Ultra-Low Temperature Testing Requirements for 316L Stainless Steel in ASME B31.3 (Projects 157 and 173)

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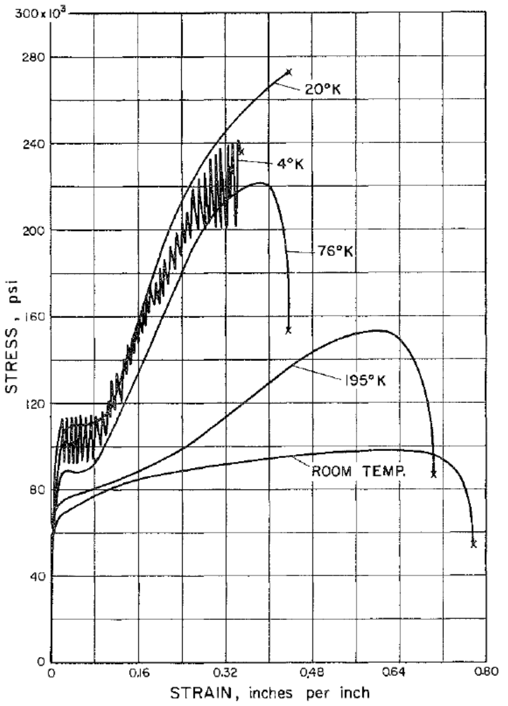
Background



Example of stress-strain curve for 304L annealed.

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

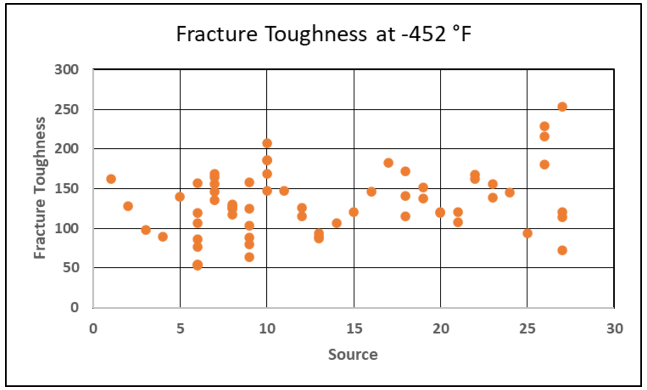
- Development of a hydrogen economy increases the need for pressure piping for ultra-low temperatures.
- Toughness testing in LH2 or LHe is difficult and extremely expensive, while adiabatic heating below -320F makes impact test results unreliable.
- Available data on LHe properties of austenitic stainless steels was limited and what was available had never been consolidated.
- Projects 157 and 173 provided more data, and a concentrated effort uncovered further historical results (total 102 test values relating to 33 material lots.

Project Goals

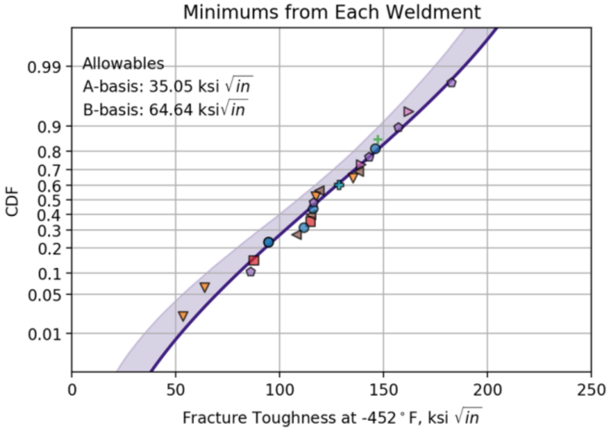
- Find a technically credible and cost effective path to ensure adequate toughness of austenitic stainless steels in ASME B31.3 and other applications at temperatures colder than -320°F (77K).
- Understand whether 316L weld metal is sufficiently tough that it can be used in pressure piping applications at all temperatures without toughness testing of individual welds or weld procedures. (Subject to further validation, it appears that it is.)
- Determine whether ASTM E23 Charpy impact testing in LN2 (−320°F, 77K)) is a suitable indicator of 316L toughness at all temperatures below 77K. (It is not.)
- Determine whether either (K_{ic}/YS) or (K_{ic}/YS)^2 at 77K is a suitable indicator of 316L toughness at all temperatures below -320°F. (As presented in April, 2023, it is not).
- Determine whether ASTM E1820 toughness testing in LN2 (−320°F, 77K)) is a suitable indicator of 316L toughness at all temperatures below -320°F. (It is not.)

Approach

Fracture toughness data from literature and ASME projects.



Statistically based lower bound fracture toughness evaluation.



Critical Stress Intensity

Welded pipe geometries:
Industry Database
ASME B36.19
- Diameter
- Wall thickness

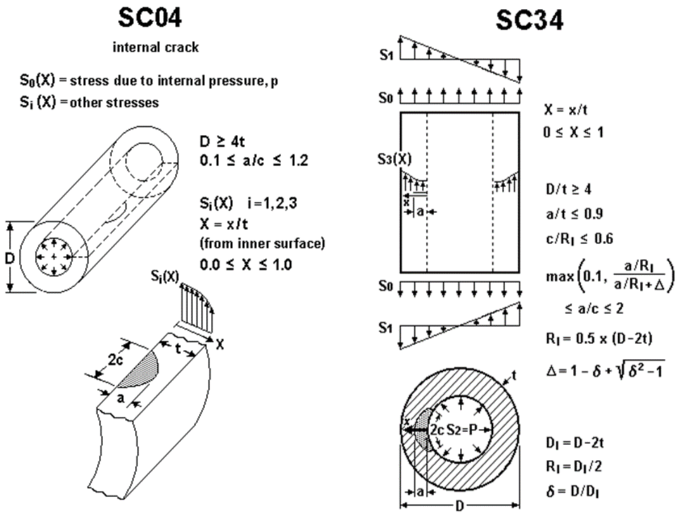
ASME B31.3 Allowable Stress

Limit Pressure

ASME B31.3 NDE Requirements

Flaw Geometry
- Length
- Depth

NASGRO® stress intensity calculation



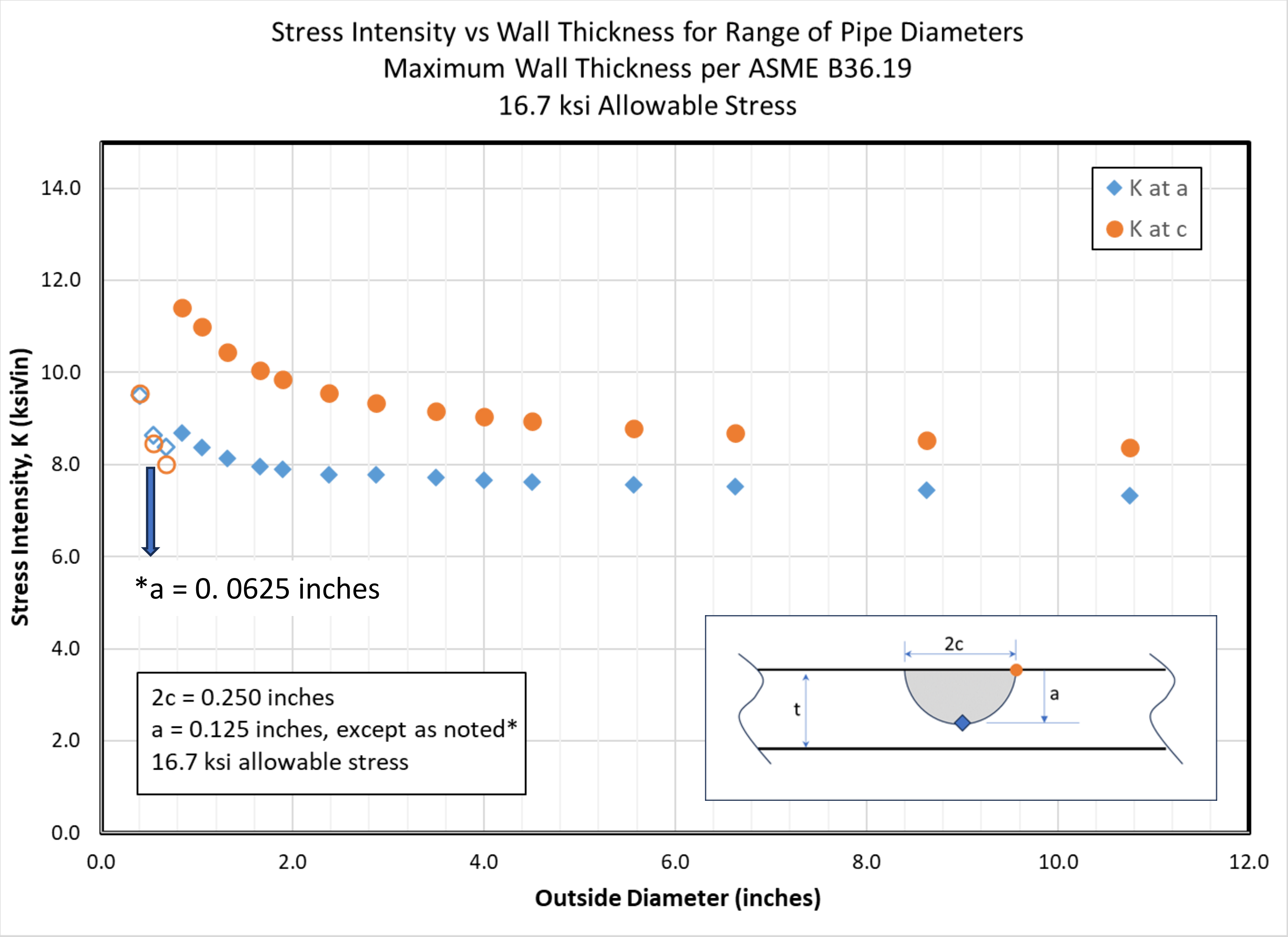
"NASGRO® Fracture Mechanics and Fatigue Crack Growth Analysis Software," v10.2, Southwest Research Institute and NASA Johnson Space Center, October 2023. (www.nasgro.swri.org)

Operational Stress Intensity

$$\textit{Factor of Safety} = \frac{\textit{Critical Stress Intensity}}{\textit{Operational Stress Intensity}}$$

Fracture Analysis

Stress Intensity as a Function of Wall Thickness: Various Diameters, ASME B36.19, 16.7 ksi Stress



Notes:

- Pipe diameters vary.
- Maximum wall thickness for each diameter per ASME B36.19.
- Flaw Sizes:
  - 2c = 0.250 inches
  - a = 0.125 inches, except as noted*
  - In smaller size pipes a = 0.0625 inches (open diamonds and circles)
  - See ASME B31.3, paragraph 344.6.2
- Linear elastic fracture analysis.
- 16.7 ksi allowable stress.
- Tabulated values on Slide 19.

Summary of Results

- Using all currently available reliable data, we expect the worst case -452°F toughness to be greater than 35 ksi√inches (99% of the time, with 95% confidence).
- The lowest observed individual -452°F 316L weld toughness test result was 53 ksi√inches.

- (This study has not addressed issues of fatigue and crack growth, stress concentrations, or welding residual stress at low temperature.)

Conclusion

- With appropriate controls (see next slide), 316L weld metal can likely be used for ASME B31.3 applications at reduced temperatures without toughness testing.

Recommendations

- Accept use of 316L weld metal at all temperatures in B31.3 applications without toughness testing, provided:
  - ASME Section IX qualified welders and welds
  - GTAW, SMAW, FCAW, SAW processes are used
  - 100% UT inspection of welds
  - Leak testing is performed on all welds
  - Stress not to exceed 16.7 ksi
  - Pipe size not to exceed 10 inch IPS
  - Pipe wall not to exceed maximum schedule specified in ASME B36.19
- Basis:
  - Successful history of austenitic stainless steels in LH2 and LHe service.
  - Analysis of sample cases (CGA examples and maximum pipe walls) at allowable stress, with comparison of damage tolerance based critical stress values to a highly conservative toughness value (99% exceedance with 95% confidence). (This does not include cyclic analysis, stress concentrations, or residual stress.)
  - 33 independent data sets representing the recommended welding processes.

Backup Slides

- Standards for Toughness Testing – Slide 10
- Testing Validity – Slides 11-13
- Current B31.3 and Section VIII Toughness Testing Rqmts – Slide 14
- Fracture Analysis and Results – Slides 15-23
- Test Measurements Assessed – Slide 24
- Summary of Results – more details – Slides 25-27
- Data Sets – Slide 28
- Other Possible Recommendations – Slide 29
- Further Discussion – Slide 30
- Backup slides from presentation in April, 2023 – Slides 31-56

Standards for Toughness Testing

- Current: ASTM E1820 Standard Test Method for Measurement of Fracture Toughness. Testing on Projects 157 and 173 was all performed in accordance with this standard (both by NIST and by Westmoreland).
- Previous: ASTM E813-89 Standard Test Method for Jic, a Measure of Fracture Toughness (first promulgated 1981, withdrawn 1997) was used for testing reported by Rana in 2001 (Testing performed at MIT.)
- Pre-standard: when testing was performed by researchers in the 1980s, there was no elastic-plastic fracture toughness testing standard available. The only fracture standard at the time was ASTM E399 Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials. Testing data presented in the various other research papers prior to the two ASME/NASA projects was all obtained through rigorous testing and procedures by the National Bureau of Standards (predecessor of NIST).

