Deformation and Fracture Research on Fusion Reactor Alloy Systems - Status and Future Directions

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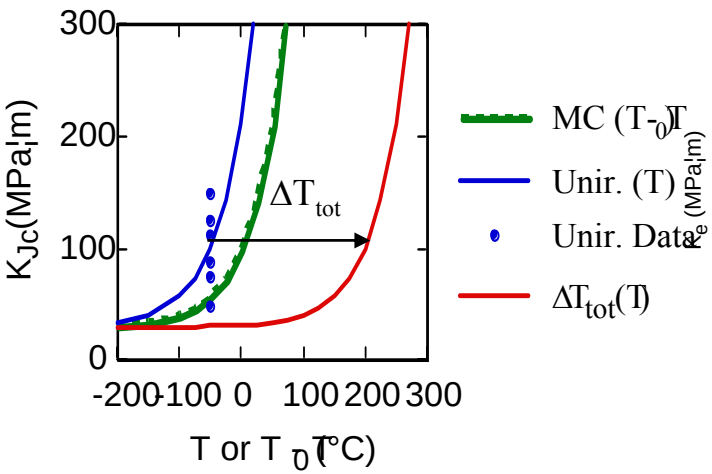
Key Cross-Cutting Issues

- Fracture toughness for defect tolerant assessments of fast fracture including irradiation embrittlement
  - Master Curve (MC)-Shifts (ΔT) Method
  - *underpinning* macro-micromechanical mechanistic models of size, rate, microstructure and embrittlement effects
- Constitutive-plasticity laws including irradiation hardening & softening processes and ductility loss
  - implications to structural integrity
  - *underpinning* dislocation-based constitutive laws and multiscale models of flow localization and ductility
- High performance materials
- Structural integrity assessments

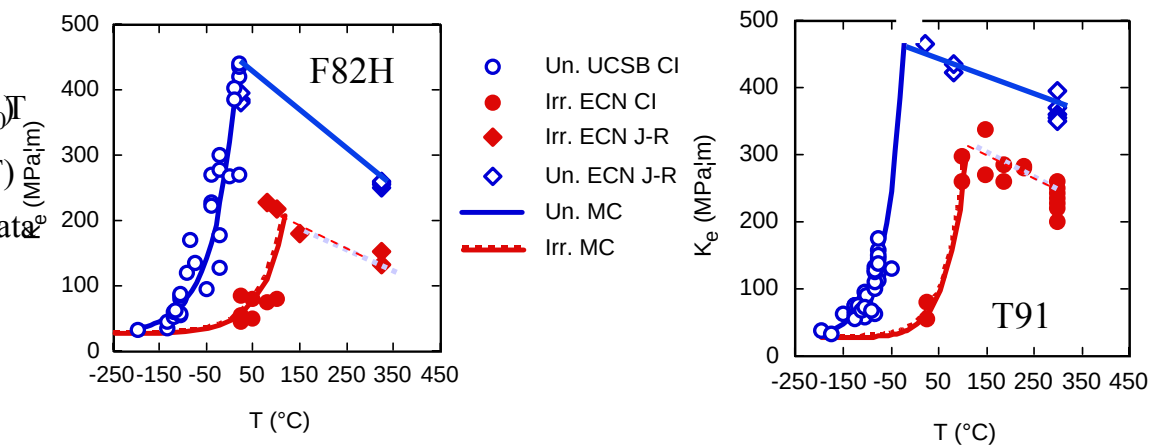
The MC-ΔT Method

- Select appropriate $K(T-T_o)$ shapes and measure baseline T_{ob}
- $T_o \approx T_{ob} + \Delta T_{irr} + \Delta T_{rate} + \Delta T_{size/geom} + \Delta T_{stat.} + \Delta T_{marg}$
- Need physical basis, models, test methods for shape & ΔTs
- Verification-implementation research underway - subject of international collaborations

Concept

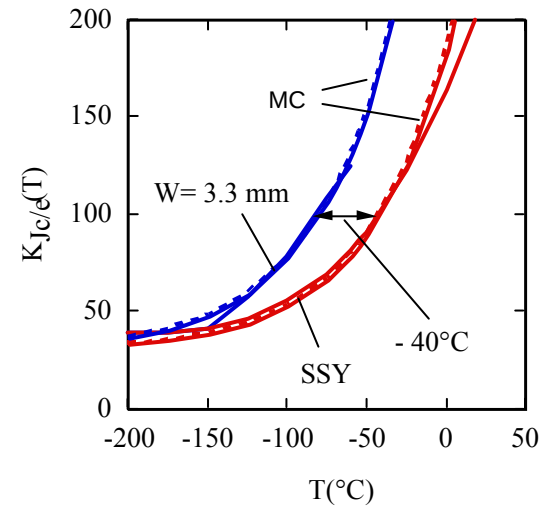


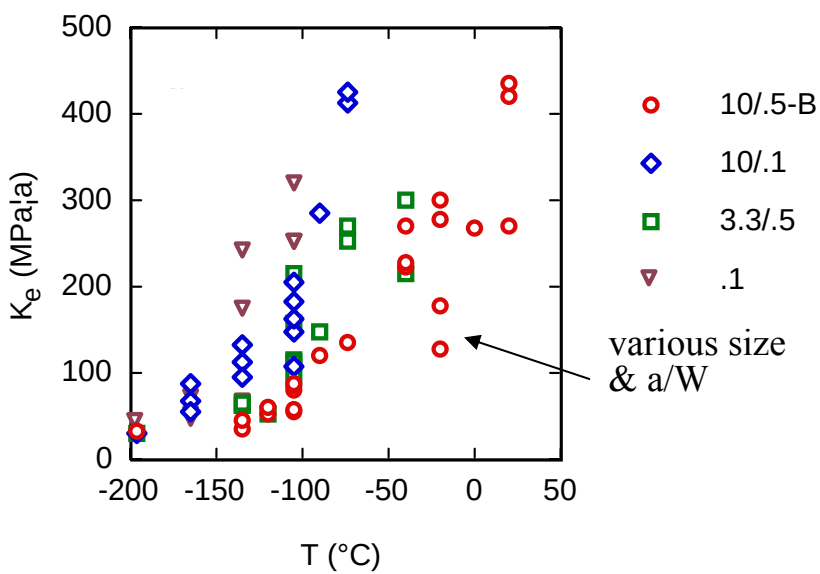
US- NRG Collaboration

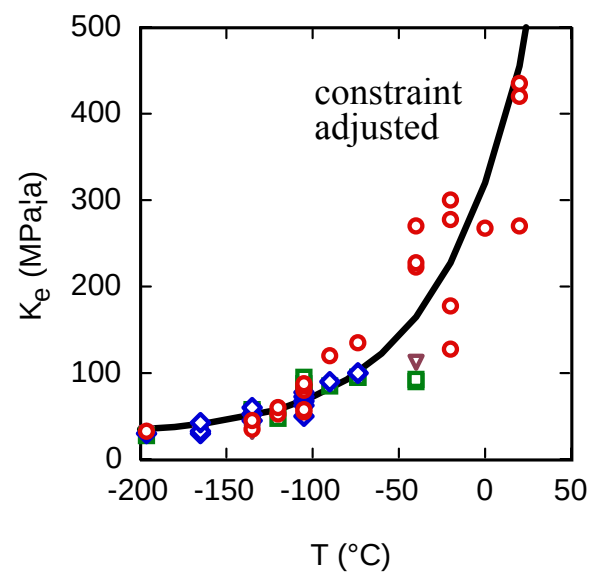


Micromechanical Models

- Physical models treat:
  - constraint-statistical size effects ΔT_o (small specimens to structures)
  - loading rate and irradiation effects
  - invariance of $K_{mc}(T - T_o)$ in small scale yielding







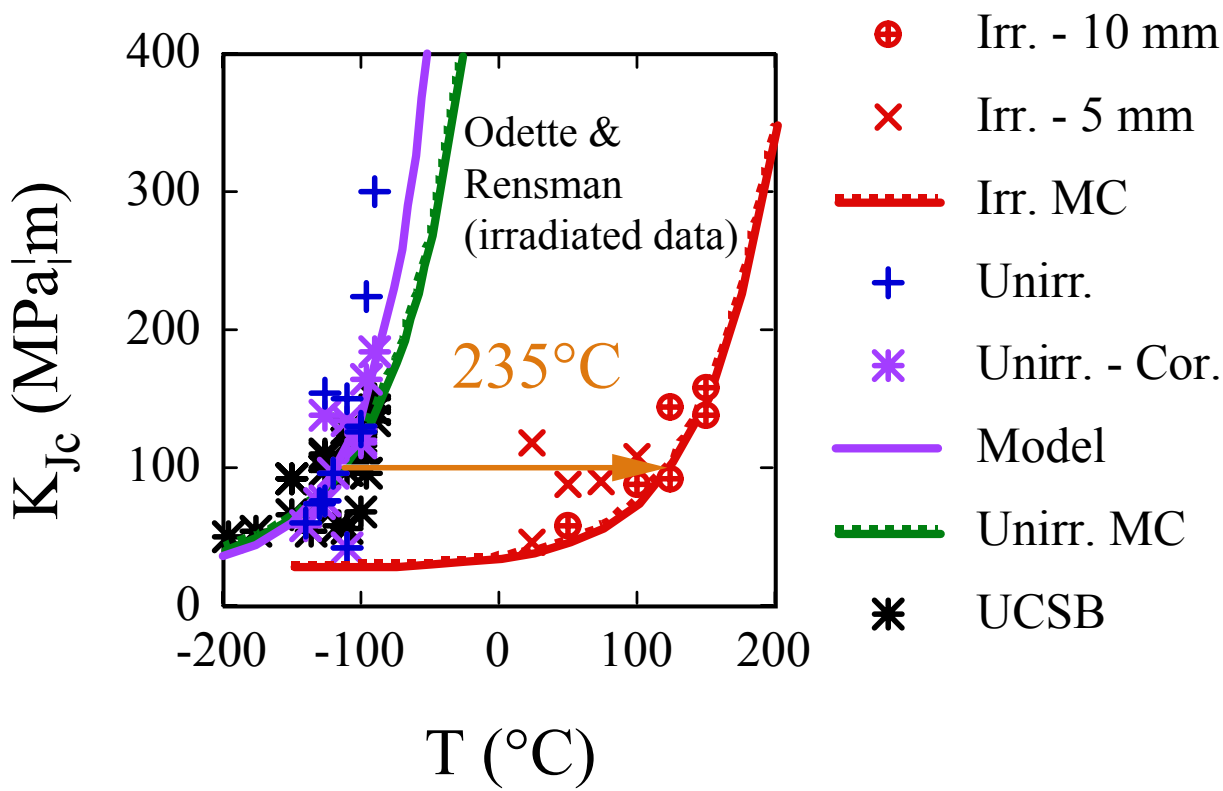
Master Curve (MC)-Shifts (ΔT) Method

- Status & recent progress (UCSB-ORNL-NRG-PSI-JAERI)

  - continued excellent promise & progress for LAMS & vanadium alloys for fundamental underpinning of invariant shape, modeling constraint and loading rate effects mostly unirradiated and but *limited* irradiated studies
  - large ΔT_o track $\Delta\sigma_y$ (bad news?) - consistent with models including post-yield constitutive properties
  - build on a massive study de-coupling and modeling of RPV steel(Rathbun et. al.) to demonstrate statistical crack front scaling in Eurofer 97 (Rensman et. al.)
  - completed irradiations for 'large' specimens JP11-12 (some tested), (MACE-PSI) and 1/3-PCC (NRG)
  - a core component of US-JAERI & JUPITER collaborations
  - extend to potential for ultra-small specimens (dfmb's)

