TRACTEBEL Engineering
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Comparison of embrittlement trend curves to high fluence surveillance results

A-S Bogaert, R. Gérard, R. Chaouadi

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How well can trend curves predict embrittlement of Belgian reactor pressure vessel steels?

Let's compare some of the existing trend curves to Belgian surveillance data

- Regulatory Guide 1.99 revision 2
- EONY (Eason, Odette, Nanstad, Yamamoto)
- ASTM E900-02
- RSEM FIM
- WR-C(5)
- Hardening Model from SCK•CEN

Overview of Belgian surveillance data

	%Cu	%Ni	%P	# results	name
Base materials from Belgian vessels	Medium copper 0.04-0.076	0.71-0.77	0.006-0.014	48	Forging A,B,C,D,E,G
Monitors irradiated in Belgian power plants	High copper 0.14-0.17	0.59-0.64	0.006-0.013	13	Forging H1, HSST02
Weld materials	Medium copper 0.048-0.08	0.8-0.98	0.015-0.017	12	Weld 1,2,3
Weld material	High copper 0.09	Low nickel 0.075	0.021	4	Weld 4
TOTAL				77	

77 data points among which 30 have received a fluence between 4 - 10.10^{19} n/cm², E> 1MeV

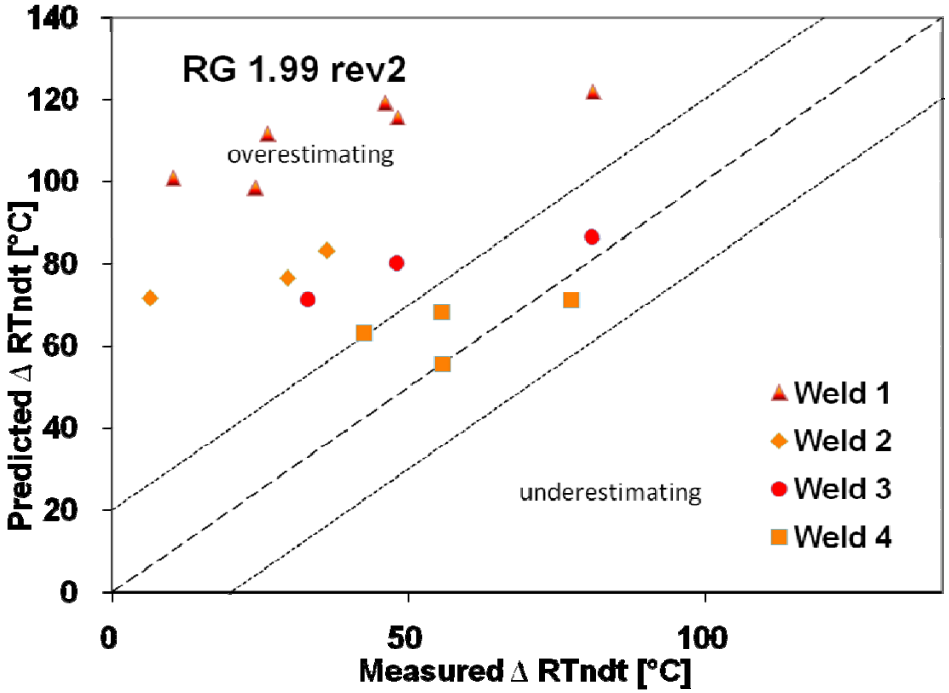
Regulatory Guide 1.99 rev.2 embrittlement correlation:

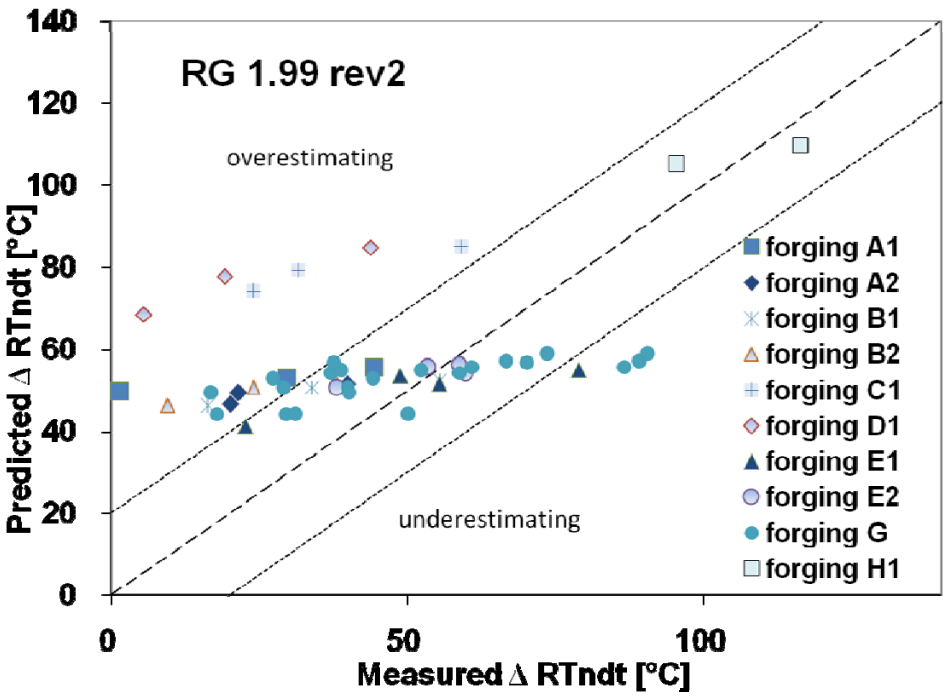
$$\Delta RT_{NDT} = CF.\ \Phi^{0.28-0.10\log\Phi}$$

Derived prior to 1985, physical understanding of mechanisms limited

Based on a relatively small surveillance database (177 data), exclusively American RPV steels (mostly high copper) and at low fluence

Application of Regulatory Guide 1.99 rev.2 embrittlement correlation to Belgian data:





