NEUP Integrated Research Project Workshop 2:
FHR Benchmarking and VVUQ

Session 1.5: Multiphysics discussion

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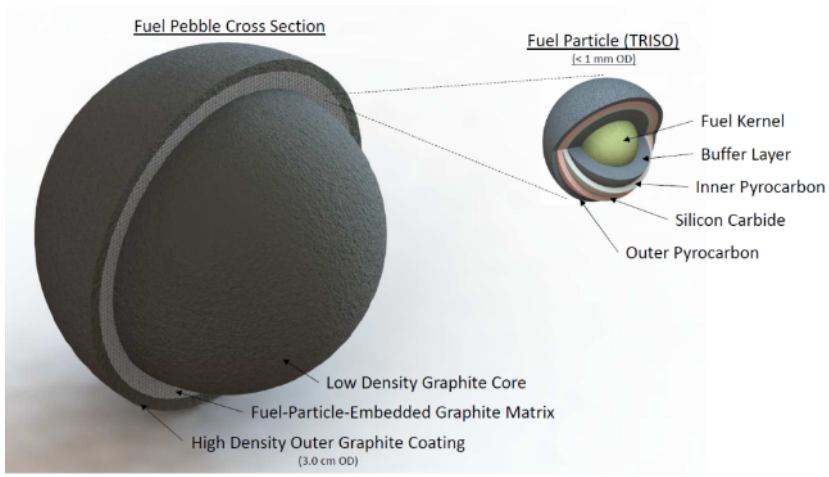
Overview

To study FHR transients, different approaches are adopted for multiphysics modeling:

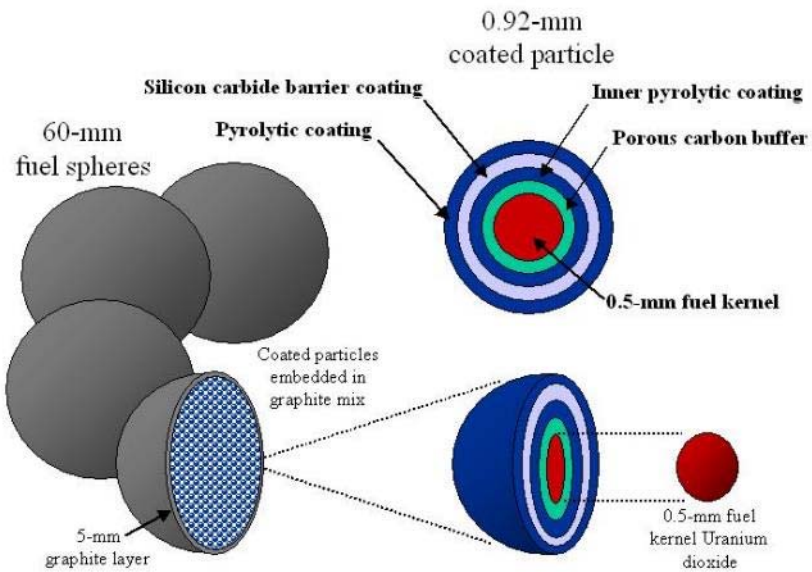
- **Point kinetics/unit cell heat transfer model(Pyrk)**
  - **Average behavior**
  - **Quick**
- **Coupled Monte Carlo/CFD/DEM model (SerpentFOAM)**
  - **Accurate but computationally expensive**
  - **For optimization and benchmarking**
- **Deterministic/CFD model (Comsol model)**
  - **Less flexible but quick**
  - **For production calculations, scoping analysis**

FHR fuel

Mk1(UCB) design

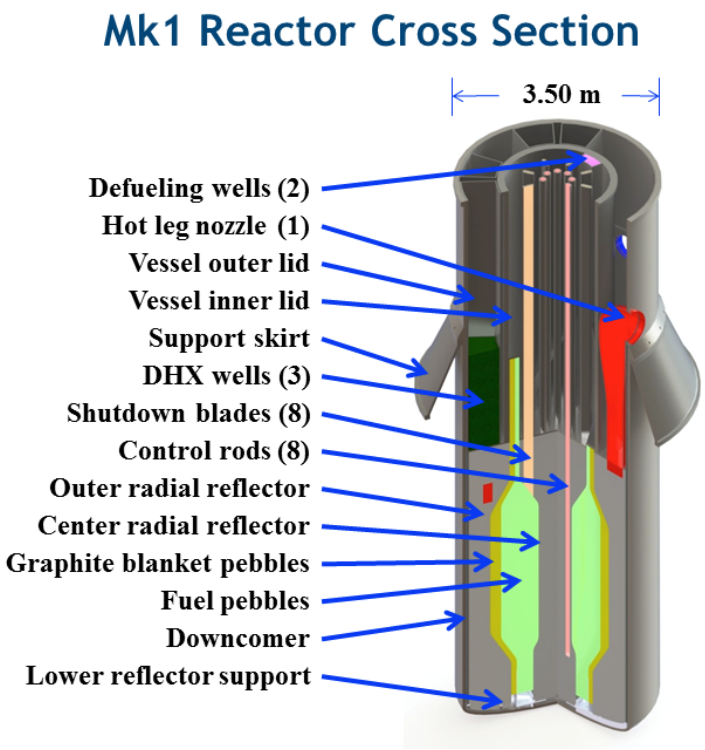


TMSR(China) design

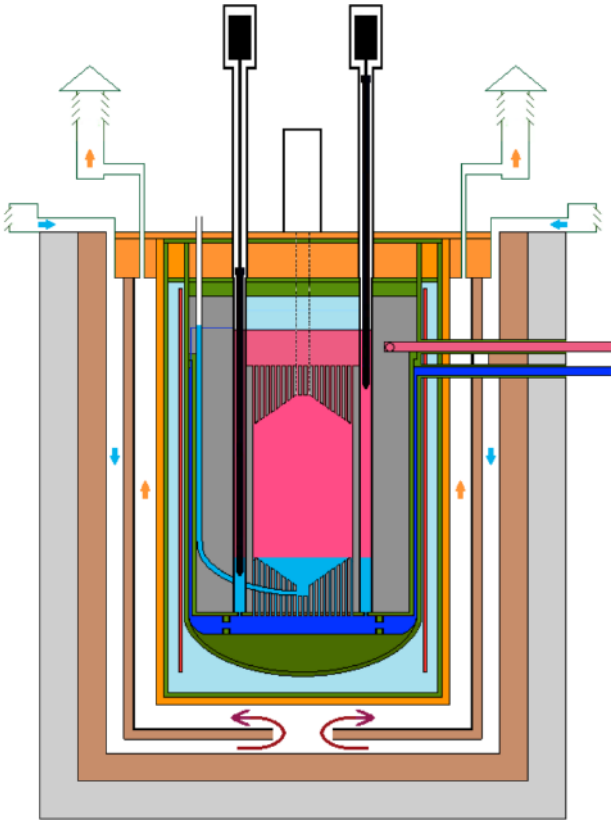


FHR core

Mk1(UCB)



