Ultra-Low Temperature Testing Requirements for 316L Stainless Steel in ASME B31.3

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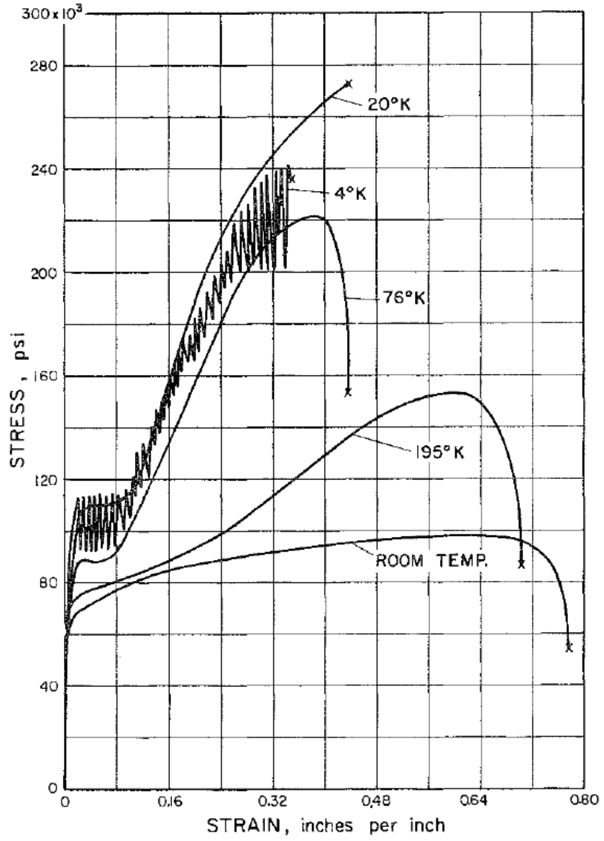
Background (1 of 2)



(Chart from *Tensile and Impact Properties of Selected Materials from 20 to 300 °K, National Bureau of Standards*.)

- The need for pressure piping for ultra-low temperatures is increasing.
- Toughness testing in LHe is difficult and extremely expensive.
- About eight years ago a letter ballot drew attention to problems inherent in the current B31.3 requirement for Charpy impact testing at liquid helium (LHe) and liquid hydrogen (LH2) temperatures:
  - Adiabatic heating at temperatures below -325F causes rapid temperature increases such that test results cannot be assumed representative of material properties at the testing temperatures.

Background (2 of 2)

- Potential problems with the proposal at that time (testing in LN2 for use at all lower temperatures) led to this ASME and NASA jointly funded project to increase the available test data.
- In the first phase of this project, two samples-of welds and one sample of base metal were tested in LHe in an attempt either to validate or to disprove the proposed new approach.
- Phase 1 results suggested that 316SS base metal and weld metal are both very tough, but the data set remained too small.
- Phase 2 gained addition ASME funding with the intent of increasing statistical credibility of results.

Project Goals

- Find a technically credible and cost effective path forward for ensuring toughness of austenitic stainless steels in ASME B31.3 and other applications at temperatures colder than -320°F (77K).
- Understand whether 316L weld metal is sufficiently tough that it can be used in pressure piping applications at all temperatures below -320°F without testing of individual welds or weld procedures.
- Failing that, determine whether ASTM E23 Charpy impact testing in LN2 (−320°F, 77K)) can be used as a suitable indicator of 316L toughness at all temperatures below -320°F without -452°F testing of individual welds or weld procedures.
- Failing that, determine whether ASTM E1820 toughness testing in LN2 (−320°F, 77K)) can be used as a suitable indicator of 316L toughness at all temperatures below -320°F without -452°F testing of individual welds or weld procedures.

Current B31.3 Toughness Testing Requirements

- Table 323.2.2 Austenitic Stainless Steels: B-4 Base metal and weld metal deposits shall be impact tested in accordance with para. 323.3.
- When impact testing is required by Table 323.2.2, paragraph 323.3.4 and sub-paragraphs require Charpy impact testing at a temperature not higher than the design minimum temperature.

Note: Section VIII Division 1, UHA-51(a)(3) only requires impact testing at -320°F for operation at all lower temperatures for 316L if (1) FN<=10 for 316L weld metal, or 4<=FN<=14 for 308L weld metal, (2) impacts taken in base metal, HAZ, and weld metal, and (3) lateral expansion >=0.021 inches (0.53 mm).

If those three requirements are not met, then KJIC testing in accordance with E1820 is performed at a test temperature no warmer than MDMT is required, with KJIC >= 120 ksi √in.

- The concern is that a sufficient technical basis for accepting -320°F testing for lower temperature operations had not been provided.

Test Measurements Assessed

- Whether 316L material might be sufficiently robust that no $KJ_{-452°F}$ testing is required. (I.e., is any testing even necessary?)
- Charpy impact test energy (ASTM E-23-18) absorbed at −320°F correlation with K_{JIC} at −320°F (ASTM E-1820-21)
- Charpy impact test lateral expansion (mils) at −320°F correlation with K_{JIC} at −452°F
- ASTM E1820 K_{JIC} toughness testing at −320°F correlation with K_{JIC} at −452°F

Preparation and Testing of Specimens

- Phase 1 (two welds and two parent material samples tested):
  - Base material: ASTM A240 Type 316L plate
  - Weld Process: GTAW-SS/LT welding protocol for cryogenic applications
  - Supplier: Myers Tool and Manufacturing
  - Testing Organization: Westmoreland Mechanical Testing and Research Laboratory
- Phase 2 (four weld samples, focusing on ASME Code compliant weld specimens):
  - Base material: ASTM A240 Type 316L plate
  - Weld processes: GTAW, and GTAW root with FCAW fill and cover
  - Suppliers: 4 Commercial pipe fabricators using their preferred welding processes and procedures.
  - Testing Organization: NIST
- All testing and preparation were performed in accordance with ASTM E23 for Charpy impact tests and ASTM E1820 for toughness.

Summary of Results

- Typical cryo-enhancement of basic strength properties for both parent and weld material, with similar slopes
- Parent material had significantly higher impact energies at −320°F than did weld material (about 210 ft lbs. vs about 60 ft lbs.)
- Weld and parent material both showed a significant drop in fracture properties from −320°F to −452°F.
- All samples tested were in the range of “tough” material (lowest result above 50 ksi√in), but well below the 120 ksi√in used in the ASME BPVC.
- Correlation between Charpy lateral expansion (LE) at -320°F and toughness at −452°F K_{JIC} appears insufficient to allow LE to be used to validate −452°F K_{JIC} either directly or using a proposed dimensionally compatible formula.
- Ferrite number showed little correlation with either −320°F K_{JIC} or −452°F K_{JIC} toughness.
- −320°F K_{JIC} may provide a means of ensuring sufficient −452°F K_{JIC}

Is 316L Tough Enough to be Used at -452°F Without Toughness Testing?

If the requirement is $K_{Ic} \geq 120$ ksi√in, the answer is "No."

