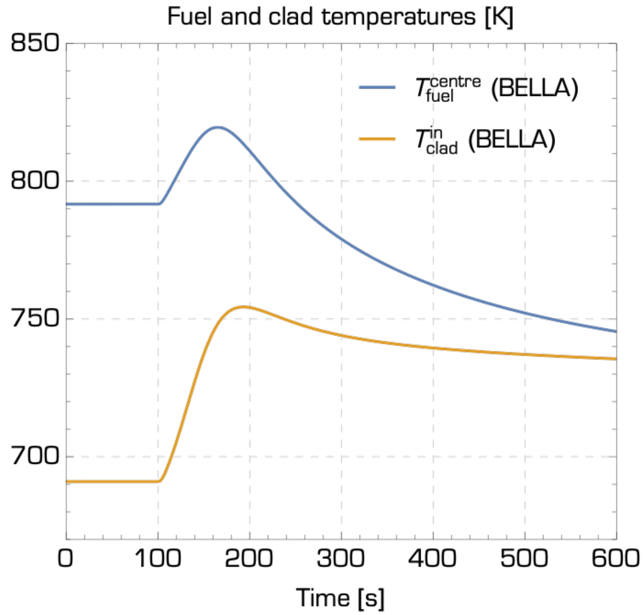
Introduction of BELLA Code



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Nuclear Engineering, KTH

Intended learning outcomes

Simulation of transients in fast reactors using BELLA

By "transient" is meant a transition from one steady state to another.
This may entail

Start-up & shut-down

Intended change in power and/or flow

Un-intended change in power and/or flow followed by shut-down

Un-intended change in power and/or flow without shut-down

After this lecture you will be able to:

- **Write a simple code for the simulation of transients in a fast reactor**
- **Simulate reactivity insertion and loss of flow transients**

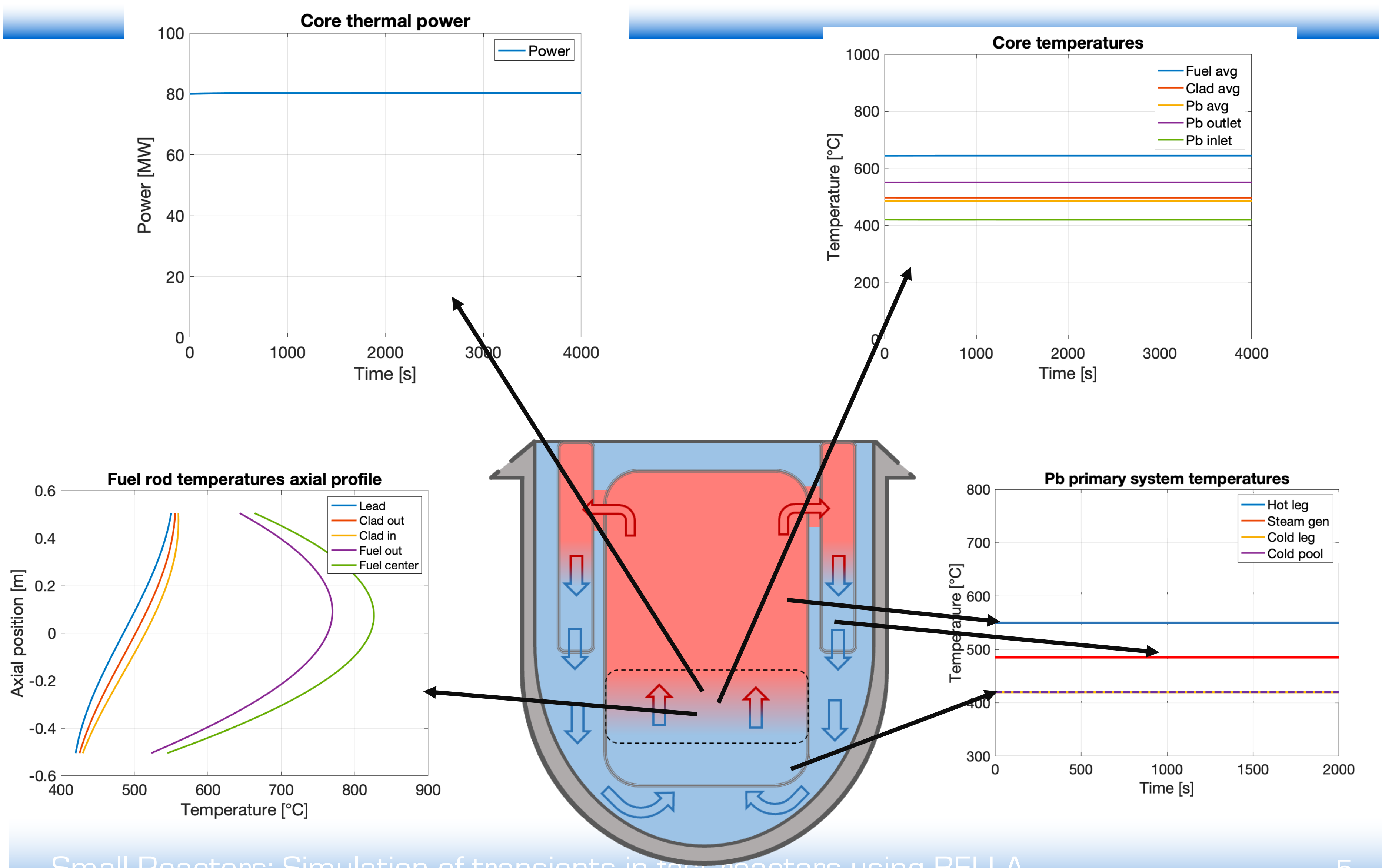
BELLA Code

- BELLA - Bortot's Elegant Liquid LFR Analysis tool.
- BELLA provides a non-linear solution for the coupled **neutron kinetic** and **thermal-hydraulic** equations of the primary system of an arbitrary liquid metal-cooled reactor.
- The code is based on point kinetics and balance equations for mass, energy and momentum, which are generally applied to the core, primary system components and RVAC system.
- Developed in the **Fortran language**. This language was chosen because it is easy to learn and provides efficient constructs that are useful for numerical calculations.

