Innovative Pipe Thickness Verification for Feedwater Flow at Darlington Nuclear Power Generating Station

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Abstract

Darlington nuclear generating station (DNGS) uses externally mounted Ultrasonic Flow Meter (UFM) to verify its feedwater flow rate for the heat balance program. Recently a WANO operating experience (OPEX – WER ATL 14-0448) has identified an issue with the pipe thinning under the externally mounted UFM transducer area in PWR plants, consequently the flow correction factor had been slowly trending in the non-conservative direction. Therefore, DNGS needs to assess the implication of this OPEX and confirm if the pipe thinning is occurring beneath DNGS's UFM brackets. This report is to summarize the action taken on the piping thickness measurements and the results in a cost effective way. Additional, the results are also verified with FAC (flow accelerated corrosion) monitoring data.

1. Introduction

In December 2013, an Operation Experience (OPEX) was published under a WANO event report (WER ATL 14-0448). This OPEX is related to pipe thinning under the externally mounted UFM transducers. Pipe wall thinning causes the UFM reading to be biased in the non-conservative direction (lower than actual). If the reactor power calculation is based on the UFM reading, this results in an under estimation of actual reactor thermal power. Therefore, the station reactor thermal power output could be greater than 100%, which is a violation of its operating license.

At DNGS, externally mounted UFM transducers are used to verify the feedwater flow reading accuracy. Feedwater flow is an input parameter to the heat balance calculation (reactor thermal power measurement process). If the pipe under the UFM transducers has thinned, DNGS reactor thermal power may be higher than heat balance calculation result. Plant Performance Section (PPS) was assigned to verify if any pipe wall thinning has occurred.

2. Purpose

The purpose of this work is to develop an innovative method to verify and monitor feedwater pipe thickness under the UFM transducers, with safety and cost as primary considerations.

3. Methodology

There are two methods to measure the feedwater pipe thickness under the UFM transducers: direct and indirect. The direct thickness measurement method is simpler to understand. It involves measuring the thickness at the same points measured prior to original transducer installation in 2001 [1], as shown in Figure 1. This method involves: removing the transducer, performing the thickness measurement, and then re-installing the transducer. In the WER ATL 14-0448 event report, the UFM vendor employed the direct measurement method. This method poses two issues: safety and cost.

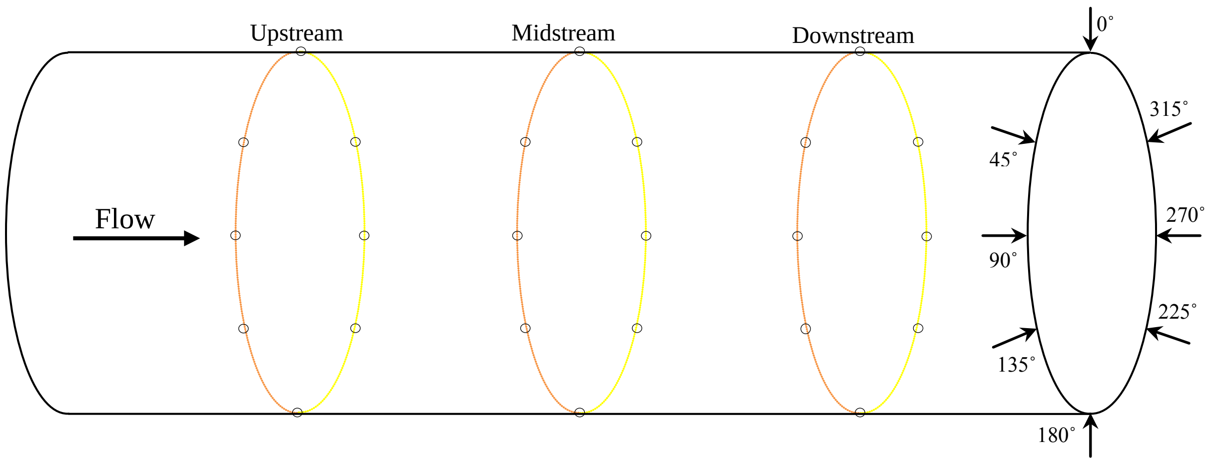

Figure 1   Pipe thickness measurement points prior to transducer installation

The safety issue is that the feedwater pipe surface temperature is around 170˚C. With the insulation removed to access the pipe surface for measurement, the surrounding temperature is also elevated. In between the pipes, the temperature there can be as high as 60˚C. This high surrounding temperature is a hazardous working environment.

