Quarterly Report – Public Page

Date of Report: 5th Quarterly Report-December 31, 2023
Contract Number: *693JK322RA0001*
Prepared for: *DOT/PHMSA*
Project Title: Determining the Required Modifications to Safely Repurpose Existing Pipelines to Transport Pure Hydrogen and Hydrogen-Blends
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For quarterly period ending: *December 31, 2023*
DOT/PHMSA TTI: Louis G. Cardenas

1: Items Completed During this Quarterly Period:

The following items were delivered in this quarterly period. We have caught up on all items that were not completed last quarter. The literature review was completed this quarter. The total to be billed for this quarter is $84,500.00.

Item #	Task #	Activity/Deliverable	Title	Federal Cost	Cost Share
19	2	Task 2 – Identify potential limitations in components and pipeline conditions	Potential component and condition limitations identified	$8,000	$0
20	3	Task 3 – Evaluate metallic and non-metallic components for retrofit or replacement	Components retrofit or replacement evaluated	$20,000	$0
21	4	Task 4 – Develop assessment and repair procedure for identified anomalies	Assessment procedure development	$29,000	$0
22	5	Task 5 – Assess critical flaw sizes and respective detection thresholds	Critical flaw sizes and thresholds assessed	$25,000	$20,000
24	8	5th Quarterly Status Report	Submit 3rd quarterly report	$2,500	$0

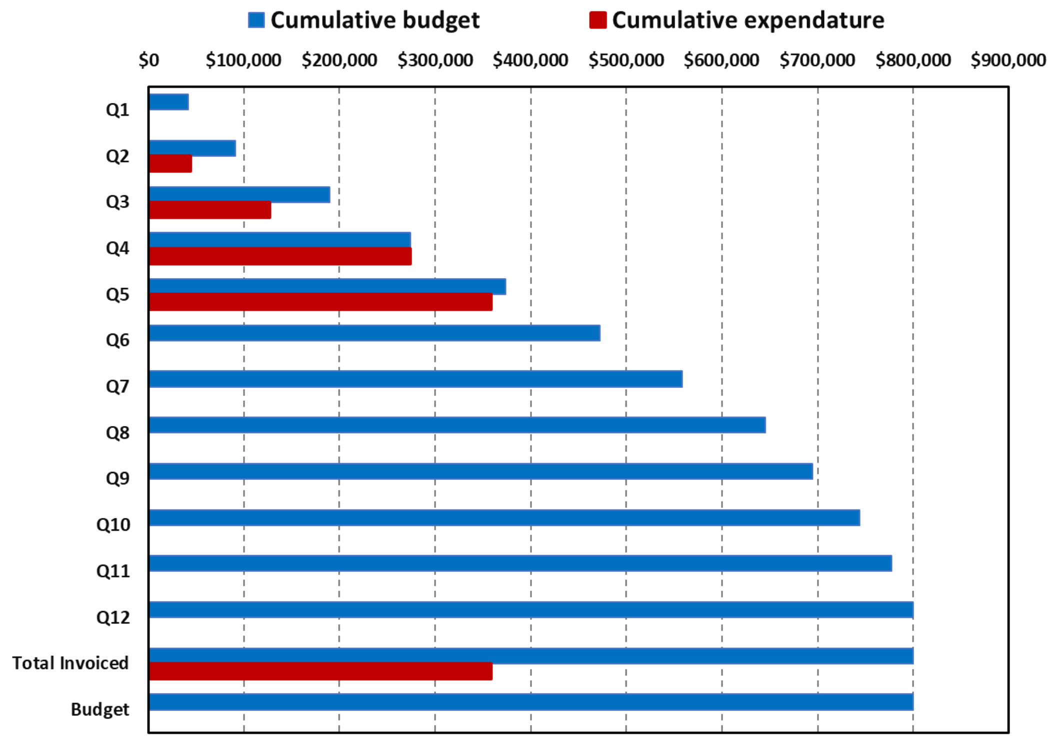
2: Items Not Completed During this Quarterly Period:

Milestone 23 on Task 6 for the Review of regulatory requirements for safety implications of pipeline conversion was not started this quarter. This task has a duration of 6 quarters, so there will be no problem in catching up on this task before the completion of this task is required.

Item #	Task #	Activity/Deliverable	Title	Federal Cost	Cost Share
23	6	Task 6 – Review regulatory requirements for safety implications of pipeline conversion	Regulatory requirements for conversion reviewed	$8,000	$0

3: Project Financial Tracking During this Quarterly Period:

The financial tracking bar graph was put on a cumulative basis rather than a quarterly basis. This shows that we have caught up on the prior milestones and are on track.



4: Project Technical Status

Work was slower during the last quarter due to the holidays and other staff commitments. It will pick up next quarter.

Task 1 – Literature Review

Completed.

Task 2 – Identify Potential Limitations in Components and Pipeline Conditions

As additional guidance to determining the limitations in components and pipeline conditions that were reviewed in the last quarterly report, we have started an elicitation effort in a companion DOT/PHMSA project at Emc^2. In this elicitation effort, we have 35 to 40 US and international experts in pipeline operation, materials, failure mechanisms, NDE, Codes and Standards, etc., who agreed to provide input to a relative ranking scale of various aspects affecting the integrity of pipelines carrying hydrogen. Since the initial release of the elicitation questions in mid-December, several other knowledgeable engineers have heard of the effort and asked to be involved as well. This evaluation includes new and repurposed vintage lines and various levels of hydrogen. We have requested their opinions on the many topics below (although the ranking system is not shown in the list below). No one person would be knowledgeable in all these topics at a high level, so we also asked them about their confidence in their answers and if they want to expand on any of the questions (those questions are not in the list below for brevity).

As of now, we have elicited responses from about 1/3 of those who said they would like to be involved. We will continue to prod them along until we have at least 2/3 of them replying before starting the statistical analysis of the results. The SMEs are not identified in the responses, and no Emc^2 project staff are involved in this evaluation either.

The plan is to have a review meeting of these responses with some statistical evaluation of the responses. There may be some qualifying comments for people's answers so that those comments will be reviewed. In a traditional elicitation format that we have been involved with for the US Nuclear Regulatory Commission, the questions are first asked of the group without them having any interaction, i.e., totally independent. Then, after the review of the responses, there is an opportunity for those with unique opinions to discuss those with the SME group. Those opinions may provide additional information that the group was unaware of or could be false beliefs. Then, the elicitation SMEs can adjust their answers if they feel warranted.

Currently, the Elicitation Workshop is a one-day event planned for some time during March. A second adjacent day will be the meeting of the technical advisory panel for this project and the companion DOT/PHMSA project at Emc^2. The Technical Advisory Panel discussions will be a half day for each of the two DOT/PHMSA hydrogen-related pipeline projects. We will send out a questionnaire on what days are better for the key SMEs to attend. The meeting will be in person at Emc^2 offices and a web meeting (GoToMeeting) for those who can't travel.