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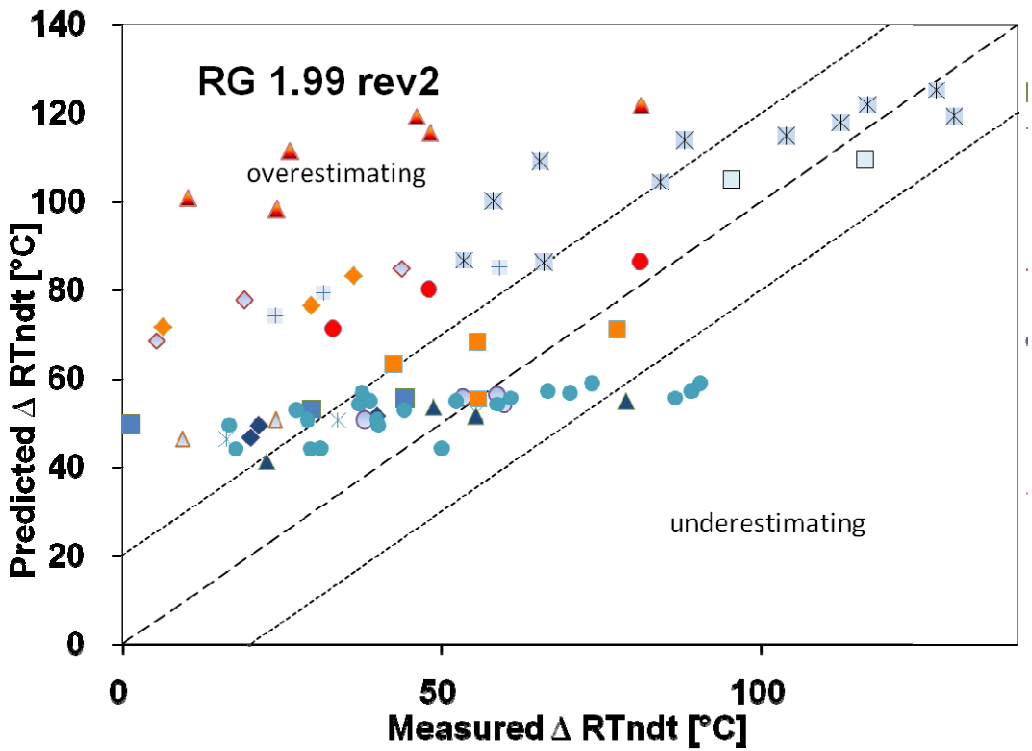


There is little correlation between predictions and actual results

Both at low and high fluence

Both for base materials and weld materials

Need for an improved correlation

EONY embrittlement correlation:
(Eason, Odette, Nanstad and Yamamoto)

$$\Delta T_{41J} = \Delta T_{MD} + \Delta T_{CRP}$$

$$\Delta T_{MD} = A \cdot \left(1 - 0.001718 \cdot T_{irrad}\right) \cdot \left(1 + 6.13 \cdot P \cdot Mn^{2.47}\right) \cdot \sqrt{\varphi t_e}$$

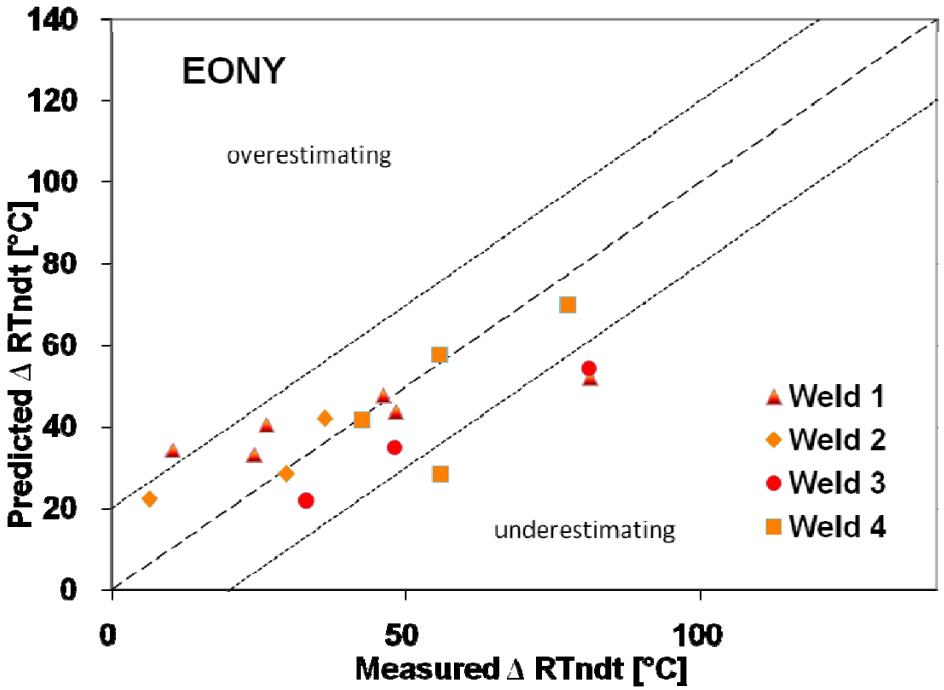
$$\Delta T_{CRP} = B \cdot \left(1 + 3.77 \cdot Ni^{1.191}\right) \cdot f\left(Cu_e, P\right) \cdot g\left(Cu_e, Ni, \varphi t_e\right)$$

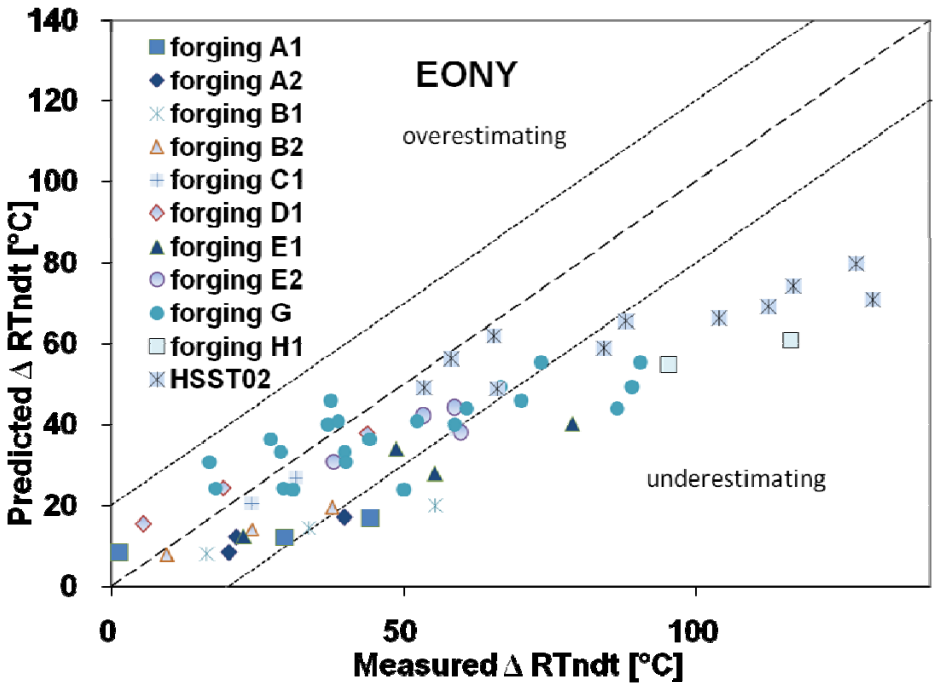
Used in the recently revised PTS rule 10CFR50.61a