Once installed and tuned, UFM transducer continues to function unless disturbed. The costs involved in direct thickness measurement are described below:

- UFM transducers need to be removed and re-installed. This process takes four persons 1.5 days (per pipe) to complete: 0.5 day to remove and 1 day to install and tune the transducer. This labour cost is $1850.
- During installation, the probes contact is deformed to take the shape of the pipe for proper contact (see contact deformation in Figure 2). The contacts can only be used once; as such, probe contacts need to be reconditioned by the vendor upon re-installation. The cost for probe reconditioning is about $1000 per probe, and each transducer has four probes. The probe reconditioning cost is about $4000.
- Threads and fasteners on UFM transducer frame are damaged during removal process (see Figure 3) due to thermal cycling. They need to be replaced, or reconditioned prior to re-installation (this cost about $3000).

Each unit at DNGS has four pipes, resulting in cost of $35,400 per unit. DNGS is a four unit station. The total cost can be as high as $141,600. This is equivalent to 1.8 full time employee’s wage. For a section of seven workers, this is a 25% work load saving; as well as, eliminating the hazard the workers are being subjected to.

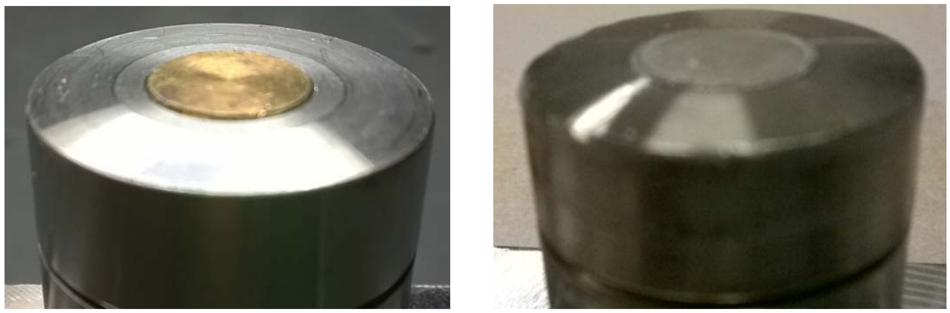

Figure 2 Probe contact comparison new (left) verse used (right)

(a) (b) (c)

Figure 3 Thread damage due to thermal cycling of UFM transducers

(a) Sample of a small bolt used to secure probe to transducer frame
(b) Sample of large bolt used to secure transducer frame to pipe
(c) Example of a small bolt seized in the frame

The indirect measurement involves measuring the pipe thickness around the transducer, as shown in Figure 4, where measurement points are not the same as the original measurement performed in 2001 [1]. However, the thickness of seamless pipe is non-uniform due to their manufacturing process [2]. This method of measurement improves safety and reduces and cost issues associated with direct measurement method. The concern is whether the indirect thickness measurement can provide the same results as the direct measurement. To address this concern, the new thickness measurement points are measured twice by two different teams, where each team performs independent measurements. This is to ensure that each measurement remains bias free. The difference between the new data sets of measurement is used to gauge the difference and compare against the original thickness measurement that was performed in 2001 [1]. The thickness measurement is performed to address the concerns raised by the OPEX WER ATL 14-0448.

Although, the indirect measurement reducers the workers' exposure to hazardous environment, it does not eliminate the hazard. An alternate method is to use the Flow Accelerated Corrosion (FAC) data, which is gathered near the boiler LCVs (upstream of the transducer mounting locations) as part of the DNGS piping monitoring program [3], [4]. The FAC method has its own limitations. It only serves as a reference when the result shows no pipe thinning. If the FAC results show signs of thinning, the direct or indirect thickness measurement under or around the UFM transducer mounting location must be performed. This method can be used as long term monitoring of pipe thickness as recommended by WER ATL 14-0448.

