Together beyond standards

# Engineering Critical Assessment of Vintage Girth Welds

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AGA Operations Conference, June 27, 2018 Washington DC

# Outline

1 Background

2 Approach of Engineering Critical Assessment

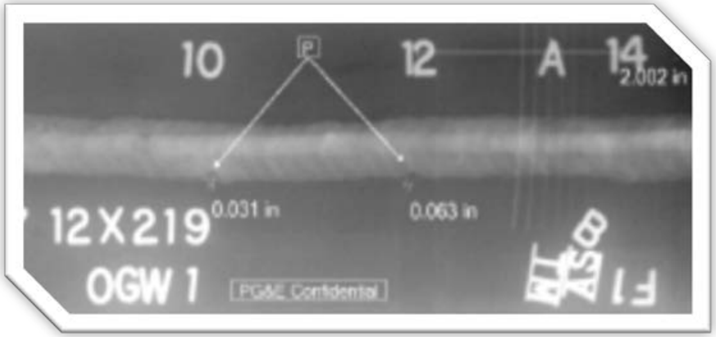
3 Regulatory Acceptance

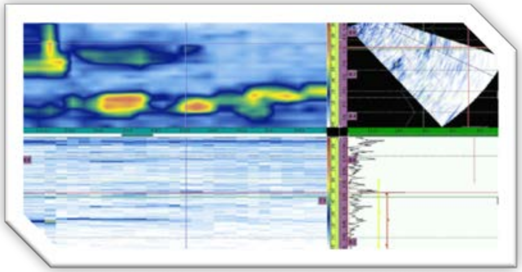
4 Working Examples

5 Conclusions

# Background – PG&E Efforts

1. Pacific Gas and Electric Company (PG&E) inspected girth welds excavated for direct examination or maintenance activities.
2. The purpose was to verify the quality of the girth welds and the accuracy of previous radiographic inspection.



# Background – Overview of Girth Weld

1 Girth weld failures are **infrequent** occurrences within the US natural gas pipeline network.

2 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**.

3 **Small imperfections** are understood **not to degrade** a weld's ability to tolerate loads under usual conditions. API 1104 provide **criteria for workmanship quality** to allow some imperfections in a weld if they are not overly large or numerous.

# Background – ECA

1 **The engineering critical assessment (ECA) process can be applied to situations including**

- development of **alternative quality acceptance standards** for new or existing welds not meeting the conventional criteria;
- 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.

# Background – Brief History of ECA in U.S.

## 1 Trans-Alaska Pipeline System (TAPS)

Audit discovery of noncompliant welding inspections and weld quality following the construction of the TAPS.

## 2 Department of Transportation (DOT)

Based on extensive fracture mechanics testing and analysis, DOT accepted the approach as an exception to the regulations at that time.

## 3 Appendix A in API 1104

Appendix A was first published in the 16$^{th}$ Edition of API 1104 in 1983.

## 4 Failure Assessment Diagram (FAD)

In the 20$^{th}$ Edition of API 1104, Appendix A incorporates the FAD method.

# Background – ECA on Vintage Girth Weld

1 **Special factors should be considered to adequately apply the ECA on vintage girth welds**

- **Flaw Sizes**
  The accuracy tolerance should be considered in the imperfection/flaw sizes measured by nondestructive examination (NDE) techniques.
- **Material Properties**
  The information regarding the material properties of a vintage pipeline is generally very limited.
- **Applied Stress**
  The longitudinal stress at the girth welds can be complex if the girth weld is near a bend, under road crossings, or connecting two joints with different wall thicknesses.

# Outline

1 Background

2 Approach of Engineering Critical Assessment

- Framework of ECA – Failure and Fatigue
- Flaw Size
- Material Properties
- Applied Stress

