PennState
College of Engineering

*NucE 497: Reactor Fuel Performance*

# Lecture 26: Densification, Swelling, Creep, and fracture

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Content taken from slides from ANT international

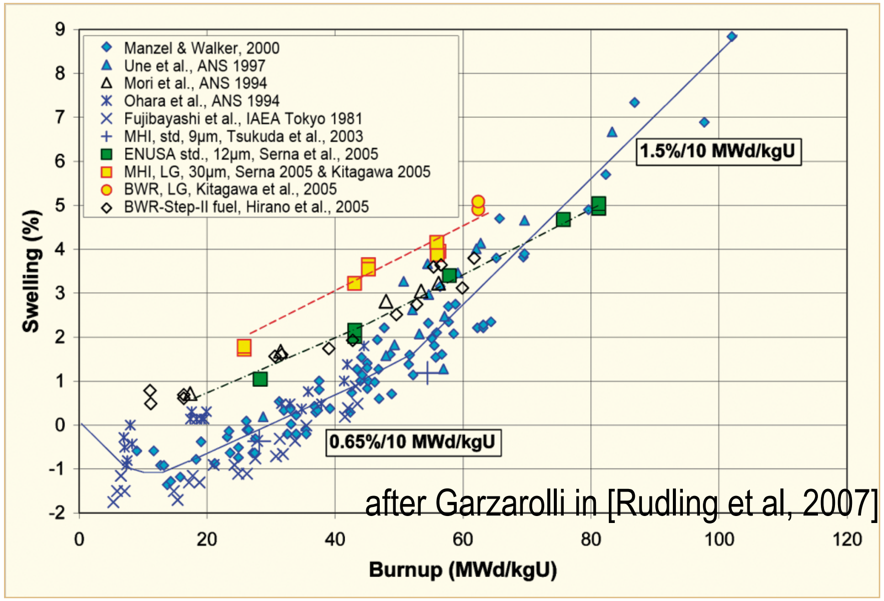
# Today we will discuss dimensional changes in $UO_2$ due to densification, swelling, creep, and fracture

- Module 1: Fuel basics
- Module 2: Heat transport
- Module 3: Mechanical behavior
- Module 4: Materials issues in the fuel
  - Property evolution and Intro to materials science
  - Chemistry
  - Grain growth
  - Fission products and fission gas
  - **Densification, swelling, and creep**
  - HBS
  - Fracture
  - Thermal conductivity
- Module 5: Materials issues in the cladding
- Module 6: Accidents, used fuel, and fuel cycle

# Here is some review from last time

- Which statement is true about the Booth fission gas release model?
  a) It considers stages 1 and 2 of fission gas release
  b) It uses a realistic distribution of grain sizes
  c) It predicts the fraction of total gas that has been released
  d) It only considers stage 3 of fission gas release
- What is post-irradiation annealing?
  a) Heating up irradiated steals to reduce irradiation induced hardening
  b) Heating up irradiated cladding to reduce hydride content
  c) Nothing, you made it up
  d) Heat up irradiated fuel to induce fission gas release

# Many models of reactor fuel behavior are fits to experimental data




- They are typically correlated to burnup
- Burnup is a measure of how much fissioning has taken place. Typical units are:
  - MWD/kgU
  - FIMA
- It can be calculated from the volumetric fission rate

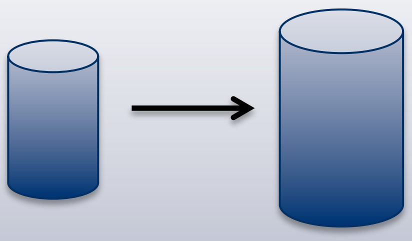
$$\beta = \frac{\dot{F}t}{N_U}$$

- What are the units from this equation?
  - Fissions/(cm$^3$ s)*s*(initial U atoms/cm$^3$)$^{-1}$
  - So, the units are FIMA
- To convert from FIMA to MWD/kgU, multiply by 950

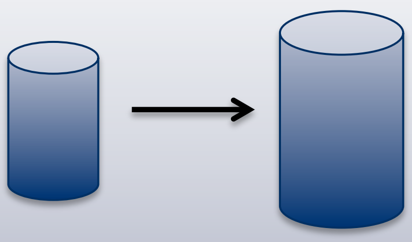
# Fuel pellets change size and shape during reactor operation

- We have already talked about thermal expansion. However, shape changes also occur due to irradiation and fissioning.

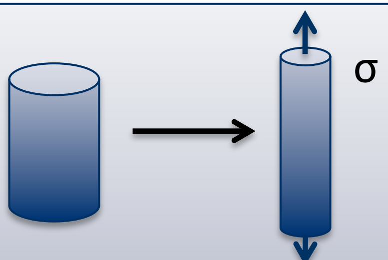
**Densification**
- Decrease in volume
- Increase in density
- Caused by shrinking of porosity left after sintering



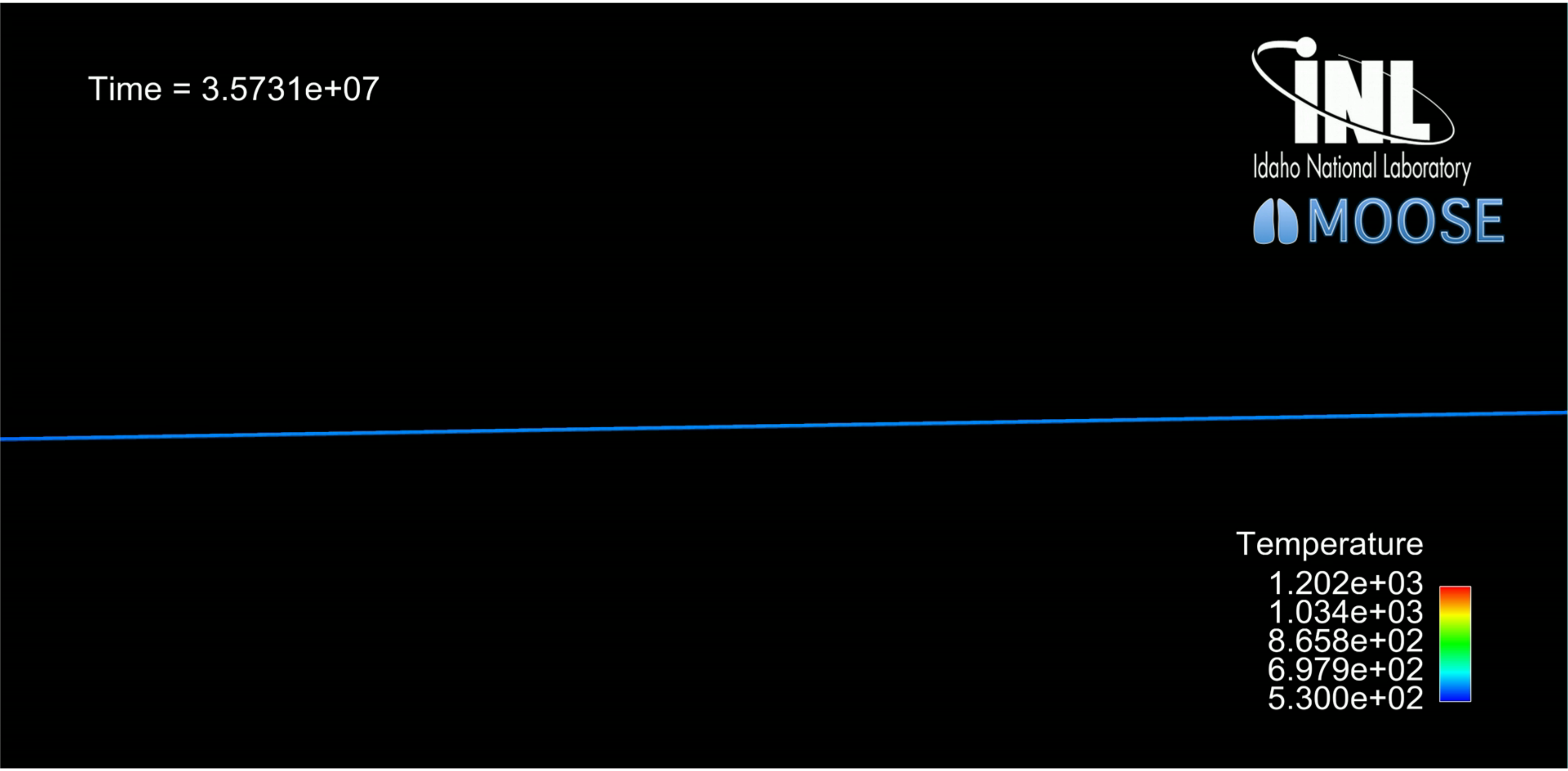
**Swelling**
- Increase in volume
- Decrease in density
- Caused by fission products



