Two-Dimensional Modeling of Spent Nuclear Fuel Using Uncertainty Quantification

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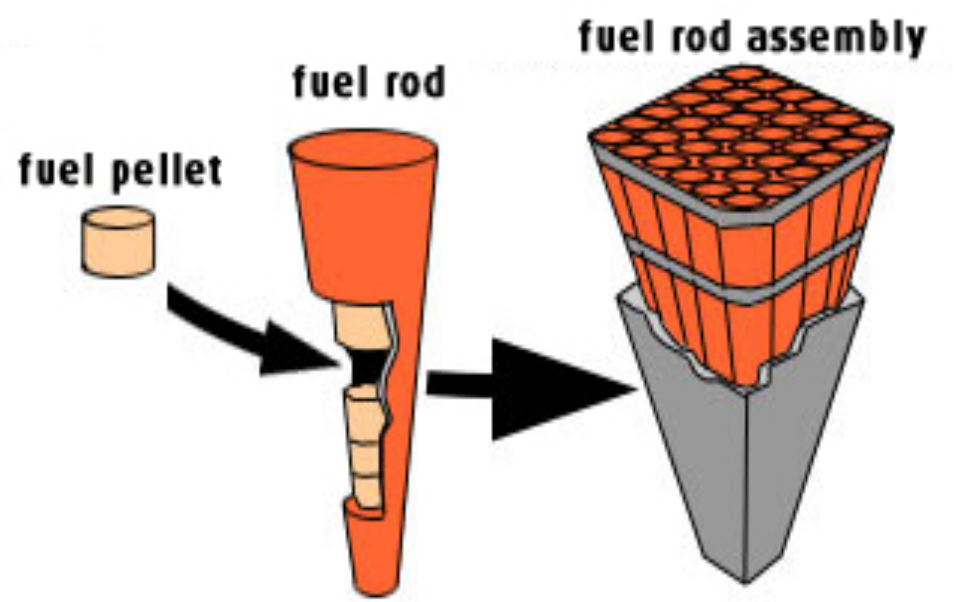
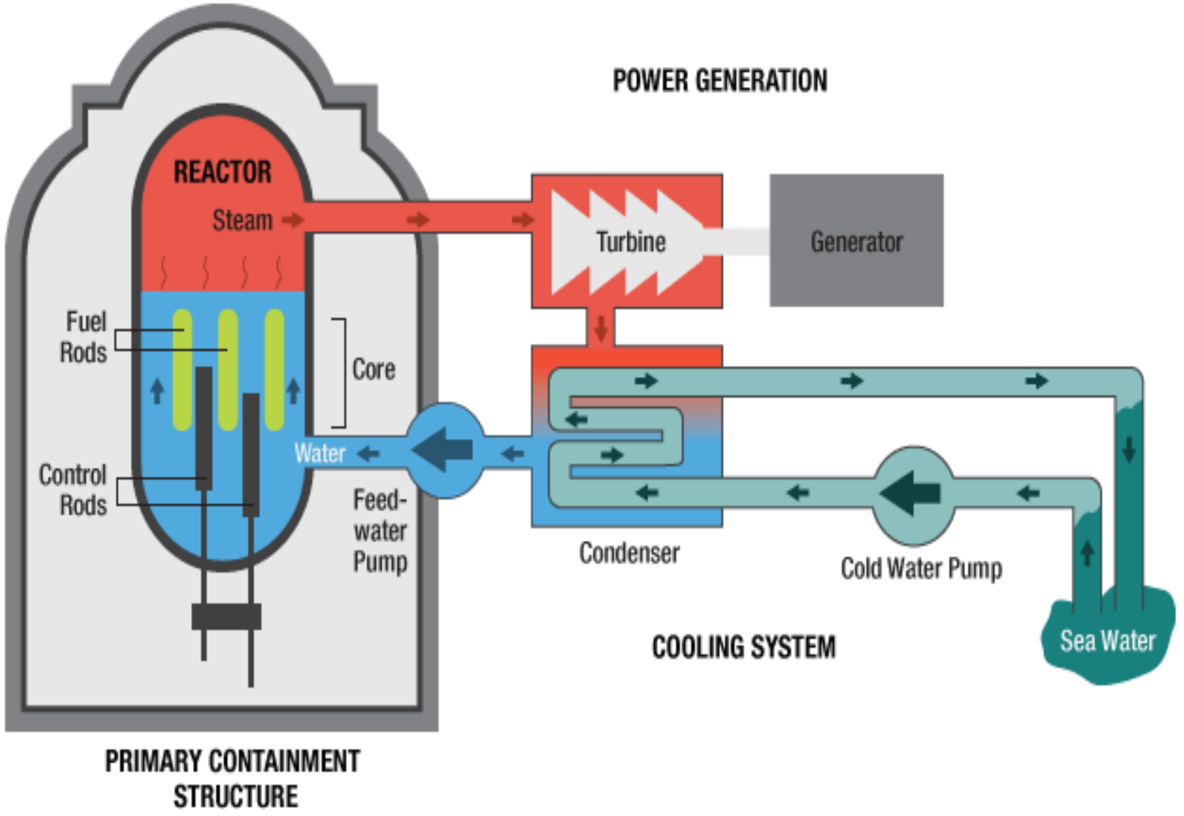
Outline