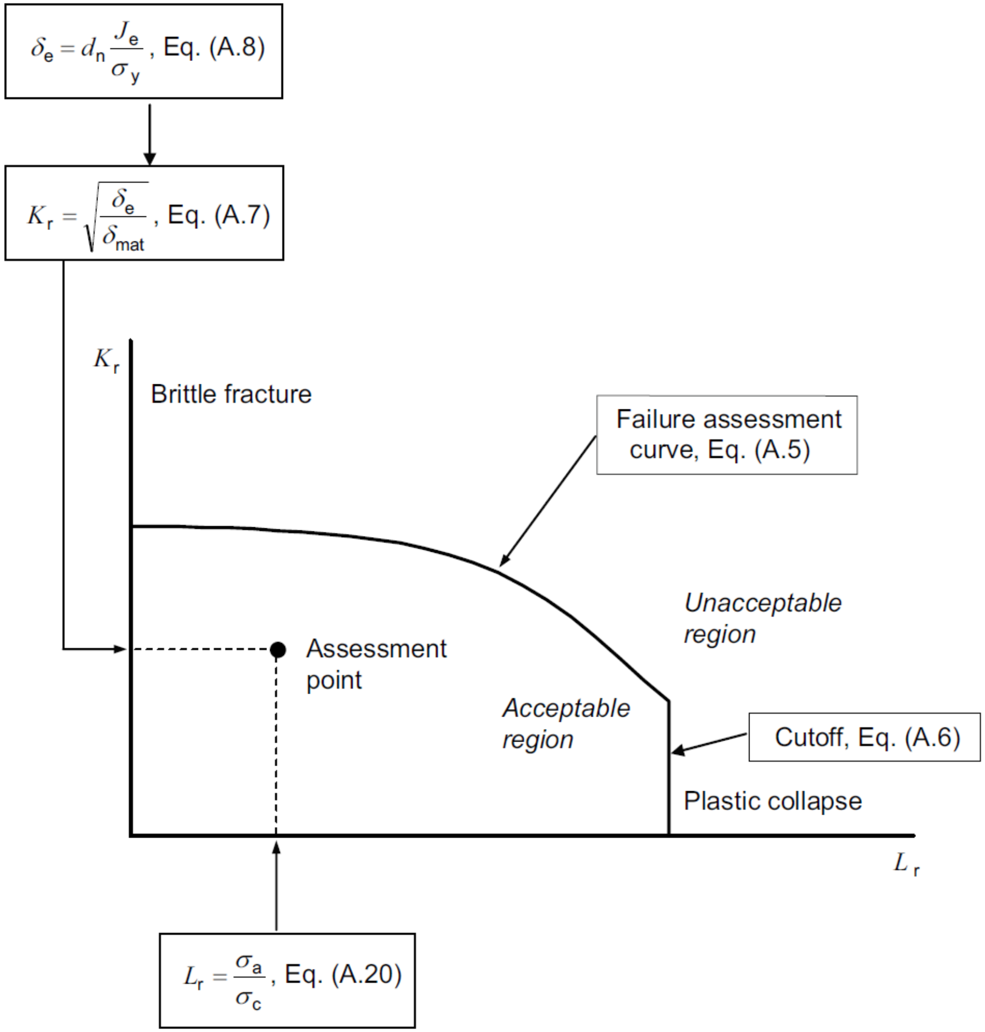
3 Regulatory Acceptance

4 Working Examples

5 Conclusions

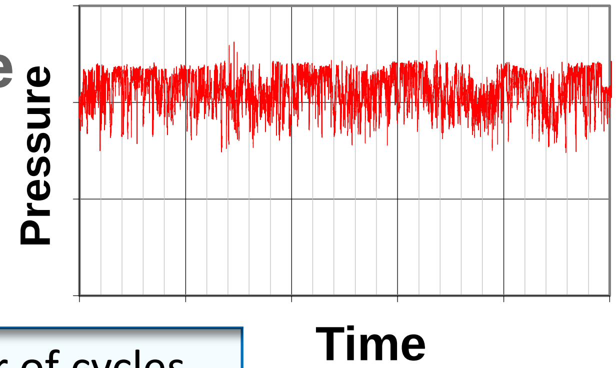
# Framework of ECA – FAD for Failure

1. **FAD in API 1104 Appendix A**
   - $L_r$ – ratio of applied stress ($\sigma_a$) over plastic collapse stress ($\sigma_c$)
   - $K_r$ – ratio of elastic driving force at crack tip over material toughness
2. **Crack is acceptable if the assessment point $(L_r, K_r)$ is inside "Acceptable Region".**



**1 An imperfection may grow under cyclic load and trigger failure in the future.**

- **Fluctuation of internal pressure**
  A conservative criterion from API 1104 Appendix A
  $S^* = \sum_{i=1}^{k} N_i(\Delta\sigma_i)^3 \leq 5 \times 10^6$ ksi³



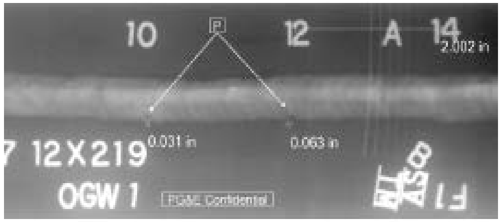

| | | | |
|---|---|---|---|
| $S^*$ | Spectrum severity factor (SSF) | $N_i$ | Number of cycles |
| $k$ | Number of cyclic stress levels | $\Delta\sigma_i$ | Cyclic stress ranges |

- **Vehicles crossing**
  Only for girth welds under a road crossing without casing. API RP 1102 recommends a fatigue endurance limit of **12 ksi** for girth welds.

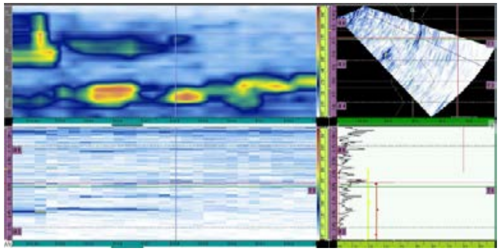
# Flaw Size – NDE Techniques

## 1 PG&E identified and measured the weld imperfections during in-ditch NDE

- **Radiographic Testing (RT)**
  For all cases. Reliable for the detection and sizing of volumetric flaws. Accurately indicate the lengths of such flaws but not the radial dimensions.




- **Ultrasonic Testing (UT)**
  Supplementary. Measure the radial dimension (height) and embedded depth. Effective for planar or crack-like flaws.



## 2 For cases with RT only (no UT)

It is conventionally assumed that the height of the flaw equals the thickness of one weld pass (**0.1 in** in U.S. / **3 mm** in Europe)

# Flaw Size – Tolerance of Accuracy

## 1 Length from RT

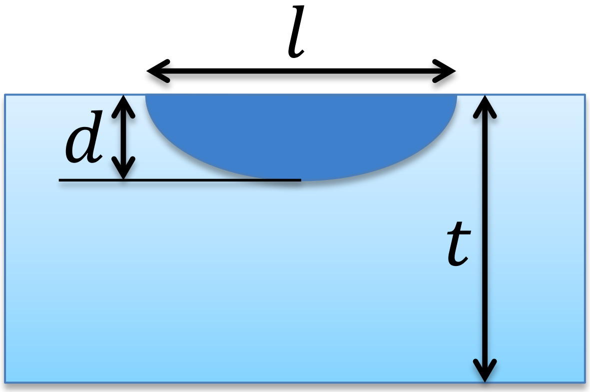
**No** tolerance needs to be considered for length to which the failure stress is generally less sensitive.

## 2 Height from UT

An tolerance of **0.02 inch** was considered for radial dimension/ height from UT#.

## 3 API 1104 Appendix A

Appendix A has included an "assumed height uncertainty" as "**the lesser of 0.060 inch (1.5 mm) and 8% of pipe wall thickness**".




$$l_{ECA} = l$$

$$d_{ECA} = d + d_{tol}$$

$$d_{tol} = \begin{cases} 0 & d_{API} \geq 0.02 \\ 0.02 - d_{API} & d_{API} < 0.02 \end{cases}$$

$$d_{API} = \min(0.08t, 0.060)$$

Units for $d_{tol}$ and $d_{API}$ are inches

*# Van Velsor, J., and Riccardella, S., "Stress Corrosion Cracking NDE Crack Truth Verification Inspection", PRCI, Catalog No. PR-335-143705-R2, November 10, 2015.*

# Flaw Size – Interaction of Multiple Flaws

1 The flaws within close proximity may interact and result in lower failure stress. A combined larger flaw should be used in the ECA.

