A Comprehensive Update in the Evaluation of Pipeline Weld Defects

Project Plan

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Overview of the Presentation

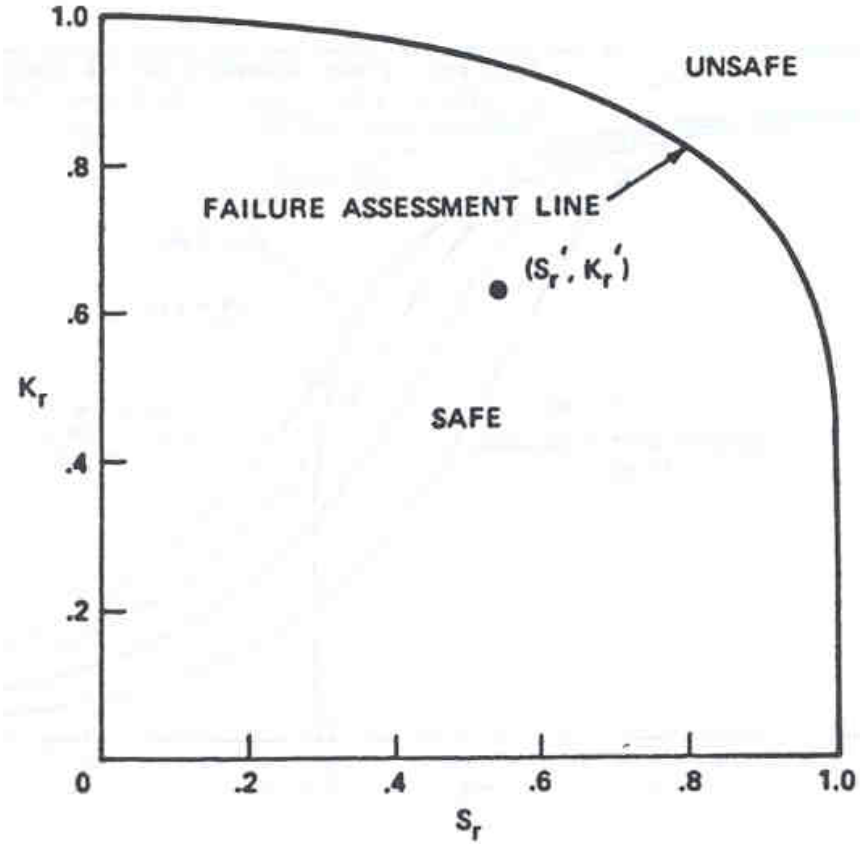
- Worldwide development in ECA since the publication of Appendix A
  - Introduction of some basic concepts in modern ECA
  - Trends in ECA
  - What technology is considered mature, what is not?
- Organization of the project
- Proposed structure of the updated alternative acceptance criteria
- Timeline of the project deliverables

PD 6493 and BS 7910

- PD 6493:1980
  - CTOD Design Curve
- PD 6493:1991
  - Level 1: equivalent to PD6493:1980, i.e., CTOD design curve
  - Level 2: FAD approach using the strip yield model
  - Level 3: Ainsworth's reference stress approach (from R6).
- BS 7910:1999
  - More refined multi-level approach
  - Adopted many features of R6, which is an ECA procedure primarily used in nuclear power generation.
- BS 7910 contains assessment procedures for
  - Fracture
  - Fatigue
  - Creep crack growth
  - Other failure modes (corrosion, buckling, leakage, erosion, etc.)

ECA in FAD Format

- **Fracture and plastic collapse are treated in the same framework.**



$$S_r = \frac{K_I^{App}}{K_\delta}$$

$$K_I^{App} = \sigma_{app} F \sqrt{\pi a}$$

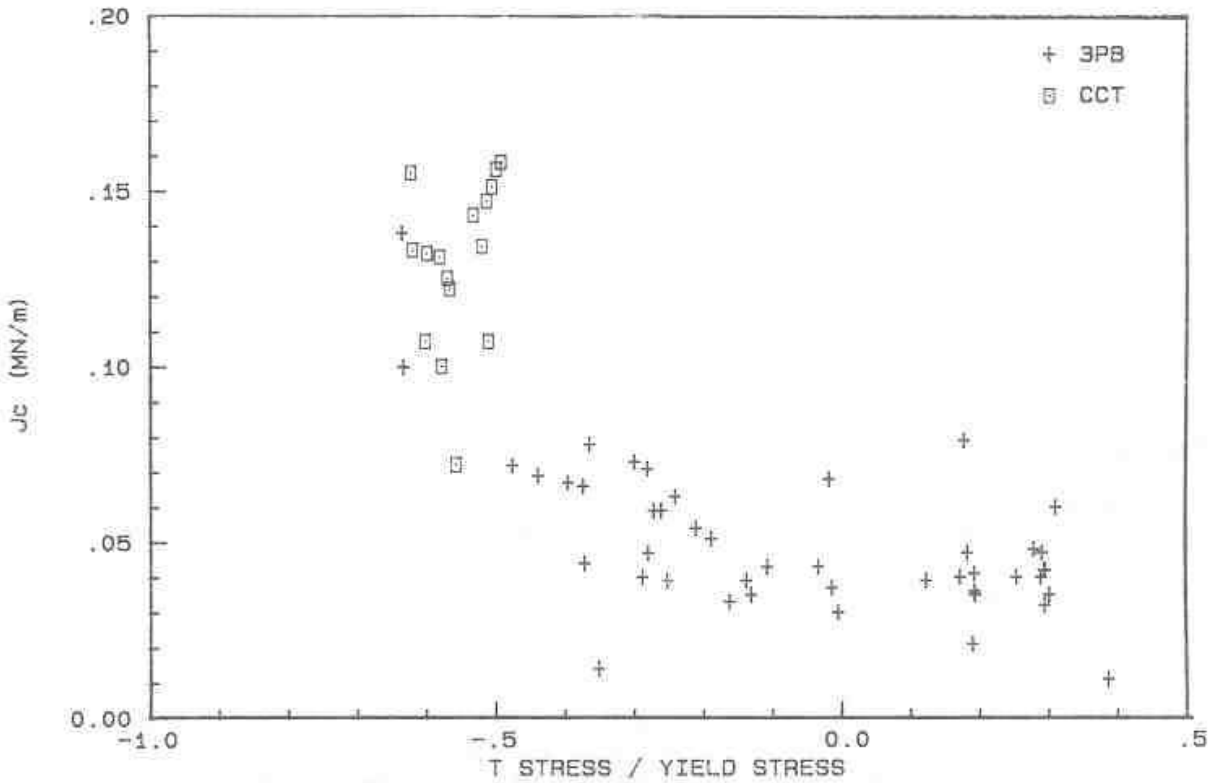
$$S_r = \frac{\sigma_{app}}{\sigma_{Lim}}$$