Expected to be implemented in revision 3 of the Regulatory Guide 1.99

Takes advantage of improved physical understanding of embrittlement and of the bigger amount of experimental data

Application of EONY embrittlement correlation to Belgian data:





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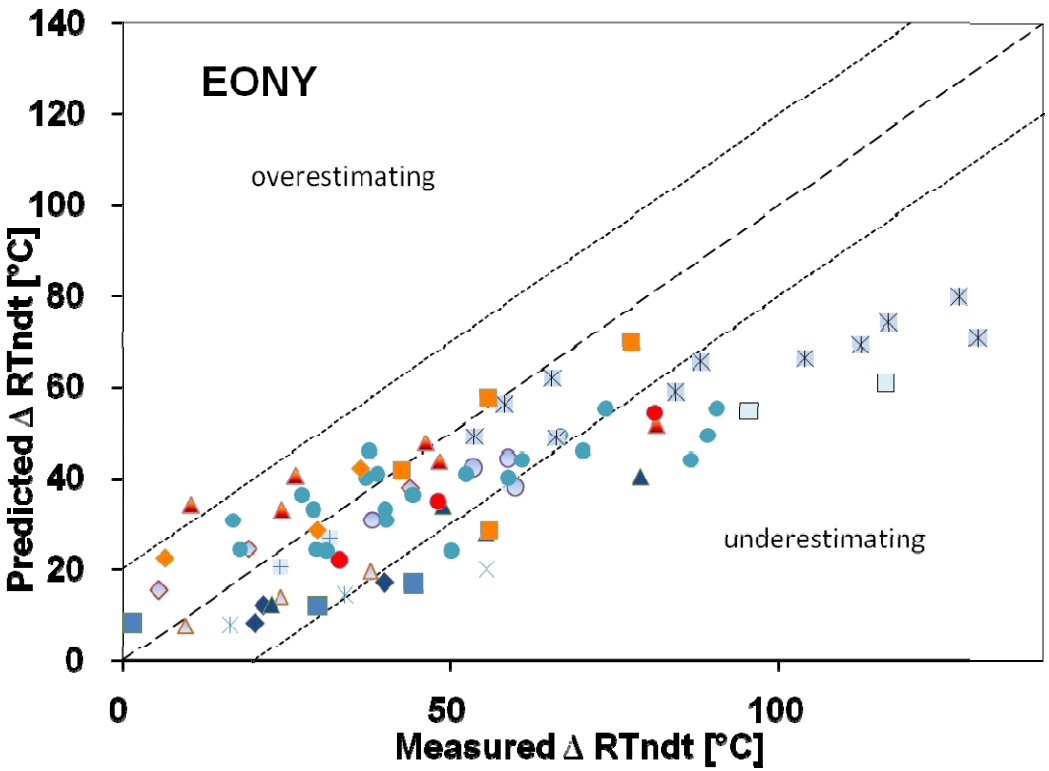


Improvement compared to previous formula used the Regulatory Guide 1.99

Shift in transition temperature underestimated at high fluence

More obvious for base materials

ASTM E900-02 embrittlement correlation:

$$\Delta RT_{NDT} = SMD + CRP$$

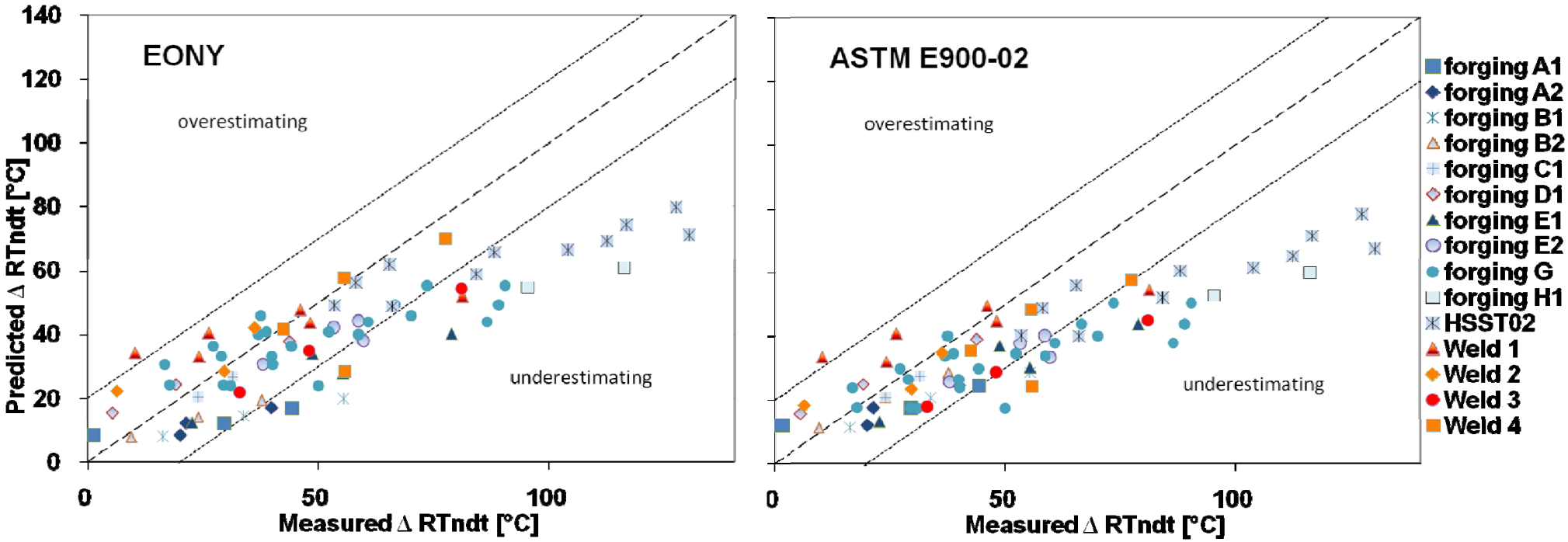
$$SMD = A \cdot e^{\frac{20730}{T_{irrad}+460}} \cdot \Phi^{0.5076}$$

$$CRP = B \cdot \left(1 + 2.106 Ni^{1.173}\right) \cdot F(Cu) \cdot \left[\frac{1}{2} + \frac{1}{2}\tanh\left(\frac{\log\Phi - 18.24}{1.052}\right)\right]$$

