Engineering Critical Assessment of Vintage Girth Welds

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Abstract

Pacific Gas and Electric Company (PG&E) examinations exposed vintage girth welds during maintenance opportunities. Engineering critical assessment (ECA) was applied on those that failed workmanship criteria. The ECA considers the tolerance in defect measurement, operating stress, and other stresses at specified locations, such as a road crossing, near an elbow, thickness transition weld, and pipe axial bending.

1. Background

Pacific Gas and Electric Company (PG&E) opportunistically examined and inspected fully exposed girth welds in pipelines that were excavated for direct examination or maintenance activities. The objective of the opportunistic inspections was to verify the quality of the exposed girth welds as well as to determine the accuracy and quality of prior radiographic inspection of girth welds.

Girth weld failures are infrequent occurrences within the US natural gas pipeline network. Major girth weld failures are typically precipitated by unusually large external loads acting on an individual weld containing some sort of imperfection that is usually not minor. The ability of a weld to withstand applied loadings is related to:

- the presence and size of imperfection;
- the weld’s inherent strength, ductility, and fracture toughness; and
- the magnitude of the applied load.

The standard for girth weld workmanship quality is API 1104 [1], which provides protocols for qualifying welding procedures, qualifying welder performance, qualifying weld inspection procedures, and evaluation of welds made in production. From historical experience, small imperfections are understood not to degrade a weld’s ability to safely tolerate expected loads acting on the pipeline under usually encountered conditions. Accordingly, API 1104 allows some imperfections to remain in a weld if they are not overly large or numerous. The specific allowable size limits of imperfections have evolved over time and depend on the types of imperfections. The standard criteria for workmanship quality in API 1104 were developed to promote welding of sufficient quality for most situations while maintaining a high rate of productivity.

The engineering critical assessment (ECA) process can be applied to situations for which the standard acceptance criteria are not well-suited, including:

- development of alternative quality acceptance standards for new or existing welds not meeting the conventional criteria for quality;
- development of quality specifications for welds in pipelines expected to experience unusual loadings; or
- development of load or strain limits in recognition of specific weld properties and quality.

The first situation listed above is probably the most common application of ECA to girth welds and pertains to how the ECA is applied to evaluate PG&E’s girth welds. The ECA process utilizes fracture mechanics principles to assure that girth welds containing flaws allowed by the alternative acceptance criteria are fit for the intended service.

API 1104 Appendix A provides procedures for applying an ECA process wherein weld imperfections are conservatively evaluated as if they are planar or crack-like, even if they are in fact volumetric or have other geometric attributes that are less severe than truly crack-like defects. The impetus for the development of Appendix A was the audit discovery of noncompliant welding inspections and weld quality following the construction of the Trans-Alaska Pipeline System (TAPS) and the consequent need to determine whether welds having flaws that did not meet the existing criteria for workmanship quality were fit for their intended service [2]. Based on extensive fracture mechanics testing and analysis which formed the basis for Appendix A, the Department of Transportation (DOT) accepted the approach as an exception to the regulations at that time. Appendix A was first published in the 16th Edition of API 1104 in 1983. At that time it was based on the "crack opening displacement (COD) design curve" method of Burdekin and Dawes[3] and also embodied other fitness-for-service standards used globally at or since that time, for example Appendices J and K of CSA Z662 [4], and BSI PD-6493 [5]. The method provided for separate assessments for the potential for failure by brittle fracture or plastic collapse. With the 20th Edition of API 1104, Appendix A was further developed to incorporate the Failure Assessment Diagram (FAD) method which considered the interacting potential for failure by these two mechanisms. The FAD method was developed originally by the Central Energy Generating Board (CEGB) as the "R6" method [6] for evaluating crack-like defects in the UK nuclear power facility vessels and piping. The FAD method is recognized globally in current fitness for service standards, notably API 579/ASME FFS-1 [7] and BS 7910 [8]. The theoretical development and validation testing of the FAD approach as embodied in API 1104 Appendix A was described by Wang, et al. [9,10,11,12,13].

2. ECA for Vintage Girth Welds

The ECA for vintage girth welds in PG&E pipelines that failed to pass workmanship criteria is conducted via the approaches recommended in API 1104 Appendix A. The analysis considers both immediate failure and fatigue. The size of the flaw used in the ECA is determined from the nondestructive examination (NDE) measurement plus the tool tolerance. The lower bound of the material properties, including toughness and strength, is assumed to ensure the conservatism of the conclusion. Finally, the longitudinal stress applied on the investigated girth weld is determined based on the external loading conditions at the location.

2.1 FAD in API 1104 Appendix A

API 1104 Appendix A offers three optional levels of assessment, depending on the data available and the complexity of the situation. Option 1 provides two sets of acceptable flaw size curves, depending on the toughness value. Option 2 uses the FAD method. Option 3 is designed for assessment when significant growth of the imperfection is expected. Option 2 results are more generous with acceptable flaw sizes with the requirement for more information than Option 1. No significant growth of an imperfection is expected in a gas pipeline where the pressure cycles are usually mild, so Option 3 is not necessary. Therefore, Option 2 with the FAD method was selected to assess the vintage girth welds in PG&E's pipelines.

A schematic of the FAD in API 1104 Appendix A is plotted in Figure 1. The x-axis, L_r, is the ratio of the applied longitudinal stress, σ_a, over the plastic collapse stress, σ_c. The y-axis, K_r, is the ratio of the applied crack-tip stress intensity factor to the reference limit determined by the toughness of the material. The acceptable region is confined by a failure assessment curve and a cutoff line as shown in the figure. The equations from API 1104 Appendix A used to define each item in the FAD are also marked in the figure. With the FAD one must determine the coordinate pair, $(L_\mathrm{r}, K_\mathrm{r})$ of the investigated imperfection, which depends on pipe dimensions, the size of the imperfection, material properties of the girth weld, and the applied loads. The determination of the key parameters in the list above is discussed in Section 2.3 through 2.5.

