Determination of Erosion/Corrosion Rates in Hanford Tank Farms Radioactive Waste Transfer System Pipelines – 16395

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ABSTRACT

The twenty-eight double-shell underground radioactive waste storage tanks at the U.S. Department of Energy's Hanford Site near Richland, WA are interconnected by the Waste Transfer System network of buried steel encased pipelines and pipe jumpers in below-grade pits. The pipeline material is stainless steel or carbon steel in 51 mm to 152 mm (2 in. to 6 in.) sizes. The pipelines carry slurries ranging up to 20 volume percent solids and supernatants with less than one volume percent solids at velocities necessary to prevent settling. The pipelines, installed between 1976 and 2011, were originally intended to last until the 2028 completion of the double-shell tank storage mission. The mission has been subsequently extended.

In 2010 the Tank Operating Contractor began a systematic evaluation of the Waste Transfer System pipeline conditions applying guidelines from API 579-1/ASME FFS-1 (2007), *Fitness-For-Service* [1]. Between 2010 and 2014 Fitness-for-Service examinations of the Waste Transfer System pipeline materials, sizes, and components were completed. In parallel, waste throughput histories were prepared allowing side-by-side pipeline wall thinning rate comparisons between carbon and stainless steel, slurries and supernatants and throughput volumes.

The work showed that for transfer volumes up to 6.1E+05 m^3 (161 million gallons), the highest throughput of any pipeline segment examined, there has been no detectable wall thinning in either stainless or carbon steel pipeline material regardless of waste fluid characteristics or throughput. The paper describes the field and laboratory evaluation methods used for the Fitness-for-Service examinations, the results of the examinations, and the data reduction methodologies used to support Hanford Waste Transfer System pipeline wall thinning conclusions.

INTRODUCTION

The U.S. Department of Energy's Hanford Site stores radioactive, high-level waste in 28 underground, double-shell tanks of nominal 3.8E+03 m^3 (1,000,000 gallon [1 Mgal]) capacity[1]. The tanks are interconnected by an underground network of steel encased pipelines. The pipelines terminate with fixed wall connections located inside below-grade concrete pits. Within the pits, remotely-changeable, steel pipe jumpers in various configurations are installed between the wall

[1] Throughout the paper measurements and dimensions are expressed as SI metric values, followed by equivalent English values in parentheses. All measurements and dimensional analyses were performed in English units. The metric values are approximations that include small conversion and rounding errors.

connections to provide transfer routing flexibility. The Waste Transfer System design, fabrication, installation and operation are regulated by Code of Federal Regulations 40 CFR 265, *Interim Status Standards For Owners And Operators Of Hazardous Waste Treatment, Storage, And Disposal Facilities, Subpart J—Tank Systems*, and State of Washington Administrative Code WAC 173-303-640, *Tank Systems* [2, 3].

The primary pipelines in contact with the radioactive waste during transfers are 51 mm and 76 mm (2 in. and 3 in.) diameter Schedule 40 ASTM A312/A312M stainless steel, ASTM A53, Type S, Gr. B, or ASTM Al06, Gr. A or B carbon steel [4, 5, 6]. The 102 mm and 152 mm (4 in. and 6 in.) diameter Schedule 40 ASTM A53 Schedule 40, Type S, Gr. B or ASTM Al06, Gr. A or B carbon steel secondary pipelines, or "encasements", enclose the 51 mm and 76 mm (2 in. and 3 in.) primary pipelines, respectively. The encasements confine any leakage from a primary pipeline and route it into one of the tanks. Figure 1 illustrates the current design used for Hanford Tank Farms pipeline installations.

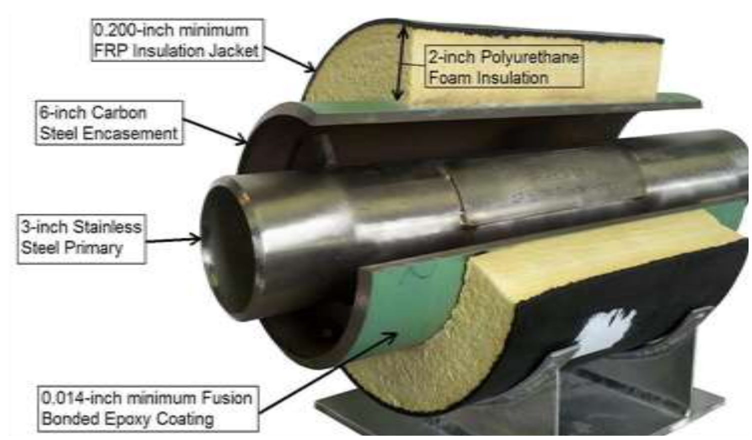

Fig. 1. Hanford Tank Farm Pipeline Design

The radioactive liquid waste carried by the Waste Transfer System consists principally of high pH, sodium bearing supernatants with densities averaging about 1.18 g/cm^3; slurries containing up to 20 volume percent $NaNO_3$, $NaNO_2$, and $NaAlO_2$ crystalline solids with slurry density as high as 1.4 g/cm^3; and slurries containing between 3 and 15 volume percent hydrated metal oxides, principally $Al(OH)_3$ ("gibbsite") and AlO(OH) ("boehmite") [7]. The supernatants are transferred through 76 mm (3 in.) pipelines and slurries through 51 mm (2 in.) pipelines, both at 2.1 – 3.0 m/s (7 – 10 ft/s) to prevent particle settling. Transfer temperatures range up to 54^{o}C (130^{o}F) but are typically 21 – 38^{o}C (70 – 100^{o}F).