**Irradiation Creep**
- Change in shape
- Constant density
- Occurs under stress with $\sigma < \sigma_y$



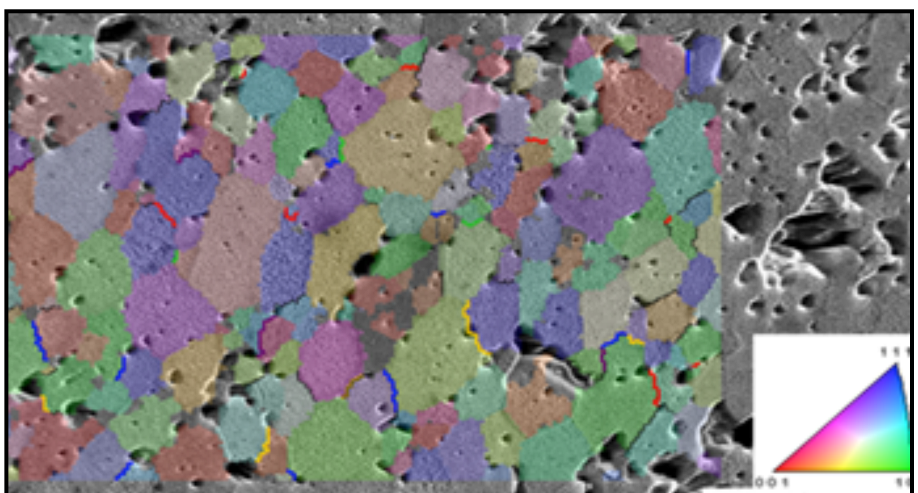
# In this simulation, you can see the various types of volumetric changes that occur

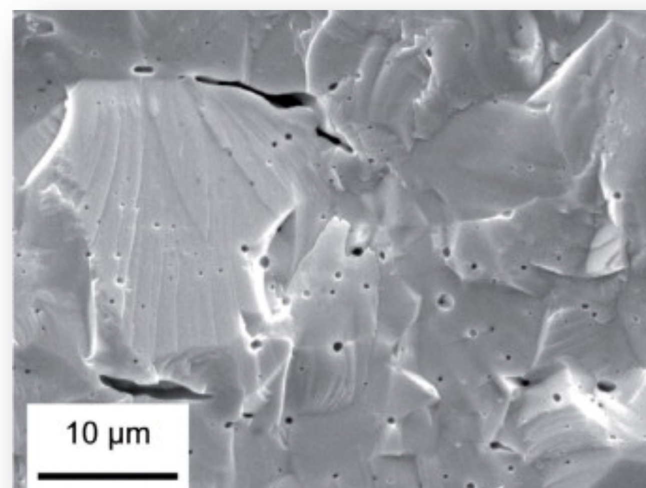


# Remember that fresh fuel pellets are not fabricated to be 100% dense

**Fabrication:**
powder-compact, sintering
**Dimensions:**
diameter (~ 1 cm)
height (~ 1.2 cm)
**Enrichment:**
5% ($U^{235}$) (used to be 3%)
**Microstructure**

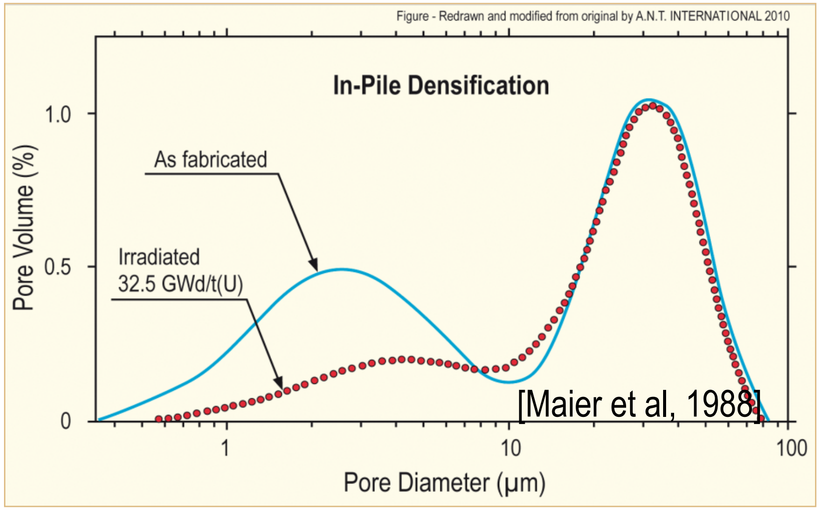
| | |
|---|---|
| Grain Size | ≈ 10 µm |
| Pore Size | ≈ 3 µm |
| Density | ≈ 95 - 99% |





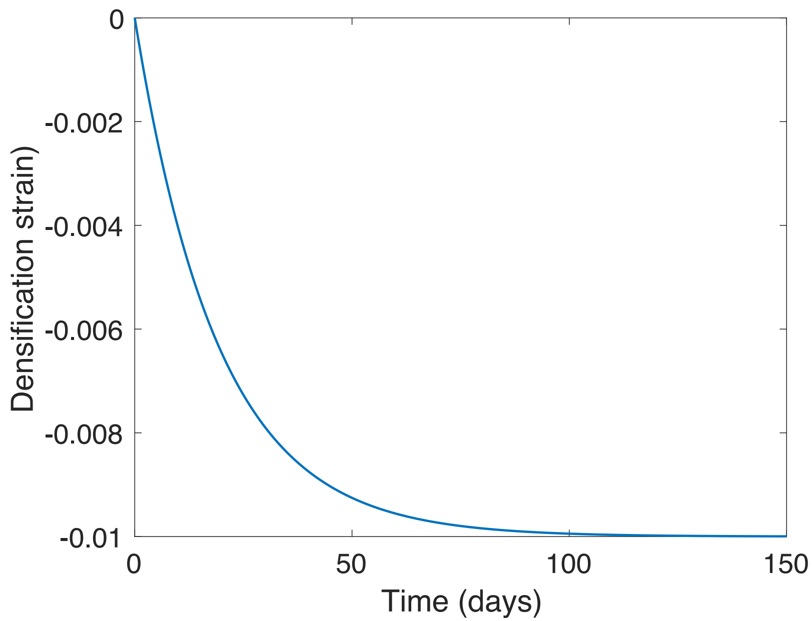
# Early in life, fuel pellets shrink the initial porosity is eliminated