BELLA Code

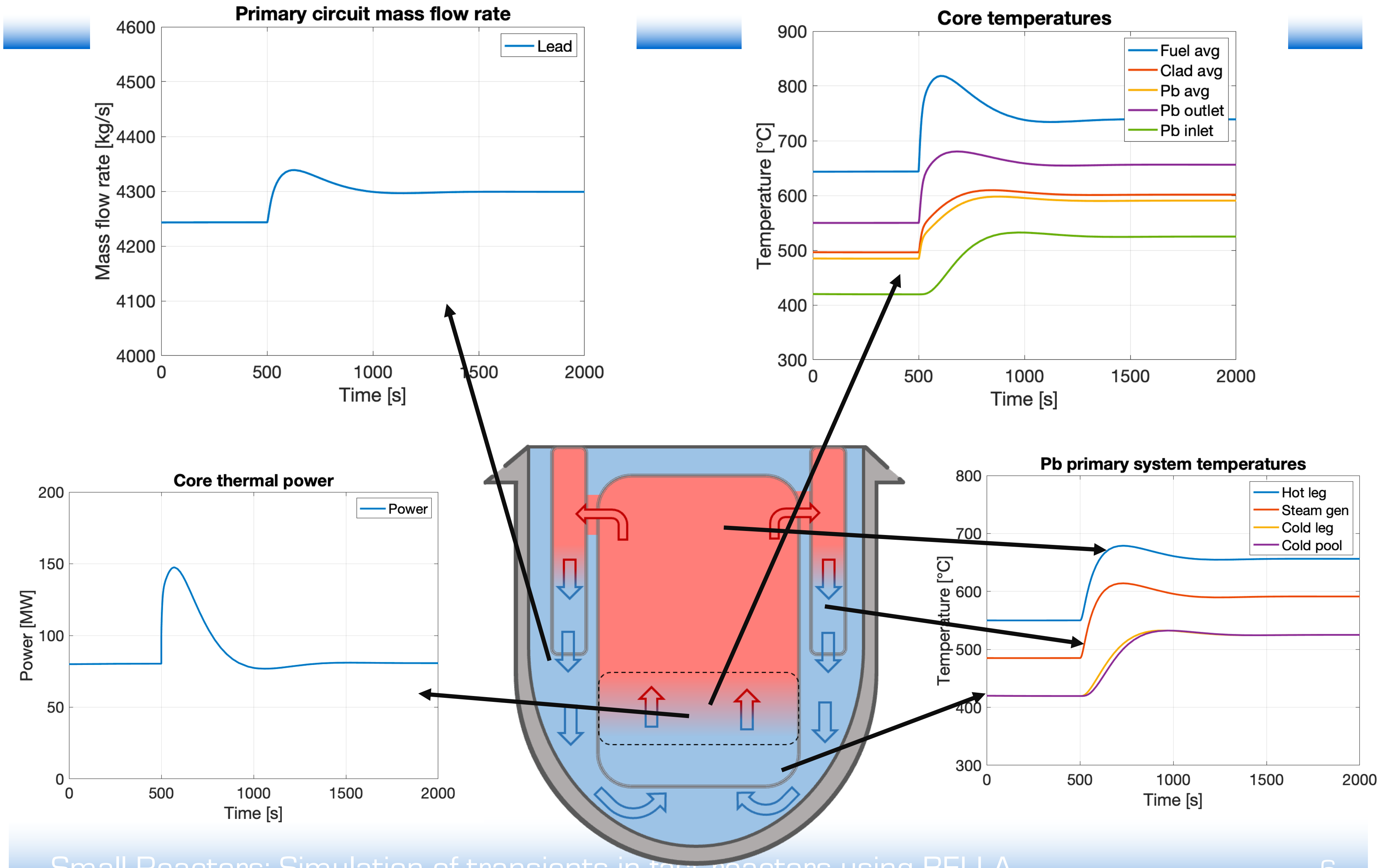
Module	Description	Output
REACTOR CORE	Heat transfer applied of fuel rod and coolant.	Temperature
PRIMARY SYSTEM	Hot leg Steam generator Cold leg Cold pool	Temperature Mass flux
NEUTRONICS	Point Kinetics Decay heat model REACTIVITY	Reactivity Heat source
THERMO - MECHANICS	Fuel performance analysis	Displacement Stress Strain
RVACS	Reactor Vessel Auxiliary Cooling System	Temperature Air mass flow Heat removed
ACTINIDES	Model of minor actinide bearing fuel	Mass fraction

BELLA Code - Current capabilities

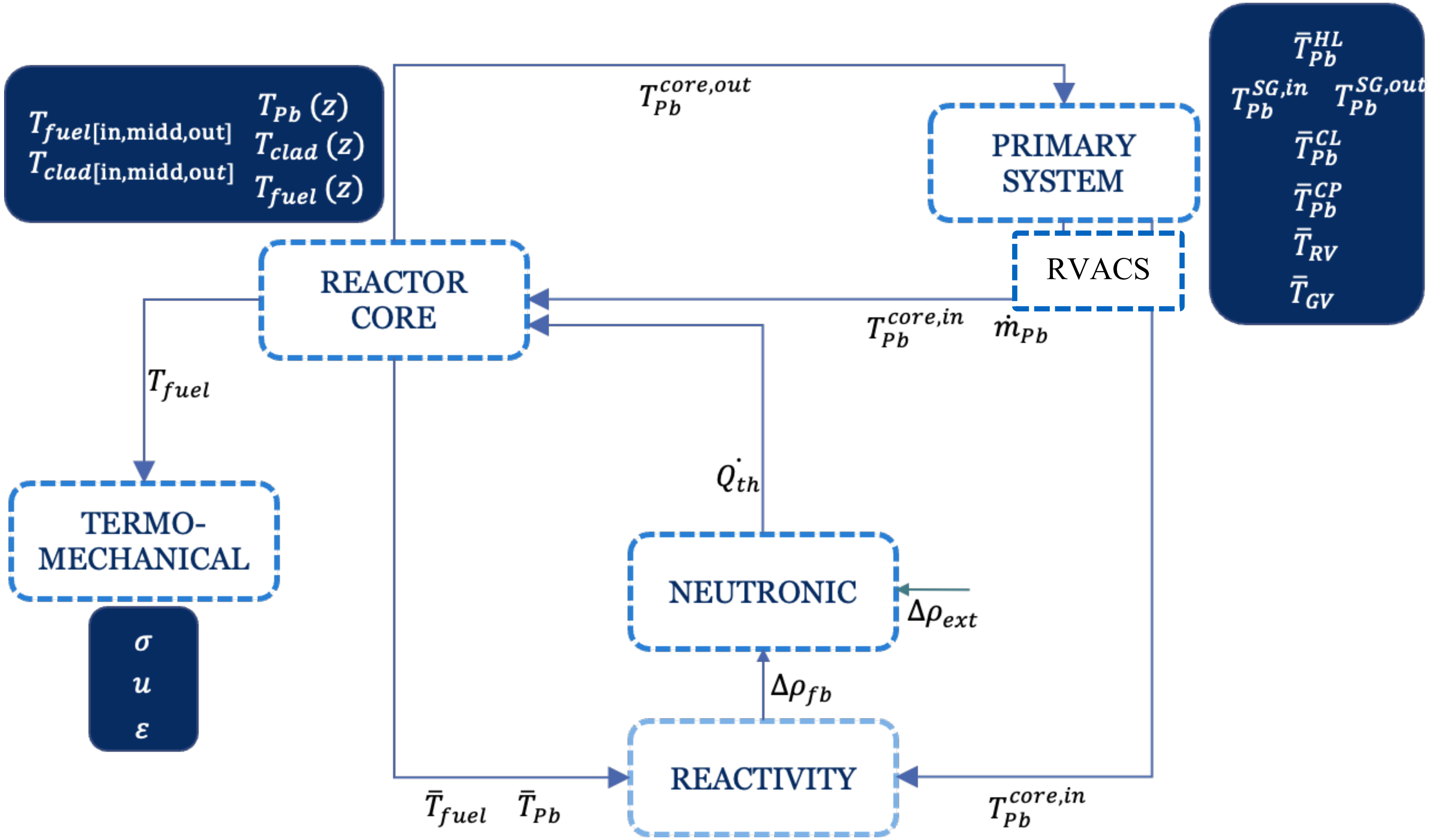


BELLA Code - Current capabilities

- Un-protected Transient over-power (UTOP)
- Un-protected Loss-of-flow (ULOF)
- Un-protected Loss-of-heat-sink (ULOHS)
- Combination of ULOF and ULOHS (station blackout)