Prior to the 2010 no empirical measurements of time-based or throughput-based Waste Transfer System wall thinning had been performed. Traditional working estimates of wall thinning were 1.5E-02 - 3.6E-02 mm/yr (0.6 - 1.4 mil/yr) for carbon steel, and 7.6E-03 - 2.0E-02 mm/yr (0.3 - 0.8 mil/yr]) for stainless steel, based on buried stainless steel coupons in contact with the soil and a carbon steel pipeline partially submerged in standing water [8, 9].

A 2006 double-shell tank system integrity assessment, performed in compliance with Code of Federal Regulations 40 CFR 265, and State of Washington Administrative Code WAC 173-303-640 requirements, used wall thinning rates of 3.0E-03 mm/yr (1.2 mil/yr) for carbon steel and

3.0E-03 mm/yr (0.12 mil/yr) for stainless steel to estimate the Waste Transfer System remaining useful life. The assessment recommended that pipelines removed from service be evaluated to obtain actual wall thinning rates.

Beginning in 2010, 35 straight and 17 elbow specimens from primary pipelines and encasements were examined for wall thinning. About 3,200 ultrasonic wall thickness measurements were made longitudinally along the length of the specimens and radially around the circumference using a 25 mm (1 in.) spacing grid. Straight sections and components including 1 Diameter (1D [short radius]), 1.5 Diameter (1.5D [long radius]) and 5 Diameter (5D) bend elbows were examined.

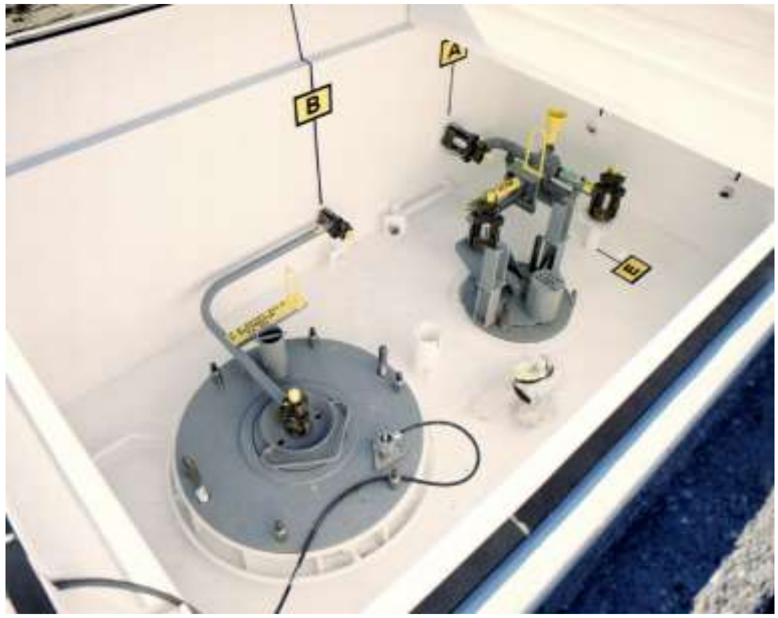

Fig. 2. Tank Farm Pump Pit with Concrete Shielding Cover Blocks Removed to Illustrate Typical Pipe Jumper Installation

All wall thickness testing was conducted by Level II Ultrasonic Test (UT) Examiners, qualified per the American Society for Nondestructive Testing (ASNT) document SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing* [10]. Certified calibration blocks, traceable to the National Institute for Standards and Technology (NIST), or other nationally recognized standards, were used to set up and calibrate the UT instrument. To ensure accuracy of the reported UT measurements, instrument calibration checks were performed both before and after each set of data was collected. Differences between the standard values and measured values were typically ± 5.0E-02 mm (±2 mil); however, some recorded differences were as large as ± 1.3E-01 mm (±5 mil).

When possible wall thinning measurements were supplemented by forensic analysis at the on-site radiochemical laboratory. Analyses were performed on the pipeline interior surfaces and cross-sections, and on scrapings collected from the interior surfaces using a combination of photomicroscopy, scanning electron microscopy and energy dispersive spectrometry. These methods allowed identification and examination of material and features smaller than 20 μm (0.8 mil).

METHODOLOGY

The extent of pipeline wall thinning depends on several variables, including pipeline material, and age, throughput, transfer velocity, and transfer material characteristics. The variables contributing to Waste Transfer System pipeline wall thinning are identified in Equation 1.

Pipeline specimens were selected that, when compared to each other, would control for the wall thinning variables identified in Equation 1, allowing a determination of each variable's contribution to wall thinning in the Waste Transfer System.

$$\begin{aligned} Pipeline\ Wall\ Thinning = f(&pipeline\ material, pipeline\ diameter,\\ &pipeline\ component, pipeline\ service\ age,\\ &pipeline\ service\ environment, transfer\ volume,\\ &transfer\ velocity, transfer\ material) \end{aligned} \quad \text{(Eq. 1)}$$

To illustrate how these key comparisons were accomplished consider the wall thinning determination made using three out-of-service 76 mm (3 in.) carbon steel pipelines of identical age, installed at the same location. The pipelines varied only by their historical throughputs of 8.0E+02 m^3, 5.7E+04 m^3 and 1.1E+05 m^3 (0.21 Mgal, 15 Mgal, and 28 Mgal) of similar supernatant material. Wall thinning measurements on straight sections found no detectable difference in wall thickness with all variables were controlled except for throughput. Similar comparisons were made for each of the other variables identified in Equation 1. The experimental design that ensured the determination of each variable's contribution would be accomplished is illustrated in Figure 4.

