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Plan for Transitioning RPV Integrity to Direct Fracture Toughness

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Outline

- **Proposed Plan for Transitioning RPV Integrity to Direct Fracture Toughness**
  - Reason for Change
  - Why now?
  - Current approach for RPV integrity evaluation
  - Alternative technology
  - Ideal situation vs. what is achievable
  - Available transition temperature toughness data
  - PWROG plan
    - Develop methodology to generate substantial amount of irradiated transition temperature toughness data
  - Coordination planned with all interested parties
  - NRC feedback requested

Reason for Change

- Establishing a robust fracture toughness basis for the current license period and for Subsequent License Renewal (SLR) will help ensure public safety by better understanding the actual margin that exists in the U.S. PWR fleet reactor pressure vessels (RPVs)
- Goals are to:
  - Reduce uncertainty
  - Improve consistency of margin
  - Characterize margin statistically
- The approach will be based on actual fracture toughness measurement
- This will ensure optimum pressure-temperature (P-T) curves for SLR
- An overall cost savings for managing RPV integrity

Why Now?

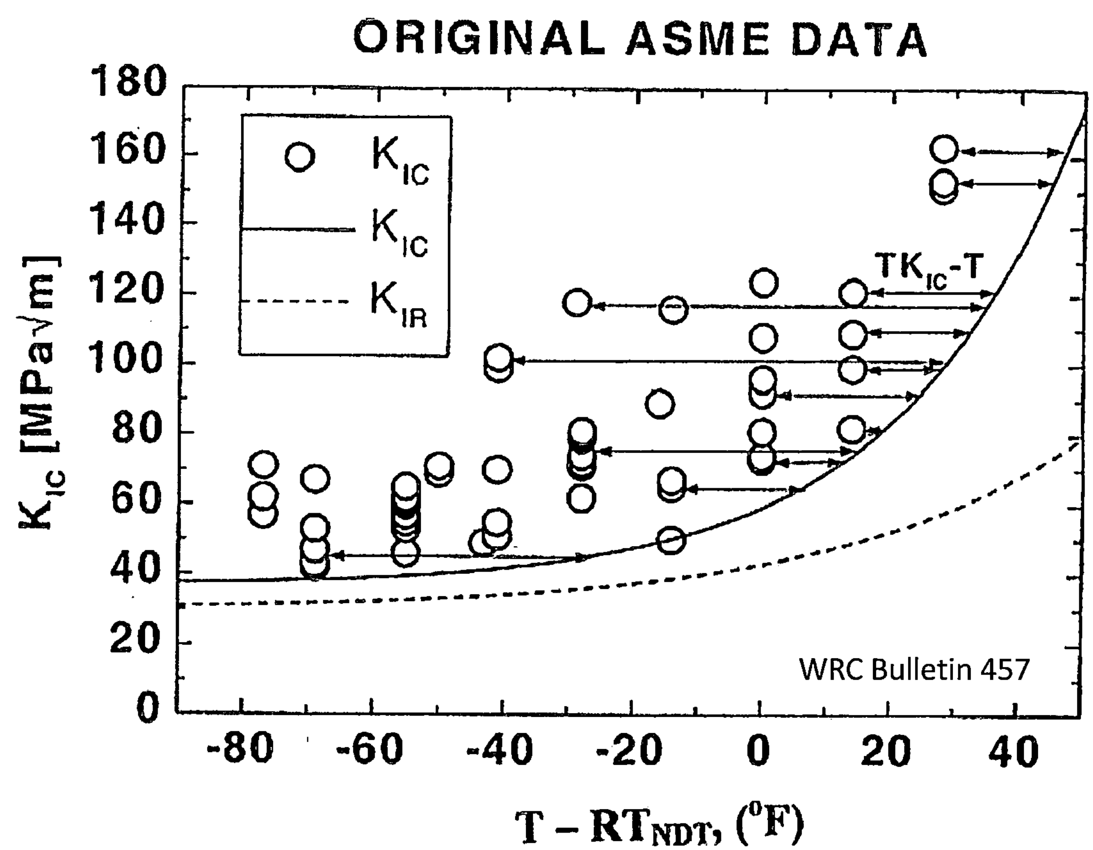
- A number of factors are converging to make this an ideal time to transition to direct fracture toughness
  - The consideration of SLR by utilities provides an opportunity to establish improved methods for assessing RPV fracture toughness through 80 years of operation to ensure safety and public confidence
  - Recent industry experience has highlighted the potential benefits of a better quantification of RPV fracture toughness

Why Now? (cont'd)

- A number of factors are converging to make this an ideal time to transition to direct fracture toughness
  - Measurement of transition temperature fracture toughness per ASTM E1921 is now a mature technology
  - The development of the miniature compact tension (mini-CT) fracture toughness specimen geometry enables the testing of the small amount of available irradiated material to obtain fracture toughness results
  - The ASME Section XI Code committees are expanding the use of direct fracture toughness data
  - Dept. of Energy (DOE) and EPRI have on-going programs supporting related technologies, which are complimentary to the PWROG effort of moving to direct fracture toughness measurement

