Radiation Resiliency for 80 Year Cores

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Radiation Effects-GALL Examples

Loss of Toughness/Neutron Radiation Embrittlement

- PWR Inlet, Outlet, Safety, and Injection Nozzles; Vessel Shell including Beltline Welds, Baffle/former assemblies, Core barrel, Lower internal assembly
- BWR fuel supports and control rod drive assemblies, jet pump assemblies, Class 1 pump casings, and valve bodies and bonnets

Creep

- PWR Baffle/former assemblies, Lower internal assembly, upper internals assembly

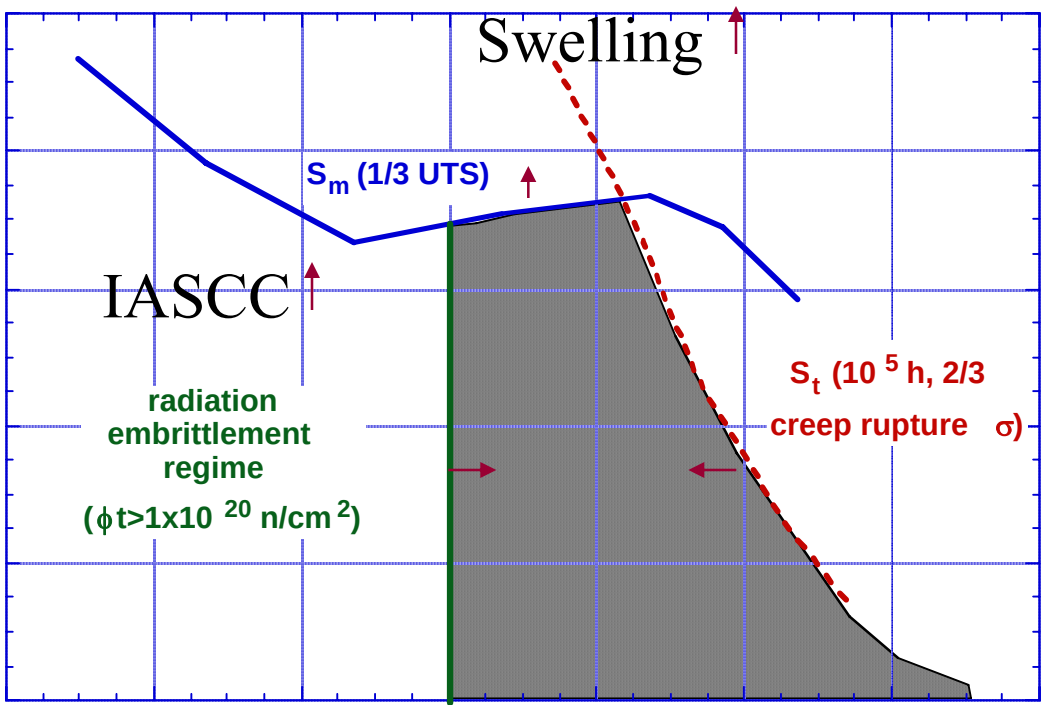
Swelling

- PWR Baffle/former assemblies, Core Barrel, Instrumentation support structures, Lower internal assembly, RCCA guide tube assemblies, upper internals assembly

IASCC

- PWR Baffle/former assemblies, Core Barrel, Instrumentation support structures, Lower internal assembly, RCCA guide tube assemblies
- BWR Jet Pump Assemblies

Design Windows



Properties change with radiation →

S. M. Zinkle, ORNL

Irradiation Effects on Mechanical Properties

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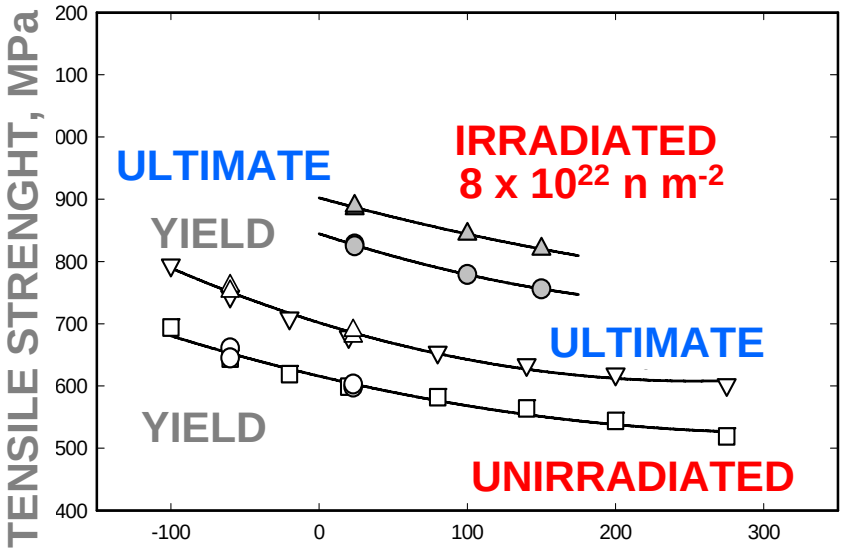

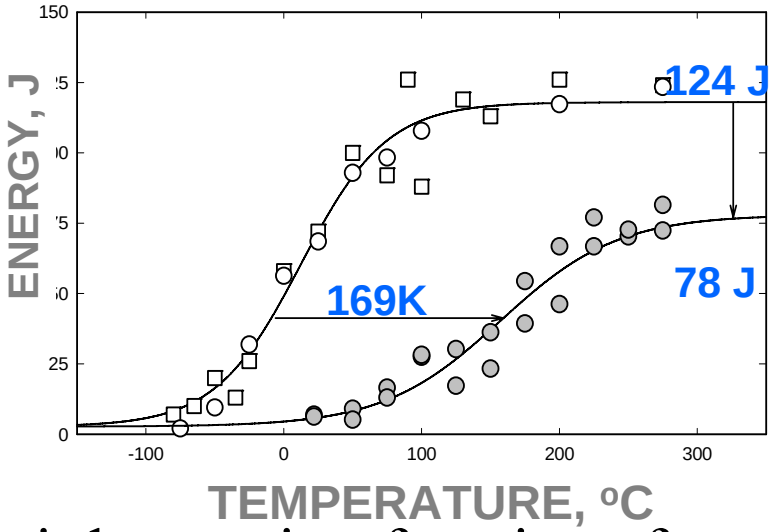

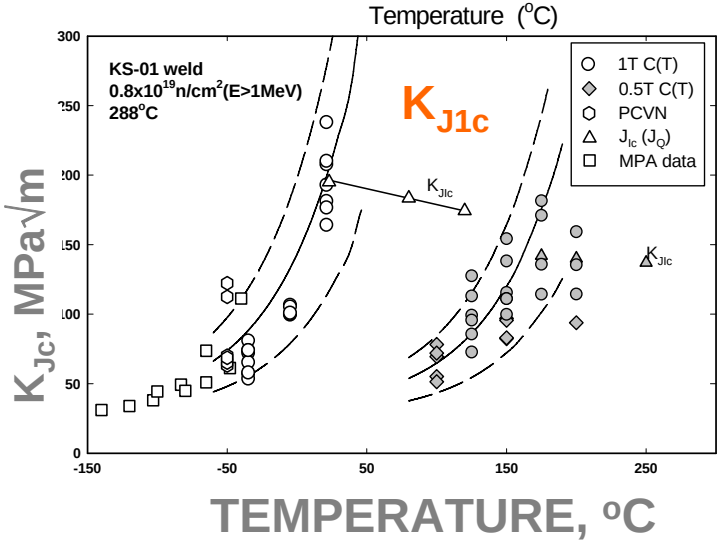

Embrittlement is a function of radiation dose, dose rate, temperature, composition.

Can limit dose to vessel by changing fuel management scheme

Reactor Pressure Vessels

RPVs are exposed to fast neutron fluxes (E>0.1 MeV) in the range of 10^{12}-10^{15} n/m^{2}s (10^{-9} to 10^{-11} dpa/s).

- PWR fluxes are higher than BWR fluxes
- Flux decreases by ~ a factor of 20 across an 8 inch PWR RPV
- Flux decreases by ~ a factor of 12 across an 6 inch PWR RPV

Design Windows

QuickTime™ and a
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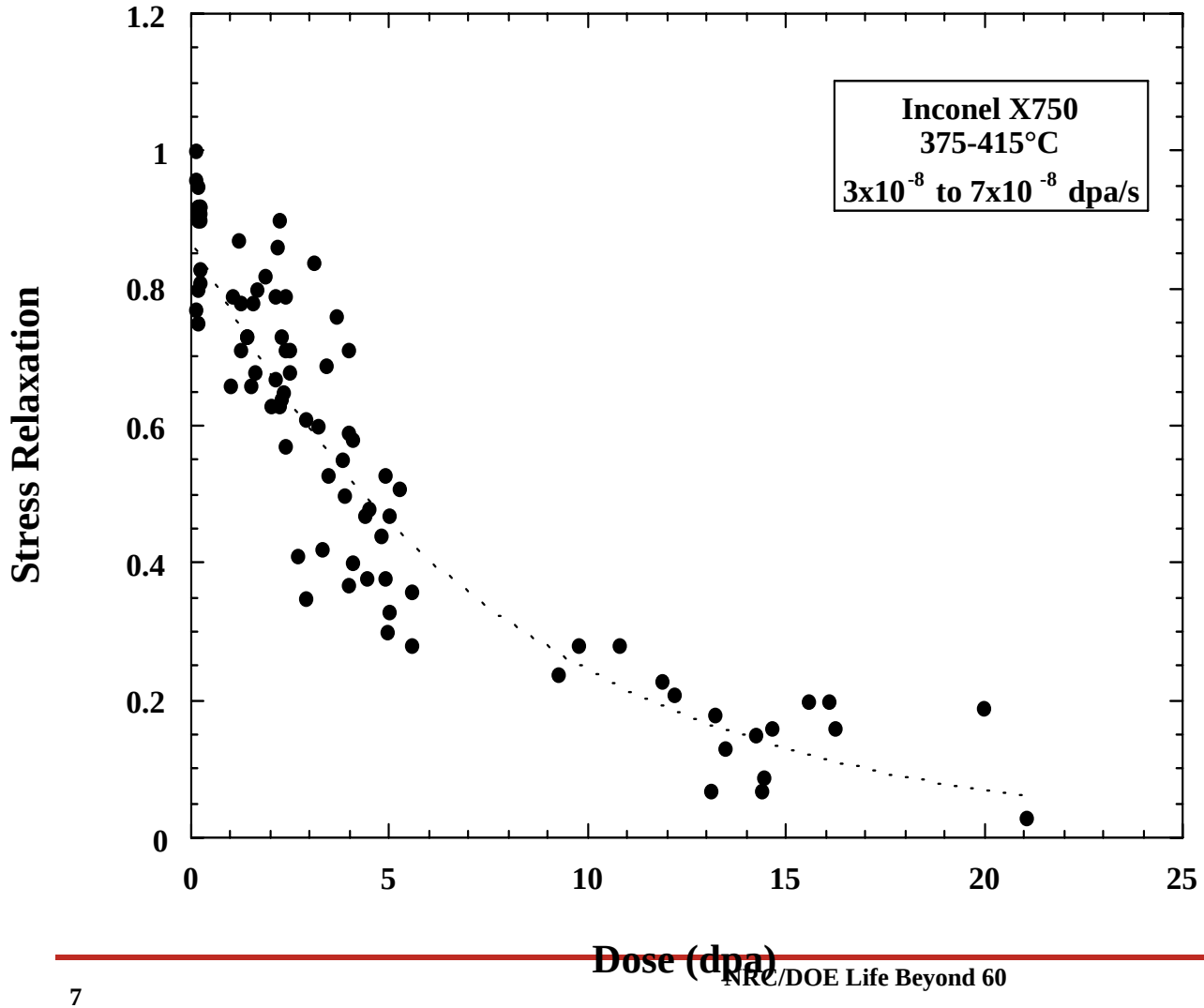
Creep: Radiation-induced Stress Relaxation

