IAEA
International Atomic Energy Agency

*"Atoms for Peace and Development"*

IAEA Regional Workshop on
Advances in Modelling and Simulation of Thermal Hydraulics in
Liquid Metal Cooled Fast Reactors
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# Temperature Field in a Fuel Pin of Lead cooled Fast Reactor: *Simple Exercise*

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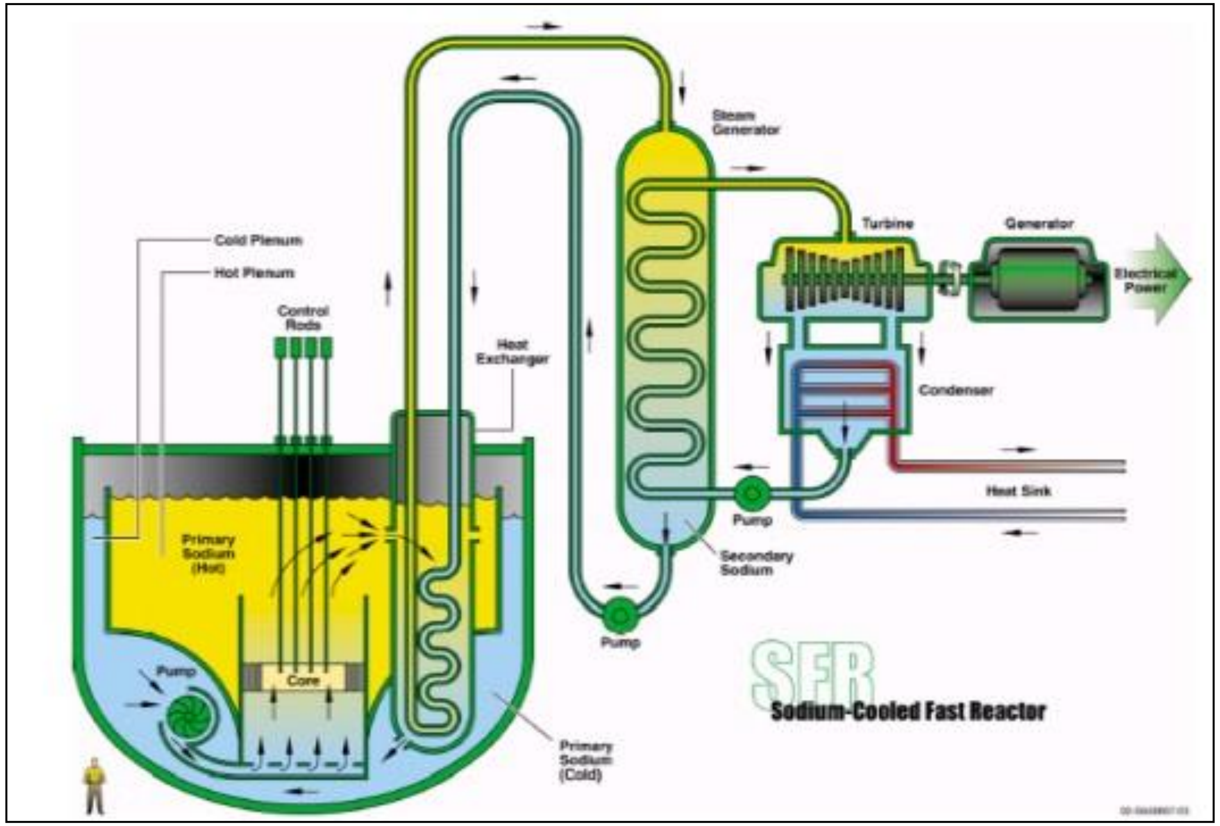
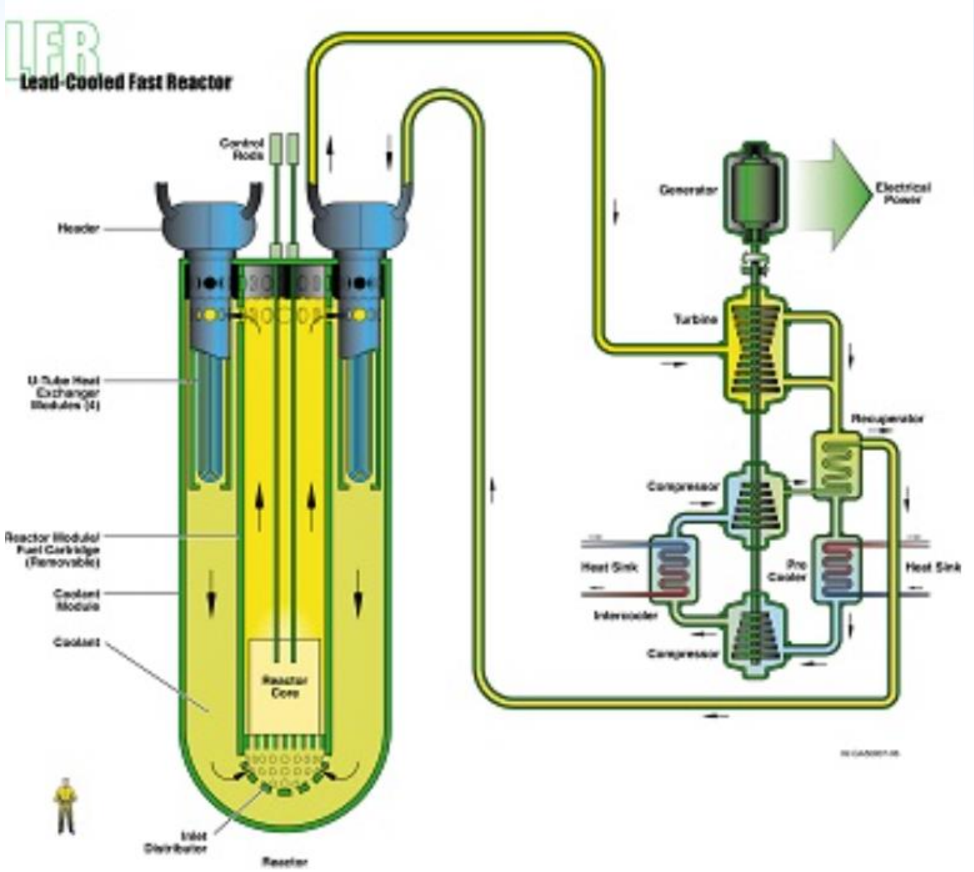
# Sodium and Lead cooled Fast Reactors: SFR and LFR



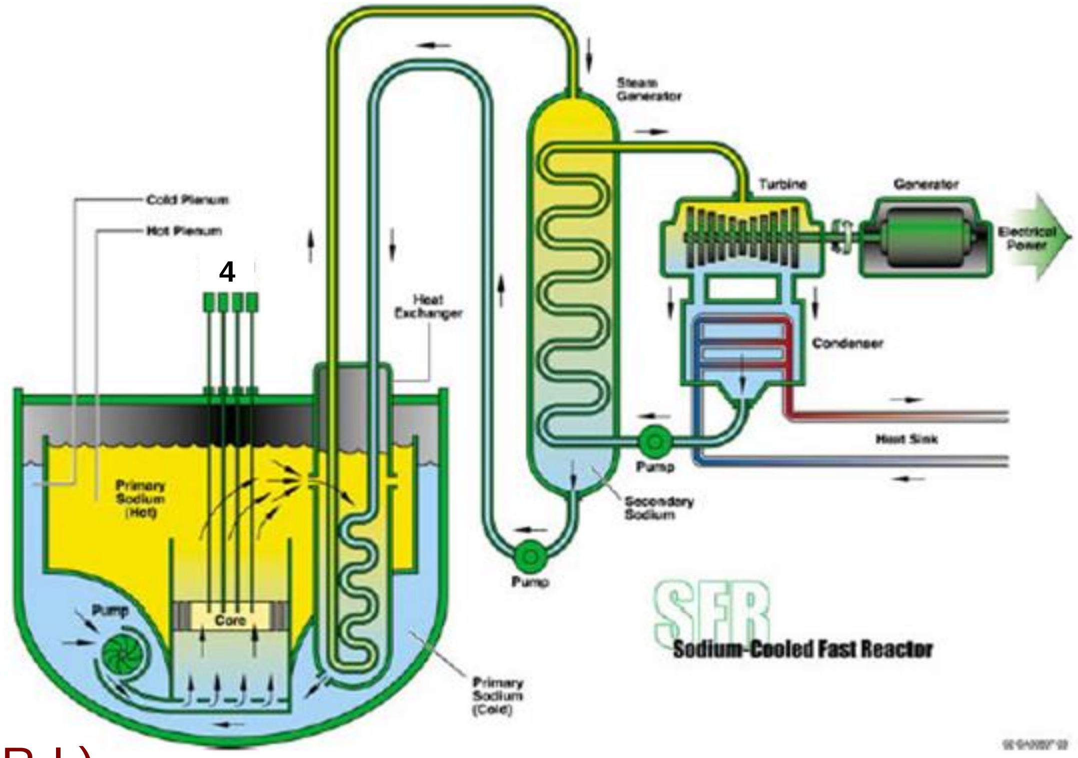


GIF website: www.gen-4.org

# Sodium Properties: *several advantages*

- ➢ Low melting point (97.8° C at 1 bar)
- ➢ Large range of the liquid phase (97.8° C – 881.5° C at 1 bar)
- ➢ Low saturation vapor pressure
- ➢ Low density and viscosity
- ➢ Very high thermal conductivity and good heat capacity
- ➢ Excellent electrical conductivity
- ➢ Low activation and no alpha emitters
- ➢ No specific toxicity
- ➢ Cheap and largely available
- ➢ Perfectly compatible with steels
- ➢ Very limited amount of particles in sodium
- ➢ Low oxygen and hydrogen solubility
- ➢ Very good wetting

