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Belgian R&D using the Enhanced Surveillance Strategy for RPV Embrittlement Assessment

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Surveillance Philosophy

- Surveillance of RPV (mandatory)
  - Regulatory : essentially based on the Charpy impact test
    - Conventional surveillance determines DBTT shift due to irradiation
    - Fracture toughness properties are deduced from this information
  - This approach is more than 50 years old
  - Only part of the available information is used

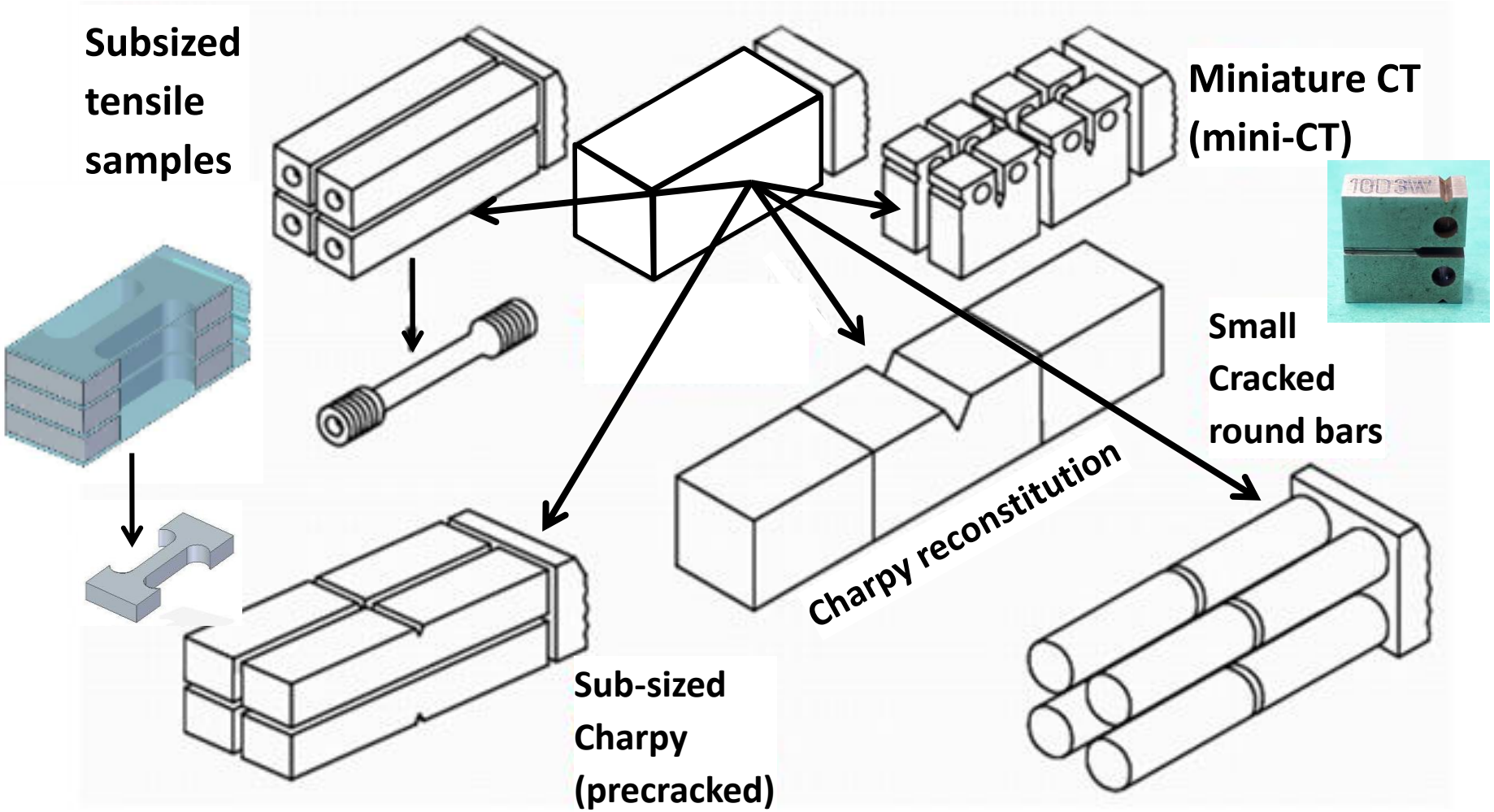
- Enhanced surveillance (Supplementary)
  - Tensile testing (static and dynamic) with subsized specimens
  - Reconstitution of additional Charpy impact (instrumented)
  - Reconstitution of PCCv (precracked Charpy specimens) for fracture toughness testing in the transition and ductile regime

PART 1:

Reconstitution

What can be done with a broken Charpy impact specimen?

Specimen Reconstitution and Miniaturization



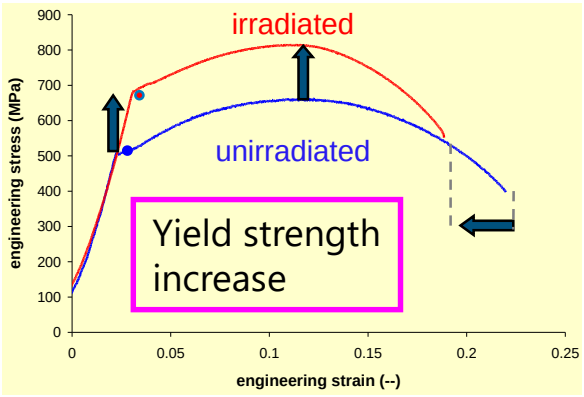
PART 2:

Tensile and Fracture toughness testing

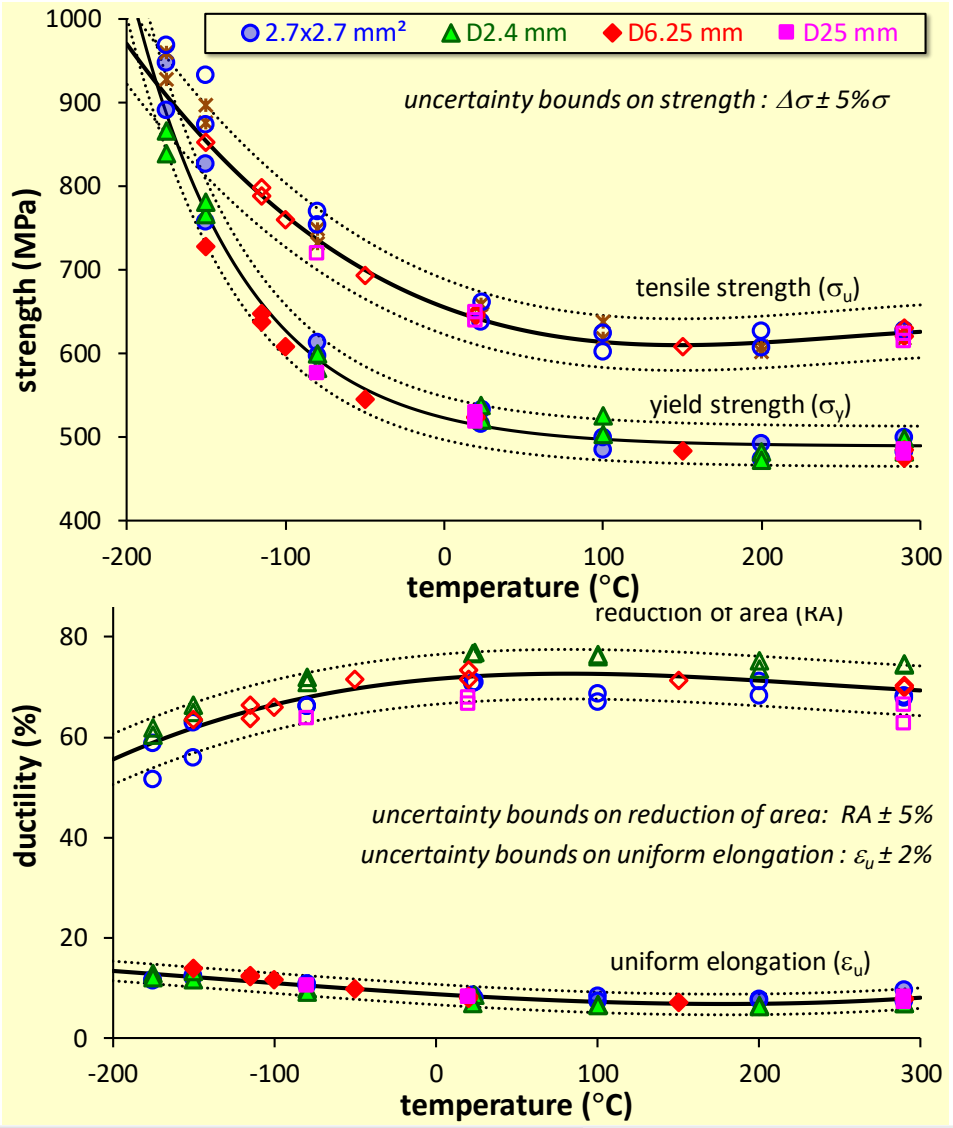
More than Charpy impact

Tensile testing

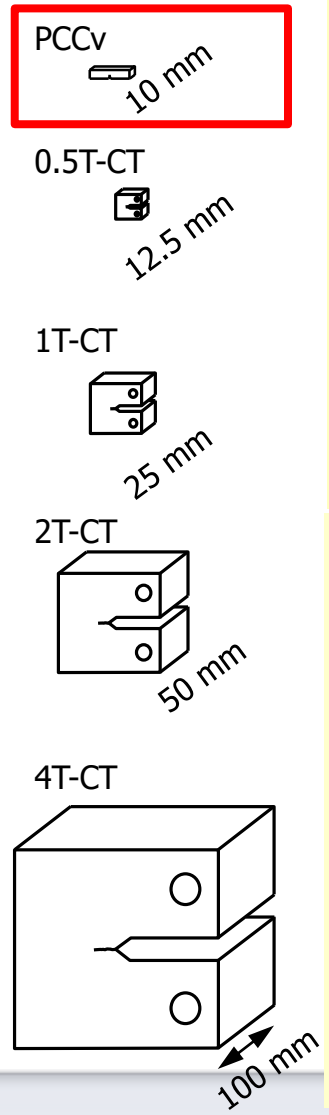
Tensile Testing

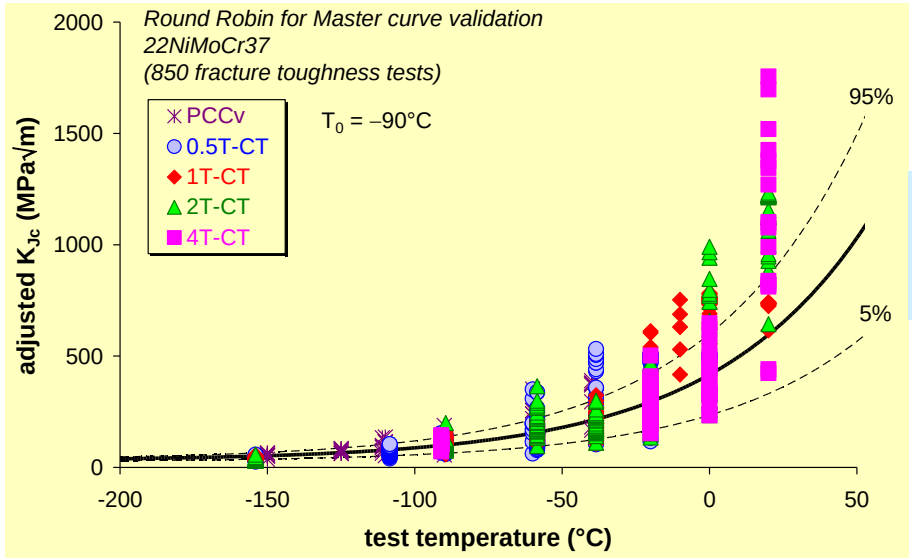


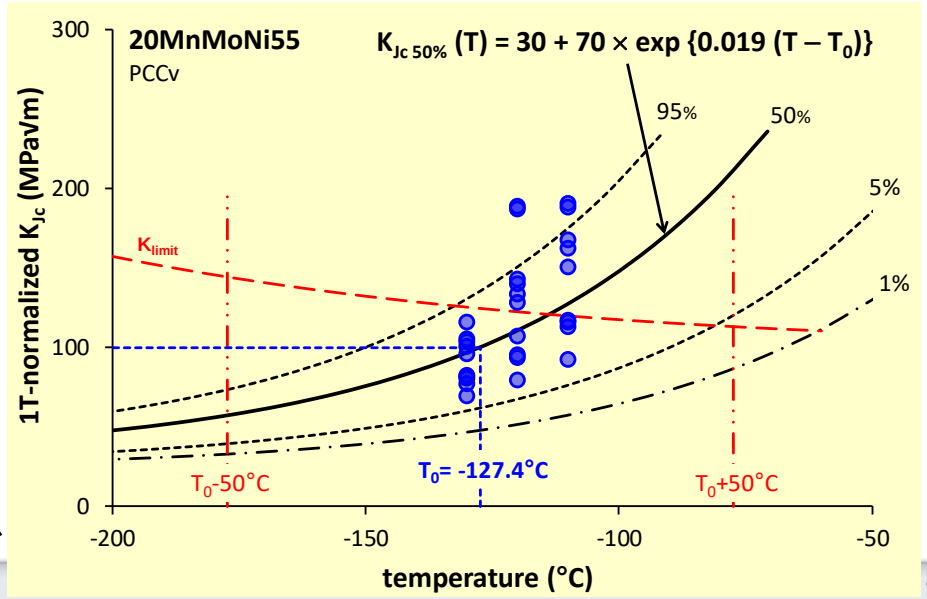
➔ Radiation Damage Modeling



Master Curve and Crack Resistance Curve







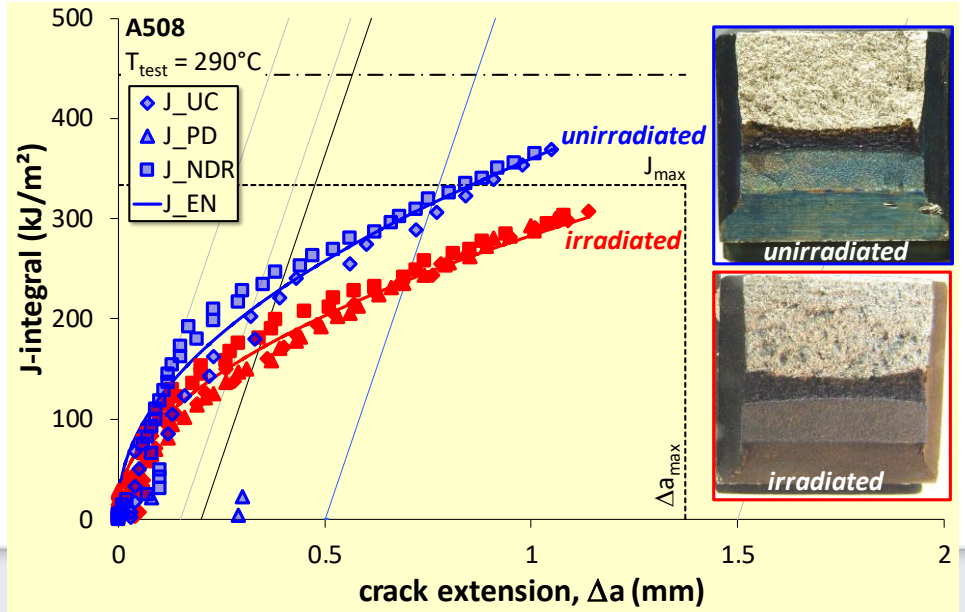
➔ ASTM E1921