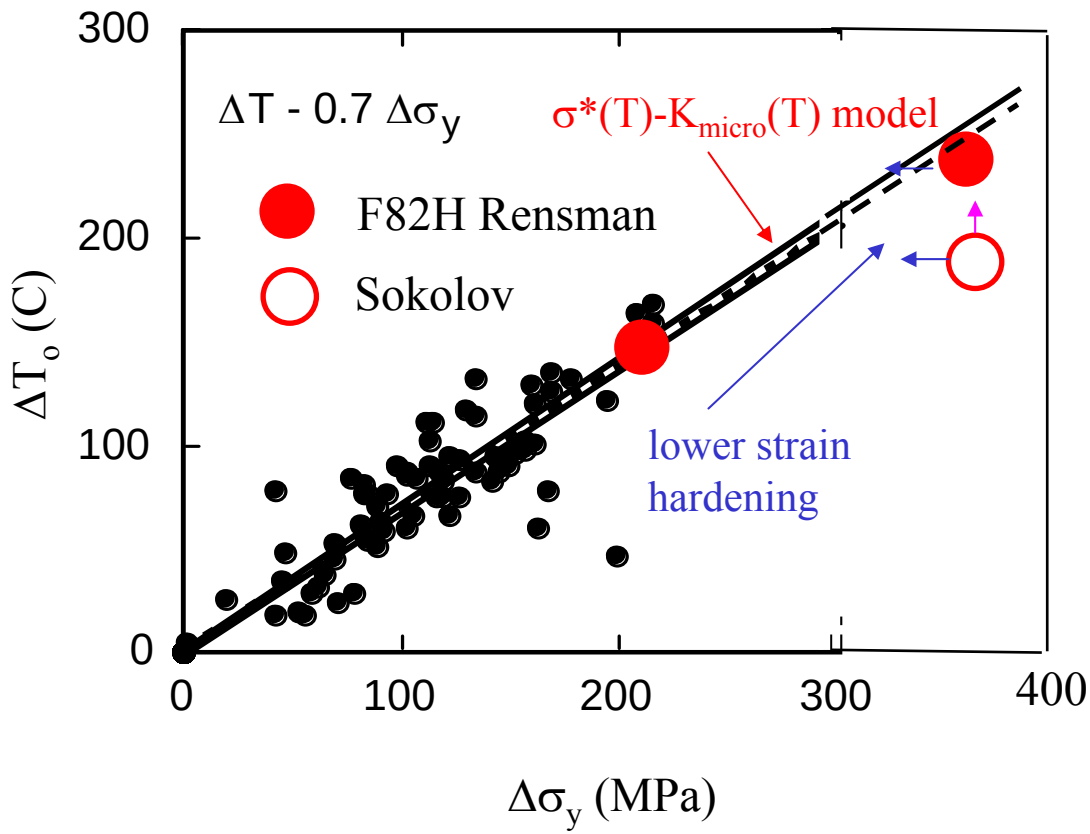
Irradiation ΔT_o - F82H

- Large shifts in T_o MC-ΔT analysis of 5 dpa-300°C



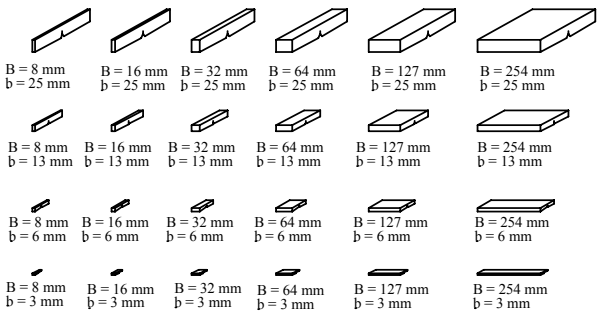
F82H ΔT_o-$\Delta\sigma_y$

- Consistent with RPV steel data and $\sigma^*(T)$-$K_{micro}(T)$ model
- Uncertainties in T_o, $\Delta\sigma_y$ due to factors like uncertainties in T_i
- Modest to strong effects of changes in post yield strain hardening



Summary - Shoreham Study (UCSB/NRC)

•b-B matrix Rathbun et. al.

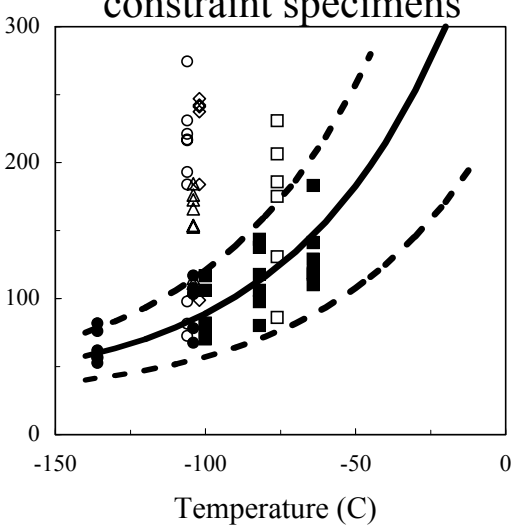


• PLUS 1TCT, PCC, 1/2PCC, 1/3PCC, Shallow-cracked PCC

b-B data

All 489 data - points

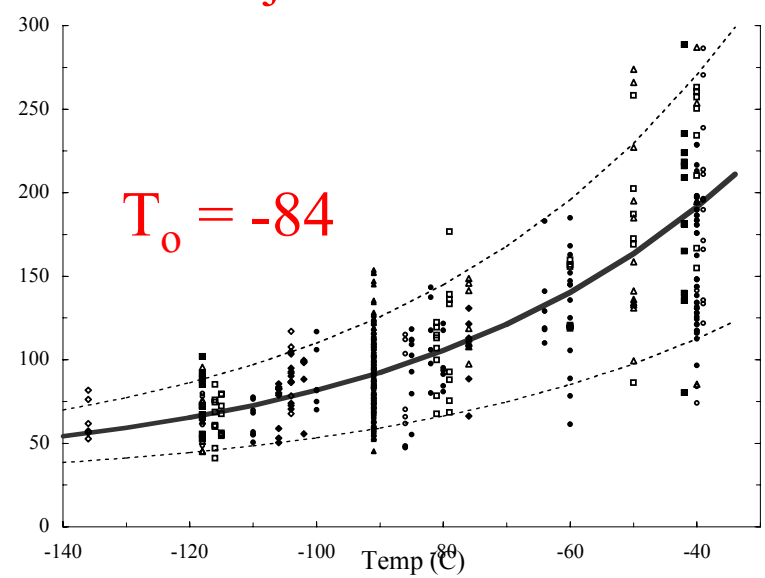
Calibration and low constraint specimens



Micromechanical constraint J/J_{ssy} and $B^{-1/4}$-K_{min} statistical size adjustments

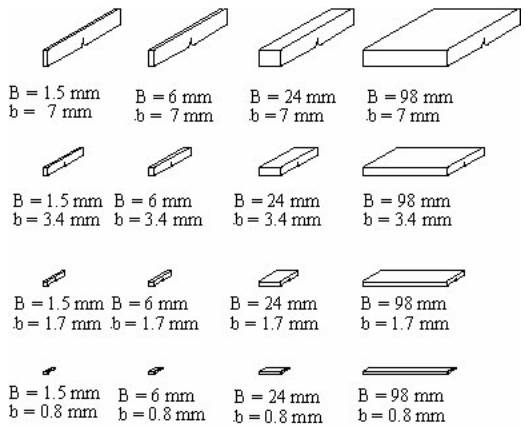
Independent database cf. Tregoning

Adjusted Data - MC



Summary - Eurofer 97 Study (UCSB/NRG)

- Rensman et. al (UCSB visit 6/15-8/15) - potentially enormous beneficial implications to FW&B structures

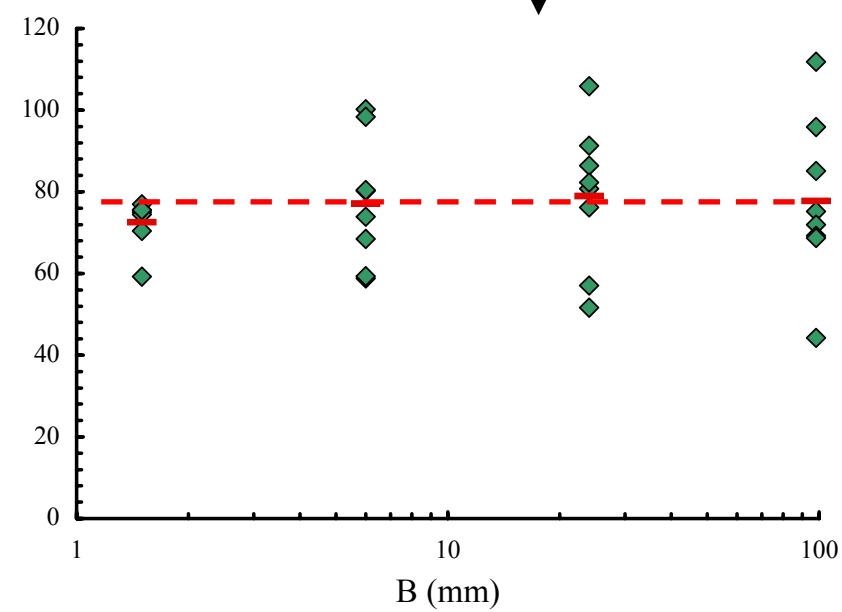


tested

Micromechanical constraint J/J_{ssy} and $B^{-1/4}$-K_{min} statistical size adjustments

constraint loss

$(K_{Jr} - 20)[25.4/B]^{1/4} + 20$



Key Unresolved Fracture Issues

- Unresolved issues

- MC-ΔT method verification - particularly larger, high dose specimens (*some* data from European-HFR irradiations) & data base accuracy/adequacy (e.g., T_i uncertainty)
- ductile tearing, shear band decohesion, interactions with cleavage, mixed mode (K_I/K_{III})
- effects of 'flow localization' and strain softening constitutive laws
- orientation (e.g, T/L-S) & alloy homogeniety effects as general issue - also confound experimentals and impose database requirements
- non-irradiation hardening (or softening) embrittlement - - including applicability of the MC method intergranular fracture

Non-Irradiation Hardening ΔT

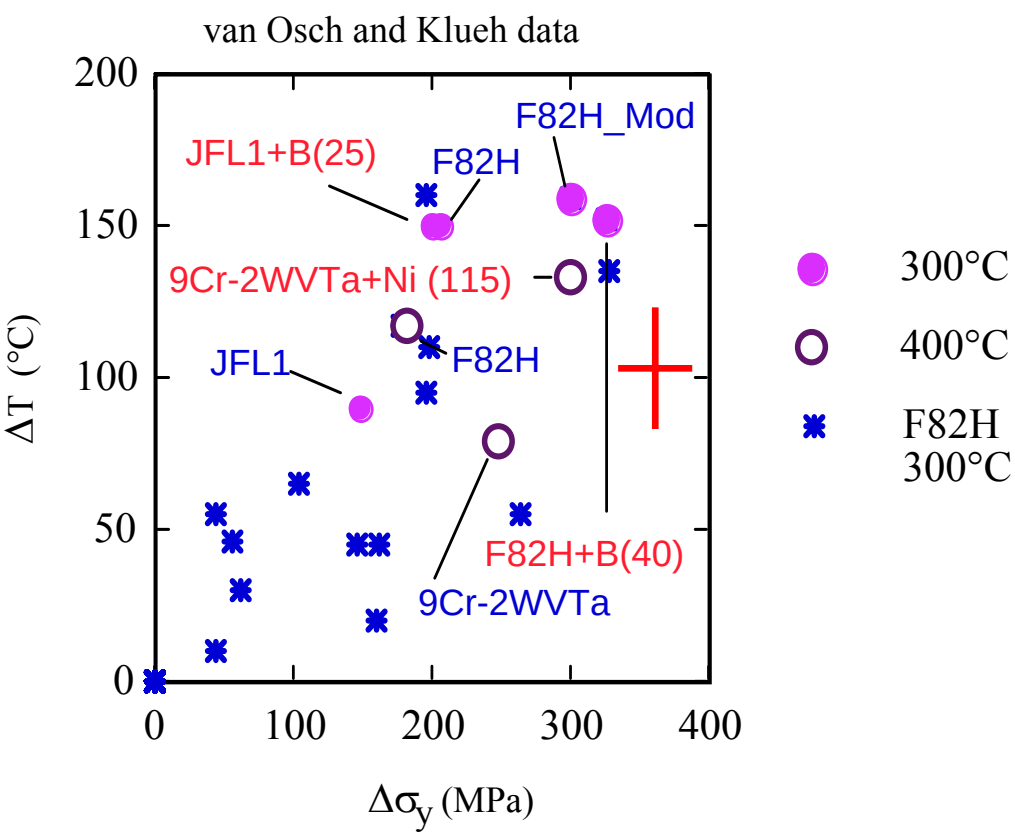
- Embrittlement also caused by a number of thermal processes (e.g. DSA) - often assisted by irradiation - associated with
  - structural instabilities, precipitation or coarsening of brittle (Laves) or hardening (α') phases, substructure recovery/grain growth (softening)
  - solute segregation
  - damage - deformation (creep) and fatigue
- These processes are *synergistic* with irradiation hardening and signaled by a large ($> \approx 0.8$ C/MPa) or even negative (softening) $\Delta T/\Delta\sigma_y$ - with values up to 5 - often marked by IG fracture and occur more at higher temperatures (> 400°C)
- Confused with He effect on fast fracture/embrittlement?

