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PWROG Materials Committee RPV Integrity Projects

Industry/NRC Exchange Meeting

June 2015

Chris Koehler – Xcel Energy, Chairman PWROG MSC

Brian Hall – Westinghouse

Date: June 3, 2015

PWROG RPV Projects Agenda

- Material Orientation Toughness Assessment (MOTA) for the Purpose of Mitigating Branch Technical Position (BTP) 5-3 Uncertainties
- Demonstrate Appendix G Margins for PWR RPV Nozzles
- Update of Surveillance Capsule Fluence Summary Report
- Plan for Transitioning RV Integrity to Direct Fracture Toughness

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

Chris Koehler – Xcel Energy, Chairman PWROG MSC
Elliot Long/Brian Hall – Westinghouse

Introduction

- 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
- Some data calls into question the conservativeness of the baseline RT_{NDT} values of reactor vessels for whose materials BTP 5-3 methods were used
- EPRI investigated and quantified the BTP 5-3 uncertainties and performed Probabilistic Fracture Mechanics (PFM) evaluations to assess the impact

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

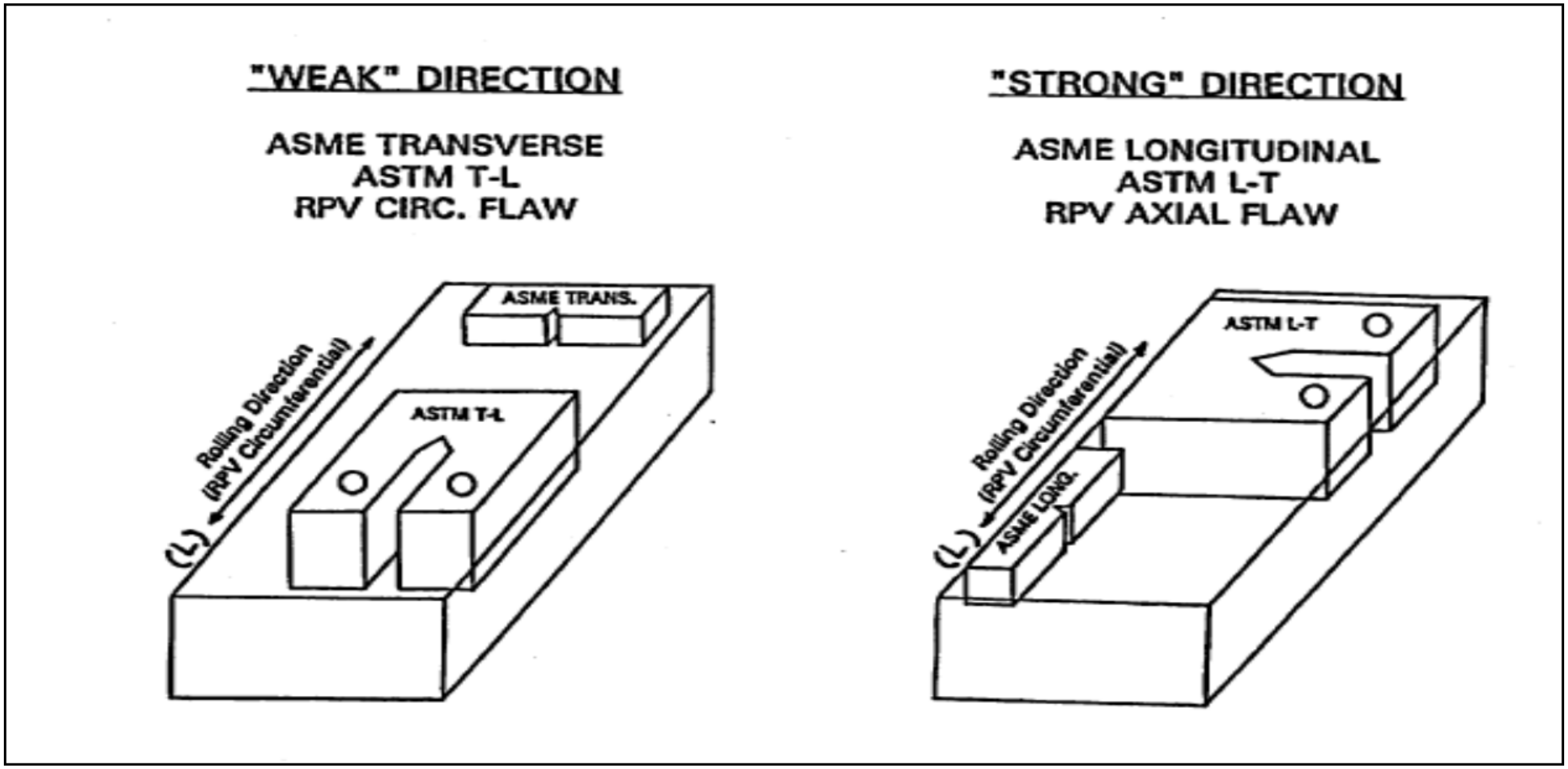
Regulatory Guide 1.161 Text

- 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."

