Effect of radiation embrittlement to reactor pressure vessel steels and its surveillance

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http://www.jrc.ec.europa.eu

Trieste, April 2009

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CONTENT

- EC-JRC-IE
- AGEING NPPs in the EU
- RPV Embrittlement
- MATERIAL ISSUES
- Modeling / Assessment
- Surveillance of RPV
- Towards GEN IV
- CONCLUSIONS

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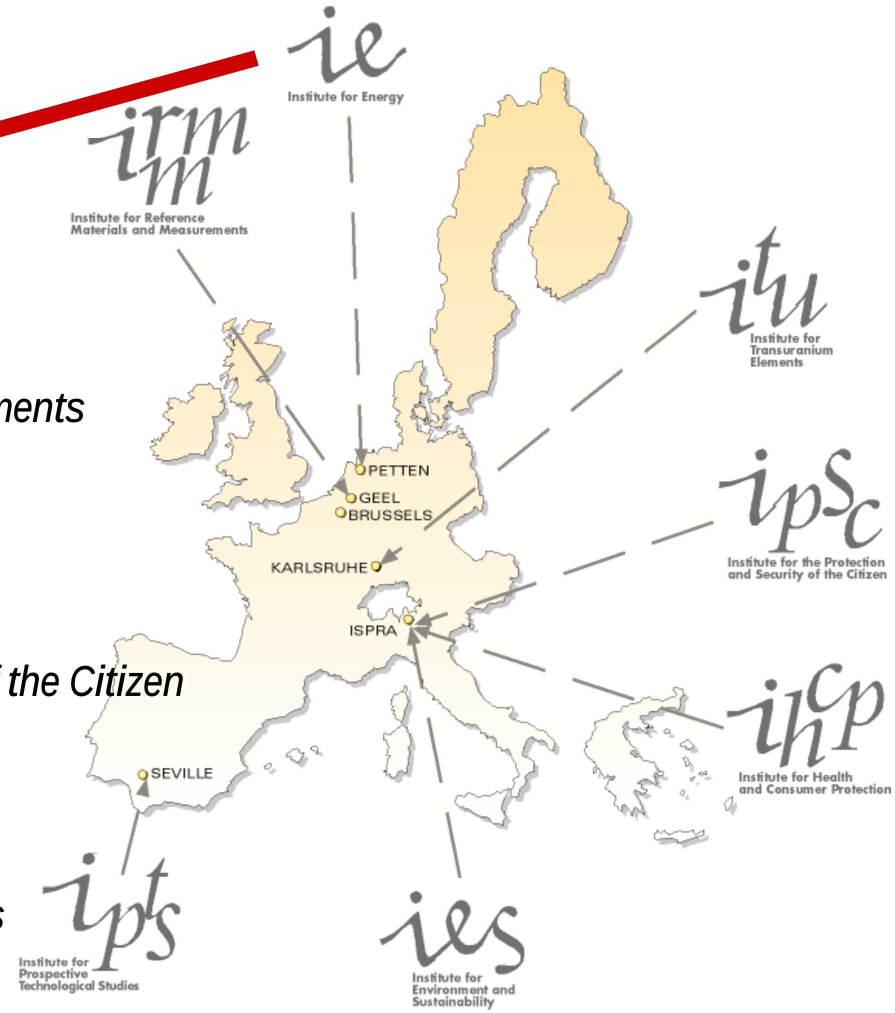
JRC - Joint Research Centre

7 Institutes in 5 Member States:



IE - Petten The Netherlands

- Institute for Energy

IRMM - Geel Belgium

- Institute for Reference Materials and Measurements

ITU - Karlsruhe Germany

- Institute for Transuranium elements

IPSC - IHCP - IES - Ispra Italy

- Institute for the Protection and the Security of the Citizen

- Institute for Health and Consumer Protection

- Institute for Environment and Sustainability

IPTS - Seville Spain

- Institute for Prospective Technological Studies

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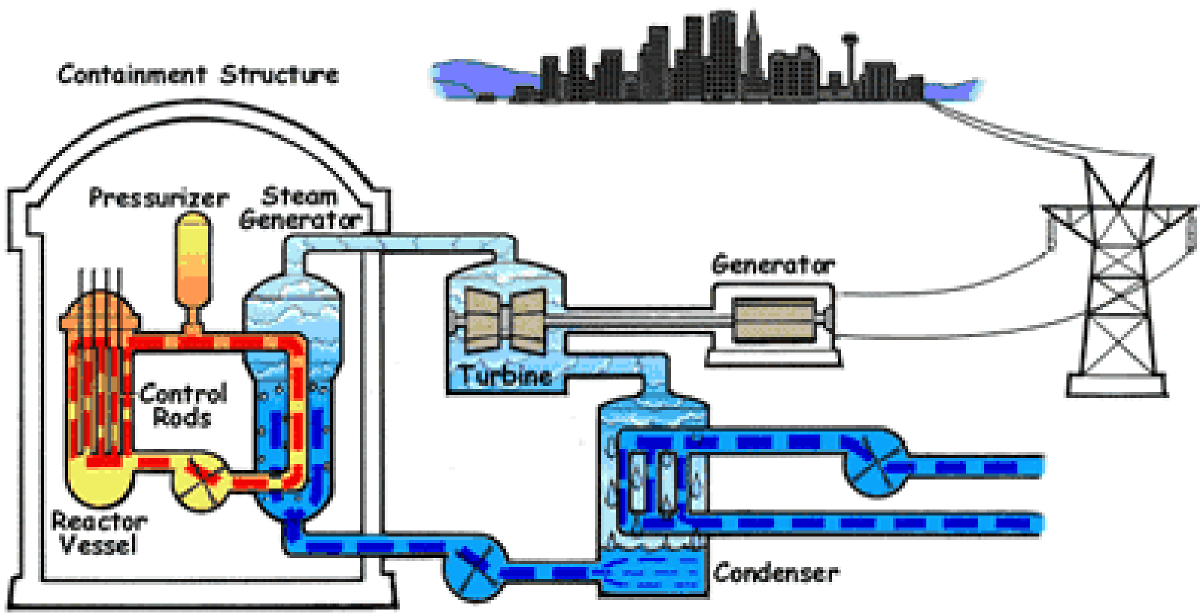
Petten site

AGEING NPPs in the EU

Nuclear Safety
- **Cross-national** issue
- **Public concern**
- Needs for EU **guidelines**
    - **Best-practices**
- Deterministic & **risk-based**
- National standards

Factors/issues:
- **Deregulation**
- **Probabilistic approaches**
- **Economical/cost saving**



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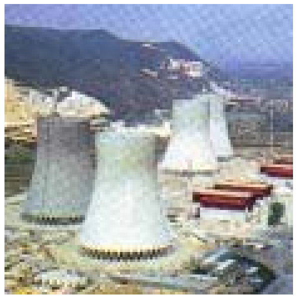
AGEING NPPs in the EU

PWR,
BWR,
VVER,
RBMK,
CANDU,
MAGNOX,
AGR,
HTR,
FR

Evolution

GEN IV
Future reactors

EPR



GEN III
Advanced LWR

GEN II
Commercial reactors

GEN I
Early prototypes

50s-60s 70s-80s (devel. 90s)

Note: GEN III expected till 2015-2020

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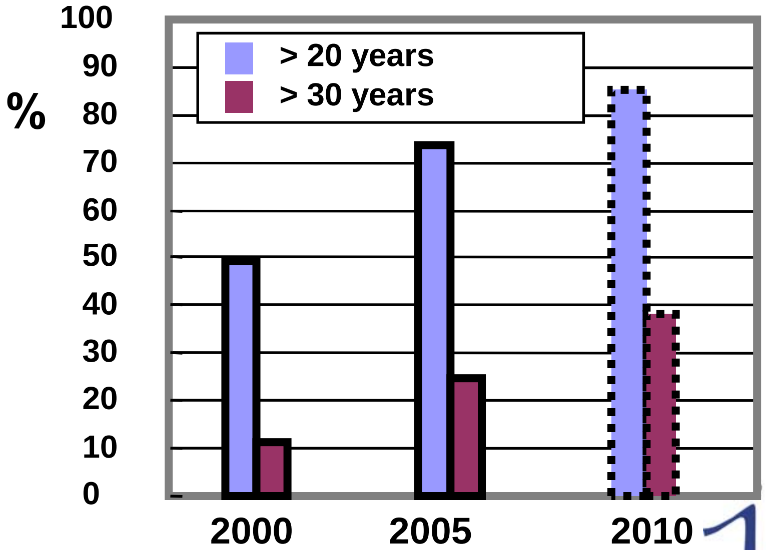
Present generation

LWR → PWR, BWR, VVER, RBMK
HW → CANDU
GCR → MAGNOX, AGR
LM → FR

- **>100 NPPS**
- **>30% electricity**
- **<u>ageing!</u>**



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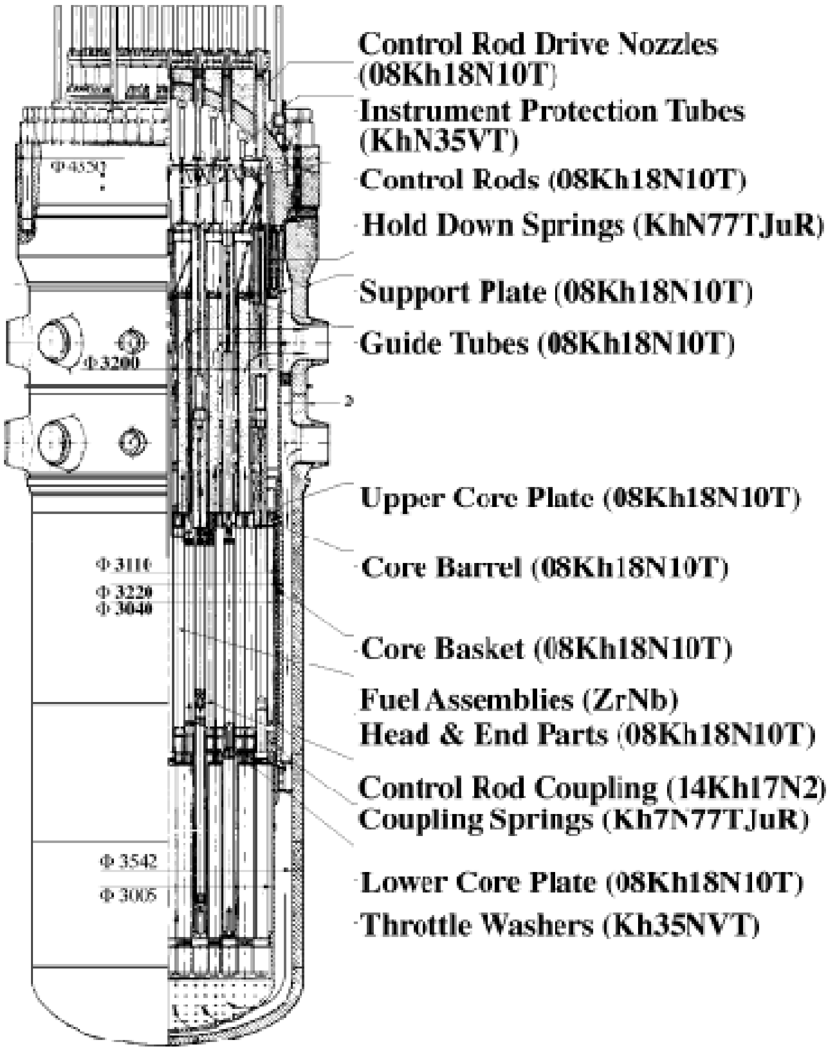
Ageing mechanisms of RPV & RVI



Irradiation hardening
Irradiation embrittlement
- loss of work hardening capability
Thermal embrittlement
Swelling
- incl. void induced embrittlement
Irradiation creep
- incl. creep-swelling interaction
Stress relaxation
- thermal
- radiation assisted
Fatigue (vibration or/and environment)
Corrosion – SCC - IASCC
Pitting
Wear

Synergisms

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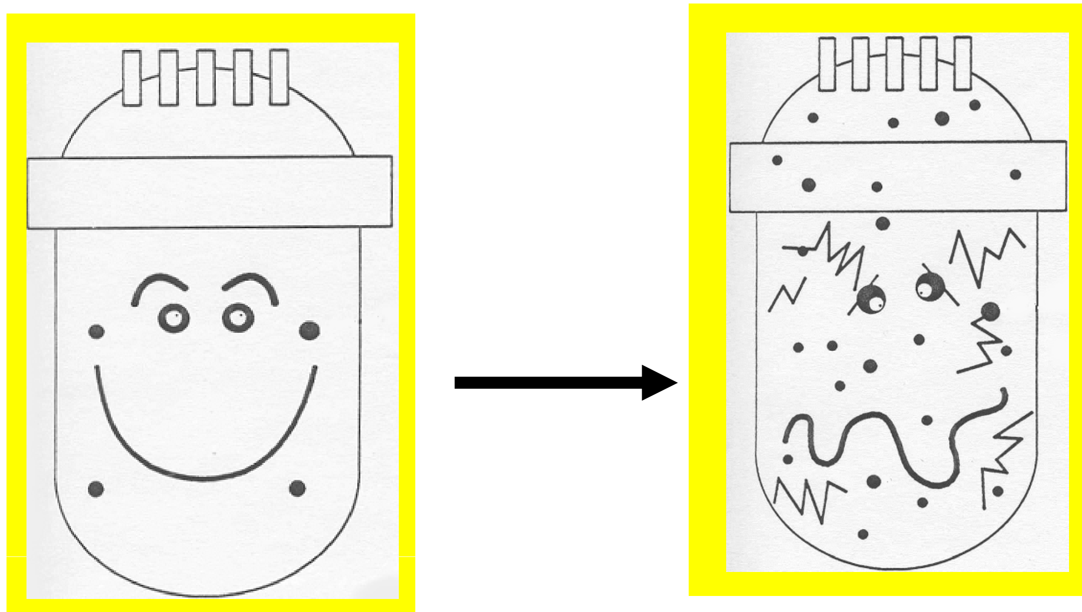
embrittlement



Use of the Semi-Mechanistic Analytical Model to Analyse Radiation Embrittlement of M.A.: Cu and P Effects - Debarberis, Kryukov, Gillemot, Valo, Morozov, Brumovsky et al. International Journal of Problems of Strengths, ISSN 0556-171X, 2004, No.3

Semi-mechanistic analytical model for radiation embrittlement/re-embrittlement Debarberis et al., International Journal of Pressure Vessels and Piping, Vol. 82, 2005

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RPV materials

	Russian design Cr: 2-3 % - V Cr-Mo-V & Cr-Ni-Mo-V	Western design low Cr: 0.1-0.14 % Mn-Ni-Mo
Low Ni	WWER-440 Cu: 0.10 % P: 0.02 %	A302B Cu: 0.16 % P: 0.011 %
High Ni	P: 0.009 % VVER-1000 weld seams: up to Ni ~ 1.9%	P: 0.007 % A533B Ni~0.6% A508Bcl3 Ni~0.7%
	12KhMFA, 15A2MFA, 15Kh2NMFAA	16MND5

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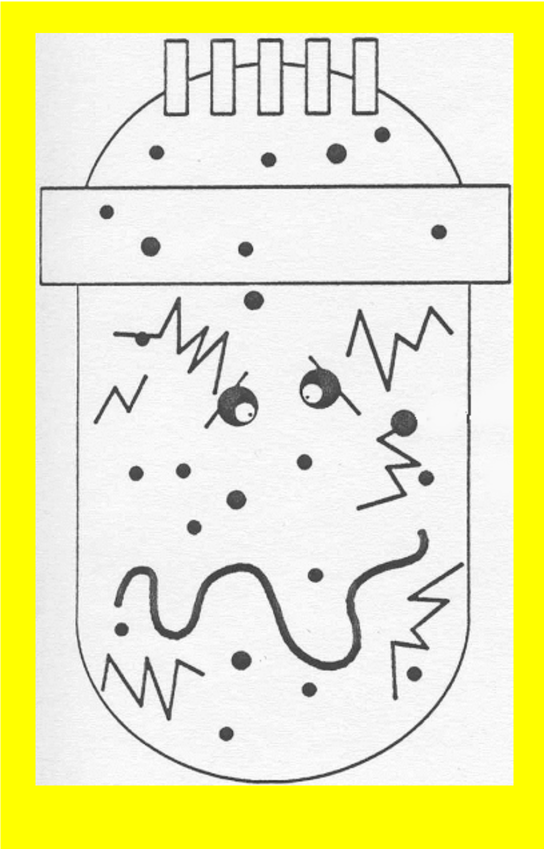
Embrittlement