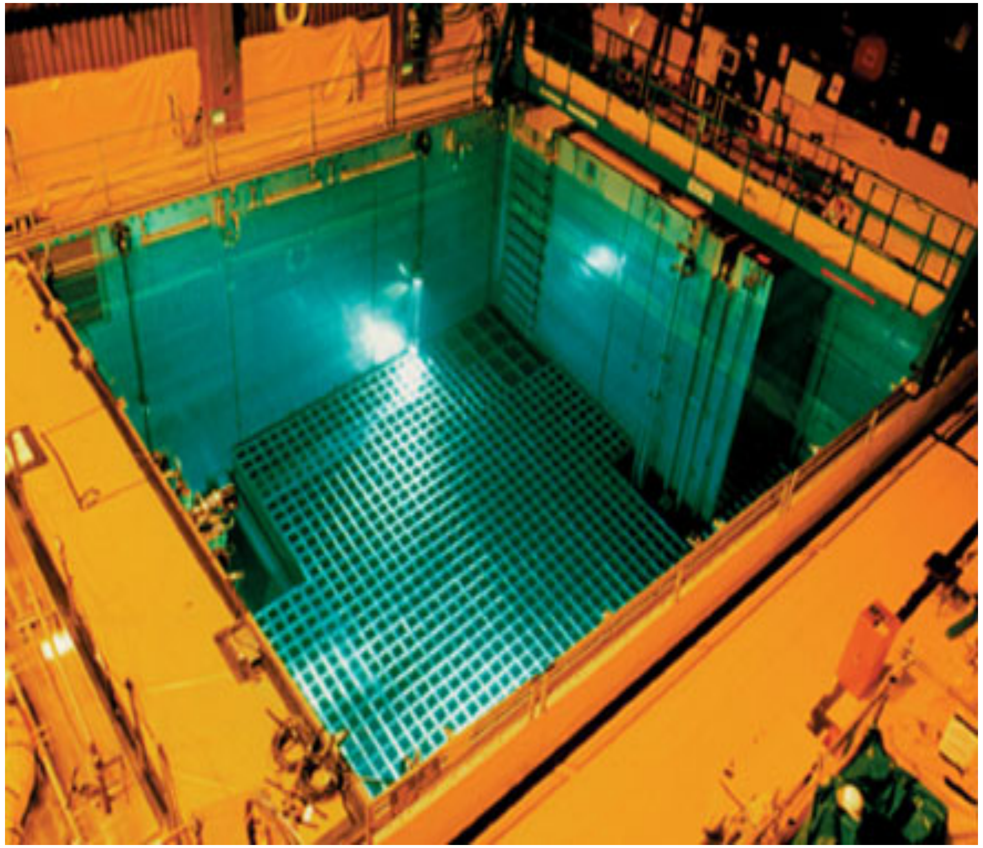
- Spent Fuel Background
- ANSYS-FLUENT Model
- Uncertainty Quantification (UQ)
- Sensitivity Analysis and Results
- Future Work

