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JUSTIFICATION FOR REDUCING IN-SERVICE WELD INSPECTION DELAY TIMES FOR LIQUID PIPELINES

Matt Boring
Kiefner and Associates, Inc.
Columbus, Ohio, USA

Mike Bongiovi
Enterprise Products
Houston, TX, USA

David Warman
Enterprise Products
Houston, TX, USA

Harold Kleeman
Enterprise Products
Houston, TX, USA

ABSTRACT

Welds that are made onto an operating pipeline cool at an accelerated rate as a result of the flowing pipeline contents cooling the weld region. The accelerated cooling rates increase the probability of forming a crack-susceptible microstructure in the heat-affected zone (HAZ) of in-service welds. The increased risk of forming such microstructures makes in-service welds more susceptible to hydrogen cracking compared to welds that do not experience accelerated cooling.

It is understood within the pipeline industry that hydrogen cracking is a time-dependent failure mechanism. Due to the time-dependent nature and susceptibility of in-service welds to hydrogen cracking, it is common to delay the final inspection of in-service welds. The intent of the delayed inspection is to allow hydrogen cracks, if they were going to occur, to form so that the inspection method could detect them and the cracks could repaired. Many industry codes provide a single inspection delay time. By providing a single inspection delay time it is implied that the inspection delay time should be applied for all situations independent of the welding conditions or any other preventative measures the company may employee.

There are many aspects that should be addressed when determining what should be considered an appropriate inspection delay time and these aspects can vary the inspection delay time considerably. Such factors include the cooling characteristics of the operating pipeline, the welding procedure that is being followed, the chemical composition of the material being welded and if any preventative measures such as post-weld heating are applied.

The objective of this work was to provide an engineering justification for realistic minimum inspection delay times for different in-service welding scenarios. The minimum inspection delay time that was determined was based on modelling results from a previously developed two-dimensional hydrogen diffusion model that predicts the time to peak hydrogen concentration at any location within a weld HAZ. The time to peak hydrogen concentration was considered equal to the minimum inspection delay time since the model uses the assumption that if a weld was to crack the cracking would occur prior to or at the time of peak hydrogen concentration.

Several factors were varied during the computer model runs to determine the effect they had on the time to peak hydrogen concentration. These factors included different welding procedures, different material thicknesses and different post-weld heating temperatures. The post-weld heating temperatures were varied between 40 F (4 C) and 300 F (149 C). The results of the analysis did provide justification for reducing the inspection delay time to 30 minutes or less depending on the post-weld heating temperature and pipeline wall thickness. This reduction in inspection delay time has the potential to significantly increase productivity and reduce associated costs without increasing the associated risk to pipeline integrity or public safety.

INTRODUCTION

In-service welds exhibit an increased susceptibility to hydrogen cracking as a result of accelerated cooling characteristics of the operating pipeline. Due to the time-dependent nature of hydrogen cracking and the increased susceptibility of in-service welds to hydrogen cracking, it is a common practice to delay the inspection of in-service welds.

Some industry pipeline codes do provide requirements for in-service weld inspection delay times; however the guidance is inconsistent. One such pipeline code is the 2016 edition of

ASME B31.4 which, in para. 451.6.1 (g), specifies an inspection delay time of no sooner than 12 hours. [1] Another pipeline code that specifies an inspection delay time is the 2015 edition of CSA Z662. [2] Note 3 of Clause 7.17.7.1 indicates that a time delay of 48 hours is generally considered a suitable delay time for carbon steels but goes on to add that shorter or longer delay times might be appropriate and whatever rationale is used to select the appropriate delay time should be documented.

There are still other industry codes that remain silent on the topic or provide broad generalities of what needs to be taken into consideration when determining an appropriate inspection delay time. One such document is 21st edition of API 1104 which discusses inspection delay time in Section B.5 but does not specify what would be considered a reasonable time. [3] API 1104 Section B.5 states "When determining appropriate delay times prior to inspection for hydrogen cracking, the time-dependent nature of cracking should be considered, as well as the probability of the weld to cracking. Longer delay times decrease the chance that cracking can occur after inspection has been completed. The probability of cracking, and thus the importance of determining an appropriate delay time, can be minimized by using more conservative welding procedures."

Based on the inconsistent industry guidance, work was performed with the intent of providing an inspection delay time justification that could be referenced when depositing in-service fillet welds. The work evaluated several different scenarios one of which was the use of post-weld heating temperature was also included in the analysis. Post-weld heating is the continued application of heat by a propane torch or other heating method after welding is completed to maintain a minimum elevated temperature. The minimum elevated temperature promotes the accelerated diffusion of hydrogen away from potentially crack-susceptible regions of the weld reducing the hydrogen cracking risk associated with the in-service weld.

