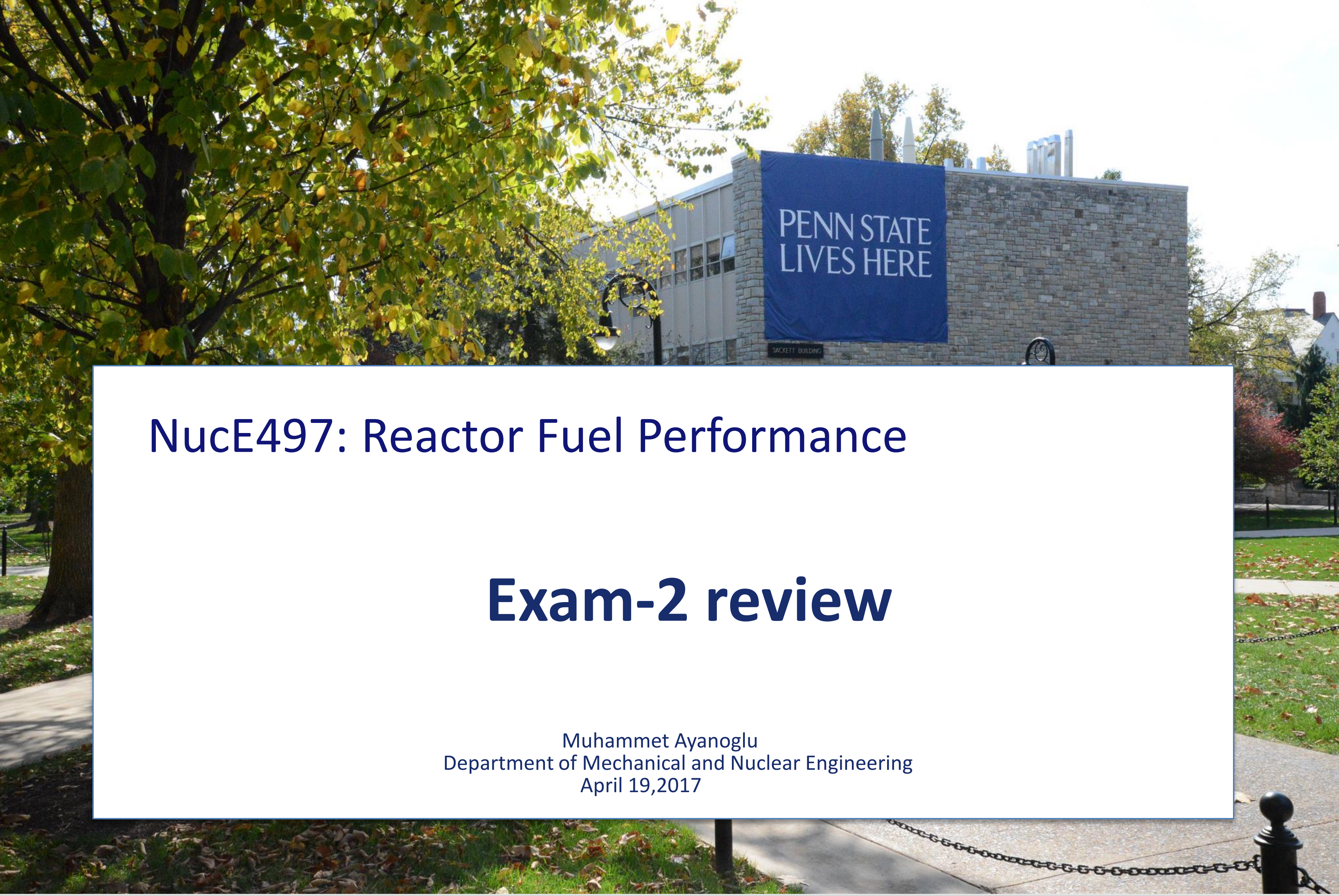

NucE497: Reactor Fuel Performance

Exam-2 review

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Department of Mechanical and Nuclear Engineering
April 19,2017

Exam Date:

April 20 at 12 am – April 21 at 11:59 pm

Total time:

TBD(Download+Solve+Convert/Upload)

If you create your PDF and then find something you would like to change, you are permitted to edit your PDF or add notes before submitting. I recommend you have two methods set up to convert your solutions to a PDF, as I will not accept "I couldn't make the PDF" as a valid excuse.