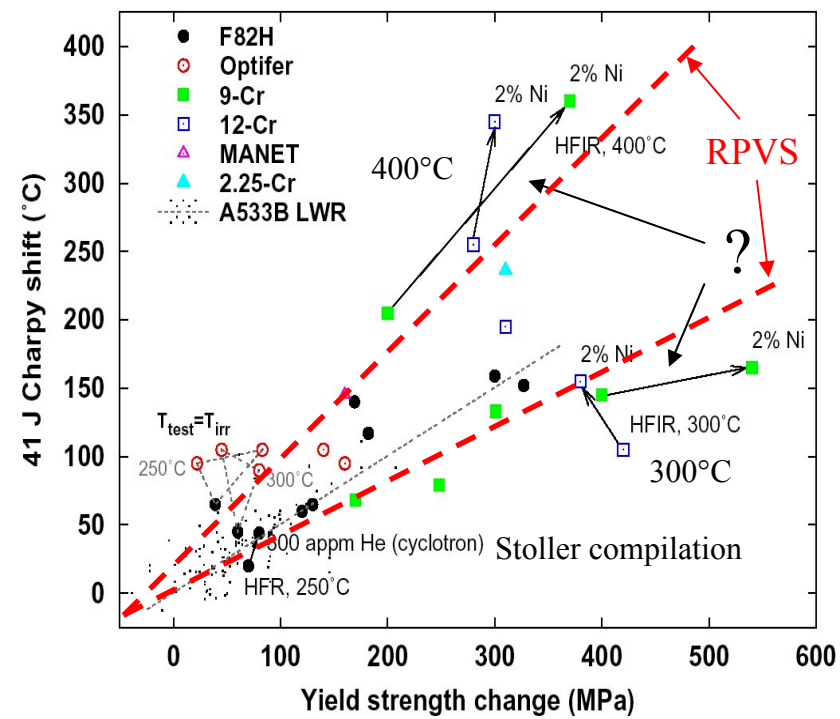
Helium Effects on Fast Fracture

- Some data sets *seem* to show He effect but <u>all</u> are highly confounded by uncontrolled variables (e.g., Ni and B additions, different alloys, anomalous heat treatment, unexplained reactor effects - including on hardening), usually absolutely minimal data and large scatter
- Higher $\Delta T/\Delta\sigma_y$ in well controlled experiments would suggest He effect, but could also be do to other mechanisms arising from factors like Ni or B additions
- Examination of the cited data shows no systematic effect of He on $\Delta T/\Delta\sigma_y$ - most show larger unexplained effects of other uncontrolled variables
- US-JAERI collaboration will attempt a semi-controlled, systematic and 'single variable' evaluation of this issue for the first time

Helium Effects on Fast Fracture

- No significant published evidence - either theoretical or experimental - of a non-hardening helium effect on fracture
- Data is limited and regime of very high He largely unexplored





D&F in US-JAERI and JUPITER

US-JAERI

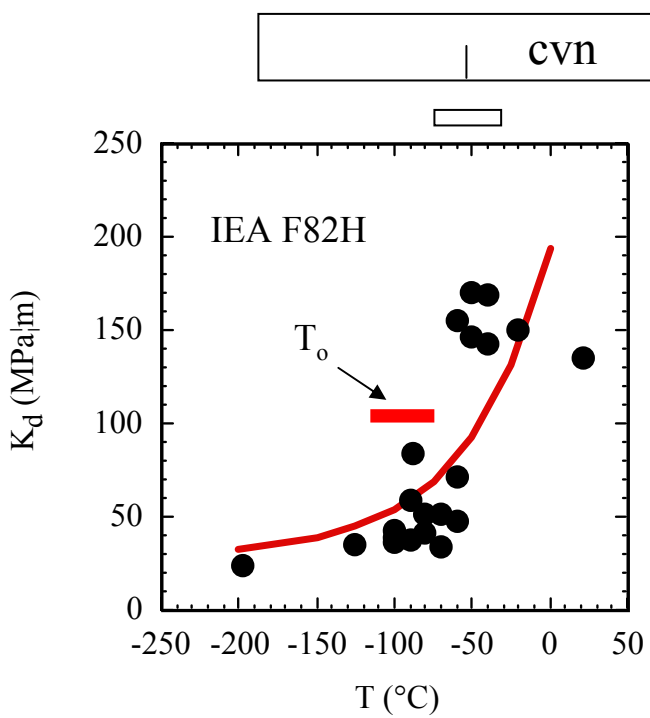
- Base materials
  - IEA-F82H, F82H-mod.1, mod.2, mod.3, F82H-HIP, Eurofer
  - F82H+1.4%Ni(^{n}Ni, ^{58}Ni, or ^{60}Ni), F82H-60ppmB(nB, 0, 50%, or 100%^{10}B)
- D & F specimens: DFMB (D & F), HT-1/3PCC, 0.18T-DCT, 1/3CVN, minitensile, shear punch hardness disc coupons
- Dose/Temperature
  - 10, 40 dpa (target), 6 dpa (unshielded/shielded RB) @ 300, 400, 500 C plus rabbits

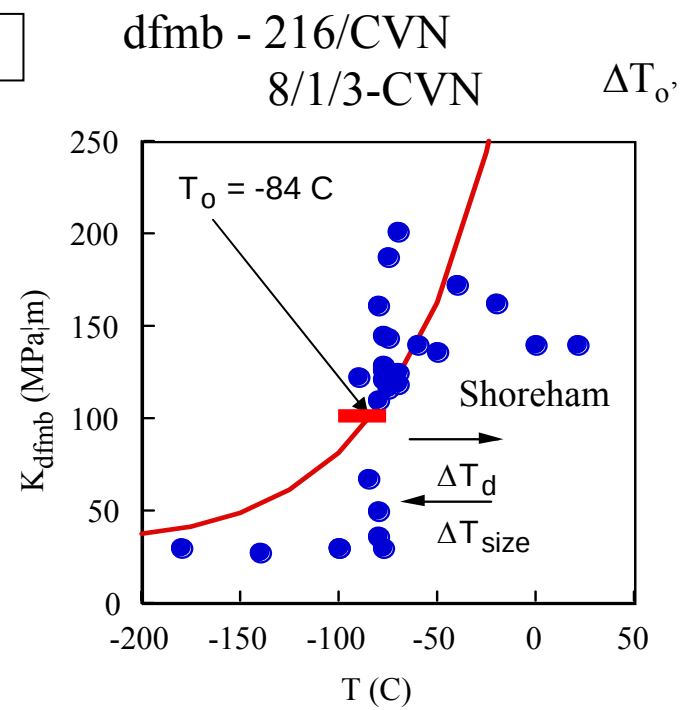
US-JUPITER

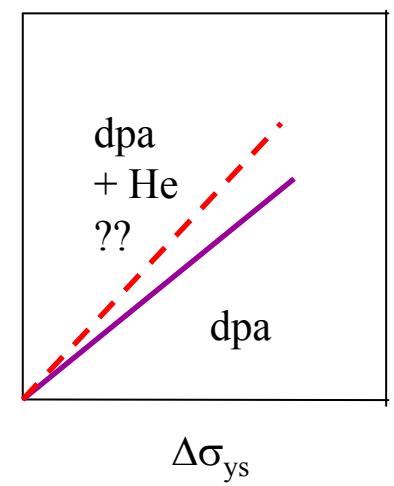
- Base materials
  - V-4Cr-4Ti (Heat832665 (Base/Weld), NIFS Heat-2)
- D & F specimens: DFMB (D and F), HT-1/3PCC, 0.18T-DCT, 1/3CVN, minitensile, shear punch hardness disc coupons
- Dose/Temperature
  - 10 dpa @ 450, 600, 700 C

DFMB Dynamic Fracture Toughness

- Pre-cracked bend bar with base 1/6 PCC dimension
- Shoreham steel dfmb data consistent with MC with T_o = - 84 C but F82 H shifted higher
- More work needed (underway) to validate & establish limits
- To be used in US-JAERI and JUPITER



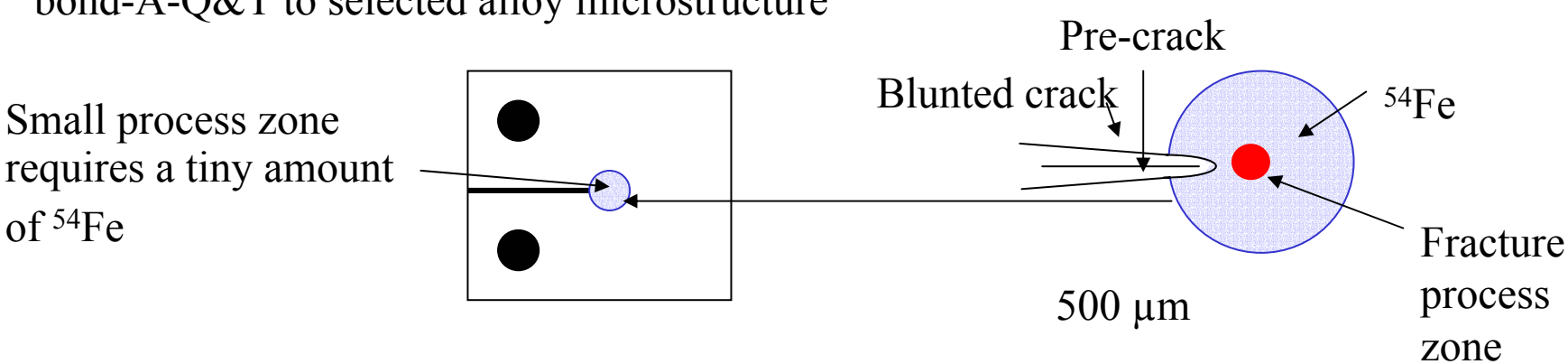




Other Small Specimen Initiatives

- Advanced microhardness techniques for $\sigma(\varepsilon, \varepsilon', T)$
- Non destructive test sequences on multipurpose specimen configurations - specially for a number of fundamental studies tasks
- Composite specimens - example using ^{54}Fe to do single variable study of high helium effects on fast fracture

Steps: fabricate ^{54}Fe alloy 'wire' -diffusion bond-A-Q&T to selected alloy microstructure

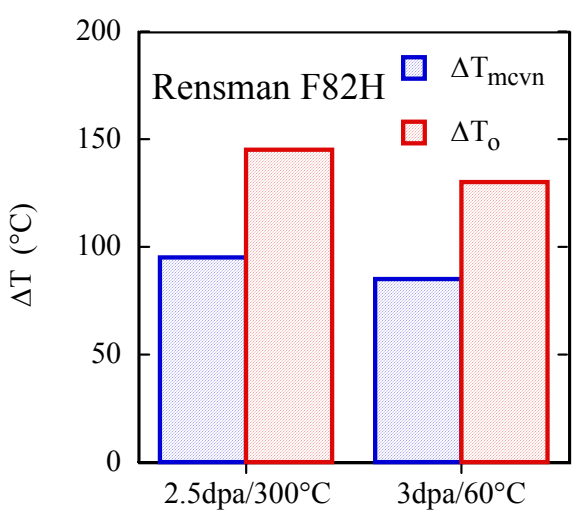


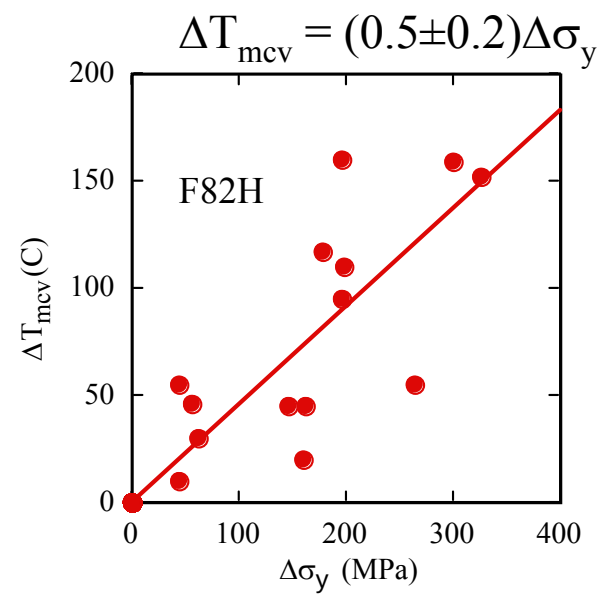
Other Fracture and Fatigue Issues

- Ultra-small specimens like dfmb's
- Use and interpretation of (subsized) Charpy data and the DBTT (in retreat but not beaten)
- Shallow, surface cracks, bi-axial stresses, secondary stresses, thermal shock, dynamic fracture
- Warm pre-stressing, creep relaxation
- Environmentally assisted cracking
- Creep crack growth
- Fatigue, fatigue crack growth, creep fatigue - monsters and merit much more attention
- Optimized LAMS, evolutionary higher performance steels and advanced nanocomposited ferritics