Testing Validity Concerns

- Concerns:
  - Testing that failed to meet validity requirements of the applicable standard.
  - Testing performed in accordance with prior standards, or no standard at all.
  - Importance of including all relevant data.
- Careful review and evaluation of each respective paper by either a NIST or a NASA expert in fracture and fracture testing indicated:
  - Extremely stringent validity requirements of E1820 often cause rejection of results that should be considered reliable and meaningful, irrespective of whether they correspond to JQc, Jc, JQ, or JIc. Some recent NIST and Westmoreland test results fall into this category.
  - Test results reported by Rana had some rejections, and might have a greater rejection rate if evaluated according to the current E1820 standard, but remain informative and useful.
  - Prior results from Read, Mazandarany, and others are valid in the sense of being reliable, meaningful, and comparable to other results.

Summary of Data Used

Source	Date	Matl. Lots / Tests	Toughness Std	Applicability of Standard	Reliable for Current Effort?	Assessment Performed By
Read	1980	5/5	ASTM E399	Linear Elastic	Yes	Lucon[1]
Mazandarany	1980	4/5	ASTM E399	Linear Elastic	Yes	Lucon[1]
Rana	2001	4/12	ASTM E813-89	Elast.-Plast.	Yes	Lucon[1]
Westmoreland	2018	4/11	ASTM E1820-15a	Elast.-Plast.	Yes	Lucon[1]
NIST	2022	2/11	ASTM E1820-21	Elast.-Plast.	Yes	Lucon[1]
McHenry & Whipple	1980	4/22	ASTM E399	Linear Elastic	Yes	McGill[2]
Whipple, McHenry, Read	1980	2/5	ASTM E399	Linear Elastic	Yes	McGill[2]
Whipple & Brown	1981	7/12	ASTM E399	Linear Elastic	Yes	McGill[2]
Whipple & Kotecki	1981	4/6	ASTM E399	Linear Elastic	Yes	McGill[2]

[1] Enrico Lucon, NIST, email 4/6/23 [2] Preston McGill, Jacobs Space Exploration Group, 2024

Testing Validity Conclusion

- Conclusion: all data from the above studies should be included in the general discussion. (Data not assessed for inclusion had heat treatment, other materials, etc.)

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.

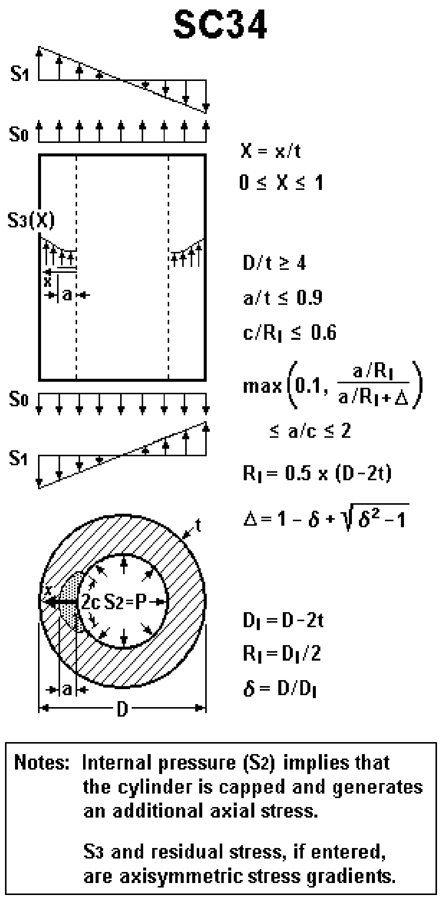
Note: Section VIII Division 1, UHA-51(a)(3) only requires impact testing at -320°F for operation at all lower temperatures for 316L if (1) FN<=10 for 316L weld metal, or 4<=FN<=14 for 308L weld metal, (2) impacts taken in base metal, HAZ, and weld metal, and (3) lateral expansion >=0.021 inches (0.53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

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

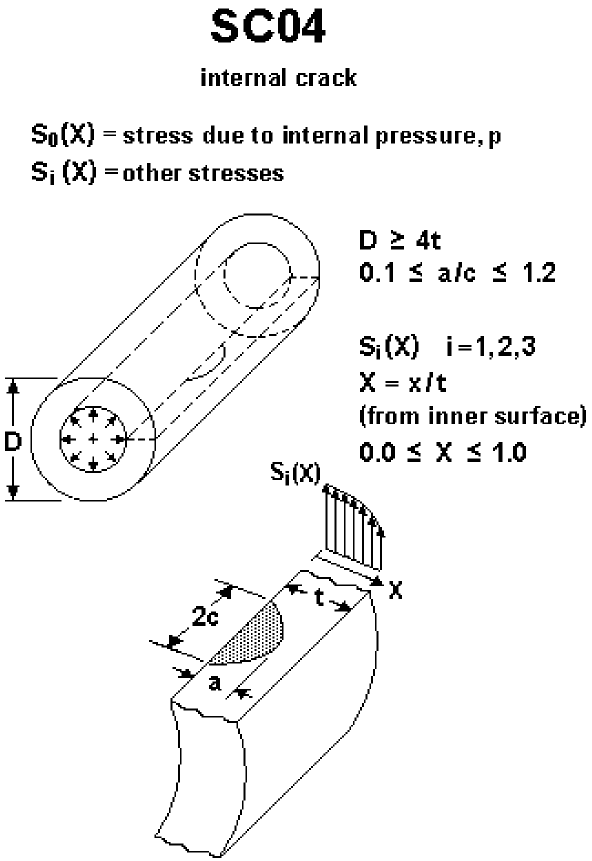
- The concern is that a sufficient technical basis for accepting -320°F testing for lower temperature operations had not been provided.

Fracture Analysis

NASGRO® Stress Intensity Solution Case 34 –
Circumferential Flaw in Cylinder



NASGRO® Stress Intensity Solution Case 04 –
Axial Flaw in Cylinder



- Fracture analysis was performed using NASGRO, a program used to analyze fracture and fatigue crack growth in structures and mechanical components.

"NASGRO® Fracture Mechanics and Fatigue Crack Growth Analysis Software," v10.2, Southwest Research Institute and NASA Johnson Space Center, October 2023. (*www.nasgro.swri.org*)

Fracture Analysis

- A study was performed using pressures to induce a maximum allowable stress of 16.7 ksi, as specified for 316L in ASME B31.3, Table A-1. (All CGA examples had stresses significantly below this.)
  - Initial analysis consisted of evaluations of representative sample sizes and wall thickness taken from the examples provided by Richard Craig of CGA in his letter dated November 16, 2015.
  - Subsequent analyses considered maximum wall thicknesses specified by ASME B36.19 for pipe sizes from 1/8 inch through 10 inch IPS.
  - All analyses used the pressure required to induce the maximum allowable stress of 16.7 ksi in the material.
  - Both longitudinal and circumferential cracks were evaluated assessing critical stress developed around a crack with 2c = 0.25 inches and a/c = 1, except where the small size of the pipe required lesser values.
  - As expected, circumferential stress and longitudinal cracks governed.

Fracture Analysis

Analysis – Stress Intensity at Limiting Pressure on Axial Flaw in Pressurized Cylinder

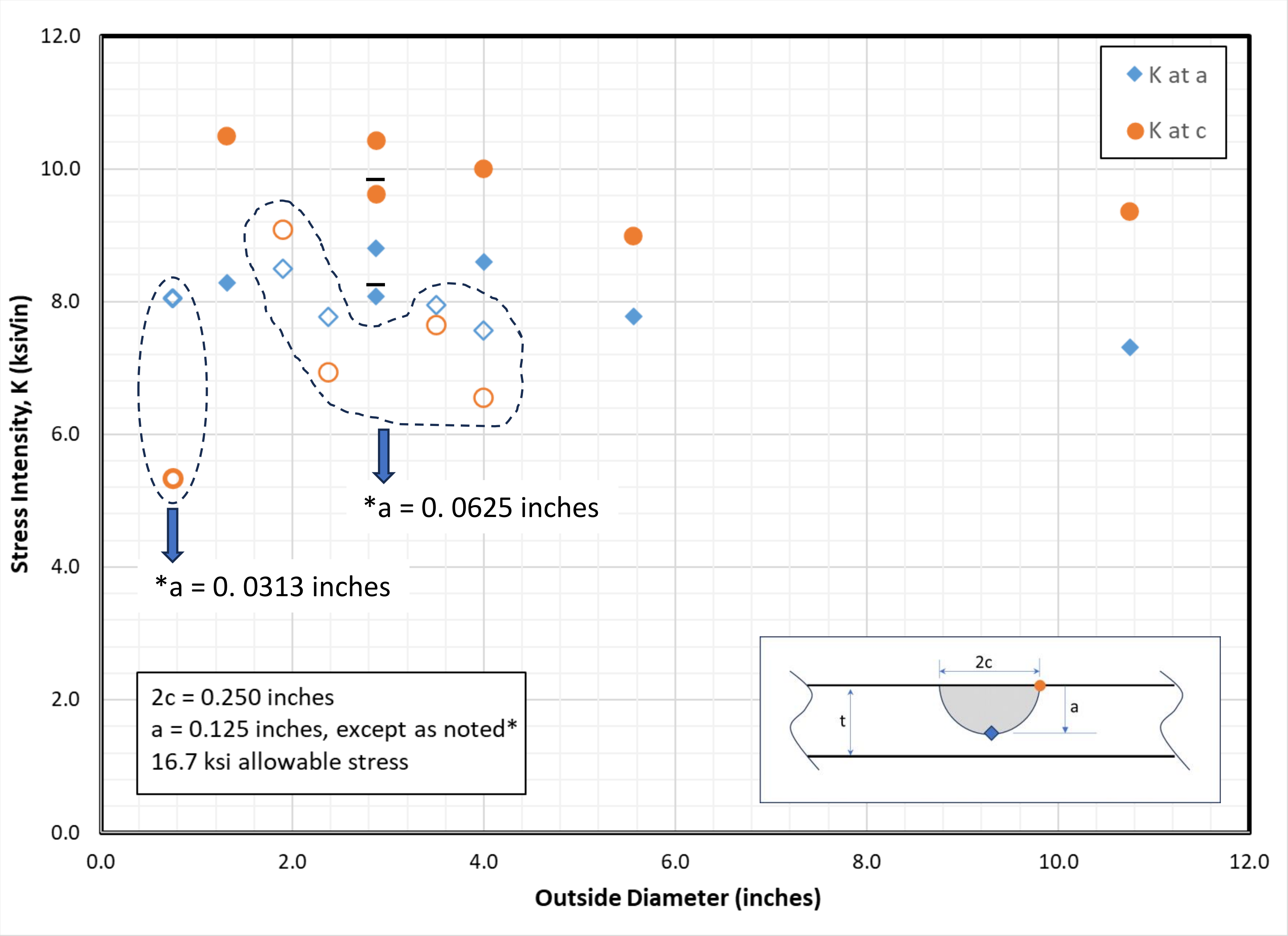
CGA pipe geometries at 16.7 ksi allowable stress (sort by ksi√in at c.)

Geometry Case	Thickness	Actual Diameter	a	2c	Limiting Pressure	MAWP (CGA)	Stress Intensity	
	(in)	(in)	(in)	(in)	(psi)	(psi)	(ksi√in)	
							a	c
1	0.049	0.750	0.0313	0.250	2323	175	8.1	5.3
2	0.065	1.900	0.0625	0.250	1182	175	8.5	9.1
3	0.083	3.500	0.0625	0.250	811	75	7.9	7.7
4	0.109	2.375	0.0625	0.250	1603	150	7.8	6.9
5	0.120	4.000	0.0625	0.250	1032	275	7.6	6.6
6	0.165	10.750	0.125	0.250	521	*	7.3	9.4
7	0.250	1.315	0.125	0.250	7431	75	8.3	10.5
8	0.375	2.875	0.125	0.250	4900	75	8.1	9.6
9	0.500	5.563	0.125	0.250	3267	175	7.8	9.0
10	0.552	2.875	0.125	0.250	7512	175	8.8	10.4
11	0.636	4.000	0.125	0.250	6097	175	8.6	10.0

*MAWP not listed.

Fracture Analysis

Stress Intensity as a Function of Pipe Diameter, CGA Industry Database, 16.7 ksi Allowable Stress



Notes:

- Pipe diameters and wall thicknesses per CGA memo to ASME, November 16, 2015.
- Flaw Sizes:
  - 2c = 0.250 inches
  - a = 0.125 inches, except as noted*
  - See ASME B31.3, paragraph 344.6.2
- Linear elastic fracture analysis.
- 16.7 ksi allowable stress.
- Tabulated values on Slide 17.
- (Two wall thicknesses are presented for 2-1/2 inch IPS.)