Exam Format

- Exam includes both conceptual and workout problems.
- Conceptual questions include everything discussed in the class.
- Workout problems will be similar to the problems you did on the homework, or that we did in class.
- Study thoroughly for the exam

Course content

- Module-1: Fuel basics
- Module-2: Heat transport
- Module-3: Mechanical Behavior
- Module-4: Materials issues in the fuel
- Module-5: Materials issues in the cladding
- Module-6: Accidents, used fuel, and fuel cycle

You are responsible for the last three modules…

- Module-1: Fuel basics
- Module-2: Heat transport
- Module-3: Mechanical Behavior
- Module-4: Materials issues in the fuel
- Module-5: Materials issues in the cladding
- Module-6: Accidents, used fuel, and fuel cycle

Module-4: Materials issues in the fuel

- Property evolution and intro to materials science
- Chemistry
- Grain growth
- Fission product and fission gas
- Densification, swelling and creep
- High burnup structure
- Fracture
- Thermal Conductivity

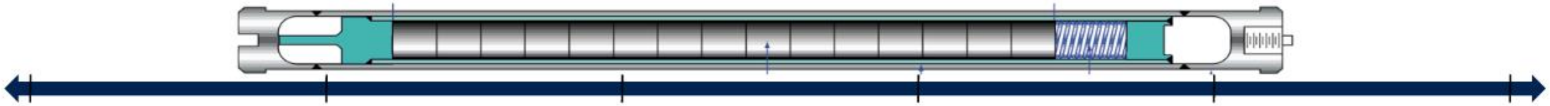
Module-5: Materials issues in the cladding

- Zirconium alloys and fabrication
- Cladding growth and creep
- Irradiation hardening
- Oxidation & Hydride formation
- Stress corrosion cracking

Module-6: Accidents, used fuel, and fuel cycle

- RIA & LOCA
- Accident tolerant fuel
- Fuel cycle and used fuel disposition

Module-4: Materials issues in the fuel

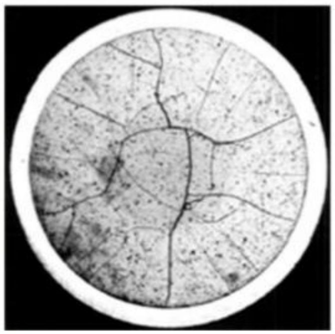


Insertion in reactor

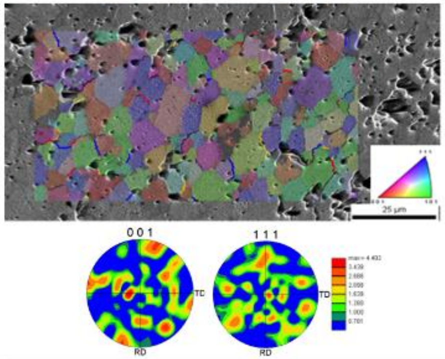
Removal from reactor

Fuel Fabrication
- Sintered UO^2
- Height 2 cm
- Diameter 1 cm
- ~10 µm grain size
- Density > 95%

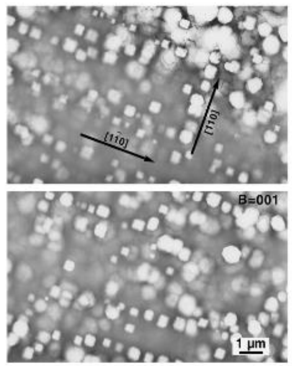
From Pedro Peralta, ASU



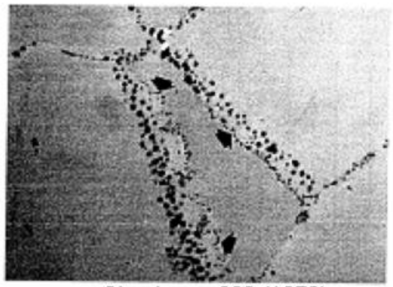
Early life
- Thermal expansion
- Fracture
- Point defect and fission gas generation
- Fuel Densification