Fig. 3. UT Measurement Templates in Place on 51 mm (2 in.) Jumper Straight Section, 1.5D Elbow and < 1 Diameter Downstream of 1.5D Elbow in Preparation for Testing

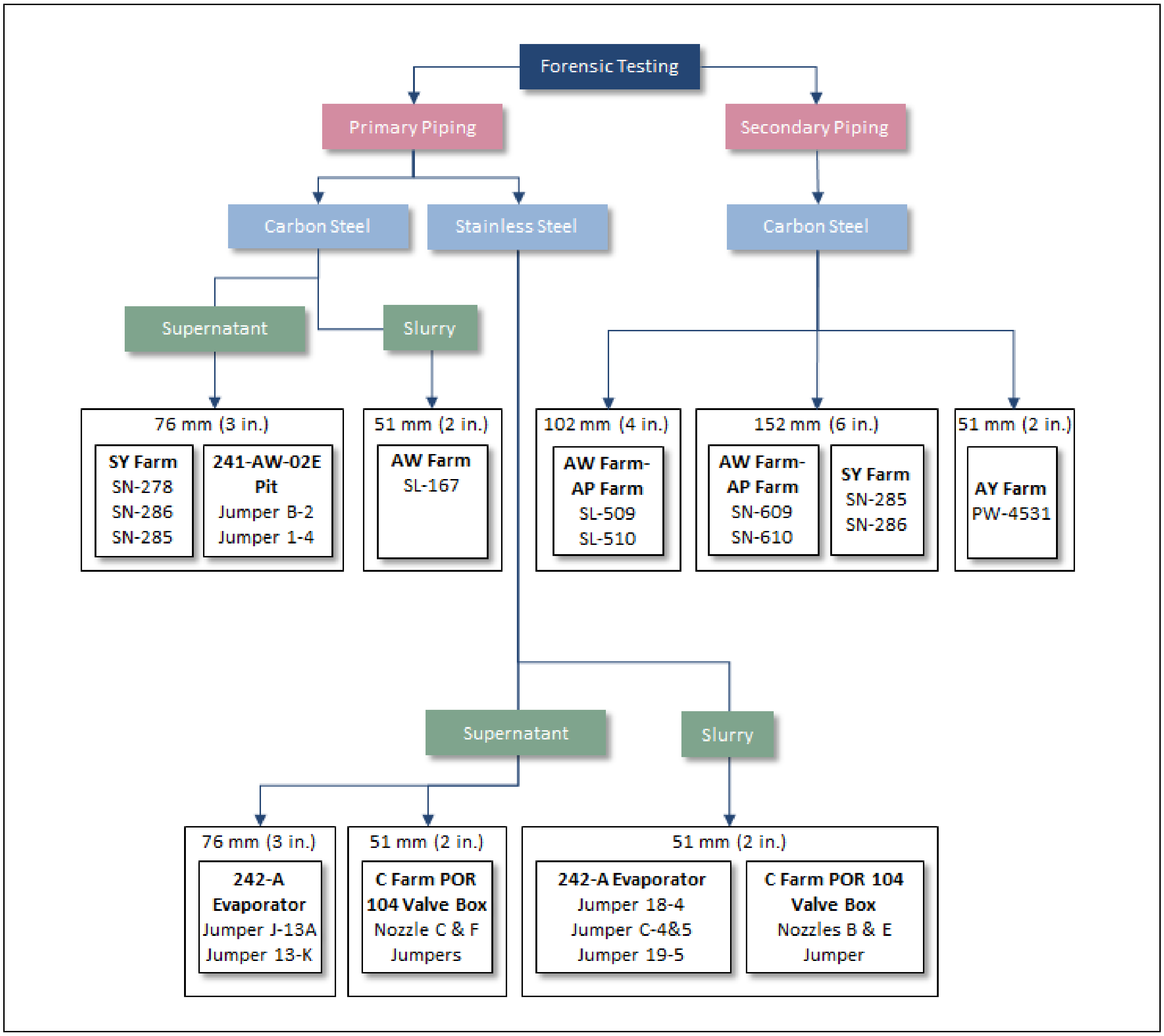

Fig. 4. Waste Transfer System Pipeline Wall Thinning Experimental Design

Straight Pipe Wall Thinning Determination

To determine the extent to which wall thinning had occurred, the pipeline specimen wall thickness was compared to the published ASTM nominal and minimum manufacturer's mill tolerance wall thicknesses. Nominal wall thickness was selected as the comparison basis because wall thinning measurements of pipeline specimens varying only by throughput showed, when the wall thickness *versus* throughput curve was extrapolated back to first use, that the wall thickness most closely matched the nominal wall thickness.

