

serviced materials, steel piping, wall thinning, FAC, LDI, JSME code, ATR Fugen power station

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1. Introduction

Investigation of wall thinning of steel piping of the secondary cooling system has been carried out using serviced materials of the decommissioned Advanced Thermal prototype Reactor (ATR) Fugen power station.

More than 1,100 measurement targets had been examined throughout 18 periodic inspections including pre-service inspection by ultrasonic thickness measurements at Fugen.

Surveying and organizing the previous periodic inspection data, then calculating wall thinning rates by using the method defined in JSME code for pipe wall thinning [1], there was a tendency that the most of the measurement points having the average thinning rate of more than 0.2mm per 10,000 hour located in condensate water or feed water system, especially elbows nearby feed water pumps and feed water heaters where flow drift expected to be occurred had heavier corrosion.

Comparing to the categories defined by JSME such as FAC-1 and FAC-S where relatively higher dissolved oxygen inhibits the wall thinning, whereas possibility is not deniable that substantial wall thinning could be caused by a significant effect of flow drift on the other hand, can be seen a lot in the secondary cooling system of Fugen, there still remains some possibilities of deterioration in reliability at the measurement points tested fewer times even they showed relatively rapid thinning rates.

Investigation of the reliability of the data regarding thinning rates has been examined based on the detailed measurement of the wall thinning with complementing to the previous inspection results on the serviced steel pipes of the decommissioning Fugen. Moreover, investigations on the wall thinning have been carried out such as accuracy improvement of the prediction formula, evaluation of validity of countermeasures and rationalization of the management as follows.

2. Wall thinning rate and wall thinning prediction formula

2.1 Investigation method

Fig. 1 shows a schematic diagram of the Fugen secondary cooling system. It is based on the

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JSME code of pipe wall thinning management, all of the measurement targets such as elbows were chosen in the area of Flow Accelerated Corrosion (FAC) and Liquid Droplet Impingement (LDI) control area, where significant wall thinning were considered tend to occur.

The investigation of the status of the pipe wall thinning has been carried out by measuring thickness of the steel pipes using a portable ultrasonic thickness gage.

In these measurements, the following method has been adopted in order to determine the status of the spatial distribution of the pipe wall thinning, and make obtained data contributable for elucidating the mechanism of the pipe wall thinning.

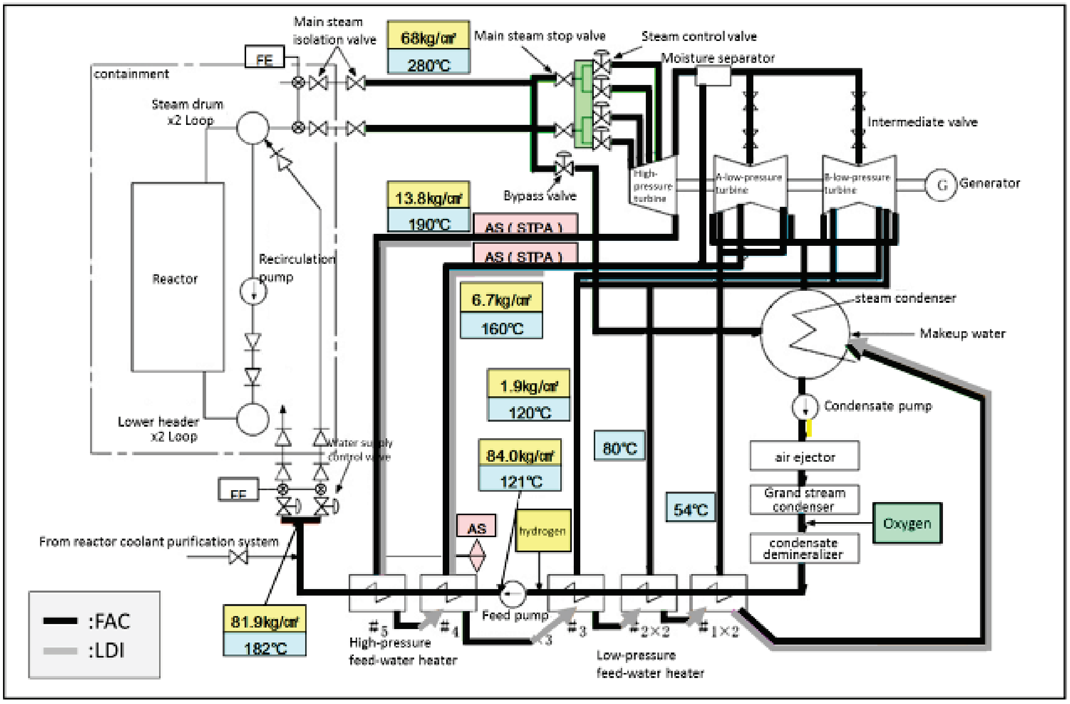

Fig.1 Schematic diagram of Fugen secondary cooling system classified to FAC and LDI control area.

The measurement was carried out by making the grid spacing of 100 mm, and then the wall thickness was measured on a grid, namely, a cross section (a measuring point, hereafter) by using an ultrasonic thickness gage.

The number of the measuring points in a radial direction was chosen more than 4 for the pipes smaller than 5B in a nominal diameter, and less number was chosen either more than 8 or 100 mm in pitch for the pipes larger than 5B.

Also, in a radial direction, either lesser length of twice in diameter or 100 mm from the end of piping parts were chosen as the measurement range at the upstream side of the elbows and tees, that can be the cause of the flow drift, and three-fold in diameter was chosen as the measurement range at the downstream side commonly.