Results Summary: Distribution Only

What $KJ_{-452°F}$ toughness value is being **exceeded at 95% probability at 95% Confidence**? (assuming Beta distribution)

1. All Data (previously with normal dist)

52.8 ksi√in

2. Read Only Data

24.5 ksi√in

What $KJ_{-452°F}$ toughness value is being **exceeded at 99% probability at 95% confidence**? (assuming Beta distribution)

1. All Data (previously with normal dist)

35.1 ksi√in

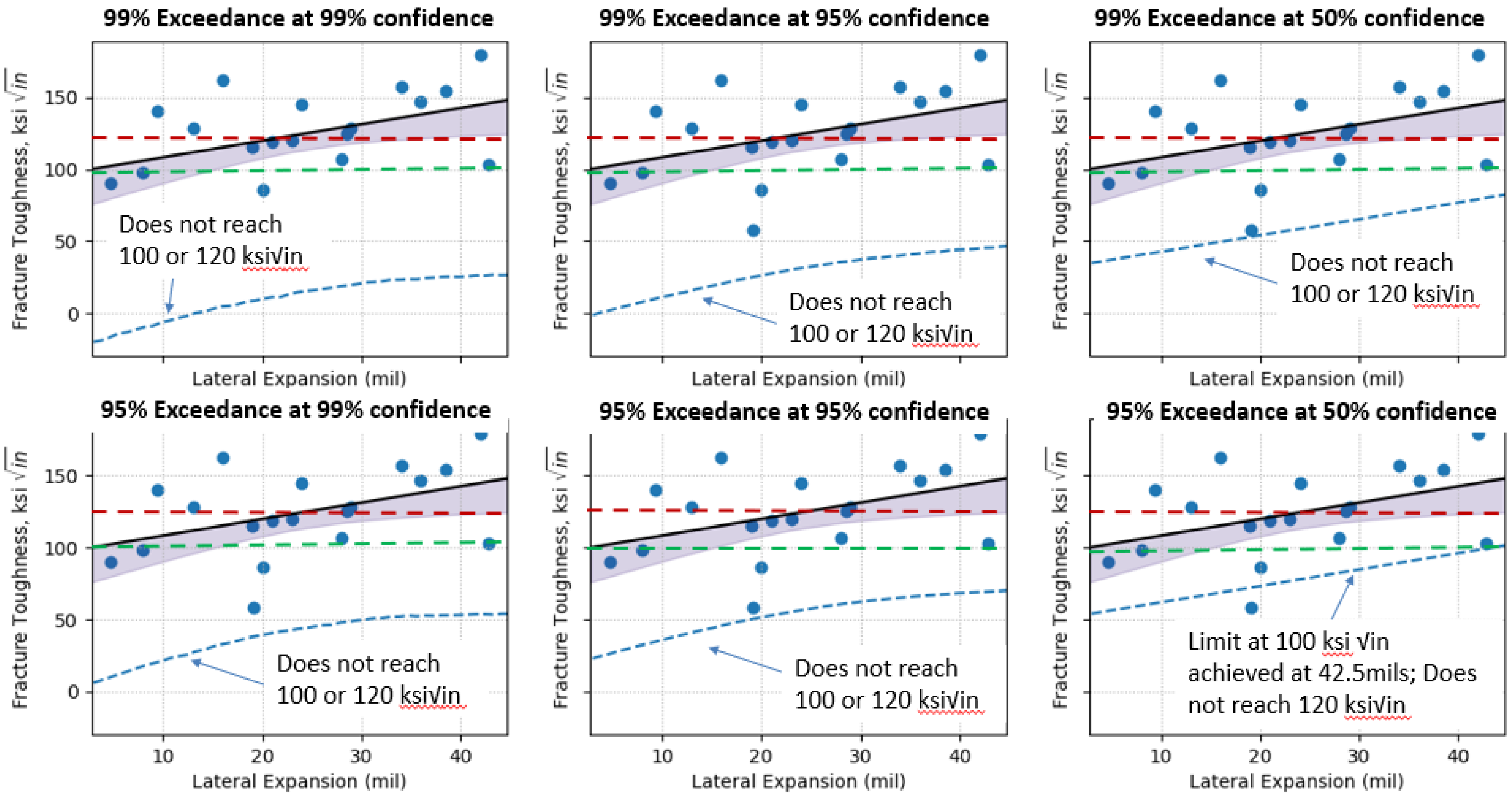
2. Read Only Data

9.02 ksi√in

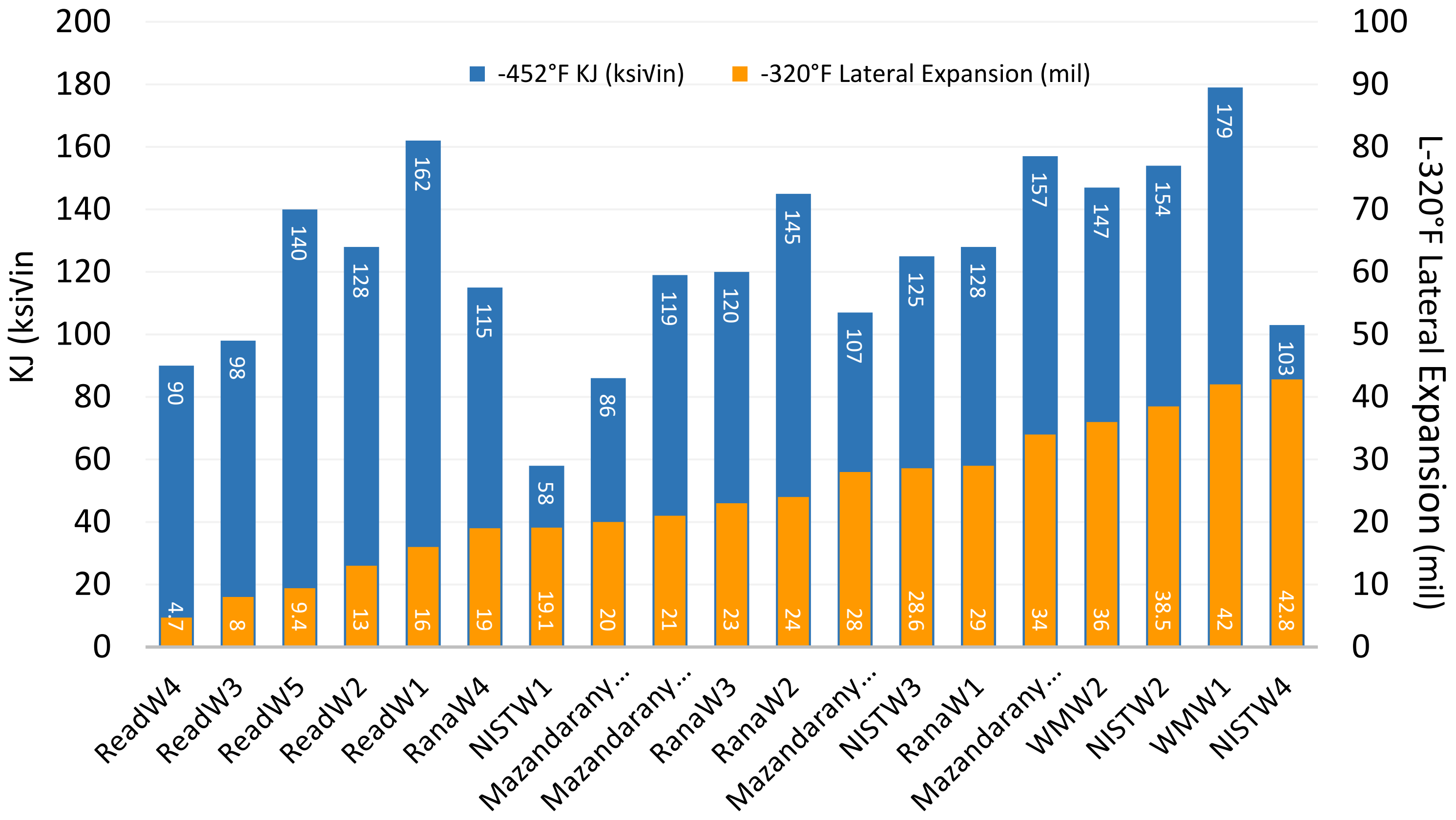
Are There Other Possible Solutions?