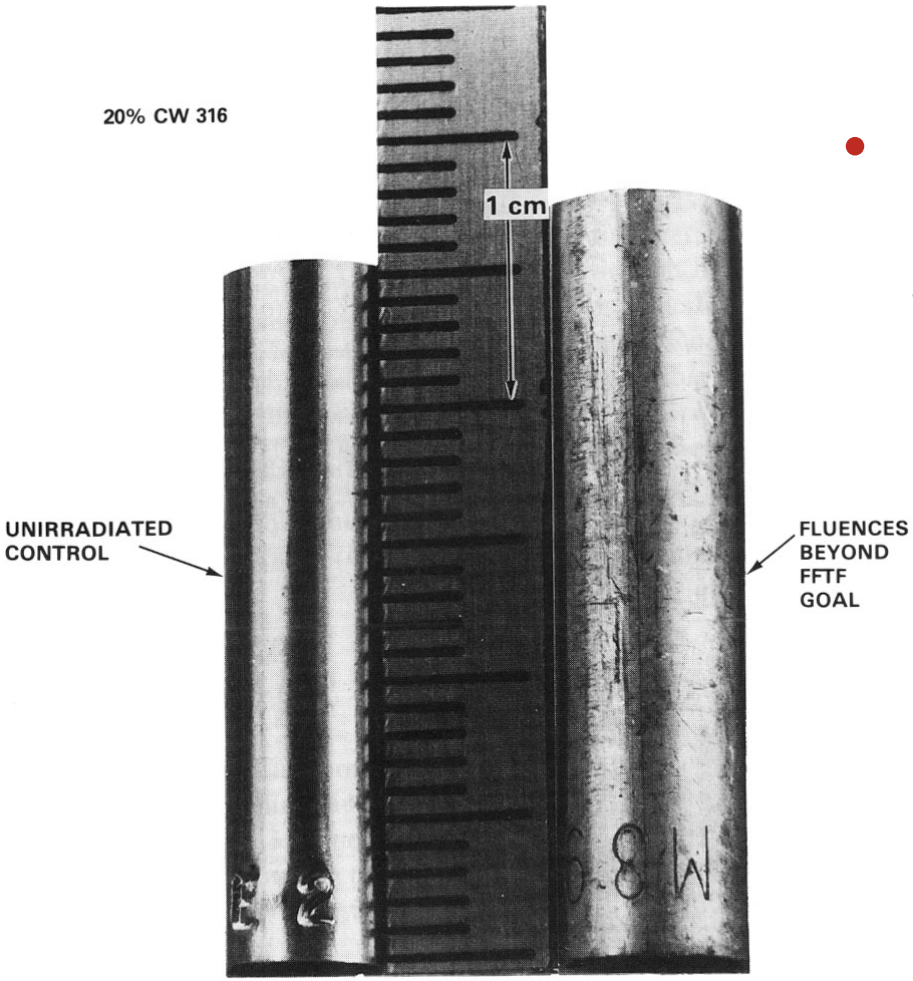
Stress Relaxation Approaches ~10% of pre-load



Loss of pre-load due to creep

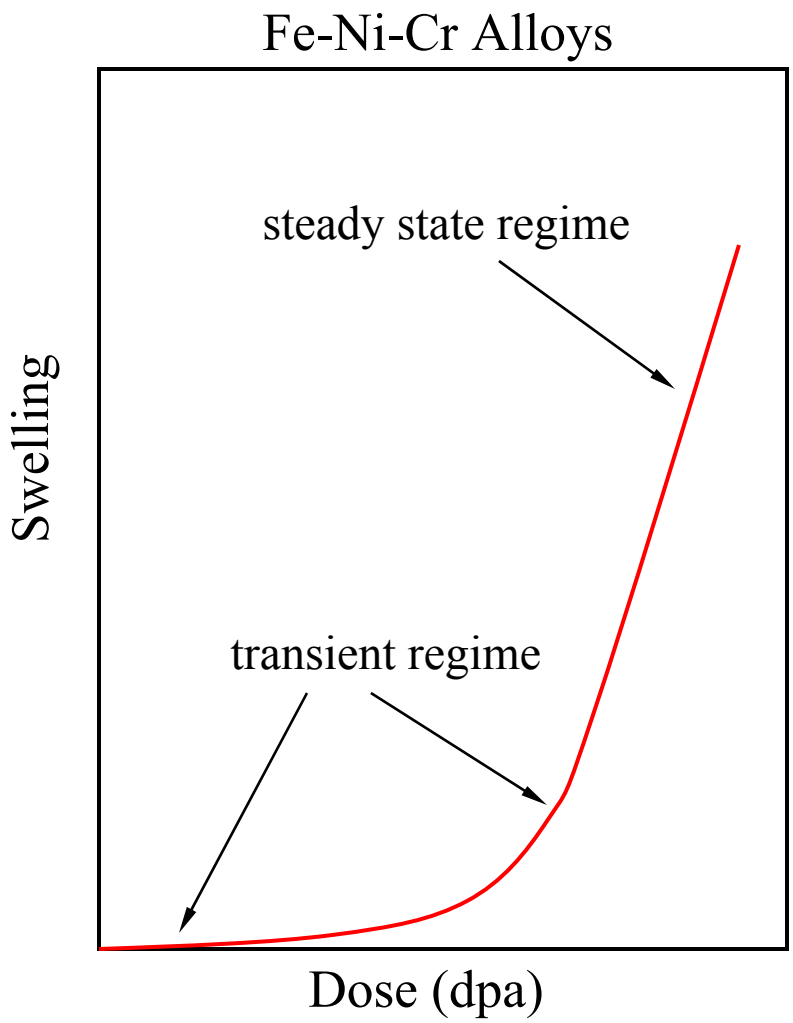
Example, springs are part of grid alignment devices in PWRs

Easily Observed Swelling



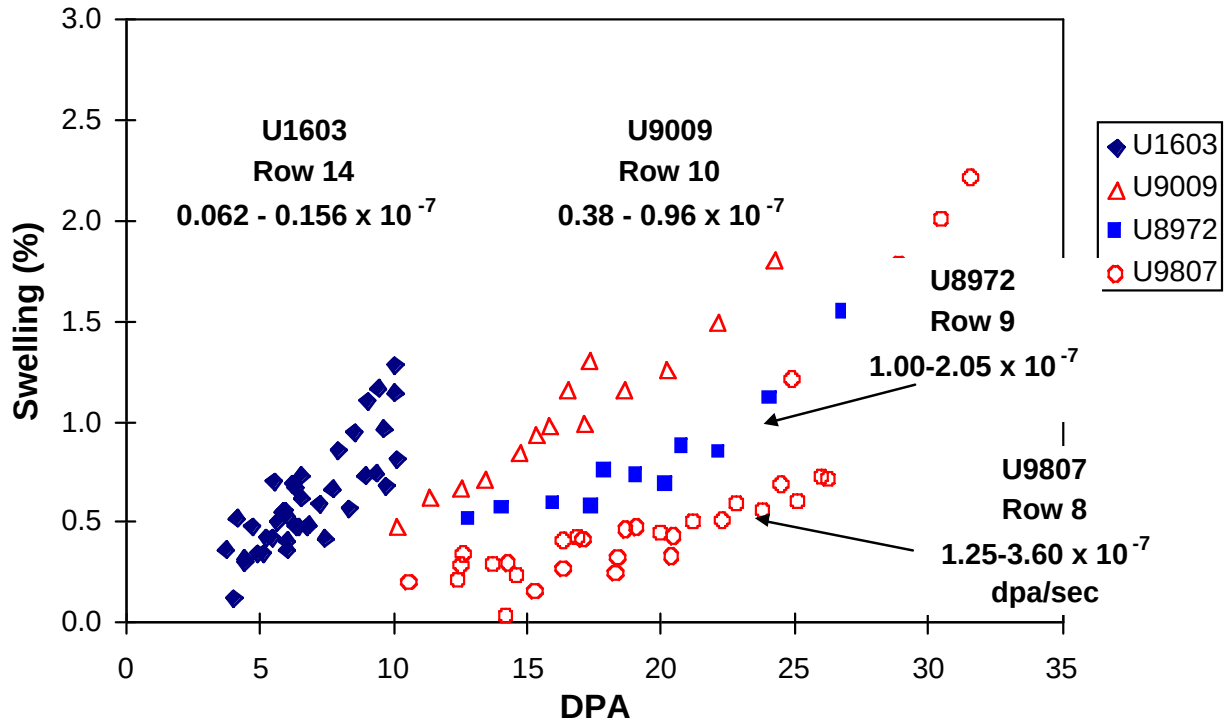
- **Swelling: Volume increase in a material caused by void formation and growth**

