Design a passively safe Gen-IV reactor

Gen-IV reactors, as all new reactors, should be designed for passive safety.

Gas pressure in fuel rods is higher, due to He formation.

Coolant temperature feedback is more positive

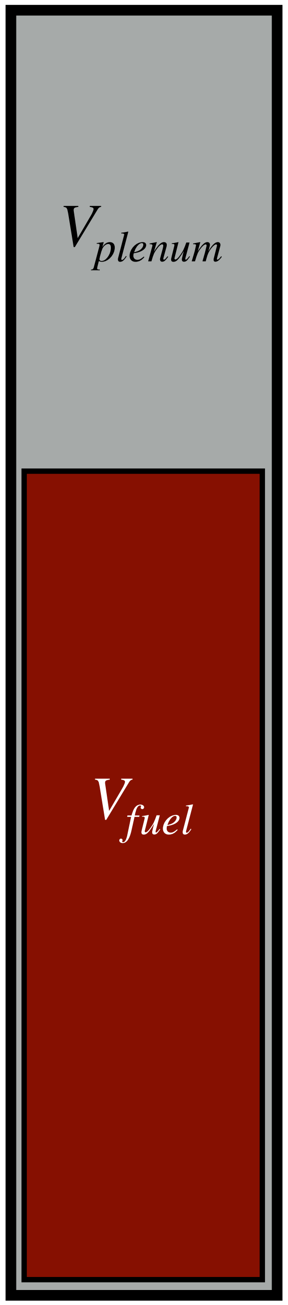
Effective delayed neutron fraction is smaller

Doppler feedback is less negative

After your final project, you will be able to:

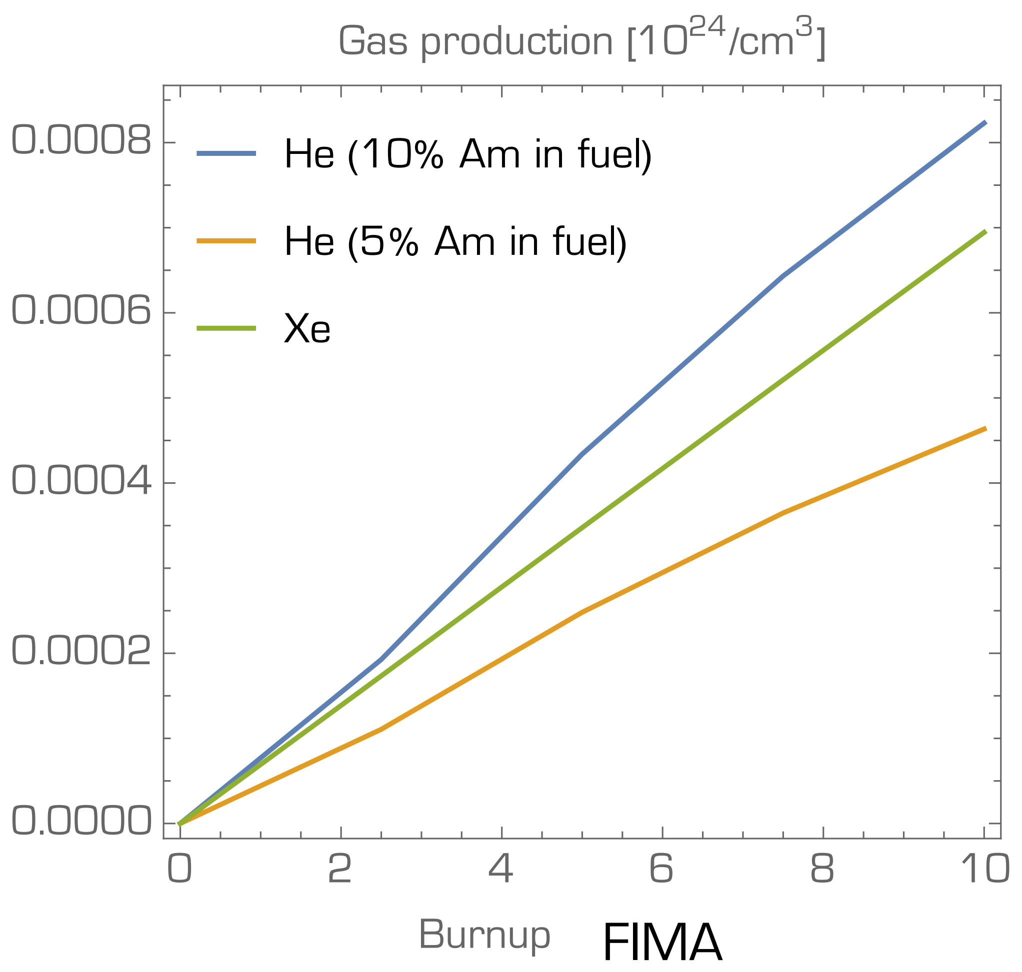
- **Design a passively safe Gen-IV reactor**