Sub-Sized Charpy Impact Tests

- Larger MCV database generally follows $\Delta\sigma_y$ - $\Delta T \approx C_m \Delta\sigma_y$
- No unique DBTT -- T_{dbt} depends on many test details
- $\Delta T_{mcv} \neq \Delta T_o$ material dependent and may not even provide proper alloy ranking -- general trend $\Delta T_{mcv} < \Delta T_o$
- Large inherent transition scatter - even with a large number of tests (few or no cases) significant uncertainties T_{mcv} & ΔT_{mcv} - also uncertainties in $\Delta\sigma_y$ and T_i





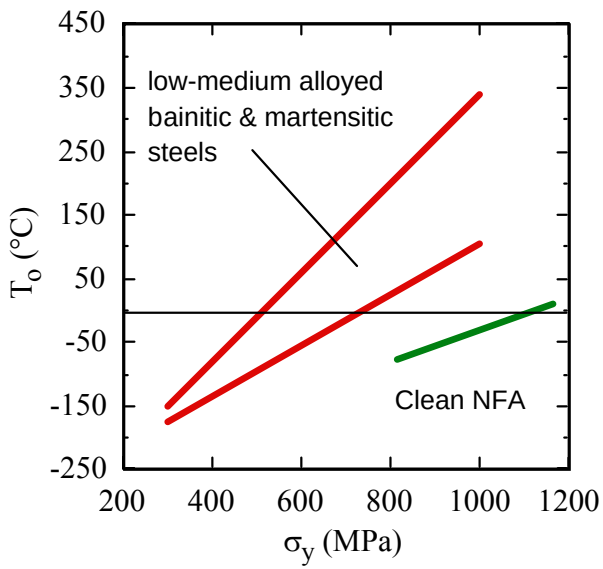
High Performance Alloys Based Systems

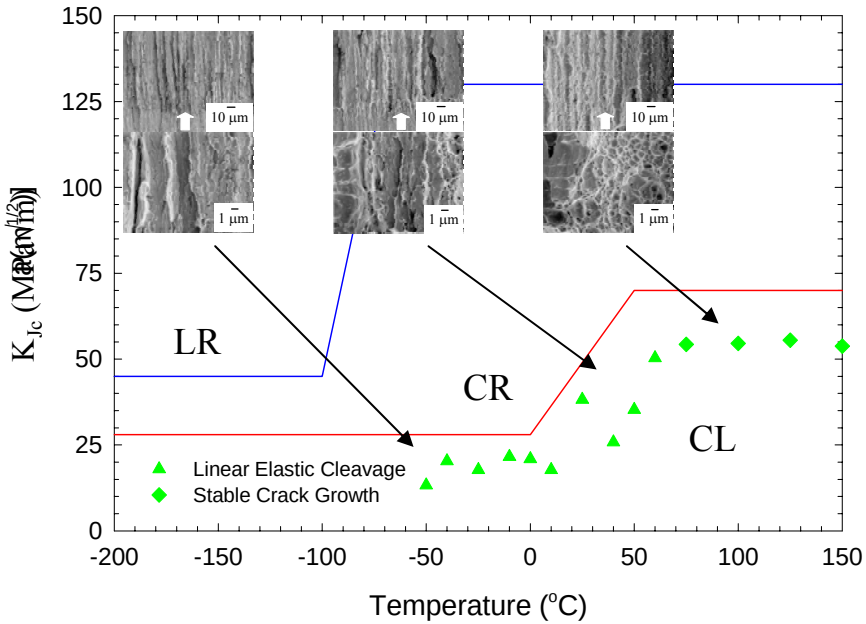
- Need materials that are stronger (static and creep) with sufficient plastic-ductility and toughness(fracture and fatigue)

  - evolutionary precipitation strengthened steels
  - vanadium alloys (beyond V-4Cr-4Ti)???
  - nanocomposited ferritics
  - functionally graded, integrally coated, reinforced (fibers & ductile alloys) microlaminates, phase blended/ transformed
  - nanolaminates, metallic glasses,….

NFA Toughness

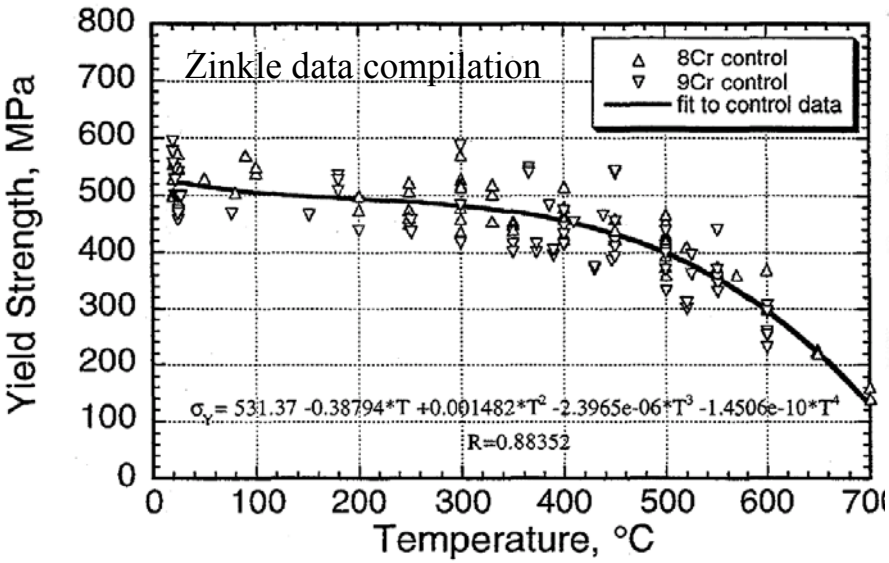
- High σ_y of NFA may lead to low toughness
- Compounded by intermediate T_i irradiation embrittlement
- K_{Jc} of MA 957 improved in orientation minimizing effects of inclusion Al_2O_3trigger particles - and better Charpy 'toughness' of clean 12Cr-WTiYO vs LAMS ODS
- Need clean carbide-inclusion free alloys

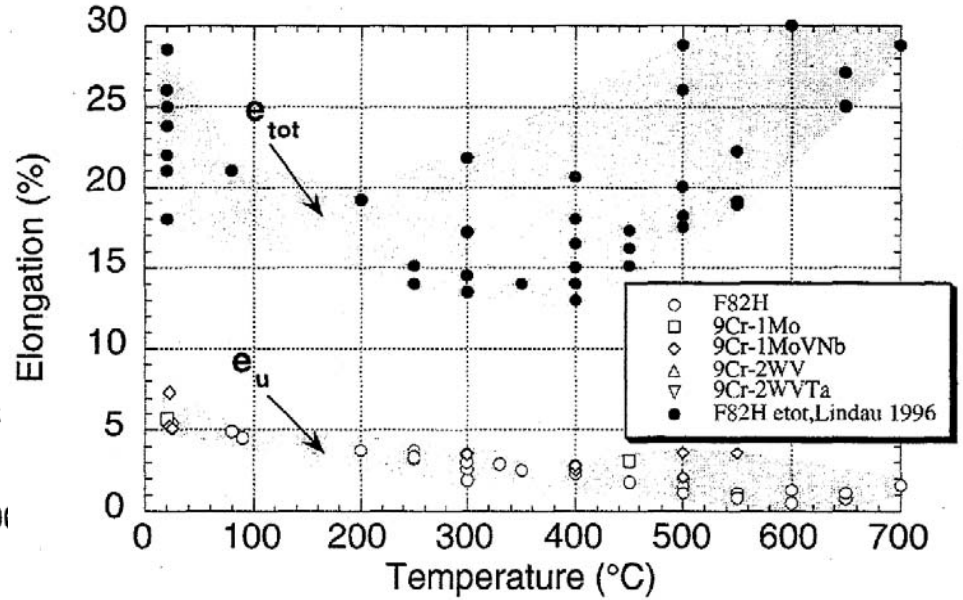




Unirradiated Strength and Ductility

- Medium (LAMS) to high (NFA) σ_{ys} with modest to substantial tensile ductility - very sensitive to alloy-microstructure (composition & heat treatment)
- Cyclic (fatigue) and high temperature age *softening*

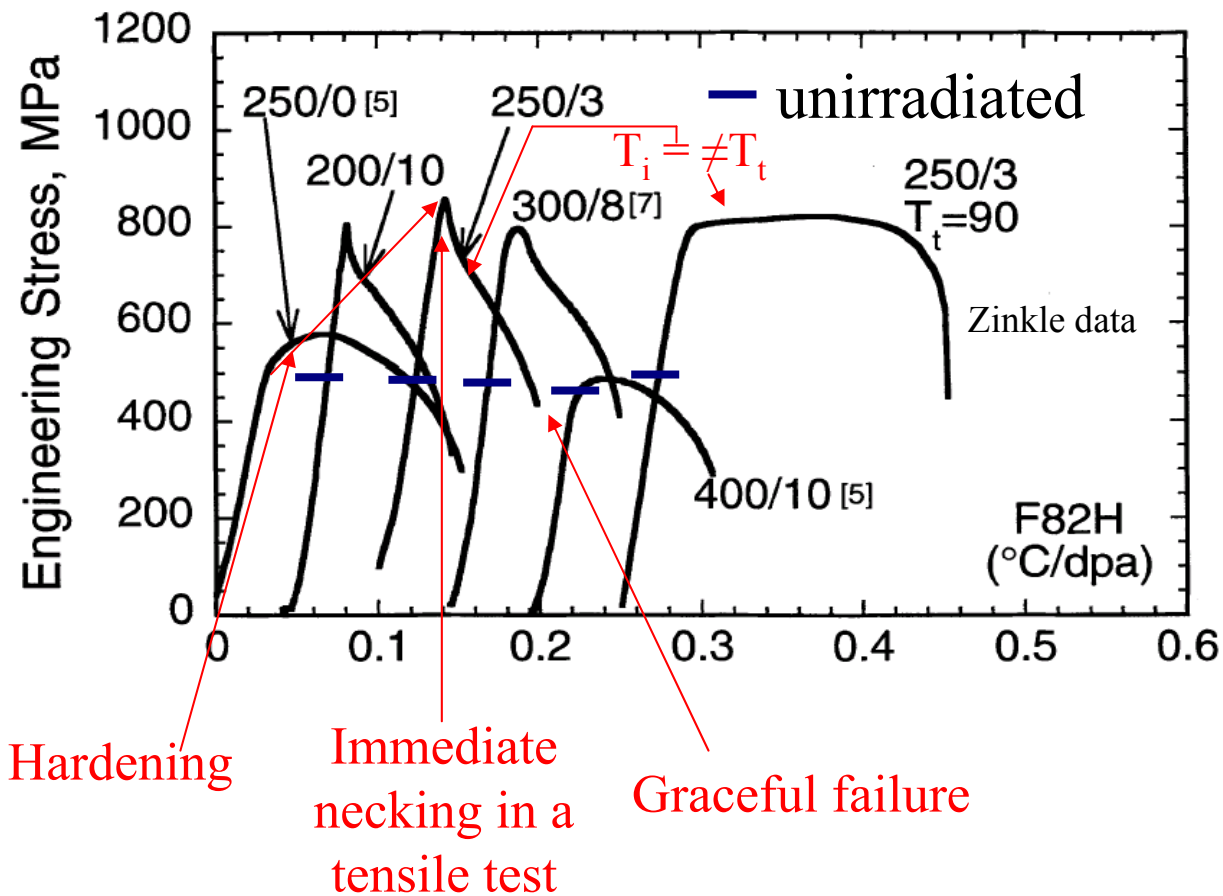




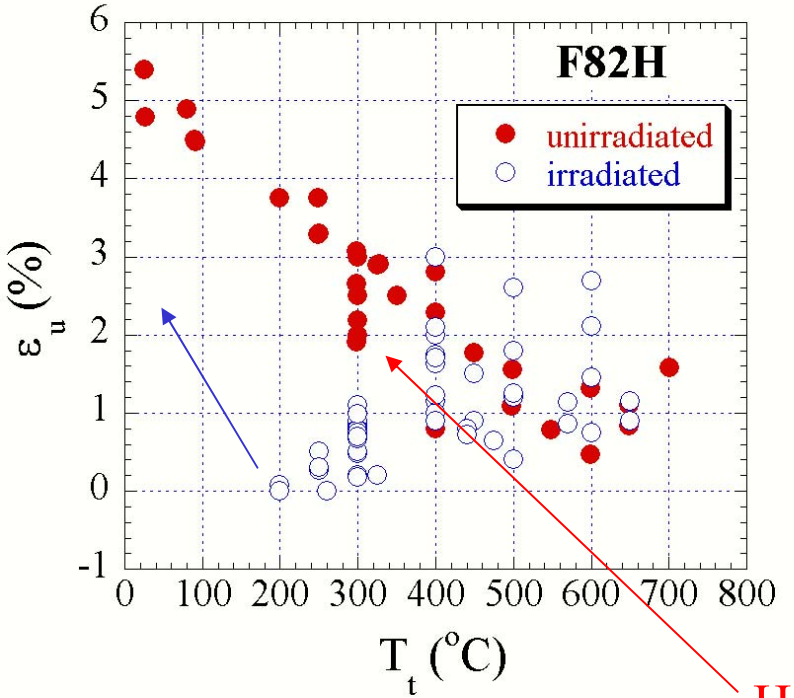
Irradiation Effects - Strength and Ductility