- In some ways, densification is a continuation of the sintering process
- However, irradiation accelerated the process
  - Small, as-built pores close due to effects of fission spikes and vacancy diffusion
  - Large pores stable (in absence of large hydrostatic stress)
- It takes place during initial 5 - 10 MWd/kgU
- Pellets with higher initial density, densify less



# An empirical model of densification has been developed

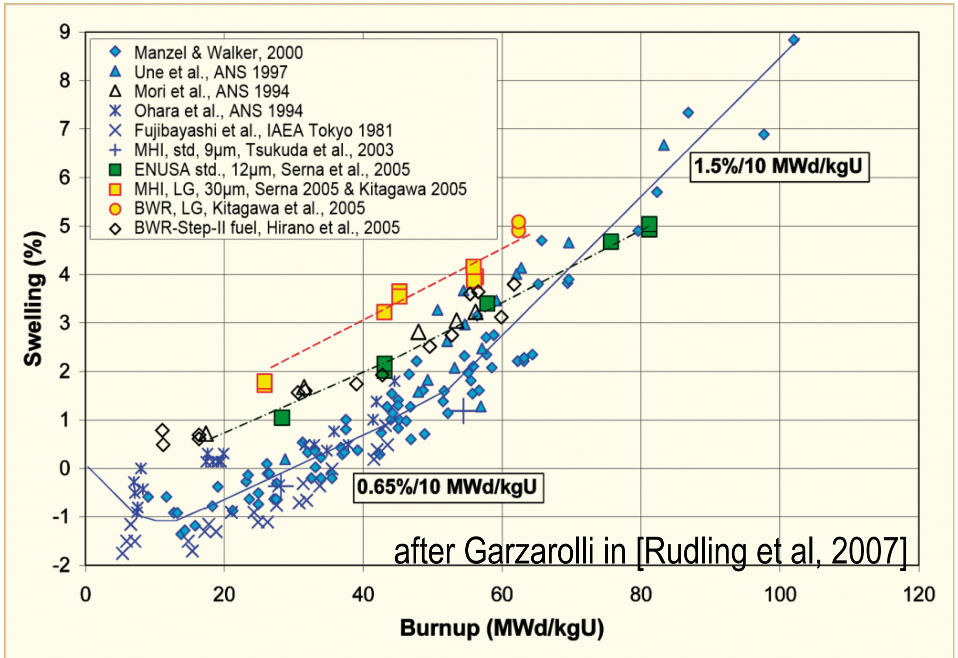
- It is a function of
  - $\beta$ - Burnup (in FIMA)
  - $\Delta\rho_0$ – Total densification that can occur (a common value is 0.01)
  - $\beta_D$ – Burnup at which densification stops ( a common value is 5 MWD/kgU)
  - $C_D$ = 7.235 – 0.0086 (T(°C) – 25) for T < 750°C and CD = 1 for T ≥ 750 °C
- $\epsilon_D = \Delta\rho_0 \left( e^{\frac{\beta \ln 0.01}{C_D \beta_D}} - 1 \right)$




Technical Report EPRI 1011308

# Fission products cause the fuel to swell

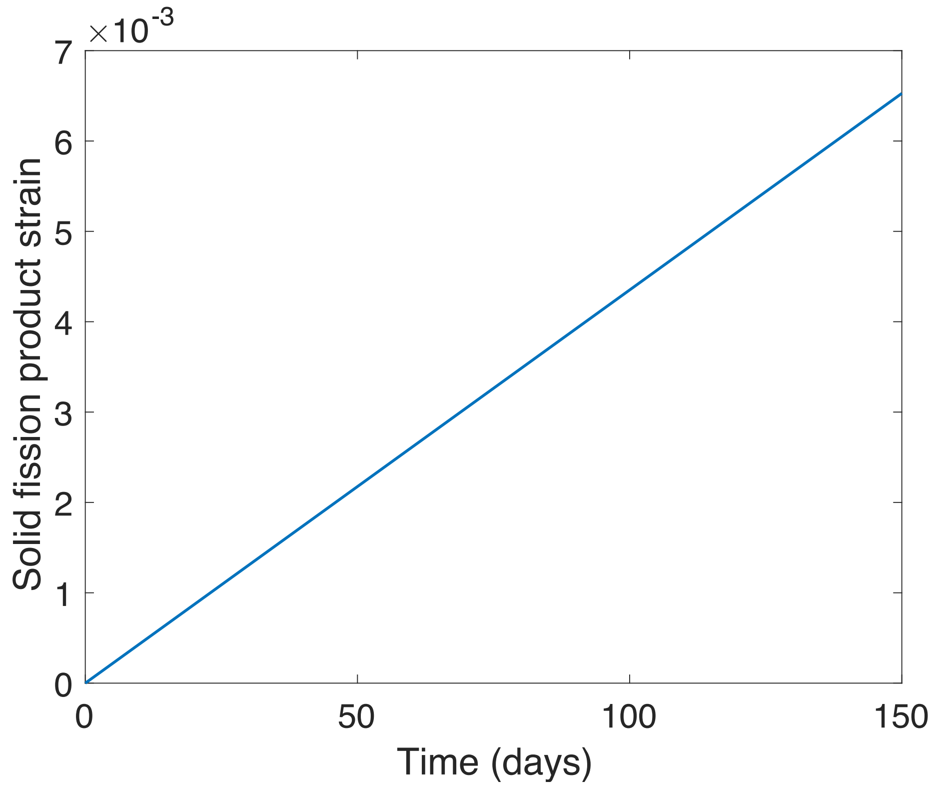
- Fission product swelling results from three changes in the fuel microstructure
  - Solid swelling: Accumulation of soluble and insoluble fission products in fuel matrix
  - Gaseous swelling: Accumulation of gaseous and volatile fission products in intragranular and intergranular pores
  - High burnup swelling: Restructuring of pellet rim with the accumulation of fission gas in a large number of small pores



after Garzarolli in [Rudling et al, 2007]

# An empirical model has been developed for solid fission product swelling

- The solid fission product swelling model is a function of:
  - B – Burnup (in FIMA)
  - ρ – Initial $UO_2$ density (g/cm$^3$)
- $\epsilon_{sfp} = 5.577 \times 10^{-2} \rho \beta$