Mid Life
- Point defect diffusion
- Point defect clustering
- Fission gas segregation to GB and voids
- Bubble nucleation



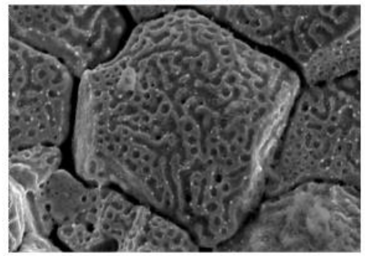
Zinkle and Singh 2000

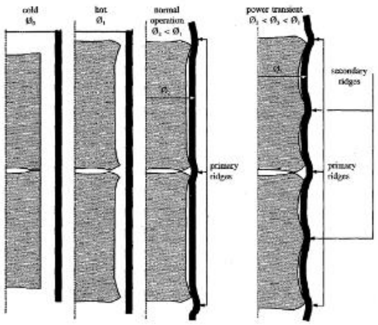


Olander, p. 323 (1978)

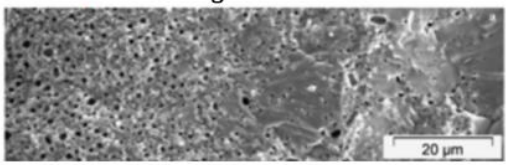
Late life
- Fission product swelling
- Bubble percolation and fission gas release
- Cladding creep
- Fuel creep

Brohan 2000

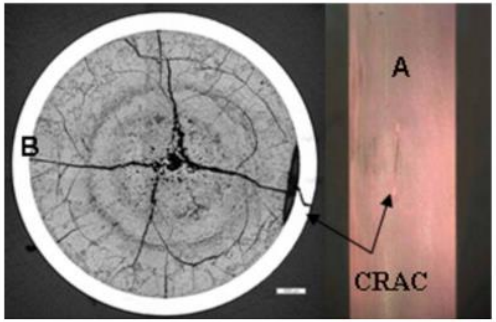




Fuel failure
- Pellet/cladding interaction
- Cladding corrosion
- Cladding fracture



Santana et al. 2011



Example: Fission gas release

What is the total number of fission gas atoms **produced** within pellets after 2 years?(fission yield of Xe and Kr is y)

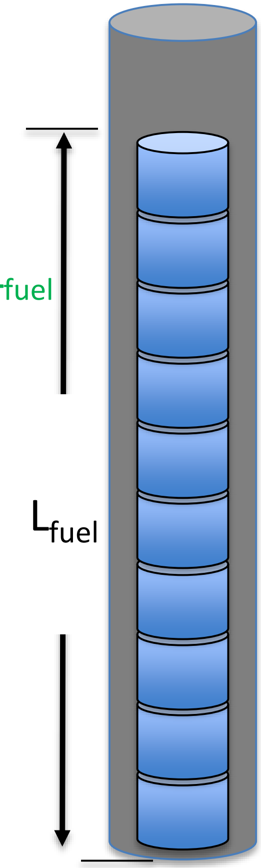
# of gas atoms produced in the fuel

$$\boxed{N_{gas}}=y\,\boxed{\dot{F}}\,\boxed{t}\,\boxed{Vfuel}$$

$V_{fuel}[cm^3]=\pi R^2 L_{fuel}$

$\dot{F}$ [fission/cm^3-s]$=q\sigma_f N\varphi$

t [s]=2x365x24x3600



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Example: Fission gas release (cont.)

What is the total number of fission gas atoms **released** to the gap+plenum after 2 years?

