Thermal & Irradiation Creep of Vanadium Alloys & RAFM Steels

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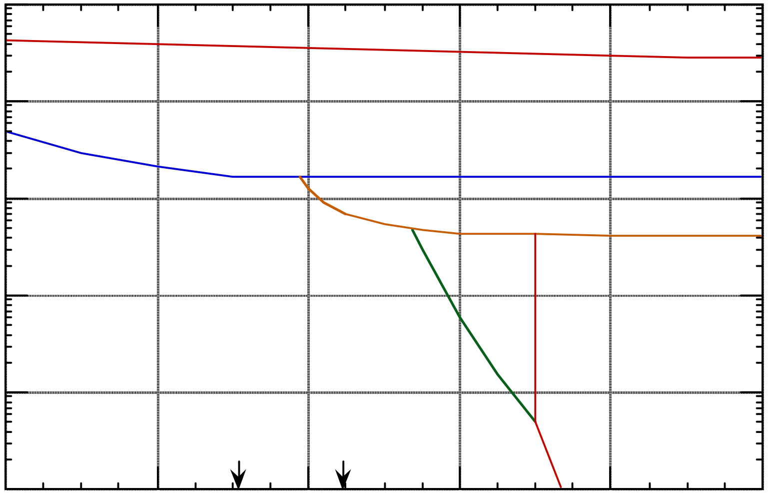
Outline

- Thermal creep data base and ongoing experiments
- Irradiation creep data base and planned near-term experiments
- What needs to be done?

Deformation Mechanism Map for V-4Cr-4Ti

Zinkle and Lucas

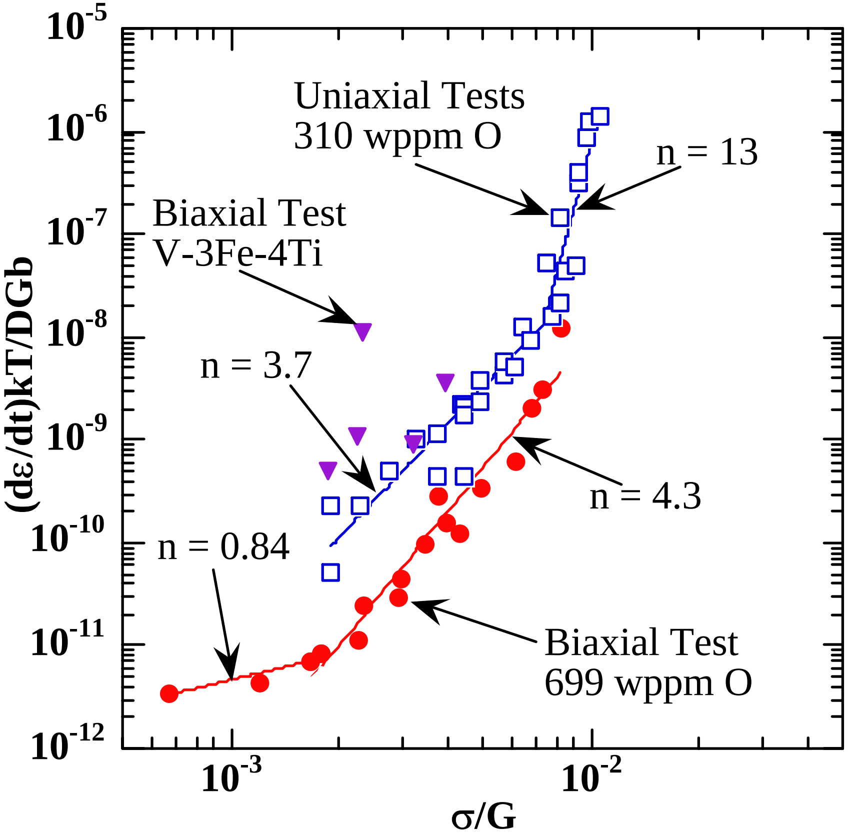
$$\dot{\varepsilon} = 10^{-8}\, s^{-1},\ \mathrm{L} = 20\,\mu m$$



Experiments Needed to Separate the Effects of Irradiation and Environment for Vanadium

1. DHCE -- Irradiation, He, Li, Thermal
2. RTHD (Real-Time Helium Doping)
   -- He, Li, Thermal
3. LTCE (Li Thermal Creep Experiment)
   -- Li, Thermal (low oxygen)
4. Thermal Creep Experiment
   -- Thermal effects (oxygen increases)