Thinning rate was calculated by subtracting the measured wall thickness at this time from the last measured wall thickness and divided by the actual operating time at exactly the same grid point.

In addition, in case significant wall thinning was observed, the grid spacing was reduced to 20 mm in pitch instead centering the very same measured point to the end of the measurement area described above.

Table 1 shows an example of the results of the wall thinning on the 148 measurement targets, namely 28,000 measurement points in all.

(system:High pressure water supply pipe   An example of the results)

Measurement point number	Caliber	outer diameter (mm)	Nominal wall thickness	Material	Necessary wall Thickness (mm)	Wall thickness criteria (mm)	Wall thickness measurement Maximum	Wall thickness measurement Minimum	figuration
FDW-SP-1	250A	267.4	28.6	STPT49	12.9	23.4	27.5	45.9	ELB:Elbow
FDW-SP-2	250A	267.4	28.6	STPT49	13.0	23.4	27.1	33.0	ELB:Elbow
FDW-SP-3	250A	267.4	28.6	STPT49	13.0	23.4	27.8	34.0	ELB:Elbow
FDW-SP-4	250A	267.4	28.6	STPT49	13.0	23.4	25.7	31.1	ELB:Elbow
FDW-SP-6	250A	267.4	28.6	STPT49	12.9	23.4	27.4	31.6	ELB:Elbow
FDW-SP-7	250A	267.4	28.6	STPT49	13.0	23.4	27.1	39.8	ELB:Elbow
FDW-SP-8	250A	267.4	28.6	STPT49	12.9	23.4	27.1	32.9	ELB:Elbow
FDW-SP-9	250A	267.4	28.6	STPT49	13.0	23.4	27.6	34.5	ELB:Elbow
FDW-SP-10	250A	267.4	28.6	STPT49	13.0	23.4	24.8	32.8	ELB:Elbow
FDW-SP-11	250A	267.4	28.6	STPT49	12.9	23.4	23.5	32.7	BND:Bent tube
FDW-SP-12	250A	267.4	28.6	STPT49	12.9	23.4	24.1	32.6	BND:Bent tube
FDW-SP-13	250A	267.4	28.6	STPT49	13.0	23.4	26.1	37.5	ELB:Elbow
FDW-SP-14	250A	267.4	28.6	STPT49	12.9	23.4	25.8	31.4	ELB:Elbow
FDW-SP-16	250A	267.4	28.6	STPT49	13.0	23.4	25.3	30.4	BND:Bent tube
FDW-SP-18	250A	267.4	28.6	STPT49	12.9	23.4	26.2	31.4	ELB:Elbow
FDW-SP-19	350A	355.6	35.7	STPT49	17.1	29.5	34.5	43.2	ELB:Elbow
FDW-SP-22	350A	355.6	35.7	STPT49	17.1	29.5	33.1	42.8	ELB:Elbow
FDW-SP-45	350A	355.6	35.7	STPT49	17.1	29.5	31.3	40.9	BND:Bent tube
FDW-SP-47	350A	355.6	35.7	STPT49	17.1	29.5	33.9	43.1	ELB:Elbow
FDW-SP-48	350A	355.6	35.7	STPT49	17.1	29.5	34.1	43.5	ELB:Elbow
FDW-SP-49	350A	355.6	35.7	STPT49	17.1	29.5	34.7	42.8	ELB:Elbow
FDW-SP-50	250A	267.4	28.6	STPT49	13.0	23.4	26.4	34.5	ELB:Elbow

Table.1 Example of the results of wall thickness measurement of Fugen serviced pipes.

The following is the summary of the investigation results.

① There is no measurement point less than the regulated minimum gage throughout entire 148 measurement targets, namely, about 28,000 measurement points examined.

② Thus, it is confirmed that the management of the wall thinning during operation at Fugen is conservative and appropriate.

2.2 Reliability of wall thinning rates

Fig. 2 shows the plots of the range and the mean values of the thinning rates of each measurement target using all of the obtained data of the measurement points which are distributed in each measurement target up to in the range of 100 to 200 points each, then the prediction results of the wall thinning using Kastner equation [2] which is used in JAEA code (PASCAL-EC) described later, the mean value of the thinning rates of the each piping system model and the total mean value of the entire 148 measurement targets, namely, about 28,000 measurement points investigated are also plotted.

