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Advanced use of fracture toughness information for RPV integrity assesssments

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Advanced use of fracture toughness information for RPV integrity assessments

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Outline

- ASME Code Cases N-629 and N-631
  - Background and approach followed
  - Master Curve applied to original data
  - Alternative definition of RT_{NDT} (RT_{To})
- Comparison between Charpy-based and Master Curve-based approaches
  - "Conventional" approach (RT_{NDT})
  - "Advanced" approach (RT_{To})
  - Application to Belgian surveillance database (19 materials)
  - Implications for utilities/regulators/engineers
- Pressure-Temperature (P-T) operating limits

The Master Curve: underlying concepts

- Ferritic steels suffer significant toughness loss with decreasing temperature $\rightarrow$ fracture mode changes from ductile to brittle (**ductile-to-brittle transition region**)
- A transition temperature is needed to characterize the steel behavior in the transition regime
- Data scatter is due to randomly sized and distributed cleavage initiators, and can be modeled by a 3-parameter Weibull cumulative probability statistical model
- Smaller specimens tends to display a higher apparent toughness (weakest link assumption)
- Most ferritic steels tend to conform to one universal toughness vs. temperature curve ("Master Curve")

The Master Curve approach (ASTM E1921)*

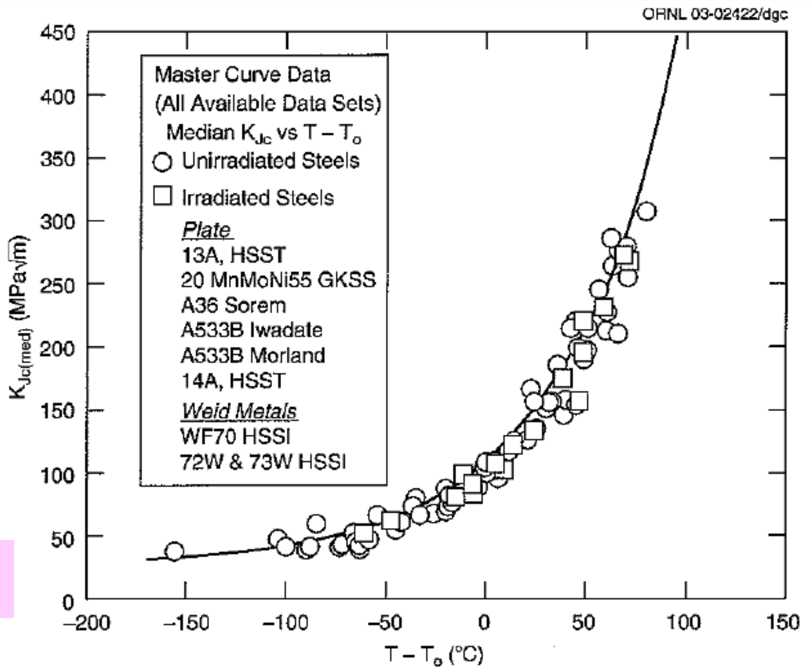
$$K_{Jc(med)} = 30 + 70\exp[0.019(T - T_0)]$$

Reference temperature (median K_{Jc} for 1T specimen is 100 MPa√m)

Treatment of size effects

$$K_{Jc(B=x)} = K_{min} + (K_{Jc(1T=25.4)} - K_{min})\left(\frac{25.4}{X}\right)^{\frac{1}{4}}$$

Data from any specimen size (ex. precracked Charpy) can be normalized to the reference thickness (1T = 25.4 mm)



* First edition: E1921-97; current version: E1921-09

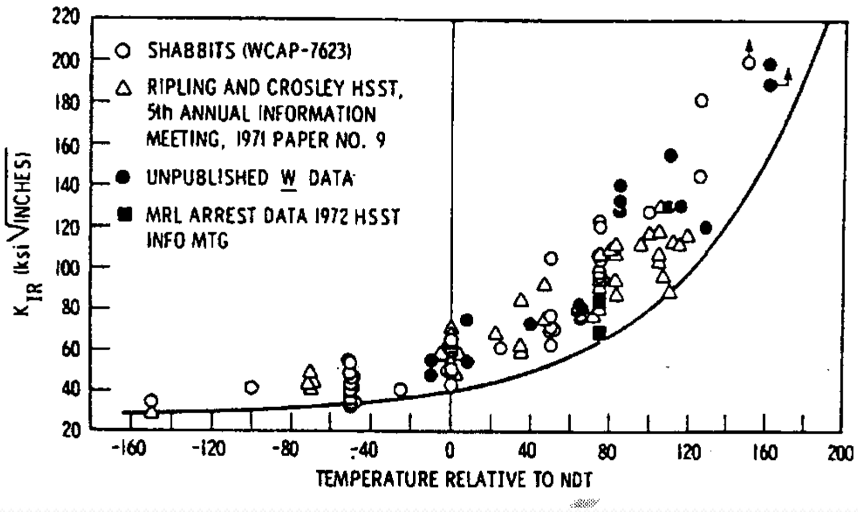
Background

- The ASME reference toughness curves (K_{Ic} and K_{IR}) are based upon a material normalizing and indexing parameter, RT_{NDT}
- In many cases, this parameter is overly conservative relative to the real toughness of ferritic RPV steels, and a more direct measure of the fracture toughness is needed
- The Master Curve method can provide a directly measured fracture toughness temperature index, as well as statistically-derived tolerance bounds for both unirradiated and irradiated materials