Stress Dependence and Activation Energy for “Steady-State” Creep

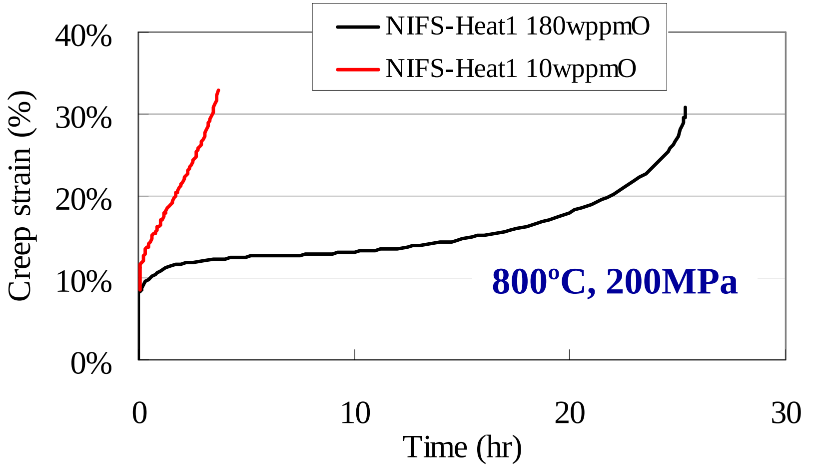


Creep tubes in ~10^{-8} torr vacuum

Stress, MPa	Activation Energy, kJ/mole
70	272
90	326
120	300

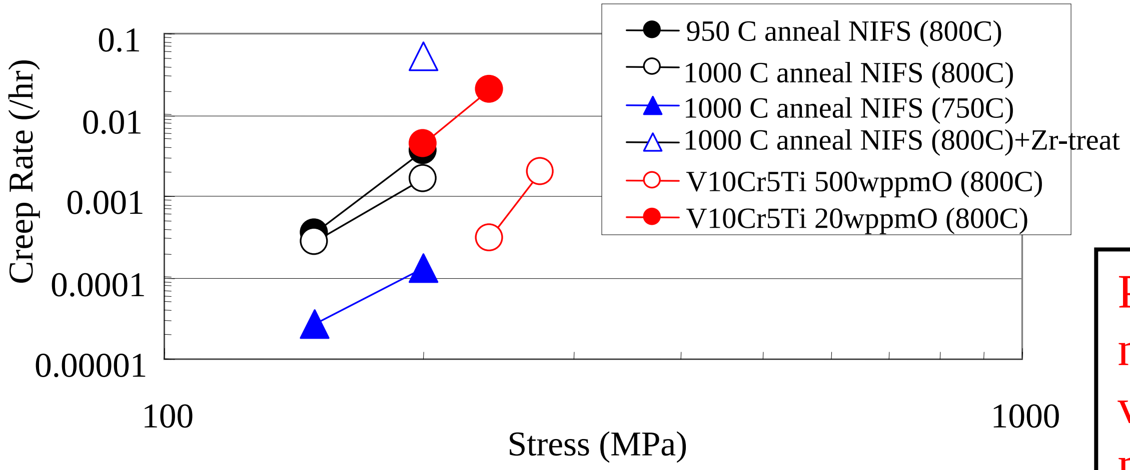
Q_{SD} ~ 270 kJ/mole (Pure V)

Effect of Alloy Purity and Cr Content on Steady-State Creep of NIFS Heat-1



The rupture time and creep strain rate of highly-purified NIFS Heat-1 are shorter and higher, respectively than NIFS Heat-1 with the original heat-treatment (1000°C,2hr).

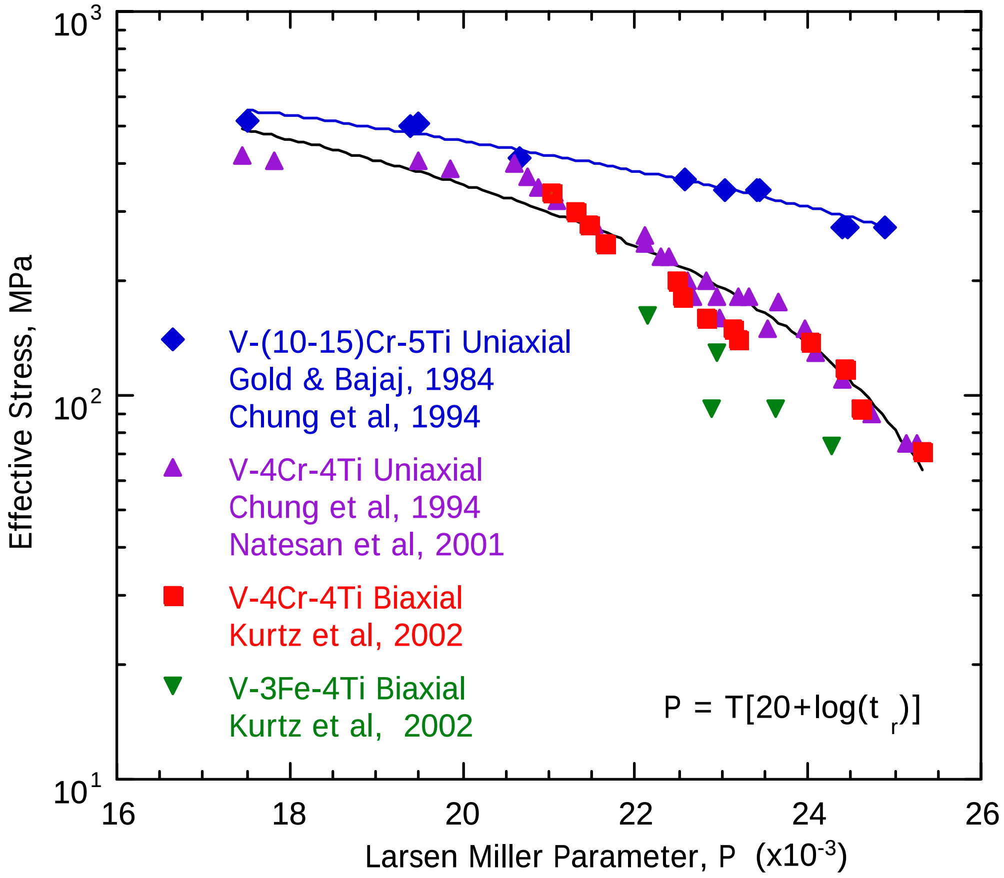
Fukumoto, et al.



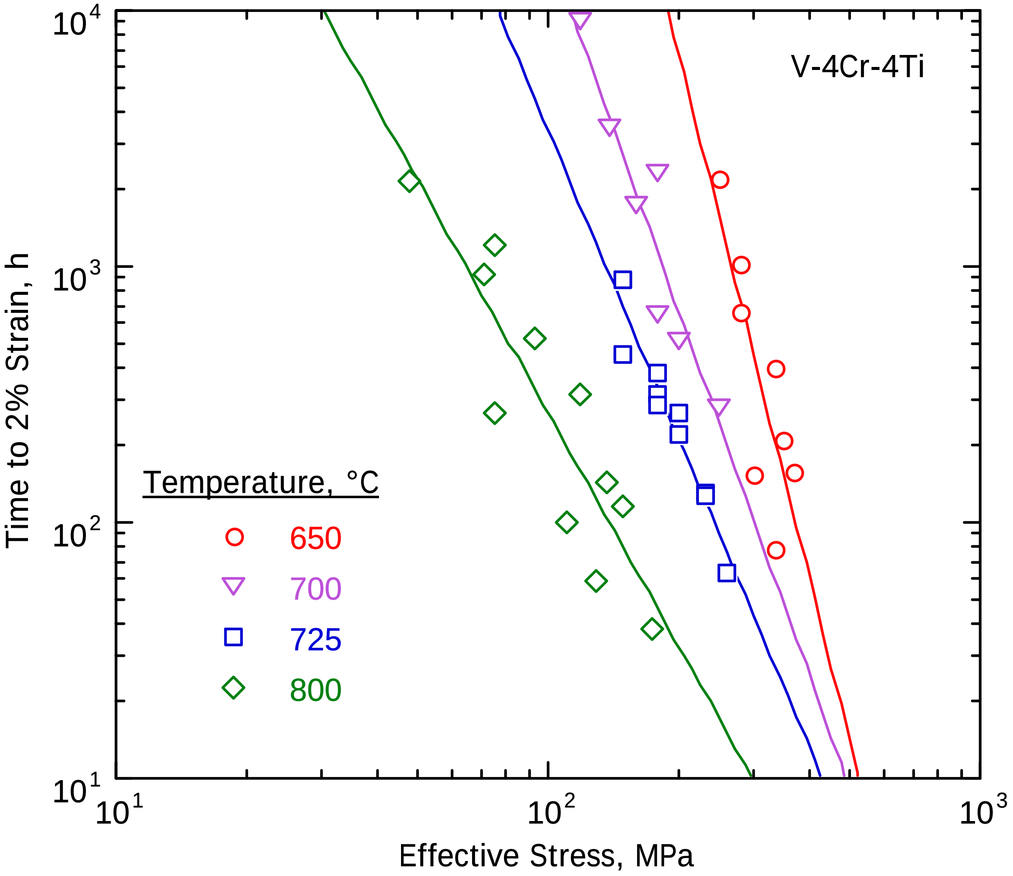
- Increasing the Cr content lowers the creep strain rate
- Increasing alloy purity increases the creep strain rate