**Primary system at atmospheric pressure**



400+ reactor-years **operational experience** (since 1951, EBR-I )

# Sodium Properties: *three main disadvantages*

- **Very violent chemical reactivity with water**
  - ✓ possible deleterious effects in Steam Generator Units (SGU), in case of pipe rupture
  - ✓ Na-$H_2O$ interaction must be avoided or mitigated by design
    - Selection of a modular SGU
  - ✓ Na-$H_2O$ interaction must be detected,
    - Thanks to the production of hydrogen
    - Risk of hydrogen explosion has to be mitigated

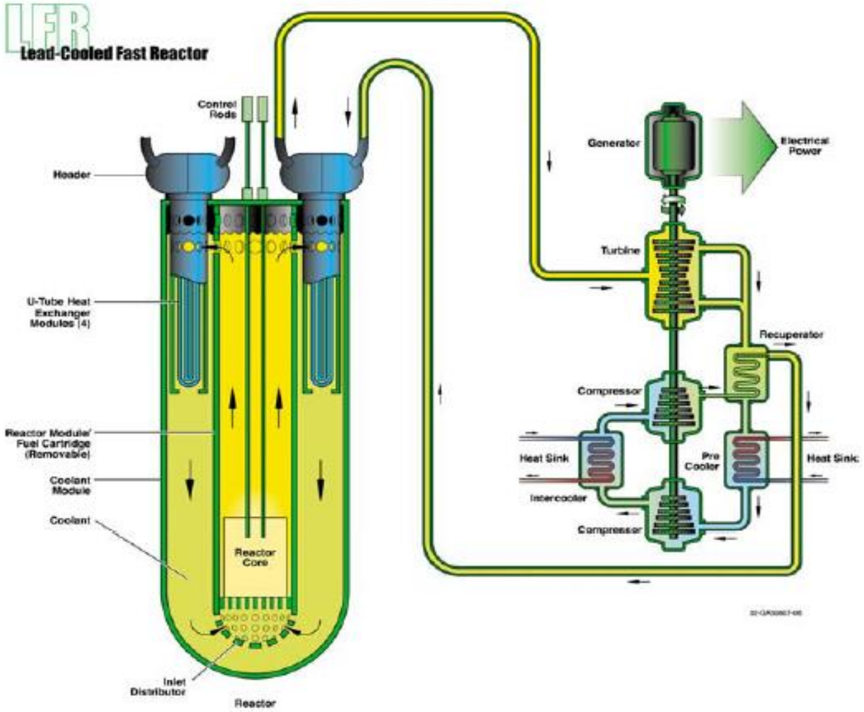
- **Violent chemical reactivity with air**
  - ✓ Can induce Na fire
  - ✓ Need inert zones and confinement
  - ✓ Need early detection

- **Opacity**
  - ✓ Need specific equipments for under-sodium viewing and measurements

# Lead/LBE Properties: *advantages*

- Low absorption and elastic scattering cross-sections (neutrons just diffuse in lead)
- Effective gamma-rays shielding
- High retention of fission products
- High boiling point (1749/1670 °C at 1 bar)
- Very low vapor pressure
- High thermal capacity
- Good heat transfer properties
- Chemically inert, in particular with water and air (allows elimin
- No hydrogen formation
- Cheap and largely available

**Primary system at atmospheric pressure**



# Lead/LBE Properties: *three main disadvantages*

- **Material compatibility: erosion, corrosion**
  - ✓ *Low coolant velocity*
  - ✓ *Limit in cladding Tmax*
  - ✓ *Hydrogen and oxygen control*
  - ✓ *New steels/coatings  need qualification*
  - ✓ *Coatings*
- **High density** (*also an advantage due to reduced risk of re-criticality in case of core melting*)
- **Opacity**
  - ✓ *Need specific equipment for under-lead viewing and measurements*

And very limited **operational experience** (Alpha-class submarines)

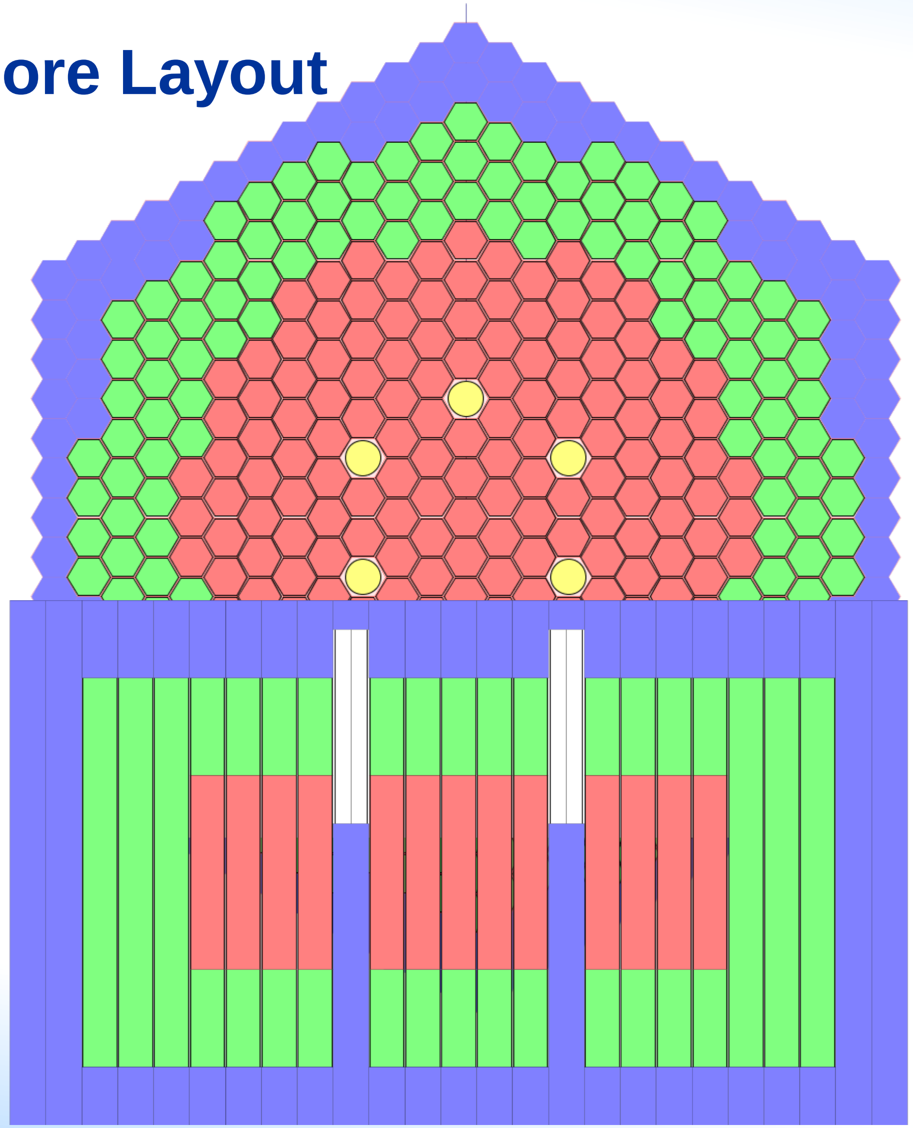
# Coolant Thermal-Physical Properties

| | | $H_2O$ | **Na** | **Pb** | **LBE** | **He** | **$LiF\text{-}BeF_2$-** $ThF_4\text{-}UF_4$ |
|---|---|---|---|---|---|---|---|
| Atomic Weight | | 18 | 23 | 207 | 208 | 4 | |
| Melting Point | °C | 0 | 97.8 | 327.4 | 123.5 | | ~500 |
| Boiling Point | °C | 100/ 350 | 892 | 1737 | 1670 | -267 | ~1700 |
| Density | kg/m3 | 1000 | 832 | 10460 | 10080 | 0.178<br>8.491 | ~3200 |
| Vol. Heat Capacity | MJ/m3/K | 4.18 | 1.05 | 1.53 | 1.47 | 0.00093<br>0.044 | ~4.5 |
| Specific Heat Capacity | J/kg/K | 4180<br>5682 | 1264 | 147 | 146 | 5200 | ~1400 |
| Thermal Conductivity | W/m/K | 0.6 | 70 | 18 | 15 | 0.152<br>0.238 | ~0.01 |
| Kinematic Viscosity | $m^2/s \times 10^6$ | 1<br>0.12 | 0.28 | 0.11 | 0.13 | 0.15<br>0.71 | ~2.3 |

