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Material Orientation Toughness Assessment (MOTA) for the Purpose of Mitigating Branch Technical Position (BTP) 5-3 Uncertainties

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Introduction

- AREVA published a paper and sent an official letter to the U.S. NRC on January 30, 2014 identifying potential problems with Branch Technical Position (BTP) 5-3
  - Position 1.1(4) of BTP 5-3 sometimes non-conservative in the determination of the initial Reference Nil-Ductility Transition Temperature (RT_{NDT}) material property for reactor vessel materials made from SA-508, Class 2 forgings.
- The BTP 5-3 methods to estimate initial RT_{NDT} were invoked for reactor pressure vessels fabricated to an ASME Boiler & Pressure Vessel Code earlier than the Summer 1972 Addenda of the 1971 Edition because the RT_{NDT} concept did not exist before that time.
- BTP 5-3 provides estimation methods for conversion of measured “Strong-Direction” Charpy data, which was required pre-Summer 72, into “Weak-Direction” materials data, which was required afterwards
- AREVA’s finding calls into question the baseline RT_{NDT} values of reactor vessels whose materials used this particular method

NRC Response to AREVA Letter

- The U.S. NRC actively began investigating this issue further in response to the AREVA letter.
- The NRC technical evaluation included both forging and plate materials
- This analysis confirmed non-conservatism of several BTP 5-3 Positions for estimation of initial RT_{NDT} and initial Upper-Shelf Energy (USE) values.
- The NRC presentation to various utility representatives on June 4, 2014 prompted the industry to request that EPRI continue addressing this issue on their behalf.

EPRI Quantification of BTP 5-3 Uncertainties

- EPRI had already issued a survey on May 27, 2014 to utilities requesting additional information related to how RT_{NDT} was determined for the plants in the U. S. Fleet.
- EPRI investigated and quantified the BTP 5-3 uncertainties
  - The results of this work are documented in, *Assessment of Potential Non-Conservatisms of NUREG-0800 Branch Technical Position 5-3 Estimation Methods for Initial Fracture Toughness Properties of Reactor Pressure Vessel Steels*.
- Based on the EPRI Probabilistic Fracture Mechanics (PFM) evaluations, there is negligible safety benefit to changing BTP 5-3 B1.1(3) or its application
  - The uncertainty in BTP 5-3, Position 1.3 (a) and (b) can be further addressed by the PWROG MOTA project

PWROG Approach

- The PWROG recognized that existing deterministic margin is potentially available in ASME Code Section XI, Appendix G and other NRC approved sources
  - Regulatory Guide (RG) 1.161 is the NRC guidance on performing an Equivalent Margins Assessment (EMA) related to Upper Shelf Energy limited plants (< 50 ft-lbs at EOL)
  - Current Pressure-Temperature limits, using the ASME Code, postulate axial flaws in plates/forgings and therefore, use “Weak-Direction” material properties
  - ASME Code Case N-588 introduced methodology specifying that only circumferential flaws are required to be postulated in circumferential welds – Code provides stress intensity factor equation for circumferential (circ.) flaws
  - As previously noted, BTP 5-3 provides estimation methods for conversion of measured “Strong-Direction” Charpy data, into “Weak-Direction” materials data
- The following slides provide additional details on this approach

By using the EMA RG and Code Case N-588 precedents, we can show significant inherent margin in Appendix G methodology sufficient to mitigate the uncertainties associated with use of BTP 5-3 methods used for vessel shell plates and forgings

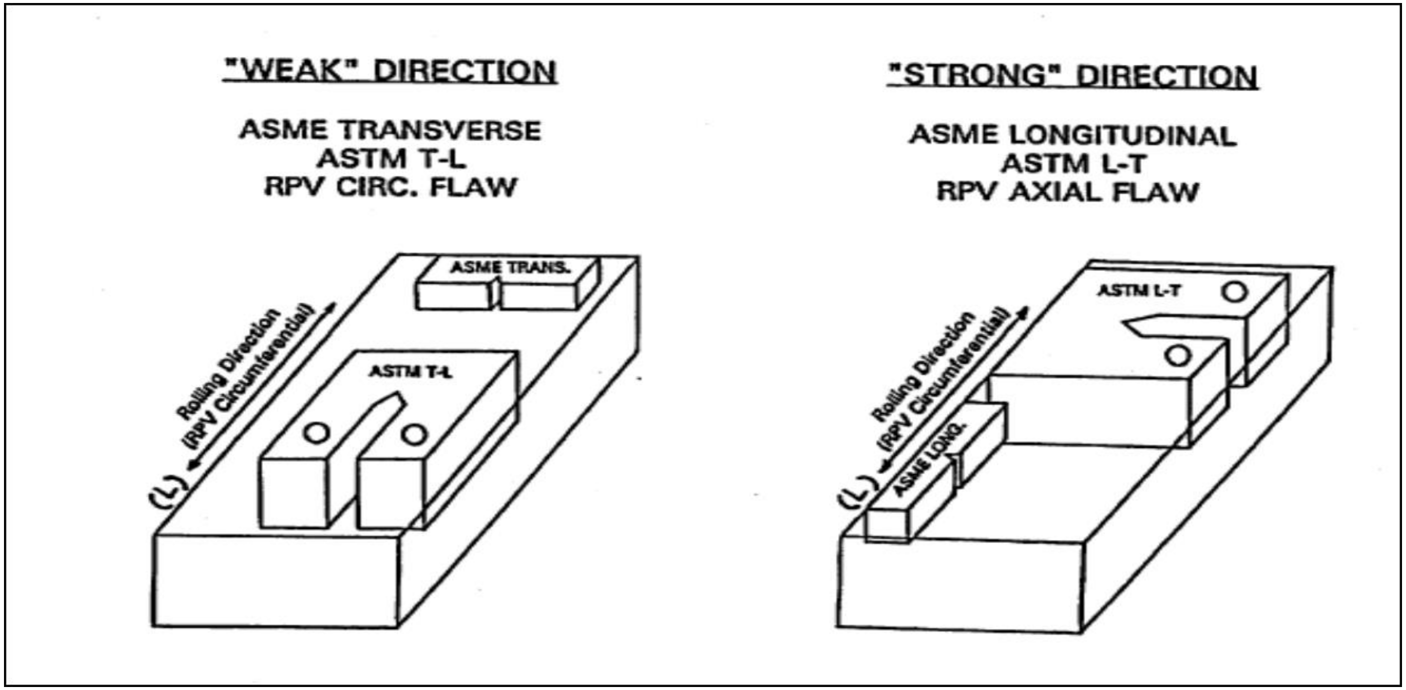
Regulatory Guide 1.161 Text

- RG 1.161 states the following:

  "The CVN value should be for the proper orientation of the plate material (see Figure 2 [recreated in the next slide]). For example, for axial flaws the CVN value for the L-T (strong) orientation in the vessel wall should be used. Similarly, for circumferential flaws the CVN value for the T-L (weak) orientation should be used."

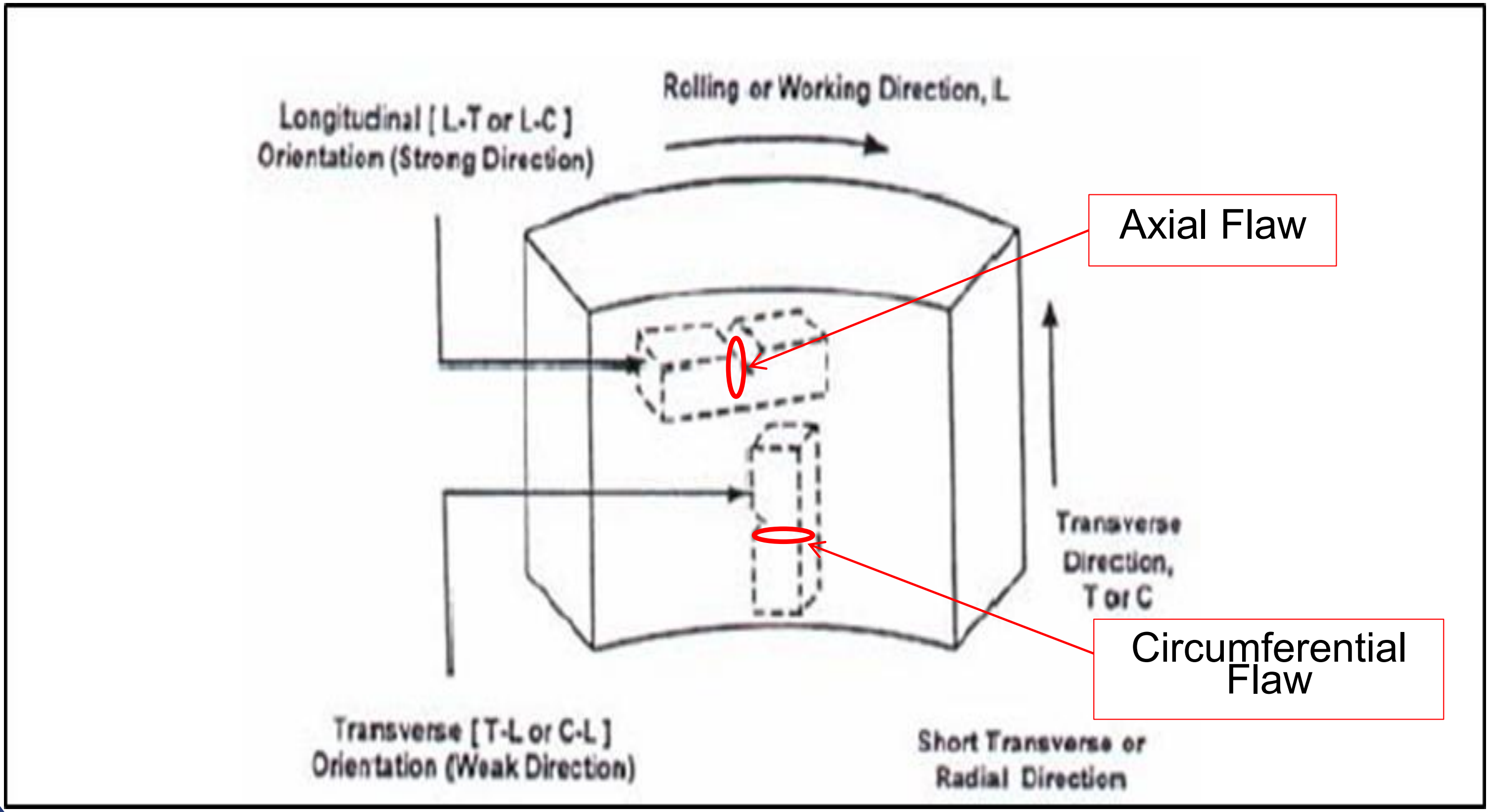
- It is our contention that this approach, as defined in RG. 1.161, is technically valid for assessing BTP 5-3 uncertainty

