REX2024
PRCI Research Exchange

"Pragmatic Application of MegaRule RIN 1 - 192.712 Toughness Values"

A Summary of PRCI IM-1-8

Dr. Gery M. Wilkowski
San Diego, California
February 28, 2024

PRCI project team members:

1. *TC Energy* — *Munendra Tomar (team leader), and Shenwei Zhang*
2. *Kinder-Morgan* — *Yohann Miglis*
3. *Williams* — *Sean Moran*
4. *ExxonMobil* — *Jing Ma*
5. *Energy Transfer* — *Brian Jimenez*
6. *Enbridge* — *Lyndon Lamborn*
7. *Boardwalk* — *Rodney Clayton*

PRCI LEADING PIPELINE RESEARCH
Pipeline Research Council International

Summary of PRCI IM-1-8 - "Pragmatic Application of MegaRule RIN 1 - 192.712 Toughness Values"

- Objective of project was to establish pragmatic guidance to DOT/PHMSA given Charpy energy values at the operating temperature if data is not available.

- The MegaRule CFR192.712 default Charpy energy values

	CVN for pipelines without PHMSA Reportable Incident (ft-lbs)	CVN for pipelines with PHMSA Reportable Incident (ft-lbs)
Pipe Body	13	5
Seam	4	1

  - No shear area values given, and need to assume some Charpy specimen size (not stated)

Approach

- **Maintain the MegaRule CFR192.712 default Charpy energy values, but *recognize that Charpy energy at temperature can be very conservative estimate of the material toughness for a surface-cracked pipe.***

- **Key step - utilized a 2005 procedure called "Master Curves of Fracture Transition Temperatures" that determines the lowest temperature for ductile initiation of surface- and through-wall-cracked pipe relative to the Charpy 85% shear area transition temperature (SATT)**
  - If ductile initiation occurs, then the Charpy plateau energy is used to estimate the toughness for burst pressure predictions. This is the constraint effect on transition temperatures.
  - Axial surface-cracked pipe can have ductile initiation at ~200F lower than the Charpy 85% SATT!
  - Possible to have 1 ft-lb of Charpy energy, but the burst pressure would correspond to the Charpy upper-shelf energy at that temperature.

Accomplishments

- **Several key technical breakthroughs;**
  - Upper-shelf toughness constraint correlations,
  - Transition temperature constraint shifts from Charpy or C(T) specimens to surface-cracked pipe burst pressure, and
  - New cleavage-fracture Reference Toughness curve and constraint shift for low CVP welds.

- **Compiled databases of Charpy and fracture toughness specimen tests with line-pipe materials from PRCI members and Emc^2 files. ~25,000 Charpy tests, ~2,000 fracture specimen tests**

- **Determined that there are 3 Material Categories:**
  - Material Category 1 – Cracks in base metals – showed these have very low transition temperatures, so *use CVP or upper-shelf toughness to predict burst pressure*
  - Material Category 2 – Cracks in welds that will have ductile initiation at the operating temperature. Example; HF-ERW, post-1970 DSAW; but many cases of vintage weld also passed screening criterion. *Can use CVP or upper-shelf toughness to predict burst pressure*
  - Material Category 3 – Cracks in welds that will have brittle initiation – some vintage EFW, LF-ERW, d-c ERW, DSAW may be in this category. *Need cleavage initiation toughness.*

Accomplishments

- **Further broke down the Levels of Analysis (flow charts developed)**
  - **Level 1 analysis** – user has no data on the pipeline material
    - Conservative. Used statical evaluations of member and Emc[2] data to show some manufacturers and vintages that fall into different material categories – update with time
    - If 90% of the material had higher toughness, then used that value for the case when no past failure
    - If 98% of the material had higher toughness, then used that value for the case for when past failures
  - **Level 2 analysis** is when the operator has Charpy data on the line of interest
  - **Level 3 analysis** is when the operator has fracture toughness test specimen data on the line of interest
- **Before reviewing guidelines, need to go over some key technical aspects so you understand the guidelines**

There is no such thing as a "True Fracture Toughness" (Important for Level 1, 2, and 3)

- **But the fracture toughness value of interest (i.e., for a surface-cracked pipe) can be determined from different constraint relationships**
  - Transition temperature changes with constraint – determined from the MC-FTT, *hugest factor*
    - Can use Charpy transition temperature as a reference temperature; or C(T), or SEN(B), or SEN(T)
    - Surface cracked pipe has similar transition temperatures to SEN(T) specimens (fcn of a/t)
  - Upper-shelf toughness changes with many constraint parameters
    - Charpy plateau energy is empirical reference energy measurement
    - CVP is related to C(T) or SEN(B) specimen J_{Ic} value – depends on specimen size (standard W/B=2; a/w=0.5)
    - C(T) related to SEN(T) J_{Ic} values – but function of a/t of the surface crack a/t
  - Lower-shelf toughness required development of new Material-Specific Reference Toughness Curve
    - Similar to Master Curve or ASME Reference toughness curve; but CVP is so low for some welds that needed new definition of the reference temperatures – which from MC-FTT
    - Lower-shelf toughness changes with constraint too – curve for surface cracks shifts from MC-FTT and upper-shelf toughness

Understanding Transition Temperature Changes with Constraint (Important for Level 1, 2, and 3)

- **Master Curves of Fracture Transition Temperatures (MC-FTT) determine lowest temperature for ductile initiation – *Constraint effect on transition temperatures***
  - Reference transition temperature used was 85% SATT of full-size Charpy Specimen
  - Statistical curve shapes of Charpy SA% versus temperature if data only at one temperature
    - Need to predict temperature where 85% SA occurs
  - Statistical relationship of 85% SATT with different specimen sizes to full-size specimen
    - Need full-size 85% SATT for MC-FTT
    - Vintage pipe too thin for full-size specimens; some databases used at thick of CVN as possible- ~80 sizes
  - Weld metals different than base metal in SA% versus temperature curves

- **Let's look at a few important examples**

Master Curves of Fracture Transition Temperatures (MC-FTT)

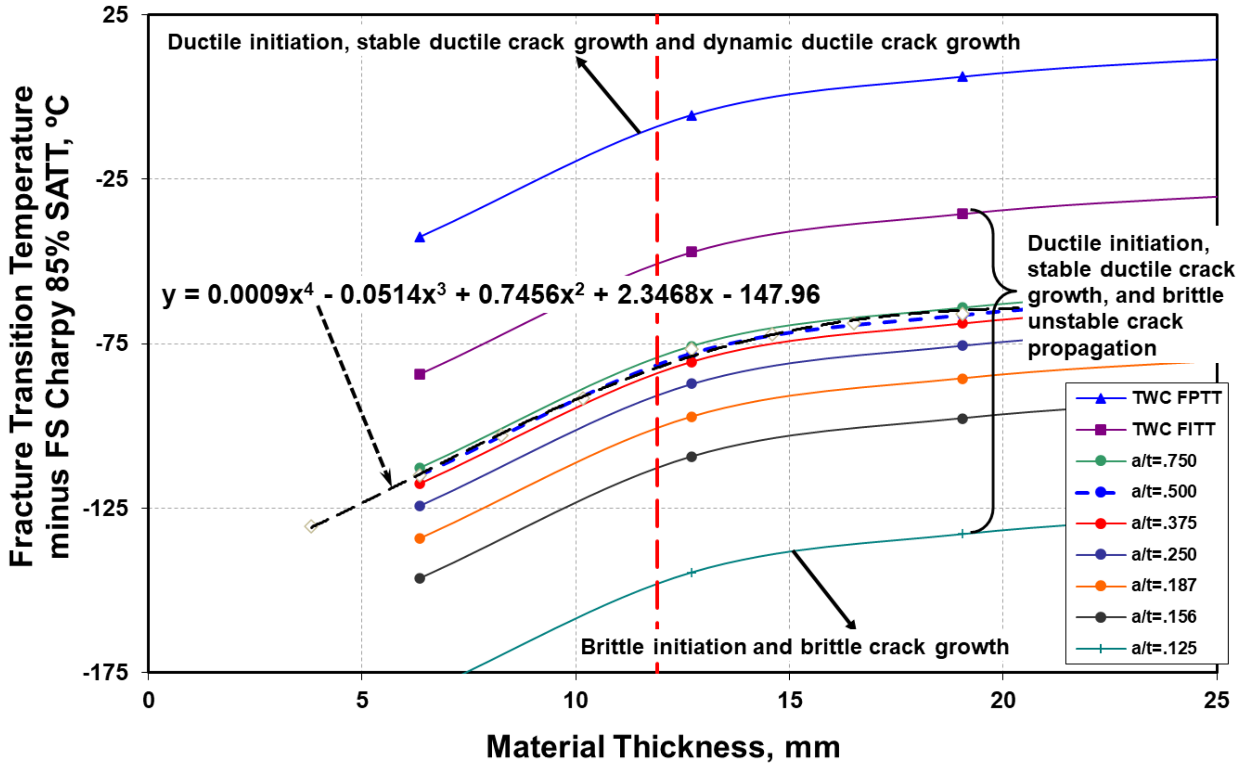
- **MC-FTT determines lowest temperature for ductile initiation – *Constraint effect on transition temperatures***
  - 1st published in 2005PVP (5 other publications since) – also in 2006 PRCI project
  - Technical basis for cleavage fracture temperature of ferritic nuclear pipe in ASME Section XI
  - Applicable for vintage pipeline materials, but trans. temp. of steel with >215J of CVP in error
  - Determines the lowest temperature for ductile initiation for through-wall or surface-cracked pipes –
    - If above this temperature use ductile fracture toughness,
    - If below this temperature go to the cleavage-fracture Reference Toughness curve
  - Together MC-FTT and the cleavage-fracture Reference Toughness (or Master Curve) are very compatible and provide powerful tools for this project, as shown later
  - MC-FTT initially used to understand why SC'ed pipe has much lower transition temperatures
    - Useful in understanding changes in L-R boundary too!