Current Approach

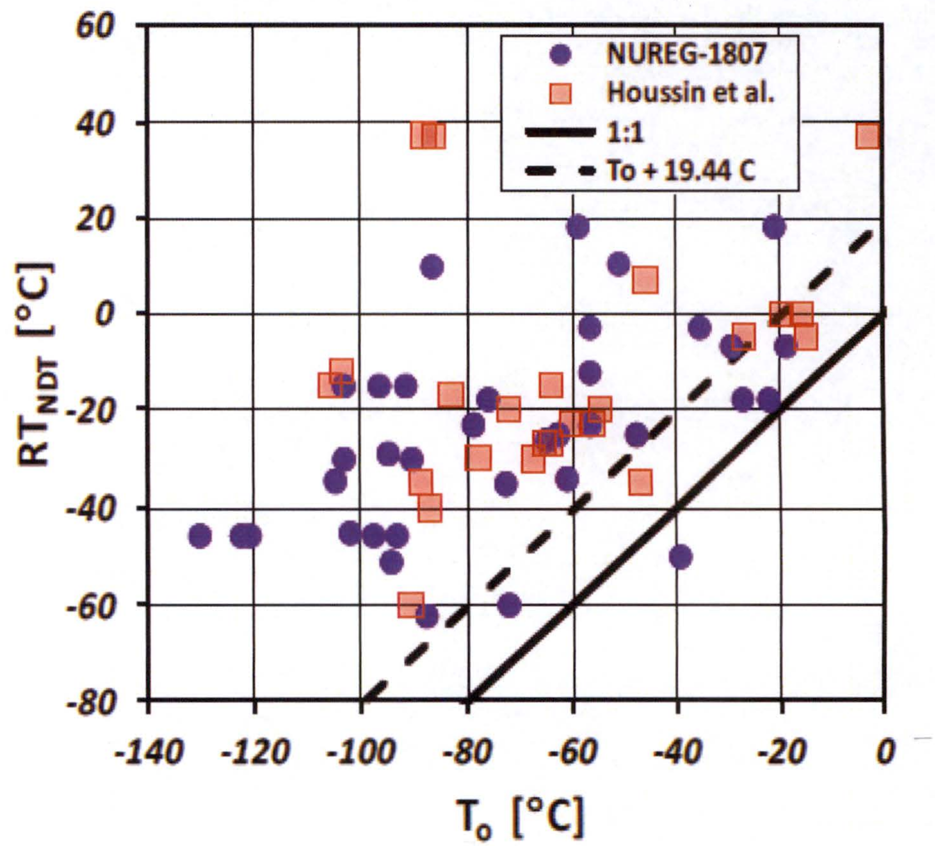
- Current Approach:
  Nil-ductility reference temperature (RT_{NDT}) + embrittlement shift
  - RT_{NDT} transition temperature fracture metric can be improved:
    - Margin for any given material inconsistent
  - Shift has substantial margin (σ_{Δ}) due to prediction uncertainty



Current Approach

- Baseline RPV material transition temperature (RT_{NDT}) based on a very conservative method from 1972
  - RT_{NDT} is composed of both drop-weight nil-ductility transition temperature (T_{NDT}) and Charpy tests
    - T_{NDT} is a measure of crack arrest transition temperature
      - Most plants no longer use the K_{IR} (crack arrest) curve for P-T curves
      - The Code now allows the use of the K_{IC} (crack initiation) curve
      - Initiation fracture toughness transition temperature (T_0) and RT_{NDT} are not well correlated (see figure)

ASME PVP2014-28540, 2014

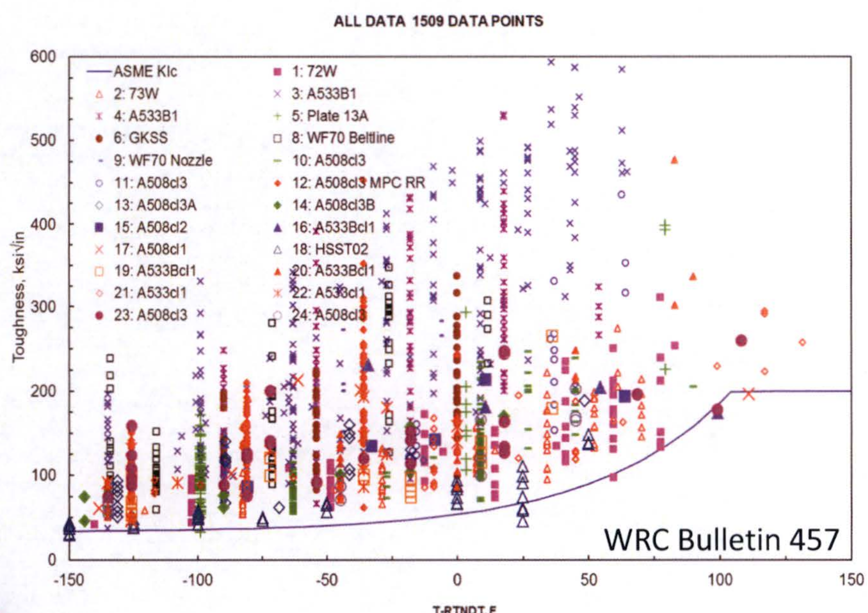


Alternative Method: Direct Fracture Toughness

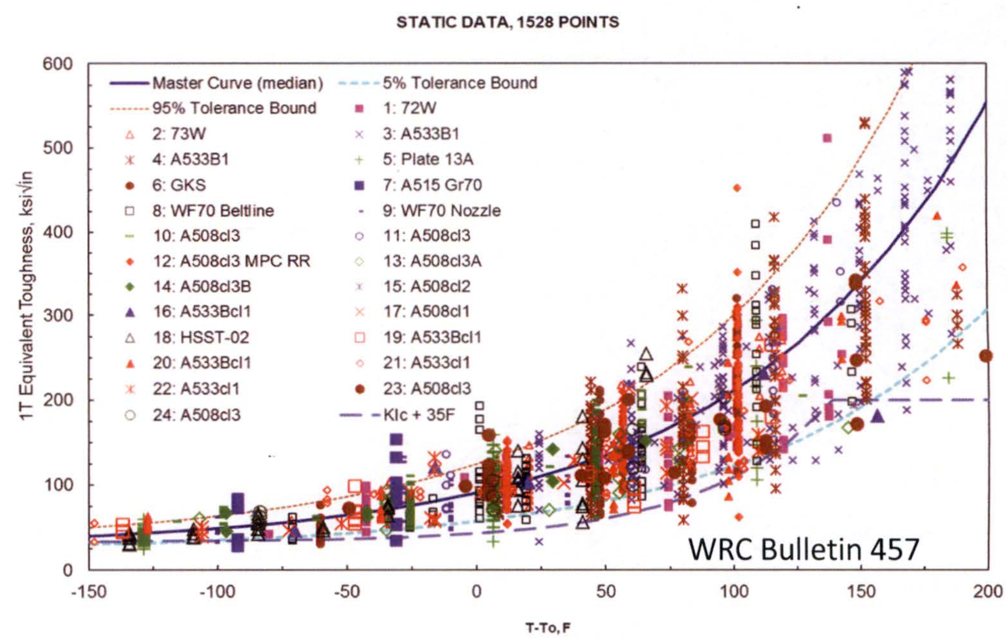
- Prior acceptance of Master Curve method
  - The test method, which has been standardized since 1997, in ASTM E1921 produces crack initiation fracture toughness transition temperature (T_0)
  - ASME Code Case N-629 (defined RT_{T0} as alternate to RT_{NDT}; $RT_{T0} = T_0 + 35°F$)
    - Approved by NRC in RG 1.147, Rev. 17
    - Now in Section XI, Appendix A & G
    - Code Case N-851 being drafted to replace N-629 for K_{IR} applications
  - Initial RT_{NDT} reset using the above standards for Linde 80 welds in BAW-2308
    - Applicable B&W and B&W fabricated Westinghouse RPVs saw significant margin improvement in PTS and ART values
  - NRC approved the master curve method for Kewaunee
  - Was indirectly used in the basis behind the Alternate PTS rule (10CFR50.61a)
- Code Case N-830 which enables direct use of Master Curve T_0 has been approved by ASME Section XI
- European regulators and utilities have moved in the direction of using direct fracture toughness