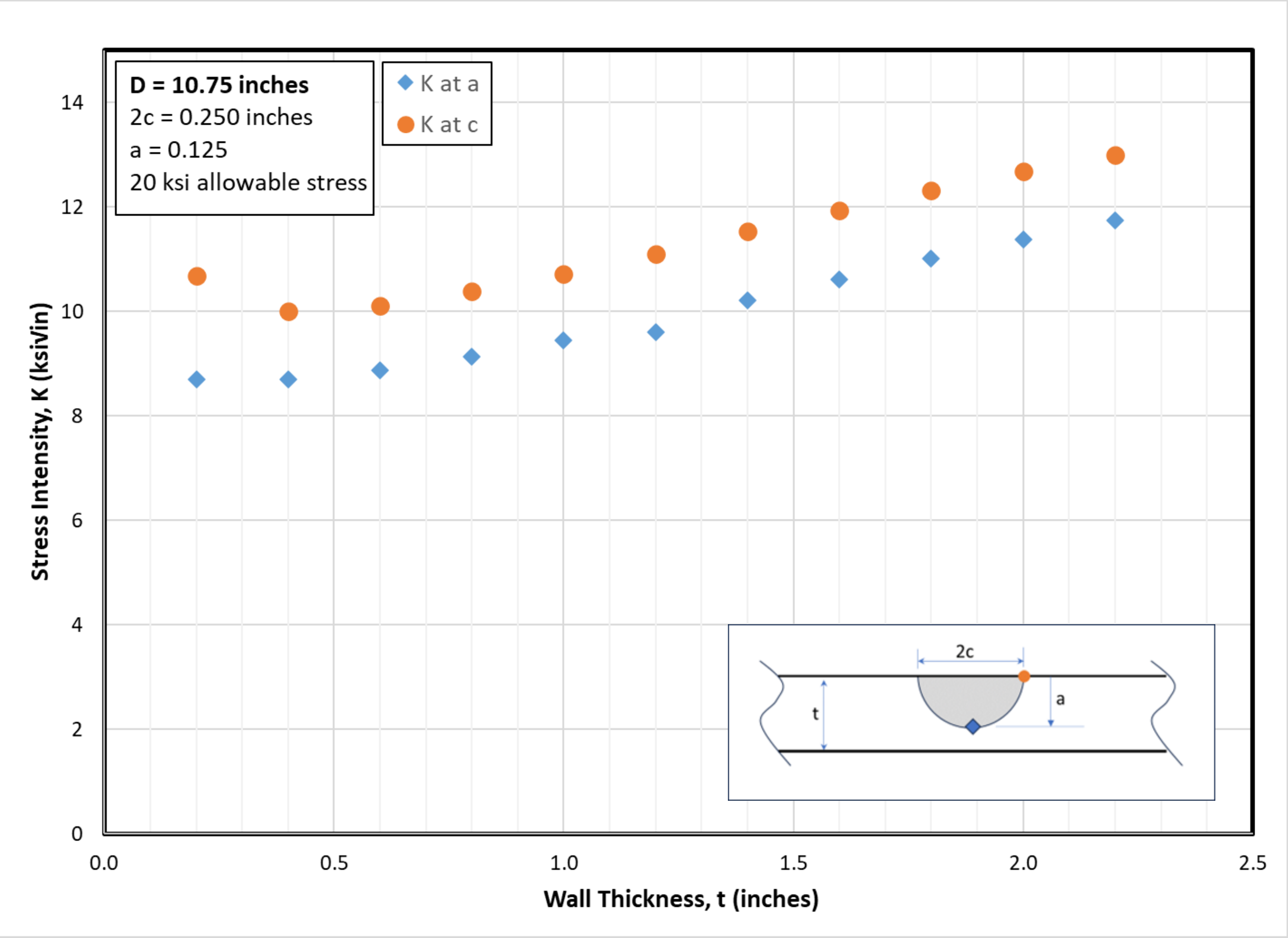
Fracture Analysis

Sample Stress Intensity Values at 16.7 ksi with axial flaw – ASME B36.19 Sizes at Maximum Schedule Wall Thickness (tabulated data for plot on slide 5)

Geometry Case	Thickness	Outside Diameter	a	a/t	2c	Limiting Pressure	Stress Intensity Axial Flaw (ksi√in)	
	(in)	(in)	(in)		(in)	(psi)	a	c
12	0.095	0.405	0.0625	0.66	0.250	9357	9.5	9.5
13	0.119	0.540	0.0625	0.53	0.250	8742	8.6	8.5
14	0.126	0.675	0.0625	0.50	0.250	7282	8.4	8.0
15	0.147	0.840	0.125	0.85	0.250	6780	8.7	11.4
16	0.154	1.050	0.125	0.81	0.250	5576	8.4	11.0
17	0.179	1.315	0.125	0.70	0.250	5135	8.1	10.5
18	0.191	1.660	0.125	0.65	0.250	4270	8.0	10.1
19	0.200	1.900	0.125	0.63	0.250	3876	7.9	9.9
20	0.218	2.375	0.125	0.57	0.250	3341	7.8	9.6
21	0.276	2.875	0.125	0.45	0.250	3507	7.8	9.3
22	0.300	3.500	0.125	0.42	0.250	3104	7.7	9.2
23	0.318	4.000	0.125	0.39	0.250	2863	7.7	9.0
24	0.337	4.500	0.125	0.37	0.250	2686	7.6	8.9
25	0.375	5.563	0.125	0.33	0.250	2402	7.6	8.8
26	0.432	6.625	0.125	0.29	0.250	2319	7.5	8.7
27	0.500	8.625	0.125	0.25	0.250	2048	7.4	8.5
28	0.500	10.750	0.125	0.25	0.250	1625	7.3	8.4

Fracture Analysis

Stress Intensity as a Function of Wall Thickness: 10.75 inch Diameter Pipe, 20 ksi Allowable Stress

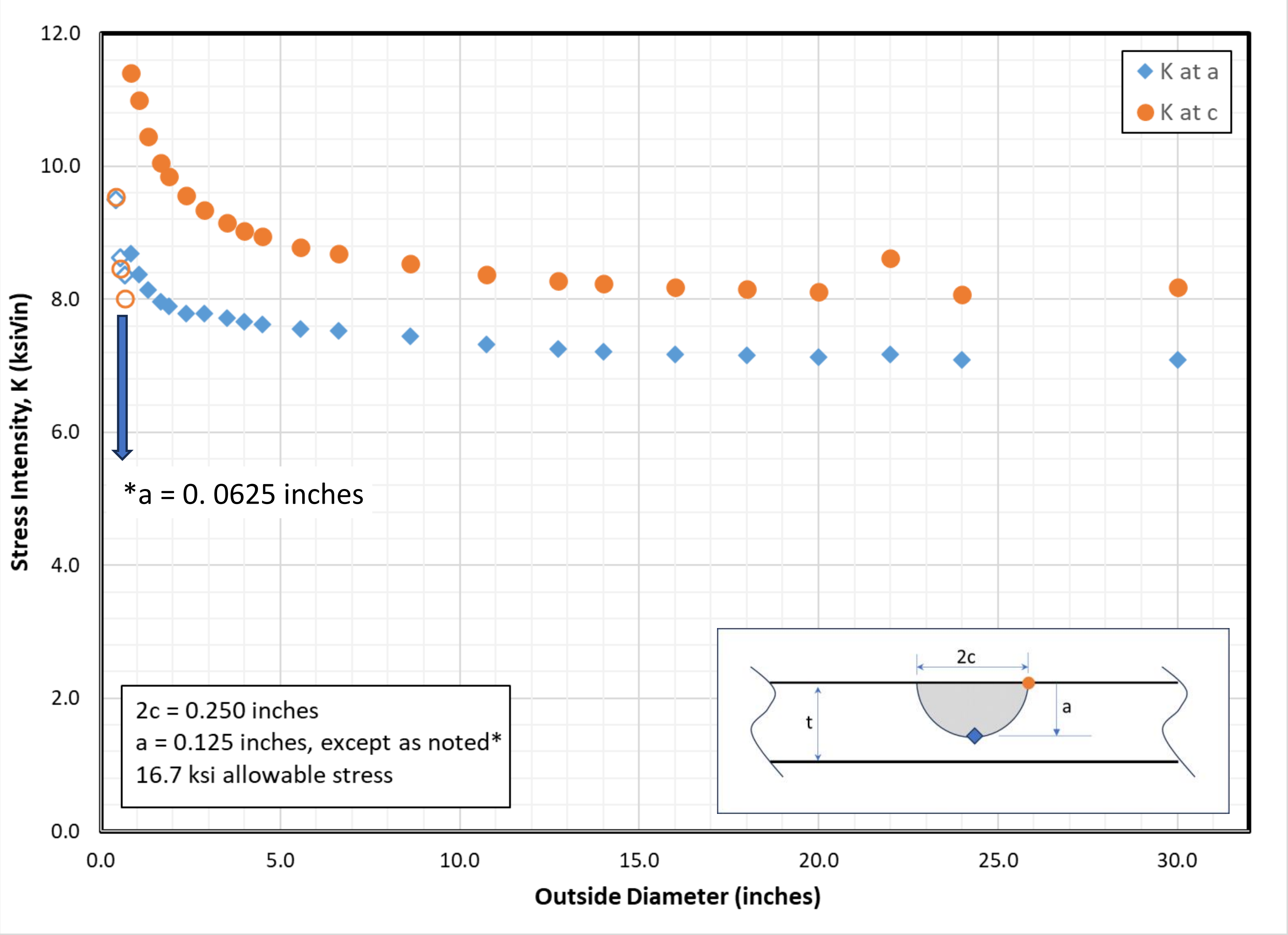


Notes:

- Semi-circular Flaw
  - 2c = 0.250 inches
  - a = 0.125 inches
- 10.75 inch Diameter Pipe
- Wall thickness per ASME B36.19.
- Stress intensity varies approximately 30% over the range of thickness.
- 20 ksi allowable stress.
- NOTE: The trend is the same for 16.7 ksi, but this example illustrates that 20 ksi allowable produces stress intensities that result in a factor of safety less than 3.0 on fracture toughness.

Fracture Analysis

Stress Intensity as a Function of Pipe Diameter per ASME B36.19 Maximum Wall Thickness, 16.7 ksi Allowable Stress

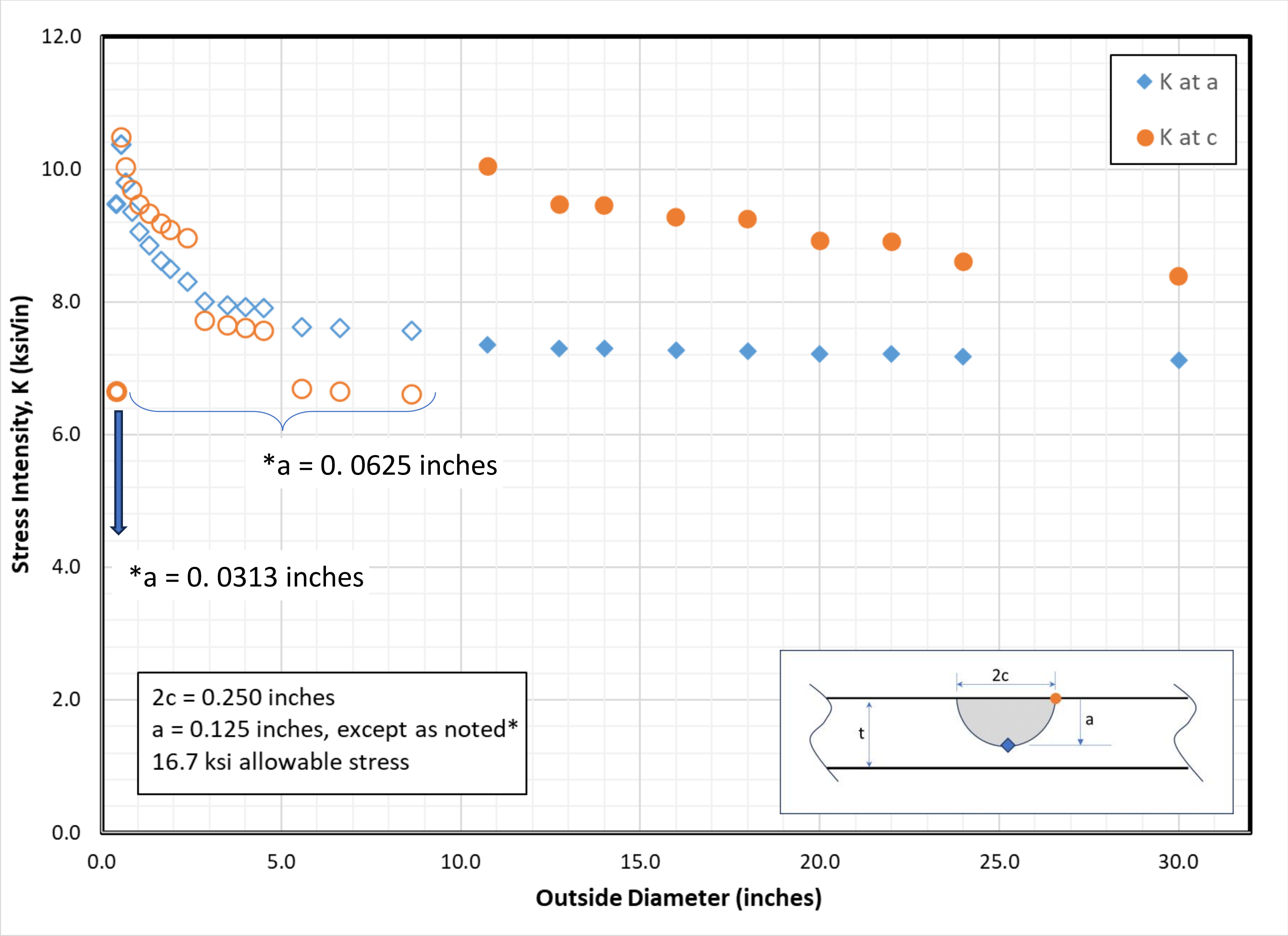


Notes:

- Pipe diameters per ASME B36.19.
- Maximum wall thickness for each diameter per ASME B36.19.
- Flaw Sizes:
  - 2c = 0.250 inches
  - a = 0.125 inches, except as noted*
  - a = 0.0625 inches (open diamonds and circles) in smaller pipe sizes
  - See ASME B31.3, paragraph 344.6.2.
- Linear elastic fracture analysis.
- 16.7 ksi allowable stress.