Master Curves of Fracture Transition Temperatures (MC-FTT) (Important for All Levels)

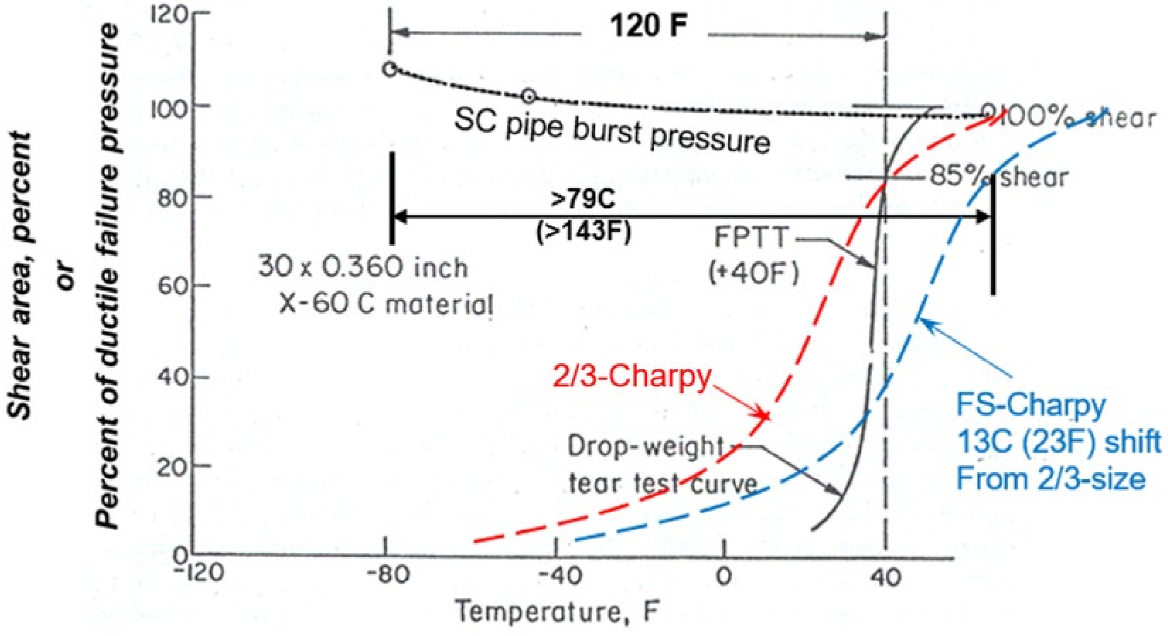
- **Upper curve for ductile initiation and dynamic crack propagation of TWC**
  - Design temperature region for modern high-energy pipelines; upper curve from valid DWTT testing

- **2nd curve from top is ductile initiation of TWC, will have brittle propagation if below upper curve**
  - If below this curve, then Leak-Rupture boundary of SC changes!
  - *TWC trans. temp ~ same as SEN(B) or C(T)*

- **Lower curves for surface cracks – fcn (a/t)**
  - SC transition temperature ~ same as SEN(T)
  - If a/t > 0.375 have about the same trans. temp.
  - Shallower flaws have lower trans. temps.
  - If below these curves, then use the Reference Toughness curve for cleavage initiation.
  - Used the more conservative deeper SC transition temperature relationship with thickness for Level 1

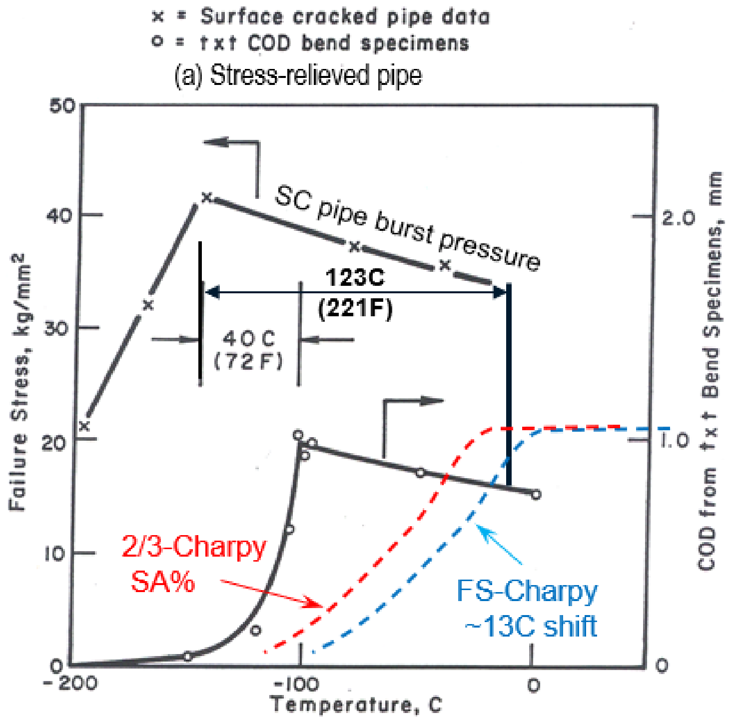


Examples of Full-Scale Pipe Tests – (Many other examples) Axial Surface Cracks in Base Metals



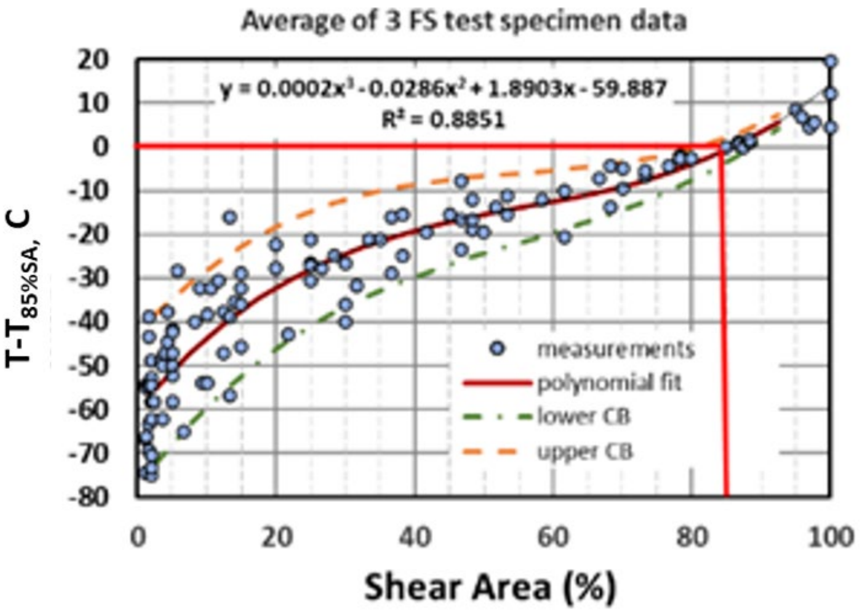
- **Kiefner 1969 (NG-18 data); 30” by 0.360” X60**
  - MC-FTT predicted SC-FITT to be 97C below FS CVN
  - Note CVN ~ 1 ft-lb with burst pressure still high

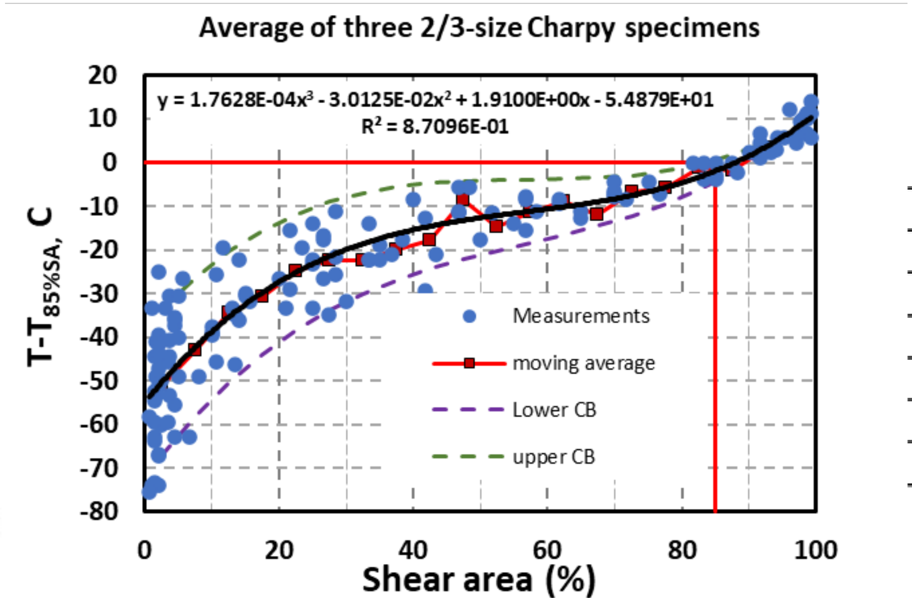
- **Sugie 1977 (Kawasaki Steel) 24” by 0.375” data**
  - MC-FTT predicted SC-FITT to be 90C below FS CVN (conservative by 33C)
  - Note SC FITT below bend specimen; CVN ~ 1 ft-lb at burst pressure transition temperature

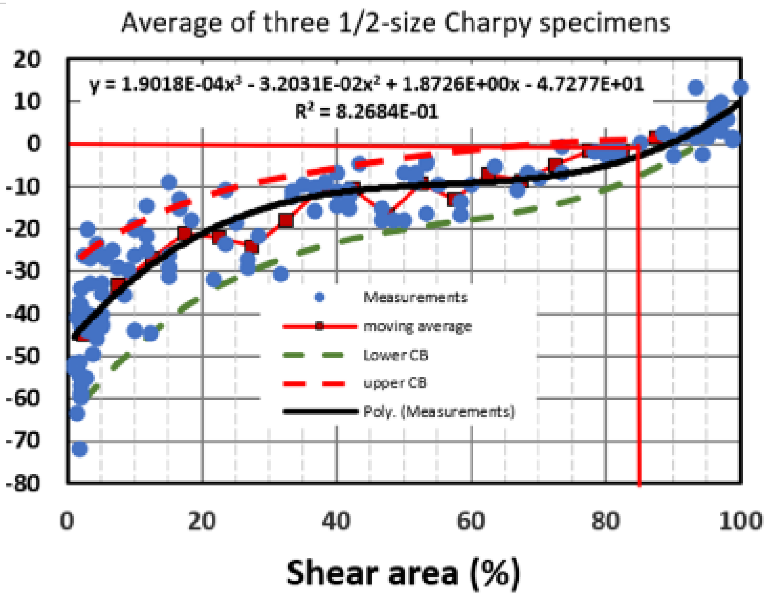


Understanding Transition Temperature Changes with Constraint (Important for Levels 1 and 2)

- **To use the Master Curves of Fracture Transition Temperatures (MC-FTT) established statistical curve shapes of Charpy SA% versus temperature if data only at one temperature**
  - Need to predict temperature where 85% SA occurs
  - Good 1970 ASTM round-robin (vintage) base metal data – ~2,000 Charpy tests on 24 heats, 3 specimen sizes per heat, 12 temperatures, triplicate specimens - Very carefully analyzed.