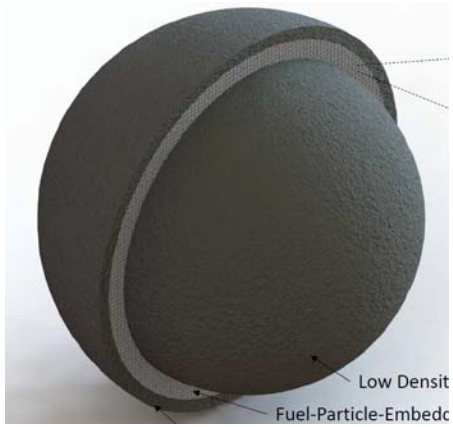
TMSR(China)



UNIT CELL MODEL
COUPLED POINT KINETICS AND HEAT DIFFUSION(PYRK)

Unit cell model

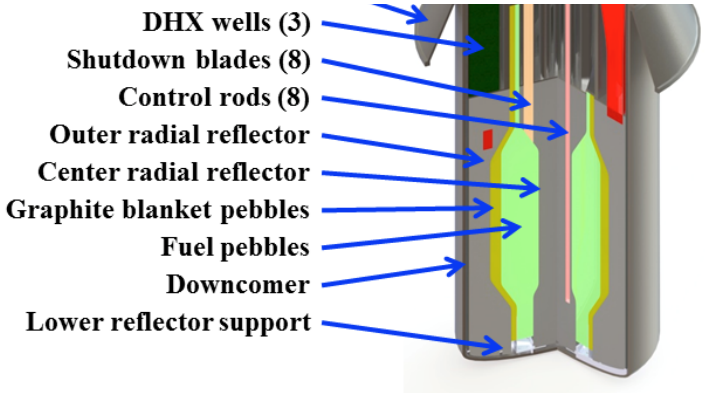
- **One average Mk1-FHR fuel pebble**
  - **Three layers: graphite moderator kernel, fuel layer, and a graphite shell**
- **Fixed inlet coolant temperature**
- **Used for reactivity insertion, sensitivity and uncertainty study**
- **(More details in reference [2] and [3])**



Schematic of the unit cell model geometry

Reflector effects in FHRs

Configuration	k_{eff}	Effective prompt neutron lifetime (s)
Fuel and both reflectors	1.03	0.000459
Fuel and outer reflector	0.95	0.000384
Fuel and inner reflector	0.88	0.000399
Fuel only	0.73	0.000227



Multi-point kinetics equations

$$\frac{dP(t)}{dt} = \frac{(\rho_{ext}(\mathrm{t})\text{-}\beta - \rho_{Ri} - \rho_{Ro})}{\Lambda_c}\mathrm{P(t)}$$

$$+ \sum_{i=1}^{nd} \lambda_i \ \mathrm{C}_i \ (\mathrm{t}) \ + \lambda_R \mathrm{C}_R(\mathrm{t})$$

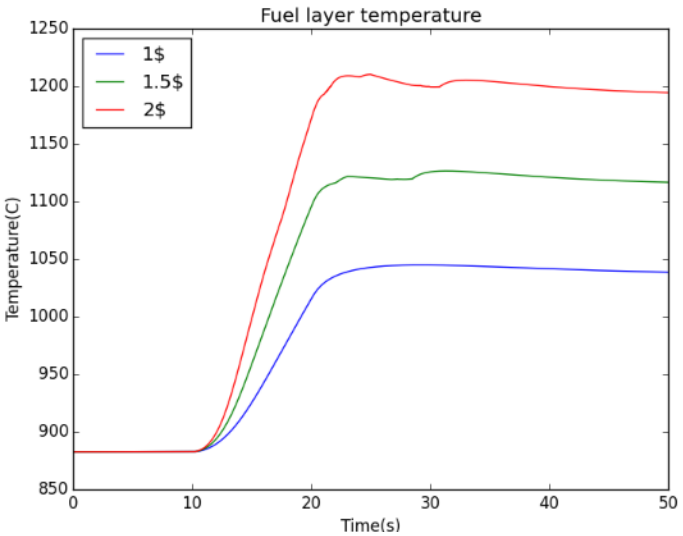
$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda_c}\mathrm{P(t)}\text{-}\ \lambda_i \ \mathrm{C}_i \ (\mathrm{t}),\ \mathrm{i} = 1 \ldots \mathrm{nd}$$

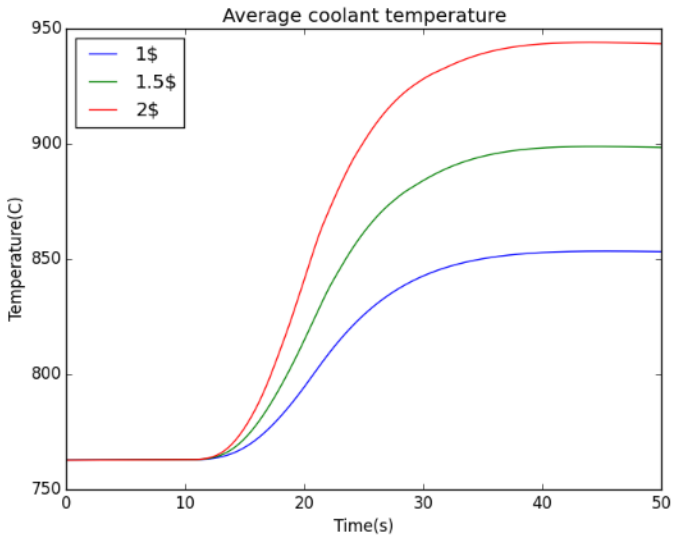
$$\frac{dC_{Rj}(t)}{dt} = \frac{\rho_{Rj}}{\Lambda_c}\mathrm{P(t)}\text{-}\ \lambda_{Rj}\mathrm{C}_{Rj}(\mathrm{t}),\ \mathrm{j}=1 \ldots \mathrm{nr}$$

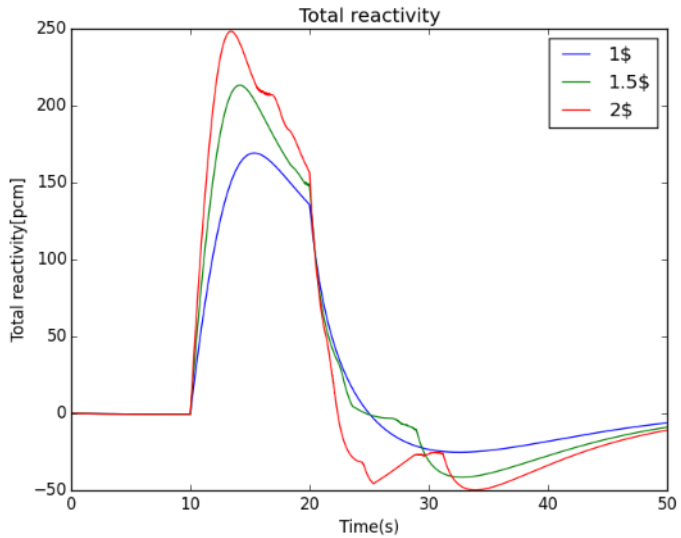
Open source python package(Pyrk)