Purification below 300 wppm may not be suitable from the point of view of high-temperature mechanical properties

Creep-Rupture of Vanadium Alloys



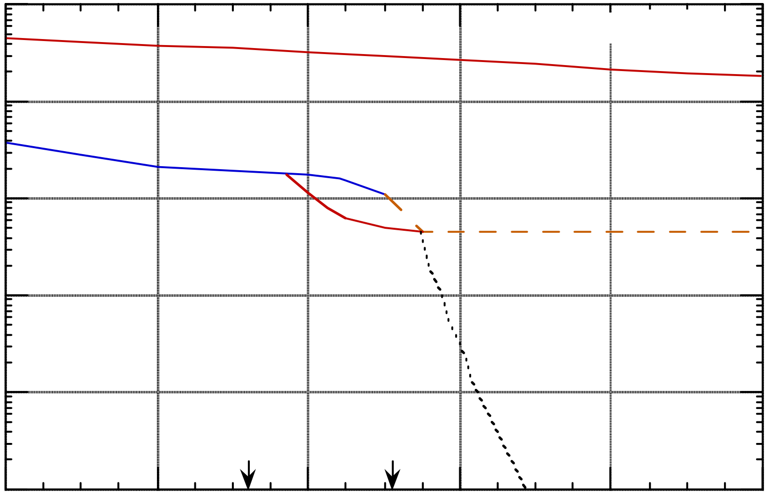
Stress Dependence of Time to 2% Strain



Deformation Mechanism Map for Fe-8Cr-2WVTa

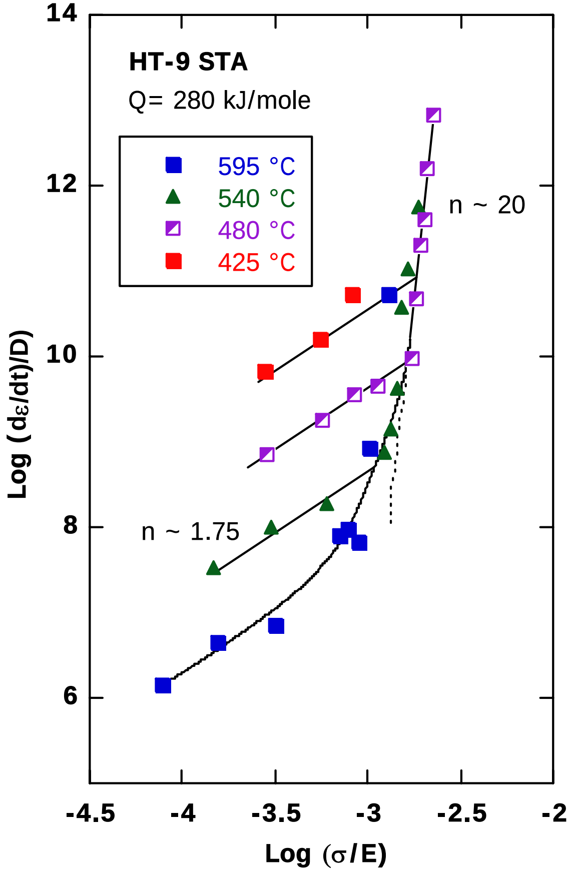
Zinkle and Lucas

$$\dot{\varepsilon} = 10^{-8}\, s^{-1},\ \mathrm{L} = 22\mu m$$



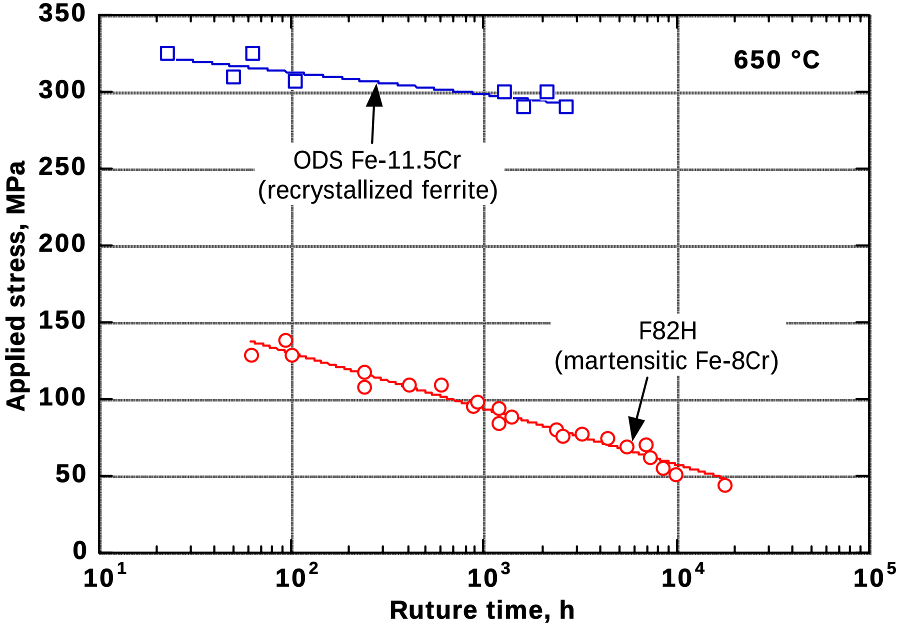
Thermal Creep of Tempered Martensitic Steels