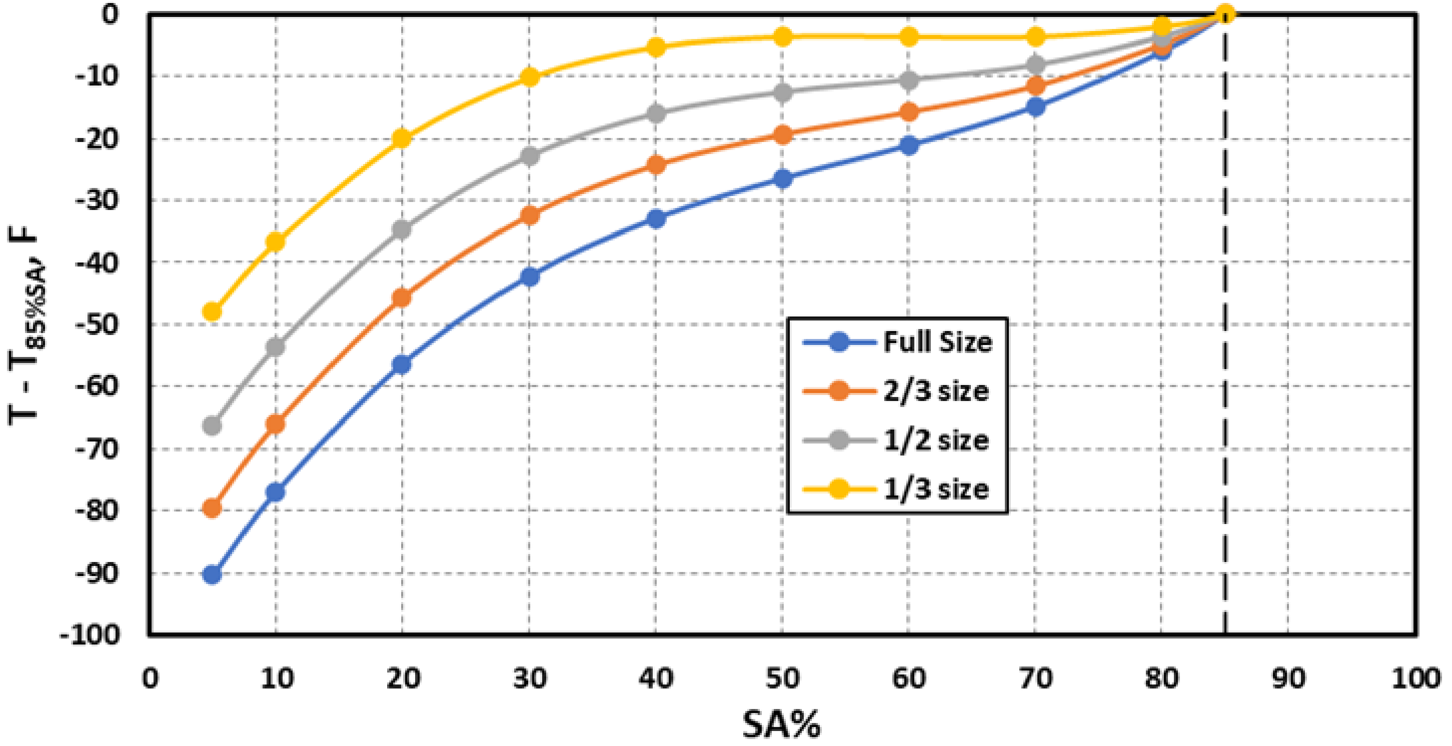






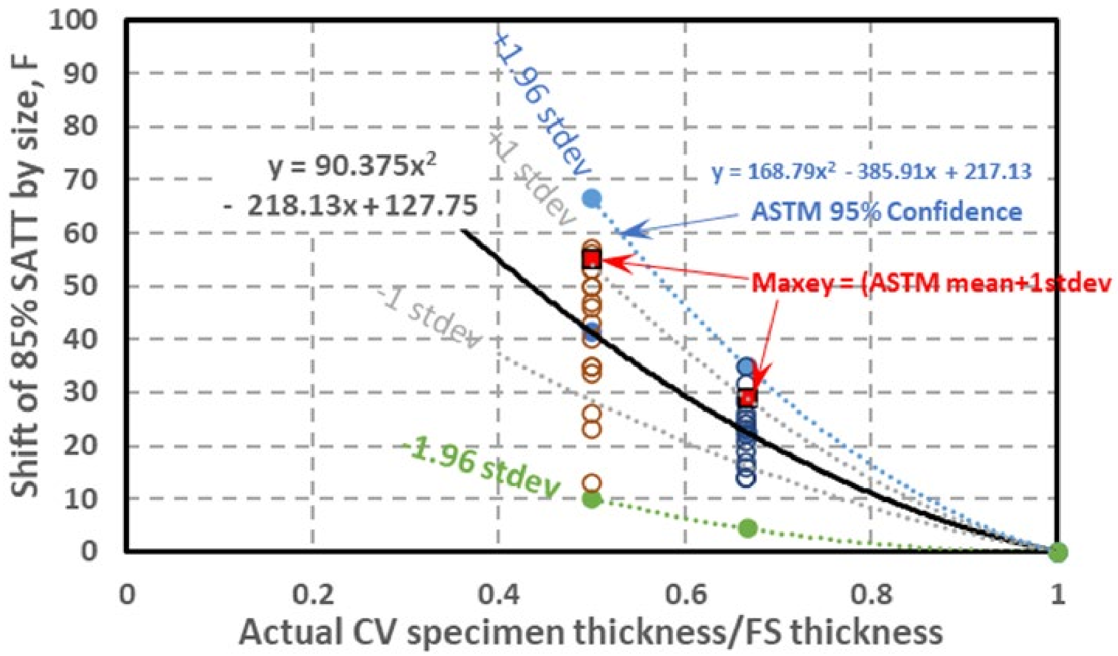
Understanding Transition Temperature Changes with Constraint (Important for Levels 1 and 2)

- **Good 1970 ASTM round-robin base metal data**
- **Trends to predict 85% SATT given SA% at one temperature**
  - General equation developed for any thickness specimens, so could go into any database with different specimen sizes (lots of coefficients in the equations, but easy in Excel)



Understanding Transition Temperature Changes with Constraint (Important for Levels 1 and 2)

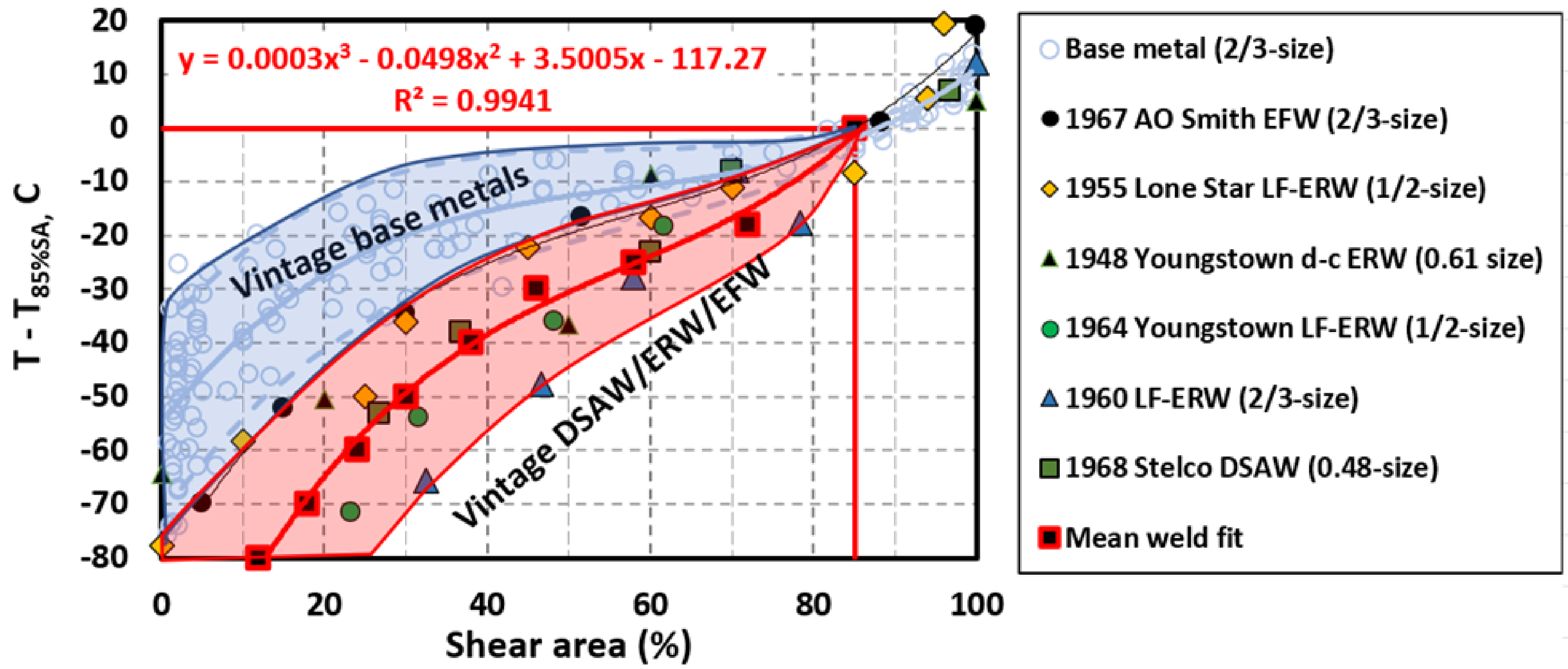
- **Good 1970 ASTM round-robin base metal data**
- **But need to predict Full-Size Charpy 85% SATT to use the MC-FTT**
  - So sub-size to full-size transition temperature shift from same data set established
  - Maxey 1970's data comparable to mean + 1 std dev for the larger ASTM dataset
  - Use the 95% confidence temperature shift for the ASTM dataset in the Level 1 analysis



REX2024
PRCI Research Exchange

Understanding Transition Temperature Changes with Constraint (Important for Levels 1 and 2)

- **Vintage welds had different CVN SA% vs temp. curves than base metals**
  - No nice single database like the ASTM base-metal effort, so used data from different sources
  - One contributing reason why some vintage welds may have cleavage initiation
    - Vintage EFW/d-c ERW/LF-ERW/DSAW had reasonably similar shape (1/2 to 2/3 size)

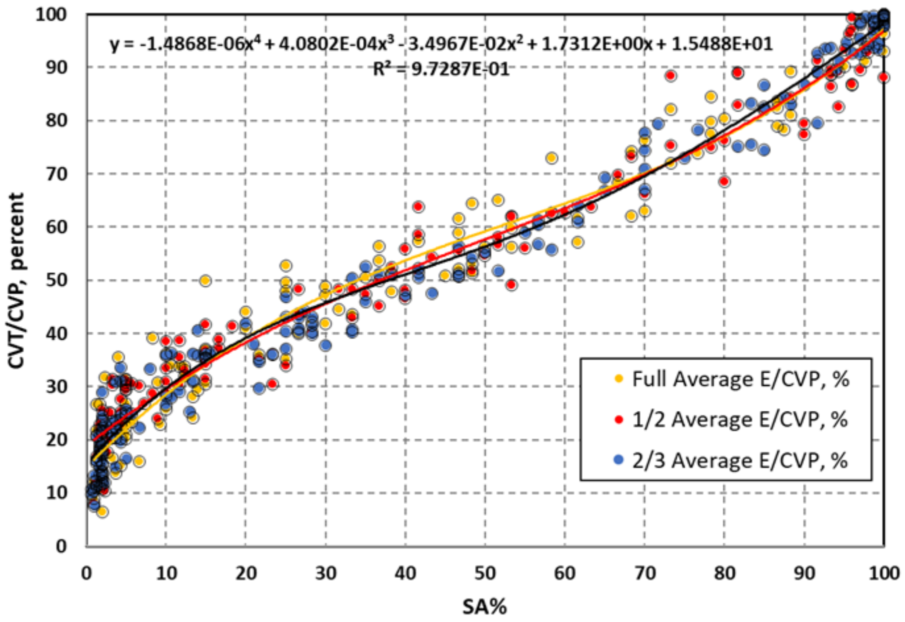


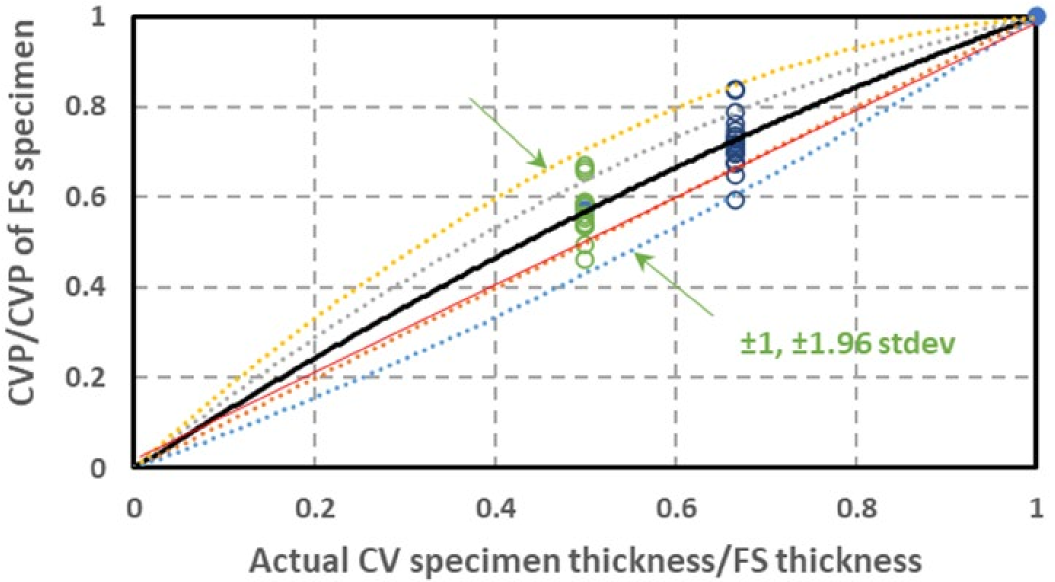
There is no such thing as a "True Fracture Toughness" (Important for All Levels)