RG 1.161 Material Orientation Figure



Match up Flaw to Material Orientation Properties in EMA is Allowed

EPRI MRP Report Figure with Flaws Added



WRC-175 “PVRC Recommendations on Toughness Requirements for Ferritic Materials”

- WRC-175 is basis for 1972 changes to ASME Section III, which brought in the requirements for flaw tolerance in Appendix G
- With respect to shells:

> 2. Properties are to be determined in the direction of the maximum general primary membrane stress. This is the hoop direction in a cylindrical shell, but in a spherical shell or head the specified properties are required in both tangential-longitudinal and tangential-transverse direc-

Transverse properties for shells was not recommended by PVRC

- ASME required transverse properties for all components, which is conservative

ASME Code Case N-588

- Implemented in 1997 time frame to add a more realistic methodology for the use of circumferential flaws when considering circumferential welds for P-T limit curves
- Postulated that any flaws in a circumferential weld would be in the circumferential direction
- ASME Code stress intensity factor (SIF) values for Axial Flaws are ~2 times the Circumferential Flaw results due to the higher pressure stresses (more details to come)
- This Code case has been endorsed per RG 1.147

Pressure-Temperature Limit Curve Methodology

Governing equation for P-T Limit Curve analysis:

$$C*K_{Im} + K_{It} < K_{Ic}$$

where,

- K_{Im} = stress intensity factor caused by membrane (pressure) stress [ksi]
- K_{It} = stress intensity factor caused by thermal stress [ksi]
- K_{Ic} = fracture toughness, a function of the RT_{NDT} of the material [ksi]
- C = Safety Factor on membrane stress

Pressure-Temperature Limit Curve Margins

- Appendix G allowable limits are established using the following three required margins
  - Postulate ¼ thickness reference flaw with semi-elliptical (6:1) shape
  - Lower bound crack initiation (K_{Ic} curve) fracture toughness
    - Material RT_{NDT} and metal temperature
  - Safety factor, C, of 2 on membrane pressure stress

MOTA Margin Definition

- The MOTA Margin is defined as the ART difference between an Axial Flaw based P-T limit curve and a Circumferential Flaw based P-T limit curve
  - It is calculated by subtracting the Circumferential Flaw ART value (weak direction properties) from the original Axial Flaw ART value (strong direction properties) at the point of intersection
- MOTA Margin is applicable to all base metal cylindrical shell sections away from discontinuities
- The MOTA Margin compensates for the uncertainty that have been summarized in the EPRI BTP 5-3 assessment
  - Applies to the full range of reactor vessel dimensions in the domestic PWR fleet

This demonstration determines the margin that circumferential flaw (weak property) P-T curves have before they would become governing relative to the axial flaw (strong property) Appendix G curves

How to Determine MOTA Margin

- Combine the methodologies of Regulatory Guide 1.161 and Code Case N-588 to:
  - match up material property orientations to appropriate flaws
  - provide a “Circumferential Flaw” stress intensity factor correlation
- Extrapolation to P-T Limits:
  - Use Strong Direction Axial Flaw ART with standard ASME Section XI Appendix G Pressure stress
  - Use Weak Direction Circumferential Flaw ART with Code Case N-588
  - Increase Circumferential Flaw ART value to force Circumferential Flaw curve to just intersect the Axial Flaw Curve
  - The MOTA Margin can then be determined between the two flaw orientations

Parameters for Analysis

- Plants selected to cover the geometries of the entire PWROG Fleet
- Test Cases were run on four Westinghouse-Design, Two CE Design, and the B&W Design Plants
- Utilized ASME Appendix G, K_{Ic} for Axial Flaws (Strong Properties) and Code Case N-588 for Circumferential Flaws (Weak Properties)
- Bounding cases were performed for Steady-State Case and all heat-up and cooldown rates

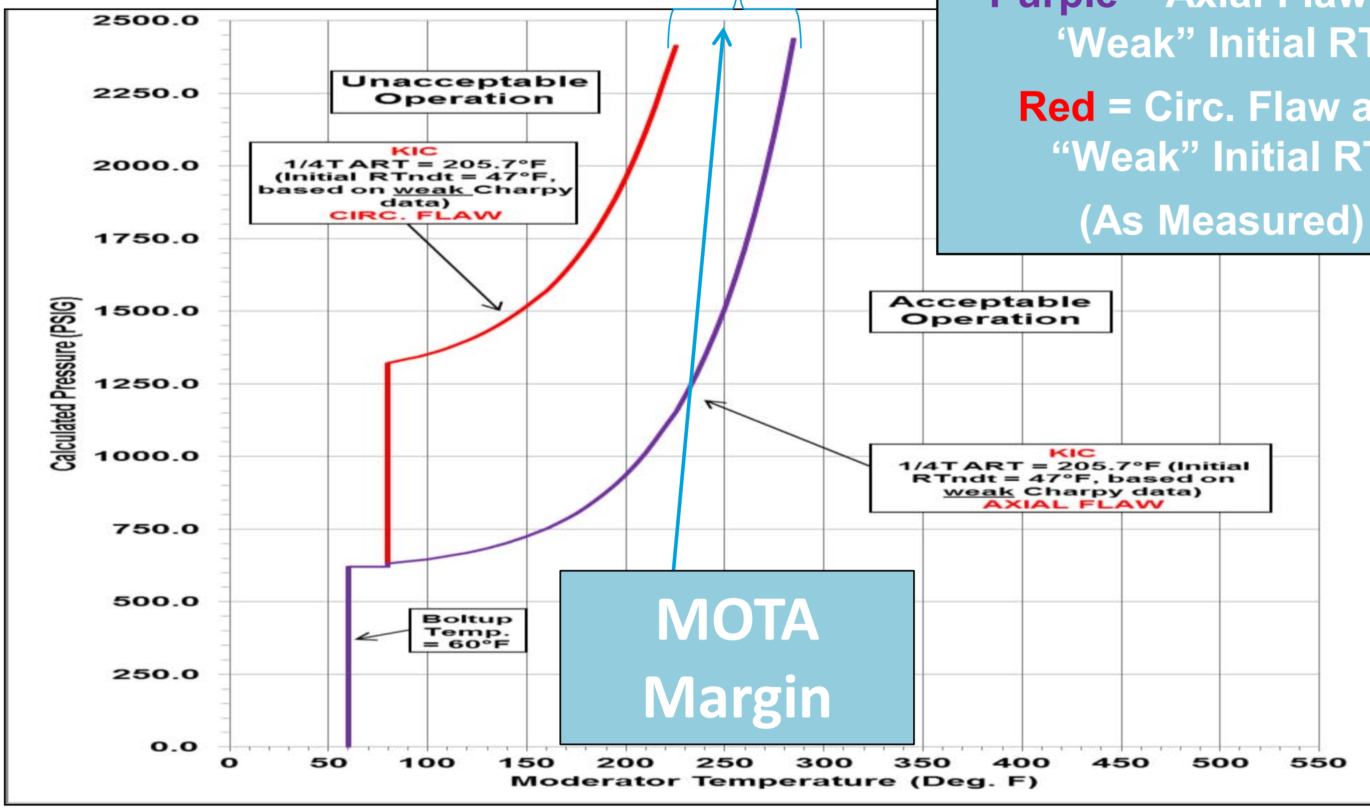
General Plant Information and Geometries Utilized for MOTA Investigation

Information					Dimensions (in.)		
Plant	Design	Rated Power (MW)	Vessel Manufacturer	Plate / Forging	Vessel ID	Vessel Wall	Cladding
A	W – 2-Loop	585	B&W	Forging	132	6.5	0.156
B	W – 3-Loop	855	CE	Plate	157	7.875	0.156
C	W – 4-Loop	1060	RDM	Forging	173	8.465	0.156
D	CE	805	CE	Plate	172.7	8.79	0.1875
E	CE	1333	CE	Plate	183.9	11.19	0.16
F	W – 4 -Loop	1048	CE	Plate	173.375	8.625	0.21875
G	B&W-177	870	B&W	Plate	171	8.44	0.1875