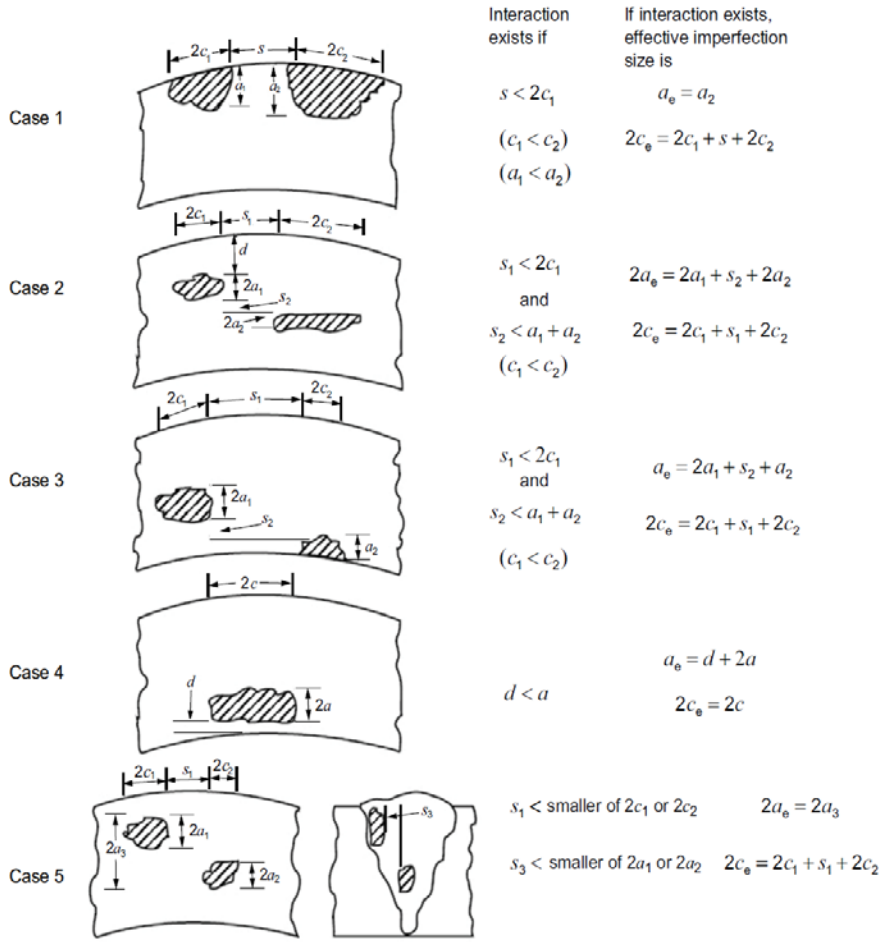
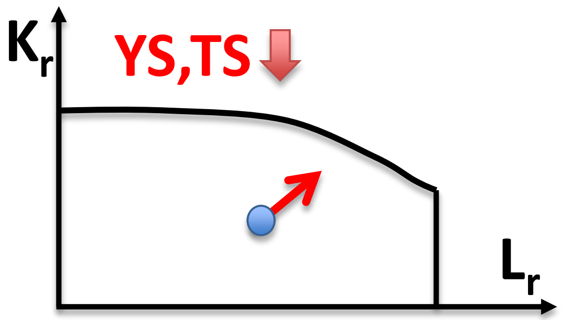



**Figure A.11 in API 1104**

# Material Properties – Strength




## 1 FAD

The **decrease** of yield strength (YS) and tensile strength (TS) tends to move the assessment point in FAD toward the **upper-right** direction.

## 2 Weld vs Base

The strength of the weld metal is usually **superior** compared to that of the base metal.

## 3 A conservative assumption

**YS** of weld metal = **SMYS** of base metal
**TS** of weld metal = **SMTS** of base metal
SMYS: specified minimum yield strength
SMTS: specified minimum tensile strength

# Material Properties – Toughness

## 1 Crack-Tip Opening Displacement (CTOD)

ECA in API 1104 Appendix A uses CTOD to describe the material toughness. Unfortunately, the toughness in CTOD is not available for most pipelines.

## 2 To determine CTOD at the investigated girth weld

- CTOD test on similar vintage pipeline constructed using similar pipe and welding process, or
- Recommendations vs test results

| CTOD | Comments |
|---|---|
| **0.050 mm/0.0020 in** | Minimum CTOD to avoid non-ductile fracture initiation and is conservative for most vintage pipes |
| 0.066 mm/0.0026 in | Minimum CTOD from 42 CTOD tests on seven 1950s-vintage girth welds from PG&E's Line 132 |
| 0.195 mm/0.0077 in | Average CTOD from above tests |

# Applied Stress

## 1 Resources

The failure at a girth weld depends on the longitudinal stress which may be generated by

- Normal operation
- Thrust forces near changes in piping direction
- Surface loading at road crossings

## 2 Stress Concentration Factor (SCF)

If the girth weld connects two pipes with different wall thicknesses, the mid-wall misalignment generates a SCF which can be calculated following Annex D of BS7910-2013.