Task 3 – Evaluate Non-Metallic Components for Retrofit or Replacement

In this task, the "three R" [Reuse, Repair, Replace] methodology will be applied to the non-metallic components described in Task 2 for the purpose of pre-qualification of a vintage pipeline system for hydrogen or hydrogen-blended service. Based on the identified limitations for each component type, a general judgment will be formulated with the basic premise that, if possible, "reuse" of components would be the technically and economically preferred option. REUSE example: A material qualification of the linepipe steel, long-seam welds, and girth welds must be acceptable. If the identified limitations require a "repair" (defined as a partial retrofit of an existing component) is possible, then this will be described. REPAIR example: Certain non-compatible parts within an existing component (e.g., a valve) could be swapped out with a similar part made of a hydrogen-compatible material. In contrast, the main components are not changed out. If the identified limitations indicate that the component is made of a non-compatible material or was fabricated in a manner that would affect safe operation when exposed to hydrogen, then a full replacement would be needed. REPLACE example: Sensors made of rare-earth metals prone to disintegrate from hydride formation when exposed to hydrogen and, therefore, would no longer function reliably. The task deliverable will be a list of component types with an evaluation justifying if repair, reuse, or replacement would be most likely. The final report will also include the repair/reuse/ replacement evaluation.

Summary of Efforts during this Quarter

Most of the previous efforts involved completing the literature review on the effect of hydrogen on metallic components and preparing the draft report titled "*Literature Survey on Repurposing Pipelines for Hydrogen Service.*" This deliverable is provided as a separate attachment to the last Quarterly Report.

During this reporting period, additional literature and references were compiled on the effects of hydrogen on non-metallic components in the gas transmission and distribution systems. This updated list is appended below [Ref. 1-24]. A detailed review of all these references has just been completed. Therefore, this progress report provides a high-level summary of these studies reviewed below. Detailed analysis of the data presented in these references is still being conducted and will be included in the next quarterly progress report.

1. *Gas distribution piping*: It is not explicitly clear whether the scope of the current project involves a review of hydrogen on gas distribution networks or is exclusively focused on transmission and piping. Nevertheless, for the sake of completeness, literature on the effect of hydrogen on non-metallic gas distribution components is also being reviewed. A significant number of studies reviewed relate to the effect of hydrogen on polyethylene (PE) piping (both medium density and high density, i.e., MDPE and HDPE) - used extensively in gas distribution piping. Most of the technical research on the effect of hydrogen on PE piping in the US is carried out by GTI Energy (formerly Gas Technology Institute) in Des Plaines, IL. The major conclusions to date are that there are no compatibility issues between hydrogen gas and PE and no concerns about the effect of hydrogen on the aging/ durability of PE with regard to service life. Other studies with specific experiments conducted to study the effect of hydrogen on fatigue life and on fusion joints are still being reviewed.

2. *Compatibility, diffusion, permeability/leakage, and solubility of hydrogen on non-metallics*: A significant number of studies listed in the references below focus on these issues. To date, the limited available literature concludes that while compatibility with almost all polymers and elastomers is not an issue, the major concern for gaseous hydrogen is increased permeability in non-metallics and hence leakage, rather than specific threats to integrity. The leakage rate for hydrogen is roughly a factor of 3 greater than that for natural gas.

3. *Effect of high pressure hydrogen on elastomeric components*: The third major area of study on the impact of hydrogen in non-metallics involves the effect of high pressure (> 2000 psi) on elastomeric components. This is likely motivated by hydrogen fuel cell studies where the impact of hydrogen on elastomeric seals and O-rings. Critical properties of elastomers such as compression set, modulus/stiffness, and degree of swell for filled and unfilled polymers used in hydrogen service environments are affected more by pressure-cycling. The primary takeaway from some of the experiments conducted is that material property changes in elastomeric seals at high pressure can cause leaks in industrial systems used to seal hydrogen, which could be a safety concern.

4. *International Efforts*: As part of this effort, work in this area outside the US is also being reviewed. Specifically, the work of the European Industrial Gases Association (EIGA) and European Pipeline Research Group (EPRG), which have undertaken efforts since 2004 to study the issues involving the effects of hydrogen on non-metallics, is being investigated in detail. These studies address very similar issues as those described above conducted in the US and also identify research needs to be undertaken where gaps exist – including the need for any new test method, studying possible new failure modes, the effect of gas decompression, fatigue loading and wear of non-metallics in the presence of hydrogen. Separately, the Australian Pipeline Gas Association has developed a complete 'Code' that consolidates 'current knowledge' with a focus on hydrogen fluid compatibility with pipeline materials and components. Specifically,

Chapter 11, involving the use of Composite Pipes for hydrogen transport, is being reviewed in detail as part of this effort.

Updated List of References Compiled to date on the Effect of Hydrogen on Non-Metallics

1. EIGA Report on "*Hydrogen Transportation Pipelines*," Report No. IGC Doc 121/04/E, Globally Harmonized Document from the European Industrial Gases Association, Brussels, 2004.

2. Foulc, Marie-Pierre and others, "*Durability and transport properties of polyethylene pipes for distributing mixtures of hydrogen and natural gas*," 16th World Hydrogen Energy Conference, Lyon, France, June 2006.

3. Kane, M.C., "*Permeability, Solubility, and Interaction of Hydrogen in Polymers- An Assessment of Materials for Hydrogen Transport*," Report No. WSRC-STI-2008-00009, Rev. 0 by Savannah River National Laboratory, Washington Savannah River Company, 2008.

4. Klopffer, Marie-Helene, and others, "*Polymer pipes for distributing mixtures of hydrogen and natural gas: evolution of their transport and mechanical properties after an aging under a hydrogen environment*," Proceedings of the 18th World Hydrogen Energy Conference, Essen, Germany, May 2010.

5. Marchi, San, and others, "*Technical Reference for Hydrogen Compatibility of Materials*," SANDIA REPORT No. SAND2012-7321 under DOE Contract DE-AC04-94AL85000, Sandia National Laboratories, September 2012.

6. Melaina, M. W. and others, "*Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*," Technical Report No. NREL/TP-5600-51995 by National Renewal Energy Laboratory under DOE Contract No. DE-AC36-08GO28308, March 2013.

7. Kloppfer, Marie-Helene, and others, "*Development of Innovating Materials for Distributing Mixtures of Hydrogen and Natural Gas - Study of the Barrier Properties and Durability of Polymer Pipes*," Oil & Gas Science and Technology, Vol 70 (2), pp. 305-325, 2015.

8. Menon, Nalini, and Others, "*Behavior of Polymers in High Pressure Environments as Applicable to the Hydrogen Infrastructure*," Sandia National Laboratories, ASME PVP 2016 Conference, Vancouver, Canada, July 2016

9. Birkitt, K. and others, "*Materials aspects associated with the addition of up to 20 mol% hydrogen into an existing natural gas distribution network*," Copyright report by Cadent Gas Limited / Northern Gas Networks Limited, UK, 2019.

10. Project report on "*Hydrogen in the Gas Distribution Networks*," by the National Hydrogen Strategy for Australia, prepared by GPA Engineering for the Government of South Australian with Future Fuels CRC and COAG Energy Council, 2019.

11. Gallon, Neil and others, "*Hydrogen Pipelines – Design and Material Challenges and Mitigations*," EPRG Project Number ROSEN UK 14233/EPRG 221/2020 Revision 1, December 2020.

12. Weiland, Nathan, and others, "*Enabling an Accelerated and Affordable Clean Hydrogen Future— Fossil Energy Sector's Role*," Final Report on Workshop by National Energy Technology Laboratory, US DOE, September 2021.

13. Hermkens, Rene, and others, "*Leak tightness of PVC fittings with Hydrogen*," Report No. GT-210280, Project number P000019270, Kiwa Technology, The Netherlands, March 2022.

14. Sang Koo Jeon, and others, "Investigation of Physical and Mechanical Characteristics of Rubber Materials Exposed to High-Pressure Hydrogen", Published online 2022 May 31; Polymers (Basel). 2022 Jun; 14(11): 2233.