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

Fracture toughness transition curve characterized by one single parameter, $\mathbf{T_0}$

Consistency

UC : Unloading Compliance
PD : Potential Drop
NDR : Normalization Data Reduction
EN : Energy Normalization

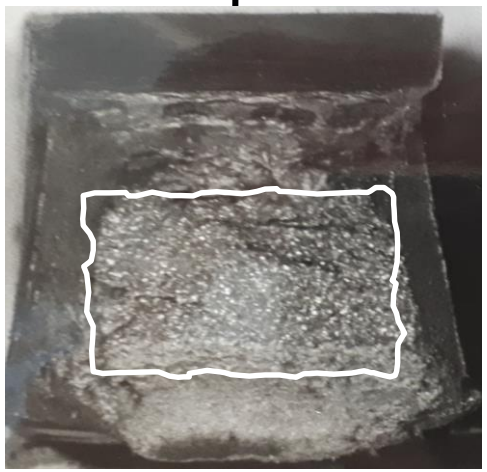


PART 3:

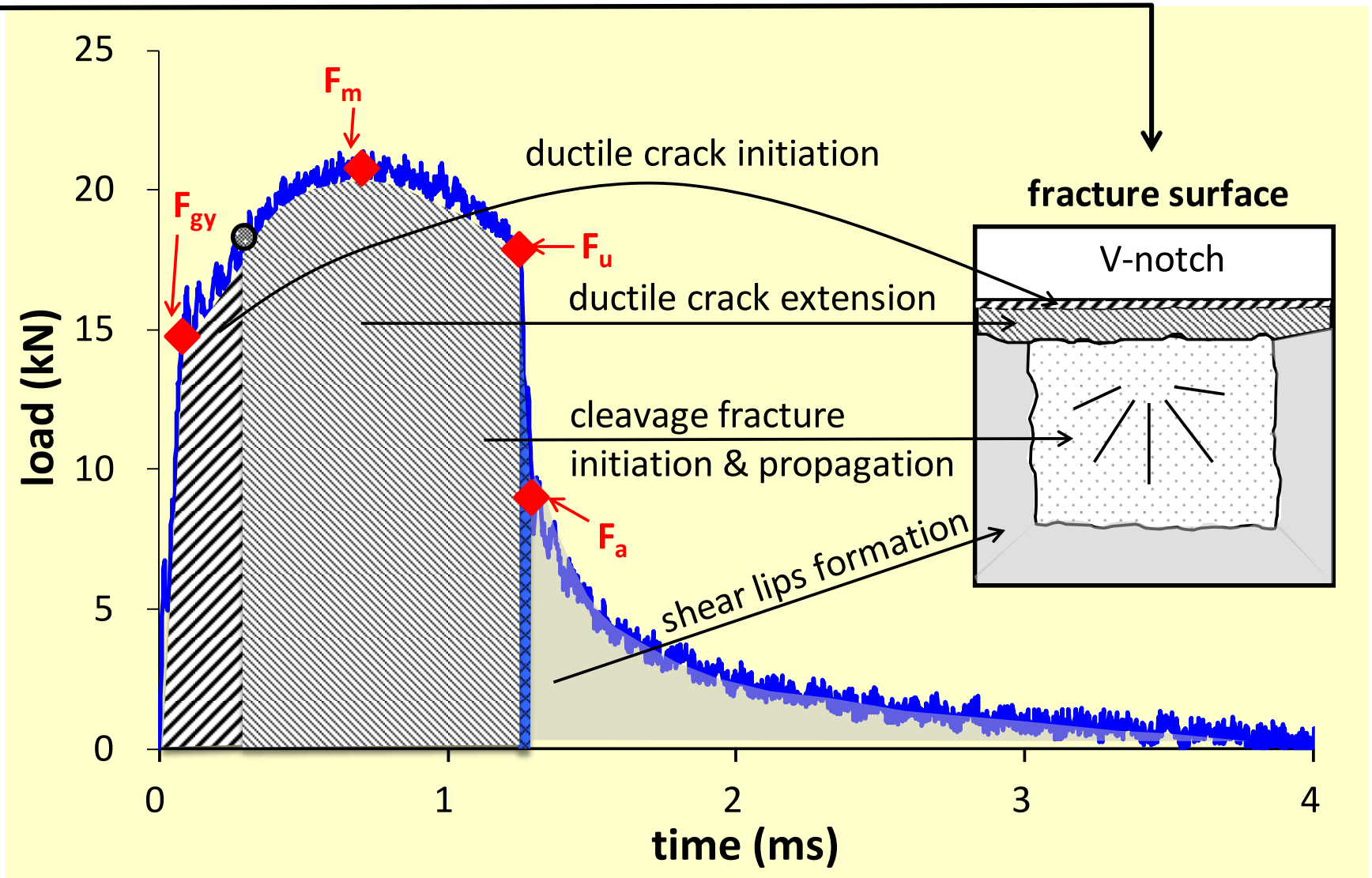
All What You Can Extract from the Instrumented Charpy Impact Test