Fuel rod internal gas pressure



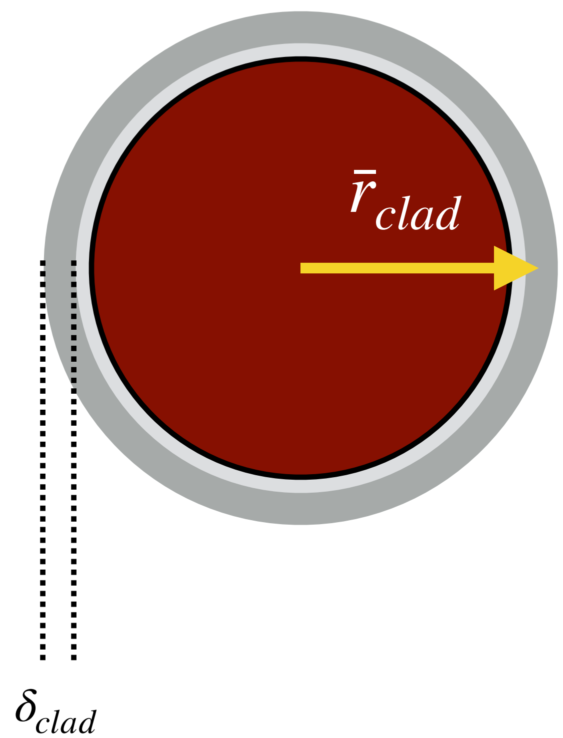
- During transients, oxide and metallic alloy fuels may release their entire inventory of fission gases (FG) to the gas plenum of the rod.
- In a solid fuel, the number density of actinides is
- $n_{An}/V_{fuel} = \rho_{fuel}/M_{fuel}$
- Xenon and Krypton atom production: Y_{FG} = 25% per fission
- The number of fission gas atoms: $n_{FG} = n_{An} \times Y_{FG} \times BU_{FIMA}$
- Pressure of fission gas: $p_{FG} = \dfrac{n_{FG} \times R_{gas} \times T_{FG}}{V_{plenum}}$
- $P_{FG} = \dfrac{\rho_{fuel}}{M_{fuel}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{FG} \times \dfrac{V_{fuel}}{V_{plenum}}$

He production vs Am concentration



- $(U_{0.88-x},Pu_{0.12},Am_x)N$ fuel
- Xe yield ≈ 25% per fission
- He production exceeds Xe yield when Am concentration in the fuel is 10%.
- He is released with a high probability, requires to increase the internal gas plenum height of the fuel rod.

Fuel clad hoop stress due to noble gas release



- The released gas causes a hoop stress on the cladding tube:

$$\sigma_{hoop} \simeq \frac{\bar{r}_{clad}}{\delta_{clad}} P_{gas}$$

- For a fuel cladding tube: $r_{clad}/\delta_{clad} \simeq 10$

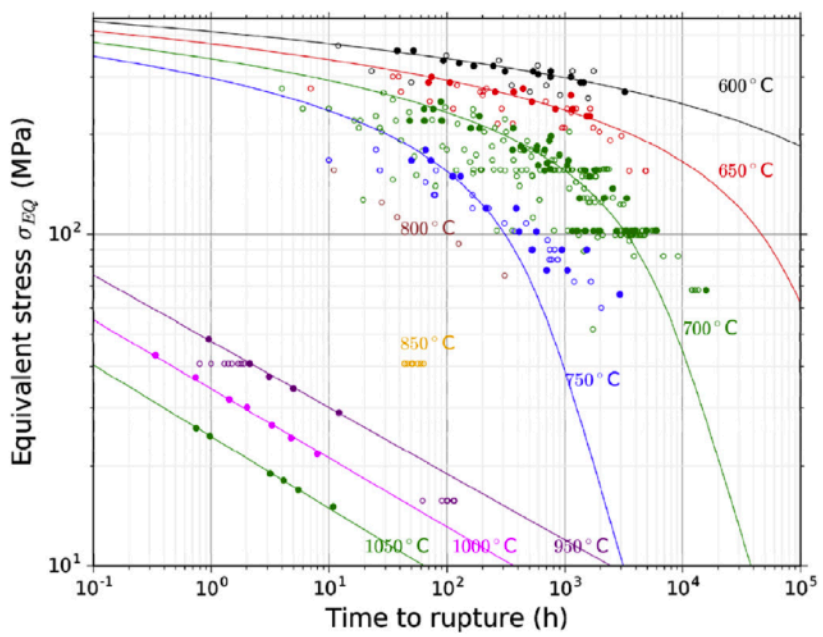
$$V_{plenum} = \frac{\rho_{fuel}}{M_{fuel}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{NG} \times \frac{V_{fuel}}{P_{gas}}$$