Direct Fracture Toughness

- Master Curve
  - Reduces data scatter
  - Characterizes margin statistically
  - Based on actual fracture toughness measurements



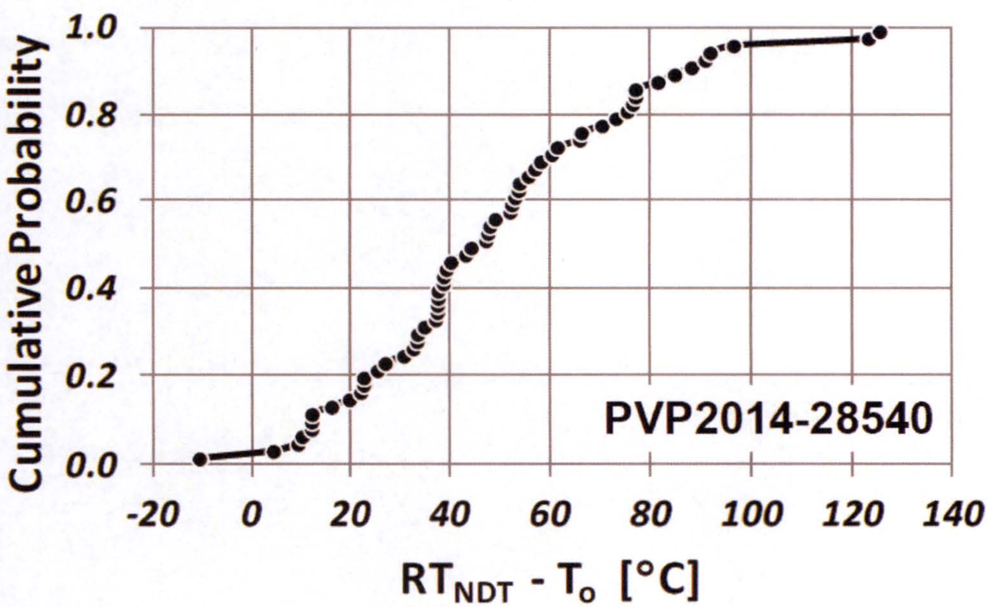
Large Scatter with RT_{NDT}



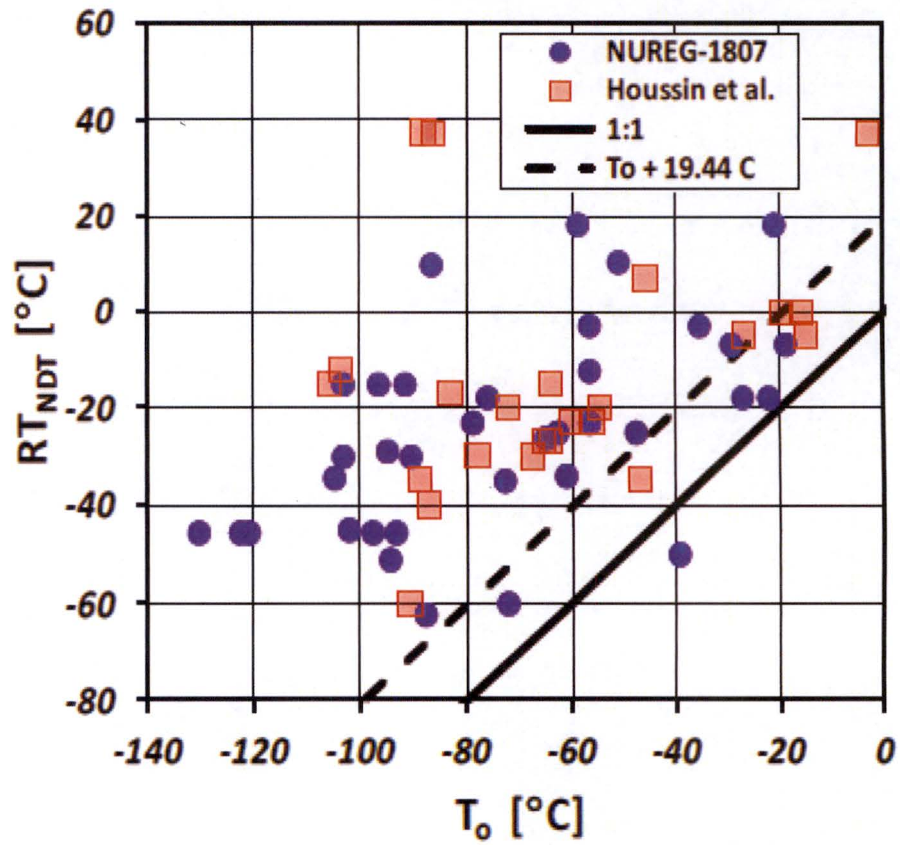
Smaller Scatter with Known Statistical Distribution

Direct Fracture Toughness

- Master Curve
  - Reduced inconsistency



ASME PVP2014-28540, 2014



Ideal Situation

- Ideally, for RPV integrity, there would be a T_0 Master Curve value for every beltline material with a fluence greater than the RPV licensed fluence (e.g. 80 years considering SLR) using a consistent and accepted specimen geometry.
- Furthermore, the nuclear utility licensees would have the ability to routinely use this T_0 data with a well-defined methodology and uncertainty term(s) in application for PTS (10 CFR 50.61) and P-T limit curves (10 CFR 50, Appendix G).