Everything you always wanted to know about the Charpy impact test

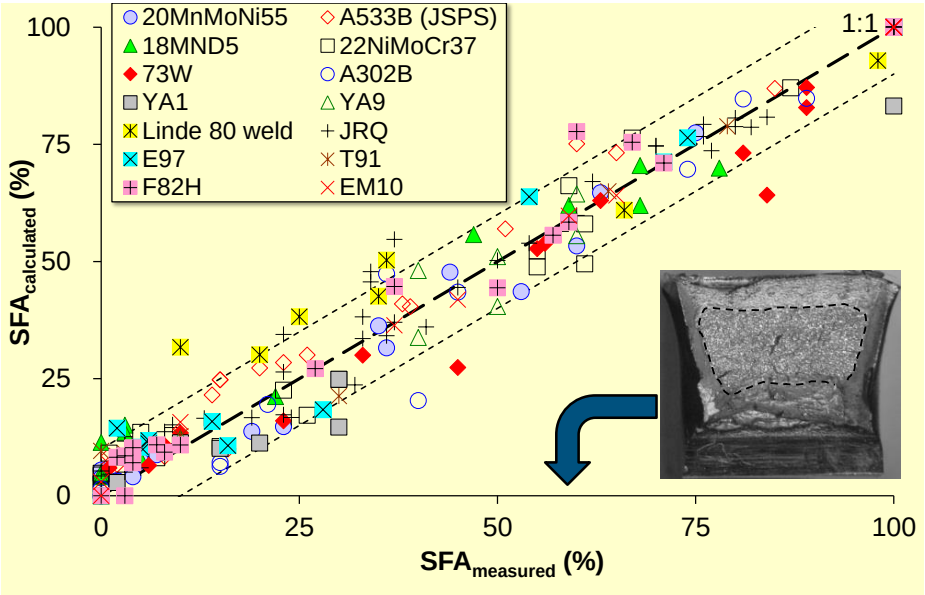
Instrumented Charpy Impact Test : Load Diagram



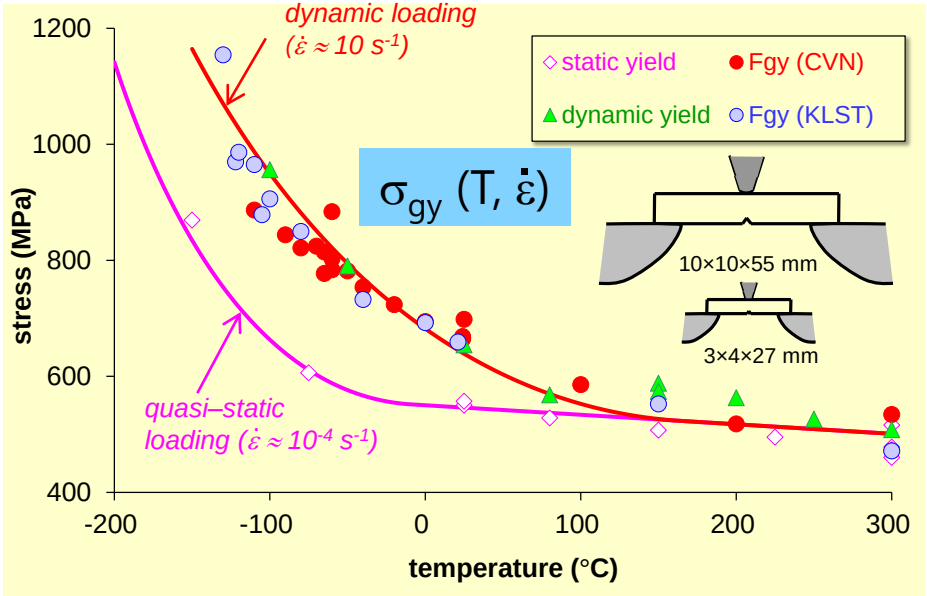
Characteristic loads
- F_{gy} (general yield load)
- F_m (maximum load)
- F_u (unstable fracture load)
- F_a (arrest load)

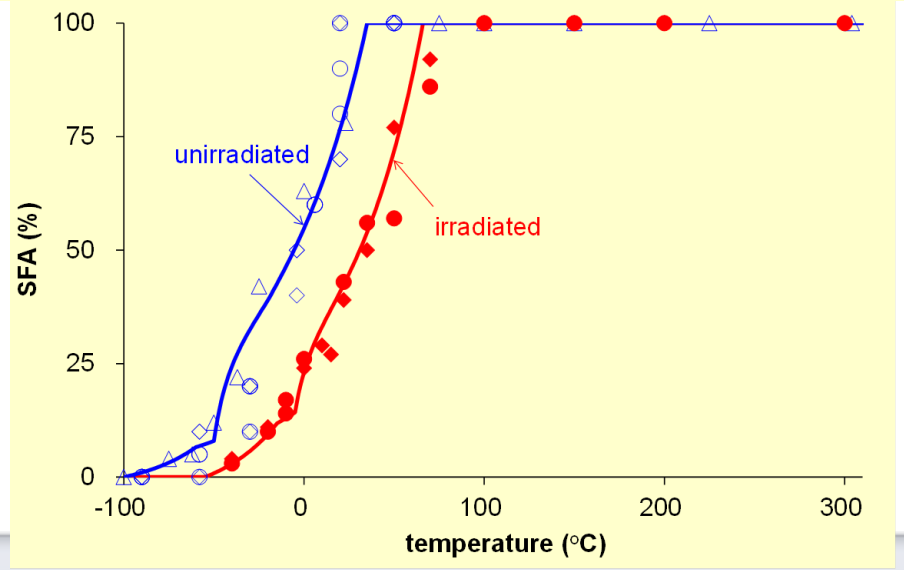


Parameters from instrumented Charpy curve : SFA & tensile yield



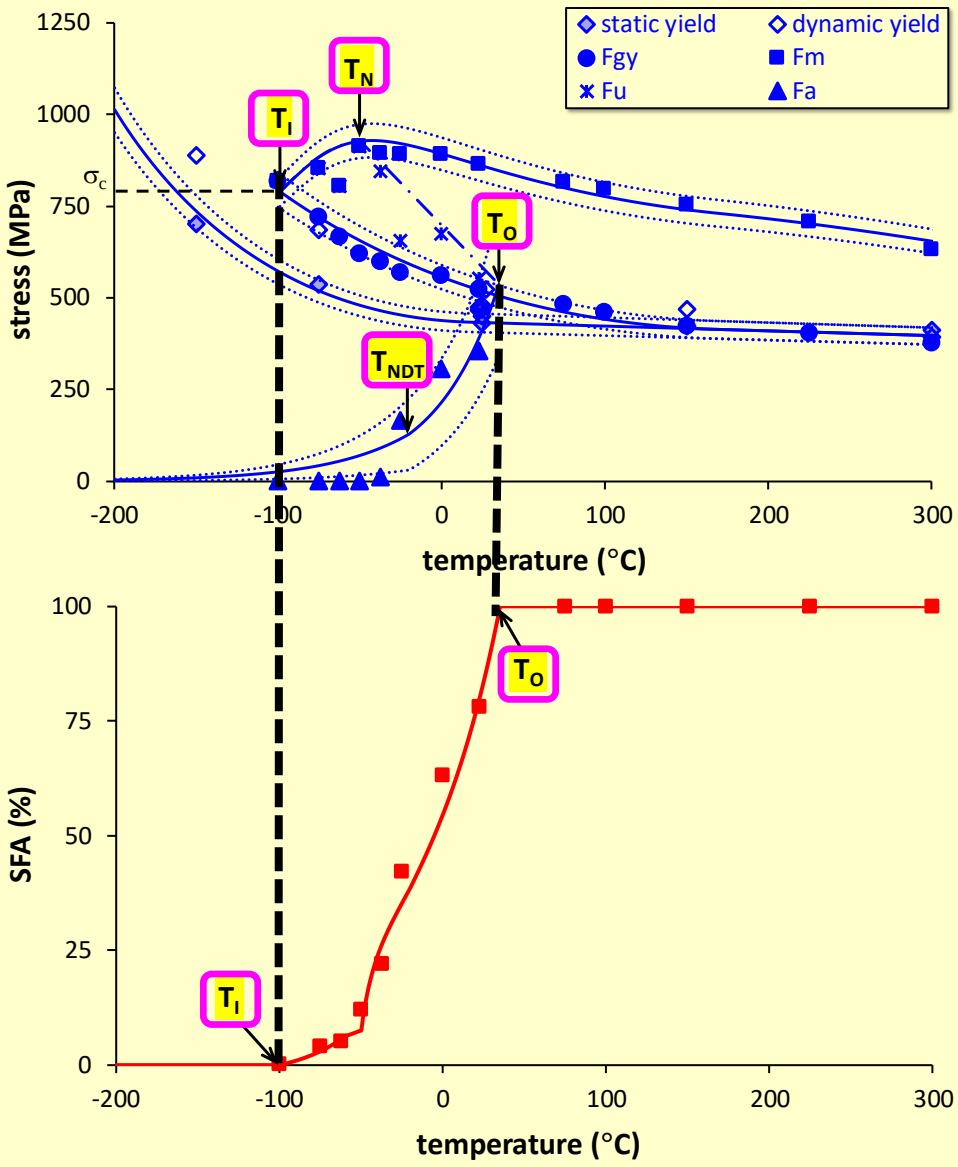
$SFA_{calculated} = f(F_{gy}, F_m, F_u, F_a)$ 1