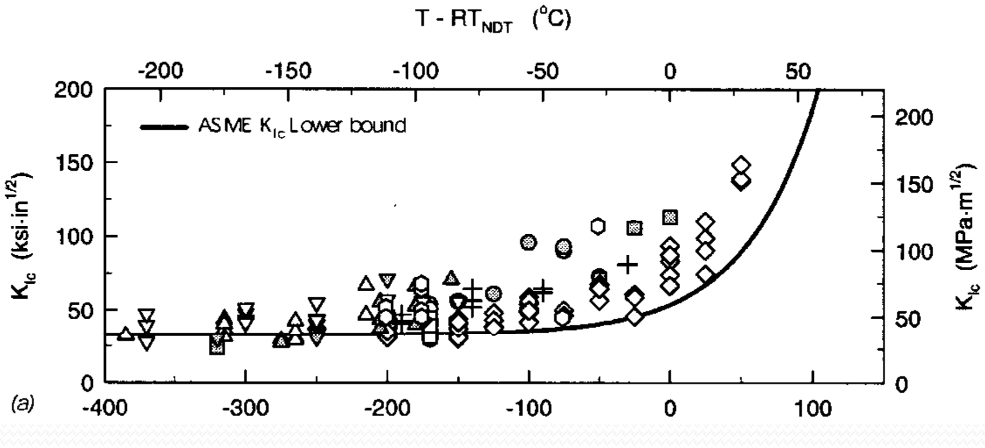
Approach

- In the late 90's, a task group under the Pressure Vessel Research Council (PVRC) has evaluated the application of the Master Curve methodology to the ASME Code, using international databases collected for this purpose
- The final recommendations of the task group have allowed this approach to be applied within the ASME Code through two "Code Cases":
  - Code Case N-631 (Section III, Division 1)
  - Code Case N-629 (Section XI, Division 1)
- The application is foreseen as a two-step process:
  - first, a new temperature index (RT_{To}) has replaced RT_{NDT} for the existing ASME lower bound curves [ACHIEVED]
  - later, new statistically-defined lower bound tolerance bounds will replace the ASME lower bound curves

Derivation of the ASME K_{Ic} and K_{IR} lower bound curves

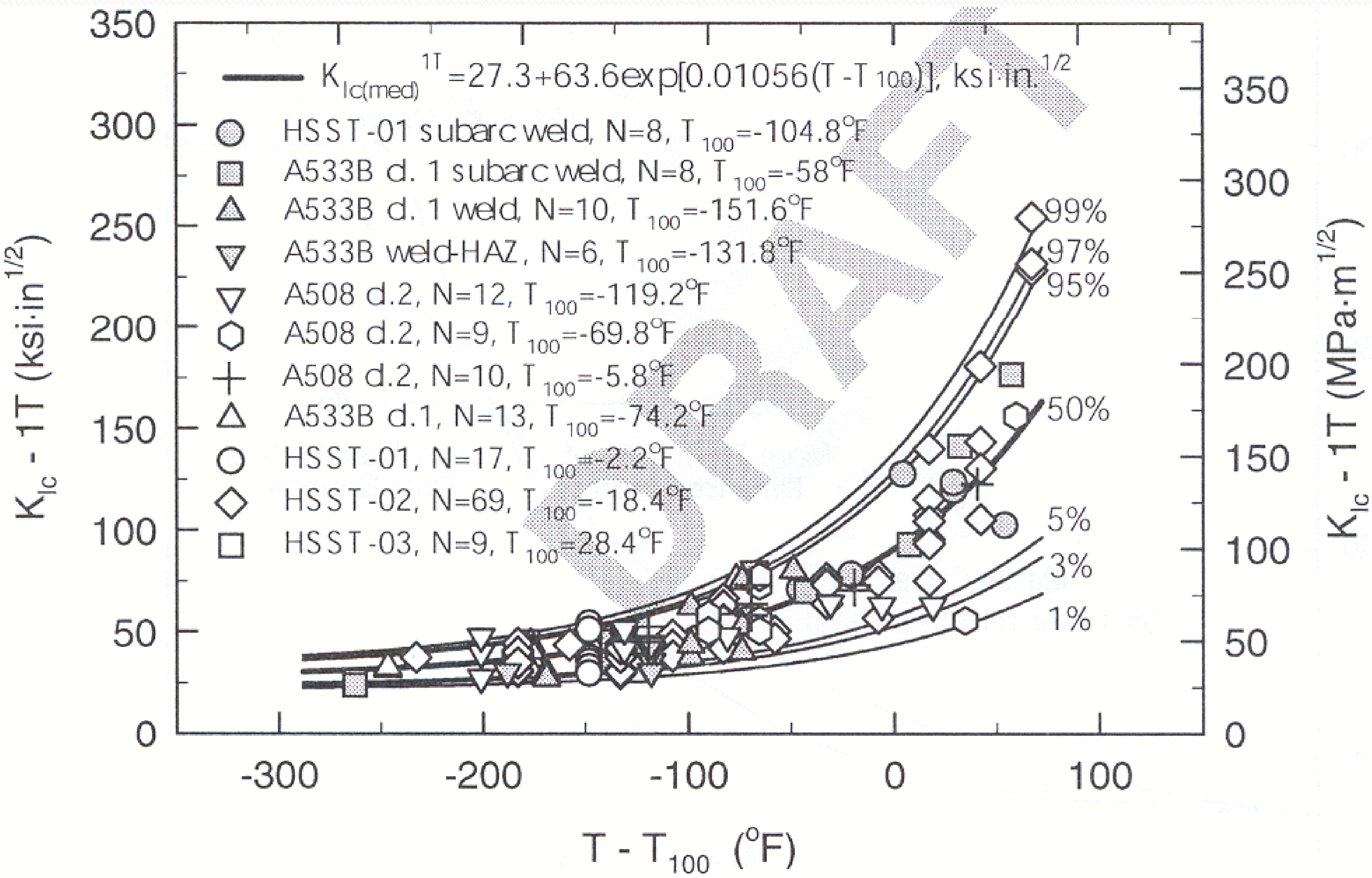


K_{IR} curve: 3σ lower confidence bound to existing dynamic and crack arrest data