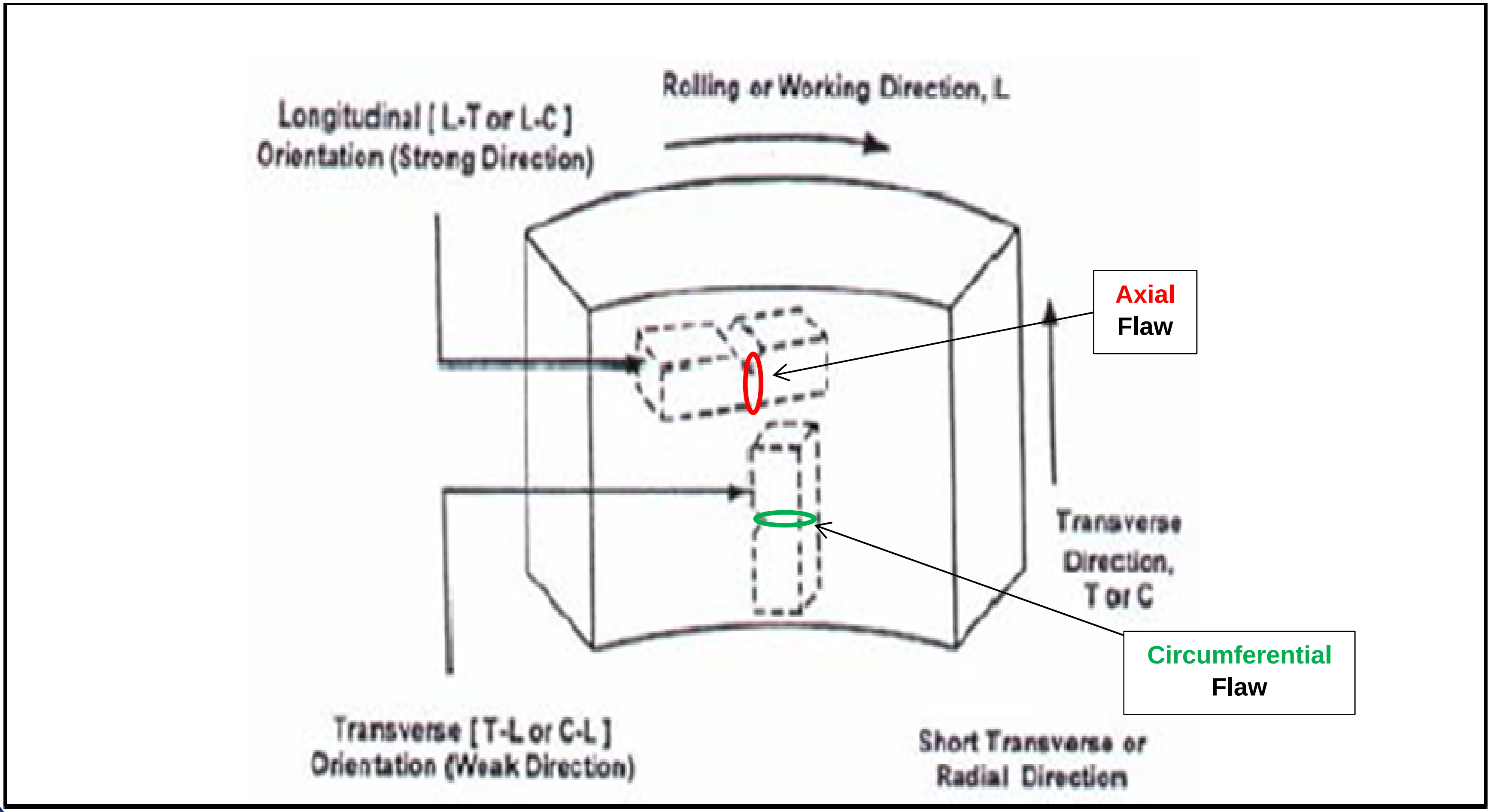
- This approach, as defined in RG. 1.161, is technically valid for assessing BTP 5-3 uncertainty

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

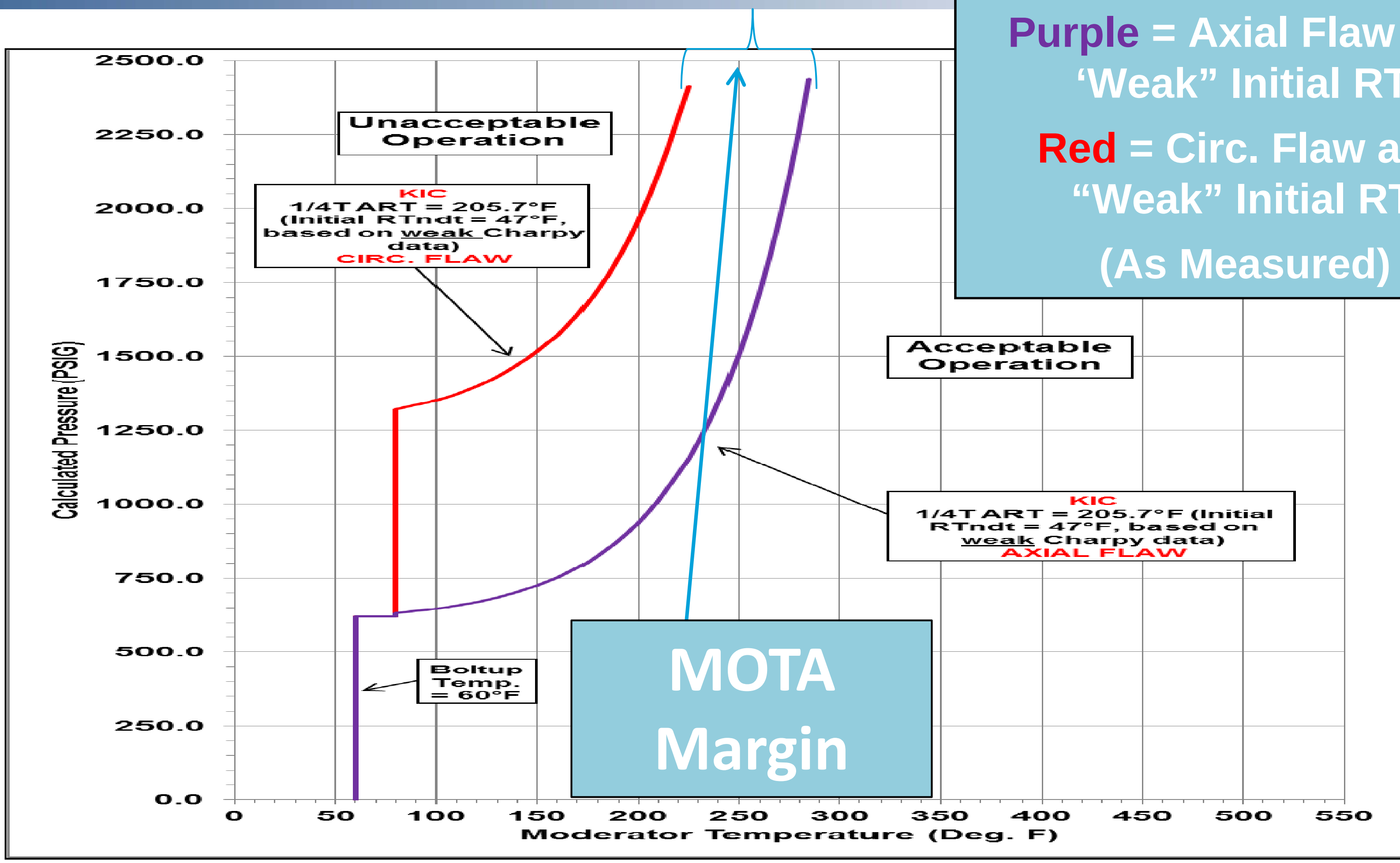
- ASME required transverse properties for all components, which is conservative

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

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



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

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

(As Measured)

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.
- The BTP 5-3 uncertainty in estimating RT_{NDT} in the weak direction (circumferential flaw) identified by the industry can be compared to the deterministic margin identified herein for the circumferential flaw.
- The current methods for developing P-T curves are acceptable in light of the identified BTP 5-3 estimation uncertainties.