# Applied Stress – Normal Operation

## 1 Buried Straight Pipes

$$\sigma_L = \nu\sigma_H - \alpha E(T_o - T_i)$$

## 2 Unrestrained Straight Pipes

$$\sigma_L = \sigma_H/2$$

| | |
|---|---|
| $\sigma_H$ | Hoop stress due to internal pressure |
| $\alpha$ | Coefficient of thermal expansion |
| $E$ | Elastic modulus |
| $T_o$ | Operating temperature |
| $T_i$ | Installation temperature |

*Equations from ASME B31.8*

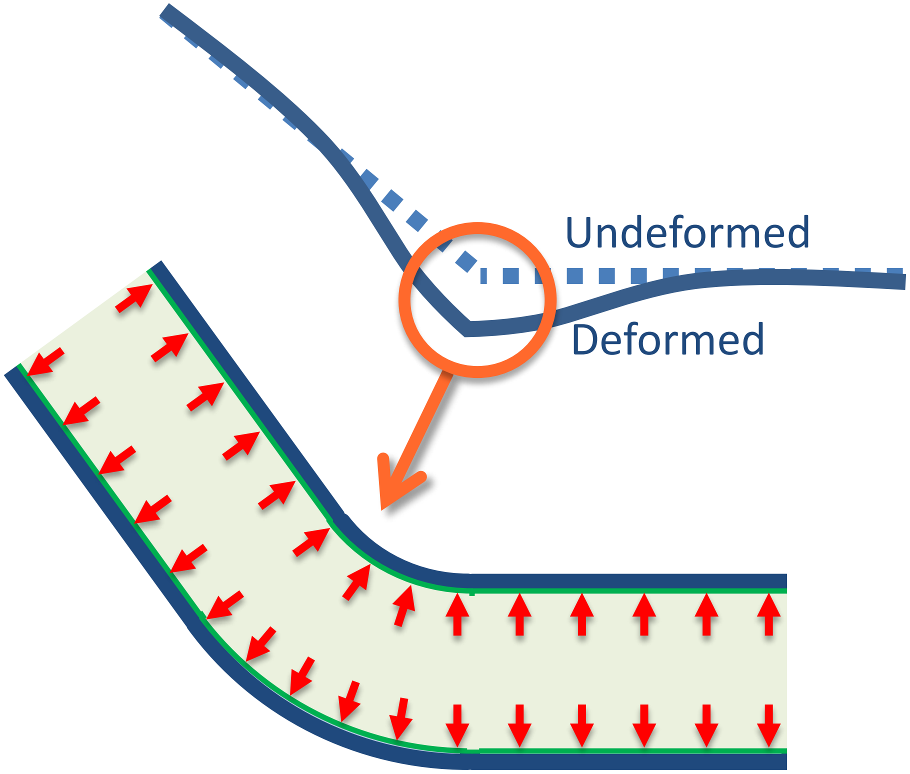
# Applied Stress – Change in Pipe Direction

## 1 Description

**Thrust force** results in displacement at the bend and bending deformation in tangent pipes.

## 2 Calculation

The stress can be determined by an approach developed by Zhang and Rosenfeld#.




*# Zhang, F., and Rosenfeld, M.J., "Longitudinal Stress in Buried Pipelines near Bends or End Caps", Journal of Pipeline Engineering, 17(2), June 2018, pp. 73-89.*

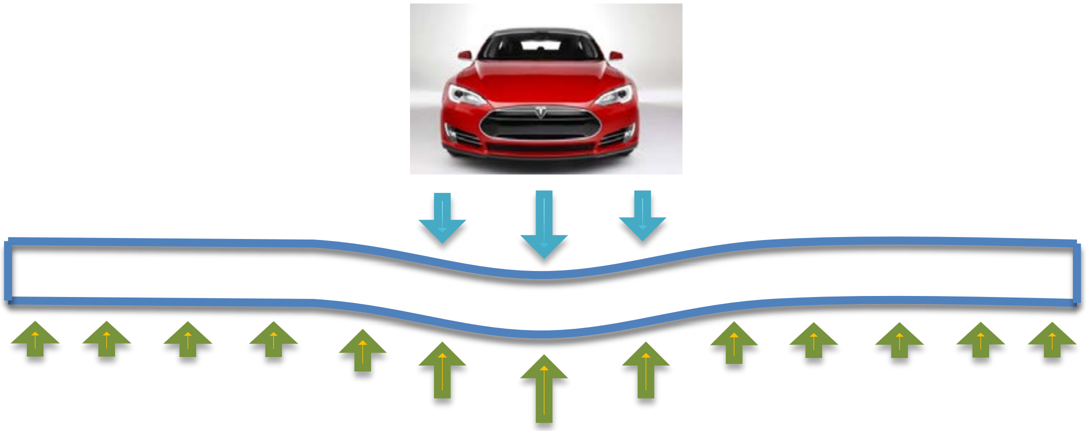
# Applied Stress – Under Road Crossing

## 1 Description

Loads on ground surface result in longitudinal stress in a pipeline buried underneath the road.

## 2 Calculation

The resulting stress can be determined by API RP 1102 or an approach published by Zhang et al. in IPC 2016[#].



*# Zhang, F., Branam, N., Zand, B., and Van Auker, M., "A New Approach to Determine the Stresses in Buried Pipes Under Surface Loading", IPC2016-64050, Proc. of the 11th International Pipeline Conference, Calgary, AB, Canada, Sep. 26-30, 2016.*

# Outline

1 Background

2 Approach of Engineering Critical Assessment

3 **Regulatory Acceptance**

4 Working Examples

5 Conclusions

# Regulatory Acceptance

**1 API 1104 Appendix A is incorporated into 49 CFR parts 192, 193 and 195.**

§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.*"


**2 California Public Utility Commission (CPUC) incorporates and supplements 49 CFR Part 192 in its General Order 112-F. (for PG&E)**