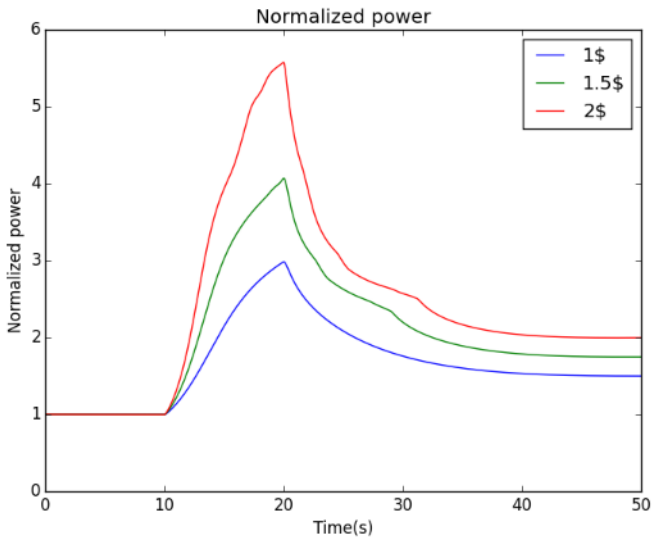
- **1-D spherical heat transfer equation**
  - **Meshing**
  - **Spherical coordinate**
  - **Heat diffusion solver**
- **Multi-point kinetics**
  - **Fictitious delayed neutron groups to represent the reflector effects on neutron lifetime**
- **https://github.com/pyrk/pyrk**
  - **Tests**
  - **Version control**
  - **Documentation**

10s Ramp Reactivity insertion results









Questions

- **How to use results from this average unit cell to reconstruct full core behavior?**
  - **e.g. maximum power and temperature**

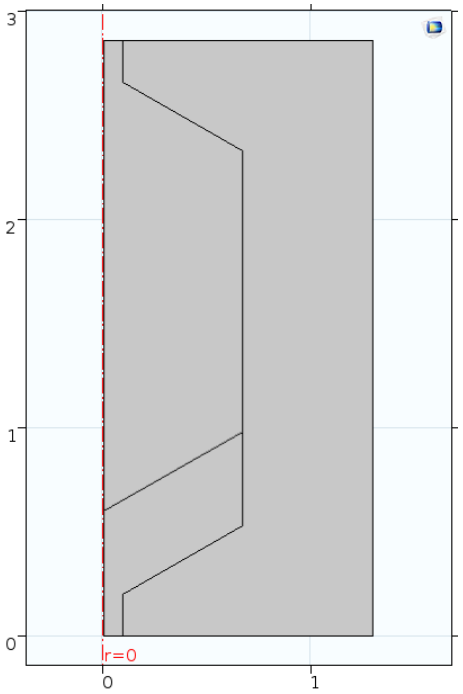
Questions

- How to use this model to study effects of burn-up?
- Pebbles with different burn-ups behave differently during transient:
  - different powers
  - different feedbacks
  - different thermal properties

2D FULL CORE MODEL COUPLED DETERMINISTIC/POROUS MEDIA

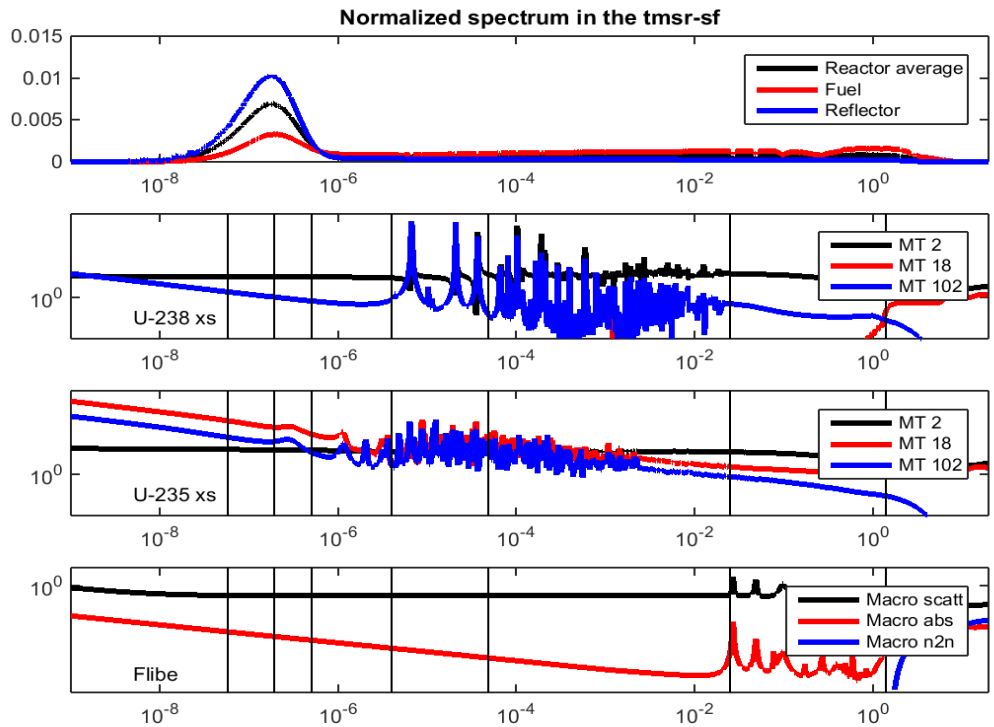
Model Overview

- 2-D geometry with axial-symmetry, expendable to 3-D
- Multi-group neutron diffusion model
  - Cross-section from Serpent full core model
- Porous media thermal-hydraulics model
  - Convective heat transfer coefficient from wakao correlation
  - Uniform velocity
  - Adiabatic boundary condition
- Multi-scale temperature profiles in the fue pebbles and in the TRISO particles are computed
- (More details in reference[3])