Existing U.S. T_0 Data

- Irradiated data compared to ART and PTS values
  - Available U.S. PWR RPV irradiated T_0 data
  - T_0 data with fluence higher than PTS or ART value was compared to RPV end of license PTS and ART values
    - (even 80 year fluence data could be used for 60 year operation)
  - Substantial difference in every example
  - Average difference ~60ºF (RT_{NDT} + shift vs. Irradiated RT_{T0})

Plant	Parameter	Limiting Weld Material (Heat #)	RT_{NDT} – Based Data		Irradiated Master Curve Data		Difference (°F)
			Fluence ($x10^{19}$ n/cm^2)	¼ ART or PTS (°F)	Fluence ($x10^{19}$ n/cm^2)	$RT_{T0} + 2\sigma_I$ (°F)	
Plant 1	PTS	IS to LS Circumferential Weld (1P3571)	2.78	282	3.36	213	69
Plant 2	1/4T ART	IS and LS Long Welds (W5214)	1.3	253	1.5	207	46
Plant 2	1/4T ART	LS Long Welds (34B009)	1.3	242	1.5	172	70
Plant 3	PTS	IS and LS Long Welds (W5214)	1.3	258	1.5	207	51
Plant 4	PTS	IS and LS Long Welds (34B009)	1.56	258	1.5	172	86
Plant 5	PTS	IS and LS Long Welds (27204)	1.5 2.0	226 243	1.5	176	50

P

Existing U.S. T_0 Data

- Irradiated data compared to ART and PTS values for the Linde 80 welds where initial RT_{NDT} was already reset using fracture toughness data as presented in BAW-2308, Rev. 1/2-A
  - Significant difference seen in most cases
  - Average difference ~60°F (Initial RT_{T0} + shift vs. Irradiated RT_{T0})

Plant	Parameter	Limiting Weld Material (Heat #)	RT_{NDT} – Based Data		Irradiated Master Curve Data		Difference (°F)
			Fluence ($x10^{19}$ n/cm^2)	¼ ART or PTS (°F)	Fluence ($x10^{19}$ n/cm^2)	$RT_{T0} + 2\sigma_I$ (°F)	
Linde 80 Plant 1	¼ ART	Lower Nozzle Belt/Upper Shell Circumferential Weld (72105)	0.77	216	1.19	137	79
Linde 80 Plant 1	PTS	Lower Nozzle Belt/Upper Shell Circumferential Weld (72105)	1.84	264	1.90	166	98
Linde 80 Plant 1	¼ ART	LS Long Weld (299L44)	0.68	184	0.78	139	45
Linde 80 Plant 2	PTS	LS Long Weld (299L44)	1.04	210	1.6	149	61
Linde 80 Plant 3	PTS	US to LS Circumferential Weld (299L44)	1.35	226	1.6	149	77
Linde 80 Plant 4	PTS	US to LS Circumferential Weld (72442)	1.34	223	1.7	184	37
Linde 80 Plant 5	¼ ART	US to LS Circumferential Weld (821T44)	~1.3	156	1.2	148	8

Irradiated T_0 Data

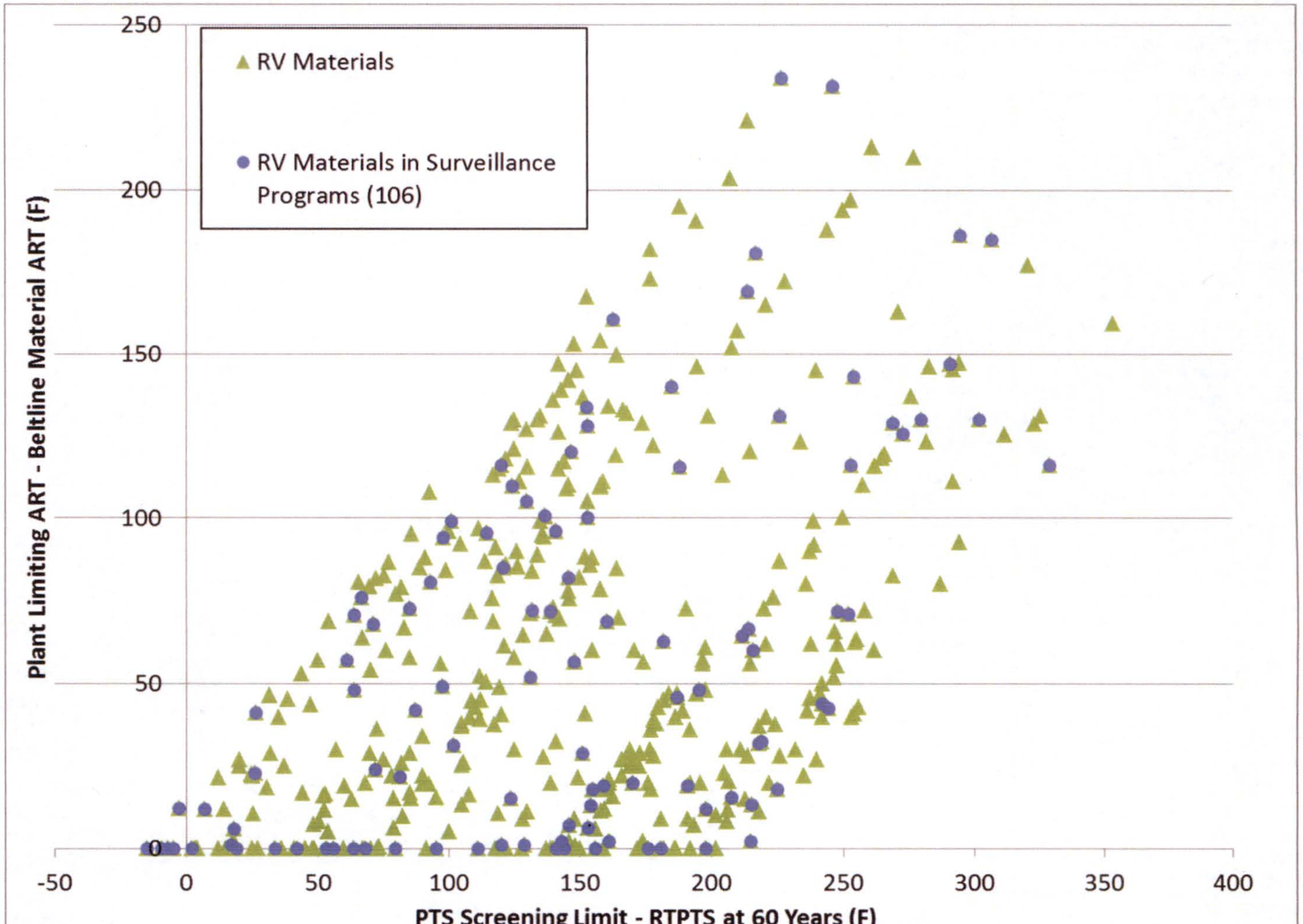
- To date, not much 80 year irradiated material available
  - Many plants have capsules that can be used for 80 years with reinsertion or additional irradiation time
- Surveillance programs typically include 1 weld and 1 base metal as required
  - May not include limiting material
  - In many plants more than one material is near limiting; measurement in the limiting material provides no information regarding next near limiting material
    - For example:
      - One unit has 3 plates with similar ART values with one in surveillance program
      - Another unit has 2 forgings with ART values within 30°F
      - A third has 4 plates with ART values within 30°F
- Many materials are not available in the irradiated condition, but most are available in the baseline unirradiated archive