K_{Ic} curve: approximate 2σ lower confidence bound

The Master Curve is also able to bound the original K_{Ic} data



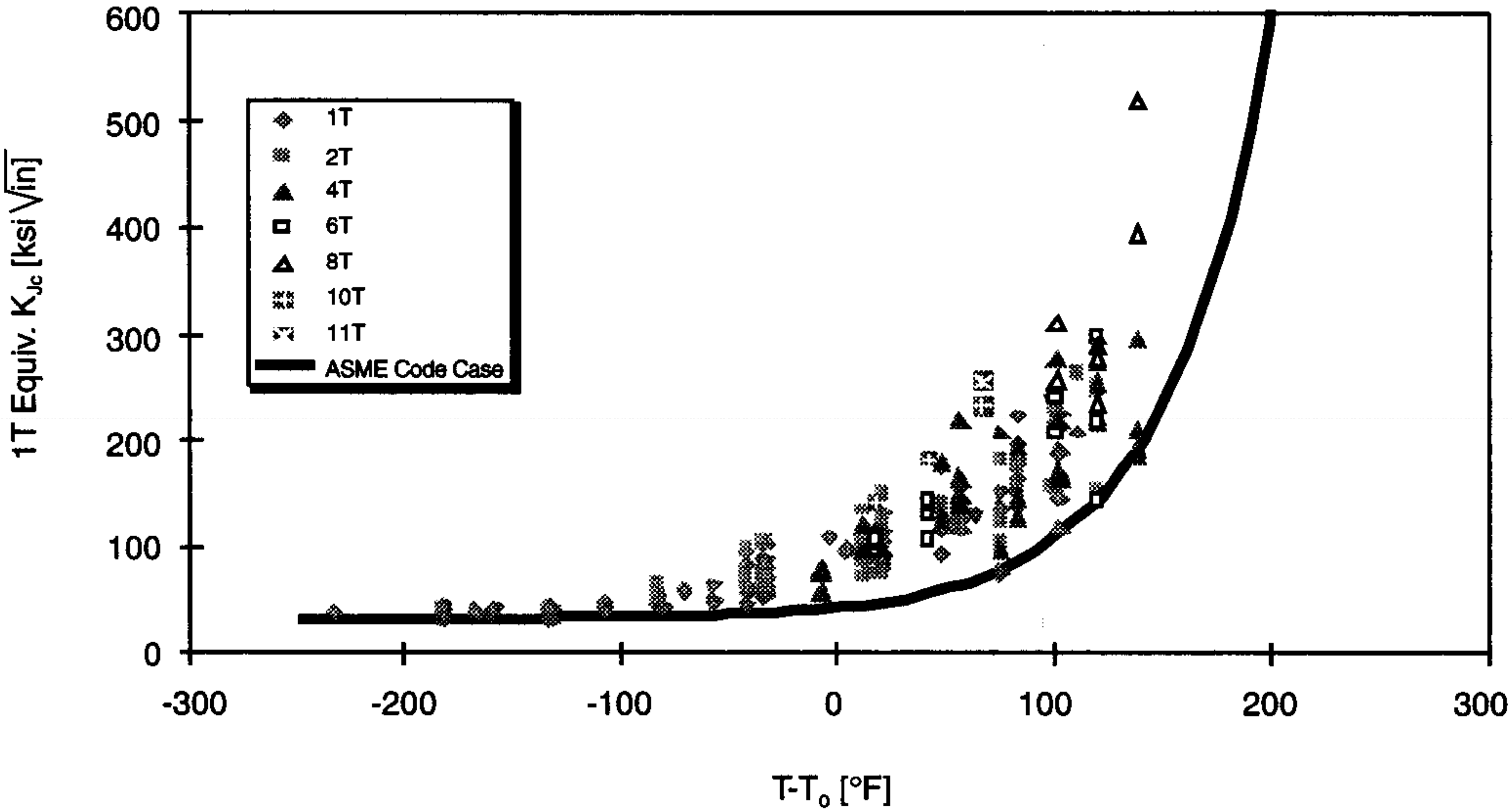
The philosophy of the current ASME Code Cases N-631 and N-629

- The equivalent, Master Curve-based reference temperature used for indexing the ASME K_{Ic} and K_{IR} lower bound curves and appropriately bounding the data is defined as:

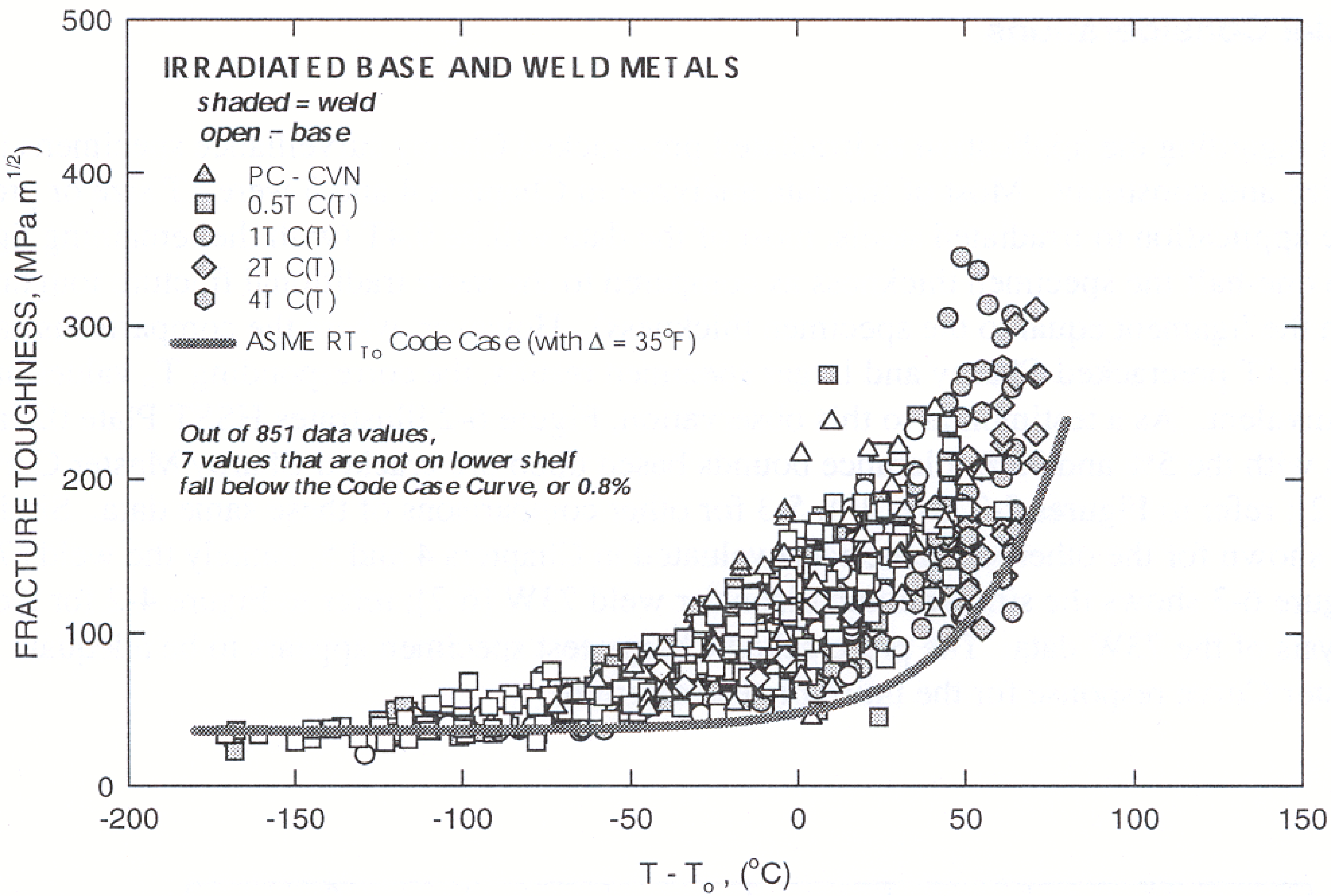
$$RT_{To} = T_o + 35\ °F = T_o + 19.4\ °C$$