BELLA Code - FEEDBACK



Neutronic - Point Kinetics Model

- In the point-kinetic approximation, we may describe the power evolution of a reactor according to the following set of coupled differential equations:

$$\frac{d\dot{Q}}{dt} = \frac{dn(t)}{dt} = \frac{\rho(t) - \beta_{eff}}{\Lambda_{eff}} n(t) + \sum_{i=1}^{8} \lambda_i C_i(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda_{eff}} n(t) - \lambda_i C_i(t)$$

Initial conditions

$$n(0) = n_0$$

$$C_i(0) = \frac{\beta_i}{\Lambda_{eff} \lambda_i} n(0)$$

$$\beta_{eff} = \sum_{i=1}^{8} \beta i$$

Group	β_i (pcm)	λ_i (1/s)
1	15.9	0.0125
2	92.1	0.0283
3	50.4	0.0425
4	117.1	0.133
5	205.1	0.292
6	84.6	0.666
7	67.8	1.63
8	32.2	3.55

SUNRISE-LFR point kinetics parameters for all neutron precursors.

Parameter	Value	Unit
β_{eff}	665.2	pcm
λ_{eff}	0.089	1/s
Λ_{eff}	0.88	μs

SUNRISE-LFR point kinetics main effective parameters.

*Data obtained from: Persico, A. (2022). Master Degree thesis. In progress.

Reactivity feedback

$$\delta\rho(t) = K_D \ln\left(\frac{\overline{T}_{fuel}(t)}{\overline{T}_{fuel}(0)}\right) + \alpha_{axial}\delta\overline{T}_{fuel}(t) + \alpha_{coolant}\delta\overline{T}_{coolant}(t) + \alpha_{radial}\delta\overline{T}^{in}_{coolant}(t) + \delta\rho_{external}$$

Fuel Doppler feedback

Fuel axial expansion

Coolant density change

Fuel SA diagrid radial expansion

External reactivity

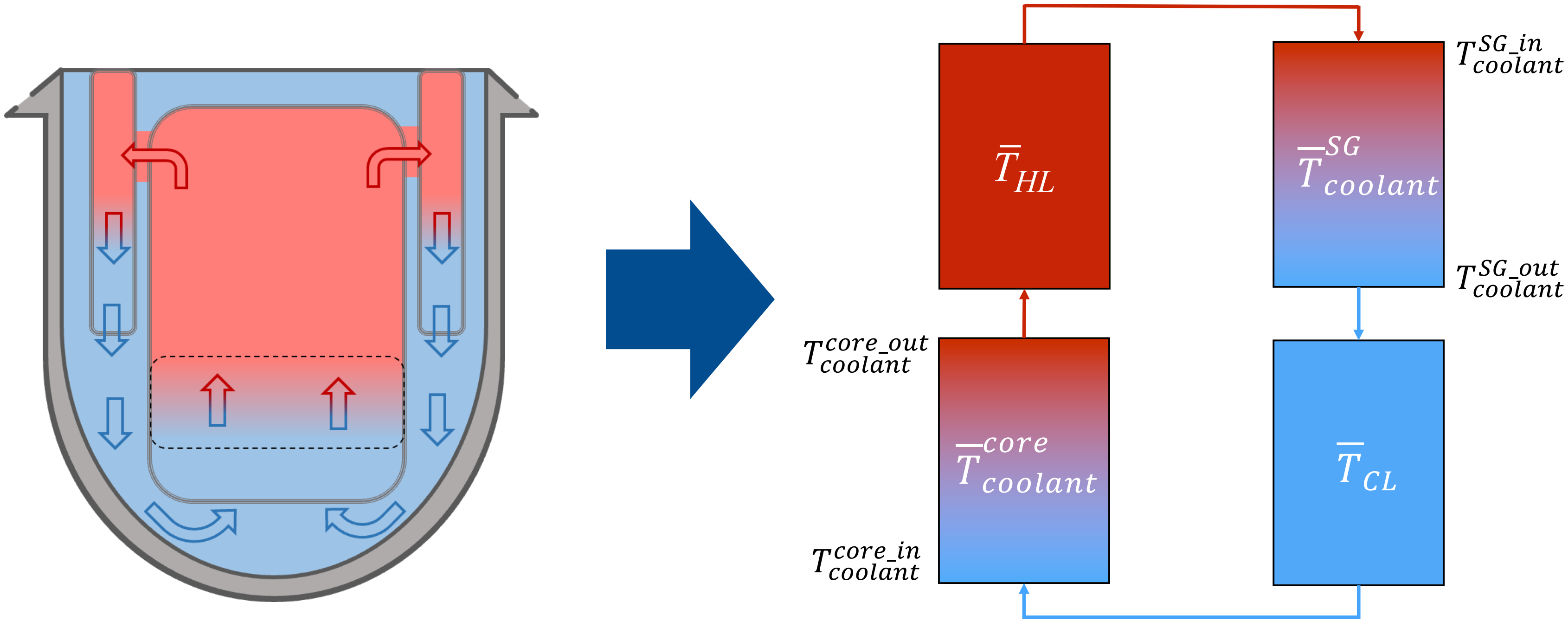
Parameter	Value	Unit
K_D	-530	pcm
α_{ax}	-0.15	pcm/K
α_{Pb}	-0.66	pcm/K
α_{rad}	0.03	pcm/K

lists the feedback coefficients at the middle of life (MoL) of SUNRISE-LFR.

*Data obtained from: Persico, A. (2022). Master Degree thesis.

Thermalhydraulic

Lumped parameter approach



- Treat the primary system as a collection of single points, featuring average and boundary temperatures:
- $\overline{T}^{core}_{coolant}$, $T^{core\_in}_{coolant}$, $T^{core\_out}_{coolant}$, $\overline{T}_{HL}$, $\overline{T}^{SG}_{coolant}$, $T^{SG\_in}_{coolant}$, $T^{SG\_out}_{coolant}$, $\overline{T}_{CL}$
- $\overline{T}^{outer}_{clad}$, $\overline{T}^{inner}_{clad}$, $\overline{T}^{outer}_{fuel}$, $\overline{T}^{middle}_{fuel}$, $\overline{T}^{central}_{fuel}$

Initialise coolant flow and clad surface temperature

- Set inlet and outlet temperatures (T_{in} & T_{out}) of your core coolant
- Steam generator Inlet temperature = Outlet temperature of core
- Outlet temperature of steam generator = Inlet temperature of core

$$\dot{m}_{coolant}^{core} = \frac{\dot{Q}_{core}}{c_p^{core} \Delta T_{core}}, \qquad \bar{v}_{coolant}^{core} = \frac{\dot{m}}{A_{flow} \times \bar{\rho}_{coolant}^{core}}$$

$$\bar{T}_{clad}^{surface} = \bar{T}_{coolant}^{core} + \dot{Q} \frac{D_h}{\lambda_{coolant} \times Nu_{coolant}}$$

- c_p, λ, Nu, are to be evaluated at the coolant average temperature and average velocity.