Fracture Analysis

Stress Intensity as a Function of Pipe Diameter per ASME B36.19 Minimum Wall Thickness, 16.7 ksi Allowable Stress

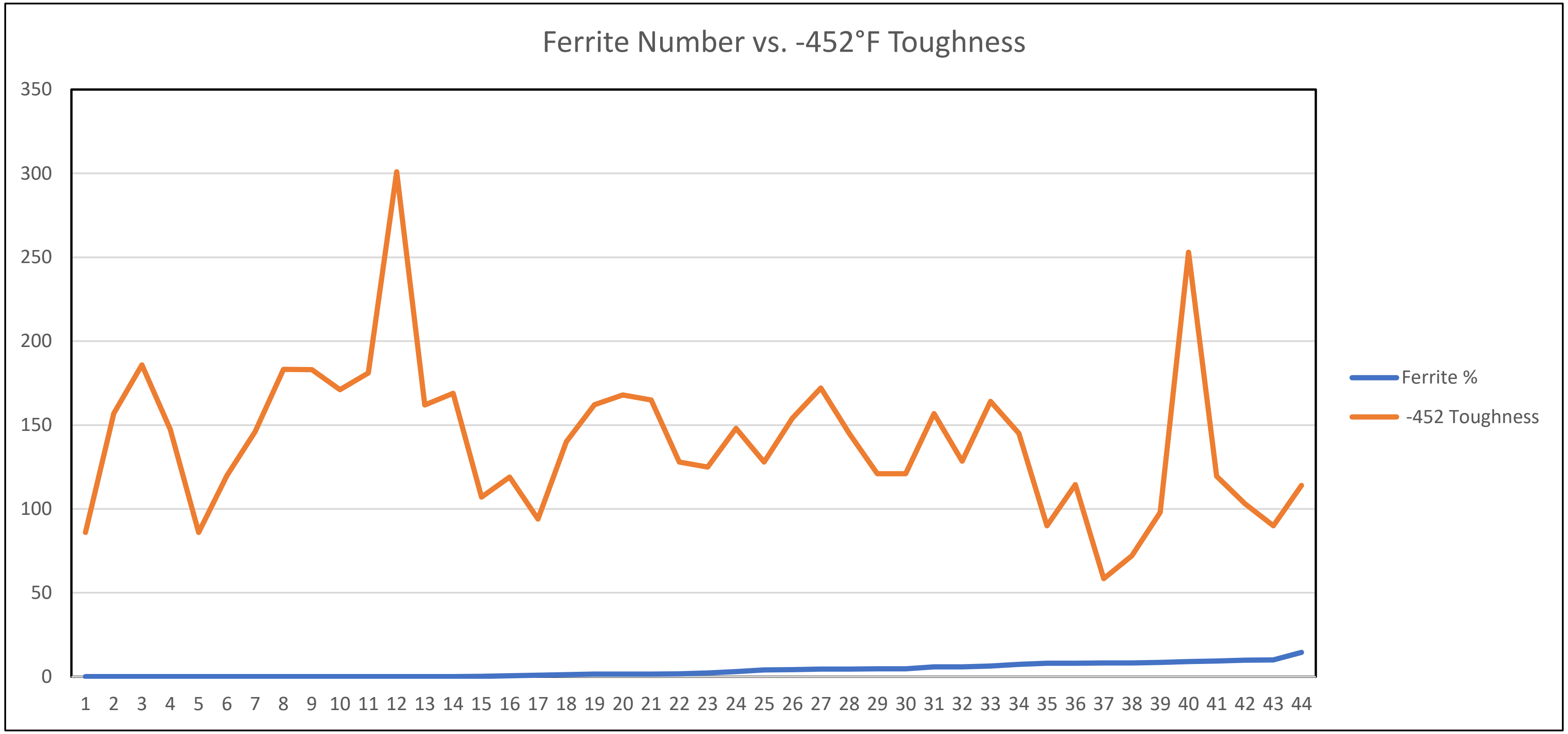


Notes:

- Pipe diameters per ASME B36.19.
- Minimum wall thickness for each diameter per ASME B36.19.
- Semi-circular Flaw:
  - 2c = 0.250 inches
  - a = 0.125 inches, except as noted*
  - a = 0.0625 inches (open diamond and circles) in smaller pipe sizes
  - a = 0.0313 inches (heavy border open diamond and circles) in smaller pipe sizes
  - See ASME B31.3, paragraph 344.6.2.
- Linear elastic fracture analysis.
- Step function with respect to *K at c* is due to step function in a/t ratio related to pipe wall thickness change.
- 16.7 ksi allowable stress.

Fracture Analysis

Toughness (K_{JIc}) versus Ferrite Number



Test Measurements Assessed

- Whether 316L material might be sufficiently robust that no $KJ_{-452°F}$ toughness 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 −452°F (ASTM E-1820-21)
- Charpy impact test lateral expansion (mils) at −320°F correlation with K_{JIC} at −452°F
- Proposed dimensionally consistent correlation for predicting K_{JIC} at −452°F

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

- ASTM E1820 K_{JIC} toughness testing at −320°F correlation with K_{JIC} at −452°F

Summary of Results (1 of 3)

- 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 E1820 fracture toughness from −320°F to −452°F.
- While the approach to producing the data was evaluated and found acceptable in each case, there was variability in the amount of data available on each individual weld. This varied as follows:
  - Some lots of material had a single test value
  - For some lots of material, multiple tests were run, but only an average reported
  - For some lots of material, multiple tests were run, and all data was available.
- As a result, we looked at the data using a number of different statistical perspectives to assess how much difference in final value would result from the various approaches. Results varied somewhat, but not significantly, depending on distribution type, use of individual points versus weldment average test results or worst case values, and a conservative and physical credible approach was used.

Summary of Results (2 of 3)

- Using all currently available reliable data, we expect the toughness to be greater than 35 ksi√inches 99% of the time, with 95% confidence.
- Using the same data, we expect that the toughness will exceed 64 ksi√inches 90% of the time, with 95% confidence.

Data Evaluation Approach	99% Exceedance with 95% Confidence	90% Exceedance with 95% Confidence
Individual Values Only	37.4	70.5
Individual Values and Single Values	39.8	72.6
Average Values Only	39.0	71.0
Average Values Plus Single Values	43.3	74.8
Minimum Values for Each Material Lot	35.4	64.6

Summary of Results (3 of 3)

- With stress not exceeding 16.7 ksi, fracture analysis shows that for either a circumferential or a longitudinal flaw not exceeding 0.25 inches in length and 0.125 inches (code detectable) in depth where credible, there will be at least a safety factor of three before reaching a critical stress intensity of 35 ksi√, the worst case toughness based on analysis of existing data.
- Ferrite number showed little correlation with either −320°F K_{JIC} or −452°F K_{JIC} toughness.
- GTAW welds showed better than average toughness properties at −452°F.
- While number of weld passes was available only for a limited set of welds, higher number of weld passes correlated with higher toughness.

Data Sets

1. Individual Data – 69 individual samples
2. Averages – 24 averages from each weldment with $\geq$ 2 samples
3. Individual (69) plus Single Values Reported (9) – 78 total
    - Singles from Mazandarany [2], Whipple, McHenry, Read [6], Whipple & Brown [7], and Whipple & Kotecki [9]
4. Averages (24) plus Single Values Reported (9) – 33 total
5. Minimums from Each Weldment – 24 minimums from each weldment with $\geq$ 2 samples

Other Possible Alternatives

Possible options include:

- Allow use of 316L stainless steel without testing up to some specified wall thickness to be determined 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 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.

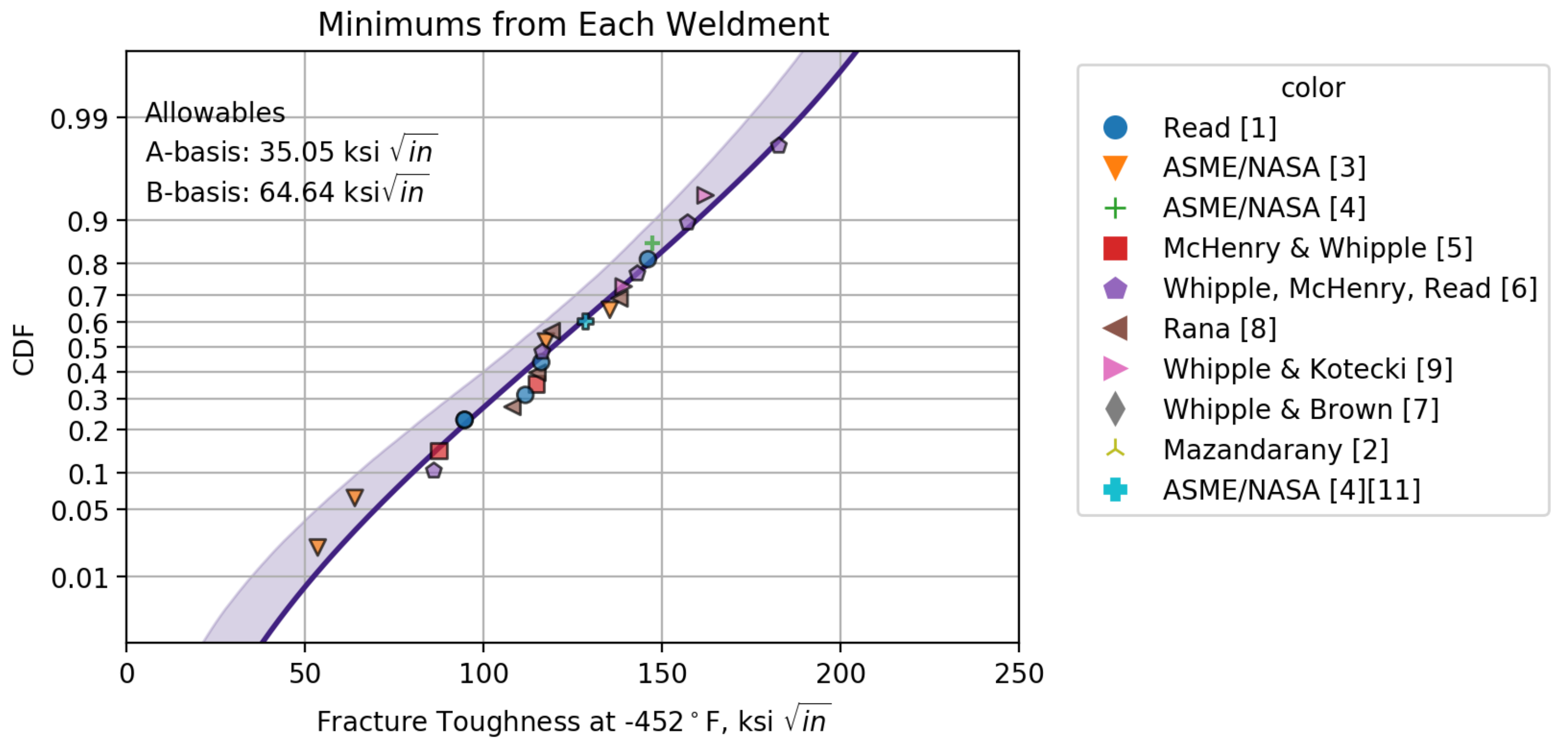
Is 316L Tough Enough to be Used at -452°F Without Toughness Testing?

- Not if the requirement is $K_{Ic} \geq 120$ ksi√in.
- Recommendation:
  - Accept use of 316L weld metal at all temperatures without toughness testing, provided:
    - ASME Section IX qualified welders and welds
    - GTAW, SMAW, FCAW, SAW processes are used
    - 100% UT inspection of welds
    - Leak testing is performed on all welds
    - Stress not to exceed 16.7 ksi
    - Pipe size not to exceed 10 inch IPS.
    - Pipe wall not to exceed maximum schedule specified in ASME B36.19.

- Basis:
  - Successful history of austenitic stainless steels in LH2 and LHe service.
  - Analysis of sample cases (CGA examples) at allowable stress, with comparison of damage tolerance based critical stress values to a highly conservative toughness value (99% exceedance with 95% confidence). (This does not include a cyclic analysis.)
  - 33 independent data sets representing the recommended welding processes provided the basis for the toughness values presented.