# of gas atoms released to the gap+plenum

$$\boxed{N_{released}} = \boxed{f} N_{gas}$$

Fraction of gas atoms released

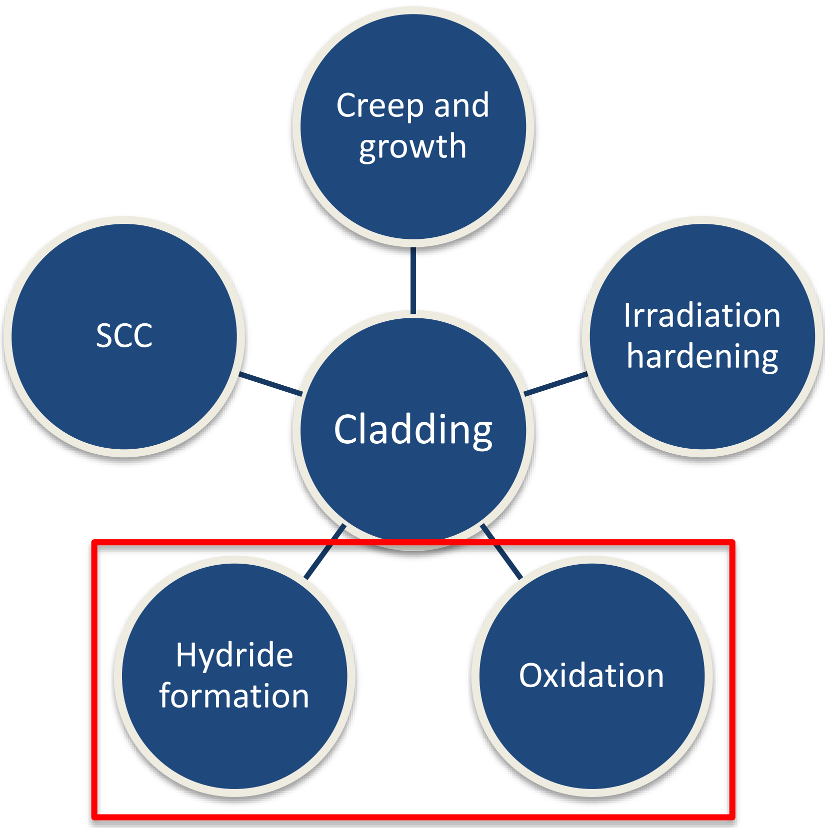
$$in - pile \Rightarrow \ f = 4\sqrt{\frac{Dt}{\pi a^2}} - \frac{3}{2}\frac{Dt}{a^2}$$

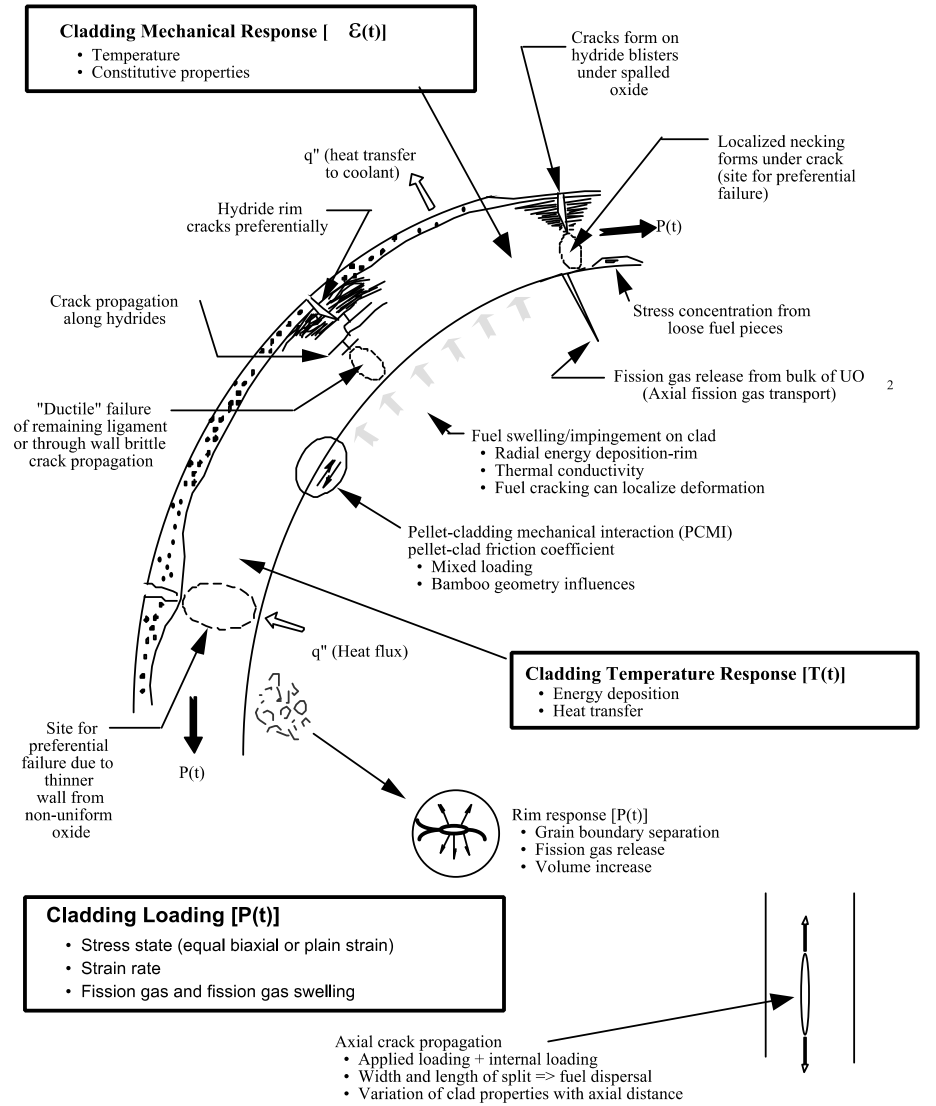
$$out - of - pile \Rightarrow f = 6\sqrt{\frac{Dt}{\pi a^2}} - 3\frac{Dt}{a^2}$$