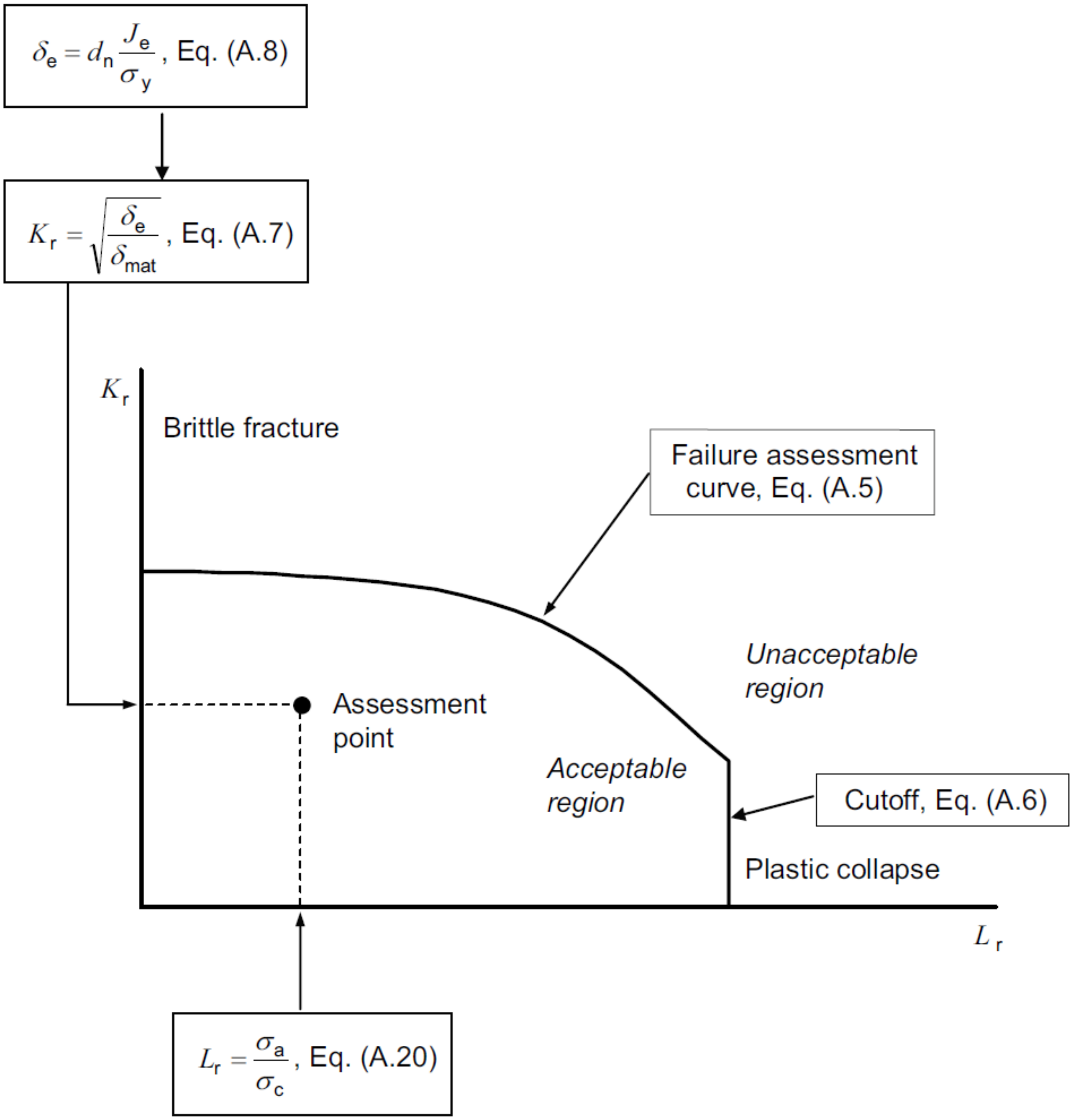

Figure 1 Failure Assessment Diagram from API 1104 Appendix A

2.2 Fatigue

The FAD method assesses the immediate failure at an imperfection. If the imperfection passes the FAD assessment, it may still grow incrementally under cyclic load and trigger failure in the future after enlarging to the critical size. Such damage is known as fatigue.

The cyclic load at a girth weld comes from two sources. The first source is the fluctuation of internal pressure. If the pipeline is buried, the surrounding soil restrains the movement of the pipe along longitudinal direction. Such restraint results in a longitudinal stress equal to 30% of the hoop stress in a steel pipe due to the Poisson effect. If the pipeline is aboveground, the end cap effect creates a longitudinal stress equal to one half of the hoop stress. API 1104 Appendix A provides an Equation (A-1) to characterize the fatigue damage via a spectrum severity factor as $S^* = \sum_{i=1}^{k} N_i(\Delta\sigma_i)^3$, where k is the total number of cyclic stress levels, and N_i and $\Delta\sigma_i$ are the number of cycles and the cyclic stress ranges at the i^{th} cyclic stress level, respectively. API 1104 suggests that the FAD (Option 2) method can be applied without any further fatigue analysis if $S^* < 5 \times 10^6$ ksi^3 and no environmentally assisted crack growth is expected (i.e., the crack growth curve follows that of "steel in-air"). The threshold value for S^* specified in Appendix A is very conservative compared with what is used in some other fitness-for-service standards.[1] The fluctuation of internal pressure is not with uniform amplitude during operations. A cycle-counting process [14], such as the "rainflow" method, should be used to decompose the randomly fluctuating pressure spectrum from SCADA or other monitoring records. The output of the cycle-counting process should be in terms of magnitude, frequency, and sequence of occurrence of the fluctuation. Most randomly fluctuating pressure records consist of a broad spectrum of load range magnitudes, characterized by a large number of occurrences of small fluctuations and a small number of occurrences of large fluctuations. The pressure spectrum record used for the cycle-counting process should cover at least a one-year period. The pipeline is assumed to have operated previously in a similar manner, and to continue operating similarly in the future.

The other source of cyclic loading is from vehicles crossing the buried pipeline, which only applies to imperfections in girth welds at or near road crossings. The vehicle crossing is independent of the fluctuation in internal pressure and the fatigue assessment from the two sources should be decoupled. Unlike pressure fluctuation, the number of vehicles crossing the pipeline is hard to estimate and therefore Equation (A-1) in API 1104 cannot be applied. The fatigue due to cyclic live loading is resolved through an alternative approach. Steel exhibits a fatigue endurance limit, the amplitude of cyclic stress below which it is not expected to initiate fatigue damage. In the absence of initial defects, the steel can resist an infinite number of cycles of stress below the fatigue endurance limit. API RP 1102 recommends a fatigue endurance limit of 12 ksi for girth welds in pipelines of any grade. This threshold was based on fatigue tests of sample welds (likely not containing gross imperfections). Although this is a less conservative criterion than that of API 1104 Equation (A-1), it is noted that in all cases of PG&E's girth weld ECA it was determined that the cyclical stress range due to live loadings was between 10% and 40% of this threshold, resulting in relative damaging effects between 0.1% and 6.4% of the threshold damage[2]. Given the large residual damage tolerance after accounting for pressure cycle effects, and the fact that pipeline girth weld failures due to traffic vehicle live loadings are as yet unknown in the industry, it was concluded that fatigue effects would not be significant.[3]

2.3 Flaw Size

PG&E identified the weld imperfections during in-ditch NDE using radiographic testing (RT) in all cases, and supplementing RT with ultrasonic testing (UT) if needed. RT is a standard technique applied to welds made using the manual shielded metal-arc welding (SMAW) or "stick welding" technique, and is reliable for the detection and sizing of volumetric flaws (such as porosity, slag inclusions, lack of penetration, lack of fusion, and undercut) associated with SMAW. RT can accurately indicate the lengths of such flaws but not the radial dimensions. RT is less effective for detecting planar or crack-like flaws that lie at an angle to the direction of radiographic illumination, particularly where significant thickness gradients are also present. UT is effective for accurately detecting and sizing planar

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[1] By comparison, BS 7910 would allow cyclic stresses to be 2.4 times greater for the same number of cycles, or would allow 14.5 times more cycles for the same cyclic stress range with the lowest-quality weld.