Chin, 1983



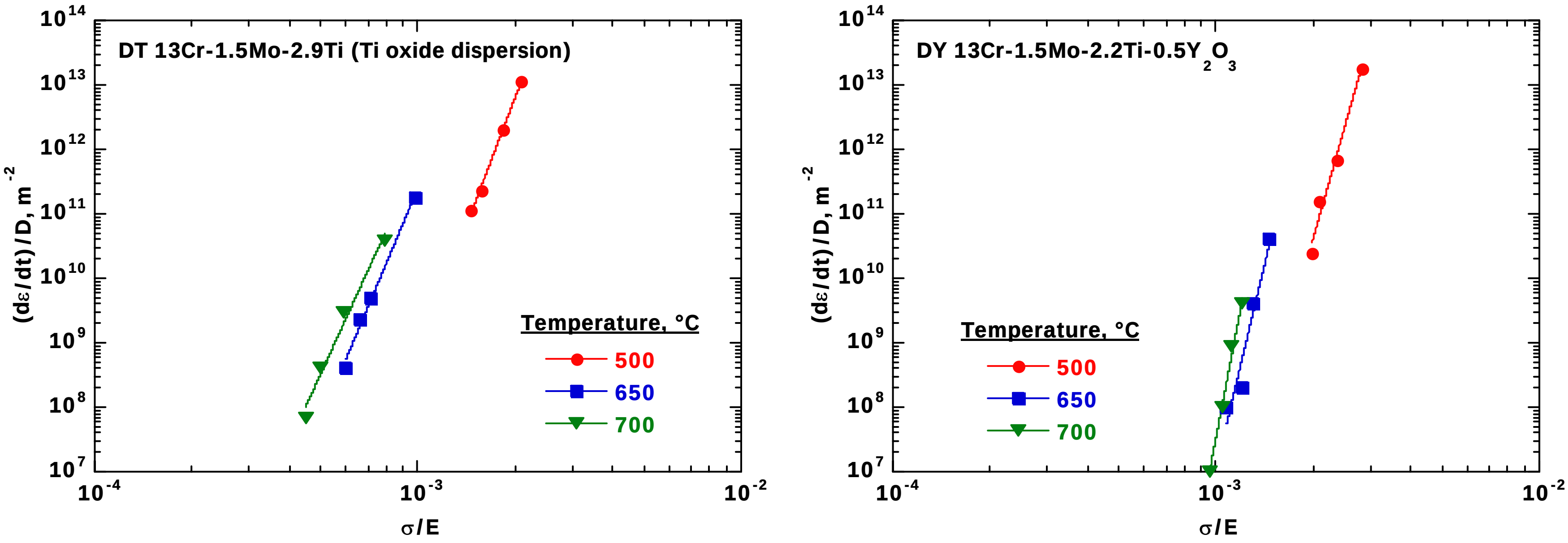
Nano-composited steels offer potential route to significantly improved creep resistance

Yamamouchi et al, 1992; Shiba et al, 1997
Ukai et al, 1996; Ukai et al, 1998



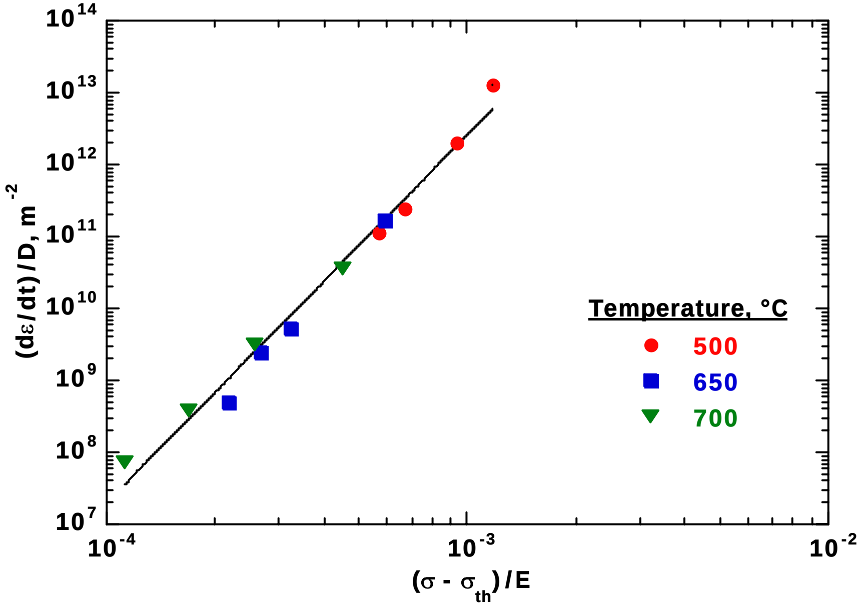
Stress Dependence of Steady State Strain Rate for DT and DY ODS Steels