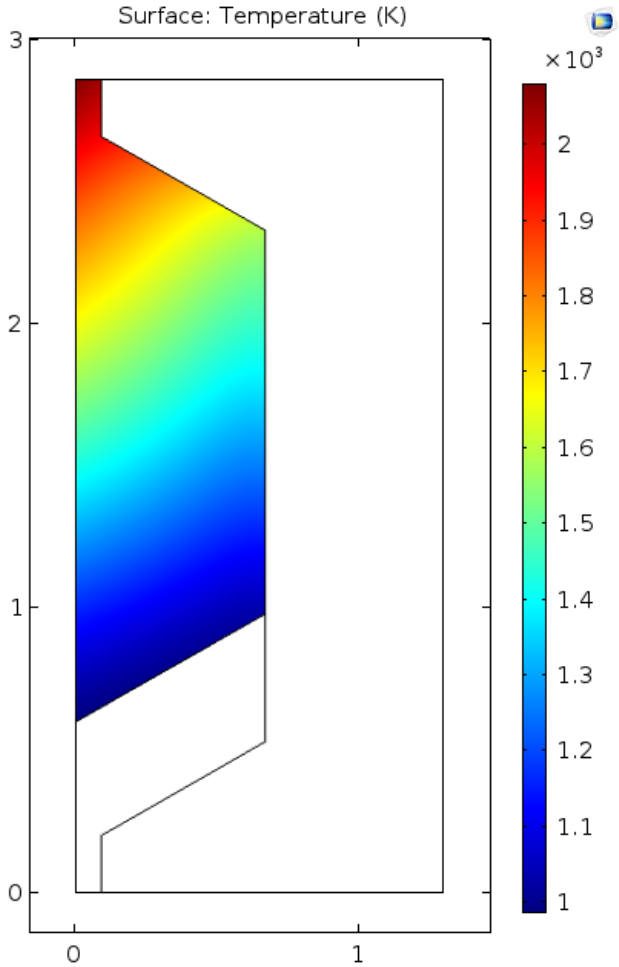


Multi-group structure

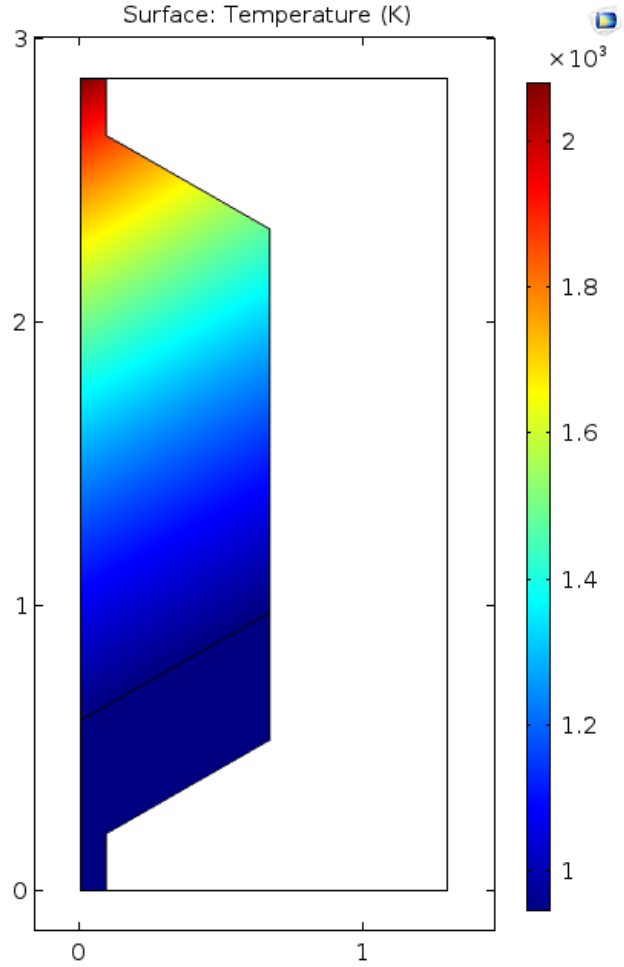
Group	Lower bound [MeV]
1	1.40E+00
2	2.50E-02
3	4.80E-05
4	4.00E-06
5	5.00E-07
6	1.90E-07
7	5.80E-08
8	0.00E+00