Transient Swelling Regime

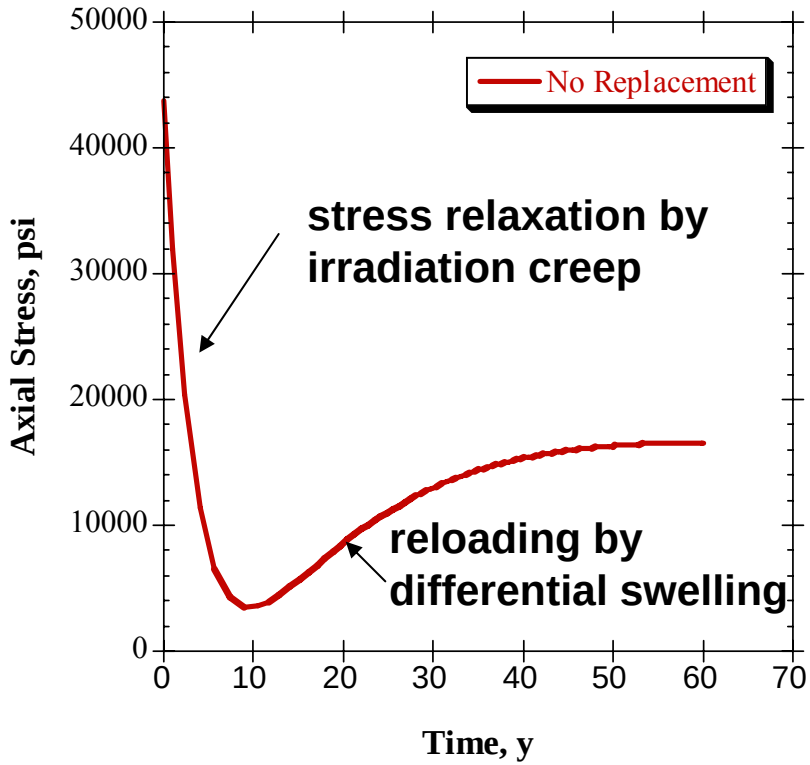


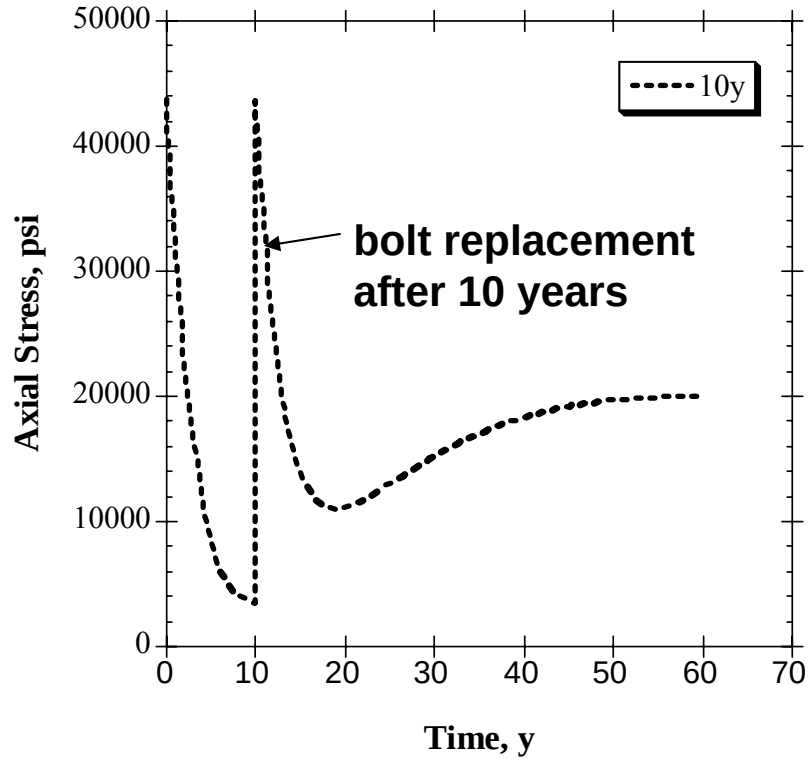
The length of the transient regime determines component lifetimes and is affected by composition, dose rate, dose, temperature, and cold-work

Swelling and Displacement Rate



Stress Relaxation





Garner

Irradiation Assisted Stress Corrosion Cracking

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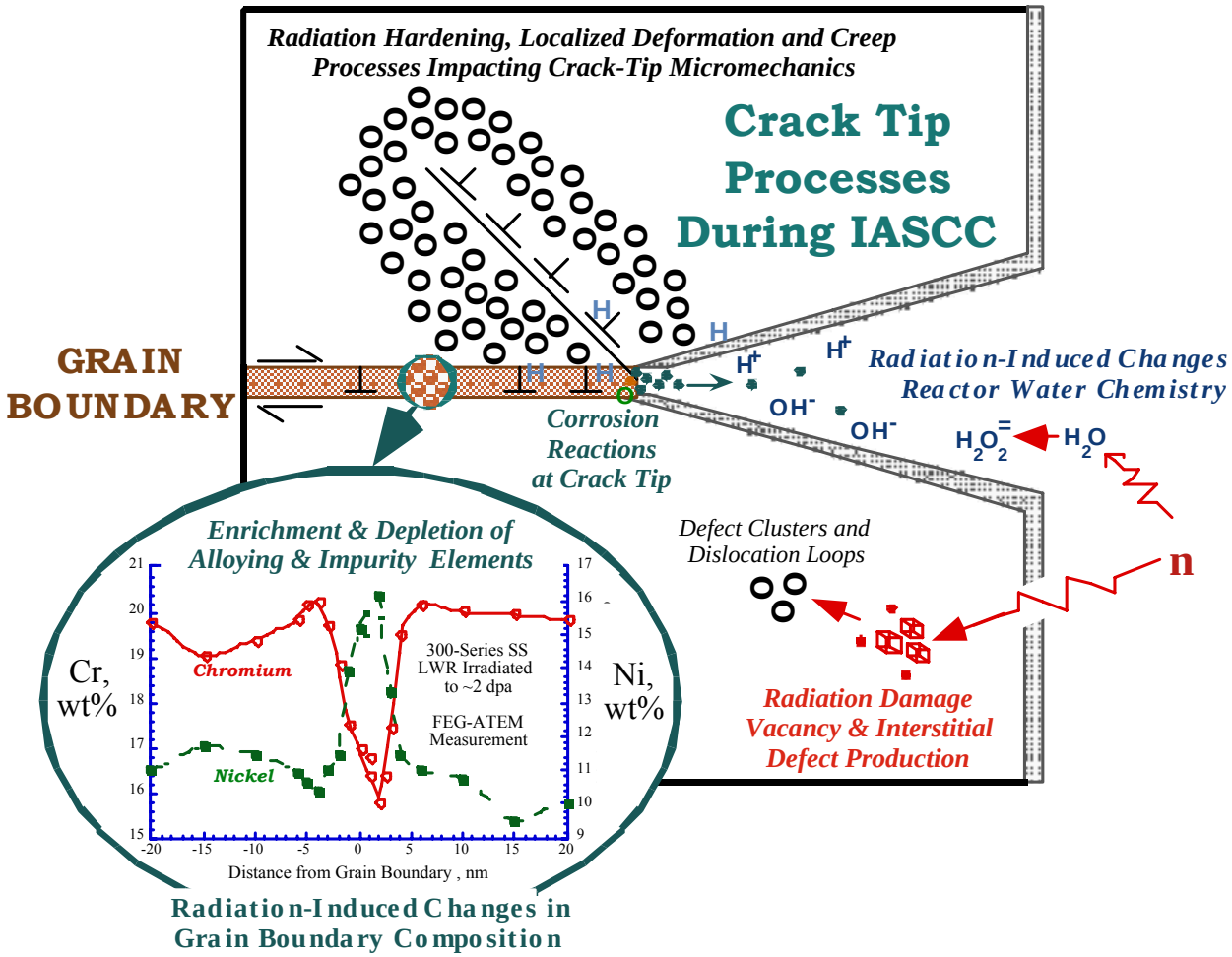

Seen in PWRs and BWRs

Combined effects of radiation hardening, radiation-induced grain boundary composition changes, and changes to water chemistry due to radiolysis

S. M. Bruemmer, 2001 Env. Deg. Conf

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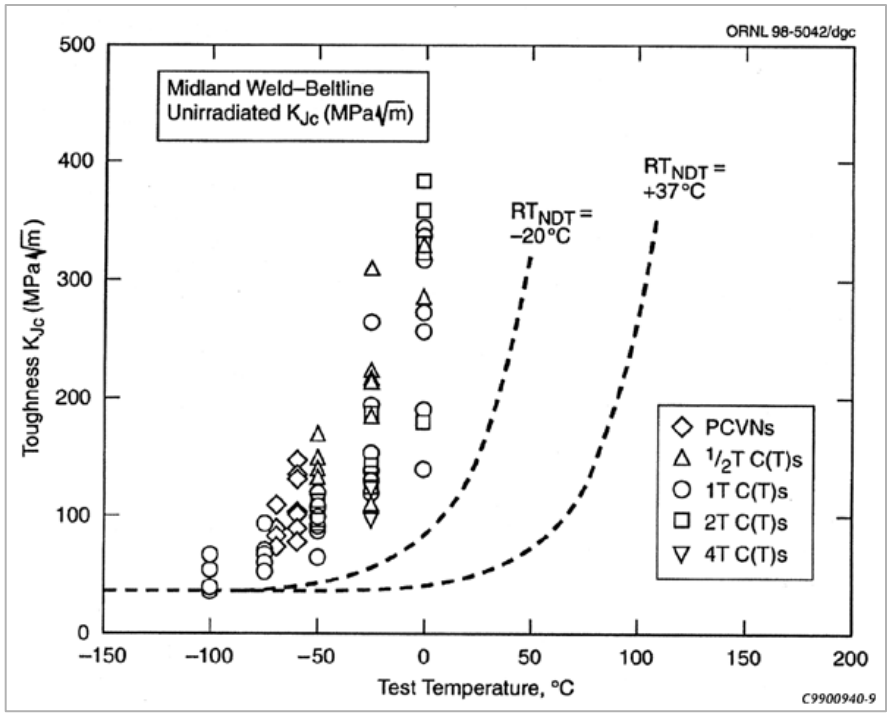
Theme 1

Reduction in uncertainty allows for extended component lifetime

Fracture Toughness



Desire to use plant specific fracture toughness to determine allowed operational limits