- Can -320°F LE predict -452°F K_{Ic} in a direct correlation?
- Can -320°F LE predict -452°F K_{Ic} in more complex relationship?
- Can -320°F K_{Ic} be used to predict -452°F K_{Ic}?
- Can weld process control be used to ensure -452°F $K_{Ic} \geq 120$ ksi√in.
- A reduction in Allowable Stress could reduce the toughness requirement.
- It may be possible to reduce toughness requirement from 120 ksi√in.

Capturing the Effect of Variability ($KJ_{-452°F}$)



-320F Charpy Lateral Expansion and -452F Fracture Toughness – All Data



-452°F K_{JIc} Prediction Formula (Sampath) Based on -320°F Charpy Lateral Expansion

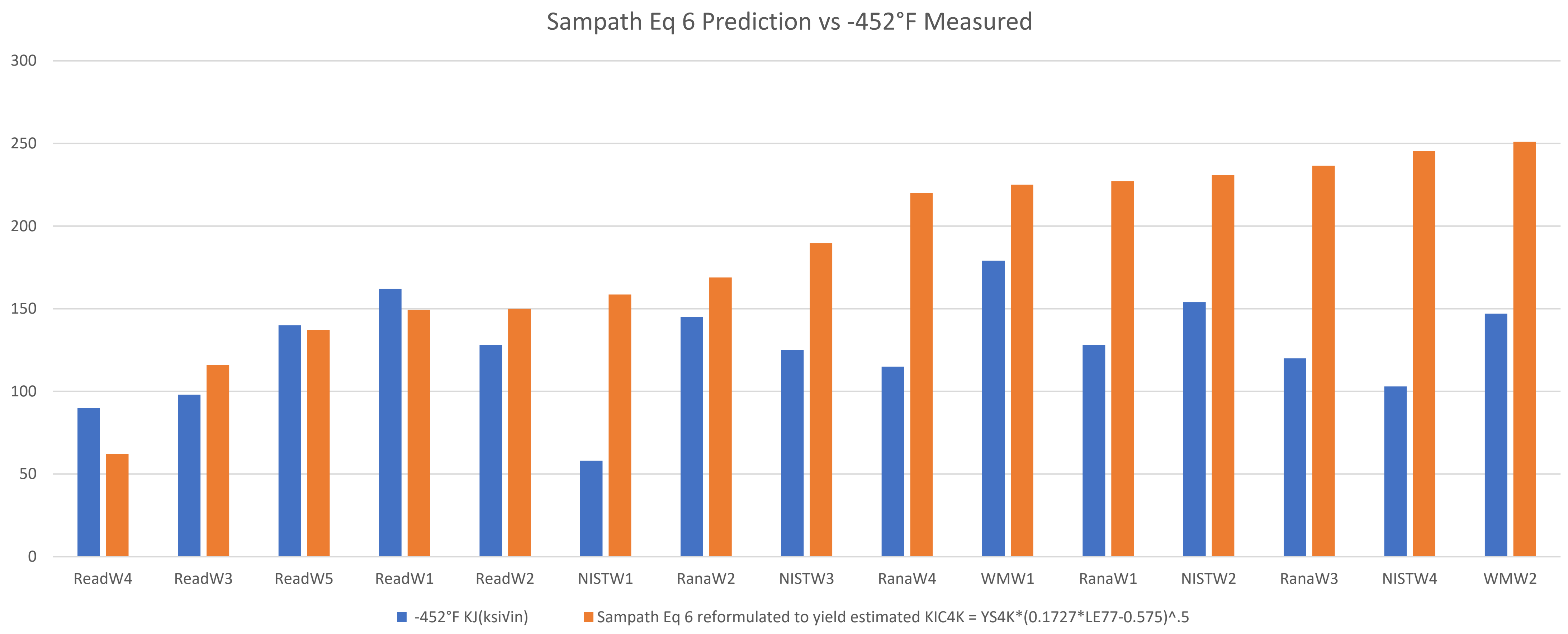
- Sampath, in his 2017 paper *A Reaffirmation of Fracture Toughness Requirements for ASME Section VIII Vessels for Service Temperatures Colder than 77K* proposed a formula for predicting -320°F LE based on -452°F K_{JIc}. The value of the formula, if it works, is of course allowing the use of -320°F LE to predict -452°F K_{JIc}.
- It is given as:

$$[K_{JIc}/\mathrm{YS}]4_{\mathrm{K}}{}^{2} = 0.1727\mathrm{LE}_{77\mathrm{K}} - 0.575$$

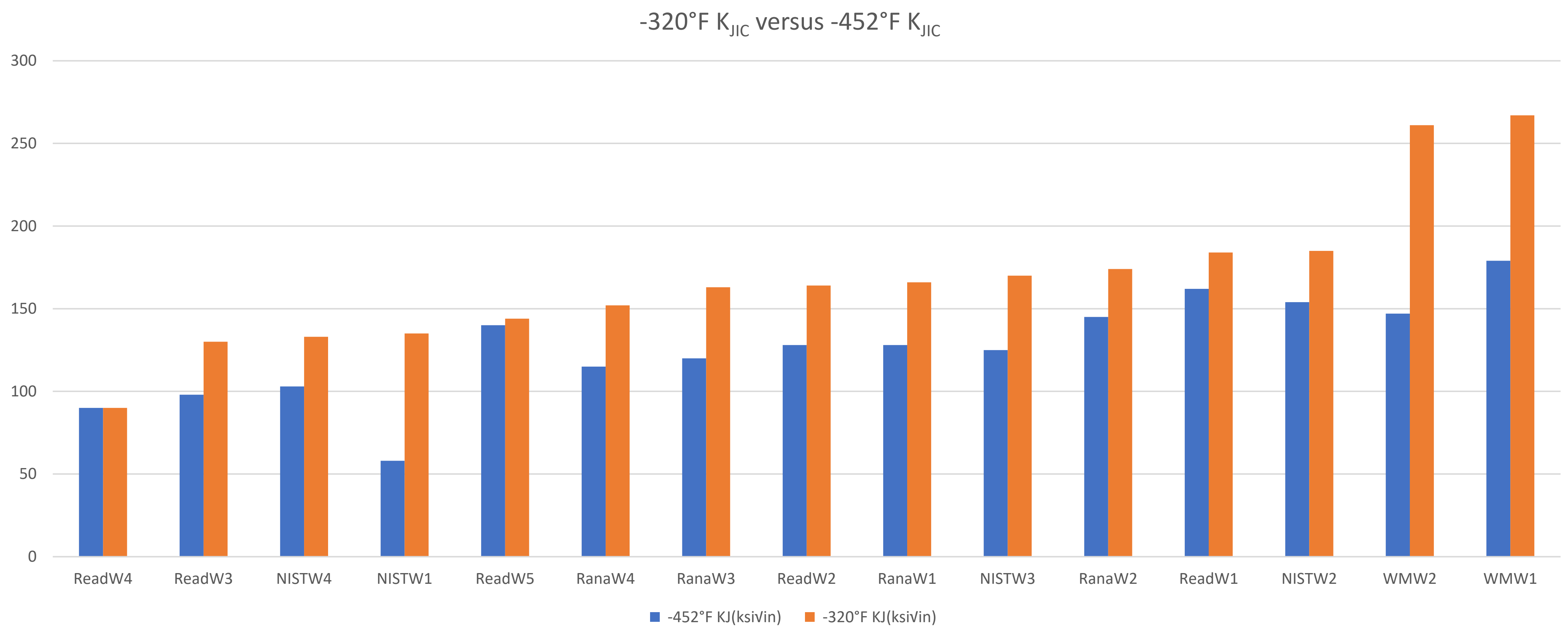
- Which transposes to the formula used for predictions on the following two charts:

$$K_{JIc4K} = \ YS_{4\mathrm{K}}\sqrt{0.1727\mathrm{LE}_{77\mathrm{K}} - 0.575}$$