Temperature profile

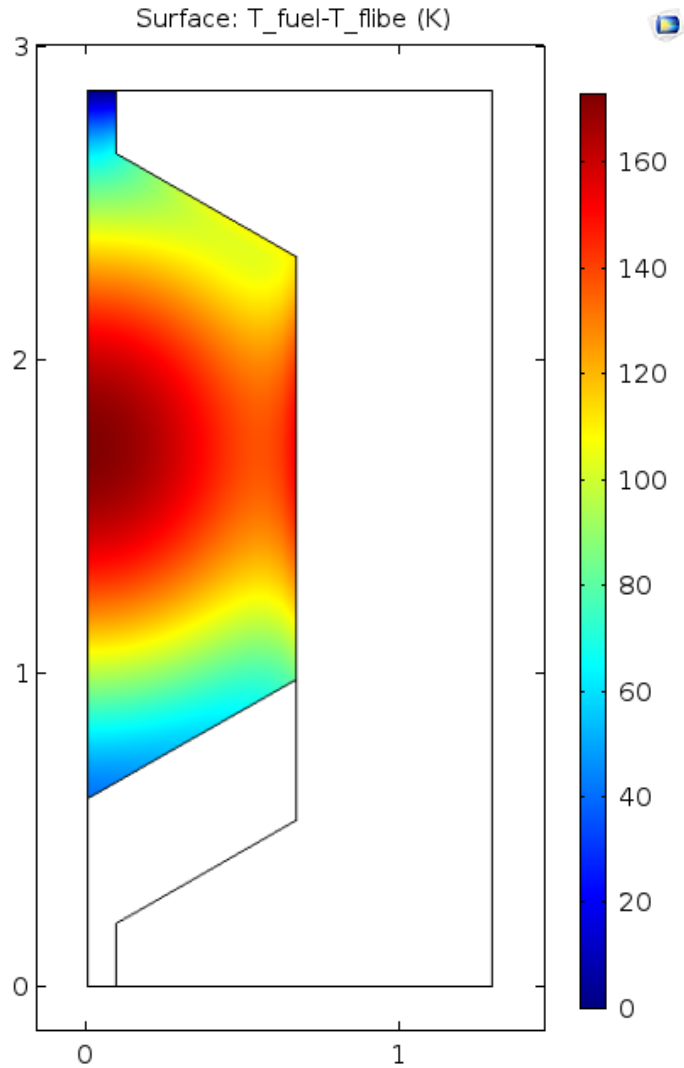


Average pebble temperature



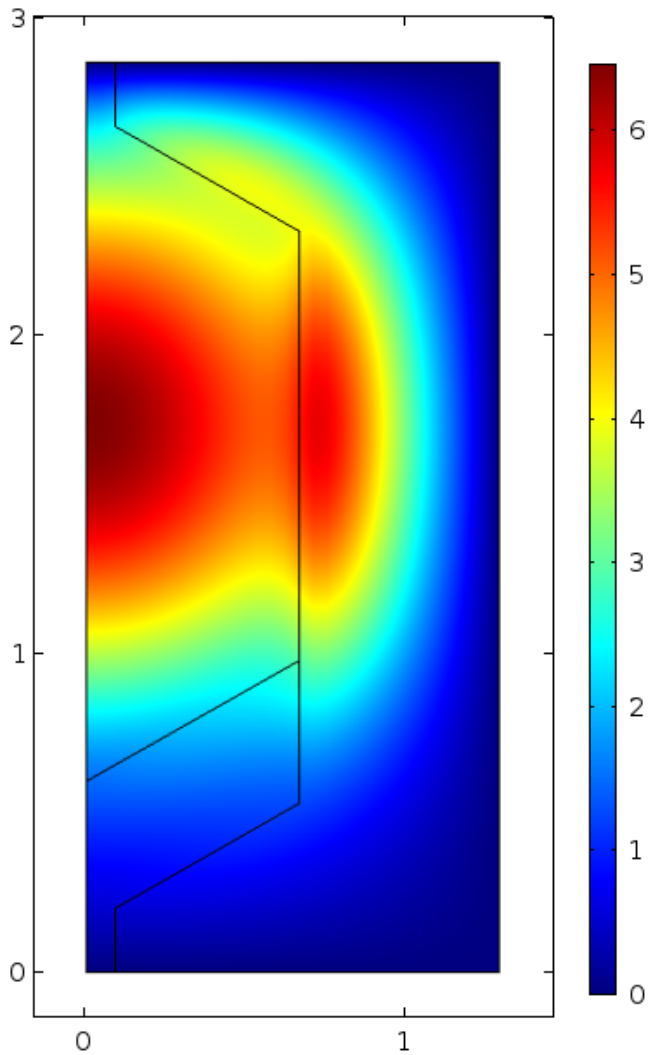
Coolant temperature

Temperature profile

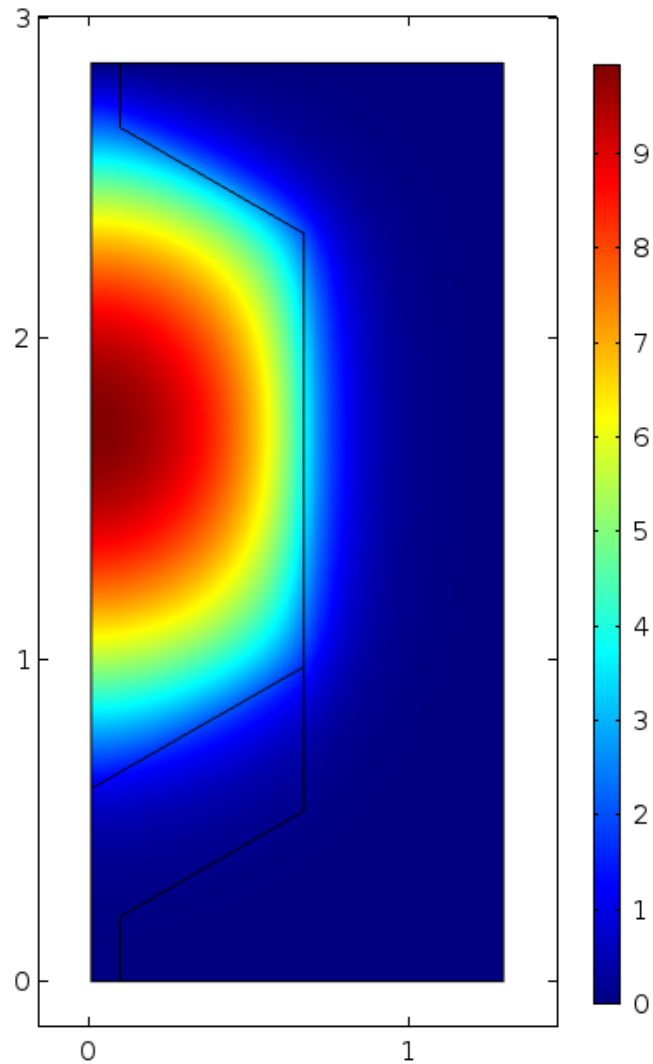


Difference between fuel temperature and coolant temperature

Neutron flux

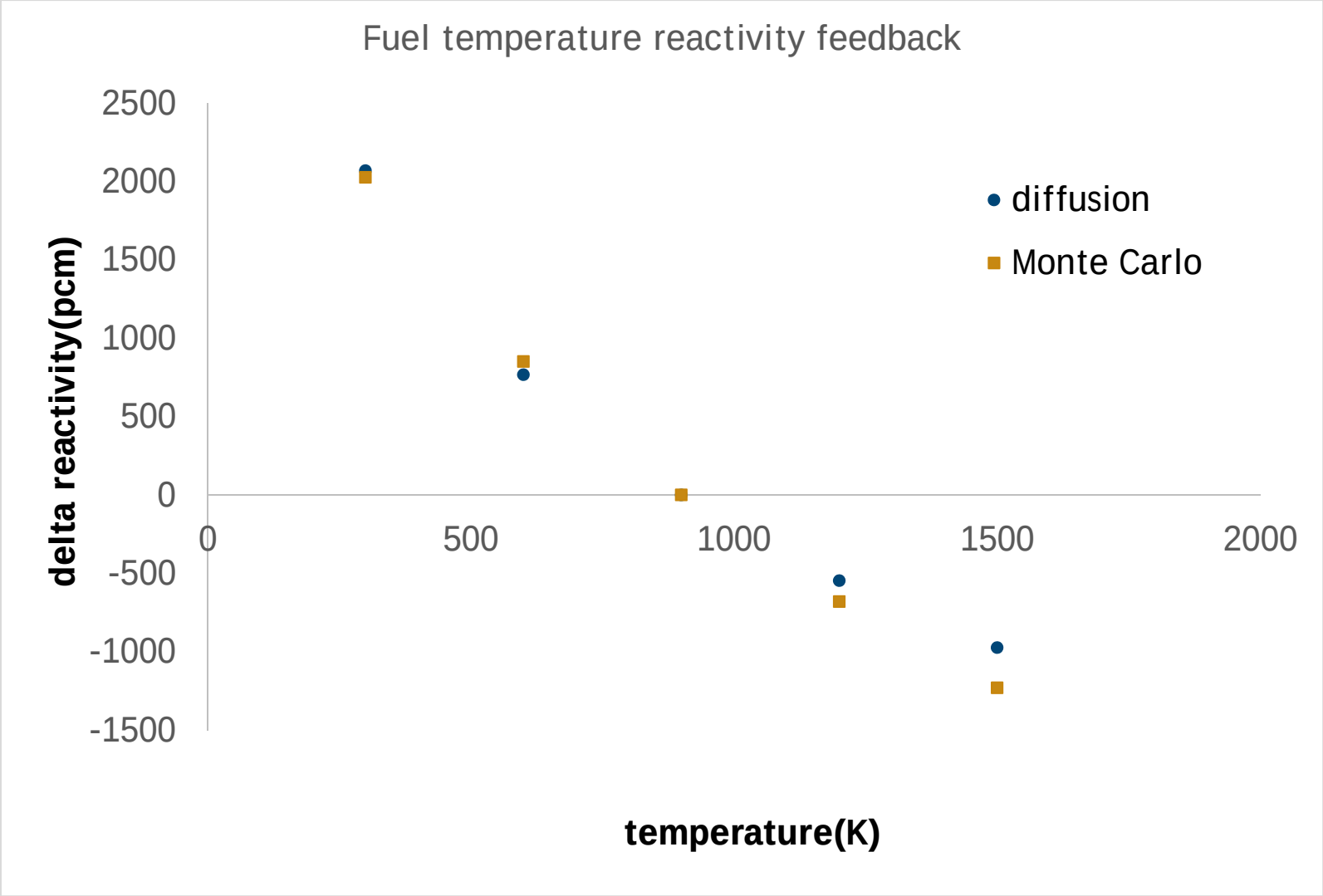


Thermal neutron flux

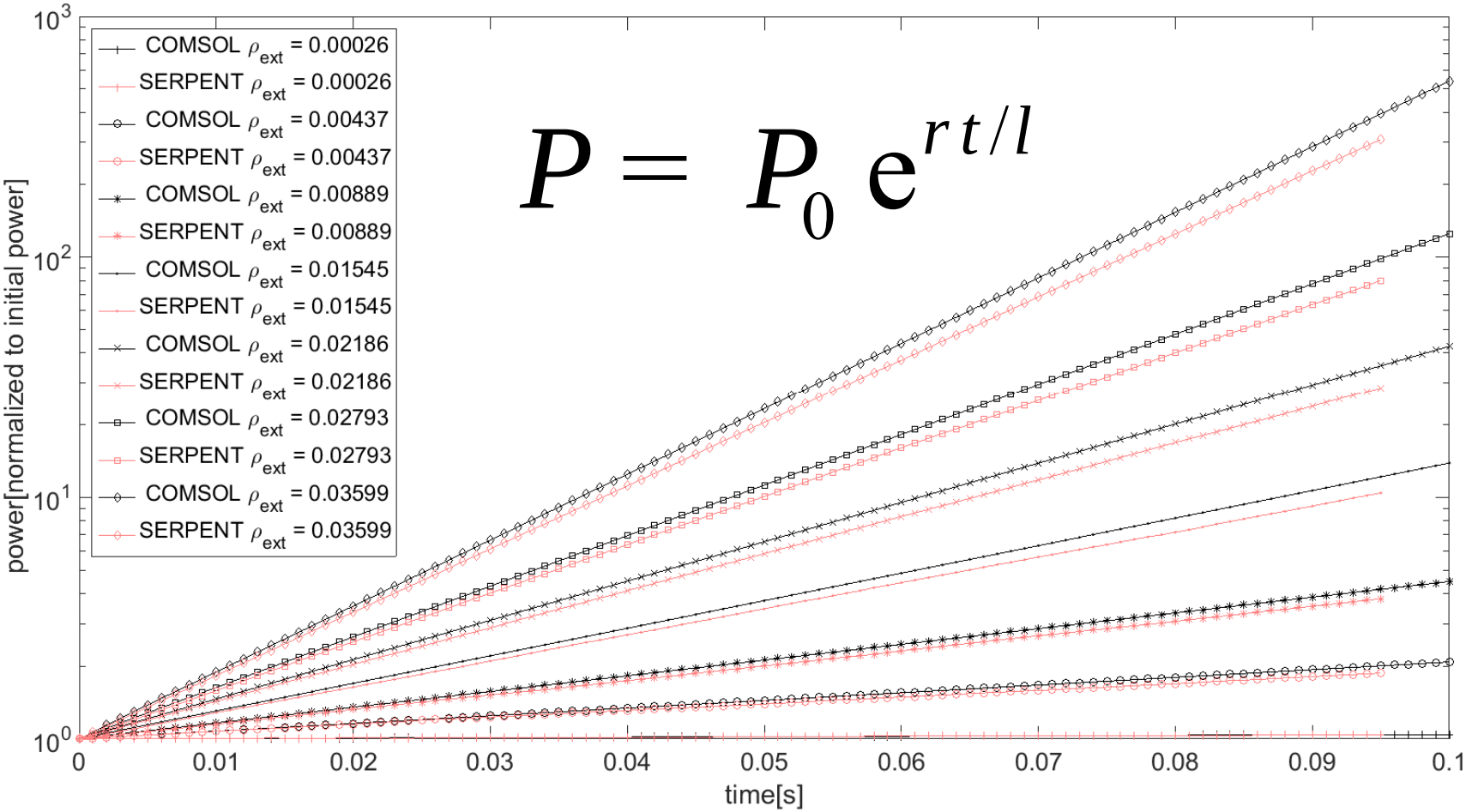


Fast neutron flux

Validation-Temperature feedback

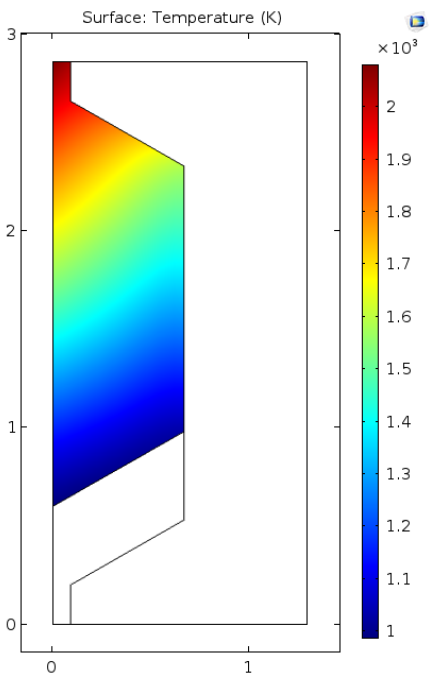


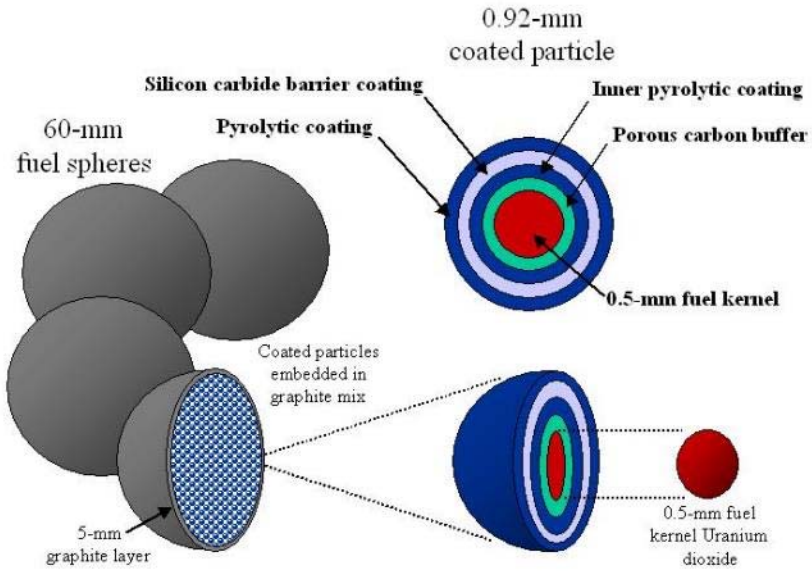
Validation-Reactivity insertion



Questions

- **Multi-scale treatment for temperature**
  - **How do we model the temperature profile inside pebbles and TRISO particles during transient, while keeping the computational advantage of diffusion model?**





Questions

- **From 2-D to 3-D?**
  - **The model is currently 2-D axisymmetric**
  - **Should we expand it to 3-D to capture localized effects, such as control rod insertion?**
  - **(But the diffusion theory is fundamentally flawed in strong absorber materials and close to boundaries.)**

UNCERTAINTY QUANTIFICATION

DEFINITION OF UNCERTAINTY: OUTPUT UNCERTAINTIES THAT IS INDUCED BY UNCERTAINTY IN THE INPUTS

Motivation

- **Uncertainties in input parameters**
  - » **Novel material**
  - » **Unconventional isotopes**
  - » **New TH phenomena (pebble bed convection coefficient)**