# Outline

# Example I –Information and Stress

**General Information**

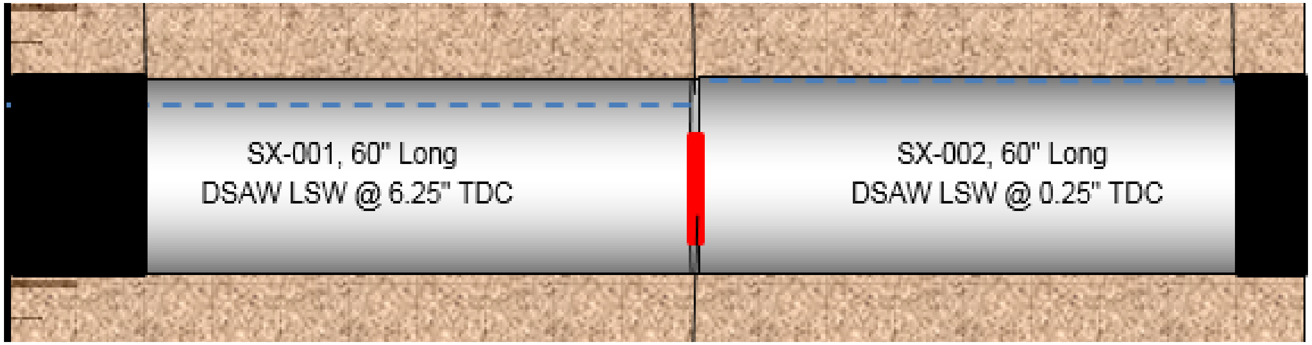
| | |
|---|---|
| Diameter | 30 inches |
| Wall Thickness | 0.375 inch |
| Grade | API 5LX X52 |
| Constructed | October 1954 |
| MAOP | 590 psig |
| Others | 25 feet offset to an parallel road |

**Longitudinal Stress at Girth Weld**

| | |
|---|---|
| From Internal Pressure | 7.08 ksi |
| Thermal Stress | 4.99 ksi |
| Bending of Pipe Axis | 11.80 ksi |
| Traffic at Road Crossing | 0 ksi |
| Total | **23.87 ksi** |

**Material Properties of Girth Weld**

| | |
|---|---|
| Yield Strength | 52 ksi |
| Tensile Strength | 66 ksi |
| CTOD | 0.02/0.05/0.10 mm |



# Example I – Flaws

**Indication of Flaws**

| No. | Length inch | Height inch | Depth inch | Location* inch |
|---|---|---|---|---|
| 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 |

* "Location" is measured from the top of pipe and along the pipe circumference

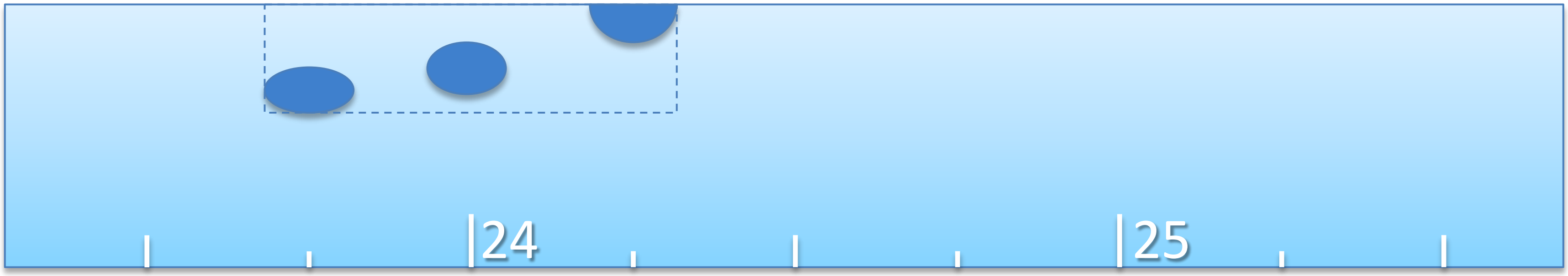
**Combined Flaw**

**Flaw for ECA**

| Length inch | Height inch | Depth inch | Location inch |
|---|---|---|---|
| 0.635 | 0.169 | Cap | 24.02 |

$0.08 \times 0.375 = 0.03 \text{ inch} > 0.02 \text{ inch}$

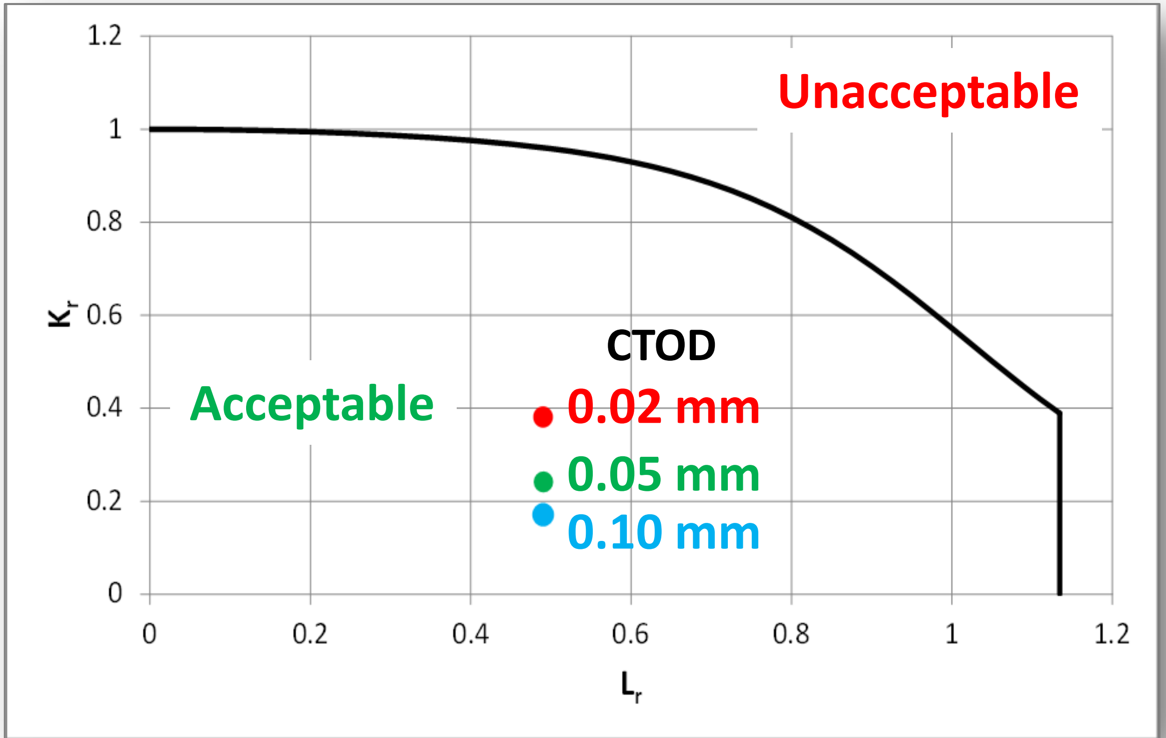
No additional tolerance in height is needed



# Example I – Results

## 1 FAD

The points for all three assumed CTODs are within acceptable region.