BACKGROUND

There are several references that discuss the importance of delaying the final inspection of in-service welds; however, the duration tends to vary widely. One reference that suggested a specific delay time for in-service welds was by Bruce and Threadgill. [4] The authors suggested that waiting 48 to 72 hours after the weld has cooled prior to inspecting the in-service weld would be an appropriate inspection delay time. However, the authors did acknowledge that waiting such a long time would have an adverse effect on production schedules.

Around the same time The Welding Institute (TWI) published a report that evaluated hydrogen cracking delay times. [5] The TWI report referenced a US Department of Transportation directive that indicated a possible need for a 48 hour delay prior to inspection. The authors performed a literature review and found very limited data to justify why 48 hours was determined to be an appropriate delay time.

Because of a lack of experimental data, one objective of the TWI work was to generate quantitative data which could be used as the basis for realistic guidelines for in-service weld inspection delay times. The TWI test welds were deposited using shielded metal-arc welding (SMAW) with cellulosic electrodes (i.e., E6010G, E7010G and E8010G) in 0.437-inch (11-mm) thick, X48 pipeline material with a carbon equivalent, using the IIW equation, (CE_{IIW}) of 0.47 and carbon content of 0.27%. The shallow groove welds were deposited under enhanced cooling using a water mist spray to simulate the cooling conditions of an operating pipeline. The majority of the TWI tests results supported the observation that hydrogen cracking initiated within 30 minutes after the completion of the weld; however, there were two isolated cases where the cracking was delayed for 15 hours. The data showed that there was no significant crack growth 30 hours after the weld was completed. The authors did include a cautionary statement in the summation about the interpretation of these results due to the limited data set.

More recently Pargeter, the primary author of the original TWI report, published another paper in the Welding Journal which was an expansion of the work originally performed at TWI. [6] Pargeter stated that several industry standards still require an inspection delay time between 16 and 48 hours and that there is still no firm basis for those values. Pargeter's more recent work was similar in nature to the original TWI work with the exception that higher strength materials with varying chemical compositions were used along with low-hydrogen welding processes such as SMAW with low-hydrogen electrodes (i.e., E7018, E8018G and E9016G). The more recent experimental welds supported the recommendation that an inspection delay time of 12 hours would be considered adequate for low-hydrogen SMAW welds in 2-inch (50-mm) or thinner carbon-manganese steels with yield strength values of 65 ksi (448 MPa) or less. The 12-hour recommendation was based on the greatest observed time to actual cracking of 4.7 hours.

More recent industry discussions have focused on using post-weld heating as the basis for further reducing the inspection delay time. Post-weld heating would maintain the pipe wall temperature above a specific temperature allowing for hydrogen to more readily diffuse from the susceptible areas in the weld. The increased diffusion rate concept is illustrated in Fig. 1 which provides hydrogen diffusivity coefficients at different steel temperatures. [7] Considering the midpoint of the data in Fig. 1, increasing the steel temperature from 68 F (20 C) to 212 F (100 C) will increase the hydrogen diffusivity coefficient from 5 x 10^{-7} cm^2 per sec to 5 x 10^{-5} cm^2 per sec. In other words, by maintaining a 212 F (100 C) minimum temperature of the weld after it is completed, hydrogen will diffuse away 100 times more quickly than that same weld that is allowed to cool down to 68 F (20 C).

The concept of post-weld heating was originally suggested by Bruce, et al. in early 2005. [8] The authors suggested post-weld heating completed in-service welds for a minimum of 15 minutes at a temperature between 200 to 250 F (93 to 121 C). The 15 minute was selected as a reasonable time to permit hydrogen to diffuse away from the susceptible areas of the weld for the most common pipeline thicknesses but longer times may be required for thicker materials.