Input Values to P-T Curve Determination

Information	Dimensions (in.)		Initial (Axial) ART Values (°F)	
Plant	Inside Radius (in)	Outside Radius (in)	¼ T	¾ T
A	66.156	72.656	262	231
B	78.656	86.531	200	165
C	86.656	95.121	205.7	171.2
D	86.35	95.14	252.7	185.8
E	92.11	103.3	200	175
F	86.906	95.531	245	198.2
G	85.5	93.94	180	146

Steady-State Assessment Existing Axial K_{Ic} P-T Curve vs. "Circ." Curve – Plant "C"

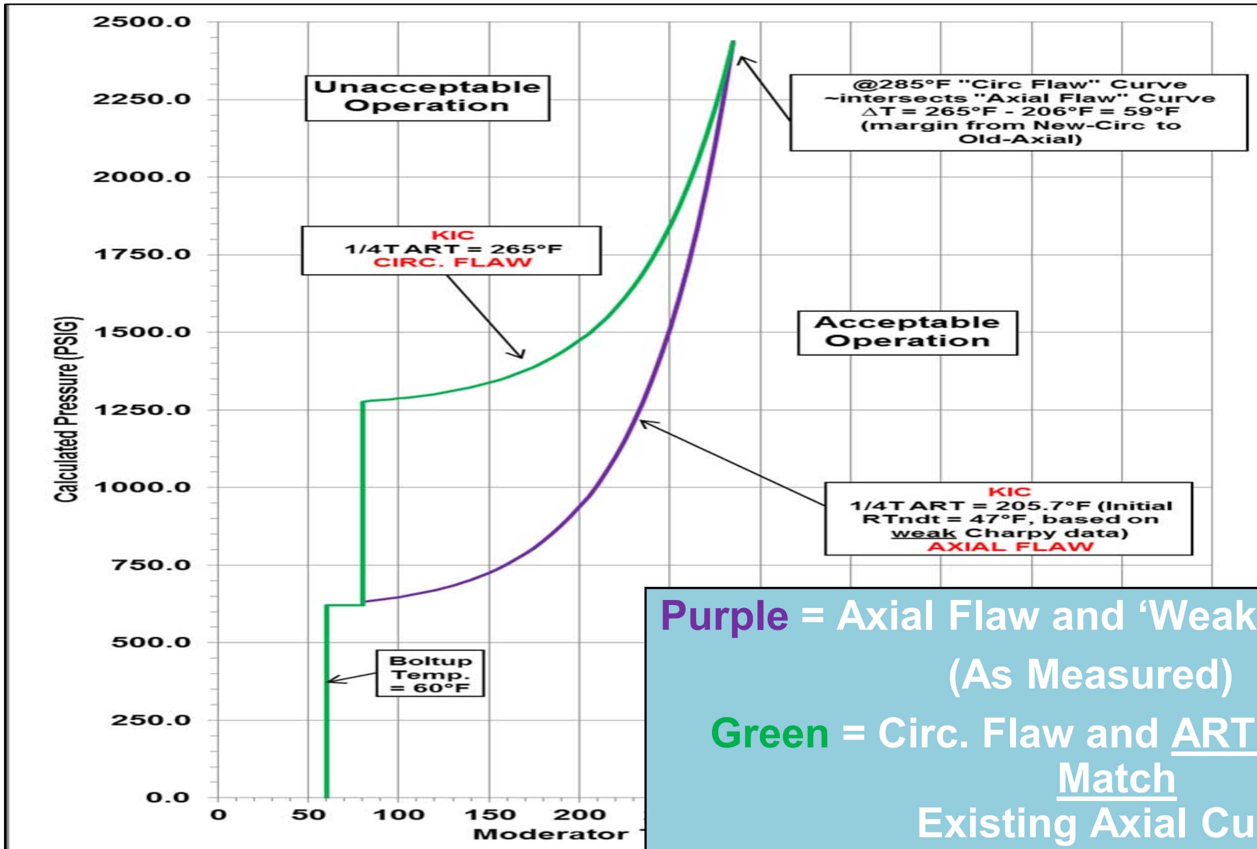


Purple = Axial Flaw and "Weak" Initial RT_{NDT}

Red = Circ. Flaw and "Weak" Initial RT_{NDT}

(As Measured)

Steady-State Assessment Existing Axial K_{Ic} P-T Curve vs. “Circ.” ART to Intersect – Plant “C”



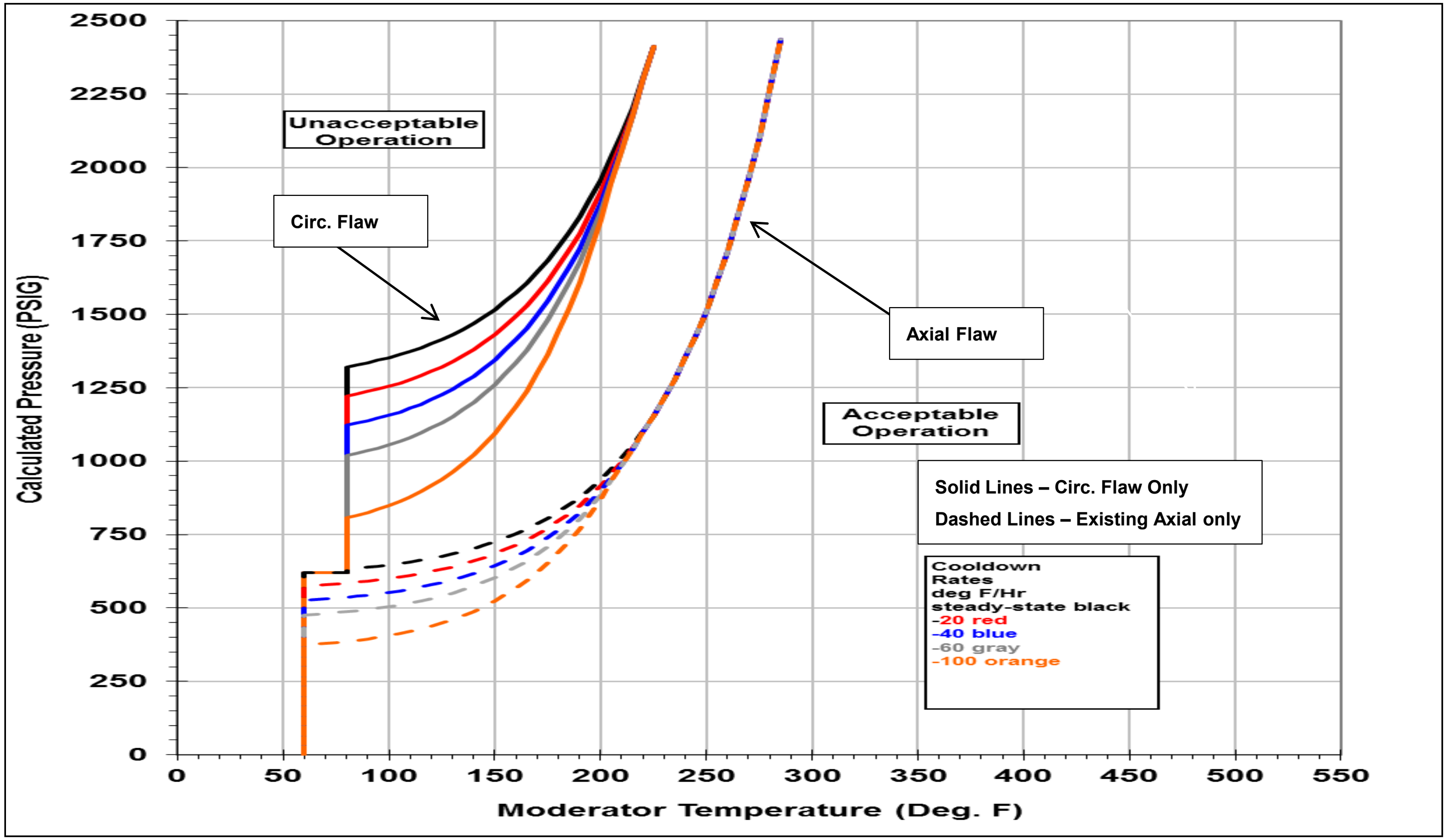
Purple = Axial Flaw and ‘Weak” Initial RT_{NDT} (As Measured)

Green = Circ. Flaw and <u>ART MOVED to Match</u> Existing Axial Curve (Raised Initial RT_{NDT})