Zakine, Prioul & Francois, 1996



Normalized Creep Results

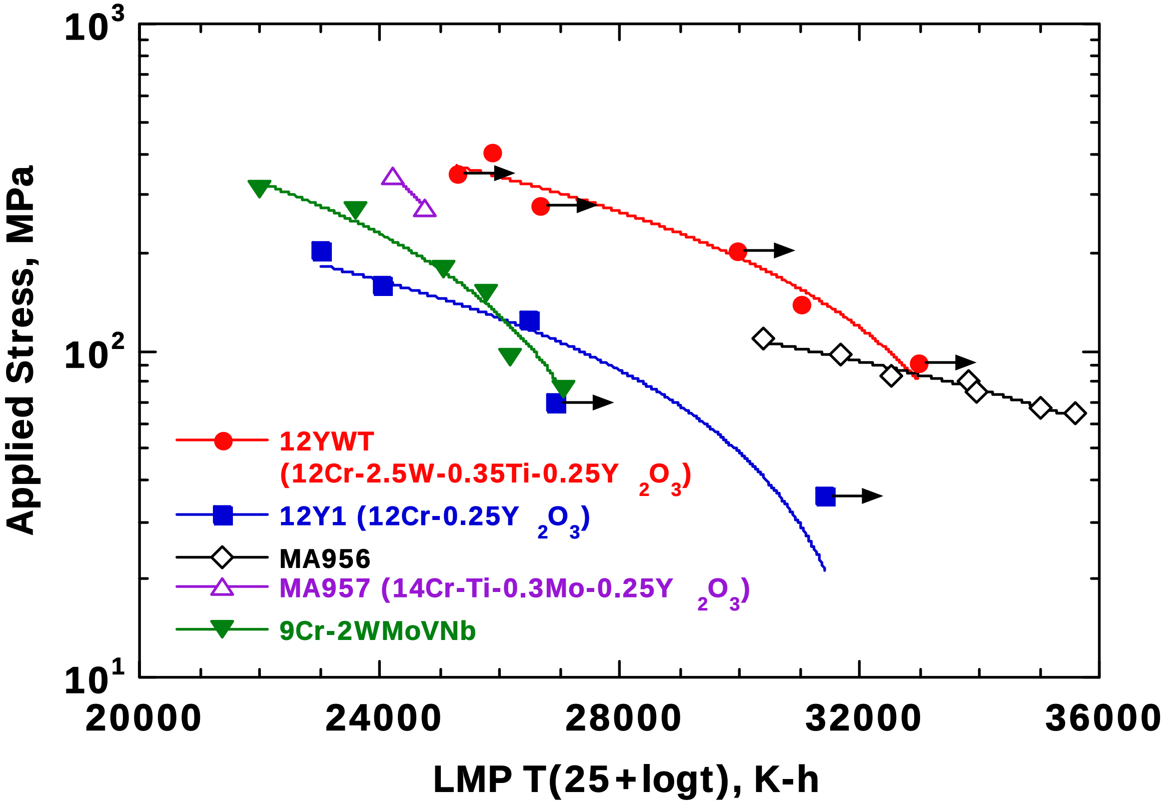
Zakine, Prioul & Francois, 1996



- Creep results normalized by introduction of “threshold stress”
- Below the threshold stress the creep strain rate is negligible
- The threshold stress was evaluated by stress dip test techniques and found to decrease as the temperature increased
- Following creep deformation, dislocations were pinned to the departure side of oxide particles, suggesting an attractive interaction between dislocations and particles