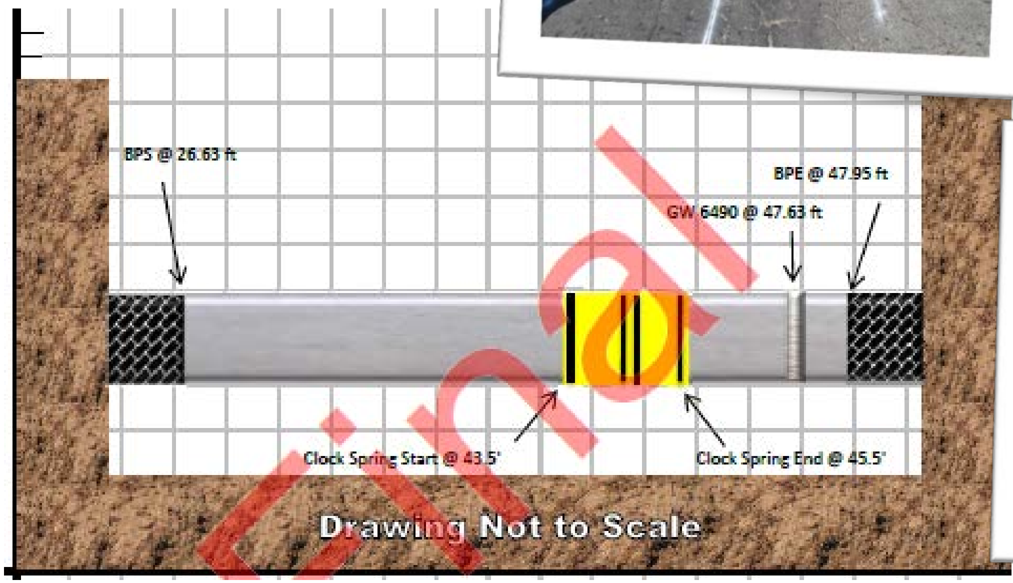

## 2 Fatigue

The spectrum severity factor (SSF) $S^* = 674$ ksi³/year $<<5 \times 10^6$ ksi³ (threshold).

## 3 Final Conclusion: Accepted

# Example II

1 **The girth weld was under an asphalt road and connected a straight pipe and a 90-degree elbow.**




# Example II – Information and Stress

PG&E | Kiefner an Applus+ Company

### General Information

| | |
|---|---|
| Diameter | 12.75 inches |
| Wall Thickness | 0.219 inch – Pipe<br>0.375 inch – Elbow |
| Bend Radius | 1.5 x OD |
| Grade | API 5LX X42 |
| Constructed | October 1971 |
| MAOP | 650 psig |
| Cover Depth | 92 inches |
| Backfill | Sand |

### Longitudinal Stress at Girth Weld

| | |
|---|---|
| Operational Stress after Considering Bend | 12.67 ksi |
| Bending of Pipe Axis | 11.80 ksi |
| Road Crossing | 1.78 ksi |
| Sum of above | 26.31 ksi |
| SCF due to Hi-Low | 1.72 |
| Used for ECA (Sum x SCF) | **45.26 ksi** |

### Material Properties of Girth Weld

| | |
|---|---|
| Yield Strength | 42 ksi |
| Tensile Strength | 60 ksi |
| CTOD | 0.02/0.05/0.10 mm |

# Example II – Flaws

**Indication of Flaws**

| No. | Length inch | Height inch | Depth inch | Location inch | Type | API 1104 Criteria | |
|---|---|---|---|---|---|---|---|
| | | | | | | 11th Ed. | 20th Ed. |
| 1 | 0.047 | N/A | N/A | 6 | P[a] | Accepted | Accepted |
| 2 | 0.031 | N/A | N/A | 10 | P | Accepted | Accepted |
| 3 | 0.063 | 0.025 | Cap | 12 | P | Rejected | Rejected |
| 4 | 0.078 | N/A | N/A | 31.5 | IU[b] | Accepted | Accepted |
| 5 | 0.500 | N/A | N/A | 39.5 | ESI[c] | Accepted | Accepted |