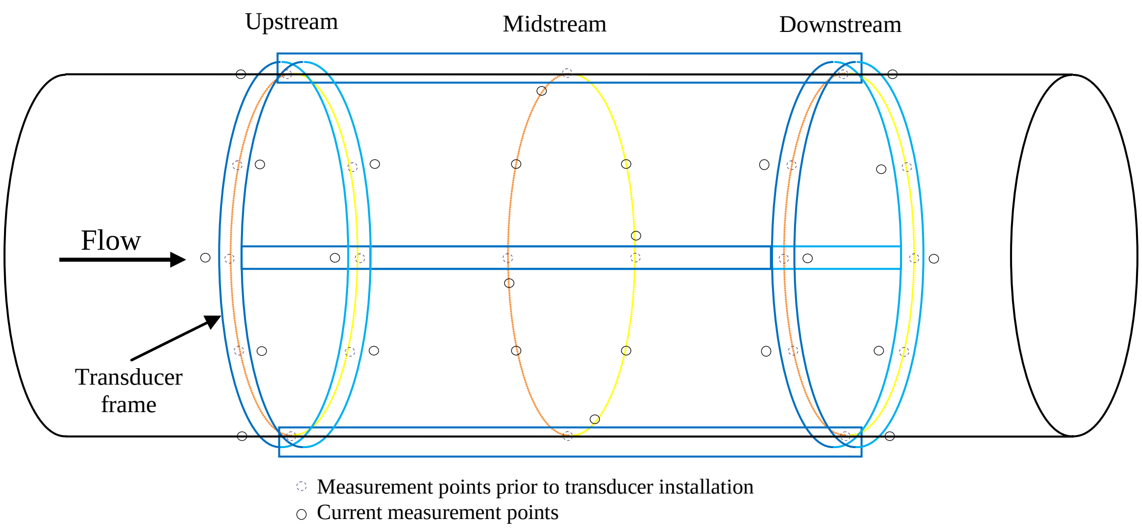

Figure 4 Pipe thickness measurement points with transducer installed

4. Measured Thickness Data Analysis and Results

Thickness data analysis is performed as per I-INS-30611-50008 [5]. The average thickness and measurement uncertainties are calculated for comparison. The uncertainties calculations are based on ASME PTC 19.1-2005 [5]. The different comparison methods employed in this document are to ensure that the thickness measurement at different points on the pipe does provide the same average thickness.

4.1 Overall Average Comparison

The overall average of the thickness measurements is summarized in Table 1. This value is used in the UFM as part of the conversion from measured time delay to physical flow unit. Hence, the overall thickness average directly affects the measured flow. Table 1 shows that, the overall averages of pipe thickness (for all pipes in Unit 4) agree within measurement uncertainties. The agreement of the results is independent of measurement points (direct or indirect) or time when the measurements are taken. Results in Table 1 indicate there is no pipe wall thinning in the location where the UFM transducers are mounted for Unit 4.

The maximum difference between these measurements (Table 1) is 0.005”, which is within the measurement uncertainty for Boiler 1. This difference in average is between PPS measurements by Team A and Team B of the same points. These results confirm that there is no pipe wall thinning at the UFM transducer mounting locations.

The results in Table 1 indicate that the indirect thickness measurement is sufficient. However, this result does not provide the assurance that the thickness measured at different points reflects the same reading as the direct measurement. Sections 4.2 and 4.3 provide further analysis to assure that indirect measurement results reflect the same thickness measured in 2001 [1] when the transducers were installed.

Table 1 Overall average thickness comparisons

Boiler	Average Measurement Thickness			Max Difference	Min Uncertainty
	Team A	Team B	Data from 2001		
1	0.997	1.002	0.997	0.005	0.005
2	0.982	0.985	0.981	0.004	0.006
3	0.977	0.978	0.976	0.002	0.005
4	0.985	0.985	0.982	0.003	0.004

- All measurement units are in inches
- Data for indirect measurement are being collected using an ultrasonic (Panametrics® 37DL Plus) thickness gage
- New measurement data performed by teams A and B are indirect measurements, and data from 2001 are direct measurements

4.2 Point by Point Comparison of PPS data

In this section, the point by point comparison of data collected by PPS personnel is analysed. As there are large amount of data to compare, only the data from Boiler 2 and Boiler 3 are presented in this section. Figure 5 displays the point by point thickness measurement of Boiler 2, and Figure 6 displays the point by point thickness measurement of Boiler 3. The error bars on these figures indicate the measurement uncertainties (also known as confidence interval) of the points.

Both Figure 5 and Figure 6 show that the measured thickness varies in range which is greater than the measurement uncertainties. This fact confirms the assumption that the thickness of a seamless pipe is non-uniform. However, when the measurement data from the same point is compared between two teams, most results are within the uncertainty, but some points do not agree and are outside of the uncertainty. This is because there are only three measurements per point for the estimated uncertainty. With only three points, the statistical relation is weak, and can be easily over whelmed by potential human performance issues. Regardless of these points' misalignment, the overall average of the measured thickness agrees within the overall measurement uncertainty (section 4.1).

The details for Figure 5 and Figure 6 are hard to see due to the number of plots on the graphs. For simplicity, the differences between the measurements are plotted in Figure 7 and Figure 8. The error bars in these plots are the combined uncertainties of the two measurements. These plots show that most of the points' error bars cross the zero of the Y-axis; while, a few of them do not. The measurements agree within combined uncertainty, if error bar of a point crosses zero of the Y-axis; otherwise, they do not agree. This analysis mirrors the analysis of Figure 5 and Figure 6. This result indicates that the overall average value of the pipe thickness does not depend on the measurement locations. As long as enough data points are collected, they cover the section of the pipe where the transducer is installed.