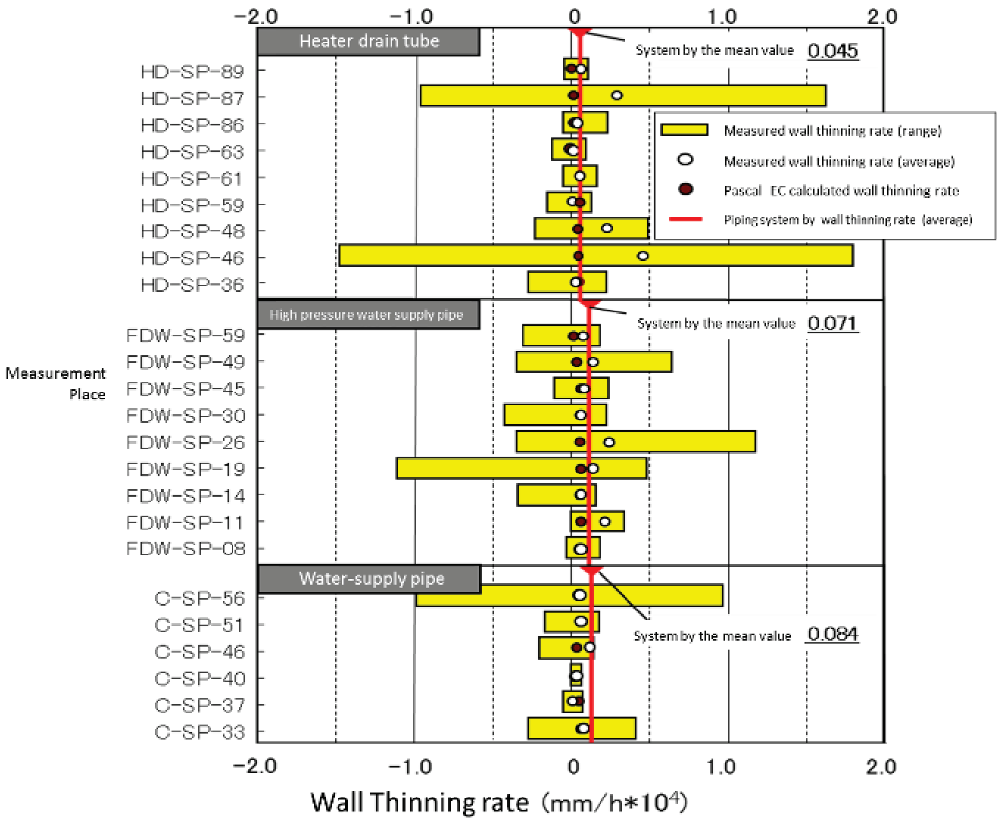

Fig.2 Comparison of wall thinning rate between measured and predicted.

From the results, the following were shown on the value of the thinning rates and reliability.

① Total mean value of the thinning rates of the entire 148 measurement targets, namely, about 28,000 measurement points investigated is less than 0.1 mm per 10,000 hour, which is less than one-fifth of the one caused by the flow accelerated corrosion (FAC), 0.5 to 1.0 mm per 10,000 hour.

② Although the independent value of the thinning rates of the measurement points varies a lot, the mean value of the thinning rates of the each piping system is equal to the total mean value i.e. less than 0.1 mm per 10,000 hour.

③ The measurement points having significant variation of the thinning rates show a tendency to alter in between positive to negative value widely.

④ Predicted thinning rate of each measurement target, calculated by a wall thinning analysis code, PASCAL-EC, shows a little smaller value than the total mean value.

⑤ The measurement points having significant variation of the thinning rates, particularly showing negative values, need to obtain proper information on the cause.

It is well known that corrosion rates of carbon steel can be inhibited less than 0.1 mm per 10,000 hour by controlling the oxygen content, pH and restricting the contaminants of the ambient water so that the passivation file on the surface the steel cannot be damaged in anticorrosion, the results of our investigation seem to be rational and it is said to be confirmed that the management of the cooling water quality of Fugen during its operation was appropriate.

2.3 Detailed measurement using three dimensional measuring equipment and LASER microscope

Three dimensional measurements of the distribution of wall thinning of serviced steel pipes by using a contact type three dimensional measuring equipment (3DME) and high resolution observation of corrosive surface by using a LASER microscope have been applied as the detailed investigation.

For selection of the measurement targets for the detailed investigation, the following are considered.

① Corrosion rate: The target must be located in the control area of FAC and LDI and having comparatively rapid or widely varying corrosion rates.

② Heat flow condition: Comparison between vapor-liquid two phase flow and single phase flow, and comparison of the measurement points having different corrosion rates under the same heat flow condition, can be carried out.

③ Unsteady parts such as type of materials and weld joint: Comparison between carbon steel and low alloyed steel, and comparison between unsteady parts such as weld joint and steady parts, can be carried out.

Thus, the measurement targets for the detailed investigation were chosen as shown in Fig. 3.

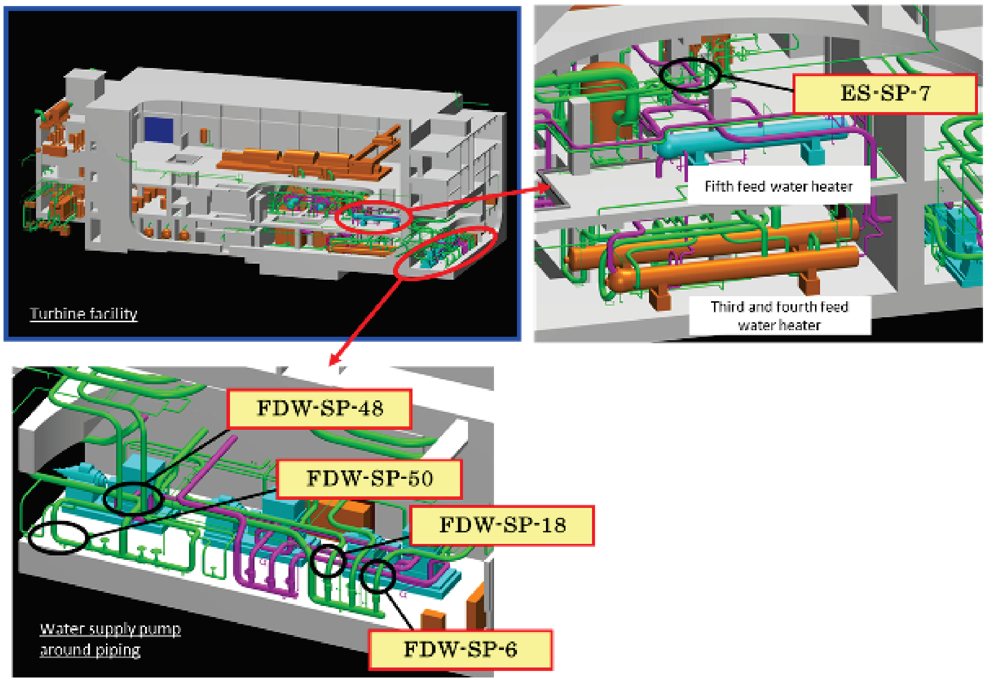

Fig.3 The view of the measurement targets detailed investigation carried out.

