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Flux Effects and the Prediction of Embrittlement at High Fluence

IAEA Regional Workshop on Structure, Systems and Components Integrity

Centro de Desenvolvimento da Tecnologia Nuclear (CDTN)
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Historical Perspective on Radiation Effects

- Some radiation effects were observed in minerals in the 19th century, but their origin was not understood
- E. P. Wigner, 1946, Journal of Applied Physics 17

  "The matter has great scientific interest because pile irradiation should permit the artificial formation of displacements in definite numbers and a study of the effect of these on thermal and electrical conductivity, tensile strength, ductility, etc. as demanded by the theory."
- The full scope of radiation effects in materials was only appreciated after high neutron flux fast spectrum reactors were operated in the 1950's and 1960's
- Targets of high power accelerators experience roughly the same levels of damage as the highest flux fission reactor cores and first walls of future fusion reactors

Origins of Radiation Effects in Materials

- **Displacement of atoms (nuclear stopping)**
  - **Dominant damage process for metals**
  - **Significant for ceramics, semiconductors**
  - **Can be significant for polymers (usually neglected)**
  - **Dose unit--displacement per atom, *dpa***
  - **One dpa is the dose at which on average every atom in the material has been energetically displaced once**
    - **But, does dpa tell the story of damage?**

- **Ionization and excitation (electronic stopping)**
  - **Generally can be neglected for metals**
  - **Important for polymers, ceramics, semiconductors**
  - **Dose unit--Gray, *Gy*, the dose for absorption of 1 J/Kg**

Time and Energy Scales for Radiation Effects by Displacement Damage

Time	Energy
Cascade Creation **10^{-13} s**	**Neutron or Proton** **10^{5} - 10^{9} eV**
Unstable Matrix **10^{-11} s**	**Primary Knock-on Atom** **10^{4} - 10^{5} eV**
Interstitial Diffusion **10^{-6} s**	**Displaced Secondary** **10^{2} - 10^{3} eV**
Vacancy Diffusion **10^{0} s**	**Unstable Matrix** **10^{0} eV**
Microstructural Evolution **10^{6} s**	**Thermal Diffusion** **kT**

Hierarchy of Reactions Leading to Property Changes in Metallic Alloys

Displacement of Atoms

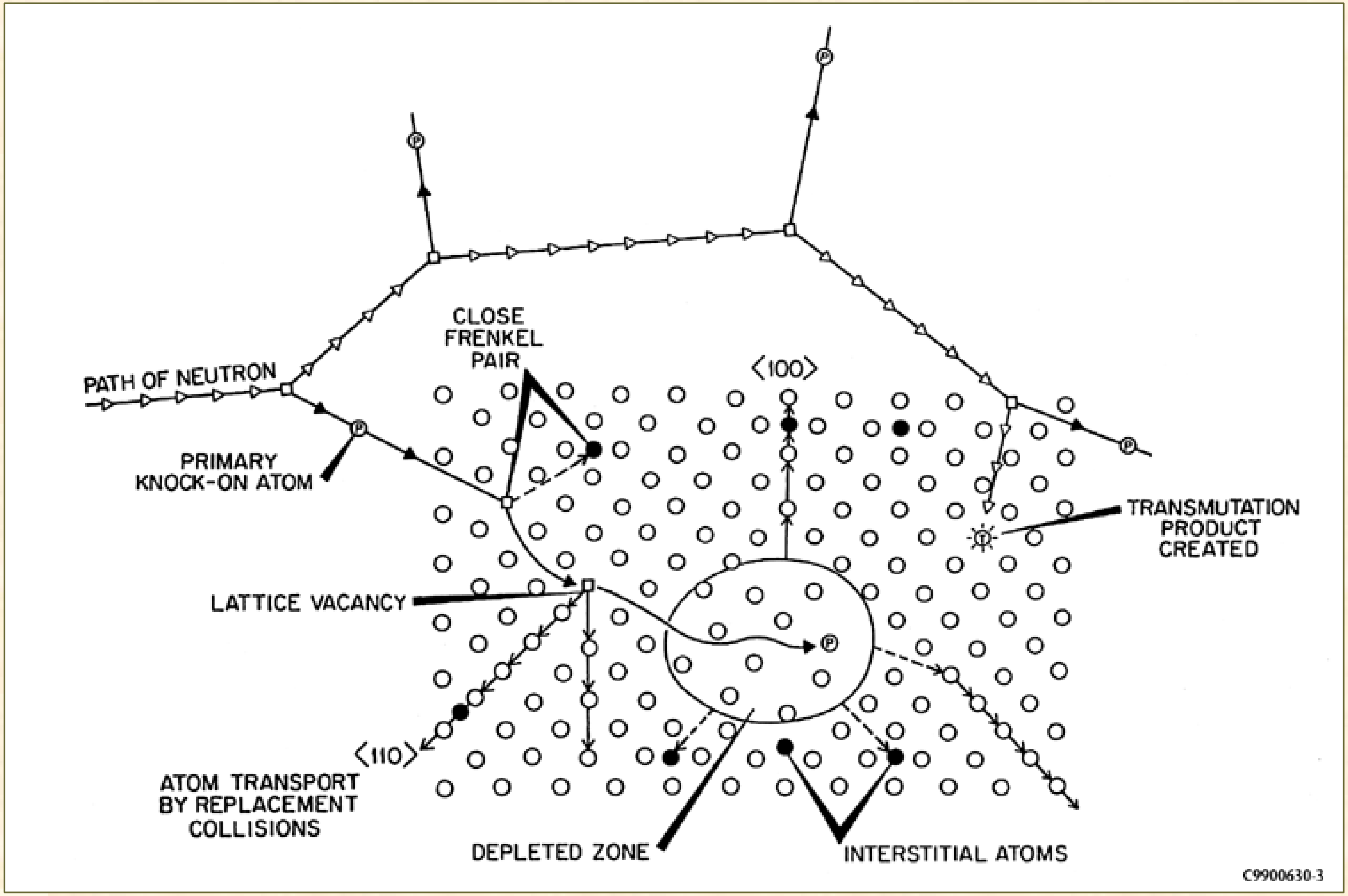
Diffusion and Aggregation of Defects

Evolution of Microstructure

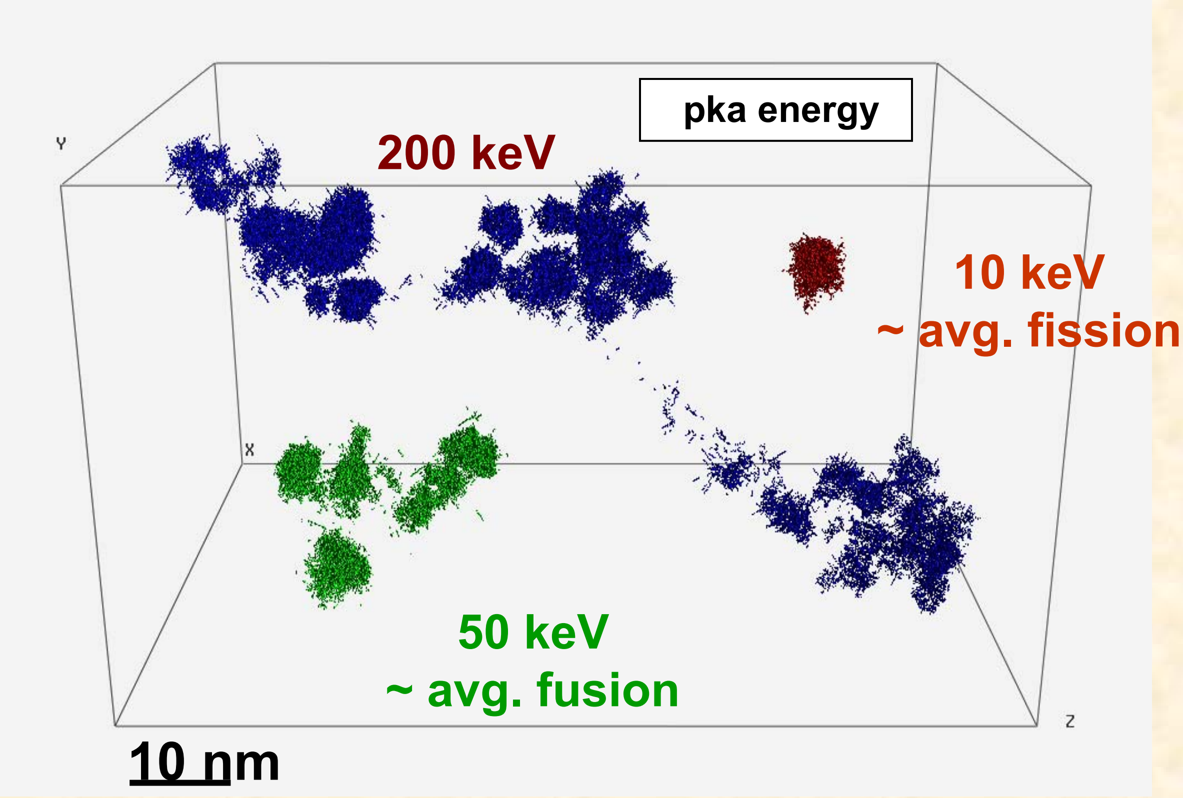
Embrittlement, Swelling, Irradiation Creep

Only embrittlement is significant for LWR RPVs

Energetic Neutrons Create Damage In The Steel By Displacing Atoms Which Result In Various Defects In Microstructure



Displacement Damage Occurs in Cascades



- **Particle (e.g., beam proton or spallation neutron) transfers its energy to the primary knock-on atom (pka)**
- **High energy particles, e.g., GeV protons or fusion neutrons may produce atomic recoils at much higher energies than fission neutrons**
- **Large-scale atomic simulations demonstrate that subcascade formation leads to similar defect production**

Molecular Dynamics Simulations of peak damage state in iron cascades at 100 K
R. E. Stoller, ORNL

Neutron Irradiation Of RPV Steels Results In Creation Of Ultrafine (Nanometer) Microstructural Features

- **The Nature and Significance of These Features to RPV embrittlement are a Function of**
  - **Neutron flux, fluence, and energy spectrum**
  - **Irradiation temperature**
  - **Chemical composition of steel**
  - **Microstructure of steel**

- **Energetic Neutrons Create Damage in the Steel by Displacing Atoms That Result in Displacement Cascades Which Produce Large Numbers of Vacancies and Interstitials**
  - **Inside surface of RPV exposed to 10^{10} to 10^{11} n/cm^2/s**
  - **At RPV temperatures, residual vacancies and interstitials diffuse relatively long distances**
  - **Mobility of small interstitial clusters and dissolution of vacancy clusters by vacancy emission tend to heal crystal lattice, but small percentage of defects may survive**

Neutron Irradiation of RPV Steels Results In Creation Of Ultrafine (Nanometer) Microstructural Features (Cont'd)

- **Substantial Increase in Number Density of Vacancies Allows for Rapid Migration of Solutes Like Copper and Phosphorus by Vacancy-Solute Exchange Process to Result in Formation Of, for Example, Copper-rich Precipitates (CRP)**
  - **Diffuse atmospheres form during early stages of irradiation**
  - **Atmospheres become enriched in solute and become clusters**
  - **Clusters develop into precipitates after long-term exposure**
  - **CRP also contain nickel, manganese, silicon, and sometimes phosphorus and other elements**

- **Defect Clusters and Defect Cluster-Solute Complexes Suspected As Primary Hardening Sources - These Unidentified Features Are generally designated As Matrix Defects, Both Stable (SMD) And Unstable (UMD)**

Neutron Irradiation Of RPV Steels Results In Creation Of Ultrafine (Nanometer) Microstructural Features (Cont'd)

- **Other Radiation-Enhanced Phases Include Phosphorus-Rich Precipitates, Manganese-Nickel-Rich Precipitates, Phosphides, Nitrides, and Carbonitrides**

- **In High-Copper Steels (>0.1 wt %), The Copper-Rich Precipitates Are the Primary Embrittling Feature - CRPs Have Been Clearly Identified but Most of the Matrix Defects Have Not**

Radiation-Induced Embrittlement In RPV Steels Is Primarily Due To Yield Stress Increases Caused By Ultrafine Microstructural Features

- Yield Stress Controlled by Generation and Motion of Dislocations
  - Motion of dislocations by dislocation slip causes plastic strain, interruption of crystal structure impedes dislocation motion
  - Solutes, clusters, or precipitate particles act as effective obstacles and require increased stress to move dislocations through or around the obstacles
  - Increasing numbers of obstacles require increasing stress for yielding, also manifested by material hardening

- As Radiation Exposure Increases, Number of Ultrafine Scale Obstacles Increases and Higher Stresses Are Required for Dislocation Motion and Yield Strength Increases.