- **neutron fluence (matrix damage)**
- **impurities** (late 60s: **Cu** & later **P** - L.E. Steele and co-workers at ONRL)
- **alloying elements**
  - **Ni i**dentified ~10 y later
  - Today, indications on **Mn, etc.**
- **thermal ageing, etc.**
- **Prediction models & formulas**
- **Surveillance programmes**

Radiation Embrittlement Understanding for PLIM Activities at EC-JRC-IE
Debarberis, Sevini, Acosta, Pirfo, Bieth, Weisshaeupl, Törrönen, Kryukov & Valo
International Journal Strength of Materials, ISSN 0556-171X, No. 1 (367) 2004

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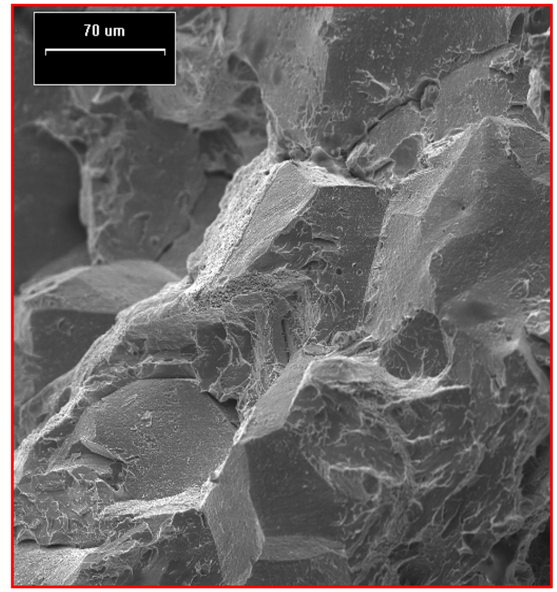
Radiation-induced micro-structure and micro-chemistry



Micro-chemistry evolution

↑

At grain boundary

↑

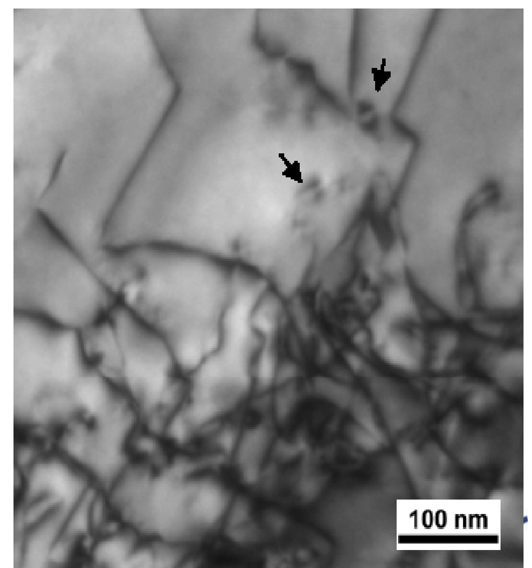
dpa → **Freely Migrating Defects** → **Re-combination/ annihilation**

↓

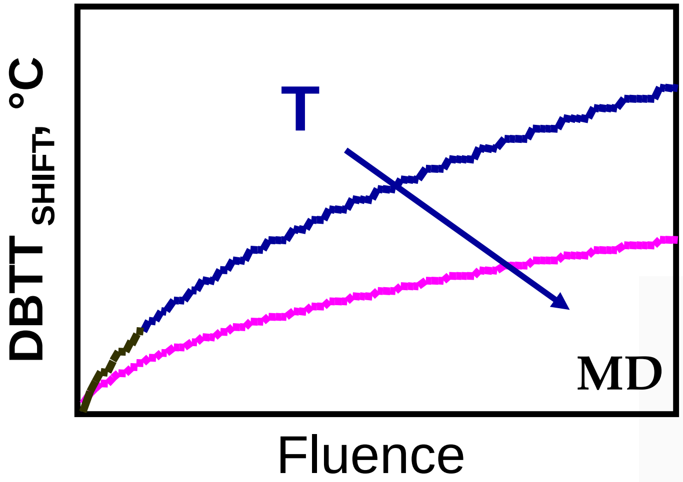
At matrix sink

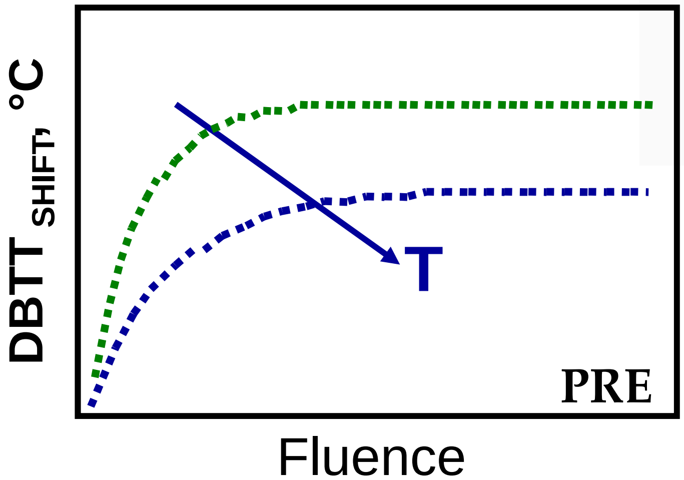
↓

Micro-structural evolution

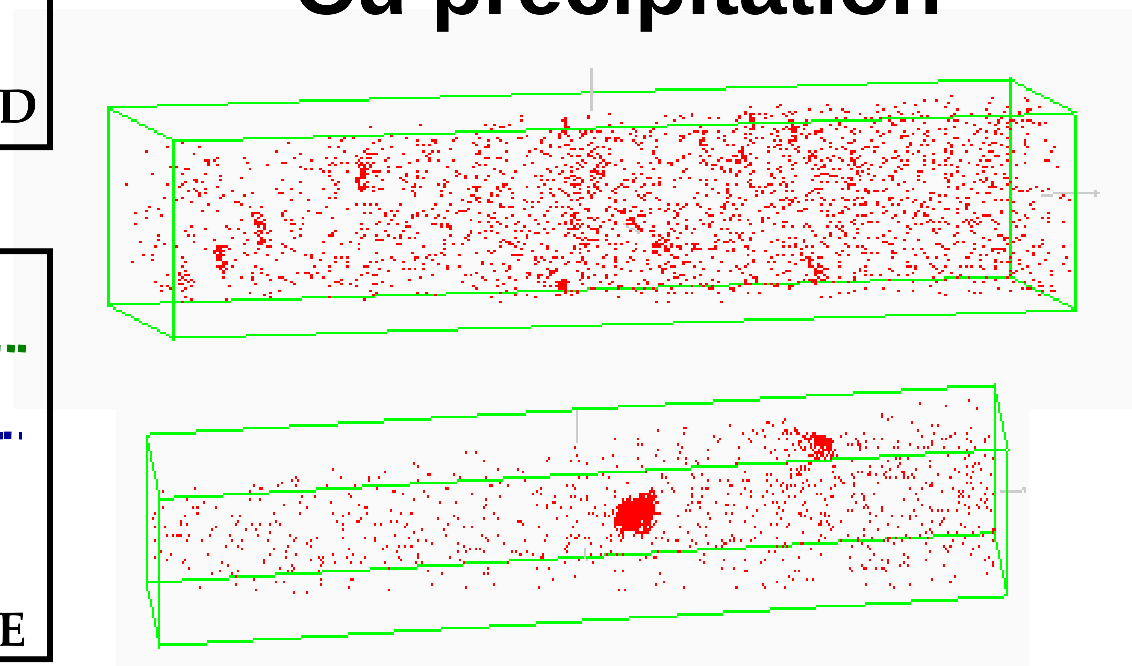


direct MATRIX DAMAGE





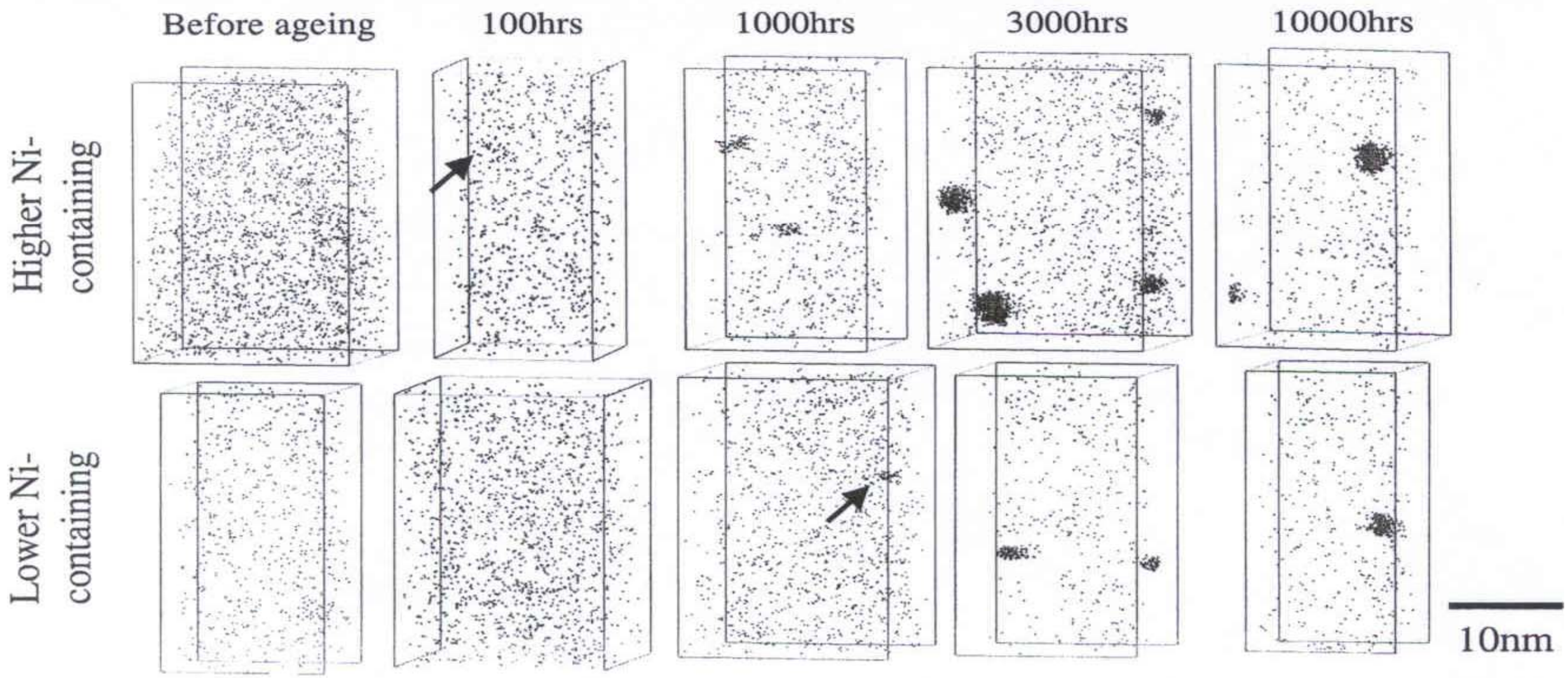
Radiation-induced Cu precipitation



Effect of irradiation temperature in PWR RPV materials and its inclusion in semi-mechanistic model - Debarberis et. al, - Scripta Materialia, Vol. 53, 2005

Reactor Pressure Vessel Materials

3DAP data on microstructure evolution of Cu clusters in higher and lower Ni-containing alloys during ageing at 365°C



- Cu clusters are formed more rapidly and densely with Ni addition

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DEPARTMENT OF MATERIALS

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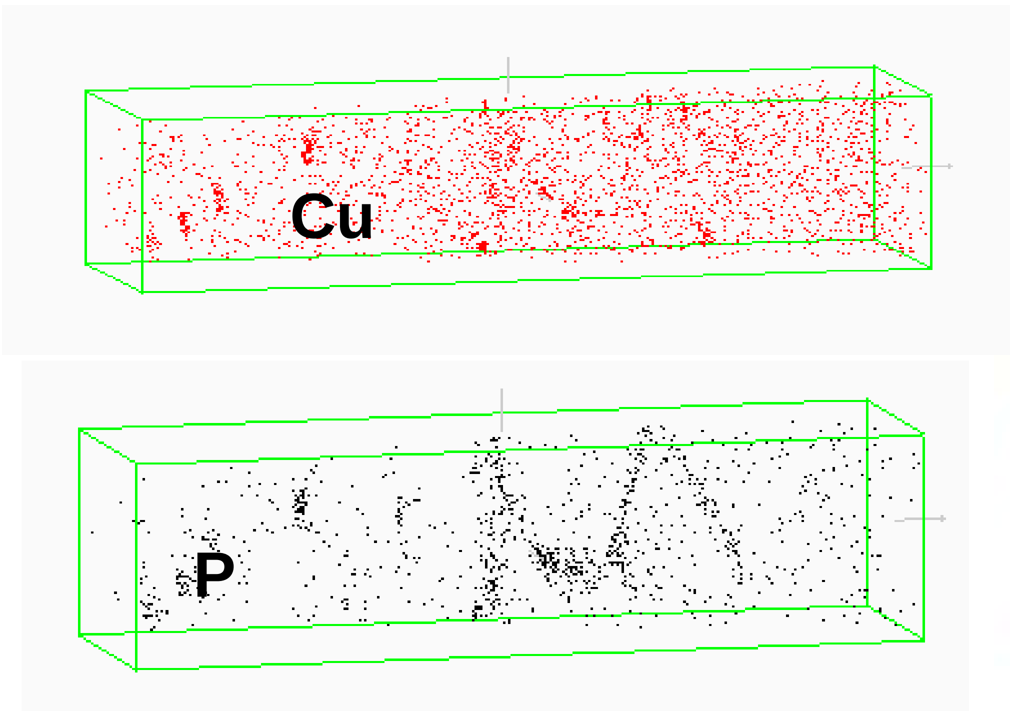

”Comparison of Nickel Effects on Embrittlement Mechanisms in Prototypic WWER-1000 and A533B Steels"; R.K. Nanstad, M.A. Sokolov, M.K. Miller, and G.R. Odette - ORNL - UCSB

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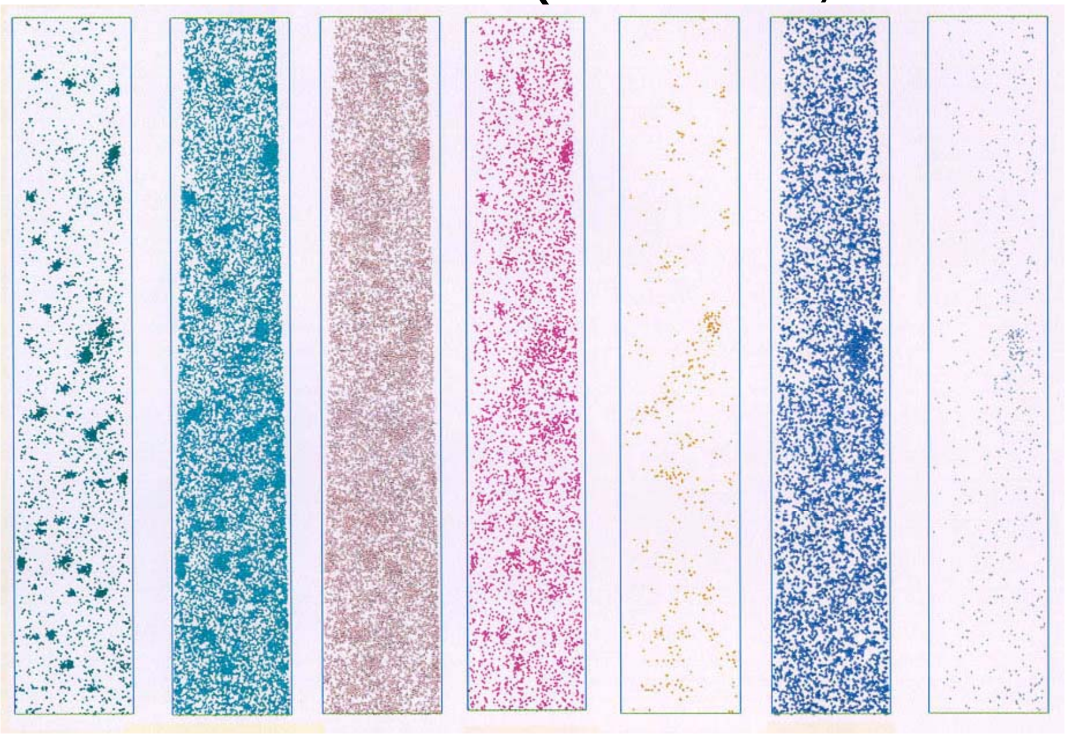
Atom Maps Reveal Irradiation-Induced Precipitates Enriched in Cu, Mn, Ni, P, and Si in the KS-01 Weld

(M.Miller, ORNL, USA)



Each dot is an atom.
Box is 19 x 19 x 110 nm
and contains 1.5M ions.