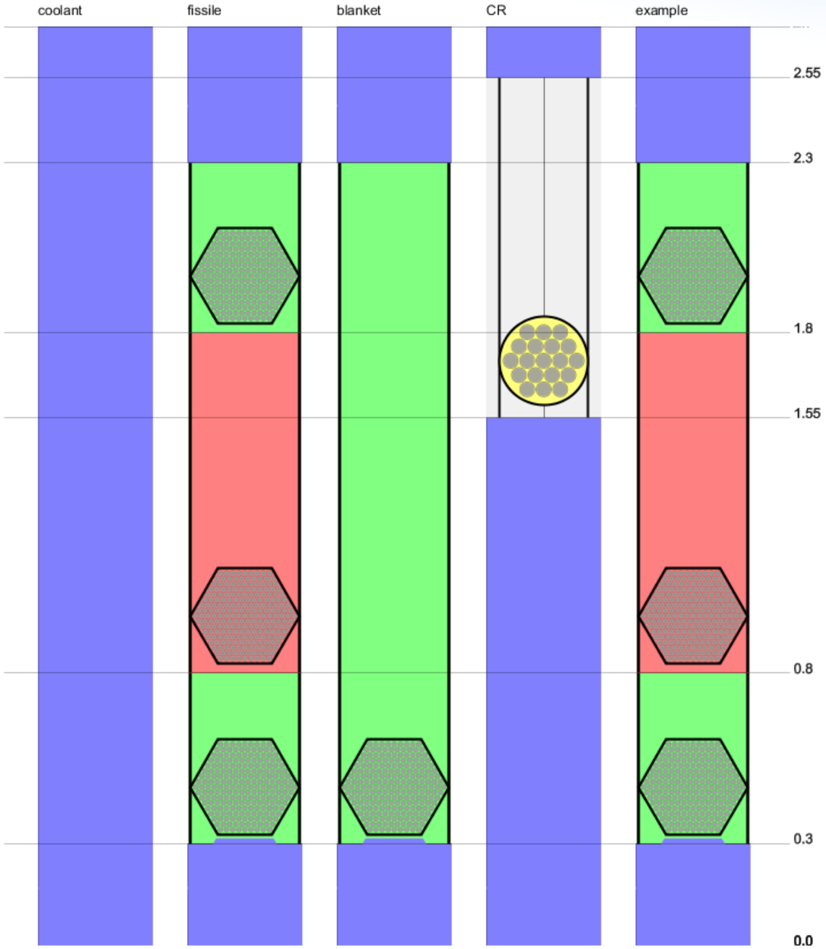
cold 20 °C
water at 17Mpa
hot water 300 °C
hot LM, 500 °C,
hot He 850 °C, 20 MPa

# Reactor Core

## Core Layout

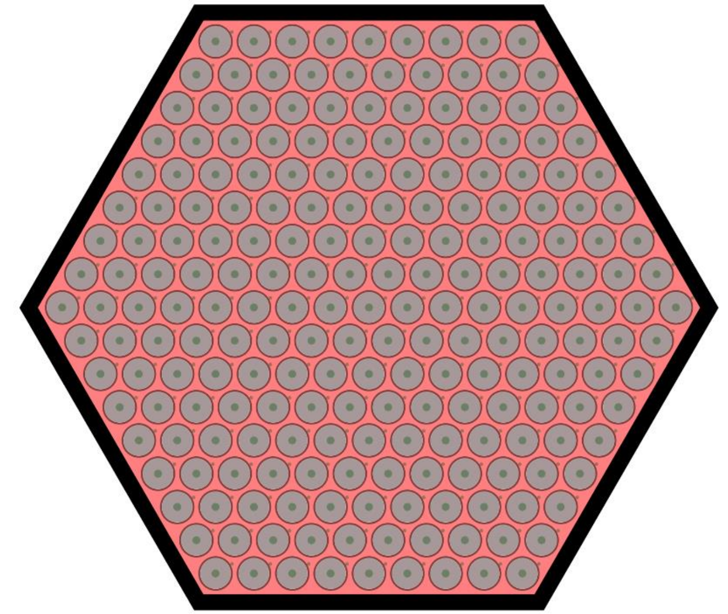


## Sub-Assemblies (S/A)

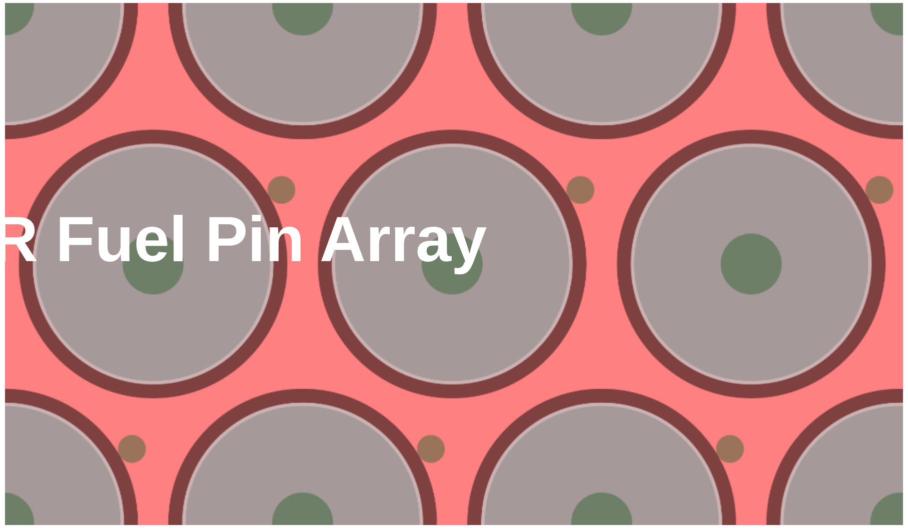


# Fuel S/A: Pin Arrangement

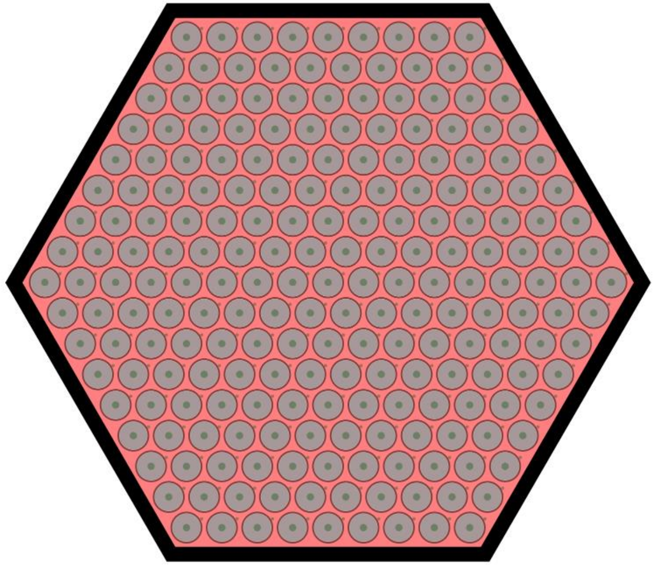
| | LFR | SFR |
|---|---|---|
| **Fuel Pin/Rod OD, mm** | 7-10 | 6 - 7 |
| **Cladding Wall, mm** | ~0.5 | ~0.5 |
| **Fuel Pellet Diameter, mm** | 5 - 8 | 5 - 6 |
| **Pitch-to-Diameter Ratio** | 1.2 - 1.4 | 1.1 - 1.2 |
| **Fuel Fraction** | 30 - 40 % | 40 - 50 % |
| **Coolant Fraction** | 50 - 60 % | 35 - 50 % |



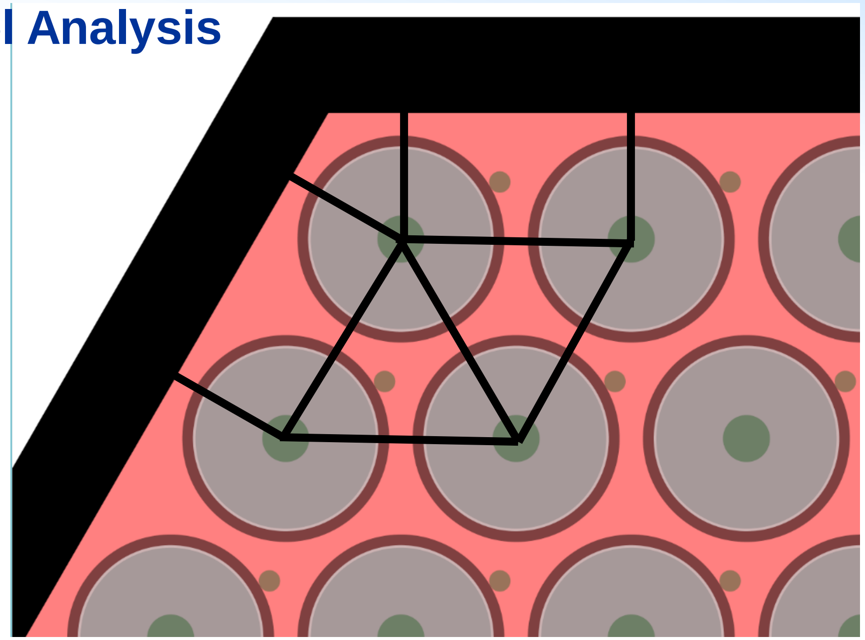
- Triangular Array (in HexCan)
- Small P/D Ratio (SFR)
  - Cannot use grid spacers
  - >> wire wrap
- Wide P/D (LFR)
  - Both wire and grid spacers can be used