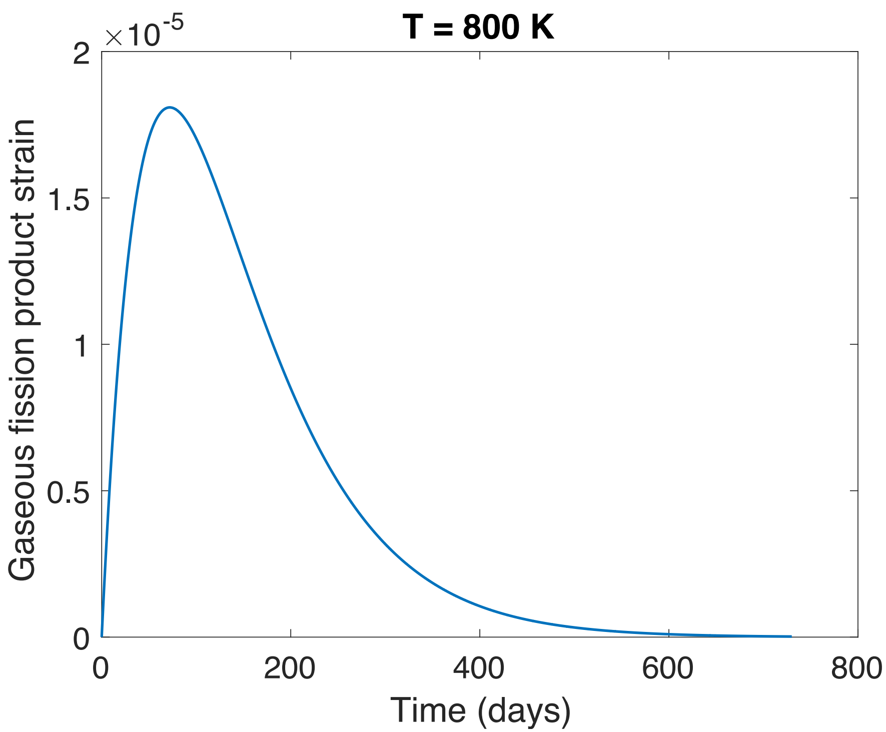


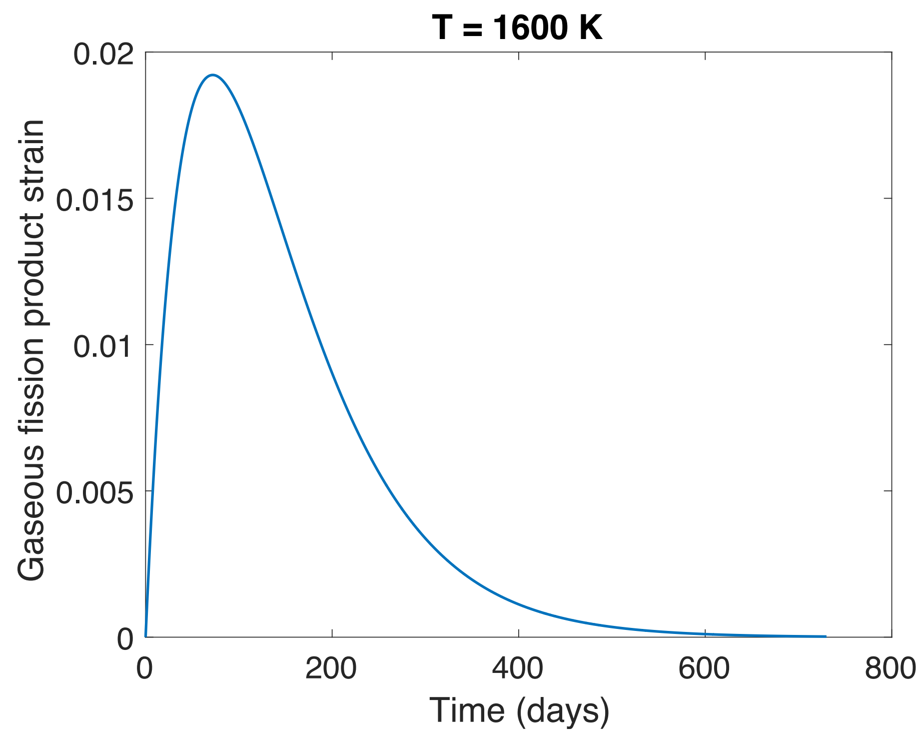
# Gaseous swelling varies strongly with temperature, fission rate and stress

- T < 1000K
  - Fission gas atoms remain in fuel matrix or collect in small, isolated, intragranular pores (<1 nm)
  - Intragranular pore size limited by fission spikes that drive gas back into fuel matrix
- T = 1000 to 1700-2000K
  - Swelling takes place at hot interior of pellet
  - Gas atoms in fuel matrix diffuse to grain boundaries and collect in pores
  - Gas pressure causes bubbles to increase in size and to coalesce into larger pores
  - Gaseous swelling opposed by applied stress (opposite of hot pressing)
  - Gaseous swelling also constrained by fission gas release
- T > 1700-2000K: Gas released by grain growth; gaseous swelling reduced or eliminated

# There is also an empirical gaseous swelling model

- The gaseous fission product swelling model is also a function of:
  - B – Burnup (in FIMA)
  - ρ – Initial $UO_2$ density (g/cm$^3$)
- $\epsilon_{gfp} = 1.96 \times 10^{-28} \rho\beta (2800 - T)^{11.73} e^{-0.0162(2800-T)}\, e^{-17.8\rho\beta}$



# Now, let's work a problem

- Consider material within a fuel pellet that is experiencing a volumetric fission rate of 2.5e13 fissions/($cm^3$ s) and has a temperature of 1400 K. Determine the total amount of volumetric change it experiences after 2 weeks. Consider thermal expansion ($T_{fab}$ = 300 K), Densification ($\Delta\rho_0$ = 0.01 and $\beta_D$ = 5 MWD/kgU), and both kinds of swelling.
- First, we need to calculate the burnup, $\beta = \dot{F}t/N_U$
  - $N_U = N_a\, \delta_U/M_U$ = 6.022e23*9.65/238 = 2.44e22 atoms of U/$cm^3$
  - $\beta$ = 2.5e13*3600*24*7*2/2.44e22 = 0.0012 FIMA
- Next, we need to determine the strain from thermal expansion
  - $\varepsilon_{th} = \alpha\Delta T$ = 11e-6*(1400 – 300) = 0.0121
- Then, we consider densification, $\epsilon_D = \Delta\rho_0 \left( e^{\frac{\beta \ln 0.01}{C_D \beta_D}} - 1 \right)$
  - We need to calculate $C_D$, but because we are higher than 750 °C, $C_D$ = 1
  - We need to convert the burnup to FIMA, $\beta_D$ = 5 MWD/kgU/950 = 0.0053 FIMA
  - $\varepsilon_D$ = 0.01*(exp(0.0012*log(0.01)/(1*0.0053)) – 1) = -0.0065