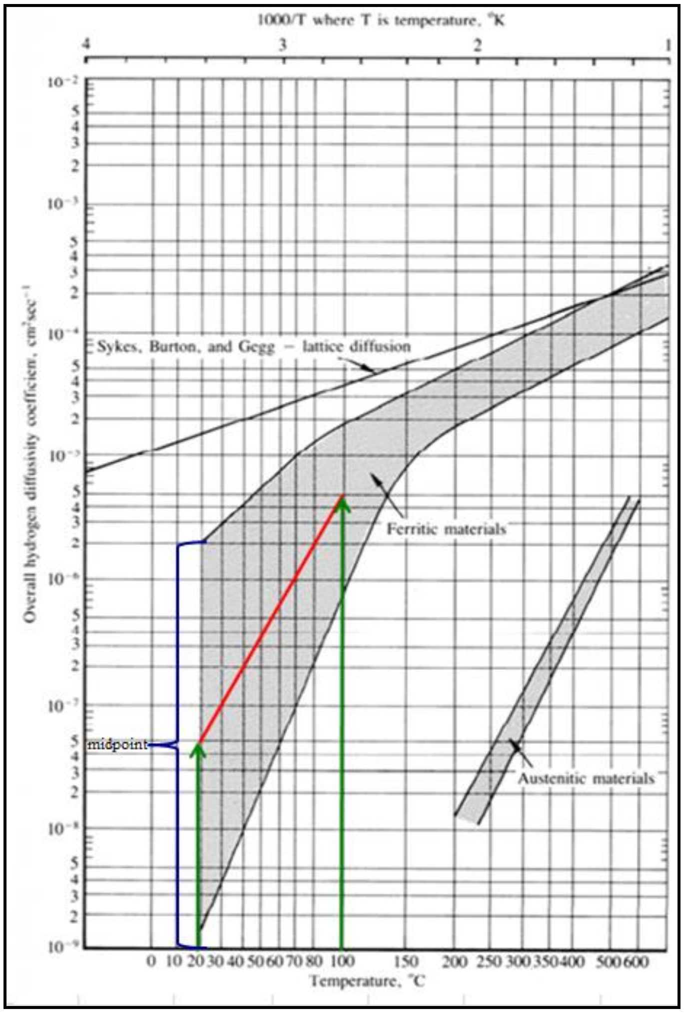

Figure 1. Hydrogen Diffusivity Coefficients in Steel Based on the Steel Temperature [7]

Edison Welding Institute (EWI) made an attempt to experimentally evaluate preheating as well as post-weld heating. [9] The EWI work evaluated three different methods of post-weld heating (i.e., flame, resistance, and induction) on simulated in-service sleeve fillet welds deposited under flowing water conditions. The welds were deposited with SMAW using electrodes with an average diffusible hydrogen concentration of 8.7 ml/100g onto 0.375-inch (9.5-mm) thick, X52 material having a CE_{IIW} of 0.49. Immediately after welding was completed the welds were post-weld heated for 10 minutes to a target temperature of 212 F (100 C) and then allowed to cool. The temperature during the welding and post-weld heating cycle was monitored using thermocouples that were attached at different locations around the weld. None of the heating methods were able to achieve the target temperature of 212 F (100 C) at all the thermocouple locations for the entire 10 minute duration. The inability of the three methods to maintain the minimum temperature of 212 F (100 C) was contributed to the cooling conditions associated with the flowing water in the pipe.

All the simulated in-service sleeve welds were destructively tested a minimum of 24 hours after the weld was cooled. Even with the post-weld heating, several test welds still showed evidence of cracking which was attributed again to the severity of the experimental conditions (e.g., high CE_{IIW} material, 8.7 versus $\leq$4 ml/100g of diffusible hydrogen electrodes and water cooling). Only the test welds using the induction heating method were crack free but it was not determined if the absence of cracking was a result of the initial preheating of the weld joint or the post-weld heating. Even though the results may be considered inconclusive, the authors suggested that preheating and post-weld heating is still beneficial from a hydrogen diffusion standpoint and that this approach could be used to justify shortening or eliminating the inspection time delay for some in-service welding scenarios.

INVESTIGATION AND DISCUSSION

This work focused on developing an approach for selecting an appropriate inspection delay time for a given welding procedure and, if applicable post-weld heating temperature. The inspection delay times reported are based on modelling results using a computer model developed at BMT Fleet Technology Limited (BMT). [10] The two dimensional (2D) computer model (BMT Model) predicts the time to the peak hydrogen concentration at a user-determined location. The locations are most often in the weld HAZ. The time to peak hydrogen concentration is often considered synonymous with inspection delay time because the BMT Model assumes that if hydrogen cracking were going to occur, it would occur prior to or at the time to peak hydrogen concentration assuming all other factors the same.

The BMT Model was used to evaluate three different welding procedures which apply to three different pipe and sleeve wall thicknesses. A summary of the welding procedures is provided in Table 1. Because of the different wall thickness values the model evaluated three different fillet weld sizes. The 0.156 inch (4.0 mm) and 0.250 inch (6.4 mm) thick pipe fillet welds consisted of 4 passes whereas the 0.375 inch (9.5 mm) thick pipe fillet weld consisted of six passes. The four and six pass fillet weld deposition sequences are shown in Fig. 2.