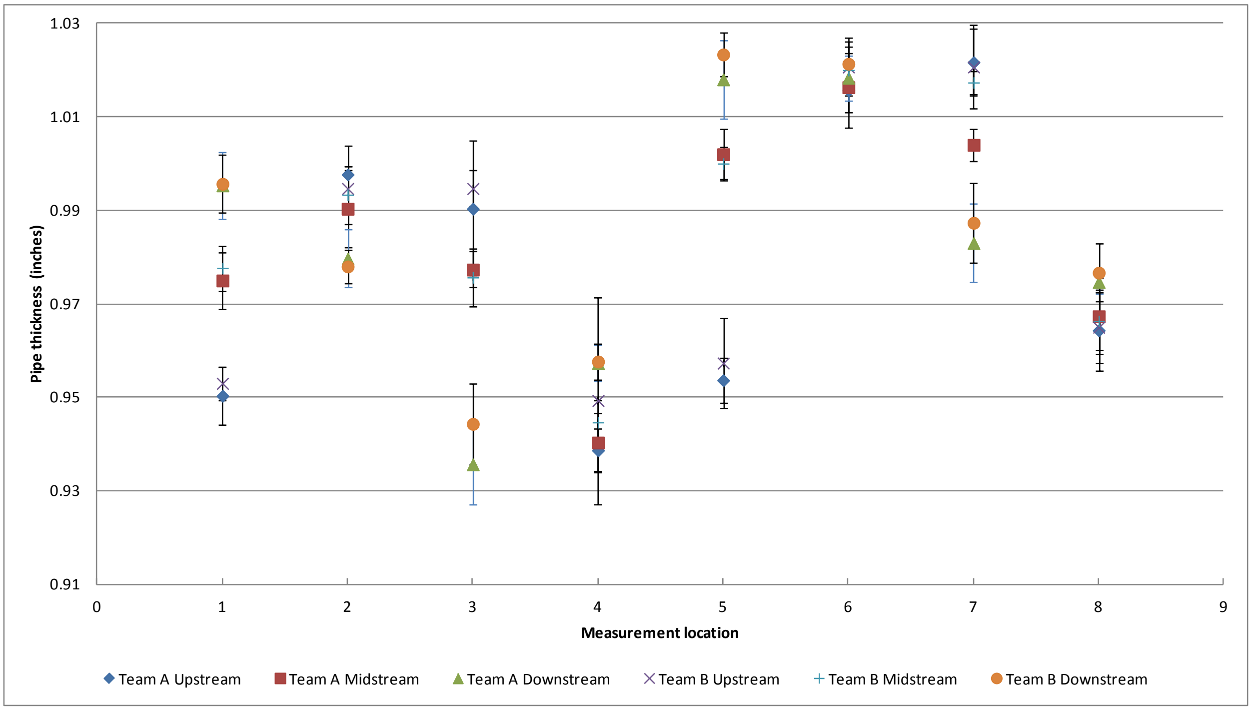

Figure 5 Point by point thickness measurement for Boiler 2

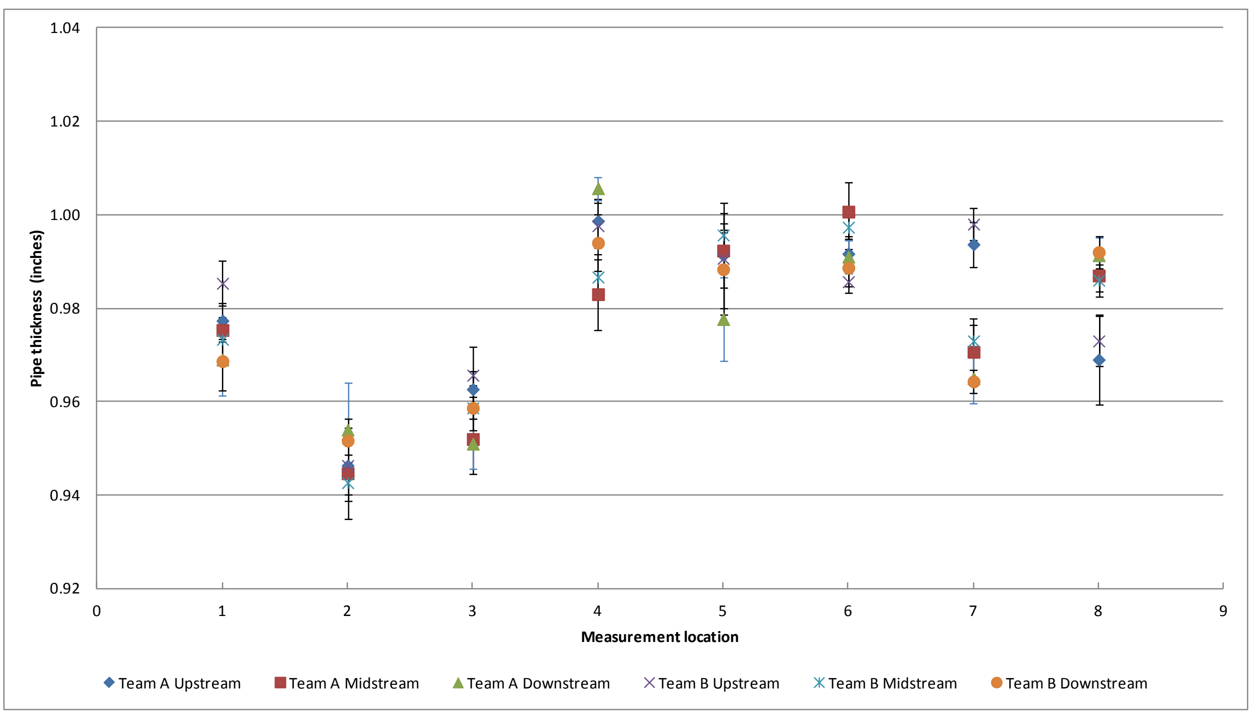

Figure 6 Point by point thickness measurement for Boiler 3

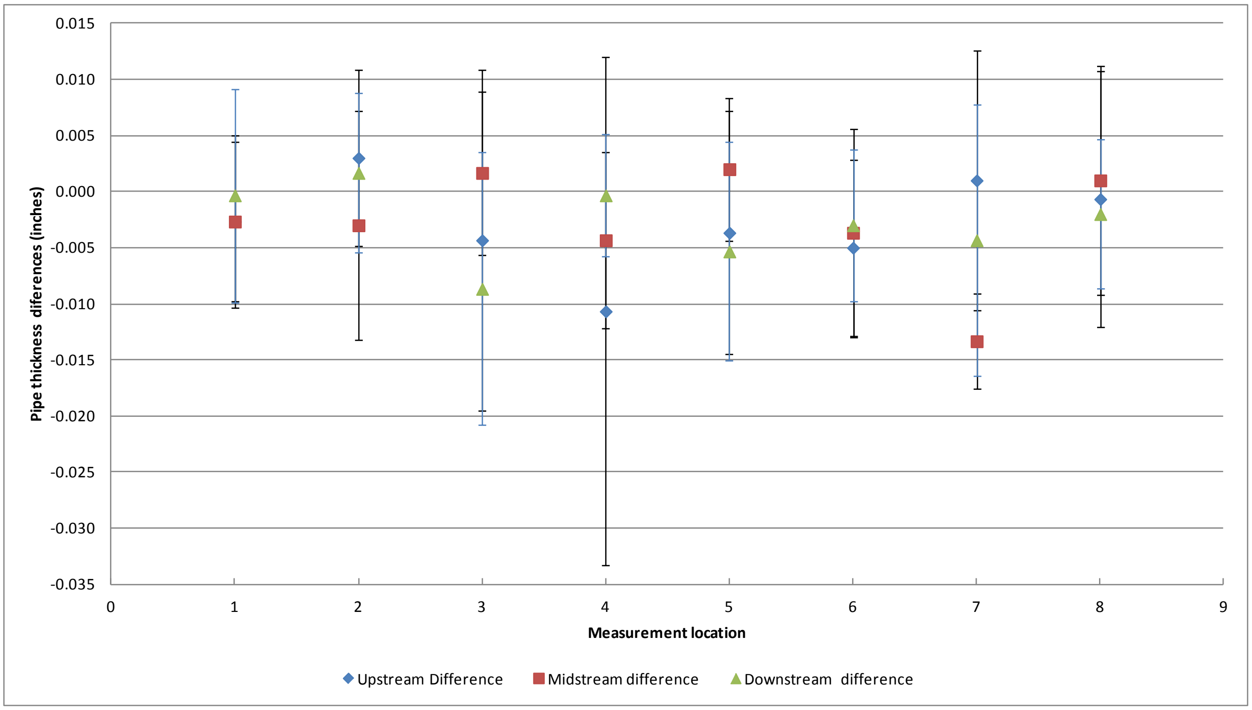

Figure 7 Difference in thickness measurement between teams A and B for Boiler 2

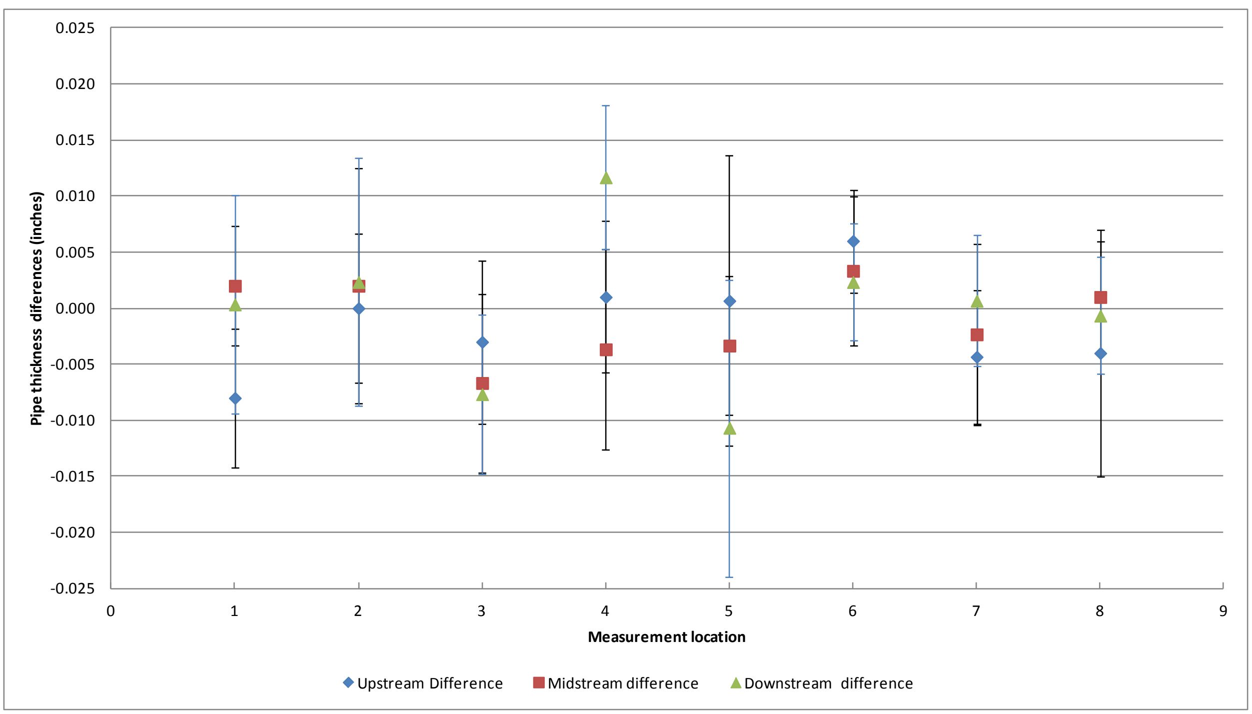

Figure 8 Difference in thickness measurement between teams A and B for Boiler 3

For better comparison, the overall plane averages and measurement uncertainties by the two teams are also calculated and listed in Table 2. This table shows that the plane maximum differences between the two teams are smaller than the minimum uncertainty, even though, some individual points are misaligned. The number of data points to calculate each plane average is 24.

Table 2 Summary of plane averages comparison by teams

Boiler	Plane	Team A Average	Team B Average	Max Difference	Min Uncertainty
2	**Upstream**	0.979	0.982	0.003	0.013
	Midstream	0.984	0.987	0.003	0.011
	Downstream	0.983	0.986	0.003	0.012
3	**Upstream**	0.979	0.980	0.001	0.008