MOTA Status

- Presented technical case at February 19th, 2015 public meeting
- Deterministic PWROG MOTA evaluation compliments MRP/BWRVIP probabilistic work
- Final report to be completed in June 2015
- Submittal to NRC for information is planned

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Demonstrate Appendix G Margins for PWR RPV Nozzles

Chris Koehler – Xcel Energy, Chairman PWROG MSC

Brian Hall – Westinghouse

Background

- Multiple RAIs have been issued to various licensees with regards to consideration of the reactor vessel nozzle corner in P/T curves
- Responding to RAIs has been costly for utilities
- RIS 2014-11 states:
  - "All addressees should ensure that P-T limits sufficiently address all ferritic materials of the reactor vessel, including the impact of structural discontinuities, and address the impact of neutron fluence accumulation in accordance with the requirements of 10 CFR Part 50, Appendix G."
- Recent traditional approach uses very conservative 1/4T nozzle flaw
  - All nozzle P-T curve RAI responses to date have shown that existing plant P/T curves bound the nozzle curves

Purpose

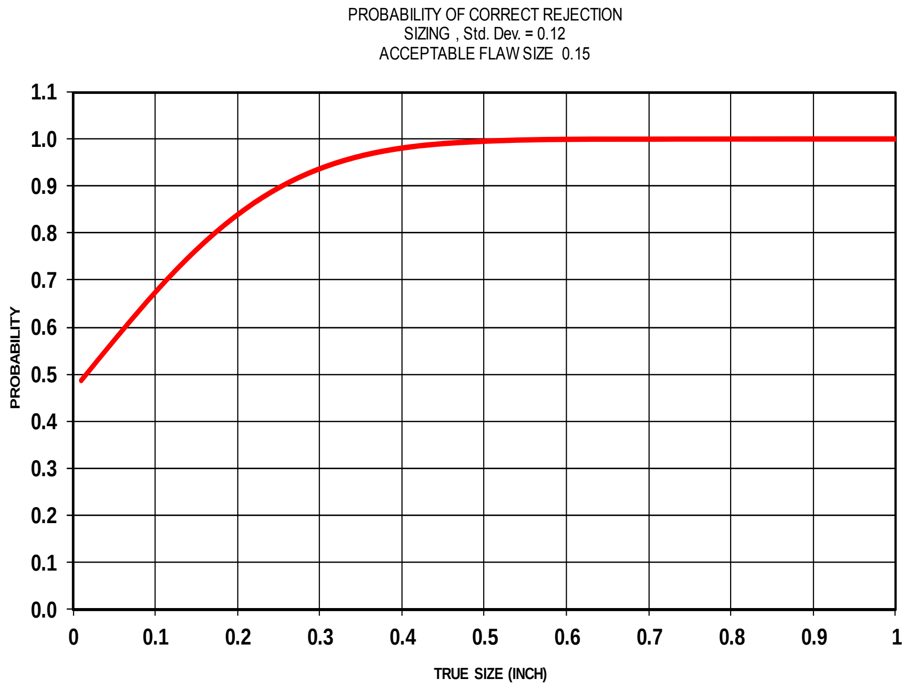
- Identify the magnitude of the various ASME Appendix G margins related to assessment of the PWR inlet/outlet nozzles
- Develop a basis for generically addressing nozzles supporting P-T curve submittals
- Justify the use of the RPV beltline region as the limiting region to be used for P-T curves thereby demonstrating that current approved methodologies comply with Appendix G

Approach

- Document the following conservatisms for the PWR inlet/outlet nozzles
  - Establish acceptable smaller postulated flaws
  - Generic near surface alternate RT_{NDT} (RTT_0)
    - Previously approved Code Case N-629
      - » Now incorporated into Appendices A and G
    - Avoids BTP 5-3 uncertainties
  - Constraint condition

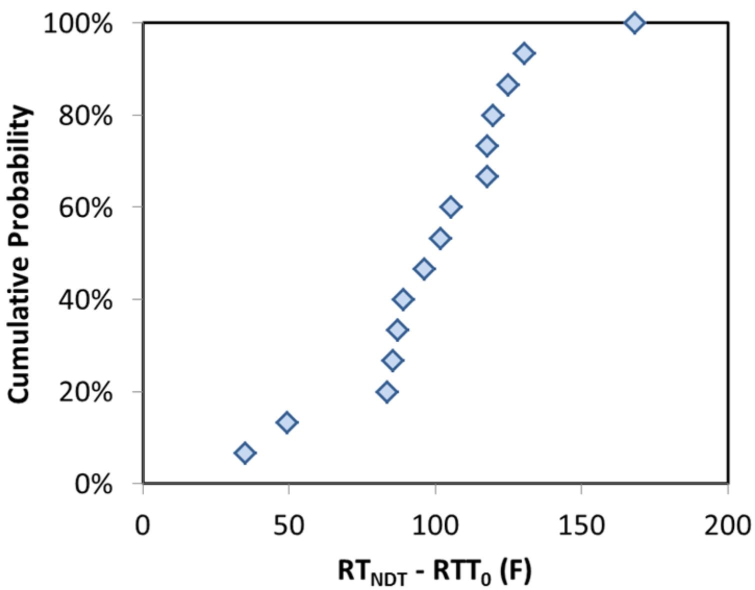
Postulated Flaws

- It is not necessary to postulate large flaws
  - Small flaws are detectable with high probability
  - No indications have been found in over 2000 reactor years in nozzle ID exams
  - ASME Section XI Appendix G allows use of smaller postulated flaws in regions of discontinuity