- Upper-shelf toughness changes with many constraint parameters
- Starting with basic Charpy energy at any temperature – if predict ductile initiation then use CVP or appropriate fracture toughness
- Step 1 – Calculate CVP if you have one CVN energy and SA% at one temperature
- Step 2 – Correlate to C(T) or SEN(B) specimen's J_{Ic} value
- Step 3 – Correlate to SEN(T) to get toughness a surface crack exhibits

Understanding Transition Temperature Changes with Constraint (Important for Levels 1 and 2)

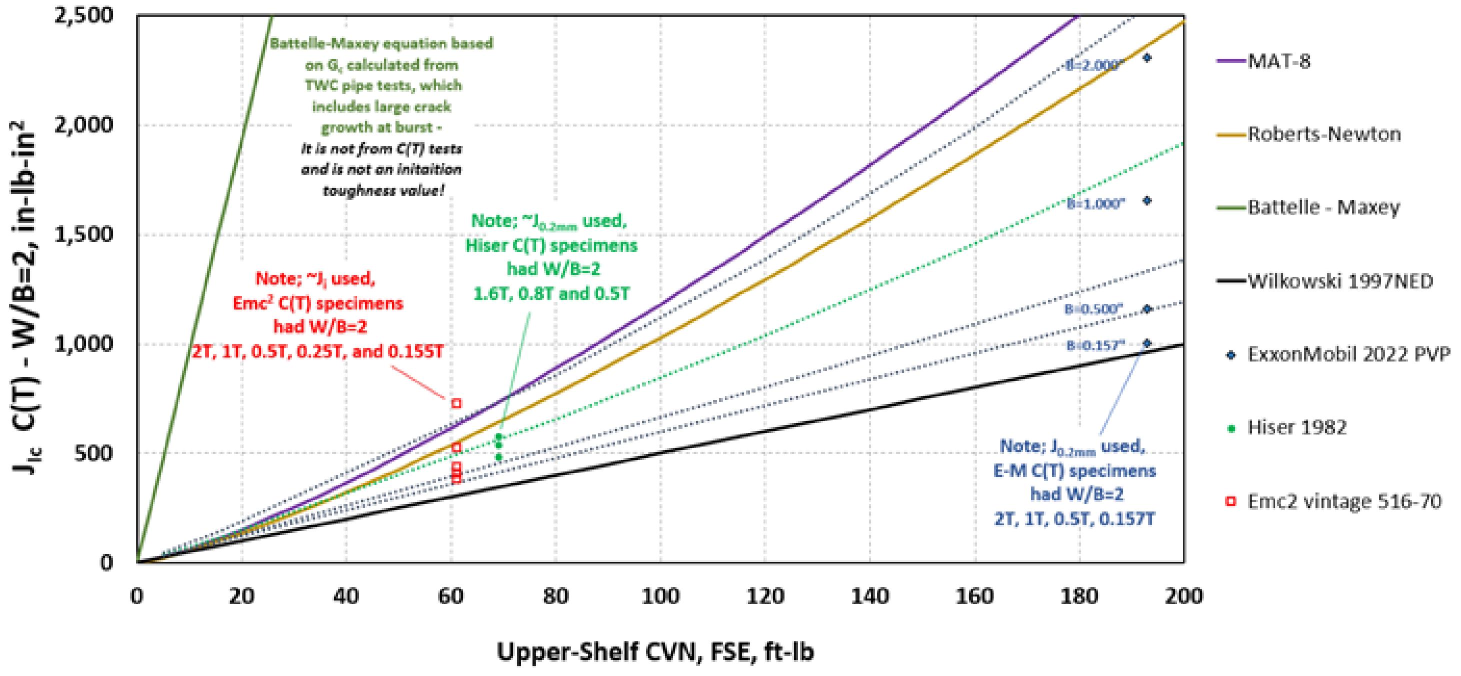
- **Once determined that material is on the upper-shelf, then you can calculate the CVP knowing the SA% and energy for any specimen size**
  - Again, used the ~2,000 data points from the 1970 ASTM base metal
    - CVN/CVP vs SA% correlation independent of specimen size
  - Once have CVP for any specimen size, then linearly scaled to get full-size CVP energy
    - Slight statistical variation if probabilistic work done

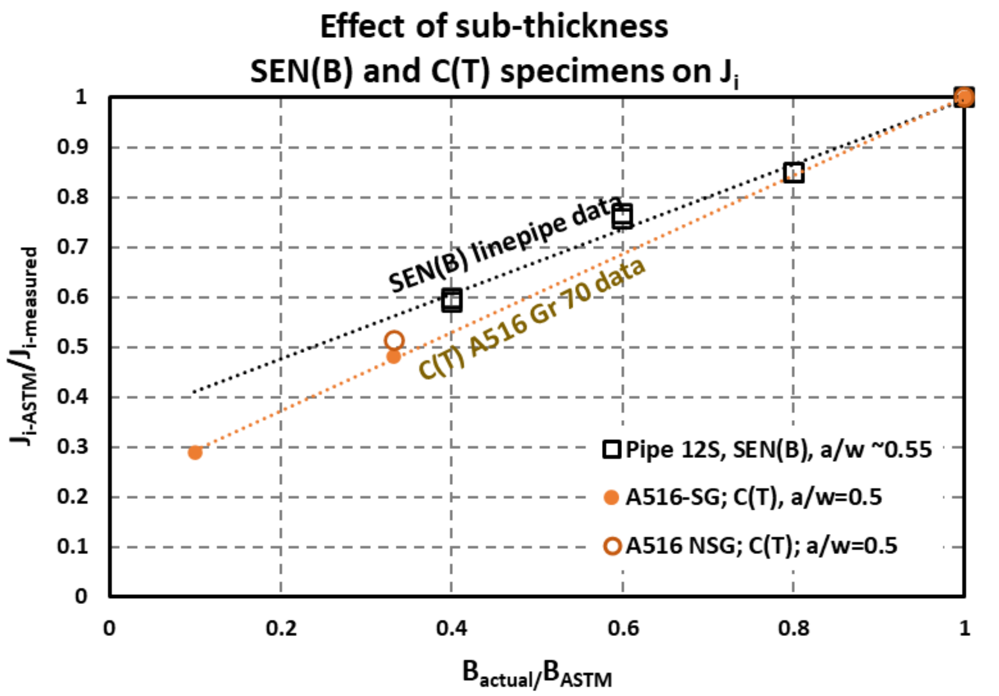




Knowing the CVP can calculate C(T) or SEN(B) specimen J_{Ic}

- **Constraint work shows that the C(T) toughness depends on specimen size (keeping preferred W/B=2 and a/w=0.5 geometry)**
  - Warning, if W/B > 2 then J_{Ic} is elevated, and these correlations don't work unless corrected back to standard W/B=2 dimension!



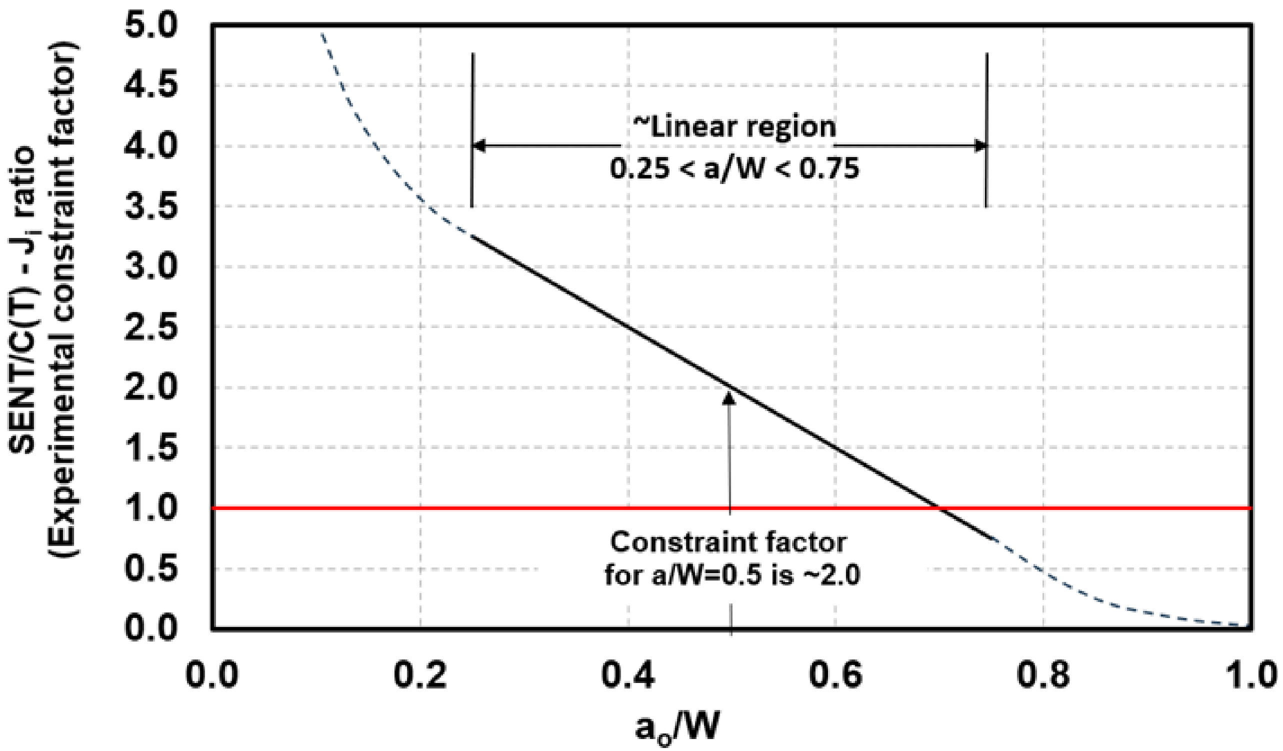


Can calculate SEN(T) toughness from C(T) or correlate back to CVP

- **Every material has similar SEN(T) constraint trend with a/w (or a/t for surface cracked pipe)**
  - More recent constraint work with 3-constaint parameters explains the trend (J-Q and σ_{zz})
  - Toughness in linear region is proportional to (1-a/t)
  - Remember Maxey's empirical surface-cracked pipe bulging factor?