  - » **Evolving design (geometry)**

- **Knowing uncertainty helps to**
  - » **Move from conservative modeling to best estimate plus uncertainty modeling**
  - » **Prioritize research efforts**
  - » **Have more confidence in safety margins**

Uncertainty study step 1

- **Specify an uncertainty distribution for each model input- elicited from experts**

10 INPUTS:

Coolant feedback
Doppler feedback
Moderator_k
Fuel_k
Shell_k
Moderator_cp
Fuel_cp
Shell_cp
Coolant_cp
h

$$\frac{d}{dt}\begin{bmatrix} p \\ \zeta_1 \\ \cdot \\ \cdot \\ \cdot \\ \zeta_j \\ \cdot \\ \cdot \\ \cdot \\ \zeta_J \\ \omega_1 \\ \cdot \\ \cdot \\ \cdot \\ \omega_k \\ \cdot \\ \cdot \\ \cdot \\ \omega_K \\ T_{fuel} \\ T_{cool} \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} = \begin{bmatrix} \frac{\rho(t,T^{fuel},T_{cool},\cdots)-\beta}{\Lambda}p + \sum_{j=1}^{j=J}\lambda_j\zeta_j \\ \frac{\beta_1}{\Lambda}p - \lambda_1\zeta_1 \\ \cdot \\ \cdot \\ \cdot \\ \frac{\beta_j}{\Lambda}p - \lambda_j\zeta_j \\ \cdot \\ \cdot \\ \cdot \\ \frac{\beta_J}{\Lambda}p - \lambda_J\zeta_J \\ \kappa_1 p - \lambda_1\omega_1 \\ \cdot \\ \cdot \\ \cdot \\ \kappa_k p - \lambda_k\omega_k \\ \cdot \\ \cdot \\ \cdot \\ \kappa_{kp} - \lambda_k\omega_k \\ f(p, C_p^{fuel}, T_{fuel}, T_{cool}, \cdots) \\ g(C_p^{cool}, T_{fuel}, T_{cool}, \cdots) \\ \cdot \\ \cdot \\ \cdot \end{bmatrix}$$