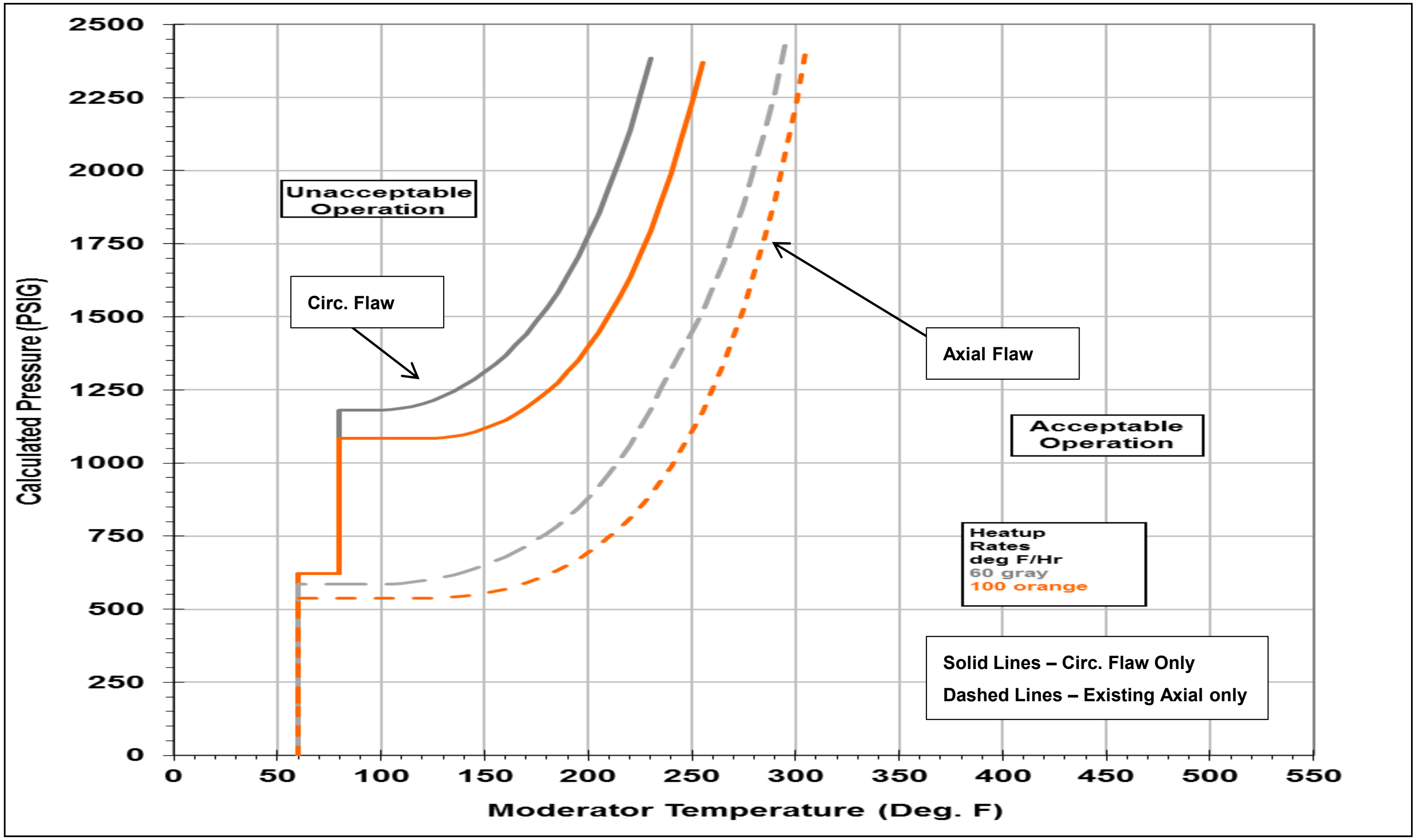
1/4T MOTA Margin Calculation – Plant "C"

- Axial Flaw ART = 205.7°F (Purple Curves)
- Circumferential Flaw ART Comparison = 205.7°F (Red Curve)
- Increased Circumferential Flaw ART to Just Intersect Axial Curve = 265°F (Green Curve)
- MOTA Margin = ART Circ. – ART Axial
- MOTA Margin = 265°F – 205.7°F = **59°F**

Cooldown - All Rates – Plant "C" Same ART Value



Heat-up - All Rates – Plant "C" Same ART Value



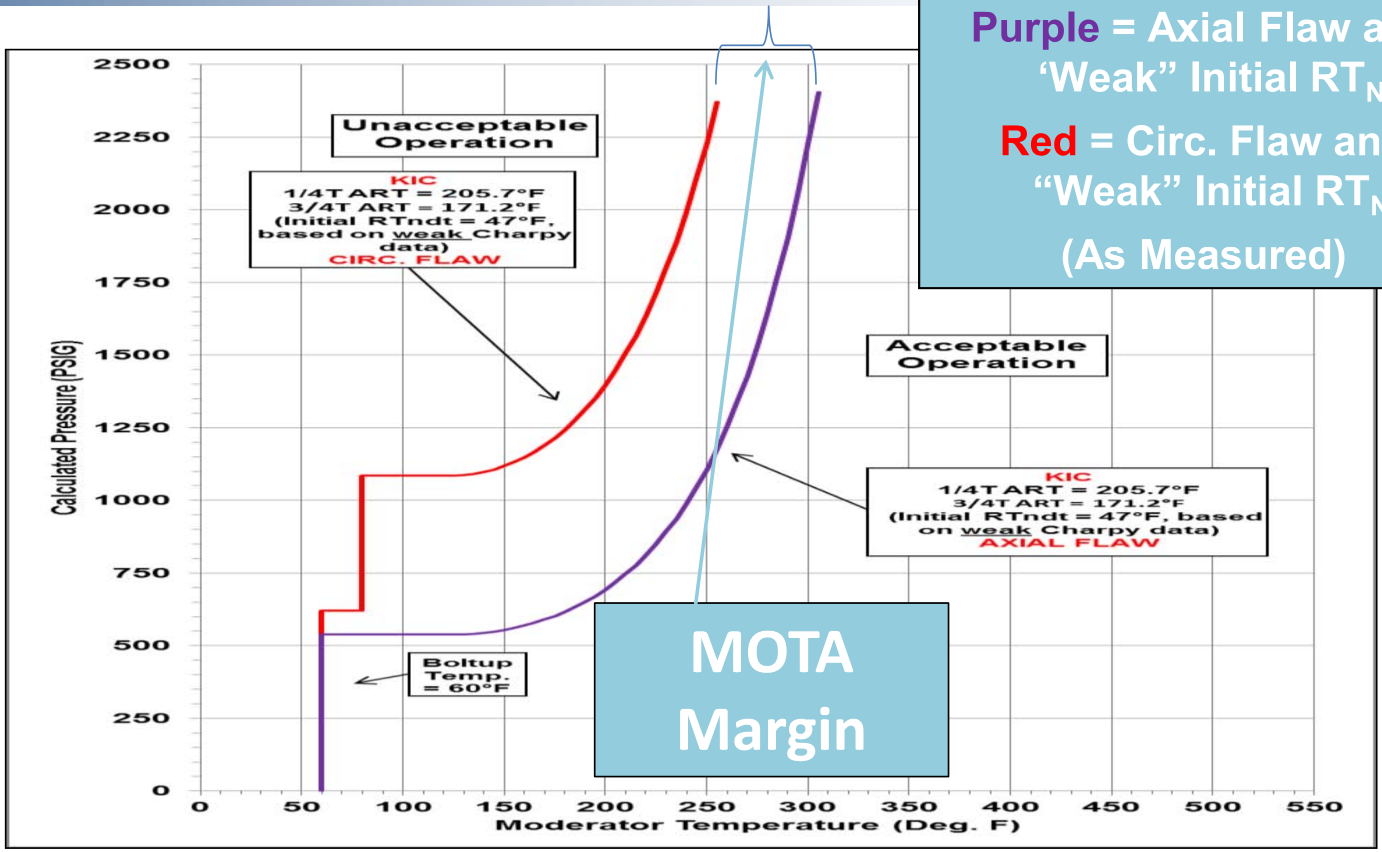
Final MOTA Margin (1/4T) Results

Plant Design		Plant	Vessel Mfr.	Plate / Forging	MOTA Margin (°F)
Westinghouse	2-Loop	A	B&W	Forging	66
	3-Loop	B	CE	Plate	61
	4-Loop	C	RDM	Forging	59
		F	CE	Plate	58.5
CE	2-Loop	D	CE	Plate	60
	Sys. 80	E	CE	Plate	61
B&W	B&W-177	G	B&W	Plate	60

Effect of Heatup Curve (3/4T)

- Flaw Orientation Limiting Locations
  - Axial – Low Temperature/Pressure
  - Circumferential – High Temperature/Pressure
- 1/4T ART values dominate the steady-state curve
  - High Temperature/Pressure, Steady-State is limiting as shown previously
- 3/4T Value dominates the heatup curves
  - Still applicable at high temperature and pressure regions
- Further investigation was performed for MOTA margin on the heat-up transient, 3/4T ART value – See slides below

100°F/hr Assessment (3/4T Limiting) Existing Axial K_{Ic} P-T Curve vs. "Circ." Curve – Plant "C"