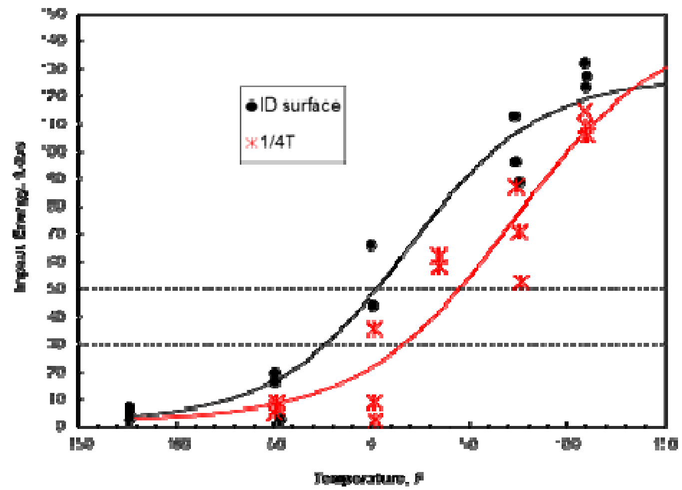
Generic RTT_0

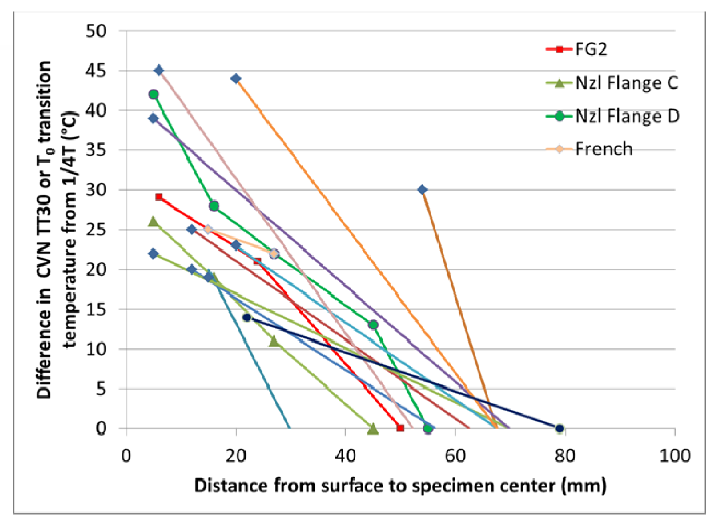
- **Generic RTT_0 Value Determination**
  - Master Curve reference temperature data gathered on the following equivalent grades:
    - SA-508 Class 2 (also ASTM A-508 Class 2)
    - 22NiMoCr37 which is a DIN comparable
    - SFVQ2A which is Japanese equivalent
  - Results summary (22 distinct A-508 Cl. 2 type forgings)
    - Alternate generic mean RT_{NDT} = RTT_0 = -66°F
    - Margin = 2 σ_I = 109°F
    - ART = 43°F (with no embrittlement)
  - This is better than the generally accepted upper bound RT_{NDT} of 60°F
  - Avoids the use of BTP 5-3 and GE procedure which would be necessary for many nozzles
  - True measure of fracture toughness transition temperature
  - Significant margin between RTT_0 and RT_{NDT} in all cases



Near Surface Toughness

- Small flaw enables use of near surface toughness data
- Surface properties are better due to faster cooling rate during quenching
  - Produces a finer microstructure, smaller carbide phases, reduced length of linear phase boundaries, and some tempered martensite
  - Results in better Charpy properties and fracture toughness
  - NB-2223.2 For thick and complex forgings specimens may be taken as close as ¾” (19mm) to any heat treated surface





Nozzle Corner Embrittlement

- RIS 2014-11 “all ferritic components within the entire reactor vessel must be considered in the development of P-T limits, and the effects of neutron radiation must be considered for any locations that are predicted to experience a neutron fluence exposure greater than $1x10^{17}$ n/cm^2 (E > 1 MeV) at the end of the licensed operating period.”
- Maximum fluence projected near nozzle inside corner surface ~$1.5x10^{17}$ n/cm^2 at 60 years for some plants
  - Cu = 0.18% and Ni = 0.91% (Upper bound values per ORNL/TM-2006/530)

3D Finite Element Analysis (FEA)

- 3D FEA will be performed for an inlet and an outlet nozzle with two postulated small flaw depths and two aspect ratios each for the Westinghouse 4-loop design
- The Westinghouse 4-loop nozzle configurations will be demonstrated to be limiting relative to the 2 and 3-loop Westinghouse, B&W and CE designs
- The analysis will take into account
  - crack-face pressure,
  - bounding applicable piping loads,
  - cladding/low alloy steel differential thermal expansion,
  - and the cladding residual stress
- Stress intensity factors (K_I) will be calculated along the crack front
- Constraint condition will be determined
  - Loss of constraint leads to a reduction of the crack opening stress and, as a result, to a reduction of the failure probability
  - Published papers show significant increase in toughness at nozzle corner due to loss of constraint

Summary of Approach

- Small postulated flaw
  - Basis and precedent set with Code Case N-648-1 and BWRVIP-108
- Generic near surface alternate RT_{NDT} (RTT_0)
  - Conservative values used
  - Code Case N-629 (ASME XI Appendix G)
  - Avoids BTP 5-3 uncertainties
- Conservative fluence and chemistry to account for embrittlement
- 3D FEA
  - Detailed K_I
  - Constraint condition

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Update of Surveillance Capsule Fluence Summary Report

Chris Koehler – Xcel Energy, Chairman PWROG MSC
Brian Hall - Westinghouse

Purpose

- Provide single source for latest PWR capsule fluence values
  - Updated fluence values for each capsule
  - Includes latest capsules
  - Include irradiation temperatures
  - Effective Full Power Years (EFPY)

Benefits

- Provide a single point of reference for a set of fluence estimates for surveillance capsules withdrawn from Westinghouse, CE and B&W designed reactors through 2014
- This data, most of which are compliant with the requirements of Regulatory Guide 1.190, will improve the ability to cross-correlate data for common materials irradiated in different reactors
- Ability to easily find temperature and current fluence data for specific pressure vessel materials irradiated in sister plants and for evaluations using modern methods