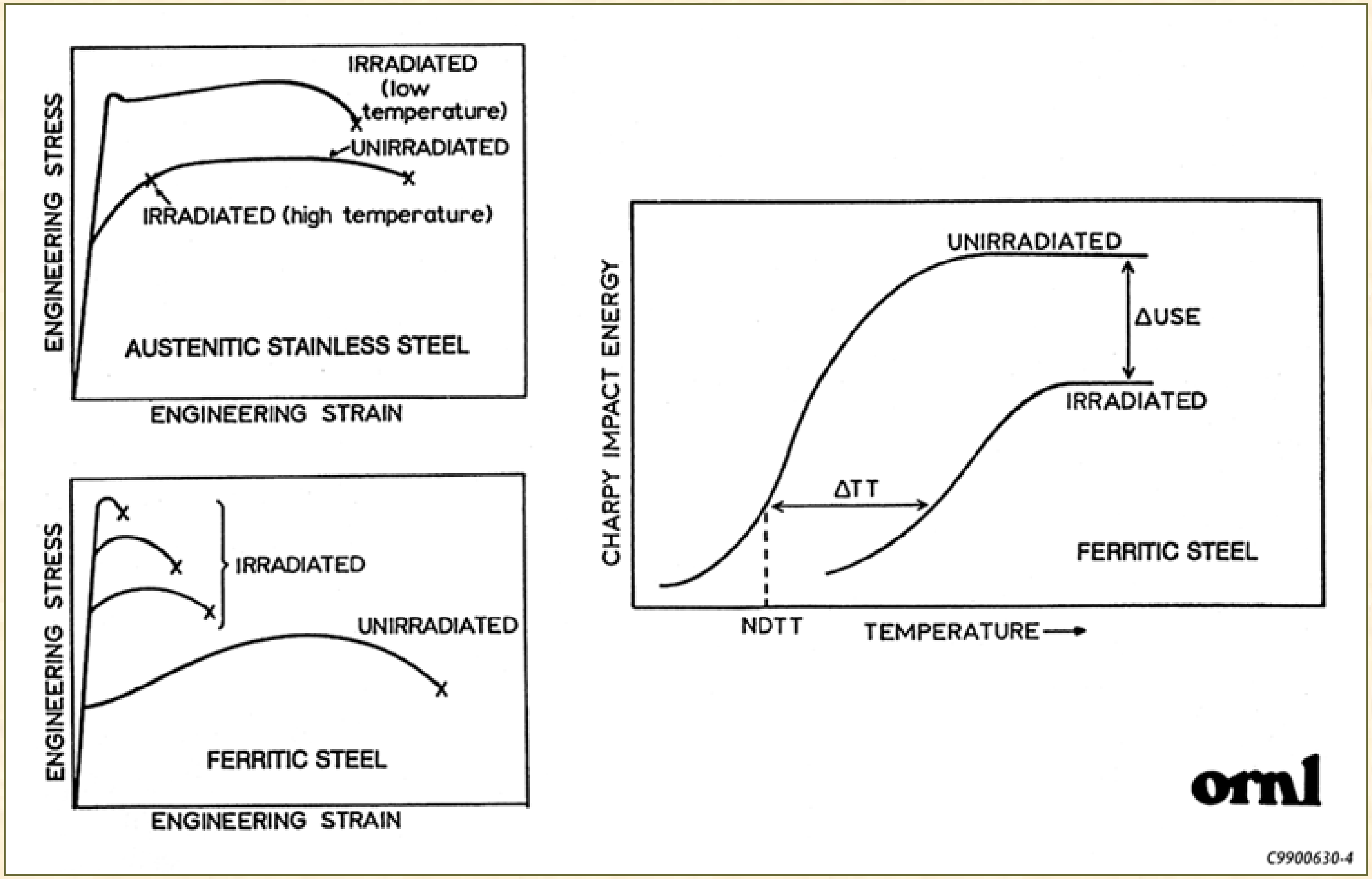
Radiation-Induced Embrittlement In RPV Steels Is Primarily Due To Yield Stress Increases Caused By Ultrafine Microstructural Features (Cont’d)

- Yield Strength Increases Result in Higher Temperatures Required to Keep Yield Strength Below Cleavage Fracture Strength, Especially Near Tip of Sharp Flaw Where Large Stress and Strain Concentrations Exist

- Thus, the Brittle-To-Ductile Fracture Transition Temperature Range Is Increased - the Temperature Increase Is a Measure of Embrittlement Due to So-called Radiation Hardening

- Non-hardening Embrittlement Can Also Be Caused by Radiation-Induced Solute Segregation Such As Phosphorus Segregation at Grain boundaries

Neutron Irradiation Of Steels Increases Strength, Decreases Ductility and Toughness - Ferritic Steels More Susceptible Than Austenitic Stainless Steels



Molecular Dynamics Displacement Cascade Simulations Provide Information On The Effect of Neutron Energy Spectrum And Insight Into Primary Defect Formation

- **Total Point Defect Survival, i.e. As a Fraction of the Standard NRT Displacement Model, Radiation Damage Source Term**

- **Fraction of Point Defects Contained in In-Cascade Clusters and Cluster Size Distribution, Has a Strong Impact on Nucleation of Extended Defects**

- **Relative Fraction of Vacancy and Interstitial Clusters**

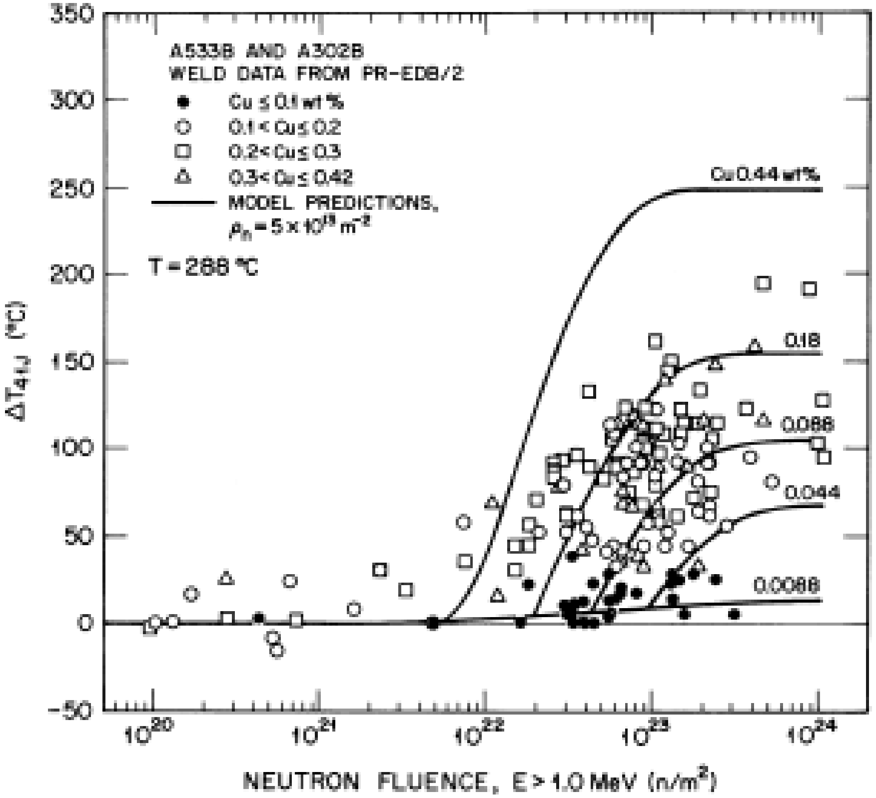
- **Stability and Mobility of Point Defect Clusters Influence Microstructural Evolution**

MD Results Feed Directly Into Kinetic Embrittlement Models

A Kinetic Embrittlement Model is Under Continuing Development to Investigate Behavior of Copper-Rich Precipitates (CRP) and Point Defect Clusters (PDC) Under LWR Operating Conditions

- Model Using Kinetic Rate Theory Developed Previously to Describe Evolution Of Point Defects and point defects clusters (PDCs) (Stoller in ASTM STP 1175)
- Interstitial Cluster Formation Can Occur in the Model by Essentially Classical Nucleation (Random Collisions Between Single Interstititials) or Directly in Displacement Cascade. Vacancy Clusters Form Only Due to Cascade Collapse
- Results of Molecular Dynamics Simulation Studies Were Used to Provide Guidance for In-Cascade Clustering Fractions and Defect Survival Fractions
- Matrix Hardening Computed Based on Dispersed-Barrier Model for PDCs And Russel-Brown Model for CRPs

Preliminary Kinetic Embrittlement Model Evolves from Ab Initio Modeling and Provides Reasonable Comparisons with Experimental Results for Cu-Containing Steels



- with original baseline model and parameters, obtain reasonably good agreement with surveillance data from PR-EDB, e.g. copper and fluence dependence
  - considerable data scatter, but mean behavior, e.g. copper dependence of data is similar to data
  - copper dependence stronger in model since all copper is available for precipitation
- rather abrupt transition due to simple copper precipitate model, i.e. no nucleation component

Three Basic Micro Mechanisms of Radiation Embrittlement Have Been Identified and Agreed on World-Wide to Control RPV Embrittlement in Western RPV Steels at Irradiation Temperatures > 150°C

- The formation of matrix damage (i.e., defect clusters and dislocation loops). It is well established that in low copper steels the shift in impact toughness or yield strength properties depends on $\sqrt{\text{dose}}$.
- The irradiation-enhanced formation of copper-enriched clusters. It has been demonstrated that, in many low to medium Ni steels and alloys, the yield strength change due to copper precipitation rises to a plateau value that is then unchanged by subsequent irradiation.
- The irradiation induced/enhanced grain boundary segregation of embrittling elements such as P.