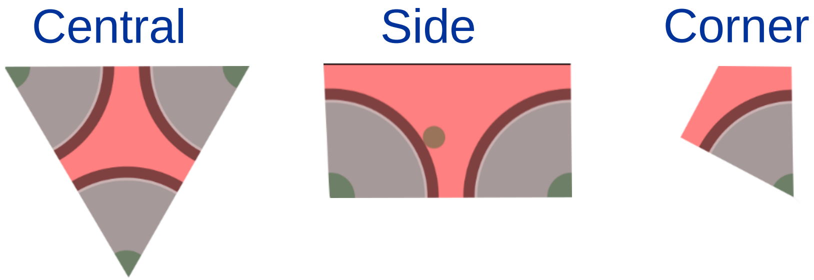


# Temperature Distribution within S/A



## Subchannel Analysis





Power-to-Flow Ratio

$$\frac{Power}{Flowrate}=\frac{Heat\,Flux\times\Pi}{Velocity\times Area}$$

Power-to-Flow Ratio in Central Subchannel is
- 1.2 – 1.4 higher (if isolated)
- 1.1 – 1.15 in real S/A, thanks to mixing

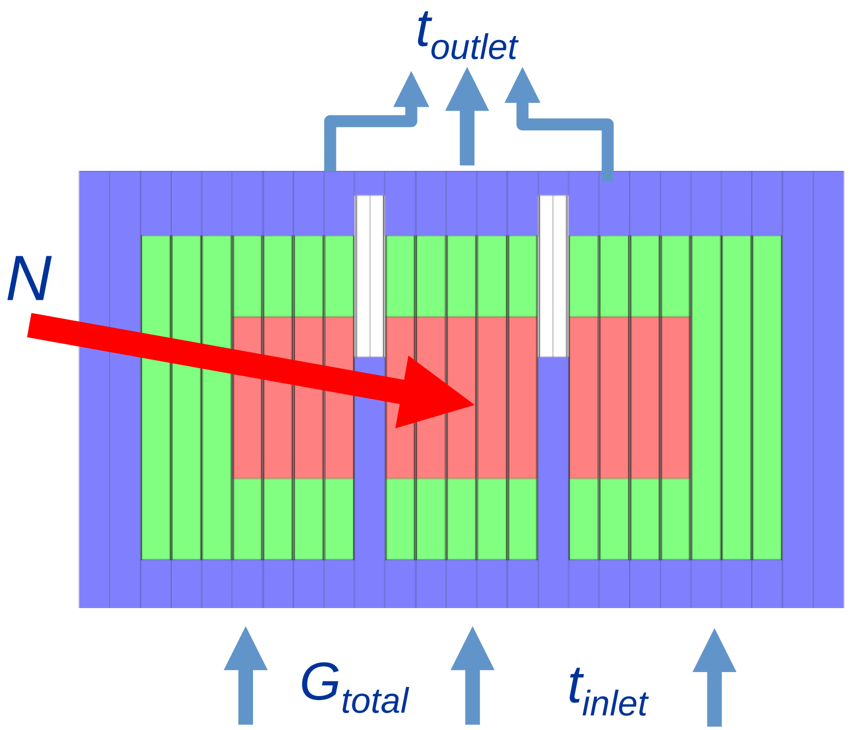
# TH Core Analysis: at Nominal Power

- What could be a Max Nominal Power?
  - For the given core configuration, what can be a maximal pin/SA/core thermal power?
  - Input
    - Core Design, S/A and Pin Geometry
    - Inlet Coolant Temperature
    - Axial and Radial Power Profiles (or peaking factors)
  - Output
    - Max Pin or S/A Power; Total Reactor Power

- Are limits exceeded?
  - For the given core design and power, to check if temperatures and velocities are below the limits
  - Input
    - Core Design, S/A and Pin Geometry
    - Max Pin or S/A Power (number of pins/SA) (from Reactor Power Distribution)
    - Axial Power Profile (or peaking factor)
    - Inlet Coolant Temperature
    - Coolant Velocity or Flowrate/SA
  - Output
    - Outlet Coolant Temperature
    - Maximal Cladding Temperature (or Distribution)
    - Maximal Fuel Temperature (or Distribution)

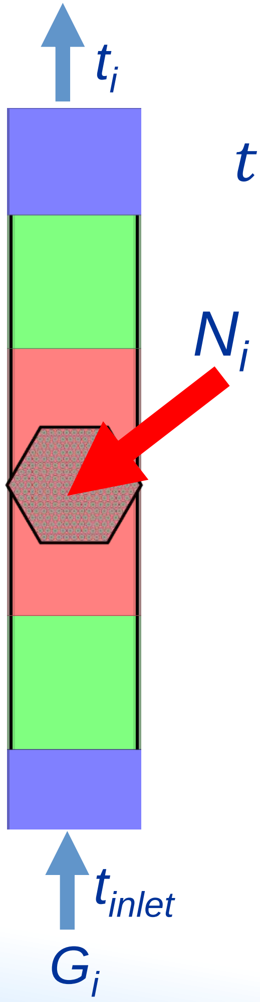
# Reactor Core Power Balance

**Core:** $N = GC_p(t_{outlet} - t_{inlet})$



| | |
|---|---|
| $G_{total}$ | Total Flowrate through the Core, kg/s |
| $t_{inlet}$ | Core Inlet Temperature, C |
| $t_{outlet}$ | Bulk Outlet Core Temperature, C |
| $N$ | Reactor Thermal Power, W |