Neutron irradiation produces an extremely high number density $N_v = 3 \times 10^{24}\ m^{-3}$ of nanoscale copper-, manganese-, nickel-, phosphorus- and silicon-enriched precipitates.

The number density is significantly higher than other RPV steels irradiated to similar or higher fluences.

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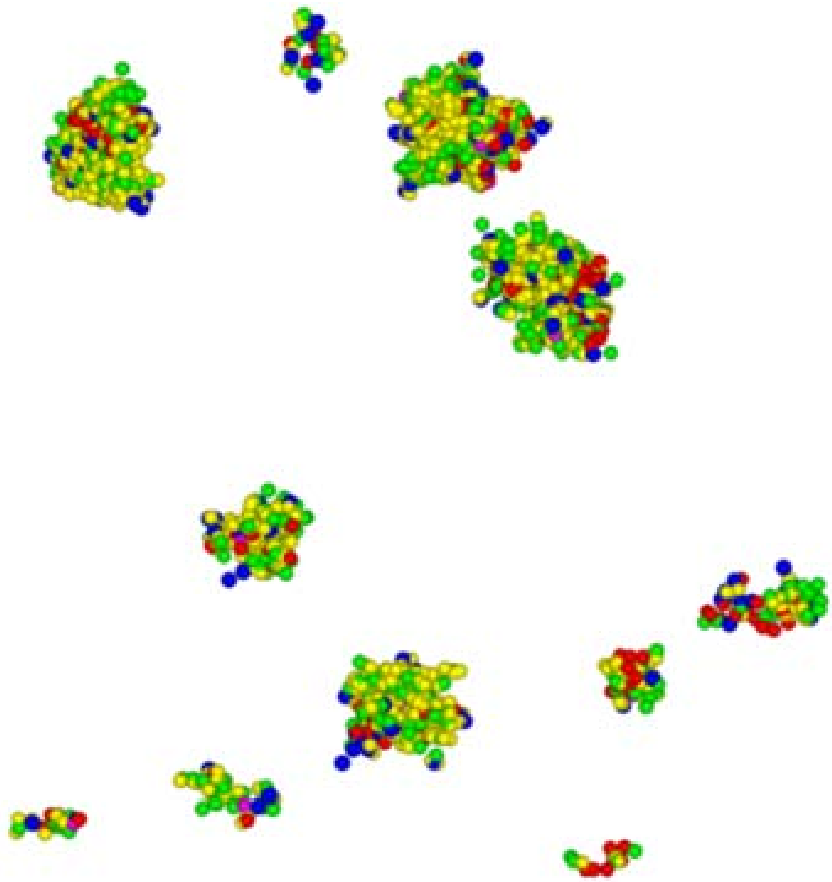
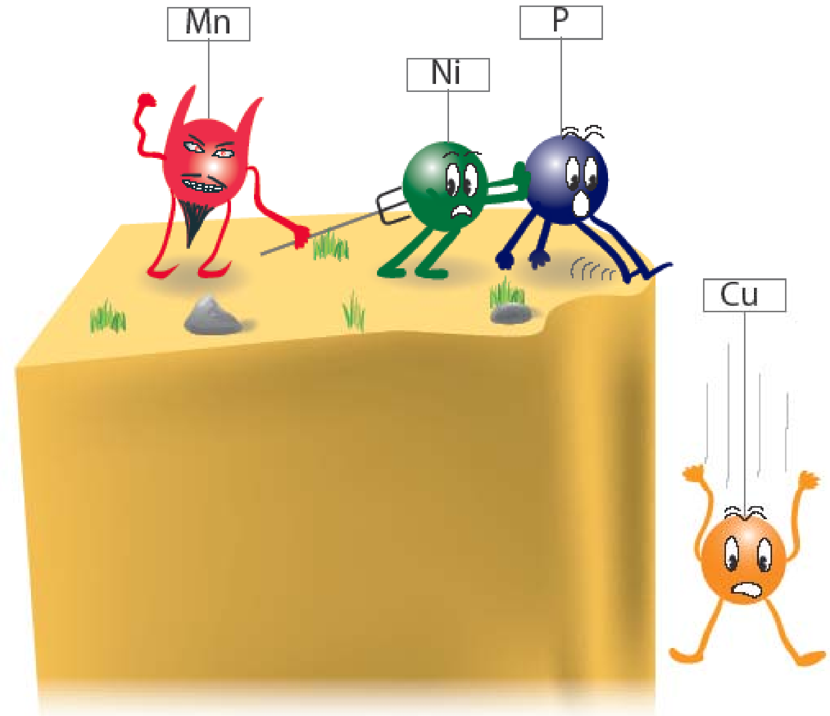
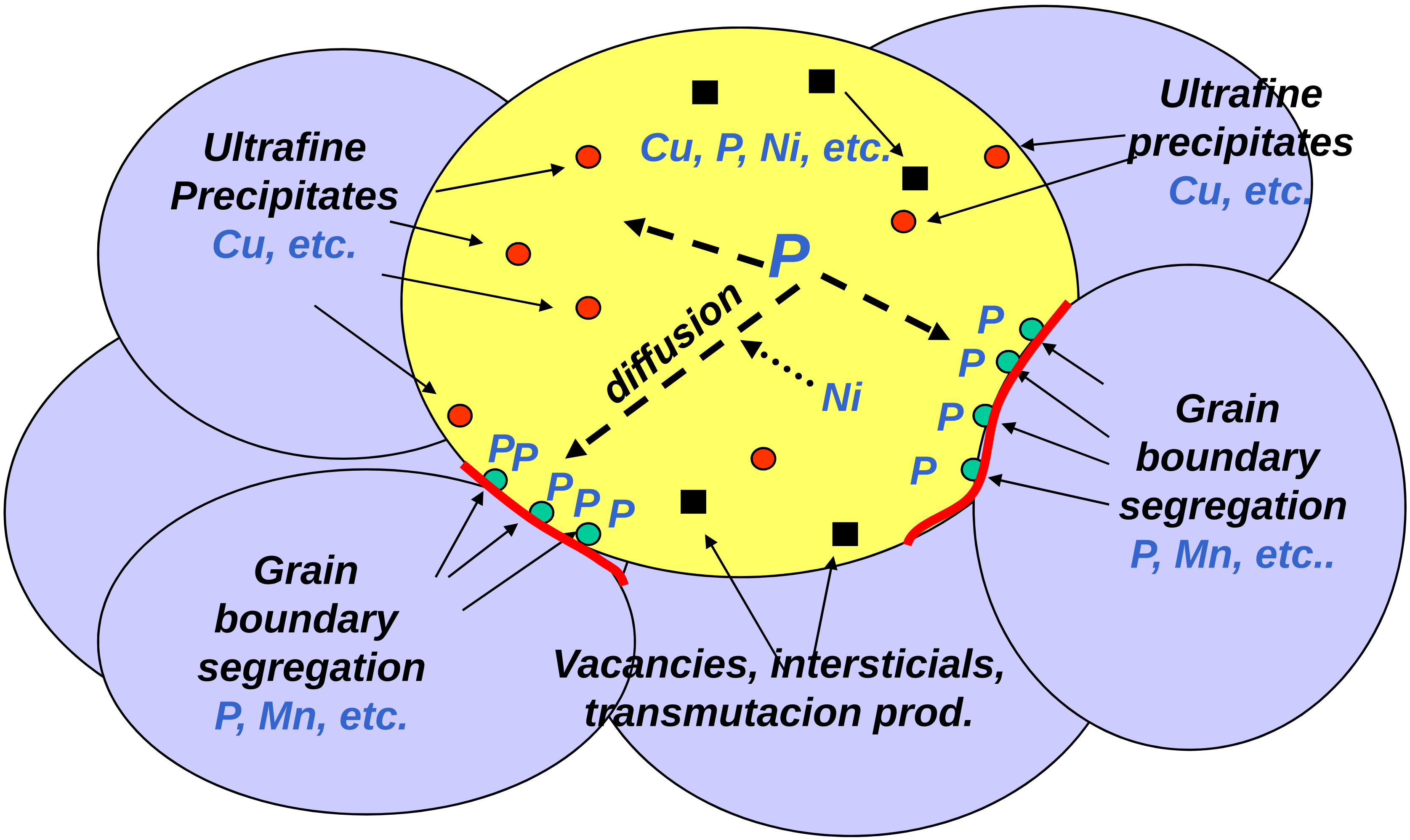


Fe Cu Ni Mn Si P atoms



"Comparison of Nickel Effects on Embrittlement Mechanisms in Prototypic WWER-1000 and A533B Steels"; R.K. Nanstad, M.A. Sokolov, M.K. Miller, and G.R. Odette - ORNL - UCSB

Schematic Embrittlement Process



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Prediction formulas

FIM (PWR)

$$\Delta RT_{NDT} = [17.3+1537*(\mathbf{P}-\underline{0.008})+238*(\mathbf{Cu}-\underline{0.08})+191*\mathbf{Ni^{2}*Cu}]*\ \Phi_{FIM}^{0.35}$$

PNAE (VVER)

$$\Delta RT_{NDT} = 800*(\mathbf{P}+0.07*\mathbf{Cu})*\Phi_{PNAE}^{1/3}$$

P, Cu , Ni concentrations in wt%

Φ_{FIM} neutron fluence (10^{19} cm^{-2} s^{-1}, E>1 MeV)

Φ_{PNAE} neutron fluence (10^{18} cm^{-2} s^{-1}, E>0.5 MeV)

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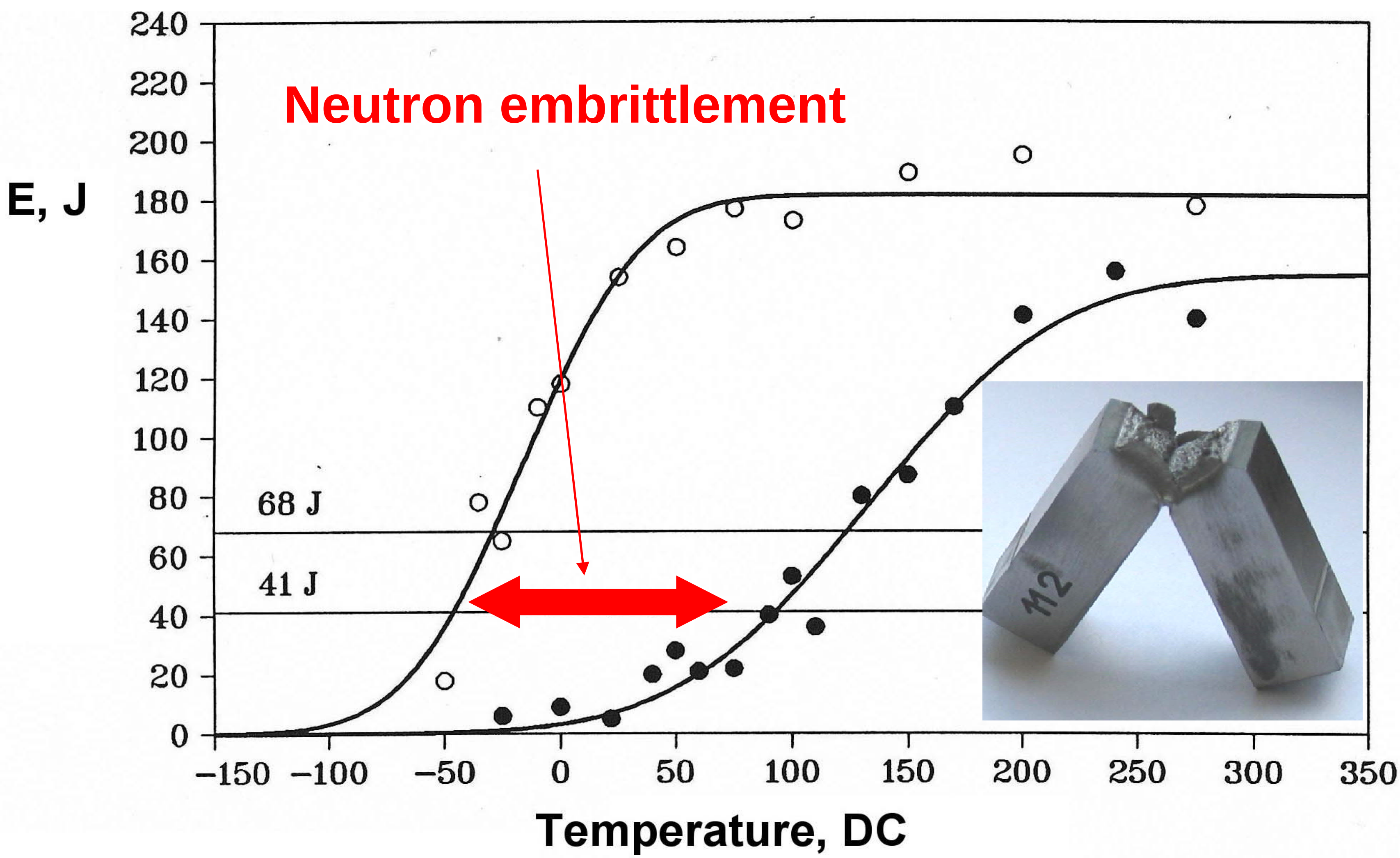
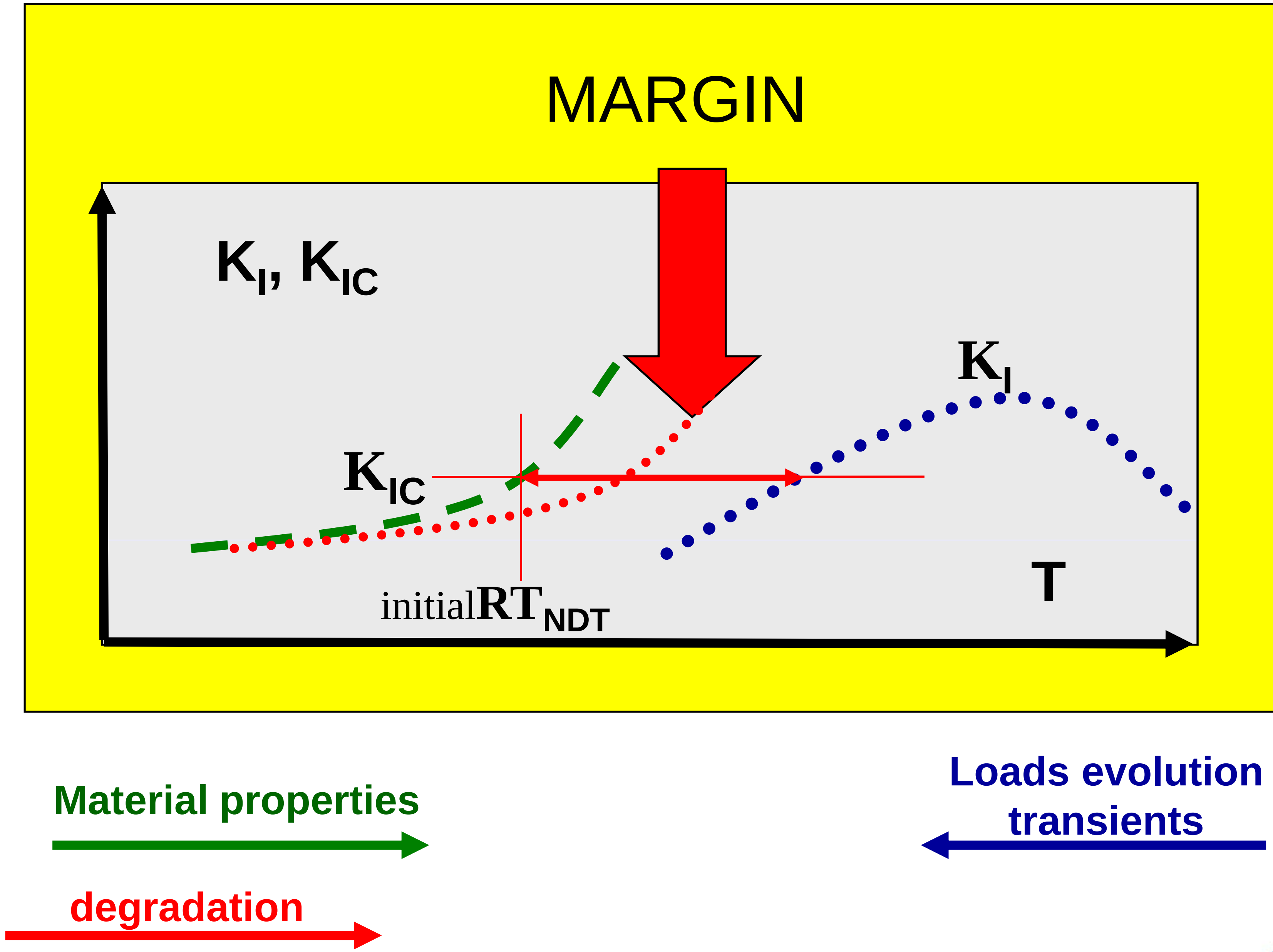
EMBRITTLEMENT SURVEILLANCE