# Now let's work a problem (cont)

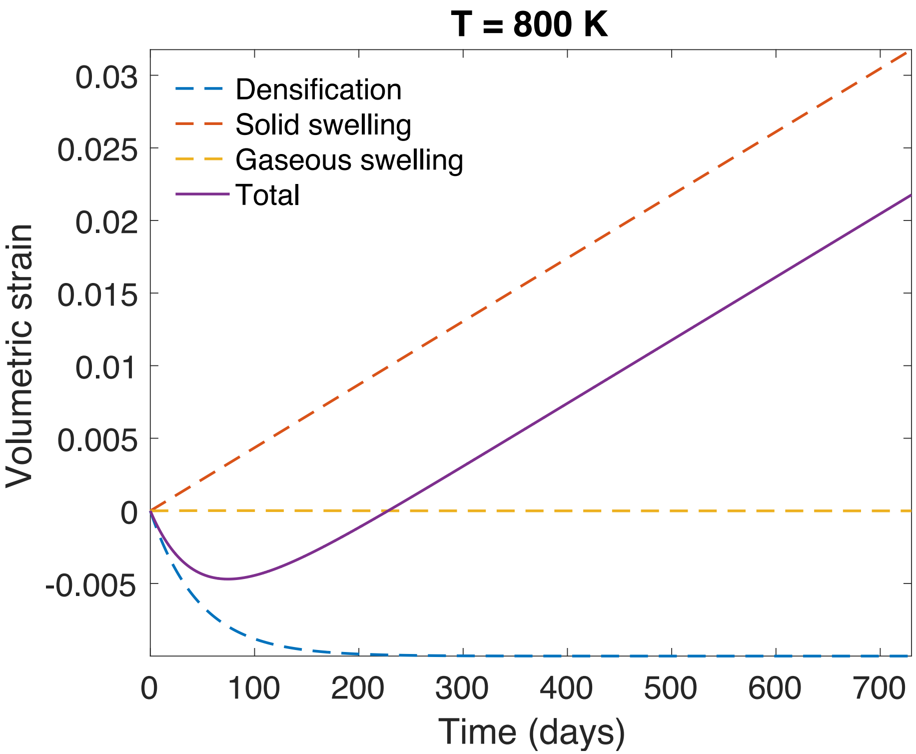
- For solid fission product swelling, $\epsilon_{sfp} = 5.577 \times 10^{-2} \rho\beta$
  - For the density of $UO_2$, $\rho = 10.97$ g/cm$^3$
  - $\varepsilon_{sfp}$ = 5.577e-2*10.97*0.0012 = 7.34e-4
- Finally, gaseous fission product swelling $\epsilon_{gfp} = 1.96 \times 10^{-28} \rho\beta(2800 - T)^{11.73} e^{-0.0162(2800-T)} e^{-17.8\rho\beta}$
  - $\varepsilon_{gfp}$ = 1.96e-28*10.97*0.0012*(2800 – 1400)^11.73* exp(-0.0162*(2800 – 1400))*exp(-17.8*10.97*0.0012) = 0.0023
- The total change in volume is found by adding them all up
  - $\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_D + \varepsilon_{sfp} + \varepsilon_{gfp}$ = 0.0121 – 0.0065 + 7.34e-4 + 0.0023 = 0.0086

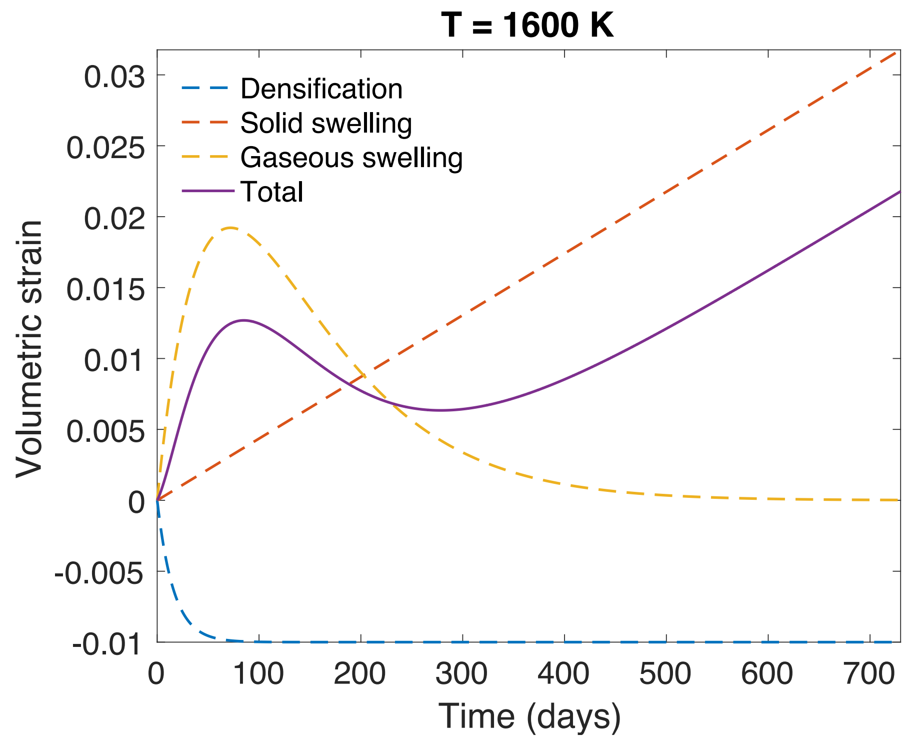
# Now you do one

- What is the highest temperature for which densification would eventually cancel out thermal expansion (use $\Delta\rho_0 = 0.01$ and $\beta_D = 5$ MWD/kgU)? At this T, what would the densification strain be at a burnup of 5 MWD/kgU
  - $\varepsilon_{th} = \alpha(T - T_{fab})$, with $\alpha = 11e\text{-}6$ 1/K and $T_{fab} = 300$ K. $\epsilon_D = \Delta\rho_0 \left( e^{\frac{\beta \ln 0.01}{C_D \beta_D}} - 1 \right)$

- What is the largest magnitude strain that can come from densification?
  - $\varepsilon_D = -0.01$
- So, solve for T when thermal expansion = 0.01
  - $\varepsilon_{th} = \alpha(T - T_{fab})$
  - $T = \varepsilon_{th}/\alpha + T_{fab} = 0.01/11e\text{-}6 + 300 = 1209.1$ K
- Now, solve for the strain at a burnup of 5 MWD/kgU
  - T > 750 °C, so $C_D = 1$
  - $\varepsilon_D$ = 0.01*(exp(5/5*log(0.01)) – 1) = 0.01*(0.01 – 1) = -0.0099

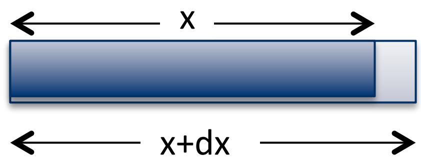
# The overall swelling behavior depends on temperature



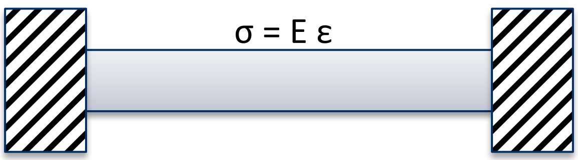



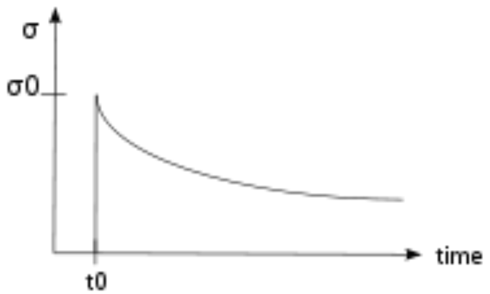
# Creep is a general mechanism for plastic deformation that occurs over time when $\sigma < \sigma_y$

