Nuclear Fuel Performance

NE 533: Spring 2023

Last Time

- Developed analytical solutions for temperature profile
- This time, we move from the analytical into the numerical framework
- Parabolic profile of temperature in fuel
- Cosine profile of LHR as a function of z on fuel rod

- $T_0 - T_{fuel} = \frac{Q}{4k} R_{fuel}^2$ $\quad T_0 - T_{fuel} = \frac{LHR}{4\pi k}$
- $T_{fuel} - T_{gap} = \frac{Q}{2h_{gap}} R_{fuel}$ $\quad T_{fuel} - T_{gap} = \frac{LHR}{2\pi R_{fuel} h_{gap}}$ $\quad h_{gap} = \frac{k_{gap}}{t_{gap}}$
- $T_{gap} - T_{clad} = \frac{Q t_{clad}}{2k_{clad}} R_{fuel}$ $\quad T_{gap} - T_{clad} = \frac{LHR\, t_{clad}}{2\pi R_{fuel} k_{clad}}$
- $T_{clad} - T_{cool} = \frac{Q}{2h_{cool}} R_{fuel}$ $\quad T_{clad} - T_{cool} = \frac{LHR}{2\pi R_{fuel} h_{cool}}$

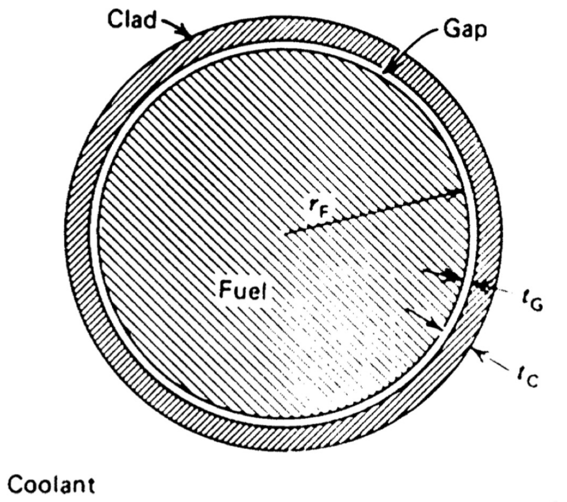
Review of Assumptions

- Analytical solution requires:
  - Steady-state solution
  - Temperature is axisymmetric
  - T is constant in Z
  - Thermal conductivity is independent of temperature
  - Temperature profile in the fuel is parabolic, linear profiles in gap, clad and coolant

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk(T)\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) + Q(r,z)$$

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk(T)\frac{\partial T}{\partial r}\right) + Q(r)$$



THERMAL CONDUCTIVITY

Thermal Conductivity

- Knowledge of the thermal conductivity of the fuel, gap, and cladding is essential to determine the temperature distribution and transient thermal response
- Sintering creates a porous oxide with about 95% theoretical density
- The pores provide space to accommodate fission gases, and thus reduce swelling, but diminish the thermal conductivity
- Additional porosity develops from fission gas accumulation
- Porosity will degrade thermal conductivity
- Approximations for that degradation can be developed based upon a parallel thermal resistance framework
- This framework accounts for porosity volume, assuming that the pores are approximately cubic
- If we assume that the thermal conductivity of the oxide is much larger than the k_{th} of the pore, then:

$$\frac{k_f}{k_{ox}} = 1 - P^{2/3}$$

- where k_f is the effective therm. cond. of the fuel, k_{ox} is the therm. cond. of the oxide, and P is the porosity