OUTPUTS:

Temperature rise Dt
Steady state temperature
Maximum temperature

Choice of uncertain inputs

- **Based on experts opinion**

	Input parameters	μ	σ	distribution
Neutronics	α_c [pcm/K]	0.23	0.11	Gaussian
	α_d [pcm/K]	-3.19	0.1595	Gaussian
Heat transfer	k_m [W/m/K]	17	1.15	uniform
	k_l [W/m/K]	15	1.15	uniform
	k_s [W/m/K]	17	1.15	uniform
	cp_m [J/kg/K]	1818	90.9	Gaussian
	cp_f [J/kg/K]	1818	90.9	Gaussian
	cp_s [J/kg/K]	1818	90.9	Gaussian
	cp_c [J/kg.K]	2415.78	120.789	Gaussian
	h [W/m^2.K]	4700	940	Gaussian

Uncertainty study step 2

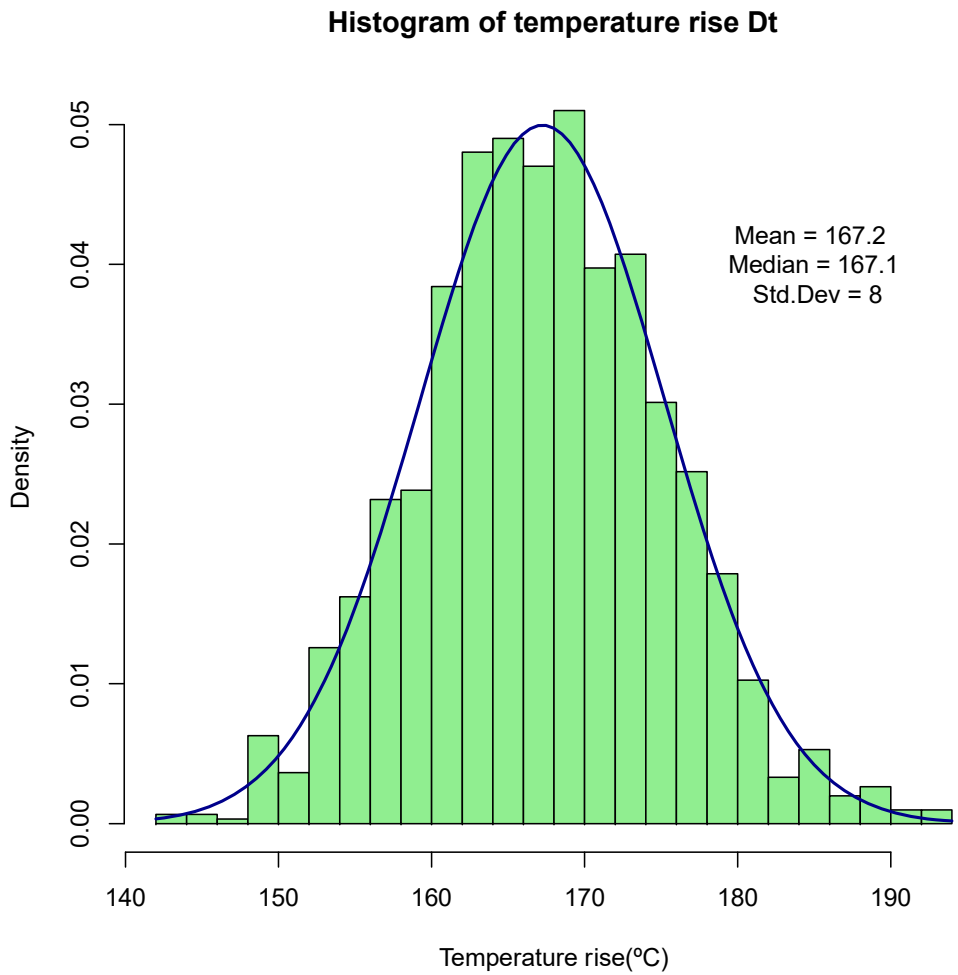
- **Run a designed set of well-spaced model runs to span this parameter space(Monte Carlo, Latin hypercube sampling)**
- **The number of model runs required to achieve a reasonable model fit depends on the number of uncertain input parameters and the smoothness of the function**

	cool_feedback	doppler	mod_k	fuel_k	shell_k	mod_cp	fuel_cp	shell_cp	cool_cp	h	Dt
1	0.1154383	-3.026271	18.34374	17.80483	16.68679	1760.854	1842.131	1547.357	2484.680	4982.261	170.6410
2	0.1717792	-3.119675	17.02161	15.67616	16.00231	1602.780	1885.646	1675.547	2272.889	4431.900	169.6308
3	0.2988082	-3.271187	17.32368	18.74827	17.52011	1732.596	1910.097	1616.834	2276.261	4551.533	166.1481
4	0.4075317	-3.310707	17.95279	18.43102	15.60367	1516.513	1700.568	1568.107	2480.840	4952.686	161.8268
5	0.3461750	-3.214413	16.91174	18.13168	16.45140	1760.394	1708.300	1657.268	2286.223	4455.835	168.5866
6	0.2605036	-3.183660	17.14117	15.45851	17.68195	1728.469	1795.249	1626.774	2432.908	4119.109	168.7764