Initialise temperature state of cladding

- Calculate average ΔT_{clad} between outer and inner surfaces of the fuel clad by iteration process:

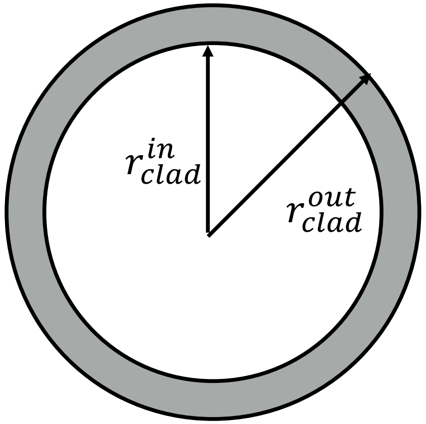
$$\Delta T_{clad}^{(1)} = \frac{\overline{\chi}}{2\pi\lambda_{clad}(T_{clad}^{out})} \ln\left(\frac{r_{clad}^{out}}{r_{clad}^{in}}\right)$$

$$\overline{\lambda}_{clad}^{(1)} = \lambda_{clad}\left(\overline{T}_{clad}^{out} + \frac{1}{2}\Delta T_{clad}^{(1)}\right)$$

$$\Delta T_{clad}^{(2)} = \frac{\overline{\chi}}{2\pi\overline{\lambda}_{clad}^{(1)}} \ln\left(\frac{r_{clad}^{out}}{r_{clad}^{in}}\right)$$

$$\overline{\lambda}_{clad}^{(2)} = \lambda_{clad}\left(\overline{T}_{clad}^{out} + \frac{1}{2}\Delta T_{clad}^{(2)}\right)$$

… until $\Delta T_{clad}, \overline{\lambda}_{clad}$ converges



Initialise temperature increase over fuel-clad gap

- Calculate average ΔT_{gap} between clad inner surface and fuel pellet by iteration:

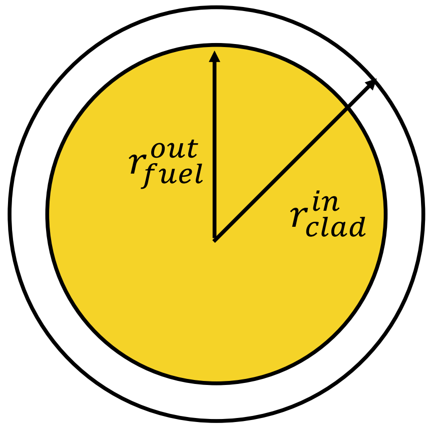
$$\Delta T_{gap}^{(1)} = \frac{\overline{\chi}}{2\pi\lambda_{gap}(T_{clad}^{in})}\ln\left(\frac{r_{clad}^{in}}{r_{fuel}^{out}}\right)$$

$$\overline{\lambda}_{gap}^{(1)} = \lambda_{gap}\left(\overline{T}_{clad}^{in} + \frac{1}{2}\Delta T_{gap}^{(1)}\right)$$

$$\Delta T_{gap}^{(2)} = \frac{\overline{\chi}}{2\pi\overline{\lambda}_{gap}^{(1)}}\ln\left(\frac{r_{clad}^{in}}{r_{fuel}^{out}}\right)$$

$$\overline{\lambda}_{gap}^{(2)} = \lambda_{gap}\left(\overline{T}_{clad}^{in} + \frac{1}{2}\Delta T_{gap}^{(2)}\right)$$

… until $\Delta T_{gap}, \overline{\lambda}_{gap}$ converges

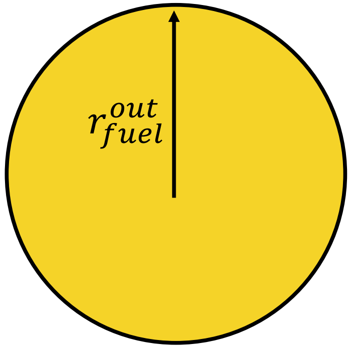


Initialise temperature state of fuel pellet

- Calculate average ΔT_{fuel} between fuel outer surface and centre-line by iteration:

$$\Delta T_{fuel}^{(1)} = \frac{\overline{\chi}}{4\pi\lambda_{fuel}(T_{fuel}^{out})}$$

$$\overline{\lambda}_{fuel}^{(1)} = \lambda_{fuel}\left(\overline{T}_{fuel}^{out} + \frac{1}{2}\Delta T_{fuel}^{(1)}\right)$$



$$\Delta T_{fuel}^{(2)} = \frac{\overline{\chi}}{4\pi\overline{\lambda}_{fuel}^{(1)}}$$

$$\overline{\lambda}_{fuel}^{(2)} = \lambda_{fuel}\left(\overline{T}_{fuel}^{out} + \frac{1}{2}\Delta T_{fuel}^{(2)}\right)$$ … until $\Delta T_{fuel}, \overline{\lambda}_{fuel}$ converges

Transient heat transfer

- The following set of differential equations is solved to evaluate the evolution of component temperatures in the core during a transient:

$$m_{fuel}^{centre} c_p^{fuel} \frac{dT_{fuel}^{centre}}{dt} = \dot{Q}_{fuel}^{centre}(t) - \frac{r_{fuel}}{r_{centre}} h_{fuel}\left(T_{fuel}^{centre}(t) - T_{fuel}^{middle}(t)\right)$$

$$m_{fuel}^{middle} c_p^{fuel} \frac{dT_{fuel}^{middle}}{dt} = \dot{Q}_{fuel}^{middle}(t) + \frac{r_{fuel}}{r_{centre}} h_{fuel}\left(T_{fuel}^{centre}(t) - T_{fuel}^{middle}(t)\right) - \frac{r_{fuel}}{r_{middle}} h_{fuel}\left(T_{fuel}^{middle}(t) - T_{fuel}^{outer}(t)\right)$$

$$m_{fuel}^{outer} c_p^{fuel} \frac{dT_{fuel}^{outer}}{dt} = \dot{Q}_{fuel}^{outer}(t) + \frac{r_{fuel}}{r_{middle}} h_{fuel}\left(T_{fuel}^{middle}(t) - T_{fuel}^{outer}(t)\right) - h_{gap}\left(T_{fuel}^{outer}(t) - T_{clad}^{inner}\right)$$

$$m_{clad}^{inner} c_p^{clad} \frac{dT_{clad}^{inner}}{dt} = h_{gap}\left(T_{fuel}^{outer}(t) - T_{clad}^{inner}(t)\right) - h_{clad}\left(T_{clad}^{inner}(t) - T_{clad}^{outer}(t)\right)$$

$$m_{clad}^{outer} c_p^{clad} \frac{dT_{clad}^{outer}}{dt} = h_{clad}\left(T_{clad}^{inner}(t) - T_{clad}^{outer}(t)\right) - h_{coolant}\left(T_{clad}^{outer}(t) - \bar{T}_{coolant}^{core}(t)\right)$$

$$m_{coolant} c_p^{coolant} \frac{dT_{coolant}^{out}}{dt} = h_{coolant}\left(T_{clad}^{outer}(t) - \bar{T}_{coolant}^{core}(t)\right) - \dot{m}_{coolant}^{core}(t) c_p^{coolant} \Delta T_{coolant}^{core}(t)$$