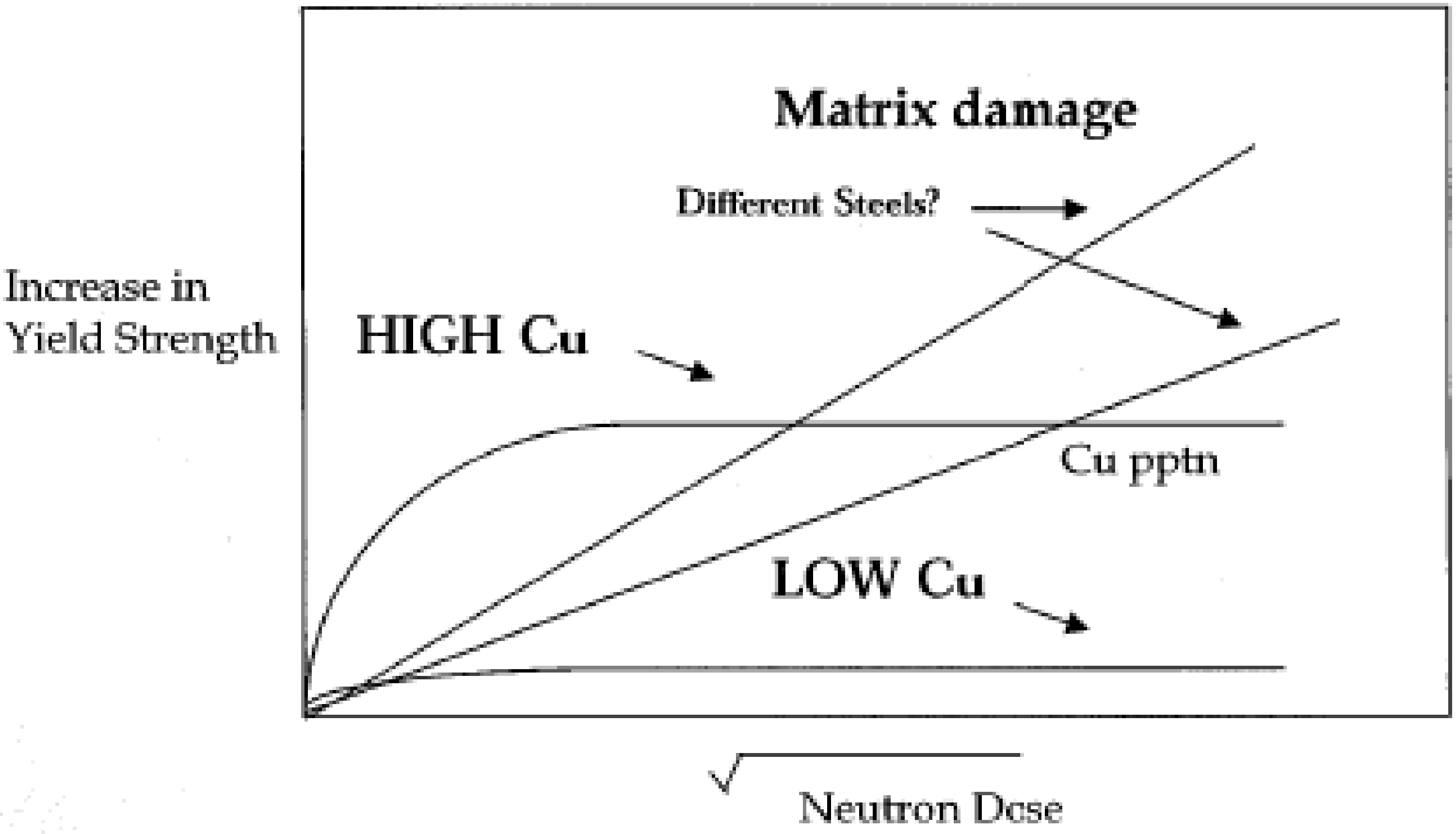
First two mechanisms contribute to embrittlement by hardening, while the third mechanism induces embrittlement without hardening. This third mechanism is not observed in all RPV steels under reactor operating conditions.

EPRI Sponsored a Workshop on Dose Rate Effects in 2004

- Agreed that there were three different material compositional classes for discussion:
  - Steels containing low levels of copper (in which hardening and embrittlement on irradiation will be will be dominated by the formation of matrix damage)
  - Steels containing significant amounts of copper irradiated to doses lower than that required to reach the plateau in copper related hardening.
  - Steels containing significant amounts of copper irradiated to doses above that at which the plateau in copper related hardening is reached.
- In all regimes, observed there was significant scatter associated with the experimental measurements of embrittlement (or hardening).
- Also expected uncertainties in measurements of dose, dose rate, etc. Statistical significance of apparent correlations require careful consideration.

Mechanistic Framework for Irradiation Embrittlement Considers Effects of Matrix Damage and Precipitation

Mechanism: Cluster Hardening



3-6

Steels containing low levels of copper (in which hardening and embrittlement on irradiation will be dominated by the formation of matrix damage)

- **Data from low-Cu C-Mn and MnMoNi steels support dose rate independence, provided that the:**
  - **Dose rate is below that for unstable matrix damage (UMD) formation.**
  - **Level of bulk Cu is less than 0.1 wt% [In certain circumstances the threshold Cu level may be higher (e.g., at lower irradiation temperatures) or if Cu is precipitqted out in second phases during fabrication].**
  - **Irradiation temperature is between 150 and 300°C.**

- **Dose rate dependence will be introduced once significant amounts of UMD forms. UMD is produced in high dose rate MTR irradiations. The threshold dose rate is approximately 10^{12} n/cm^2-s for E>1 MeV at 290°C.**

Steels containing low levels of copper (in which hardening and embrittlement on irradiation will be dominated by the formation of matrix damage)

- **It is becoming increasingly clear that high levels of both Ni and Mn can influence the response of low-Cu steels by producing clusters containing very little Cu.**

- **Practically, in typical MnMoNi or C-Mn steels containing low levels of Cu (and standard levels of Ni and Mn, there is no significant evidence to suggest that dose rate effects will occur at the rates in vessels or most surveillance specimens. Thus, dose rate corrections need not be made when using most surveillance data to predict vessel properties.**

- **However, a dependence on dose rate must be expected when comparing data from irradiation in MTRs or acceleerated in-core positions at dose rates above approximately 10^{12} n/cm^2-s (E>1 MeV) and at 290°C to data obtained at lower dose rates. This is because of the of formation of UMD at the higher dose rate. The UMD dose rate regime depends on the irradiation temperature.**

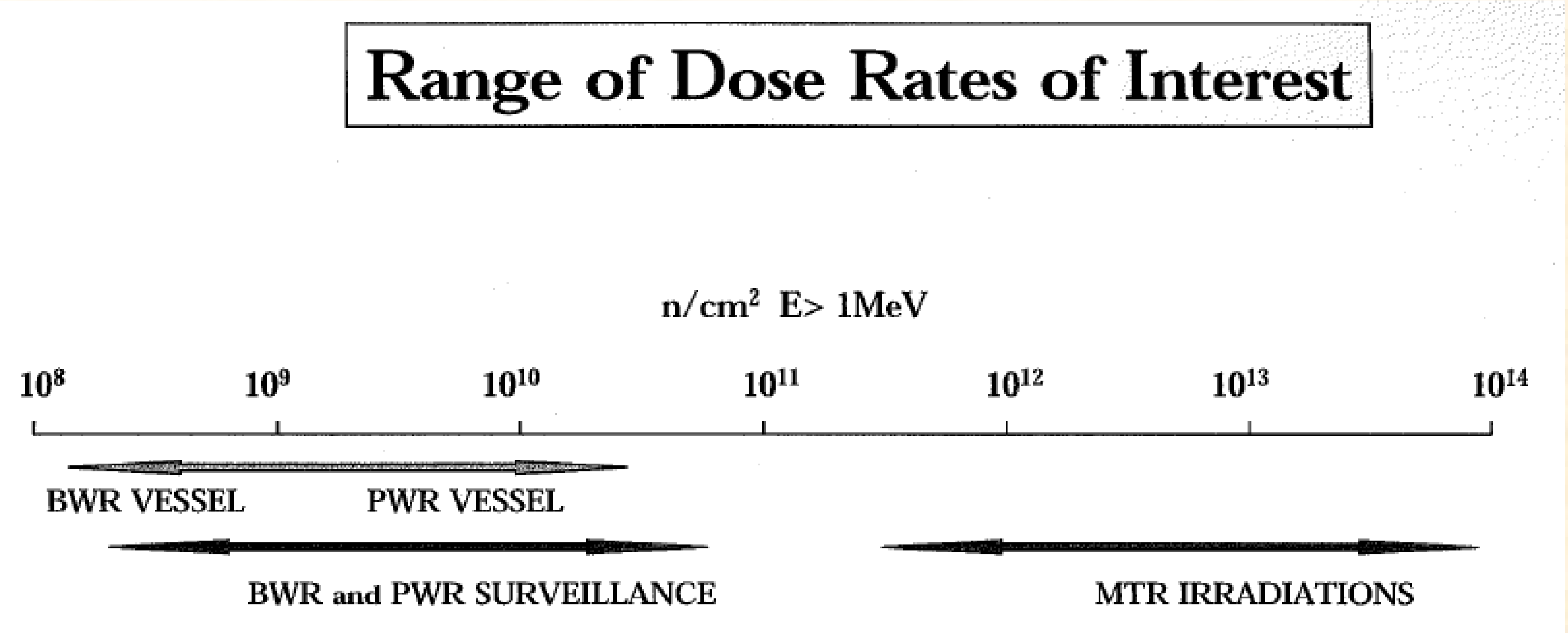
Steels containing significant amounts of copper irradiated to doses lower than that required to reach the plateau in copper related hardening.

- **There are at least two regions of dose rate dependence on the dose required to reach the plateau in copper-related hardening. One operates at high, and the other at low dose rates. The underlying mechanism is usually described in terms of the dependence on dose rate of the freely migrating vacancies. This is because Cu clustering occurs through interaction of vacancies with Cu.**

- **The role of freely migrating vacancies is to determine how rapidly (with either time or dose) the clustering process occurs.**

- **At very low dose rates, thermal vacancy concentrations become comparable with the radiation-induced concentrations so precipitation becomes time dependent. The dose at which the plateau is reached thus becomes sensitive to dose rate.**

Discussion of Flux (Dose Rate) Effects Encompasses Wide Range of Fast Neutron Flux



Steels containing significant amounts of copper irradiated to doses lower than that required to reach the plateau in copper related hardening (Cont'd)

- As the dose rate increases beyond this low dose rate regime, the radiation-induced level of vacancies increases. The effect is dependent on:
  - Whether additional sinks are produced by irradiation,
  - If additional sinks are produced and such concentration is dependent on dose rate, then point defect recombination in the matrix becomes important.
  - The extent of recombination will increase with increasing dose rate.

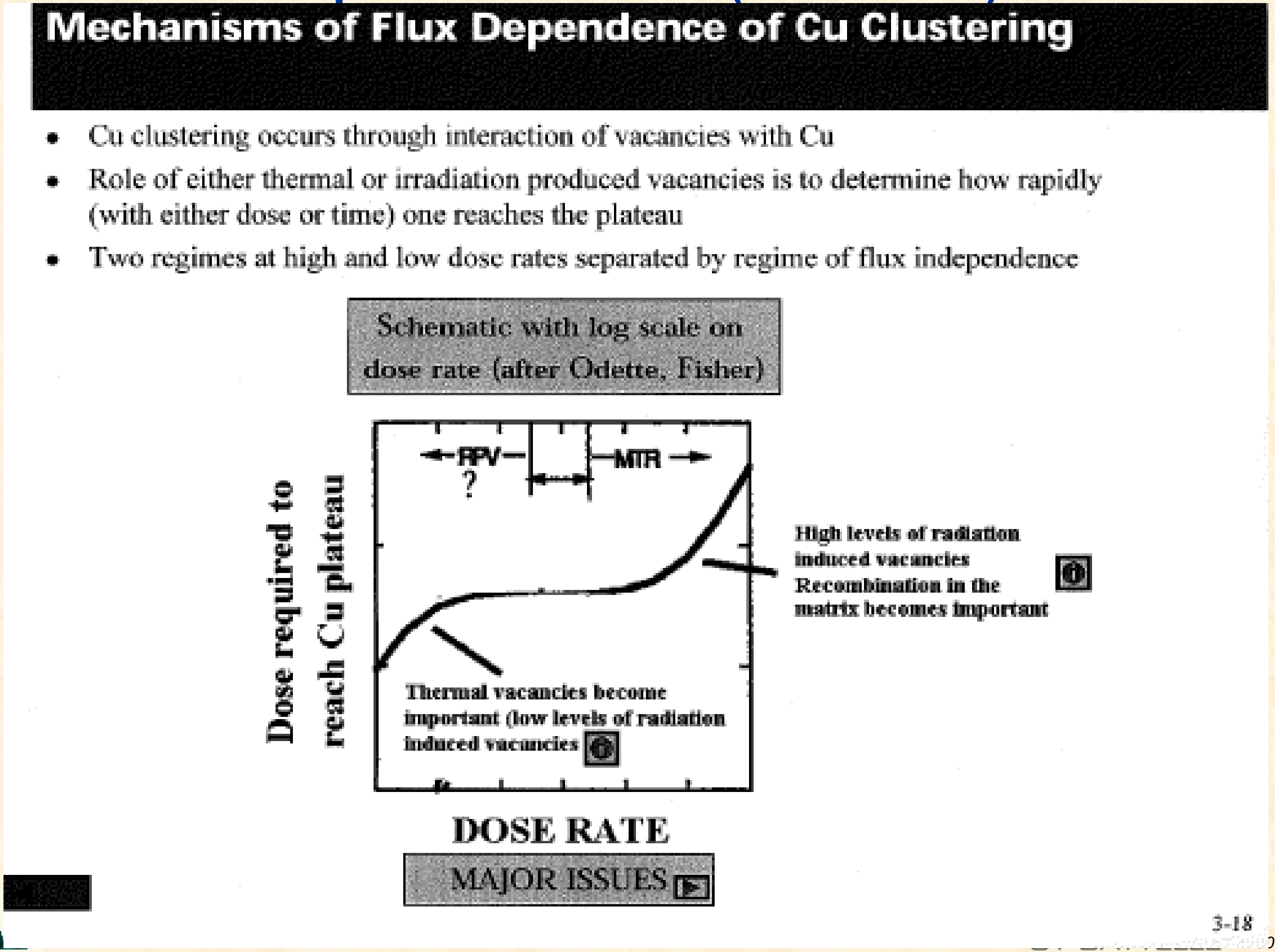
- Thus, this again produces a range of dose rates within which vacancy concentration is not linearly dependent on flux, so the dose to reach the plateau becomes dependent on dose rate.
- It was agreed that the low-dose rate region of dose rate dependence would exist, but there was no consensus as to the exact dose rate range in which it would be found. Highest value suggested was less than 5×10^9 n/cm^2-s (E>1 MeV).