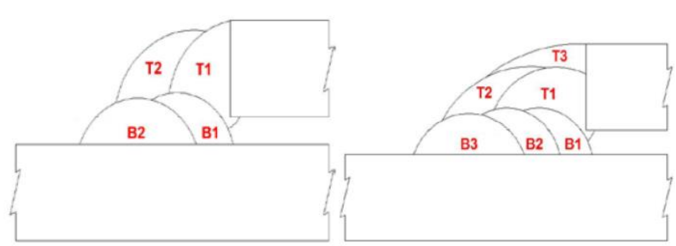

Figure 2. Fillet Weld Deposition Sequence

Table 1. Welding Procedure Inputs to the BMT Model

Wall Thickness	Fillet Weld Leg Length	Pass	Heat Input
0.156 in. (4.0 mm)	0.312 in. (7.9 mm)	B1 and B2	14.4 kJ/in. (0.57 kJ/mm)
		T1	20.2 kJ/in. (0.80 kJ/mm)
		T2	22.2 kJ/in. (0.87 kJ/mm)
0.250 in. (6.4 mm)	0.407 in. (10.3 mm)	B1 and B2	13.9 kJ/in. (0.55 kJ/mm)
		T1 and T2	19.5 kJ/in. (0.77 kJ/mm)
0.375 in. (9.5 mm)	0.620 in. (15.7 mm)	B1, B2 and B3	15.4 kJ/in. (0.61 kJ/mm)
		T1 and T2	22.0 kJ/in. (0.87 kJ/mm)
		T3	24.0 kJ/in. (0.94 kJ/mm)

Each welding procedure scenario that was evaluated included a different post-weld heat temperature. These temperatures included 40 F (4 C), 150 F (66 C), 212 F (100 C), 250 F (121 C) and 300 F (149 C). The post-weld heating temperatures were applied to outside diameter of the pipe and the sleeve. There was no preheat temperature included in the analysis and in all cases the product temperature and the pipe inside diameter temperature was 40 F (4.4 C) prior to the welding simulation. After the simulation started the inside diameter temperature was allowed to increase while the product temperature remained at 40 F (4.4 C). The post-weld heating was applied directly after welding was completed and was continued until the peak hydrogen concentration was achieved meaning different post-weld heating times were used for the different scenarios. The initial hydrogen concentration of each weld bead was 4 ml/100g which is the maximum permitted diffusible hydrogen concentration for the classification of electrode specified by the welding procedures.

For hydrogen cracking to occur there needs to be hydrogen, a crack susceptible microstructure and a tensile stress all present in the weld region. The six locations specified in the BMT model are areas where hydrogen cracks have historically been discovered. Fig. 3 shows the six different HAZ locations around the fillet weld as monitored during the analysis and have historically been locations were hydrogen cracks have been located. Location 1 and 6 were in the pipe HAZ a distance of 0.080 inch (2 mm) and 0.040 inch (1 mm), respectively, from the fusion line near the root of the weld and Location 4 was in the pipe HAZ a distance of 0.080 inch (2 mm) from the fusion line near the cap pass of the weld. These areas of the HAZ tend to experience the highest cooling rates as a result of the cooling potential of the flowing pipeline products and as such have the highest probability of forming a crack-susceptible microstructure. A typical pipeline HAZ hydrogen crack that is located at the cap pass of a fillet weld is shown in Fig. 4.

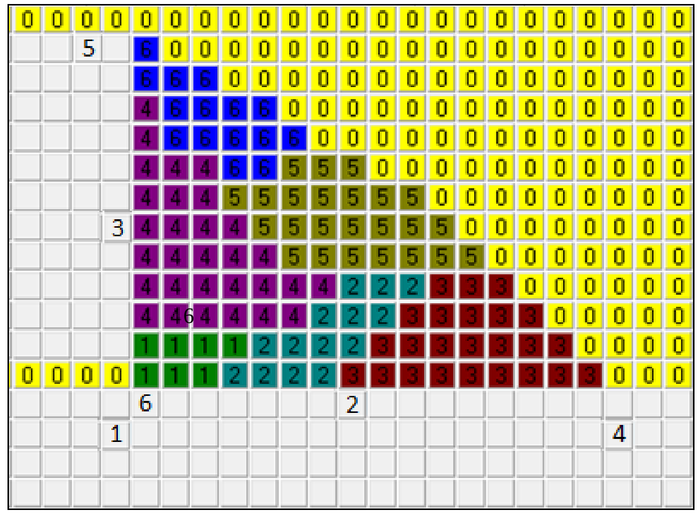

Figure 3. Locations of Hydrogen Concentration Monitoring

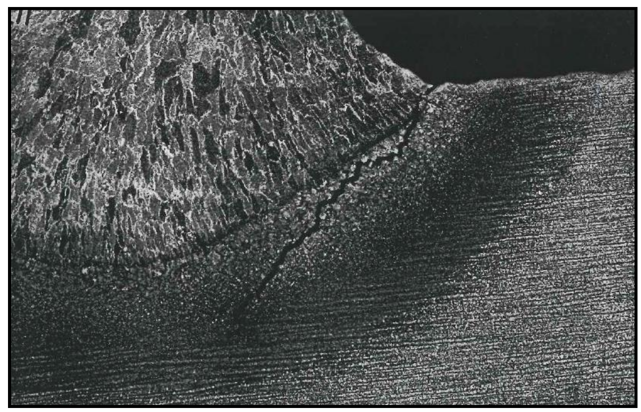

Figure 4. Image of a Fillet Weld HAZ Hydrogen Crack [7]

Location 2 was in the pipe HAZ a distance of 0.080 inch (2 mm) from the fusion line in the center of the weld. Hydrogen cracks at this location are often referred to as underbead cracks. Even though these cracks are not located at the weld toe, hydrogen cracks can still form when sufficient hydrogen is present or when extremely hard microstructures are present. An example of underbead cracking is shown in Fig. 5.