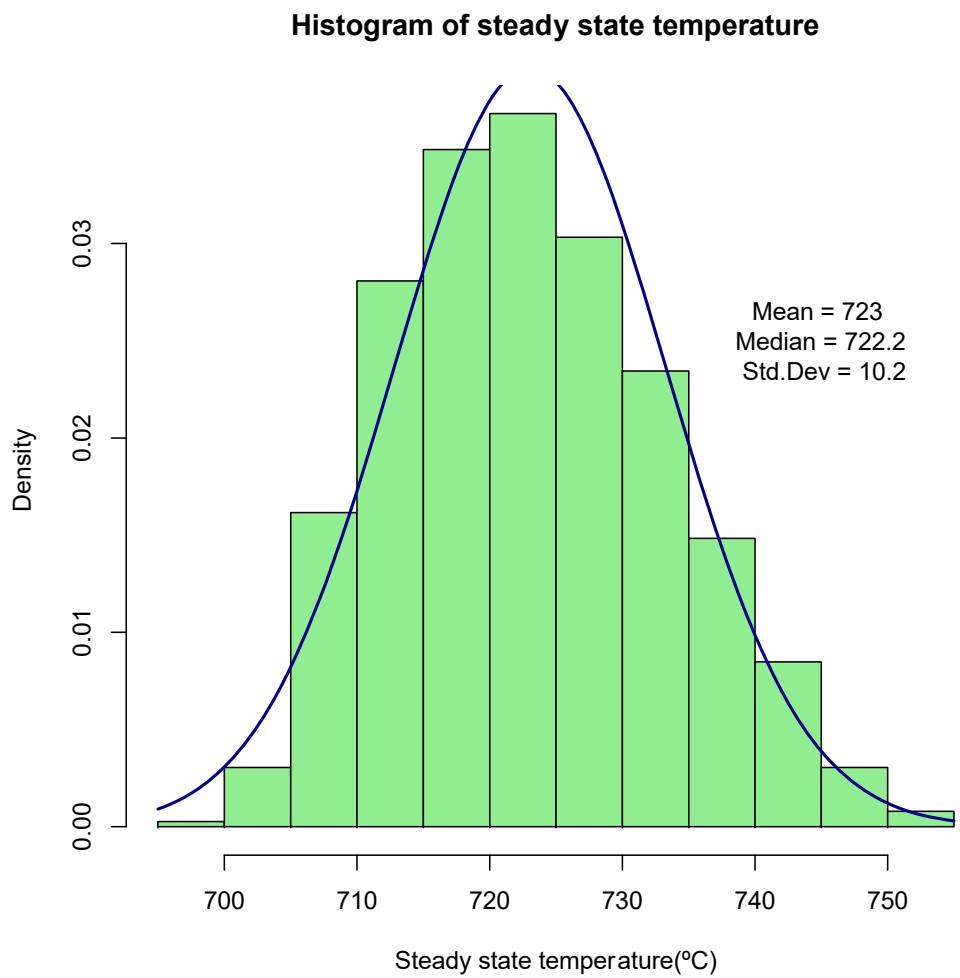
Uncertainty study

- **Uncertainty study investigates the output variation due to uncertain input parameters**
  - **Approximate mean with sample average**
  - **Approximate variance with sample variance**

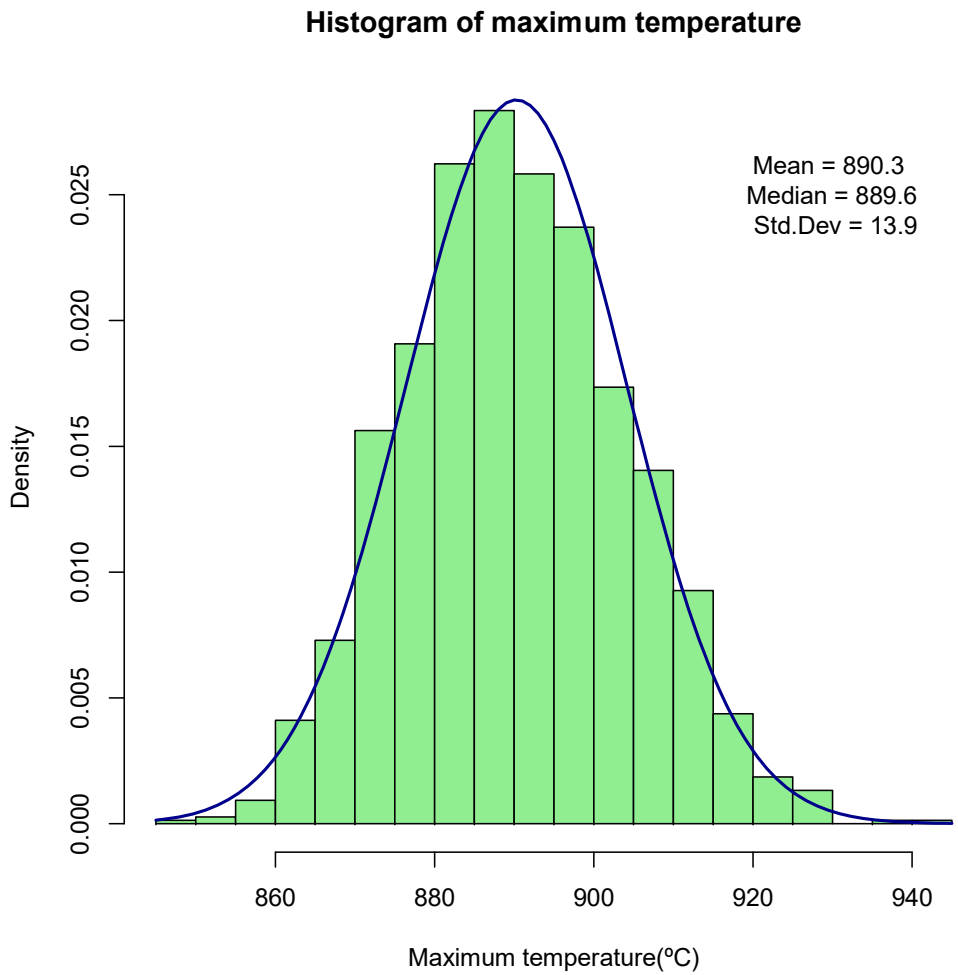
Results


Histogram of temperature rise Dt
Mean = 167.2
Median = 167.1
Std.Dev = 8
Density
0.00
0.01
0.02
0.03
0.04
0.05
140
150
160
170
180
190
Temperature rise(ºC)

Results


Histogram of steady state temperature
Mean = 723
Median = 722.2
Std.Dev = 10.2
Density
0.00
0.01
0.02
0.03
700
710
720
730
740
750
Steady state temperature(ºC)

Results


Histogram of maximum temperature
Mean = 890.3
Median = 889.6
Std.Dev = 13.9
Density
0.000
0.005
0.010
0.015
0.020
0.025
860
880
900
920
940
Maximum temperature(ºC)

Sensitivity study

- Standardized regression coefficients (SRC)
- Standardized data
  - Each of the parameters is converted to zero mean and unit variance variables
- A fitted linear regression model from the data

Sensitivity study results

Standardized regression coefficients of input parameters.

Temperature rise		Maximum temperature		Steady state temperature	
Input	SRC	Input	SRC	Input	SRC
α_d	0.925	k_f	-0.642	k_f	-0.813
α_c	0.305	α_d	0.541	k_s	0.453
cp_c	-0.112	k_s	0.384	cp_c	-0.351
k_s	0.082	cp_c	-0.333	h	-0.101
k_f	-0.058	α_c	0.179	k_m	-0.004
cp_f	0.053	h	-0.062	α_c	0.003
k_m	-0.037	cp_f	0.031	cp_m	0.002
cp_m	0.036	k_m	-0.024	α_d	-0.002
h	0.022	cp_m	0.020	cp_s	-0.001
cp_s	0.013	cp_s	0.007	cp_f	0.000

Reference

[1] M. Aufiero and M. Fratoni, "DEVELOPMENT OF MULTIPHYSICS MODELS FOR FOR FLUORIDE-COOLED HIGH TEMPERATURE REACTORS," in *PHYSOR 2016* , Sun Valley, 2015.

[2] X. Wang, et al, "A sensitivity study of a coupled kinetics and thermal-hydraulics model for Fluoride-salt-cooled, High-temperature Reactor (FHR) transient analysis," San Francisco, 2016.

[3] X. Wang, K. D. Huff, M. Aufiero and P. F. Peterson, "COUPLED REACTOR KINETICS AND HEAT TRANSFER MODEL FOR NUCLEAR REACTOR TRANSIENT ANALYSIS," in Proceedings of the 2016 24th International Conference on Nuclear Engineering, Charlotte, 2016.

[4] M. Aufiero et al., "A collision history-based approach to sensitivity/perturbation calculations in the continuous energy Monte Carlo code SERPENT", ANNALS OF NUCLEAR ENERGY 85 page245 - 258 · NOVEMBER 2015