SINTAP (1999)

- SINTAP stands for Structural Integrity Assessment Procedure for European Industry)
- Funded by European Union
- Final publication in November 1999
- Covered a wide range of issues related to ECA
- Some of the new features:
  - Constraint-sensitive failure assessment curve
  - Refined treatment of residual stresses
  - Partial safety factors for reliability-based assessment

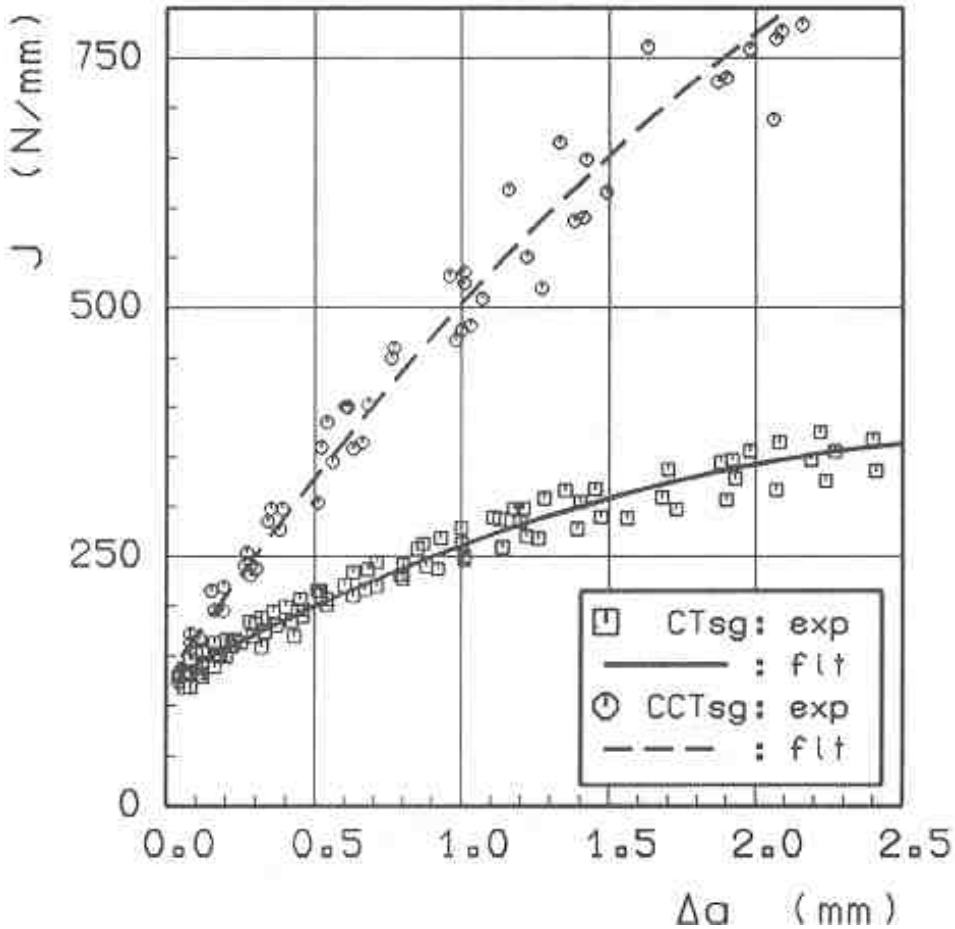
Constraint Effect on Fracture Toughness

- Material generally exhibits higher toughness in low-constraint configuration.
- CTOD specimens: high constraint -> low toughness
- Girth welds: low constraint -> high toughness



Constraint Effect (Continued)

- *J* resistance curves for high-constraint (CTsg) and low-constraint (CCTsg) specimens. Pressure vessel steel StE 460



DNV Offshore Standard OS-F101 (2000)

- **ECA of girth welds uses input of accumulated plastic strain (APS).**
- **The meaning of APS and computation of it is not well defined.**
- **If APS is less than 0.3%, no ECA is required. The defect acceptance criteria are given in Tables D-4 and D-5 in Appendix D. These criteria are substantially similar to the workmanship criteria in the main body of API 1104. *Is ECA allowed?***
- **If APS is greater than 0.3% and less than 2.0%, ECA is required in accordance with the Level 3 procedure of BS 7910.**
- **It requires weld qualification by consumable batch. It's technically sound, but can be very expensive. May choose to order the entire manufacturer lot to avoid testing of every batch.**

EPRG Guidelines (1996)

- Tier 1
  - workmanship
- Tier 2
  - plastic collapse based criteria with minimum Charpy
  - Based primarily on wide plate test data
  - Grade ≤ X70, Y/T ≤ 0.90, Applied Strain ≤ 0.5%
- Tier 3:
  - Based on full-scale test data at BG Tech
  - Grade ≤ X70, Y/T ≤ 0.85, Applied Stress ≤ Yield (pipe)
- A new version is under consideration.

AS 2885.2 (1995)

- Tier 1
  - workmanship
- Tier 2
  - Equivalent to the Tier 2 of EPRG Guidelines
- Tier 3:
  - Refers to other ECA procedures, in particular BS 7910
- A new version is under consideration

Japan Welding Engineering Society (2000)

- WES TR 2808, "Method for Assessment of Brittle Fracture in Steel Weldments Subjected to Cyclic and Dynamic Large Straining"
- The work was initiated to address earthquake damage to civil structures.
- Addressed a number of issues related to dynamic loading:
  - Flow stress increase due to dynamic loading and pre-strain
  - Fracture toughness reduction due to dynamic loading and pre-strain
  - Fracture toughness increase from high-constraint test specimen to real structures

API 579 (2000)

- Targeted at refining industry
- Multi-level approach
- A very comprehensive document
- Have received continuous updates

PRCI Work in ECA

- Reliability and accuracy of UT inspection
- Girth weld defect acceptance criteria
  - Stress based design (longitudinal strain < 0.5%)
  - Strain based design (longitudinal strain > 0.5%)
- Limit states (reliability-based) design
- Defect interaction rules

Trends in ECA Procedures

- Several major procedures have been published or updated since 1995.
- FAD format is becoming the norm for stress-based design (applied strain < 0.5%)
- Advanced features are being incorporated into the FAD format
  - Constraint effect
  - Weld strength mismatch
  - FADs that provide reliability index
- Multi-level approach is set to relate to
  - Availability of data
  - Magnitude of applied stress/strain
- Large-scale efforts in European and collaborations between industry and government have produced advanced and practical tools.