Backup and Slides from Previous Presentation

Minimums from Each Weldment



Project 173 - 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 (1 weld), and GTAW root with FCAW fill and cover (3 welds)
  - 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.

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

52.8 ksi√in

2. Data from only Read

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

- **35.1 ksi√in**

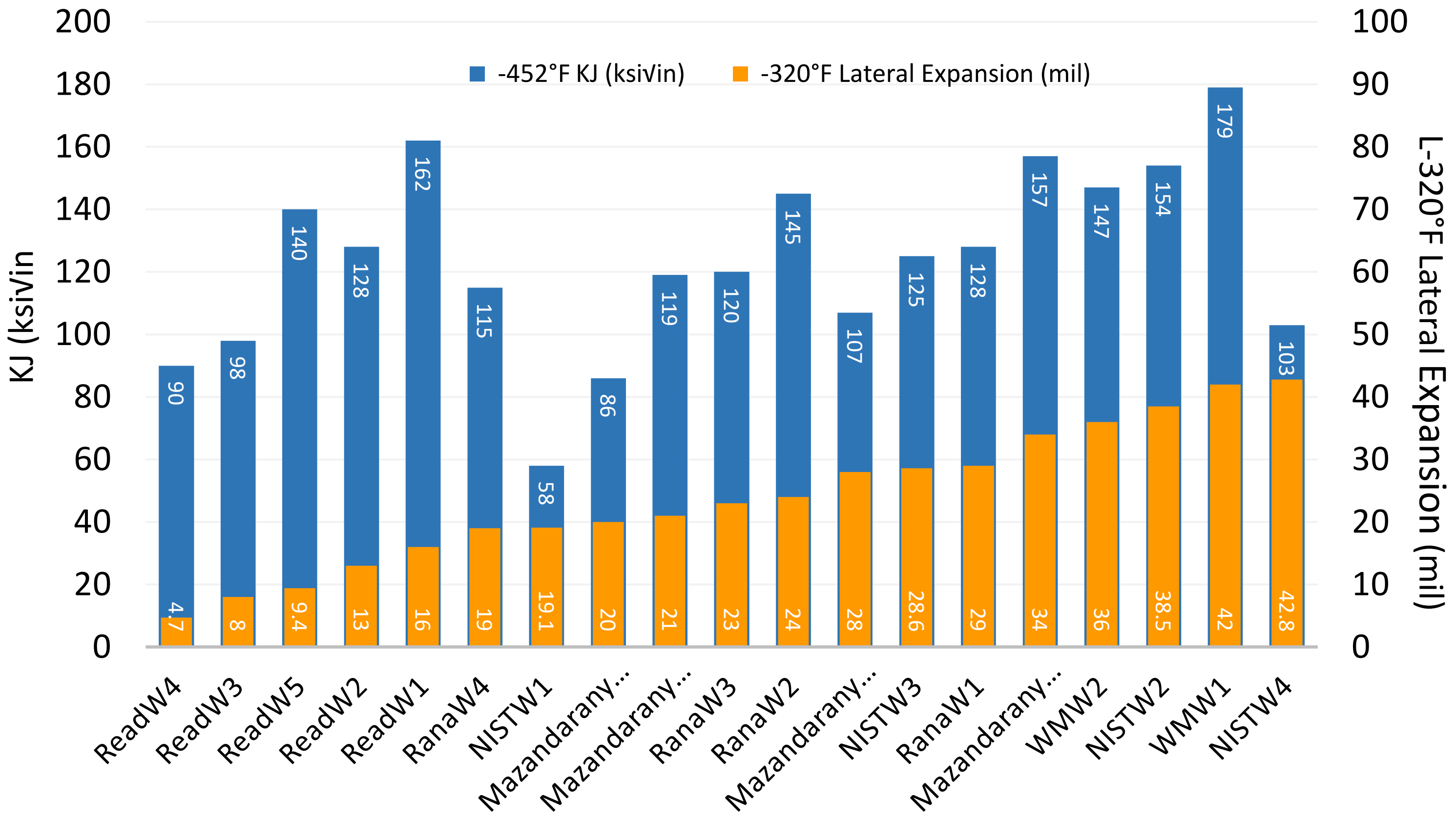
2. Data from only Read

- **9.02 ksi√in**

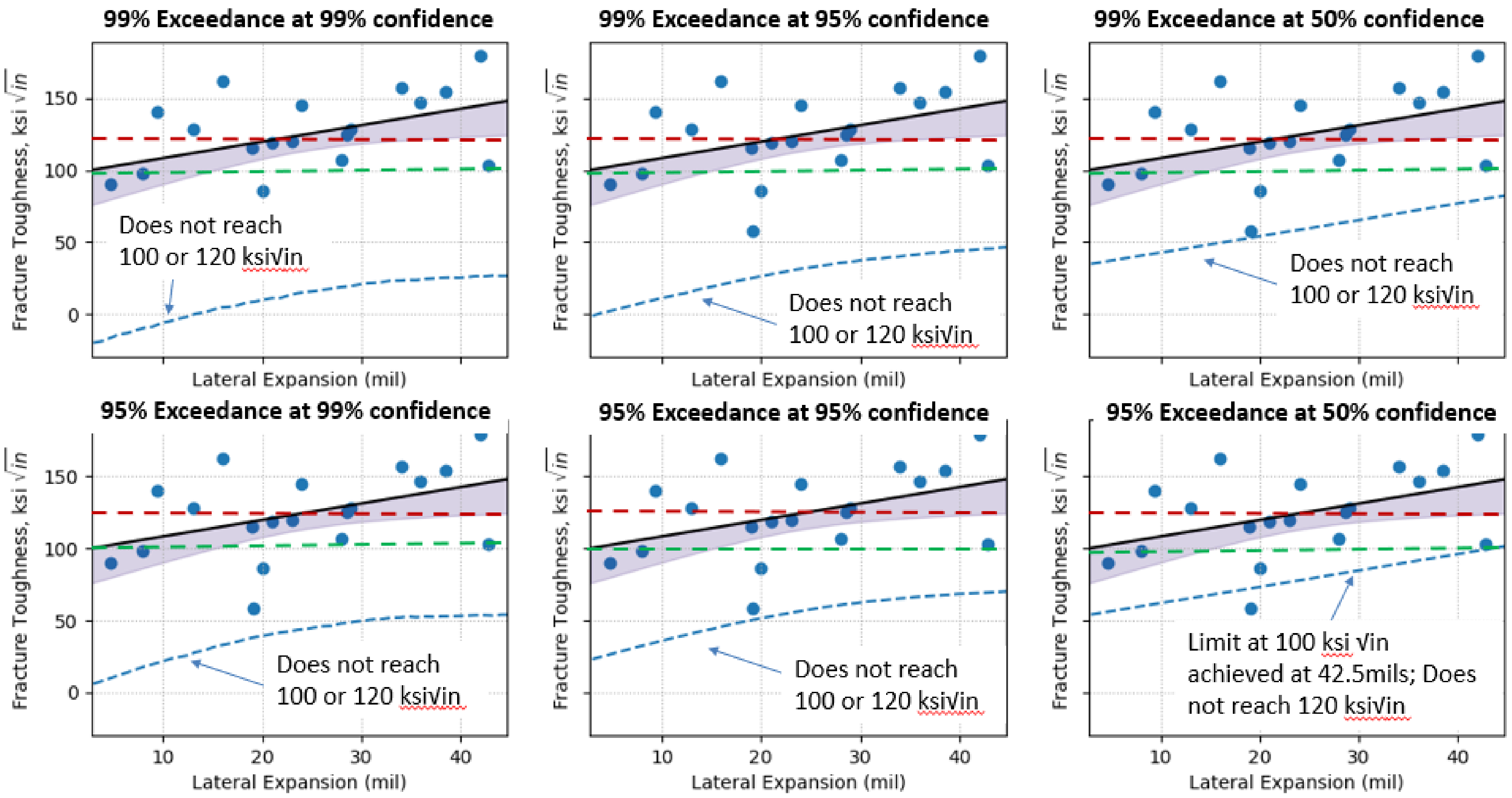
Are There Other Possible Solutions?

- 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.

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



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



Note: No amount of LE correlates with 120ksi√in with reasonable confidence level.

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

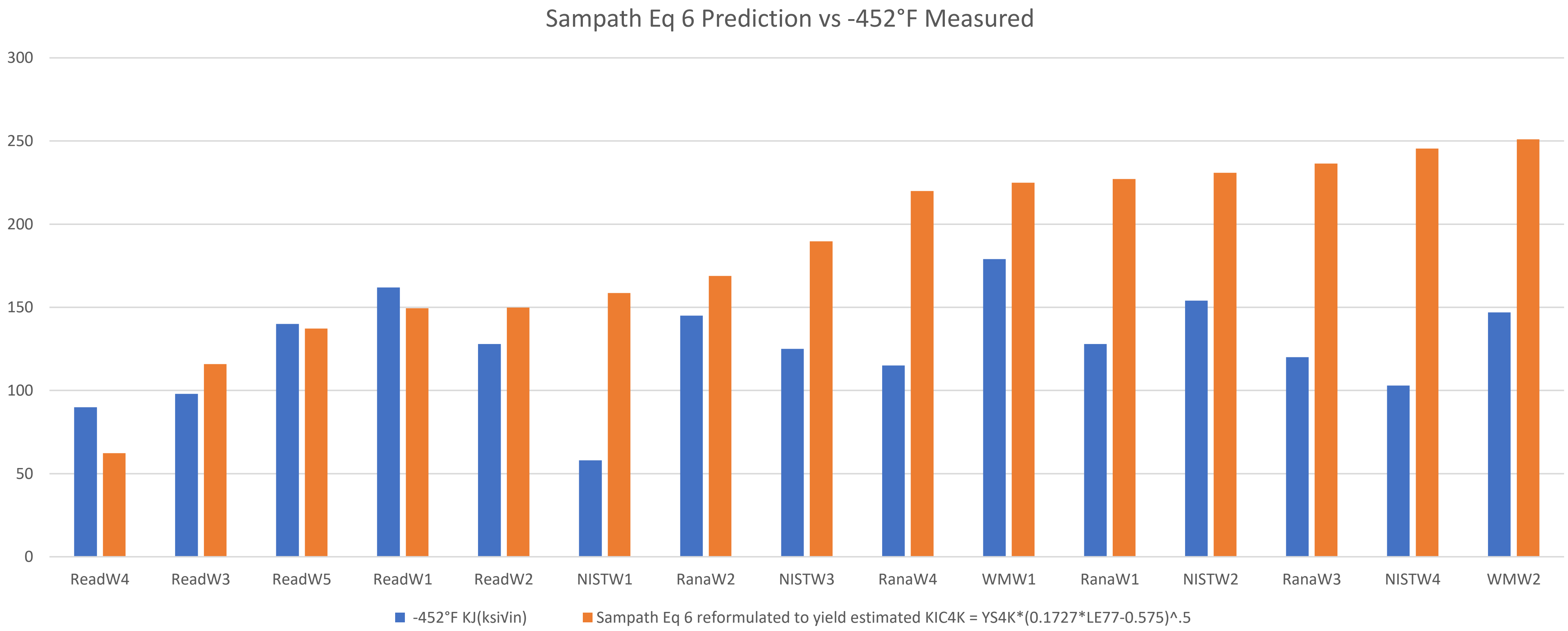
- Sampath, in his 2017 paper *A Reaffirmation of Fracture Toughness Requirements for ASME Section VIII Vessels for Service Temperatures Colder than 77K* proposed a formula for predicting -320°F LE based on -452°F K_{JIc}. The value of the formula, if it works, is of course allowing the use of -320°F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