Matrix damage term + copper rich precipitate term as in the EONY formula

Established in ASTM E900-02, *Standard Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials*

Application of ASTM-E900 embrittlement correlation to Belgian data:



Although the expressions of the matrix damage term and copper rich precipitate term are different than in EONY, predictions for Belgian RPVs are comparable

RSEM-FIM embrittlement correlation:

$$\Delta RT_{NDT} = \left[17.3 + 1537\left(P - 0.008\right) + 238\left(Cu - 0.08\right) + 191 \cdot Cu \cdot Ni^2\right] \cdot \left(\frac{\Phi}{10^{19}}\right)^{0.35}$$

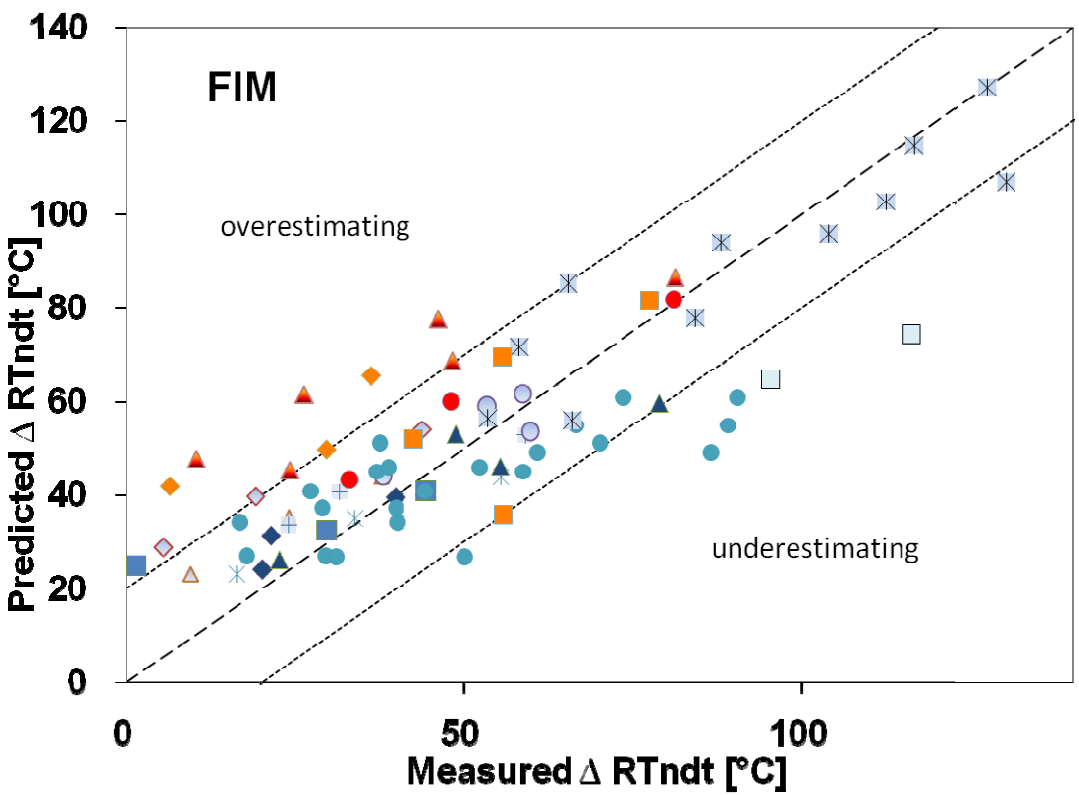
Based on French RPV steels data exclusively

Applied since 1989 to most Belgian RPV steels due to similarities between French and Belgian RPV steels.

No terms to represent physically based mechanisms such as matrix damage and precipitates

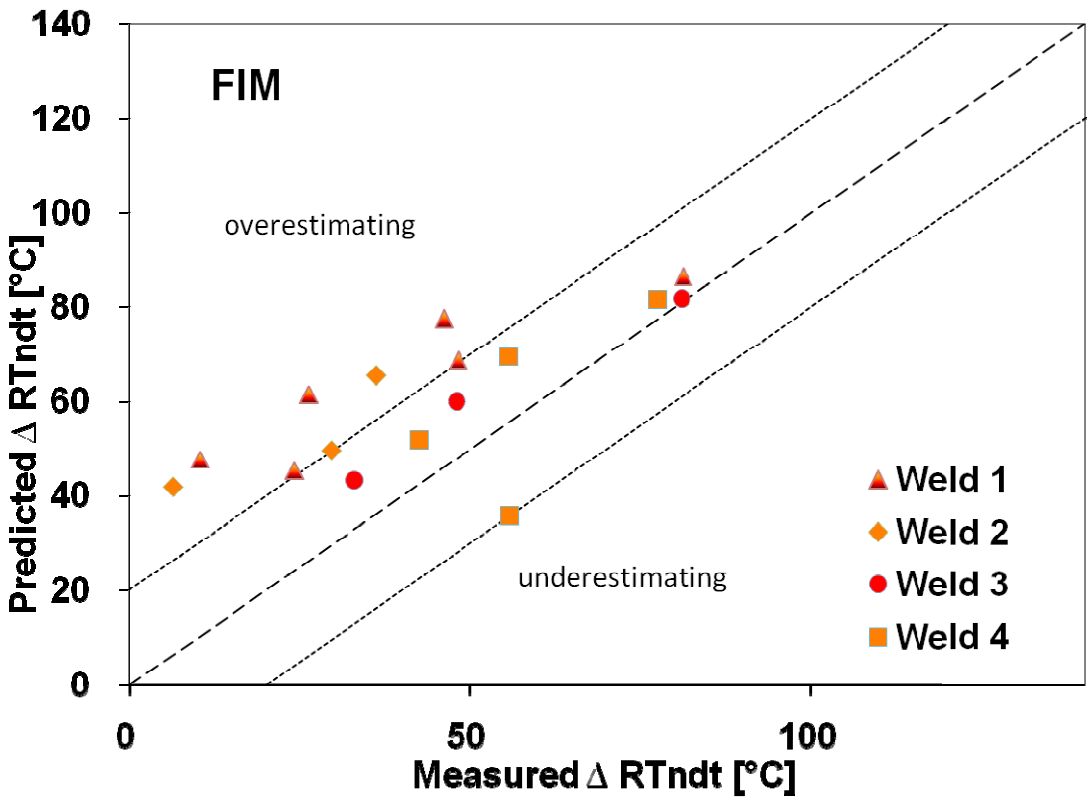
Higher exponent of the fluence than in the present formula of the Regulatory Guide 1.99.