- The definition of RT_{To} uses a 5% Master Curve tolerance bound
- This alternative reference temperature can be calculated by direct toughness measurements (without using Charpy information) for pressure-retaining materials, in both the unirradiated and irradiated conditions

Applicability of the new curve to the original K_{Ic} database



Excellent results for irradiated materials (851 base/weld)



Full references for the ASME Code Cases

- ASME Boiler and Pressure Vessel Code Case N-629 *Use of Fracture Toughness Test Data to Establish Reference Temperature for Pressure Retaining Materials*, Section XI, Division 1
- ASME Boiler and Pressure Vessel Code Case N-631 *Use of Fracture Toughness Test Data to Establish Reference Temperature for Pressure Retaining Materials Other Than Bolting for Class 1 Vessels*, Section III, Division 1

Comparison between Charpy-based (RT_{NDT}) and Master Curve-based (RT_{To}) approaches

- Source: E. Lucon, M. Scibetta, R. Chaouadi, E. van Walle and R. Gérard, *Improved Safety Margins for Belgian Nuclear Power Plants by the Application of the Master Curve Approach to RPV Surveillance Materials*
  - Presented at the Advanced Fracture Methods for Light Water Reactor Components Workshop – Baltimore, MD (US), July 2006
  - Published in International Journal for Pressure Vessel and Piping 84 (9), p.536-544, Sep 2007

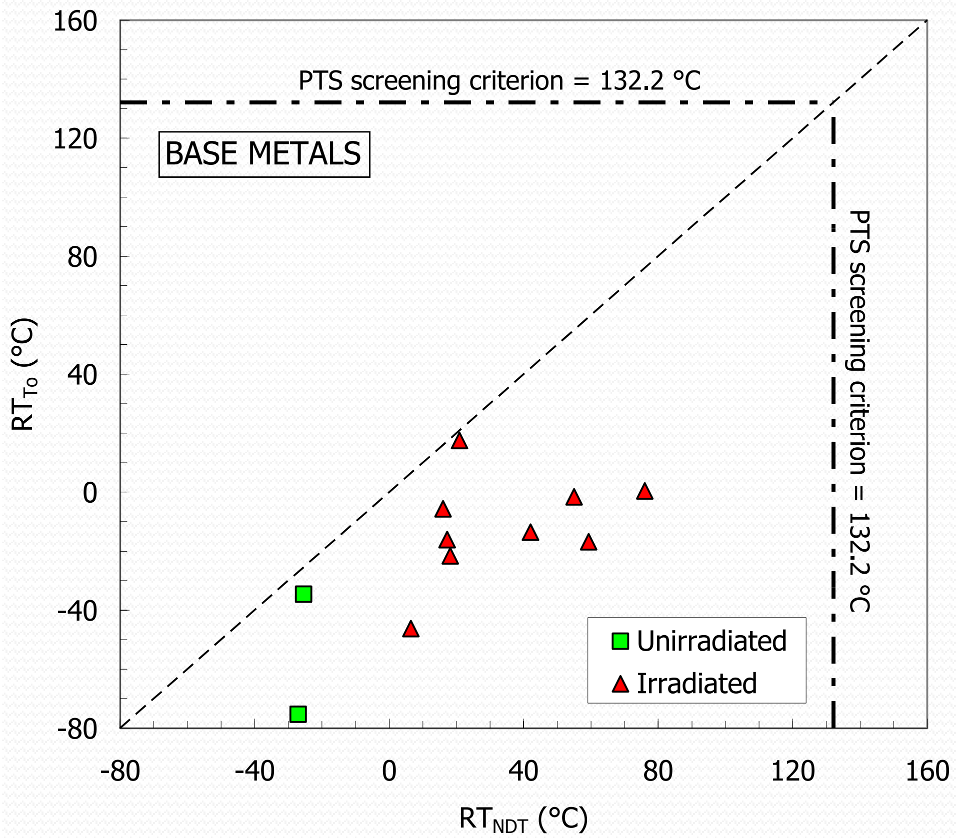
Intrinsic drawbacks of the "conventional" RT_{NDT} approach