- Consider a metal beam. We heat it up so it expands some distance dx




- We then fix it between two walls and let it cool down



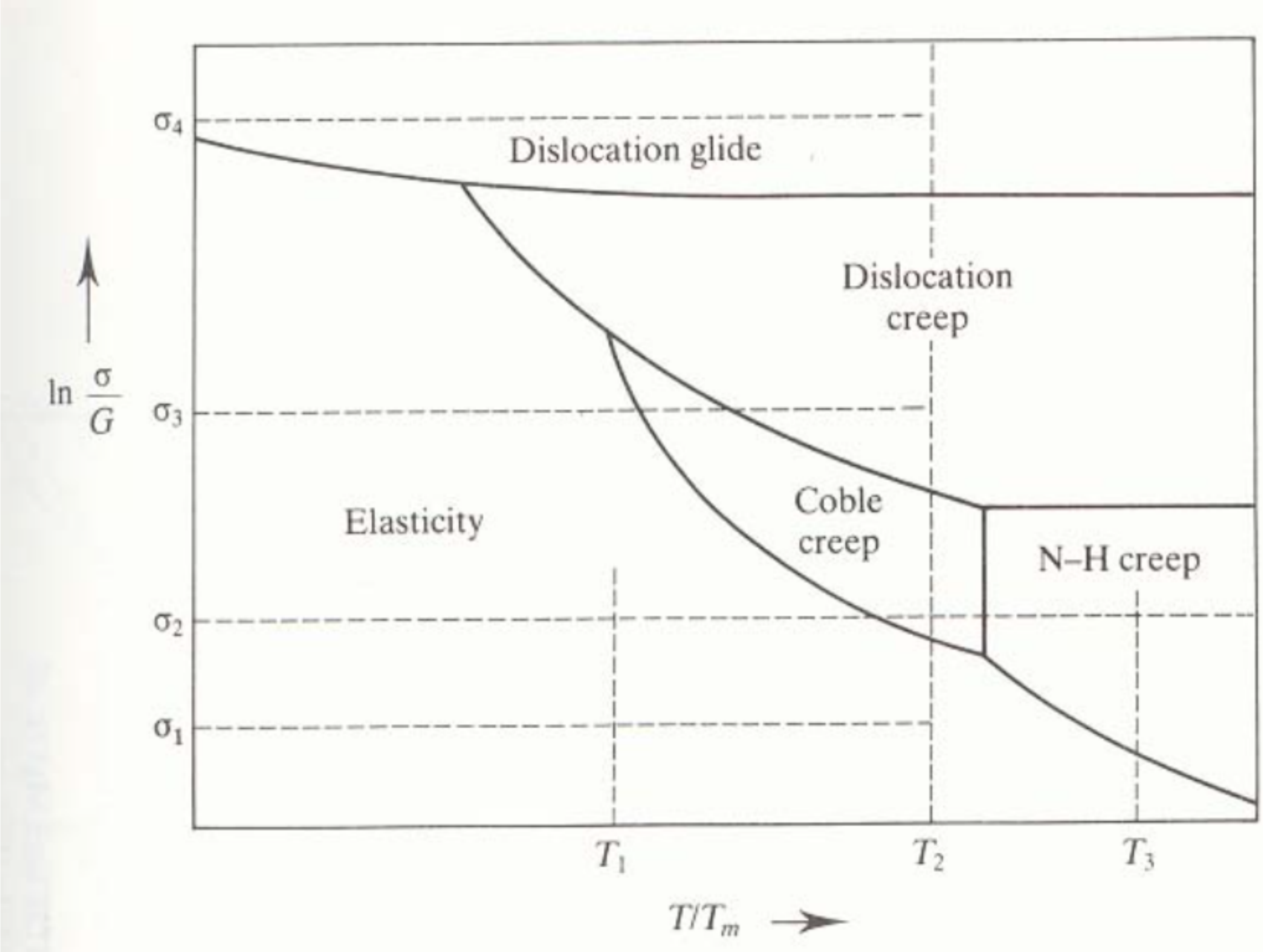

- Because $\sigma < \sigma_y$, that stress remains constant
- In creep, defect diffusion is induced by the stress to cause permanent deformation and reduce the stress.
- Therefore, creep
    - Occurs over time
    - Increases with increasing number of diffusing defects
        - High temperature (**thermal creep**)
        - Irradiation (**irradiation creep**)

# Creep can be caused by various microstructural mechanisms

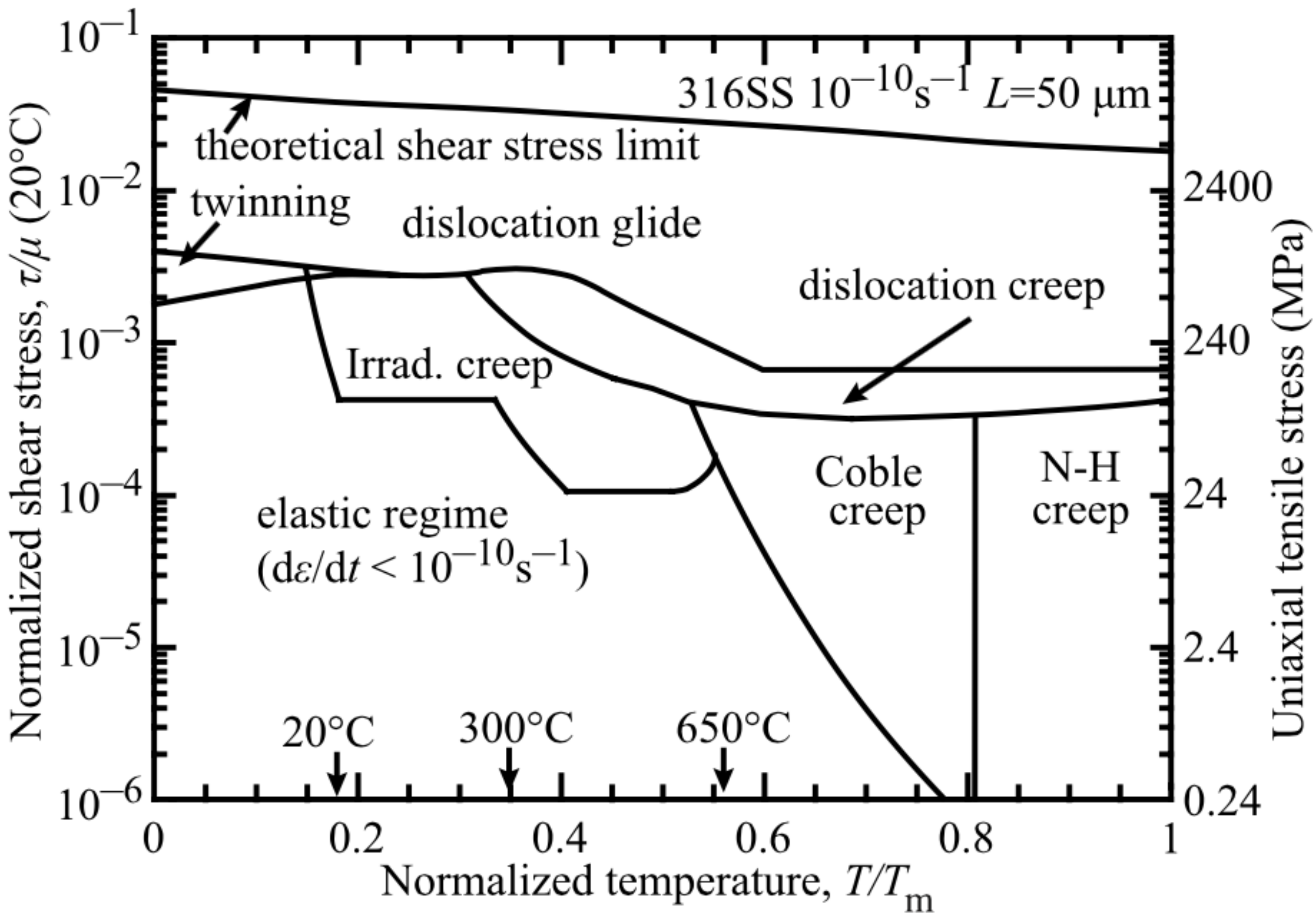
$$\dot{\epsilon} = \frac{C\sigma^m}{D_{gr}^b} e^{\frac{-Q}{k_b T}}$$