Application of RSEM-FIM embrittlement correlation to Belgian data:



As expected, the FIM correlation fits better Belgian experimental data

Application of RSEM-FIM embrittlement correlation to Belgian data:



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However, tendency to overestimate the welds embrittlement

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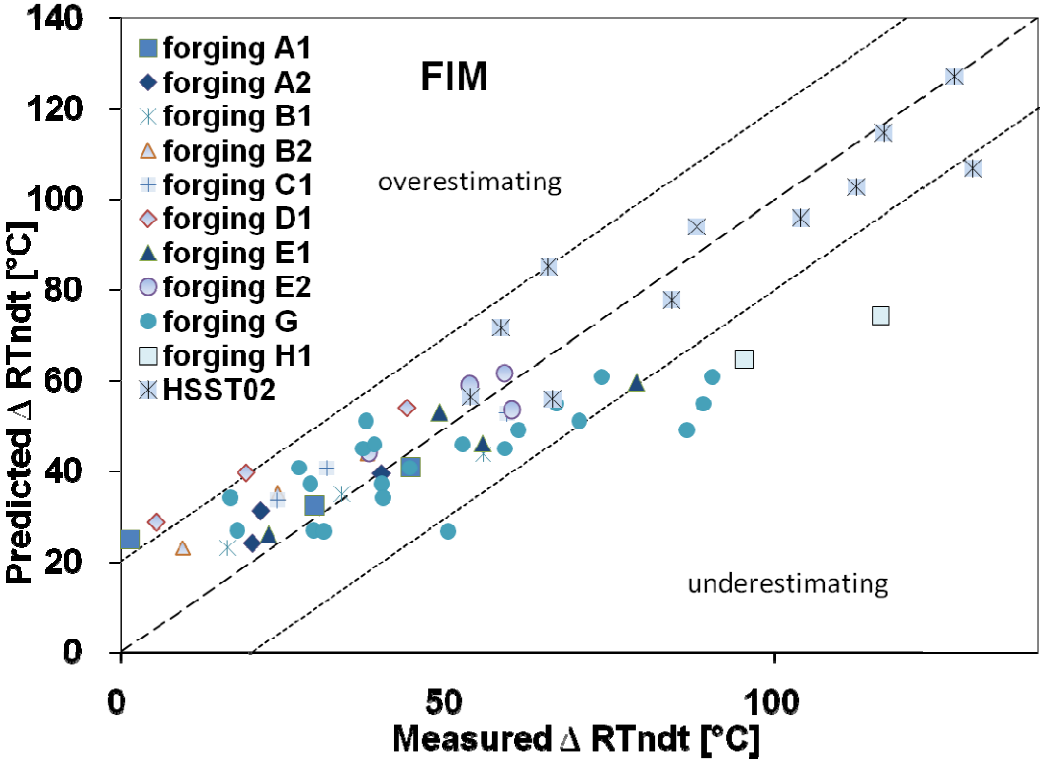


As expected, the FIM correlation fits better Belgian experimental data

However, tendency to overestimate the welds embrittlement while underestimating the base materials embrittlement at high fluence

WR-C(5) Correlation

$$\Delta RT_{NDT} = f(Cu) \cdot M + B$$

$$M = M_{W,P,F} MAX\left\langle MIN\{(\ln \Phi - \ln(1.67 \cdot 10^{17})) \cdot 171.3, 733.5\}, 0\right\rangle \left(\frac{T}{550}\right)^{E_{T(M)}-3.84} \left(\frac{Ni^{1.155}}{0.63}\right)^{0.28}$$

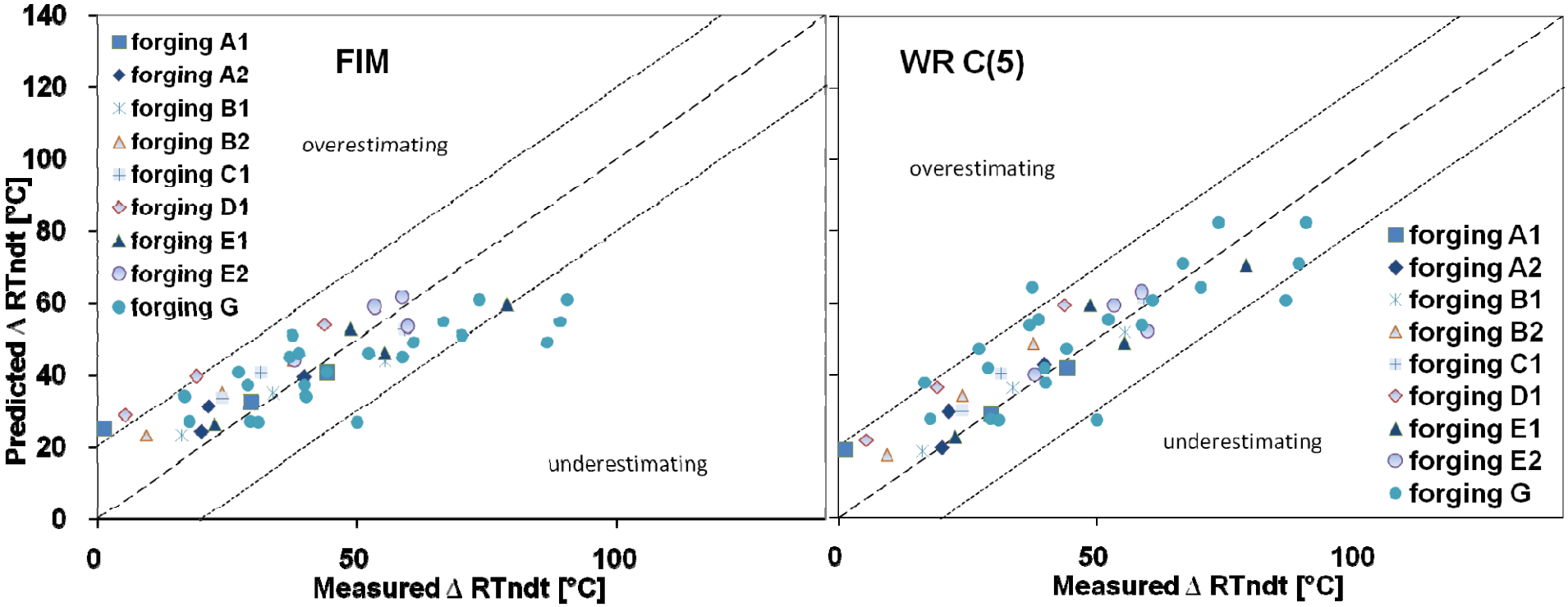
$$B = B_{W,P,F} \left\{9.78 \cdot 10^{-10} \cdot \Phi^{0.5564}\right\} \left(\frac{T}{550}\right)^{-4.74} \left(\frac{P}{0.012}\right)^{0.24} \left(\frac{Ni^{0.865}}{0.63}\right)^{0.48} \left(\frac{Mn}{1.36}\right)^{0.15}$$