Project Overview

- Data being compiled for US PWRs:
  - o Year withdrawn
  - o EFPY for each capsule (at time of withdrawal)
  - o Latest calculated fast neutron fluence (E > 1.0 MeV)
  - o Time weighted average irradiation temperature of cold leg (downcomer)
  - o Iron atom displacement (if available)
  - o Indication if capsule analysis is not compliant with Reg. Guide 1.190
- Proprietary report
  - Nearly complete
- Intend to provide to NRC reactor embrittlement archive project (REAP) database, which can handle proprietary data
  - Very useful in evaluating/developing embrittlement prediction models

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Plan for Transitioning RV Integrity to Direct Fracture Toughness

Chris Koehler – Xcel Energy, Chairman PWROG MSC

Brian Hall - Westinghouse

Purpose

- Develop a plan for transitioning to direct fracture toughness measurement for RV integrity
- Plan benefits
  - Enable an evaluation of the costs & benefits
  - Provide for an orderly, planned progression
  - The ultimate use of direct fracture toughness will establish a better basis for RV integrity which will:
    - Support 80 years of operation,
    - Reduce uncertainty,
    - Prevent future issues and
    - Identify margin to P-T curves

Background

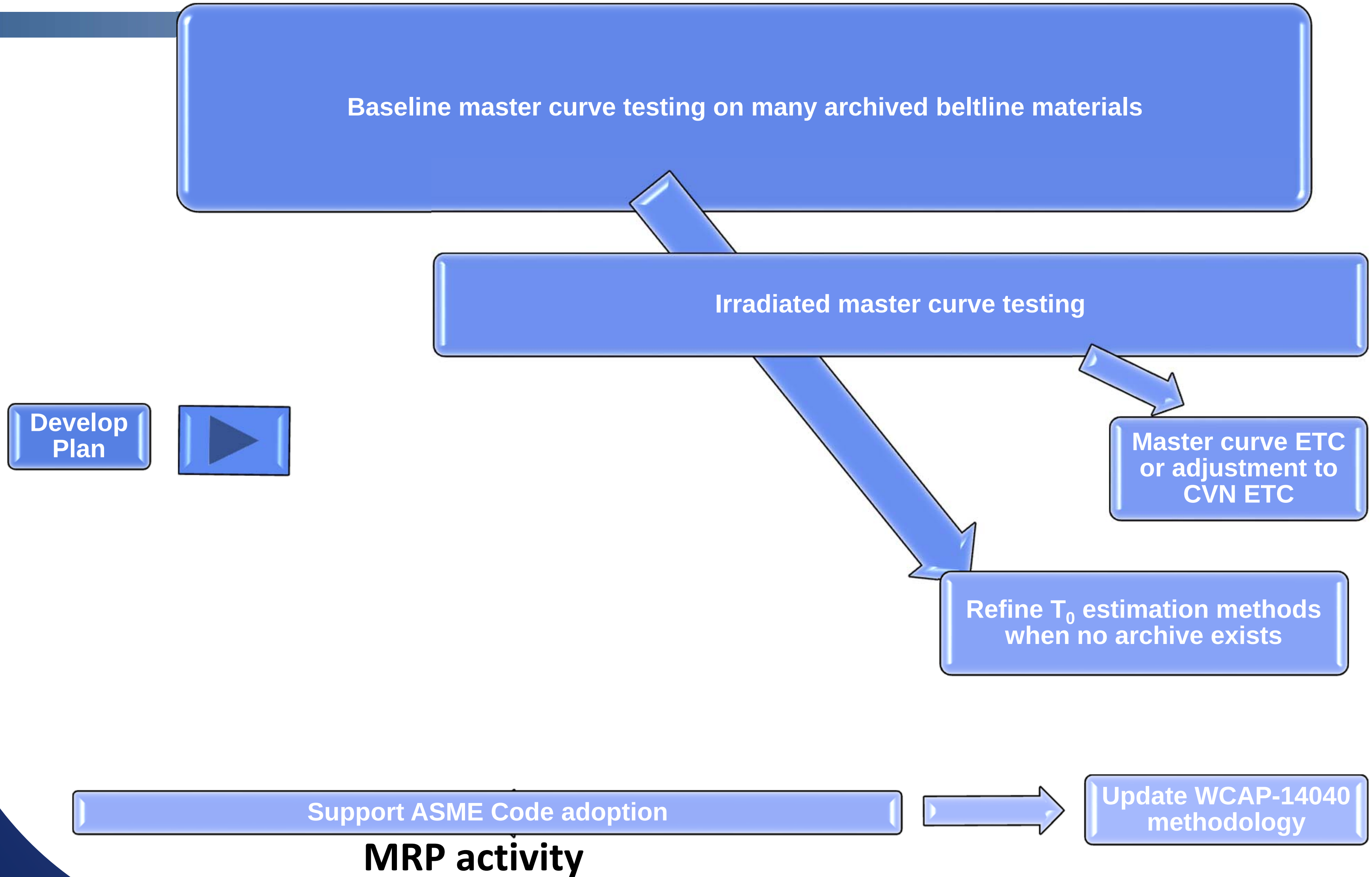
- Baseline RV material transition temperature based on old conservative method and at times incomplete information
  - RT_{NDT} is a crude conservative measure of transition temperature composed of NDT and Charpy
    - NDT is a measure of crack arrest transition temperature
      - We no longer use the K_{IR} (crack arrest) curve for P-T curves
      - We now use the K_{IC} (crack initiation) curve
    - Charpy 50ft-lb, 35MLE
      - Affected by USE
      - Not designed to establish transition temperature
      - Not a good measure of transition temperature
  - ASME NB-2300 RT_{NDT} data not always available for pre '72 plants or for nozzles/flanges for many plants
    - Approximation methods have been used: BTP 5-3, GE method

Long Term Solution: Master Curve

- The use of the master curve method (direct fracture toughness) is the correct long term solution to understanding the RV fracture toughness.
  - The Europeans have continued to develop and implement the master curve technology. While the US stopped with the imminent acceptance of the alternate PTS rule (10CFR50.61a).
- ASME has codified N-629 into Appendix G and is working on a code case to directly implement the master curve technology (Code Case N-830) with NRC support.
- Regardless of what the RT_{NDT} value or estimated value is, the master curve technology provides the best available understanding of the actual transition temperature fracture toughness. This has been demonstrated numerous times and in many ways for the RPV steels.
- The Master Curve technology has been successfully applied in the US for Kewaunee and the B&W fabricated RPVs containing high Cu Linde 80 welds.
  - Nearly all the high Cu Linde 80 weld plants have applied the use of BAW-2308 to reduce their ART and PTS values.