D: Diffusion coefficient
a : Grain size

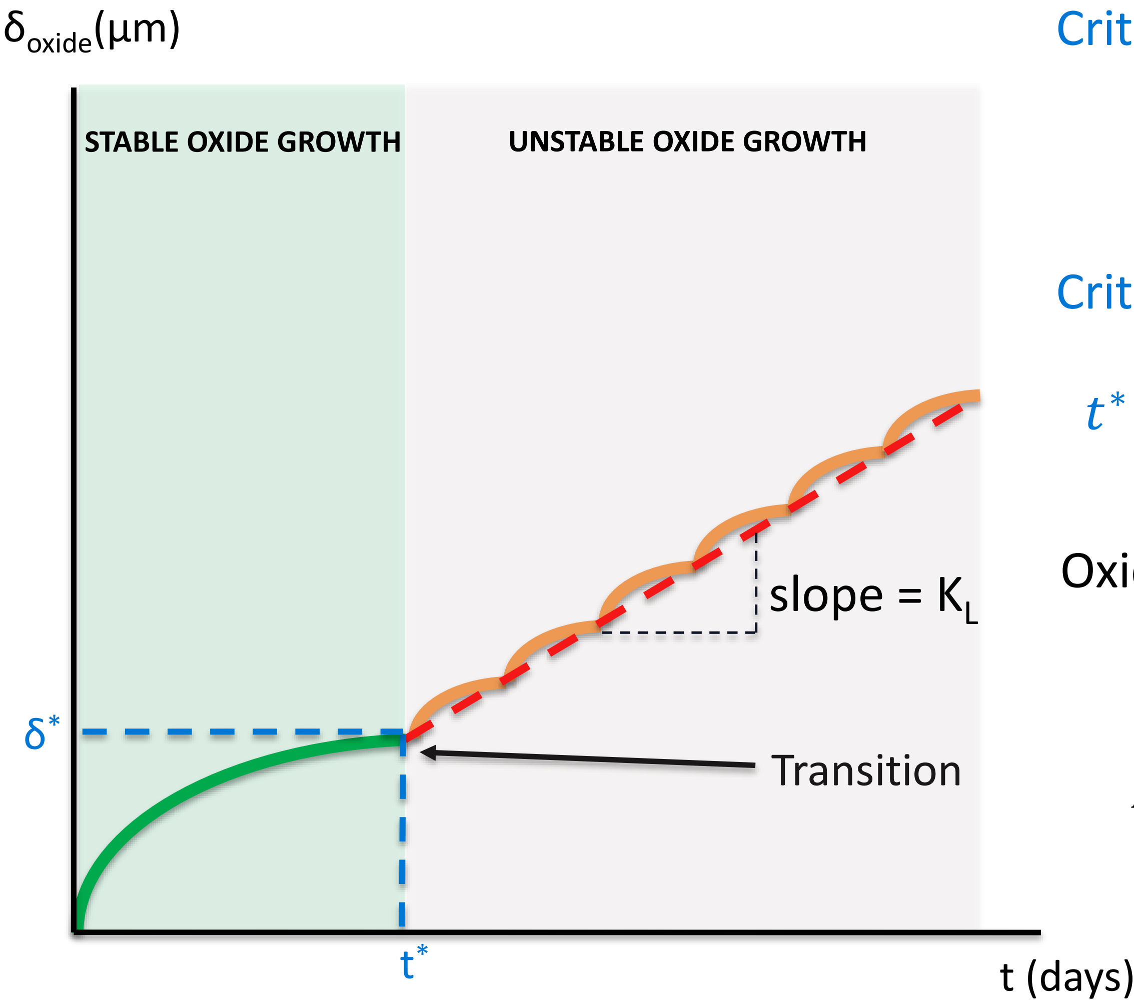
- Constant
- Temperature dependent(Lec 25, Slide 21)