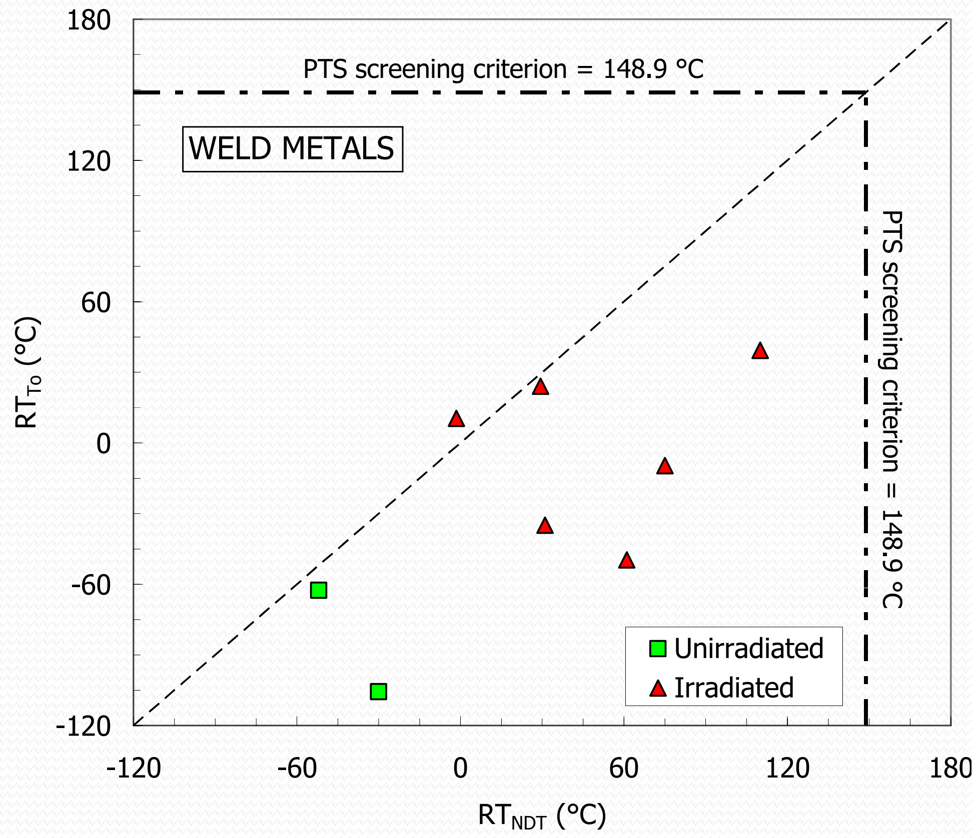
- Empirical in nature
- Couples dynamic (Charpy) test data with a static fracture toughness curve
- Uncertainties are accounted for through imposition of conservative bounds
- This can penalize plant operation and life management decisions (premature shut-downs of plants)
- The obvious solution: using direct fracture toughness measurements

The “advanced” MC-based approach: reconstitution + toughness tests

- Fracture toughness specimens included in some surveillance capsules are too few for a Master Curve analysis
- Charpy specimens have to be tested within the regulatory framework
- New fracture toughness (PCC) specimens can be fabricated from broken Cv’s using reconstitution
- Test results are analyzed according to the Master Curve approach ⇨ T_o is obtained
- A revised reference temperature is obtained for indexing the ASME curve: $RT_{To} = T_o + 35°F$

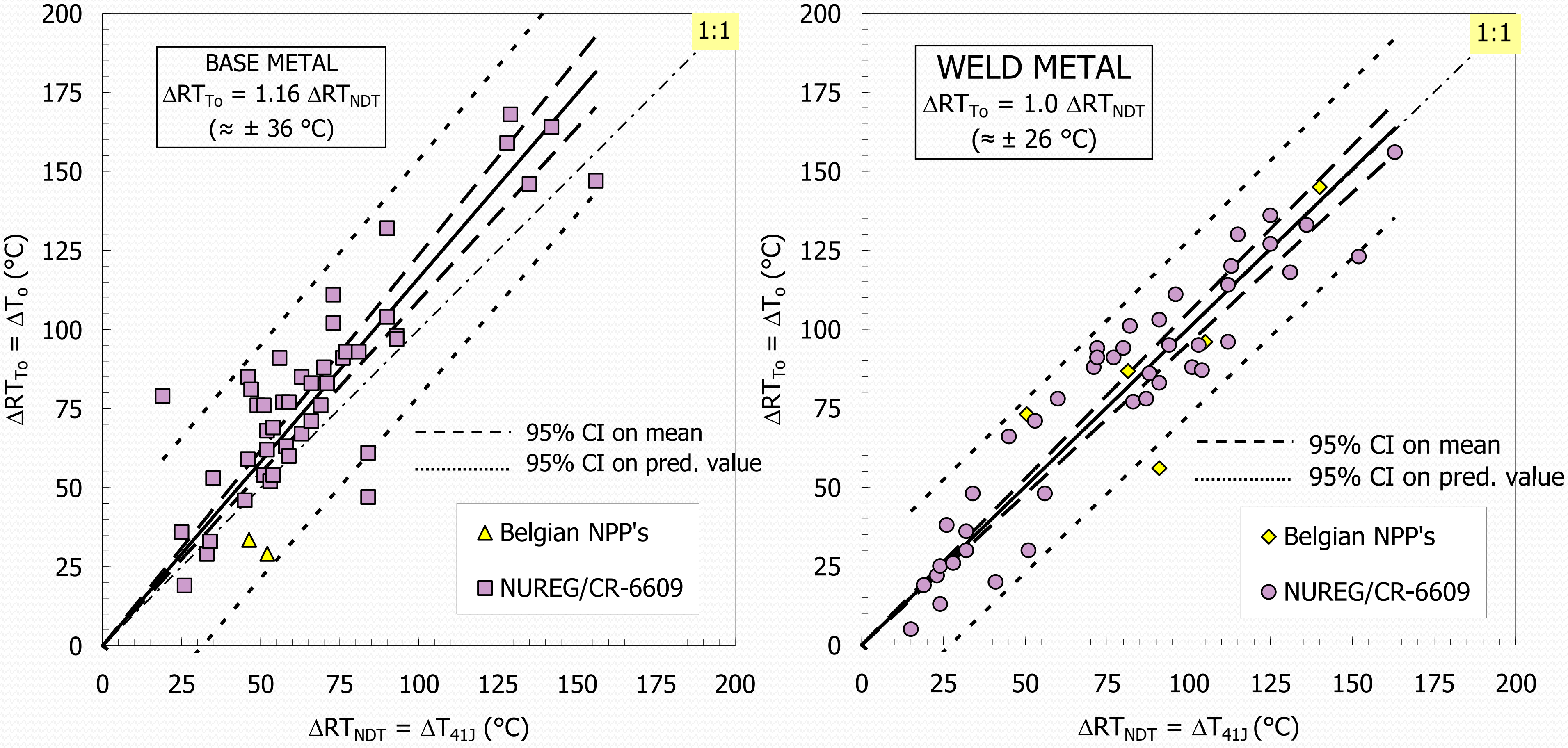
"Conventional" vs "advanced": results for 19 Belgian surveillance materials