Positioning of ASME K_{Ic} and K_{Ia} Curves By RT_{NDT} Shows Potentially Significant Overconservatism For Midland Reactor Low Upper-Shelf Weld

Theme 2

Degradation of properties is driven by changes in microstructures that are driven by radiation

Prediction of properties requires prediction of microstructures

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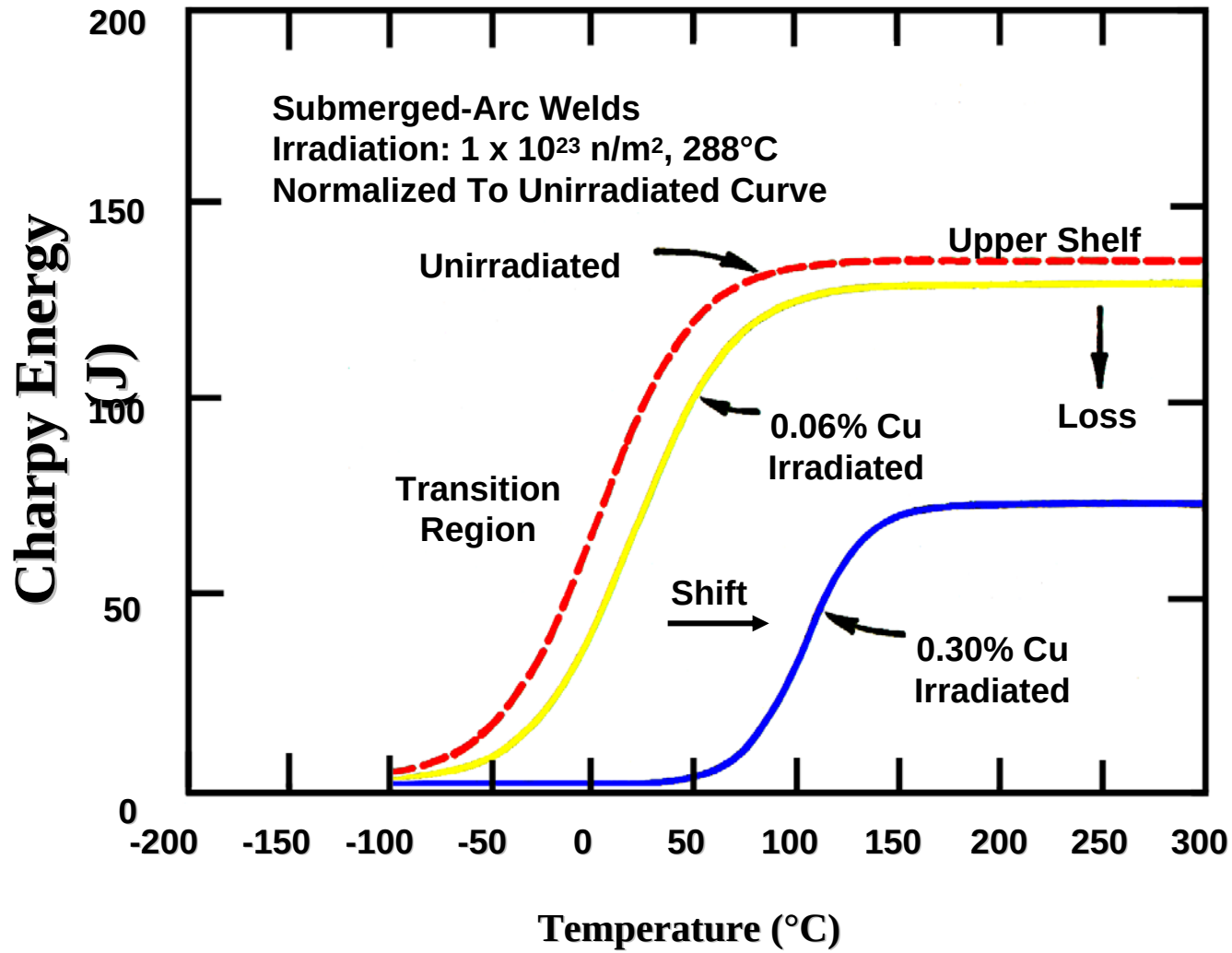
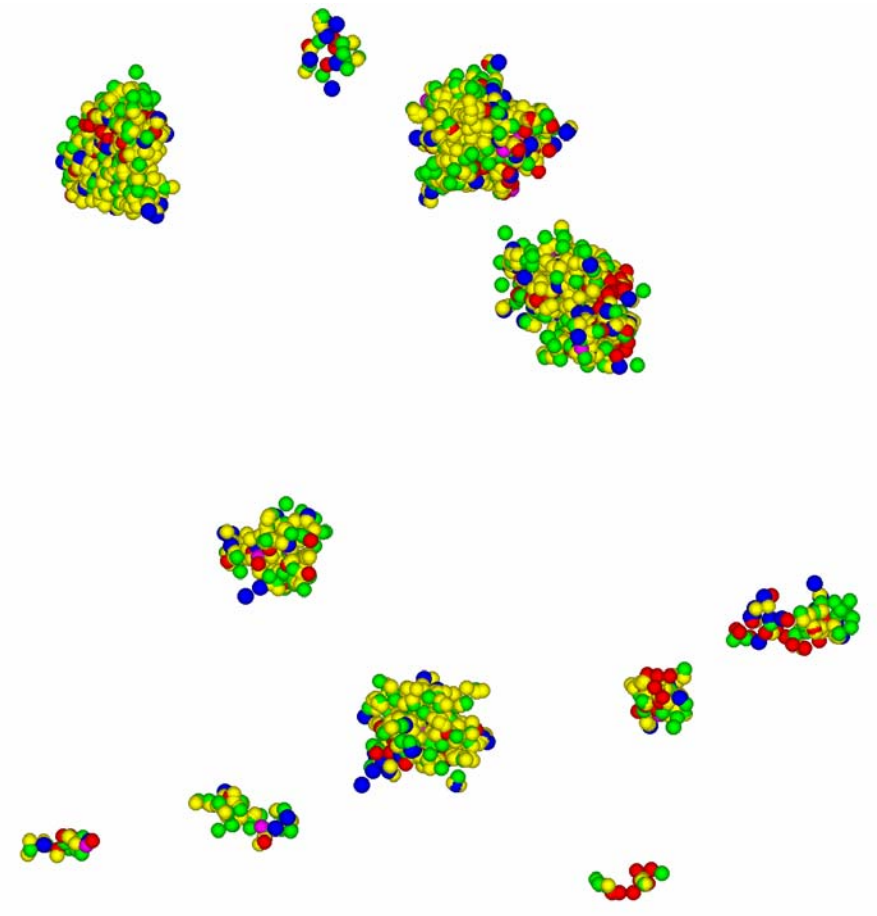
Charpy Energy-Composition



Irradiation Causes Ductile/Brittle Transition Temperature Shift and Upper Shelf Energy Loss — Copper Increases The Effect

Atom Probe Tomography



- Copper-rich precipitates (CRP) would form at RPV temperatures with no irradiation but extremely slowly
- Build up of CRP depends on displacement damage rate but density will saturate when copper is depleted from matrix
- Binding of Ni and Mn increase size, increasing effect on embrittlement
- Manganese Rich Precipitates may form at low copper concentrations

Fe Cu Ni Mn Si P atoms

Theme 3

Accurate modeling of radiation induced microstructural development requires the ability to model microchemical changes in complex alloys