2 Unique yield strength function σ_y (T, ε̇)

Load Diagram : Characteristic temperatures



T_I : brittle fracture temperature (SFA=0%)

T_O : ductile fracture temperature (SFA=100%)

$T \leq T_I$ → SFA = 0%

$T_I < T < T_O$ → 0% < SFA < 100%

$T \geq T_O$ → SFA = 100%

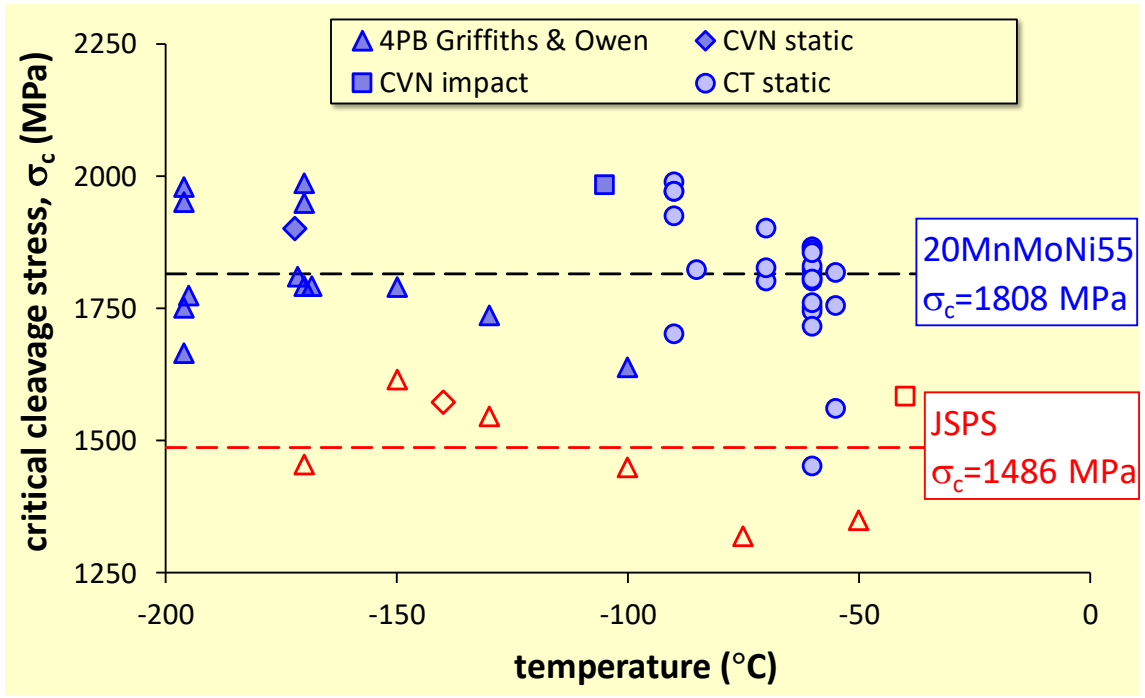
➔ $\sigma(T_I)$ → microcleavage fracture stress (σ_c)

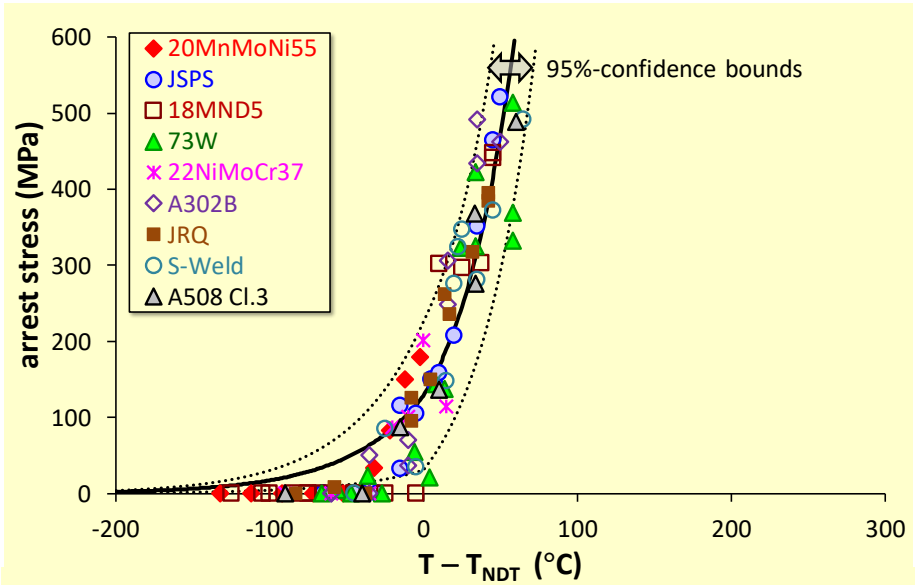
➔ T_{NDT} (based on arrest loads) correlation to Pellini NDT

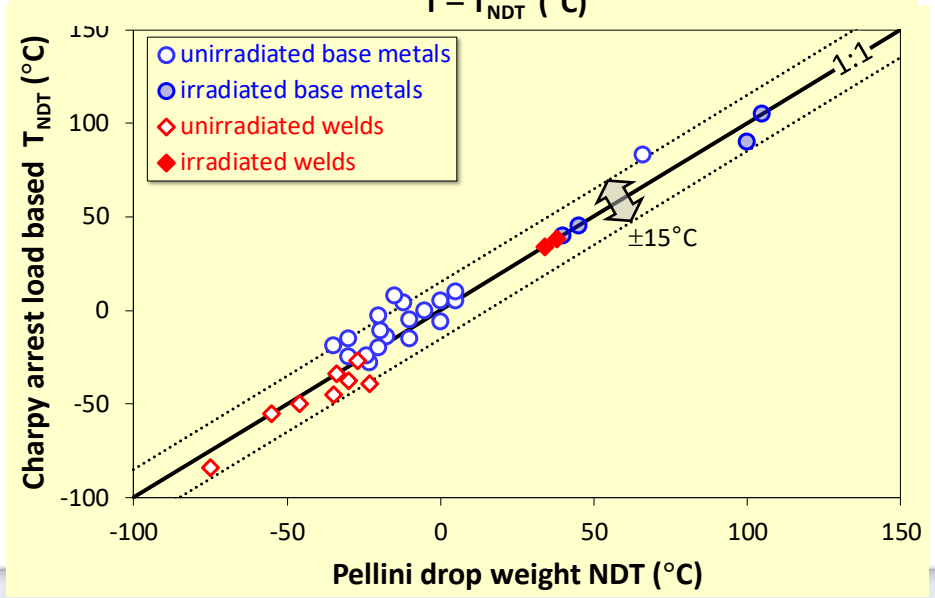
➔ T_I (CVN) correlation to $T_{100MPa\sqrt{m}}$ (static fracture toughness) correlation