Steels containing significant amounts of copper irradiated to doses lower than that required to reach the plateau in copper related hardening (Cont'd)

- Dose rate dependence in the high dose rate region is well-established at pre-plateau doses in both C-Mn and MnMoNi Cu-containing steels. The threshold dose rate of the high-dose rate region is becoming established at about 7×10^{10} n/cm^2-s (E>1 MeV) at 290°C.
- Given their expected lifetime doses, BWRs and some PWRs will operate within the pre-plateau region through most, if not all, of their operating lives. Many PWRs will receive a plateau dose at the inner surface of the RPV well within their operating lives.
  - Of course, license extensions to 80 y may change such conclusions!

- The high dose rate region is primarily of interest to PWR operators, whereas the low dose rate region is applicable to BWRs.
- It is probable that data obtained in accelerated tests in MTRs will not provide a conservative prediction of Cu-related embrittlement in the pre-plateau region at lower dose rates.

Fluence (Dose) Required to Reach the Plateau is Dependent on Flux (Dose Rate)



Mechanisms of Flux Dependence of Cu Clustering

- Cu clustering occurs through interaction of vacancies with Cu
- Role of either thermal or irradiation produced vacancies is to determine how rapidly (with either dose or time) one reaches the plateau
- Two regimes at high and low dose rates separated by regime of flux independence

Schematic with log scale on dose rate (after Odette, Fisher)

High levels of radiation induced vacancies Recombination in the matrix becomes important

Thermal vacancies become important (low levels of radiation induced vacancies

MAJOR ISSUES

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Steels containing significant amounts of copper irradiated to doses above that at which the plateau in copper related hardening is reached.

- A plateau has not been observed, even at high doses, in RPV steels with high Ni and Mn contents.

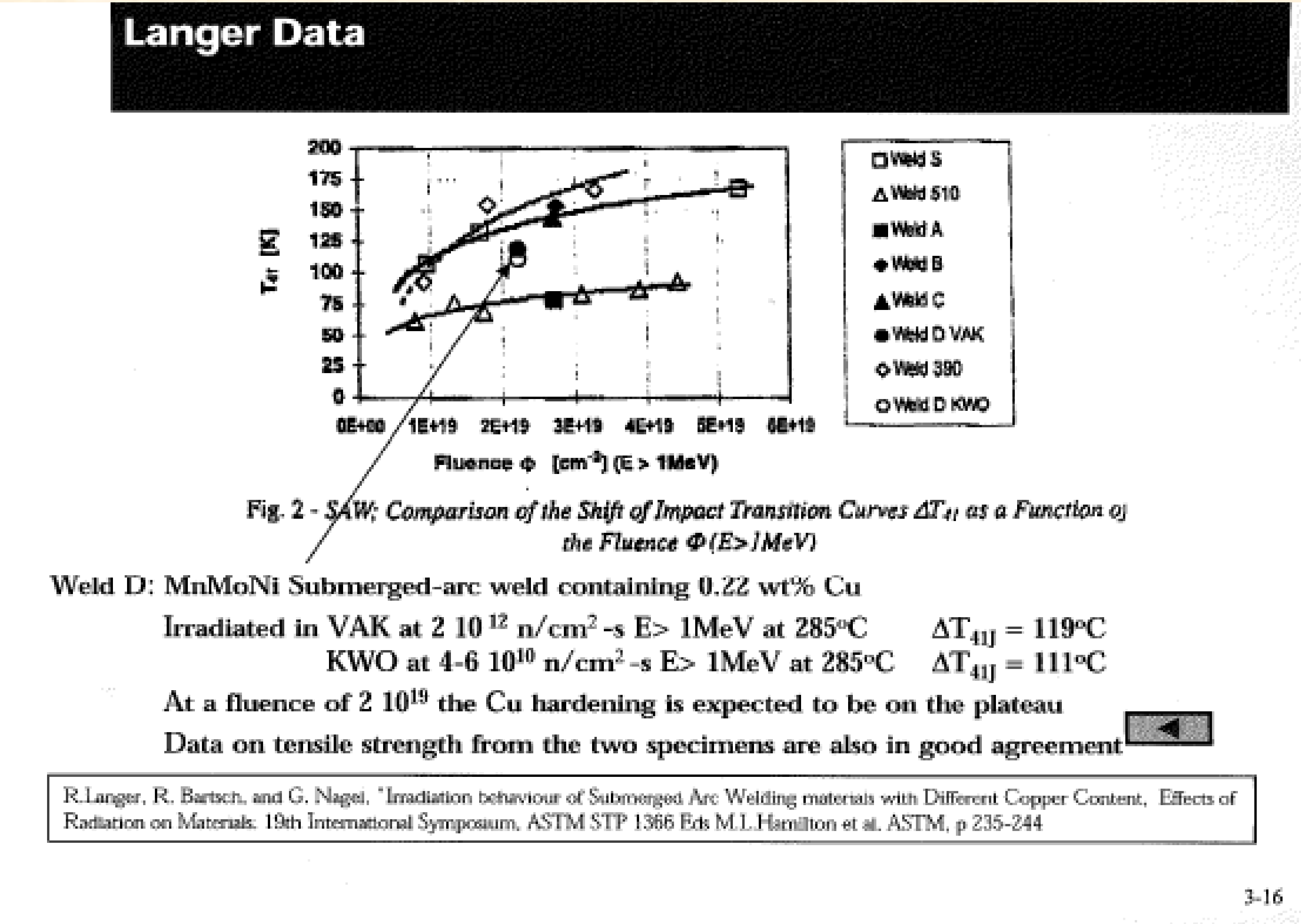
- Data on MnMoNi steels support the dose rate independence of the magnitude of Cu-related hardening on the plateau.

- In general, the dose at which the plateau is reached has yet to be determined. For PWR surveillance dose rates at ~290°C, the plateau is reached at approximately $1\text{-}2\times10^{10}$ n/cm^2-s (E>1 MeV).
  - It is important to note that the dose at which the plateau is reached will be sensitive to dose rate. In addition, the plateau dose might also be sensitive to composition (levels of Cu, Ni, Mn, etc.).

Steels containing significant amounts of copper irradiated to doses above that at which the plateau in copper related hardening is reached (Cont'd).

- **The position is more complex in steels containing high levels of Ni and Mn. There are data on the embrittlement of Cu-containing high Ni (1.6 wt%) Mn-containing steels demonstrating that the plateau is not reached at a dose of about 6×10^{19} n/cm^2-s (E>1 MeV).**
  - **There is not yet a consensus on the bulk Ni level at which non-plateau behavior is encountered.**
  - **There are even data for high-Ni steels showing a return of increasing embrittlement after an increment of dose on an apparent plateau (Late-Blooming Phases??)**
  - **Once the plateau in Cu-related hardening has been reached in low to medium Ni steels, the Cu contribution to the embrittlement will be dose rate independent.**

Langer Data For High Cu Weld at Surveillance and MTR Fluxes and at Relatively High Fluence with No Evidence of Flux Effect at 2E19 n/cm^2



Langer Data

Fig. 2 - *SAW; Comparison of the Shift of Impact Transition Curves ΔT_{41} as a Function of the Fluence Φ (E>1MeV)*

Weld D: MnMoNi Submerged-arc weld containing 0.22 wt% Cu

Irradiated in VAK at 2 10^{12} n/cm^2-s E> 1MeV at 285°C ΔT_{41J} = 119°C

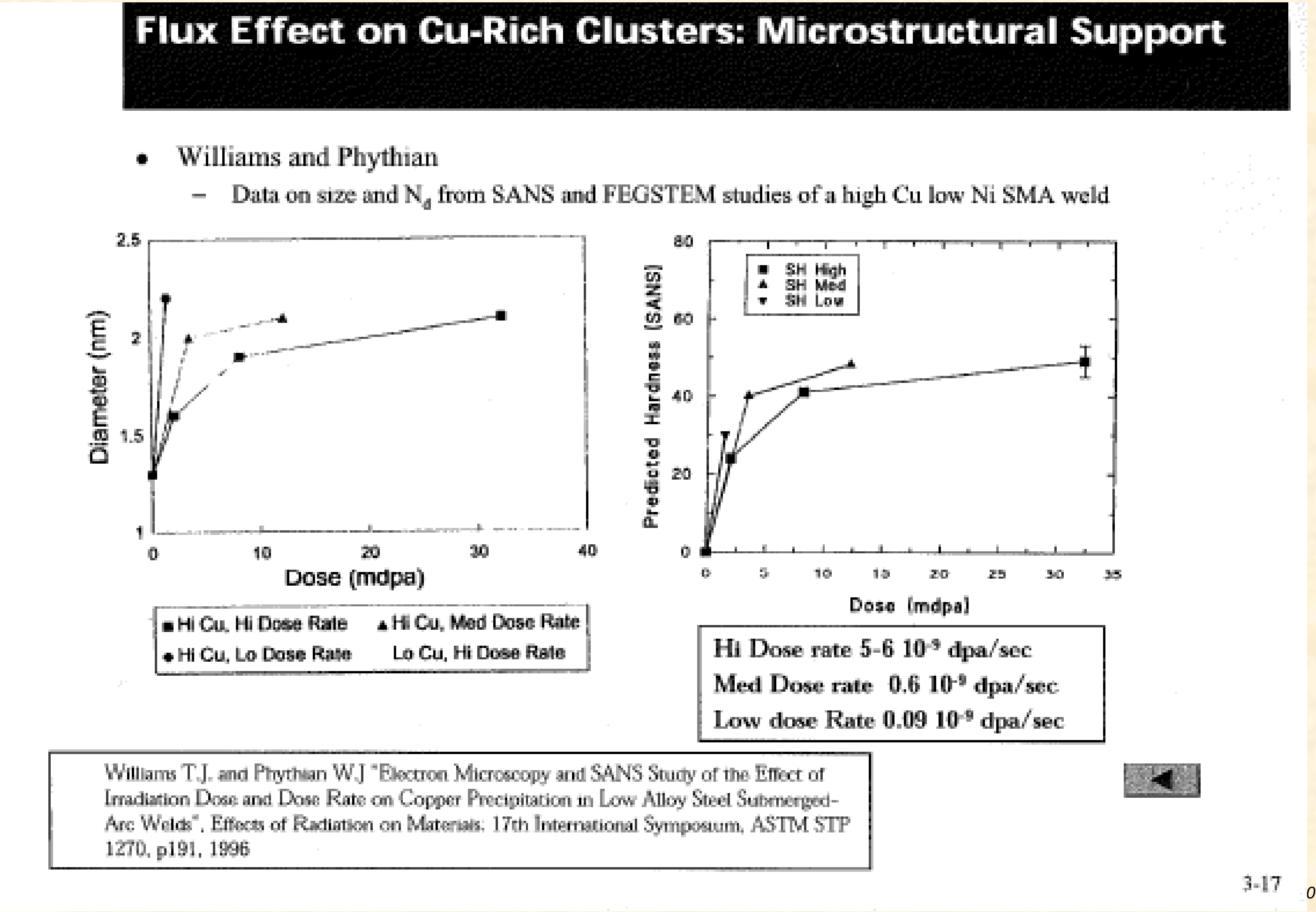
KWO at 4-6 10^{10} n/cm^2-s E> 1MeV at 285°C ΔT_{41J} = 111°C