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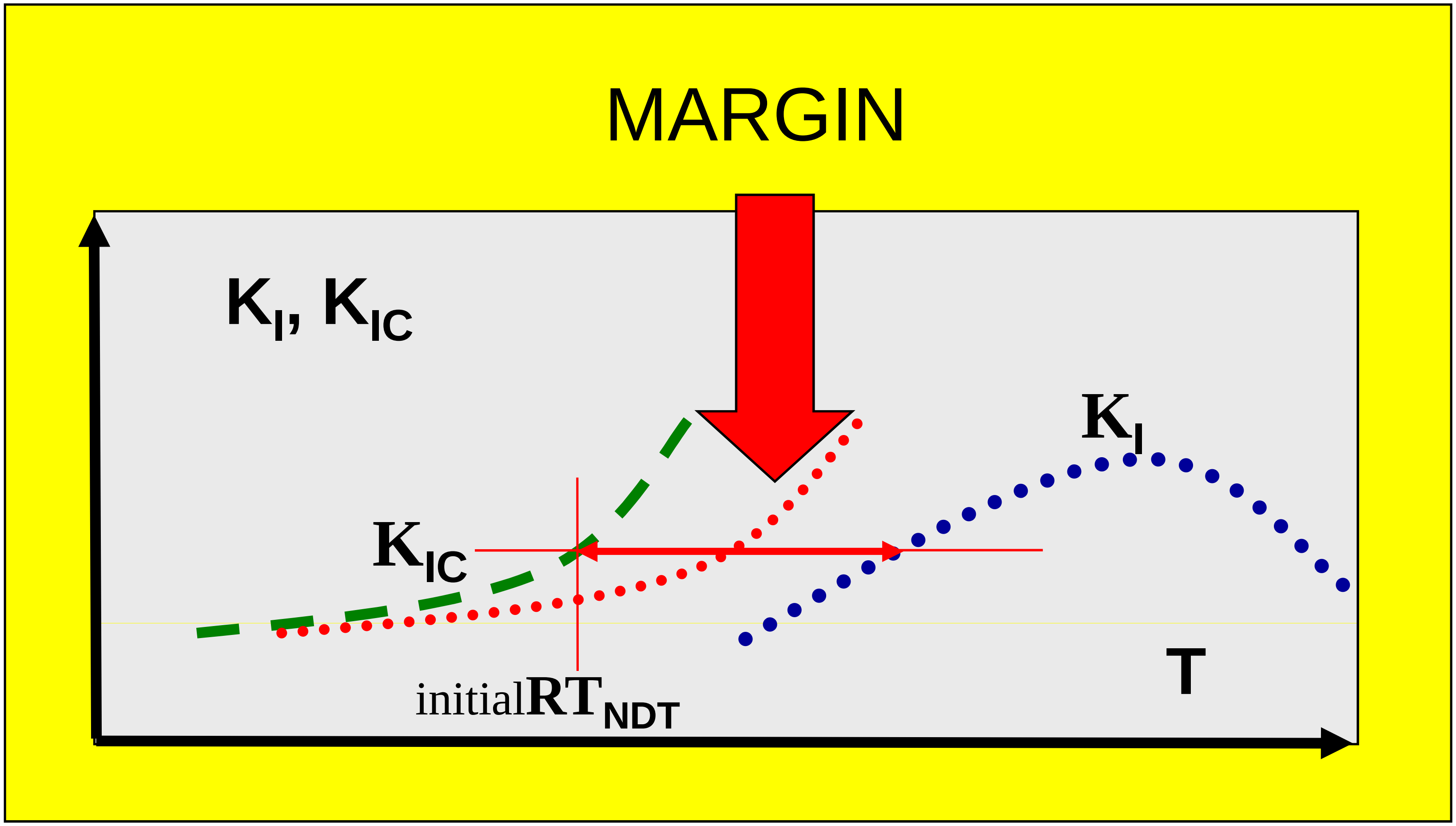
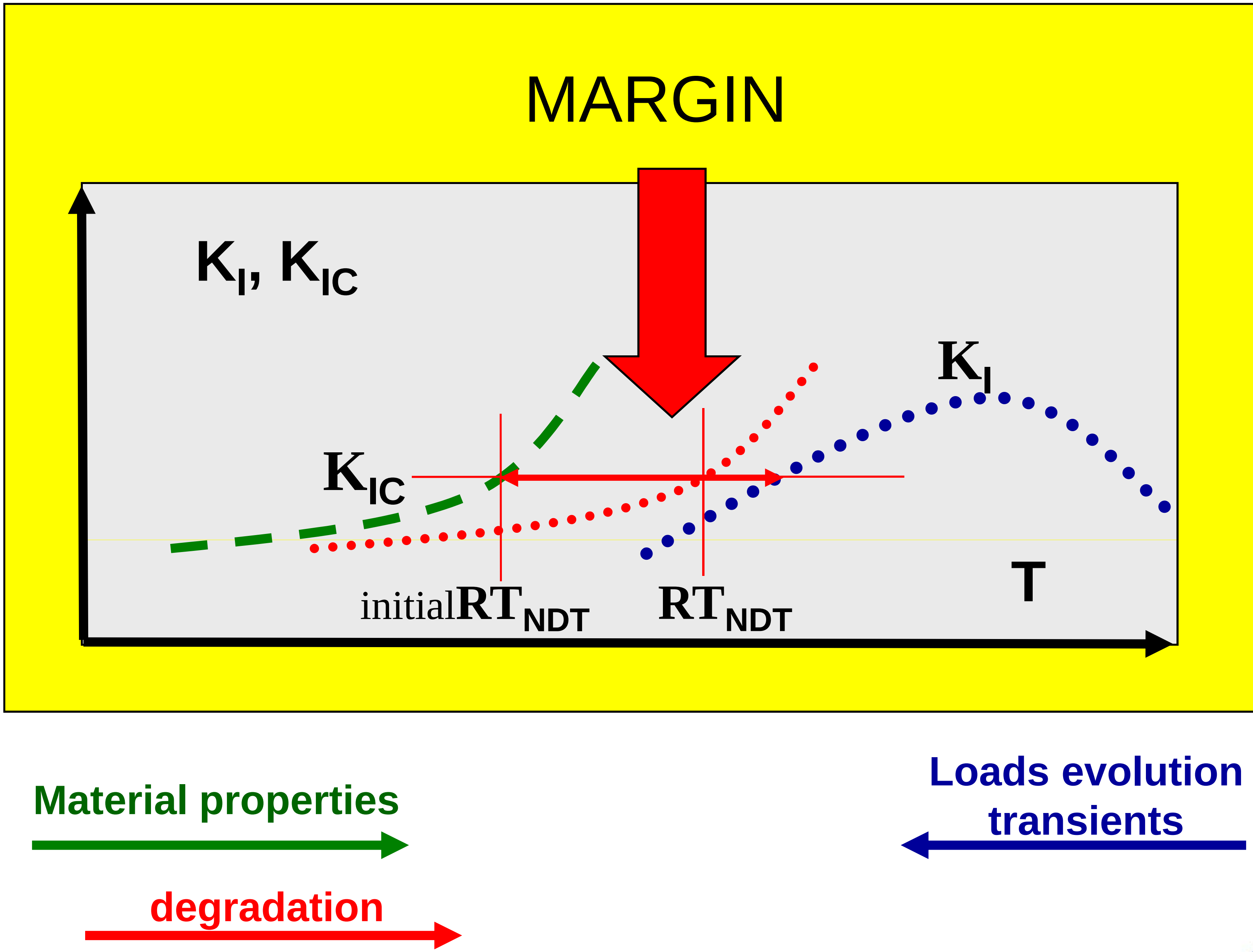


Material properties →

degradation →

← **Loads evolution transients**


MARGIN
K_I, K_{IC}
K_I
K_{IC}
initialRT_{NDT}
RT_{NDT}
T
Material properties
degradation
Loads evolution
transients

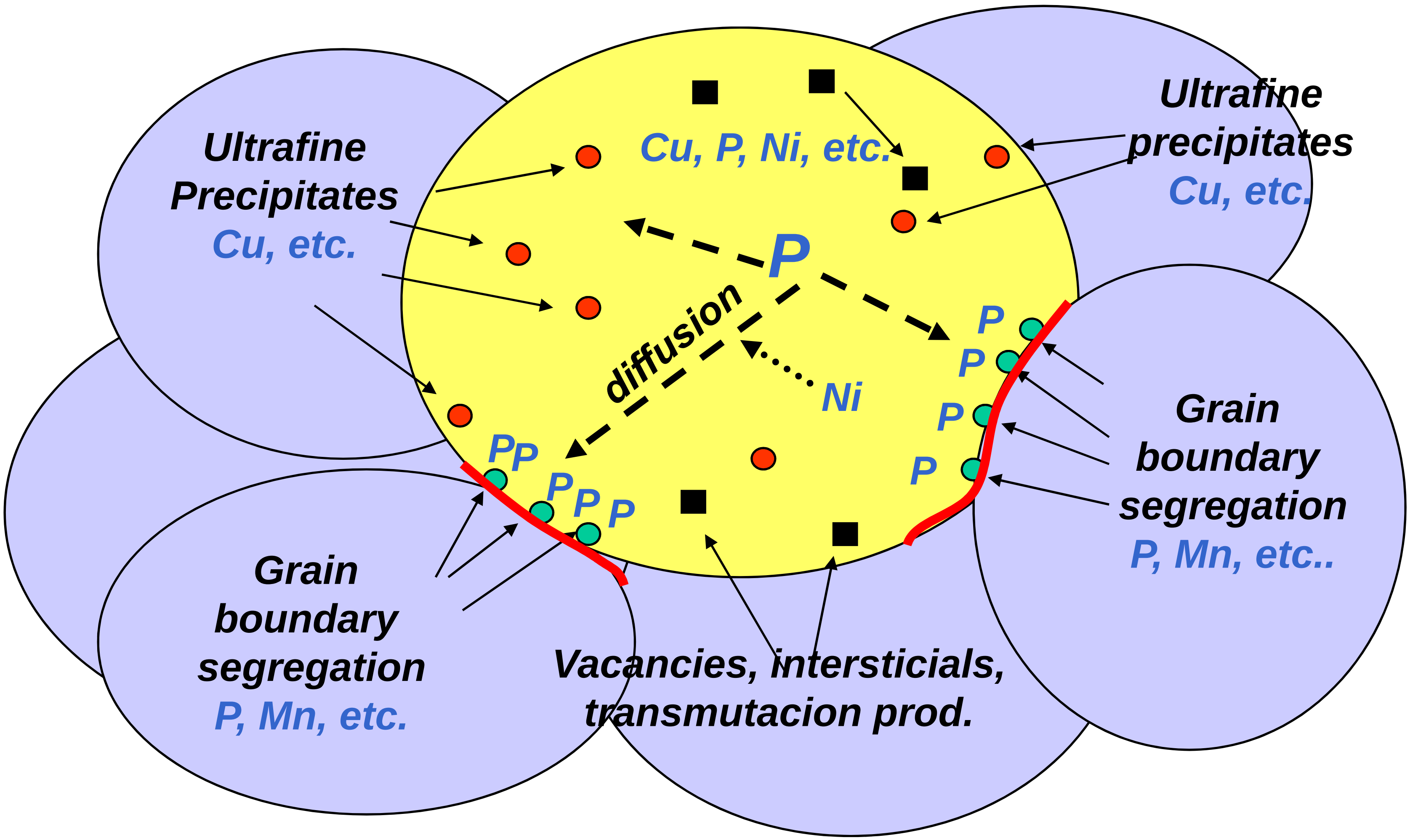
Different prediction formulas accepted by Regulators

Cu, P	**Russia**	**PNAE**	**0.33**	**No cross factors - No thresholds**
Cu, P, Ni	**France**	**FIS, FIM**	**0.35**	**Cross factor Ni-Cu – Thresholds**

Different prediction formulas accepted by Regulators

Elements considered	Country		Fluence power exponent	Remarks
Cu, P	USA	Reg.Guide 1.99 Rev.1	0.5	No cross factors – Thresholds
Cu, Ni	USA	Reg.Guide 1.99 Rev.2	0.28-0.10Logϕ	Cross factor Ni-Cu - No thresholds
Cu, P	Germany	KTA	Not given	No cross factors – Thresholds
Cu, P	**Russia**	**PNAE**	**0.33**	**No cross factors - No thresholds**
Cu, P, Ni	**France**	**FIS, FIM**	**0.35**	**Cross factor Ni-Cu – Thresholds**
Cu, P, Ni	France	Miannay et al.	0.7	Cross factor Ni-Cu – Thresholds
Cu, P, Ni	Japan	JEPE BASE	0.29-0.04Logϕ	Cross factor Ni-Cu - No thresholds
Cu, P, Ni, Si	Japan	JEPE WELD	0.25-0.10Logϕ	Cross factor Ni-Cu - No thresholds

Schematic Embrittlement Process



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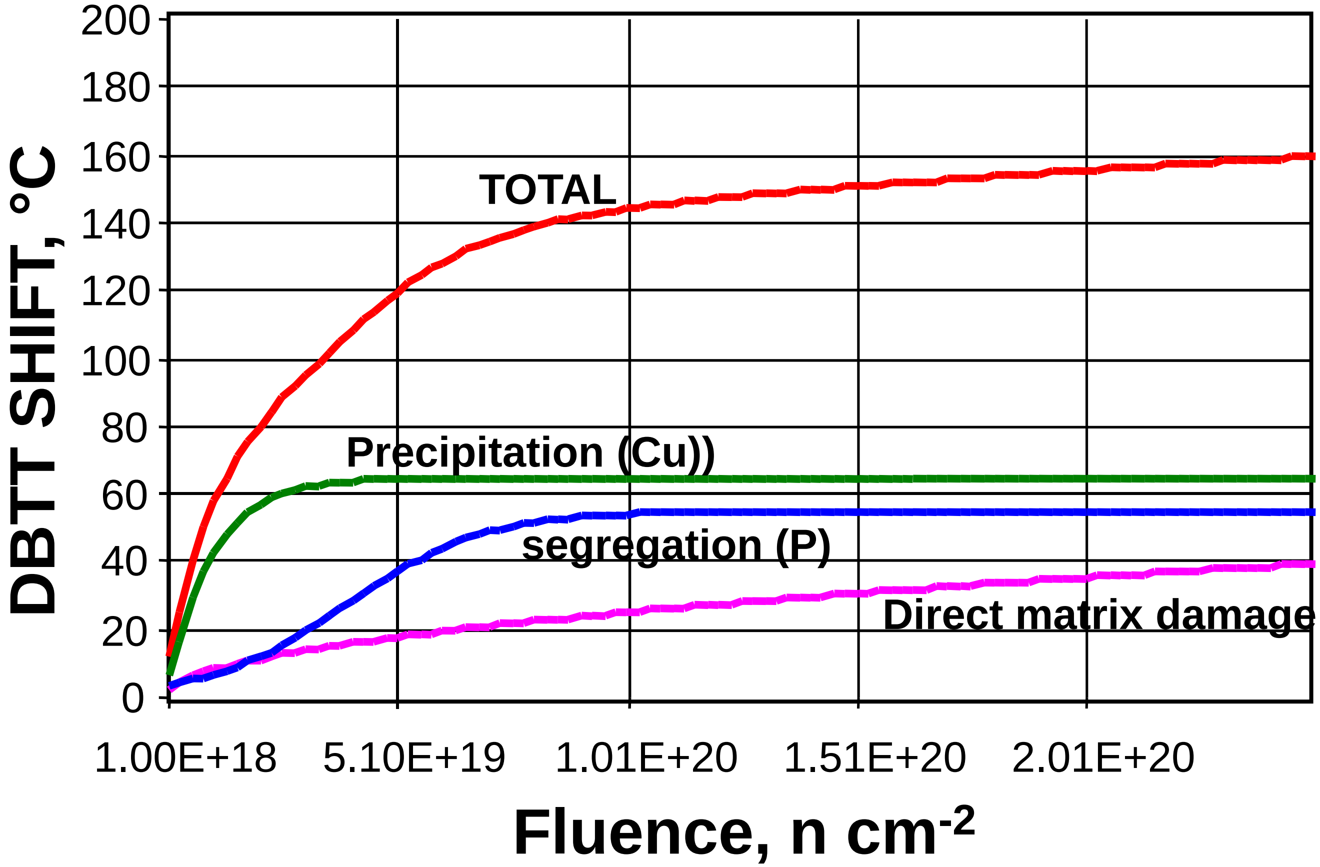
Damage = $\sum$(MD, PRE, SEG, …)

