Assessment of the French and US embrittlement trend curves applied to RPV materials irradiated in the BR2 materials test reactor

Rachid Chaouadi (SCK•CEN), Belgium
Robert Gérard (GDF-Suez), Belgium
Anne-Sophie Bogaert (GDF-Suez), Belgium

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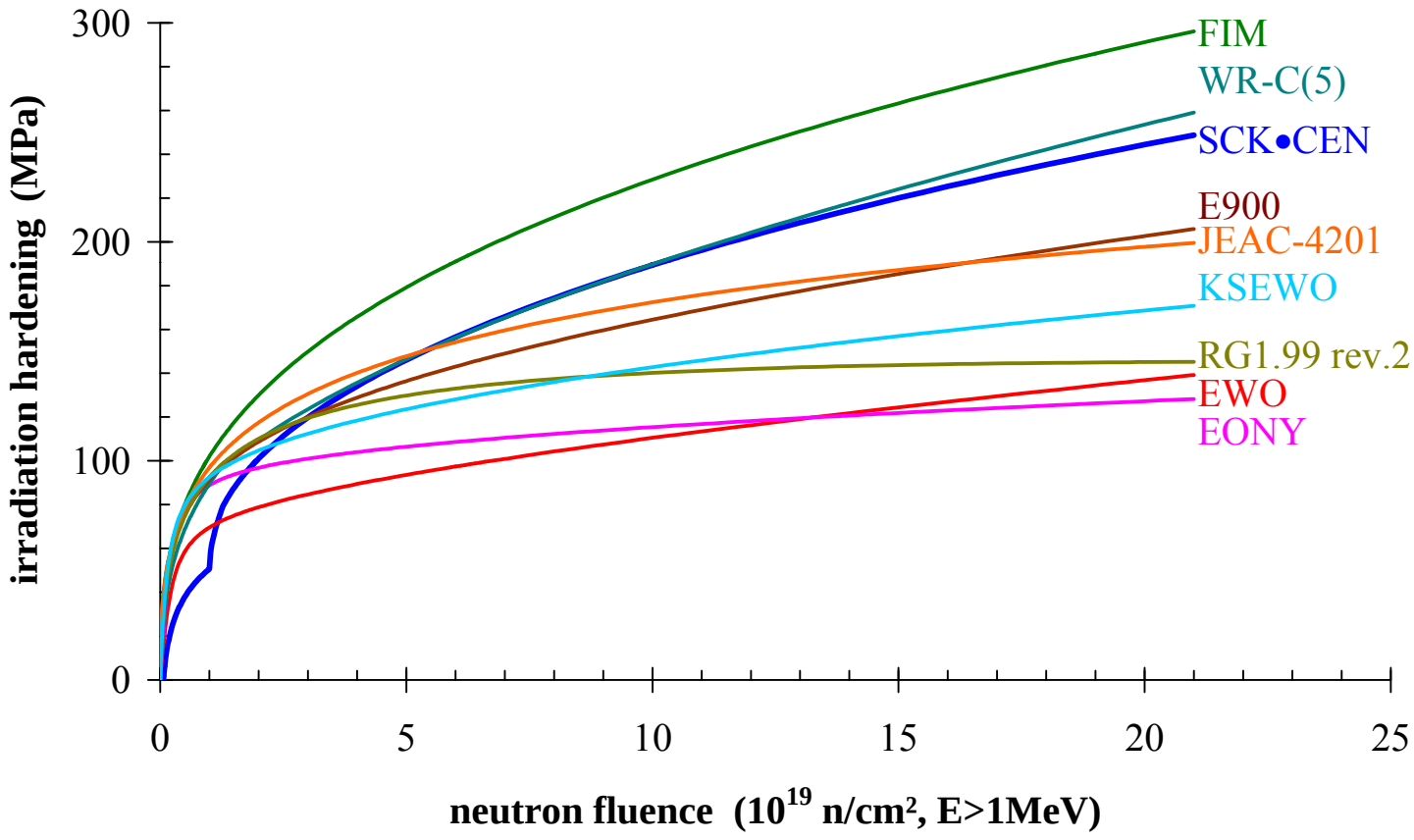
Background and motivation

- **Development of embrittlement trend curves for RPV assessment**
  - Variety of trend curves
  - No convergence between the various trend curves
  - Long–term operation (LTO) in the perspective of plant life extension

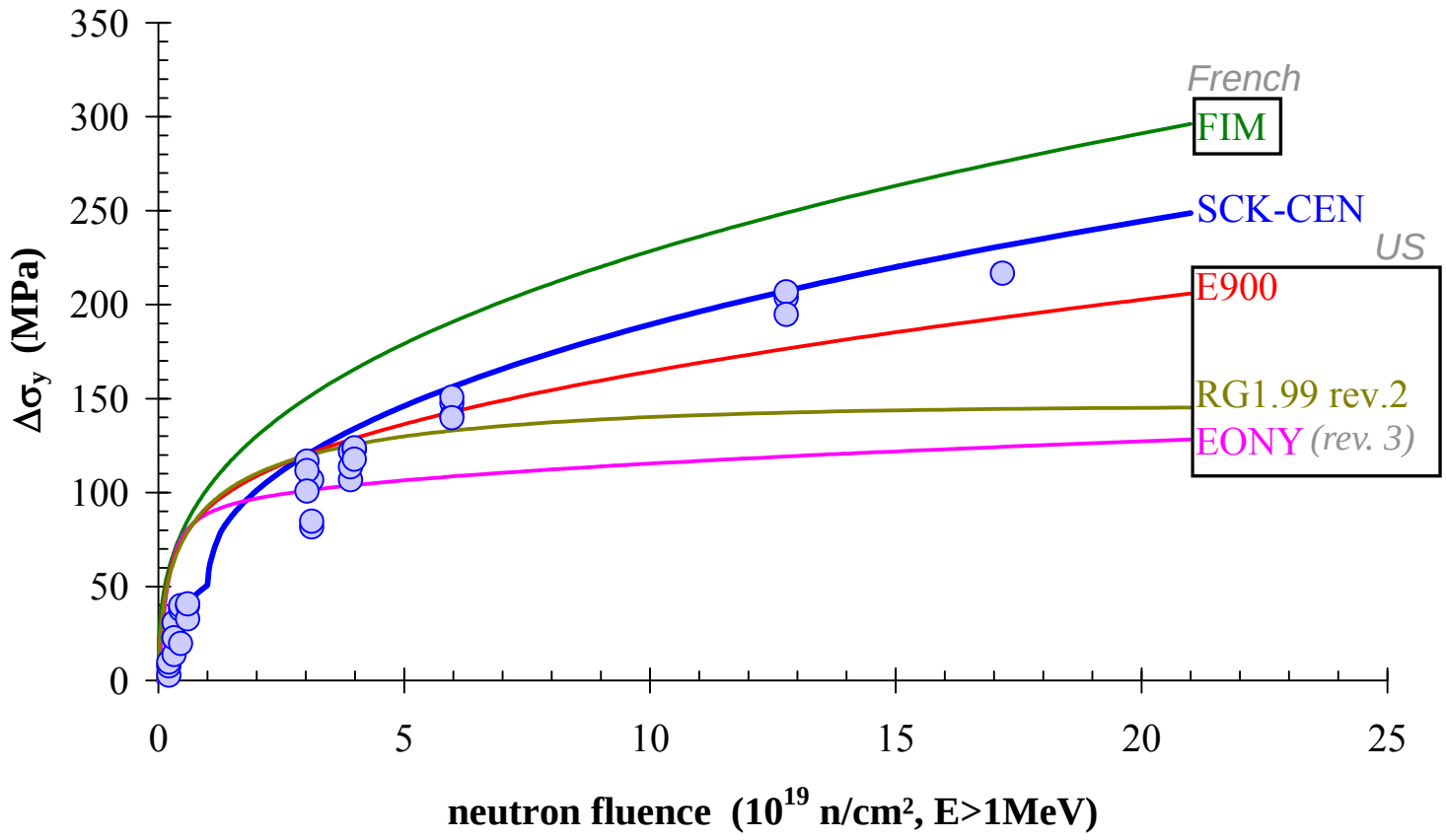
- **Belgian RPV embrittlement**
  - US and French trend curves (regulatory)
  - SCK•CEN model based on BR2 high flux data (R&D)