15. Simmons, L. Kevin, and others "*Gap Analysis on the Impacts of Hydrogen Addition to the North American Natural Gas Infrastructure Polyethylene Pipelines*," Report Number PNNL-33736 under DOE Contract Number DE-AC05-76RL01830, July 2022.

16. Raju, Arun S. K., and others, "*Hydrogen Blending Impacts Study*," The California Public Utilities Commission Final Report Number R13-02-008 under Agreement Number: 19NS1662, July 2022.

17. Byrne, Nolene and others, "*Influence of Hydrogen on Vintage Polyethylene Pipes: Slow Crack Growth Performance and Material Properties*," International Journal of Energy Research Volume 2023, Article ID 6056999, December 2022.

18. Byrne, Nolene, and others, "*Hydrogen interactions with plastic pipes and elastomeric materials*," Report No. PRCI-EFS2023-010, Proceedings of the 2023 Emerging Fuels Symposium, Orlando, FL, June 2023.

19. Menon, Nalini and others, "*Compatibility of polymers in hydrogen environments as applicable to hydrogen pipelines and contributing infrastructure*," Paper Number PRCI-EFS2023-061 at Sandia National Laboratories and Pacific Northwest National Laboratories, Proceedings of the 2023 Emerging Fuels Symposium, Orlando, FL, June 2023.

20. Wikham, Josh, and others, "*Australia's Hydrogen Pipeline Code of Practice – Research Driven Advancement*," Paper Number PRCI-EFS2023-005, GPA Engineering, Future Fuels Cooperative Research Centre, Australian Pipeline Gas Association, Proceedings of the 2023 Emerging Fuels Symposium, Orlando, FL, June 2023.

21. Presentation by the Pipeline Safety Trust, "*Safe Energy Transition: Zero Incidents - The Public's Perspective on Hydrogen Pipeline Safety*," Proceedings of the 2023 Emerging Fuels Symposium, Orlando, FL, June 2023.

22. EWI Work on effect of hydrogen on elastomers O rings; The Effects of Pressurized Hydrogen on Polymeric Elastomers, Jeff Ellis for polymers (jellis@ewi.org); https://ewi.org/the-effects-of-pressurized-hydrogen-on-polymeric-elastomers/

23. https://www.pnnl.gov/news-media/hydrogen-compatibility-study-characterizes-performance-rubber-additives; Oil-based plasticizer separates and migrates under high-pressure hydrogen

24. Kim, Mina, and others, "Hydrogenation of High-Density Polyethylene during Decompression of Pressurized Hydrogen at 90 MPa: A Molecular Perspective," https://www.mdpi.com/2073-4360/15/13/2880; Polymers, 15(13), 2880, 2023.

Additionally, the elicitation efforts described in Task 2 will greatly enhance the evaluation of non-metallic components in transmission and distribution pipelines.

Task 4 – Develop Assessment and Repair Procedures for Identified Anomalies

One of the commonly used repair procedures in older pipelines is a Type B steel sleeve. These sleeves have circumferential welds to be pressure containing if there is concern of a leak being developed in the carrier pipe. A Type B repair sleeve generally involves taking a piece of the same size pipe, cutting it to an axial length sufficient to cover the defect of concern, and cutting the pipe segment axially into two 180-degree sections. Those two sections are fit around the pipe and welded together, preferably without side straps, see Figure 1. A solid filler, like autobody fiber filling paste, may be used in the annular region if there is a dent or other indentation.

The fillet welds are made in the field and perhaps are the most difficult to make without any fabrication imperfections. The fillet welds are also not stress-relieved, so there can be higher residual stresses. For a pipe in hydrogen service, or if the repair was made before going into hydrogen service, the fillet weld is a prime location for hydrogen damage.

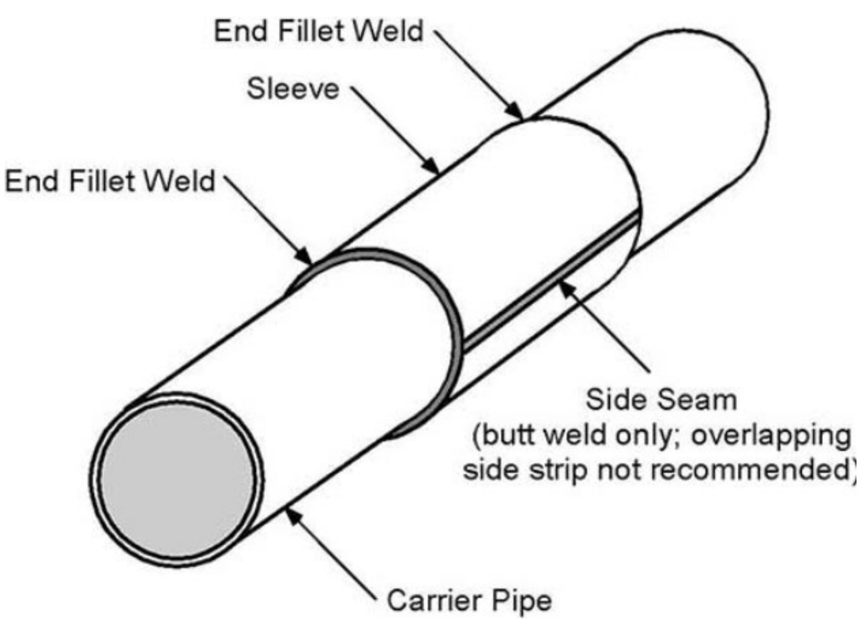


Figure 1 Illustration of a Type B repair sleeve intended to contain leakage

Work has been ongoing during the last quarter to explore the effects of hydrogen on the fillet weld used for Type B sleeve repairs within Task 5, but a specific evaluation was made for the repair sleeves of interest to this task, so it is documented here. This is a preliminary effort designed to explore the methodology of Gao et al., who developed numerical techniques for simulating the effects of hydrogen embrittlement. This basic approach, described in previous updates, employs a phenomenological model for both the HEDE and HELP mechanisms to explore the effects of hydrogen on mechanical integrity.

This work simulated the welding process using Emc^2's commercially available VFT® (Virtual Fabrication Technology) FEA software to evaluate the resulting stress-strain fields based on typical welding parameters. This software has been used extensively for nuclear piping evaluations, as well as in validation efforts. The resulting hydrogen distribution, which is a function of stress-strain, is then simulated. A key aspect of this effort is to explore modified welding procedures for installing Type B sleeves that minimize the potential damage caused by hydrogen. In this first effort, the hydrogen distributions were assessed based on one initial set of welding parameters as proof of concept only, and results should not be used to draw any final conclusions. Shown in Figure 2 is a schematic of the basic axisymmetric geometry that includes the carrier pipe (red), half of the repair sleeve (blue), the filled weld on one side (green), and the possible addition of a weld overlay (grey). The weld overlay is a procedure used for repairing girth weld with circumferential cracks in nuclear plants [1]. It was felt that the overlay procedure is worth evaluating for not only mechanically reinforcing the fillet weld but also inducing compressive residual stresses that might eliminate the potential of hydrogen accumulation at the root of the fillet weld. This is only an initial evaluation without trying to make any optimization efforts to reduce cost. The method could be used on new hydrogen pipelines but also might have a potential for vintage pipelines if warranted (although the cost might be burdensome if there are too many repair sleeves on a vintage pipeline converted to hydrogen service).