MD(Φ,T,Ni)
PRE(Φ,Cu,T,Ni, Φ_{rate},Mn)
SEG(Φ,T,P,Ni, Φ_{rate})



- **linear** summation
- quadratic option
- **synergisms**

Semi-mechanistic analytical model for radiation embrittlement and re-embrittlement data analysis- Debarberis, Kryukov, Gillemot, Acosta and Sevini
International Journal of Pressure Vessels and Piping, Volume 82, Issue 3, March 2005, 195-200

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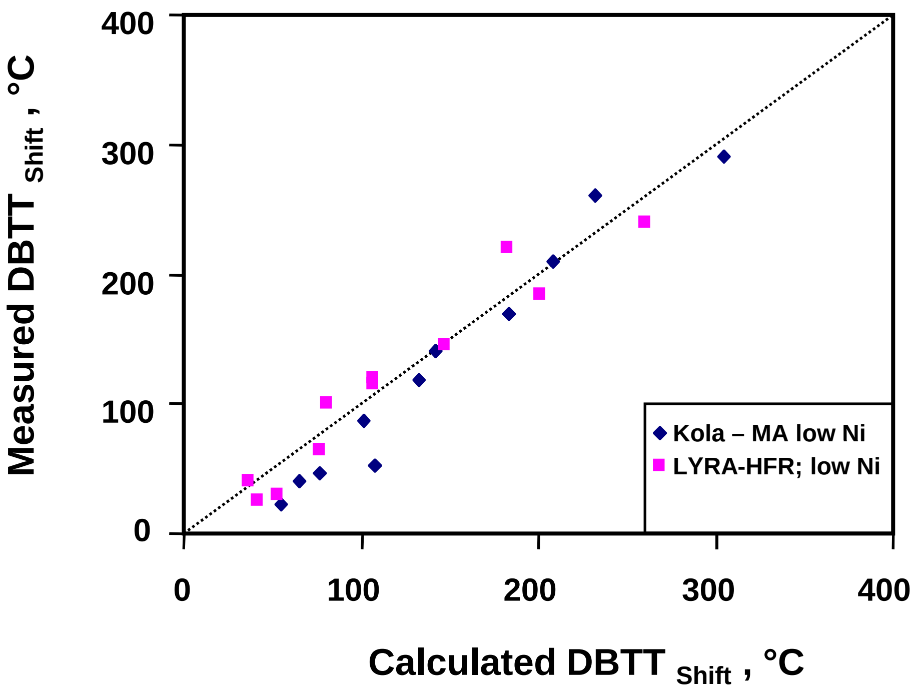
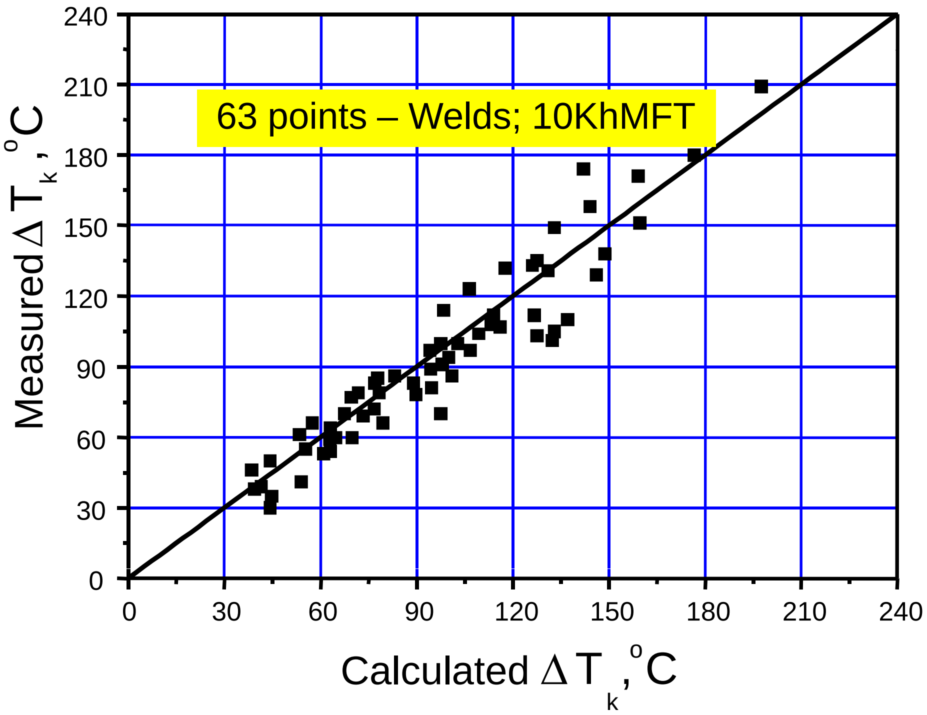
low Ni model alloys – HFR-LYRA + KOLA



VVER 440



Evaluation of WWER440 radiation embrittlement data using the semi-mechanistic model
Zhurko, Krasikov, Kryukov, Debarberis
IAEA Specialist Meeting on Radiation Embrittlement, Gus, Russia, May 2004

Advanced method for WWER RPV embrittlement assessment,
L. Debarberis et al., International Journal of Pressure Vessels and Piping, Vol. 81, 2004

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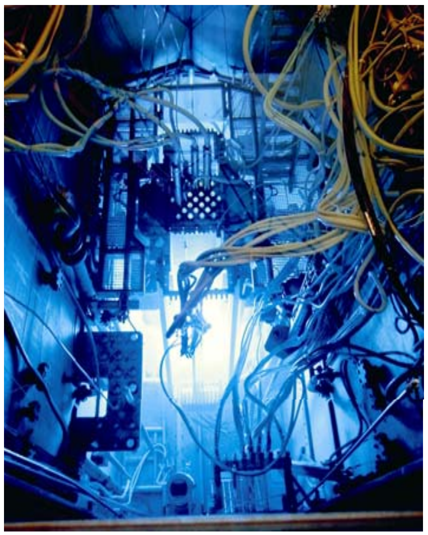
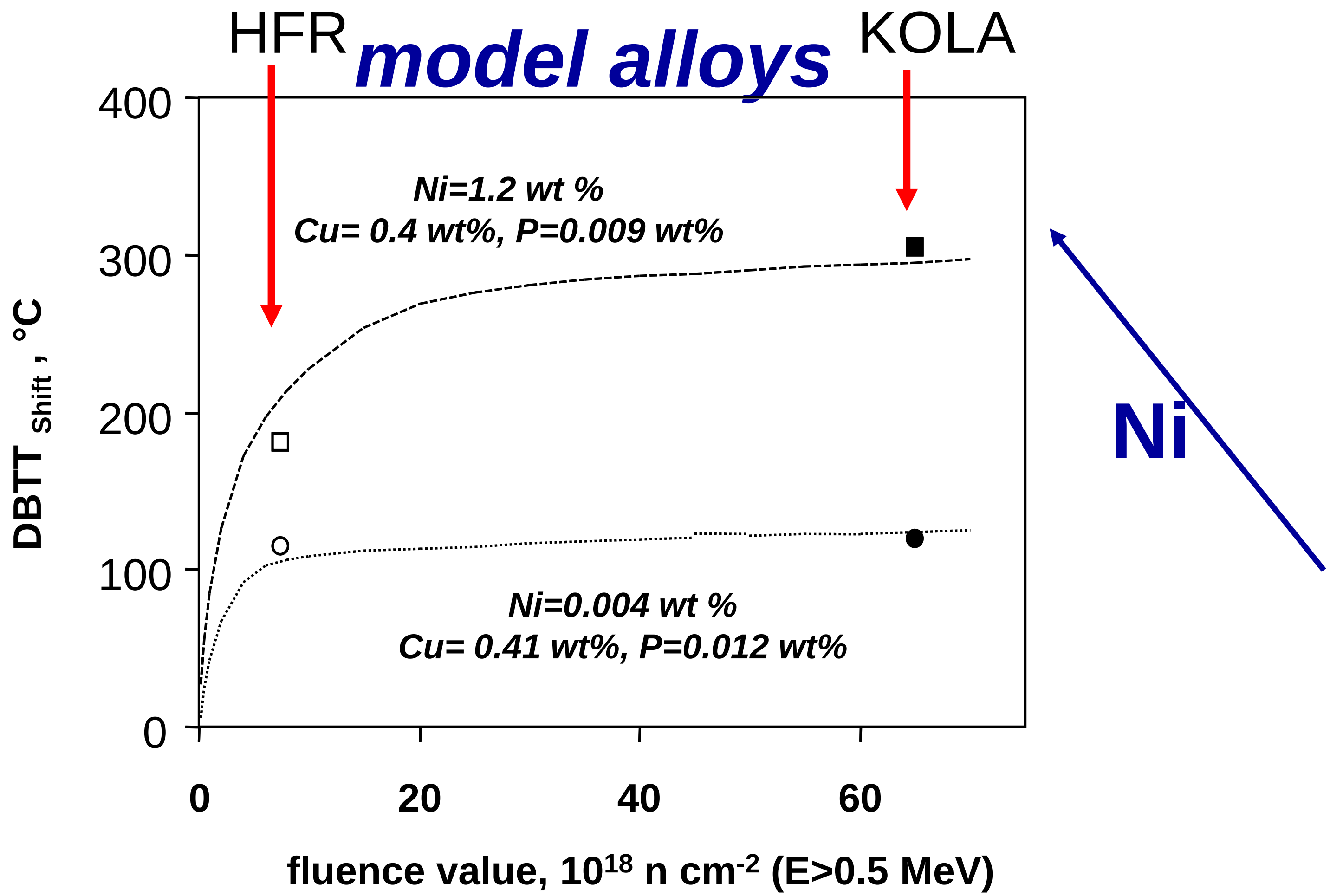
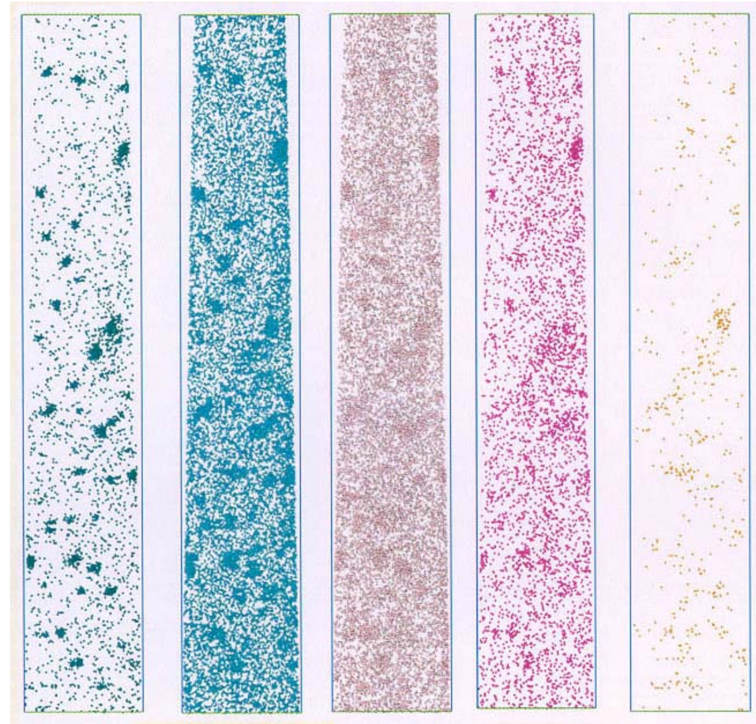
Extended analysis of VVER-1000 surveillance data, *Kryukov, Debarberis et al., International Journal of Pressure Vessels and Piping, Vol. 79, 2002*





Ni inclusion in semi-mechanistic analytical model for Radiation embrittlement of model alloys and combined effects with Cu and P
Debarberis, Kryukov, Gillemot, Valo, Nikolaev, Brumovsky, Acosta & Sevini, Specialist Meeting, Gus, Russia, May 2004

Nickel inclusion



$$DBTT_{shift} = a \cdot \Phi^{0.5} + b \cdot \left[1 - e^{-\Phi/\Phi_{sat}}\right] + c \cdot \left[0.5 + 0.5 \tanh\left(\frac{\Phi - \Phi_{start}}{d}\right)\right]$$

b = b_1*Cu ***c = c_1*P***

f(Ni) (→ a, b)

Role of nickel in a semi-mechanistic analytical model for radiation embrittlement of model alloys
Journal of Nuclear Materials, Volume 336, Issues 2-3, February 2005, Pages 210-216
Debarberis, Acosta, Sevini, Kryukov, Gillemot, Valo, Nikolaev, Brumovsky

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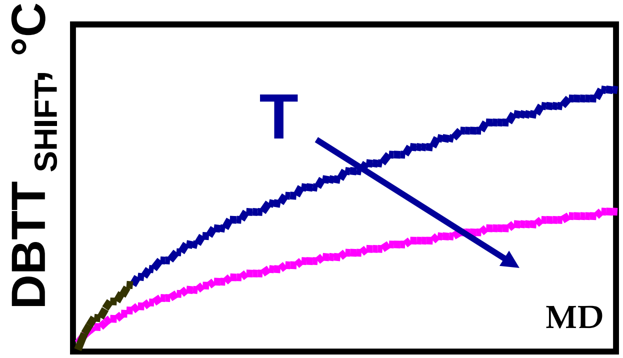
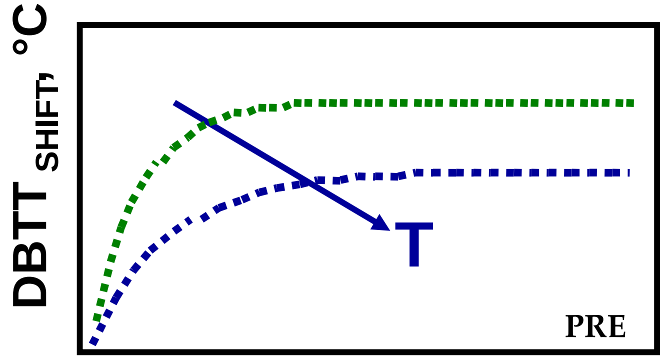
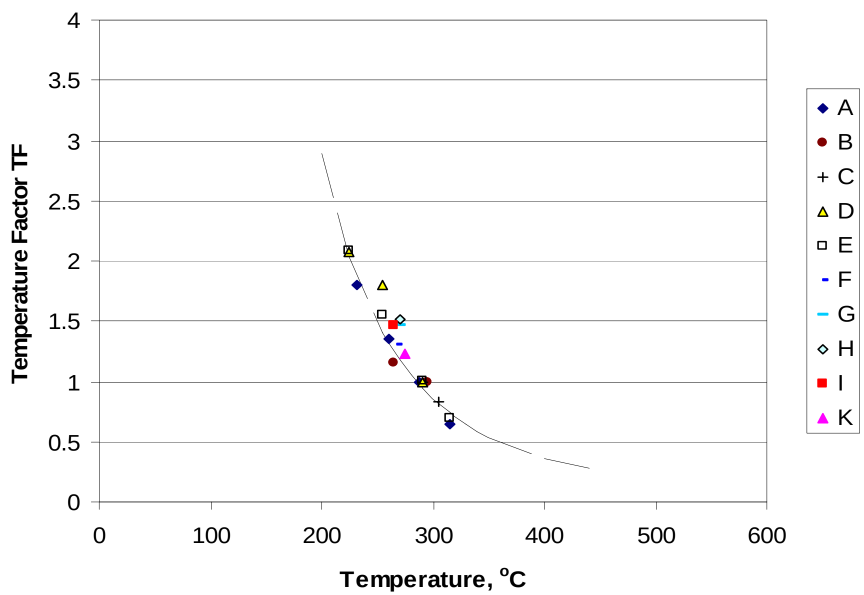
Temperature effect