[2] The relative damage is proportional to cyclic stress to the third power as shown in Equation (A-1) in API 1104 for calculating S^*.

[3] The alternative approach would involve developing a site-specific traffic loading spectrum, converted to an equivalent number of standard truck axle crossings. Generic traffic loading spectra typically are available for major state highways, but they are likely to be overly conservative for roads that are not heavily travelled thoroughfares.

or crack-like flaws, including those that are a challenge to RT, and is effective for determining the radial dimension and the embedded distance from the interior or exterior pipe surface of flaws conventionally identified by RT. In the absence of supplemental UT, RT indications are conventionally assumed to have a radial dimension equal to the thickness of one weld pass because they are associated with the weld deposition process.[4] The lateral position within the weld deposit as indicated by the radiographic image can be used to infer whether a feature is surface-breaking at the interior or fully embedded.

The length of the imperfection along the pipe circumference is determined from RT measurement. Since the failure stress is generally less sensitive to the length, no accuracy tolerance needs to be considered. On the other hand, the failure stress is sensitive to the radial dimension of the imperfection. Therefore, a conservative height of the imperfection should be used in the analysis based on the measured radial dimension and the tolerance of UT accuracy. In the analysis for this project, an accuracy tolerance of 0.02 inch was considered based on research for PRCI [15]. Furthermore, API 1104 Appendix A suggests that “the built-in safety factor in the acceptable imperfection size can accommodate a certain amount of undersizing of the imperfection height without negatively impacting weld integrity. The assumed height uncertainty is the lesser of 0.060 inch (1.5 mm) and 8% of pipe wall thickness. No reduction in allowable imperfection size is necessary if the allowance for inspection is better than the assumed height uncertainty.” and “The allowable imperfection height shall be reduced by the difference between the allowance for inspection and the assumed height uncertainty if the above condition cannot be met.” To summarize, the measured radial dimension of the imperfection can be used in the ECA directly if the pipe wall thickness (WT) exceeds 0.25 inch. For thinner pipe, the radial dimension used in the ECA should be the measured value plus the amount of 0.02 inch minus 0.08*t*, where *t* is pipe WT.

Finally, the imperfections within close proximity may interact and result in lower failure stress than that due to any single imperfection alone. In this scenario, a combined larger imperfection should be used in the ECA. API 1104 Figure A.11 illustrates the approach to determine whether nearby imperfections will interact and how to determine the effective sizes of the combined one.

2.4 Material Properties

The material properties used in ECA include the yield strength, tensile strength, and toughness of the girth weld.

The yield and tensile strengths affect the coordinate, L_r, of the assessment point via the plastic collapse stress, σ_c, which equals the average of the yield and tensile strengths. Lower yield and tensile strengths result in larger L_r. The assessment point moves to the right side of FAD with less allowable K_r and meets the cutoff line earlier. The influence of the yield and tensile strengths on the coordinate K_r is more complicated but generally a decrease in strength results in increased K_r as well. Based on the above observation, the yield strength and tensile strength of a girth weld can be conservatively assumed as the specified minimum yield strength (SMYS) and the specified minimum tensile strength (SMTS) of the base metal if no further information is available. The strength of the weld metal is usually superior compared to that of the base metal because:

- welding procedures typically specify a welding consumable (electrode or rod) grade that meets or exceeds the base metal specified minimum tensile strength;
- the protocol for welding procedure qualification requires that a test weld break at an applied stress equal to or greater than the base metal specified minimum tensile strength;

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[4] Volumetric flaws are produced during the deposition of a single weld pass and thus do not typically extend radially through multiple weld passes. US applications tend to assume the weld pass is 0.1 inch (2.5 mm) thick while European applications tend to assume the weld pass is 3 mm (0.12 inch). These rounding differences are mainly for convenience in respective units systems.

- deposited weld metal cools quickly, resulting in higher actual strength than the specified minimum strength of the welding consumable; and
- base materials of the welds of interest are generally of moderate strength grades which are easily overmatched by deposited weld metal.

Finally, the net metal thickness in the girth weld is generally greater than the pipe wall, which could offset an unlikely occurrence of deposited weld metal somehow not meeting the target strength.

The toughness of girth weld used in the ECA is crack-tip opening displacement (CTOD), which measures the material resistance to fracture under quasi-static conditions. The CTOD is not regularly requested for qualifying welding procedures or welder performance. The CTOD testing might only be performed in conjunction with new construction when an ECA is expected at the design stage. No pipeline built earlier than the mid-1980s would have incorporated a girth weld ECA in the design process and most new pipeline construction projects today have no need for the ECA. As a result, the CTOD data for most pipelines are not available. In such pipelines, determining the CTOD value for girth welds is problematic because it requires that the pipeline be shut down in order to cut out specimen welds for destructive CTOD tests. If there are CTOD test data from other pipelines of similar vintage and constructed using similar pipe and welding processes, these data can be assumed to be representative. If no such data are available, very low values for CTOD can be assumed in an effort to assure that the assessment is conservative. A CTOD of 0.05 mm (0.002 inch) is the minimum to avoid non-ductile fracture initiation [16,17,18], which should be a conservative selection for most vintage pipes. In comparison, 42 CTOD test results from seven 1950s-vintage girth welds in PG&E's Line 132 exhibited a minimum CTOD of 0.066 mm (0.0026 inch) and a mean of 0.195 mm (0.0077 inch). The Line 132 test results are representative of the ductility properties that could be expected from welds made using the SMAW process in various eras within the scope of PG&E's girth weld mitigation program, based on Kiefner's review of CTOD data from other projects.

2.5 Applied Stress

The failure at a girth weld depends on the longitudinal stress. The longitudinal stress may be generated by multiple sources, including normal operation, thrust forces near changes in piping direction, and surface loading at road crossings.

All the pipelines have a component of longitudinal stress from normal operation. The internal pressure expands on the pipe in the hoop direction and results in hoop stress. Due to the Poisson effect, the expansion along the hoop direction tends to shrink the pipe along its axis. For buried pipelines, the movement along the pipe axis is restrained by the friction with surrounding soil. Therefore, a tensile longitudinal stress is generated whose amount equals the hoop stress multiplied by Poisson's ratio. For above ground pipes, there is no constraint on the axial movement. However, the end cap effect associated with any change in piping direction introduces a longitudinal stress component with an amount equal to one half of the hoop stress. The temperature differential between operation and installation also results in thermal stress in buried pipelines because thermal contraction or expansion in the longitudinal direction is restrained by friction at the interface with the surrounding soil. The calculation of the longitudinal stress due to internal pressure and temperature differential in a straight pipe segment is well established and the equations are provided in pipeline design standards such as ASME B31.4 [19] and B31.8 [20].