For ASTM A53, Type S, Gr. B or ASTM Al06, Gr. A or B carbon steel primary pipelines and encasements the nominal wall thicknesses for Schedule 40 pipe were from Table X2.2, ASTM A53/A53M-12 , *Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated,* *Welded and Seamless*. The minimum mill tolerance is listed in Table X2.4. The maximum mill tolerance is not provided in the standard; the maximum mill thickness was determined from ASTM A53/53M-12, Paragraph 10.2. This paragraph states that the outside diameter (OD) should not vary more than ±1 percent from the standard specified. The OD was obtained from ASTM A53, 1976, Table X1 (now ASTM A53/53M-12, Table X2.2)[2]. Using this information, the maximum thickness can be determined by finding 1 percent of OD, dividing the obtained value by two, and adding the value to the nominal wall thickness.

For ASTM A312/A312M TP304L stainless steel primary pipelines the nominal wall thickness for Schedule 40 pipe is listed in Table X1.1, ASTM A312/A312M-15a, *Standard Specification for Seamless, Welded, and Heavily Cold Worked Austenitic Stainless Steel Pipes*. Minimum and maximum mill tolerances are calculated from ASTM A312/A312M-15a, Table 3, which provides threshold percentages over and under nominal wall thickness. For 51 mm (2 in.) nominal pipe size, these percentages are 20 percent over and 12.5 percent under nominal wall thickness. For 76 mm (3 in.) nominal pipe size, these percentages are 15 percent over and 12.5 percent under nominal wall thickness.

TABLE I. ASTM Nominal Wall Thickness and Minimum and Maximum Mill Tolerances for As-Installed Waste Transfer System Pipelines

Pipe Attribute	ASTM A53, Type S, Gr. B or ASTM Al06, Gr. A or B Schedule 40 Carbon Steel Pipe				ASTM A312/A312M TP304L Schedule 40 Stainless Steel Pipe	
Nominal Pipe Size (Diameter)	51 mm (2 in.)	76 mm (3 in.)	102 mm (4 in.)	152 mm (6 in.)	51 mm (2 in.)	76 mm (3 in.)
Manufacturer Nominal Wall Thickness	3.91 mm (0.154 in.)	5.49 mm (0.216 in.)	6.02 mm (0.237 in.)	7.11 mm (0.280 in.)	3.91 mm (0.154 in.)	5.49 mm (0.216 in.)
Minimum Mill Tolerance	3.43 mm (0.135 in.)	4.80 mm (0.189 in.)	5.26 mm (0.207 in.)	6.22 mm (0.245 in.)	3.43 mm (0.135 in.)	4.80 mm (0.189 in.)
Maximum Mill Tolerance	4.19 mm (0.165 in.)	5.94 mm (0.234 in.)	6.60 Mm (0.260 in.)	7.90 mm (0.311 in.)	4.70 mm (0.185 in.)	6.30 mm (0.248 in.)

The use of the nominal wall thickness, and minimum and maximum mill tolerance as a graphical overlay to determine if wall thinning has occurred in specimens of straight pipe is illustrated in Figure 4. Here the radial average, and maximum and minimum wall thickness measurements for each of the four longitudinal positions PS-1 through PS-4 for the specimen from Line SN-278, a 76 mm (3 in.) Schedule 40 carbon steel primary pipeline, are shown as green dots, and the range of thicknesses shown as green vertical bars intersecting the dots. The radial positions where the

[2] The ASTM A53/A53M, ASTM A106/A106M and ASTM A312/A312M editions having the latest publication date prior to installation of the pipeline were used to determine nominal thickness and allowable mill minimum and maximum wall tolerances for the individual pipeline specimens. The earliest editions used in the analyses were 1976, and 1977, respectively. The dimensions have remained unchanged through the current 2012 and 2015 editions.

maximum and minimum wall thicknesses were obtained are identified. Note that the radial average wall thickness at each longitudinal position exceeds the ASTM A53/A53M nominal wall thickness (*i.e.*, the purple line), and none of the minimum thicknesses is less than the minimum mill tolerance (*i.e.*, the red line). Because the radial average thicknesses exceeded the nominal wall thickness, and the minimum thicknesses were greater than the minimum mill tolerance, a determination was made that no wall thinning had occurred. This was later confirmed by laboratory forensic analysis.