At a fluence of 2 10^{19} the Cu hardening is expected to be on the plateau

Data on tensile strength from the two specimens are also in good agreement

R.Langer, R. Bartsch, and G. Nagel, "Irradiation behaviour of Submerged Arc Welding materials with Different Copper Content, Effects of Radiation on Materials: 19th International Symposium, ASTM STP 1366 Eds M.L.Hamilton et al. ASTM, p 235-244

Microstructural Evidence Indicating Flux Effect on Precipitate Character for High-Cu Weld



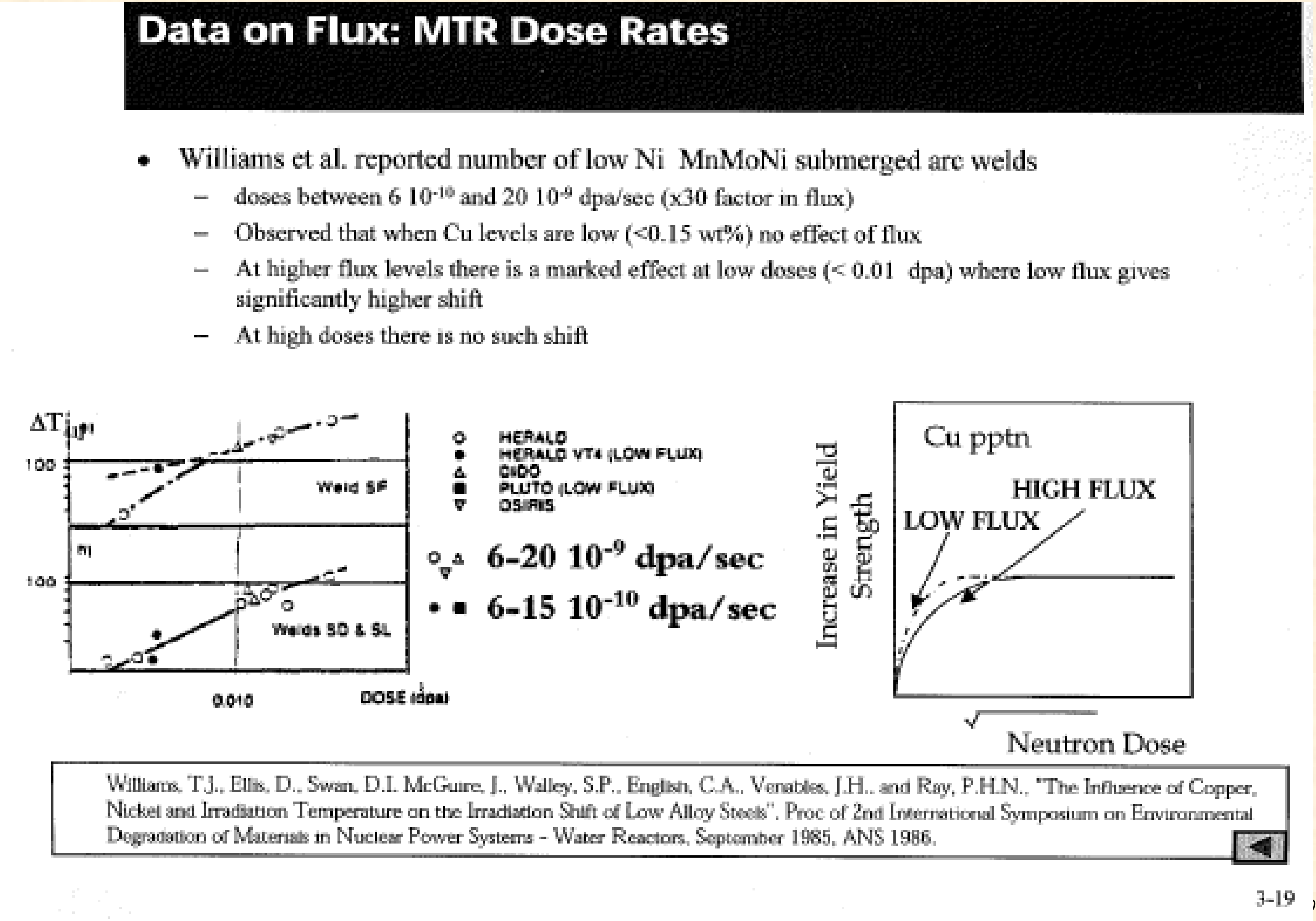
Flux Effect on Cu-Rich Clusters: Microstructural Support

- Williams and Phythian
  - Data on size and N_d from SANS and FEGSTEM studies of a high Cu low Ni SMA weld

Hi Dose rate 5-6 10^{-9} dpa/sec
Med Dose rate 0.6 10^{-9} dpa/sec
Low dose Rate 0.09 10^{-9} dpa/sec

Williams T.J. and Phythian W.J "Electron Microscopy and SANS Study of the Effect of Irradiation Dose and Dose Rate on Copper Precipitation in Low Alloy Steel Submerged-Arc Welds", Effects of Radiation on Materials: 17th International Symposium, ASTM STP 1270, p191, 1996

Data on Low Ni Welds Indicate Flux Effects at Relatively Low Values of Fluence



Data on Flux: MTR Dose Rates

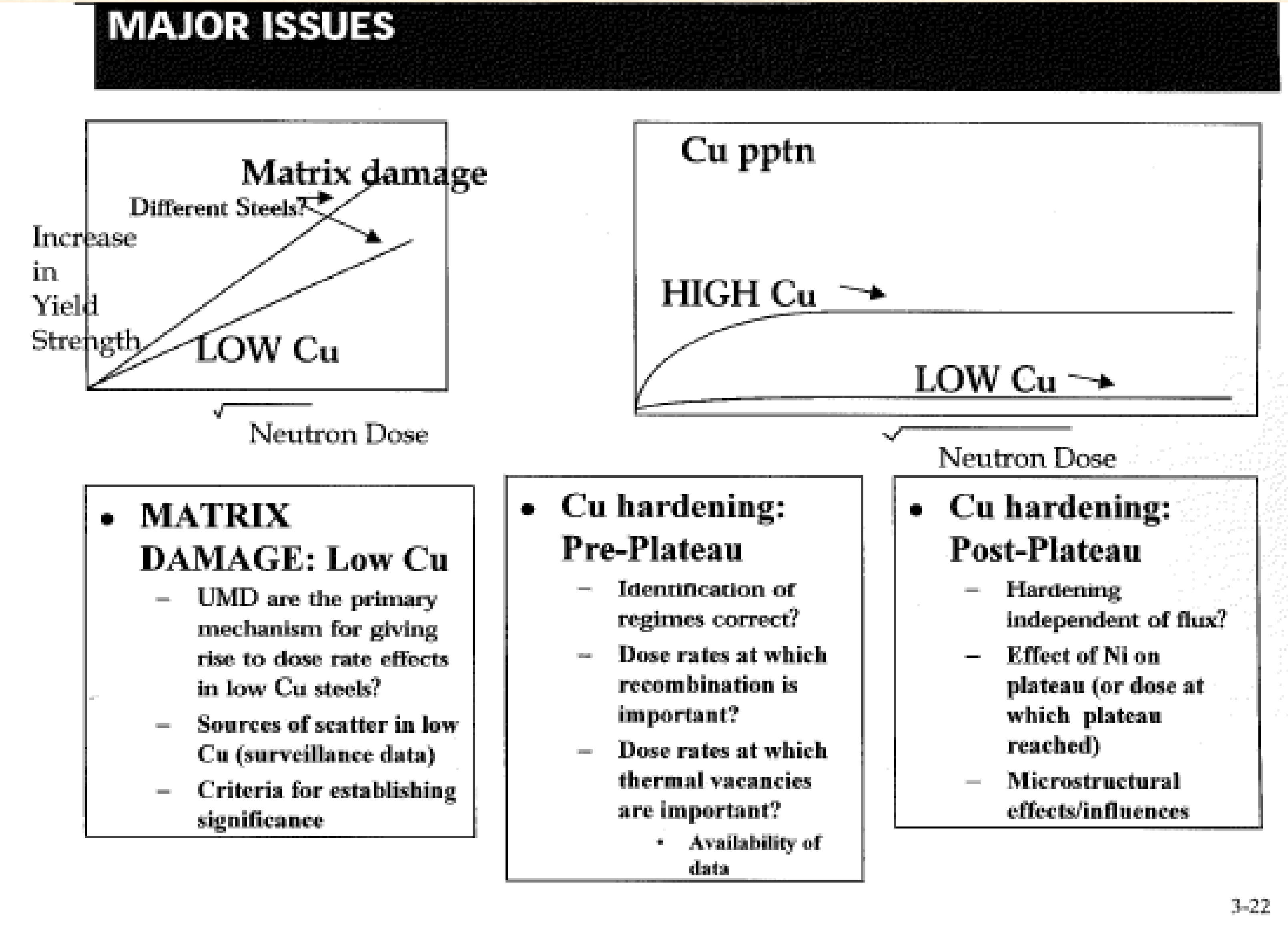
- Williams et al. reported number of low Ni MnMoNi submerged arc welds
  - doses between 6 10^{-10} and 20 10^{-9} dpa/sec (x30 factor in flux)
  - Observed that when Cu levels are low (<0.15 wt%) no effect of flux
  - At higher flux levels there is a marked effect at low doses (< 0.01 dpa) where low flux gives significantly higher shift
  - At high doses there is no such shift

○ HERALD
● HERALD VT4 (LOW FLUX)
△ CIDO
■ PLUTO (LOW FLUX)
▽ OSIRIS

○ △ ▽ 6-20 10^{-9} dpa/sec
● ■ 6-15 10^{-10} dpa/sec

Williams, T.J., Ellis, D., Swan, D.I. McGuire, J., Walley, S.P., English, C.A., Venables, J.H., and Ray, P.H.N., "The Influence of Copper, Nickel and Irradiation Temperature on the Irradiation Shift of Low Alloy Steels", Proc of 2nd International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, September 1985, ANS 1986.