Potential Materials for Testing

- Almost 500 PWR beltline materials
- ~350 archive beltline materials available
- Focus on materials near PTS and P-T limits for measurement of fracture toughness
  - Materials near PTS screening limits
  - Materials controlling and nearly controlling P-T limit curves

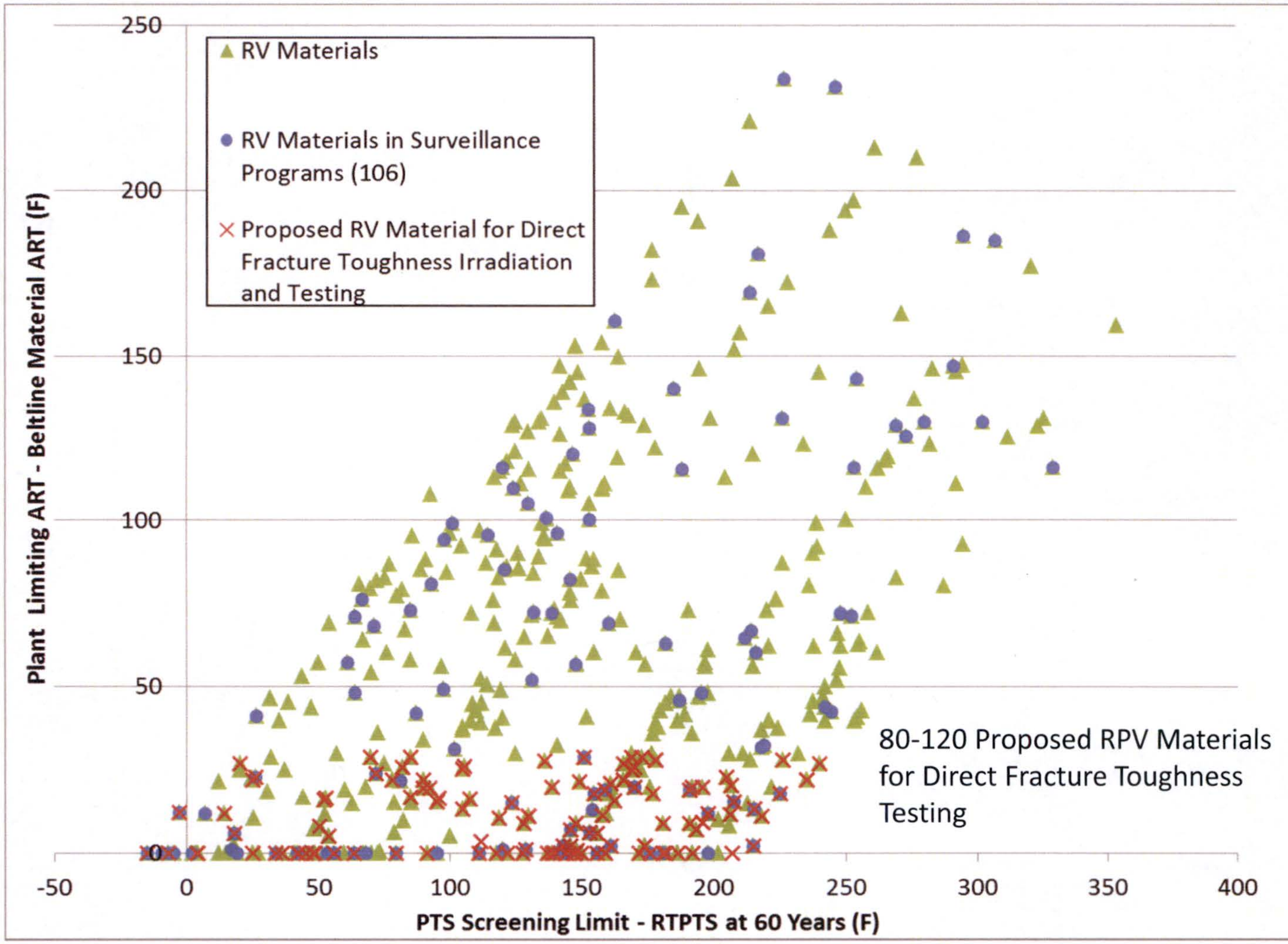
PWR Limiting Materials

- Not all tested surveillance materials are limiting



Focus on Limiting Materials

- Preliminary selection criteria:
  - Focused on beltline P-T limiting materials and those with ART within 30ºF of plant limiting ART
  - Unirradiated material available
- Will consider additional materials with development of final test matrix