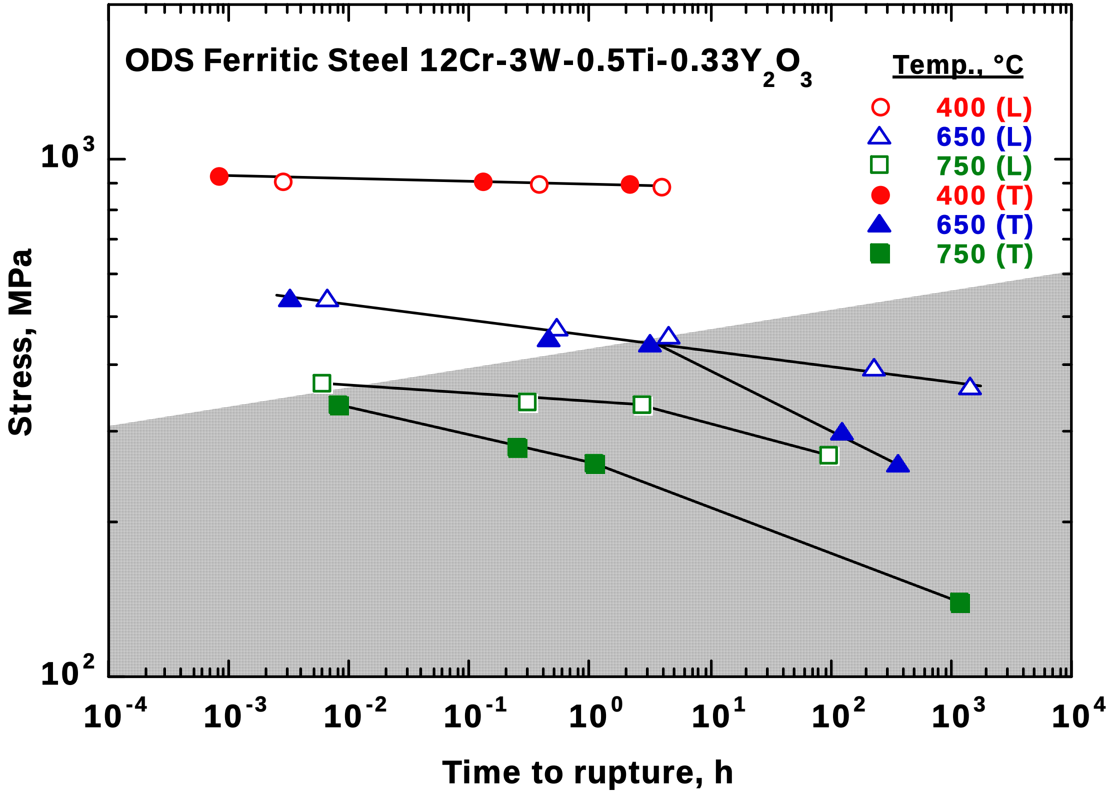
Creep-Rupture of ODS Ferritic Steels

Klueh, et al., ICFRM-10, 2001

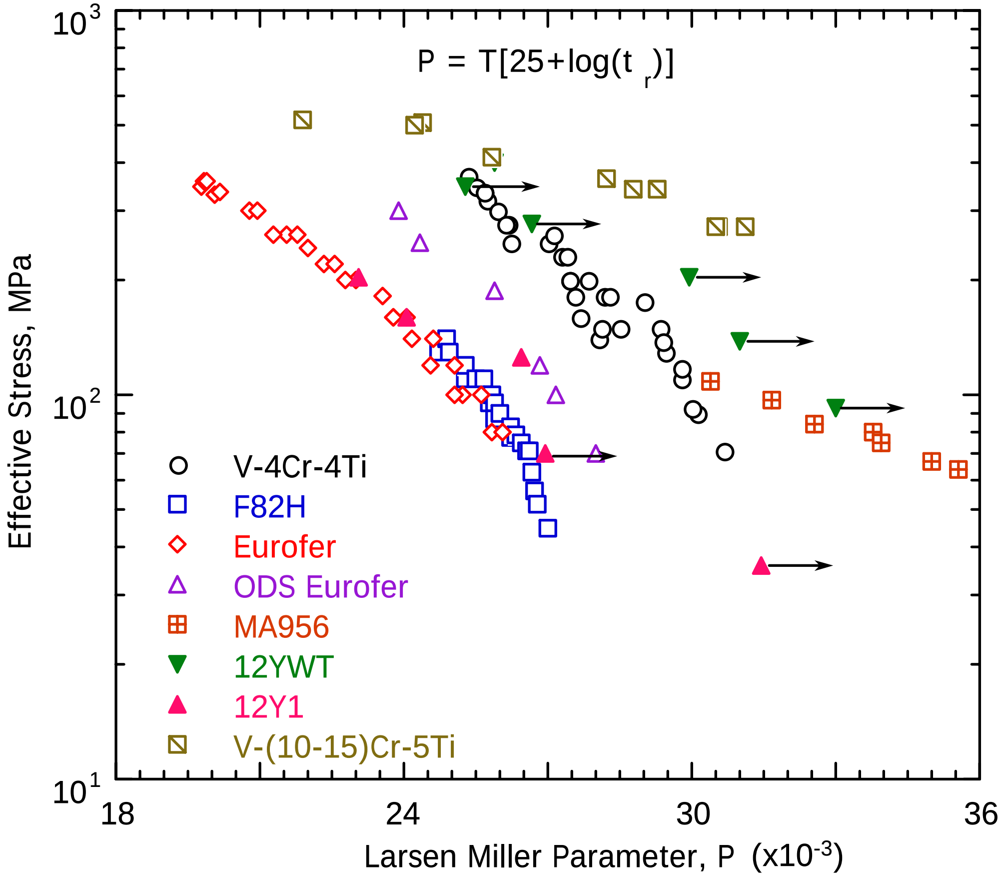


Temperature Dependence of Strength Anisotropy

Okada, et al., 1998



Comparison of Creep-Rupture Properties of Vanadium Alloys, RAFM Steels, and ODS Steels



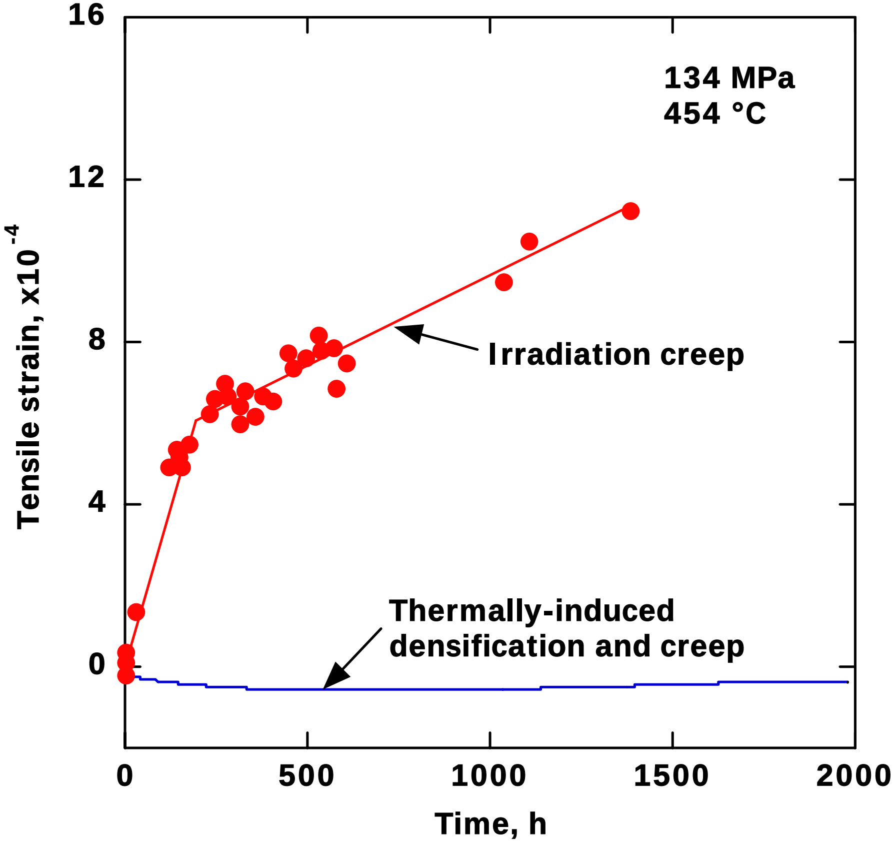
Irradiation Creep - Phenomenological Description

- Orders of magnitude increase in creep strain during relatively low-temperature irradiation
- Degree of creep enhancement is greatest at low temperature, decreasing as the thermal creep regime is approached
- Constitutive equation:

$$\frac{\partial \varepsilon_c}{\partial \phi} = B(\phi,T)\sigma^n, n \approx 1$$

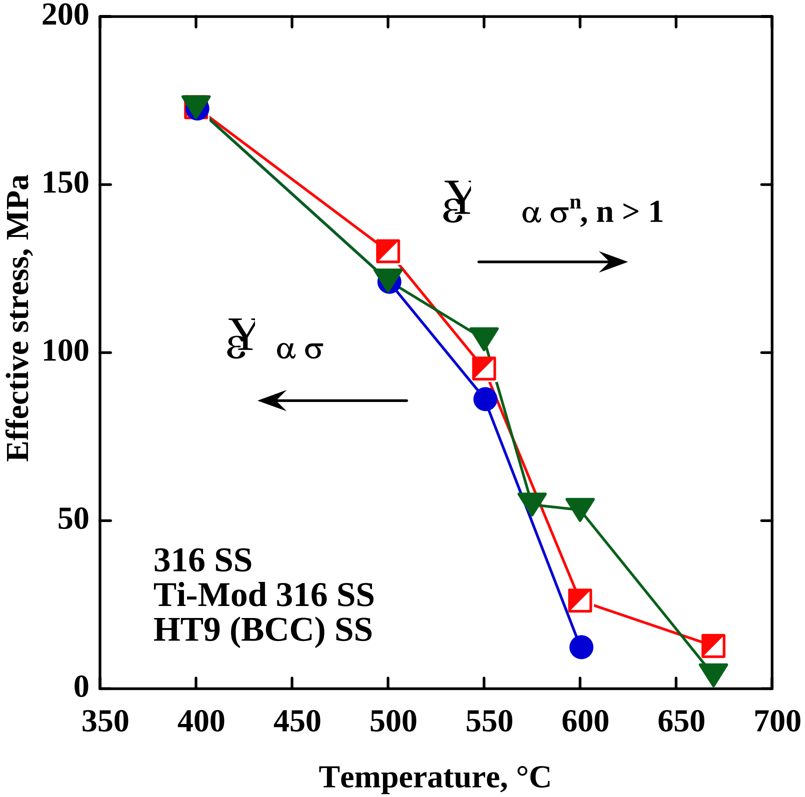
$$B(\phi,T) = B_o + D\frac{\partial S(\phi,T)}{\partial \phi}$$