EPRI Workshop Identified Many Issues Regarding Flux Effects that Require Further Research



MAJOR ISSUES

- **MATRIX DAMAGE: Low Cu**
  - UMD are the primary mechanism for giving rise to dose rate effects in low Cu steels?
  - Sources of scatter in low Cu (surveillance data)
  - Criteria for establishing significance

- **Cu hardening: Pre-Plateau**
  - Identification of regimes correct?
  - Dose rates at which recombination is important?
  - Dose rates at which thermal vacancies are important?
    - Availability of data

- **Cu hardening: Post-Plateau**
  - Hardening independent of flux?
  - Effect of Ni on plateau (or dose at which plateau reached)
  - Microstructural effects/influences

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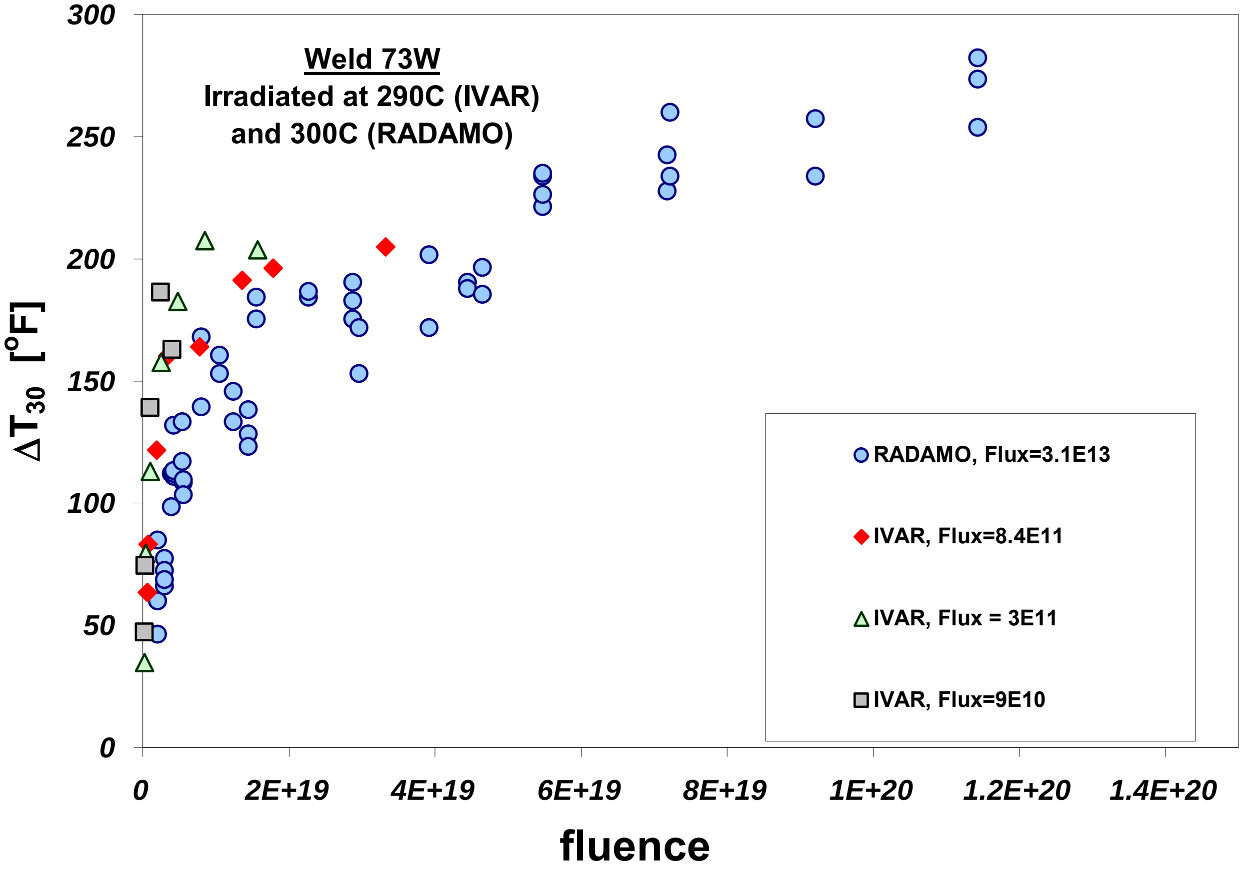
RADAMO Data (From SCK-CEN) Indicate Higher Shift at Lower Flux in the Low fluence Regime for a High-Cu Weld


Weld 73W
Irradiated at 290C (IVAR) and 300C (RADAMO)

X-axis	Log10(fluence)	FALSE
	Sqrt(fluence)	FALSE
	Fluence	TRUE

Sort?	TRUE
Alloy	73W

Temp	300

FALSE	Min	Max
Cu	0	1000
Ni	0	1000
Mn	0	1000
P	0	1000
Si	0	1000
Temp	0	1000
Flux	0.00E+00	1.00E+20

Cu = 0.31
Ni = 0.6

Mn = 1.56

P = 0.005

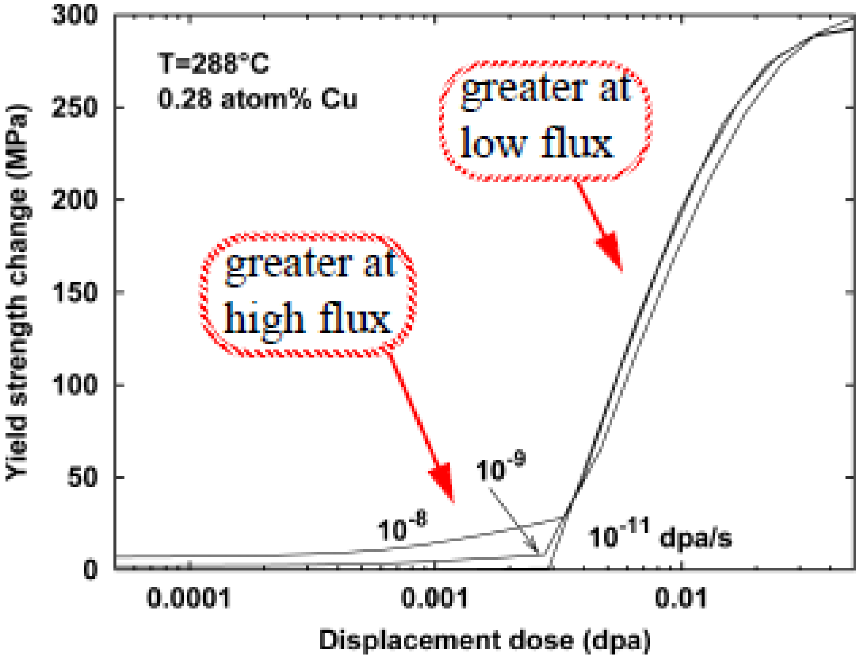
BASIC MECHANISMS RESPONSIBLE FOR A DISPLACEMENT RATE EFFECT

Radiation-induced property changes are driven by the excess point defects fluxes created by displacive irradiation.

- Details of microstructural evolution and effects such as solute segregation are determined by the transport and fate of mobile point defects and solutes
- Displacement rate effects in RPV steels arise primarily from two processes:
  - the competition between formation and dissolution of unstable defects (this component is nearly inseparable from the effects of irradiation temperature)
  - the influence of the displacement rate on radiation-enhanced diffusion
- Hardening from point defect clusters is most strongly influenced by the first process, and that from copper precipitates by the second
- However, when the unstable defects provide a significant sink for mobile point defects, they will have an impact on radiation-enhanced diffusion
- Thus, an increase in displacement rate may lead to either an increase or decrease in hardening

EXAMPLES OF MODEL PREDICTIONS

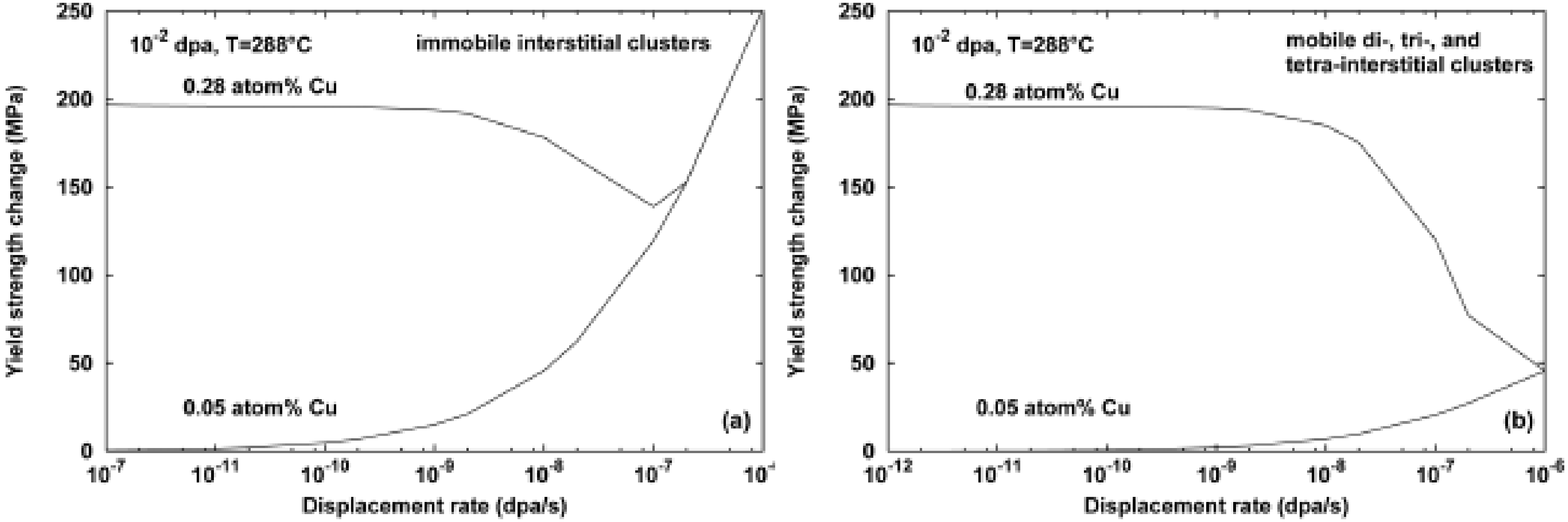
Effect of displacement rate on fluence dependence of hardening (base-case model parameters)



- In high-copper steels, primary effect of lower displacement rate is a reduced fluence to initiate hardening from copper-rich precipitates. Little effect on peak hardening.
- At low fluences, hardening is reduced at lower displacement rates. Can lead to a crossover at intermediate fluences.
- Note: for typical displacement cross section of 1500 barn, 1×10^{19} n/cm^2 (E>1.0 MeV)= 0.015 dpa

EXAMPLES OF MODEL PREDICTIONS

Influence of interstitial cluster mobility on rate effect: predicted yield strength change at 10^{-2} dpa for low and high copper steel