Generalised heat transfer coefficients

$$h_{fuel} = 4\pi\lambda_{fuel} n_{rods} H_{fuel} \qquad [\mathrm{W/K}]$$

$$h_{gap} = \frac{2\pi\lambda_{gap} n_{rods} H_{fuel}}{\ln(r_{clad}^{in}/r_{fuel})} \qquad [\mathrm{W/K}]$$

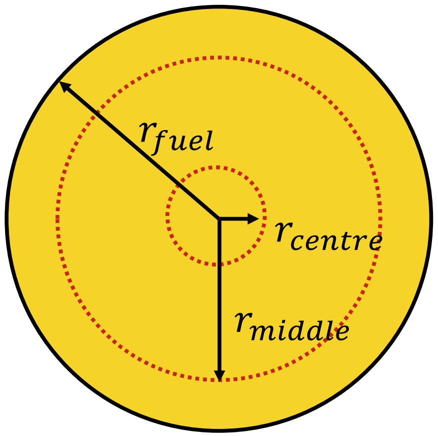
$$h_{clad} = \frac{2\pi\lambda_{clad} n_{rods} H_{fuel}}{\ln(r_{clad}^{out}/r_{clad}^{in})} \qquad [\mathrm{W/K}]$$

$$h_{coolant} = 2\pi r_{clad}^{out} \lambda_{coolant} n_{rods} H_{fuel} \frac{Nu_{coolant}^{core}}{D_h^{core}} \qquad [\mathrm{W/K}]$$

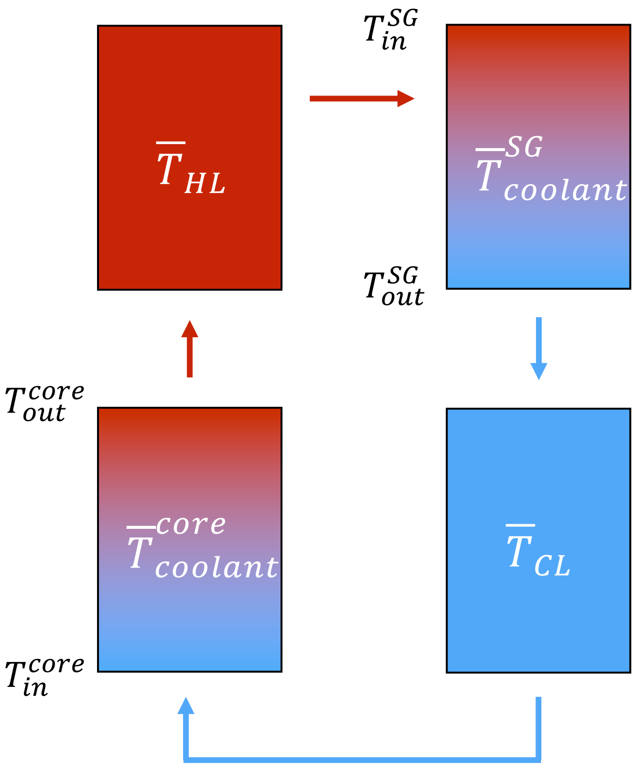
Fuel average temperature

- The fuel average temperature $\overline{T}_{fuel}$ to be used for Doppler and axial expansion feedback is obtained as:

$$\overline{T}_{fuel} = T_{fuel}^{centre}\left(\frac{r_{centre}}{r_{fuel}}\right)^2 + T_{fuel}^{middle}\left(\frac{r_{middle} - r_{centre}}{r_{fuel}}\right)^2 + T_{fuel}^{centre}\left(\frac{r_{outer} - r_{middle}}{r_{fuel}}\right)^2$$



Hot/cold leg and steam generator temperatures



- The coolant exiting the core is diluted into the hot leg:

$$\frac{d\bar{T}^{HL}_{coolant}}{dT} = \frac{\dot{m}^{core}_{coolant}}{m^{HL}_{coolant}}\left(T^{core}_{out} - \bar{T}^{HL}_{coolant}\right)$$

- For the steam generator inlet, we assume

$$T^{SG}_{in} = \bar{T}^{HL}_{coolant}$$

- Here, a simplified assumption is made for the outlet temperature of the steam generator. Either

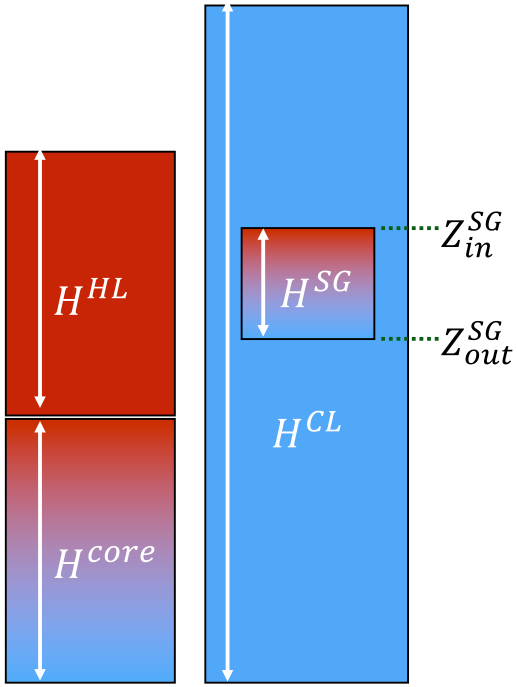
$$T^{SG}_{out} = T^{SG}_{in} - \Delta T^{SG}_{coolant}$$ constant temperature difference, or

$$T^{SG}_{out} = T^{SG}_{in} - \frac{\dot{Q}_{SG}}{\dot{m}^{SG}_{coolant} \times c_p^{coolant}}$$ constant power removal.