Module-5: Materials issues in the cladding





Oxidation of Zr cladding



Critical oxide thickness for transition:

$$\delta^* = 5.1\exp\left[\frac{-550}{T}\right]$$

Critical time for transition:

$$t^* = 6.62 \times 10^{-7}\exp\left[\frac{11949}{T}\right]$$

Oxide thickness after transition is:

$$\delta\ [\mu m] = \delta^* + K_L(t - t^*)$$

$$K_L = 7.48 \times 10^{6}\exp\left[\frac{-12500}{T}\right]$$

Values are given for zirlo cladding

Example-1: Oxidation of Zr cladding

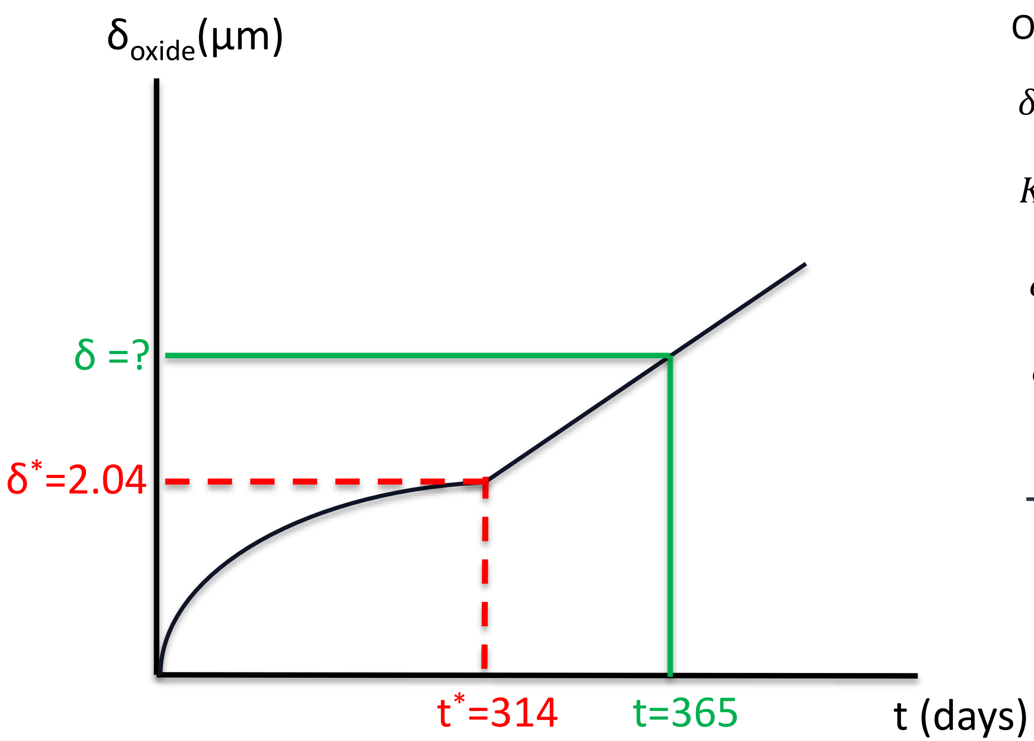
For zirlo cladding, what is the oxide thickness after 1 year of irradiation at 325°C?