Fig. 4 shows an example of the results of the detailed investigation and general investigation. As shown cross section #2 in Fig. 4 of the ultrasonic thickness test results, it is revealed that the thickness at the outer curve of the elbow tends to be thinner than the normal thickness and thicker than both at the inner curve. By the test results of 3DME, it is revealed further that there exists distinct difference in thickness between the outer curve and inner curve of the elbow seems to have been formed by bending of the pipe with cold working. Besides, the profile of thickness deviation of an elbow shows much more clearly by 3DME which has higher resolution of 0.1 mm in pitch compare to the unclear results by ultrasonic thickness measurement of 100 mm in pitch.

Based on the information obtained, an observation result on the inner surface of the outer curve of an elbow is shown in the same figure. The observation result confirms that a lot of groove-like recesses and projections, like wrinkles, made by cold work exist on the inner surface of an elbow in a vertical direction of the flow.

Furthermore, by measuring the profile of thickness deviation of the cross sections #2, #13 and #16 in the same manner, it is confirmed that there exists distinct deviation of the thickness that the thickness at the outer curve of the elbow tends to be thinner than the one at the inner curve and it disappears in the straight portion of the pipe like cross section #16.

In addition, it is confirmed the facts that there is no wrinkle like structure observed on the inner surface like G in the cross section #13, where the effect of the cold working for pipe bending is negligible, and that the inner corrosive surface appears to be covered by flat and substantially uniform general corrosion.

Unit : mm

	1	2	3	4	12	13	14	15	16	17	18	19
A	30.1	27.5	27.7	27.7	27.8	27.7	27.8	27.6	28.1	29.3	29.3	28.9
	30.0	27.7	27.9	27.9	28.0	27.9	28.0	28.0	28.3	29.5	29.6	29.2
	+0.1	−0.2	−0.2	−0.2	−0.2	−0.2	−0.2	−0.4	−0.2	−0.2	−0.3	−0.3
B	29.9	28.4	28.2	28.2	28.2	28.2	28.1	28.0	28.3	29.1	29.2	29.1
	30.0	28.6	28.4	28.5	28.4	28.4	28.3	28.3	28.7	29.5	29.6	29.4
	−0.1	−0.2	−0.2	−0.3	−0.2	−0.2	−0.2	−0.3	−0.4	−0.4	−0.4	−0.3
C	29.1	29.8	29.5	29.3	28.8	28.9	28.9	28.9	28.8	28.8	28.8	28.7
	29.3	29.9	29.7	30.1	29.1	29.3	29.1	29.3	29.8	28.9	29.1	29.3
	−0.2	−0.1	−0.2	−0.8	−0.3	−0.4	−0.2	−0.4	−1.0	−0.1	−0.3	−0.6
D	28.5	31.0	30.9	30.6	30.2	30.2	30.4	30.3	29.0	28.4	28.5	28.6
	28.7	31.1	31.2	31.0	30.3	31.2	30.6	30.4	29.4	28.7	28.6	29.0
	−0.2	−0.1	−0.3	−0.4	−0.1	−1.0	−0.2	−0.1	−0.4	−0.3	−0.1	−0.4
E	28.0	30.9	31.3	31.3	31.5	31.4	31.5	31.2	29.2	28.3	28.5	28.7
	28.2	31.3	31.6	31.5	31.5	32.4	31.7	31.4	29.8	28.5	28.7	29.0
	−0.2	−0.4	−0.3	−0.2	+0.0	−1.0	−0.2	−0.2	−0.6	−0.2	−0.2	−0.3
F	27.4	29.9	30.0	29.9	30.3	30.3	30.2	30.1	29.0	27.9	28.1	28.2
	27.8	30.7	30.9	30.2	30.5	30.6	30.6	30.4	29.3	28.1	28.5	28.4
	−0.4	−0.8	−0.9	−0.3	−0.2	−0.3	−0.4	−0.3	−0.3	−0.2	−0.4	−0.2
G	28.0	28.6	28.5	28.4	28.9	28.9	28.9	28.9	28.9	28.5	28.4	28.3
	28.1	29.1	28.7	28.8	29.1	29.8	29.1	29.0	28.9	28.7	28.6	28.8
	−0.1	−0.5	−0.2	−0.4	−0.2	−0.9	−0.2	−0.1	+0.0	−0.2	−0.2	−0.5
H	28.9	27.4	27.6	27.6	27.9	27.6	27.6	27.6	27.7	28.9	28.7	28.6
	29.2	27.7	27.8	27.8	28.1	27.9	27.8	27.9	28.1	29.0	29.0	28.9
	−0.3	−0.3	−0.2	−0.2	−0.2	−0.3	−0.2	−0.3	−0.4	−0.1	−0.3	−0.3