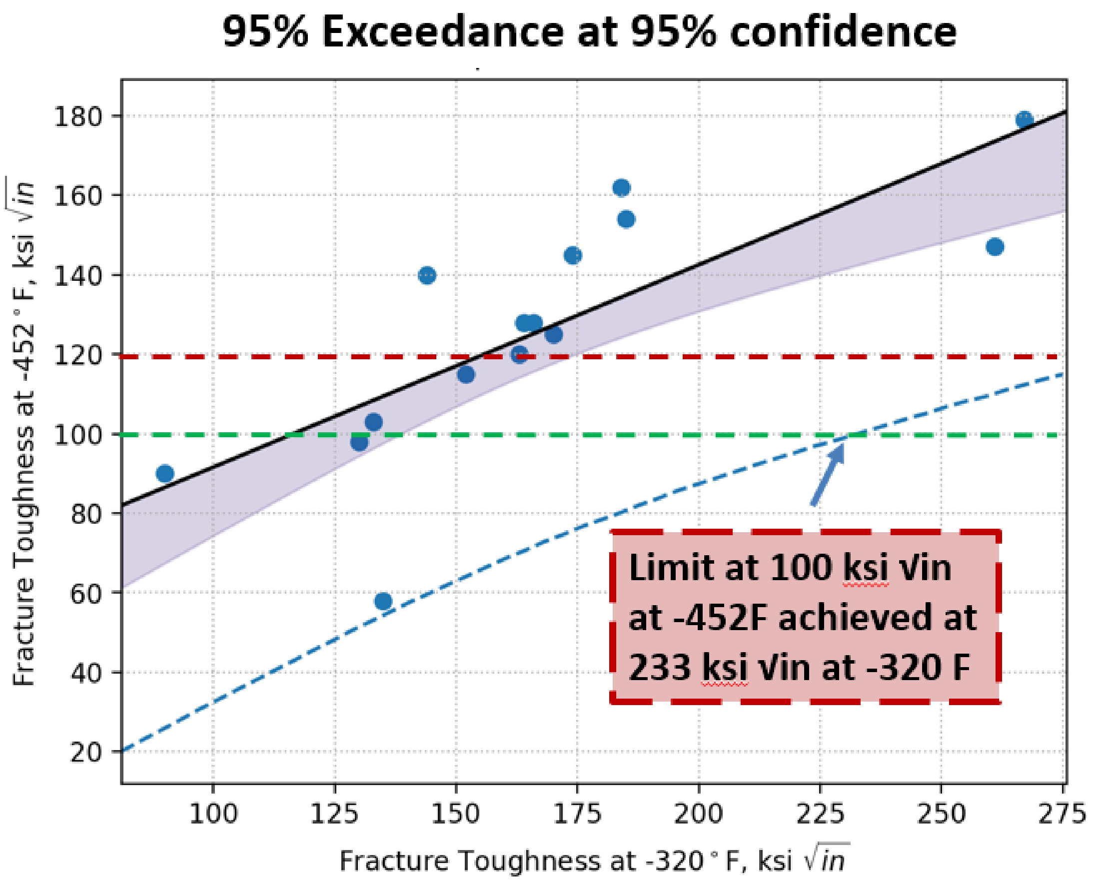
Sampath Eq 6 Prediction vs -452°F Measured All Data (K_{JIC})



Predicting -452°F K_{JIC} from -320°F K_{JIC}



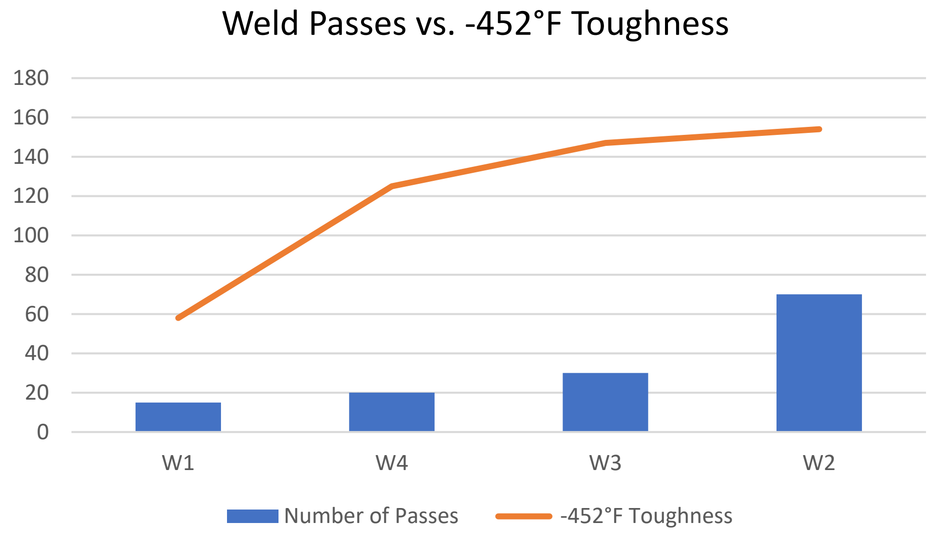
Predicting -452°F K_{JIC} from -320°F K_{JIC}



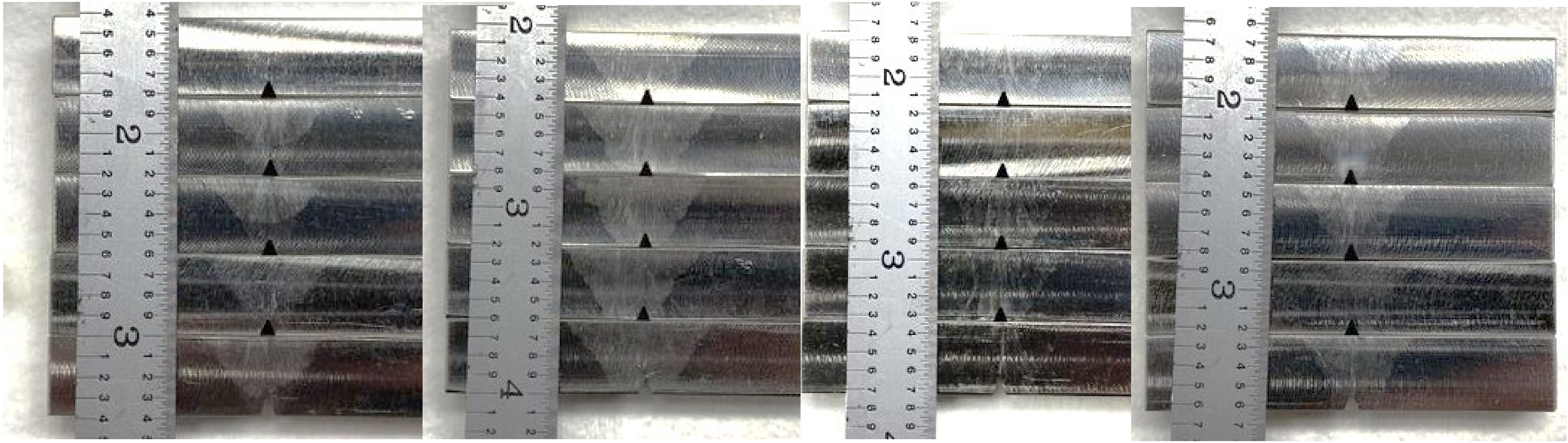
ASTM E1820 K_{JIC} testing at -320°F can be used to predict K_{JIC} -452°F, but a value of 233 ksi√in at -320°F only leads to 100 ksi√in at -452°F.