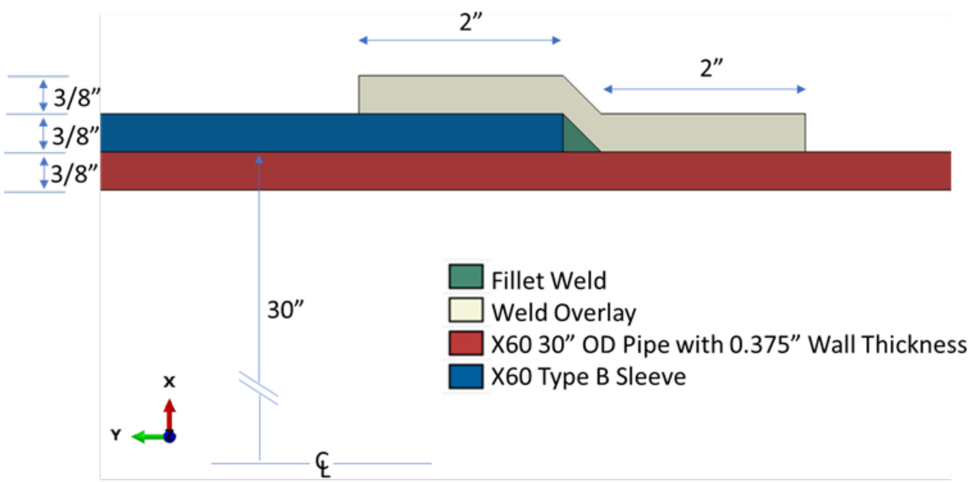


Figure 2 Axisymmetric representation of Type B repair sleeve with potential overlay

The simulation involved reproducing the multi-bead welding process, permitting cooldown to 20ºC, and then pressurizing to 72% SMYS. The resulting hydrogen distribution was then determined. Model parameters are also defined in Figure 2. The results for hydrostatic stress and plastic strain are shown in Figure 3.

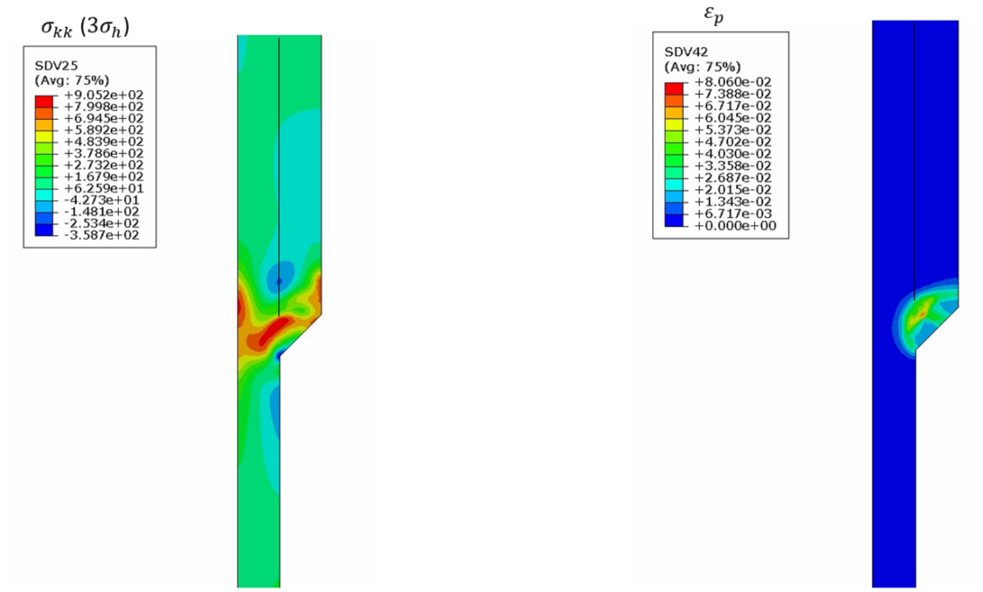


Figure 3 Triaxial stress and plastic strain results for Type B sleeve fillet weld simulation at 72% SMYS pressure (no overlay)

The second simulation looks at the stress-strain field as modified by performing a weld overlay on the fillet weld. This practice has been used in other industries (e.g., nuclear) to mitigate stress corrosion cracking by altering the residual stress field [1]. Figure 4 shows the results of this simulation.

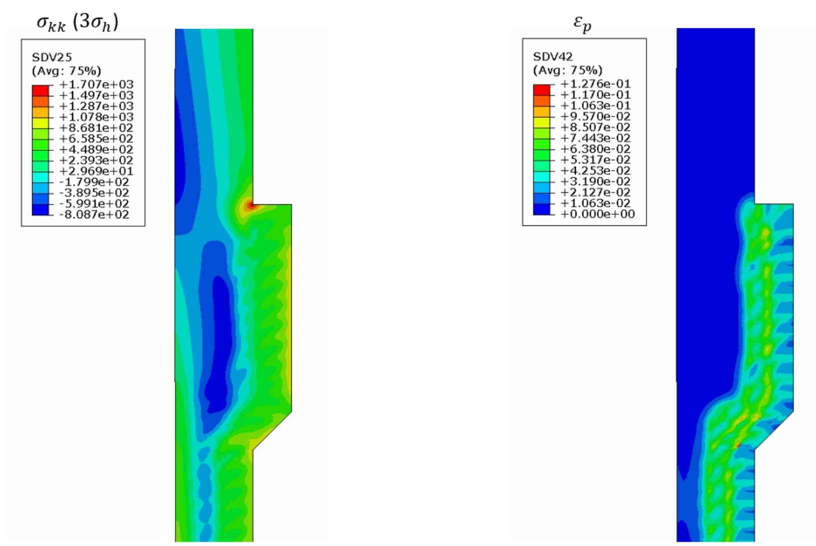


Figure 4 Triaxial stress and plastic-strain field following weld overlay repair at 72% SMYS

As is evident comparing Figure 3 and Figure 4, the presence of the weld overlay causes a significant alteration in the through-thickness stress and strain profiles and will result in a correspondingly different hydrogen distribution.

The initial boundary conditions for the hydrogen diffusion analysis were:

- Initial hydrogen concentration: 0
- Hydrogen concentration at ID: $C_L = 2.084 \times 10^{12}$ atoms/mm^3
- Hydrogen concentration at OD: $C_L = 0$
- Diffusion coefficient (D_L): 0.0127 mm^2/s

Figure 5 shows some preliminary results comparing the two different weld configurations to estimate both the lattice hydrogen concentration (C_L) and the trapped hydrogen (C_T), but only the total hydrogen concentration is shown for brevity. Interestingly, the hydrogen concentration is predicted to increase with the overlay in the original fillet weld region (dashed triangle region). However, as shown in Figure 6. The hoop stress from the overlay welding puts the original root, and about 1/3 of the fillet weld cross section is in compression, and about 2/3 of the original fillet weld is at very low tensile hoop stress. So, although hydrogen could be present in the fillet weld with the overlay, the compressive stresses mean that a crack will not develop or cause fracture from the discontinuity of the fillet weld root.