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

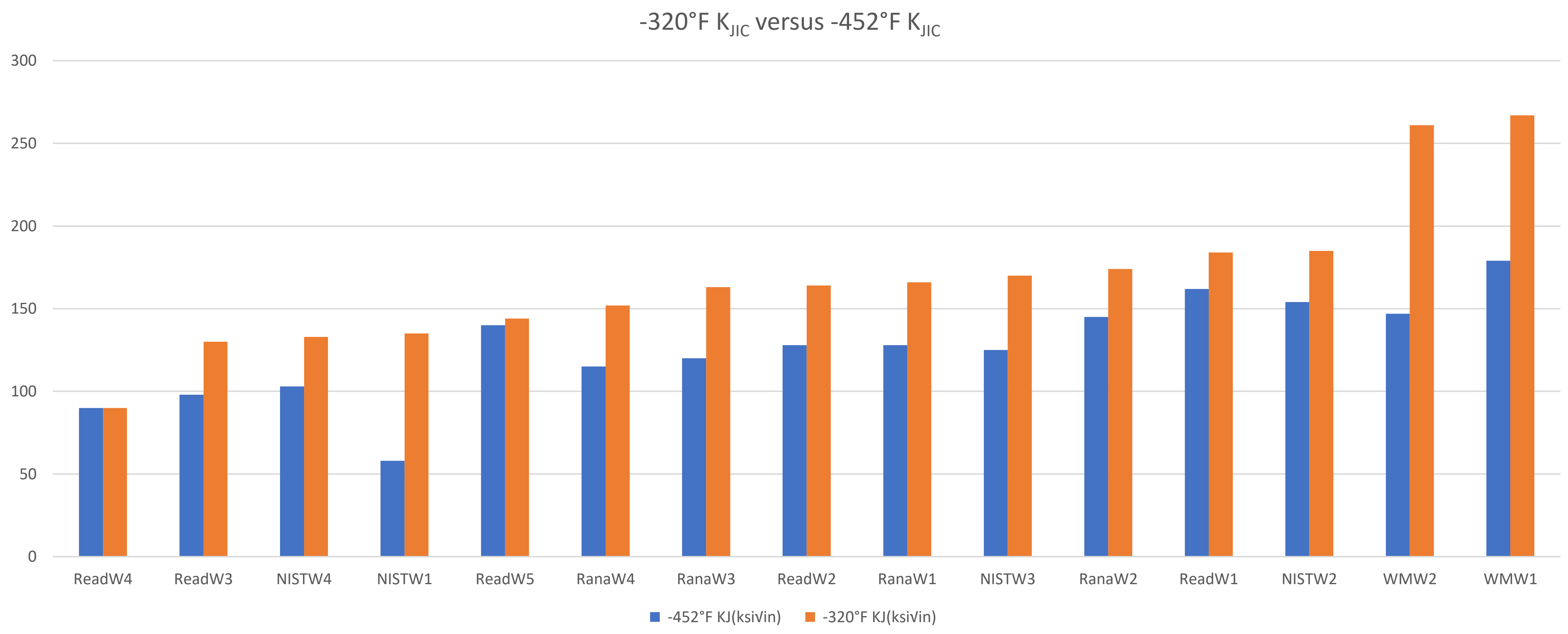
- Which transposes to the formula used for predictions on the following two charts:

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

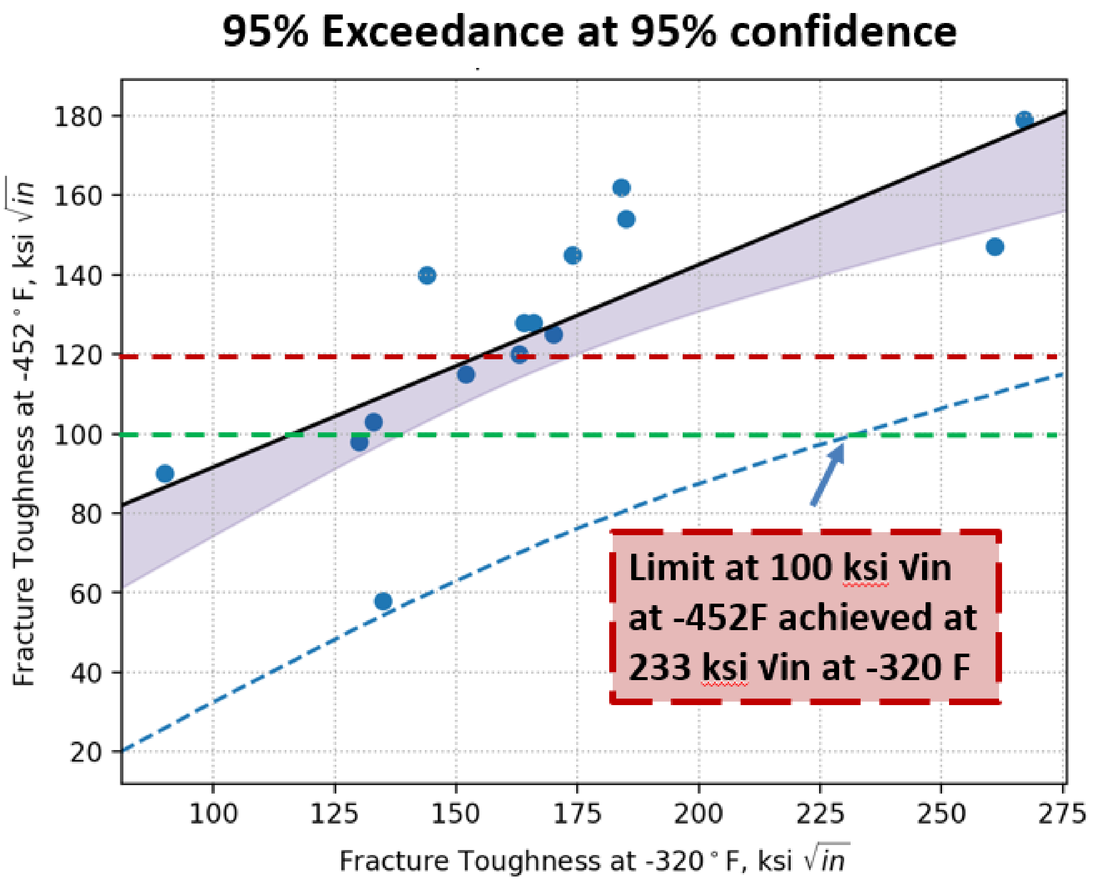
Sampath Eq 6 Prediction vs -452°F Measured All Data (K_{JIC})



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



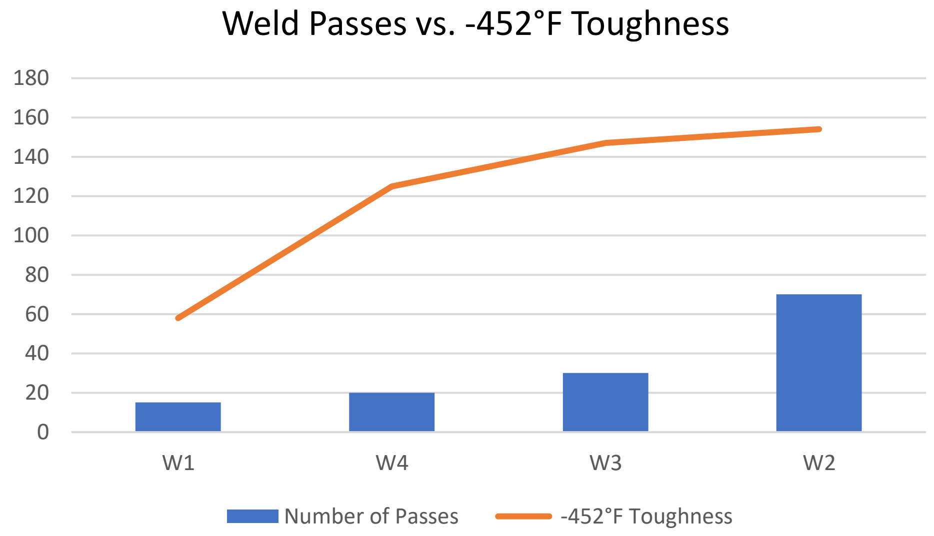
Predicting -452°F K_{JIC} from -320°F K_{JIC}



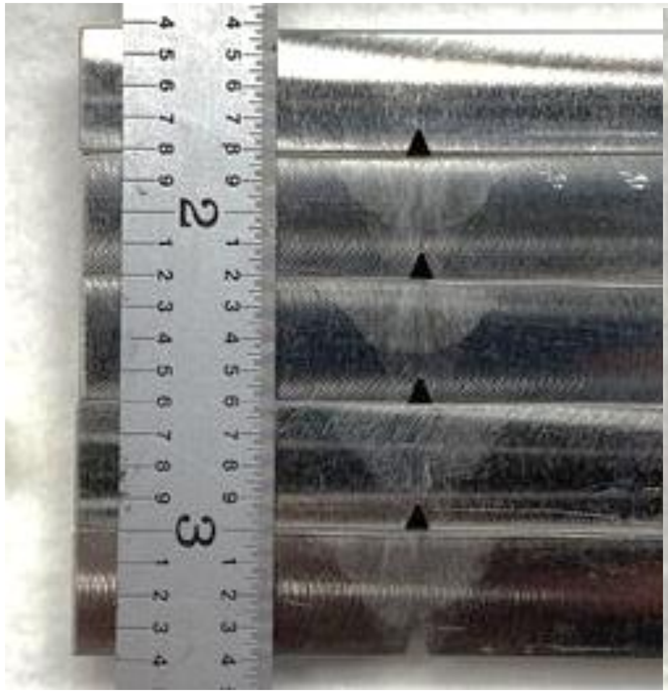
ASTM E1820 K_{JIC} testing at -320°F can be used to predict K_{JIC} -452°F, but a value of 233 ksi√in at -320°F only leads to 100 ksi√in at -452°F.

Weld Practices

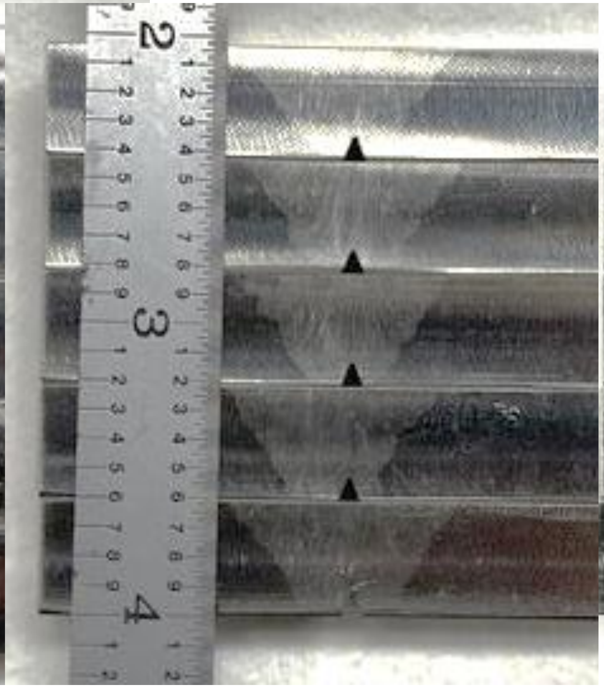
- All fabricator's overall weld configurations were essentially the same: V-Groove approximately ¾ wide at the top, GTAW root, fill and cover with either GTAW or FCAW.
- Estimated number of weld passes and measured toughness:
  - Weld # Passes KJIC$_{-452°F}$
  - W-2 50-70 154
  - W-3 30 147
  - W-4 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.