Trends in ECA Procedures (Continued)

- In the domain of "strain-based" design, DNV OS F101 has taken the approach of BS 7910 Level 3 FAD, i.e., tearing analysis.
- Continued use of FAD is questionable when the load is in the plastic range.
- PRCI work has focused on correlating crack driving force with applied strain and apply the "apparent CTOD toughness" concept (more later).

Overall Work Plan of this Project

- **Two focus areas:**
  - **Revise/add acceptance criteria for longitudinal strains up to 0.5%**
  - **Develop acceptance criteria for longitudinal strains greater than 0.5%**
- **First focus area:**
  - **Code implementation of existing technology**
  - **Significantly based on PRCI projects**
  - **Make use of recent code developments in Europe, U.S., Japan, and Canada**
- **Second focus area:**
  - **Technology development and implementation**
  - **Target new linepipe materials in arctic and deep water offshore applications**
  - **Same technology can be used for existing pipelines experiencing high longitudinal strains**

Format of Update

- Two focus areas based on:
  - Maturity of the technology
  - Range of application

Essential Parameter	Focus Area 1	Focus Area 2
	Applicable Range	Applicable Range
Diameter	No Limit	No Limit
Grade and Tensile Prop.	<=X100	<=X100
Longitudinal Strain	<=0.5%	<=3.0-4.0%

Procedure of Focus Area 1

- Assessment procedure based on FAD format
- Extensively developed and validated from a number of PRCI projects
- Significant Features
  - Updated stress intensity factor solution for girth welds
  - Plastic collapse solution for girth welds
  - Weld strength mismatch
- Review some significant issues using public domain data, NOT doing further research on these topics:
  - Notching procedure in CTOD testing
  - Defect accumulation rules
  - Treatment of buried defects
  - Defect interaction rules
  - Treatment of volumetric defects
  - Longitudinal versus circumferential properties

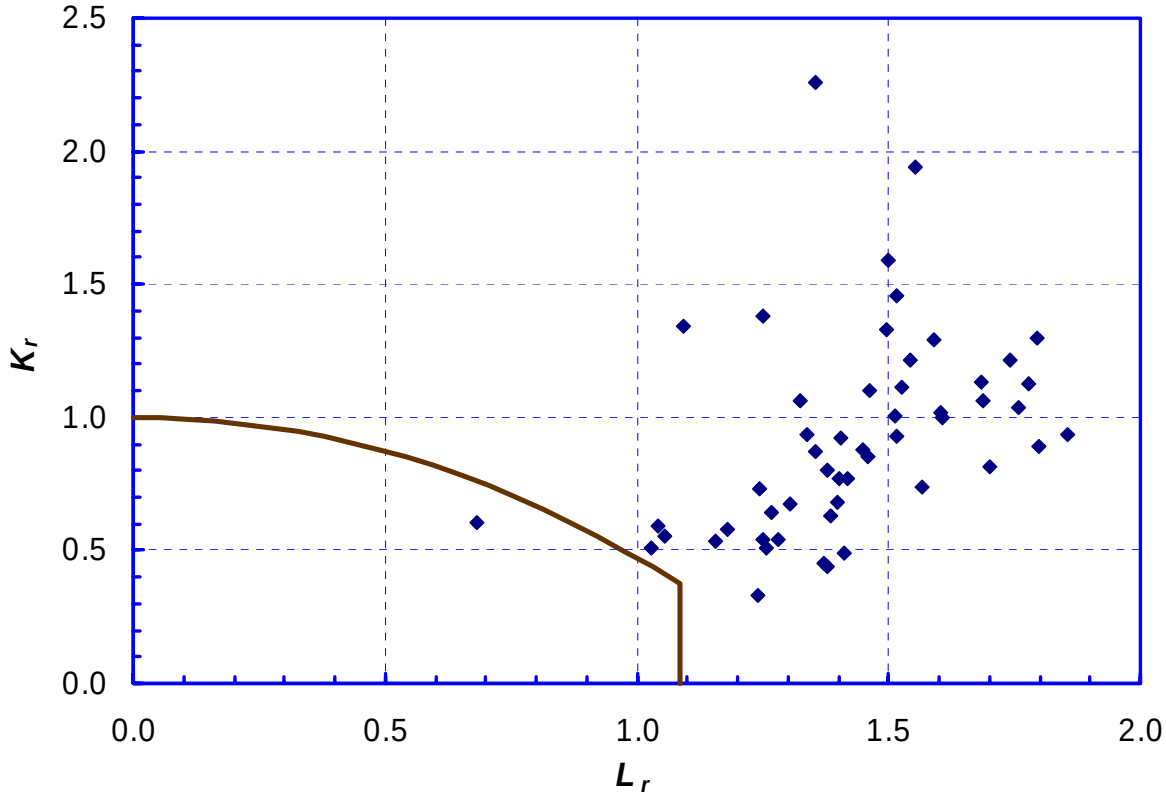
Procedure of Focus Area 1

- Procedure qualification and essential variables. These issues will be reviewed based on available data, but no further research will be done under the current work scope.
  - Measuring weld strength mismatch
  - Weld failure to include failure in the weld metal and HAZ?
  - Interpass temperature
  - Future welding processes, e.g. laser and GMAW
- We will not have answers to all questions. But we intend to make the procedure flexible enough to accommodate future developments.