Weld Practices

- All fabricator's overall weld configurations were essentially the same: V-Groove approximately ¾ wide at the top, GTAW root, fill and cover with either GTAW or FCAW.
- Estimated number of weld passes and measured toughness:
    - Weld # Passes KJIC$_{-452°F}$
    - W-2 50-70 154
    - W-3 30 147
    - W-4 20 125
    - W-1 10-15 58
- Clearly other factors are involved, but that the weld toughness appears (at least for this small sample set) to have a direct relationship with the number of weld passes.



Weld Cross Sections



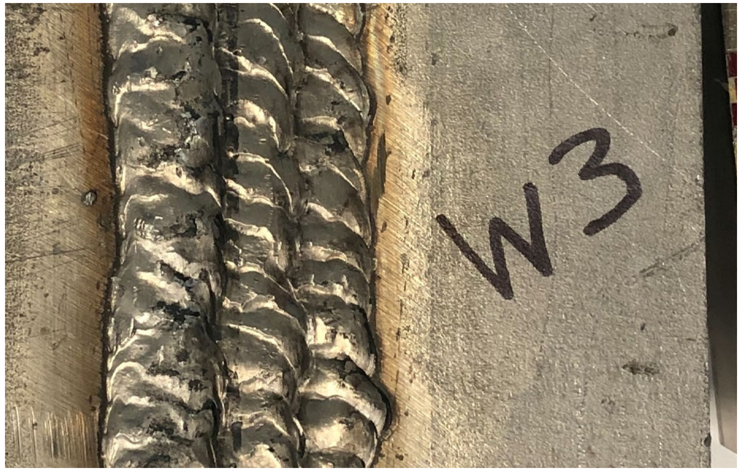
W1 W2 W3 W4

Image source: NIST

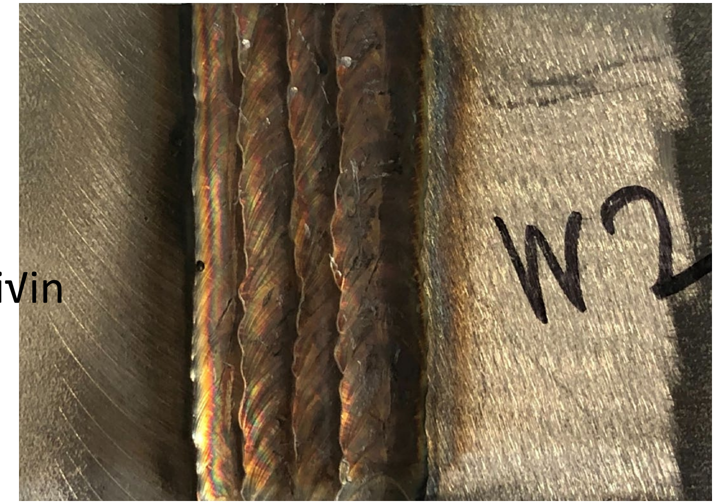
Weld Practice Effects on Fracture Toughness

W1:
Root: GTAW
Cover: FCAW
$KJ_{-452°F}$: 58.4ksi√in

W4:
Root: GTAW
Cover: FCAW
$KJ_{-452°F}$: 103.1ksi√in



W3:
Root: GTAW
Cover: FCAW
$KJ_{-452°F}$: 125.0ksi√in



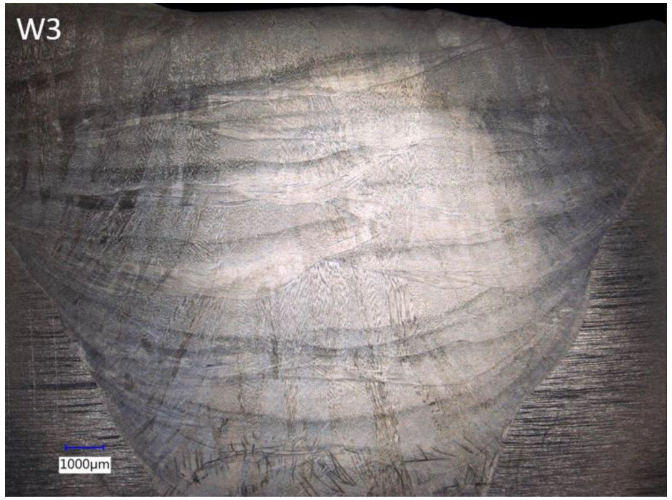
W2:
Root: GTAW
Cover: GTAW
$KJ_{-452°F}$: 154.2ksi√in