➔ RADAMO database

Large discrepancies between various trend curves

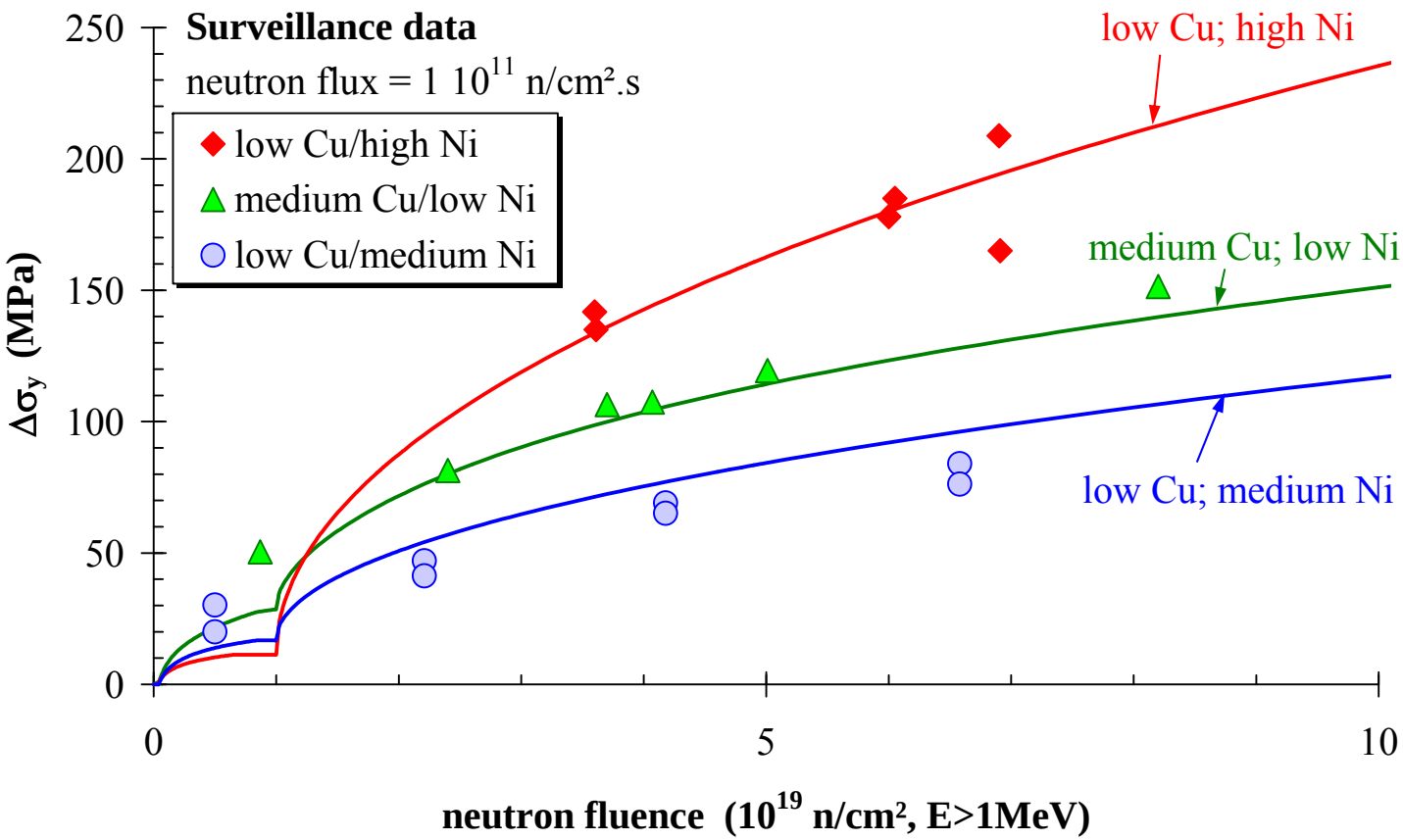


Focus on French and US regulatory trend curves



➔ *SCK•CEN model based on material test reactor (MTR) data (high flux)*

Application of the SCK•CEN model to surveillance data



Flux effect is assumed to be negligible at high fluence levels.