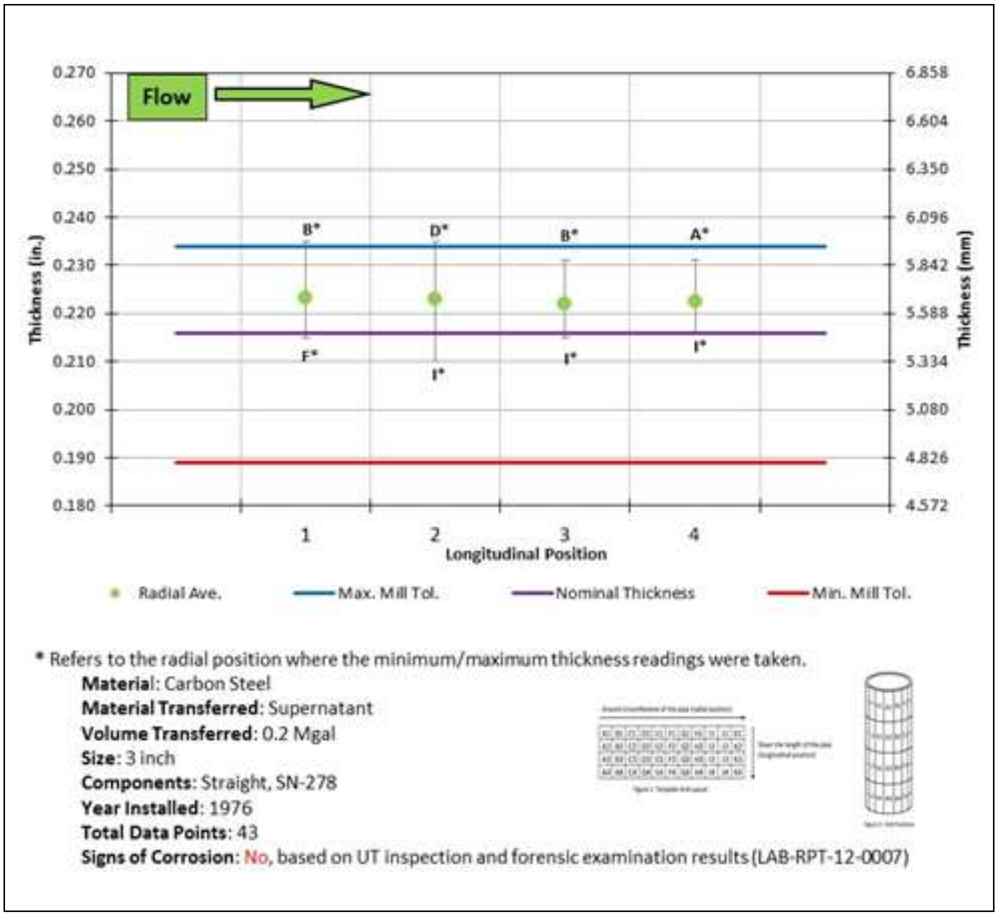

Fig. 4. Wall Thinning Presence Determined by Comparison With Mill Tolerances for 3-in. Schedule 40 Carbon Steel Straight Section

90º Elbow Pipe Wall Thinning Determination

During manufacture of elbows formed by bending straight pipe sections, the extrados wall thins, and the intrados wall thickens. In order to develop the graphical overlay complement to that created for straight sections, the wall thinning predicted to occur during manufacture is taken into account.

For 90^{o} bend elbows the 45^{o} longitudinal position on the extrados, identified as Position PS-2, is the location of greatest manufacture wall thinning. Extrados longitudinal positions, PS-1 and PS-3, located ± 22.5^{o} on either side of PS-2, represent one-half of the distance between position PS-2 and the ± 45^{o} elbow position having the nominal wall thickness of straight pipe, and therefore are assumed to have one-half of the wall thinning present at position PS-2. To illustrate, if the manufacture maximum wall thinning was 10.4% at the 0^{o} position PS-2, the wall thinning at the ± 22.5^{o} positions PS-1 and PS-3 would be 5.2%, and at the± 45^{o} positions wall thinning would be 0%. After fitting the predicted longitudinal minimum thinning values along the elbow extrados with a 4^{th} order polynomial regression curve, the orange line shown in Figure 7 represents the minimum wall thickness for the elbows, equivalent to the red line minimum wall thickness for straight sections shown in Figure 4.

In order to predict 90^{o} bend elbow nominal wall thickness at longitudinal positions PS-1, PS-2 and PS-3, and create a line equivalent to the straight section nominal thickness blue line in Figure 4, three equal spaced radial locations were selected on either side of the PS-1, PS-2 and PS-3, at ± 30^{o}, ± 60^{o} and ± 90^{o} from the extrados. The radial thinning was apportioned similarly to the allocation of the extrados longitudinal thinning: For position PS-2, starting at 0^{o} and 10.4% thinning at the extrados, predicted radial values are 6.9% (± 30^{o}); 3.5% (± 60^{o}); and 0% (± 90^{o}) (refer to Figure 5). For positions PS-1 and PS-3, starting at 0^{o} and 5.2% thinning at the extrados, predicted radial thinning is 3.5% (± 30^{o}); 1.7% (± 60^{o}); and 0% (± 90^{o}) (refer to Figure 6). When these radial wall thinning predictions are averaged for the seven positions a nominal wall thickness value is derived for each longitudinal position PS-1, PS-2 and PS-3. Plotted on Figure 7, the radial averages establish the predicted manufacture nominal wall thickness curve for the elbows. After fitting the predicted radial average thinning values for positions PS-1, PS-2 and PS-3 with a 4^{th} order polynomial regression curve, the black line shown in Figure 7 represents the nominal elbow thickness, equivalent to the nominal thickness blue line for straight sections shown in Figure 4.