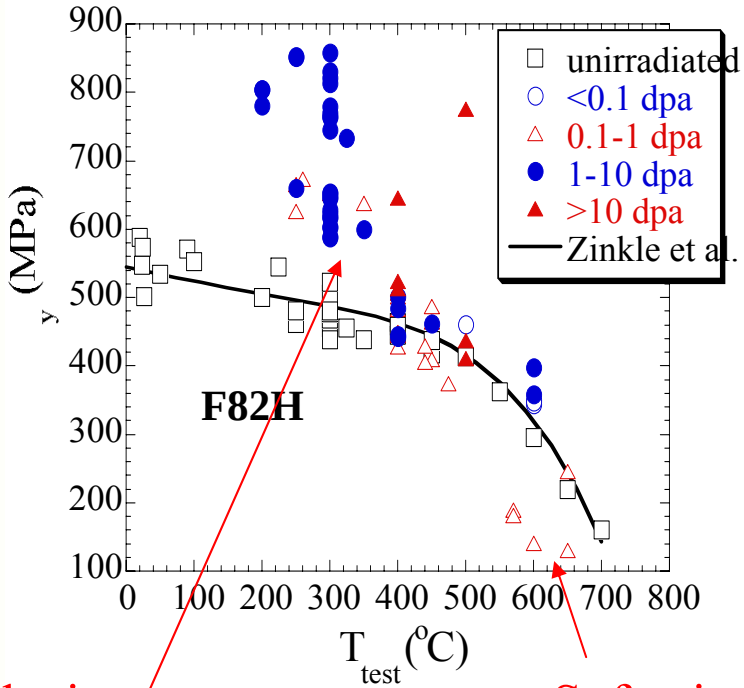
- Hardening - $\Delta\sigma_y = f(dpa, T_i, ...)$ below $T_{ih} \approx 400°C$ (at relatively low dose) - high dose-temperature softening
- Corresponding loss of strain hardening and uniform strain capacity (Δe_u) in *tensile tests*
- Smaller effects on ductile failure strains (Δe_t, ΔRA)
- Little hardening $T_i > T_{ih}$ and soften $T_i >> T_{ih}$
- But $T_{ih} = f(dpa)$?? - with T_{ih} increasing at higher dose
- $\Delta\sigma_y = f(\text{composition-microstructure})$ - e.g., high Cr - α'
- Ductility $e_{t/u}$ & $\Delta e_{t/u}$ (and $\Delta\sigma_y$,..) depend on the deformation temperature T_d
- 'Other' variables helium, dose rate, history,…?
- Cyclic strain-fatigue reduce σ_y & $\Delta\sigma_y$

Irradiation Hardening and Ductility Loss



Irradiation Effects - Strength and Ductility

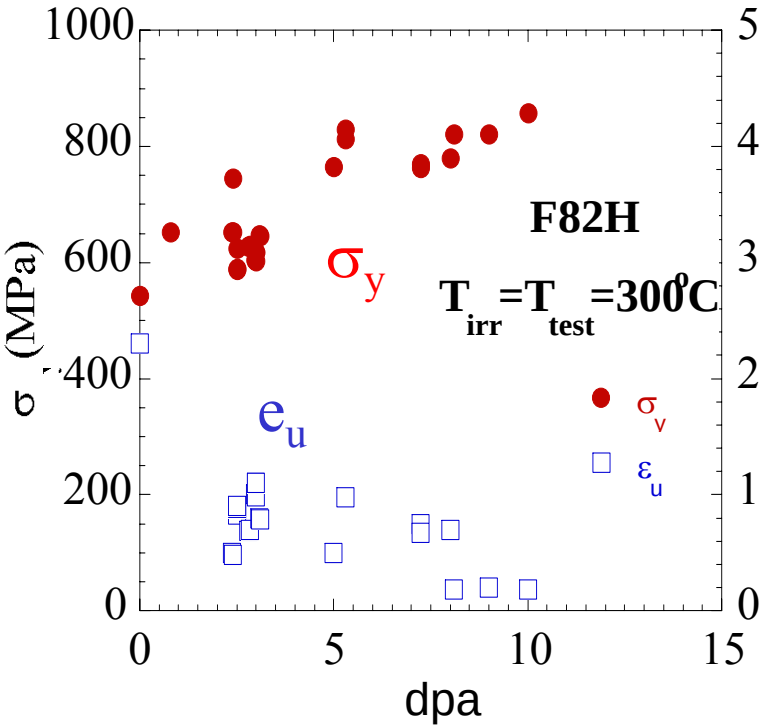


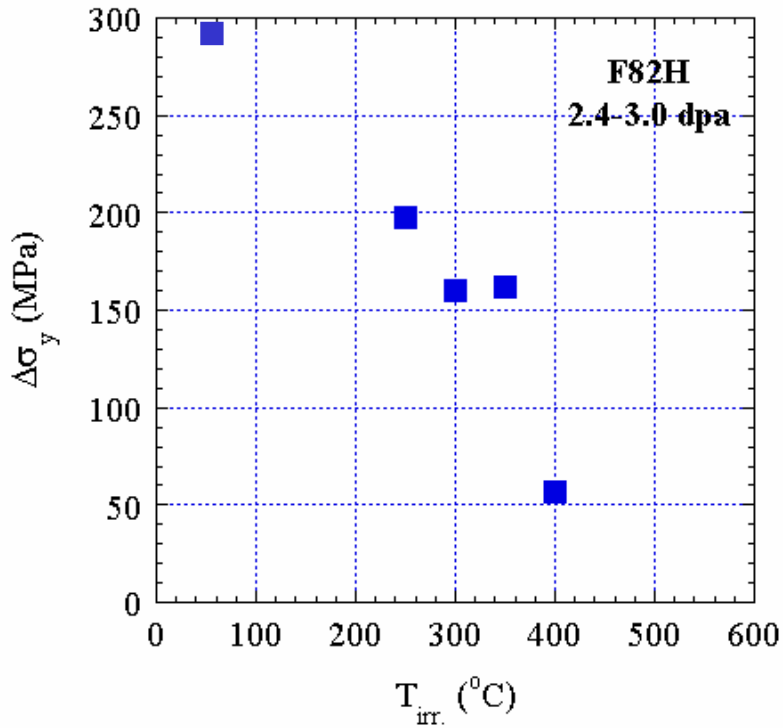


Hardening and ductility loss T_{ih} regime

Softening

Irradiation Hardening and Ductility Loss





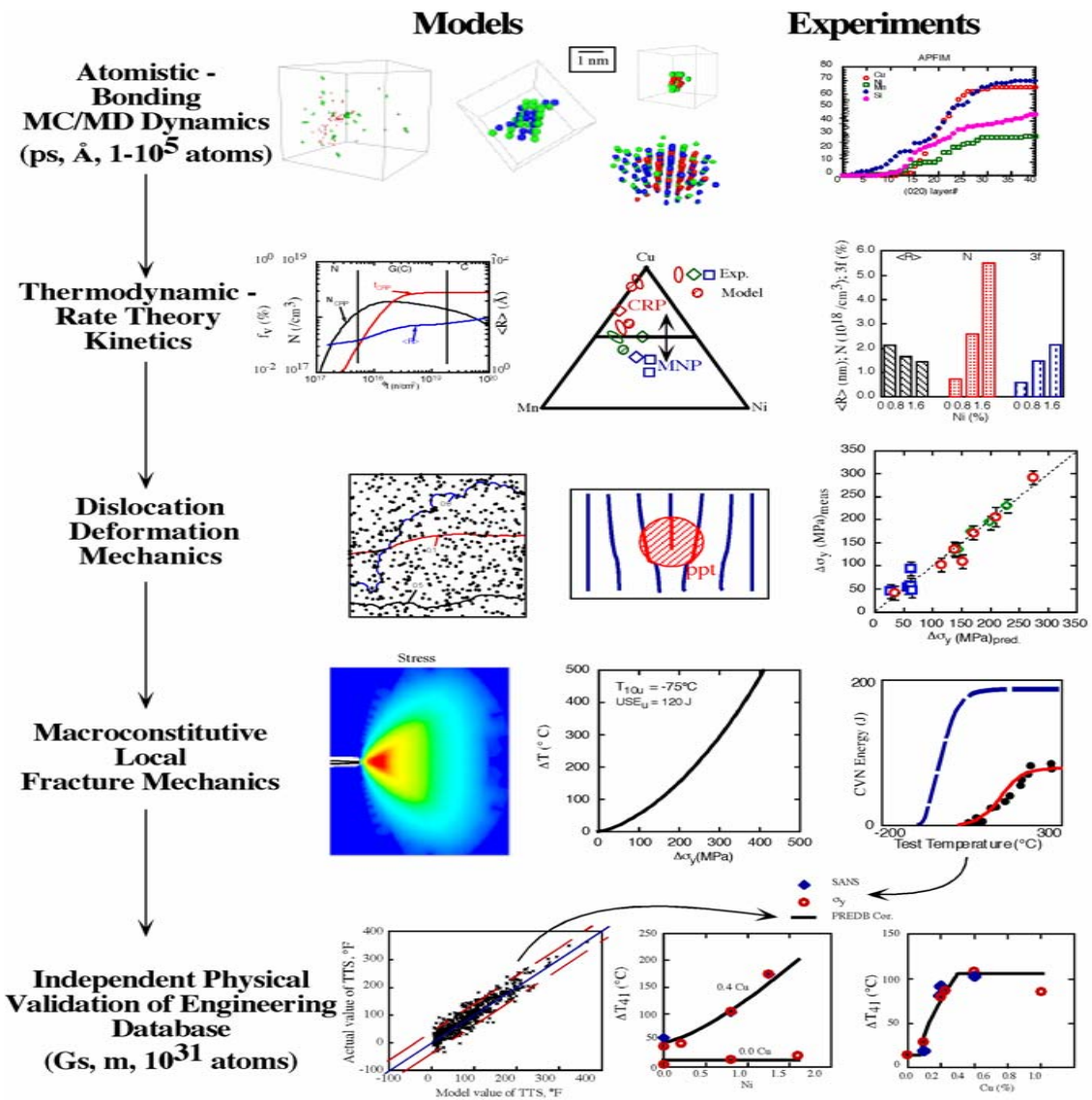
Predictive Models

- K_{Jc} (T_t, P',….) & $\sigma(\varepsilon, \varepsilon', T_t, \ldots)$ = function[deformation & fracture variables, environmental variables, material variables -- in combination]
  - f[] physical models of effects of variables and variable interactions - detailed/computational but also need simplified versions to fit the property data base
  - deformation & fracture variables - geometry and size, temperature, loading conditions and rates,…
  - environmental variables - ϕ, ϕt, $\phi(E)$, T_i, σ, history…
  - material variables - SOL composition, microstructure,..