If the girth weld is close to a change in piping direction, the longitudinal stress component due to internal pressure is much more complicated than that in a straight segment. The flow of fluid and internal pressure generate thrust forces which result in displacement at changes in piping direction. The movement of the fitting is restrained by friction between the soil and the connected pipe tangents along a virtual anchor length. As a result, the thrust force generates both bending and axial loadings on the pipe section near the change of piping direction. The longitudinal stress depends on pipe dimension, angle change, distance from the fitting, and the soil condition around the pipe. Zhang and Rosenfeld have derived analytical solutions to determine the longitudinal stress near a bend or an end cap [21].

If the girth weld is under a crossing with a highway or railroad without a casing, the additional stress due to the loading from the ground surface should also be considered. The longitudinal stress due to surface loading includes two components: one is generated by the Poisson effect from ovalization of the pipe under the vertical external soil pressure; the other is generated by bending of the pipe axis due to vertical deflection. The calculation of longitudinal stress from surface loading can be accomplished using API RP 1102 [22] or other engineering methods such as that of Zhang, et al [23].

If the girth weld connects two pipes with different wall thicknesses, the mid-wall misalignment generates a localized through-wall bending stress. The associated stress concentration factor can be calculated through equations provided in Annex D of BS7910-2013 [8].

Finally, for scenarios such as a complex piping alignment or a pipeline crossing sites with geotechnical hazards, the longitudinal stress can be determined through finite element analysis (FEA).

3. Discussion of Regulatory Acceptance

The initial implementation of a fracture mechanics-based ECA process to the development of alternative flaw acceptance criteria for girth welds in a US pipeline, namely the Trans-Alaska Pipeline System, required a petition for regulatory waiver submitted to the DOT Office of Pipeline Safety (OPS).[24] Following extensive third-party expert review of the methods and procedures used, DOT granted a partial waiver[5]. [25,26] The waiver set the precedent for applying fracture mechanics to the evaluation of girth welds in regulated pipelines, although only by special permission.

DOT eventually accepted the use of fracture mechanics-based ECA for pipeline girth welds when the 1988 17th Edition of API 1104, with Appendix A, was incorporated by reference into 49 CFR Parts 192, 193, and 195.[27] Part 192, Subpart E – Welding of Steel in Pipelines, §192.24 “Inspection and test of welds”, Clause (c) states: “The acceptability of a weld that is nondestructively tested or visually inspected is determined according to the standards in Section 9 or Appendix A of API 1104. Appendix A of API 1104 may not be used to accept cracks.” This language clearly establishes regulatory allowance for implementing a fracture mechanics-based ECA in the evaluation of imperfections in pipeline girth welds, provided the imperfections are not actually cracks (despite the fact that the non-crack imperfections are evaluated as if they are cracks using the Appendix A method). California Public Utility Commission incorporates and supplements 49 CFR Part 192 in its General Order 112-F [28], thereby also accepts the use of fracture mechanics-based ECA for pipeline girth welds. The practice of evaluating the quality of girth welds using fracture mechanics and specifically the ECA process embodied in Appendix A has a long and successful track record.[6]

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[5] The waiver was partial in that not all welds originally requested for exemption were exempted, for various reasons, including that many had been remediated by the time the waiver was granted. However, DOT concluded that for the exempted welds the probability of a failure in the noncompliant welds were low and correcting the condition would not warrant the environmental damage that would be caused in the attempt to make the repairs.

[6] To the authors’ knowledge, there has not been a failure in a pipeline girth weld previously evaluated and accepted using ECA in accordance with API 1104, Appendix A. An informal inquiry to PHMSA welding subject-matter experts confirmed that they are unaware of failures of that nature in onshore pipelines.

4. Examples

Three examples are provided in this section to demonstrate the application of ECA to vintage girth welds in PG&E's pipeline system that exhibit imperfections that were found not to meet the API 1104 workmanship criteria.[7]

4.1 Example I

In the first example, the investigated girth weld was in a pipeline segment comprised of 30-inch OD API 5LX Grade X52 pipe. The pipeline was constructed in October 1954 and operates in a Class 3 location at a maximum allowable operating pressure (MAOP) of 590 psig. As shown in Figure 1, the girth weld connected two straight pipes of the same WT of 0.375 inch. The investigated girth weld was located in a segment of the pipeline which parallels an asphalt road about 25 feet offset from the edge of the road. Eight indications were found by NDE as listed in Table 1. The length of the indications along the pipe circumferential direction was determined from RT. The height is the dimension of the indications along the radial direction and the depth was the distance between the pipe OD surface and the top of the indications. Both height and depth were measured by UT.

As the girth weld is about 25 feet offset from the road, the stress due to the vehicles on the road is negligible. The longitudinal stress applied at the girth weld only includes the components due to internal pressure and thermal expansion. The internal pressure at MAOP results in a hoop stress of 23.60 ksi following Barlow's equation. The longitudinal stress component due to internal pressure is 7.08 ksi. The temperature differential between the operating temperature and the installation temperature produces a thermal stress. PG&E suggests the temperature of the underground pipeline during operation is about 50 F. According to local climate data, the average high temperature for October is 76 F, which provides the maximum temperature difference of -26 F. The negative temperature differential results in a tensile longitudinal stress of 4.99 ksi. Furthermore, the installation or ground subsidence may introduce some bending stress. PG&E measured the curvature of the pipeline using the inertial measurement unit (IMU) of an in-line inspection (ILI) tool and reported locations having bending strain exceeding 0.04%. The investigated girth weld was not reported by the IMU to be affected by curvature, but to be conservative, a longitudinal stress of 11.80 ksi due to pipe bending equivalent to 0.04% bending strain was added to the other stresses. The total longitudinal stress estimated at the girth weld was 23.87 ksi.

Eight indications were identified by NDE as porosity. Multiple flaws within close proximity of each other may interact. API 1104 Appendix A provides guidance for determining whether flaws could interact and how to determine the effective size of the combined flaw if they do interact. Indications No. 3 (0.132 inch x 0.071 inch), No. 4 (0.128 inch x 0.075 inch), and No. 5 (0.137 inch x 0.062 inch) were very close and deemed to interact. These three indications were analyzed as a single surface breaking flaw with an effective size of 0.635 inch x 0.169 inch. This combined flaw is more severe than any single indication listed in Table 1 and was evaluated for the ECA. If this flaw is safe, then any smaller flaw would be safe; if this flaw fails the ECA, the girth weld should be repaired or cut out regardless of whether other flaws are safe or not.

To be conservative, the yield strength was assumed to be 52 ksi and the tensile strength was assumed to be 66 ksi, which are the specified minimum strengths of the pipe grade. (Most pipe is stronger than the specified minimum properties.) The ECA was conducted considering three toughness levels with CTOD of 0.02 mm (to represent the extreme lower bound of toughness), 0.05 mm and 0.10 mm (to represent more probable scenarios).

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[7] It is not unusual to discover girth welds in older vintage pipelines that do not meet workmanship criteria. Historically, welds have often only been inspected on a sampling basis during construction and weld inspection technology has evolved significantly.