Parameters from instrumented Charpy curve: Cleavage Fracture Stress & T_{NDT}

3 $\sigma_c = K_p \times \sigma_{gy}(T_l)$







4 $T_{NDT} = f(F_a)$

$T_{NDT\ (Charpy)}$–$NDT_{Pellini}$ correlation

Parameters from instrumented Charpy curve : Master Curve

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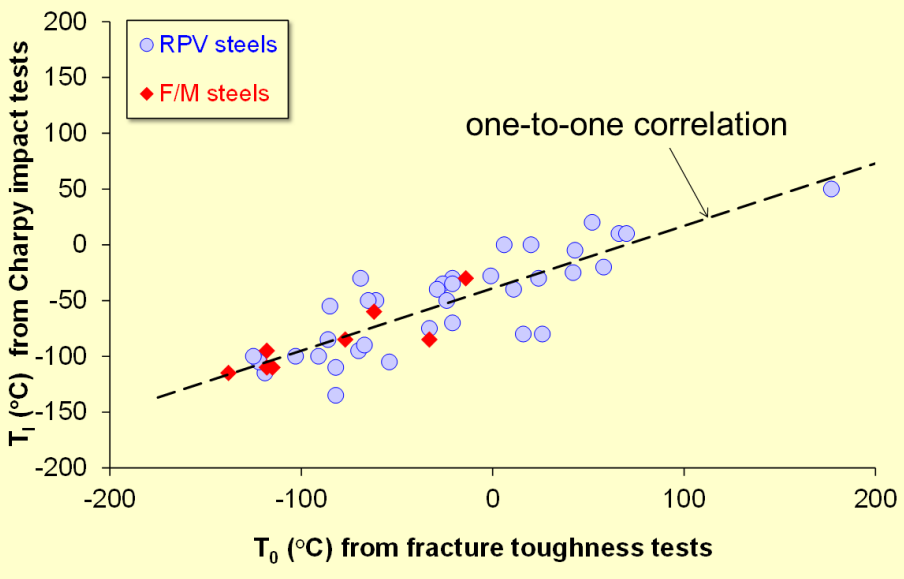
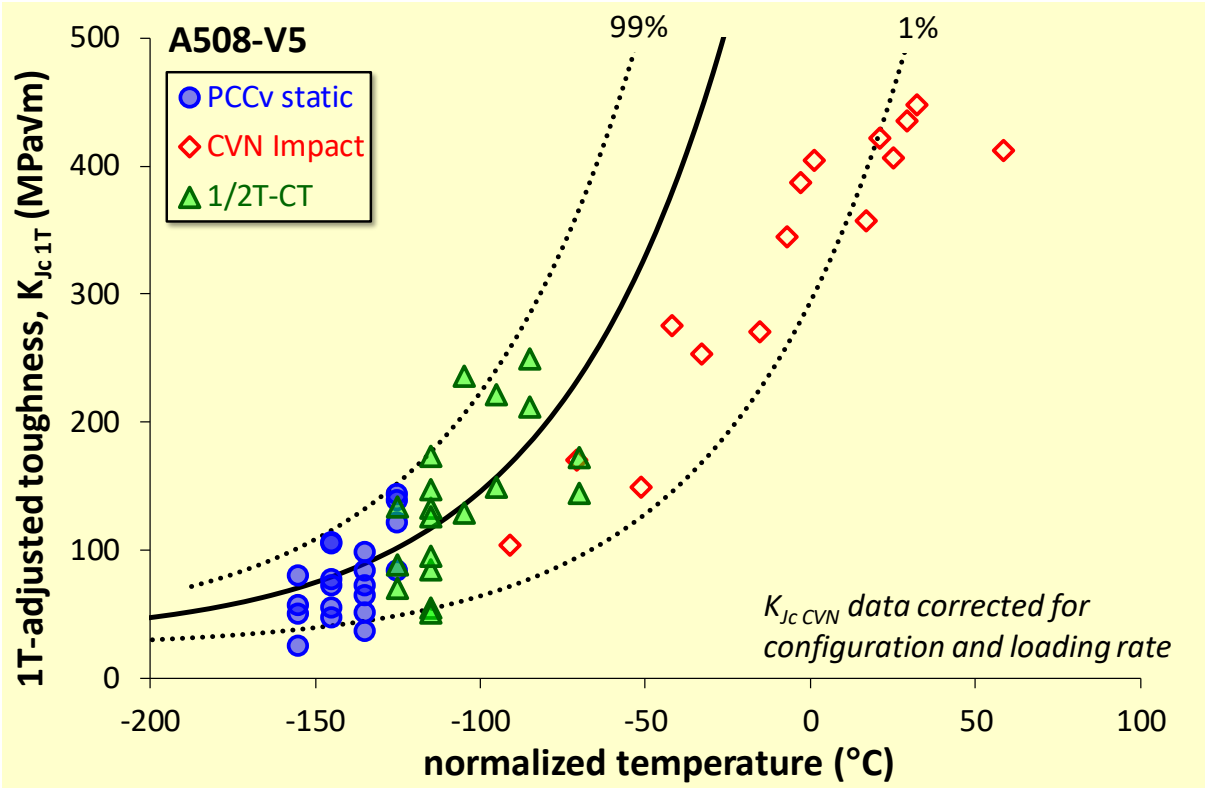
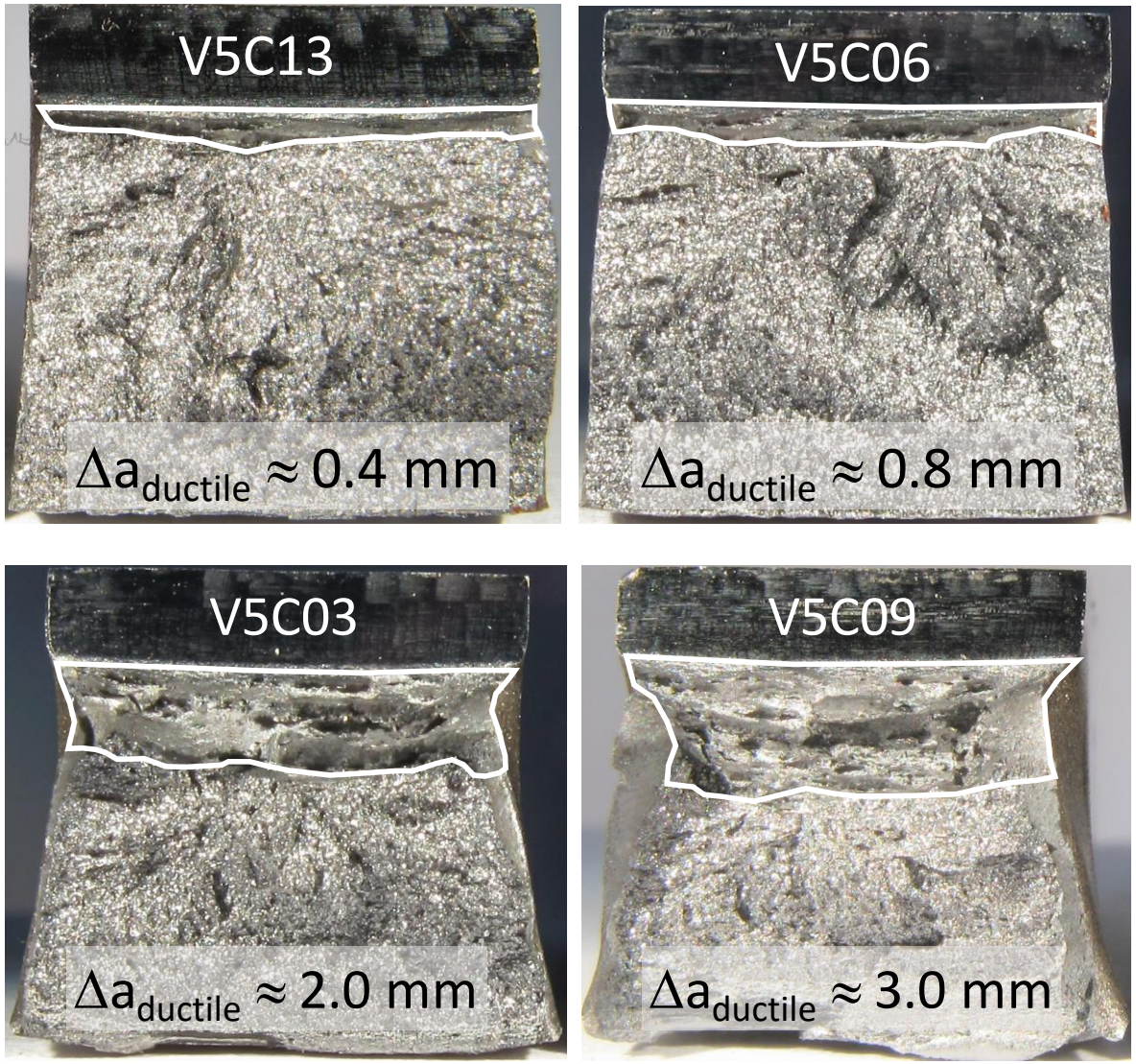
$T_{I\ (Charpy\ impact)}$–$T_{0\ (fracture\ toughness)}$ correlation