Thermal Conductivity

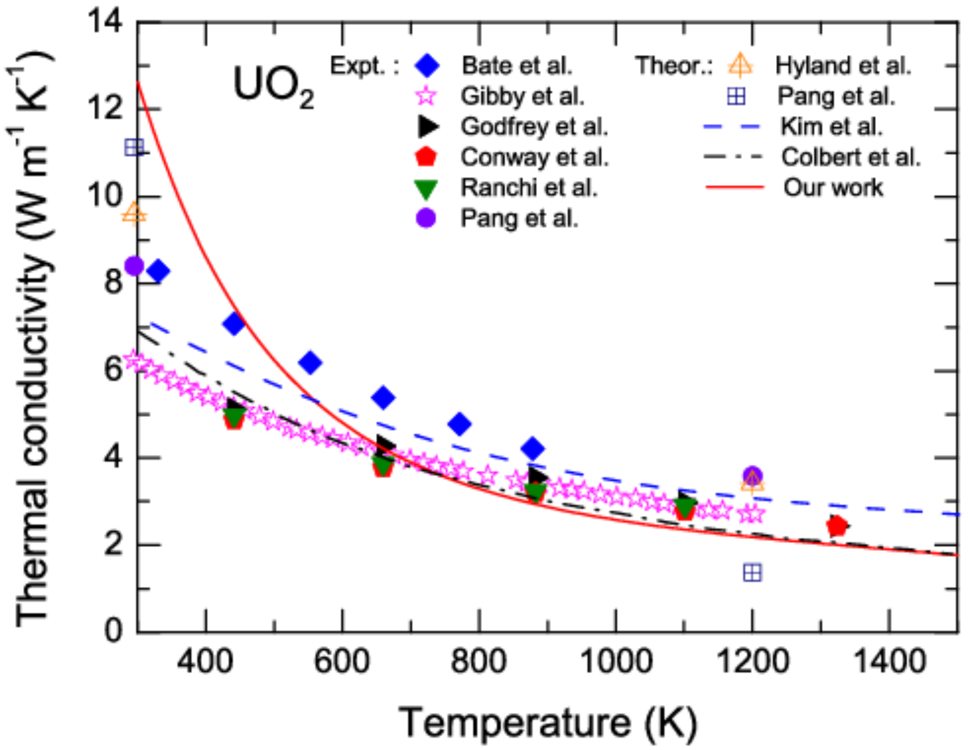
- Typical thermal conductivity of UO2 varies as:

$$k_{ox} = \frac{1}{A + BT}$$

- A=3.8+200xFIMA (cmK/W)
- B=0.0217 (cm/W)
- Neglecting porosity, the temperature at the fuel centerline and fuel surface are related by:

$$\frac{1}{B} \ln\left(\frac{A + BT_0}{A + BT_s}\right) = \frac{LHR}{4\pi}$$

- Solving the heat conduction equation with temperature-dependent k_{th} requires numerical methods