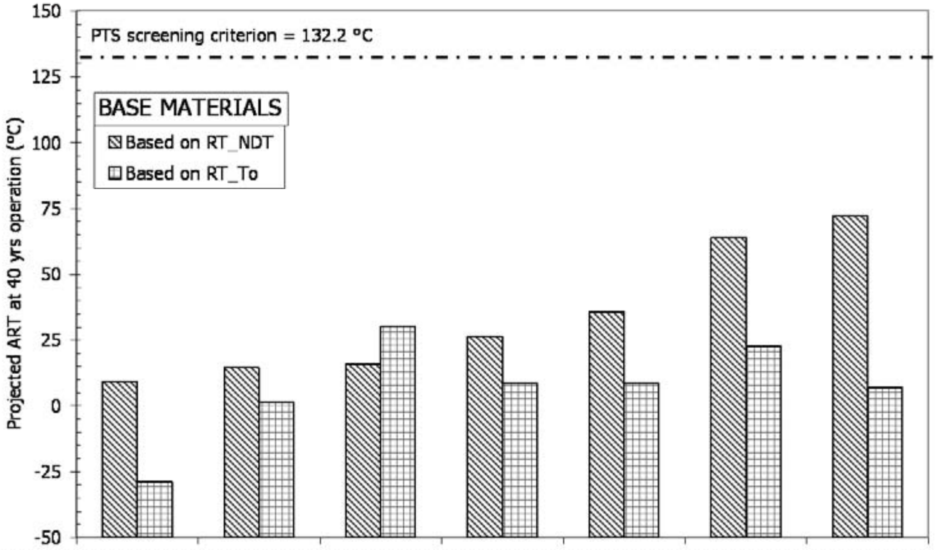
- Large margins with respect to PTS screening criteria, especially when using RT_{To} and for highly irradiated materials
- RT_{To} is lower than RT_{NDT} in all cases except one

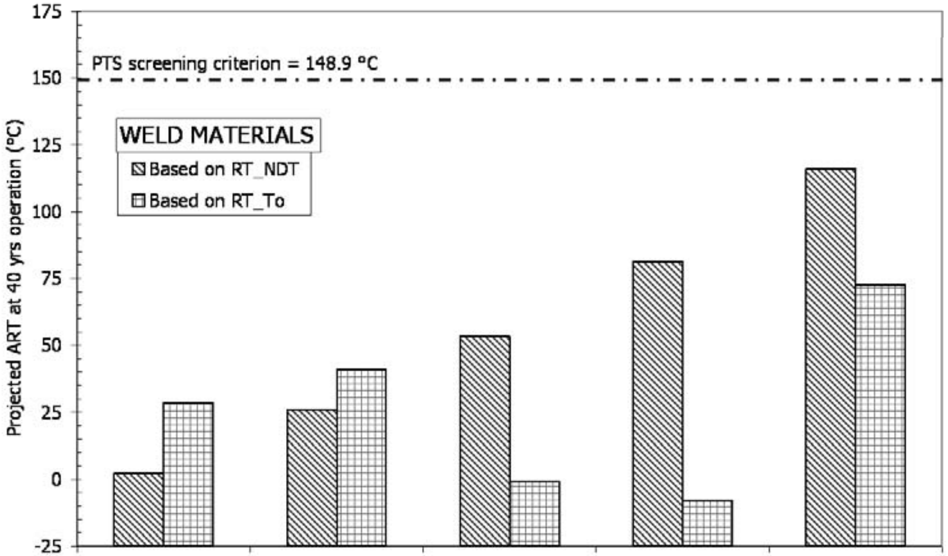
RT_{NDT} and RT_{To} are not correlated, but their shifts ΔRT_{NDT} and ΔRT_{To} are correlated



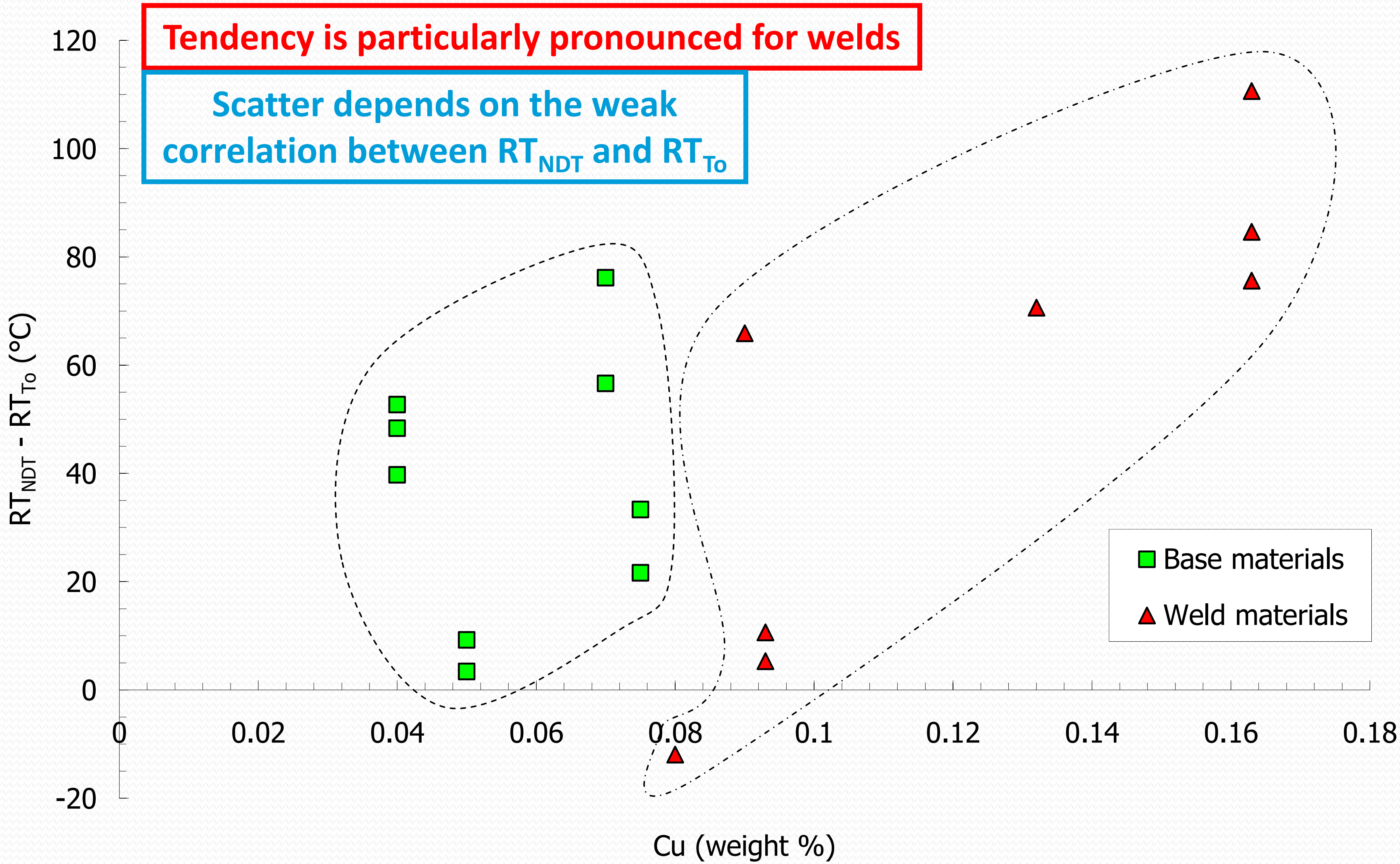
Source: Sokolov/Nanstad, ASTM STP 1325, 1999 & NUREG/CR-6609, Nov 2001