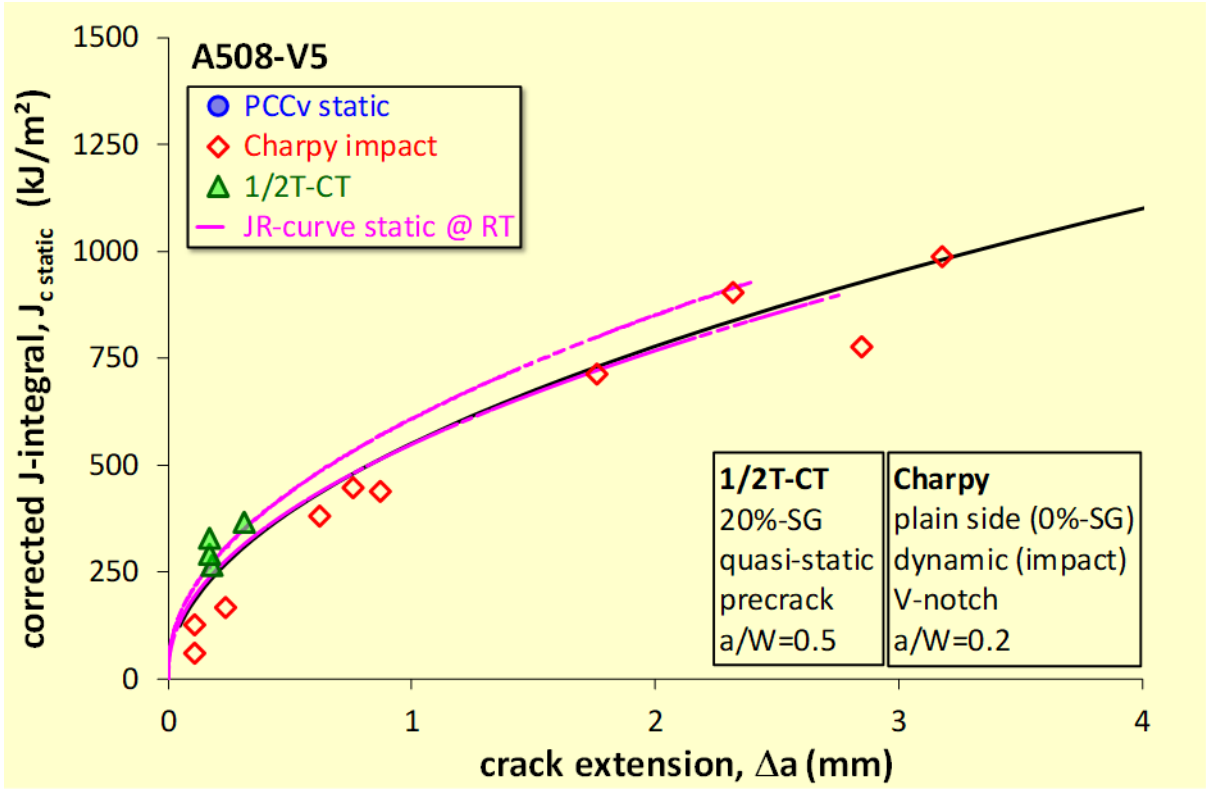


Correction for difference in geometry and test conditions.
The correction factors are established once for all and are not modified to fit the data.