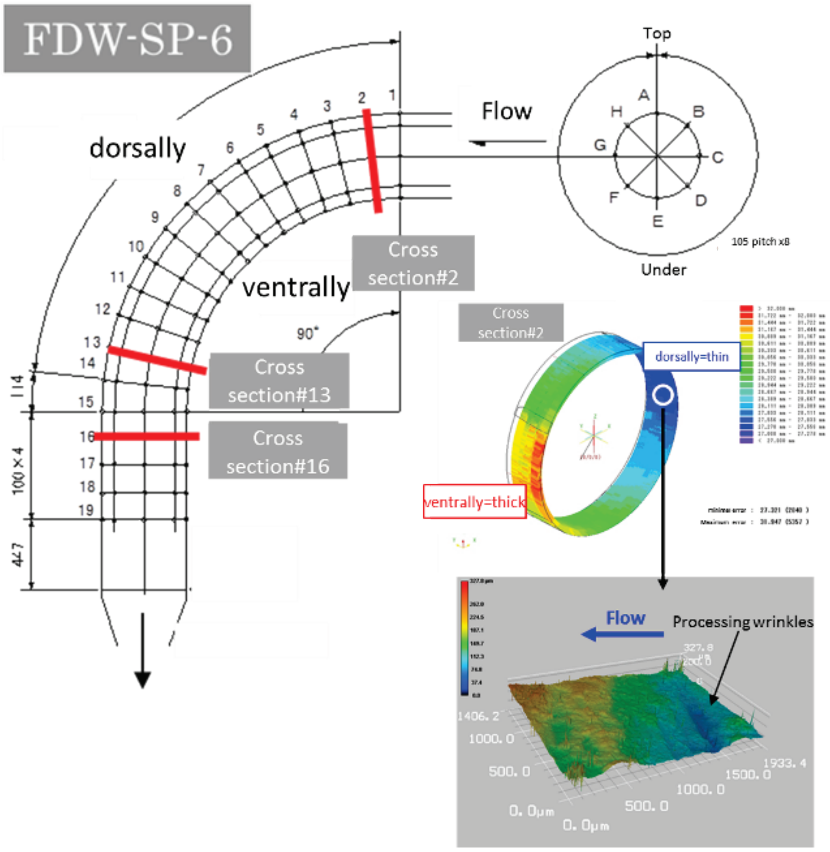

Fig.4 An example of the results of the detailed investigation.

Fig. 5 shows the results of the detailed investigation on the welded area in the same manner. It is shown that there exists thinner area along with the welding line in a radial direction corresponding to the heat affected zone (HAZ). Although it is confirmed again by the LASER microscopy the existence of the thinner area along with the weld line, no local corrosion has been confirmed. It is assumed that the thinner area along with the weld line was formed by the thermal shrinkage caused by welding heat input.

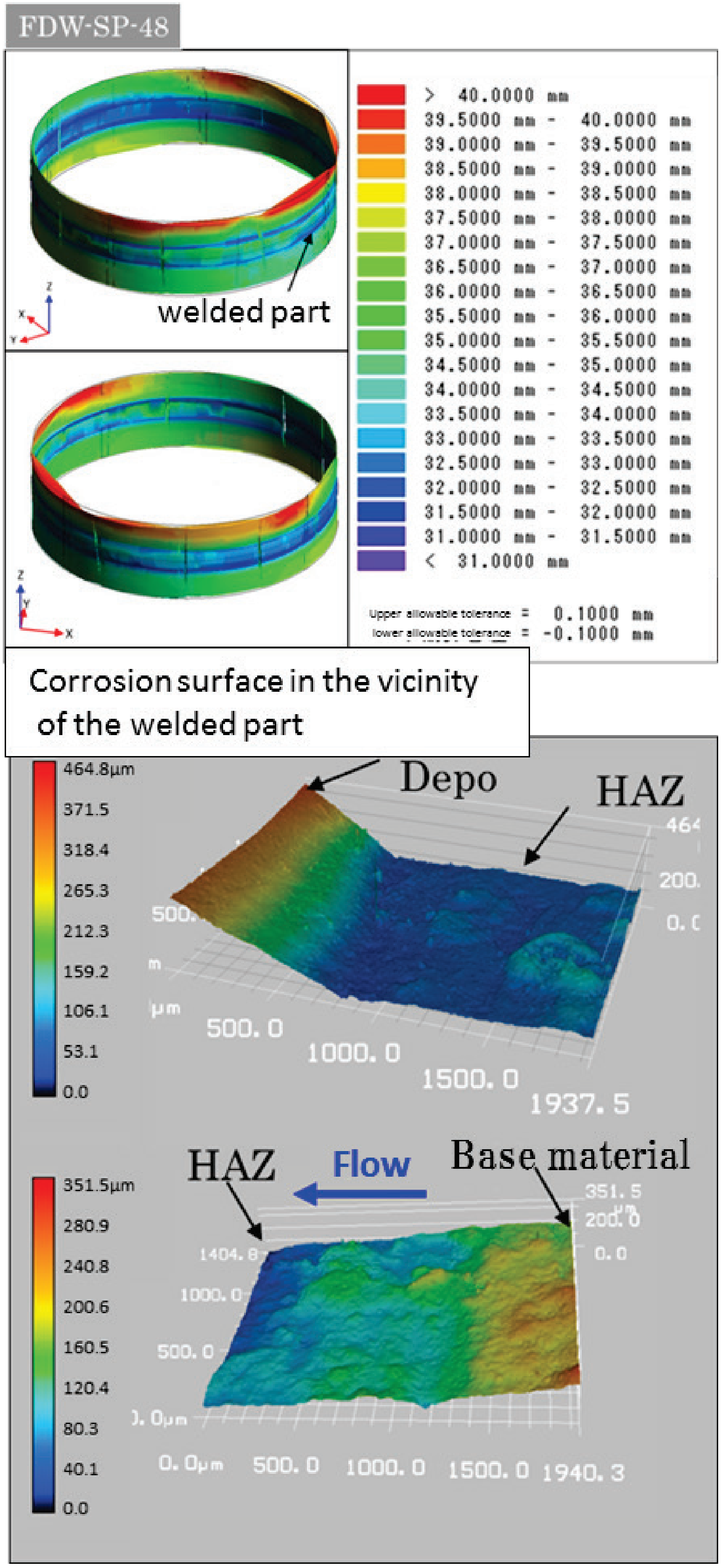

Fig.5 Results of the precise measurement at welded area using three dimensional wall thickness measuring device