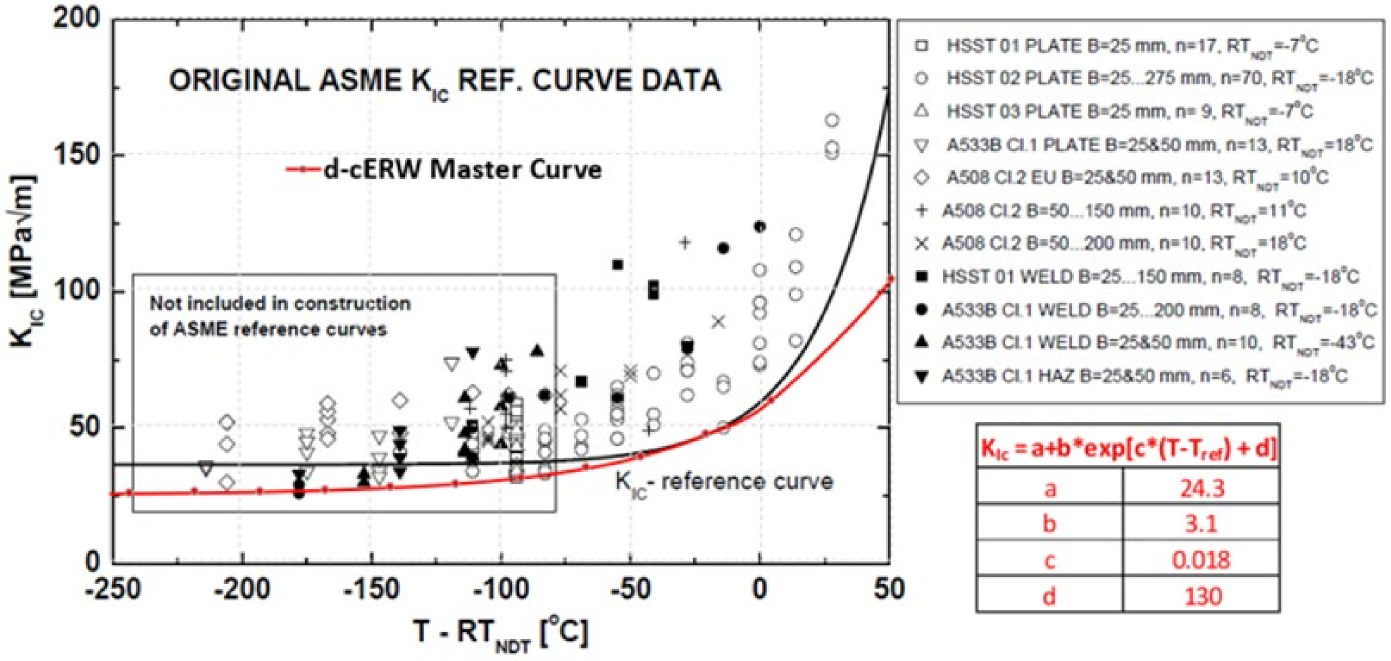
$M_s = (1\text{-}a/t)/[1\text{-}a/(M_T*t)]$ with M_T being the TWC bulging factor.

The (1/a/t) term is the toughness correction for surface crack depth, with an actual much smaller bulging factor – he just didn't know that both bulging and toughness corrections in the empirical equ.



Understanding Cleavage-Initiation Toughness Changes with Constraint (Important for Levels 2 and 3)

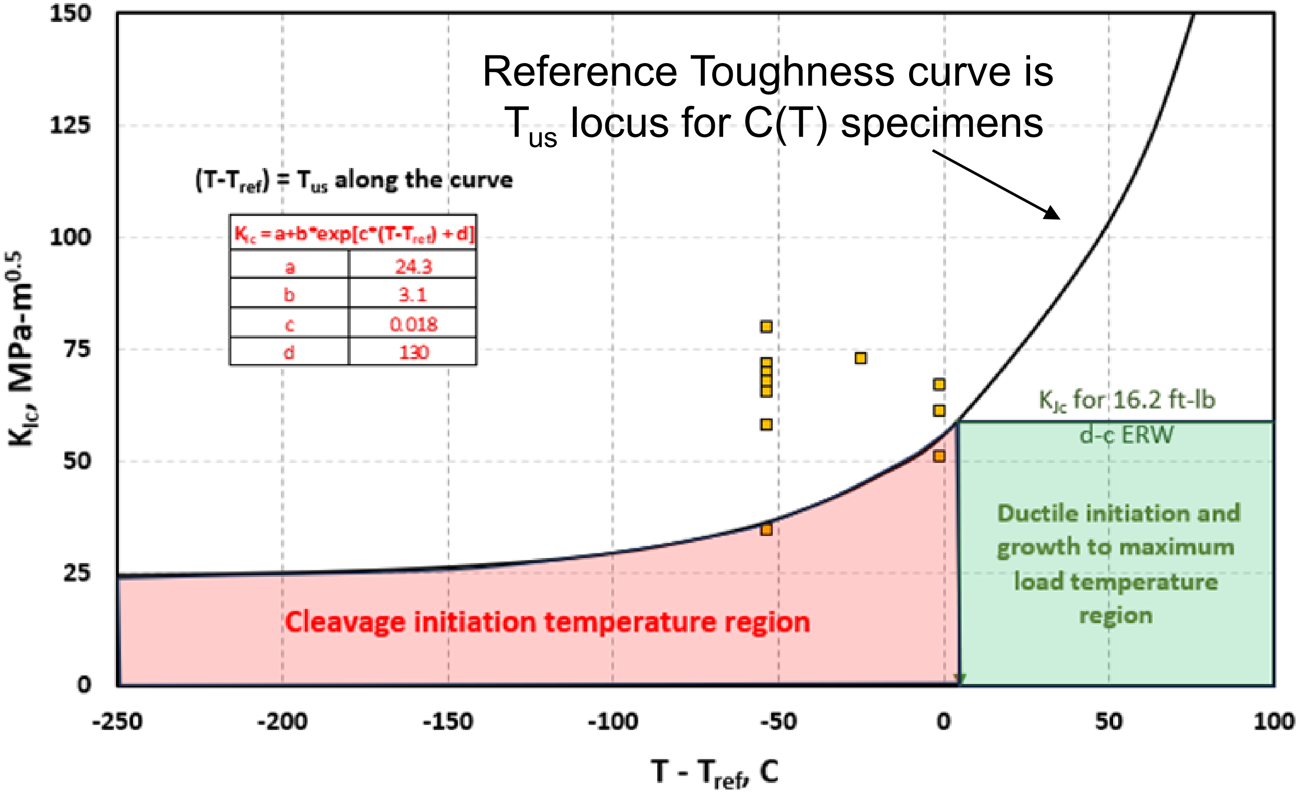
- **If fail the ductile initiation criterion, then need a cleavage fracture reference toughness curve.**
- **Could not use the ASME Reference Toughness or newer Master Curve approach since the normalizing reference toughness (or T_o) could not be defined for low toughness ERW welds.**
- **Defined the reference toughness from the MC-FTT – lowest toughness for ductile initiation**
- **Used member company C(T) data on LF-ERW C(T) tests**
- **Started with ASTM database for new curve fitting (data and figures courtesy of Kim Wallin)**



$K_{Ic} = a+b*\exp[c*(T-T_{ref})+d]$	
a	24.3
b	3.1
c	0.018
d	130

Can use the MC-FTT to Show Constraint Shifts in the Reference Toughness Curve -- Examples:

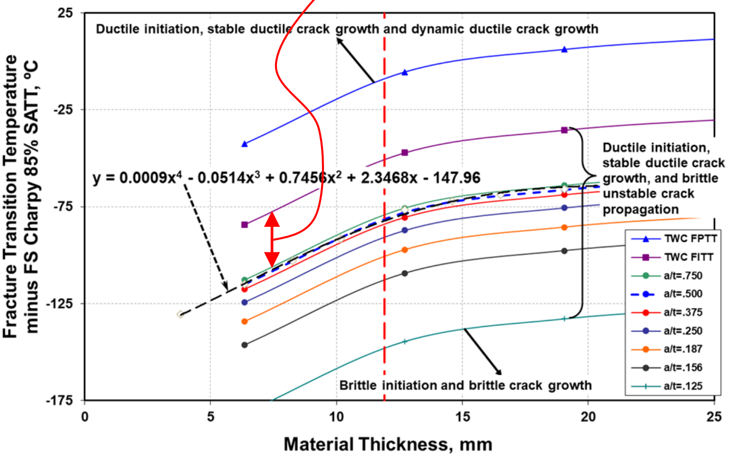
- The reference toughness curve is based on C(T) specimens – high-constraint test specimen conditions.
- T_{us} is locus of points on the curve for a C(T), or SENB, specimen – temp when upper-shelf initiation is reached
- But what happens for surface cracks that have lower constraint conditions; transition temp is lower, and upper shelf toughness can be higher???? Next set of VGs!

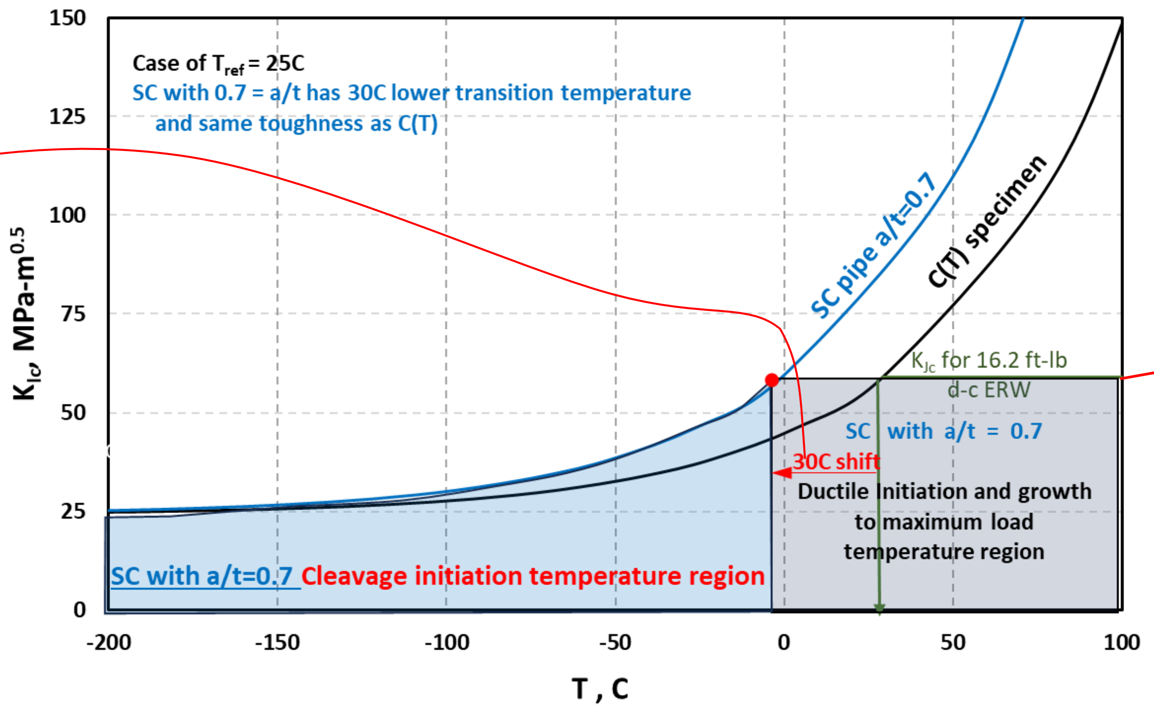


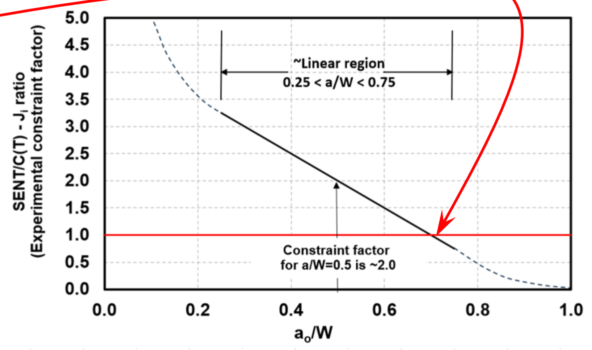
Can use the MC-FTT to Show Constraint Shifts in the Reference Toughness Curve -- Example for SC'ed Pipe with a/t=0.7

- Surface cracks a/t>0.375 have trans. temp. ~30˚C (55˚F) lower than C(T) specimen – left figure
- C(T) specimen upper-shelf toughness same as a surface crack that is 70% deep – right figure.
- **Red dot** is <u>constraint shift point</u> for a/t=0.7.
- Similar looking to API-579 approximate constraint shift of T_o.