Hierarchical Modeling

- Since properties depend on microstructure can use hierarchical multiscale-multiphysics modeling approach
  - microstructure evolution = f(SOL composition & microstructure + ϕ, ϕt, $\phi(E)$, T_i, ,,)
  - microstucture-basic property relations (e.g., $\Delta\sigma_y$)
  - basic-complex property relations (ΔT_{100})
- Very successful for RPV steels and very transferable to fusion applications
- Problems of interfaces-information transfers enormously over-exaggerated but needs a overall architecture

MSMP Modeling: RPV Embrittlement



Multiscale Modeling of Irradiation Damaged Materials: Embrittlement of Pressure Vessel Steels, R. Odette, B. Wirth,, N. Ghoniem and D. Bacon, *MRS Bulletin* , March 2001

Elements of Hardening Modeling

- Modeling changes in σ_y ($\Delta\sigma_y$) due to dispersed barriers - the major source of irradiation hardening - pretty well established
- Require better information (modeling and experiment) on individual dislocation-obstacle interaction strength factors (β_j), how from pre- and post-irradiation strengthening superimpose (S_j, not simple linear or root square) and polycrystalline-substructure effects

$$\tau_{yj} = M\beta_i(r_i,..)Gb\sqrt{(N_i d_i)} \text{ -- individual}$$

$$\Delta\tau_y = \Sigma_i S_j(b_j, b_k,..)\tau_{yj} + \{\Sigma_i[(1-S_j)]^2\tau_{yj}\}^{1/2} \text{ -- } \tau_{yu} \text{ - superposition}$$

$$\Delta\sigma_y = M\Delta\tau_y \text{ -- polycrystalline}$$

- Interactive effects & other contributions (e.g., source hardening), softening effects - but second order
- Cavity hardening (nanovoids to helium bubbles) a controversy

Simplest Example

- For specified material - e.g., IEA F82H

$$\Delta\sigma_y = f_\sigma(\phi t, T_i) \text{ [or } \Delta T_{100} = f_{k\sigma}(\phi t, T_i)]$$

- 'Models' relating to $\Delta\sigma_y$ underlying microstructure (loops, precipitates, cavities, complexes) & basic form available,- e.g.

$$\Delta\sigma_y = A(T)[1-\exp(-B(T)dpa)]^{1/2}$$

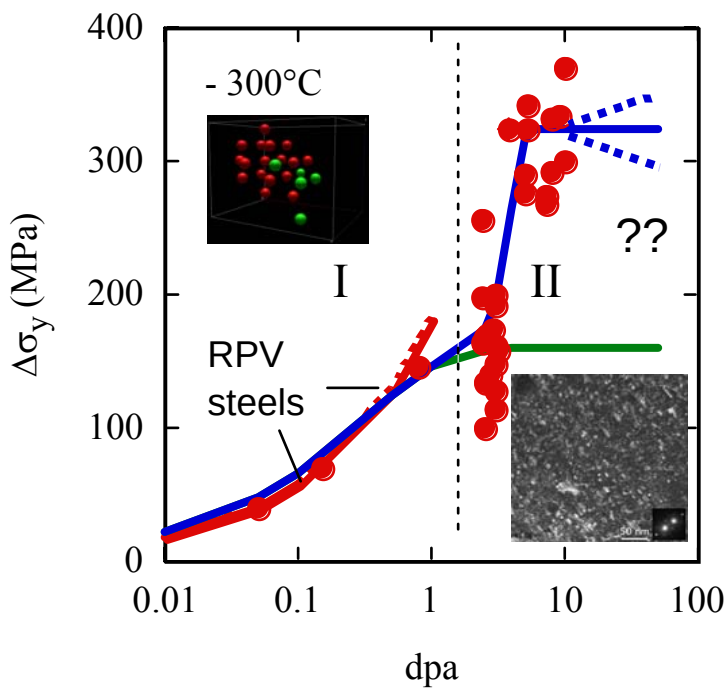
- Substantial 'data' no qualified database & large uncertainties (e.g. uncertainties in T_i)
- To date no quantitative or fundamentally based models are available - major missing link comprehensive measurements - models of microstructural evolution

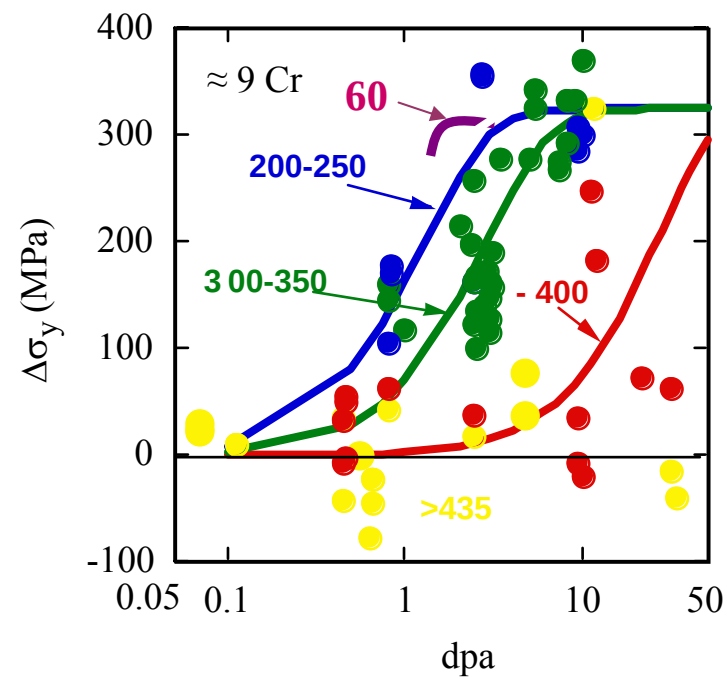
Irradiation Hardening Correlation

- Need to develop robust analytically represented but *physically based* and statistically calibrated $\Delta\sigma_{ys}$, Δe_u,.. models including high dose

$$\Delta\sigma_{ys}(\text{and } \Delta e_u\ldots) = f_{model}(T_i, T_d, \text{dpa}, \ldots\ldots)$$

- Multiple defect-hardening stages - *microstructure* is critical





Status of Single-Combined Variable Database

- To date we do not have a sufficient database provide a basis either 'simple' data correlations or proper support for models of the effects of key variables for a single alloy or alloy system

  - metallurgical: composition and SOL microstructure (processing-fabrication history)

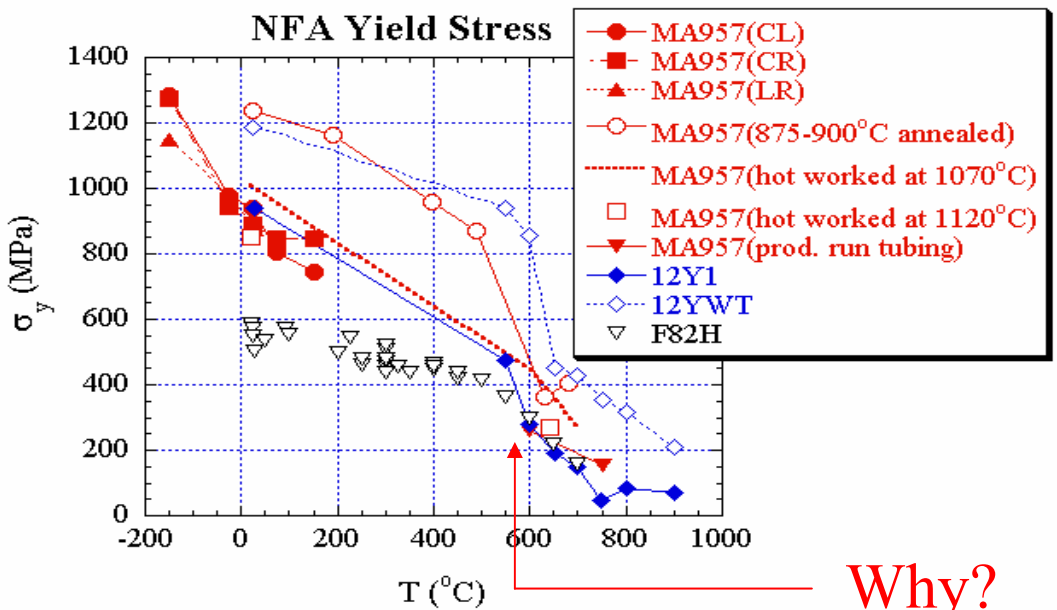
  - environmental: ϕ, ϕt, $\phi(E)$, T, σ, history

  which not only act singly but in combination

- Single-combined variable experiments needed for both microstructure and properties

Nanocomposted Ferritic Alloys (NFA)

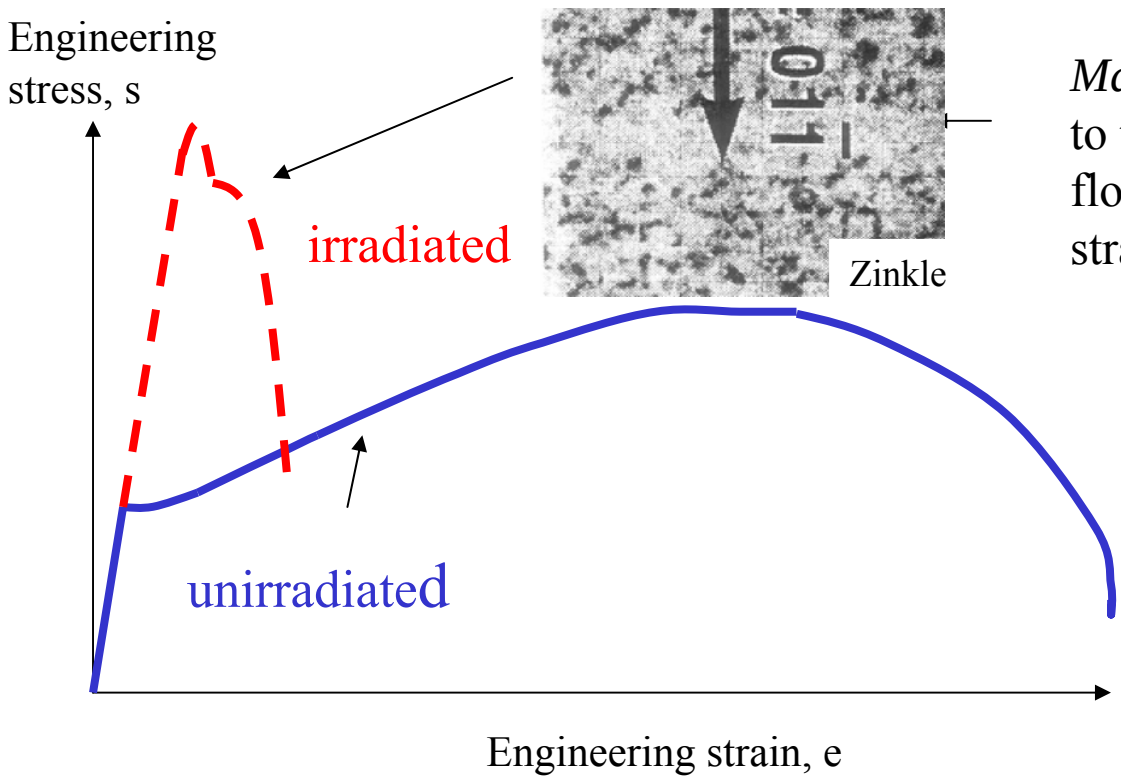
- NFA much stronger while maintaining comparable ductility and much more stable at high temperature and probably under cyclic loads compared to LAMS
- Similar rapid strength fall-off at $T_t > \approx 600$ C - better understand and improve (?) further
- Irradiation hardening similar



Why?