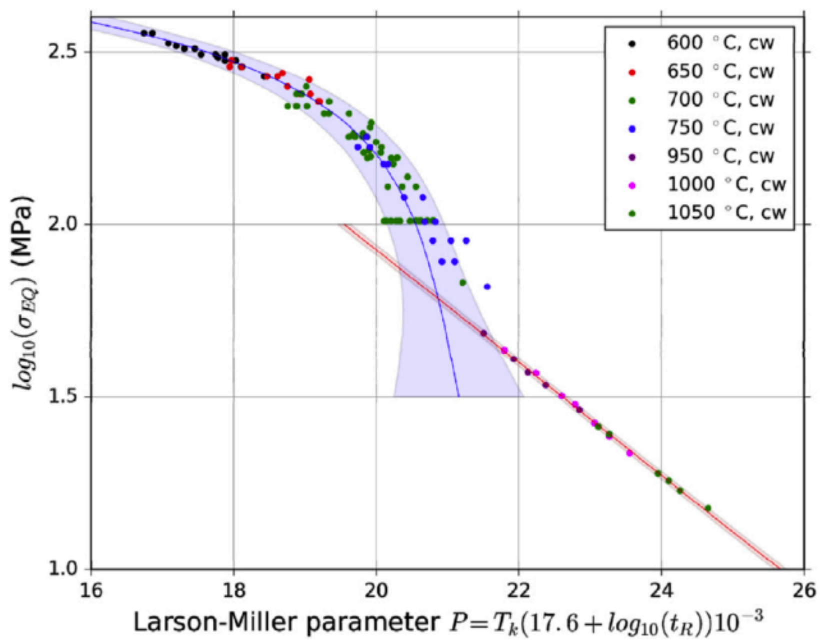
$$= \frac{\rho_{fuel}}{M_{fuel}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{NG} \times \frac{V_{fuel}}{\sigma_{hoop}^{max}} \frac{\delta_{clad}}{\bar{r}_{clad}}$$

$$H_{plenum} = \frac{\rho_{fuel}}{M_{fuel}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{NG} \times \frac{H_{fuel}}{\sigma_{hoop}^{max}} \frac{\delta_{clad}}{\bar{r}_{clad}}$$

Creep rupture life due to hoop stress

Time to rupture of 15-15Ti tubes





- The time to creep rupture of a cladding tube can be derived from the Larson-Miller parameter:

$$P = T\left(17.6 + log_{10}(t_r)\right) \rightarrow t_r = 10^{P/T - 17.6}$$

- Time for rupture t_r is expressed in hours, temperature T of cladding tube in Kelvin.

- When hoop stress is between 100 and 400 MPa, experimental data for time to rupture of 15-15Ti can be parametrized as