[a] P: Porosity; [b] IU: Internal Undercut; [c] ESI: Elongated Slag Inclusion

$$0.08 \times 0.219 = 0.0175 \text{ inch} < 0.02 \text{ inch}$$

The NDE measured depth should add $0.02 - 0.0175 = 0.0025$ inch for ECA

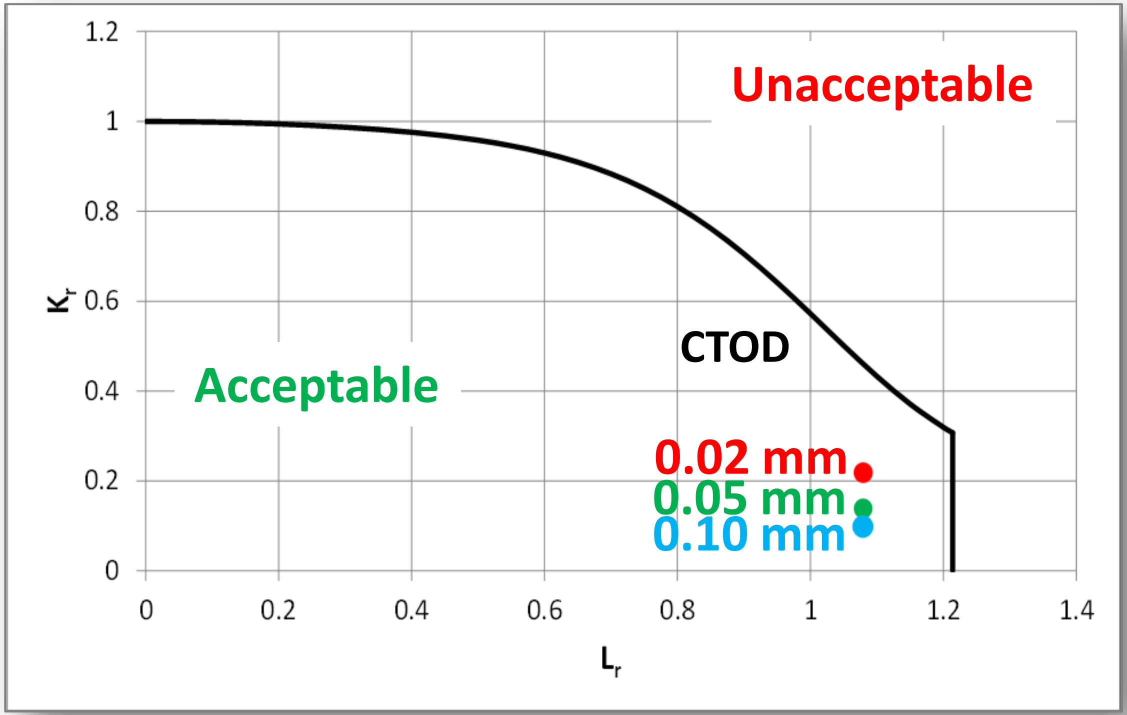
**Flaw for ECA**

| Length inch | Height inch | Depth inch | Location inch |
|---|---|---|---|
| 0.063 | 0.0275 | Cap | 12 |

# Example II – Results

## 1 FAD

The points for all three assumed CTODs are within acceptable region.



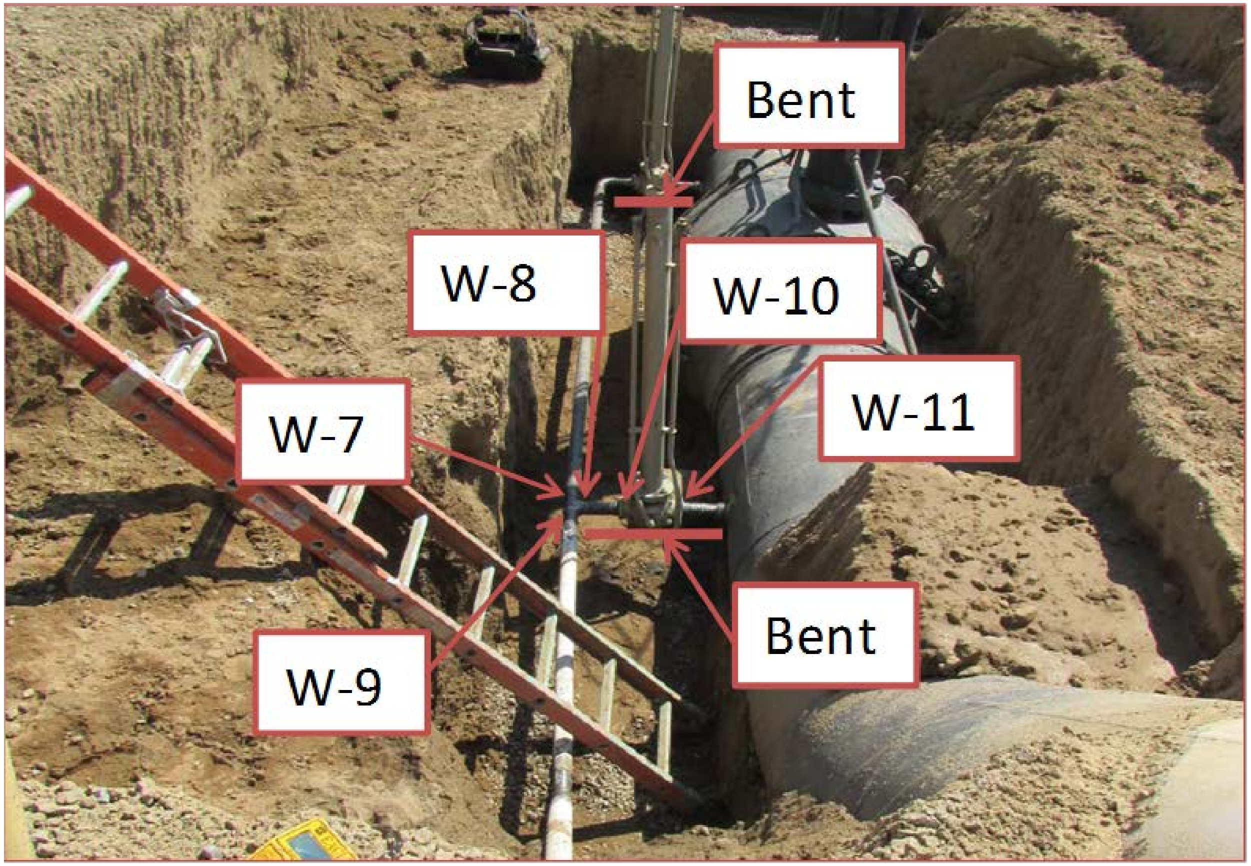

## 2 Fatigue

- The cyclic stress from live load = 1.12 ksi < 12 ksi (fatigue endurance limit)
- The SSF $S^* = 478$ ksi³/year <<$5 \times 10^6$ ksi³ (threshold).