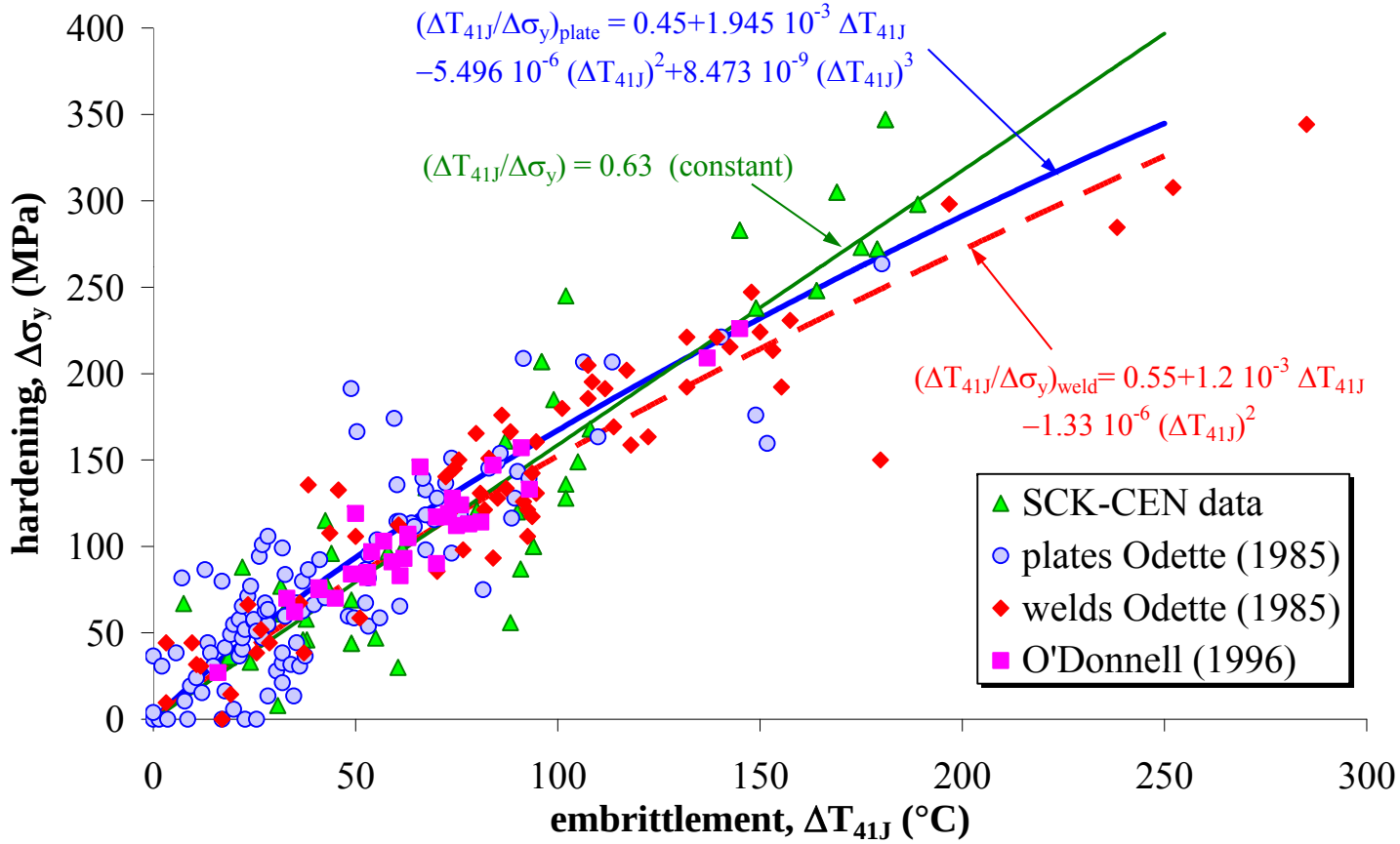
Moderate flux effect below ~1 10^{19} n/cm², E>1MeV

Experimental database

- **RADAMO database**
  - 10 PWR RPV materials (plates, forgings and welds)
  - T_{irrad} = 300°C
  - Flux ϕ = 2 10^{12} – 9 10^{13} n/cm²s, E>1MeV
  - Fluence Φ = 1.3 10^{18} – 1.7 10^{20} n/cm², E>1MeV

material	form	Cu	Ni	P	C	Si	Mn	S	Cr	Mo
JRQ	plate	0.14	0.84	0.017	0.18	0.24	1.42	0.004	0.14	0.51
HSST-03	plate	0.12	0.62	0.011	0.26	0.26	1.36	0.017	0.14	0.50
73W	weld	0.31	0.60	0.005	0.10	0.45	1.56	0.005	0.25	0.58
18MND5 BM	forging	0.13	0.64	0.008	0.18	0.25	1.55	0.002	0.18	0.50
18MND5 weld	weld	0.12	1.01	0.021	0.05	0.19	1.30	0.008	0.12	0.45
A508 Cl.3 BM	forging	0.05	0.75	0.008	0.20	0.28	1.43	0.008	0.11	0.53
A508 Cl.3 weld	weld	0.07	0.83	0.015	0.07	0.22	1.57	0.005	0.14	0.48
20MnMoNi55	forging	0.11	0.80	0.007	0.19	0.20	1.29	0.008	0.12	0.53
72W	weld	0.23	0.60	0.006	0.09	0.44	1.60	0.006	0.27	0.58
16MND5	forging	0.065	0.69	0.013	0.14	0.04	1.37	0.009	0.13	0.52

Hardening–embrittlement correlation



Embrittlement trend curves

FIM (Formule Irradiation Moyenne)

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

RG 1.99 rev.2

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

CF = f(%Cu, %Ni)

ASTM E900

$$\Delta RT_{NDT} = A \cdot e^{\frac{20730}{T_{irrad} + 460}} \cdot \Phi^{0.5076} + B \cdot \left(1 + 2.106 Ni^{1.173}\right) \cdot F(Cu) \cdot \left[\frac{1}{2} + \frac{1}{2} \tanh\left(\frac{\log \Phi - 18.24}{1.052}\right)\right]$$

EONY (→RG 1.99 rev.3)

$$\Delta RT_{NDT} = A \cdot \left(1 - 0.001718 \cdot T_{irrad}\right) \cdot \left(1 + 6.13 \cdot P \cdot Mn^{2.47}\right) \cdot \sqrt{\varphi t_e} + B \cdot \left(1 + 3.77 \cdot Ni^{1.191}\right) \cdot \left(\frac{T_{irrad}}{543}\right)^{1.10} \cdot f\left(Cu_e, P\right) \cdot g\left(Cu_e, Ni, \varphi t_e\right)$$

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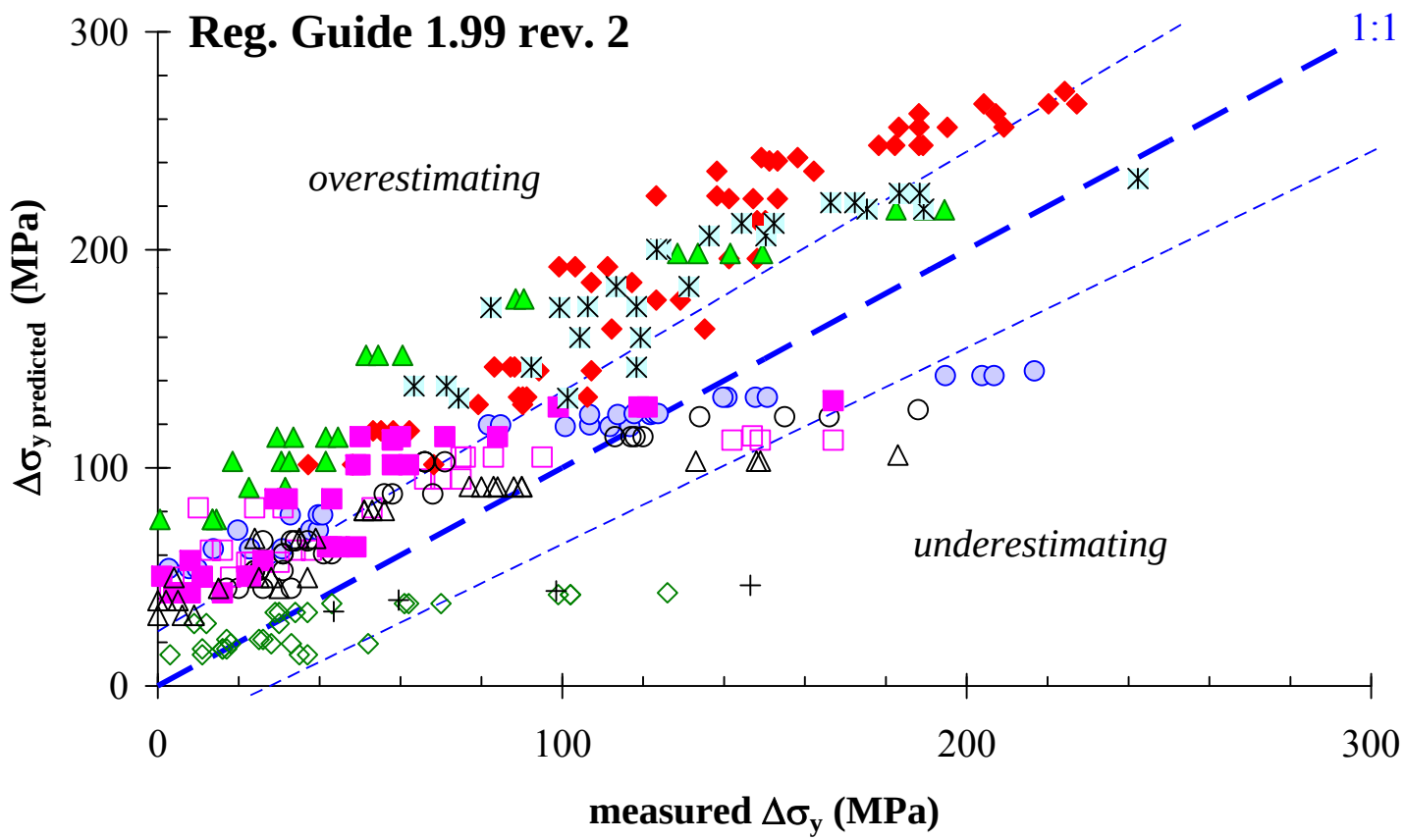
$$\Delta \sigma_y = \left(f(Cu, T_{irrad}, \phi, \Phi)^2 + g(P, Cu, T_{irrad}, \Phi)^2\right)^{1/2} + h(Ni, T_{irrad}, \Phi)$$