Master Curve

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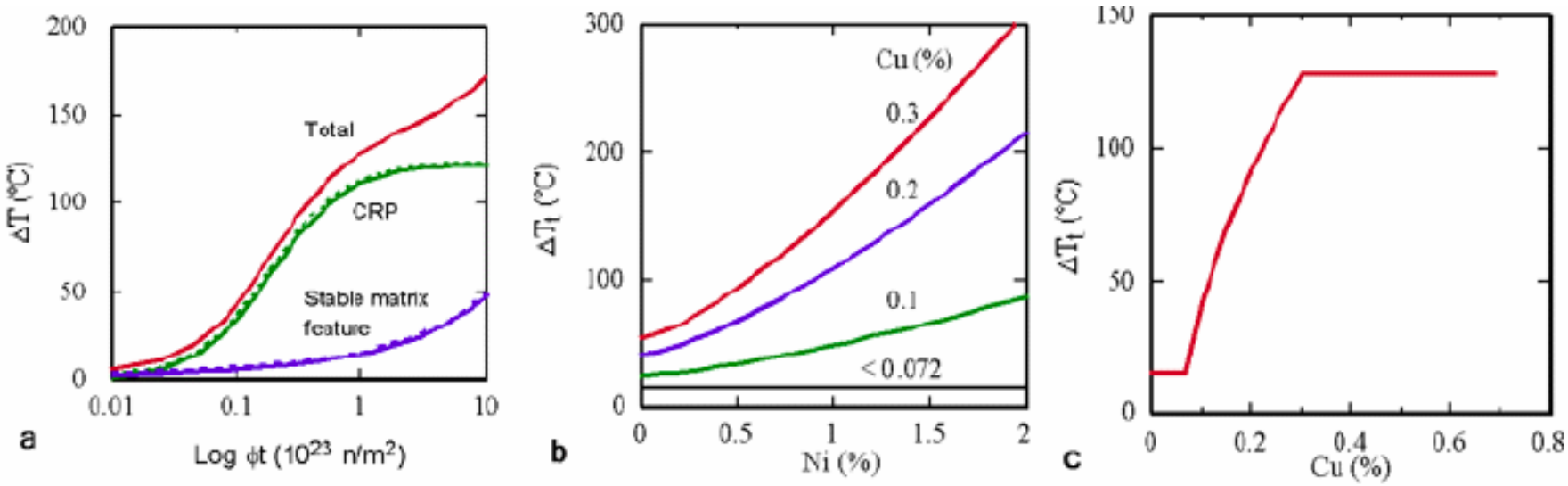
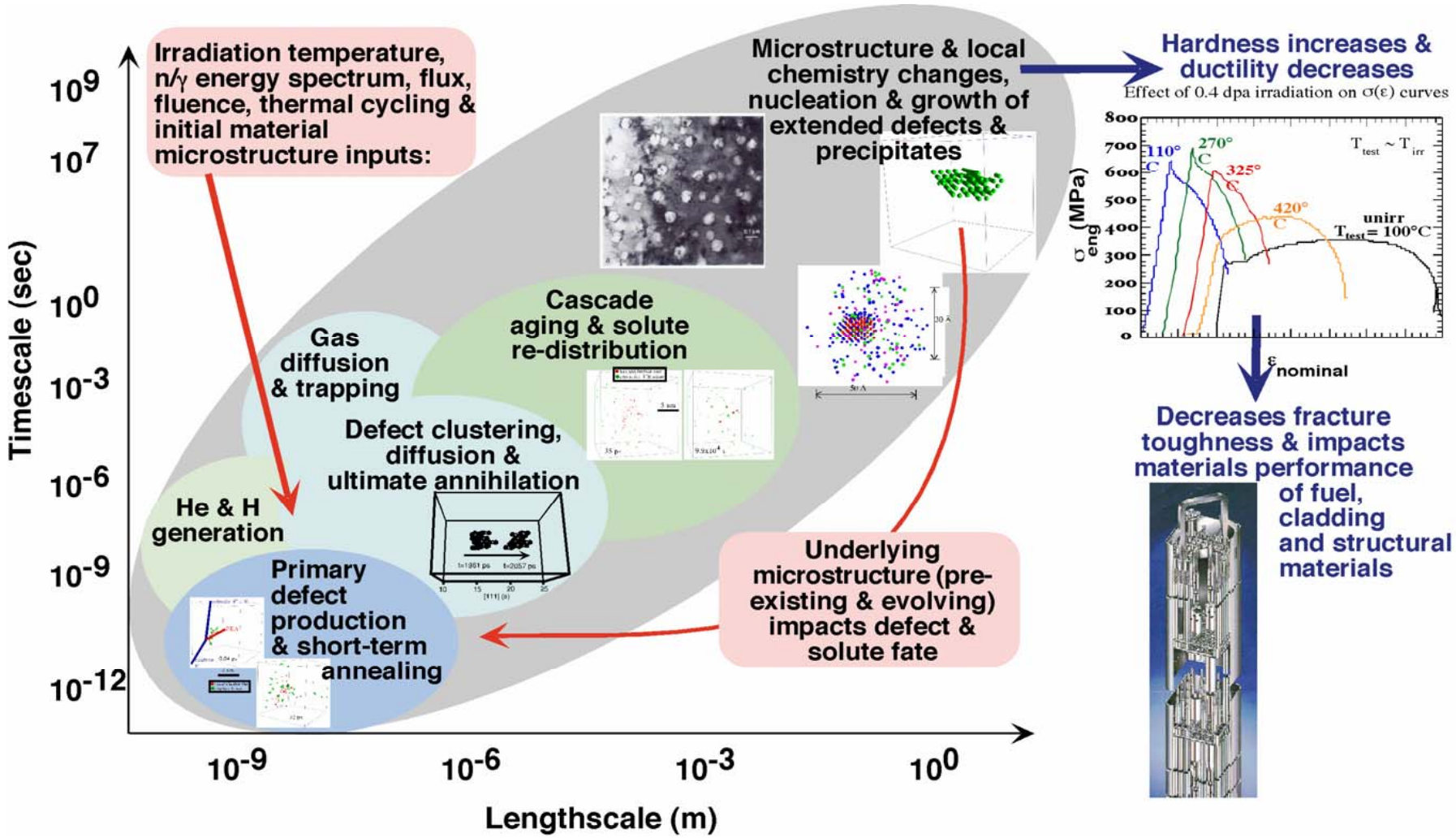
Courtesy S. Rosinski

Embrittlement Models



- Physically-based statistical model correlations for temperature shifts for:
  - a. Fluence
  - b. Bulk Ni and Cu concentration
  - c. Bulk Cu concentration

Odette and Lucas, JOM 53(7) 2001, 18-22



William Wolfer, LLNL

Needs

Understanding and predicting radiation response of complex materials requires coupled studies that include:

- Modeling technique advancements
- Improved models and interpretations of models of physical systems
- Experiments that provide data to support the advancements in theory
- Availability of improved experimental probes.

An aggressive research agenda would make available modern material science manufacturing and analysis techniques to the study of systems with inherent radioactivity.

Backups

Embrittlement Models

•The best predictive models for temperature shifts show most hardening comes from SMF and CRP

$$\Delta T_t = A f_{smf}(T_i, \Phi t, P) + B f_{crp}(Cu, Ni, \Phi, \Phi t)$$

These models still lack detailed descriptions of many variables, some of which are

- •Effect of dose rate in the intermediate Φ regime
- •Effects of secondary variables such as manganese or phosphorus
- •Through-wall attenuation
- •Potential for forming late blooming phases in low-copper steels
- •Thermal embrittlement or other new phenomena that might occur at long-times or very high Φt, beyond the current database

Odette and Lucas, JOM 53(7) 2001, 18-22

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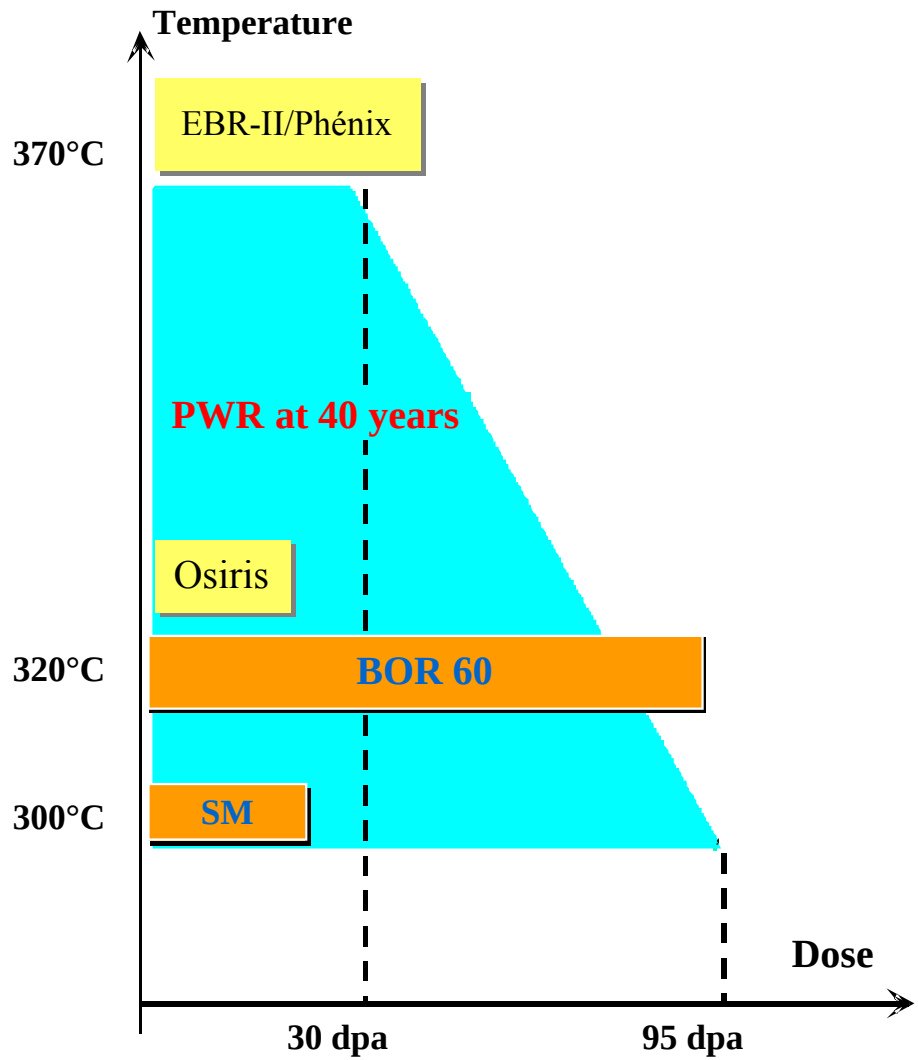
PWR Operating Conditions



Segregation and Swelling

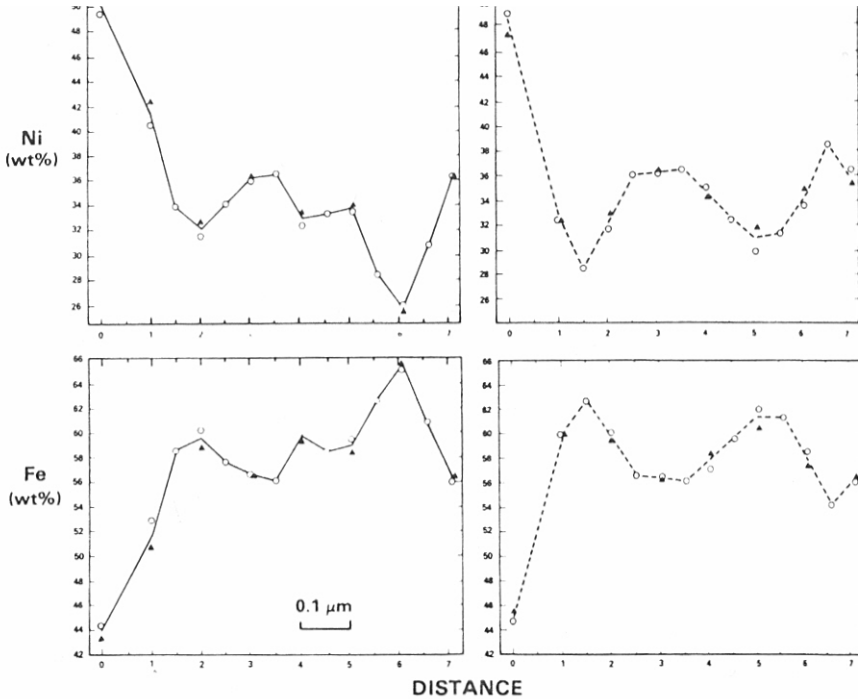


FIG. 8—*Compositional traverses starting from void or inclusion-precipitate markers. Note the reproducibility when measured twice on separate days.*