Recent “Wide range” trend curve, based on over 2500 data

Based on US and non-US data, on test and power reactors

Based on observed trends rather than on assumed physical mechanisms

Application of WR-C(5) embrittlement correlation to Belgian data:



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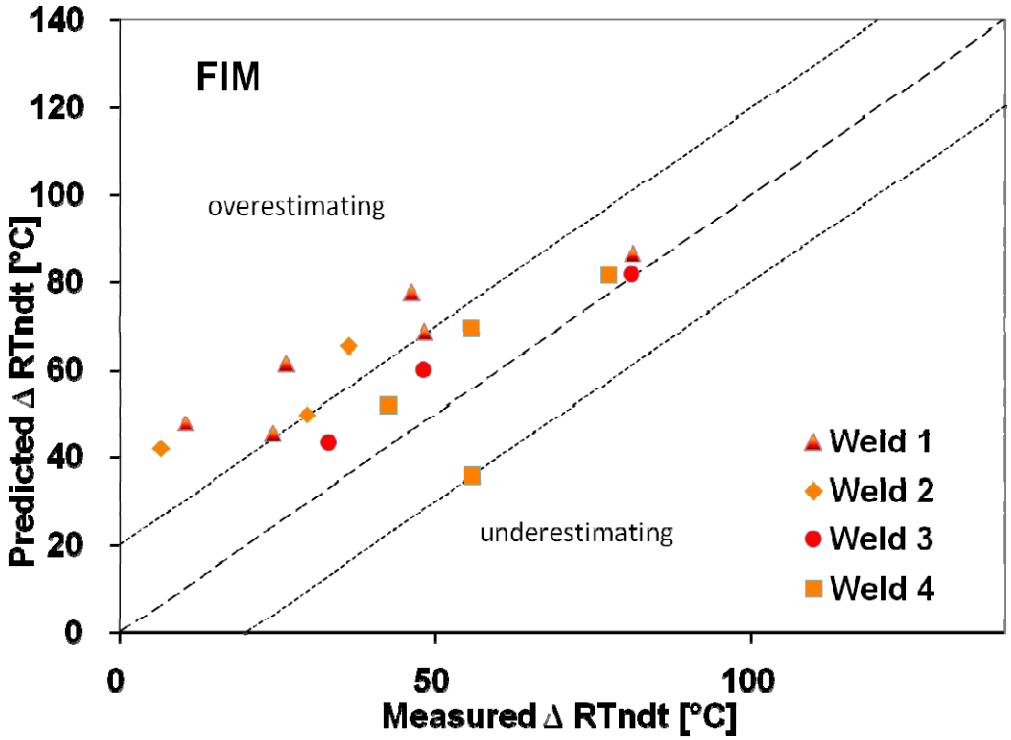