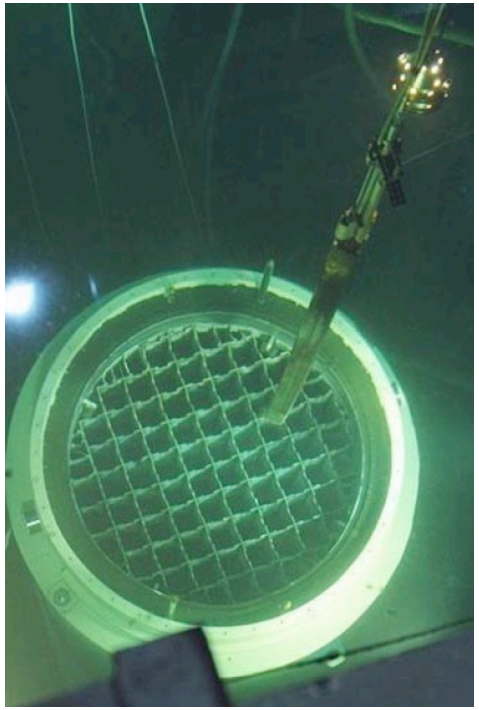
Nuclear Energy

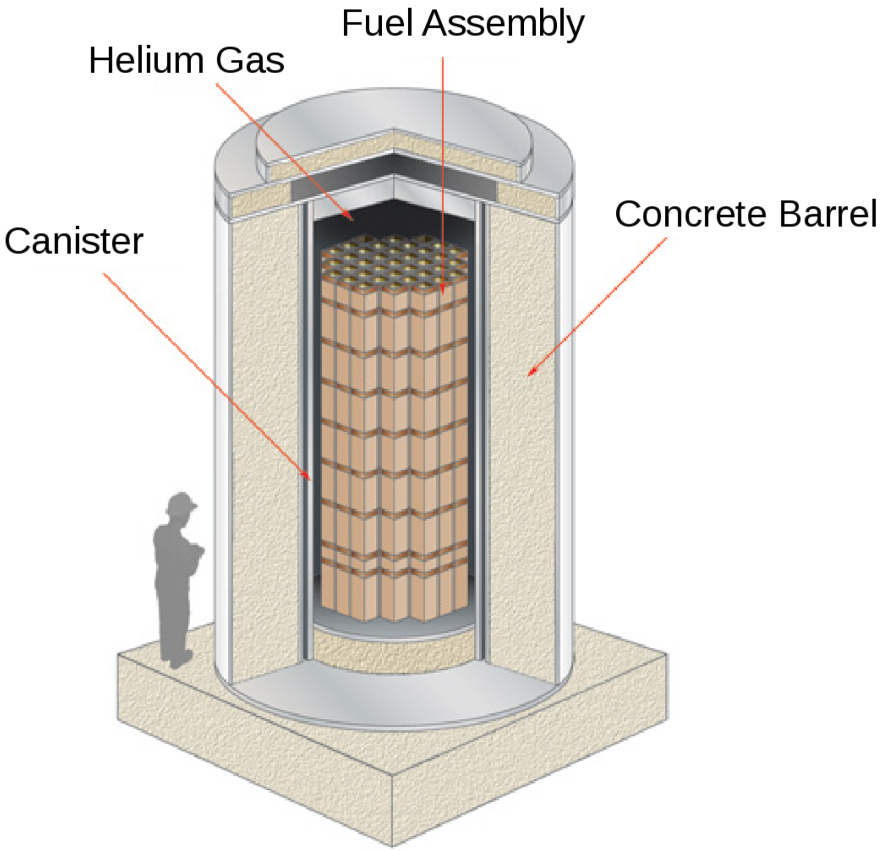




Spent Fuel Storage Casks



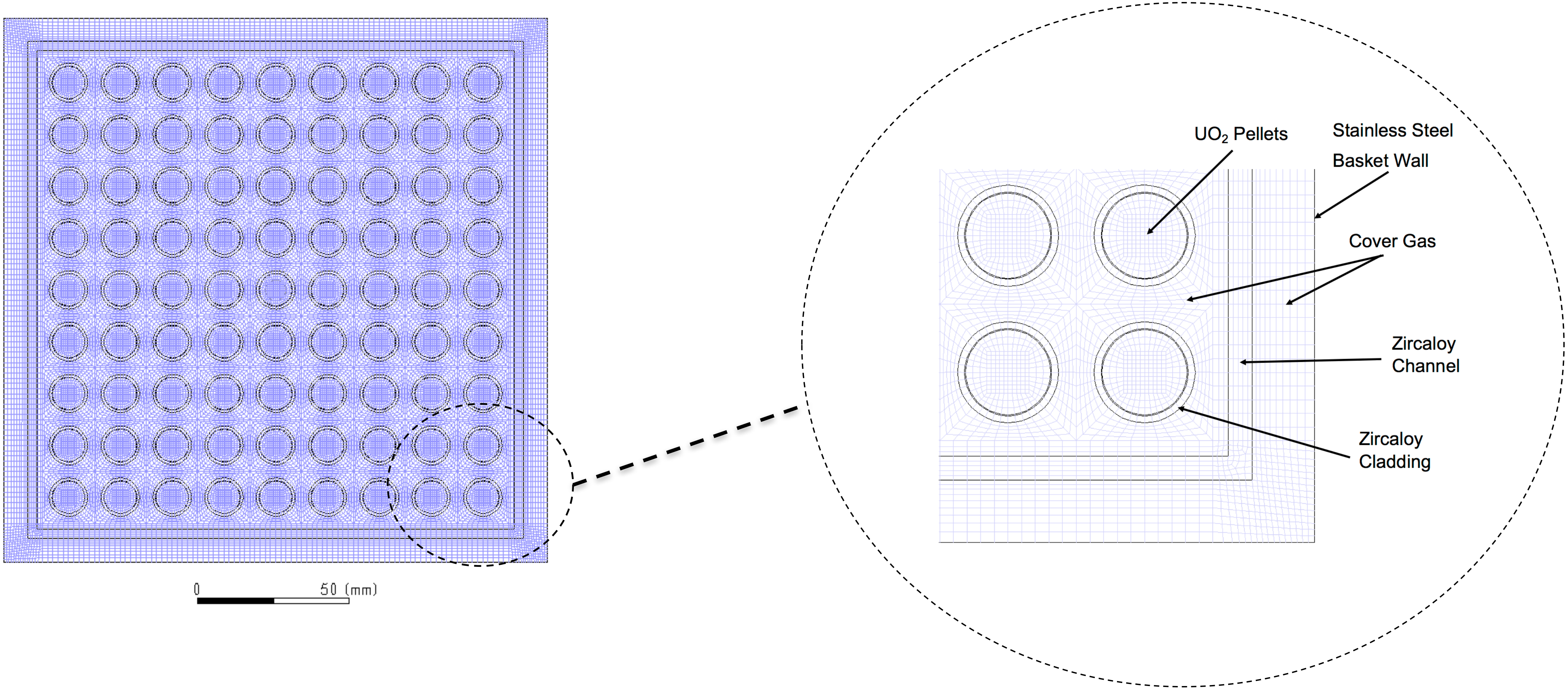




Spent Fuel Pool to Shield Radiation and Cool Fuel Rods

Fluent Geometry

47,944 nodes
47,702 elements



Fluent Model

- Steady State 2D simulations using Pressure-based solver in Fluent
- Gravity in Y direction
- Energy Equation ON to model:
  - Conduction heat transfer in solid region
  - Buoyancy induced gas motion and natural convection heat transfer within the gas filled regions
  - Radiation heat transfer across all gas filled regions

Fluent Model Input and B.C.