Master Curve technology is well established

Conceptual Long Term Plan to Transition from RT_{NDT} to Master Curve T_0



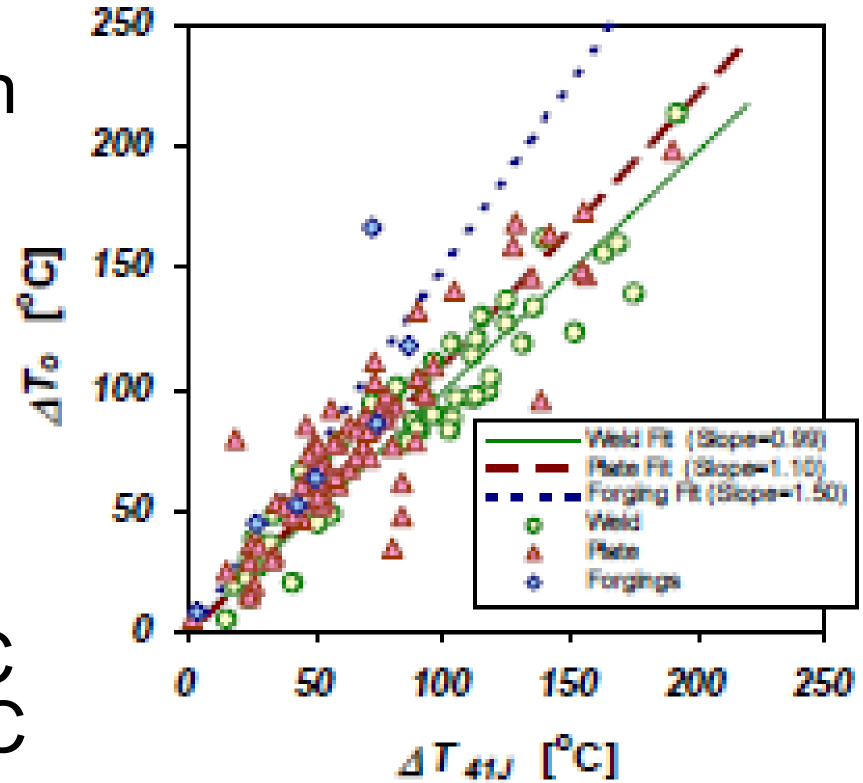
Master Curve Data Generation

- Baseline Master Curve Testing on Many Archived Beltline Materials
  - PWROG has extensive archive of most beltline materials
- Master curve testing
  - Correct orientation
  - 8-10 CT specimens from 1/4T location
  - Small study on T_0 orientation (TL vs. LT) effect vs. CVN

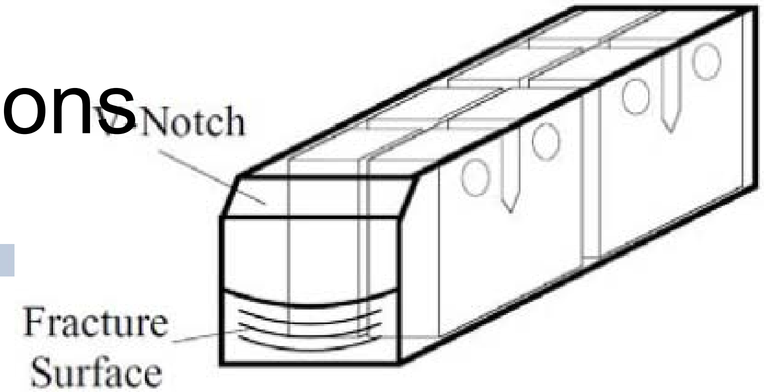
Establish definitive starting point using latest technology

Irradiated Master Curve Data

- Irradiated master curve shifts can be different than Charpy 30ft-lb shifts
  - Welds: 1:1 – OK
  - Plates: a little worse
  - Forgings: potentially significantly more T_0 shift than CVN; however, very little data!
- Master curve specific ETC or adjustment to CVN ETC to account for any difference

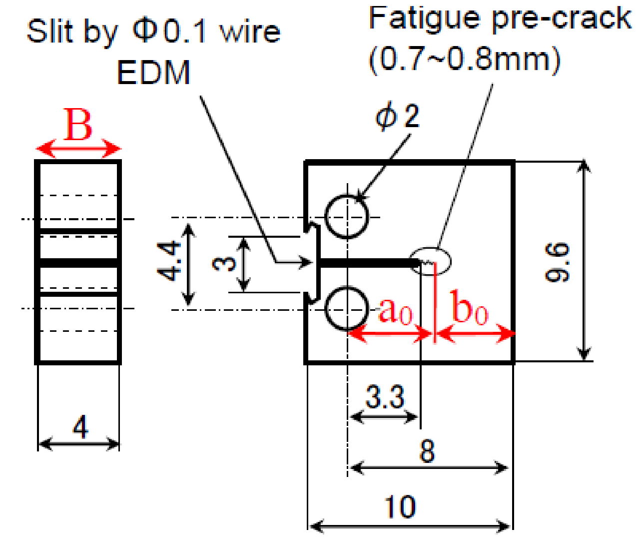


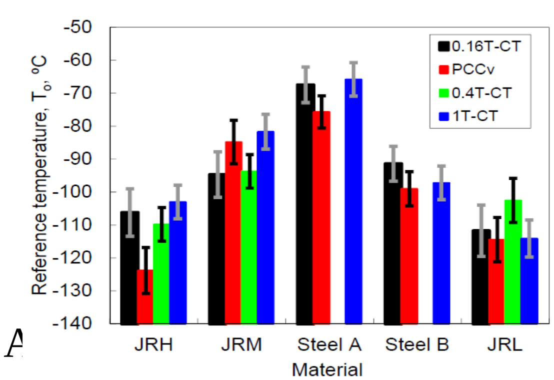
Irradiated Material Test Options



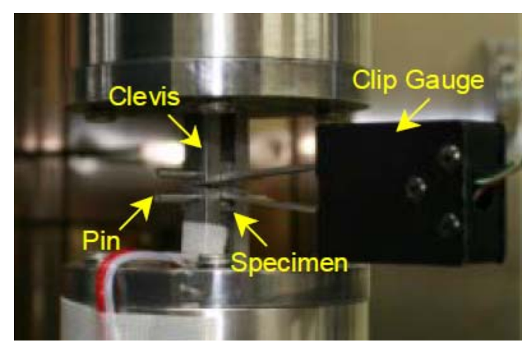
- Limited irradiated testing
  - Carefully select materials
  - Select standard specimen geometry
- Some tested capsules have 1/2TCT specimens that are stored and untested
  - They are anxiously waiting to reveal their toughness
- Reconstitute and test Charpy size 3 point bend
- Mini-CTs where only broken CVNs are available
  - One full set (8 mini-CTs) can be removed from 1 full broken CVN specimen
  - CRIEPI program qualifying mini-CT
  - W participated in CRIEPI international round robin
  - Very good agreement with standard larger specimens