Parameters from instrumented Charpy curve : J_R–Curve

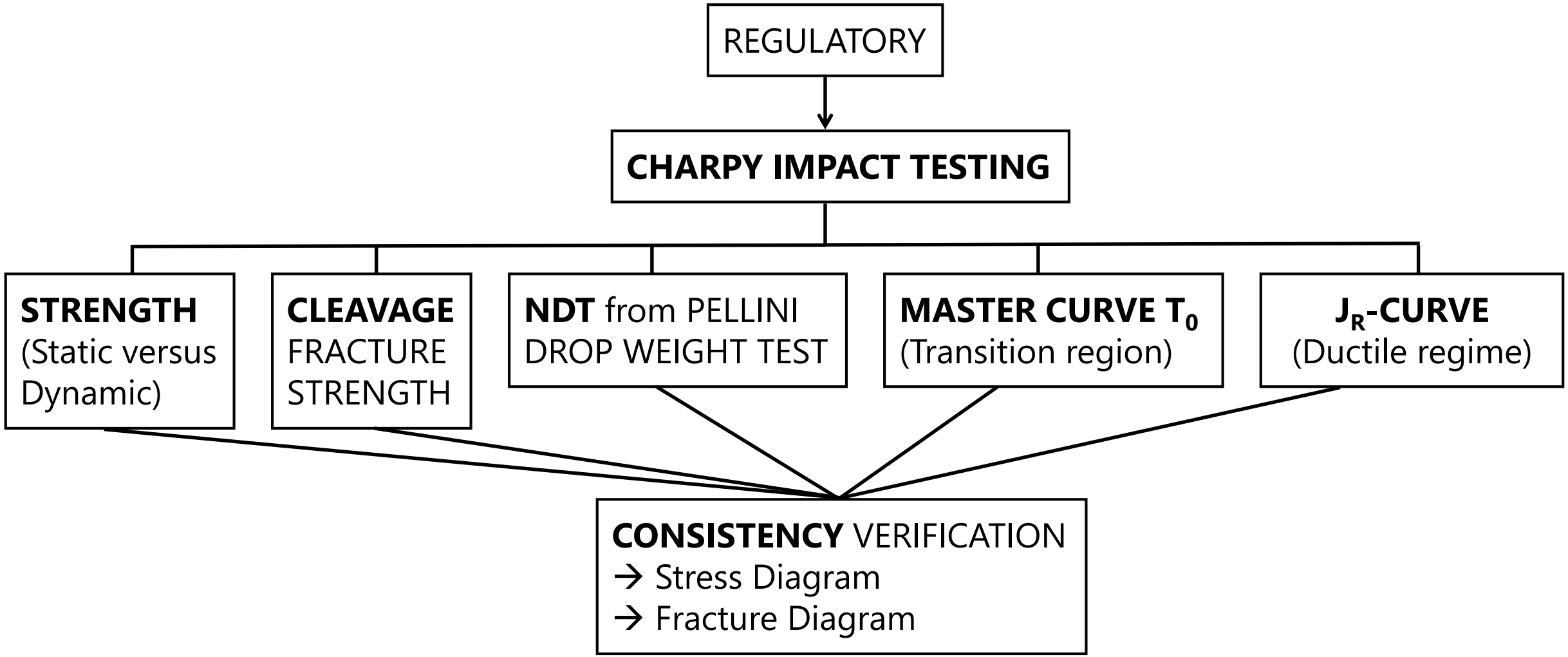


6 J–Δa curve



Correction of $J_R^{CVN\ impact}$ to obtain J_R^{static} accounting for effects of geometry and loading conditions

The Central Role of the Charpy Impact Test

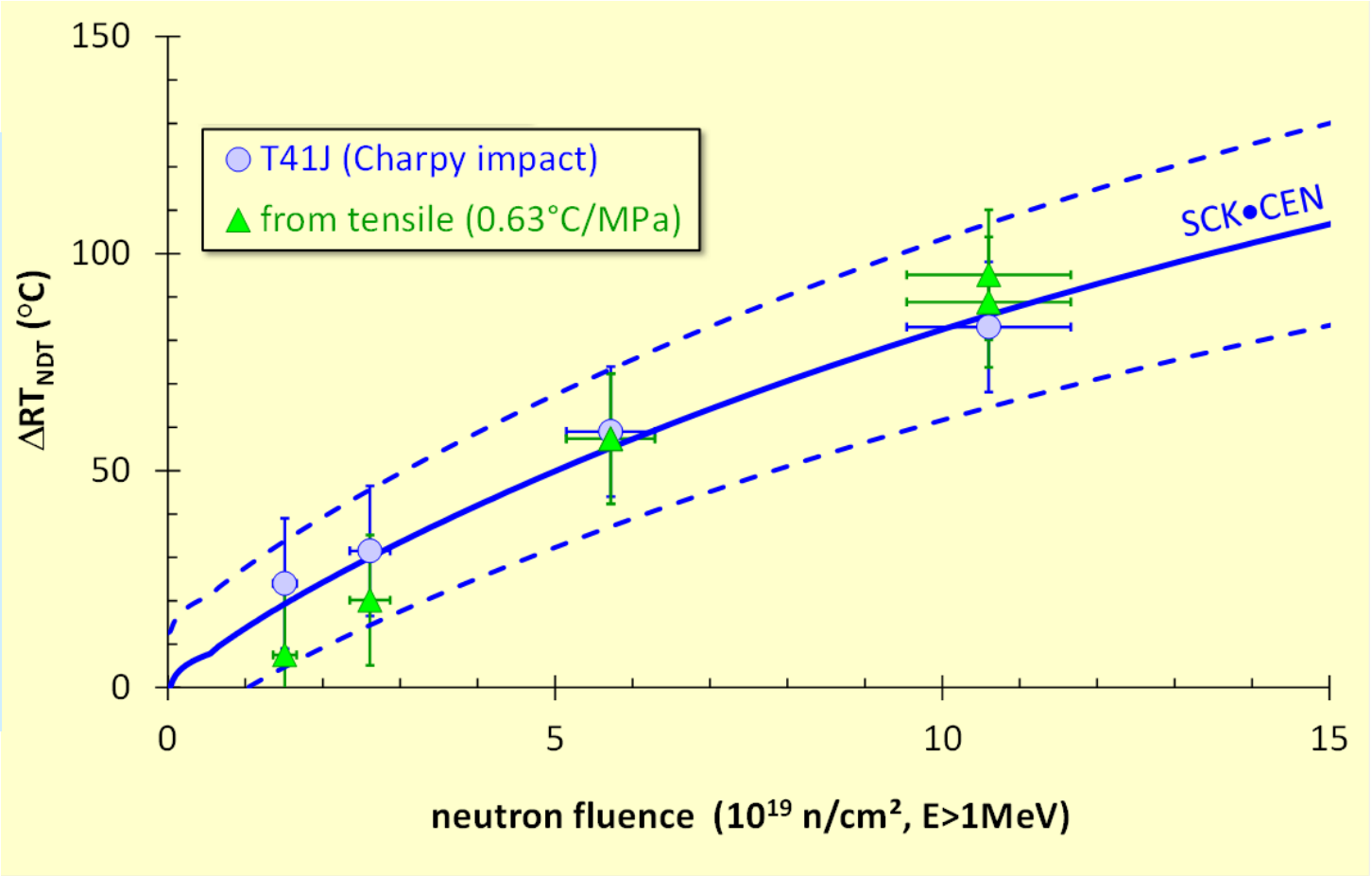


Summary and Conclusions : RPV Surveillance : Belgian Practice

- Surveillance programs of the Belgian reactors → two reports per surveillance capsule :
  - First report : **Regulatory** surveillance based on the RT_{NDT} concept (typically, Charpy impact tests and a few tensile tests)
  - Second report : Enhanced surveillance → **enhanced reliability**
    - Additional tensile tests in a wide range of test temperature, sometimes at other strain rates
    - Specimen reconstitution (precracked Charpy specimens) for fracture toughness tests in the transition and at upper shelf temperature (operation temperature)
    - Radiation damage modeling and embrittlement trend curves
- **Property-to-property correlation** (tensile, Charpy impact and fracture toughness) and **modeling**
- **Increased reliability** in the surveillance database in the perspective of **long term operation** (LTO)
- Database supported by MTR data (mainly BR2)

Embrittlement Trend Curve

- Physically-based embrittlement trend curve accounting for material variables (Cu, Ni, P) and irradiation variables (ϕ, Φ, T_{irrad})
- Continuous development and improvement of the model with the support of MTR BR2 data and reliable databases



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