**S/A:** $N_i = G_i C_p(t_i - t_{inlet})$



$$t_{outlet} = \frac{\sum G_i t_i}{G}$$

$$N = \sum N_i$$

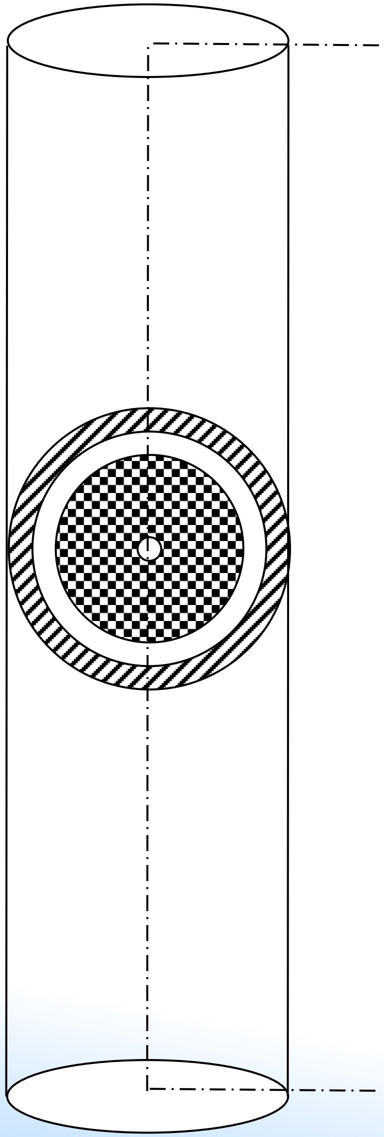
$$G = \sum G_i$$

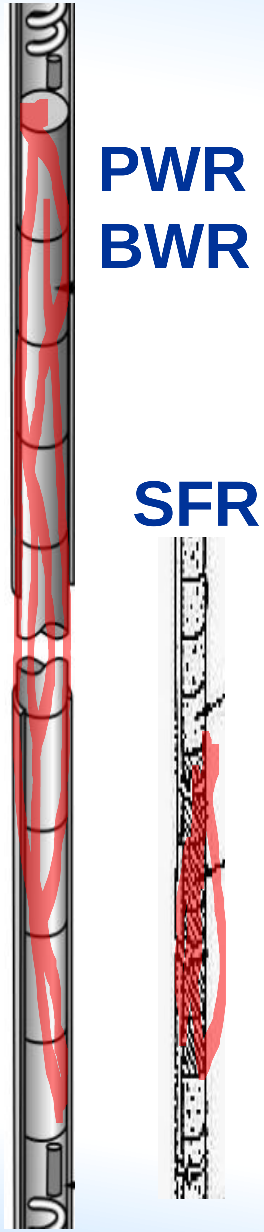
**Power Density**

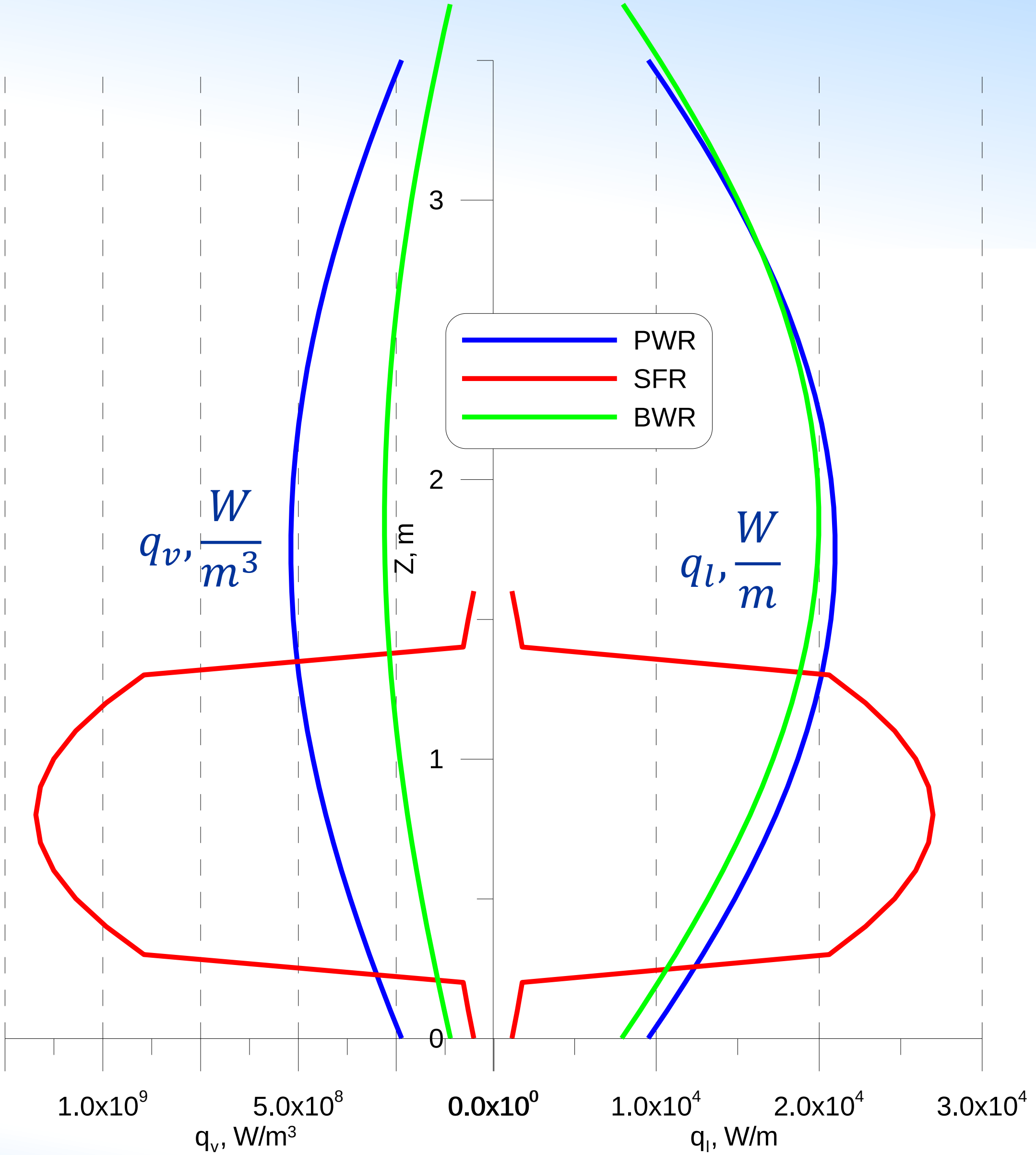
$$q_l = \frac{dN}{dz}$$

$$q_v = \frac{dN}{dV}$$

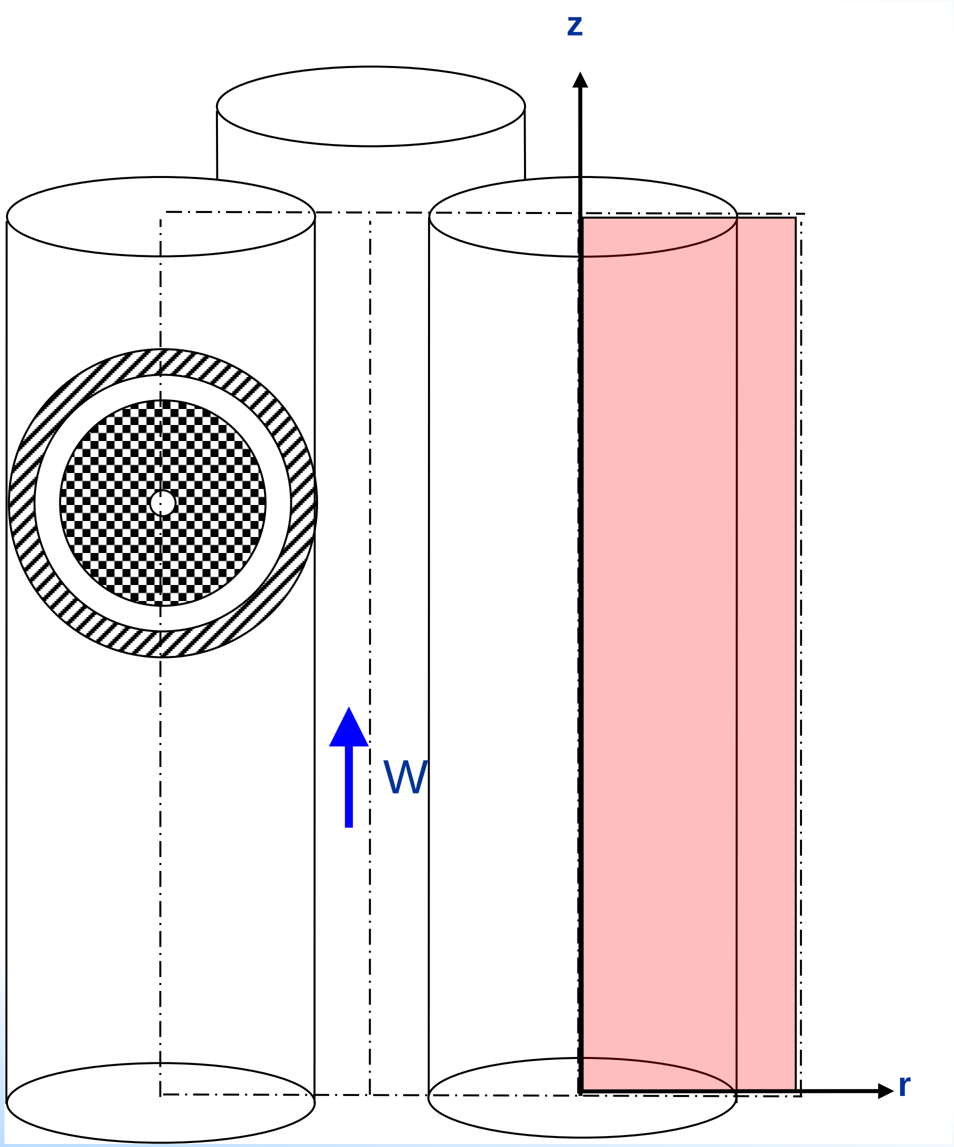
# Fuel Pin: Power Density





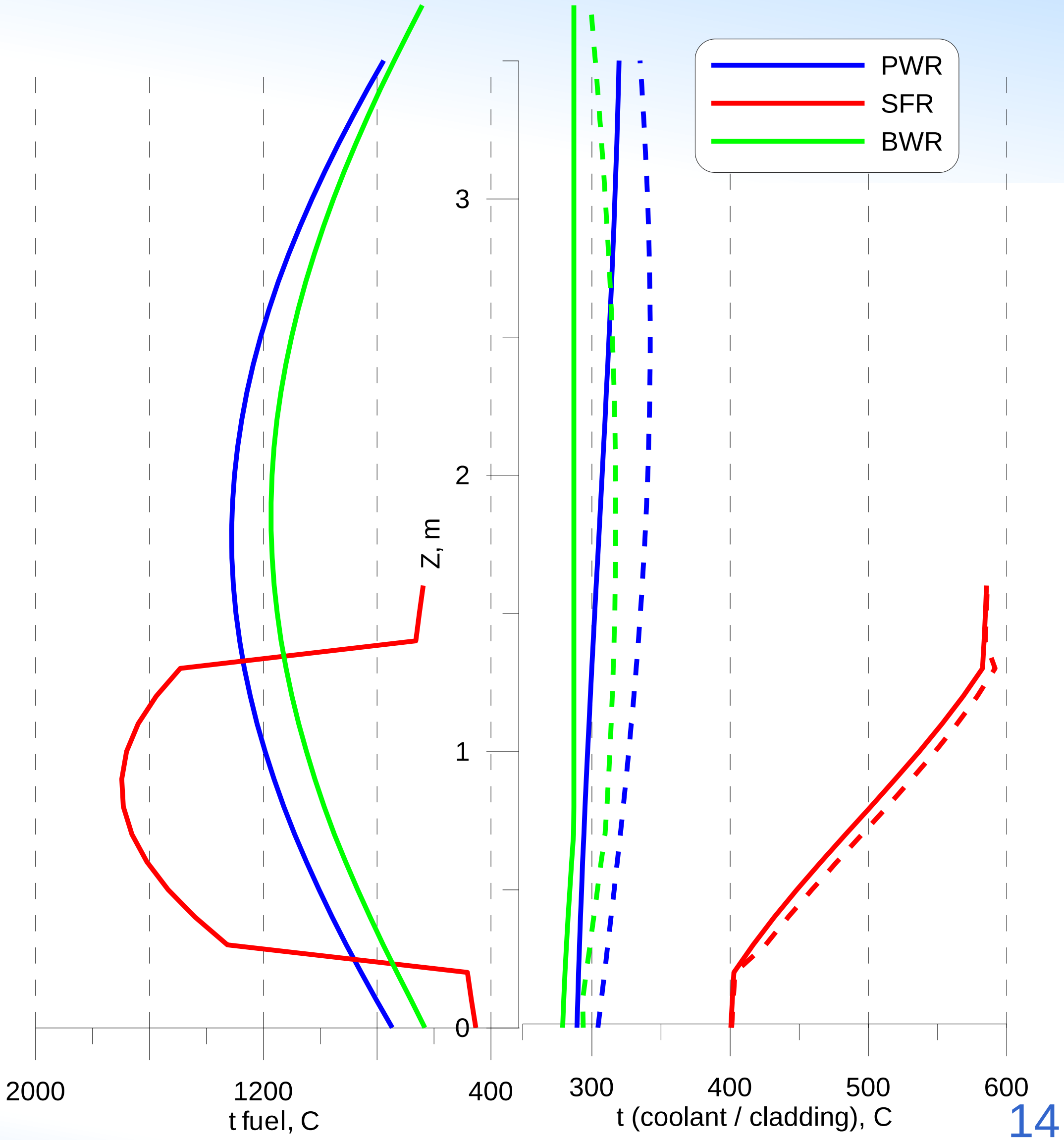


# Fuel Pin: Temperature Profiles

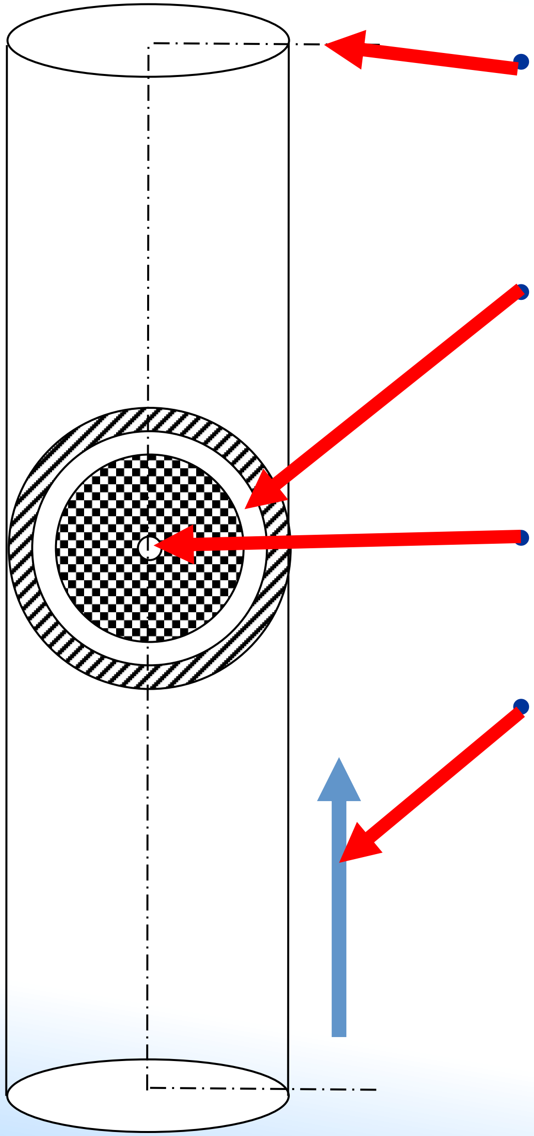


**PWR**
**BWR**

**SFR**

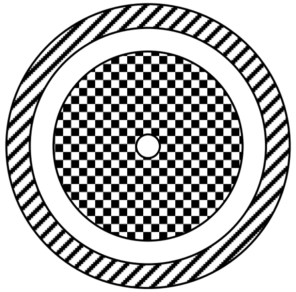


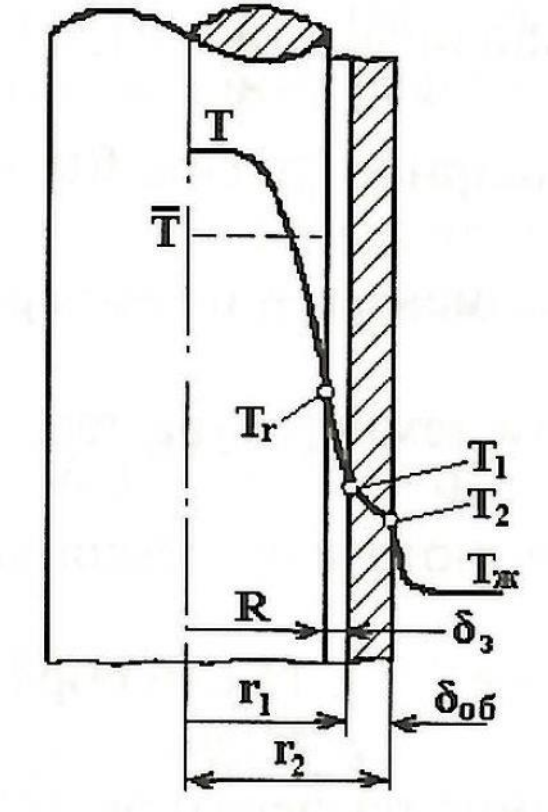
# TH Limiting Parameters



- Maximal Coolant Temperature
  - Below Boiling Point (at least)
    - ( ex: BWR, SCWR)
- Maximal Cladding Temperature
  - Zr: < 350 °C (< 1000°C under accident)
  - SS: < 700 °C (< 1000°C under accident)
- Maximal Fuel Temperature
  - Below Melting Point ( < 2700C)
- Maximal Coolant Velocity
  - To prevent erosion and vibration problems