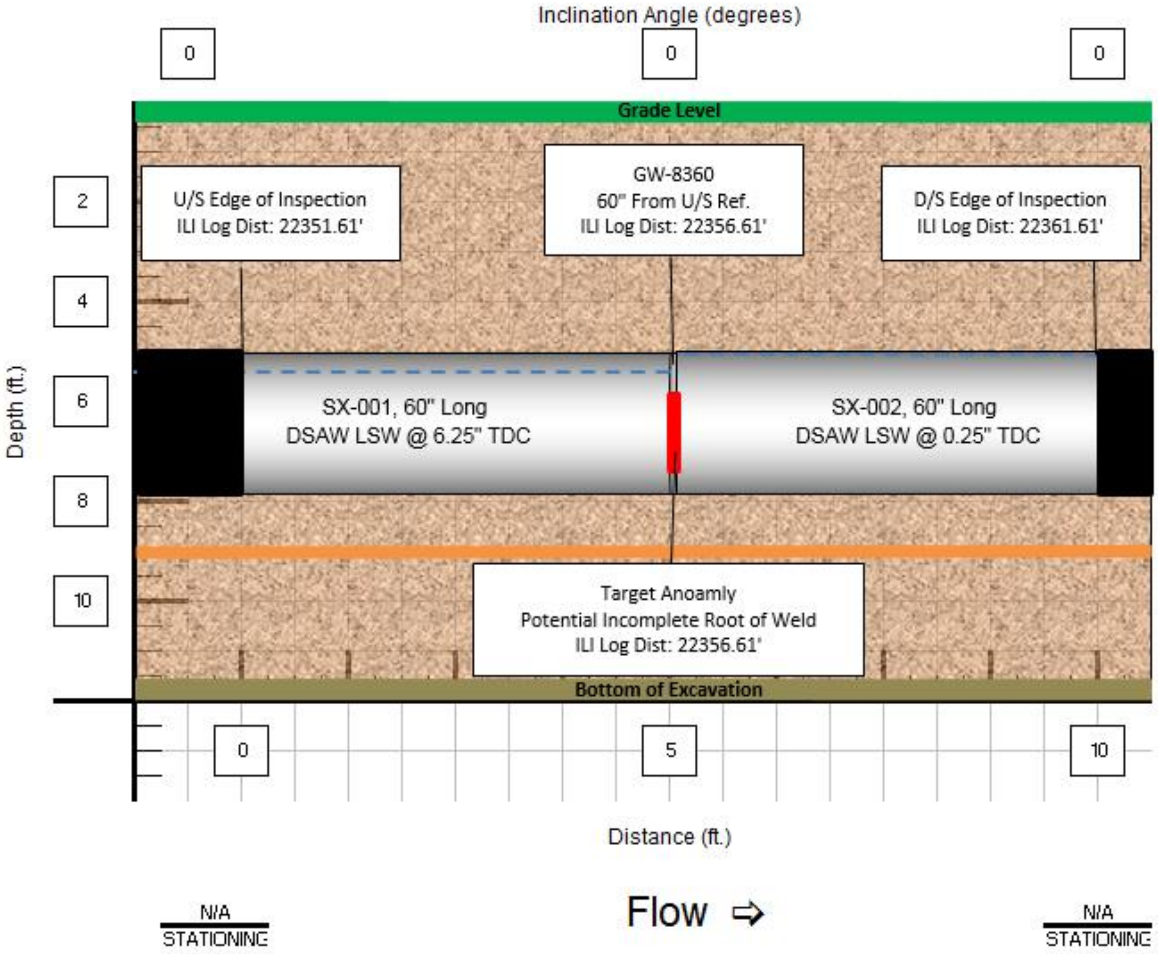

Figure 2 Configuration of the Investigated Segment in Example I

Table 1 NDE Indications in the Investigated Girth Weld in Example I

No.	Flaw Length, inch	Flaw Height, inch	Flaw Depth, inch	Location along Pipe Circumference, inches (from top of pipe)
1	0.136	0.071	0.141	14.750
2	0.328	0.100	Cap	23.0
3	0.132	0.071	0.098	23.75
4	0.128	0.075	0.080	24.0
5	0.137	0.062	Cap	24.25
6	0.128	0.067	0.048	48.0
7	0.132	0.130	Root	49.5
8	0.142	0.100	Root	75.5

Based on the information above, the K_r and L_r were calculated for the assumed single imperfection combining Indication Nos. 3 through 5. The points with various CTODs are plotted on the FAD in Figure 3. The points for all three CTOD values were within the acceptable region and the girth weld was considered safe and acceptable.

The potential for fatigue was also checked. The hourly minimum and maximum pressure data recorded at the closest supervisory control and data acquisition (SCADA) monitoring point over a 3+ year period was analyzed. The equivalent MAOP cycle was determined to be 1.90 cycles per year. From this equivalent MAOP cycle frequency and the amplitude of stress change within a MAOP cycle, the calculated spectrum severity factor S^* per year is 674 ksi^3. In comparison with the S^* threshold of 5×10^6 ksi^3, there is no fatigue concern for the imperfections in this girth weld in the service life of the pipeline assuming the internal pressure cycling continues to operate in a similar pattern to the cycles recorded.