Image source: NIST

Weld Cross Sections

W1:
Root: GTAW
Cover: FCAW
$KJ_{-452°F}$: 58.4ksi√in

W4:
Root: GTAW
Cover: FCAW
$KJ_{-452°F}$: 103.1ksi√in



W3:
Root: GTAW
Cover: FCAW
$KJ_{-452°F}$:
125.0ksi√in

W2:
Root: GTAW
Cover: GTAW
$KJ_{-452°F}$: 154.2ksi√in

Image source: NIST

Reduction in Allowable Stress

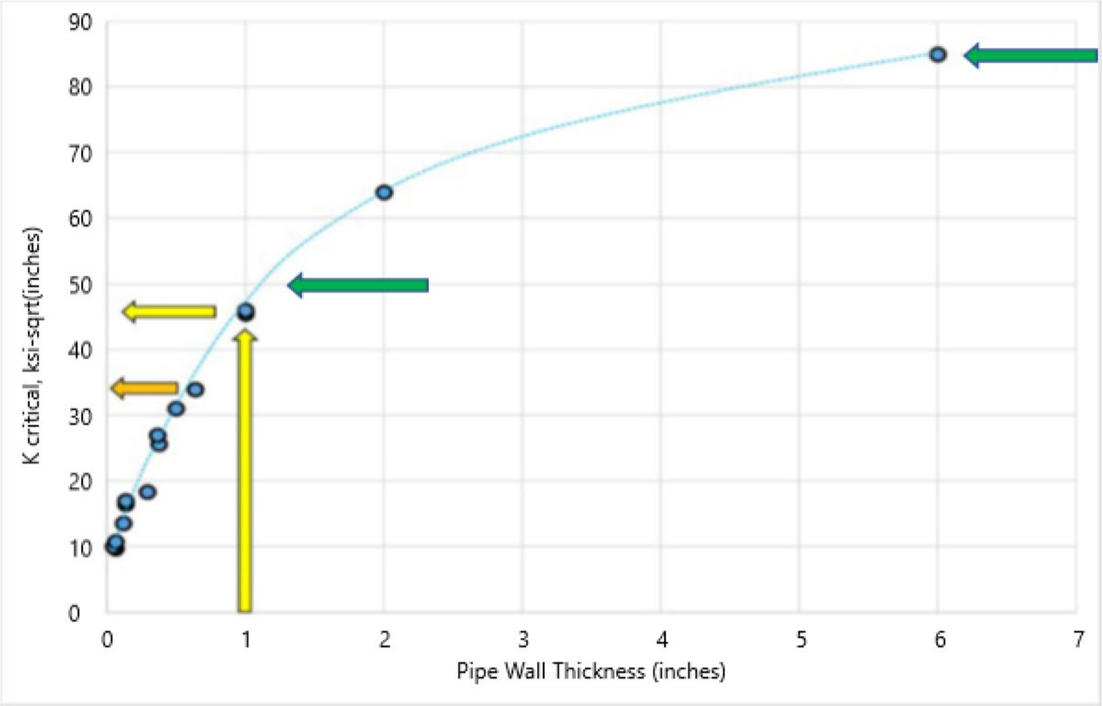
- Without testing, the 316L can be expected to have a minimum 50ksi√in
- 316L material is an inherently tough material
- Most piping systems built for service in LH2 or LHe apparently are designed with relatively low hoop stresses. System examples in CGA letter of concern had maximum stress of less than 8 ksi, most were under 5 ksi, and many were under 1 ksi.
- A reduced allowable stress could allow a reduced toughness requirement.

CGA Expression of Concern

- CGA Letter of November 16, 2015 expressed concern regarding addition of a requirement for toughness testing at ultra-low temperature. It provided seventy-seven examples of systems operating successfully at a temperature of either -425°F or -425°F without toughness testing. All were 304 or 304L material.
- The highest (Lame hoop) stress in any of the seventy-two examples analyzed was 7839 psi. Sixty-six of the examples had stress below 5000 psi.
- Sample wall thicknesses were 0.049 inches to 0.636 inches, and diameters ranged from ¼ IPS to 10 IPS.
- Incomplete information prevented analysis of five of the examples.

Practical Application of Data to Pressure Systems

- The chart below shows critical fracture toughness versus pipe wall thickness (Lambert). Yellow arrow indicates required toughness (46 ksi*in^.5) at 1 inch wall thickness (with no safety factor on toughness, but with 30 ksi residual stress added to the calculated hoop stress). Thickest wall in CGA survey was 0.636 inches.



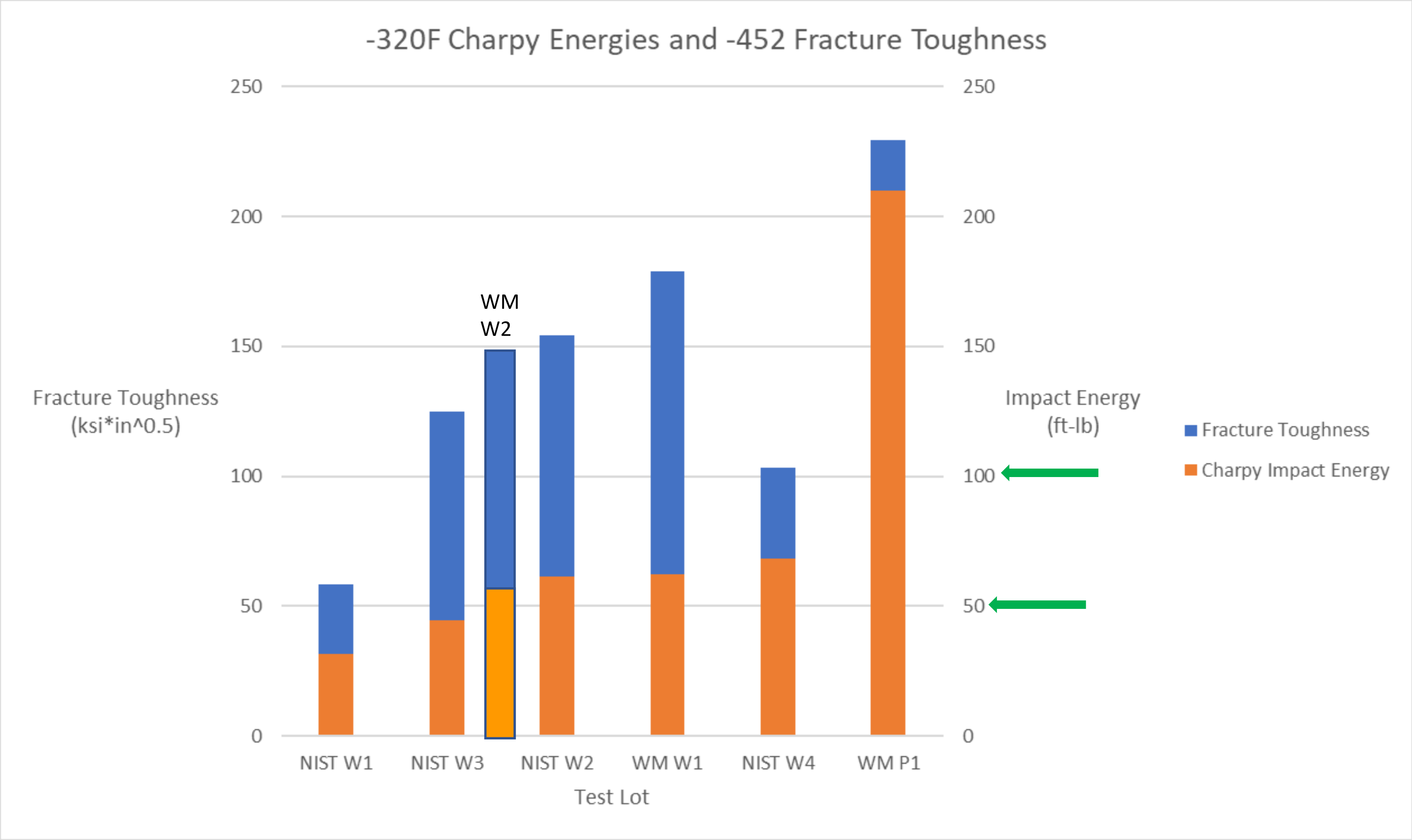
Recommendations

Possible options include:

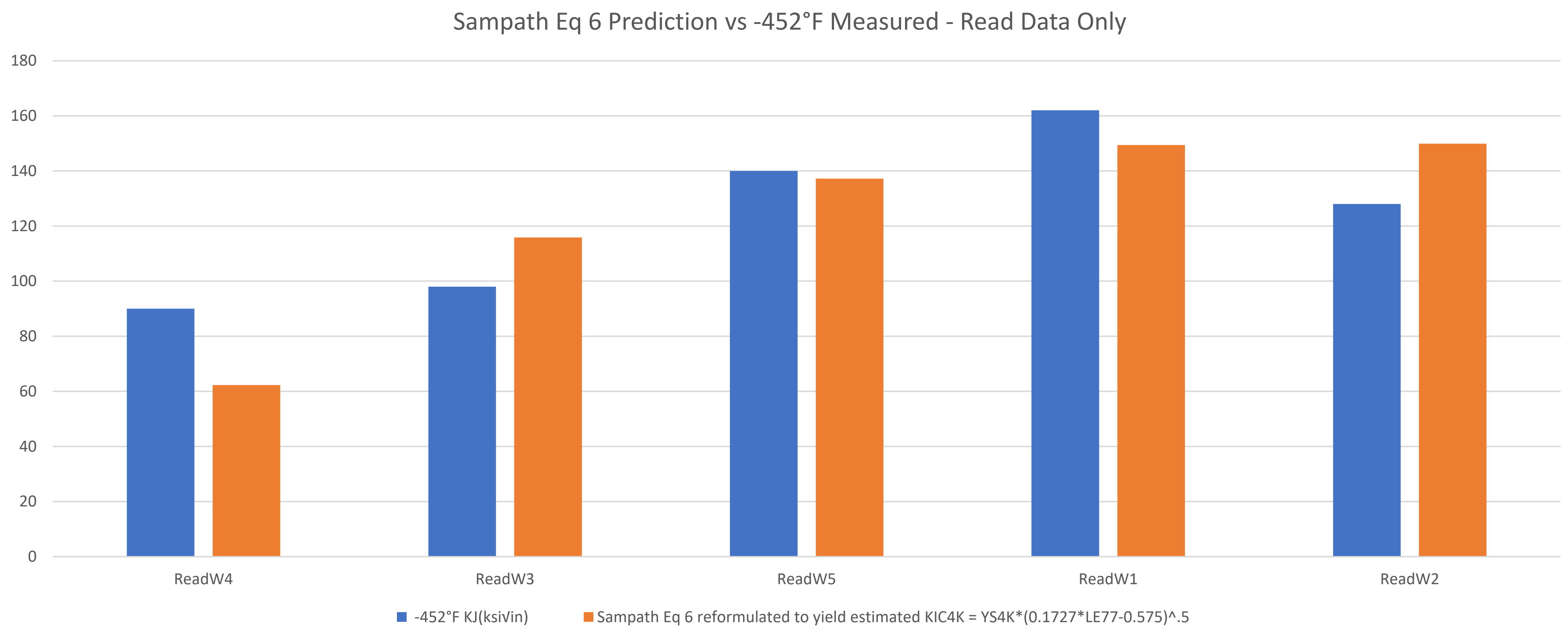
- Allow use of 316L stainless steel without testing up to a wall thickness of one inch at a stress not to exceed 20 ksi.
- Limit stress to conform to 50 ksi√in with specified limits of defect detection.
- Consider allowing use of 316L stainless steel for a thicker wall with reduced allowable stress.
- Consider use of -320 K_{JIc} for prediction of -452°F K_{JIc} in conjunction with fracture mechanics analysis related to reduced - 452°F K_{JIc}.
- Consider welding process controls such as provision of pre-qualified welding procedures to insure weld toughness and minimize potential crack initiation points and crack-like features.
- Allow use of 316L stainless steel with qualified welding procedure and minimum KJIC of 120 ksi√in at design minimum temperature.

Backup Slides

-320F Charpy Energy vs. -452F Fracture Toughness



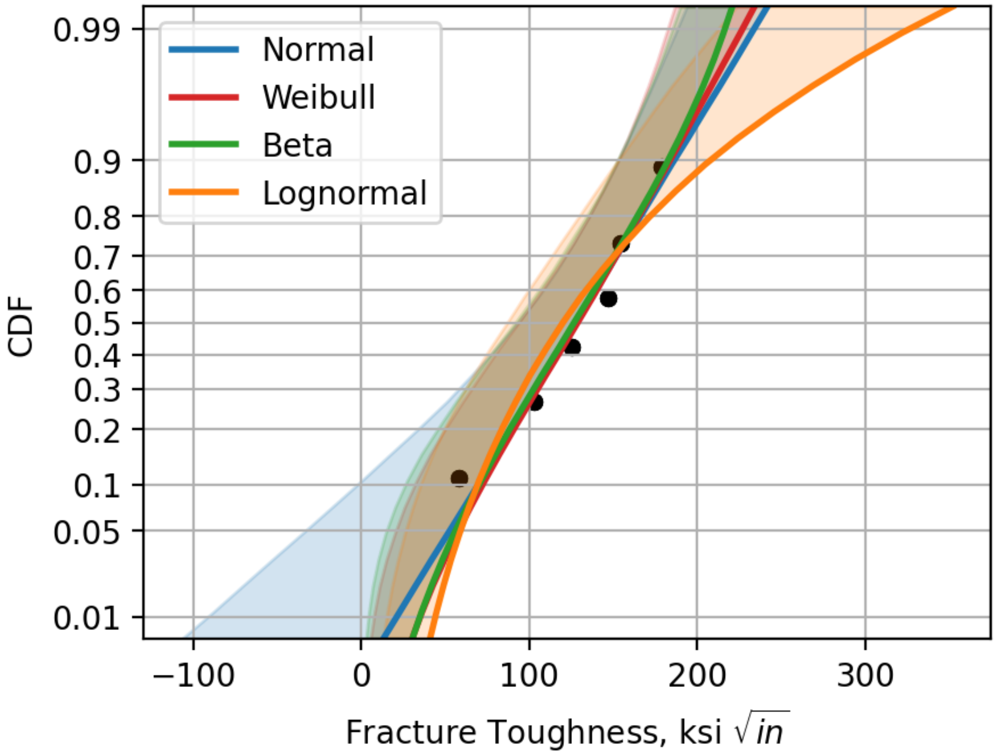
Sampath Eq 6 Prediction vs. Only -452°F Measured Data from Read