Zircaloy
Thermal Conductivity
Specific Heat
Emissivity

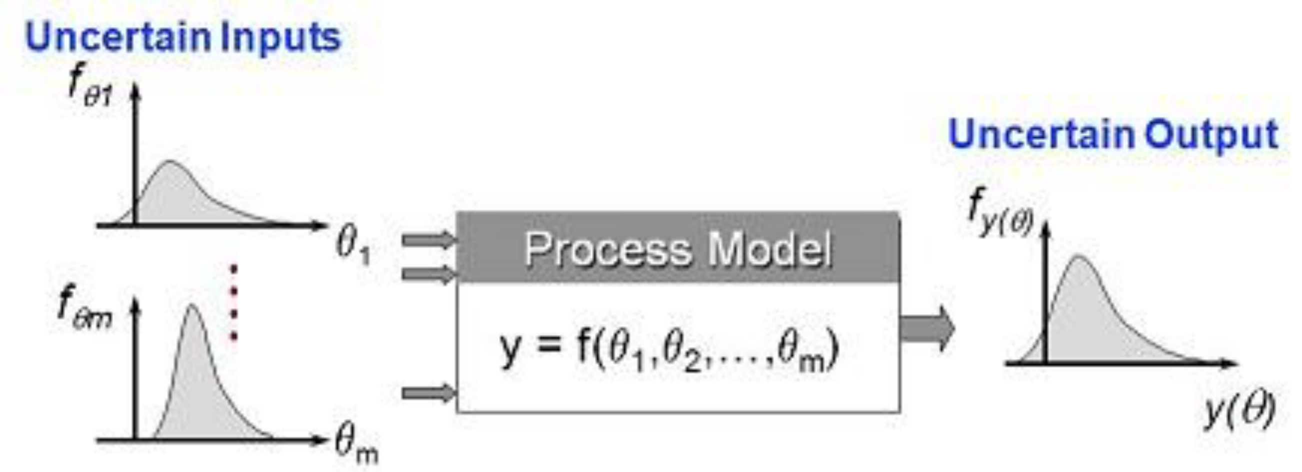
Helium
Thermal Conductivity
Specific Heat

Uranium Dioxide
Thermal Conductivity
Specific Heat
Emissivity
Power

Stainless Steel
Wall Temperature

Uncertainty Quantification

- Mathematical models of heat transfer are often challenged by random/uncertain properties
- Uncertainty quantification is needed in order to get a predictive fidelity of the simulation



Introduction to Polynomial Chaos Expansion PCE

p = N-ord (Highest order Legendre Present).
n = N-dim (Number of uncertain dimensions).

Univariate Case: For one input parameter, we model the propagation of uncertainty through our model

1. Assume our input variable can be expressed as a polynomial expansion. Where ξ represents a uniform random variable, and ψ represents Legendre Polynomials
2. After propagating X through our model we can model the output of the model as a similar expansion
3. We can then perform non-intrusive spectral projection (NISP) to extract the coefficients of t expansion

$$X = \sum_{i=0}^{p} x_i \psi_i(\xi)$$

$$T = \sum_{i=0}^{p} T_i \psi_i(\xi)$$

$$K = \frac{\langle x_i, \psi_i \rangle}{\langle \psi_i, \psi_i \rangle} \qquad T_i = K * T$$

PCE Multivariate Case

For n-input parameters, we model the propagation of uncertainty through our model

p = N-ord (Highest order Legendre Present).
n = N-dim (Number of uncertain dimensions).