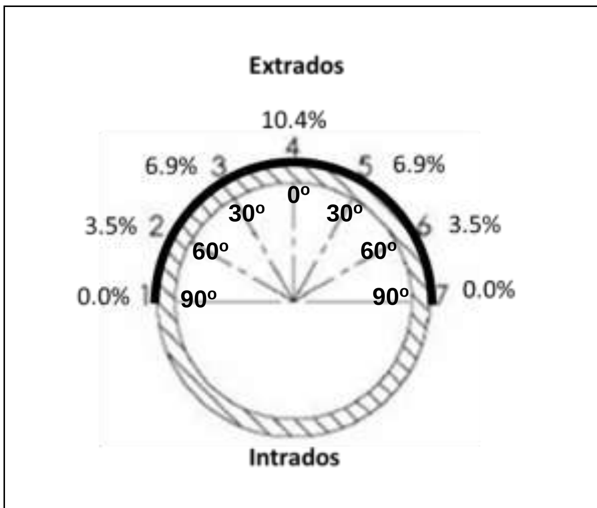

Fig. 5. Predicted Radial Wall Thinning for ASTM A312/A312M TP304L Schedule 40 Stainless Steel Pipe 5D Bend at Position PS-2

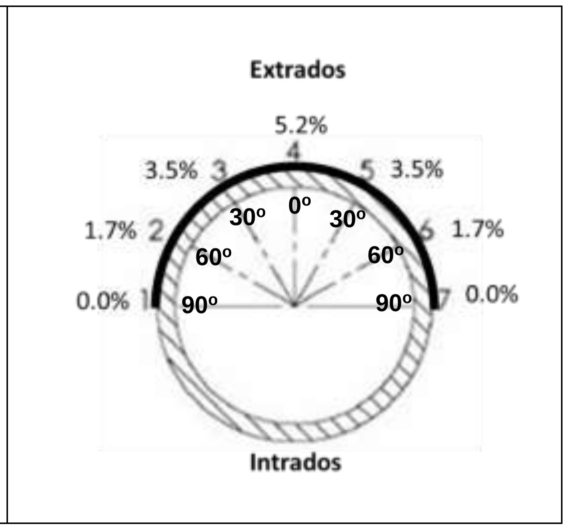

Fig. 6. Predicted Radial Wall Thinning for ASTM A312/A312M TP304L Schedule 40 Stainless Steel Pipe 5D Bend at Positions PS-1 and PS-3

The extent of extrados wall thinning that occurs during pipe bending is not discussed in the ASTM standards. However predicted extrados wall thinning is discussed in the *Piping Handbook* [11]. Because of uncertainties introduced by the pipe manufacturing method, pipe tolerances, and the pipe bending operation itself, predetermining the exact extent of thinning is not possible. However, the thinning percentage can be approximated by applying the following equation (Nayykar 1999, Equation A6.1):

$$Predicted\ Extrados\ Wall\ Thinning\ (\%) = 100 \times \left(1 - \frac{\mathrm{R}}{\mathrm{R} + \mathrm{r}}\right)$$

r = the radius of the pipe (1/2 the outside diameter)
R = the radius of the bend (Eq. 2)

Using Equation 2, the calculated 5D extrados wall thinning at the apex is presented in Table II for A312/A312M TP304L Schedule 40 stainless steel 51 mm (2 in.) and 76 mm (3 in.) pipe.

TABLE II. Extrados Wall Thinning Expected During Elbow Manufacture – ASTM A312/A312M TP304L Schedule 40 Stainless Steel Pipe -

Nominal Pipe Size	**51 mm (2 in.)**	**76 mm (3 in.)**
Nominal Straight Pipe Wall Thickness	3.91 mm (0.154 in.)	5.49 mm (0.216 in.)
Elbow Radius	5D	5D
Pipe Bend Radius	254 mm (10 in.)	381 mm (15 in.)
Pipe Radius	30 mm (1.1875 in)	44 mm (1.75 in.)
Predicted Extrados PS-2 Wall Thinning Percentage	10.6%	10.4%
Predicted Extrados PS-2 Wall Thinning	0.41 mm (0.016 in.)	0.58 mm (0.023 in.)
Predicted Extrados PS-2 Wall Thickness	3.51 mm (0.138 in)	4.90 mm (0.193 in.)
Predicted Extrados PS-2 Nominal Radial Wall Thickness Reduction Percentage (refer to Figure 5)	4.5%	4.5%
Predicted Extrados PS-2 Nominal Radial Wall Thickness Reduction	0.18 mm (0.007 in.)	0.25 mm (0.010 in.)
Predicted Extrados PS-2 Nominal Radial Wall Thickness	3.73 mm (0.147 in.)	5.23 mm (0.206 in.)

In the event either the measured minimum wall thickness was less than the predicted wall thickness, or the measured nominal radial wall thickness was less than the predicted nominal radial wall thickness, then a “worst case” wall thinning rate would have been calculated using the difference between predicted wall thickness and the minimum measured wall thickness and the pipeline’s age or volume throughput.