It is presumed that the significant deviation of the thinning rates near weld shown at the first periodic inspection was due to this thickness deviation and the use of nominal thickness for the thinning rate calculation instead of the last measured thickness, and that the thinning rate became the average at the second periodic inspection and after because of the use of the last measured thickness. Bides, it can be assumed that significant deviation of the thinning rates was caused by slight positional displacement at the measurement point where the thickness alters sharply at each measurement. There is a high probability that localized deformation and steep thickness change caused by cold bending, welding and other processes can affect the deviation of the thinning rates. Those facts were observed at the all detailed measurement targets.

3. Accuracy confirmation of wall thinning prediction formula

3.1 Flow analysis

Flow analyses have been carried out around the measurement targets for the detailed investigation mentioned above with the steady state condition of Fugen during operation using a commercial flow analysis code, Fluent of ANSYS. Three dimensional analysis was adopted, and in each flow analysis, the estimation area was expanded to the upstream elbow or bent of those targeted.

Fig. 6 shows an example of the results of the flow analysis on the welded area in the same manner.

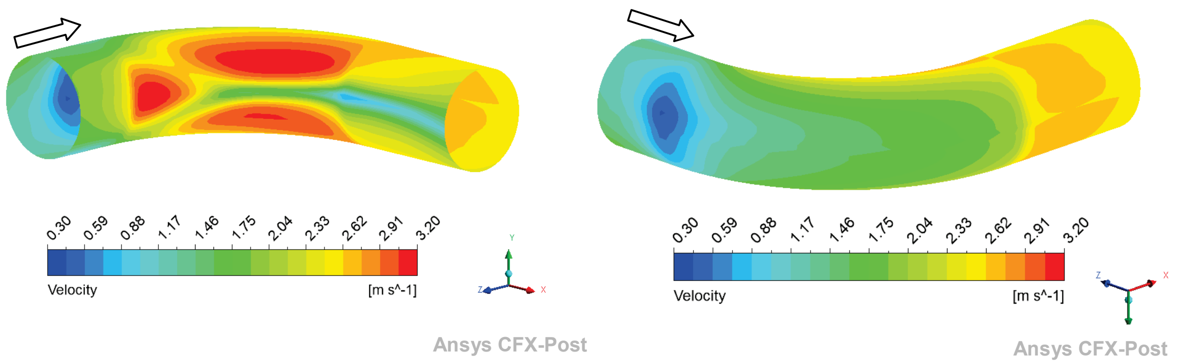

Fig.6 The synthetic flow velocity distribution on the surface of a wall in the vicinity of FDW-SP-48 elbow

Comparing the estimation results obtained by Fluent with the results obtained by other commercial three dimensional flow analysis code, OpenFOAM [3], there are no significant differences in turbulent flow energy distribution and flow velocity distribution as shown in Fig. 7.