Example

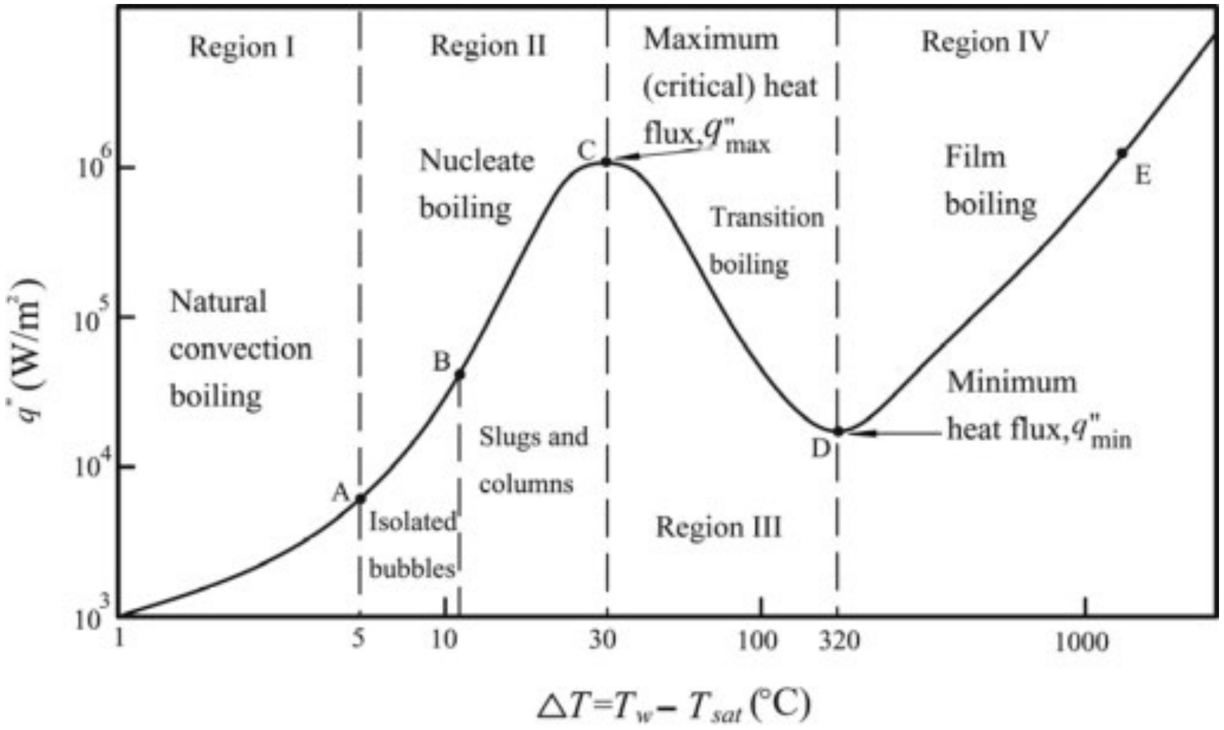
Operational Limits

- Thermal limits are prescribed for normal operation and accident conditions, with the goal of avoiding fuel damage
- Operational limits provide an envelope under which fuel failure will not occur
- LHR limits
- Centerline temperature limits
- Pellet-Clad Mechanical Interaction Limits
  - will cover later in semester

Critical Heat Flux

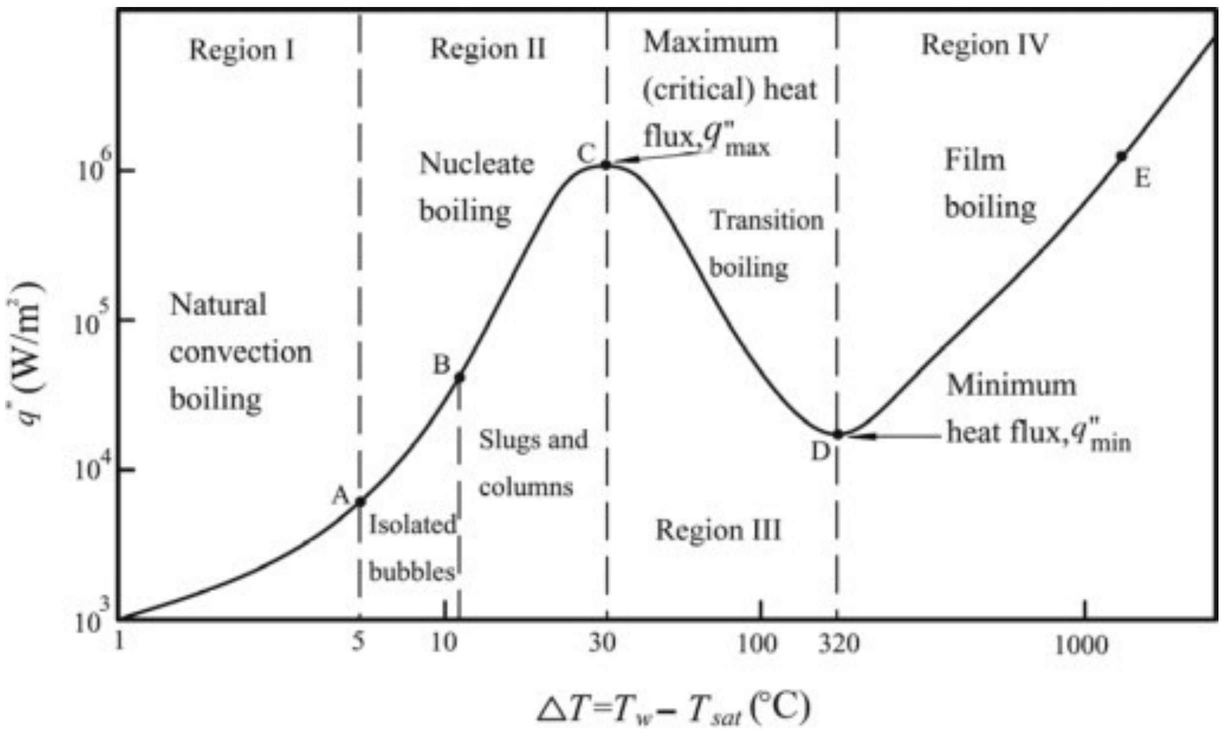
- As the outer surface of a fuel rod increases, the mode of heat transfer changes
- A boiling curve can be determined experimentally by increasing the temperature and measuring heat flux to the liquid
- In the single-phase mode (region I), flux is driven by temperature difference between the outer cladding surface and the coolant