Variables ➔ *Cu , Ni , P , Mn ,* T_{irrad} *,* ϕ *,* Φ

Upper/lower bounds :

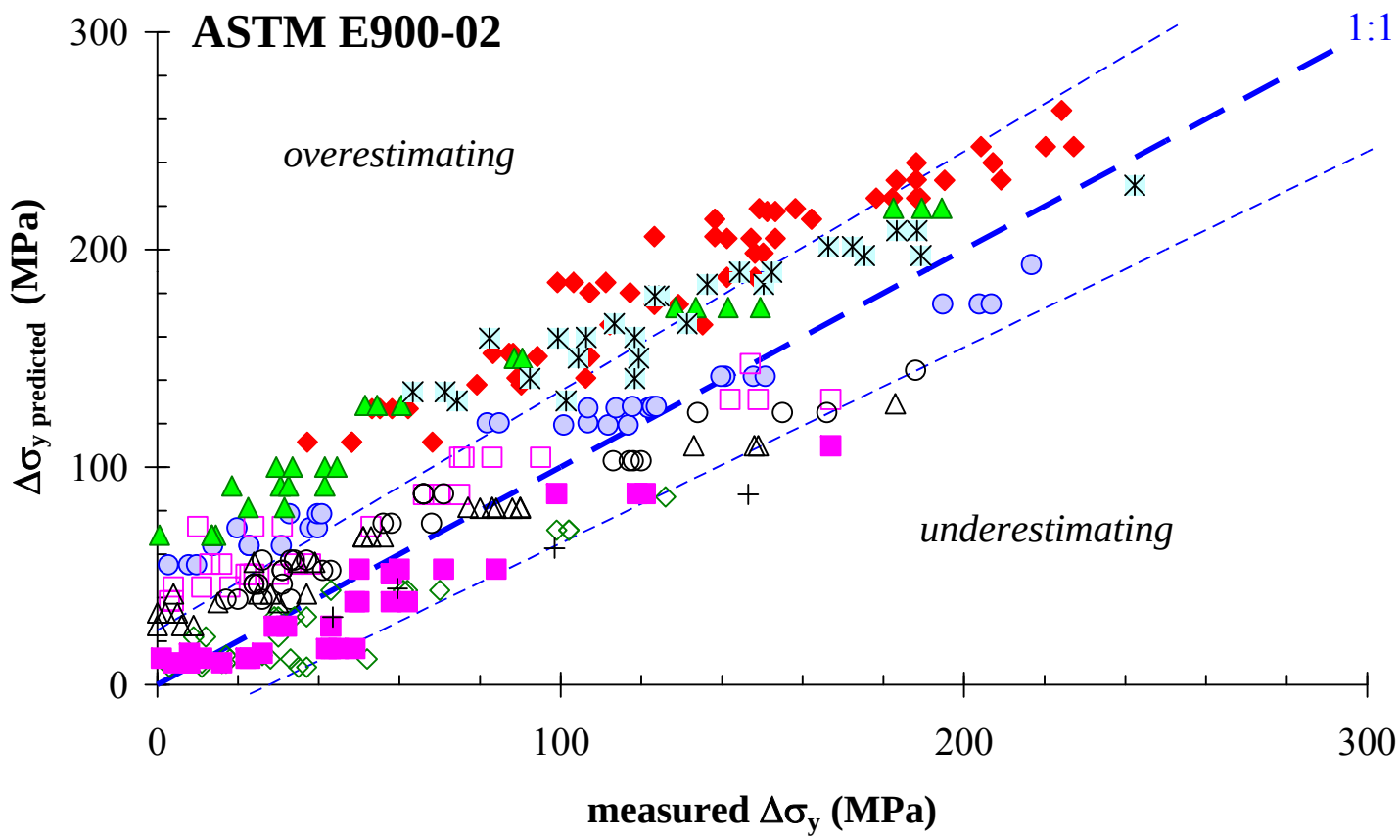
→ ±25MPa (experimental uncertainty) ± 10% $\Delta\sigma_y$ (model uncertainty)