➔Lower density of small precipitates – less effective for damage (recovery properties)

$$DBTT_{shift}(\mathrm{T}) = DBTT_{shift} \cdot \left[\frac{F}{e^{\left(-\frac{E}{k\mathrm{T}}\right)}} \right]$$

$$TF = \left[\frac{F}{e^{\left(-\frac{E}{k\mathrm{T}}\right)}} \right]$$

Effect of irradiation temperature in PWR RPV materials and its inclusion in semi-mechanistic model Debarberis, Acosta, Zeman, Sevini, Ballesteros, Kryukov, Gillemot, Brumovsky
Scripta Materialia, Volume 53, Issue 6, September 2005, Pages 769-773

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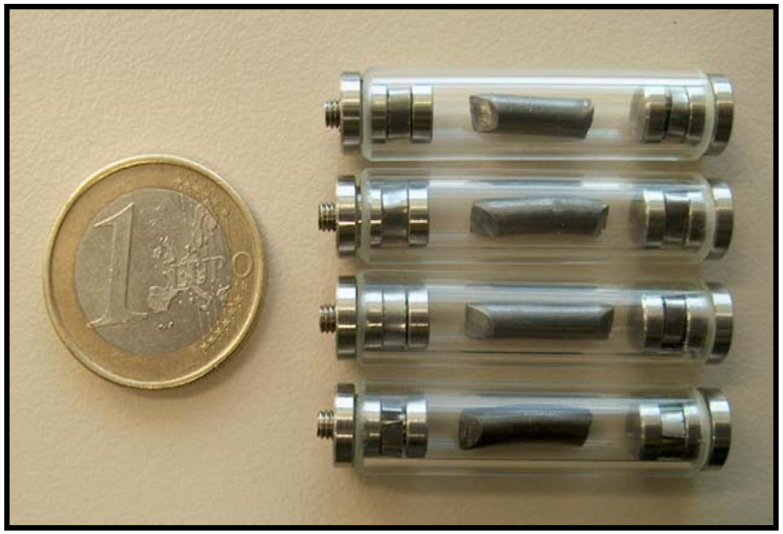
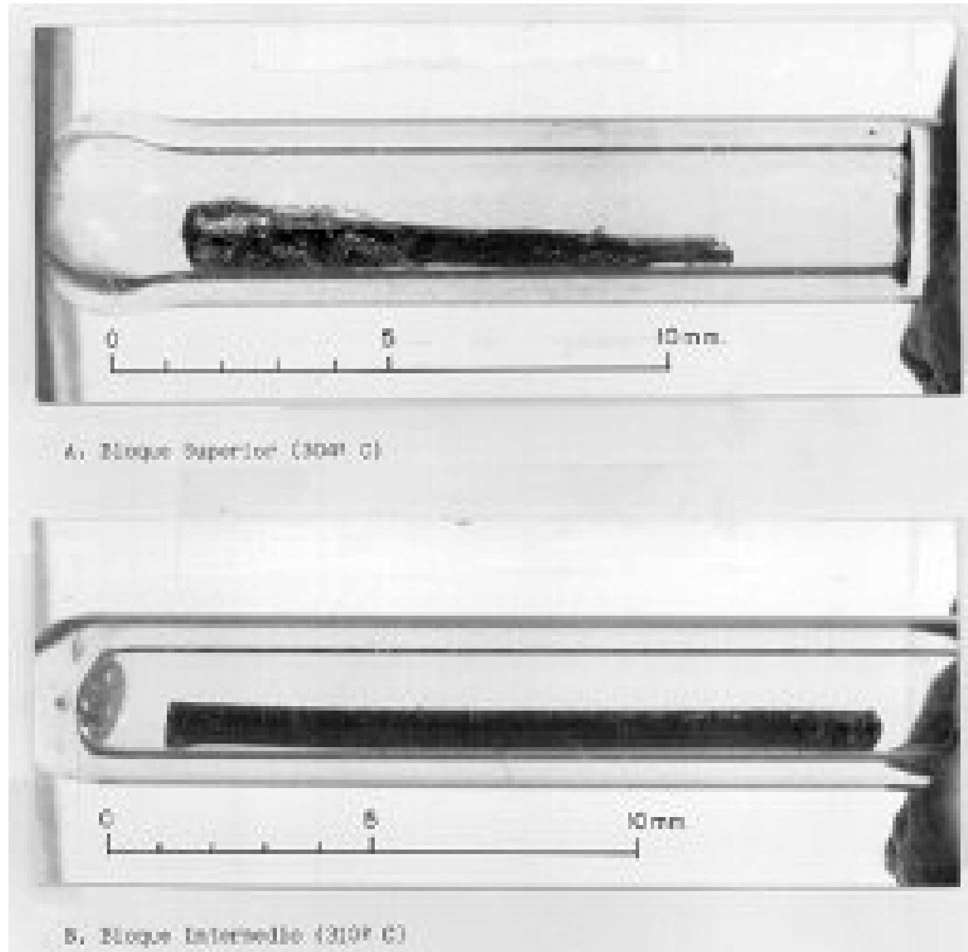
Irradiation Temperature monitoring

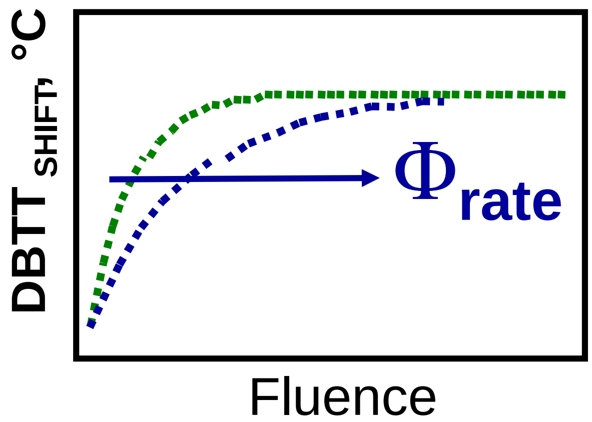




melting alloys

Fluence rate effect

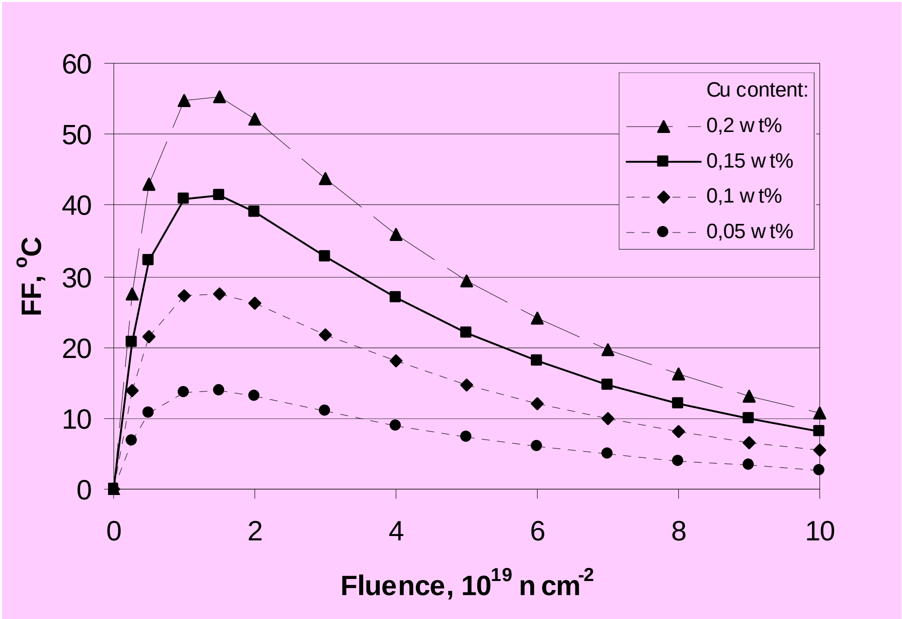
Diffusion & *precipitation* are time dependent ⇒ less time to complete the processes



$$DBTT_{shift}^{LF} = DBTT_{shift}^{HF} + FF$$

When $\Phi_{start}^{LF} \approx \Phi_{start}^{HF}$

$$FF = b_1 \cdot \mathrm{Cu} \cdot \left[e^{-\Phi/\Phi_{sat}^{HF}} - e^{-\Phi/\Phi_{sat}^{LF}} \right]$$



Fluence rate effect semi-mechanistic modelling on WWER-type RPV welds

Journal of Nuclear Materials, Volume 350, Issue 1, March 2006, Pages89-95

Debarberis, Acosta, Sevini, Chernovaeva, Kryukov

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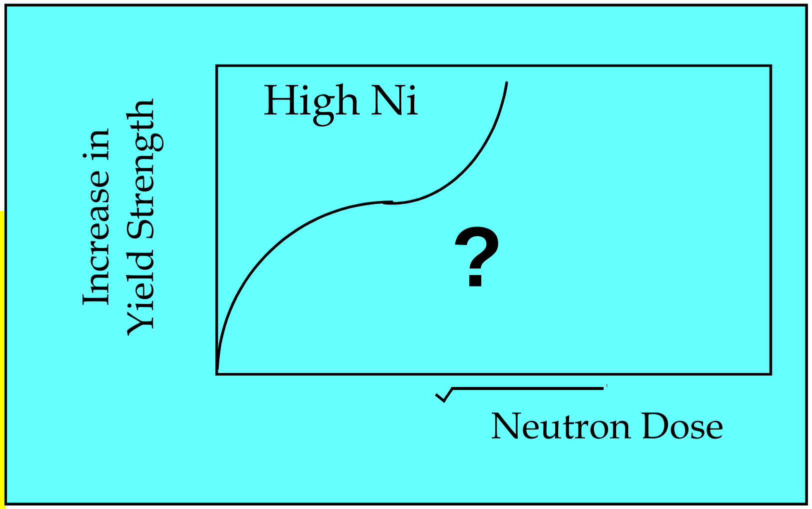
FOLLOW-UP

- **Refinements/verifications**
  - Temperature effect - Different proportion contributions to DBTTshift
  - Fluence rate - Mn effect

- **Elements influence**
  - High Cu & and High P
  - Verify Cr, Si….

- **Data on realistic materials**
  - Recent available results
  - Realistic welds
  - Model steels (Ni-Mn-Si-Cr)

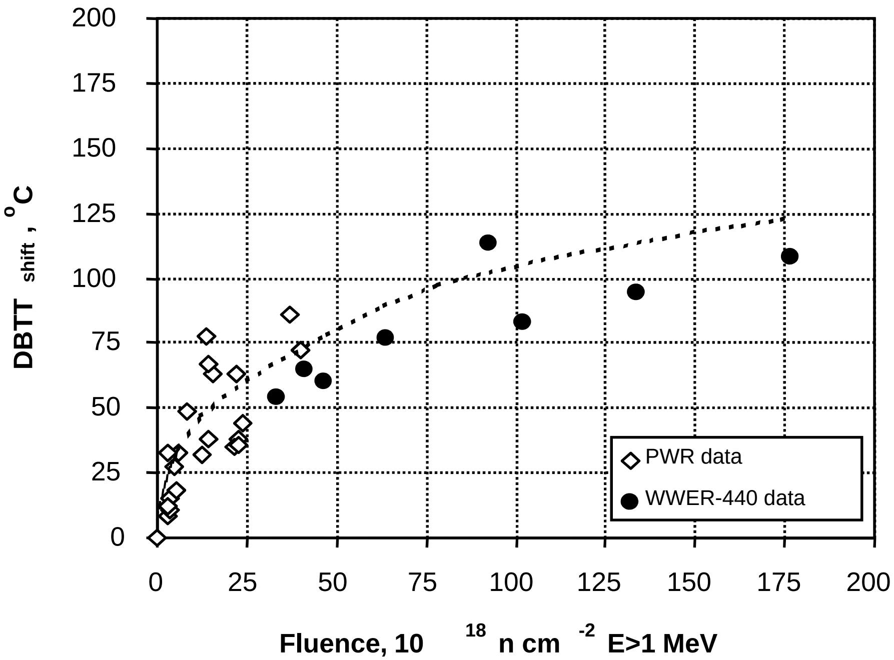
Surveillance data
- Re-evaluation, etc.
- Mechanistic interpretation

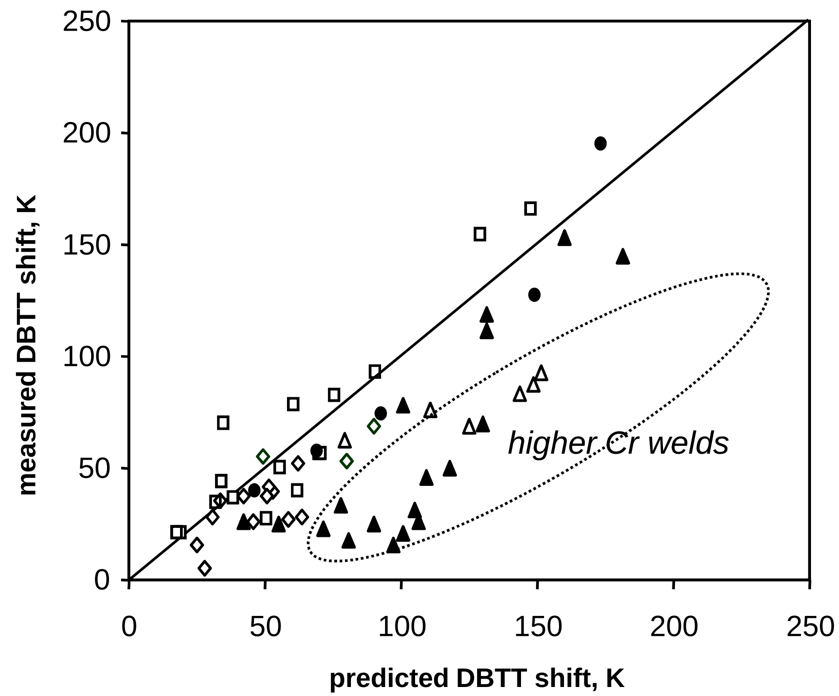


Apply the semi-mechanistic model to **New Gen.** materials!

- Higher doses, SS (SFT), Swelling-Voids,
- Gas, Irradiation creep, etc.?