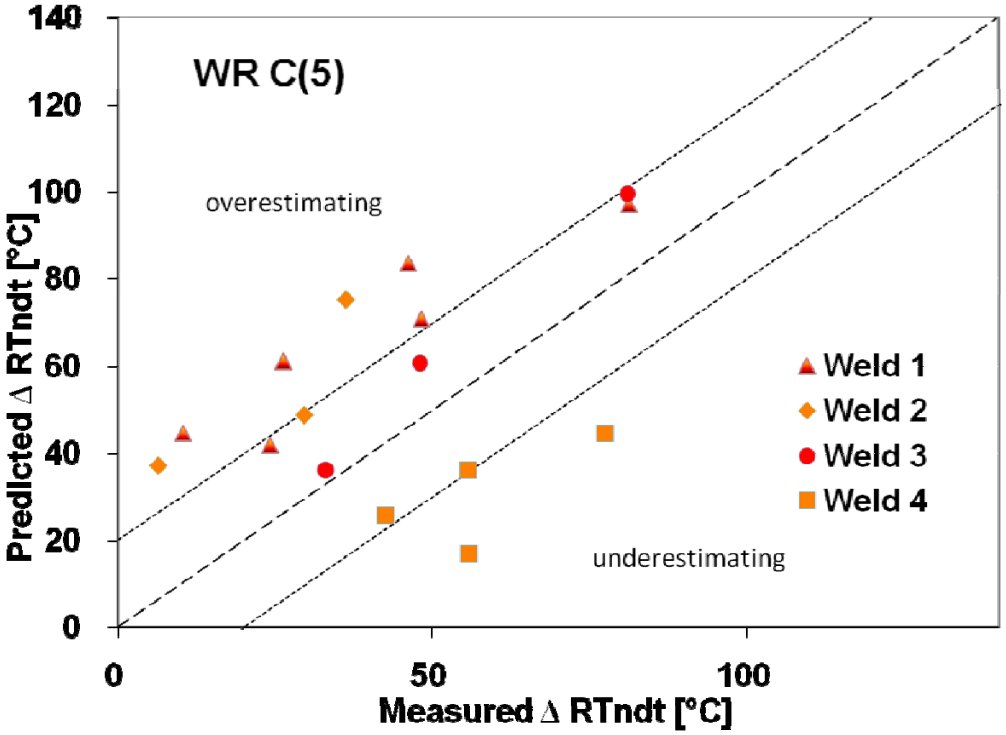

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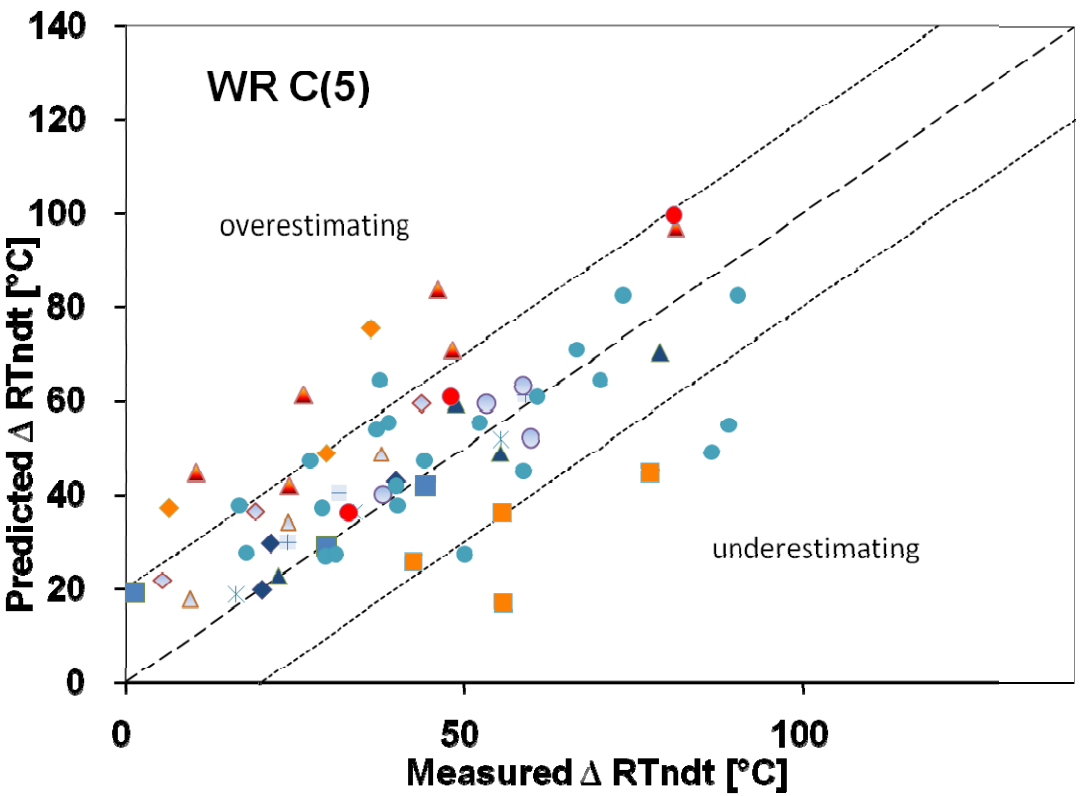
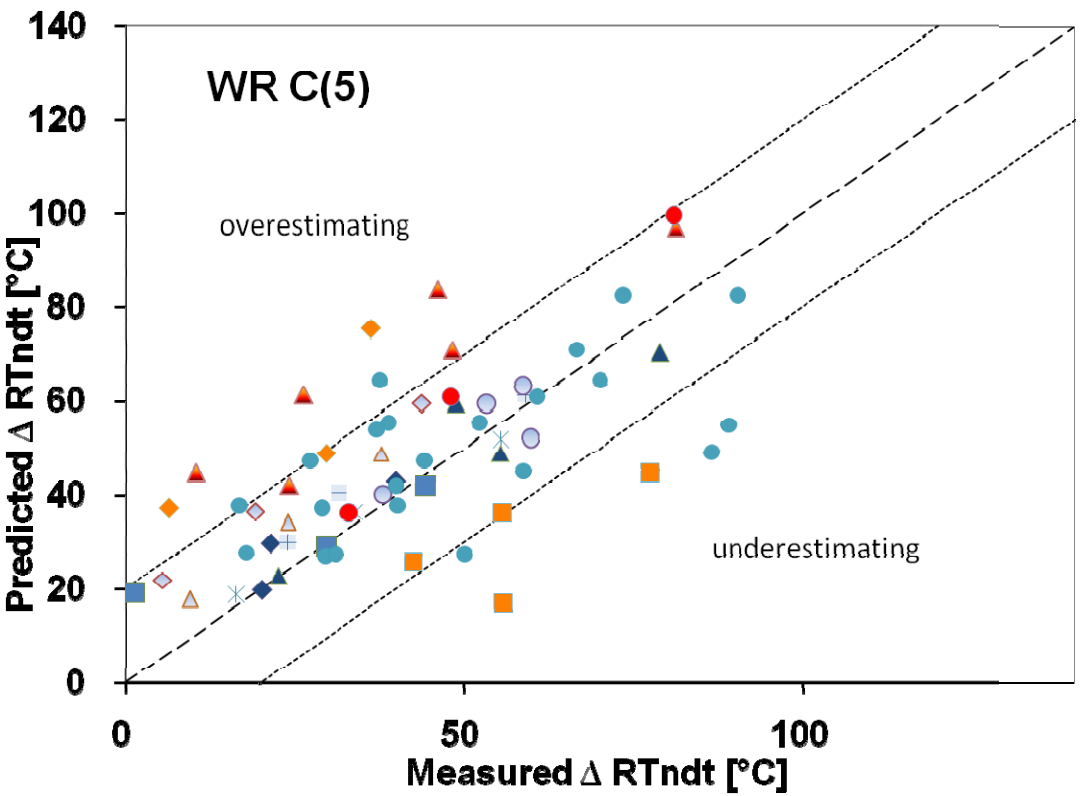


- Improvement compared to previous US formulae
- Very good fit of Belgian base materials, at low and high fluence
- Very important scatter for weld materials
- But no systematic under-, over-estimation observed

Application of WR-C(5) embrittlement correlation to Belgian data:



The WR-C(5) fits quite good to Belgian experimental data although its range of applicability is large.

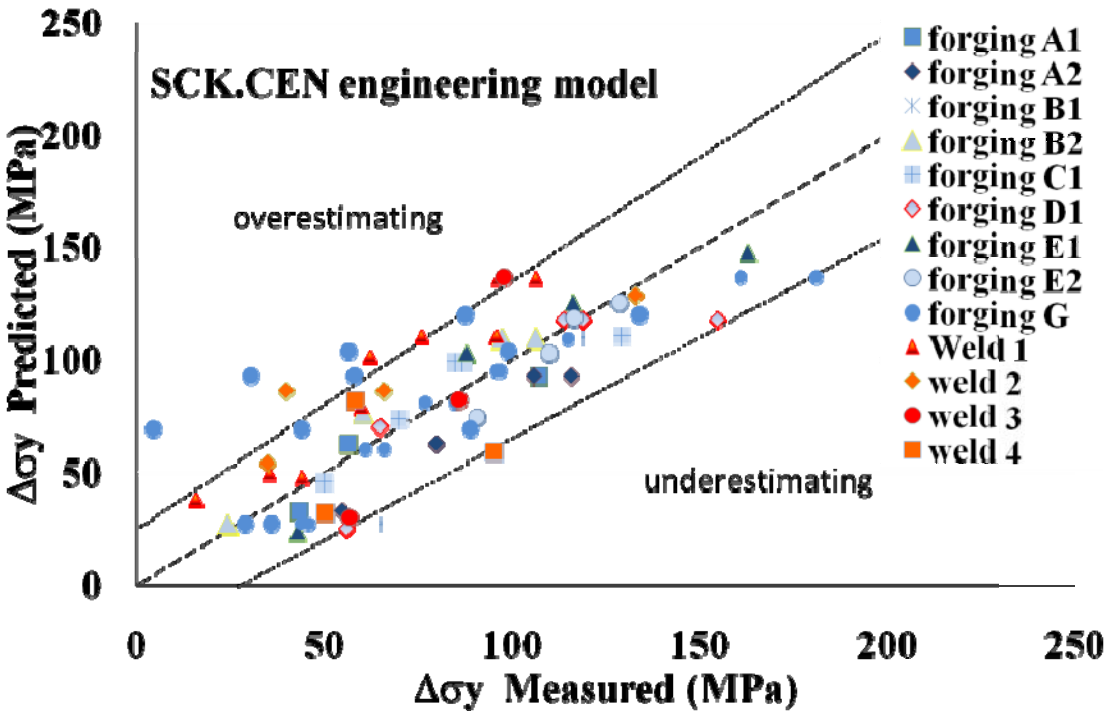
An Engineering Hardening Model from the SCK•CEN

$$\Delta\sigma_y = \sqrt{f_{CRP}^2(Cu, \phi, \Phi) + h_P^2(P, \Phi)} + g_{MD}(T_{irrad}, Ni, \Phi)$$