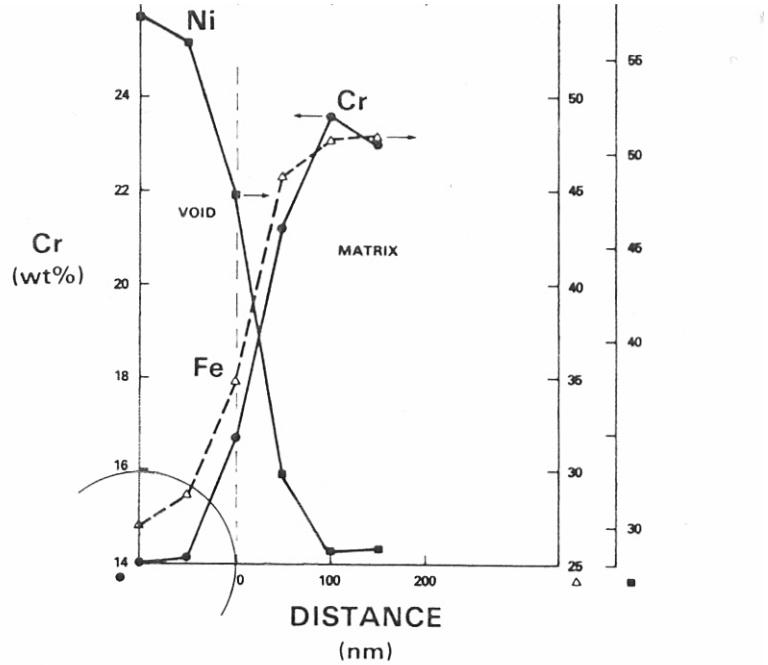


FIG. 11—*Concentration profiles observed in the vicinity of a void surface in Fe-35.1Ni-21.7Cr alloy irradiated to 7.2 × 10^{22} n/cm^2 (E > 0.1 MeV) at 538°C.* [21]. *Note the reduction in matrix nickel content due to segregation at the void surfaces.*

Brager and Garner

Charpy Energy-Composition

- **Copper has been identified as a critical element causing embrittlement through the formation of copper-rich clusters/precipitates**
- **The degrading effects of nickel in the presence of copper has been demonstrated in commercial alloys**
- **Phosphorous has been found to cause sensitivity in very low-copper alloys but a synergistic effect is not evident in high-copper alloys. In practical terms, P levels are so low in operating vessel material that they do not have a significant effect.**

Embrittlement and nanoscale features

•Unstable matrix defects (UMD) that form in cascades even in steels with low or no copper, but that anneal rapidly compared to typical low flux irradiation times

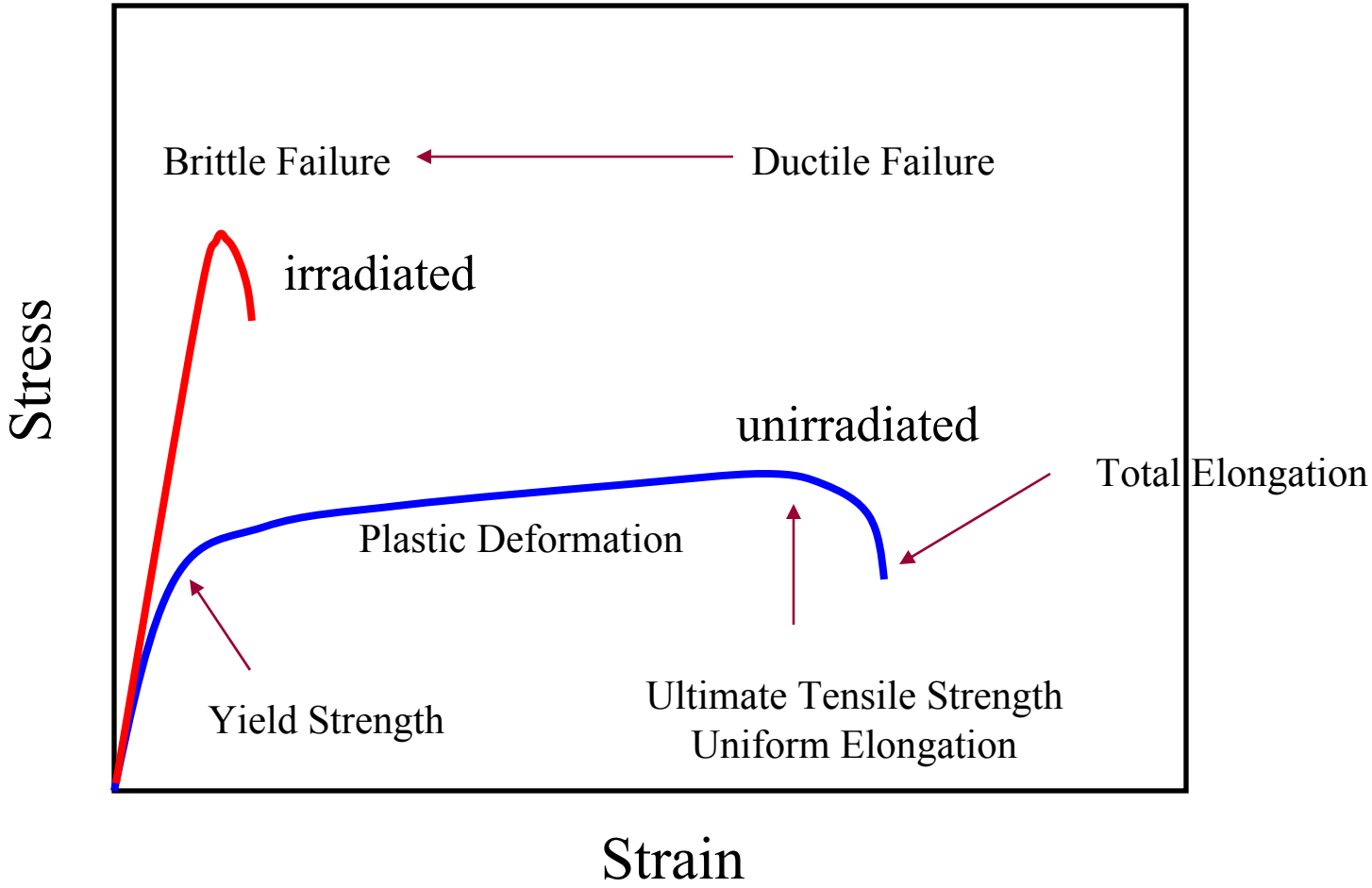
•Stable matrix features (SMF) that persist or grow under irradiation even in steels with low or no copper

•*Copper rich or catalyzed manganese-nickel rich precipitates (CRPs/MNPs)*

Odette and Lucas, JOM 53(7) 2001, 18-22

•Non-hardening embrittlement can also be caused by radiation-induced solute segregation such as phosphorus segregation at grain boundaries

Radiation Hardening



Loss of ductility is the concern

Temperature dependence of void formation in annealed 12X18H10T irradiated in BN-350

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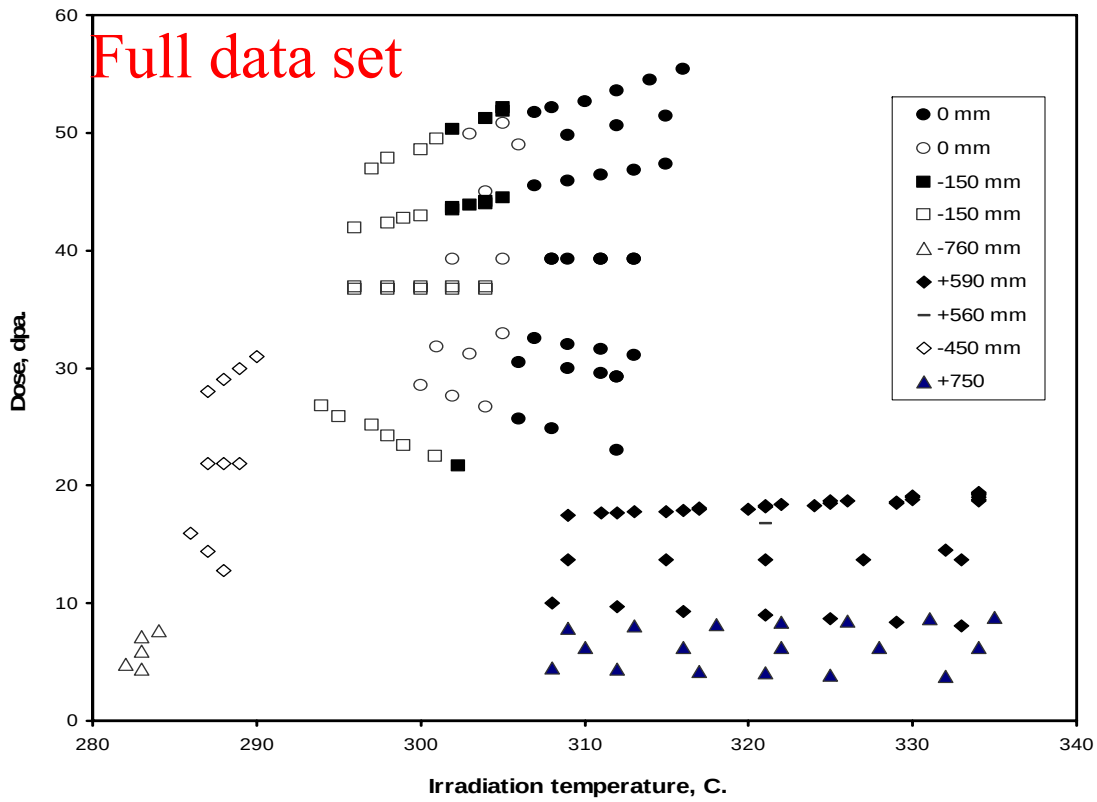

Closed symbols denote voids observed

Void formation does not occur below ~300ºC in this steel when irradiated in a fast reactor at PWR-relevant dpa rates.

Similar 300ºC limit is observed in VVER-1000 and BK-50.