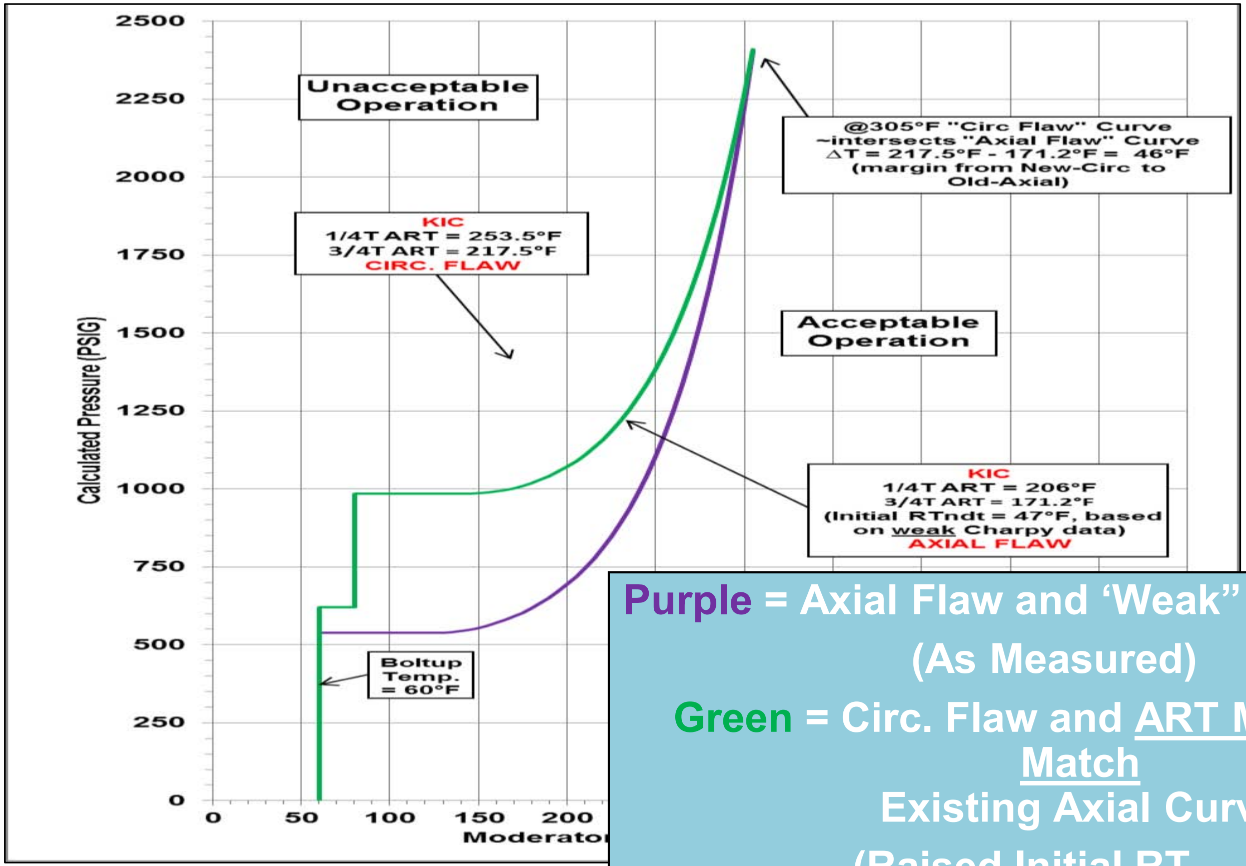


Purple = Axial Flaw and 'Weak" Initial RT_{NDT}

Red = Circ. Flaw and "Weak" Initial RT_{NDT}

(As Measured)

100°F/hr Assessment Existing Axial K_{Ic} P-T Curve vs. "Circ." ART to Intersect – Plant "C"



Purple = Axial Flaw and 'Weak" Initial RT_{NDT} (As Measured)

Green = Circ. Flaw and ART MOVED to Match Existing Axial Curve (Raised Initial RT_{NDT})

3/4T MOTA Margin Calculation – Plant "C"

- Axial Flaw ART = 171.2°F (Purple Curves)
- Circumferential Flaw ART Comparison = 171.2°F (Red Curve)
- Increased Circumferential Flaw ART to Just Intersect Axial Curve = 217.5°F (Green Curve)
- MOTA Margin = ART Circ. – ART Axial
- MOTA Margin = 217.5°F – 171.2°F = **46°F**

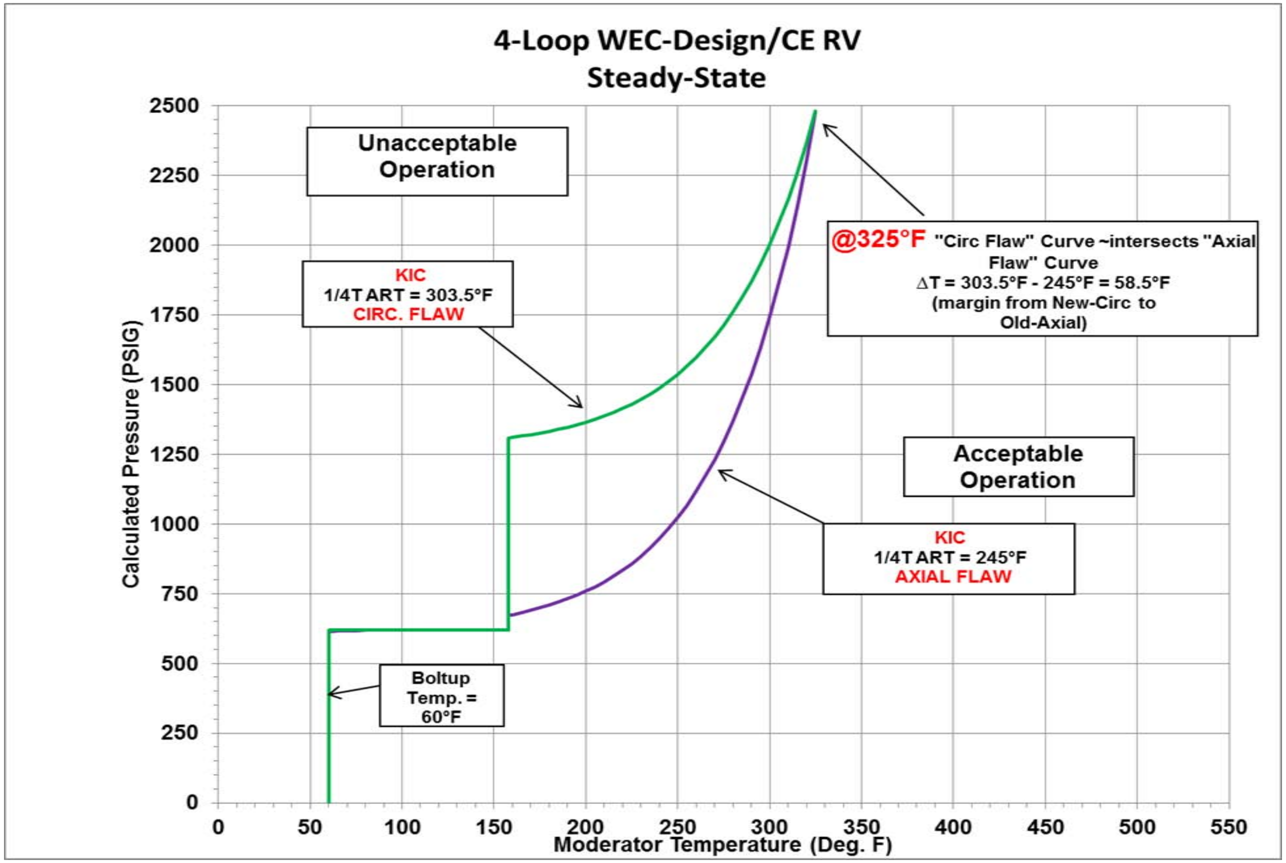
Governing MOTA Margin (3/4T) Results

Plant Design		Plant	Vessel Mfr.	Plate / Forging	MOTA Margin (°F)	
					1/4T	3/4T
Westinghouse	2-Loop	A	B&W	Forging	66	61
	3-Loop	B	CE	Plate	61	50
	4-Loop	C	RDM	Forging	59	46
		F	CE	Plate	58.5	48
CE	2-Loop	D	CE	Plate	60	62
	Sys. 80	E	CE	Plate	61	40
B&W	B&W-177	G	B&W	Plate	60	48