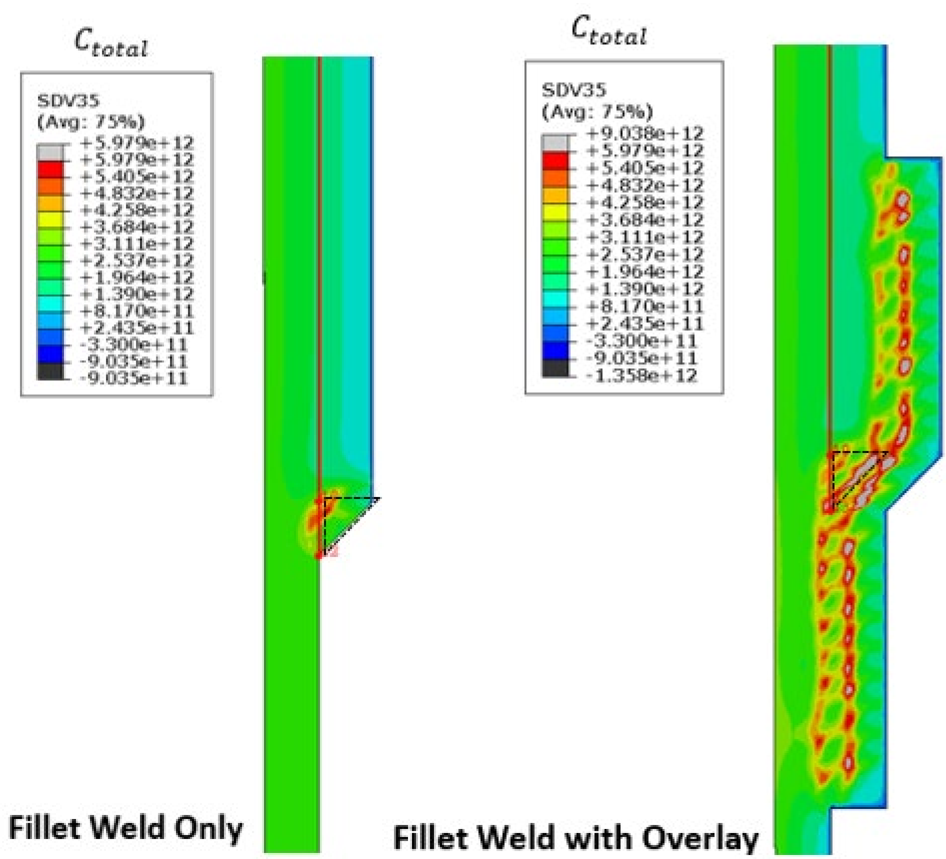


Figure 5 Predicted total hydrogen concentration profiles
(Initial fillet weld region in dashed triangle.)

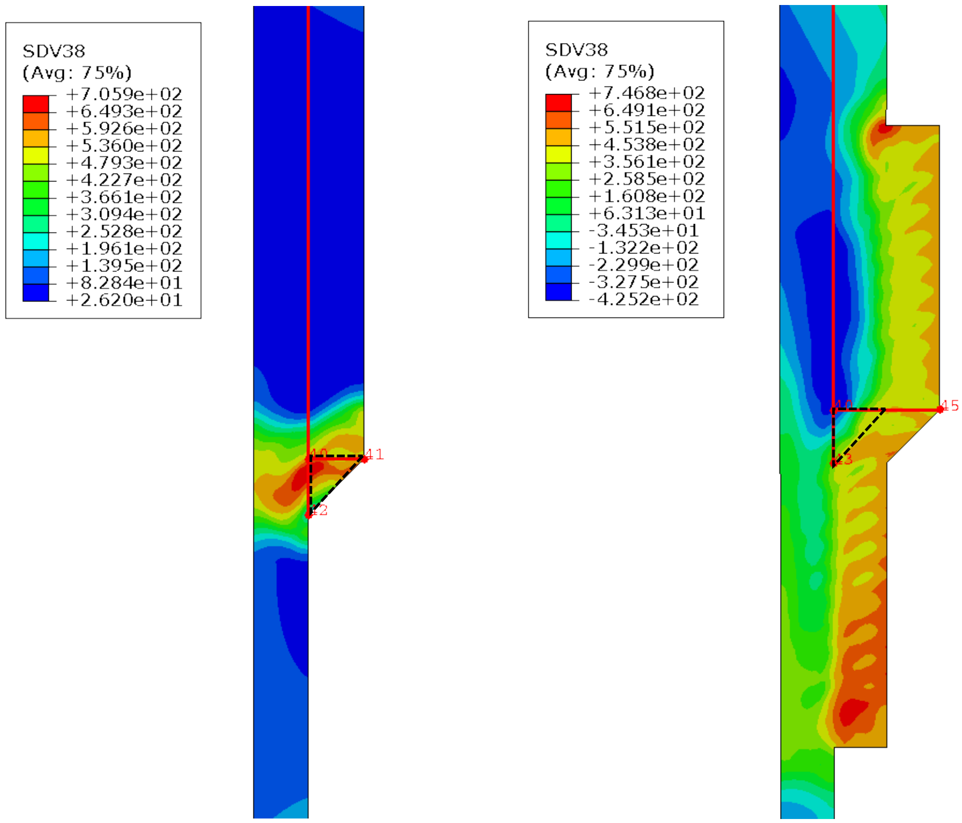


Figure 6 Hoop stress distribution in the sleeve, fillet weld, and overlay

This work demonstrated the procedural steps in combining weld simulation with the fully coupled hydrogen damage model. Significant work will be required to time the models and refine the integration of the models, but results obtained thus far are extremely promising in demonstrating that this technique may be used for exploring the implication of various weld repair strategies on transmission pipelines either containing existing sleeves or improving the reliability of future repairs.

References for this Section

[1] Tao Zhang, Bud Brust and Gery Wilkowski, S. Ranganath, Y Tsai, C. Huang, R. Liu, "Weld Residual Stress Analysis and the Effects of Structural Overlay on Various Nuclear Power Plant Nozzles," ASME Pressure Vessel and Piping Conference, July 2010.

Task 5 – Assess Critical Flaw Sizes and Respective Detection Thresholds

The efforts in this task are undertaken in two different approaches. The first is the development of fundamental aspects of hydrogen diffusion in steels under the influence of stress and plastic deformation. The resulting effects on damage progression and fracture toughness are being studied with the significant assistance of Professor Xiaosheng Gao of the Department of Mechanical Engineering of the University of Akron. This is a longer-term developmental effort that will eventually be needed to assess some complex geometries, such as the potential effects of hydrogen on weld defects in type B repair sleeves, hydrogen injection nozzle saddle welds, dents, gouges, wrinkle bends, etc. Professor Gao is first developing the fundamental aspects, while Emc^2 staff will utilize the computational developments for these more complex but pragmatic geometries. Subtask 5.1 describes the progress in those efforts during the last quarter.

The second approach is to provide some near-term pragmatic guidance for cases with and without hydrogen, such as axial cracks in pipes and crack severity within hard spots. These ongoing efforts are described in Subtask 5.2.

In a parallel DOT/PHMSA project (693JK32210013POTA) on *Reviewing of Integrity Threat Characterization Resulting from Hydrogen Gas Pipeline Service* also at Emc^2, we are tasked to develop a 5-year field-testing plan to validate integrity-management challenges. The work in Task 5 is valuable input to that effort and is repeated from both projects for information.

Subtask 5.1 – Hydrogen Diffusion in Steels under the Influence of Stress and Plastic Deformation and the Resulting Effects on Damage Progression and Fracture Toughness – Development of Fundamental FE Evaluation Methods

The efforts in this task were refocused to examine the Type B repair sleeve fillet welds and the possible repair method of an existing repair sleeve or modifying the repair method for new sleeves put on a hydrogen pipeline. This was described earlier in this quarterly report.