Validation of PRCI Procedure, Full-Scale Tests

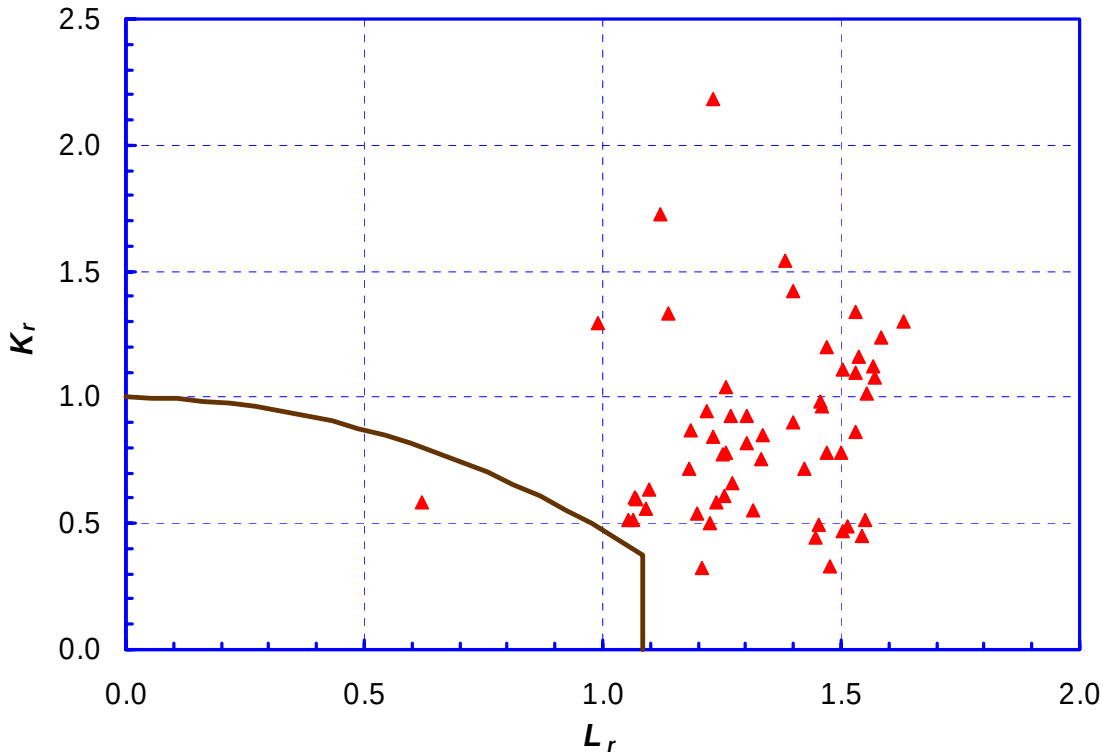
- 52 tests of Glover, etc.; Mostly X70, some X60 and X65; Diameter 24-36 inch; CTOD>0.03 mm, mostly 0.10 mm
- 4 tests of Erdogan, X60, Diameter 20 inch, CTOD=0.554 mm
- The median value of defect depth is 47% of the wall thickness
- The median value of defect length is 4.5% of the circumference.

Comparison with Full-Scale Data, Using SMYS



- Full-scale data outside the FAC => Conservative
- The non-conservative data point has defect depth of 91% of the wall thickness. All other 55 data points are conservative.
- The median value of safety factor in stress is 1.55.

Compa. Full-Scale Data, Using Measured Yield



- The only one non-conservative data point has a defect depth of 91% of the wall thickness.
- The median value of safety factor in stress is at 1.45.
- The L_r values are lower when the measured yield stresses are used.

Validation against Wide Plate Test Data

- 31 wide plate test data from PRCI Project PR-202-922
- X60 pipe, 36-inch OD, 11.6-mm (0.457-inch) W.T.
- Yield = 446 MPa (64.7 ksi), Tensile 560 MPa (81.2 ksi), Y/T=0.8
- Ten girth welds made with seven combinations of cellulosic electrodes
  - E6010/E6010
  - E7010/E7010
  - E8010/E8010
  - E6010/E8010
  - E7010/E9010
  - E6010/E9010
  - E9010/E9010

Validation against Wide Plate Data (cont'd)

- Weld strength mismatch ranges from 20% undermatching to 24% overmatching.
- Girth weld CTOD ranges from 0.06 mm to 0.37 mm.
- All the wide plates were tested in tension till failure.
- The test temperatures were –10, -30, and –50°C.
- CTOD tests were done at the same three temperatures.

Three Validation Options, Wide Plates

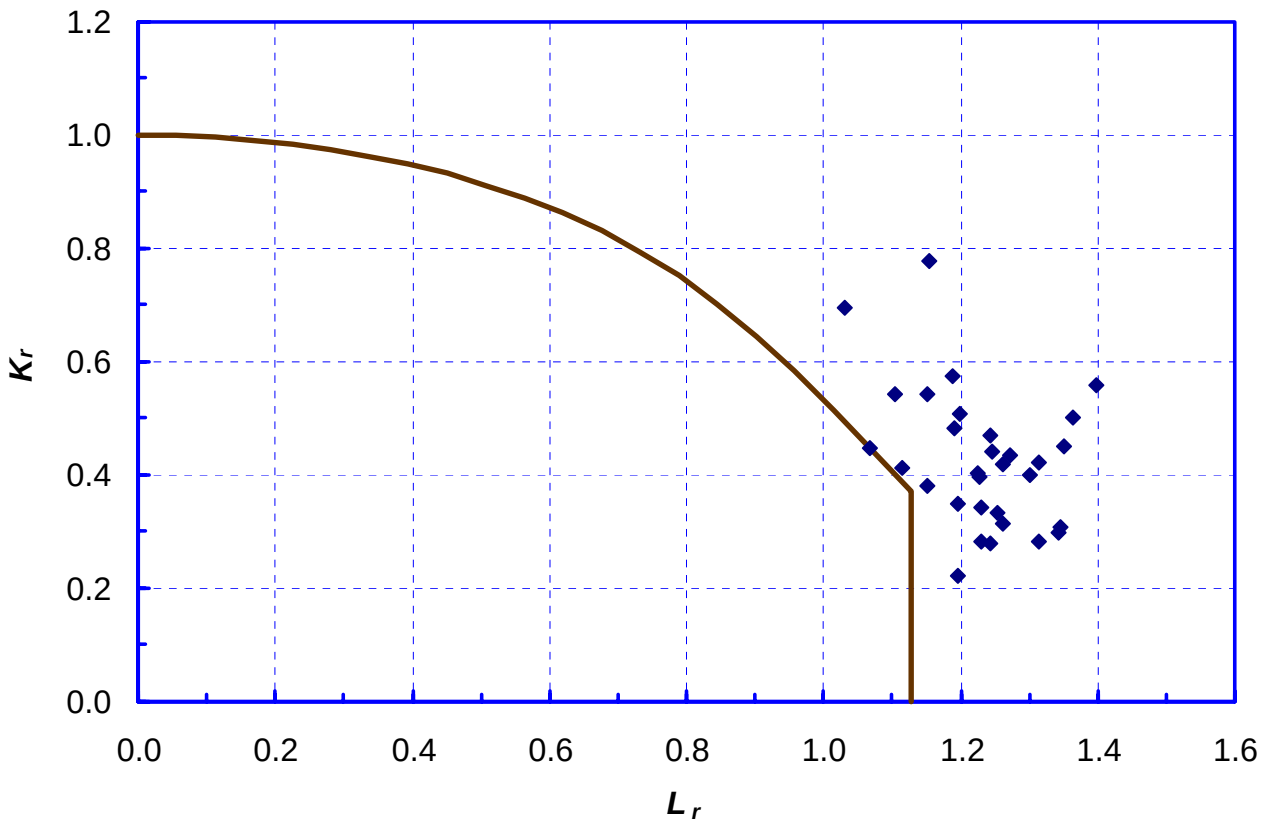
- Three validation options were selected to simulate different levels of available material properties that can exist in practice.
- Option 1: Only pipe grade is known.
- Option 2: The true pipe tensile properties (yield and tensile stresses) are known.
- Option 3: The tensile properties of the pipe material and weld metals are known.