Critical time for transition:

$$t^* = 6.62 \times 10^{-7} \exp\left[\frac{11949}{598}\right] = 314\ days$$

Critical oxide thickness for transition:

$$\delta^* = 5.1 \exp\left[\frac{-550}{598}\right] = 2.04\ \mu\text{m}$$



Oxide thickness after 1 year is:

$$\delta\ [\mu m] = \delta^* + K_L(t - t^*)$$

$$K_L = 7.48 \times 10^6 \exp\left[\frac{-12500}{598}\right] = 6.25 \times 10^{-3}$$

$$\delta\ [\mu m] = 2.04 + 6.25 \times 10^{-3}(365 - 314)$$

$$\boldsymbol{\delta\ [\mu m] = 2.34\ \mu m}$$

Total weight gain (mg/dm²):

$$\delta\ [\mu m] = \frac{w\left[\frac{mg}{dm2}\right]}{14.7} \rightarrow \boldsymbol{w = 34.4\ mg/dm^2}$$

Example-2: Hydride formation in the cladding

A cladding with an initial thickness of 600 microns undergoes corrosion to a total oxide thickness of 100 microns. What is the overall hydrogen content in wt. ppm if the hydrogen pickup fraction is 15%?

Oxide thickness δ_{ZrO2} →1→ Weight gain W →2→ # of O atoms N_O →3→ # of H atoms N_H →4→ # of H atoms in the cladding $N_{H\text{-}Zr}$ →5→ Weight of H in the cladding w_H →6→ H concentration C_H

1 $$\delta_{ZrO_2} = \frac{w(mg/dm^2)}{14.7} \Rightarrow w = 1470\ mg/dm^2$$

2 $$N_O = \frac{wN_{av}}{M_O} = \frac{1.47 \times 0.6022 \times 10^{24}}{16} \Rightarrow N_O = 5.53 \times 10^{22}\ oxygen\ atom/dm^2$$

3 $$N_H = 2N_O = 2 \times 5.53 \times 10^{22} \Rightarrow N_H = 11.1 \times 10^{22}\ hydrogen\ atom/dm^2$$

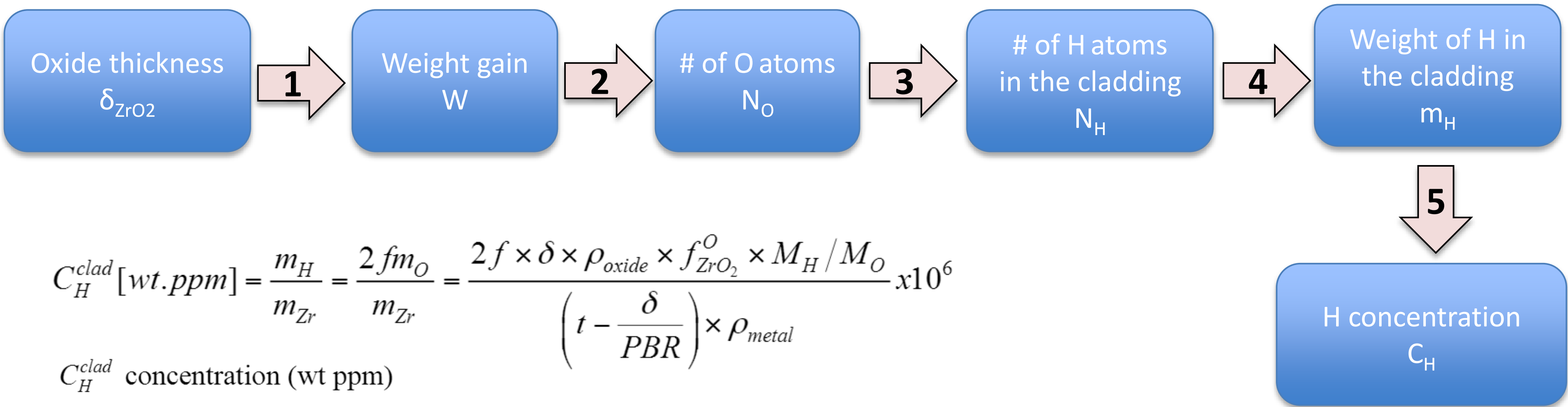
4 $$N_{H-Zr} = 2fN_O = 2 \times 0.15 \times 5.53 \times 10^{22} \Rightarrow N_{H-Zr} = 1.66 \times 10^{22}\ hydrogen\ atom/dm^2$$