  - To minimize pressure drop in the core (pump power)
  - H2O, Na: < 7-10 m/s
  - Lead, LBE: < 2 m/s

# Steady Temperature Profiles: Inside Pin





$$\cancel{\rho c_p \frac{\partial t}{\partial \tau}} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda(t) r \frac{\partial t}{\partial r}\right) + \cancel{\frac{\partial}{\partial z}\left(\lambda(t)\frac{\partial t}{\partial z}\right)} + q_v$$

- No transient term
- Axial heat conduction can be neglected

**Easy to Solve in 1D** (Analytically)

$$t_{\max}(z) = t_{coolant}(z) + \Delta t_{colant} + \Delta t_{clad} + \Delta t_{gap} + \Delta t_{fuel}$$

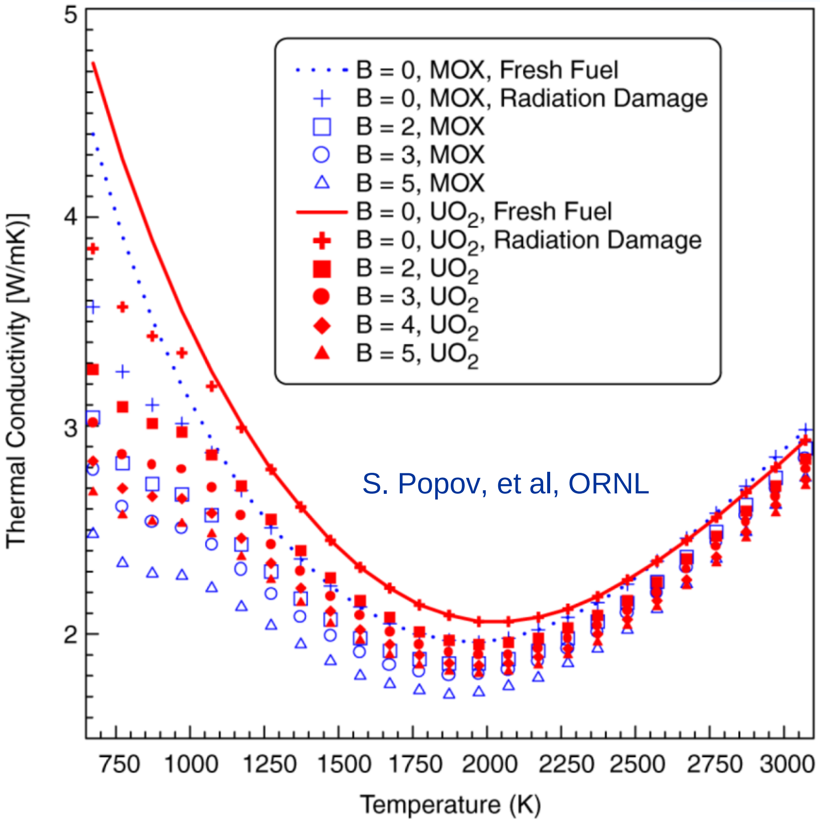
$$t_{coolant}(z) = t_{inlet} \int_{-h/2}^{z} c_p G_i q_l(z) dz$$

$$\Delta t_{coolant} = \frac{q_l(z)}{\alpha \pi d_{pin}} \qquad \Delta t_{clad} = \frac{q(z)\Delta_{clad}}{\lambda_{clad}}$$

$$\Delta t_{gap} = \frac{q(z)\Delta_{gap}}{\lambda_{gap}} \qquad \Delta t_{fuel} = \frac{q_v(z) d_{fuel}^2}{16\lambda_{fuel}}$$