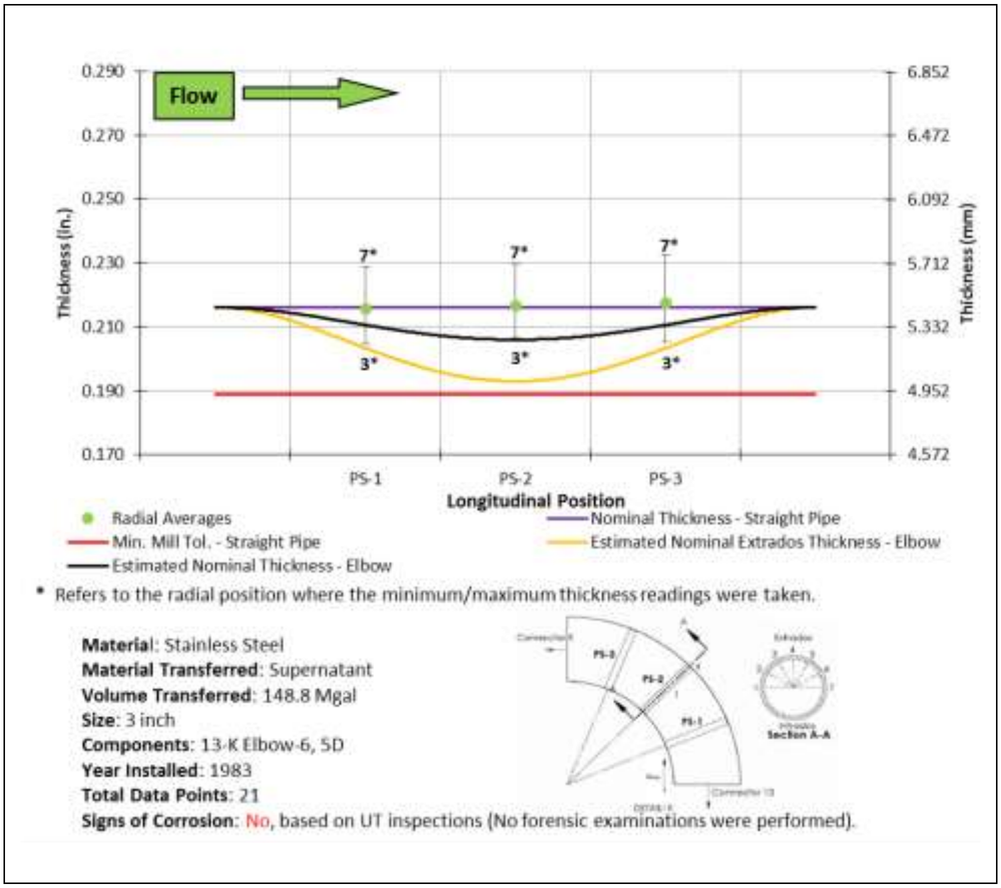

Fig. 7. Elbow Wall Thinning Presence Determined by Comparison With Predicted Mill Tolerances for 76 mm (3-in.) Schedule 40 Stainless Steel 5D Long Radius Elbow

RESULTS

The wall thinning measurements for the 35 straight and 17 elbow sections were screened according to the following criteria developed during data reduction of the UT inspections:

Presence of Localized Thinning

- Straight sections: If any wall thickness measurement is less than the ASTM minimum mill tolerance, then thinning is present. The difference between the minimum wall thickness value and the ASTM nominal wall thickness determines the thinning rate.
- Elbow sections: If any wall thickness measurement is less than the predicted nominal elbow thickness, and less than the minimum mill tolerance for equivalent straight pipe, then thinning is present. The difference between the minimum wall thickness measurement and the predicted nominal wall thickness at the longitudinal position (*i.e.*, PS-1, PS-2, or PS-3) determines the thinning rate.

Presence of General Thinning

- Straight sections: If the measured wall thickness average is less than the nominal wall thickness, then thinning is present. The difference between the measured wall thickness average value and the nominal wall thickness determines the thinning rate.

- Elbow sections: If the measured wall thickness radial average is less than the predicted nominal wall thickness average for any longitudinal position (*i.e.*, PS-1, PS-2, or PS-3), then thinning is present. The difference between the measured wall thickness radial average and the predicted nominal wall thickness determines the thinning rate.

Laboratory Forensics

- The presence or absence of wall thinning determined from laboratory forensic analysis of a pipeline specimen supersedes the results from UT wall thinning measurements performed on the specimen. If laboratory forensic analysis identifies wall thinning, then a wall thinning rate is determined from laboratory measurements, if practical.