Large safety margins and tendency to underestimate the "real" toughness

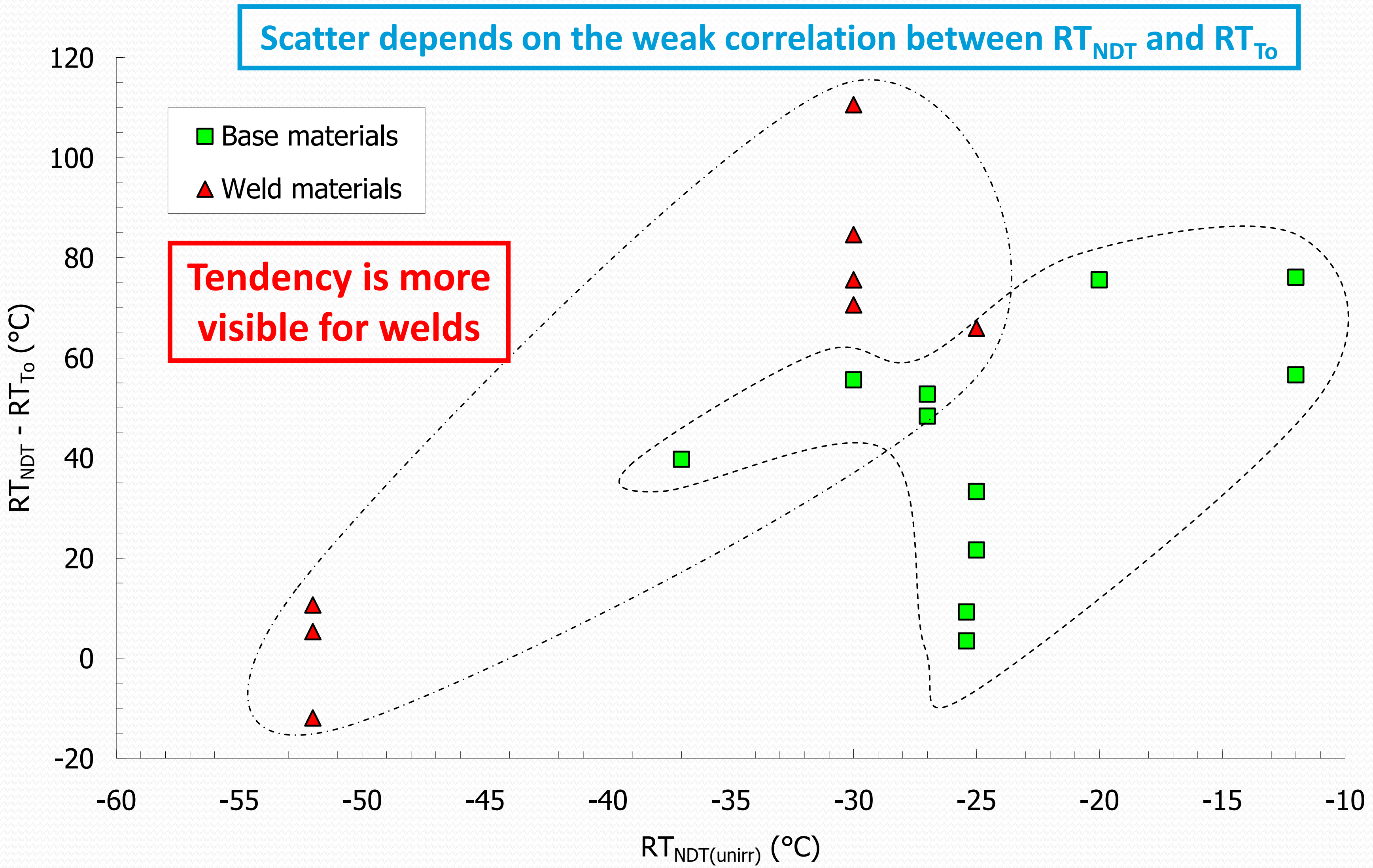




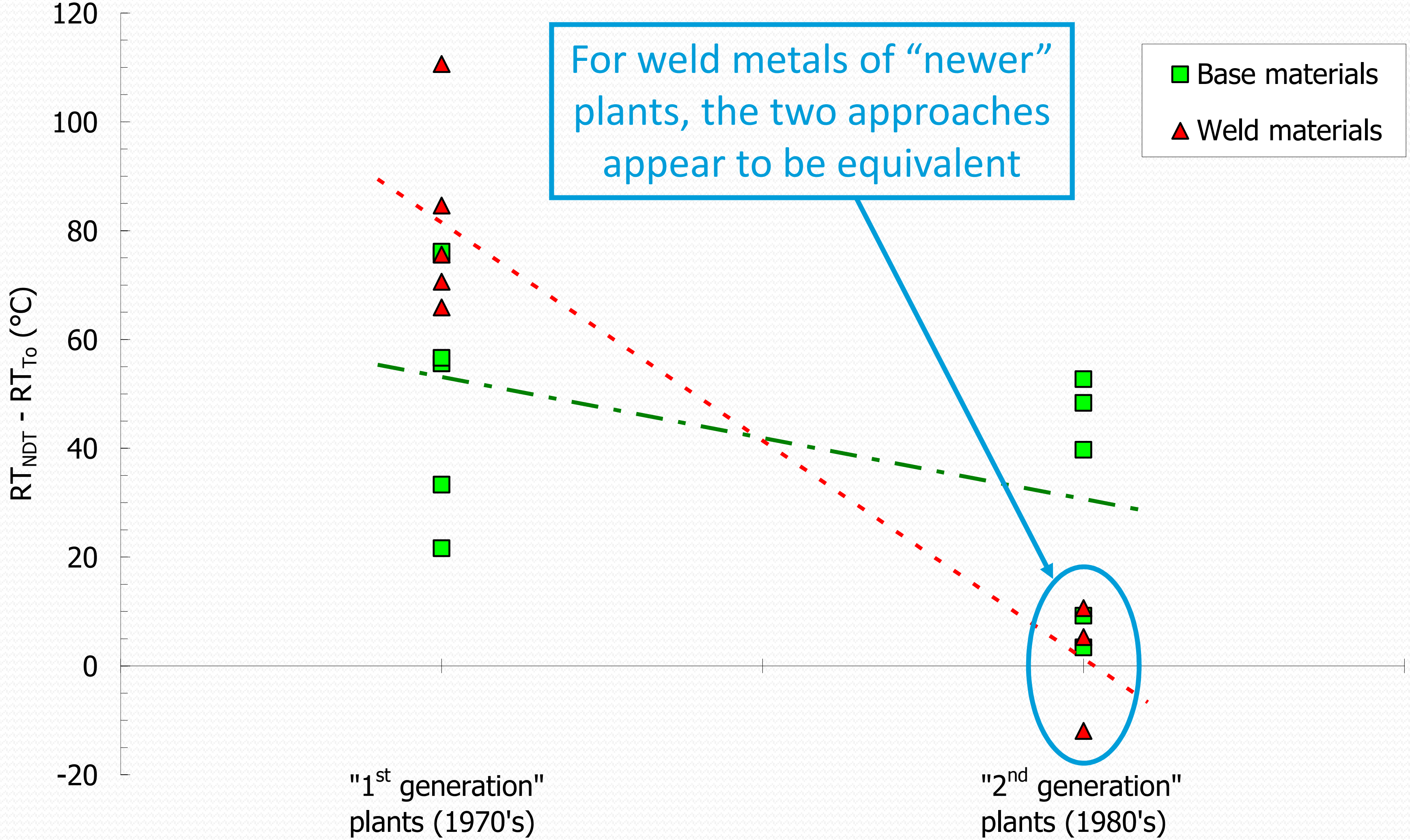
“Improved margins” of RT_{To} approach seem to depend on irradiation sensitivity (Cu content)



"Improved margins" of RT_{To} approach seem to depend on baseline properties (unirr RT_{NDT})



“Advanced” approach seems more beneficial for older plants



Conclusions of the study

- The additional margins entailed by the use of RT_{To} over RT_{NDT} appear particularly significant in case of:
  - highly irradiated materials (40 years of reactor operation and beyond)
  - materials with high irradiation sensitivity (Cu > 0.1-0.15%)
  - materials with low reference toughness ($RT_{NDT,unirr}$ > -30°C)
  - first-generation NPP's
- Toughness-based approach seems more beneficial for weld than base metals
- In Belgium, the advanced approach is used in a "defense in depth" perspective:
  - to demonstrate the existence of important safety margins
  - to give increased confidence on RPV integrity at high doses

Data presented can be considered favourable from three different viewpoints

- For the utilities which manage the plants:
  - using fracture toughness-based approach instead of Charpy-based approach can considerably increase the life margins with respect to the PTS screening criteria
- For the safety authorities:
  - legislative approach is significantly conservative, particularly for the older plants and for the most highly irradiated conditions
- For the engineer:
  - fracture toughness is used to assess … fracture toughness!

Directions for future research

- Relationship between Master Curve fracture toughness and CVN data
- Effect of irradiation on the shape of the Master Curve at high T_0 shift levels (for ex. sensitive high-Ni steels)
- Enhanced constraint loss following irradiation due to reduction in strain hardening
- Constraint limits for the Master Curve method and PCC specimens; specimen bias effects