**But…**

# Non-Linear Effects



S. Popov, et al, ORNL

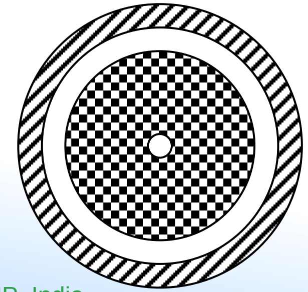
$$\cancel{\rho c_p \frac{\partial t}{\partial \tau}} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda(t) r \frac{\partial t}{\partial r}\right) + \cancel{\frac{\partial}{\partial z}\left(\lambda(t)\frac{\partial t}{\partial z}\right)} + q_v$$

Fuel Conductivity depends on temperature

$$\Delta t_{fuel} = \cancel{\frac{q_v(z) d^2_{fuel}}{16\lambda_{fuel}}}$$

Radiation Heat Transfer in the gap

$$\Delta t_{gap} = \cancel{\frac{q(z)\Delta_{gap}}{\lambda_{gap}}}$$

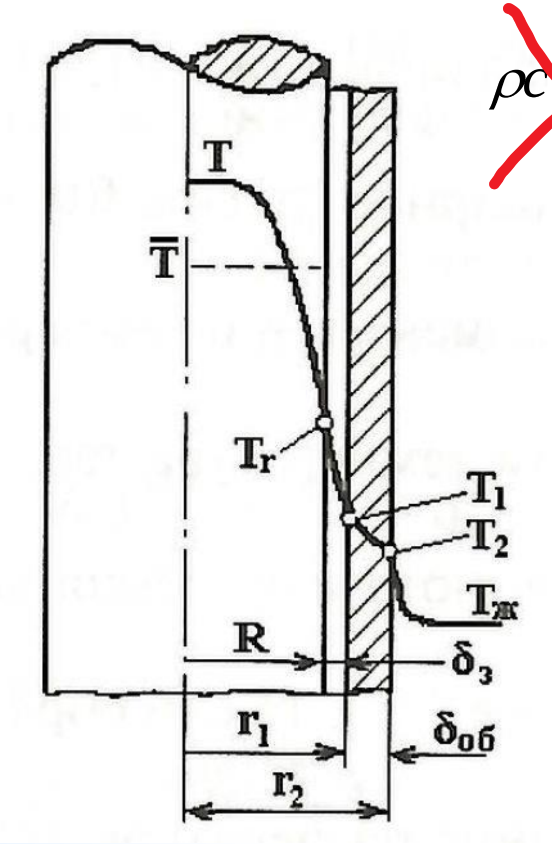


$$q = \varepsilon_{eff}\sigma\left(T^4_{pellet(out)} - T^4_{clad(in)}\right) + \lambda_{gap}\frac{T_{pellet(out)} - T_{clad(in)}}{\Delta_{gap}}$$

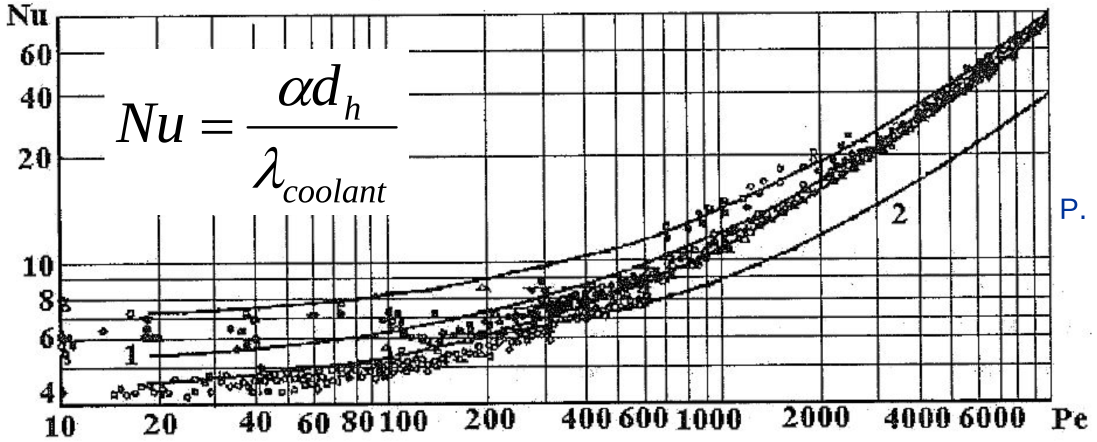
# Coolant-Cladding Heat Transfer

## Energy Conservation in Coolant

$$\cancel{\rho c_p \frac{\partial t}{\partial \tau}} + \rho c_p W(r)\frac{\partial t}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(\left(\lambda + \lambda^{r}_{turb}(r)\right) r \frac{\partial t}{\partial r}\right) + \frac{\partial}{\partial z}\cancel{\left(\left(\lambda + \lambda^{z}_{turb}(r)\right)\frac{\partial t}{\partial z}\right)}$$



$$t_{coolant}(z) = t_{inlet} \int_{-h/2}^{z} c_p G_i q_l(z)\,dz \qquad \Delta t_{coolant} = \frac{q_l(z)}{\alpha \pi d_{pin}}$$



$$Nu = \frac{\alpha d_h}{\lambda_{coolant}}$$

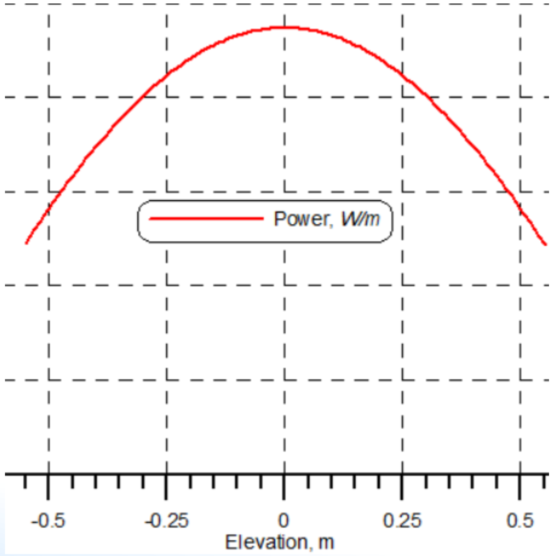
P. Kirillov, IPPE

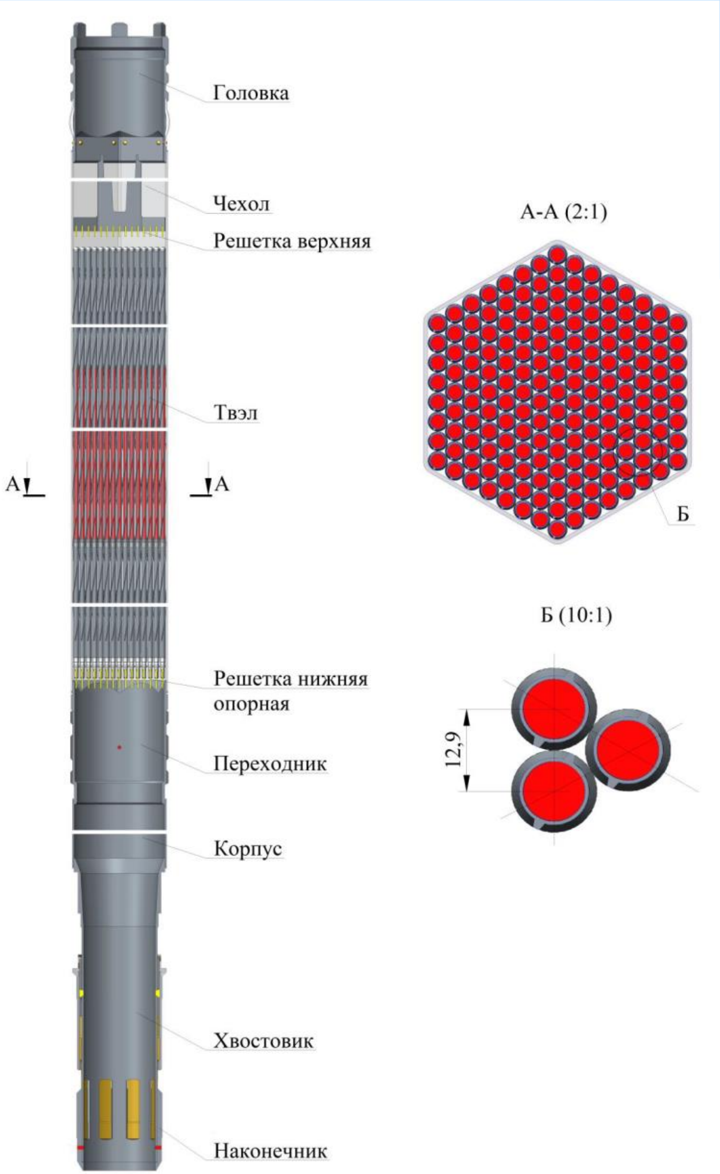
$$Nu = 0.047\left(1 - e^{-3.8\left(\frac{P}{D} - 1\right)}\right)\left(Pe^{0.77} + 250\right)$$

$$Nu = 0.58\left(1.1\left(\frac{p}{d}\right)^{2} - 1\right)^{0.55} Pe^{0.45} \quad \left(Pe = 400..4000;\ \Pr \le 0.04\right)$$