30°C shift from C(T) to deep surface crack

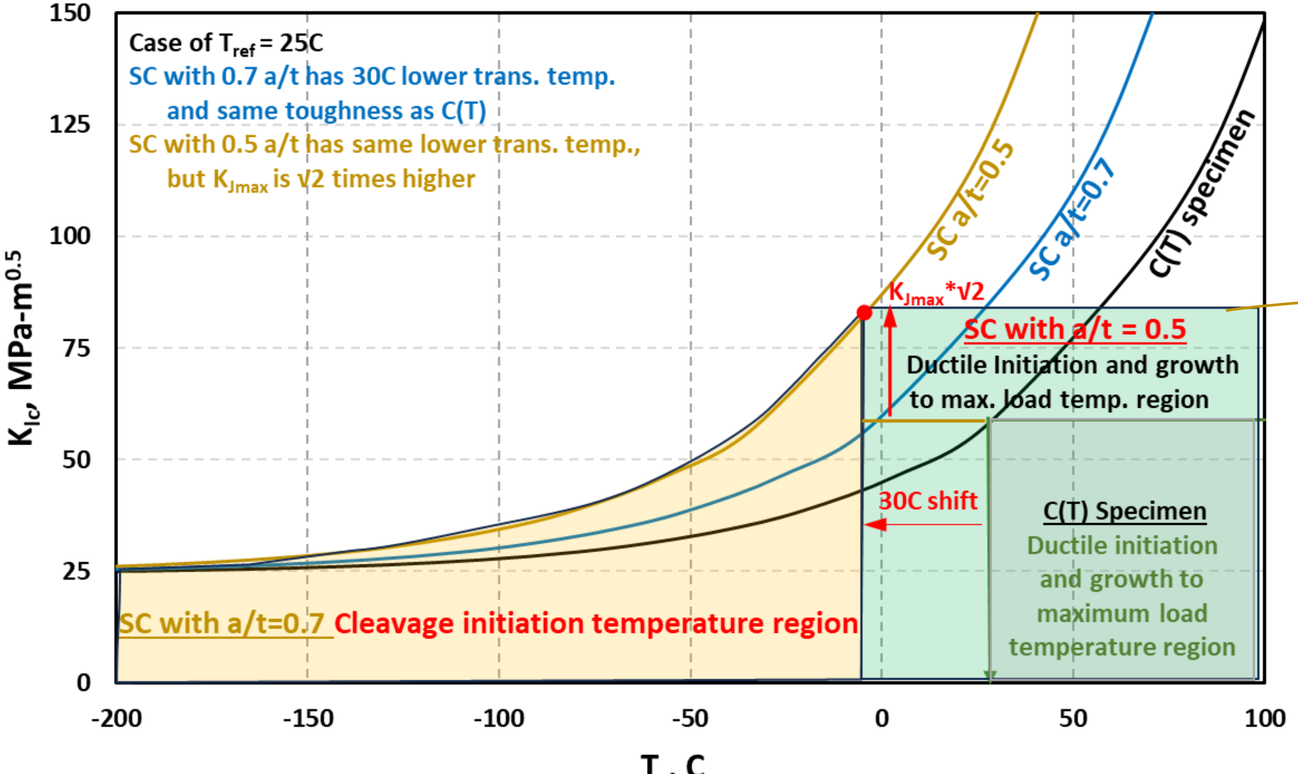


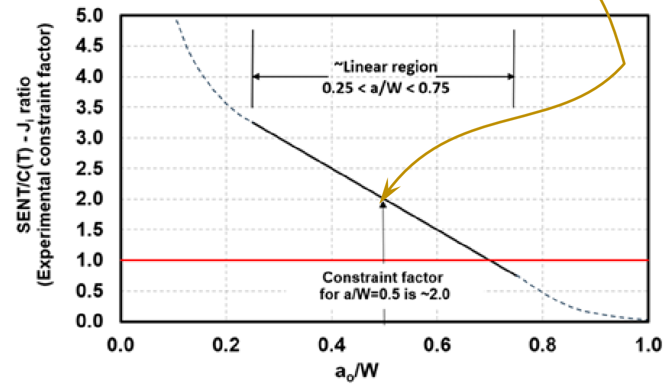




Can use the MC-FTT to Show Constraint Shifts in the Reference Toughness Curve -- Example for SC'ed Pipe with a/t=0.5

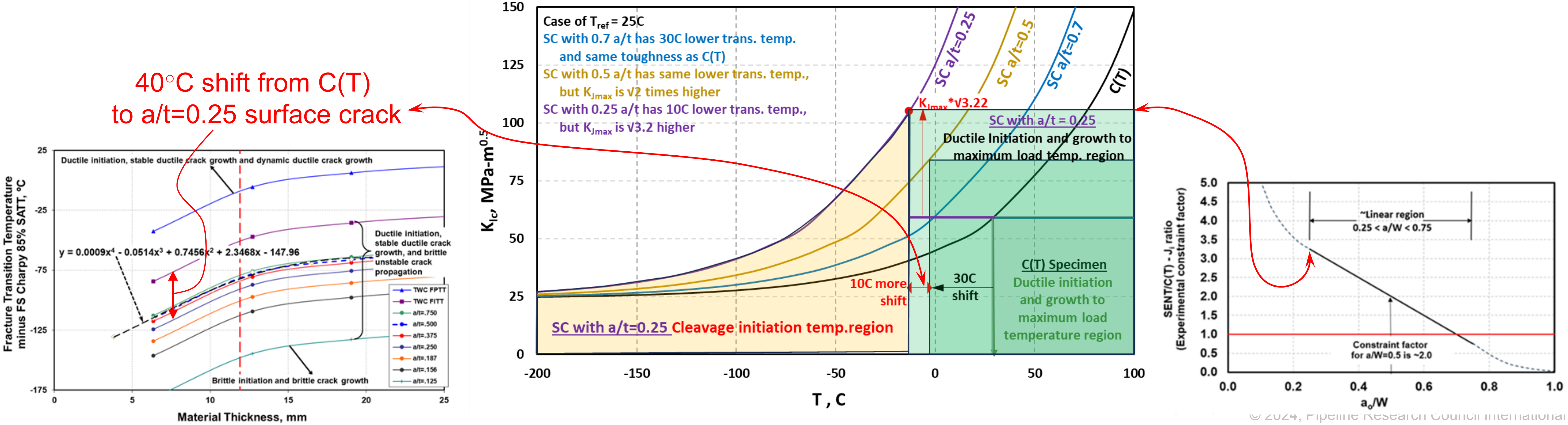
- But for a SC with a/t=0.5 has upper-shelf toughness √2 *K_{Jmax} of C(T), 2*J_{Ic} – from left figure
- With the same transition temperature as in MC-FTT
- Red dot is constraint shift point for a/t=0.5 – Reference Toughness curve moves





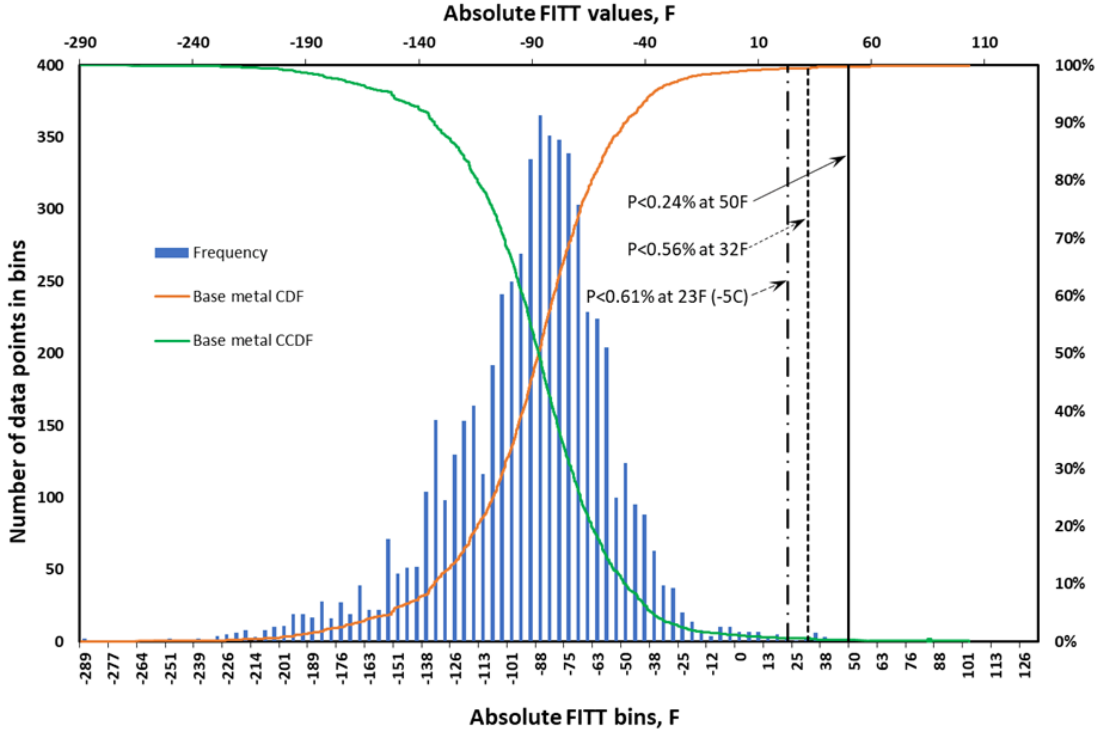
Can use the MC-FTT to Show Constraint Shifts in the Reference Toughness Curve -- Example for SC'ed Pipe with a/t=0.25