RG 1.99 rev. 2



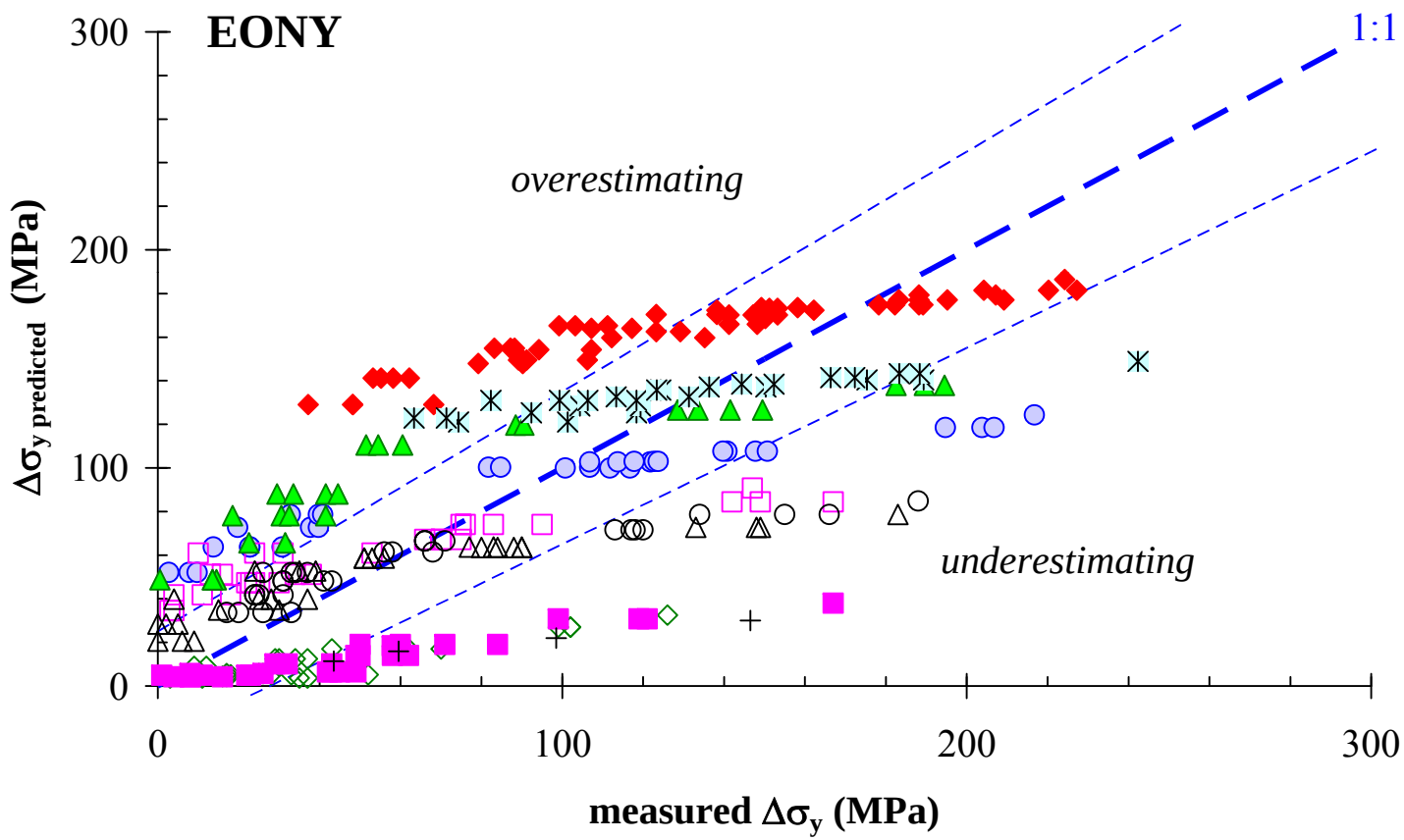
➔ *overestimated hardening for most materials*

ASTM E900



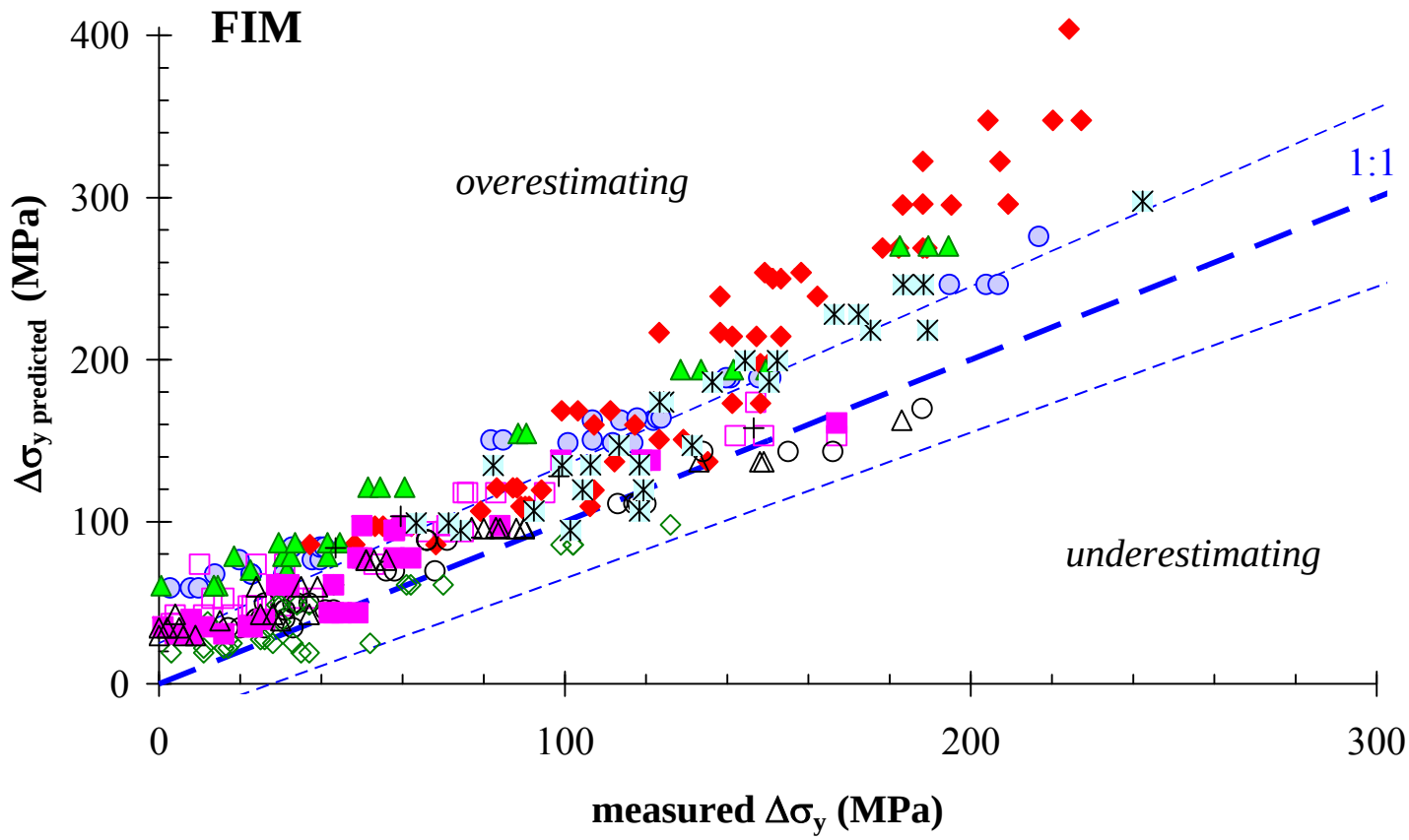
➔ *large scatter*

EONY (→ RG 1.99 rev. 3)