- For cold leg and core inlet temperatures:

$$\frac{d\bar{T}^{CL}_{coolant}}{dT} = \frac{\dot{m}^{SG}_{coolant}}{m^{CL}_{coolant}}\left(T^{SG}_{out} - \bar{T}^{CL}_{coolant}\right), \qquad T^{core}_{in} = \bar{T}^{CL}_{coolant}$$

Mass flow rates



- Change in mass flow rate through core and steam generator:

$$\frac{d\dot{m}_{coolant}^{core}}{dt} = -\frac{A_{coolant}^{core}}{H^{core}}\left(\Delta P_{HS}^{core} + g\rho_{coolant}^{core}H^{core} + K^{core}\frac{\dot{m}_{coolant}^{core}\left|\dot{m}_{coolant}^{core}\right|}{2\rho_{coolant}^{core}(A_{coolant}^{core})^2}\right)$$

$$\frac{d\dot{m}_{coolant}^{SG}}{dt} = -\frac{A_{coolant}^{SG}}{H^{SG}}\left(\Delta P_{HS}^{HS} + g\rho_{coolant}^{SG}H^{SG} + K^{SG}\frac{\dot{m}_{coolant}^{SG}\left|\dot{m}_{coolant}^{SG}\right|}{2\rho_{coolant}^{SG}(A_{coolant}^{SG})^2} + \Delta P_{pump}\right)$$

Difference in hydrostatic pressures: $\Delta P_{HS} = \left|P_{coolant}^{out} - P_{coolant}^{in}\right|$

$$\Delta P_{HS}^{core} = g\left|\rho_{coolant}^{HL}H^{HL} - \rho_{coolant}^{CL}H^{CL}\right|$$

$$\Delta P_{HS}^{SG} = g\left|\rho_{coolant}^{HL}(H^{HL} - Z_{in}^{SG}) - \rho_{coolant}^{CL}(H^{CL} - Z_{out}^{SG})\right|$$

Pressure loss coefficients

- The generalized pressure loss coefficients K are expressed in terms of the steady state pressure drops assumed to be established at t = 0:

$$K^{core}(t) = \left|\frac{\dot{m}^{core}_{coolant}(t)}{\dot{m}^{core}_{coolant}(0)}\right|^{b_{core}} \Delta P^{core}(0) \left[\frac{\dot{m}^{core}_{coolant}(0)\left|\dot{m}^{core}_{coolant}(0)\right|}{2\rho^{core}_{coolant}(0)(A^{core}_{coolant})^2}\right]^{-1}$$

$$K^{SG}(t) = \left|\frac{\dot{m}^{SG}_{coolant}(t)}{\dot{m}^{SG}_{coolant}(0)}\right|^{b_{SG}} \Delta P^{SG}(0) \left[\frac{\dot{m}^{SG}_{coolant}(0)\left|\dot{m}^{SG}_{coolant}(0)\right|}{2\rho^{SG}_{coolant}(0)(A^{SG}_{coolant})^2}\right]^{-1}$$

b: flow characteristic friction exponents

Elevation of coolant free surface levels

- Net transfer of coolant between hot and cold legs + expansion

$$\frac{dH^{HL}}{dt} = \frac{\dot{m}^{core}_{coolant} - \dot{m}^{SG}_{coolant}}{\rho^{HL}_{coolant} A^{HL}_{coolant}} - \frac{H^{HL}}{\rho^{HL}_{coolant}} \frac{d\rho_{coolant}}{dT} \frac{d\overline{T}^{HL}}{dt} - \frac{V^{core}_{coolant}}{\rho^{core}_{coolant} A^{HL}_{coolant}} \frac{d\rho_{coolant}}{dT} \frac{d\overline{T}^{core}_{coolant}}{dt}$$

$$\frac{dH^{CL}}{dt} = \frac{\dot{m}^{SG}_{coolant} - \dot{m}^{core}_{coolant}}{\rho^{CL}_{coolant} A^{CL}_{coolant}} - \frac{H^{CL}}{\rho^{CL}_{coolant}} \frac{d\rho_{coolant}}{dT} \frac{d\overline{T}^{CL}}{dt}$$

Termomechanical model

Radial equilibrium equation

radial stress & hoop stress

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0$$

Geometric equations

radial displacement & strain

$$\varepsilon_r = \frac{du}{dr} \qquad \varepsilon_\theta = \frac{u}{r} \qquad \varepsilon_z = const(r)$$

Generalized Hooke's law

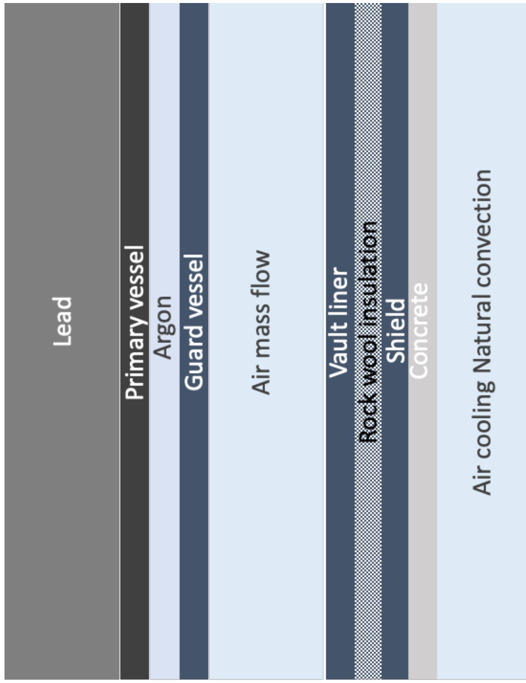
stress & strain

$$\varepsilon_r = \frac{1}{E}(\sigma_r - \nu(\sigma_\theta + \sigma_z)) + \alpha T + \varepsilon^s + \varepsilon_r^c$$

$$\varepsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu(\sigma_r + \sigma_z)) + \alpha T + \varepsilon^s + \varepsilon_\theta^c$$

$$\varepsilon_z = \frac{1}{E}(\sigma_z - \nu(\sigma_r + \sigma_\theta)) + \alpha T + \varepsilon^s + \varepsilon_z^c$$

RVAC System



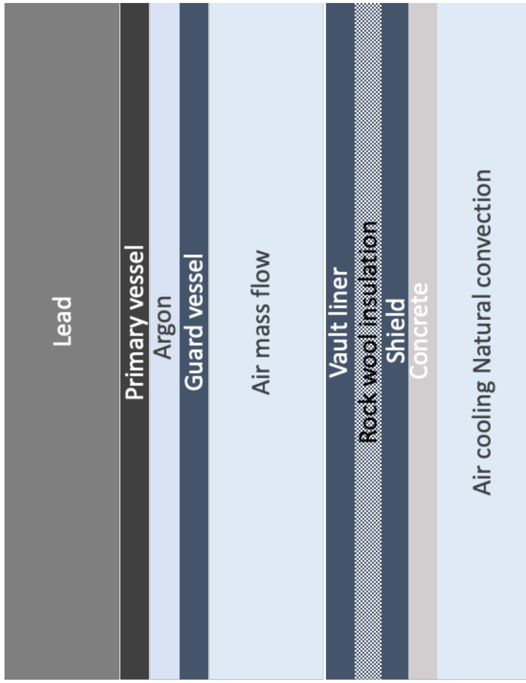
$$\frac{d\bar{T}_{Pb}}{dt} = \frac{1}{m_{Pb} c_p^{Pb}} \left(\dot{Q}(t) - h_{Pb\rightarrow 316L} A_{primary} (\bar{T}_{Pb} - \bar{T}_{primary}) \right) \tag{1}$$