Subtask 5.2 – Near-Term Critical-Flaw-Size Evaluations

Two different types of analyses are underway for this project and the companion DOT/PHMSA project. These are efforts to examine the changes in critical flaw sizes in a hard spot and the effects of hydrogen on a low-toughness ERW seam weld crack.

The hard-spot work was actually done under the other DOT/PHMSA project, while the low-toughness seam weld work is being done in this project.

5.2.1 Summary of Hard-Spot Evaluations

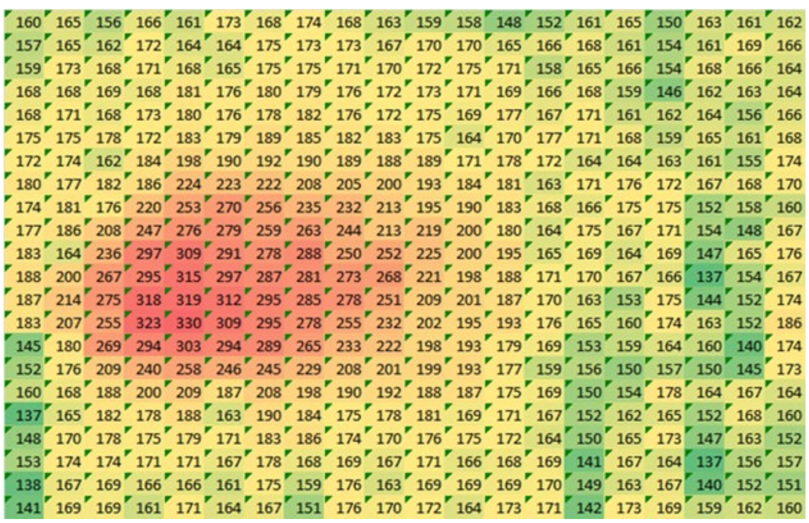
Hard spots are a unique problem to vintage pipelines, more notably to pipes made prior to 1960. Hardspots came from local overcooling when the steel was in plate form, resulting in microstructure changes to martensite and bainite, which are very hard and more susceptible to hydrogen stress cracking [2]. Of course, the hydrogen stress cracking that has occurred in natural service (past and recent) is from external hydrogen due to loss of coating by a hard spot, local soil enhancements for hydrogen formation (CP poisons in the soil), and the cathodic protection (CP) current used to protect the pipe from general corrosion.

The hard spots fail from axial cracks developing in them over time. With the external hydrogen from CP and failure of external coating, the hydrogen generated is thought to be much greater than the hydrogen flux through the pipe wall thickness from internal hydrogen gas being transported.

The HSC and fracture of the crack in the hard spot require a decent knowledge of the stresses applied in the hard spot region. The stresses in a hard spot consist of:

1. The pressure-induced hoop stress,
2. A through-thickness bending stress from the plate to pipe fabrication [3],
3. There is a flat spot in the pipe at the hard spot due to the hard region being created in plate form and not bending to the pipe's circular cross-section, and under pressure loading, this flat spot wants to round out, causing an additional through-thickness bending hoop stress; and
4. In creating the hard spot in the plate, the rapid cooling causes thermal-plastic stresses augmented by phase transformation. After total cooling, residual stresses are present in and around the hard spot.

Frequently, hard spots are characterized by the peak hardness value, although there is a significant gradient, as illustrated by the color map in Figure 7. One can further examine the hardness in circumferential or axial planes and would get contours like in Figure 8. The red curves in Figure 8 fit smoothly through the peak region and look similar to Weibull curve shapes with different shape and scale values. The skewing of the axial hardness contour suggests the plate was moving relative to the cooling source in the axial direction, which is reasonable. Those Weibull curve shapes can be used to create a 3D hardness representation that would smooth out the discrete smaller variations shown in Figure 10.



160	165	156	166	161	173	168	174	168	163	159	158	148	152	161	165	150	163	161	162
157	165	162	172	164	164	175	173	173	167	170	170	165	166	168	161	154	161	169	166
159	173	168	171	168	165	175	175	171	170	172	175	171	158	165	166	154	168	166	164
168	168	169	168	181	176	180	179	176	172	173	171	169	166	168	159	146	162	163	164
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177	186	208	247	276	279	259	263	244	213	219	200	180	164	175	167	171	154	148	167
183	164	236	297	309	291	278	288	250	252	225	200	195	165	169	164	169	147	165	176
188	200	267	295	315	297	287	281	273	268	221	198	188	171	170	167	166	137	154	167
187	214	275	318	319	312	295	285	278	251	209	201	187	170	163	153	175	144	152	174
183	207	255	323	330	309	295	278	255	232	202	195	193	176	165	160	174	163	152	186
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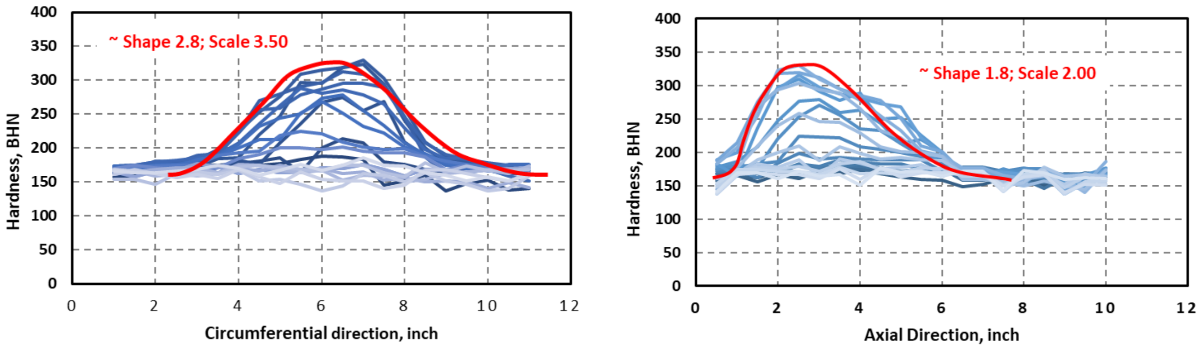
148	170	178	175	179	171	183	186	174	170	176	175	172	164	150	165	173	147	163	152
153	174	174	171	171	167	178	168	169	167	171	166	168	169	141	167	164	137	156	157
138	167	169	166	166	161	175	159	176	163	169	169	169	170	149	163	167	140	152	151
141	169	169	161	171	164	167	151	176	170	172	164	173	171	142	173	169	159	162	160

Figure 7 Illustration of hardness intensity in a hard spot region



(a) Circumferential hardness profile (b) Axial hardness profile

Figure 8 Hardness traverses in the circumferential and axial planes through the hard spot