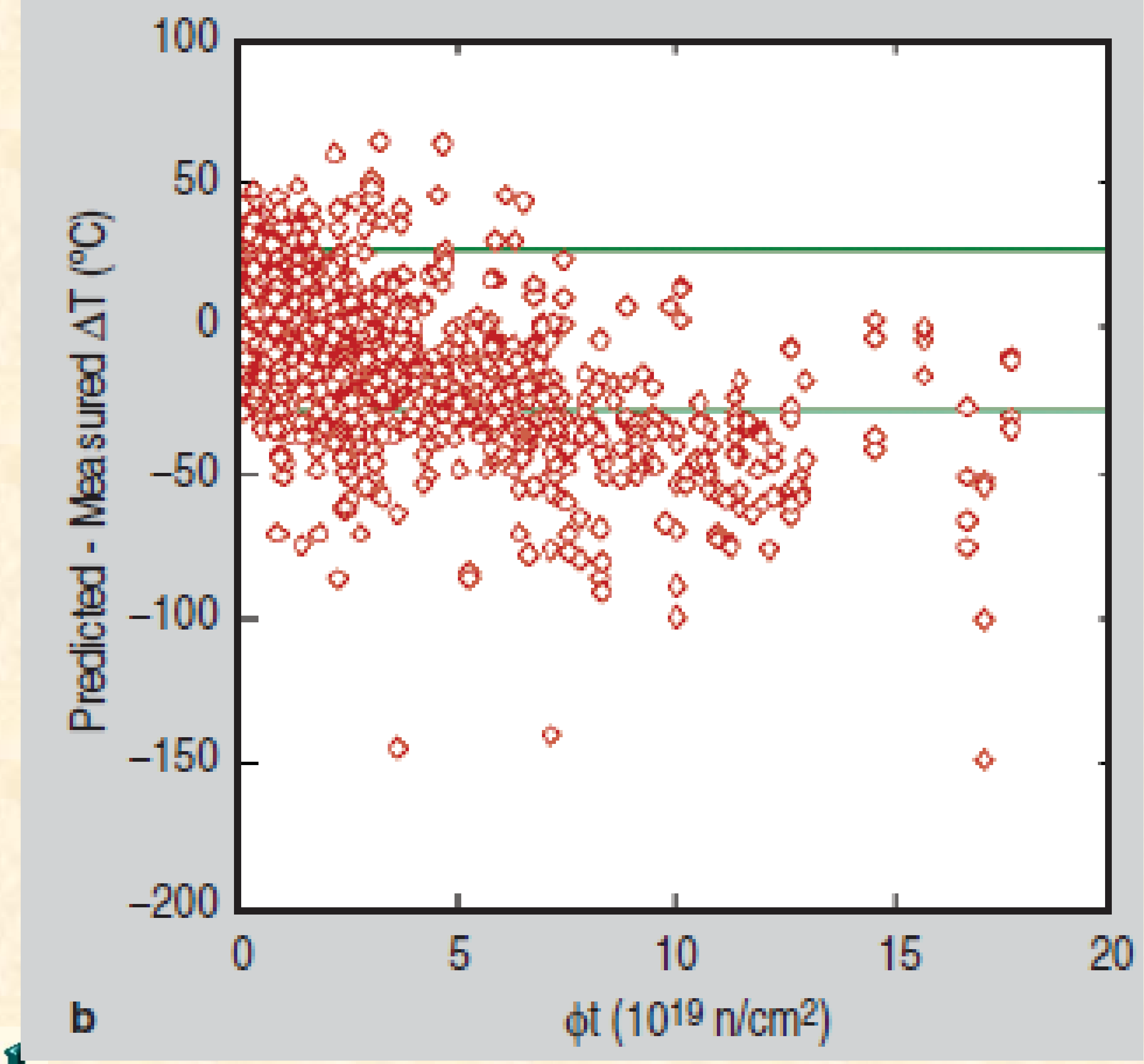
- immobile interstitial clusters, high cluster sink strength:
  - Cu-ppt dominated below ~10^{-7} dpa/s
  - point defect clusters dominate at high fluxes
- mobile interstitial clusters, reduced sink strength
  - greater radiation-enhanced diffusion
  - no interstitial cluster contribution at high fluxes

SUMMARY

A relatively simple kinetic model has been used to investigate the effect of variations in flux on radiation-induced hardening

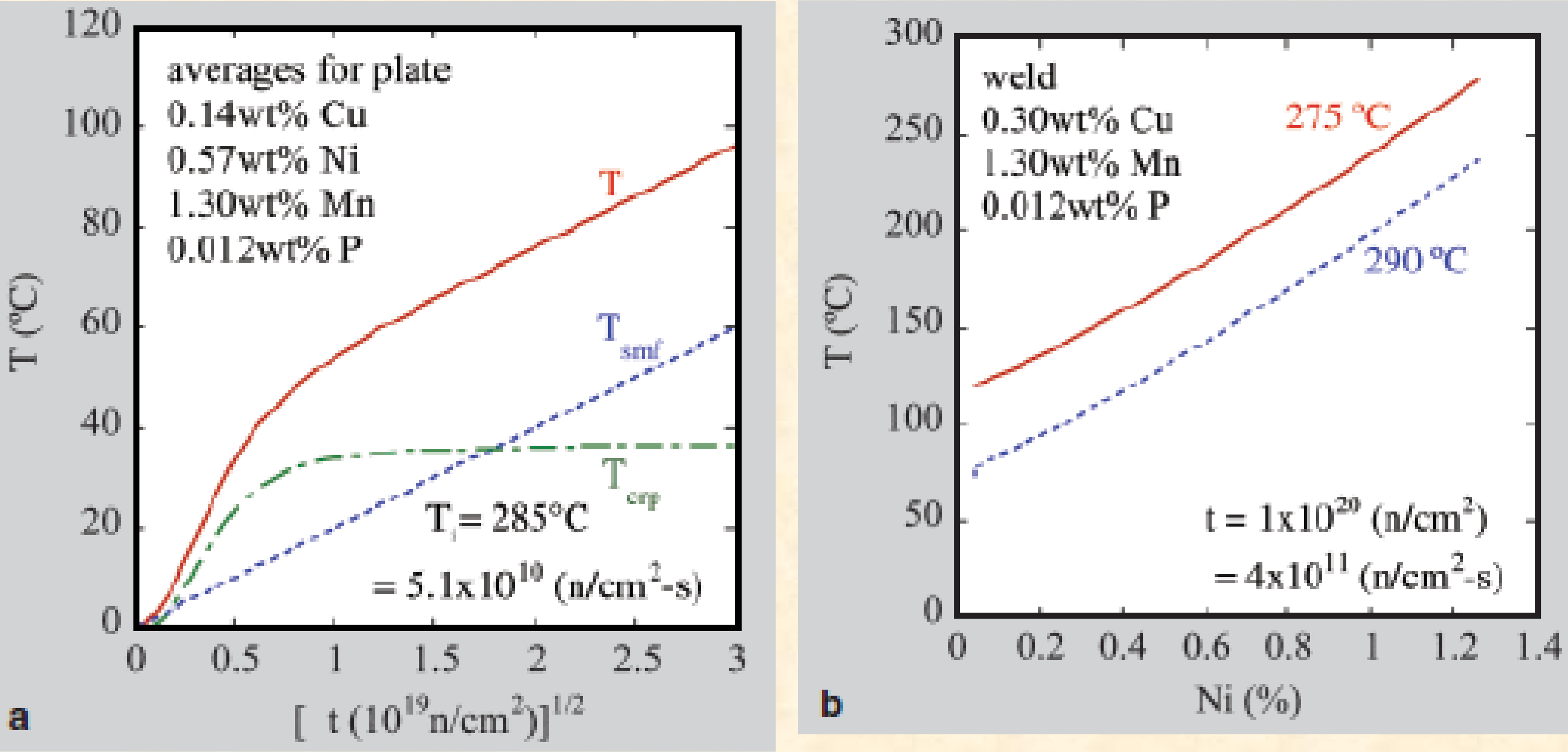
- the predicted influence of damage rate on radiation-induced hardening depends on several other material and irradiation variables:
    - copper content
    - neutron fluence
    - flux range
    - temperature (not discussed here)
- depending on which values apply, a change in flux may lead to either an increase or a decrease in hardening
- the absolute magnitude of the flux effect, and the flux range with the greatest predicted sensitivity depends on the details of the model and the chosen parameters
- model predictions are consistent with a modest effect of neutron flux for the range of fluxes of interest to LWR RPV at ~290°C

EONY model of “predicted minus measured” ΔT residuals for the test reactor database assembled by M. EricksonKirk

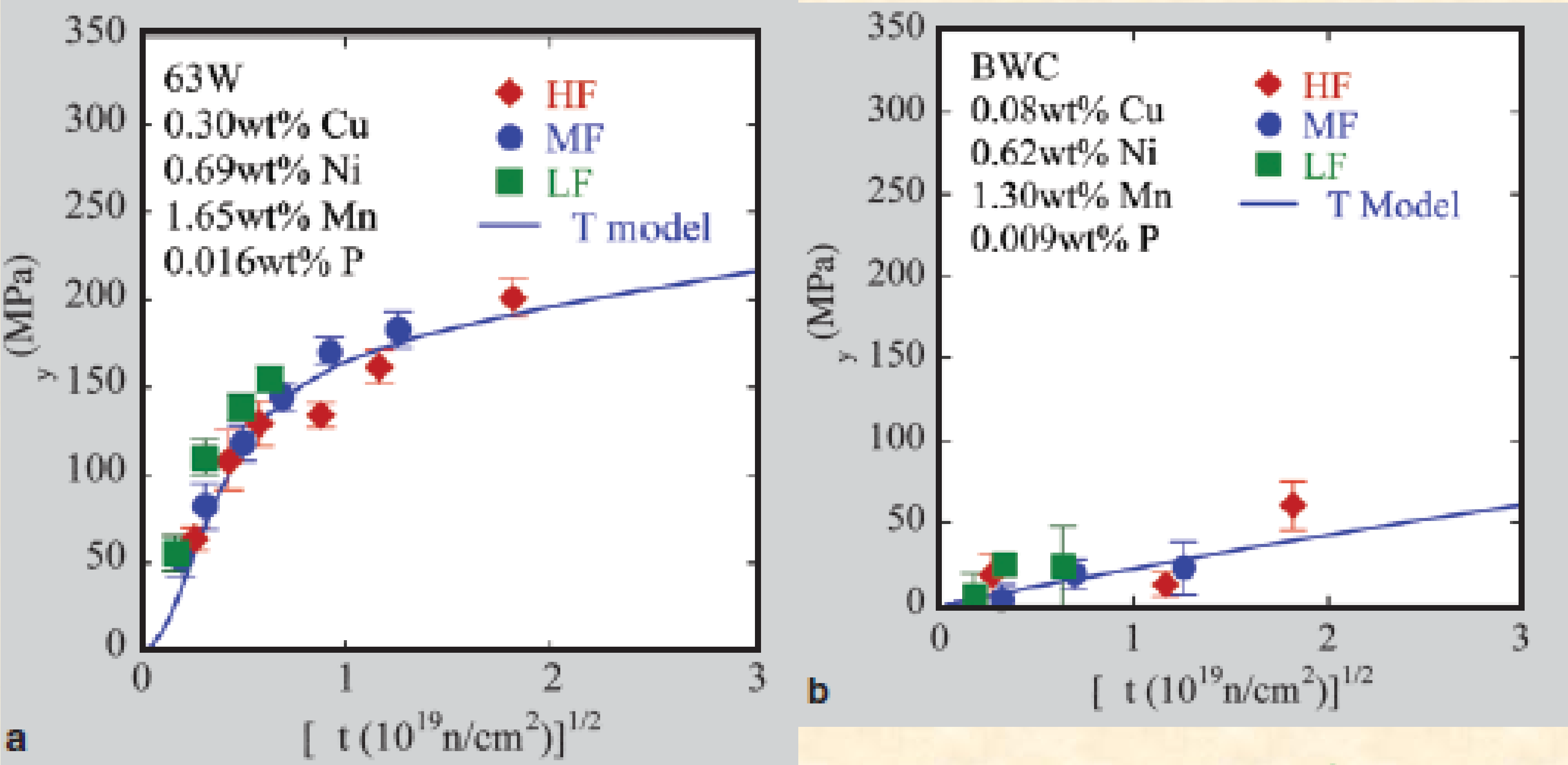


High fluence predictions for materials irradiated in test reactors are significantly under predicted.