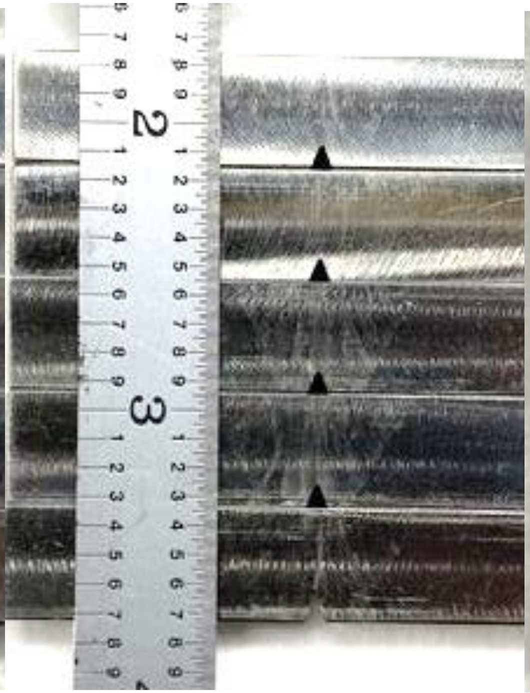
Weld Cross Sections



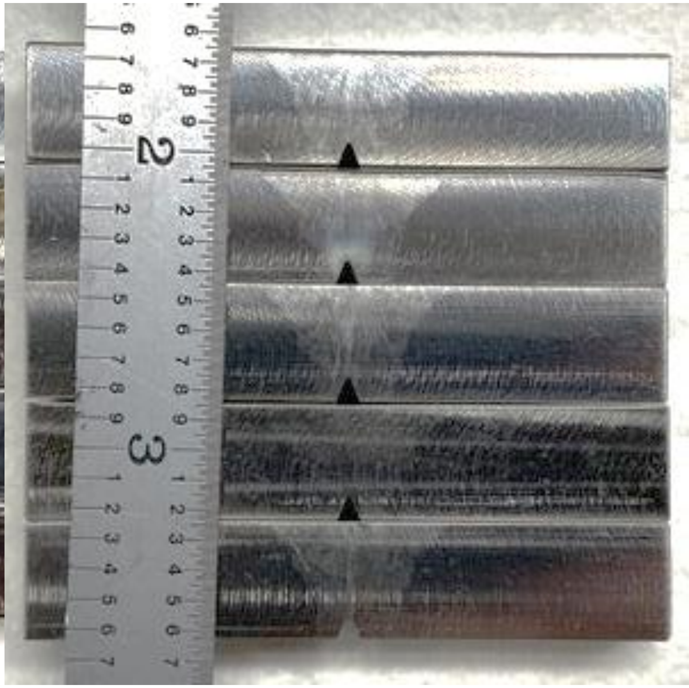
W1



W2



W3



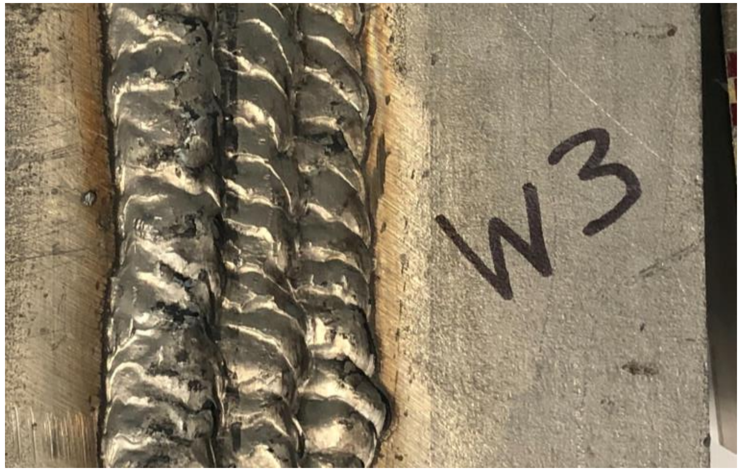
W4

Image source: NIST

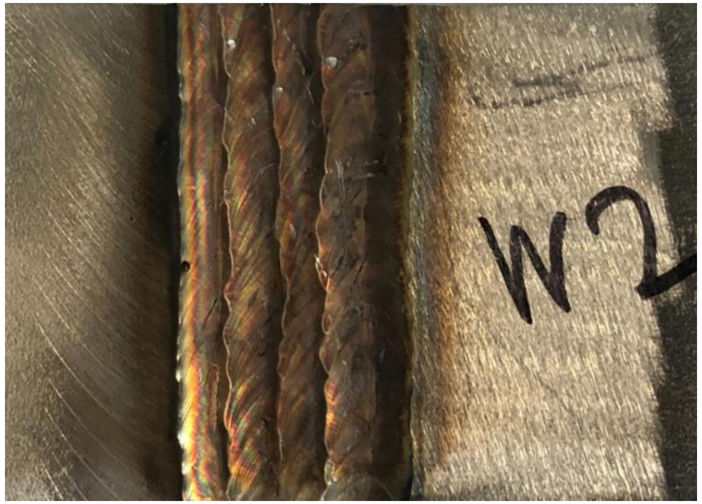
Weld Practice Effects on Fracture Toughness

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

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



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



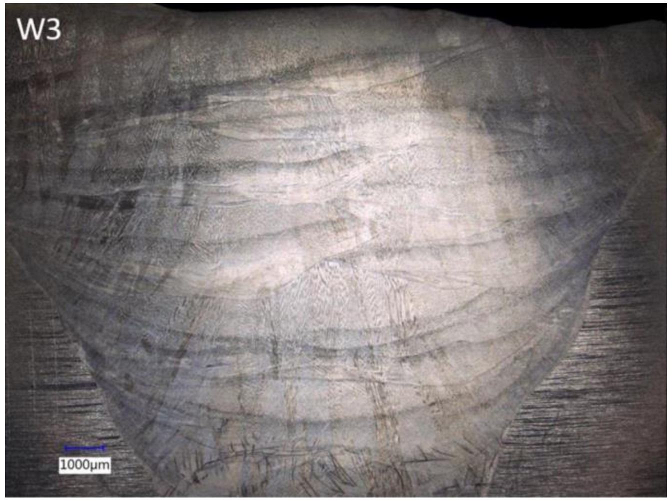
W2:
Root: GTAW
Cover: GTAW
$KJ_{-452^{\circ}F}$: 154.2ksi√in

Image source: NIST

Weld Cross Sections

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

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



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

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

Image source: NIST

Reduction in Allowable Stress

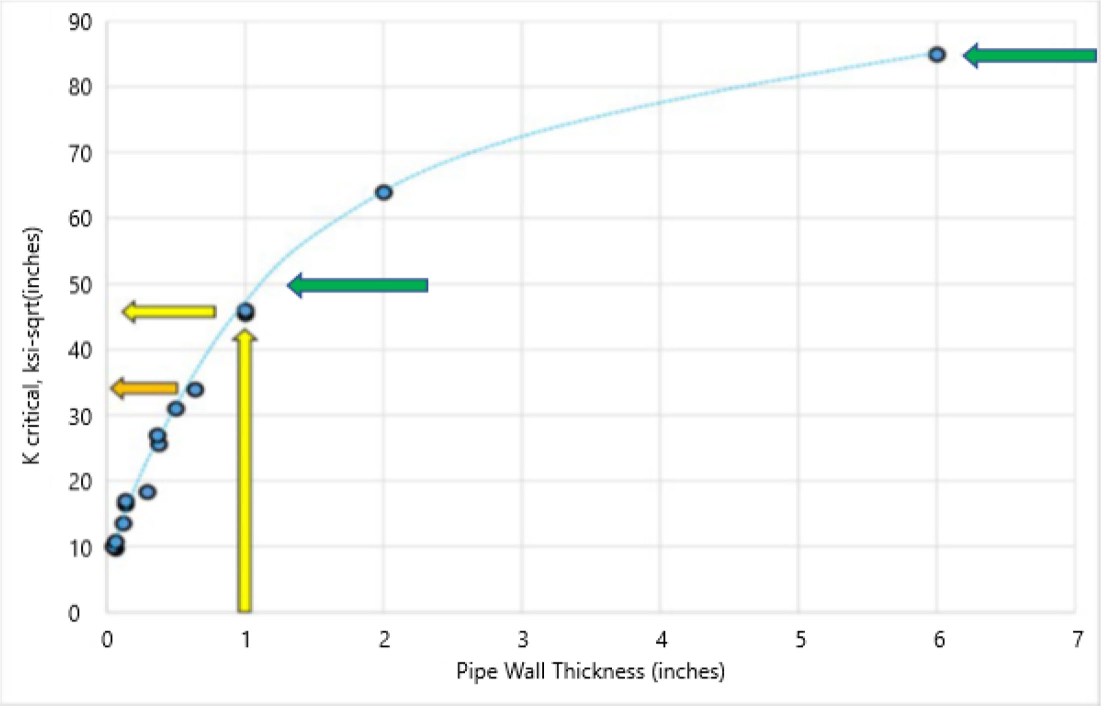
- Without testing, the 316L can be expected to exceed 50 ksi√in with 95/95 confidence
- 316L material is an inherently tough material
- Most piping systems built for service in LH2 or LHe apparently are designed with relatively low hoop stresses. System examples in CGA letter of concern had maximum stress 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 Examples

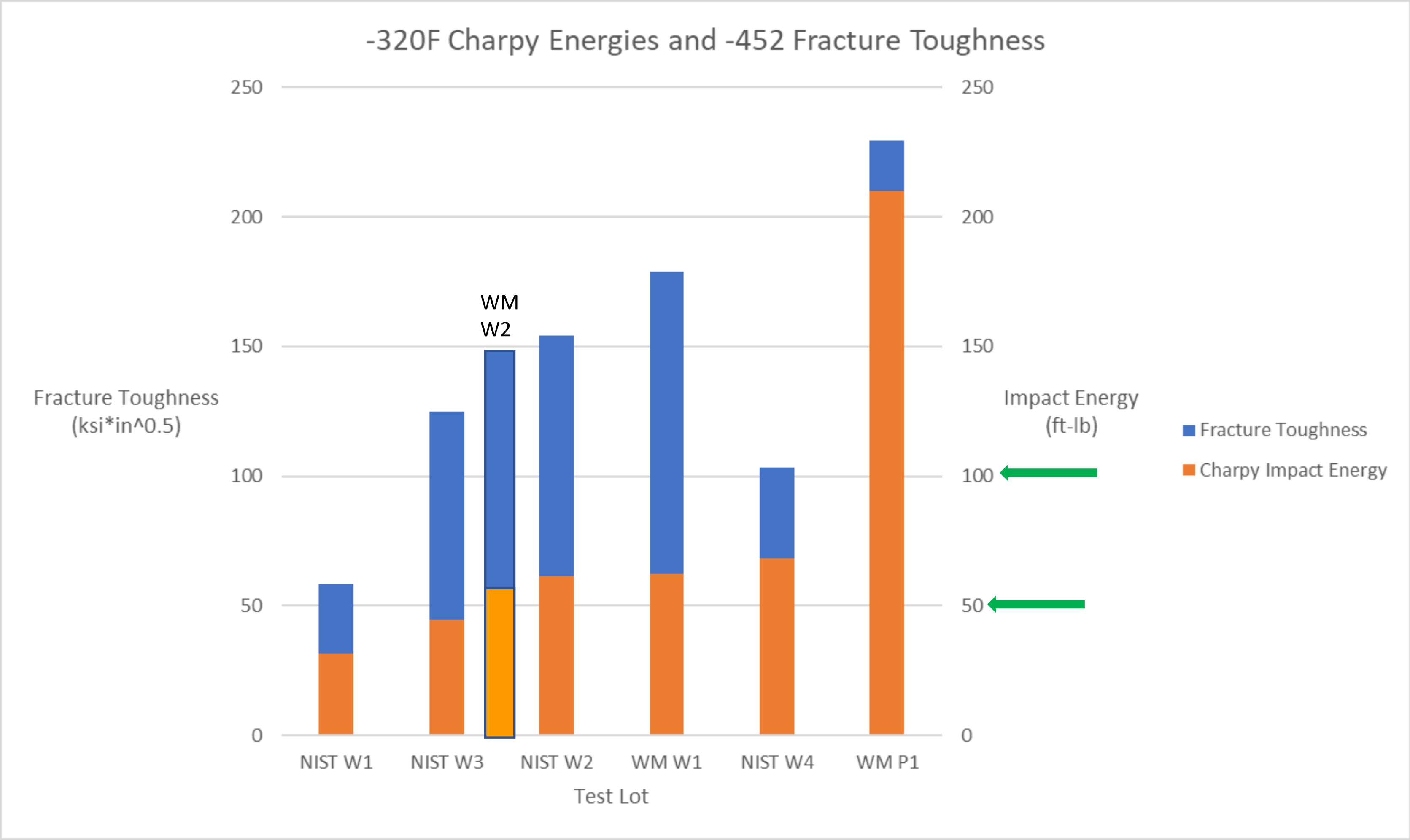
- CGA Letter of November 16, 2015 expressed concern regarding addition of a requirement for toughness testing at ultra-low temperature. It provided seventy-seven examples of systems operating successfully at a temperature of either -452°F or -425°F without toughness testing. All were 304 or 304L material.
- 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

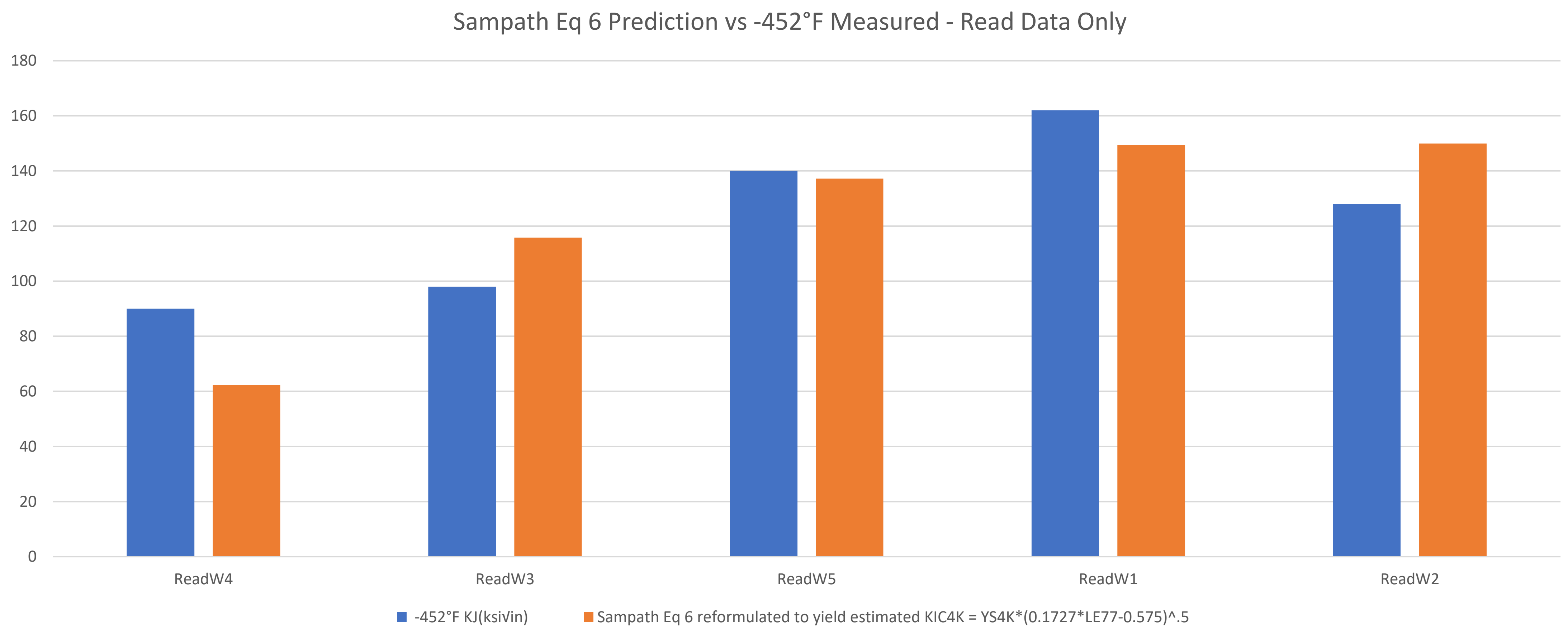
- The chart below shows critical fracture toughness versus pipe wall thickness (Lambert). Yellow arrow indicates required toughness (46 ksi*in^.5) at 1 inch wall thickness (with no safety factor on toughness, but with 30 ksi residual stress added to the calculated hoop stress). Thickest wall in CGA survey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