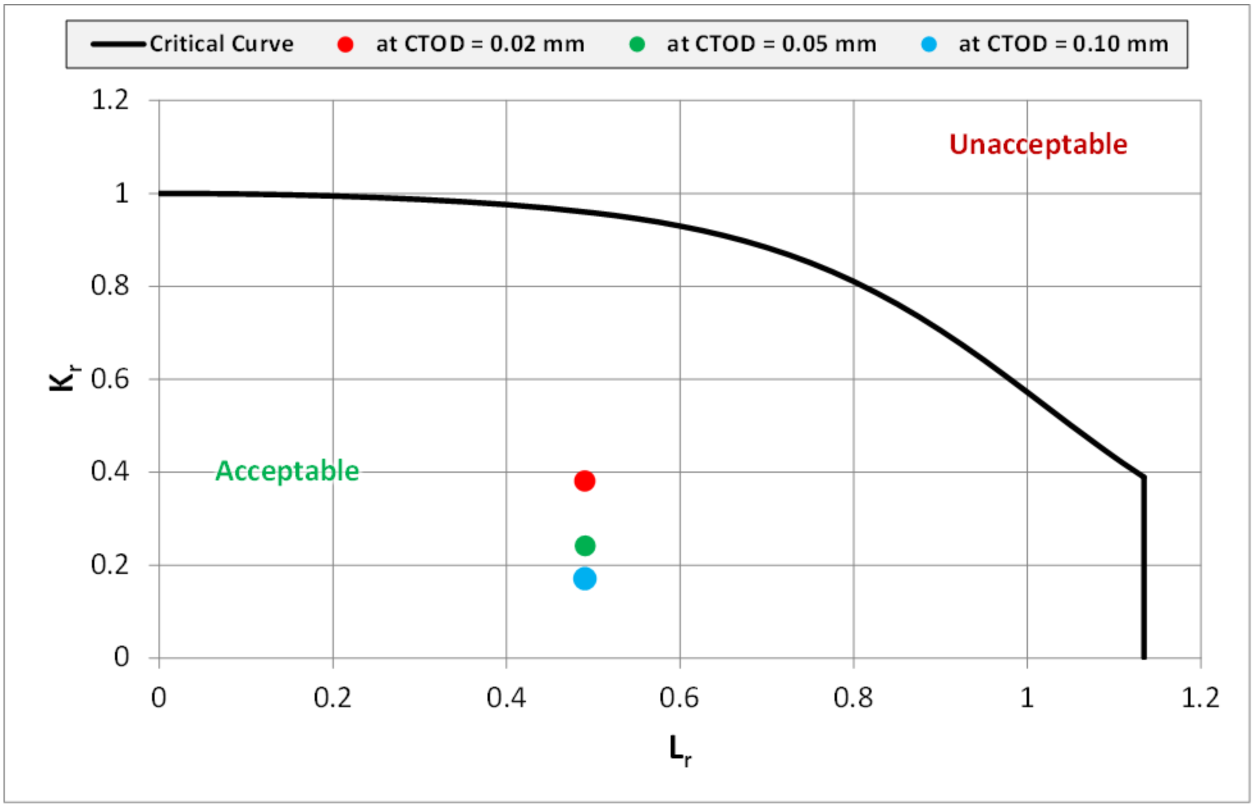

Figure 3 FAD of the Imperfection Combining Three Indications, Nos. 3 through 5, in Example I

4.2 Example II

In the second example, the investigated girth weld was in a pipeline segment comprised of 12.75-inch OD API 5LX Grade X42 pipe. The pipeline was constructed in October 1971 and operates in a Class 3 location at an MAOP of 650 psig. The girth weld connected a straight length of 0.219–inch WT pipe to a 90-degree elbow with 0.375–inch WT. The bending radius of the elbow was 1.5 times the pipe OD. An illustration of the segment configuration is shown in Figure 4. The elbow remained buried beyond the right end of the excavation in the figure. The investigated girth weld was under an asphalt road. Five indications were found by NDE as listed in Table 2. Only Indication No. 3 exceeded the acceptable workmanship flaw size criteria. The height and depth and this indication was then measured by UT.

During normal operation, the internal pressure results in thrust force at the elbow. Thermal expansion also introduces complex displacement at this location. The maximum temperature differential of -30 F was determined from the local climate data. The backfill material was sand. The longitudinal stress component due to operation was determined to be 12.67 ksi at the MAOP of 650 psig and 8.65 ksi at zero internal pressure. As the investigated girth weld was under an asphalt road, the stress due to the loading from ground surface was also considered. The depth of cover above the weld was 92 inches. Following the approach in Reference [23], the resulting longitudinal stress component was 1.78 ksi at the MAOP of 650 psig and 3.22 ksi at zero internal pressure. No high bending strain was reported by the ILI IMU so the stress component due to pipe axis bending was conservatively assumed as 11.80 ksi independent of the internal pressure level. The total stress acting at the weld was estimated to be 26.31 ksi at the MAOP. Finally, the thickness transition between the elbow and the straight pipe results in a stress concentration factor at the girth weld of 1.72 following the guidance in BS 7910. Therefore, the longitudinal stress of 45.26 ksi was eventually used in the ECA.

After examination, no interaction among the indications was found. The ECA was conducted on Indication No. 3 which was the largest flaw. The tolerance of the flaw height measured by UT is 0.02 inch while the ECA in API 1104 Appendix A has a built-in safety factor to allow height uncertainty at the lesser of 0.060 inch and 8% of WT. The height uncertainty that was included in the assessment approach was 0.0175 inch (8% of the thinner 0.219-inch WT straight pipe), which is smaller than the UT tolerance of 0.02 inch. As a result, an additional 0.0025 inch (0.02 inch less 0.0175 inch) was added to the height listed in Table 2 before ECA.

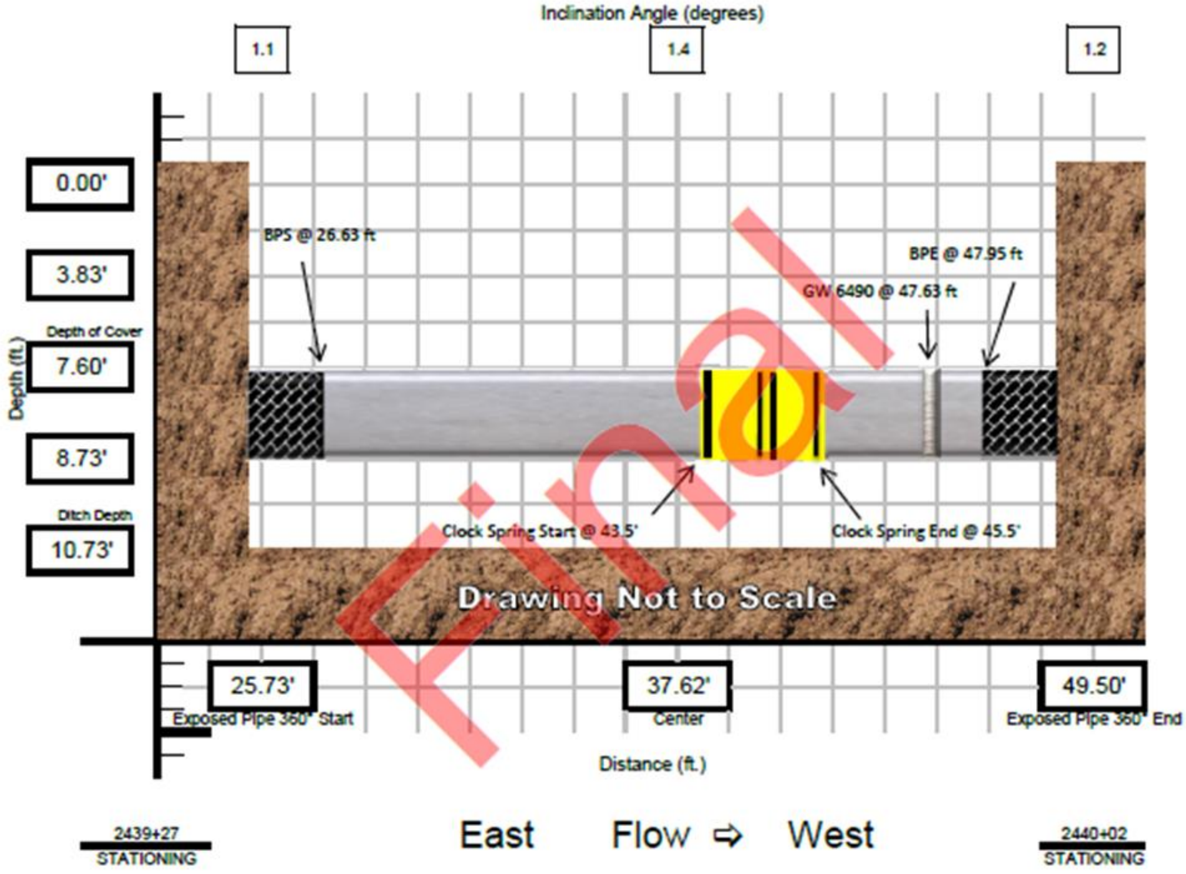

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Figure 4 Configuration of the Investigated Segment in Example II

Table 2 NDE Indications in the Investigated Girth Weld in Example II

No.	Flaw Length, inch	Flaw Height, inch	Flaw Depth, inch	Location along Pipe Circumference, inch
1	0.047	N/A	N/A	6
2	0.031	N/A	N/A	10
3	0.063	0.025	Surface	12
4	0.078	N/A	N/A	31.5
5	0.500	N/A	N/A	39.5

The yield strength and tensile strength were assumed to be 42 ksi and 60 ksi, respectively. The ECA was conducted considering the same three toughness levels as with Example I.