- Bulk Diffusion (Nabarro-Herring creep)
  - Atoms diffuse (high T), causing grains to elongate along the stress axis
  - Q = Q(self diffusion), m = 1, and b = 2
- Grain boundary diffusion (Coble creep)
  - Atoms diffuse along grain boundaries to elongate the grains along the stress axis
  - Q = Q(grain boundary diffusion), m = 1, and b = 3
- Dislocation creep
  - Dislocations glide under a high stress
  - Dislocations climb due to defects to avoid obstacles
  - Q = Q(self diffusion), m = 4–6, and b = 0

# Different creep mechanisms are active for different combinations of stress and temperature

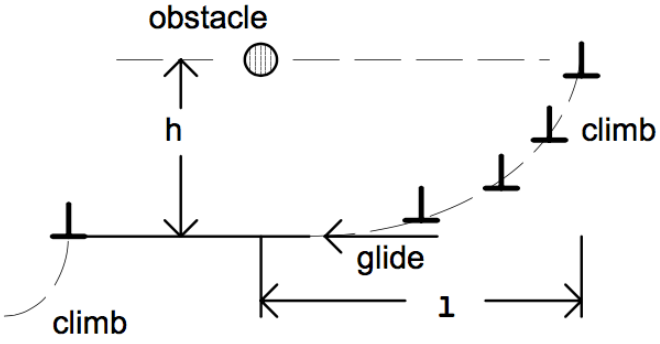


# The behavior of creep changes in irradiated materials



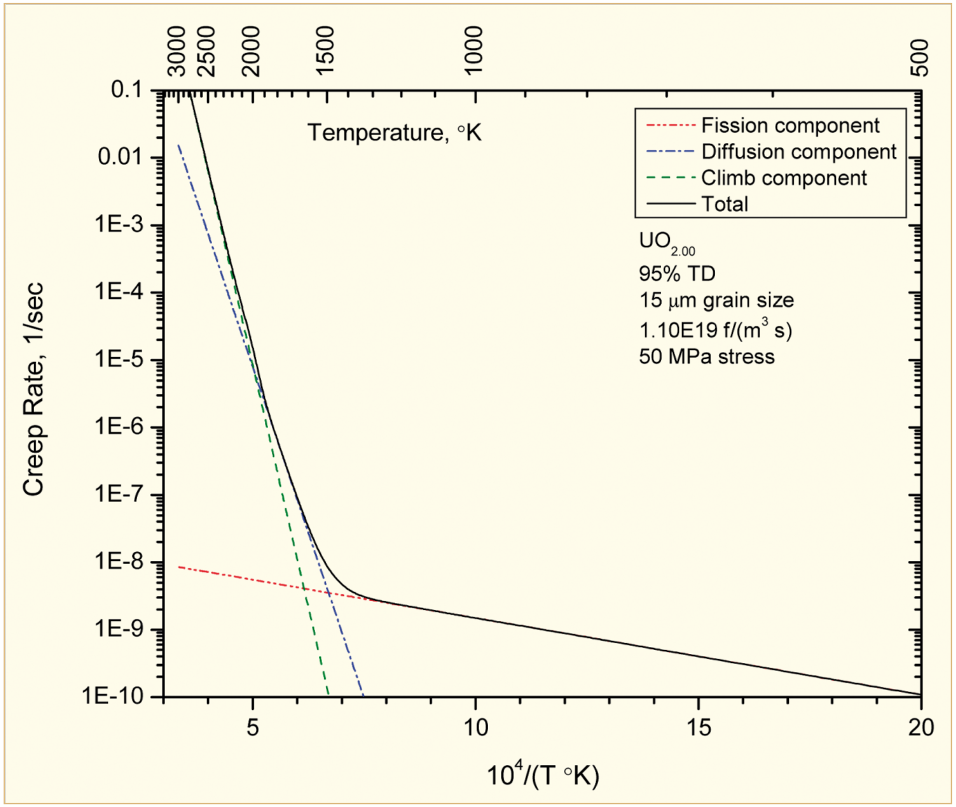
# Irradiation accelerates creep, causing it to be significant at lower temperatures

- Irradiation has little effect on diffusional creep
- However, it accelerates dislocation creep in cubic materials
- The dislocation creep rate can be written as $\dot{\varepsilon} = \rho_d^m b \mathrm{v}_d$
  - $\rho_d{}^m$ is the density of mobile dislocations
  - b is the burgers vector
  - $v_d$ is the dislocation velocity
- Gliding dislocations quickly get pinned by obstacles
- As the dislocations absorb defects created by irradiation, they climb to different slip planes to avoid the obstacles
- More interstitials are absorbed than vacancies due to the higher sink strength for interstitials



# Like other materials, the fuel also undergoes creep

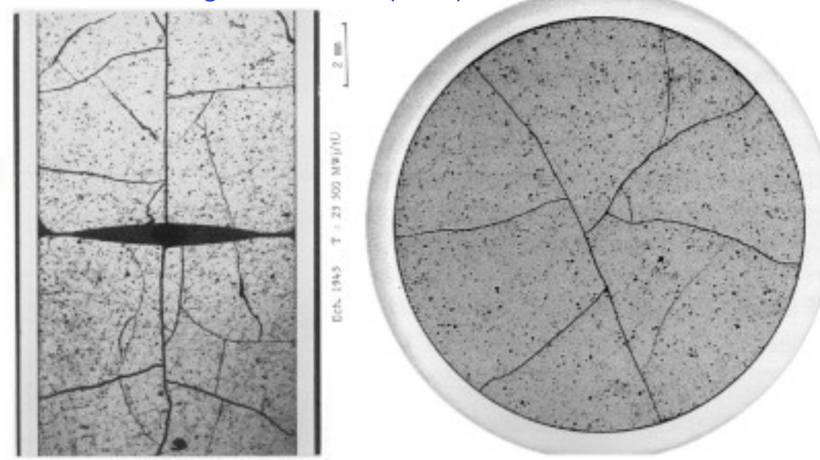
- The fuel creep is a combination of diffusion creep and irradiation creep



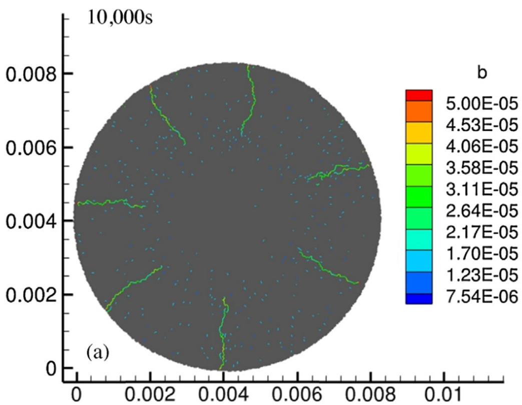

Steady state creep of $UO_2$ – MATPRO/FRAPCON [Hagman 1993]