Location 3 was in the sleeve HAZ a distance of 0.080 inch (2 mm) from the fusion line in the center of the weld and Location 5 was in the sleeve HAZ a distance of 0.080 inch (2 mm) from the fusion line near the cap pass of the weld. Hydrogen cracking of in-service welds is more often with the pipe side of the in-service fillet weld but there have been incidences when hydrogen cracks occurred in the sleeve side of the in-service fillet weld as shown in Fig. 6. Oftentimes when hydrogen cracks occur in the sleeve side of in-service welds it is due to the CE_{IIW} of the sleeve material being much higher than the CE_{IIW} of the pipeline material. Even though the sleeve HAZ experiences a slower cooling rate the high CE_{IIW} material can still form a hard microstructure which increases the probability of hydrogen cracks.

Figure 5. HAZ Underbead Hydrogen Cracks [11]

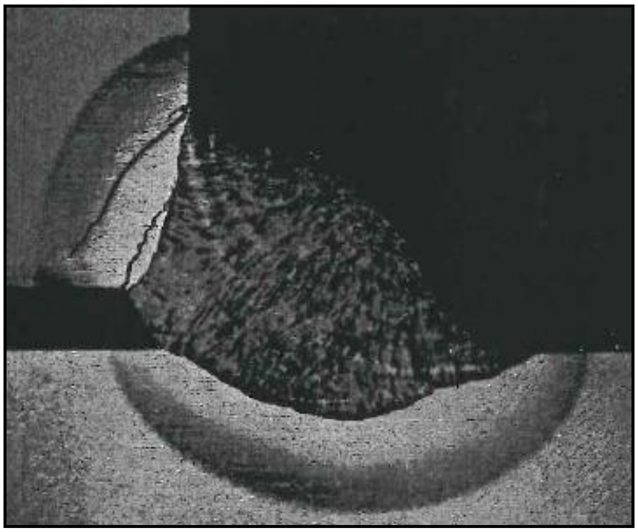

Figure 6. Image of Sleeve HAZ Hydrogen Cracks [7]

Fig. 7 is an example of a plot showing the time to peak hydrogen concentration for one of the conditions at different post-weld heating temperatures evaluated in the BMT Model for the 0.375-inch (9.5-mm) thick pipe conditions.

Table 2 summarizes the BMT-Model-predicted times to peak hydrogen concentration for each scenario evaluated. The reported time 2 mm from the fusion line was the maximum time predicted from any location that distance from the fusion line. The location the predicted the longest time to peak hydrogen concentration at 2 mm from the fusion line was Location 1. The reported time 1 mm from the fusion line was the maximum time predicted from any location that distance from the fusion line. The location the predicted the longest time to peak hydrogen concentration at 1 mm from the fusion line was Location 6.

The maximum time to peak hydrogen at Location 2 was also reported in Table 2. Location 2 was the location that reported the highest peak hydrogen concentration of any of the six locations. Comparing the values provided in the Table 2 show that even though there are locations around the weld that take a very long time to reach their peak hydrogen concentration, the location that sees the highest hydrogen concentration reaches that value in a relative short time after the weld is completed. For instance, an in-service fillet weld deposited on 0.250 inch (6.4 mm) thick at ambient temperature [i.e., 40 F (4 C) post-weld heating temperature] it will take at most 802 minutes for hydrogen to reach its peak concentration 1 mm from the fusion line. However, Location 2 would have already reached peak hydrogen concentration (i.e., 35 minutes) meaning cracks would have already occurred at the location that saw the highest peak hydrogen concentration.