Gilbert et al, 1972

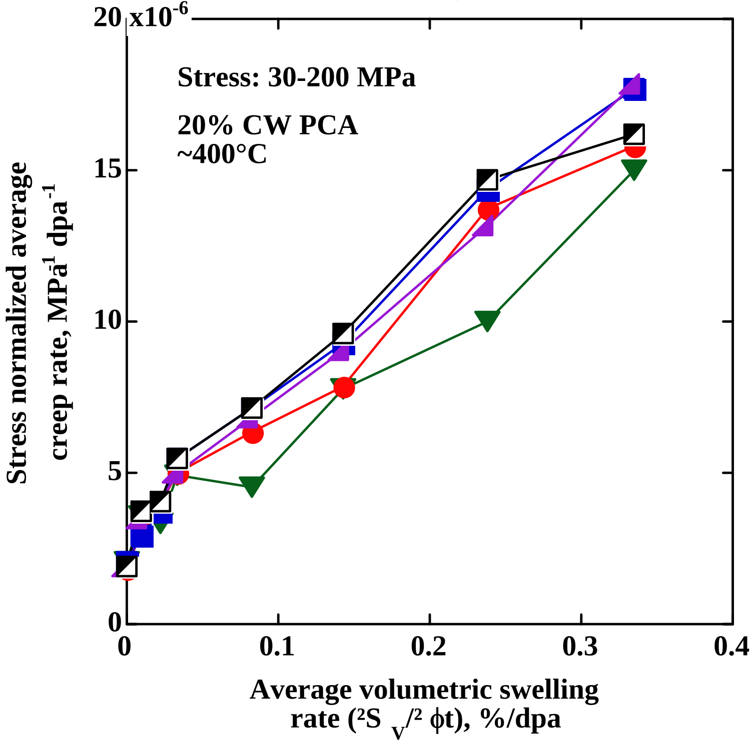


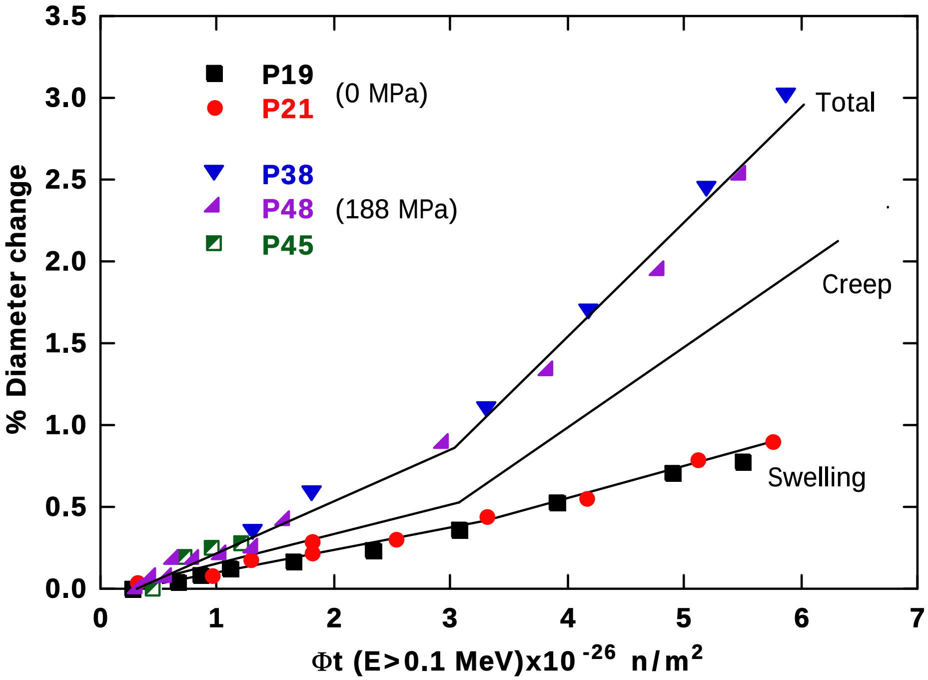
Stress Dependence of Irradiation Creep in the Absence of Swelling

- Irradiation creep exhibits a linear stress dependence over a limited stress range that is temperature dependent
- Similar behavior for FCC and BCC stainless steels