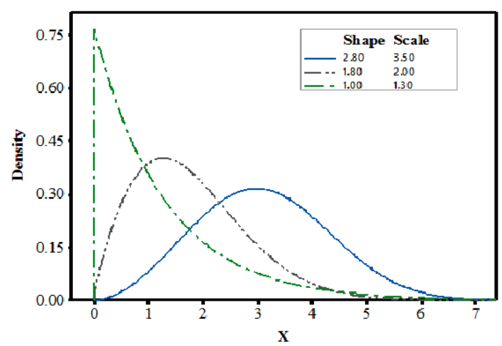


Figure 9 Weibull density distribution curve shapes

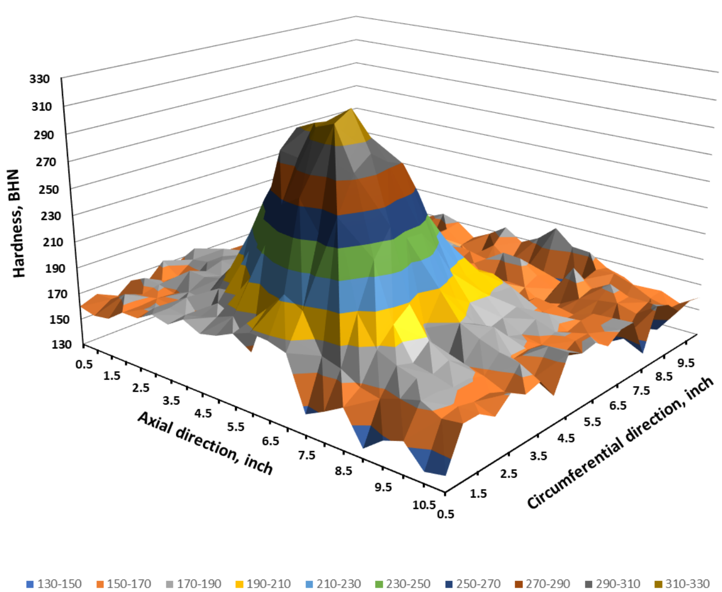


Figure 10 3D representation of the hardness in the hardspot shown in Figure 8

The 3D hardness distribution curve can then have functions to give the yield strength, strain hardening exponent, and toughness. These distributions (in the smoothed form) would then be used in an ABAQUS UMAT to provide the material property variations in the hard spot. The critical crack sizes could also be calculated with the residual stresses.

Additionally, the thermal-plastic/phase transformation stresses require a separate multiphysics FE analysis to try and reproduce the hardspot shapes as seen in service, as illustrated in Figure 10. Those analyses will then provide the residual stresses and hardness predictions using the LeBlond constitutive law. The LeBlond constitutive law accounts for phase transformation in a rapid cooling event, although its parameters depend on the steel composition. We are reviewing what material cases in the LeBlond library best represent the higher C and Mn for these older linepipe steels (C from 0.025 to 0.030 and Mn from 0.6 to 1.5).

Some initial FE analyses were performed on a hypothetical 6-inch hard spot in a 36-inch diameter and 0.44-inch pipe. The crack is an axial external canoe-shaped flaw and was evaluated at depths through the thickness ranging from 20% to 80%. The crack mesh for the a/t=0.4 case is shown in Figure 11.

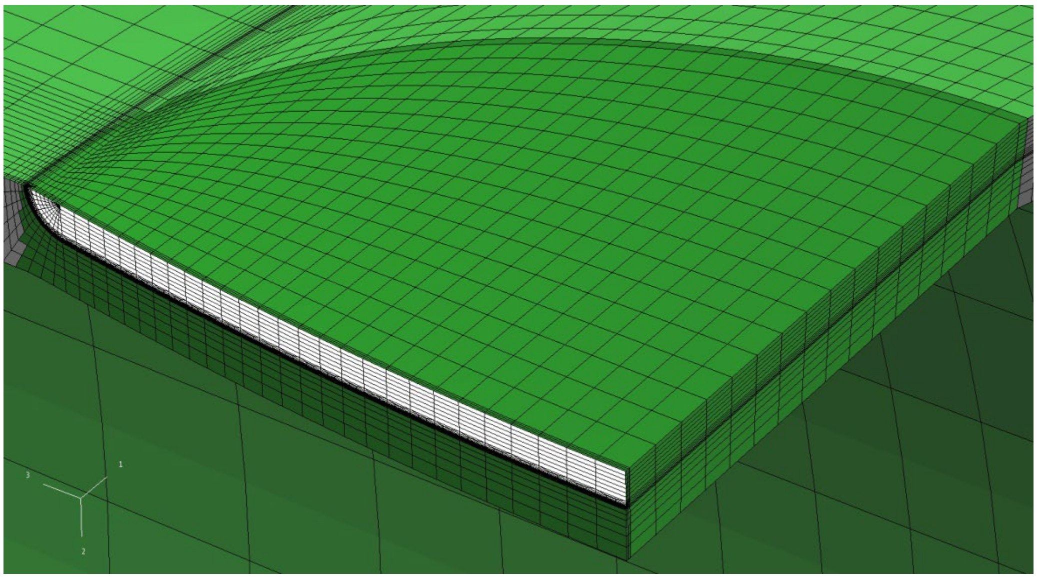


Figure 11 Mesh for 40% deep crack in a hardspot

The J values along the crack front for each of the a/t cases are shown in Figure 12.

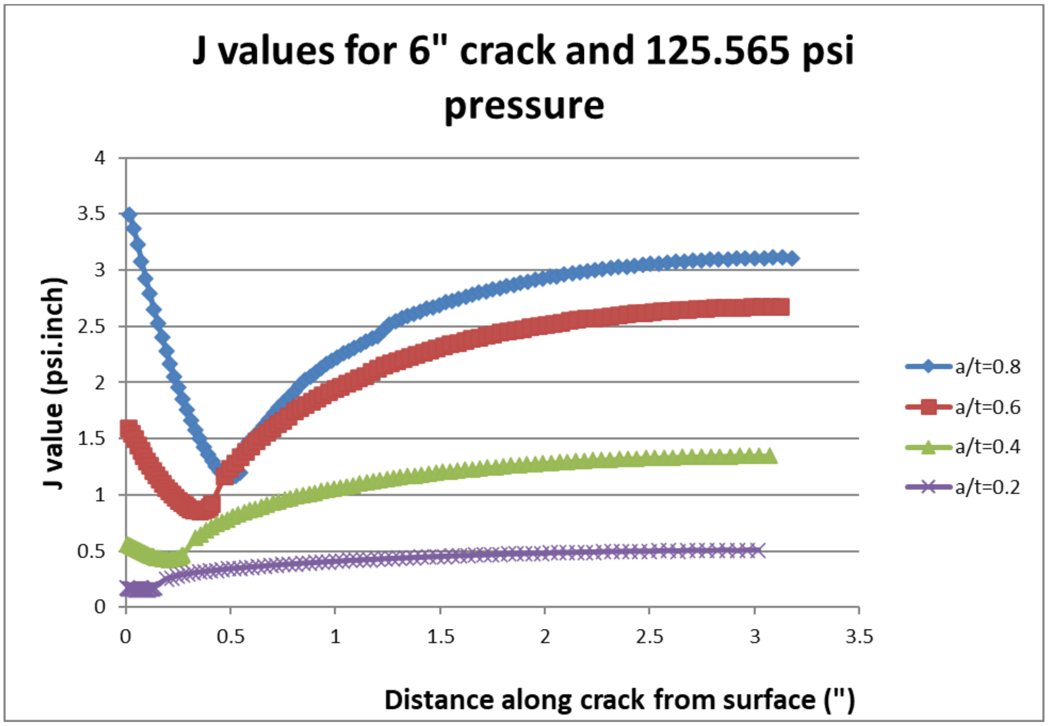


Figure 12: J value for a 6-inch crack at 125 psi for various crack depths

The FE analyses for the hardspot had difficulty in converging. Therefore, a linear elastic uncracked analysis was performed by closing the crack shown in Figure 11. The hoop stress is shown in Figure 13, and the axial stress in Figure 14. Other than a spurious localized peak in stress at the key location, the stresses are linear elastic under a 125 psi internal pressure load, as expected. Since the linear elastic uncracked analysis performs as expected, the cracked model will be further investigated in the next quarter to determine why the cracked hardspot model is having difficulty converging.