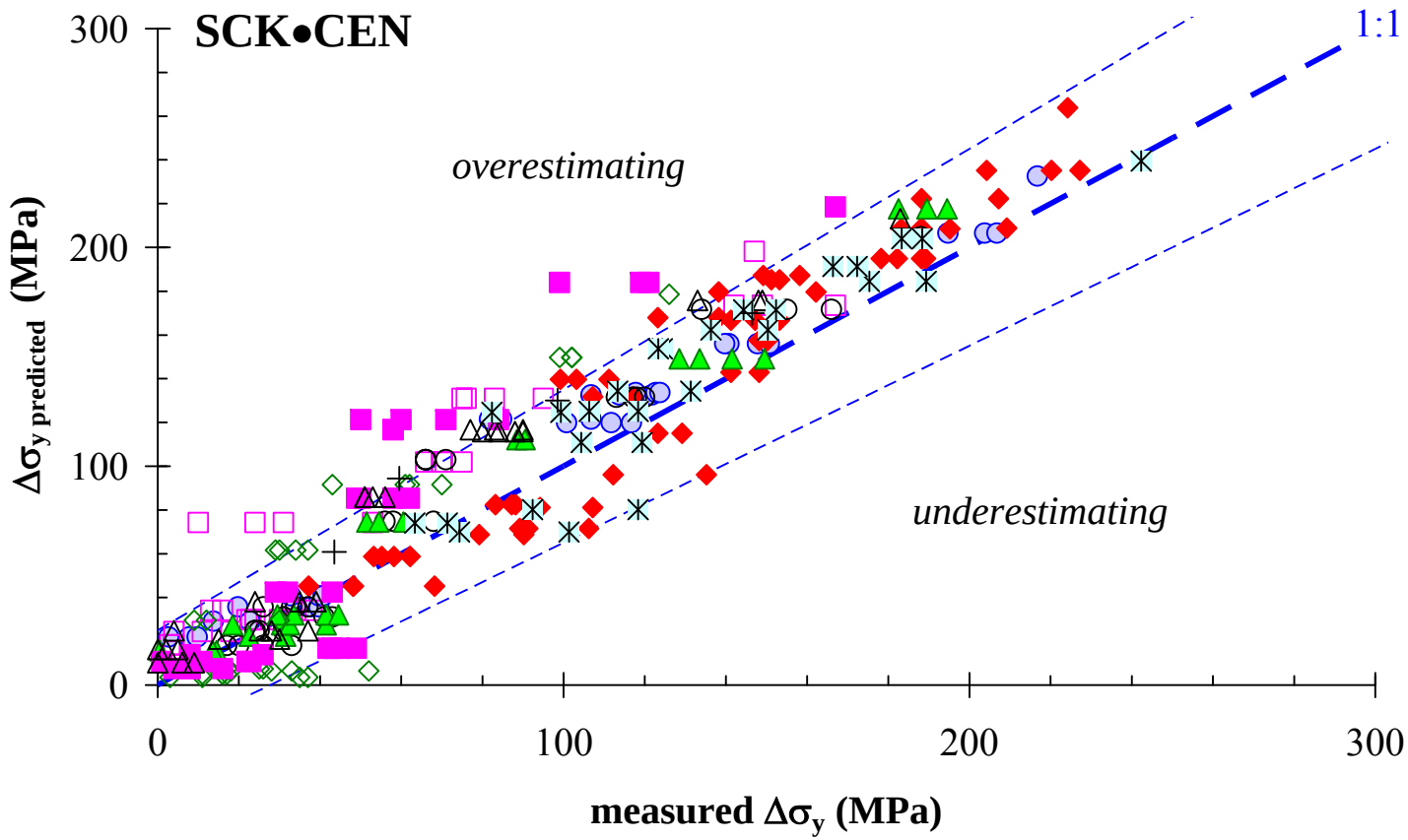


➔ *large discrepancies requiring re–assessment → unconservative*

FIM



➔ *hardening overestimated, in particular at high fluence (LTO relevant) → conservative*