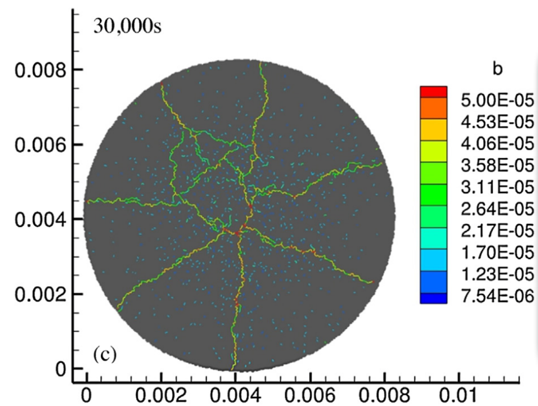
# $UO_2$ pellets fracture during changes in temperature due to large thermal stresses

Michel et al. Eng. Fract. Mech. (2008)



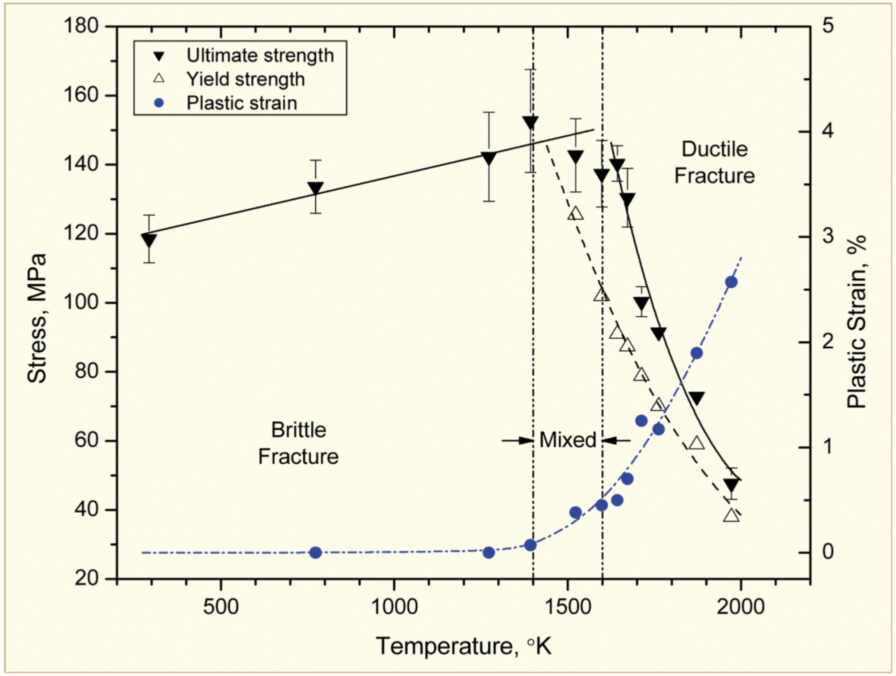
- Fracture results in:
  - Increased gap reduction
  - Reduced thermal conductivity
  - Increased avenues for fission gas release
- Fracture has been typically modeled in two ways:
  - Empirical relocation model that is a function of burnup
  - Semi-empirical smeared cracking model
- Modern methods provide means of modeling discrete cracks




- Radial cracks partially penetrate the pellet during temperature increase
- Full cracking occurs when the temperature decreases
- *From Huang et al. (2014)*

# Strength and ductility of UO2 vary strongly with temperature




after [Canon et al, 1971]

- Strength and ductility varies strongly with temperature
  - Low T: Brittle fracture without measureable ductility
  - High T: Elastic behavior to proportional limit followed by plastic deformation to ultimate strength
  - Intermediate T: Mixed behavior

# The fracture behavior of the fuel is fairly complicated

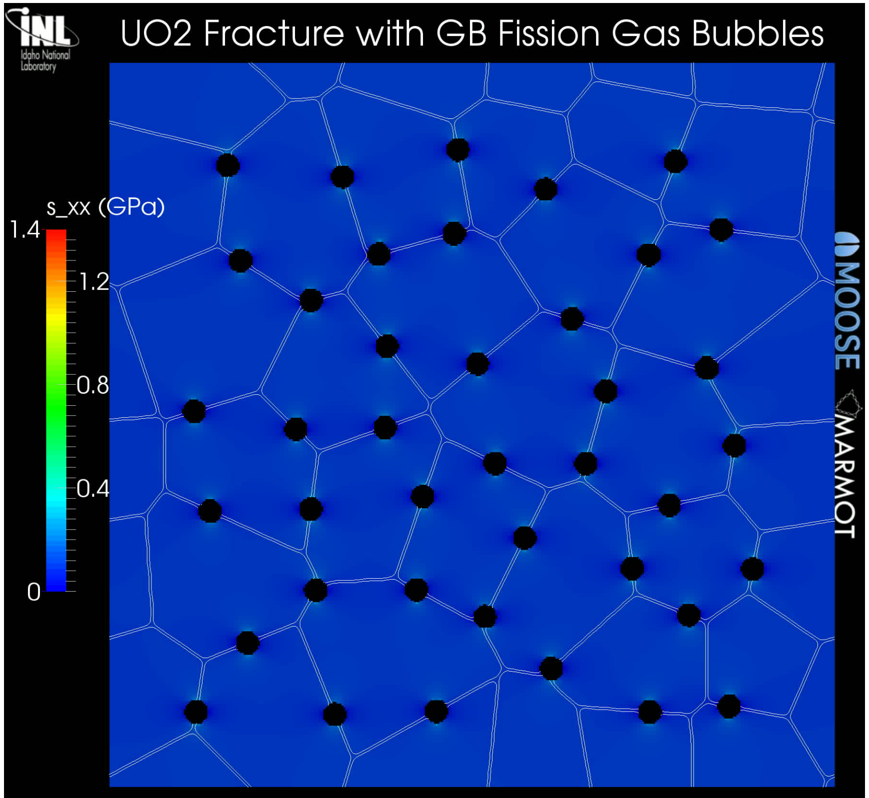
- Fracture strength varies with grain size (G)
  - $\sigma_{frac} = G^{-m}\sigma_{frac, ref}$, m = 0.04 – 0.05 (vs. m ~ 0.5 for metal)
  - Increasing grain size from 10 $\mu$m to 100 $\mu$m reduces $\sigma_{frac}$ by ~10%
- Ductility transition temperature is lower in-reactor than in thermal tests
- Fracture strength is ~10× higher in compression than in tension
- Load-deformation behavior strongly affected by creep under in-reactor conditions

# The fracture stress of the fuel changes during irradiation

- Fuel fracture is impacted by temperature, stress, grain size $d$, and grain boundary fractional coverage $f_c$

*Fracture Stress*

$$\sigma_f(\ G_c, f_c, d\ )$$



# Summary

- Many materials models for fuel are empirical and correlated to burnup
- Fuel pellets change shape due to
  - Thermal expansion (increase in volume)
  - Densification (decrease in volume)
  - Swelling (increase in volume)
  - Creep (volume stays the same)
- Fracture also decreases the gap, as fractures pieces shift outward