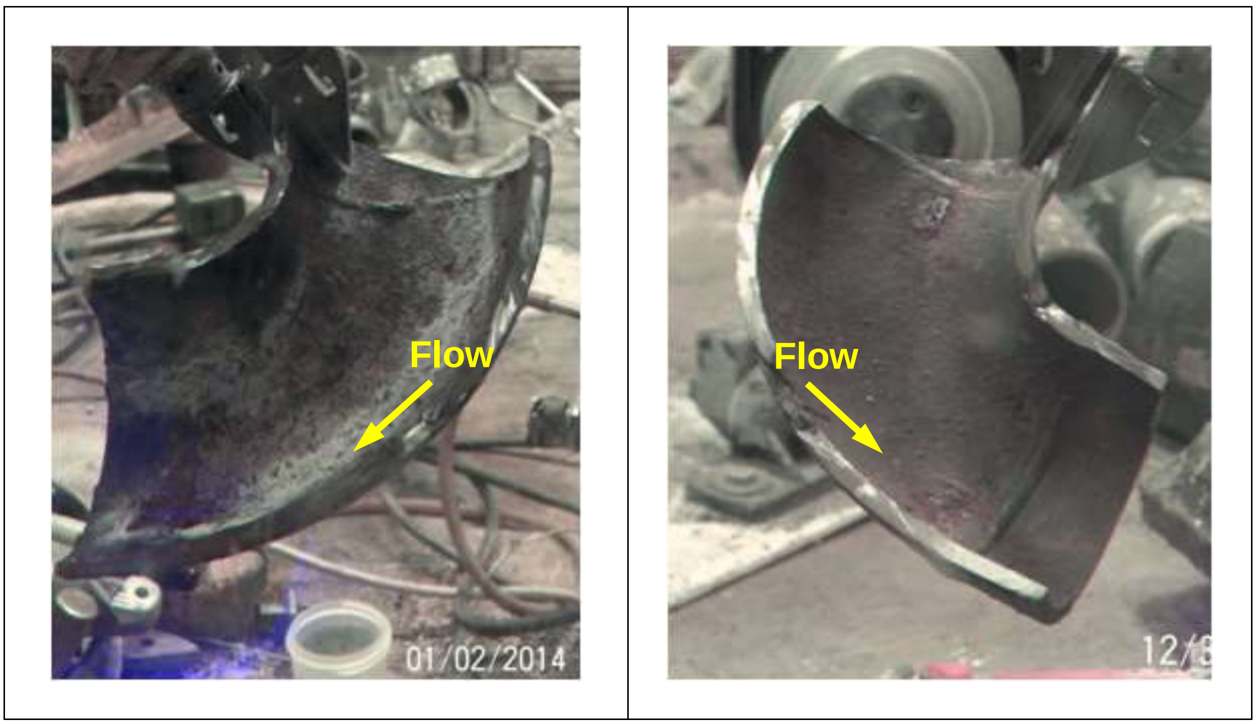

Fig. 8. Schedule 40 Carbon Steel 1D Elbow Sectioned for Laboratory Forensic Analysis Pipeline Wall Thinning Evidence

Of the 35 straight and 17 elbow sections evaluated, six sections had measurable wall thinning and two were confirmed with forensic examinations, as shown in Table III and Table IV. The difference between the measured average wall thickness and the nominal wall thickness was used to determine the wall thinning rate. The highest wall thinning rate found for primary piping was straight section

ST-3 of the 51 mm (2 in.) stainless steel slurry 19-5 jumper at -5.0E-03 mm/yr (0.2 mil/yr) based on 36 years of service.

Table III. Primary Piping Components with Measureable General Thinning

Jumper	Section	Nominal Pipe Diameter	Transfer (yr)	Transfer (Mgal)	Section Type	Nominal Value	Avg Value	Min Value	Rate (avg-nom)
19-5	ST-3	51 mm (2 in.)	36 (1977-2013)	47	Straight	3.92 mm (0.154 in.)	3.73 mm (0.147 in.)	3.58 mm (0.141 in.)	-5E-03 mm/yr (-0.2 mil/yr)
19-5	ST-4	51 mm (2 in.)	36 (1977-2013)	47	Straight	3.92 mm (0.154 in.)	3.81 mm (0.150 in.)	3.56 mm (0.140 in.)	-2E-02 mm/yr (-0.1 mil/yr)
19-5	Elbow 3	51 mm (2 in.)	36 (1977-2013)	47	Elbow, 5D	3.92 mm (0.154 in.)	3.78 mm (0.149 in.)	3.63 mm (0.143 in.)	-8E-04 mm/yr (-0.03 mil/yr)
C-4&5	ST-5	51 mm (2 in.)	21 (1992-2013)	11	Straight	3.92 mm (0.154 in.)	3.89 mm (0.153 in.)	3.68 mm (0.145 in.)	-8E-04 mm/yr (-0.03 mil/yr)

The highest wall thinning rate found for encasements was straight section of Line SN-286 at -0.6 mil/yr based on 33 years of cathodically-protected service.

Table IV. Encasement Piping Components with Measureable General Thinning

Encasements	Section	Nominal Pipe Diameter	Age (yr)	Nominal Value	Avg Value	Min Value	Rate (avg-nom)
SN-285	Straight	152 mm (6 in.)	33 (1976-2010)	7.11 mm (0.280 in)	6.81 mm (0.268 in.)	6.63 mm (0.261 in.)	-0.01 mm/yr (-0.4 mil/yr)
SN-286	Straight	152 mm (6 in.)	33 (1976-2010)	7.11 mm (0.280 in)	6.65 m (0.262 in.)	6.02 Mm (0.237 in.)	-0.02 mm/yr (-0.6 mil/yr)

CONCLUSION

Fitness-for-Service examinations have been completed for a representative cross-section of the metallic pipelines that make up the Hanford Tank Farms' Waste Transfer System. Thirty-five straight sections and 17 elbow sections were examined for the presence of wall thinning using standard UT wall thickness inspection methods and confirmatory laboratory forensic analyses.

Wall thinning rates of -0.005 mm/yr (-0.2 mil/yr) for primary piping, and -0.02 mm/yr (-0.6 mil/yr) for secondary, encasement piping were determined from the examinations. The thinning rates have been adopted for the carbon steel and stainless steel segments of the Waste Transfer System as the bases for predicting Estimated Remaining Useful Life (ERUL). Based on the wall thinning rates, the ERUL ranges from ~ 100 years to ~ 400 years [12].

Within the detection threshold of the UT pipe wall examination method employed, there was no difference in thinning rates for stainless steel and carbon steel pipeline materials, pipeline sizes, elbow and straight sections, elbow bend radii, or supernatant and slurry waste material, for service lives up to 36 years and volume throughputs as high as 161 Mgal.

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