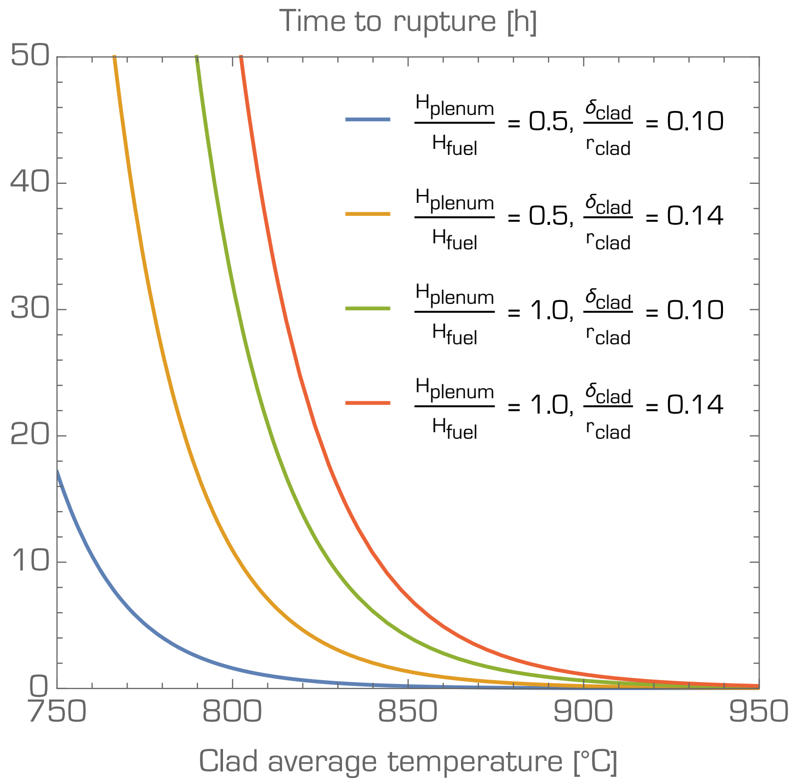
$$P = 21100 - 1.89 \times 10^{-6}\sigma_{hoop} - 0.030 * 10^{-12}\sigma_{hoop}^2$$

Creep rupture life at end-of-life

- Example of time to creep rupture for a UN fuel rod with a burn-up of 9% FIMA, assuming 100% release of Xe & Kr. He production is neglected.

$$t_r^{15-15Ti} = 10^{LMP/T_{clad}-17.6} > 10^{\frac{1}{T_{clad}}\left(21100 - 1.89\times 10^{-6}\frac{P_{FG}\times \bar{r}_{clad}}{\delta_{clad}} - 0.030\times 10^{-12}\left(\frac{P_{FG}\times \bar{r}_{clad}}{\delta_{clad}}\right)^2\right)-17.6}$$

$$P_{FG} = \frac{\rho_{UN}}{M_{UN}} \times R_{gas} \times T_{FG} \times BU_{FIMA} \times Y_{FG} \times \frac{H_{fuel}}{H_{plenum}}$$



- Time to creep rupture is exponentially dependent on ratio between gas plenum and fuel column height, as well as on ratio between cladding thickness and diameter.

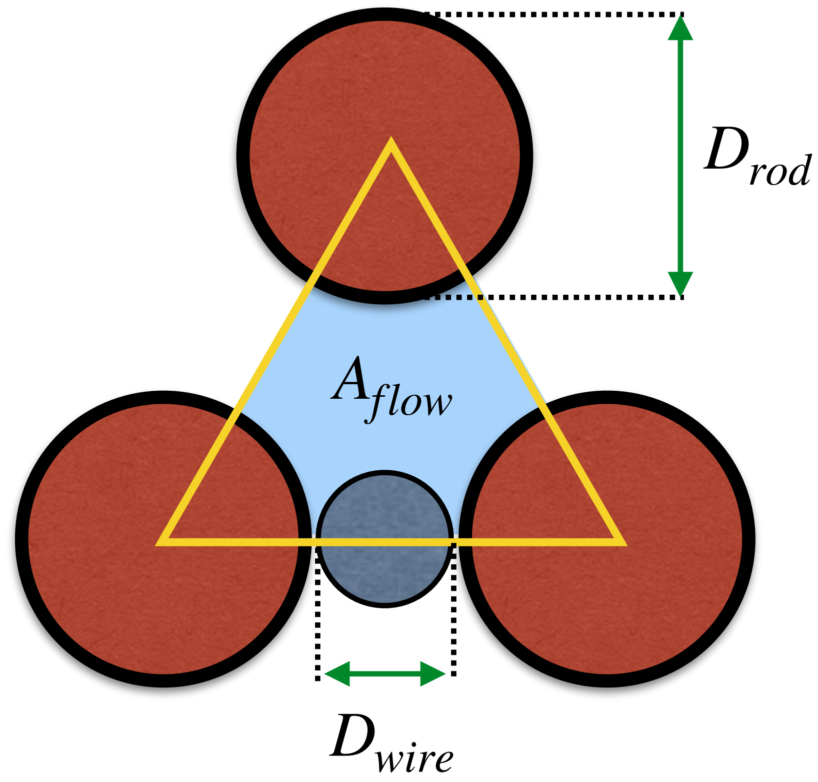
- In order to accommodate transients leading to high cladding temperature, the tube dimensions can be adjusted.