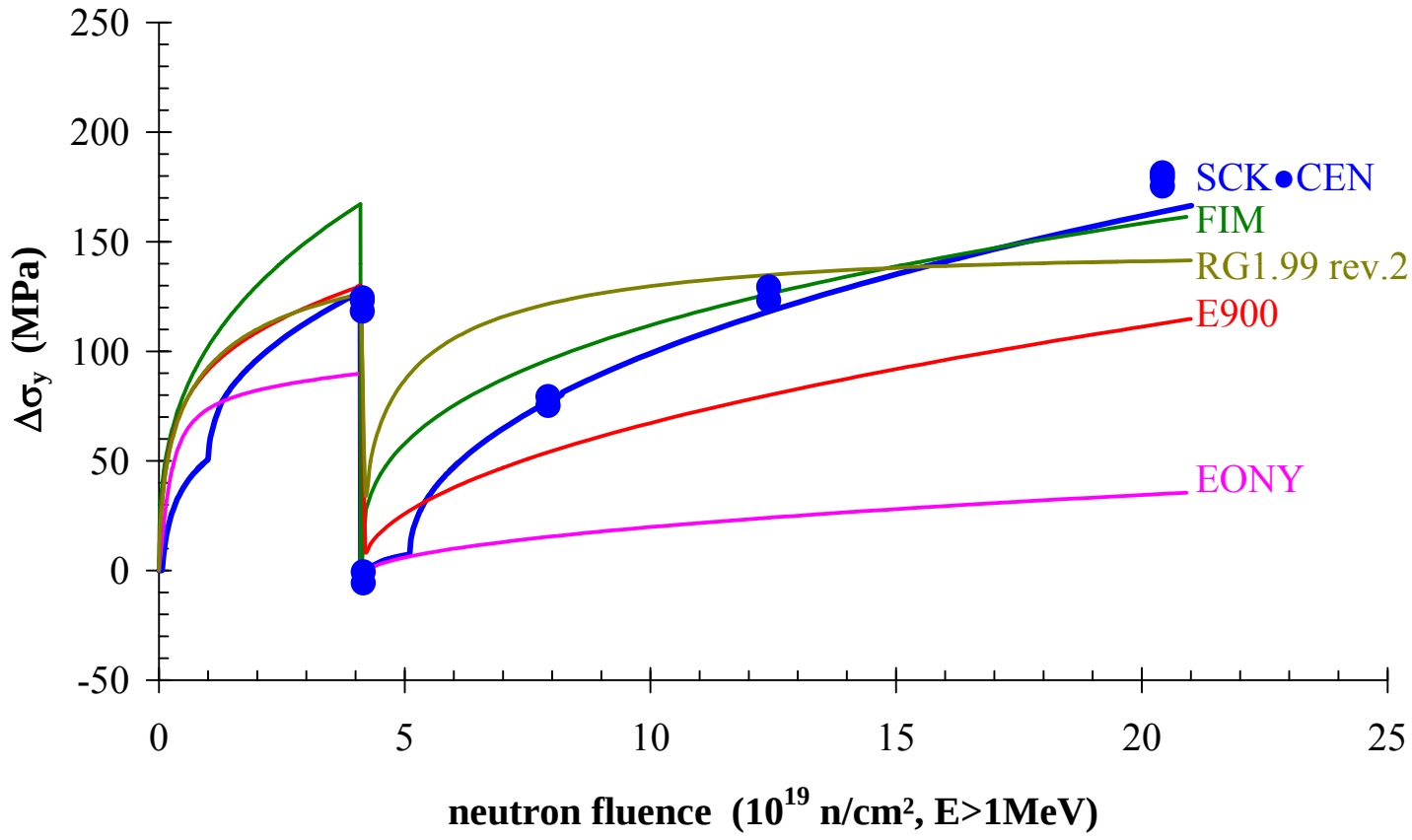


➔ *acceptable (two materials are being re-irradiated for verification)*

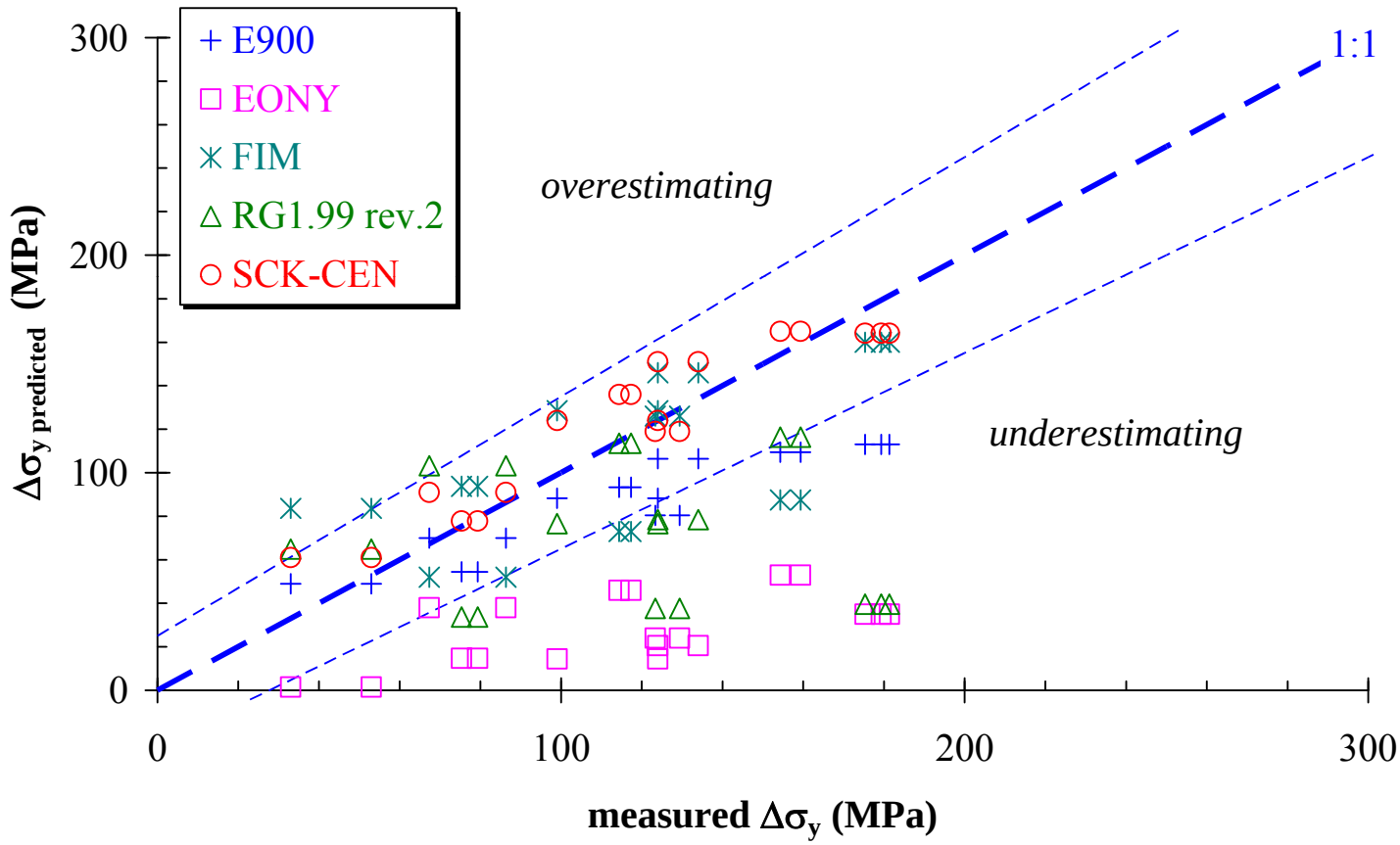
Model validation

- **Possible variables to change the interplay between the various damage mechanisms**
  - Material composition
  - Irradiation variables
    - Irradiation temperature (FIM)
    - Irradiation/annealing/re-irradiation experiments
- **IAR kinetics**
  - Three RPV materials with %Cu = 0.07, 0.14 and 0.31
  - Irradiation to $\Phi \approx 4\ 10^{19}$ n/cm² at 300°C
    → annealing 450°C/150h → re-irradiation
  - Assuming residual Cu = 0.05% after annealing

IAR kinetic


250
200
150
100
50
0
-50
0
5
10
15
20
25
$\Delta\sigma_y$ (MPa)
neutron fluence (10^{19} n/cm², E>1MeV)
SCK•CEN
FIM
RG1.99 rev.2
E900
EONY

IAR : Comparison



➔ *US trend curves clearly underestimate actual hardening with low Cu RPV materials*