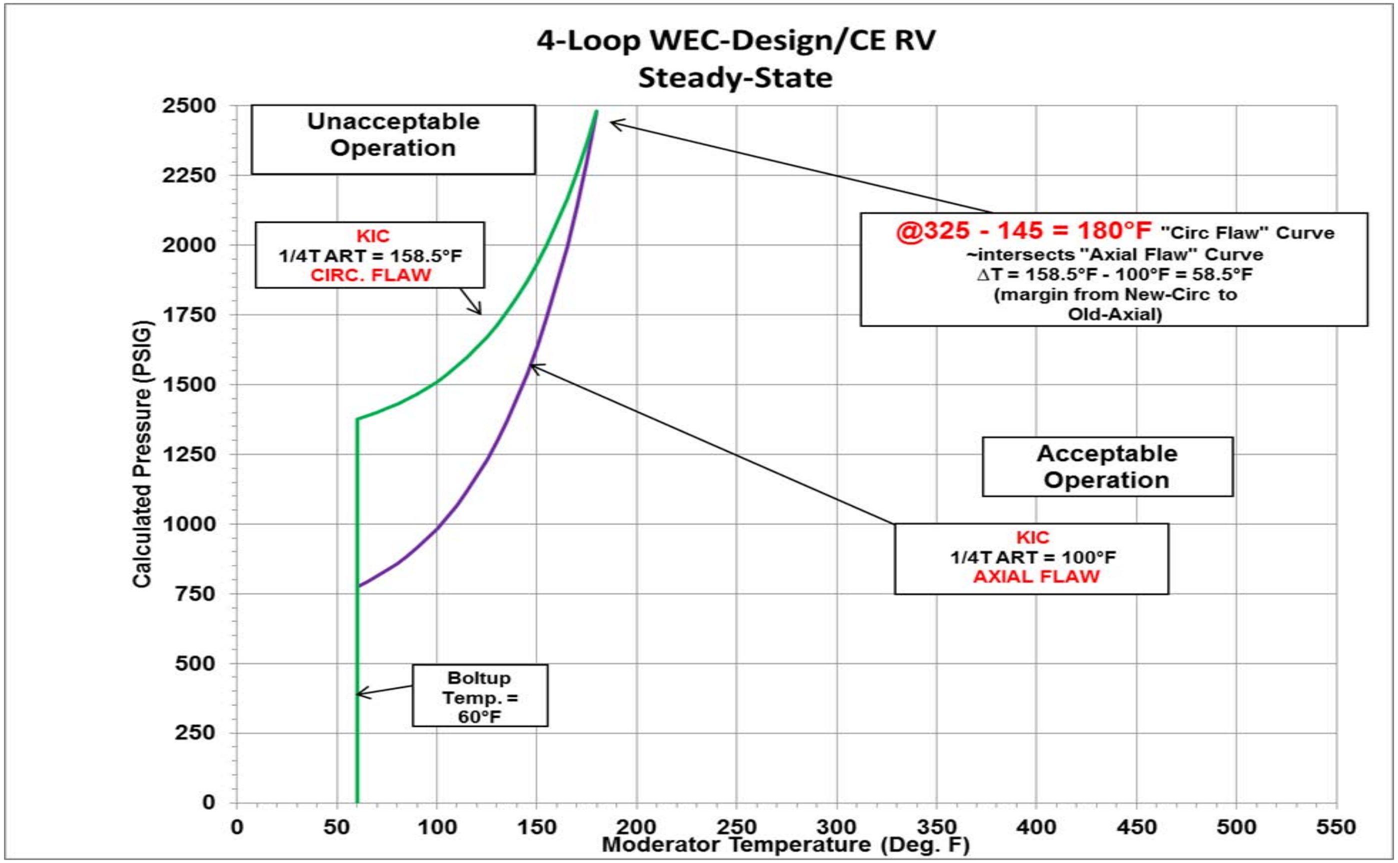
Effect of Varying 1/4T ART Values

- Selected Plant F for first sensitivity study as it had the lowest MOTA (1/4T) Margin
- Investigated effect on MOTA Margin
  - Low ART values (1/4T = 100°F)
  - High ART values (1/4T = 390°F)
- Analysis showed that 1/4T ART magnitude has no effect on the MOTA margin
- Temperature point where Circumferential flaw curve intersected Axial flaw curve = the change in ART value, as shown on the following figures

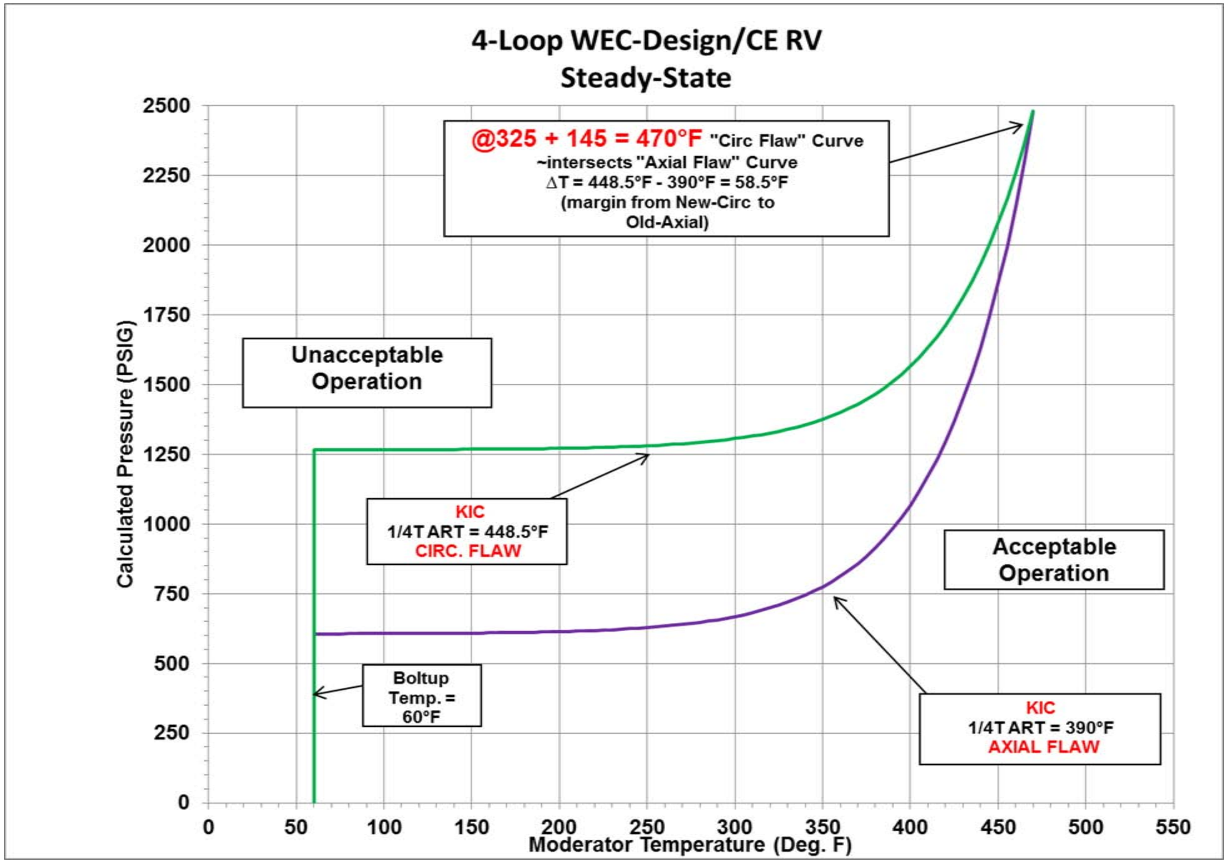
Steady-State Assessment "Nominal ART" Axial K_{Ic} P-T Curve vs. "Circ." ART to Intersect – Plant "F"



Steady-State Assessment "Low ART" Axial K_{Ic} P-T Curve vs. "Circ." ART to Intersect – Plant "F"



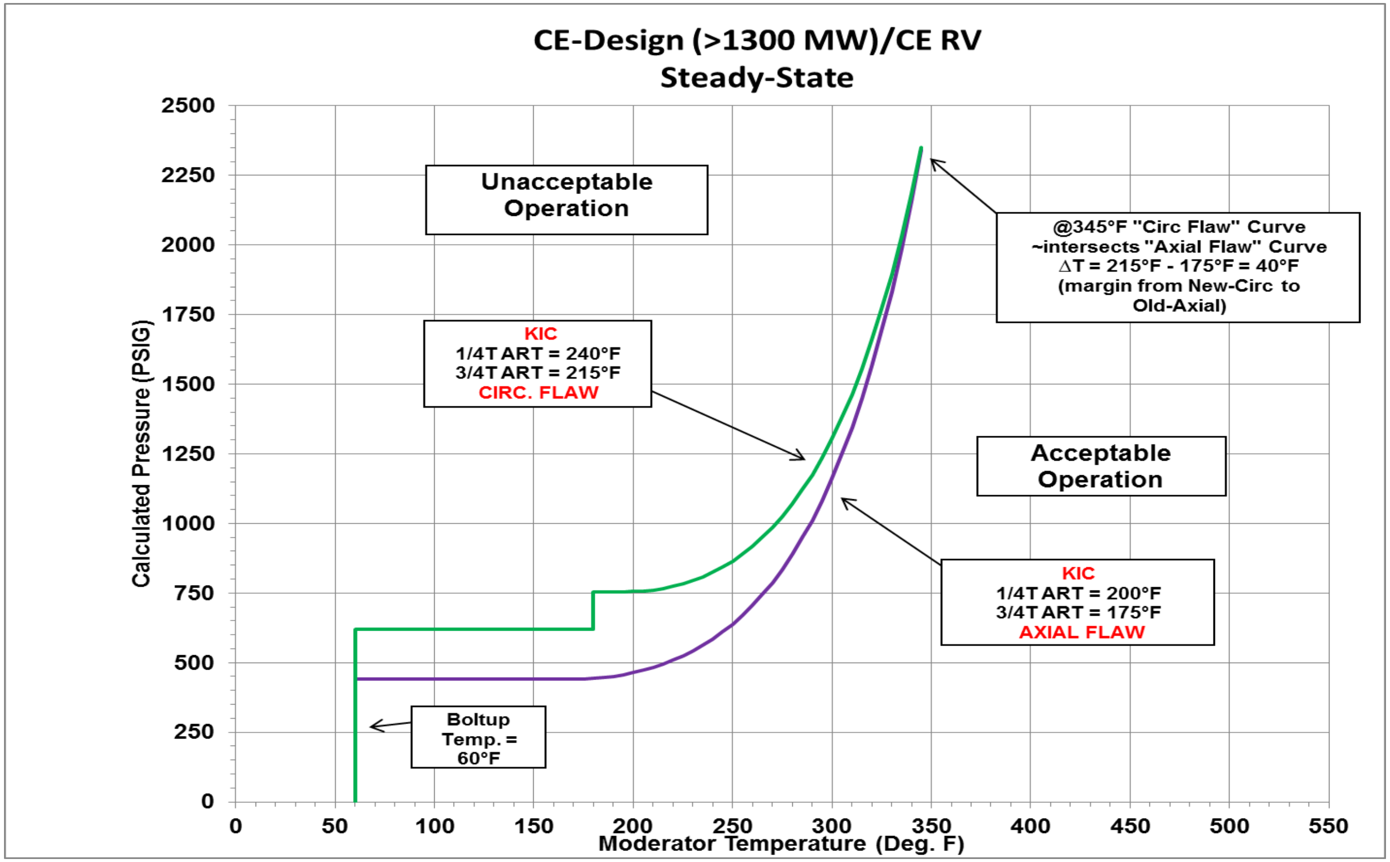
Steady-State Assessment "High ART" Axial K_{Ic} P-T Curve vs. "Circ." ART to Intersect – Plant "F"