	Midstream	0.976	0.977	0.001	0.009
	Downstream	0.976	0.976	0.000	0.008

*All measurement units are in inches

The analysis in this section shows that it is difficult to compare thickness data point by point. However, when comparing the average of enough data points they do agree within the measurement uncertainties.

4.3 Direct Comparison with Original Data in 2001

Careful examination of Figure 1 and Figure 4 show that there are four points along the midstream plane that the PPS measurement coincide with the original measurement points made in 2001 [1]. This is possible because there are openings in the middle of the transducer frame, which allow for direct comparison with the originally measured data in 2001. These points are at positions 45°, 135°, 225°, and 315° (Figure 1). This section provides the direct comparison of the three set of data at these points. Similar to section 4.2, only data for boilers 2 and 3 are used for this comparison. The average and uncertainties of the measurements are listed in Table 3.

Table 3 Thickness data for midstream locations

Boiler	Point	Average Measurement Thickness			Max Difference	Min Uncertainty
		Team A	Team B	Data from 2001		
2	45°	0.977	0.976	0.963	0.014	0.004
	135°	0.990	0.993	0.990	0.003	0.005
	225°	1.016	1.020	1.014	0.006	0.003
	315°	0.967	0.966	0.940	0.028	0.005
	Avg	**0.988**	**0.989**	**0.977**	**0.012**	**0.013**
3	45°	0.945	0.943	0.936	0.009	0.003
	135°	0.983	0.987	0.989	0.006	0.005
	225°	1.001	0.997	1.001	0.004	0.002
	315°	0.987	0.986	0.981	0.006	0.003
	Avg	**0.979**	**0.978**	**0.977**	**0.002**	**0.015**

*All measurement units are in inches

Table 3 shows that the maximum difference for point by point comparison is greater than the minimum uncertainty. This is an indication that point by point measurement comparison does not contain enough data points (only 3) to be within statistical variation. The boiler averages of the common points measured by the two teams and data from 2001 are also displayed in Table 3. Unlike the point by point comparison, the boiler averages show that the maximum difference is smaller than the minimum uncertainties, thus within measurement uncertainties. The number of data points included in the boiler common points average is 12.