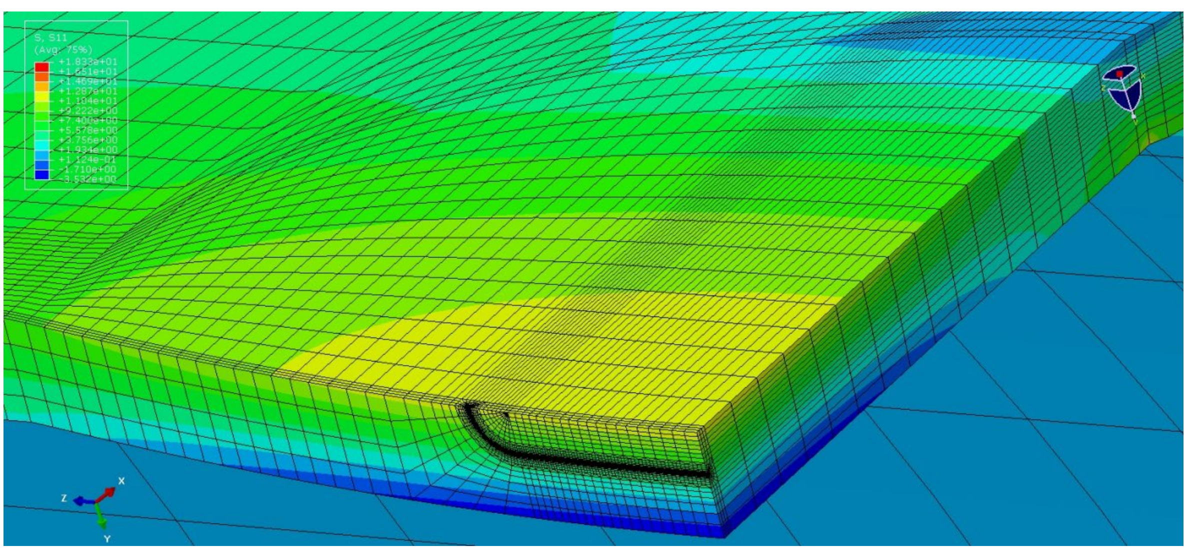


Figure 13 Hoop stress at hardspot for linear elastic uncracked analysis

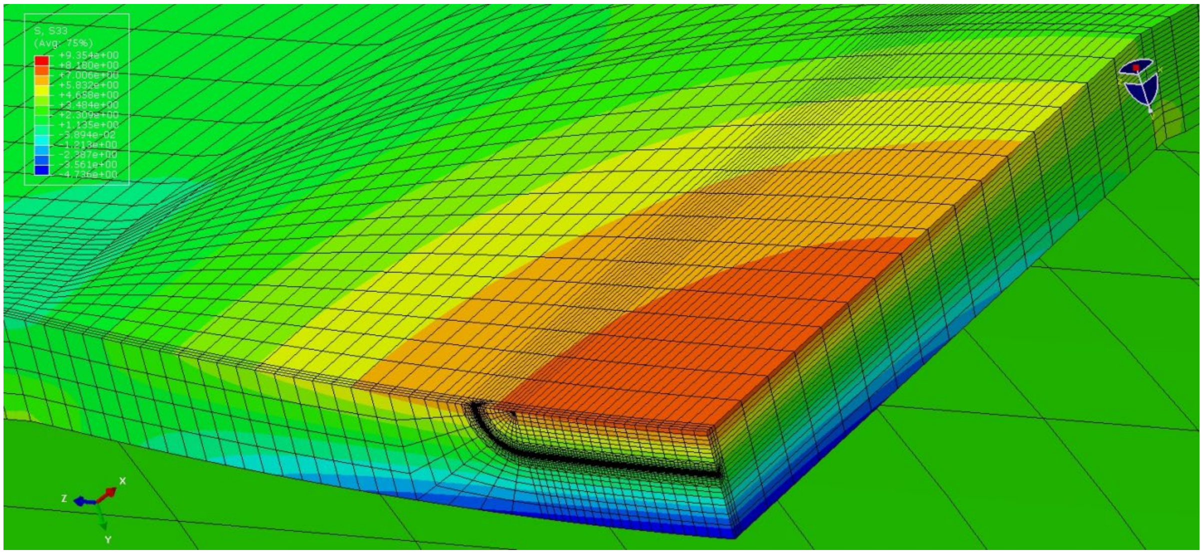


Figure 14 Axial stress at hardspot for linear elastic uncracked analysis

An interesting possibility is that once the hard spot is numerically calculated with all the material property variations and residual stresses, the time to cracking might be explored using the hydrogen concentration and Phase Field cracking procedures by Professor Gao in some future efforts. Gao's introductory work is summarized in the previous quarterly report.

5.2.2 – Axial Surface Cracks in ERW Pipe Fusion Lines

This evaluation intends to perform a more robust numerical simulation of axial surface cracks in hard ERW seam welds. These could be d-c ERW (Youngstown) or electric flash welds (EFW) made by AO Smith prior to 1965 that can have very high hardness. The flash welding or ERW process is the melting of the base metal together, which, if the carbon content is high, may result in martensite/bainite in the bond line.

The traditional critical crack evaluation procedure assumes the whole pipe and the ligament under the crack have base metal strength. In reality, the ligament where the fracture process occurs has higher strength, which could be 3 to 4 times higher than the base metal. The crack-driving force will consist of elastic and plastic components, so the higher-strength weld metal in the ligament will reduce the plastic contribution. Depending on the crack depth, some plasticity might develop in the adjacent base metal to the weld cross-section. This could affect the leak-rupture behavior of the ERW. Also, the ERW seam is sensitive to hydrogen exposure. In existing pipelines, the hydrogen exposure could be from external coating loss and CP-generated hydrogen in the right soil/water composition next to the surface. The hydrogen gas could slowly lead to atomic hydrogen at the crack without a coating loss or CP concerns for a hydrogen pipeline.

Using the base-metal properties everywhere, we have completed the pressure versus crack driving force curves for a matrix of surface crack sizes (3 depths and 3 lengths). A FE mesh generator was created to use the higher strength of the weld but the base metal properties in the bulk of the pipe model. Those calculations are ongoing.

List of References for this Section

[2] T. P. Groeneveld, R. L. Wenk, and A. R. Elsea, "Investigation of the Susceptibility of High Strength Pipeline Steels to Hydrogen-Stress Cracking," NG-18 report #37, October 1972.

[3] J. F. Kiefner, W. A. Maxey, G. M. Wilkowski, and R. J. Eiber, “The Magnitude and Effects of Residual Stress in Line Pipe,” presented at the 1977 AIME Mechanical Working Conference, January 26-27, 1977, Pittsburgh, Pennsylvania.

Task 6 – Review Regulatory Requirements for Safety Implications of Pipeline Conversion

This task will start next quarter.

Task 7 – Determine and Describe Necessary Operator Actions

This task is scheduled to start in the 6th quarter.

5: Project Schedule

The below project GANTT chart was updated from the prior quarterly report. We are behind on starting Task 6, which was supposed to begin last quarter, but that task will continue for the next 5 quarters. It should be no problem catching up on that task.