Validation Results, Wide Plates

- **Option 1: Median value of safety factor = 1.21, standard deviation = 0.11. One undermatching weld was non-conservatively predicted.**
- **Option 2: Median value of safety factor = 1.12, standard deviation = 0.11. Three undermatching welds were non-conservatively predicted.**
- **Option 3: Median value of safety factor = 1.12, standard deviation = 0.07. All welds were conservatively predicted.**

Validation Results of Option 3, Wide Plates

- Very consistent and accurate results
- Mismatch effects accounted for accurately



ECA at High Longitudinal Strains (> 0.5%)

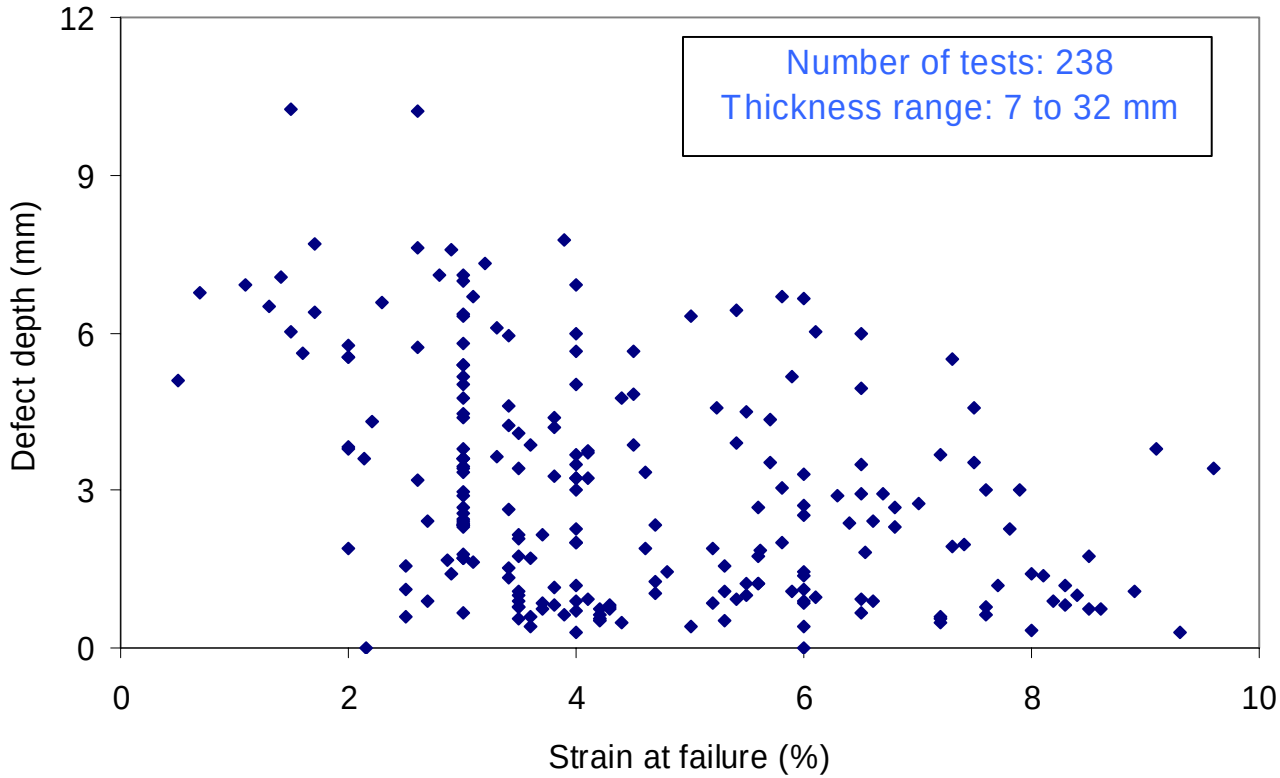
- **DNV OS F101 and BS 7910**
  - **Most recognized procedure, robustness is questionable, particularly for high *Y*/*T* materials**
- **Strain based design related to reeling, a JIP**
  - **Address material property change due to prior straining**
- **PRCI strain design procedures**
  - **Under development since 1999. Developed procedures to characterize "driving force" for a given strain level**
  - **Consideration for high strength, high *Y*/*T* materials**
- **MMS OPS supported strain design guidelines**
  - **Package of pieces from other codes and standards**
- **Wide plate tests**
  - **When everything else fails. Caution in data interpretation. Variability of test data can be a problem.**