4.4 Comparison of Average Thickness Values from Different Subsets

To summarize the results from different analysis, data from Boiler 3 is used as an example for this comparison. The summaries of the average values from Table 1, Table 2 and Table 3 for Boiler 3 are listed in Table 4. Table 4 shows that in all rows the maximum difference is smaller than the minimum uncertainty; indicating that they are within measurement uncertainties.

This summary clearly shows that the average value of the thickness measurements is consistent regardless of the position of measurement. Thus, the result of this comparison assures the fact that the indirect measurement produces statistically identical average thickness results as the original measurement performed in 2001.

Table 4 Thickness average comparisons using Boiler 3 data

Data set average		**Measurements**			**Max Difference**	**Min Uncertainty**	**# of data points**
		Team A	Team B	2001			
Overall (**Table 1**)		0.977	0.978	0.976	0.002	0.006	72
Planes (**Table 2**)	Upstream	0.979	0.980	0.976	0.004	0.007	24
	Middle	0.976	0.977	0.978	0.002	0.009	
	Downstream	0.976	0.976	0.974	0.002	0.005	
4 Points (**Table 3**)		0.979	0.978	0.977	0.002	0.015	12

*All measurement units are in inches

5. DNGS FAC Historical Data on Upstream Piping

5.1. Reason for FAC Data Analysis

Flow Accelerated Corrosion (FAC) is the process where the fluid transported in the pipe removes the protective oxide of the metal. The exposed metal forms new oxides, which is then removed by the fluid [6], [7]. This process continues and the pipe becomes thinner. The oxide is only removed from the pipe when the oxide concentration in the fluid is below saturation. If the oxide concentration is saturated, no oxide on the pipe is removed, thus the pipe thinning does not occur. If the upstream pipe is monitored, and shows no sign of thinning, this means the oxide concentration in the fluid is saturated before reaching the location of UFM transducer. In this case, the pipe under the UFM transducer is not thinned by FAC process.

OPG has procedures to monitor thinning of many pipes [3], [4] to ensure piping integrity. Particularly, many feedwater pipe sections near the boiler LCVs, upstream of the UFM transducer location, are monitored by this process (Figure 9 shows an example of Boiler 2 piping). If the FAC monitoring data show that the pipe upstream of the UFM transducer location is not thinning, then it can be deduced that the pipe under the UFM transducer is not thinning.

Also, the data collection for FAC monitoring is performed during unit outages; both the pipe and the surrounding environment are cool. Therefore, by using FAC data to monitor pipe thickness under UFM transducer eliminate workers' exposure to hazardous environment for this work. This also reduces operating cost, as pipe thickness measurement is only performed once.

The pipe segment downstream of boiler LCV201 with CHECWORKS™ identification 4-4300-L29-P13-1 (Figure 9) is chosen for sample analysis for two reasons: one, this pipe is upstream of the UFM transducer location, and two, it is situated at the exit of an LCV. As such, the turbulent condition in this pipe is more violent compared to the location under the UFM transducer. FAC is related to turbulent condition in the pipe [6], [7].