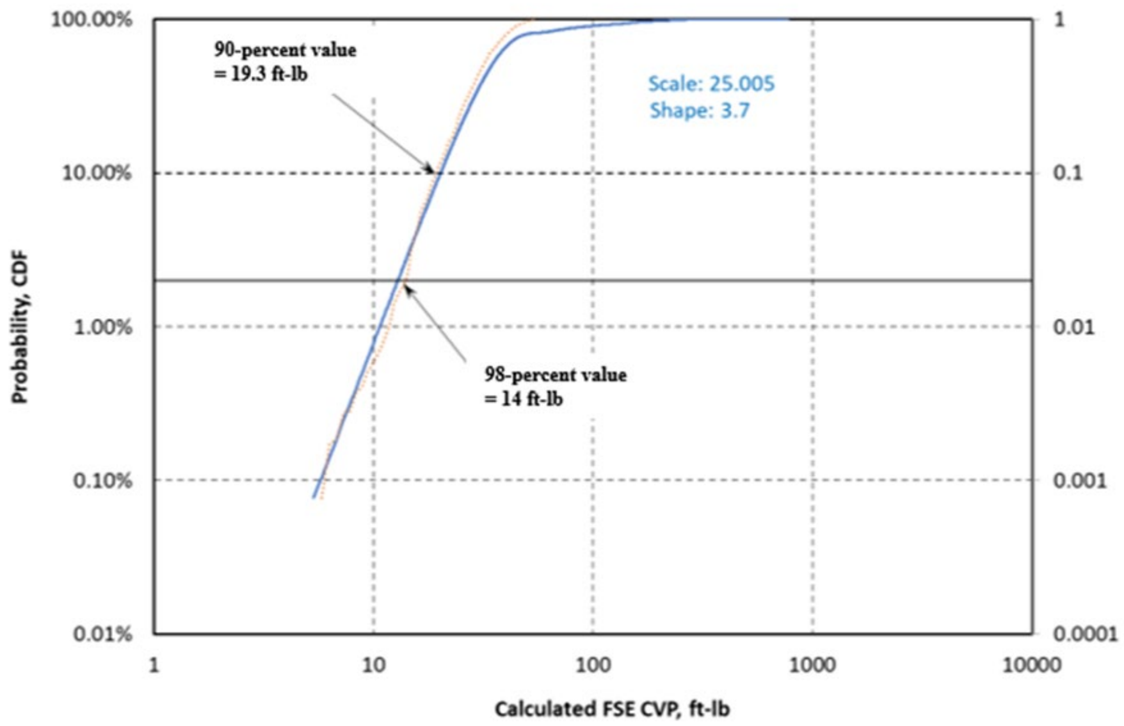
- SC with a/t = 0.25 has √3.2 *K_{Jmax} of C(T) – from right figure
- Also has additional 10C transition temperature shift over SC a/t=0.5 – from left figure
- Again, the red dot is the new <u>constraint shift point</u> for a/t=0.25 – curve moves more
- ***<u>Pragmatic implication</u>, if have shallow weld defects in a DSAW, then the apparent toughness is higher and transition temperature is lower and may not need to use Level 1 bounding value K_{Ic} = 25 ksi√in toughness. (Starting CVP of DSAW is also higher than this example)***



Level 1 Statistical Considerations For Level 1

- **Material Category 1 – Base Metals (5,760 Charpy sets from different databases)**
  - From database examinations, 99.4% of the time had transition temperature lower than -5C (24F). Consistent with trends from full-scale pipe tests; even if CVN at operating temperature was 1 ft-lb.
  - 90% had FSE CVP greater than 19.3 ft-lb (SIA INGAA report suggested 90th percentile for pipes without prior failure)
  - 98% had FSE CVP greater than 14 ft-lb (SIA INGAA report suggested 98th percentile for pipes without prior failure)





The Level 1 Report Completed and Provides Statistical Based Toughness

- Material Category 1 – base metals
  - **Equivalent toughness values for Material Category 1 for Level 1 analysis***

Prior failure in the line?	Default CVN value per 192.712 (ft-lbs)	Recommended CVP values for CVP-based burst pressure models (ft-lbs)	Recommended K_{Jc} for K_{Jc}/J_c based burst pressure models (psi-in$^{0.5}$)
No	13	19	$K_{Jc} = \sqrt{\frac{570\left(0.9 - \frac{a}{t}\right)E}{1-\nu^2}}$
Yes	5	14	$K_{Jc} = \sqrt{\frac{420\left(0.9 - \frac{a}{t}\right)E}{1-\nu^2}}$

- Constants of 570 and 420 come from 30*CVP, with CVP in ft-lb for the full-size specimen (basis from upper-shelf toughness correlations). E is elastic modulus in psi, and v is 0.3.
- CVP-based burst pressure models are; Original LnSec, Modified LnSec, and CorLAS.
- The toughness change with a/t can be used with the more fundamental fracture models such as; API-579, MAT-8, and Emc^2 2022IPC FE-based J-estimation scheme.
- KorLAS should use C(T) specimen J_i values, where $J_{i\text{-}C(T)}$ = 6*CVP, with CVP in ft-lb, and J_i is in in-lb/in^2.

The Level 1 Report Completed and Provides Statistical Based Toughness

- Material Category 2 – weld metals with toughness to fail on upper-shelf (different welds)
  - **Equivalent toughness values for Material Category 2 for Level 1 analysis <u>for DSAW; see table of pre-1970 DSAW pipe mfgr/vintage that fall in this category</u>**

Prior failure?	DSAW		
	192.712 (ft-lbs)	CVN-based model from this report (ft-lbs)	K_{Jc}/J_c based model
No	4	19	$K_{Jc} = \sqrt{\frac{570\left(0.9 - \frac{a}{t}\right)E}{1-\nu^2}}$
Yes	1	14	$K_{Jc} = \sqrt{\frac{420\left(0.9 - \frac{a}{t}\right)E}{1-\nu^2}}$

  - DSAW had CVP>bounding base metal, so used Level 1 base metal
  - Constants of 570 and 420 come from 30*CVP, with CVP in ft-lb for the full-size specimen (basis from upper-shelf toughness correlations). E is elastic modulus in psi, and v is 0.3.
  - CVP-based burst pressure models are; Original LnSec, Modified LnSec, and CorLAS.
  - The toughness change with a/t can be used with the more fundamental fracture models such as; API-579, MAT-8, and Emc^2 2022IPC FE-based J-estimation scheme.
  - KorLAS should use C(T) specimen J_i values, where $J_{i\text{-}C(T)}$ = 6*CVP, with CVP in ft-lb, and J_i is in in-lb/in^2.

The Level 1 Report Completed and Provides Statistical Based Toughness

- Material Category 2 – weld metals with toughness to fail on upper-shelf (different welds)
  - **Equivalent toughness values for Material Category 2 for Level 1 analysis for LF-ERW/EFW; see table of pre-1970 LF-ERW/EFW pipe mfgr/vintage that fall in this category. Post-1970 HF-ERW in this category.**

Prior failure?	LF-ERW/EFW		
	192.712 (ft-lbs)	CVN-based model from this report (ft-lbs)	K_{jc}/J_c based model
No	4	17	$K_{Jc} = \sqrt{\frac{510\left(0.9 - \frac{a}{t}\right)E}{1 - \nu^2}}$
Yes	1	12	$K_{Jc} = \sqrt{\frac{360\left(0.9 - \frac{a}{t}\right)E}{1 - \nu^2}}$

  - Constants of 510 and 360 come from 30*CVP, with CVP in ft-lb for the full-size specimen (basis from upper-shelf toughness correlations and statistical data). E is elastic modulus in psi, and v is 0.3.
  - CVP-based burst pressure models are; Original LnSec, Modified LnSec, and CorLAS.
  - The toughness change with a/t can be used with the more fundamental fracture models such as; API-579, MAT-8, and Emc^2 2022IPC FE-based J-estimation scheme.
  - KorLAS should use C(T) specimen J_i values, where $J_{i\text{-}C(T)}$ = 6*CVP, with CVP in ft-lb, and J_i is in in-lb/in^2.

The Level 1 Report Completed and Provides Statistical Based Toughness

- Material Category 2 – weld metals with toughness to fail on upper-shelf (different welds)
  - **Equivalent toughness values for Material Category 2 for Level 1 analysis <u>for d-c ERW; see table for mfgr/vintage d-c ERW in this category</u>**

Prior failure?	d-c ERW		
	192.712 (ft-lbs)	CVN-based model from this report (ft-lbs)	K_{jc}/J_c based model
No	4	9	$K_{Jc} = \sqrt{\dfrac{270\left(0.9 - \frac{a}{t}\right)E}{1 - \nu^2}}$
Yes	1	4	$K_{Jc} = \sqrt{\dfrac{120\left(0.9 - \frac{a}{t}\right)E}{1 - \nu^2}}$

  - Constants of 270 and 120 come from 30*CVP, with CVP in ft-lb for the full-size specimen (basis from upper-shelf toughness correlations and statistical data). E is elastic modulus in psi, and v is 0.3.
  - CVP-based burst pressure models are; Original LnSec, Modified LnSec, and CorLAS.
  - The toughness change with a/t can be used with the more fundamental fracture models such as; API-579, MAT-8, and Emc^2 2022IPC FE-based J-estimation scheme.
  - KorLAS should use C(T) specimen J_i values, where $J_{i\text{-}C(T)}$ = 6*CVP, with CVP in ft-lb, and J_i is in in-lb/in^2.

The Level 1 Report Completed and Provides Statistical Based Toughness

- Material Category 3 – weld metals with toughness that fail with cleavage initiation
  - **Equivalent toughness values for Material Category 3 for Level 1 analysis, see table of mfgr/vintages in this category**
    - For some of the vintage DSAW, EFW, and d-c ERW fusion line cases, the default toughness to use is the following

$$K_{Ic} = 25\ ksi\text{-}in^{0.5}$$

  - This conservative assumption assumes near lower-shelf behavior on the cleavage-fracture Reference Toughness curve
  - Probably more appropriate for d-c ERW and high hardness EFW
  - DSAW weld metal starts with much higher CVP, so it is higher on the Reference Toughness curve, and may not lose toughness to this level at the operating temperature. TBD in future.

The Level 1 Report Completed and Provides Statistical Based Toughness Mfgr/vintages found to be in Material Category 2 – welds on upper-shelf

Material Category 2 (Welds that qualified to use CVP for operating temperatures at or above 50F); where we have data so far!

Note, if weld fell in both Material Category 2 and 3, it was put in Category 3. Happened many times, no criteria made for retest data or further statical analysis at this time. More cases in future.

- **DSAW pipe**
  - Berg 1950, 1960; Bethlehem 1950, 1955, 1958, 1960, 1965, 1968, 1969, 1970; Consolidated Western 1949, 1951, 1955, 1956; Hoesch 1955, 1969; Kaiser 1953, 1960; National Tube 1955, 1956; Stelco 1968; and US Steel 1964, 1967

- **LF-ERW/EFW**
  - AO Smith 1944; Kaiser 1960; Republic 1964; and US Steel 1964

- **d-c ERW**
  - Youngstown 1948, 1966

The Level 1 Report Completed and Provides Statistical Based Toughness Mfgr/vintages found to be in Material Category 3 – welds with cleavage initiation

Material Category 3 (Welds that did not qualify for Material Category 2 – use lower bounding K_{Ic} for any operating temperature)

- **Note, if weld fell in both Material Category 2 and 3, it was put in Category 3. Happened many times, no criteria made for retest data or further statical analysis at this time. More cases in future.**
- **DSAW might have higher level K_{Jc} in the future.**