Toloczko, 1999

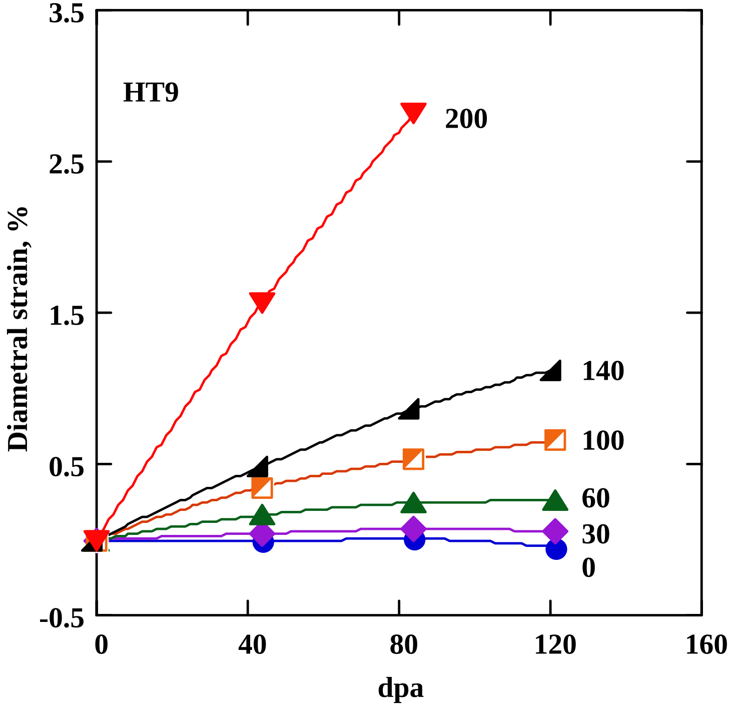
Creep-Swelling Coupling


Toloczko, 1999


Gilbert, Straalsund & Wire, 1977

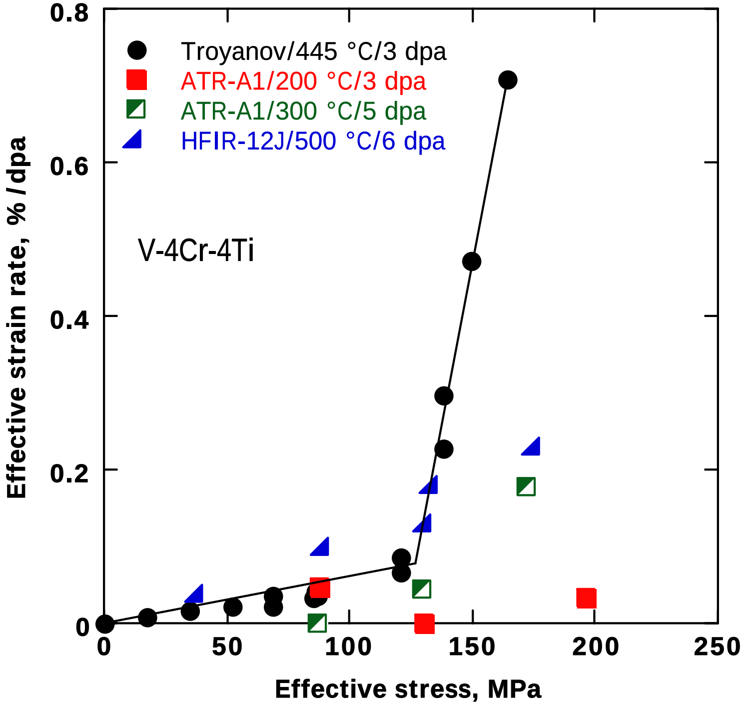
Limited Irradiation Creep Data on Tempered Martensitic Steels and Vanadium Alloys

Toloczko et al, 1999



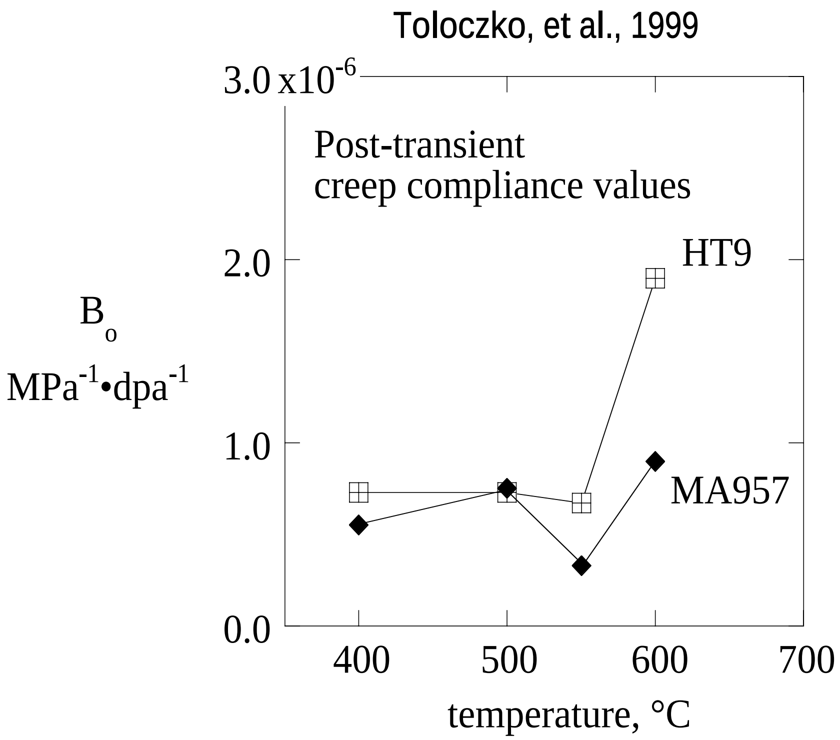
Creep rates are 3-6 times those of stainless steels

Tsai et al, 2000



MA957 & HT- 9 Steady State Irradiation Creep Rate

- Creep compliance values are for the regime where the irradiation creep (or irradiation creep rate) is linear with stress
- Creep compliance is similar to that of other HT9 alloys, except at 600°C where the creep compliance is lower



- MA957 appears to have equal or better irradiation creep resistance than HT9 when irradiated in a fast reactor at temperatures from 400°C to 600°C
- The results suggest that dispersion strengthening may improve resistance to irradiation creep at higher temperatures where traditional ferritic-martensitic steels display poor irradiation creep resistance

Ongoing and Planned Thermal Creep Studies

- Long-term tests in Li planned to develop more complete data base
- Long-term tests in vacuum at low-stress to explore transition in stress exponent
- Investigation of the affect of metallurgical variables:
  - Characterize NIFS Heat-2 creep tubing
  - Effect of grain size on creep properties
  - Alternative heat treatments to render interstitial impurities benign at low-temperature and also create obstacles to dislocation motion at high-temperature
- Real-Time Helium Doping Experiment
  - He, Li, Thermal
  - Major impediment - funding required

Summary of Planned US/Japan Irradiation Experiments

- Predominantly US/Japan collaborative irradiation capsules
  - Smaller efforts using informal EU collaborations and HFIR rabbit capsules
- DOE/JAERI Phase IV fusion materials collaboration
  - Focus is on deformation and fracture behavior of ferritic steels (and other alloys), including He effects
  - Three HFIR target capsules (~25 cm3 volume each; 10, 40dpa, 300/400/500˚C
  - Two HFIR RB* capsules: with, without Eu shielding (~200 cm3 volume each), 6dpa, 300/400˚C
  - Typical irradiation matrix: tensiles, fracture, DFMBs
- DOE/MEXT JUPITER-II “ALiVE” capsule
  - Focus is on deformation and fracture behavior of V alloys, including irrad. creep
  - Eu-shielded HFIR RB* capsule, 450/600/700˚C
- DOE/MEXT JUPITER-II HFIR PT-rabbit and RB* capsules
  - Focus is on radiation effects in 3rd-generation SiC composites (and other materials at 600-1400˚C, dpa
  - Tensile, fracture toughness, thermal conductivity

What Needs to be Done?

- Thermal creep
  - Alternative compositions and microstructures (heat treatments) for improved performance
  - High quality tubing must be fabricated
  - Thermodynamic calculations should be performed to understand vanadium alloys
- Irradiation creep
  - Lack of data at doses above a few dpa for vanadium
  - Effect of alloy composition and heat treatment on irradiation creep
  - Creep-swelling coupling effects
- Helium effects
  - Effect of He on creep and creep-rupture
  - Resolve uncertainties associated with DHCE-1
  - Optimal 2nd phase microstructure for He trapping