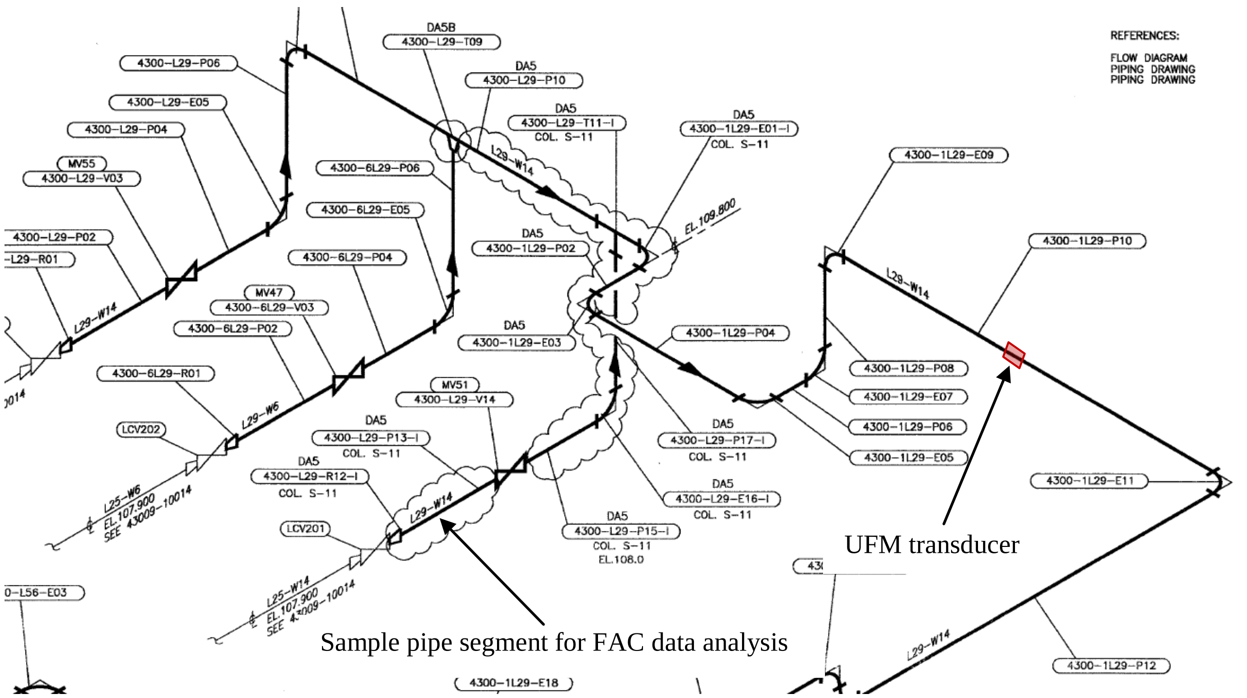

Figure 9 Piping layout of sample FAC data

5.2. FAC Data Analysis for Pipe Identified by 4-4300-L29-P13-1

After contacting the staff in Piping & Rotating Equipment section (P&RE), and searching through the reports, three data sets for this pipe segment collected in 2001 [9], 2003 [10], and 2010 [11] were found (data can be provided as required). These data were provided by the P&RE personnel.

The average, standard deviation, uncertainty, maximum, and minimum values of the data are summarized in Table 5. This table shows that all the data over the years are comparable within statistical variations. The average thickness values from these data sets are statistically identical. This result shows that there is no thinning in this pipe segment over the years (covered by the data presented).

Table 5 FAC data summary

Year	2010	2003	2001
Average	24.87	24.87	24.90
Standard deviation	0.27	0.29	0.29
Uncertainty	0.06	0.07	0.07
Maximum	25.58	25.55	25.60
Minimum	24.36	24.20	24.27

*All measurement units are in mm

FAC data are collected by industry ticketed qualified personnel based on specific grid patterns [12] at room temperature. A point by point comparison of these data provides validation to the observations noted in sections 4.2 and 4.3. Point by point comparison is cumbersome, so the differences are calculated and summarized. The average, standard deviations, uncertainty, maximum, and minimum values of the data are calculated, and summarized in Table 6.

Table 6 Summary of FAC data for the differences between the years

Difference between the years	2010-2003	2010-2001	2003-2001
Average	0.005	0.005	-0.038
Standard deviation	0.097	0.097	0.173
Uncertainty	0.024	0.024	0.041
Maximum	0.29	0.29	0.31
Minimum	-0.23	-0.23	-0.55

*All measurement units are in mm

Table 6 shows that the average value of the difference are practically zero (the uncertainty value is greater than the average value). However, in all data columns, either, the maximum or the minimum value is greater than the uncertainties. This indicates that some data points are outside the measurement uncertainties. This is in line with the observations made in sections 4.2 and 4.3.

6. Conclusion and Recommendations

In conclusion, as result of the OPEX – WER ATL 14-0448, the indirect thickness measurement for all pipes in unit 4 were performed. This measurement produces statistically identical average thickness results as the original measurement performed in 2001 (Table 1). Compared to direct measurement, the indirect measurement reduces workers' exposure to hazardous working environment and operating cost saving, equivalent to about 25% of PPS section's work load for the entire station. The indirectly measured thickness data showed that there is no pipe thickness thinning occurring in DNGS Unit 4 feedwater pipes under the UFM transducers. Additionally, data subsets analysis (sections 4.2, 4.3) have been performed to ensure that indirect thickness measurement performed around the transducer provides the same average thickness value as direct measurement.

Analysis of FAC data from a pipe segment upstream of the UFM transducer location with harsher turbulent conditions show that there is no indication of thinning on the pipe wall. In the future, it is advised to monitor FAC data to monitor pipe thickness conditions. If any signs of thinning are evident in these pipes, then indirect measurement around the UFM mounting location should be performed to confirm the pipe thickness. Otherwise, no action is required. By using FAC data to monitor feedwater pipe thickness, hazardous work and cost are further reduced. This monitoring program is to comply with OPEX – WER ATL 14-0448 recommendation for long term thickness monitoring.

7. References

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