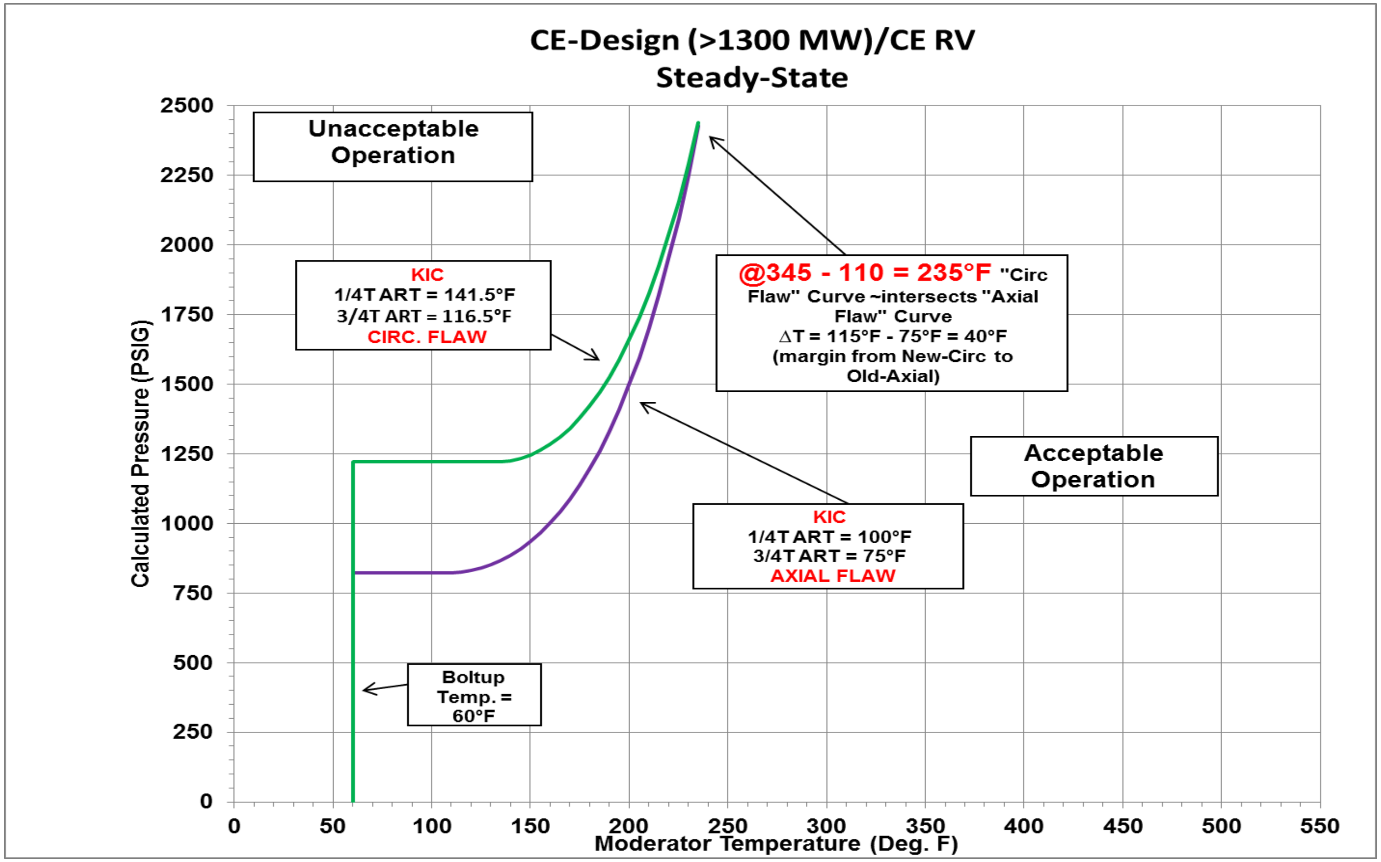
Effect of Varying 3/4T ART Values

- Selected Plant E for second sensitivity study as it had the lowest MOTA (3/4T) Margin and the thickest reactor vessel
- Investigated effect on MOTA Margin
  - Low ART values (3/4T = 75°F)
  - High ART values (3/4T = 275°F)
- Analysis shows that 3/4T ART magnitude has negligible effect on the MOTA margin
- The largest variation is +/- 1.5°F across all RV thicknesses

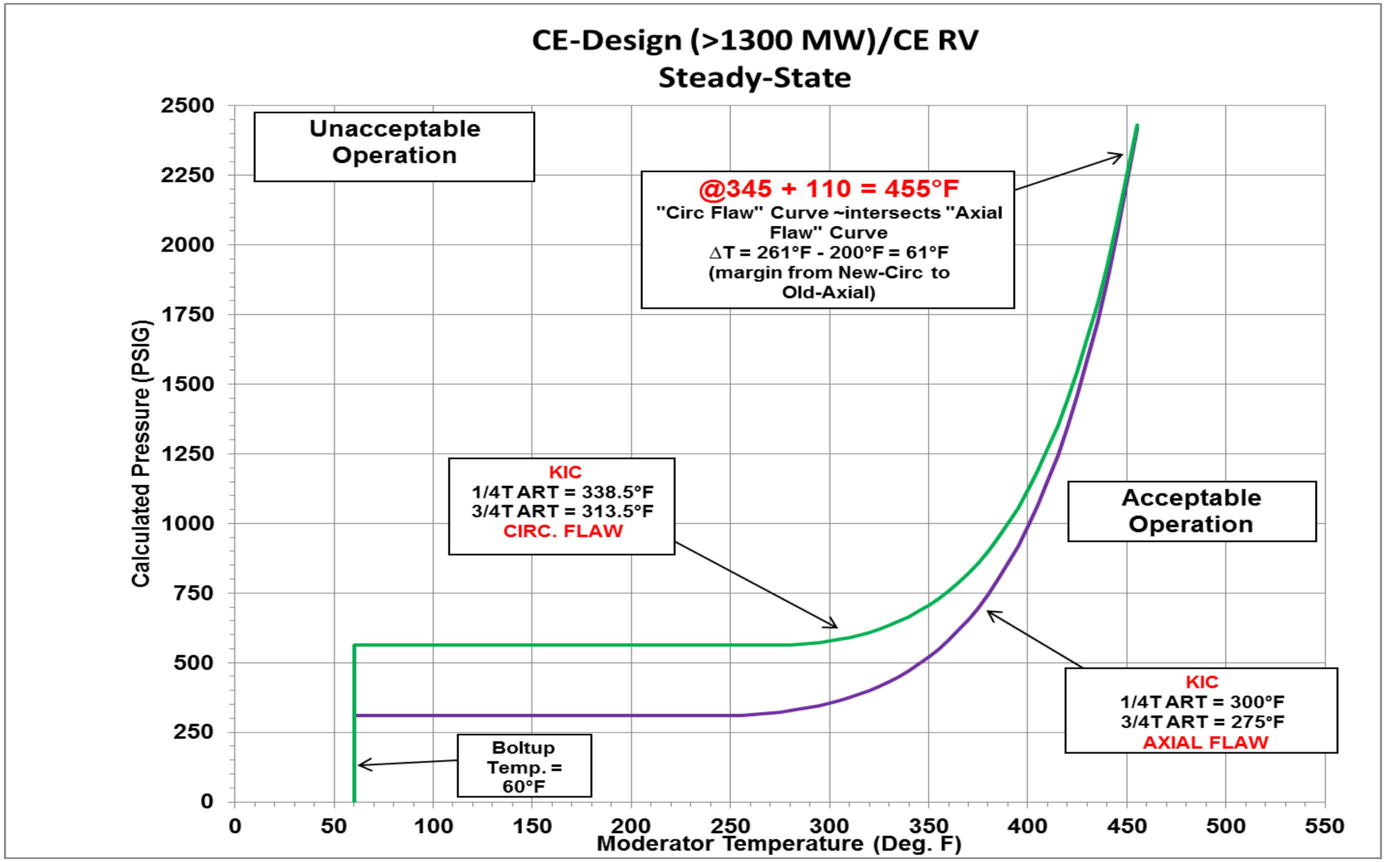
100°F/hr Assessment "Nominal ART" Axial K_{Ic} P-T Curve vs. "Circ." ART to Intersect – Plant "E"



100°F/hr Assessment "Low ART" Axial K_{Ic} P-T Curve vs. "Circ." ART to Intersect – Plant "E"



100°F/hr Assessment "High ART Axial K_{Ic} P-T Curve vs. "Circ." ART to Intersect – Plant "E"



Final MOTA Margin Analysis Results

- Minimum MOTA Margin Values

Plant	Plate/Forging	Margin (°F)	
		1/4T	3/4T
C	Forging	59	46
F	Plate	58.5	48
E	Plate	61	40

- Maximum – Plant A (Forging)
  - 1/4T of 66°F, 3/4T of 61°F
- The analysis demonstrated that there is:
  - no effect of the reactor vessel ART values on the MOTA Margin at the 1/4T location
  - negligible effect of the reactor vessel ART values on the MOTA Margin at the 3/4T location.
- MOTA Margin covers the entire US PWROG Fleet, with consistent results across all three plant designs

MOTA Conclusions

- The axial flaw fracture behavior is governed by strong direction properties in both plates and forgings in the RPV cylindrical shell sections.
- The issue of the conservatism of BTP 5-3 estimation methods pertains primarily with the uncertainty in the ability to estimate the weak Charpy impact properties from measured strong Charpy properties.
- Since the forging and plate measured strong properties are coincident with the assessed 10 CFR 50, Appendix G axial flaw, the use of an RT_{NDT} based on weak properties contains inherent margin.