- **DSAW pipe**
  - Bethlehem 1962; Consolidated Western 1950; Hoesch 1955; Republic 1953
- **LF-ERW/EFW**
  - AO Smith – 1951, 1953, 1954, 1960, 1961; Jones/Laughlin 1962; Lone Star 1955; Republic 1949, 1953
- **d-c ERW**
  - National Tube 1952; Youngstown pipe 1951, 1952, 1953, 1956, and 1964

thank you

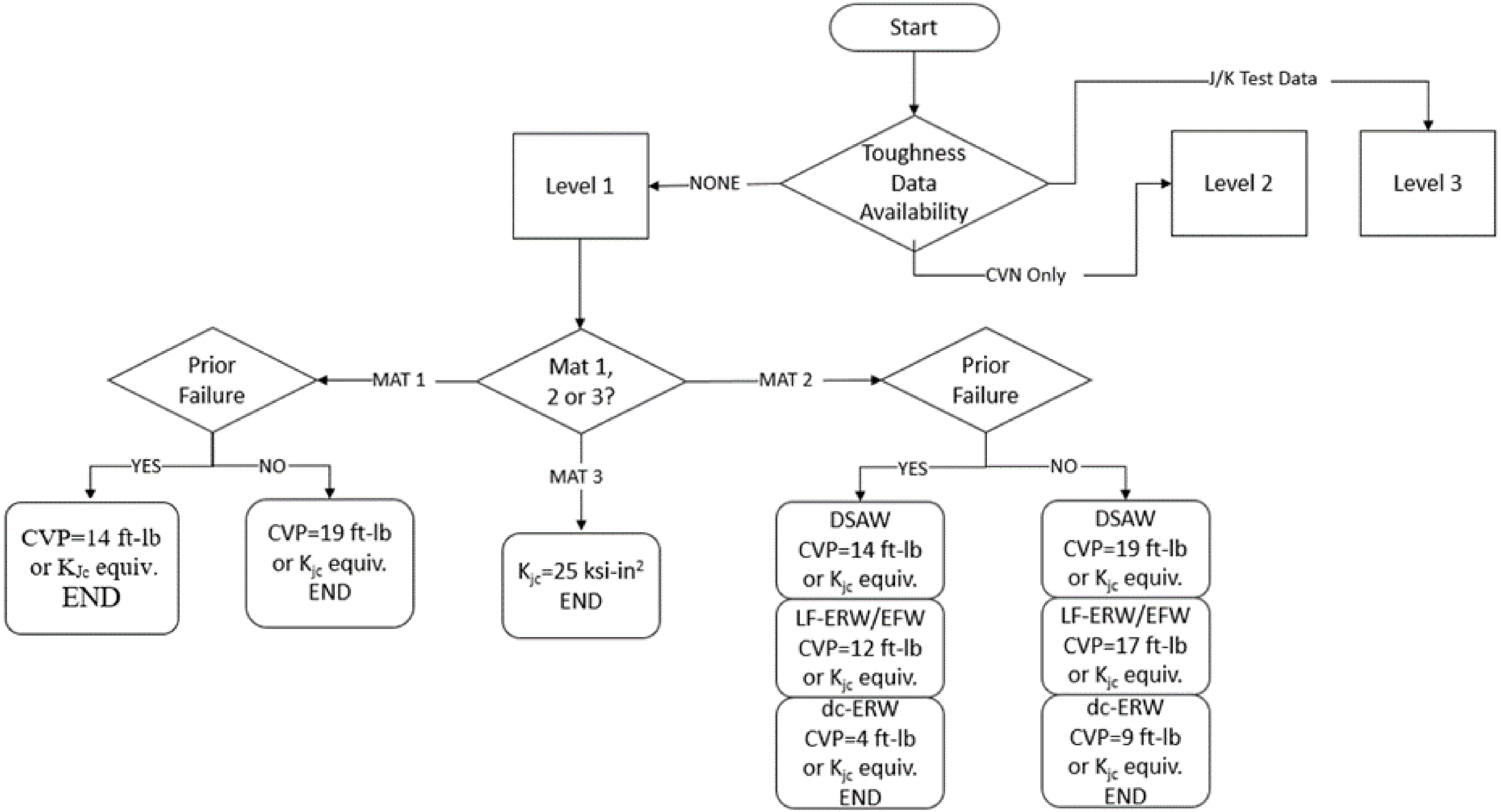
REX2024
PRCI Research Exchange

Dr. Gery M. Wilkowski
Director of Innovation, Emc^2

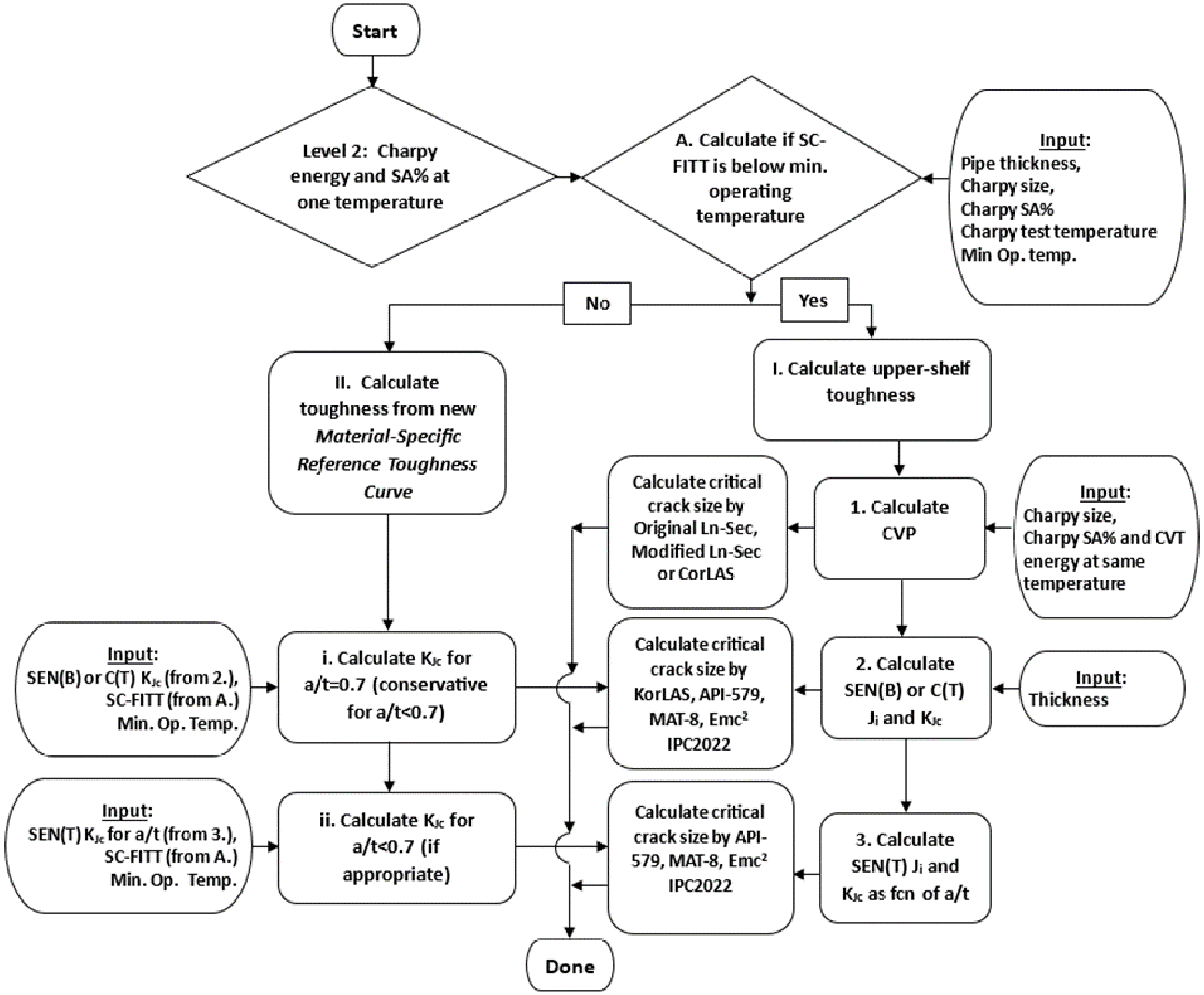
1-614-459-3200/580-0442

gwilkowski@emc-sq.com

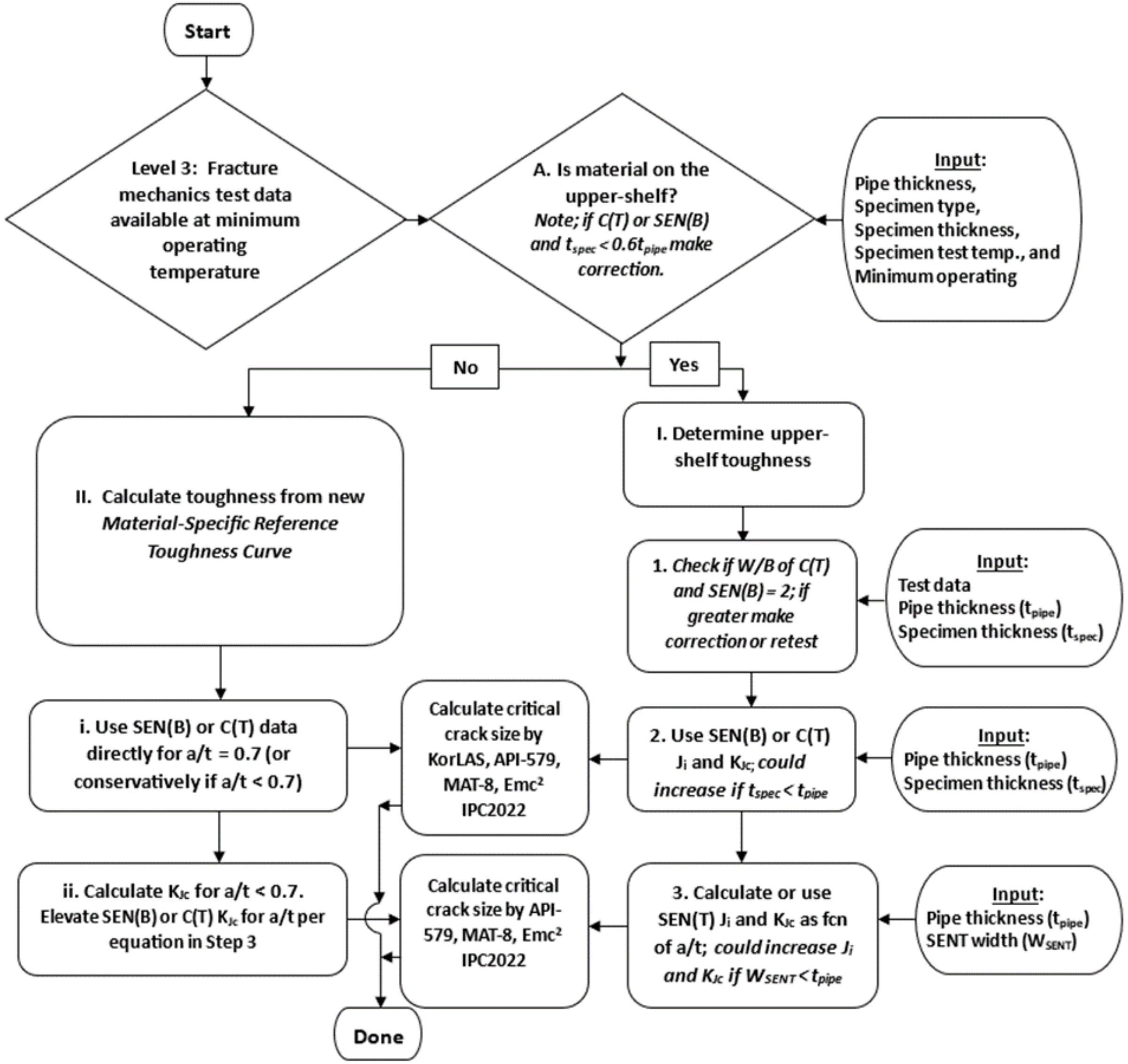
Level 3 Flow Chart



Level 2 Flow Chart



Level 3 Flow Chart



Understanding Cleavage-Initiation Toughness Changes with Constraint (Important for Levels 2 and 3)

- **Used member company C(T) data on d-c-ERW C(T) tests**
  - Instead of K_{Ic}, we used K at maximum load (K_{Jmax}, where some ductile tearing can occur, unless near the true lower shelf)
    - K_{Ic} for low-toughness ERW welds may not vary much with temperature, but K_{Jmax} does vary!
    - By knowing the upper-shelf J_{Ic} from Charpy correlation we get the ~K_{Jc} point on the new Reference Toughness curve (slight conservatism)
    - Then by knowing the lowest temperature for ductile initiation of a C(T) specimen, or TWC'ed pipe, in MC-FTT, then T_{ref} can be defined!