(a) Miniature C(T) specimen





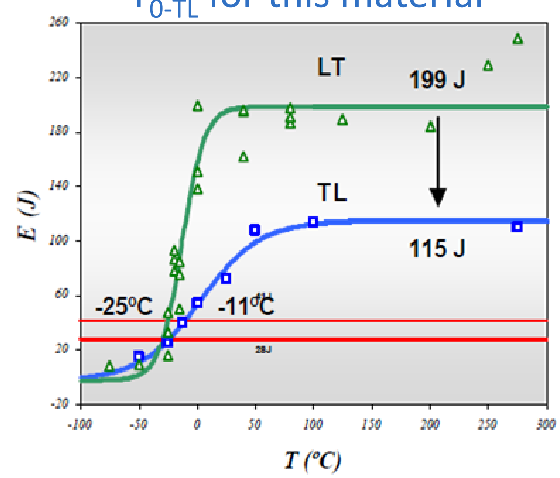
0.16T-CT



T_0 Estimation

- It will be necessary to estimate initial T_0 when no data is available for testing
  - Minimum data available includes YS, chemistry, LT CVN energy and MLE at 10F, but most have a full or partial LT CVN curve (energy, MLE, shear) when TL is not available
- Currently estimation methods exist for T_0
  - Wallin: function of CVN TT 21ft-lbs, USE, and YS
  - Erickson: exponential fit to CVN mid-lower transition data
    - EPRI 3002004416
  - Yoshimoto: CVN TT30ft-lb index
- Refine T_0 estimation methods
  - With more data specific to US fleet, T_0 estimation methods would be refined
  - Should be less difference between LT and TL for T_0 than for CVN TT50

No difference in $T_{0\text{-LT vs.}}$ $T_{0\text{-TL}}$ for this material



Transition Plan Goals

- Provide recommended plan
  - Coordination with other industry groups
  - Likely success path
  - Needed testing
  - ASME needed actions
- Identify obstacles
  - Could next RG 1.99 revision provide guidance for use of direct fracture toughness?
- Estimate of costs
- Benefits

Questions?

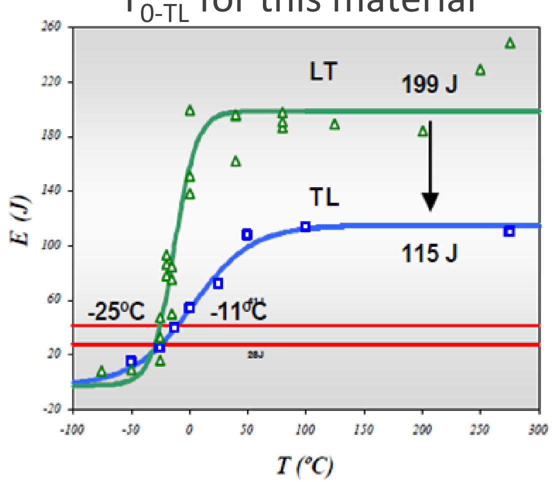
The Materials Committee is established to provide a forum for the identification and resolution of materials issues including their development, modification and implementation to enhance the safe, efficient operation of PWR plants.

Back-Up Slides

WRC-175 RT_{NDT} Basis

- WRC-175 is basis for 1972 changes to ASME Section III
- Recommended tests:►►►
- CVN 50ft-lb temperature
  - Not designed to establish transition temperature
  - Not a good measure of transition temperature

No difference in $T_{0\text{-LT}}$ vs. $T_{0\text{-TL}}$ for this material



1. The use of both drop weight and C_v tests gives protection against the possibility of errors in the conducting of tests or the reporting of test results.

The requirement of 40 mils lateral expansion or alternatively, 35 mils and 50 ft-lb at RT_{NDT} + 60° F, throughout the life of the component provides assurance of adequate fracture toughness at "upper shelf" temperatures.

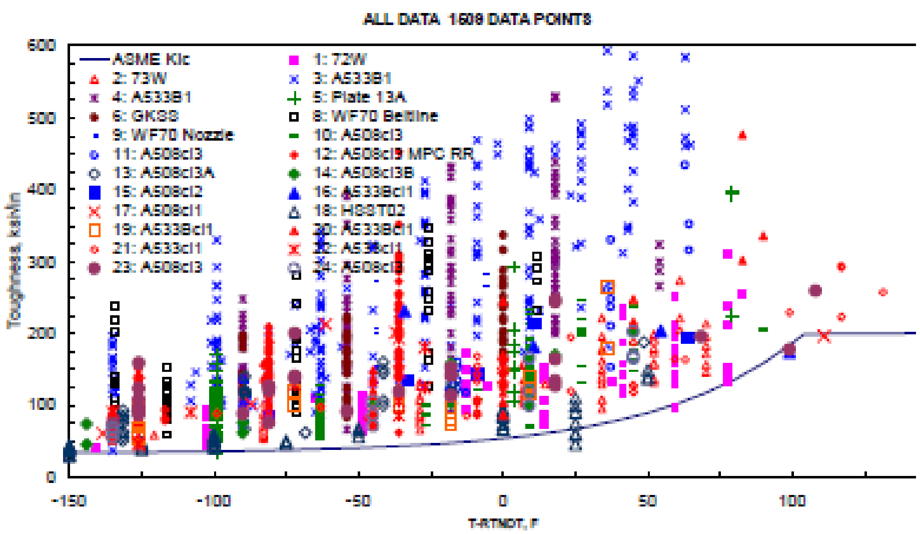
The C_v test at T_{NDT} + 60° F serves to weed out nontypical materials such as those which might have low transition temperature but abnormally low energy absorption on the upper shelf.