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

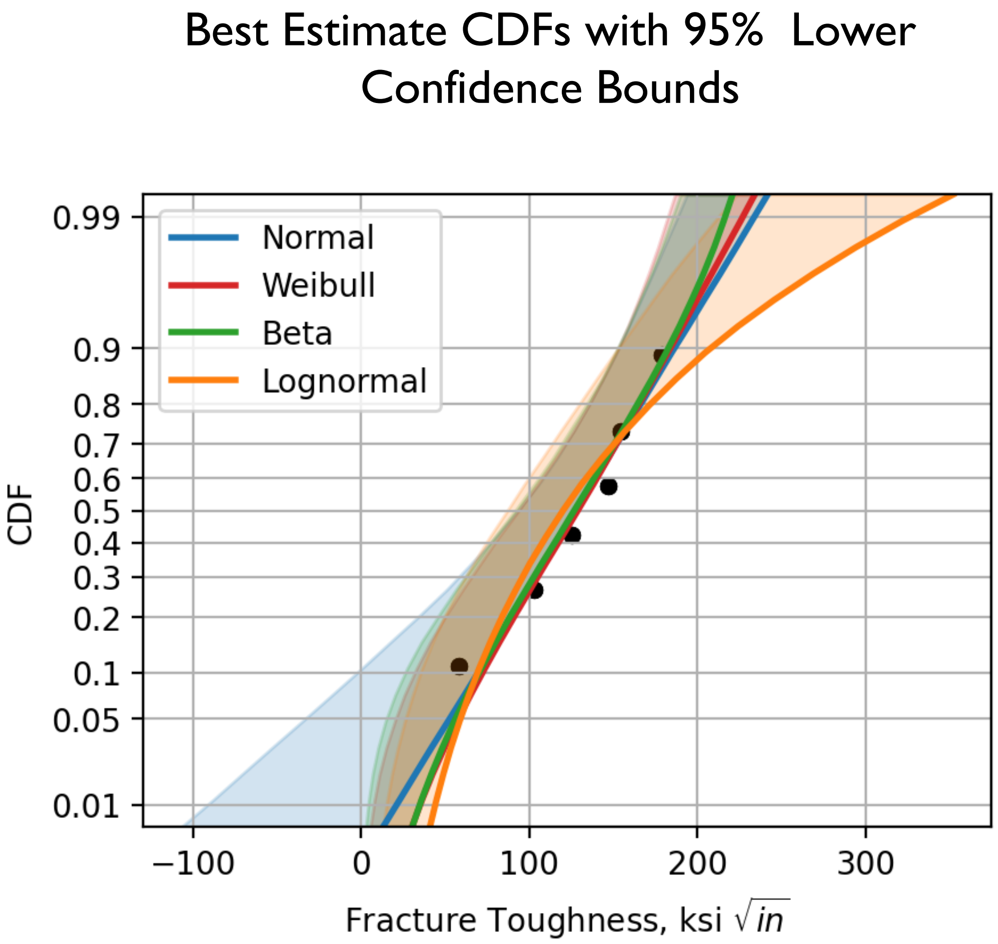


Sampath Eq 6 Prediction vs. Only -452°F Measured Data from Read

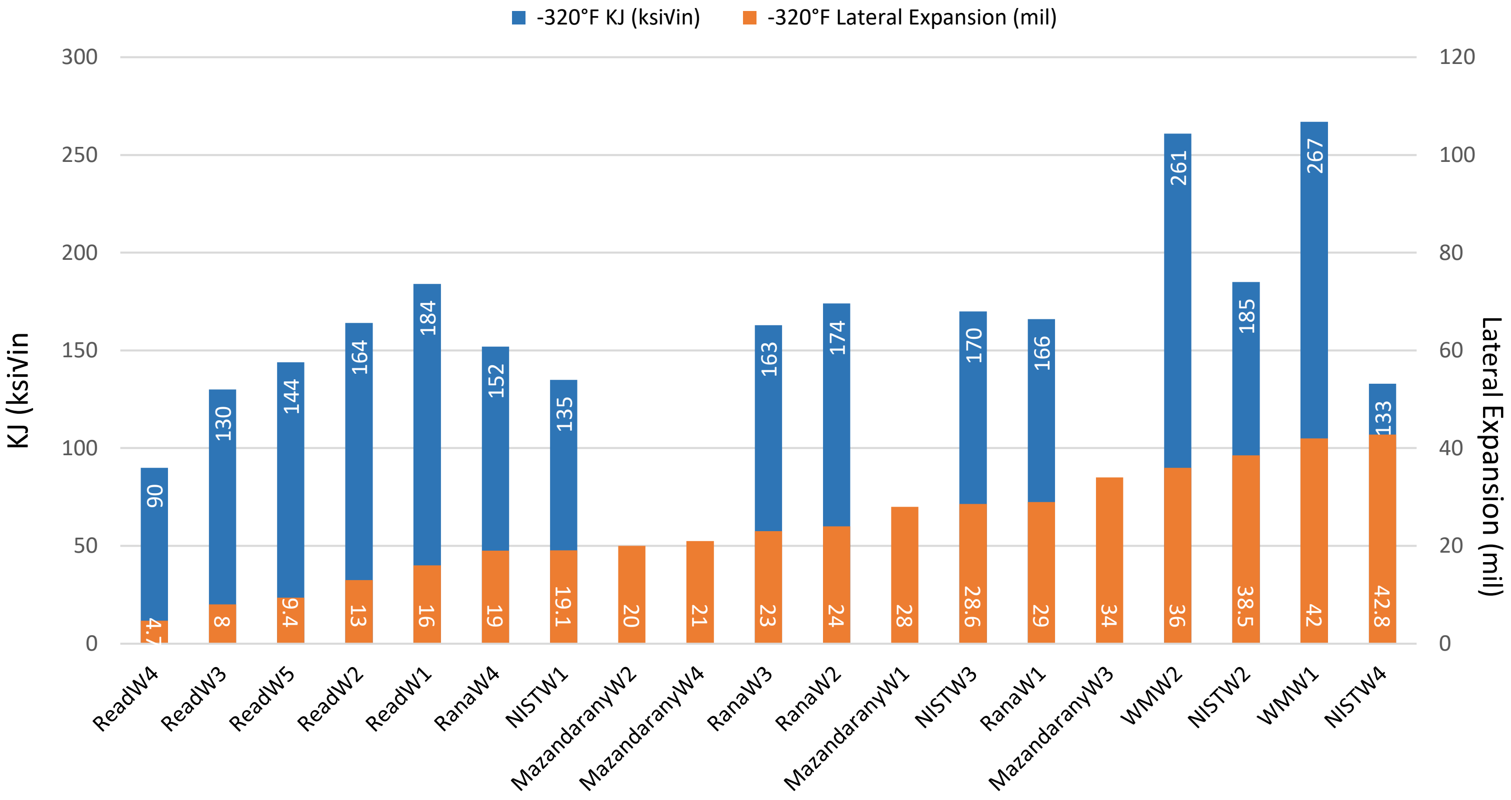


Choosing a Distribution Type

- 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

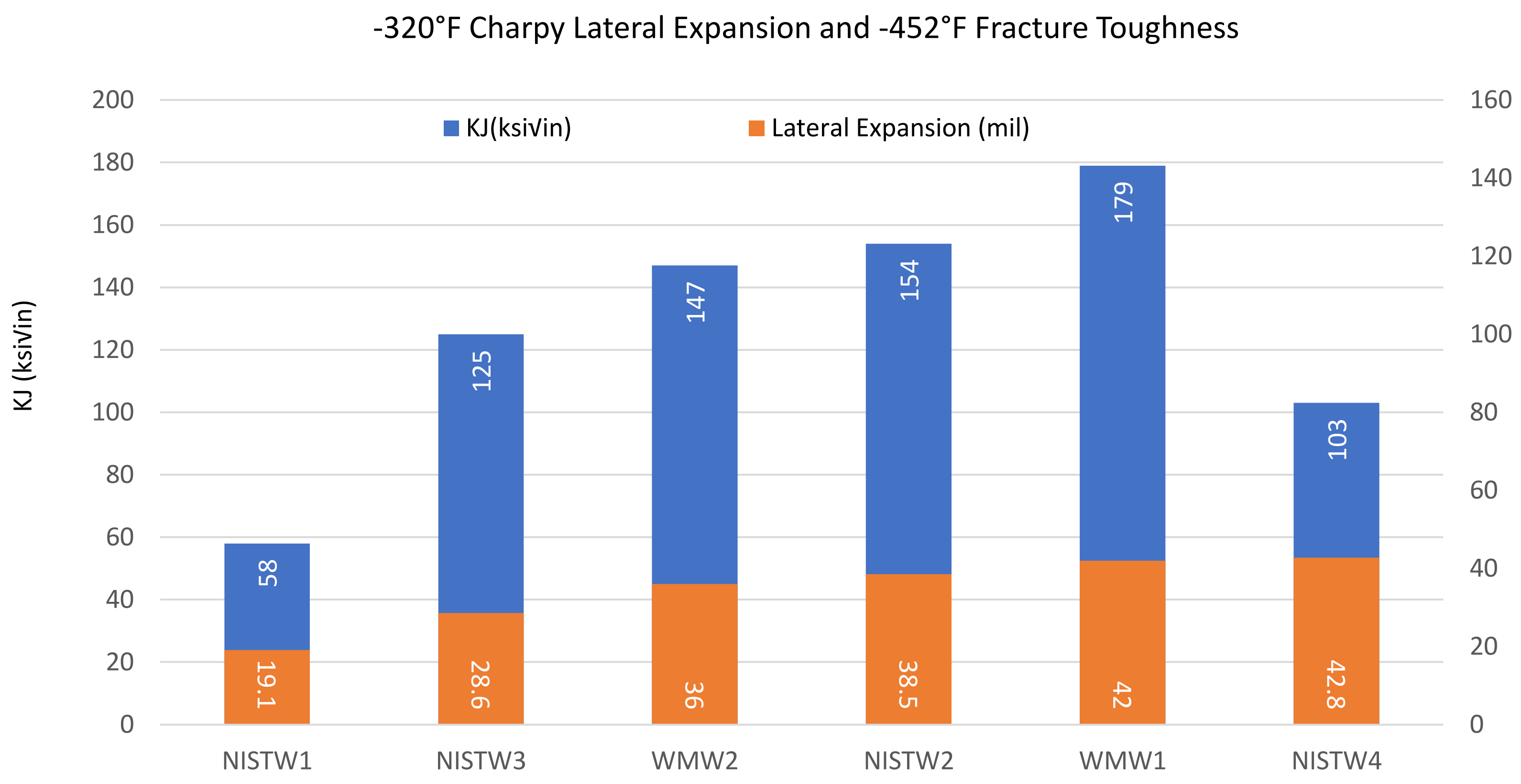


-320°F Charpy Lateral Expansion and -320°F Fracture Toughness – All Data



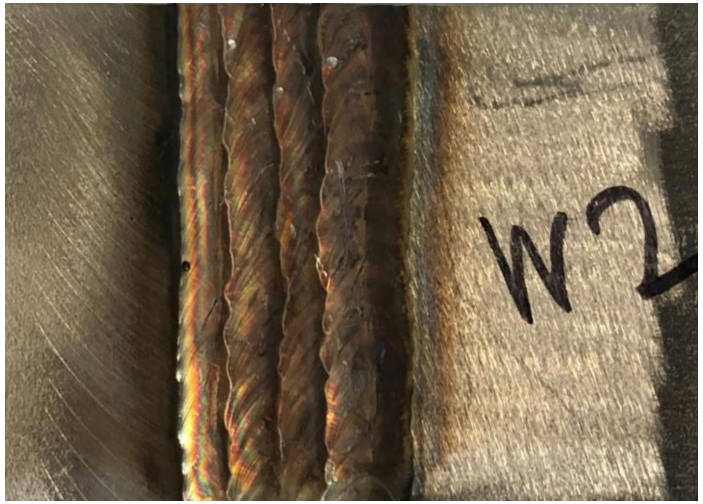
Note: Toughness data not available at -320°F for Mazandarany samples

-320°F Charpy Lateral Expansion and -452°F Fracture Toughness – Project 157 & 173 Data



Fracture Surface Comparison

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



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

Rana Conclusions

Conclusions

1 The test data indicate that the correlation between the fracture toughness and CVN LE 77K is reasonably accurate for 316L stainless steel welds. The correlation between 4K fracture toughness and 77K CVN LE is not accurate.

2 Recommendations have been provided to revise the ASME Section VIII, Div. 1 and Div. 2 Codes on CVN LE requirement for MDMT colder than 77K with additional restrictions.

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.