The FAD for Indication No. 3 is plotted in Figure 5. The points for all three CTOD values were determined to be safe and acceptable.

Two sources of cyclic loads may result in a fatigue concern at the investigated girth weld: the cyclic live load from vehicle traffic on the asphalt road crossing the pipeline and the variation in internal pressure. The cyclic longitudinal stress due to the live load was 1.12 ksi at zero internal pressure or 0.74 ksi at the MAOP. Both values were well below the API RP 1102 fatigue endurance limit of 12 ksi. The equivalent MAOP cycle of 0.61 cycle per year was determined from the closest SCADA record over a nearly 4-year period. The calculated S^* per year was 478 ksi^3, which was negligible compared with the threshold of S^* of 5×10^6 ksi^3.

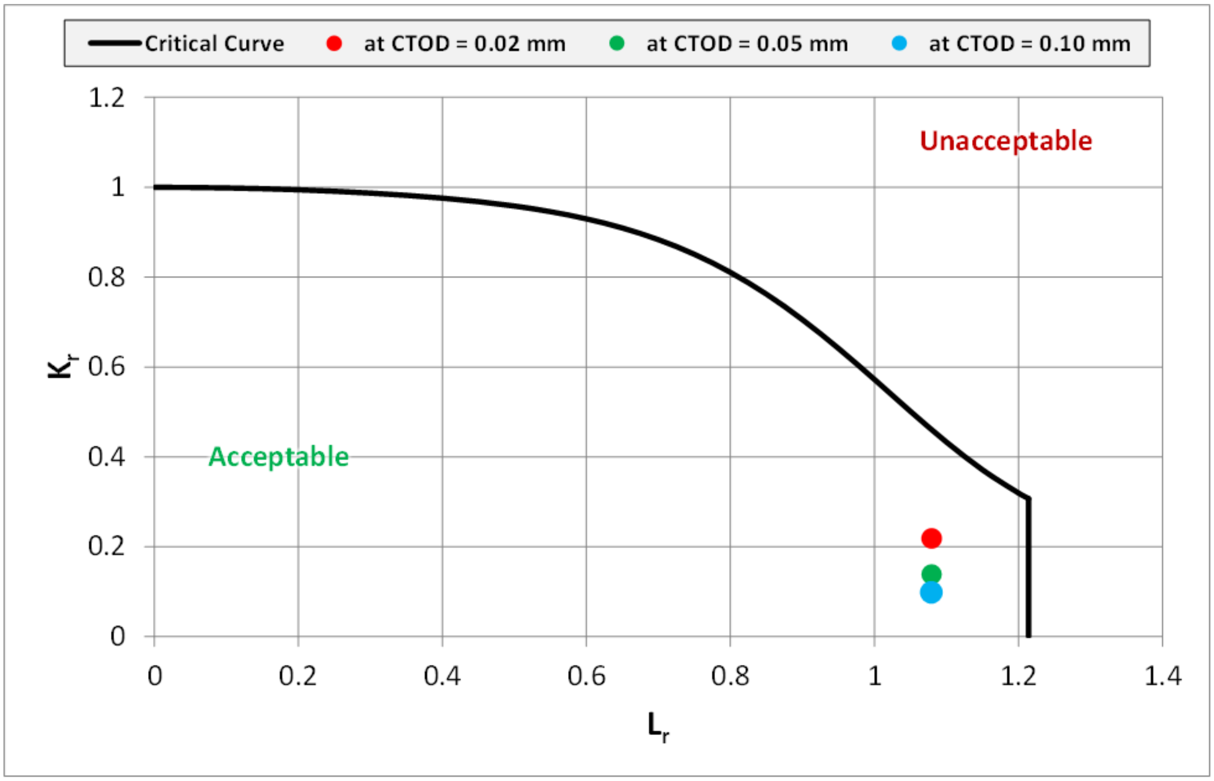

Figure 5 FAD of Indication No. 3 in Example II

4.3 Example III

The last example included five girth welds located in a bypass line of a pig launcher inside a compressor station, labelled as W-7 through W-11 in Figure 6. The bypass line was comprised of 2.375-inch OD, 0.154-inch WT, API 5L Grade B seamless pipe. The pig launcher assembly including the bypass line was installed in July 2005 and operates at an MAOP of 1,040 psig. The diameter of the pig launcher was 36 inches. Welds W-10 and W-11 connect a 2-inch full port ball valve rated as ANSI 600. On top of the valve is a high operator stem extending aboveground. The buried depth of the bypass line was 68 inches and the backfill at the site was clay.

Wet fluorescent magnetic particle testing (MPT) and dye penetrant testing (DPT) were firstly conducted. The DPT found one surface porosity feature on W-8 and one cluster of surface porosities on W-9. UT was then used to measure the radial dimensions of the porosity on W-8 and the cluster of porosities on W-9. At last, RT was performed on all five girth welds and rejectable features were found in all five welds. The measured dimensions indicated by the three NDT techniques are summarized in Table 3.

Due to the complexity of the piping arrangement, FEA was conducted to determine the longitudinal stress levels at each girth weld. The FEA accounted for multiple loadings including the weight of the pipes, the weight of soil over the buried pipes, the weight of the valves, internal pressure, and the temperature differential. Since the bypass line was very close to a pig launcher, no vehicles were expected to pass directly over it so traffic loads were not considered. The distribution of the stresses from FEA is plotted in Figure 7. The calculated stresses were 6.06 ksi, 3.61 ksi, 3.71 ksi, 2.61 ksi, and 7.44 ksi at W-7 through W-11, respectively.