$$\frac{d\bar{T}_{vessel}}{dt} = \frac{1}{m_{vessel} c_p^{316L}} \left(h_{Pb\rightarrow 316L} A_{primary} (\bar{T}_{Pb} - \bar{T}_{primary}) - \frac{\sigma_{SB}(\bar{T}^4_{vessel} - \bar{T}^4_{guard})}{\frac{1}{A_{vessel}\epsilon_{vessel}} + \frac{1}{A_{guard}\epsilon_{guard}} - \frac{1}{A_{guard}}} \right) \tag{2}$$

$$\frac{d\bar{T}_{guard}}{dt} = \frac{1}{m_{guard} c_p^{316L}} \left(\frac{\sigma_{SB}(\bar{T}^4_{vessel} - \bar{T}^4_{guard})}{\frac{1}{A_{vessel}\epsilon_{vessel}} + \frac{1}{A_{guard}\epsilon_{guard}} - \frac{1}{A_{guard}}} - \frac{\sigma_{SB}(\bar{T}^4_{guard} - \bar{T}^4_{liner})}{\frac{1}{A_{guard}\epsilon_{guard}} + \frac{1}{A_{liner}\epsilon_{liner}} - \frac{1}{A_{liner}}} - h_{316L\rightarrow air} A_{guard} (\bar{T}_{guard} - \bar{T}_{air}) \right) \tag{3}$$

$$\frac{d\bar{T}_{liner}}{dt} = \frac{1}{m_{liner} c_p^{316L}} \left(\frac{\sigma_{SB}(\bar{T}^4_{guard} - \bar{T}^4_{liner})}{\frac{1}{A_{guard}\epsilon_{guard}} + \frac{1}{A_{liner}\epsilon_{liner}} - \frac{1}{A_{liner}}} - h_{316L\rightarrow air} A_{liner} (\bar{T}_{liner} - \bar{T}_{air}) - h_{316L\rightarrow RW} A_{liner} (\bar{T}_{liner} - \bar{T}_{RW}) \right) \tag{4}$$

RVAC System



$$\frac{d\bar{T}_{RW}}{dt} = \frac{1}{m_{RW}c_p^{RW}}\left(h_{316L\to RW}A_{liner}(\bar{T}_{liner} - \bar{T}_{RW}) - h_{RW\to shield}A_{shield}(\bar{T}_{RW} - \bar{T}_{shield})\right) \quad (5)$$

$$\frac{d\bar{T}_{shield}}{dt} = \frac{1}{m_{shield}c_p^{shield}}\left(h_{RW\to shield}A_{shield}(\bar{T}_{RW} - \bar{T}_{shield}) - h_{shield\to air}A_{shield}(\bar{T}_{shield} - \bar{T}_{in})\right) \quad (6)$$

$$\frac{dT_{air}^{out}}{dt} = \frac{1}{m_{air}c_p^{air}}\left(h_{guard\to air}A_{guard}(\bar{T}_{guard} - \bar{T}_{air}) + h_{liner\to air}A_{liner}(\bar{T}_{liner} - \bar{T}_{air}) - \dot{m}_{air}c_p^{air}(T_{air}^{out} - T_{in})\right) \quad (7)$$

$$\frac{d\dot{m}_{air}}{dt} = \frac{A_{vault}}{H_{vault}}\left(g(\rho_{air}^{in} - \rho_{air}^{out})\left(\frac{H_{vault}}{2} + H_{chimney}\right) - \frac{f_D^{vault}H_{vault}\dot{m}_{air}^2}{2D_h^{vault}\rho_{air}(T_{vault})A_{vault}^2} - \frac{f_D^{chimney}H_{chimney}\dot{m}_{air}^2}{2D_h^{chimney}\rho_{air}(T_{chimney})A_{chimney}^2}\right)$$

$$-\frac{A_{vault}}{H_{vault}}\frac{\dot{m}_{air}^2}{2}\left(\frac{K_{in} + K_{bend}}{\rho_{air}(T_{in})A_{in}^2} + K_{\Delta A+}\left(\frac{A_{in}}{A_{bottom}} - 1\right)^2\frac{1}{\rho_{air}(T_{in})A_{in}^2} + K_{\Delta A-}\left(1 - \frac{A_{vault}}{A_{bottom}}\right)\frac{1}{\rho_{air}(T_{out})A_{bottom}^2} + K_{\Delta A+}\left(\frac{A_{vault}}{A_{chimney}} - 1\right)^2\frac{1}{\rho_{air}(T_{out})A_{vault}^2} + \frac{2K_{bend} + K_{out}}{\rho_{air}(T_{out})A_{out}^2}\right) \quad (8)$$

How are the models solved?

Radial temperatures

- Fuel
- Gap
- Cladding
- Lead

Simultaneous

Matrix solved by Thomas' Method

Primary System and RVAC

- Hot-leg
- Steam generator
- Cold-leg
- Cold-pool
- Reactor-vessel
- Guard-vessel

Sequential

Explicit discretization

Reactor Power

- Neutronic density
- Reactivity

Sequential

Explicit discretization

BELLA Code Routines

- User_interface.f90
- Read_input.f90
- Print_results.f90
- Transients.f90
- Input.dat
- Results.dat

- Initial.f90
- User_interface.f90
- Neutronic_model.f90
- Reactivity.f90
- Radial_temp.f90
- Axial_temp.f90
- Energy_primary.f90
- Momentum_primay.f90
- Mass_primay.f90
- Energy_RVAC.f90
- Momentum_RVAC.f90