5 $$w_H = \frac{N_{H-Zr}M_H}{N_{av}} = \frac{1.66 \times 10^{22} \times 1}{0.6022 \times 10^{24}} = 0.028\ g\ of\ H\ in\ the\ cladding$$

6 $$C_H = \frac{w_H}{w_{Zr}} = \frac{w_H}{\rho_{Zr}V_{Zr}} = \frac{w_H}{\rho_{Zr}(t_Z A)} = \frac{w_H}{\rho_{Zr}\left(t - \frac{\delta_{ZrO_2}}{PBR}\right)A} = \frac{0.028}{6.5\left(600 - \frac{100}{1.56}\right)(10 \times 10 \times 10^{-4})} = 7.91 \times 10^{-4} = 791\ wt.ppm$$

Example-2: Hydride formation in the cladding

A cladding with an initial thickness of 600 microns undergoes corrosion to a total oxide thickness of 100 microns. What is the overall hydrogen content in wt. ppm if the hydrogen pickup fraction is 15%?



$$C_H^{clad}[wt.ppm] = \frac{m_H}{m_{Zr}} = \frac{2fm_O}{m_{Zr}} = \frac{2f \times \delta \times \rho_{oxide} \times f_{ZrO_2}^{O} \times M_H / M_O}{\left(t - \frac{\delta}{PBR}\right) \times \rho_{metal}} x10^6$$

C_H^{clad} concentration (wt ppm)

ρ_{oxide} oxide density

ρ_{Zr} Zr metal density

$f_{ZrO_2}^{O}$ Fraction of oxygen in ZrO2 mass

PBR Pilling-Bedworth Ratio

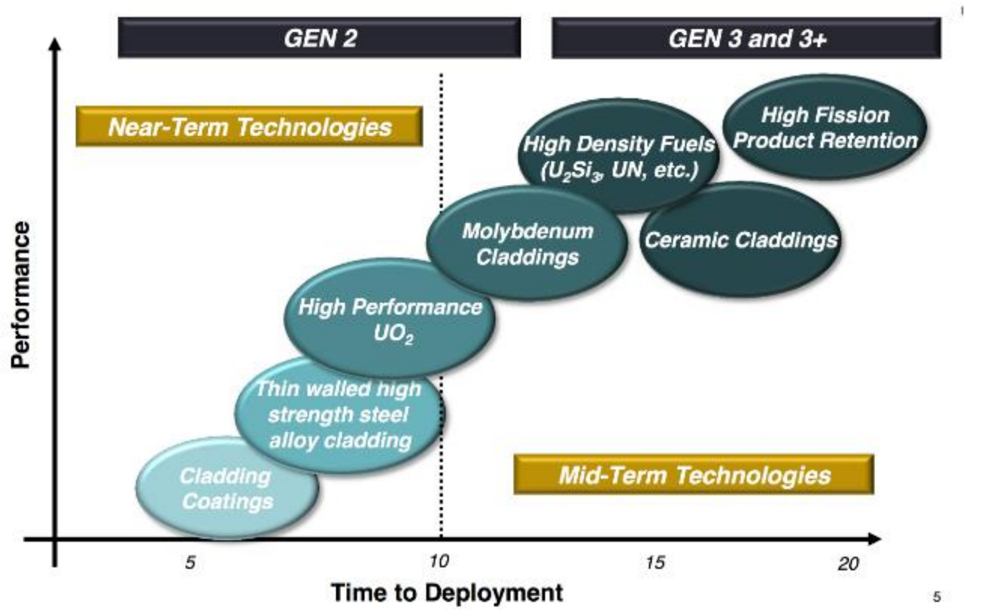
M_H moelcular mass of H

M_O molecular mass of O

t cladding thickness

Module-6: Accidents, used fuel, and fuel cycle

- RIA : Due to large and rapid insertion of reactivity
- LOCA : Due to loss of coolant
- Accident Tolerant Fuels:



S. Bragg-Sitton, 2014

- **The goal is to develop fuel that can tolerate loss of active cooling for a considerably longer period while maintaining or improving performance during normal operation**

Module-6: Accidents, used fuel, and fuel cycle