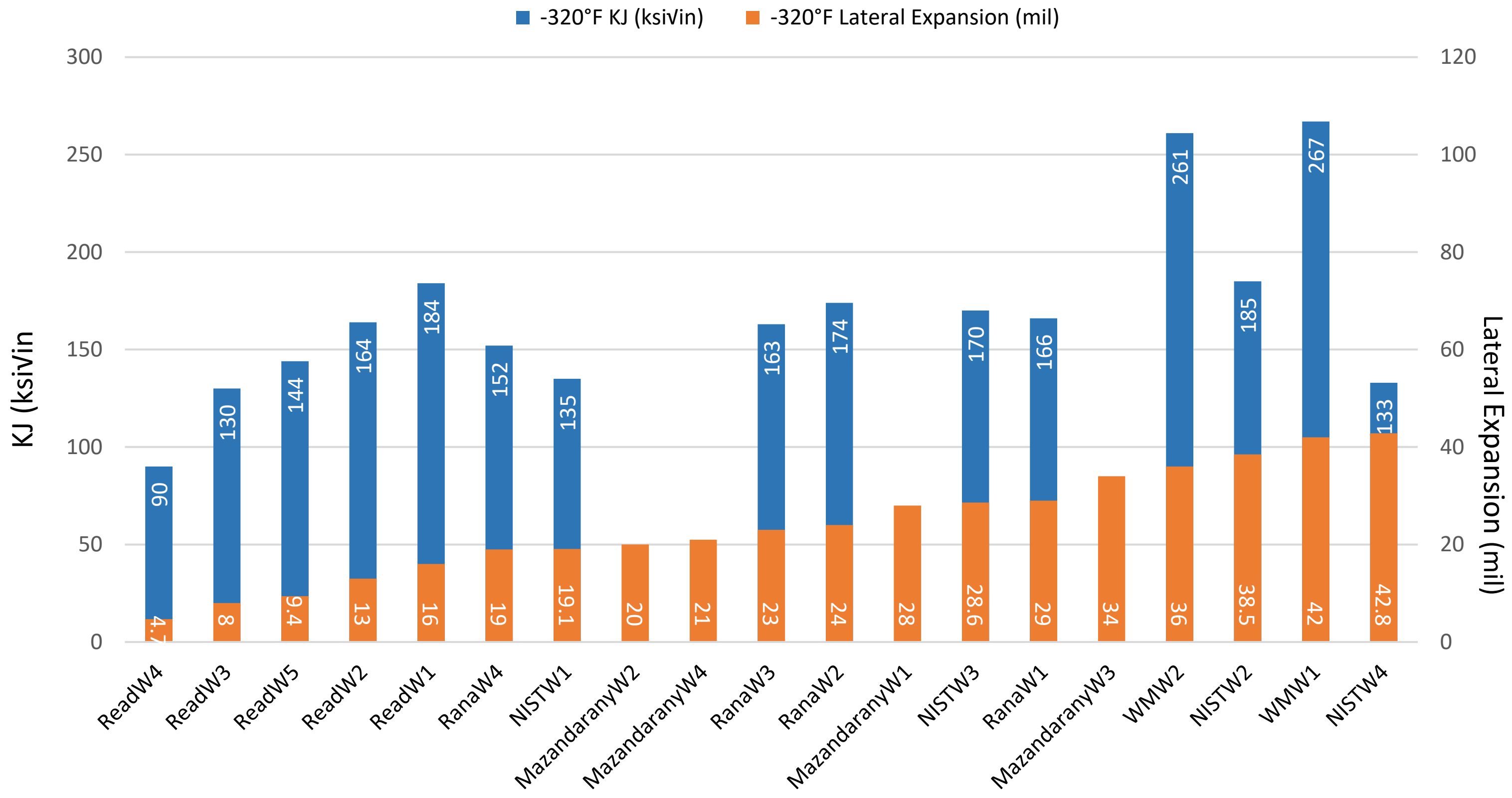
Choosing a Distribution Type

- Example: NIST and Westmoreland Data
  - Of the distributions that constrain fracture toughness to be positive, the **beta distribution** is the least conservative with confidence bounds
  - This is consistent among all data subset cases
- Moving forward with Beta distribution with upper and lower bounds of 0 and 250

Best Estimate CDFs with 95% Lower Confidence Bounds

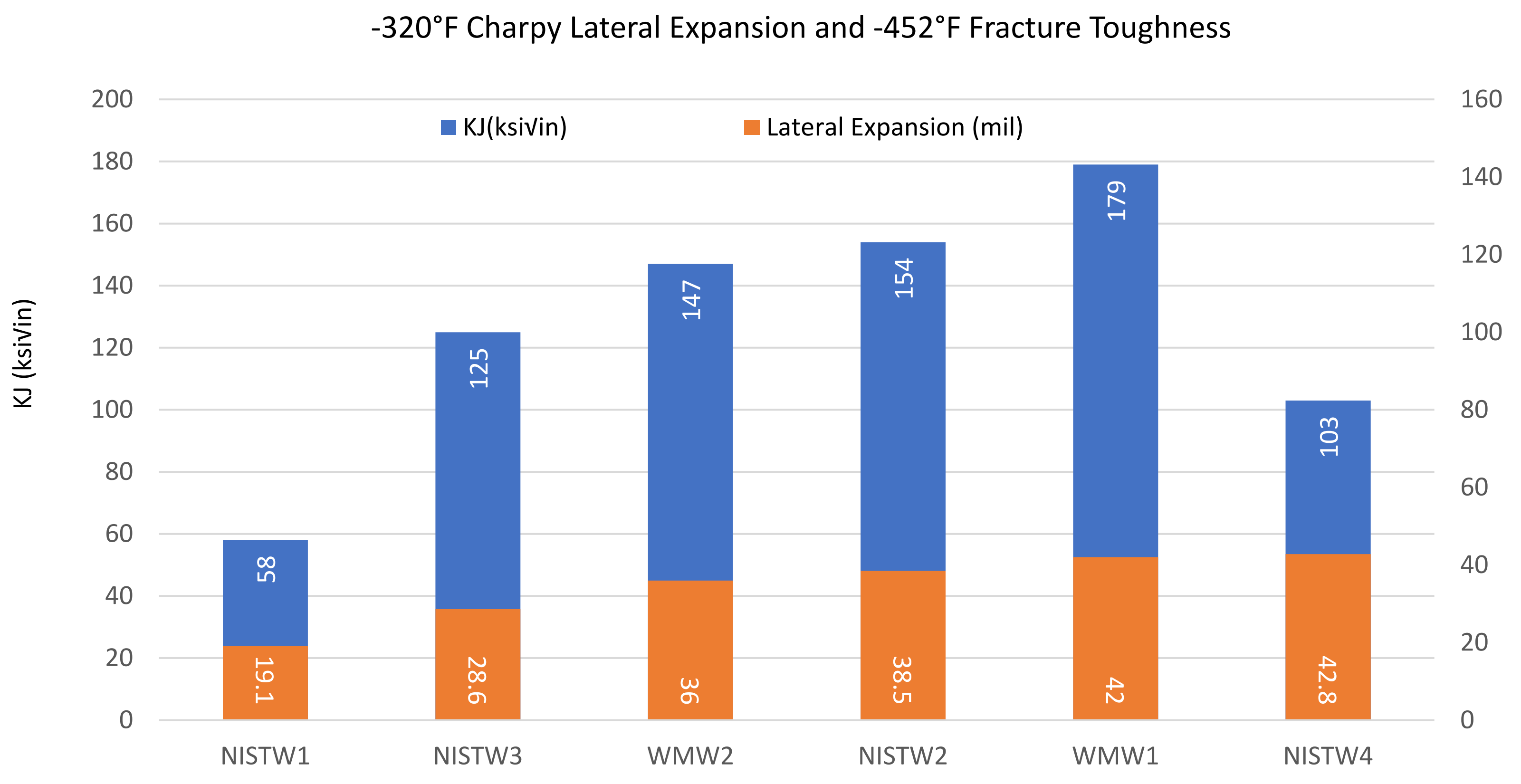


-320°F Charpy Lateral Expansion and -320°F Fracture Toughness – All Data



Note: Toughness data not available at -320°F for Mazandarany samples

-320°F Charpy Lateral Expansion and -452°F Fracture Toughness – Project 173 Data



Summary and Observations

- 316L welds show typical cryo-enhancement of strength properties at -452F.
- Charpy impact energy and lateral expansion at -320F are not good predictors of specific fracture toughness values at either -320F or -452F.
- Fracture toughness of 316L welds can vary significantly, likely due to differences in weld process controls. NIST W1 used a similar weld method to the other plates, however it displayed fracture toughness roughly 50% below the next lowest weld.
- Despite the large variation in weld material properties, none of the individual tests fell below the 46 ksi*in^0.5 minimum threshold for 1” wall thickness proposed by Lambert.
- It is however recommended that welding process controls be thoroughly examined by manufacturers, as quality of weld process seems to have greater effect than the type of process and can produce major impact to weld performance and reliability. (Weld 1 passed 100% RT but contained code acceptable defects that may have contributed to reduced lateral expansion and toughness values.)
- Any further testing should target these process controls and weld methods, as 316L has shown to be acceptable at ultra-low temperatures when proper welding procedures are applied.