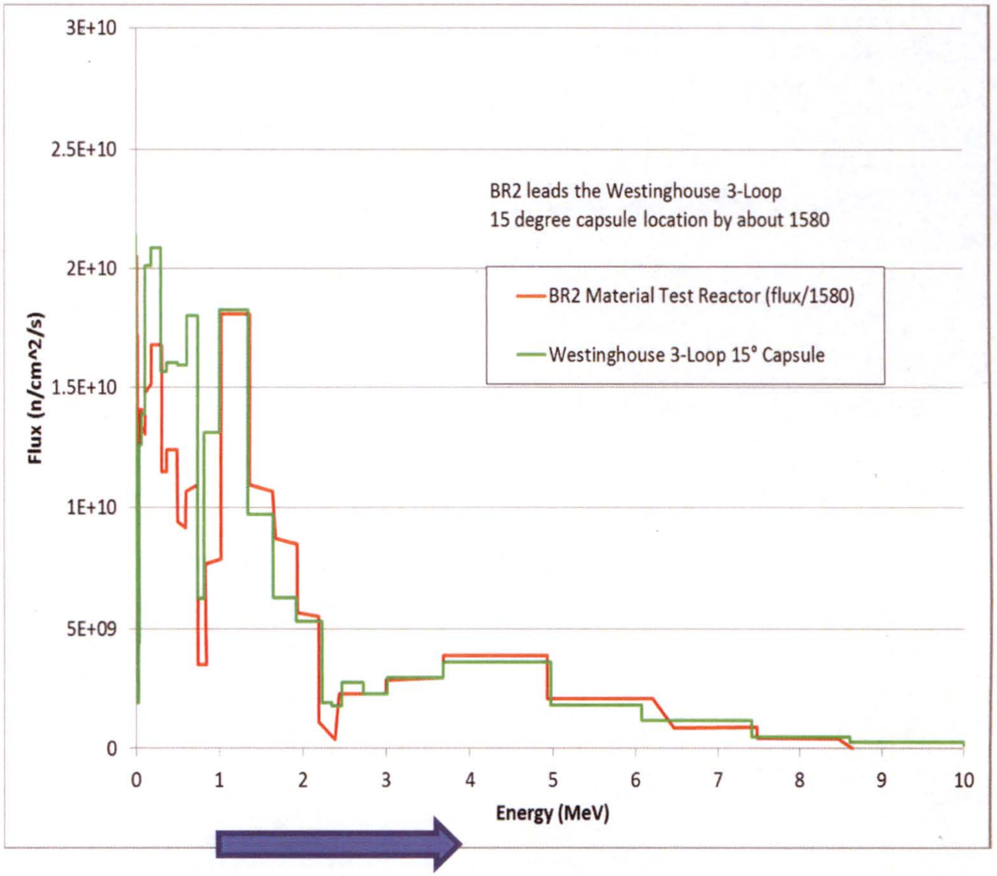


Irradiated T_0 Data

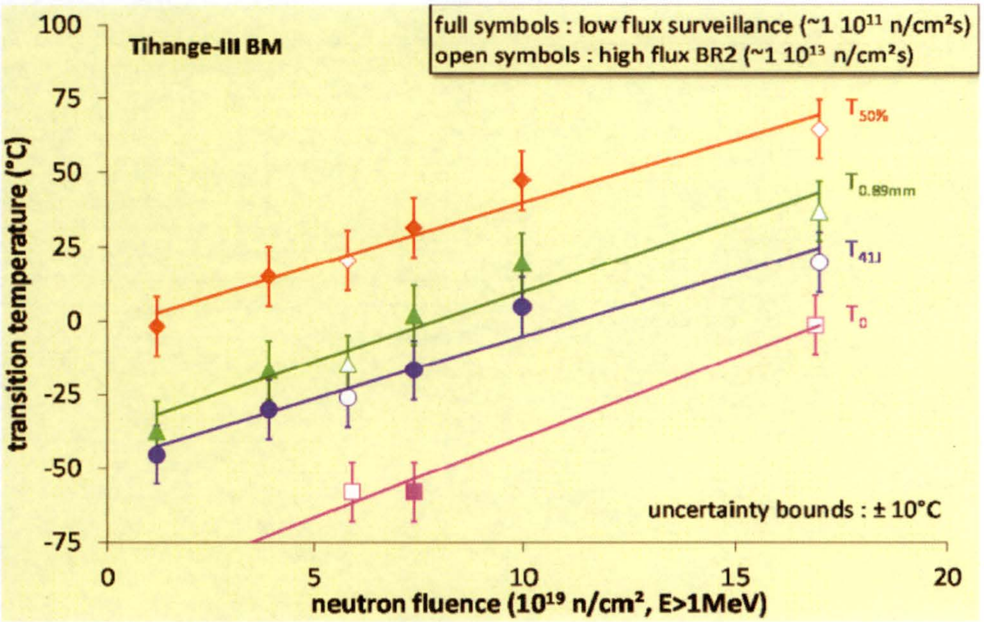
- Two options to obtain 80 year fluence data for unirradiated materials
  1. Create a few supplemental capsules with fracture toughness specimens and irradiate in Westinghouse PWRs (similar to PWR Supplemental Surveillance Program [PSSP])
     - Would take 15+ years to get any data
     - Upfront cost with no near term benefit
  2. Irradiate fracture toughness specimens in a test reactor
     - Irradiation can be done in ~2 months
       - Usable data available relatively quickly
     - Address any effect the high material test reactor (MTR) fluence rate has on fracture toughness
       - Benchmark against select available 80 year fluence surveillance program material

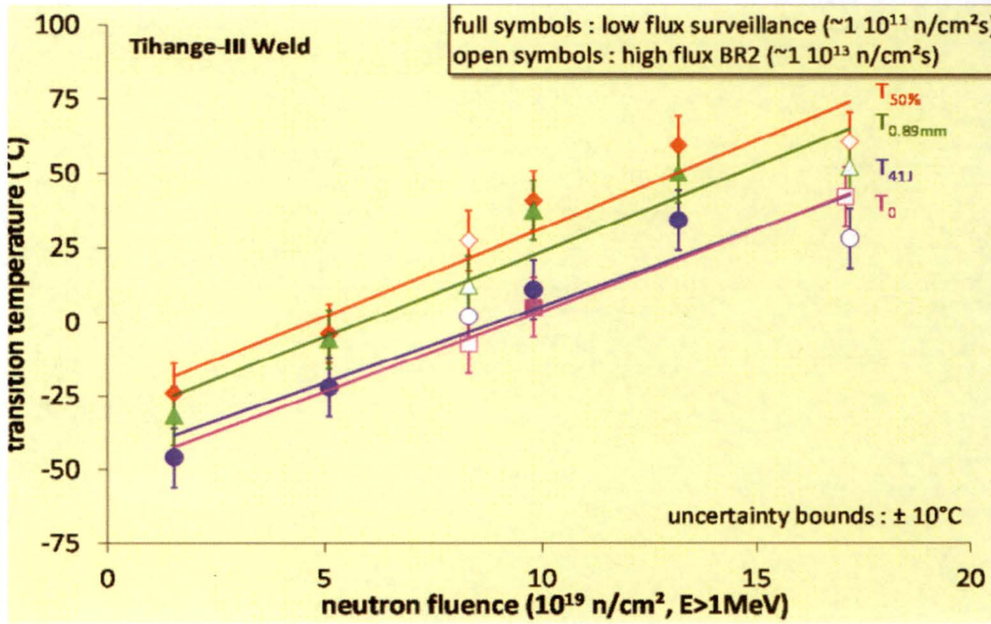
Material Test Reactor (MTR)