Factors Affecting Strain Limits of Girth Welds

- **Material property related:**
  - **strain hardening rate (*Y*/*T* ratio)**
  - **weld strength mismatch**
  - **uniform strain (strain at tensile stress)**
  - **toughness**
- **Defect related:**
  - **defect size (height and length)**
  - **defect depth**
  - **defect location**
  - **defect orientation**
- **Loading related:**
  - **prior strain history (in the case of cyclic straining)**
- **Geometry related:**
  - **weld cap height**
  - **undercut**
  - **high-low misalignment**
  - **weld bevel geometry if strength mismatch is considered.**

Need to Better Understand Strain Limits

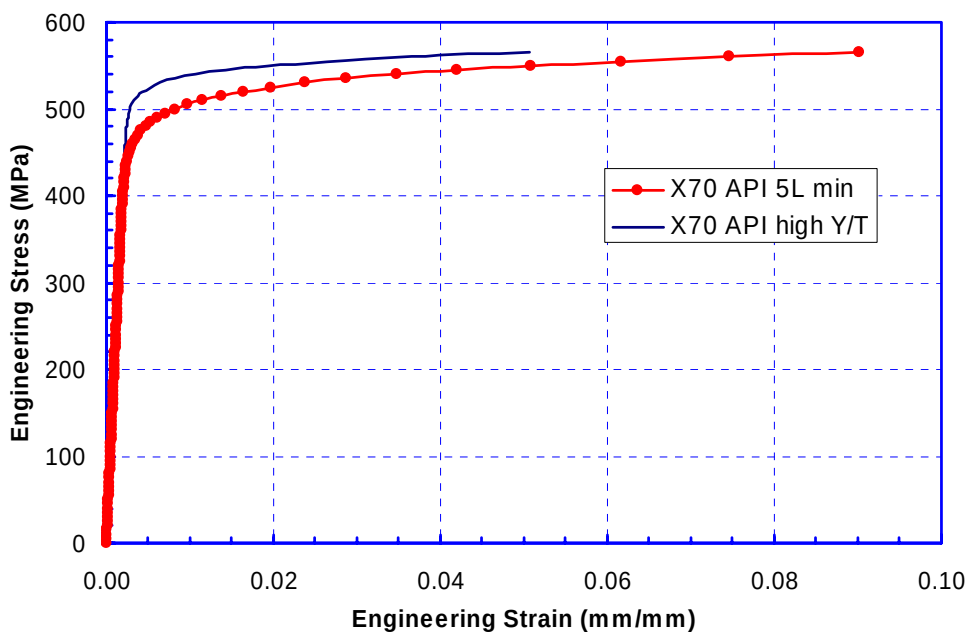
- We need to understand factors that contributed to the wide range of failure strains.



Focus Area 2, Material Tensile Prop.

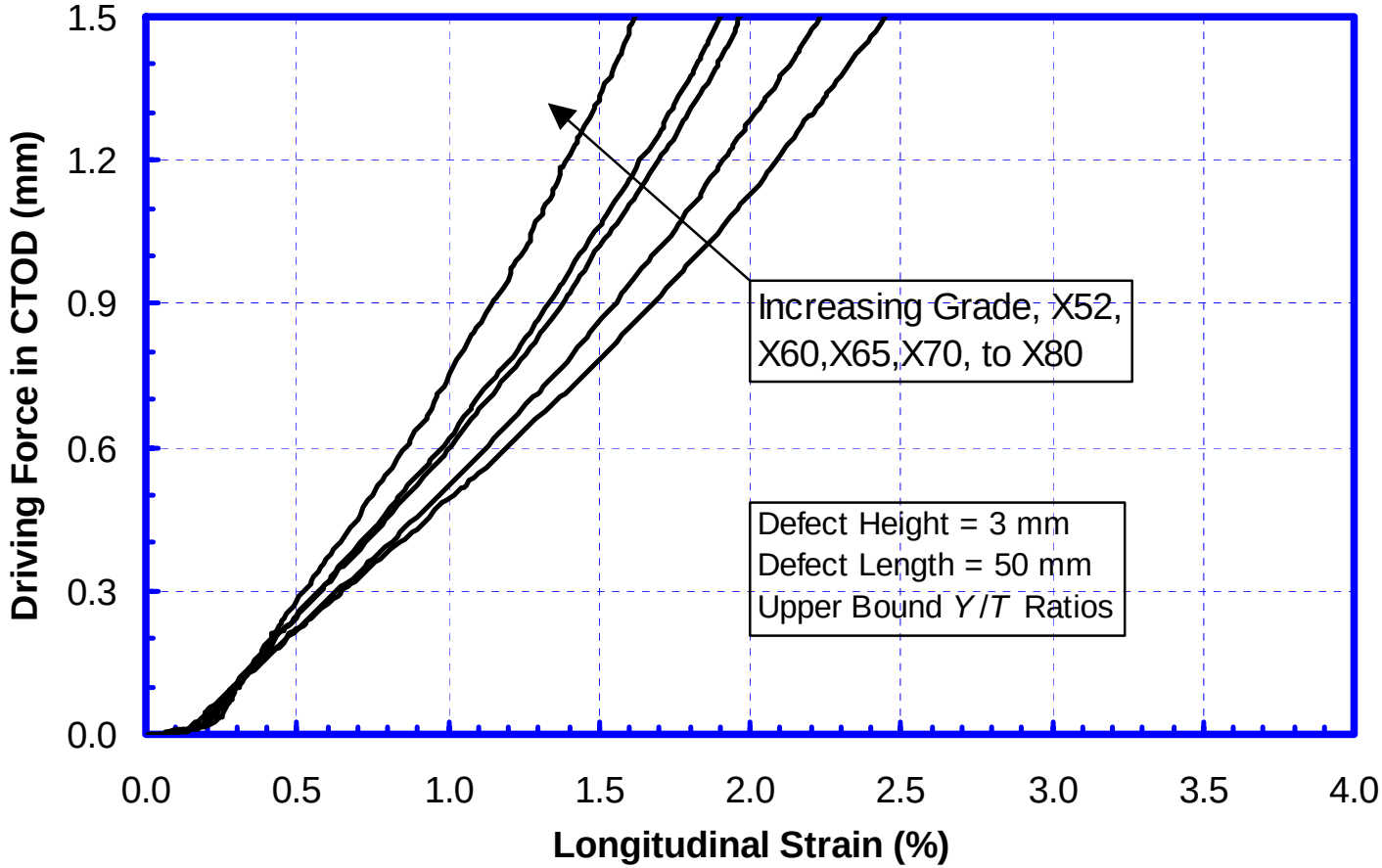
- Consider actual material tensile property versus specified minimum values