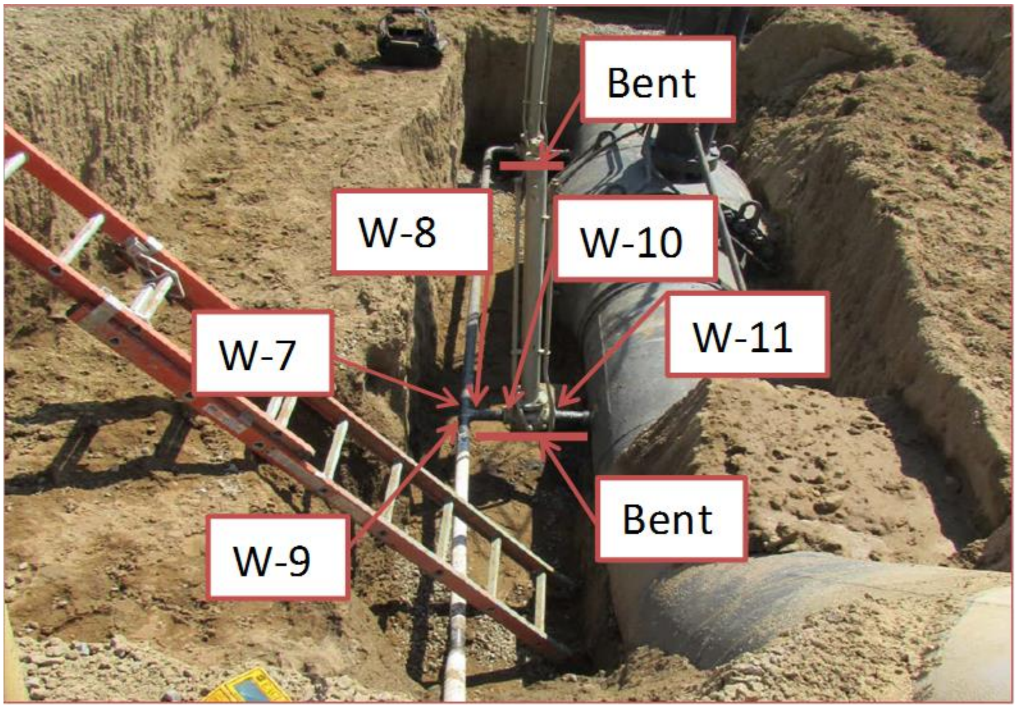

Figure 6 Configuration of the Investigated Segment in Example III

Table 3 NDE Indications in the Investigated Girth Weld in Example III

Girth Weld	Length by DP, inch	Height by UT, inch	Length by RT, inch
W-7			IP(a): 1.217 P(b): 0.048, 0.075
W-8	P: 0.250	P: 0.018-0.020	P: 0.115, 0.056, 0.063, 0.029, 0.043, 0.123
W-9	P: 0.363	P: 0.068-0.076	P: 0.044, 0.043, 0.132 CP(c): 0.324
W-10			P: 0.042, 0.038, 0.061
W-11			P: 0.049, 0.064, 0.055, 0.049, 0.028

(a) IP: improper penetrameter
(b) P: Porosity
(c) CP: cluster porosity

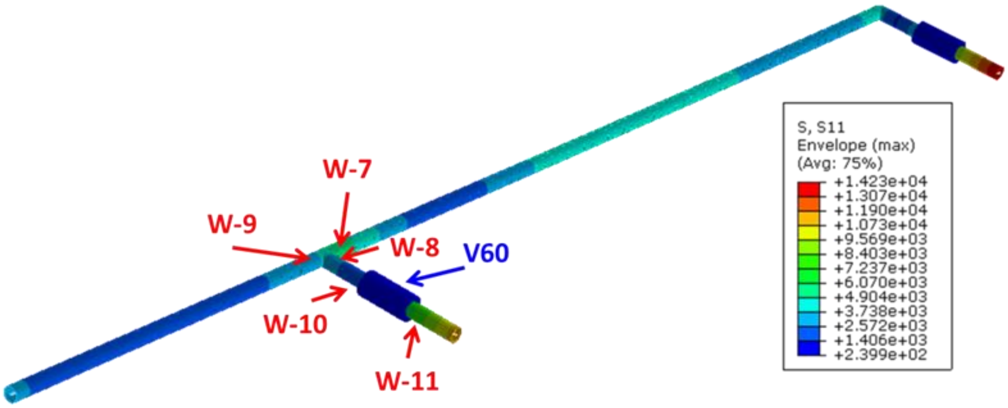

Figure 7 Distribution of Longitudinal Stresses Along the Bypass Line

Only the porosity cluster in W-9 and multiple features concentrated at a local position in W-11 were deemed to interact. The W-9 porosity cluster and W-11 feature cluster were each evaluated as a single flaw within their respective girth welds. Since the indications in W-7, W-10 and W-11 were found after completing the UT, radial heights of the features were not measured and were estimated as the height of one weld pass of 0.1 inch following standard practice. For the heights measured by UT, the 0.02-inch tolerance should be considered. Per API 1104 Appendix A, the height uncertainty that has been accounted in ECA was 8% of the 0.154-inch WT, or 0.012 inch. Therefore, an additional 0.008 inch (0.020 inch less 0.012 inch) was added to the UT measured radial heights at W-8 and W-9. Although multiple indications were found, the ECA only needed to be conducted on the most severe indication in each girth weld. The flaw dimensions for each girth weld used in the ECA are listed in Table 4.

Table 4 Imperfections Investigated in ECA

Girth Weld	Length for ECA, inch	Height for ECA, inch
W-7	1.217	0.100
W-8	0.250	0.028
W-9	0.363	0.084
W-10	0.061	0.100
W-11	0.800	0.100

The yield strength and tensile strength were assumed to be 35 ksi and 60 ksi, respectively. The ECA were conducted for the same three toughness levels as the previous examples.

Each of the analyzed imperfections were determined to be safe acceptable according to the FAD. For brevity, the FADs are not provided here.

No pressure record was available for the bypass line. However, the maximum stress among the five girth welds was only 7.44 ksi or 21% of the pipe yield strength from FEA which accounted for the combined loads from the weight of pipe, soil overburden, plus those from cyclic loads including internal pressure and thermal deformation. The magnitude of cyclic stresses should be less than this level and is not expected to generate a fatigue concern in the practical service life of a pipeline.

5. Conclusions

The ECA provided an alternative integrity assessment approach to repairing girth welds where imperfections exceeded the allowable workmanship flaw size criteria. The ECA approach was based on fracture mechanics analysis and conservatively treated different types of imperfections as surface connecting cracks. One ECA method widely accepted by the pipeline industry is provided in API 1104, Appendix A. Although the equations for applying the ECA via FAD have been well documented by the Appendix, there are a number of considerations and difficulties that must be addressed in order to apply this approach to assess the vintage girth welds with confidence. Such considerations include fatigue, the size of the imperfection and its tolerance of uncertainty from measurement, material properties including toughness, and the site-specific applied stress induced by various scenarios and conditions. This paper provides a detailed discussion of each of these aspects. Oversimplifying any of the aspects may result in an unnecessarily conservative assessment or oppositely unsafe conclusions. An understanding of the regulatory acceptance of ECA is also important to ensure compliance. Finally, three examples were provided based on girth welds found in PG&E pipelines to demonstrate the successful application of ECA with necessary considerations.

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