$$q = h(T_{CO} - T_{cool})$$



Critical Heat Flux

- The heat transfer coefficient can be determined by the Dittus-Boelter equation:
$$\frac{hd_{eq}}{k_{cool}} = 0.023Re^{0.8}Pr^{0.4}$$
- Re is the Reynolds number and Pr is the Prandtl number, d_{eq} is the equivalent diameter of the flow channel, k_{cool} is the coolant thermal cond.
- We typically assuming a nominal value for h, but in reality, it is temperature dependent

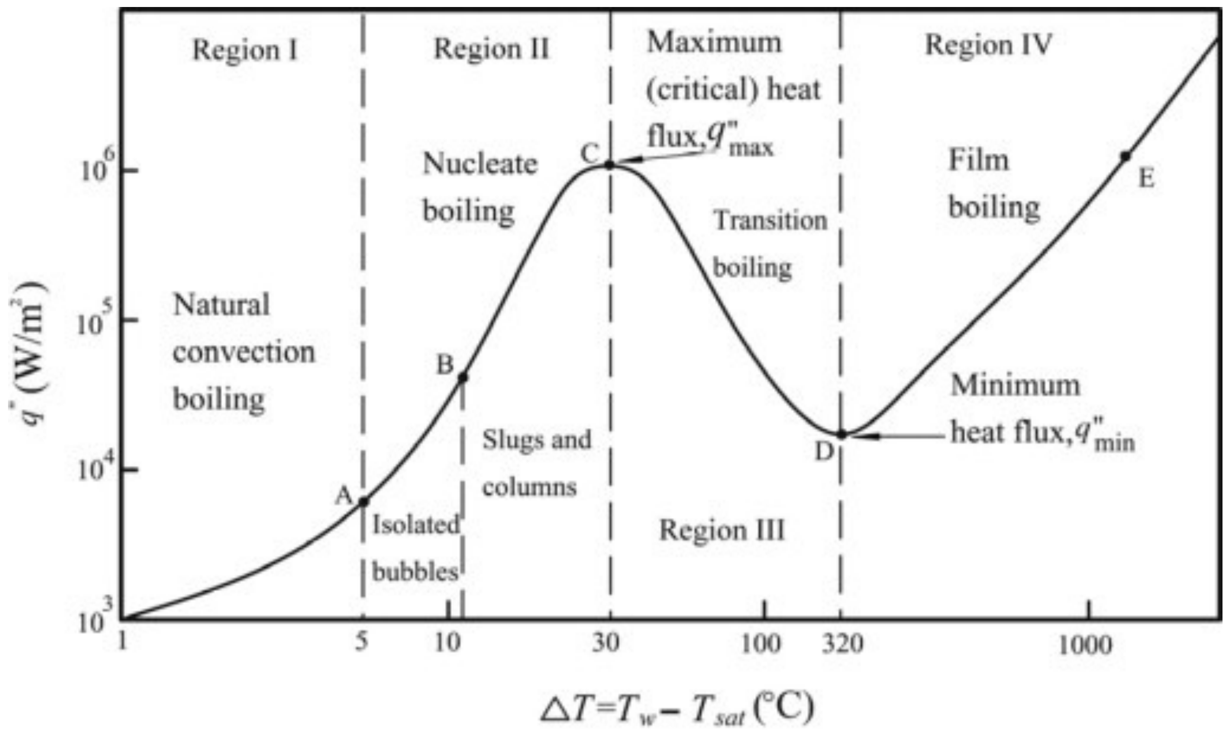


Critical Heat Flux

- At point B, the onset of nucleate boiling provides greater heat transfer to the coolant
- Typical nucleate boiling correlation relating heat flux and temperature is:

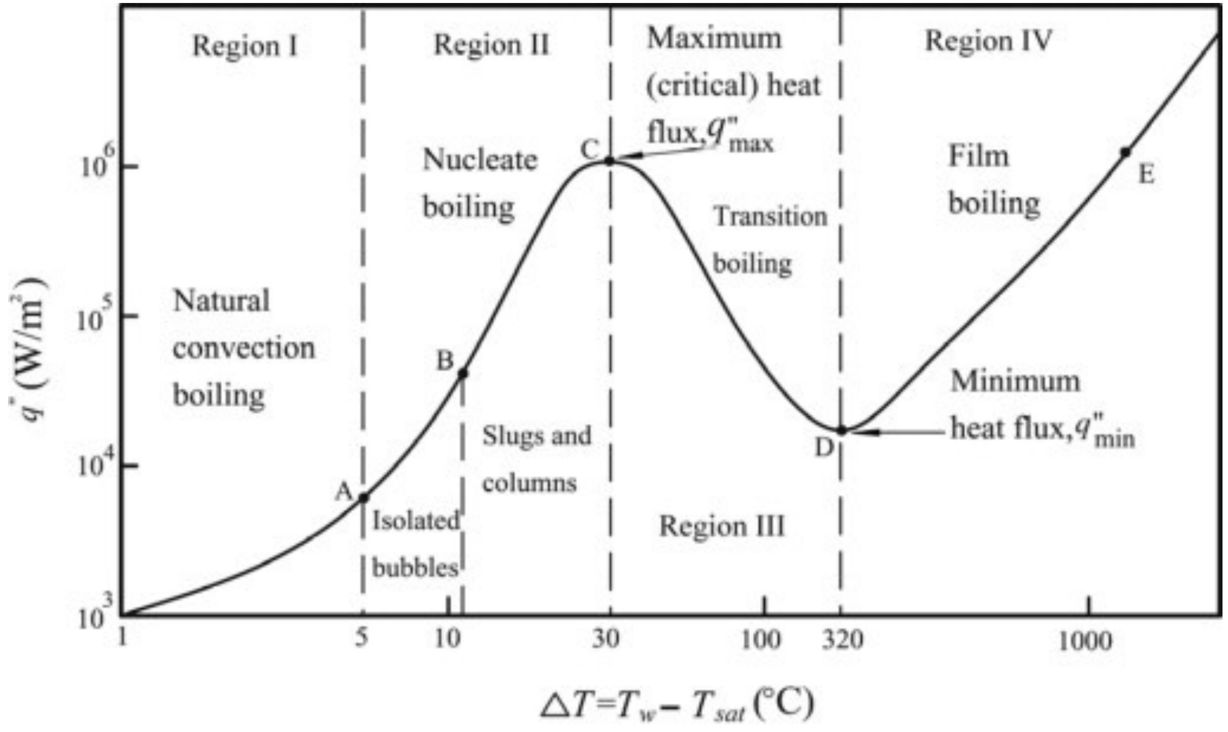
$$q\left(\frac{W}{m^2}\right) = 6(T_{CO} - T_{cool})^4$$