Predicts the yield strength increase, $\Delta\sigma_y$, rather than the ductile-to-brittle transition temperature shift, ΔRT_{NDT}.

Based on the results of the extensive experimental program, RADAMO, in which 14 RPV materials were irradiated in the BR2 test reactor under well controlled conditions at 300°C and 265°C.

Application of the Hardening Model from the SCK•CEN to Belgian data:



As already presented at IGRDM meeting in 2009, the model predicts $\Delta\sigma_y$ quite satisfactorily though it is based exclusively on test reactors data.

But how does $\Delta\sigma_y$ help predicting ΔRT_{NDT} ?

Correlation between ΔRT_{NDT} and $\Delta\sigma_y$

	%Cu	%Ni	%P	ΔRT_{NDT} / $\Delta\sigma_y$
Base materials from Belgian vessels	Medium copper 0.04-0.076	0.71-0.77	0.006-0.014	**0.42-0.45**
Weld materials	Medium copper 0.048-0.08	0.64-0.98	0.013-0.017	**0.42-0.46**
Weld material	High copper 0.09	Low nickel 0.075	0.021	**0.79**

Ratio between ΔRT_{NDT} and $\Delta\sigma_y$ turns out to be dependant on the material.

Comparison of α to values found in literature

Standard value 0.63 (Nanstad et al. ASTM STP1175)

Ericksonkirk (PVP 2007-26305):

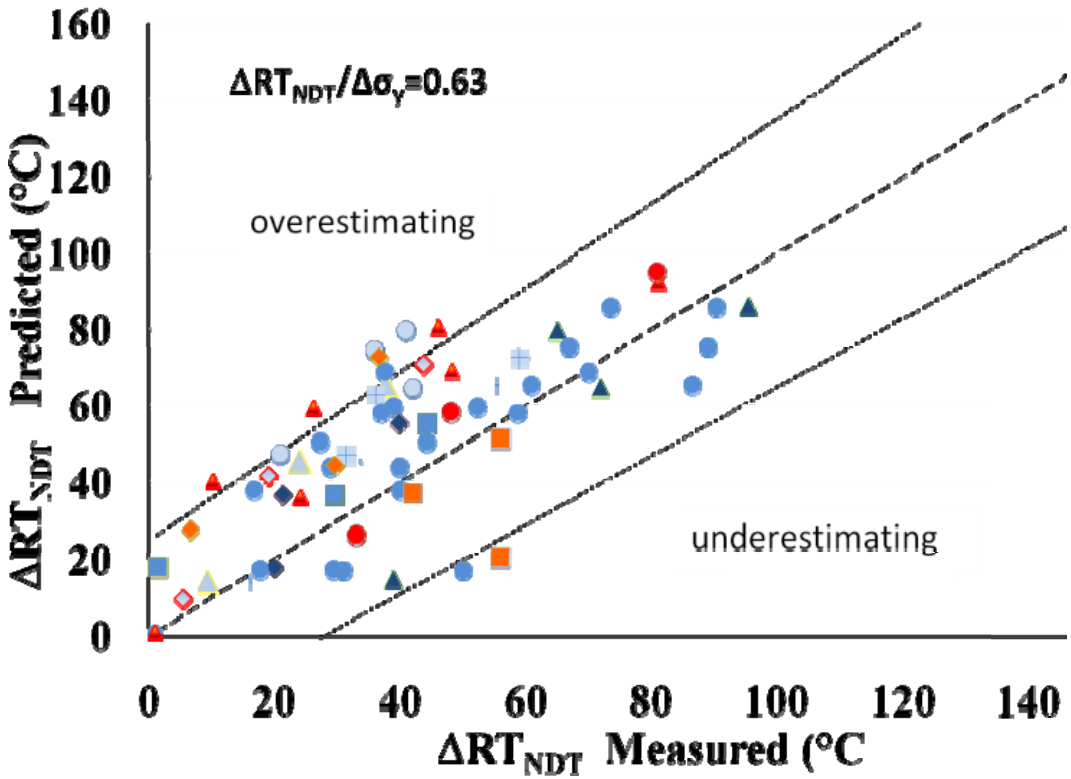
- $\alpha = 0.49$ for forgings
- $\alpha = 0.69$ for welds

EONY Model (ORNL/TM 2006-530):

- α is an increasing function of ΔRT_{NDT}
- $\alpha \sim 0.51$ (plates) or 0.59 (welds) when ΔRT_{NDT}=35°C
- $\alpha \sim 0.60$ (plates) or 0.66 (welds) when ΔRT_{NDT}=100°C

Our values of α are very close to those reported in literature, although there is no systematic difference between welds and base materials. Whether α depends upon the fluence needs to be further investigated but it doesn't seem to be the case.

Attempt to apply the Hardening Model to Charpy data:



Predictions of the model have been multiplied by 0.63°C/MPa and compared to Charpy experimental results to build the graph

The value of 0.63 is reasonable but is an approximation

Conclusions

The French RSEM-FIM correlation is used to predict the embrittlement of (almost all of) Belgian reactor pressure vessels steels and as expected, is quite appropriate to do so. Probably because it was based on data from French pressure vessel steels, similar to Belgian ones.

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The correlation from Regulatory Guide 1.99 rev. 2 is certainly not acceptable to predict embrittlement for Belgian steels.

The EONY formula would constitute an improvement but not satisfactory at high fluence.

The most recent WR-C(5) correlation on the other hand seems quite suitable even at high fluence, but still questionable for welds.

Conclusions

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The Radiation Hardening Model is a good fit for the Belgian surveillance data (yield strength) but it requires the conversion of $\Delta\sigma_y$ to ΔRT_{NDT} .

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