Analysis of WWER-440 and PWR RPV welds surveillance data to compare irradiation damage evolution, L. Debarberis et al., Journal of Nuclear Materials, Volume 350, 2006





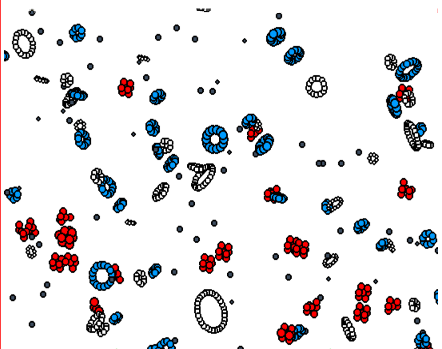
Evidence for Chromium stabilisation of irradiation damage in RPV weld metals
L. Debarberis, H. Hein, in press, International Journal of Pressure vessel and Piping, 2006

PERFECT *Radiation Damage of Materials*

Multi-scale Mechanical Modelling

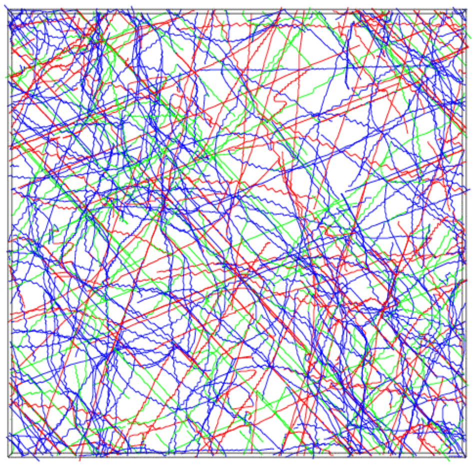
Physics modeling

Irrad. microstructure



10 nm

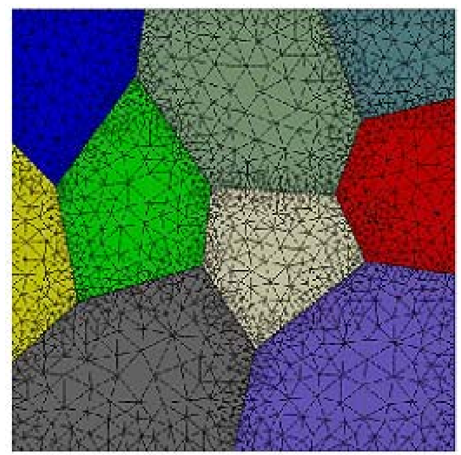
Mesoscopic scale: DD



5 µm

- Disloc. interaction
- plastic flow
- grain boundary ?

Crystalline aggregate

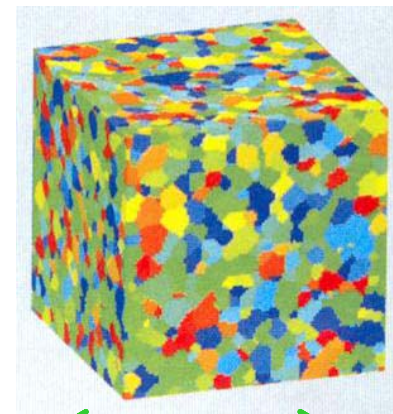


100 µm

- Complex loading
- rotation-equilibrium
- grain boundary ?

Mechanics Modeling

RVE mechanics



Homogenization micro-meso

Homogenization micro-macro

Homogenization

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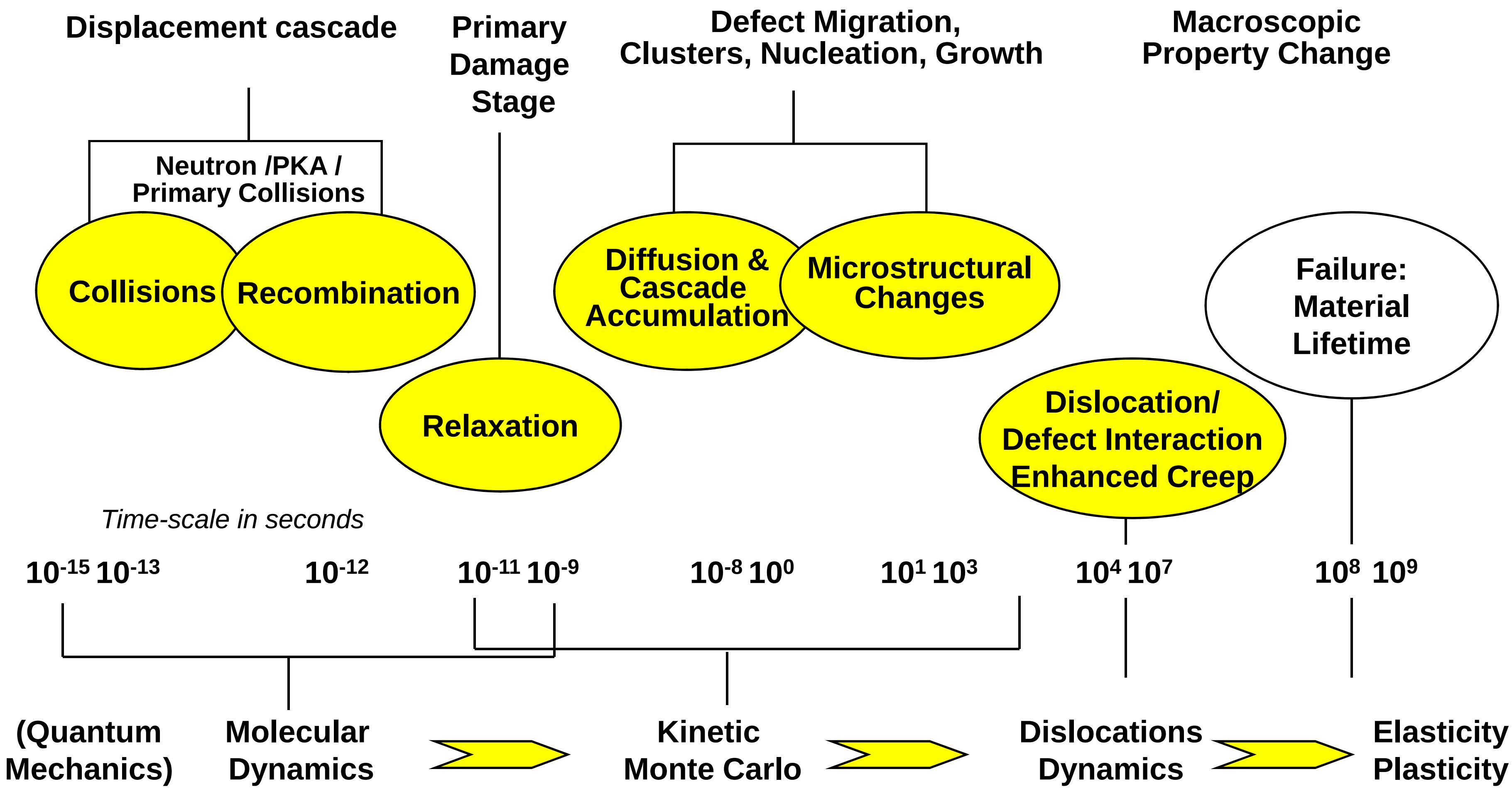
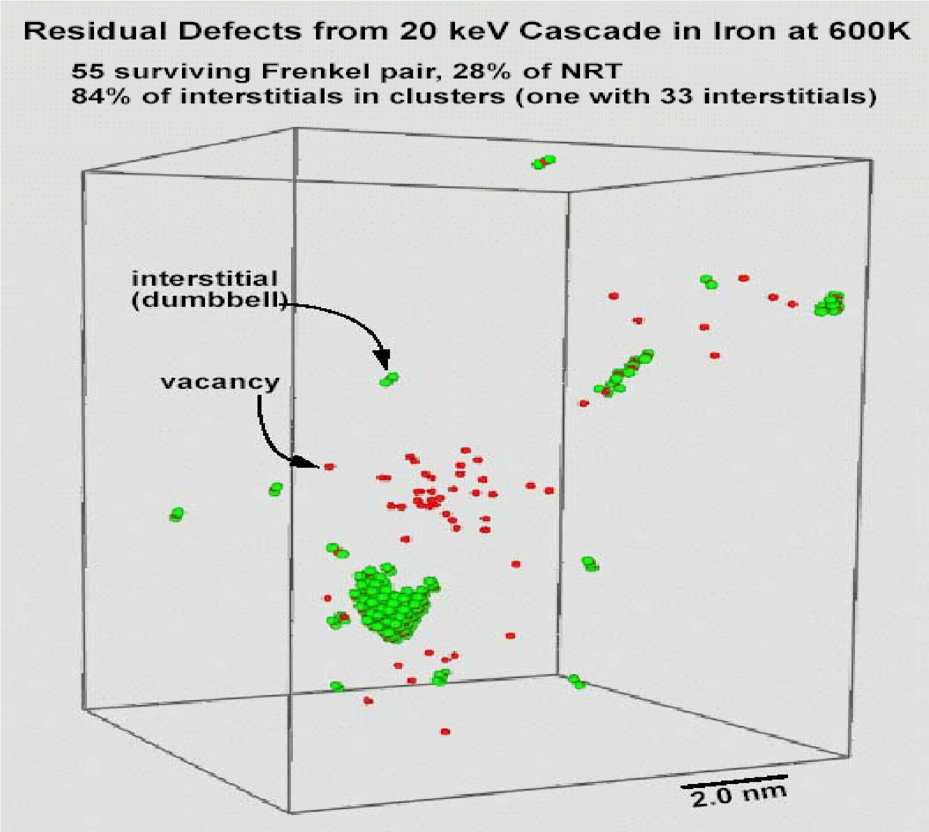
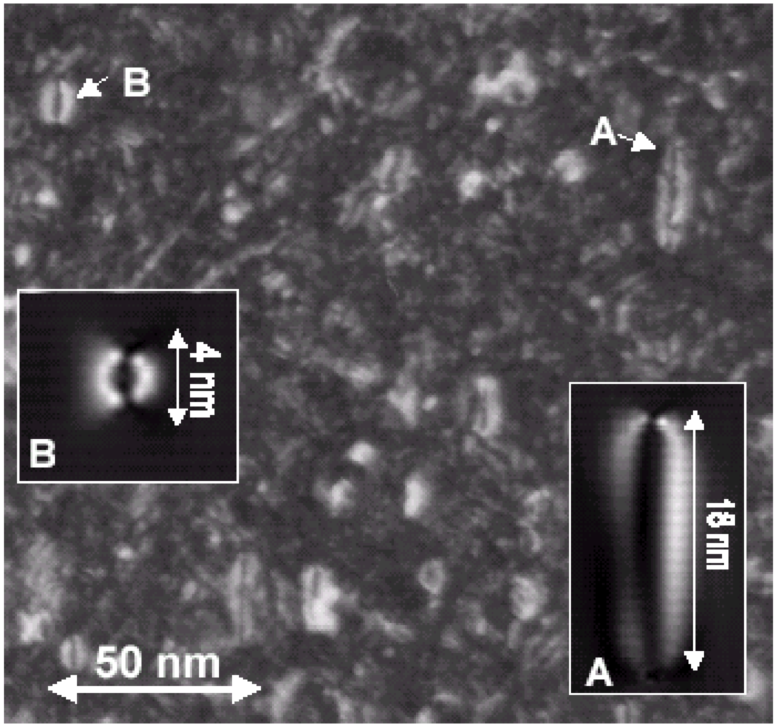
Radiation Damage of Materials: Multi-scale (space-time)



Theories & models





Manuel Perlado, University of Madrid

CONCLUSIONS

- EC-JRC-IE
- AGEING NPPs in the EU
- RPV Embrittlement
- MATERIAL ISSUES
- Modeling / Assessment
- Surveillance of RPV
- Towards GEN IV
- CONCLUSIONS

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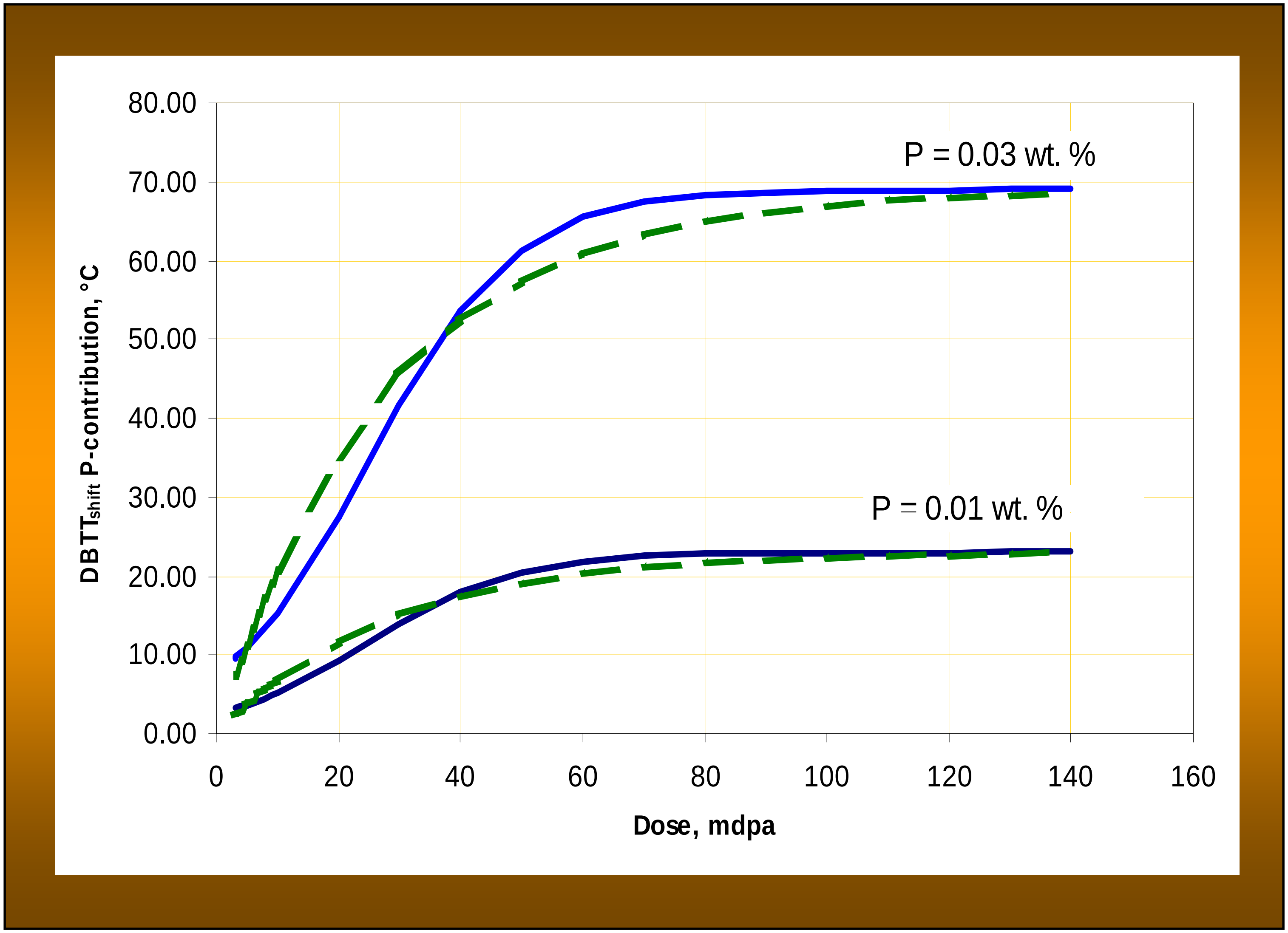
RESERVES