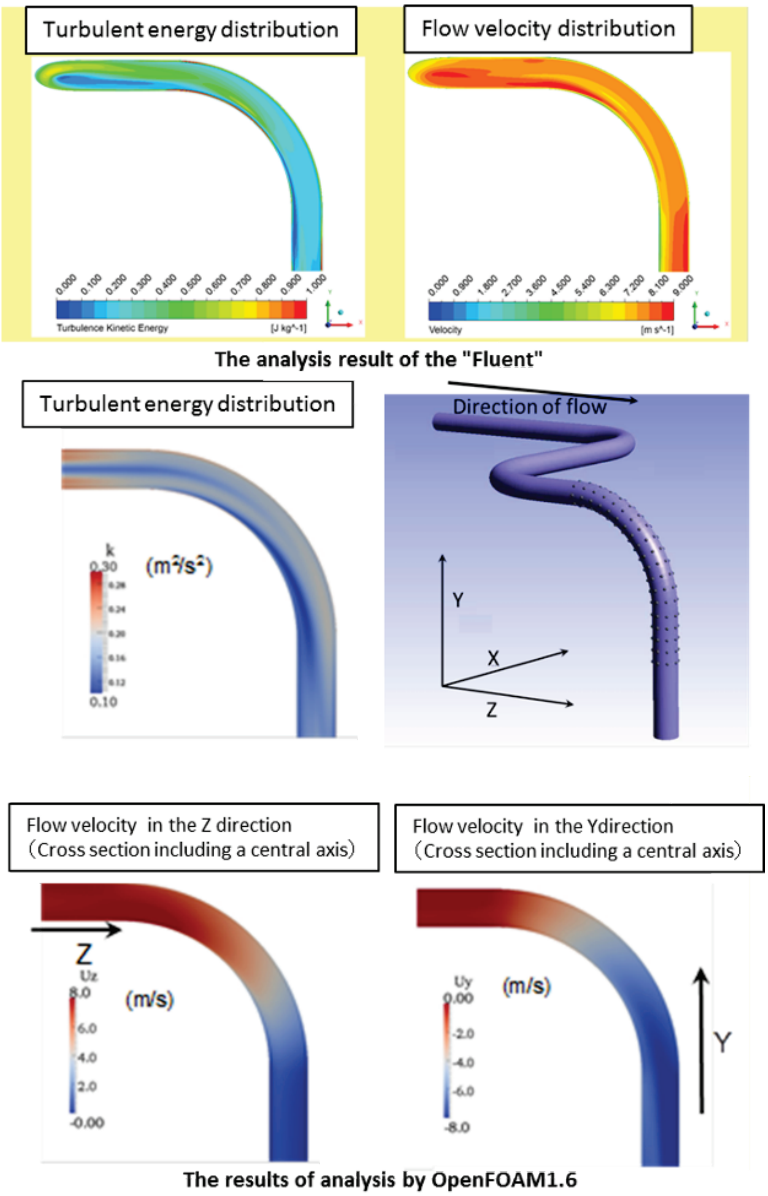

Fig.7 Comparison of flow analysis results between Fluent and OpenFOAM in the vicinity of FDW-SP-6 elbow

3.2 Estimation of thinning rate

Fig. 8 shows the estimation results of thinning rates of the targeted elbow, FDW-SP-6, calculated by PASCAL-EC and DRAWTHREE-FAC [4], based on the turbulent flow energy calculated by OpenFOAM, as contour maps on the expanding plans cut off along with the outer curve of the elbow, after converting the data into the cylindrical coordinate system.

It is confirmed that there is a certain degree of correlation between flow energy distribution and thinning rate distribution, and the estimated value by DRAWTHREE-FAC is comparable to measured data.

However, there still exists significant difference in the thinning rate between measured and calculated up to two-digit.

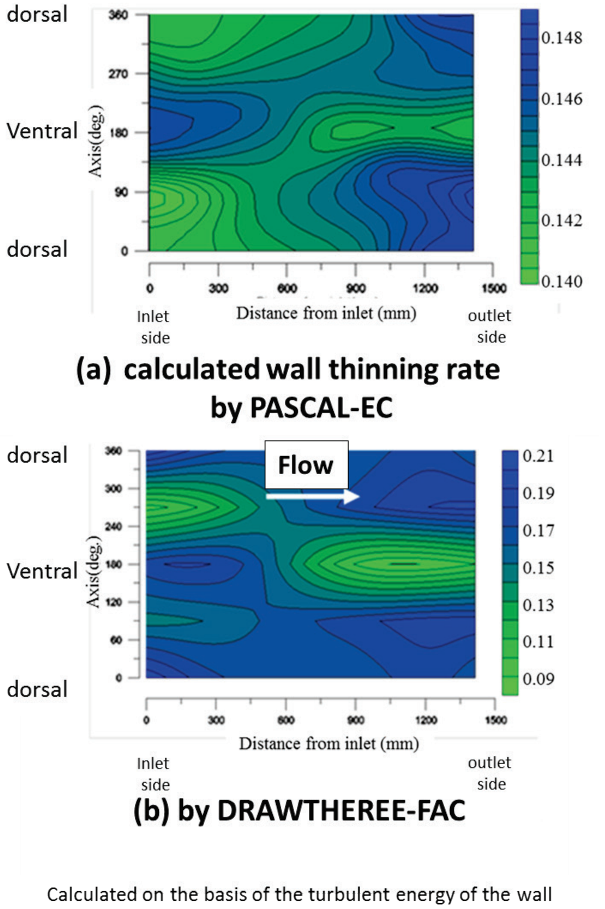

Fig.8 Comparison of calculated wall thinning rate distributions with measured

4. Validity of countermeasure for wall thinning

Fig.9 is a summary of the observation results of the corrosive surface of the detailed measurement targets. FAC corrosion organization known as orange peel and Scale patterns were not observed. There has been no corrosive surface of FAC such as scale-like or orange peer like structure observed on the corrosive surface of entire detailed measurement targets. Local corrosion also has not been observed, only uniform and general corrosion was observed. Typical examples of the corrosion surface of FAC reported by Ministry of Economy Trade and Industry [5] are shown for reference.

In addition, these observation results coincide with the fact that the total mean value of the thinning rates of entire 148 measurement targets, namely, about 28,000 measurement points investigated shows less than 0.1 mm per 10,000 hour, and This fact means that the management of the wall thinning at Fugen was appropriate.