Flow Localization

- Require robust constitutive models σ(ε, ε', T) & plasticity laws
- Model multi-scale causes of heterogeneous - localized deformation and *consequences* to σ(ε, ε', T) and very low e_u

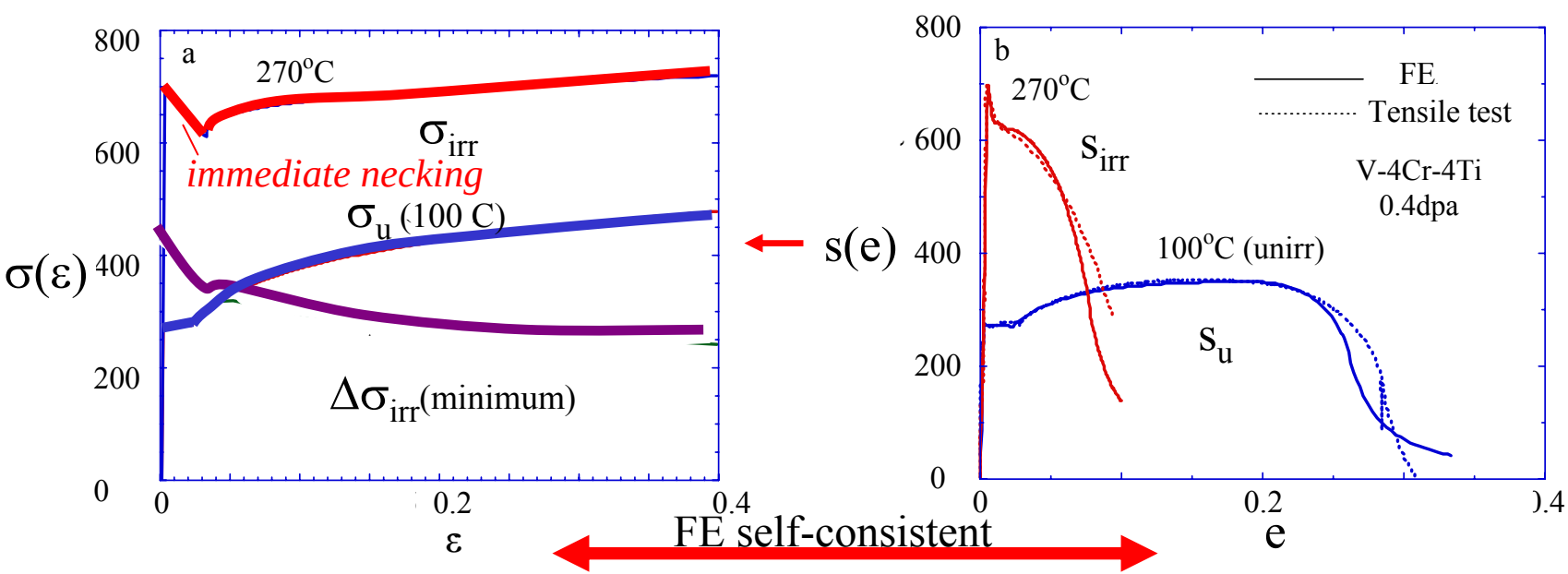


Macroscopic connection to to *microscale* localized flow - coarse slip to high strain flow channels?

<u>Mechanisms</u>
- source hardening
- defect free channels
- twinning
- retarded cross slip

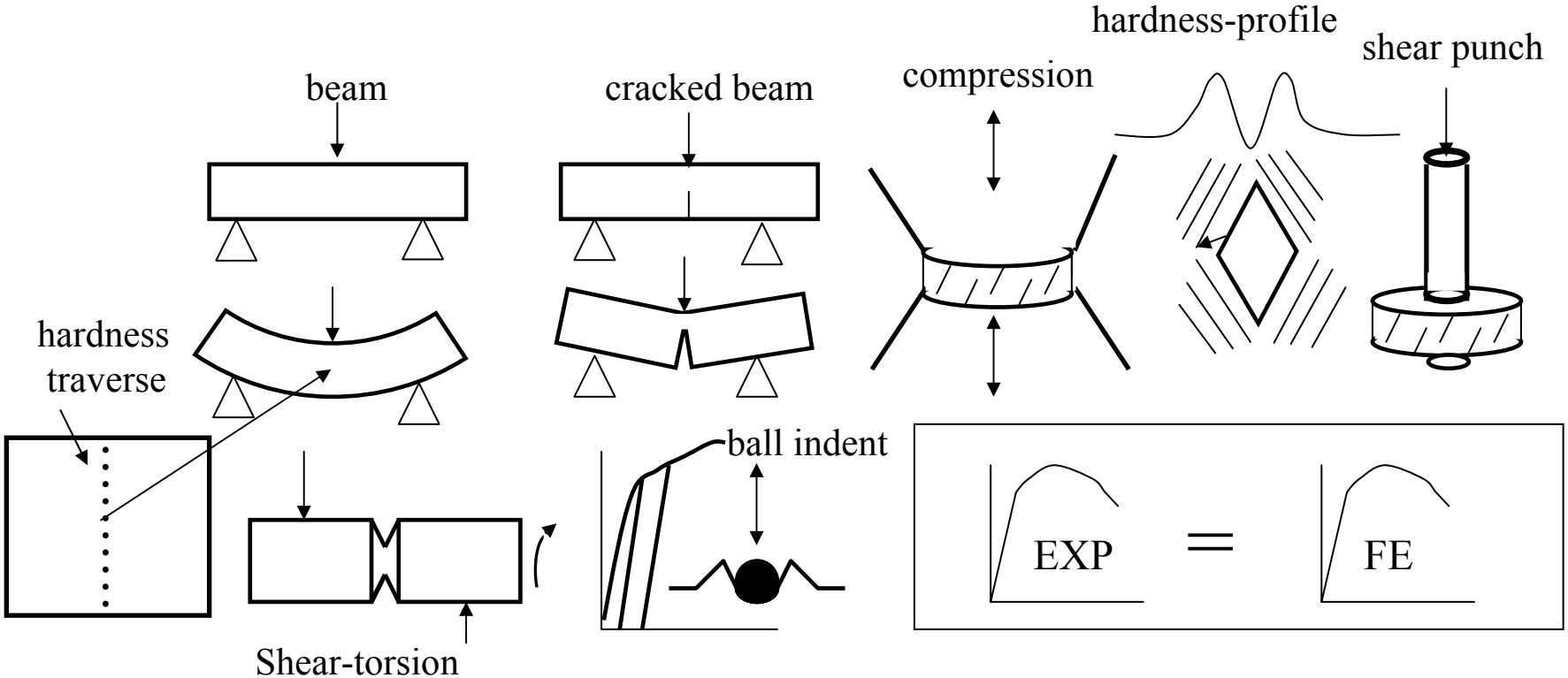
Constitutive-Plasticity Laws

- Finite Element derivation of σ(e) from s(e)
  - σ(ε) small initial strain soften causes immediate necking followed by hardening ≈ elastic- perfectly-plastic
  - Substantial irradiation hardening Δσ(ε) up to high ε
  - J_2 flow theory appears valid (may not always be the case)
  - Structural implications of low e_u + *graceful* post e_u failure?



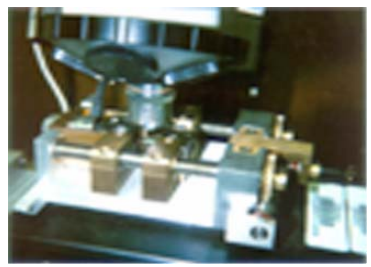
Alternate Deformation Test Geometry

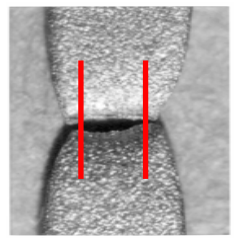
- Various geometries needed for unique $\sigma(\varepsilon, \varepsilon', T)$

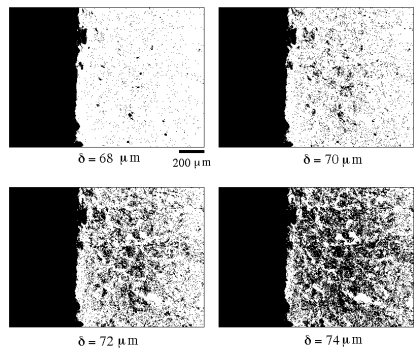


New Tools - Deformation/Fracture Research

- Need to develop and apply new tools
  - confocal microscopy (CM) and CM-fracture reconstruction (CMFR)
  - in-situ optical, SEM, AFM, TEM imaging under loading
  - FIB-TEM of local deformation structures
  - semi-automated testing
  - strain mapping
  - acoustic emission- other test instrumentation
  - potential drop - damage evolution
  - composite-multipurpose specimens
  - ….







Micro-Micromechanics

- Component parts <u>and</u> links available to create fully integrated (micro)structure-(micro)mechanics based codes for a wide range of deformation and fracture properties

  - input and link all types of test data from advanced microhardness to fracture toughness along with microstructural information at all pertinent scales

  - relate property to others properties and to underlying structures

- A dynamic tool used for optimizing experiments, self-consistent integration of data (a functional database), predicting in service performance and developing high performance materials by design

Summary

- Insufficient database to build robust models

  - modest amount of data for many different materials,...

  - large data scatter from measurements and variable uncertainties (e.g, T_i) and uncontrolled variables

  - incomplete underpinning microstructure & fundamental mechanism database and understanding - need other types

  - modeling has not been well integrated with experiment but now beginning with new experiments

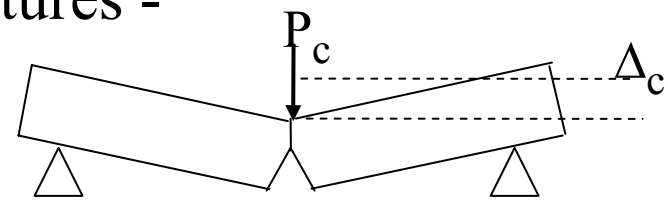
  - opportunities in US JAERI and JUPITER collaborations plus strong interactions with Europe

  - new higher performance materials and new materials systems a must (higher priority than vanadium alloys) and should exploit rather than just manage

  - develop a detailed roadmap and teaming research approach for key deformation and fracture issues & opportunities

Stress-Strain Limits for Rapid Failure

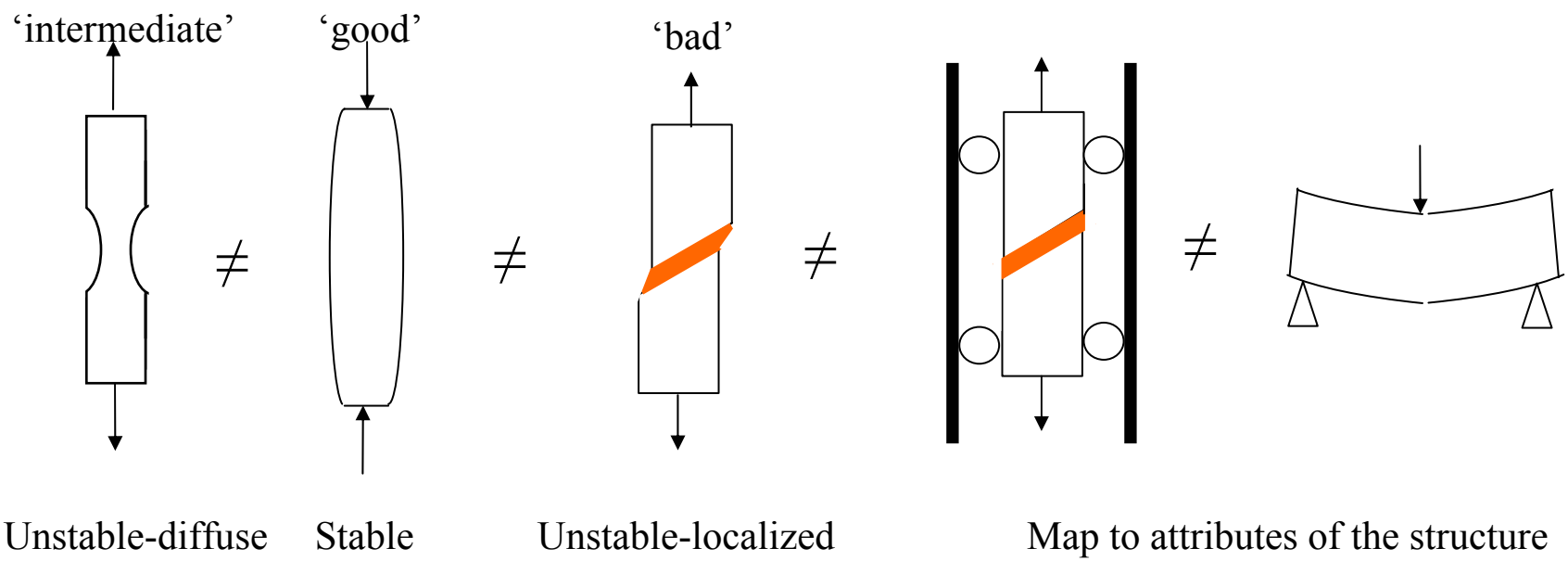
- Design & *operation* of FW&B structures require evaluation of load/stress (P_c/σ_c)-displacement/strain (Δ_c/ε_c) limits:
  - '*properties*' are intermediate to the *failure* σ_c-ε_c limit
  - 'deformation limits for unflawed structures - *strength and ductility*
  - fast fracture limits for flawed structures - *fracture toughness*



- Rapid failure also depends on:
  - time-dependent processes like *fatigue* crack growth
  - slow & rapid changes in applied σ–ε due to *creep*, *startup- shutdown and off-normal transients*
  - structural details like *load compliance*