Segregation term saturation



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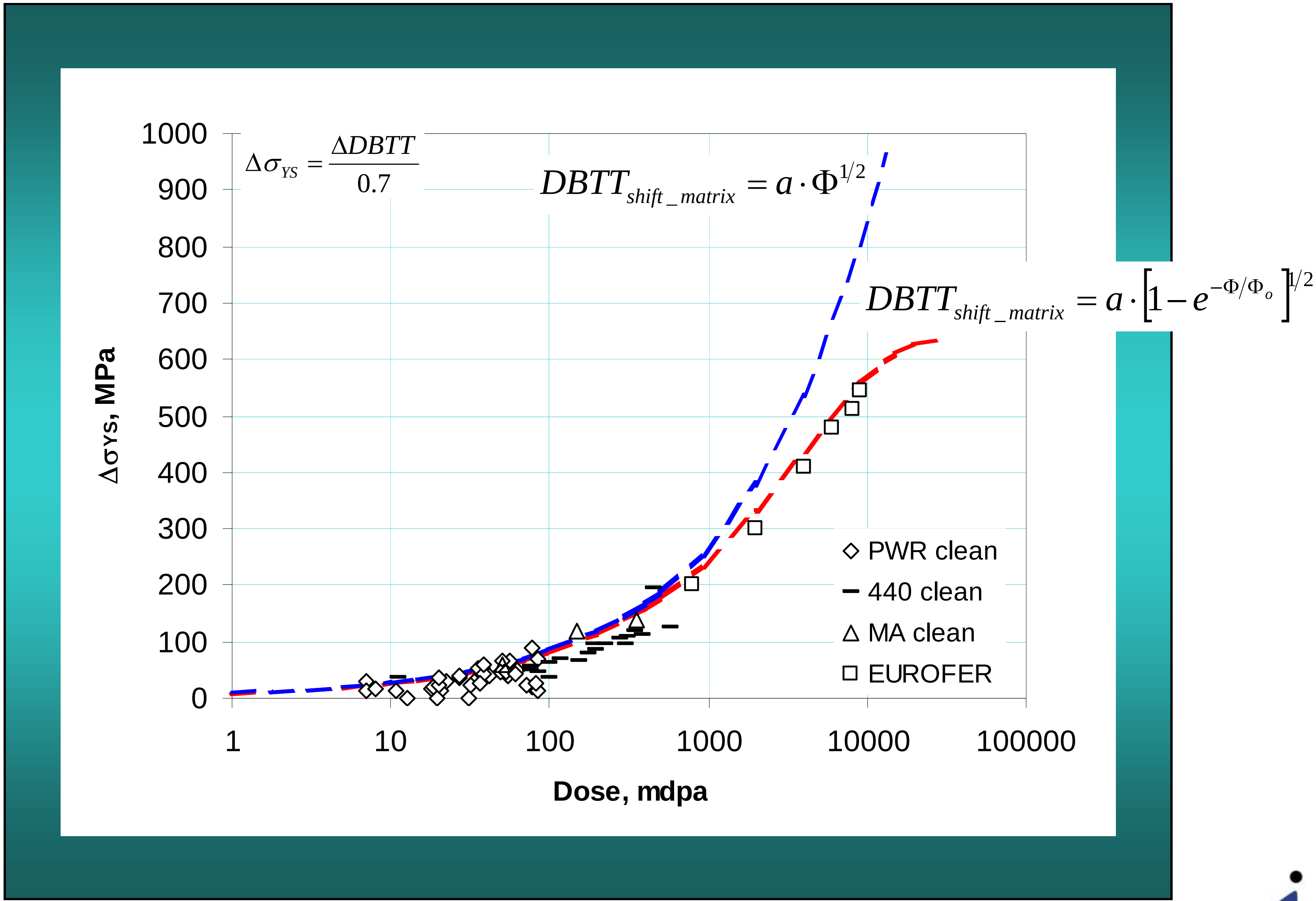
At high irradiation doses…

Matrix damage shouldn't increase till infinite ⇒ saturation of the damage



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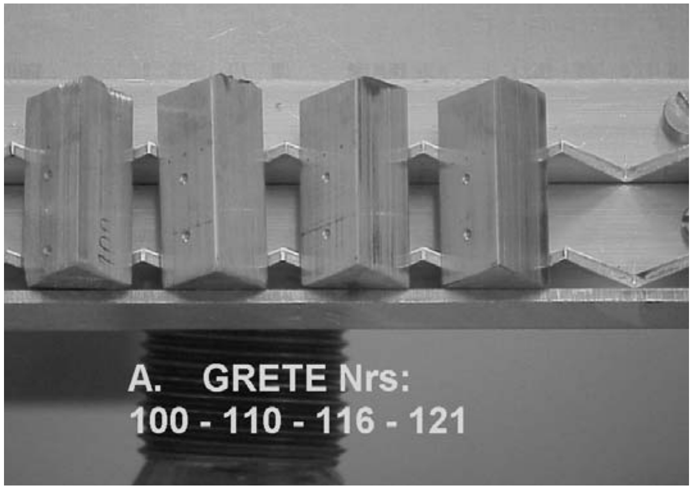
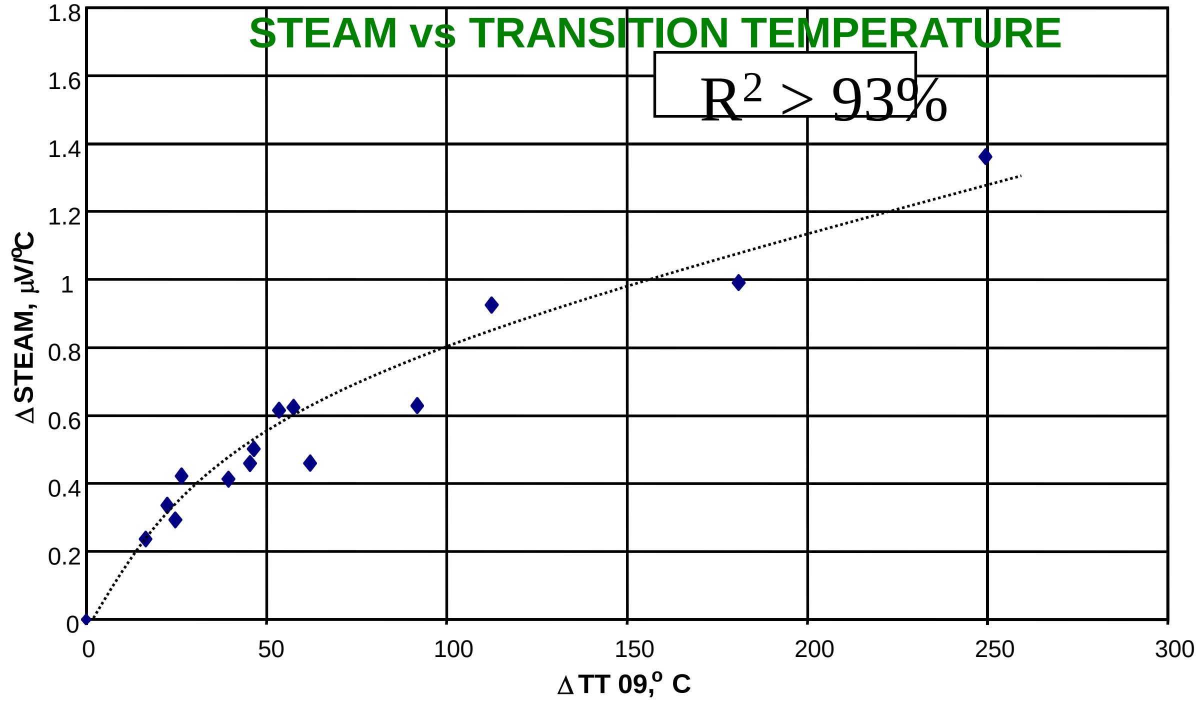
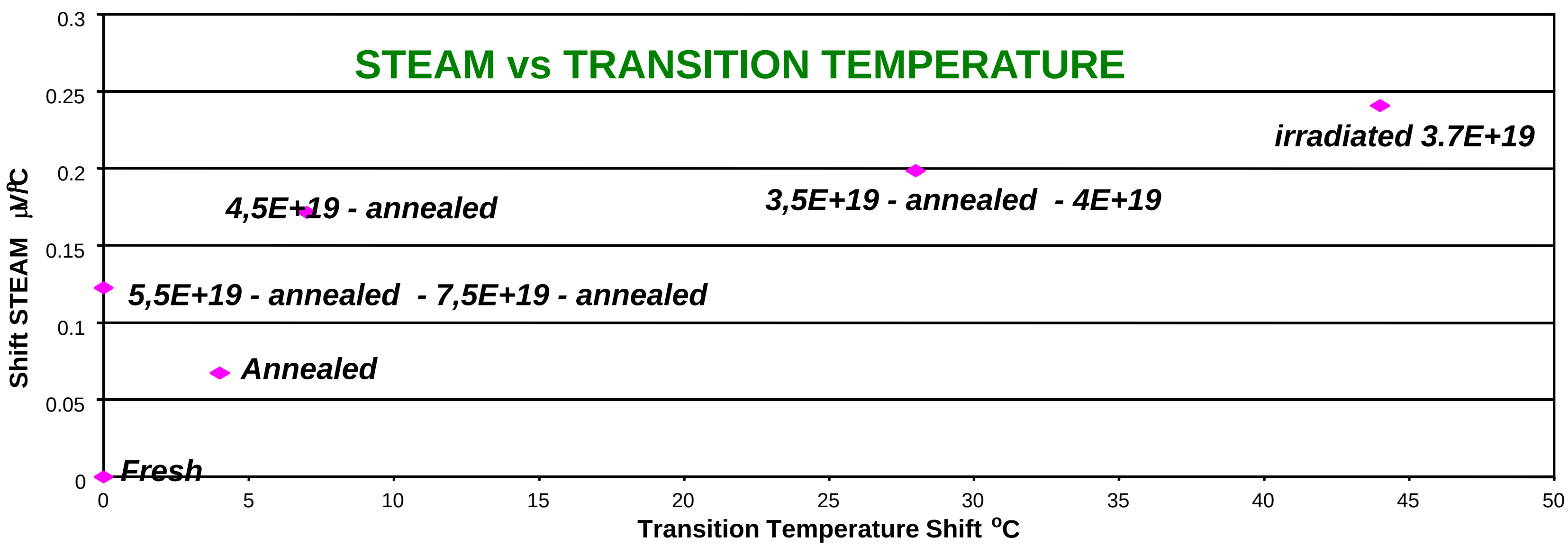




GRETE



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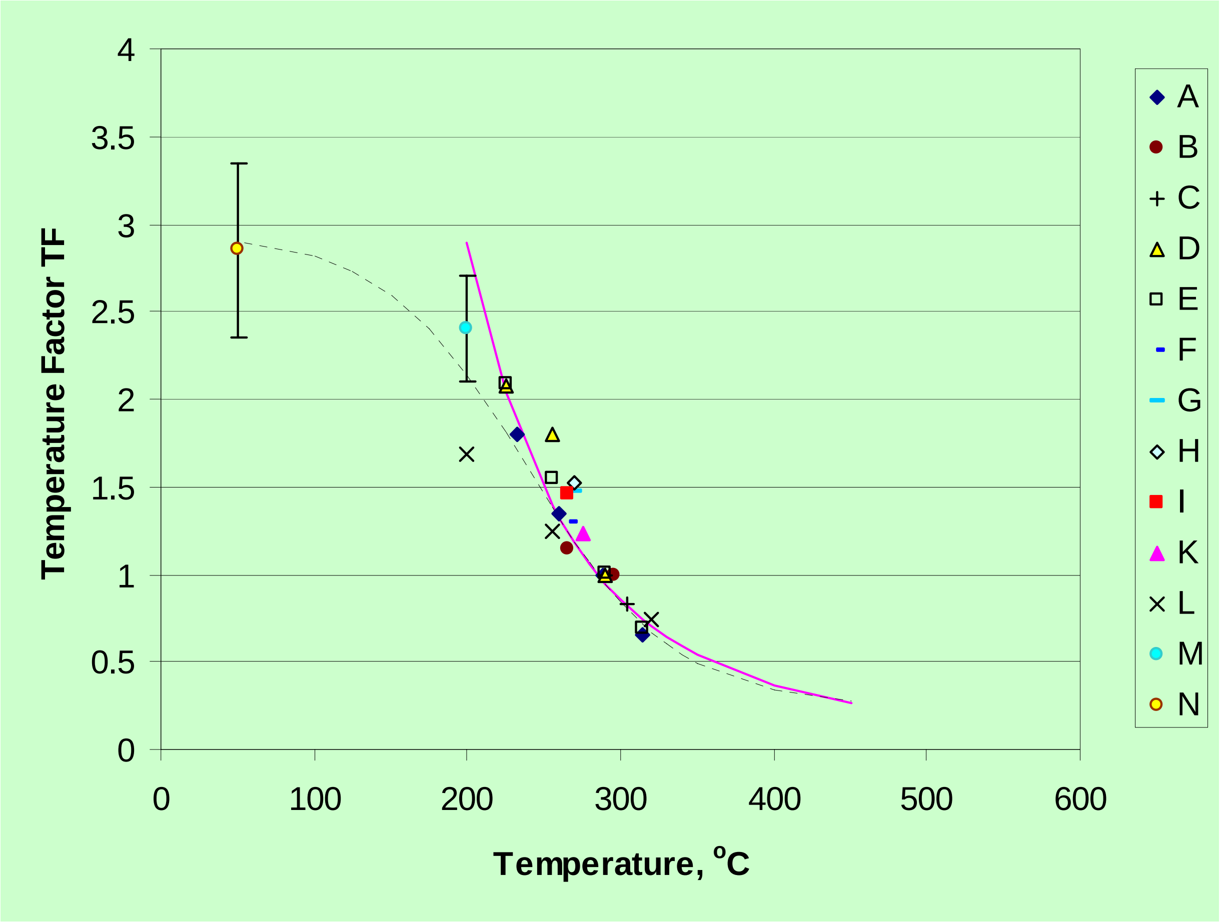
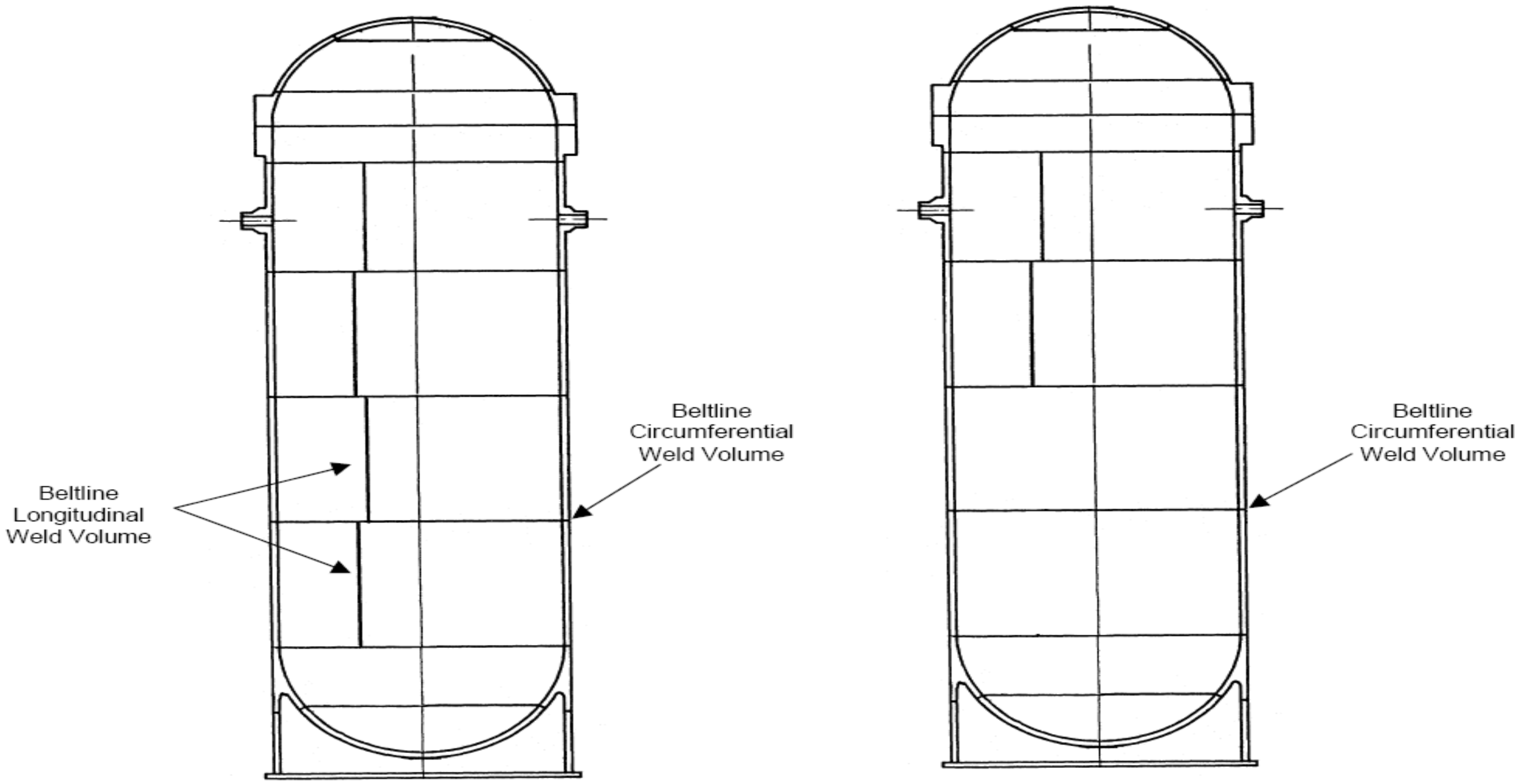
And at low temperatures?

A “**s-type**” function for TF is required to fit the data

$$TF(T) = 2.85 \cdot \left[1 + \tanh\left(\frac{T - 240}{90}\right)\right]$$



Fabrication configuration of BWR beltline shells



(a) Rolled and Welded Beltline Shell

(b) Welded – Ring – Forging Beltline Shell