- Fluence energy spectrum energy > 1MeV is nearly identical to capsule irradiation location
- SCK-CEN material test reactor in Belgium (BR2)
  - Significant experience irradiating materials for RPV assessment in Europe



MTR vs. PWR Irradiation





BR2 irradiated material shift data is indistinguishable from PWR shift data

On the Importance of MTR–Accelerated Data in Support of RPV Surveillance for Long Term Operation

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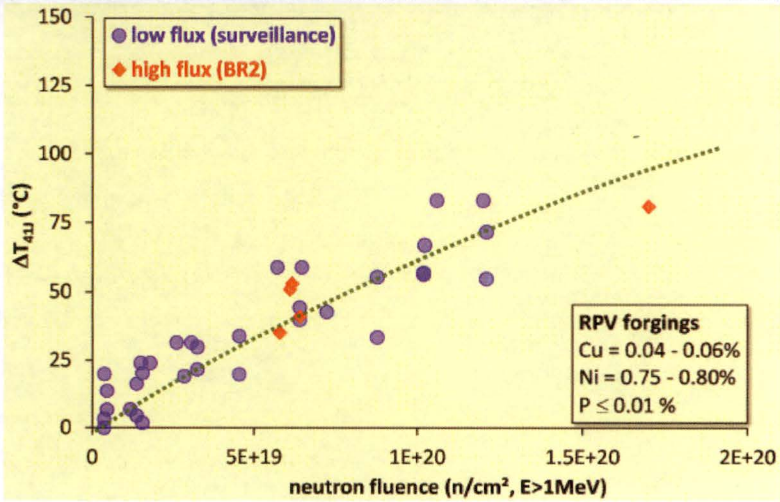
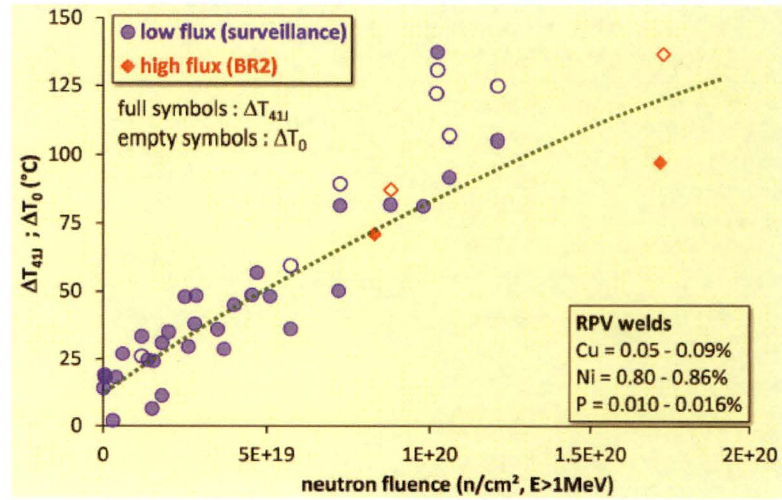
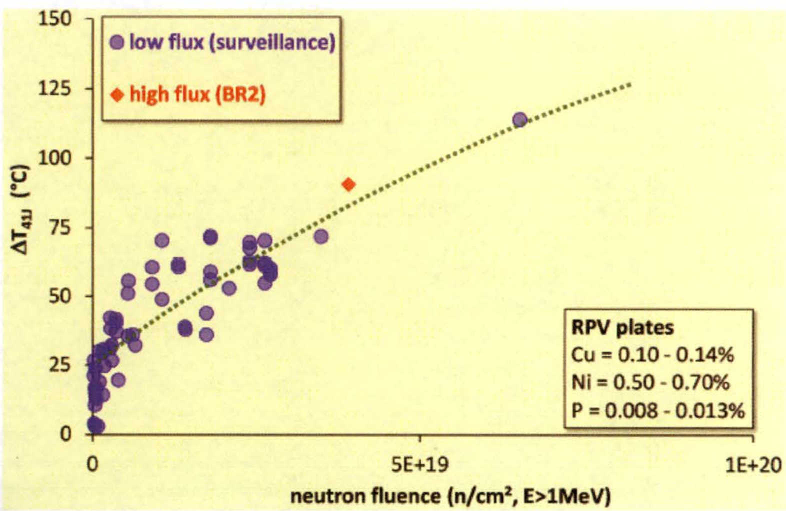
International workshop "RPV Embrittlement and Surveillance Programmes
Prague, October 13 – 15 October 2015

MTR vs. PWR Irradiation







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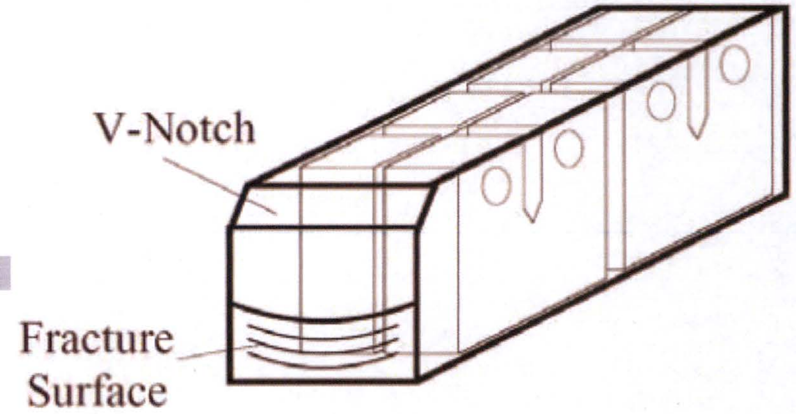
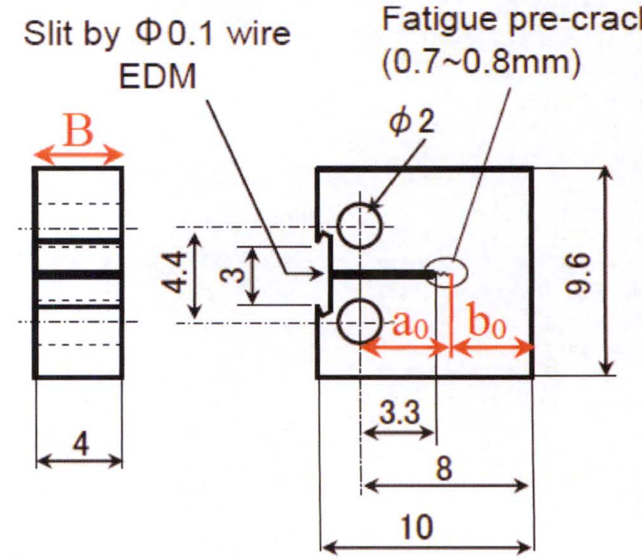
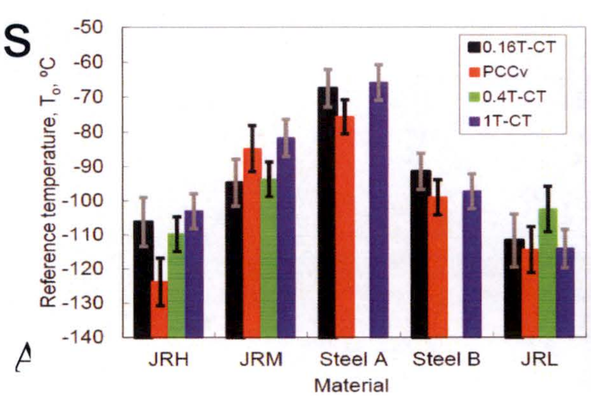
Mini-CT Specimen