Grade	API Min. Yield	API Min. Tensile	API Min. Requirements			Upper Bound Y/T		
			Y/T	Strain Hardening Exponent, *n*	Uniform Strain	*Y/T*	Strain Hardening Exponent, *n*	Uniform Strain
52	52	66	0.788	15.38	13.0%	0.894	27.95	7.2%
60	60	75	0.800	16.43	12.2%	0.900	29.70	6.7%
65	65	77	0.844	20.84	9.6%	0.922	37.33	5.4%
70	70	82	0.854	22.16	9.0%	0.927	39.42	5.1%
80	80	90	0.889	28.69	7.0%	0.944	50.32	4.0%



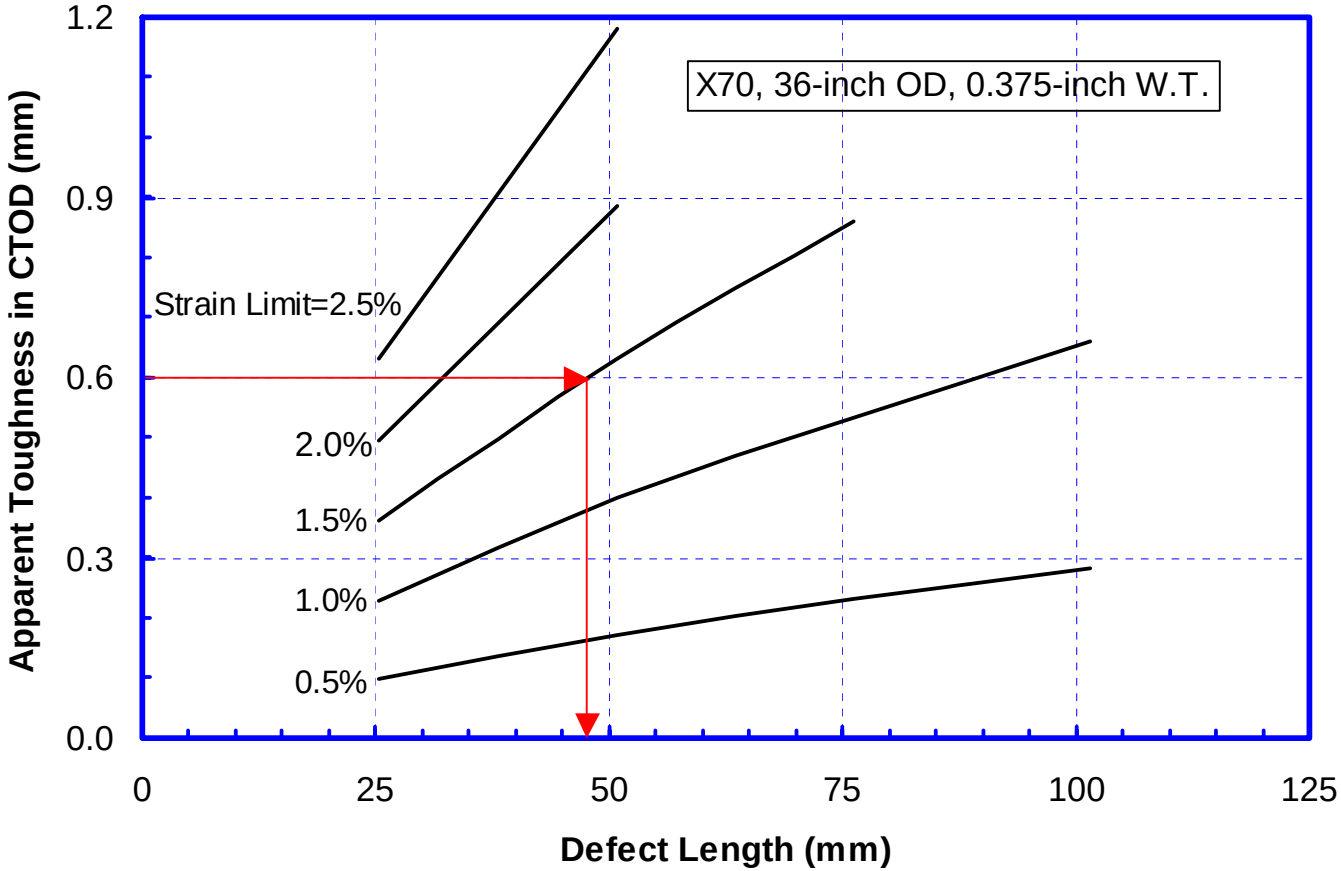
Focus Area 2, Crack Driving Force

- Relations similar to those shown here capture the essential nature of the crack driving force as a function of remotely applied strain.