# Exercise: BREST-OD-300 LFR (Basic Design Example)

| | |
|---|---|
| Reactor Power (th), *N* | 700 MW |
| Number of FAs, *nFA* | 168 |
| Pins/FAs, *nPIns* | 169 |
| Fissile Core Height, *H* | 1.1 m |
| Inlet Temperature, *Tin* | 420 C |
| Total Flowrate in Primary Circuit, *Gtot* | 40000 kg/s |
| Nominal Flowrate in FA, *Gfa* | 115 kg/s |
| FA Hex inner flat size, *h* | 17 cm |
| Fuel Pin Diameter, *D* | 9.7 mm |
| Fuel Pellet central hole, *d* | - |
| Cladding Wall Thickness, *wall* | 0.5 mm |
| Fuel Pellet Diameter (assuming no gap), *gap* | 8.7 mm |
| Pitch-to-Diameter Ratio, *P/D* | 1.33 |
| Radial Peaking Factor, *Kr* | 1.09 |
| Axial Peaking Factor, *Kz* | 1.25 |
| $H_{eff}$ in $q = q_{max}*cos(\pi*z/H_{eff})$ | ? m |





# LFR: Lead, SS and Fuel Properties

| | |
|---|---|
| Pb Heat Capacity, Cp | ~ 150 J/kg/K |
| Pb Density, $\rho$ | ~ 10.4E+3 kg/m$^3$ |
| Pb Conductivity, $k_{Pb}$ | ~18 W/m/K |
| Pb kinematic viscosity, $v$ | 1.7*10$^{-7}$ m$^2$/s |
| SS Conductivity, $k_{SS}$ | ~ 20 W/m/K |
| Fuel (UN) Conductivity, $k_{UN}$ | ~ 25 W/m/K |
| | |
| | |

$\rho = 11.42 - 0.001242 \cdot T \sim 10.4$ t/m$^3$

$k_{Pb} = 15.8 + 0.0108 \cdot (T - 600.4) \sim 18$ W/m/K

$v = (15870/T - 2.65) \cdot 10^{-8} \sim 17 \cdot 10^{-8}$

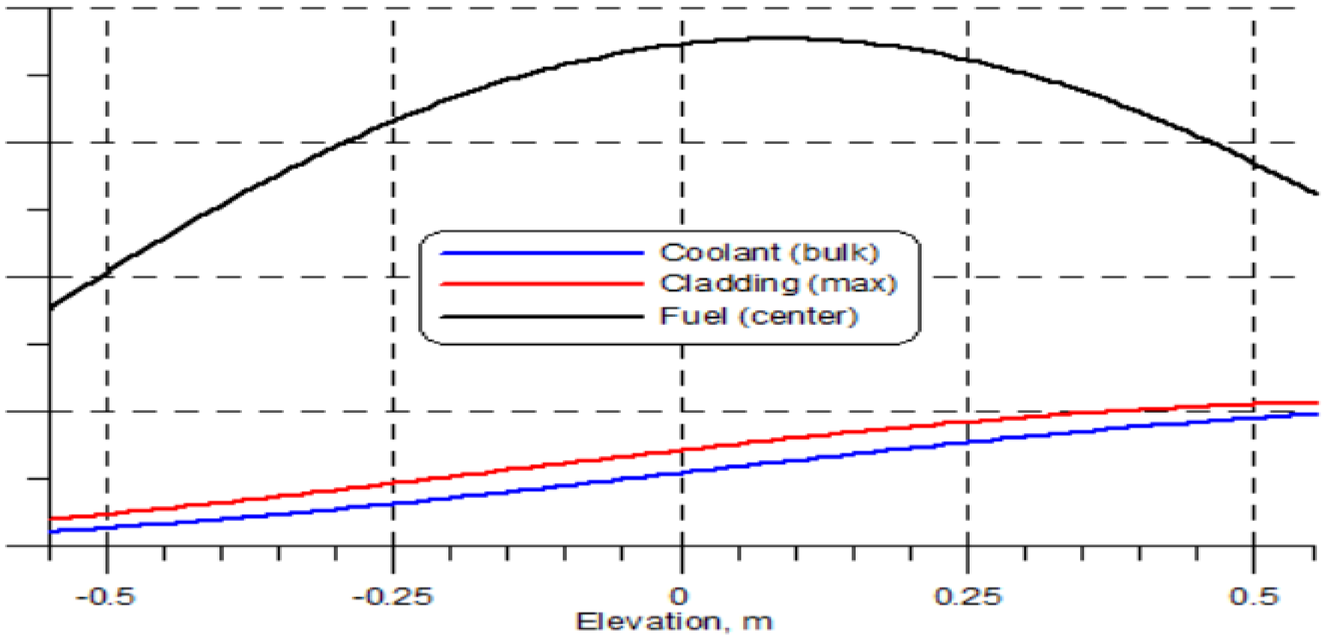
$k_{UN} = 1.37 \cdot T^{0.41} \sim 25$ W/m/K

$$Nu = 0.047\left(1 - e^{-3.8\left(\frac{P}{D}-1\right)}\right)\left(Pe^{0.77} + 250\right)$$

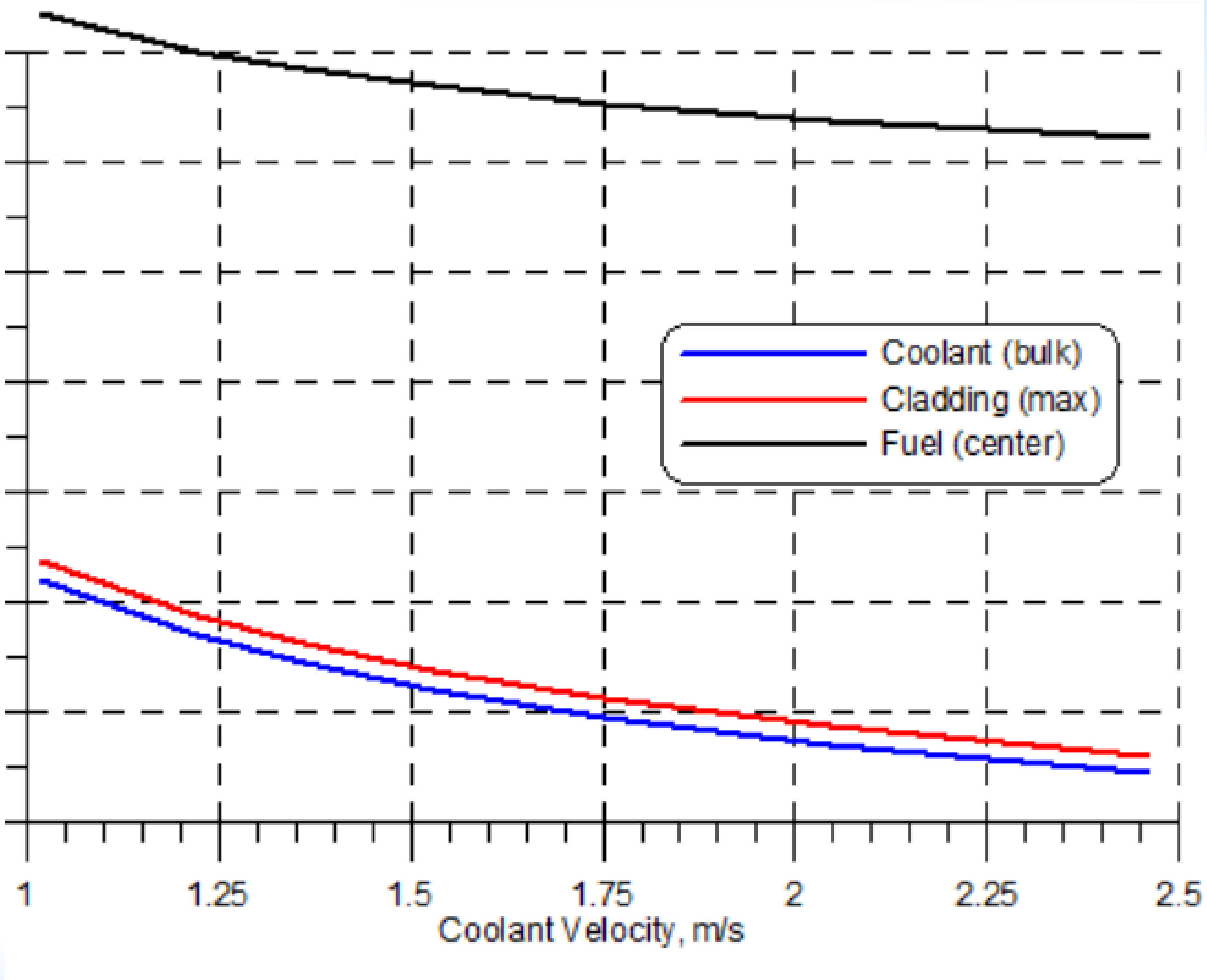
*To calculate:*

*Axial Temperature Profiles of*

- *Bulk coolant T*
- *Max cladding T*
- *Max fuel T*



# Max Coolant, Clad and Fuel Temperatures vs. coolant velocity



*To calculate:*
*Max Temperatures vs. coolant velocity*

- *Outlet coolant T*
- *Max cladding T*
- *Max fuel T*