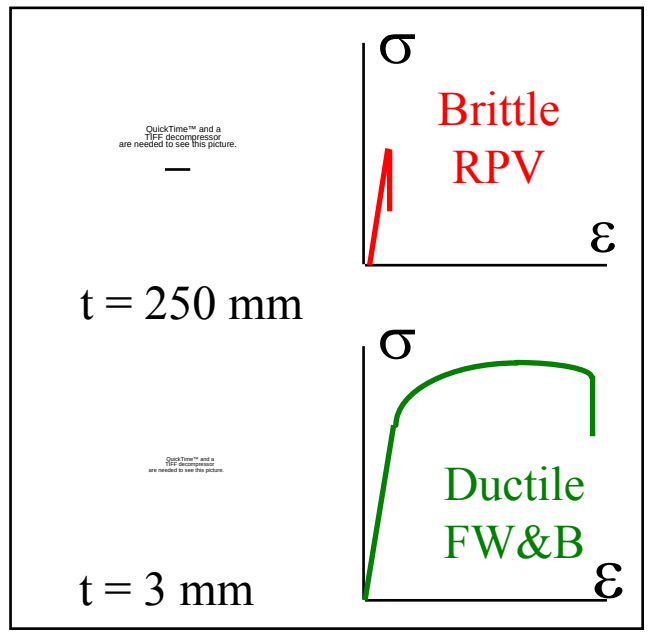
Consequences of Localization - Low ε_u

- Structural *consequences* of *low* e_u and *flow localization depend* on many *extrinsic* factors -- geometry and deformation paths and displacements constraints -- e.g., minimum in compression and bending, maximum in shear?
- Models and experiments to define *structural consequences*

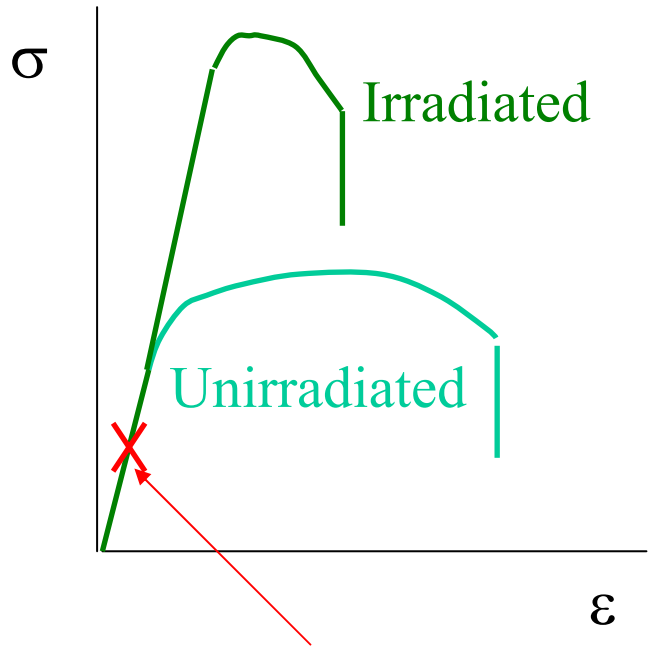


Structural Implications

- Advanced integrity assessment methods (e.g., MC-ΔT and beyond) could enormously reduce the engineering impact of irradiated property changes particularly in the hardening regime - more realistic and less conservative
- Large penalties in using old methods (e.g. heavy section fracture mechanics not pertinent to FW&B structures)
- In irradiated higher-strength regime the issue is σ_c- ε_c for flawed structures and ε_c unflawed structures - but for many FW&B conditions with shallow cracks, thin walls issue is primarily ε_c - for 'adequate' advantages of higher may outweigh disadvantages of lower 'ductility'



Opportunities

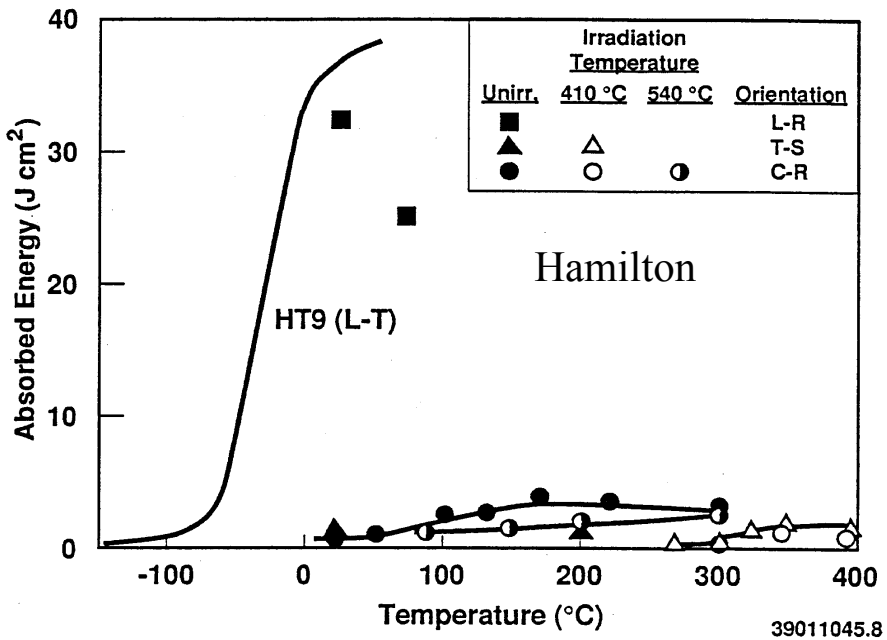


Show-stopping
miss-prediction by 'old'
physically inappropriate method

- Many potential reasons
  - statistical and constraint size effects
  - warm pre-stressing
  - creep relaxation
  - fatigue softening
  - advanced NDE and remote repair
- Requires rigorous physical basis & practical demonstration and close interactions between materials and design
- Multiscale modeling

NFA Charpy

- MA 957 - FFTF

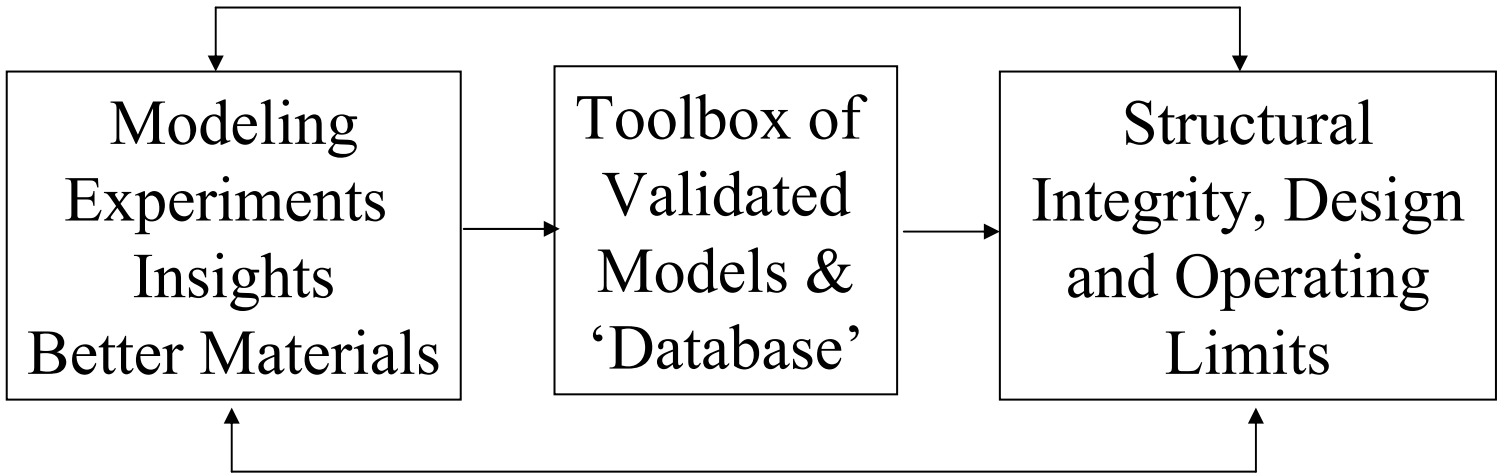


Ingredients and Products

- Right set of '*questions*' (what are key properties and variables controlling them…?) - balanced combination of mechanism based models and experiments
- Experiments three types: controlled single/combined variable; mechanism studies and integrated effects
- Products I - quantitative constitutive (deformation), damage (fracture) 'properties' and their in-service evolutions including the effects of material & environmental variable combinations - use in engineering multi-physics FW&B simulations
- Products II - tools to apply 'property' data to predict the performance of complex structures (VISTA) including insight on combined effects and structural failure paths

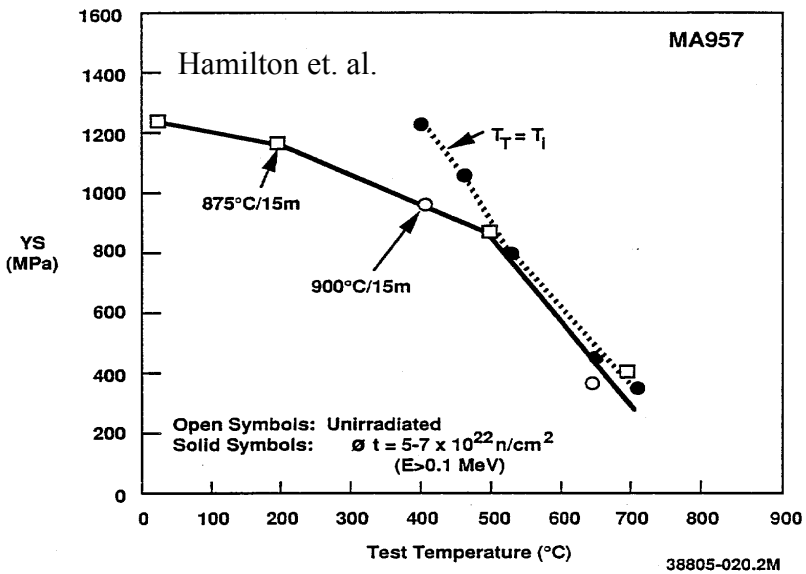
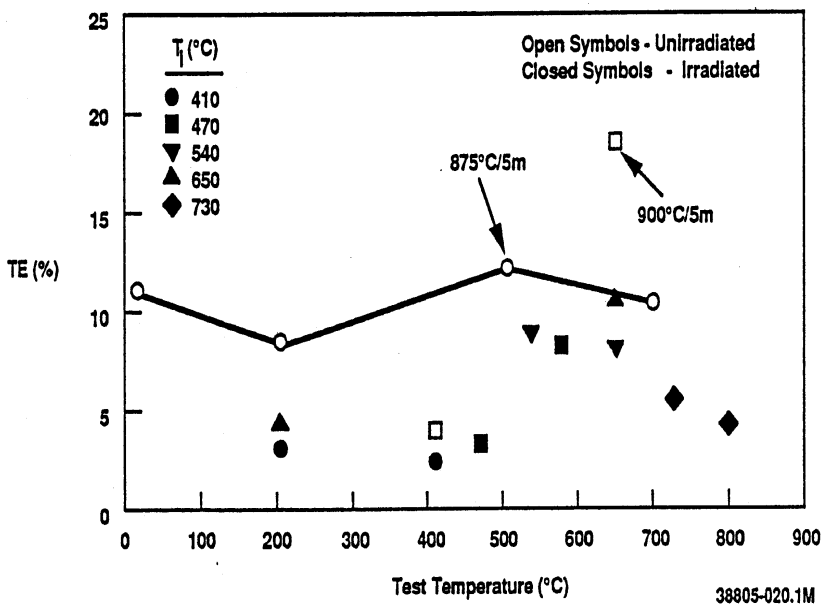
High Level Objectives

- Understand, manage and (perhaps) exploit deformation & fracture processes in fusion FW&B (& HHF) structures:
  - understand - predictions based on empirically calibrated physical models
  - manage - by good design and improved materials
  - exploit - possible but requires understanding, managing and a robust set of integrated 'tools'



Outline

- Overview ‘properties’ and *irradiation service effects* in steels, (vanadium alloys) & nano-composited ferritic alloys
  - hardening and loss of uniform tensile strain capacity
  - fast fracture and embrittlement
- Part of tools and techniques needed for going from atomic-scale materials science to structural reliability & performance engineering

NFA

- Data very limited - MA 957 breeder shows significant hardening at ≈ 30 dpa at < 500°C and modest reduction in e_t - trends likely similar to LAMS
- Ukai - '*JNC ODS maintain strength and ductility without α' up to 15 dpa at 400 to 530°C'*