Hardening–embrittlement correlation

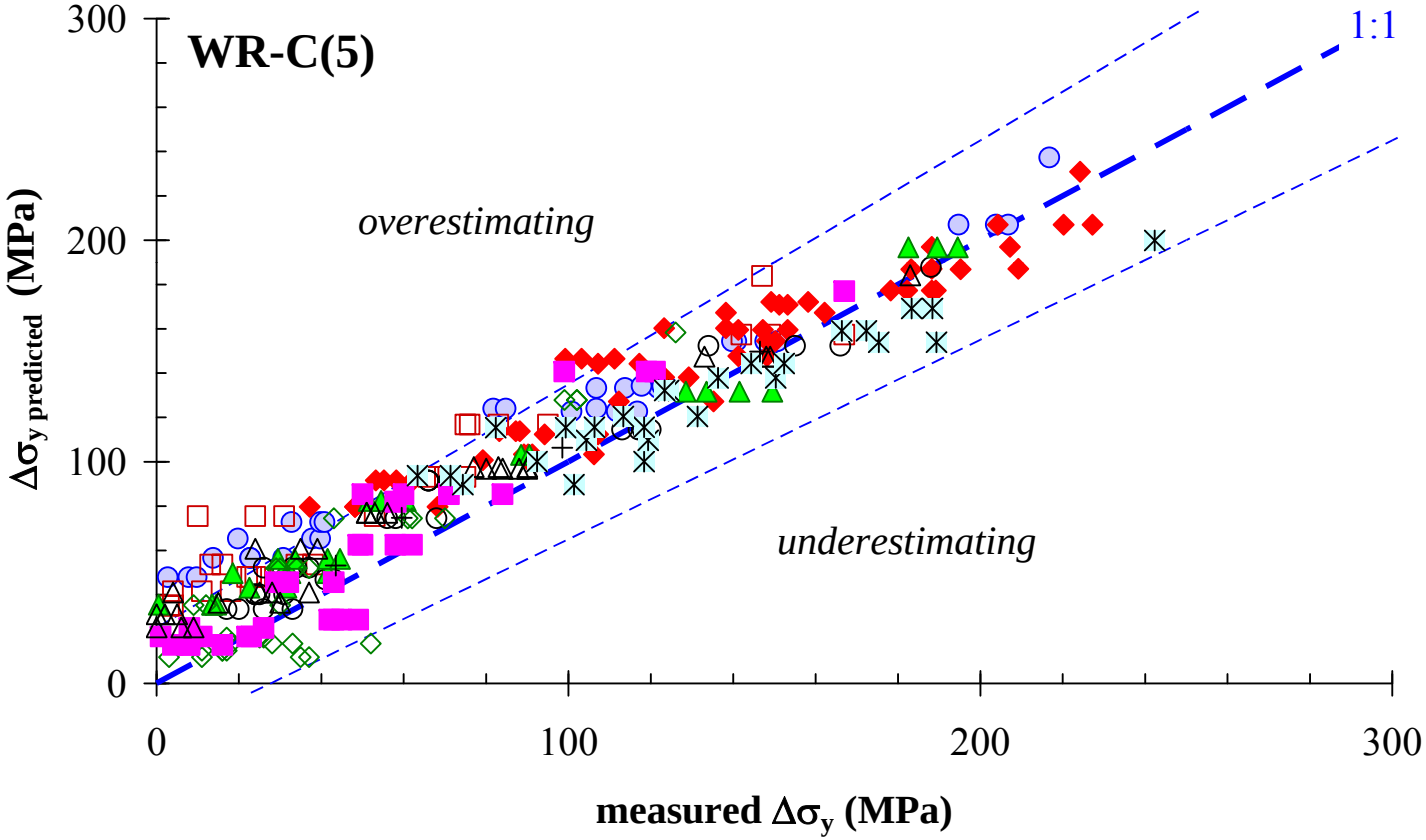
- **Charpy impact → DBTT**
  - Correlation factor $\Delta DBTT/\Delta\sigma_y$ is not constant, varies from one material to another
  - Better correlation expected between ΔT_0 and $\Delta\sigma_y$

- **Future work**
  - Establish a physically–based correlation between hardening and embrittlement (in progress)
  - Need re–assessment of the T_0–determination procedure

Conclusions

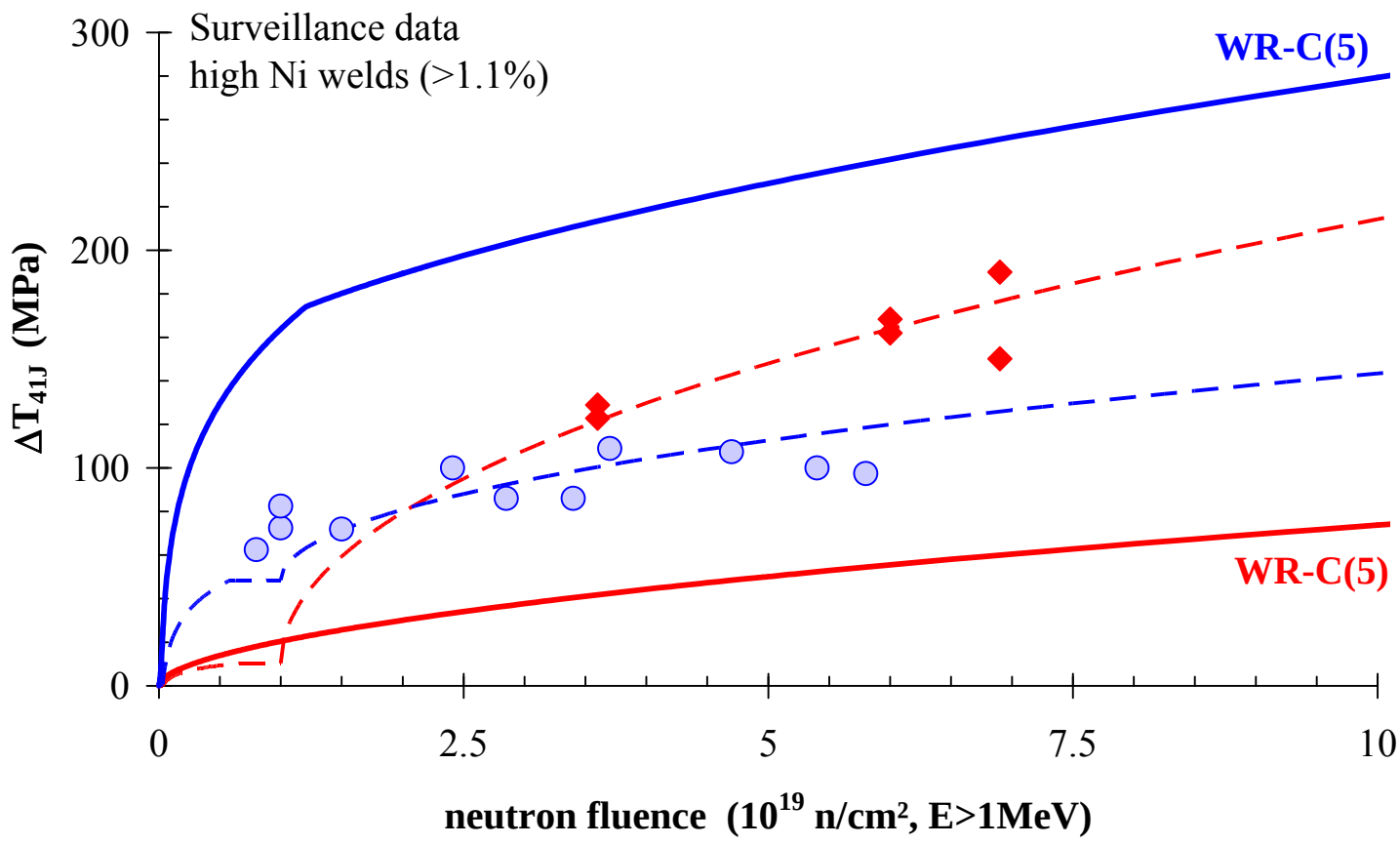
- **US and French embrittlement trend curves versus MTR high flux data**
  - US trend curves exhibit large discrepancies (scatter)
  - In the LTO perspective:
    - US trend curves tend to underestimate actual hardening
    - French trend curve tend to overestimate actual hardening (conservative for LTO)
  - Despite its empirical nature, the French FIM is in better agreement with experimental data
  - Regulatory trend curves need re–assessment by using physical models
  - MTR data should be combined to surveillance data
- **Confirmation for Surveillance data**
  - Paper A137 : Bogaert et al. (Fontevraud–7)

Mark Kirk (Paper A106 Fontevraud–7): WR-C(5)



➔ *Much better correlation when a wide range (surveillance + test reactor data) is used*

WR-C(5) Limitation → Ni–content



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SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire

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Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSEL
Operational Office: Boeretang 200 – BE-2400 MOL