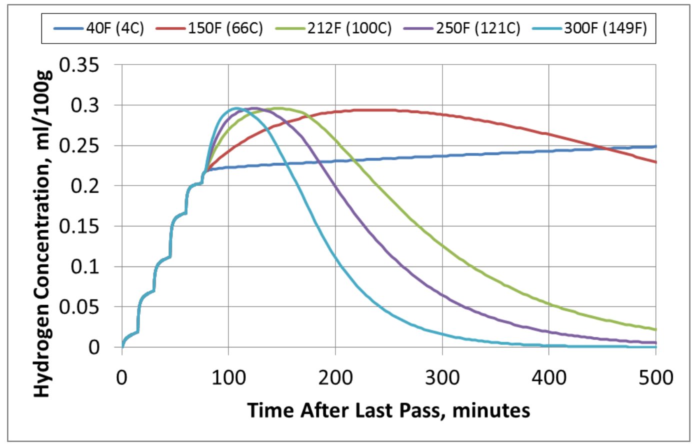

Figure 7. Example of the Time to Peak Hydrogen Concentration Plot for the 0.375-inch (9.5-mm) Thick Pipe

Table 2. Summary of Time to Peak Hydrogen in Minutes

	Pipe Wall	Post-weld Heating Temp.	2 mm from Fusion Line, Location 1	1 mm from Fusion Line, Location 6	Location 2
1	0.156 in. (4.0 mm)	40 F (4 C)	1260	402	27
2		150 F (66 C)	78	31	10
3		212 F (100 C)	33	15	5
4		250 F (121 C)	22	9	4
5	0.250 in. (6.4 mm)	40 F (4 C)	1900	802	35
6		150 F (66 C)	111	55	18
7		212 F (100 C)	49	25	7
8		250 F (121 C)	34	18	5
9	0.375 in. (9.5 mm)	40 F (4 C)	3065	1216	22
10		150 F (66 C)	160	74	13
11		212 F (100 C)	70	29	5
12		250 F (121 C)	47	20	4
13		300 F (149 C)	28	10	3

As stated previously the results from the BMT Model runs were in terms of time to peak hydrogen concentration. The post-weld heating was applied directly after welding was completed and was continued until the peak hydrogen concentration was achieved. This means the time to peak hydrogen concentration and the post-weld heating time were the same.

The results from the BMT Model runs was analyzed so that times to peak hydrogen concentration could be interpolated for pipe wall thickness values not included in the analysis. The first analysis was performed on the time to peak hydrogen concentration values predicted at Location 1 which was in the pipe HAZ 0.080 inch (2 mm) from the fusion line. Location 1 was evaluated because this location predicted the longest times to peak hydrogen concentration regardless of the magnitude of the hydrogen concentration. By performing the analysis in this manner, any inspection that is performed after the reported post-weld heating time has elapsed would be conducted after every location in the weld would have already experienced the associated peak hydrogen concentration level. Analyzing this data set as the basis for the minimum inspection delay times provides a significant level of conservative.

Fig. 8 is a graphical representation of the maximum time to peak hydrogen concentration (i.e., post-weld heating time) for Location 1. The data points used in Fig. 8 were the 150 F (66 C) to 300 F (149 C) times for the 0.375 inch (9.5 mm) cases listed in Table 1. The three trend lines were generated using the power fit option through the data points so that temperatures and times could be interpolated for the same pipe wall thickness as well as other pipe wall thicknesses not included in the BMT Model runs.

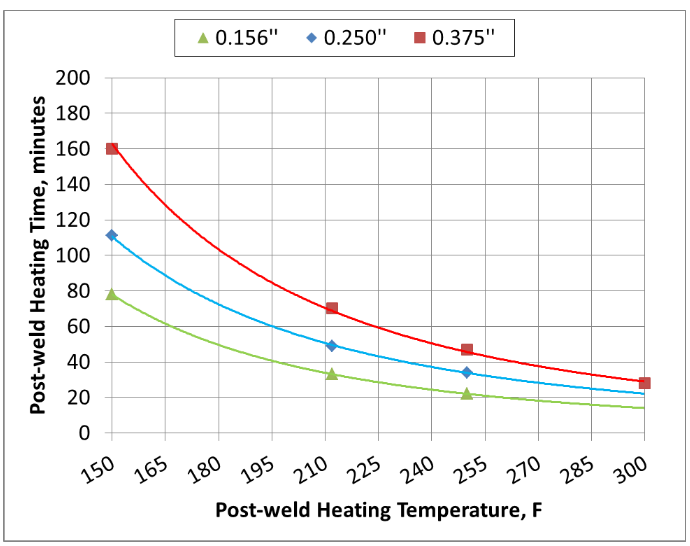

Figure 8. Post-Weld Heating Time versus Temperature at Location 1

A similar analysis that was performed on the BMT Model data from Location 1 was also performed on Location 2.