Rod radius and pitch

- The rod and wire spacer radii are given by

$$r_{rod} = \frac{2}{\pi}\left(\frac{A_{flow}}{D_h} + \sqrt{\left(\frac{A_{flow}}{D_h}\right)^2 \left(\frac{4\sqrt{3}}{\pi} - 1\right) - \frac{\pi}{4}A_{flow}}\right)$$

$$r_{wire} = \frac{2}{\pi}\left(\frac{A_{flow}}{D_h} - \sqrt{\left(\frac{A_{flow}}{D_h}\right)^2 \left(\frac{4\sqrt{3}}{\pi} - 1\right) - \frac{\pi}{4}A_{flow}}\right)$$



$$A_{flow} = \frac{\sqrt{3}}{4}(D_{rod} + D_{wire})^2 - \frac{\pi}{2}(r_{rod}^2 + r_{wire}^2) = \frac{\dot{Q}_{ch}}{\dot{m}_{nom} c_p \Delta T_{nom}}$$

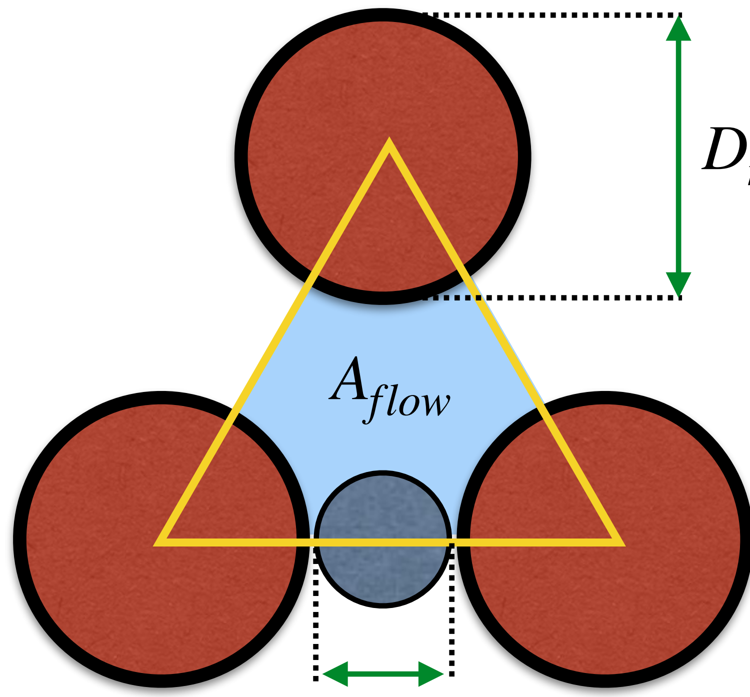
$$P = D_{rod} + D_{wire} = \frac{4}{\pi}\frac{A_{flow}}{D_h}$$

Hydraulic diameter

- The hydraulic diameter of a coolant channel is defined as:

$$D_h = 4\frac{A_{flow}}{P_{wet}}$$

$$P_{wet} = \frac{\pi}{2}(D_{rod} + D_{wire})$$



- We can relate the hydraulic diameter to the friction pressure loss due under nominal and natural flow conditions:

$$\Delta P_f = f_D \frac{H_{ch}\dot{m}^2_{flow}}{2\rho_{coolant} D_h A^2_{flow}} = f_D \frac{\rho_{coolant} H_{ch} v^2_{coolant}}{2D_h}$$

$$f_D = \frac{a}{Re^b}$$

a = 0.485, b = 0.29 in wire spaced channels under nominal and natural convection conditions

Hydraulic diameter vs Dip cooler elevation

- From the previous equations, Dehlin & Wallenius derive:

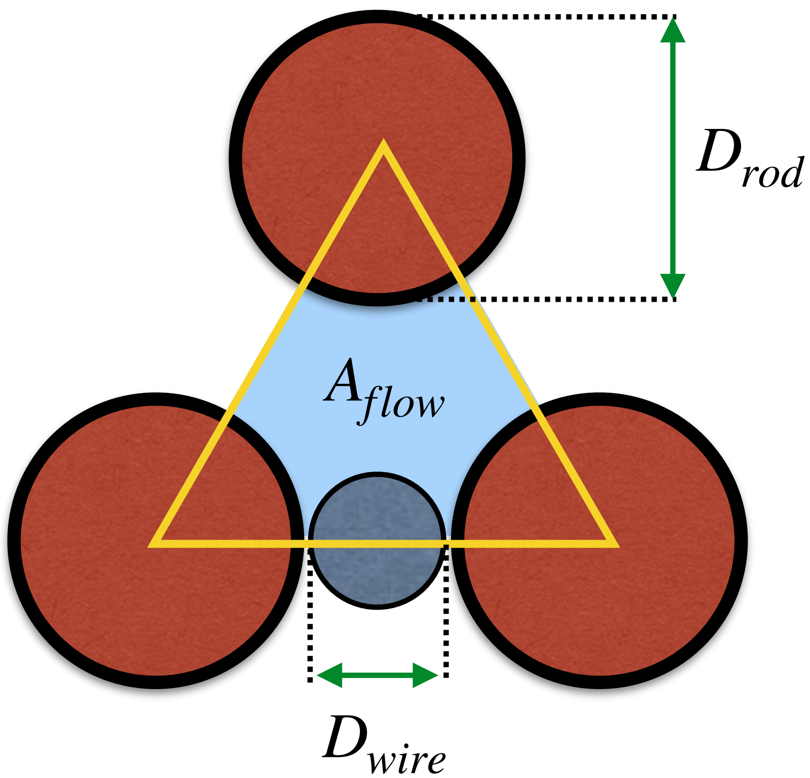
$$D_h \approx \left(\frac{a \times K}{2} \frac{H_{ch}}{\Delta P_{nom}} \right)^{1/(1+b)} \left(\rho_{coolant}^{1-b} \; v_{nom}^{2-b} \; \mu_{coolant}^{b} \right)^{1/(1+b)}$$

$$\Delta P_{nom} = \alpha_{coolant} \times g \times \Delta T \times H_{DC} \times \left(\kappa \frac{\dot{Q}_{nom}}{\dot{Q}_{res}} \right)^{2-b}$$

$$v_{nom} = \kappa v_{nat} \frac{\dot{Q}_{nom}}{\dot{Q}_{res}}$$

$$v_{nat} = \left(Re_{min}^{1+b} \frac{2 \times \alpha_{coolant}}{a \times K} \frac{g \times \Delta T \times H_{DC}}{H_{ch}} \frac{\mu_{coolant}}{\rho_{coolant}^2} \right)^{1/3}$$

$$\alpha_{coolant} = \frac{d\rho_{coolant}}{dT_{coolant}}$$



κ: Factor of increase in ΔT during transient

$K \approx 1.5$: core pressure drop scaling coefficient

$Re_{min} \approx 4000$: minimum permissible Reynolds number during natural convection

Final project: Design your passively safe Gen-IV reactor

- Postulate ΔT_{core} = 100 K for the coolant from inlet to outlet of the core
- Postulate $\dot{Q}_{res}/\dot{Q}_{nom}$ = 0.10 as the fraction of nominal power to be removed by natural convection, assuming that ΔT_{core} is permitted to double during a loss of flow transient, i.e. κ = 2.0.
- Apply H_{DC} = 2.0 m (Pb), and H_{DC} = 20.0 m (Na), for the elevation of dip-coolers.
- Postulate H_{fuel} = 1.0 m & BU_{FIMA}^{peak} = 10%.
- Determine H_{ch}, considering 100% Xe & He release from the fuel, for an Am fraction of 5%. The cladding tube shall survive a transient temperature of 1000 K for 200 seconds.
- Calculate the rod diameter and pitch, postulating $\dot{Q}_{channel}^{peak} = \chi_{fuel}^{peak} \times H_{fuel}/2$ = 5 kW.
- Use Serpent to identify a fuel composition yielding a minimum reactivity swing for BU_{FIMA} = 6%.
- Determine the critical mass & number of fuel rods using Serpent.
- Calculate the conversion ratio and minor actinide burning rate for this configuration.
- Calculate reactivity coefficients at BoL
- Simulate UTOP and ULOF transients using BELLA.

Final project:
Group assignment

- Form groups of three students and mail me the composition of the group.
- You will be assigned a group number/reactor/coolant/fuel by me.
- Apply the recommended approach to reduce impact of Monte Carlo uncertainties
- Alejandria will give you access to BELLA.
- I will be available for questions on May 15.
- Prepare a five slide presentation for May 22nd.
- Deadline for submission of four page report: June 2nd.