## 3 Final Conclusion: **Accepted**

# Example III

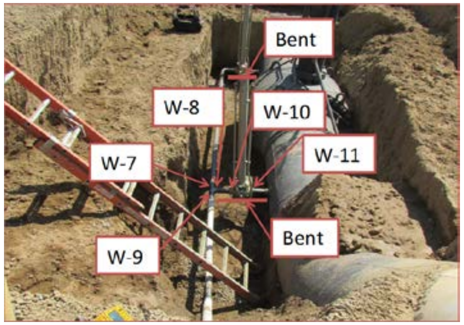
1 five girth welds were located in a bypass line of a pig launcher inside a compressor station



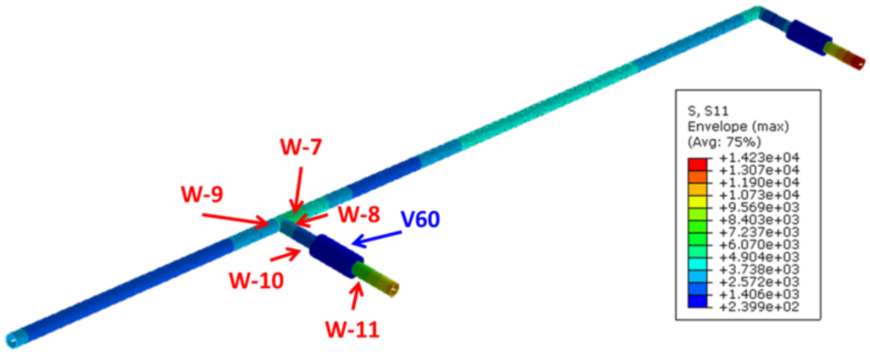
# Example III –Information and Stress

## General Information

| | |
|---|---|
| Diameter | 2.375 inches |
| Wall Thickness | 0.154 inch |
| Grade | API 5L Grd B |
| Constructed | July 2005 |
| MAOP | 1,040 psig |
| Cover Depth | 68 inches |
| Backfill | Clay |




## Finite Element Analysis for Longitudinal Stress




## Material Properties of Girth Weld

| | |
|---|---|
| Yield Strength | 35 ksi |
| Tensile Strength | 60 ksi |
| CTOD | 0.02/0.05/0.10 mm |

# Example I – Flaws

**Indication of Flaws**

| Girth Weld | Length (DP) inch | Height (UT) inch | Length (RT) inch |
|---|---|---|---|
| W-7 | | | IP[a]: 1.217<br>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<br>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 Penetration
[b] P: Porosity
[c] CP: Cluster Porosity

- **W-8 and W-9**
  Depth (UT) + 0.012 inch
- **W-7, W-10 and W-11**
  No UT. Height = 0.1 inch (one weld path)

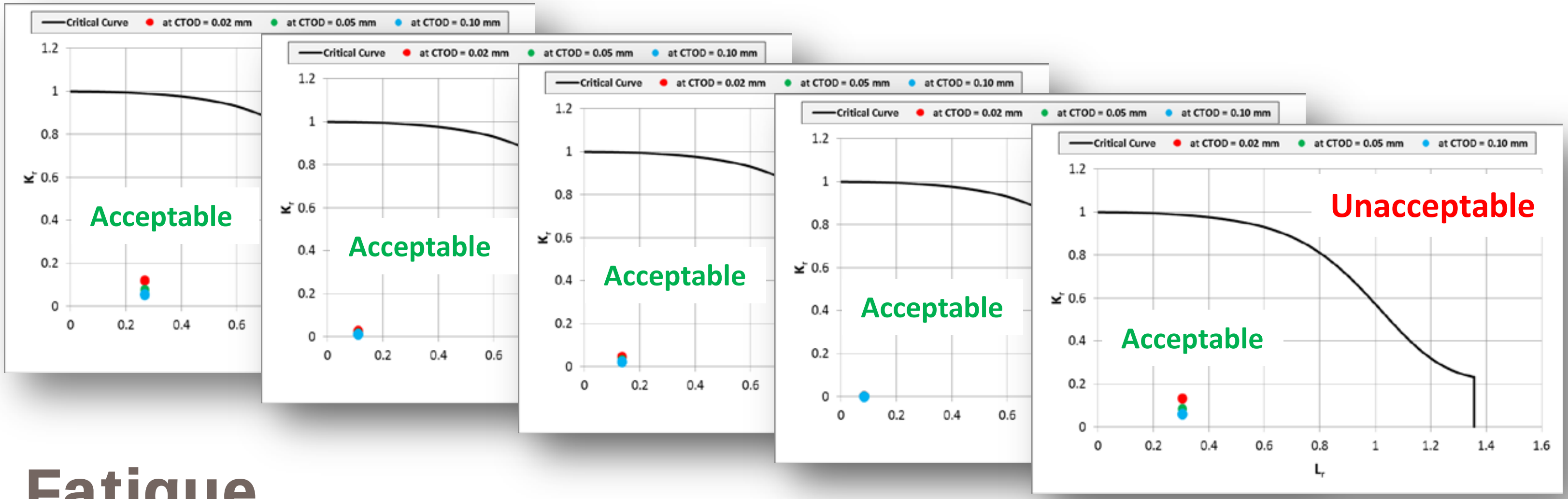
**Flaw for ECA**

| Girth Weld | Length inch | Height 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 |

# Example I – Results

## 1 FAD

All points are within acceptable region.




## 2 Fatigue

- No vehicle passage and no fatigue from live load.
- No pressure record was available. The maximum amplitude of cyclic stress was 21% of SMYS. No fatigue is expected at such low stress.

## 3 Final Conclusion: Accepted

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5 **Conclusions**

# Conclusions

1 ECA provides an alternative integrity assessment approach for girth welds with imperfections that failed workmanship criteria.

2 An ECA approach was provided in API 1104 Appendix A.

3 Considerations to apply ECA on vintage girth welds should include

- Flaw size and measurement uncertainty
- Material properties
- Applied stress based on site-specific conditions

4 Three examples are provided to demonstrate the successful application of ECA on PG&E pipelines.

PG&E Pacific Gas and Electric Company

# Thank You

Kiefner
an Applus+ Company