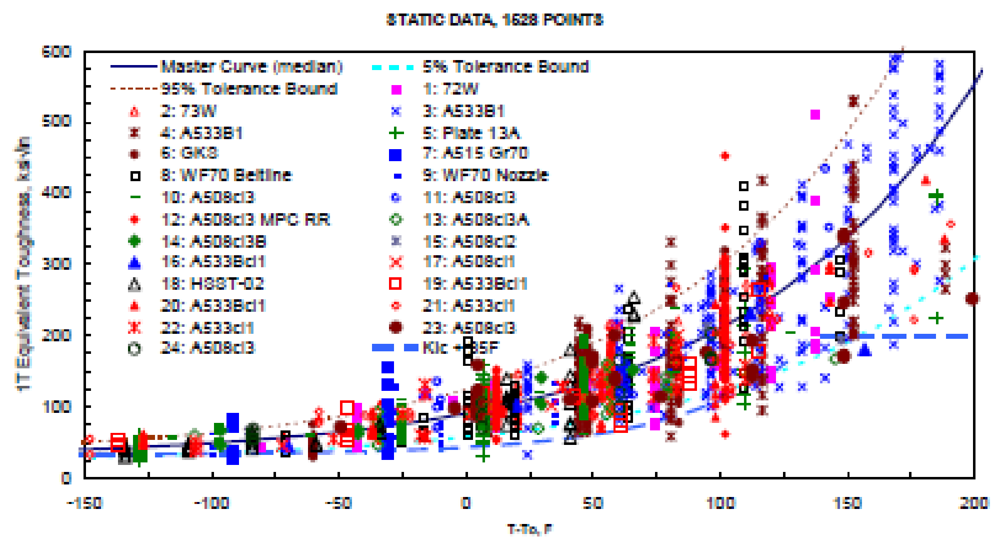
CVN tests were meant to weed out low USE materials

WRC-175 "PVRC Recommendations on Toughness Requirements for Ferritic Materials"

Long Term Solution: Master Curve

- K_{IC} curve is a lower bound of a very imprecise RT_{NDT} measurement which is being estimated from imprecise Charpy data
- Master curve technology is the correct long term solution to understanding the RV fracture toughness



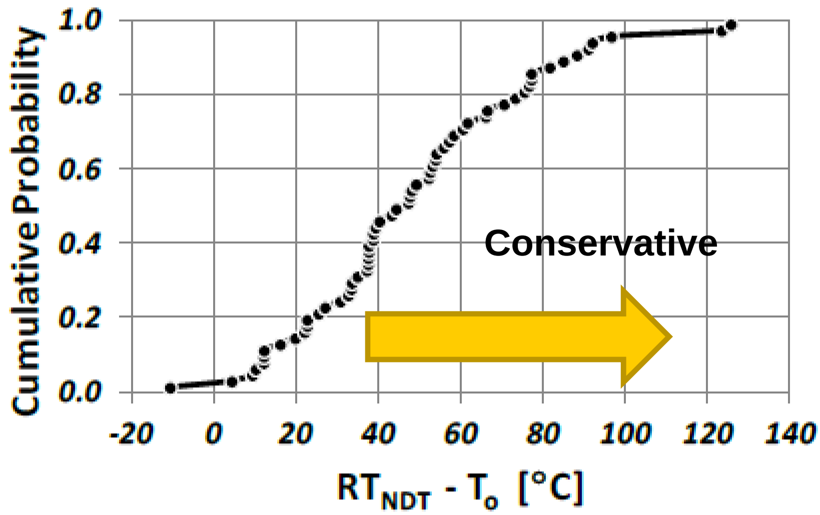


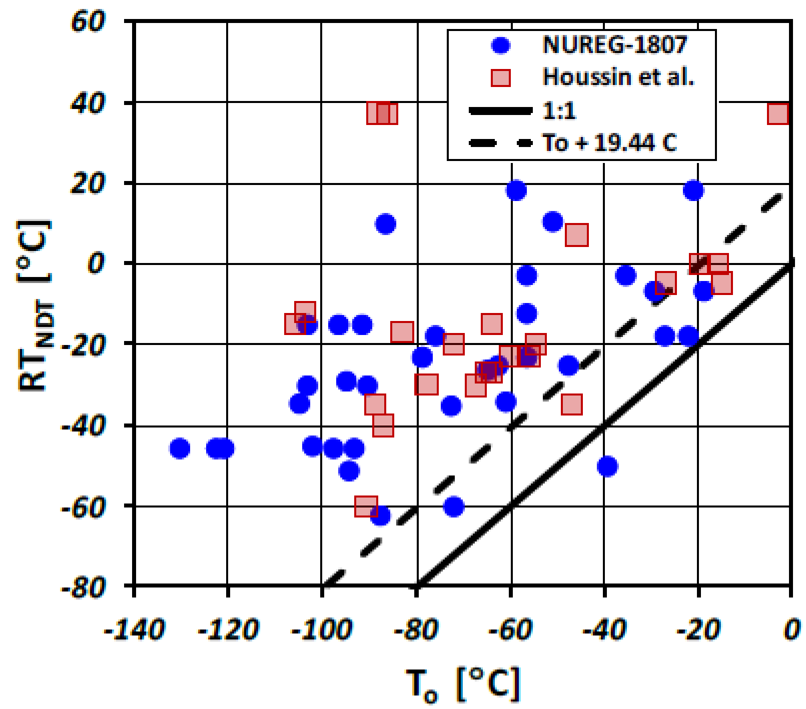
RT_{NDT} index = large scatter

T_0 index = small scatter

RT_{NDT} Margin

- RT_{NDT} is not a good predictor of T_0
- Some materials have significant margin, others not so much
- Amount of current conservatism is unknown for any given material





Proceedings of PVP2014
2014 ASME Pressure Vessels and Piping Division Conference
July 20-24, 2014, Anaheim, CA, USA

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ASSESSMENT OF FRACTURE TOUGHNESS MODELS FOR FERRITIC STEELS USED IN SECTION XI OF THE ASME CODE RELATIVE TO CURRENT DATA-BASED MODELS

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