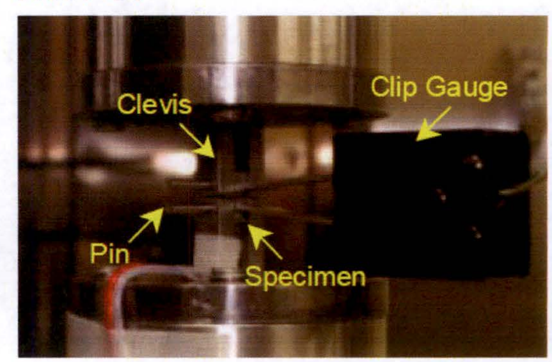
- Mini-CT specimens can be machined from broken Charpy specimens
  - One full set (~12 mini-CTs) can be removed from 2 full broken Charpy specimens
  - CRIEPI is leading a program qualifying mini-CT
  - International round robin included 12 laboratories
  - Very good agreement with standard larger specimens for forgings and welds

(a) Miniature C(T) specimen





0.16T-CT



ASME PVP2010-25862, Miura & Soneda
ASME PVP2013-97897, Tobita, et.al
ASME PVP2015-45545, Yamamoto, M.
STP 1576, ASTM International, Yamamoto, M.

Mini-CT Specimen

- EPRI work showed variation in embrittlement shift for T_0 likely due to differing test specimen geometries and test conditions
  - Important to have consistent test parameters and geometry
- Mini-CT is the recommended geometry
  - Mini-CT geometry makes much more efficient use of limited irradiated material
  - Mini-CT does not have the geometry bias question that the precracked Charpy geometry does
  - Enables many specimens to be irradiated in a small space
  - Further benchmark testing is planned to compare the mini-CT and larger specimen results for irradiated material
  - With small change to ASTM E1921, geometry will fully comply with standard

Preliminary Test Matrix

- Preliminary test matrix includes materials from most U.S. PWRs (final test matrix still to be developed with utility concurrence)
  - ~100 materials
    - Machine mini-CTs from unirradiated archive
    - Irradiate in MTR to 80 year fluence
    - Test for master curve T_0
  - ~20 surveillance materials for benchmarking
    - Duplicate materials irradiated in surveillance capsules which are already available with 80 year fluence will be machined into mini-CTs from typically broken Charpy specimens
    - Test for master curve to benchmark MTR irradiated material

Limiting and Near Limiting Materials for MTR Irradiation			Surveillance Program Irradiated Materials for Benchmarking		
Weld	Plate	Forging	Weld	Plate	Forging
21 to 28	45 to 80	14 to 19	8 to 10	8	3 or 4

Three Phase Plan (1/2)

- Phase 1 (PA-MSC-1319; Final Validation of Mini-CT, Test Matrix and Layout Diagrams) – 1.5 years
  - Inform NRC on plan, seeking feedback before proceeding (this meeting)
  - Complete validation of mini-CT through cooperation with DOE Light Water Reactor Sustainability Program and CRIEPI
    - Test irradiated weld material
  - Develop final test matrix (MTR and benchmark materials) with utility input
  - Prepare MTR specimen irradiation specification
  - Prepare unirradiated material cutting diagrams

Three Phase Plan (2/2)

- Phase 2 (Machine Mini-CTs, Irradiate in MTR and Test) – 3 years
  - Machine and precrack ~12 mini-CTs per selected unirradiated material
  - Irradiate in MTR to selected fluence (80+ year RPV fluence) at selected temperature (probably two irradiation temperatures)
  - Test per ASTM E1921
  - Machine and precrack and test ~12 mini-CTs from each selected existing benchmark PWR irradiated material
- Phase 3 (Assess Data, Prepare Topical for Submittal to NRC) – 2 years
  - Use test data to develop estimation methods for materials not available for testing
  - Develop new ART and PTS values for each plant for 80 years with applicable adjustments and margins
    - Test uncertainty defined in E1921 and material variability
    - Material variability adjustment/margin to account for potential difference between test specimens and RPV
  - Develop topical report, and send to NRC for review

Coordination

- NRC
  - Feedback
  - Consider mechanism so that data can be applied without need for exemption for each licensee
- ASME
  - Code change to NB-2331 to allow use of master curve T_0 (incorporates Code Case N-631); to be presented to Code committees May 2016
  - Continued advancement of Code Case N-830
- EPRI Materials Reliability Program
  - Support ASME Code changes
  - Develop T_0 approximation methods/embrittlement trend curve where material is not available
- ASTM, LWRS & CRIEPI
  - Validation of mini-CT on irradiated material

Benefits

- Establishing a robust fracture toughness basis for the current license period and for SLR will help ensure public safety by understanding the actual margin that exists in the U.S. PWR fleet RPVs
  - Will:
    - Increase certainty
    - Improve consistency of margin
    - Characterize margin statistically
    - Based on actual fracture toughness measurement
    - Simplify and clarify RPV integrity approach
    - Increase efficiency, reducing the number of submittals and reviews needed
- Ensure usable P-T curves for SLR
- Offset potential future increases in ART or PTS values

PWROG Requests

- Feedback from NRC
  - Are there any concerns with the proposed approach?
  - Implementation in 10CFR50

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.

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