- Fuel_prop.f90
- Gap_prop.f90
- Clad_prop.f90
- Lead_prop.f90

BELLA.f90

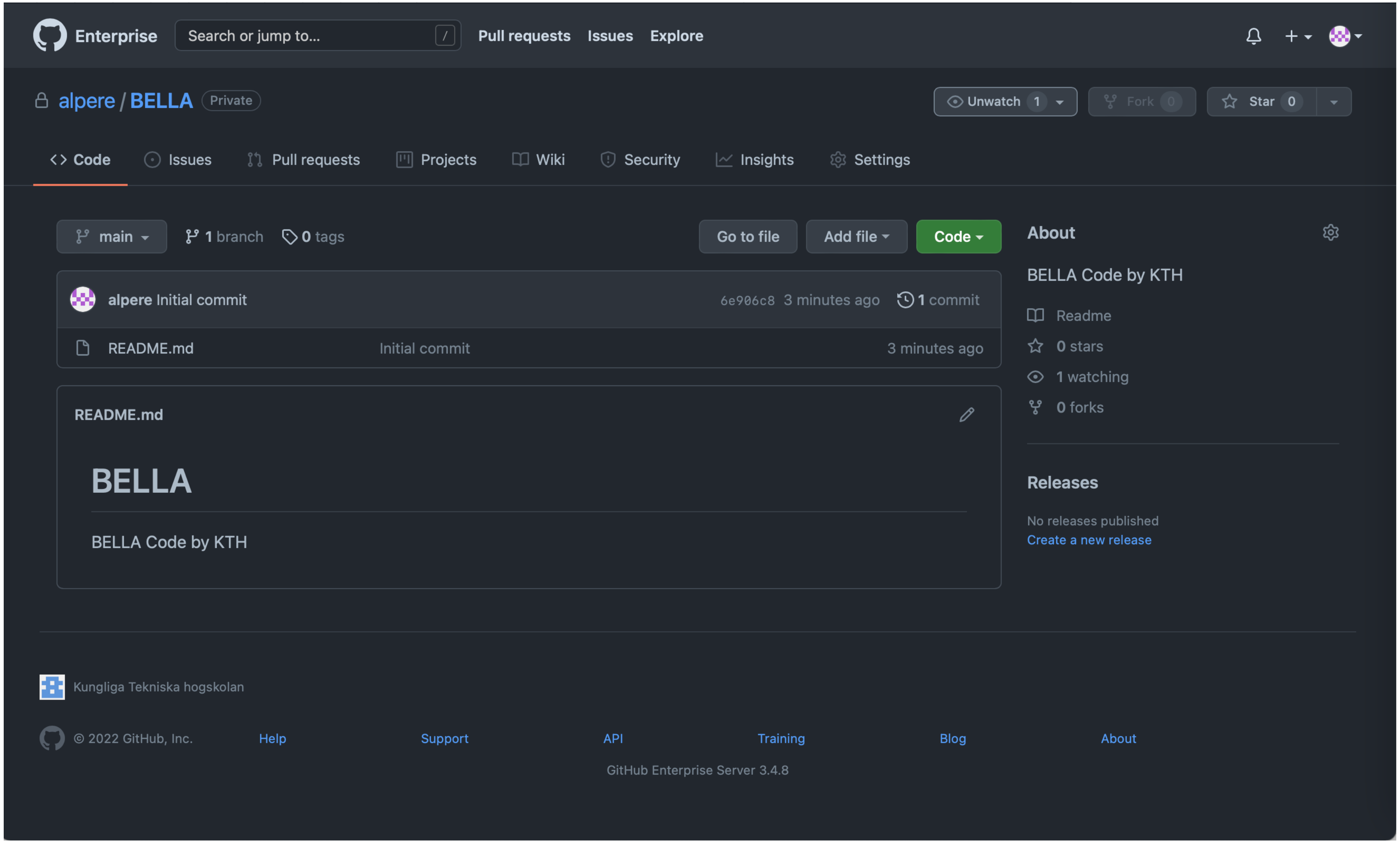
- Global_variables.mod
- Precision.mod

Users Interface : doing easy

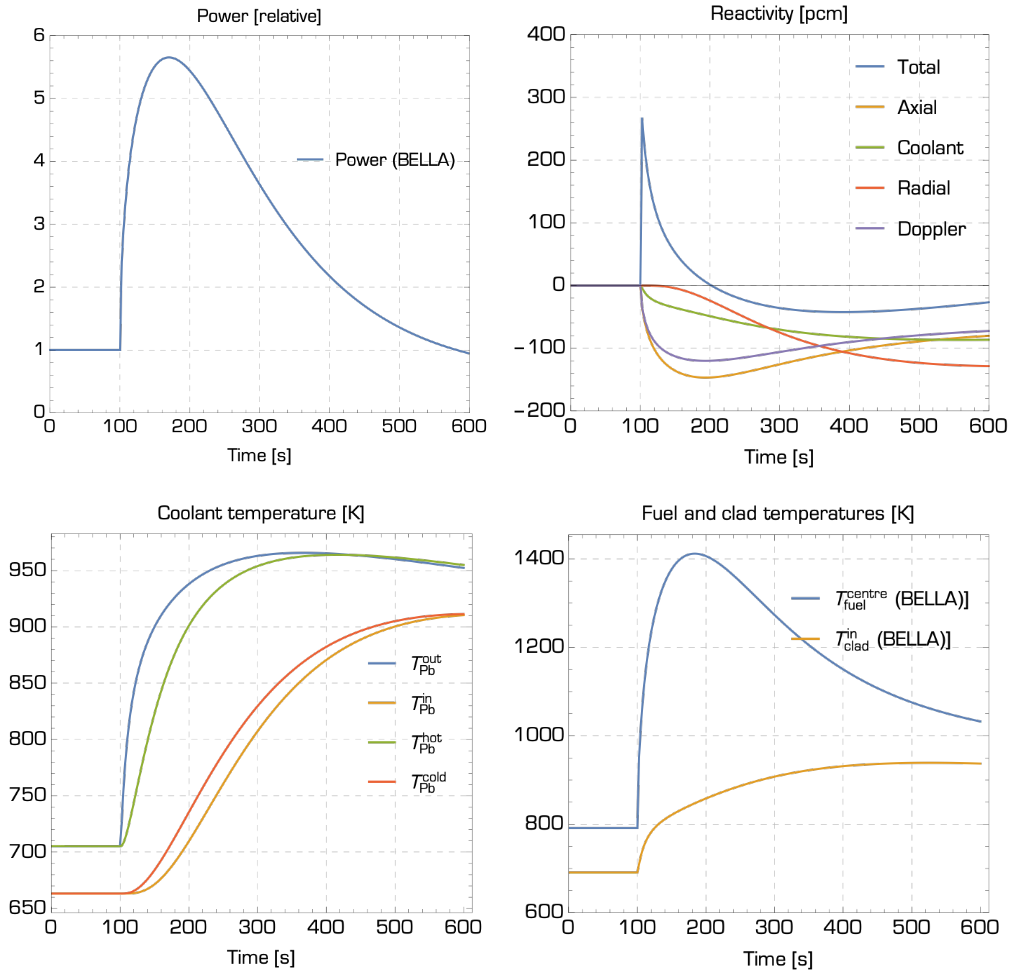
```
alejandria@eduroam-10-200-44-189 src % ./bella

     Please write the simulation time (s).
1000
     Please write simulation step (s).
1
     Do you want to simulate a transient event?
          yes = 1
           no = 2
1

     Please write the time to start the transient (s).
100

     Choose the transient event:
     ULOF           write 1
     UTOP           write 2
     ULOHS          write 3
     ULOF & ULOHS   write 4
```

```
Time                 =     1000.0000000000000      Thermal power   =     80000652.000000000

                                 Temperatures [°C]
Fuel avg             =     645.22998046875000      Fuel max        =     652.65002441406250
Clad avg             =     496.45001220703125      Clad max        =     561.34002685546875
Lead inlet           =     419.67001342773438      Lead outlet     =     550.86999511718750
Lead core            =     485.36999511718750      Lead Hot leg    =     550.86999511718750
Lead SG              =     485.23001098632812      Lead Cold leg   =     419.98999023437500
Lead Cold pool       =     419.98999023437500      Fuel max core   =     868.34002685546875
Mass flow [kg/s]     =     4241.3999023437500
```

Repository to keep it safe!



Simulation of reactivity insertion in a small lead-cooled reactor with UO_2 fuel (SEALER-3)



- Insertion of 0.5$ reactivity at t = 100 s.
- Power increases more than 400%
- Temperatures increase
- Negative reactivity feedbacks act
- Sub-criticality achieved (without insertion of shut-down rods) 100 s into the transient.
- Power reduces, as delayed neutrons continue to induce fission chains.
- Coolant & clad temperatures increase
- Fuel temperature decreases

Simulation of loss of flow in SEALER-3