- Master Curve applicability for specimens failing by intergranular fracture (irradiation + thermal annealing)

Pressure-Temperature Operating Limits

- Key features to be defined for developing operating limit curves for normal plant operations:
  - Size and shape of the assumed reference flaw
  - Safety factors on pressure and thermal stresses
  - Reference fracture toughness curve and safety factor to be used
- Reference codes:
  - US – ASME Code Section III, Appendix G and Section XI
  - Japan – JEAC 4206-2000
  - France – RCC-M Code, chapter B.3260 (two methods)
  - Russia – PNAE-G-7-002-86
  - Germany – KTA 3201.2, Paragraph 7.9 (two methods)

Assumed reference flaw

- Reference flaws are generally quite large compared to current non-destructive inspection capabilities
- Flaw dimensions:
  - US, Japan, Germany (method 2), France (method 1): depth ¼-thickness, width 1.5 × thickness
  - Russia: depth ¼-thickness, width ¾-thickness
  - France (method 1): depth 15 mm, length 90 mm (smaller, more realistic flaw)

Safety factors on stresses

- For most methodologies:
  - factor 2 on pressure stress (1.5 for leak and hydrostatic tests)
  - factor 1 on thermal stress
- Russian approach and French method 2: factor 1 on pressure stress, but fracture toughness curves have additional safety factors included

Reference fracture toughness curve

- US (similar approach in Japan)
  - ASME Code: K_{Ic} lower bound curve
  - ASME Code Case N-641: use of K_{Ia} lower bound curve allowed
- France (method 1) and Germany: only K_{Ia} curve allowed
- Russia: specific K_{Ic} curve with safety factor
- France (method 2): combination of K_{Ia} and K_{Ic} curves

Damage attenuation into RPV wall

- Values of toughness are needed at ¼-thickness and ¾-thickness location in the RPV wall
- Flux/fluence attenuates from inside surface of RPV into the wall
- dpa is used as measure of fluence change (e.g. Reg. Guide 1.99, Rev. 2 and ASTM E900-02)
- dpa is used to adjust the parameter Ø in the correlation