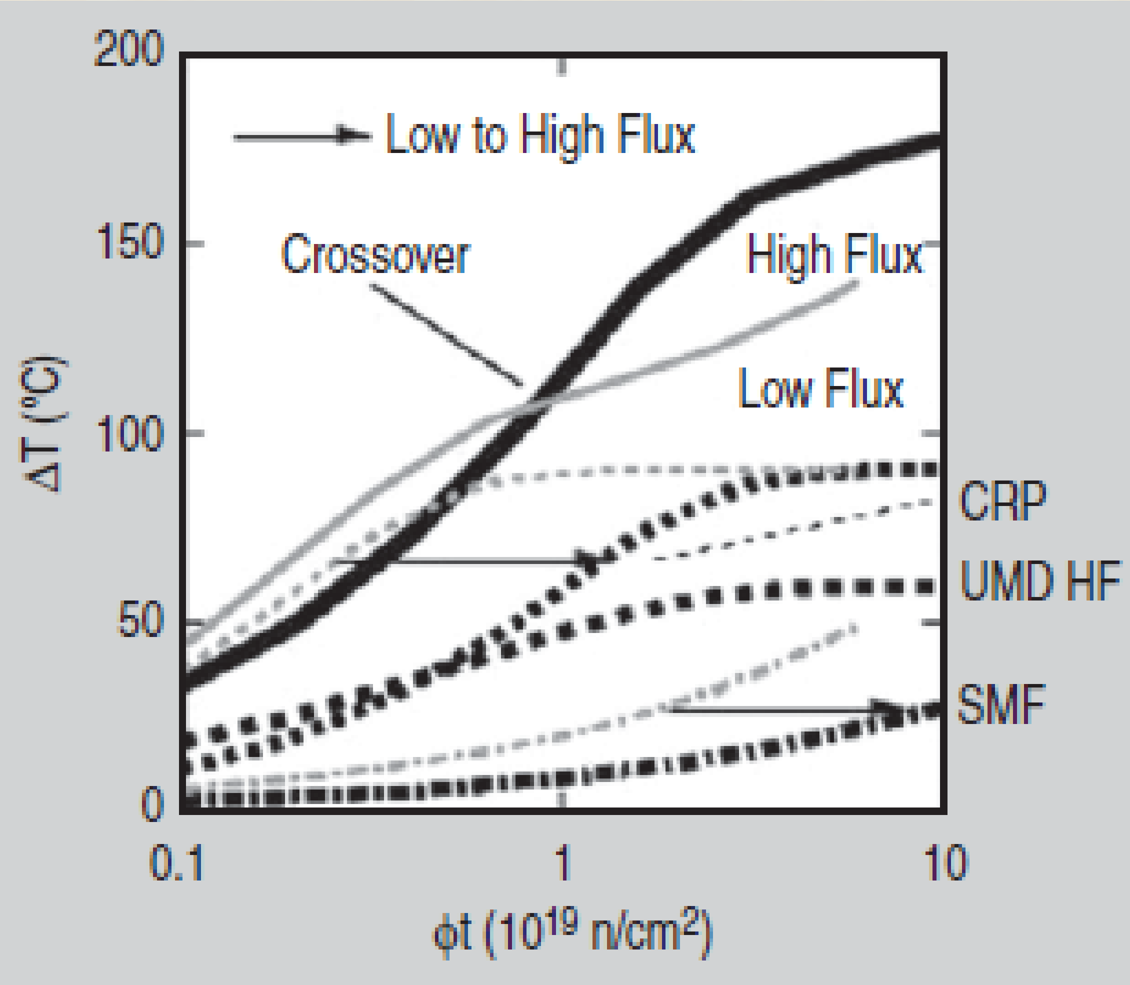
The EONY ΔT predictions: (a) for plate at the average Cu, Ni, Mn, P compositions and irradiation temperature and flux in the PREDB database; (b) the effect of nickel on ΔT for a 0.30 wt.% Cu weld at 10^{20} n/cm^2 (>1 MeV) and at two irradiation temperatures.



EONY surveillance based predictions (solid lines) of $\Delta\sigma_y$ (converted) versus the square root of fluence compared to high (HF), medium (MF), and low flux (LF) IVAR data for a high copper (a) and low copper (b) welds



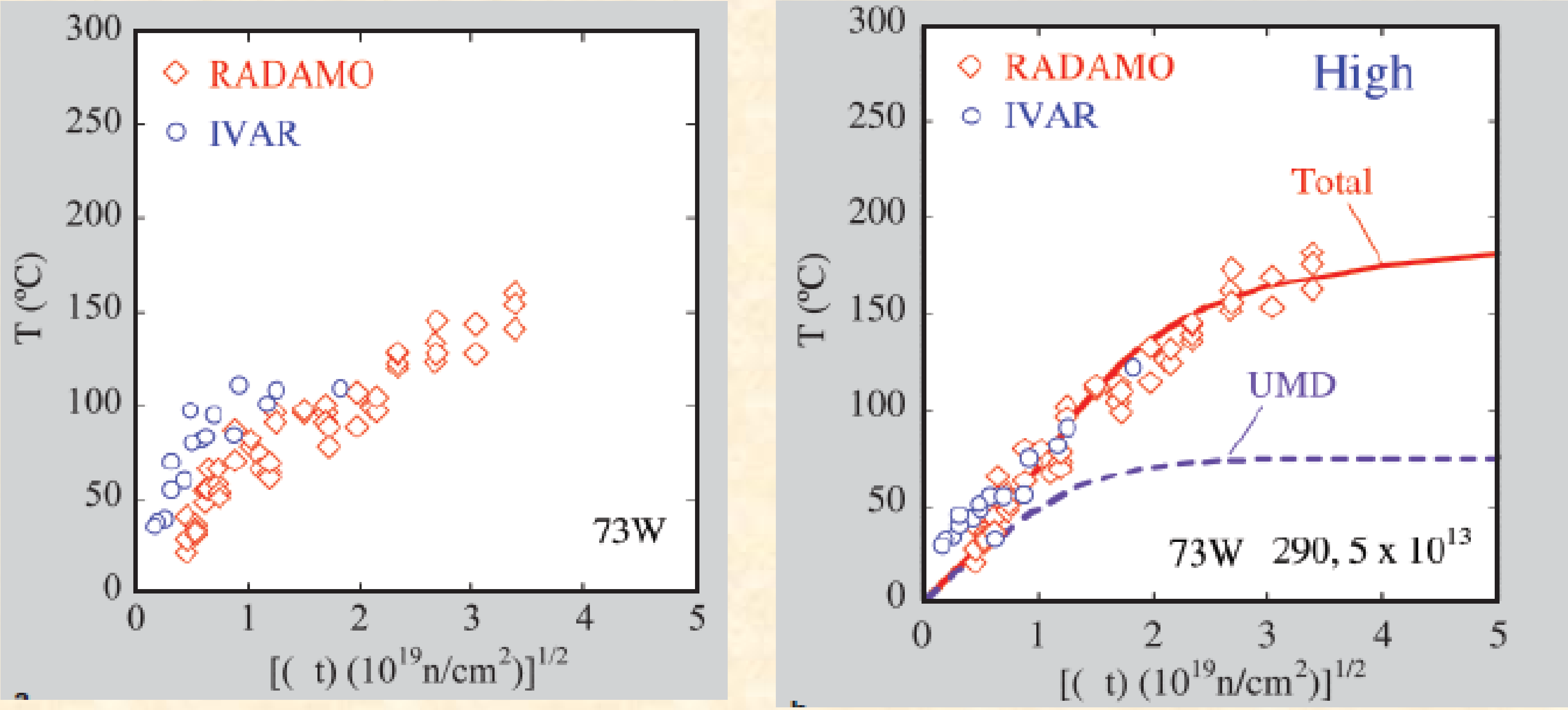
A schematic illustration of the three-feature (SMF + CRP + UMD) ΔT model for a copper-bearing steel.



The heavy and light lines are for high and low flux, respectively. The arrows show the delays in the SMF and CRP contributions at high flux. The short dashed line shows the extra UMD contibution to ΔT_{umd} at high flux. These competing effects result in a crossover in the total ΔT.

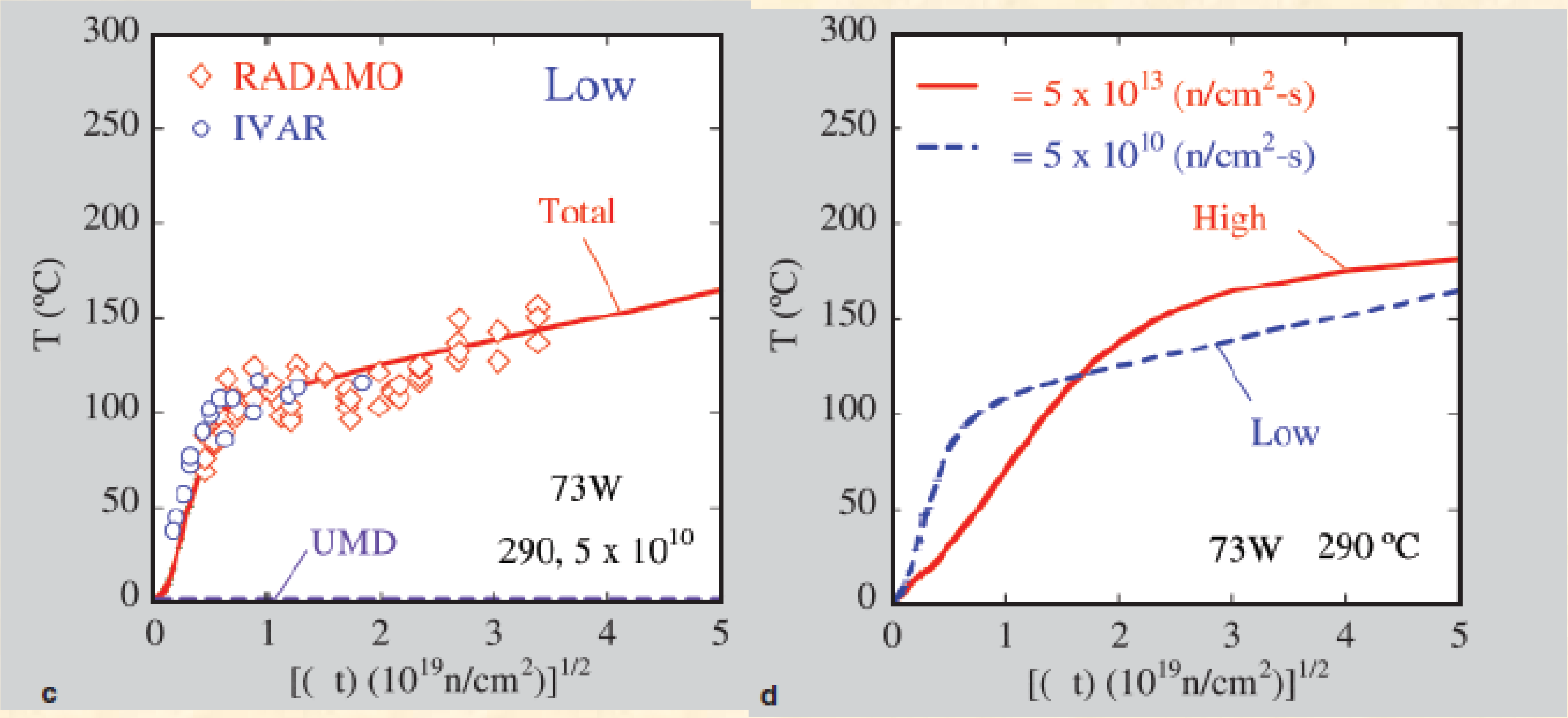
Three feature model ΔT predictions for the high 0.3 wt.% copper weld, 73W:

(a) the raw data; (b) predictions for high flux. The model has been used to adjust the ΔT data to the common irradiation condition specified.



Three feature model ΔT predictions for the high 0.3 wt.% copper weld, 73W (Cont'd)

(c) low flux at 290°C; and (d) comparisons of the high and low flux ΔT curves. The model has been used to adjust the ΔT data to the common irradiation condition specified.



(a) Illustrative model predictions of the dose (in milli-displacements per atom) dependence of hardening in a high copper, medium nickel steel due to CRP hardening and in high-nickel, low-copper steel due to Late Blooming Phase (LBP) hardening; (b) APT maps of nickel and manganese distributions and a blowup of an Mn-Ni LBP precipitate in a copper-free 1.6 wt. % Ni-1.6 wt. % Mn model alloy irradiated to $1.8x10^{19}$ n/cm^{2} at high flux and 290°C; and (c) $\Delta\sigma y$ as a function of the square root of the volume fraction of precipitates in low copper steels and model alloys.