The trend lines generated from the data analysis of Location 1 was further evaluated to generate curves for wall thickness values not include in BMT Model analysis. The wall thickness values included in the additional analysis were increased by 1/32 inch (0.8 mm) increments between 0.156 inch (4.0 mm) and 0.375 inch (9.5 mm). The resulting trend lines are provided in Fig 9 with the results also being tabulated in Table 3. The values shown in red in Table 3 represent the BMT Model results for the times to peak hydrogen concentration (i.e., post-weld heating time),

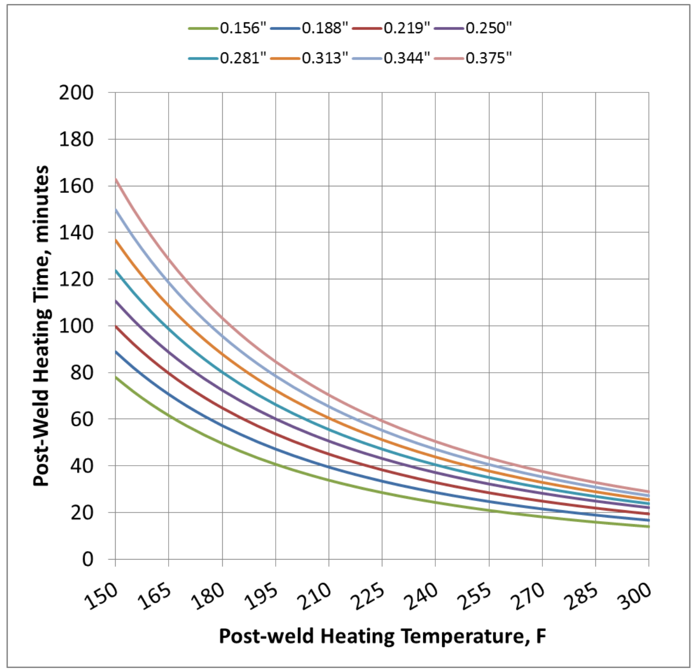

Figure 9. Post-Weld Heating Time versus Temperature at Location 1 for All Pipe Wall Thicknesses

The analysis of the BMT Model data does provide an adequate justification to reduce the inspection delay time down to a maximum of 162 minutes for the thicker pipelines as long as post-weld heating was applied for the entire duration of the delay at a temperature of 150 F (66 C). This delay time could be further reduced for thinner walled pipelines and higher post-weld heating temperatures down to 14 minutes for the thinnest materials and highest post-weld heating temperature applications.

The reduction in the inspection delay time depends on the post-weld heating temperature being achieved and maintained on the operating pipeline for the entirety of the post-weld heating time. If this is not achievable then the reductions in the inspection delay times are not applicable. For example if the wall thickness of the carrier pipe were 0.250 inch (6.4 mm); Table 3 would indicate that a minimum post-weld heating would need to be 265 F (129 C) for a period of 30 minutes. However, if the minimum temperature achievable were only 212 F (100 C) the period would have to be increased to 50 minutes. A similar table as to what is shown in Table 3 could be developed for other companies specific system and could be incorporated into an Operator's procedures to assist with defining the inspection delay times based on minimum post-weld heating.

Table 3. Predicted Post-Weld Heating Time on Temperature and Pipeline Wall Thickness at Location 1

	Pipeline Wall Thickness, inches							
Temp	**0.156**	0.1875	0.21875	**0.25**	0.28125	0.3125	0.34375	**0.375**
150F	78	89	100	111	124	137	150	163
155F	72	82	92	103	114	126	138	150
160F	66	76	86	95	106	117	128	139
165F	62	71	80	89	99	109	118	128
170F	57	66	74	83	92	101	110	119
175F	53	61	69	77	86	94	102	111
180F	50	57	65	72	80	88	96	103
185F	46	54	61	68	75	82	89	97
190F	43	50	57	64	70	77	84	90
195F	41	47	54	60	66	72	79	85
200F	38	44	51	57	62	68	74	79
205F	36	42	48	54	59	64	69	75
210F	34	39	45	51	56	60	65	70
212F	33	39	44	50	54	59	64	69
215F	32	37	43	48	53	57	62	66
220F	30	35	40	45	50	54	58	63
225F	29	33	38	43	47	51	55	59
230F	27	32	36	41	45	49	52	56
235F	26	30	35	39	43	46	50	53
240F	24	29	33	37	40	44	47	50
245F	23	27	31	35	39	42	45	48
250F	22	26	30	34	37	40	43	46
255F	21	25	28	32	35	38	41	43
260F	20	24	27	31	33	36	39	41
265F	19	23	26	29	32	34	37	39
270F	18	22	25	28	31	33	35	38
275F	17	21	24	27	29	31	34	36
280F	17	20	23	26	28	30	32	34
285F	16	19	22	25	27	29	31	33
290F	15	18	21	24	26	28	30	31
295F	15	17	20	23	25	27	28	30
300F	14	17	19	22	24	26	27	29

As stated previously, the BMT Model is based on the assumption that if hydrogen cracking were going to occur, it would occur before the minimum time to peak hydrogen concentration. However, this assumption does not address the actual hydrogen concentration. The location that required the maximum time to the peak hydrogen concentration (Location 1) reached a maximum hydrogen concentration of 0.2 to 0.3 ml/100g of diffusible hydrogen depending on the model conditions. Whereas the location that required the maximum time to the maximum hydrogen concentration (Location 2) had a maximum hydrogen concentration of 1.6 to 1.8 ml/100g of diffusible hydrogen, depending on the conditions. This is significantly higher than the maximum hydrogen concentration from Location 1.