Void ≠Significant Swelling

From Garner

Dislocation Loops in Irradiated 316 SS (2 dpa)

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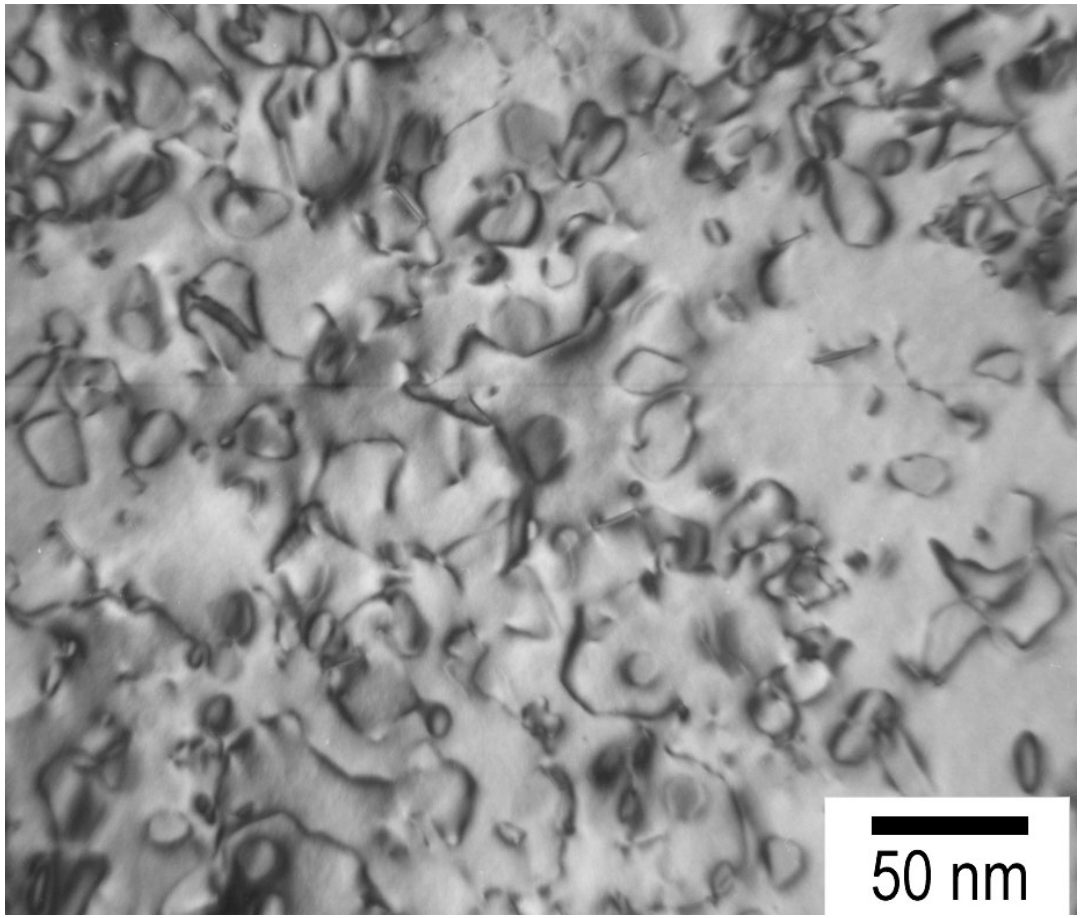

Design Windows

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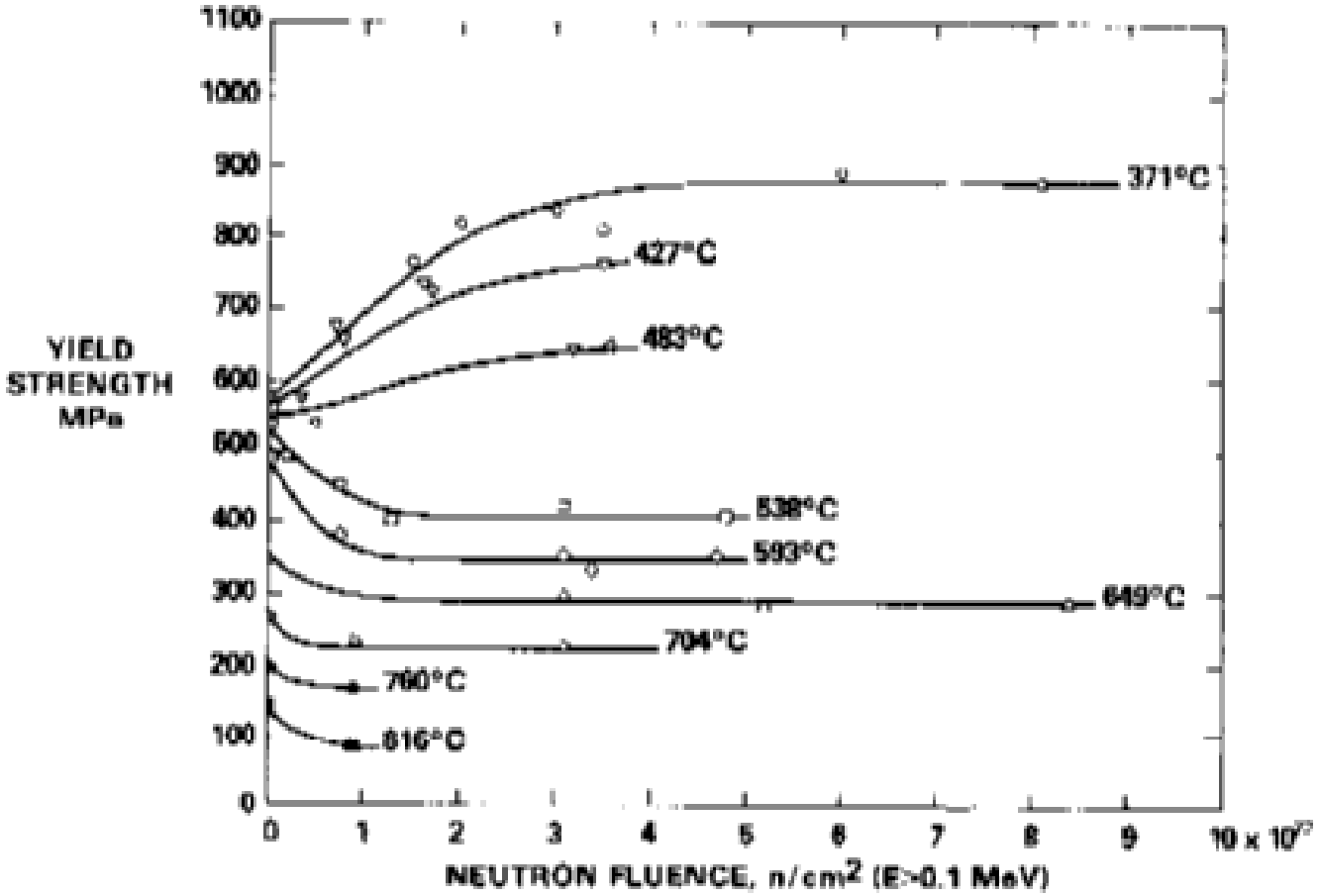
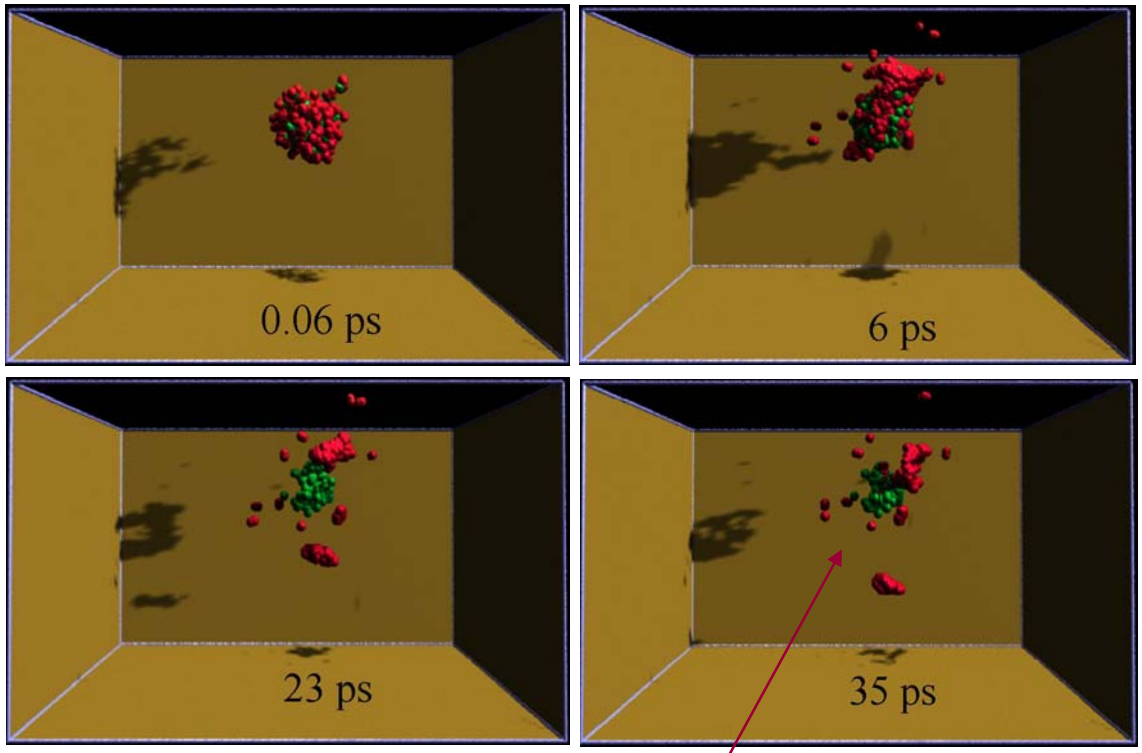
Hardening of Austenitic Steels