- Heat transfer mechanism is more complex in this region with two distinct phases
- At a critical point, C, the bubbles coalesce, and a continuous film of steam is formed
- Point C is known as the critical heat flux



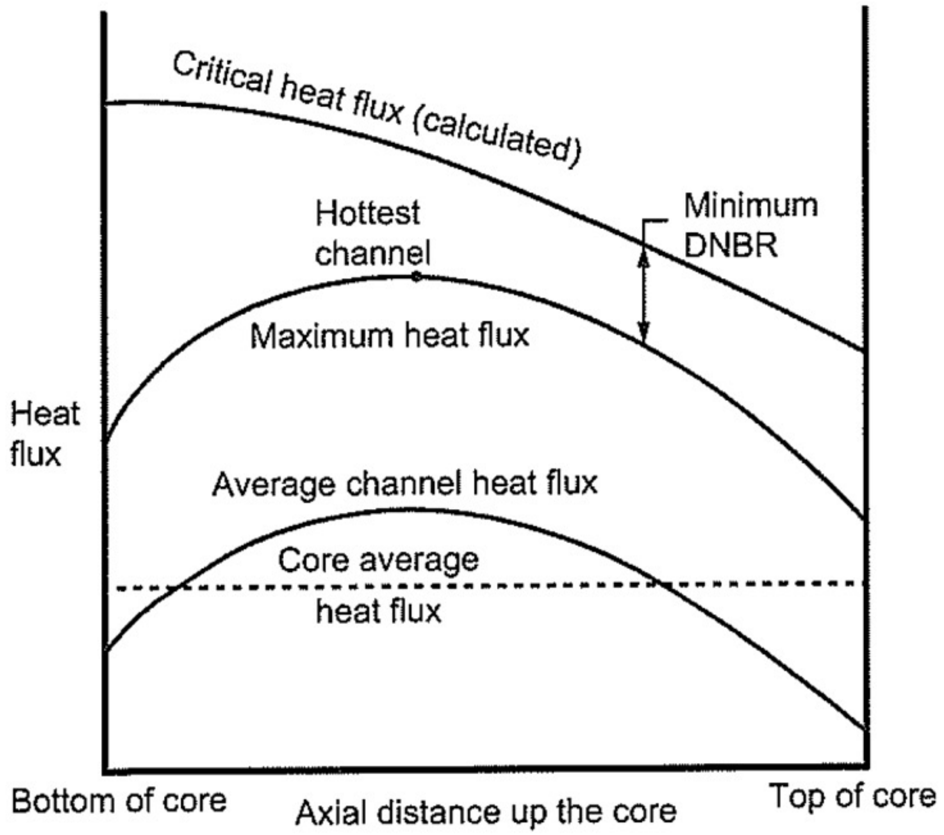
Critical Heat Flux

- Beyond point C the rod is ”coated” in steam and the heat flux is dramatically reduced
- The heat transfer coefficient from cladding to steam is much lower than from cladding to water
- T_{sat} is the saturation temperature, which is fixed for a given pressure, whereas the coolant temperature (T_{cool}) increases
- Beyond point C, film boiling can occur



DNBR

- The departure from nucleate boiling ratio (DBNR) is the ratio of the heat flux that causes dryout (the critical heat flux) to the actual heat flux
- The limits on the DBNR in the hottest channel is 1.15 to 1.3, or a margin of 15-30 percent
- The DNBR is determined by identifying the hottest channel, and the location where the heat flux most closely approaches the CHF
- When CHF is reached, cladding temperature can increase to above 1100 K



Problem Session