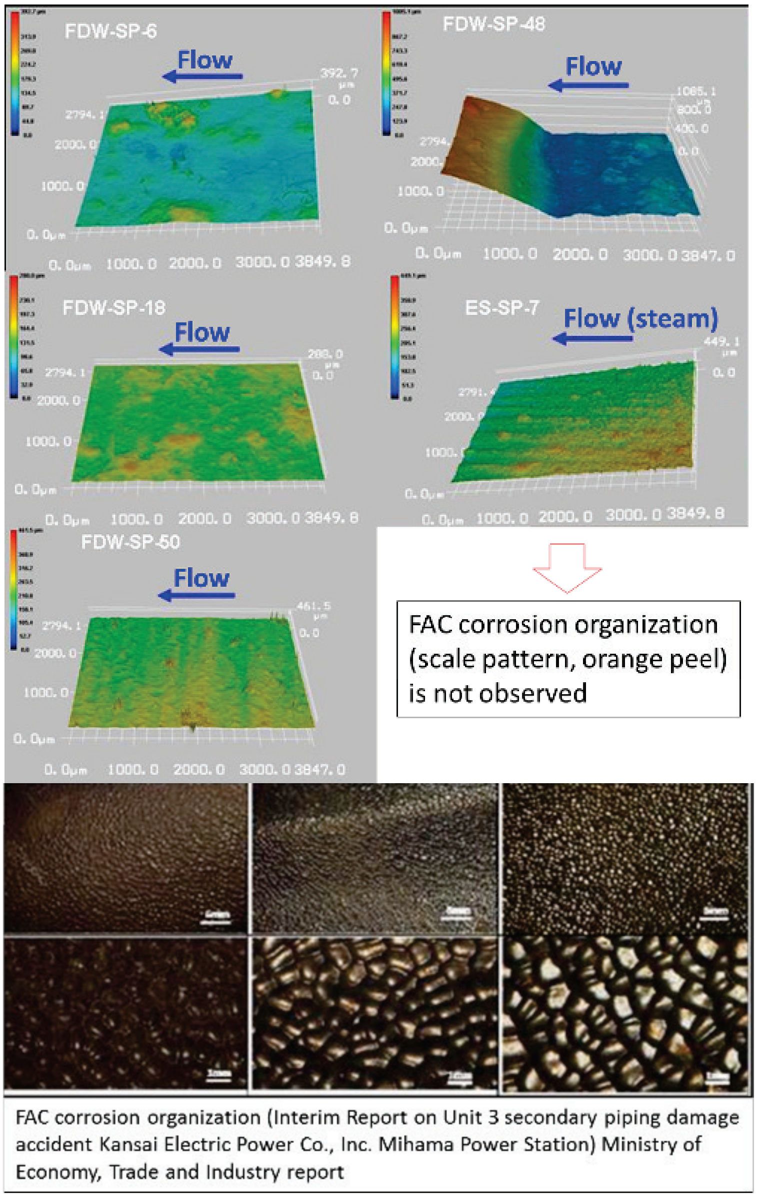

Fig.9 Comparison of corrosion surface observations and typical FAC surface

5. Rationalization of wall thinning management

A web based data base has been developed in order to contribute to the rationalization of the wall thinning management as shown Fig. 10, storing all of the wall thinning measurement results of entire Fugen piping system, flow analysis (3D-CFD) results, and estimated results of thinning rates considering the parameters on environmental conditions such as temperature, average flow velocity, flow velocity nearby inner surface of piping, water quality, and so on.

Furthermore, while the isometric figures of piping as shown in Fig. 10, CAD drawings for the use of processing of the dimensional value, and estimation results of flow analysis and wall thinning analysis have been stored on the data base, it is now available to browse and use of the information stored through web..

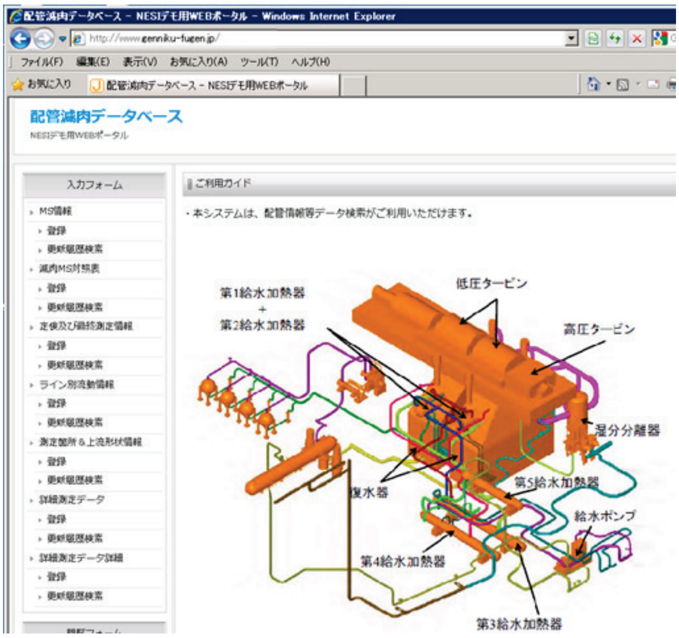

Fig.10 Overlook of Fugen wall thinning database indicating the view of the secondary cooling system

6. Conclusion

Based on the data of Fugen serviced materials, investigations have been carried out on accuracy of wall thinning prediction formulas, validity of countermeasures for wall thinning and rationalization of pipe thinning management　As a result, it was confirmed that the management of the cooling water quality of Fugen during operation was appropriate.　These results represent the tendency of the wall thinning of the serviced material of Fugen for long operating years, therefore, they can contribute to accurate understanding of wall thinning phenomena of serviced materials.

Acknowledgement

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References

For citations in the text, numbers between square brackets should be used such as [1]. All publications cited in the text should be presented in a list of references following the text of the manuscript. Footnotes should be used only if absolutely essential. Font size is 10 pt.

References should be listed in the following style:

[1] Technical standards for boiling water reactor nuclear power plant pipe thinning management" power-generating nuclear power plant standard (2006 version) JSME S NHI 2006 (Published by The Japan Society of Mechanical Engineers)
[2] Kastner W., et al., Empirical Model for the Calculation of Material Losses due to Corrosion Erosion, VGB Kraftwerkstechnik 66, 12,(1986) pp. 1023-1029.
[3] H.G. Weller, G. Tabor, H. Jasak, and C. Fureby, “A tensorial approach to computational continuum mechanics using object orientated techniques”, Computers in Physics, 12(6), 620(1998).
[4] Ministry of Economy, Trade and Industry innovative practical use nuclear technology development costs auxiliary business
「Development of vibration and corrosion evaluation method of two-phase flow of gas-liquid structure by the coupled analysis」 Result Report, March 2007.
[5] Ministry of Economy Trade and Industry, Interim report on secondary piping damage accident at Mihama power station unit 3 of Kansai Electric Power Co., Inc., Sept. 2004.