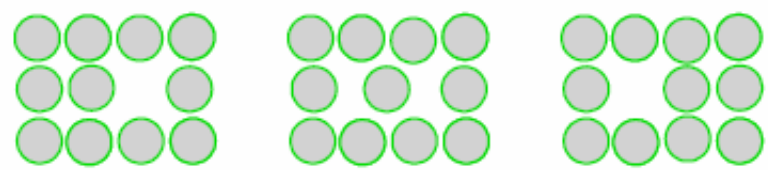
Radiation Damage



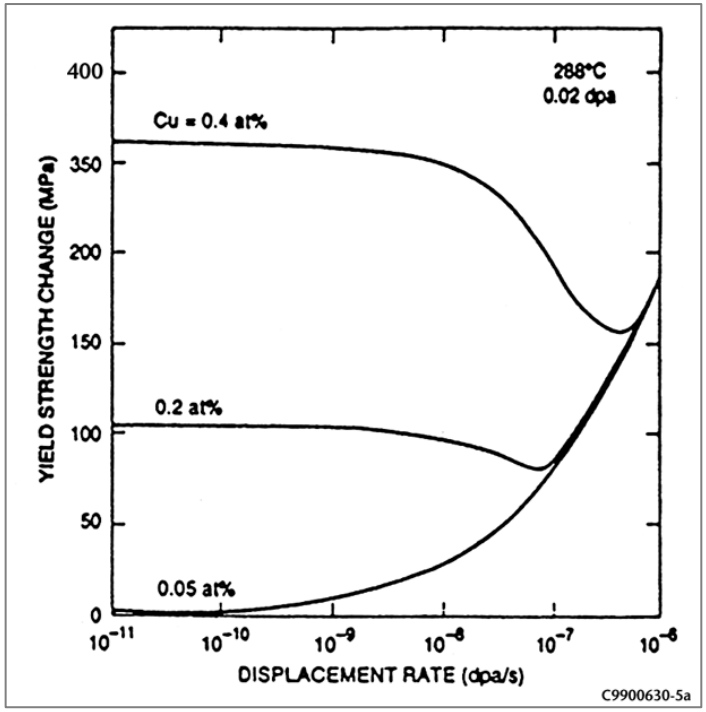
Vacancies
Interstitials

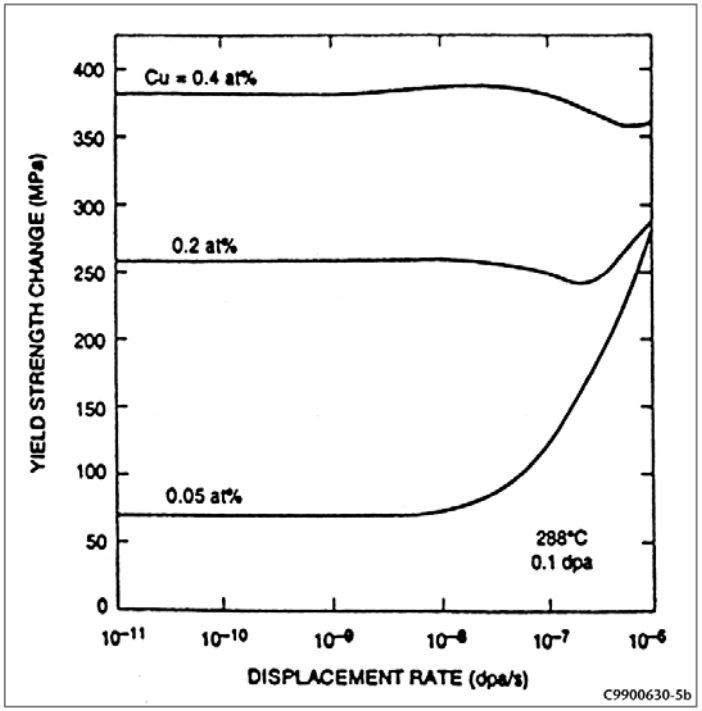
Brian Wirth, UCB

- Radiation-induced damage can come from
  - Immobile point defect clusters
  - Mobile point defects and point defect clusters



Model Dependence Of Yield Strength Change On Displacement Rate





- Results Are Relatively Insensitive Below ~5×10^{-9} dpa/s or about 3×10^{16} n/m^2/s (E>1.0 MeV)

- May Minimize Concerns About Surveillance Lead Factors and Use of Some Test Reactor Data

From Stoller

Swelling and Bulk Composition

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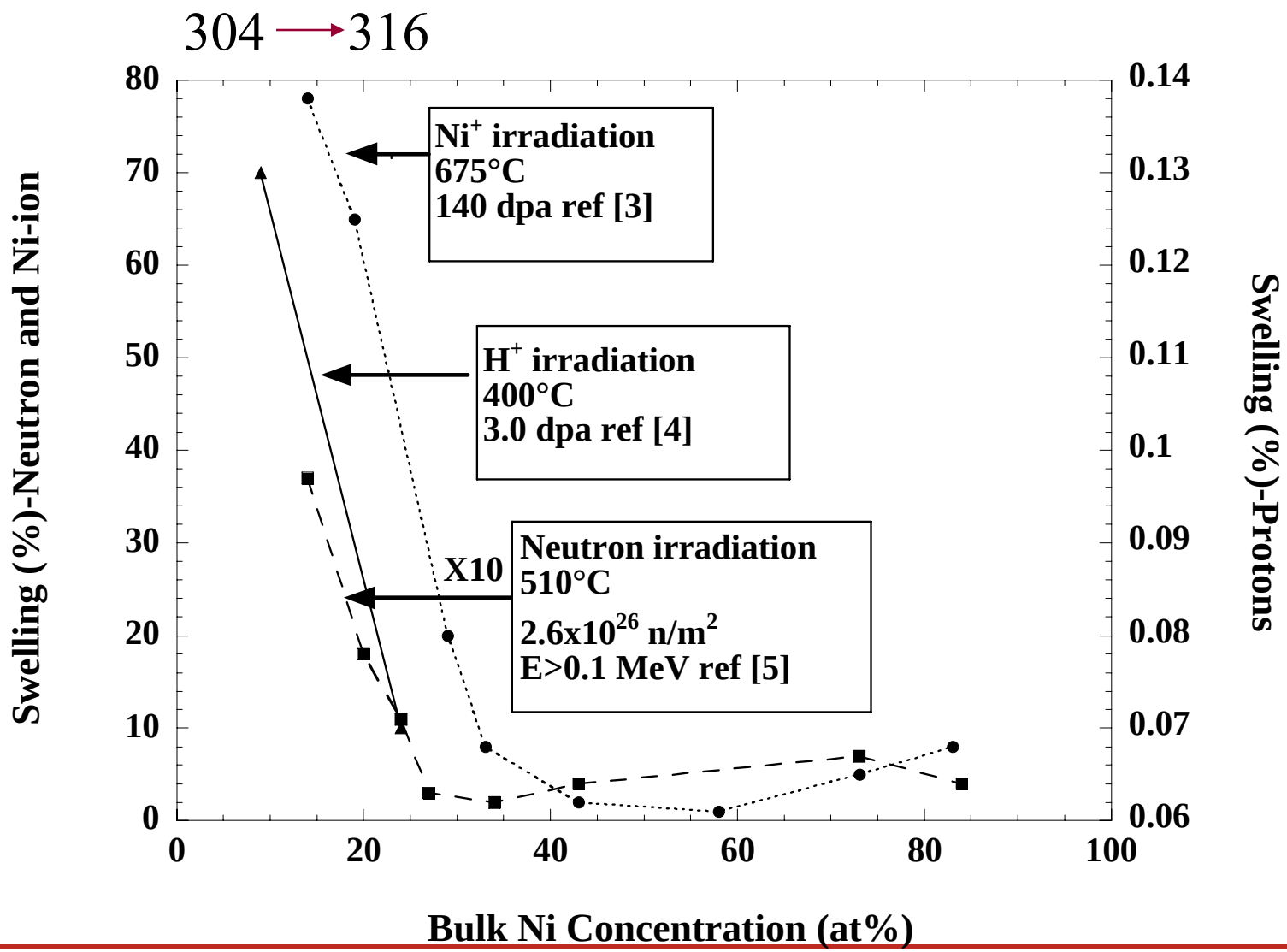
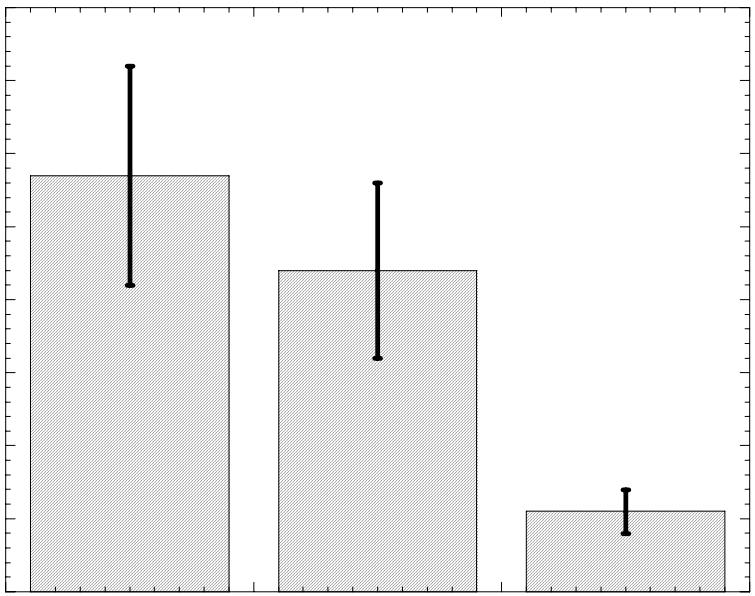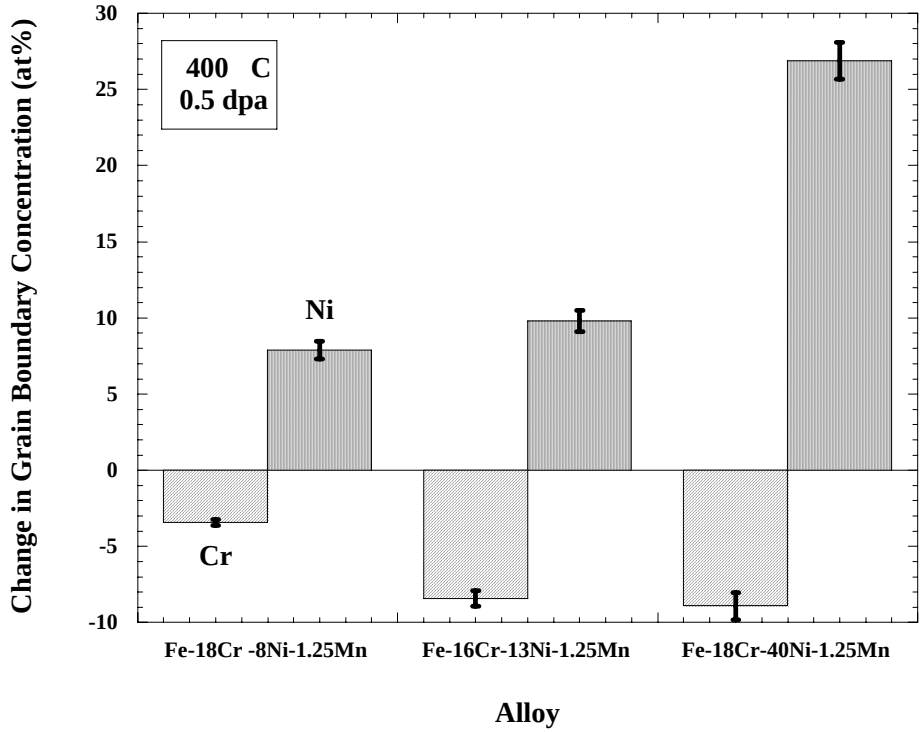
Segregation and Swelling