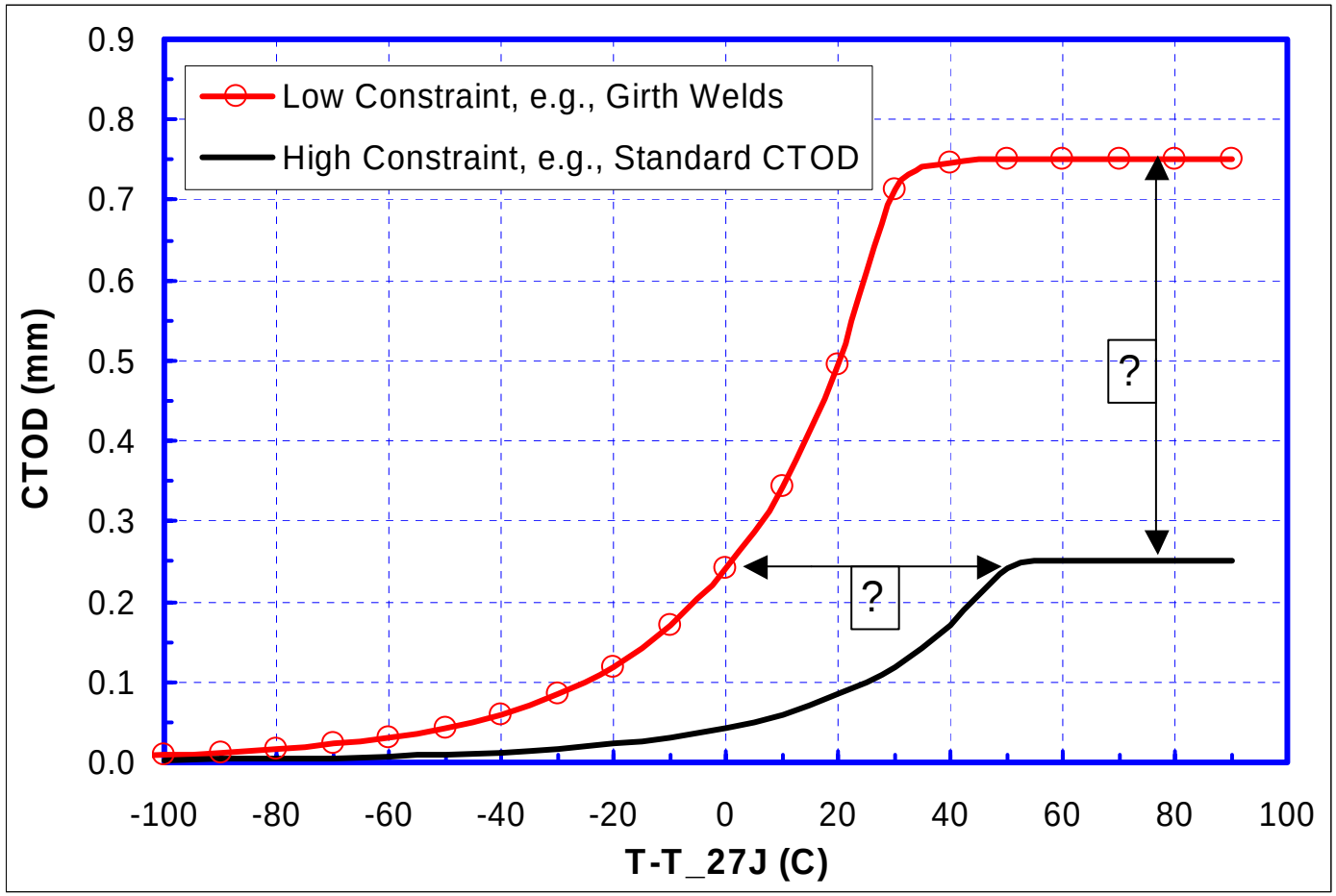
Application of Focus Area 2 Procedure

- Employ the apparent toughness concept



Concept of "Apparent CTOD Toughness"

- The apparent toughness is related to the standard CTOD toughness through the constraint effects.



Sample Tensile Strain Limits

- **Tentative, for illustration only**
- **Apparent toughness=0.45 mm (0.15-0.20 mm in standard CTOD tests)**
- **Surface-breaking defects with 3 mm height and 25 mm length**
- **Capture the effects of:**
  - **Pipe grade (though *Y/T* ratio and uniform strain)**
  - ***Y/T***
  - **Uniform strain**
  - **Wall thickness**

Grade (ksi)	Wall Thickness (mm)	Strain Limits (%)	
		API min	High Y/T
X65	9.5	1.82	1.36
	12.7	2.60	2.07
	19.1	3.52	
	25.4	3.94	
X70	9.5	1.77	1.30
	12.7	2.54	2.04
	19.1	3.50	
	25.4	3.85	

Work Plan to Develop Focus Area 2 Procedure

- Crack driving force and applied strain relations have been largely developed.
- The key is determining the "apparent toughness."
- Two ways to determine "apparent toughness"
  - Infer from standard CTOD toughness using constraint fracture mechanics
  - Develop test standard to determine "apparent toughness" directly.

Focus Area 2 Procedure (Continued)

- Work is planned in
  - Determining the constraint effects on fracture toughness of girth welds
  - Develop and verify test procedures that can measure apparent toughness directly
- The test procedure to determine "apparent toughness" has to be
  - cost-effective
  - readily applicable on a project-by-project basis

Focus Area 2 Procedure (Continued)

- A large matrix of verification planned:
  - Mini-wide plate tests of girth welds of X60 to X100
  - Wide plate test data
  - Contribution from companies specially for this project
- Materials to be tested:
  - X60-X65 thick-walled, offshore application
  - X70 thin-walled, onshore application
  - X100
- We intend to clearly define the applicable range of the developed procedure based on analysis results and available experimental data.

Focus Area 2 Procedure

- The format of Focus Area 2 acceptance criteria is not determined yet.
- A comprehensive procedure that covers all major influencing variables will be complex.
- The format can be:
  - Simplified tables for generic cases
  - More complex descriptive procedures that include more variables than the generic cases

Challenges in Procedure Format

- ***Prescriptive*** **versus** ***descriptive***
- **Leave options to use other ECA codes?**
- **Code for** ***general practitioner*** **versus for** ***specialist***
- ***Residual stress*** **effects for low toughness materials**
- ***Material property variations*****, what to test and how to test it**
- **Treatment of** ***buried defects***
- **Defect** ***accumulation*** **rules**

Comments on the Planned Work

- Technology for Focus Area 1 is mature.
- There is a large database of test data to verify the Focus Area 1 procedure
- Development work is needed for the Focus Area 2 procedure.
- Contribution of test data towards the Focus Area 2 procedure is appreciated.

Timeline of the Project

- Several iterations are expected for the Focus Area 1 acceptance criteria.
- Largely completed Focus Area 1 acceptance criteria are expected by the end of 2004.
- A draft version of the Focus Area 2 acceptance criteria is expected at the conclusion of this project.
- Further validation of the Focus Area 2 criteria may be needed beyond the scope of this project.
- Efforts will be made to ensure the procedures can be applied on a project-by-project basis.

How Can Industry Help?

- Donate materials for testing
- Donate test data for validation
- Ideally the basic properties of those materials should be available
  - Chemistry
  - Mill certs
  - Tensile data, preferably full stress strain curves (longitudinal and transverse)
  - Hardness
  - Charpy, both base metal and HAZ
  - CTOD
- Funding to expand test matrix?