The analysis that was performed for Location 1 was also performed using the results recorded at Location 2. The maximum time to peak hydrogen concentration recorded during the analysis was approximately 18 minutes using a post-weld heating time of 150 F (66 C) on 0.250 inch (6.4 mm) thick material. This time is much lower than the corresponding time of 111 minutes shown in Table 3 at Location 1.

Also, since the peak hydrogen at Location 1 is only 12% to 16% of the peak hydrogen at Location 2, using the time to reach the peak hydrogen at Location 1 is conservative. It would be expected that the magnitude of the hydrogen concentration as well as the time to the peak hydrogen concentration would both influence the inspection delay time. However it is not known at what hydrogen concentration cracking would occur, and the propensity for cracking would be expected to vary with the associated stress and microstructure.

Comparing the 200 F (93 C) post-weld heating times to the industry recommended practice suggested by Bruce, et.al [8] of a post-weld heating time of 15 minutes at 200 to 250 F (93 to 121 C) shows that the BMT Model predicted a longer post-weld heating time of 38 to 79 minutes. This comparison would indicate that the industry recommended practice would be non-conservative as it pertains to the maximum time to the maximum hydrogen concentration recorded at Location 1 which ranged from 5 to 8 minutes.

SUMMARY

The objective of the work was to provide an engineering analysis that could be used as justification for determining an appropriate inspection delay time to inspecting in-service fillet welds. The analysis was based on the times to peak hydrogen concentrations predicted using the BMT Model. [10] The time to peak hydrogen concentration was the same time that the post-weld heating time was applied which inferred that once the post-weld heating time was completed that the weld would be ready for final inspection. The results of the analysis indicate that it would be justified to reduce the inspection delay time to 30 minutes or less depending on the post-weld heating temperature and pipeline wall thickness such as those conditions highlighted by the yellow cells in Table 3.

This work focused solely on the inspection delay time and not the risk of hydrogen cracking and not the probability of a crack occuring. It is important to note that many of the maximum times to peak hydrogen concentration reported were associated with relatively low amounts of hydrogen. There was no attempt made to determine what the minimum threshold of hydrogen concentration that is required to form a crack. It is also important to note that the minimum threshold of hydrogen would be affected by the weld microstructure. The more martensite that is present in the weld HAZ the less hydrogen that would be needed to form hydrogen cracks.

ACKNOWLEDGMENTS

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REFERENCES

[1] The American Society of Mechanical Engineers, Pipeline Transportation Systems for Liquids and Slurries, ASME Codes for Pressure Piping, New York, New York, B31.4, 2016

[2] CSA Group, Oil and Gas Pipeline Systems, www.csagroup.org, CSA Z662, 2015

[3] American Petroleum Institute, Welding of Pipelines and Related Facilities, Washington, DC, API Standard 1104, 21st Edition, September 2013

[4] Bruce, W.A., Threadgill, P.L., "Welding onto In-service Pipelines," Welding Design & Fabrication, February 1991, p.p. 19-24

[5] Pargeter, R.J., "Evaluation of the Delay Time for Cold Cracking," The Welding Institute, Final Report 34056/24A/91, PRC Contract No. PR-164-195, January 1991

[6] Pargeter, R.J., "Evaluation of Necessary Delay before Inspection for Hydrogen Cracks," Welding Journal, Welding Research Supplement, November 2003, pp. 321s-329s

[7] Bailey, N., Coe, F.R., Gooch, T.G., Hart, P.H.M., Jenkins, N. and Pargeter, J., Welding Steels Without Hydrogen Cracking, Woodhead Publishing Limited, 1993

[8] Bruce, W.A., Boring, M.A. Fiore, S. R., Nolan, D., "Effect of Factors Related to Hydrogen Cracking for In-service Welds," Edison Welding Institute (EWI) Report 45567CAP, Gas Research Institute (GRI) Contract No. GRI-8546, February 2005

[9] Bruce, W.A., Boring, M.A., "Evaluation of Preheat Requirements for In-service Welding," Edison Welding Institute (EWI) Report 46347CAP, Pipeline Research International (PRCI) Contract No. PR-185-0350, July 2005

[10] Dinovitze, A., Semiga, V., Pussegoda, L. N., and Ironside, S., "Pipeline In-service Fillet Weld Inspection Delay Time," International Pipeline Conference, September 25-29, 2006, Calgary, Alberta, Canada, Paper IPC2006-10354, 2006

[11] Private Communication