MOTA Conclusions

- The BTP 5-3 uncertainty in estimating RT_{NDT} in the weak direction (circumferential flaw) identified by the industry should be compared to the margin identified herein for the circumferential flaw.
- Plate and High USE Forging (>140 ft-lb) Plant Conclusion
  - The minimum MOTA Margin (40°F) exceeds the maximum BTP 5-3 uncertainty effect on ART of 26°F
- Low USE Forging (<140 ft-lb) Plant Conclusions
  - The minimum MOTA Margin at 1/4T (59°F) exceeds the BTP 5-3 uncertainty effect on ART of 54°F
  - The minimum MOTA Margin at 3/4T (46°F) is on par with the BTP 5-3 uncertainty effect on ART of 54°F
- The current methods for developing P-T curves are acceptable in light of the identified BTP 5-3 estimation uncertainties.

Questions?

The Materials Committee is established to provide a forum for the identification and resolution of materials issues including their development, modification and implementation to enhance the safe, efficient operation of PWR plants.

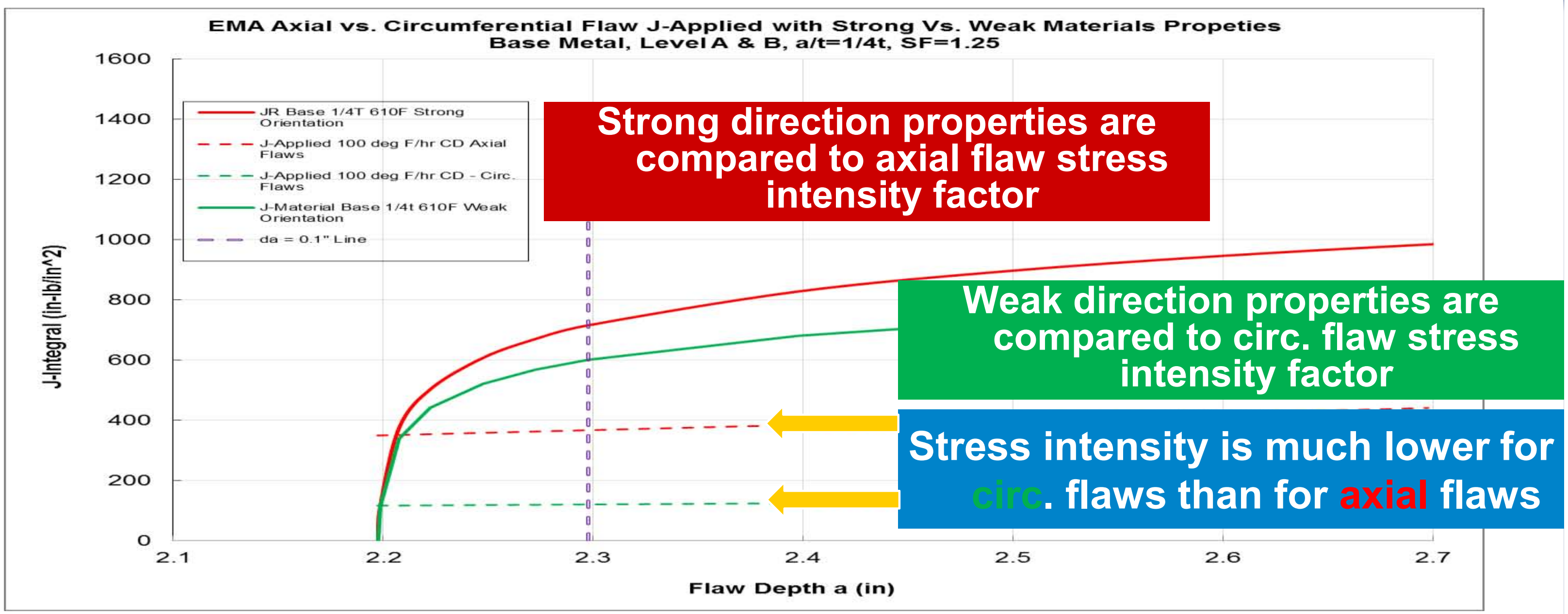
DRAFT

Back-Up Slide

EMA Visual Example: J-Applied vs. J-Material for Axial and Circ. Flaws

Solid Lines = Material Fracture Toughness

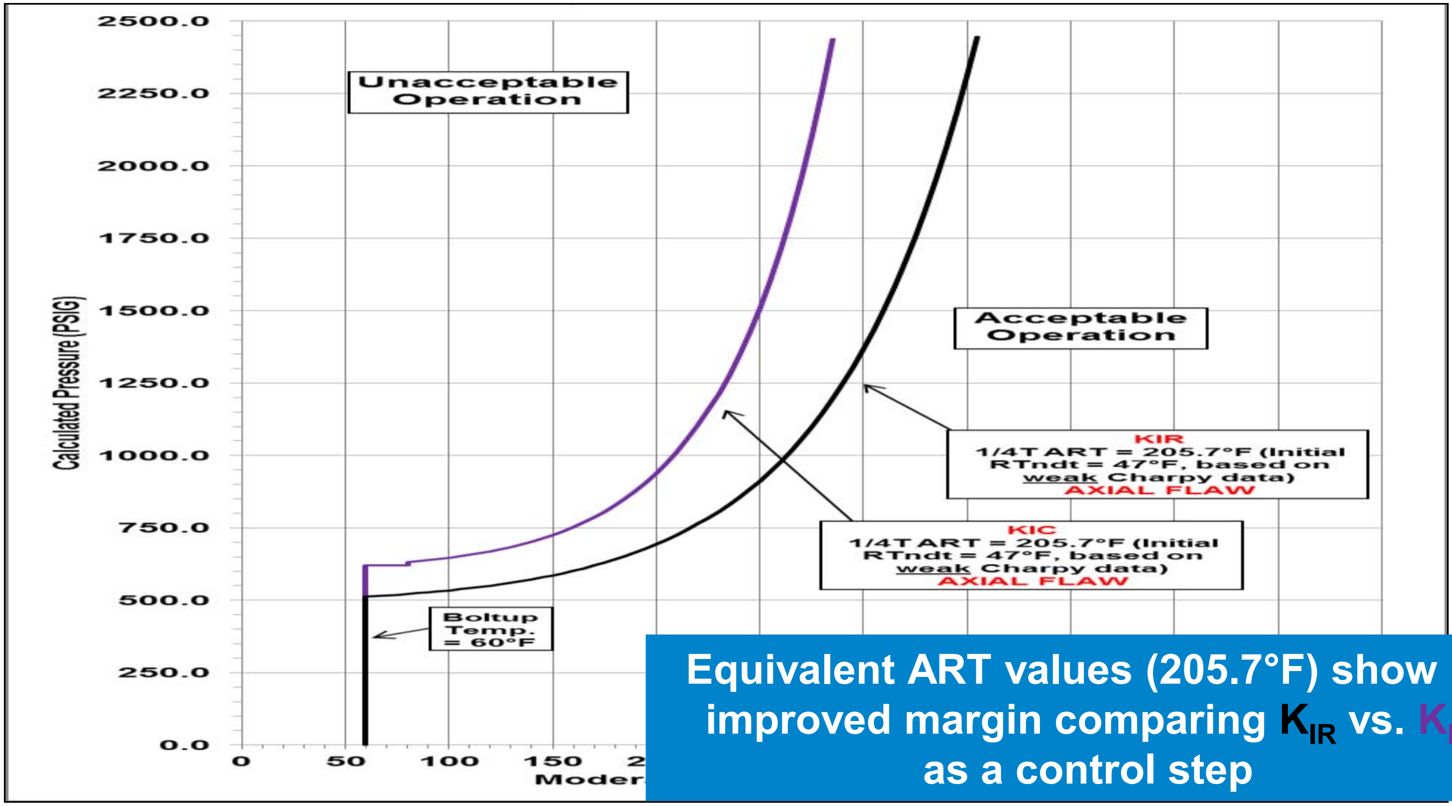
Dashed Lines = Applied Stress Intensity Factor (SIF)



Red = Axial Flaw and Strong Material Property

Green = Circ. Flaw and Weak Material Property

Steady-State Assessment K_{Ic} vs. K_{IR} Control – Plant "C"



Equivalent ART values (205.7°F) show improved margin comparing K_{IR} vs. K_{Ic} as a control step

Lower MOTA Margin for 3/4T?

- Which ART Value Dominates at Axial-Circumferential Flaw Cross-Over Point, i.e. top of the P-T curve?
  - 1/4T, Steady-State Limited
  - 3/4T, Heatup Transient Limited
- Since 3/4T values are limiting at cross-over point for heat-up, the K_{It} thermal SIF component of P-T limit curves is non-zero
- This higher stress state leads to a lower MOTA Margin

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