1. When modeling the propagation of multiple uncertain parameters we introduce a Multi-index (**M**) showing the ordering of polynomials in the expansion. The number of terms in our expansion is N_pc.
2. Using identical methods from the univariate case we are able to extract an expansion for the output parameter as a function of our multiple input variables

$$N_{pc} = \frac{(n+p)!}{n!p!}$$

$$\begin{aligned} T &= \sum_{i=0}^{N_{pc}} T_i \Psi_i(\Xi) \\ &= \sum_{i=0}^{N_{pc}} T_i \prod_{j=1}^{n} \psi_l^j(\xi^j) \qquad \text{where} \qquad l = M_i^j \end{aligned}$$

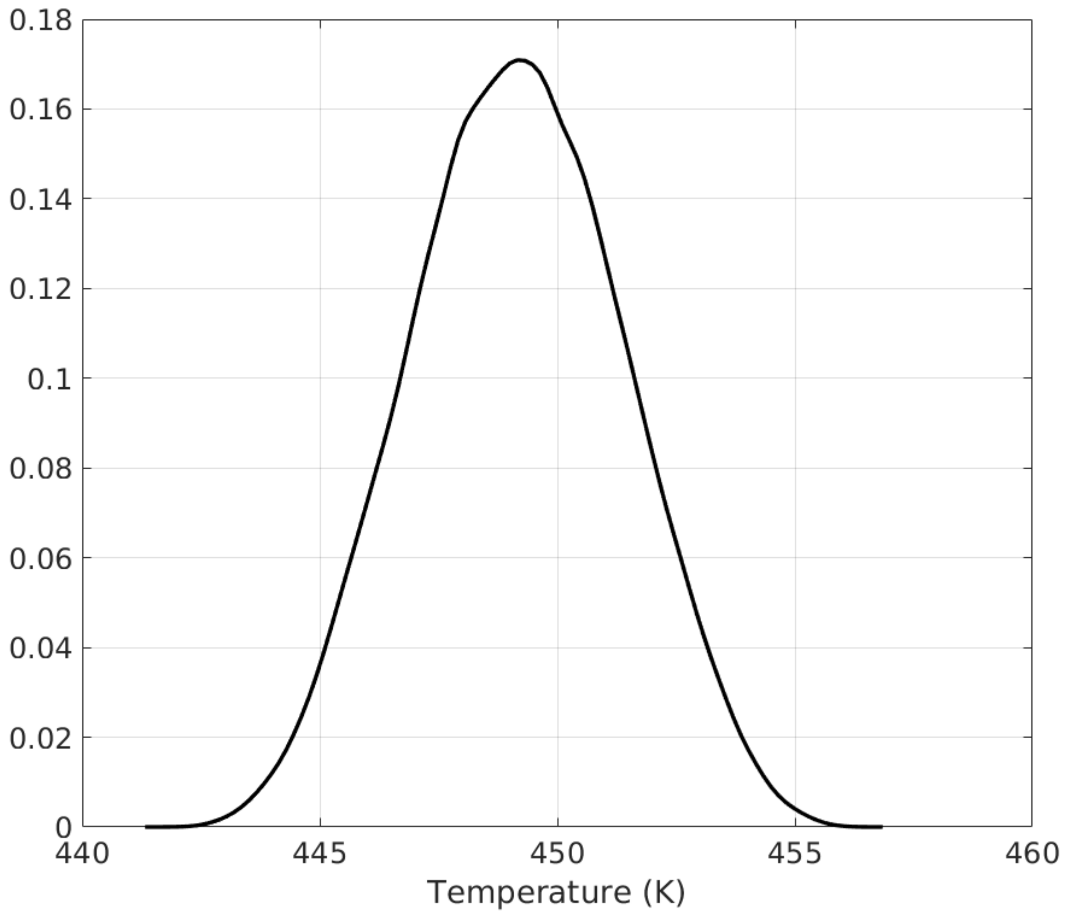
Matlab-Fluent Interface

ANSYS FLUENT

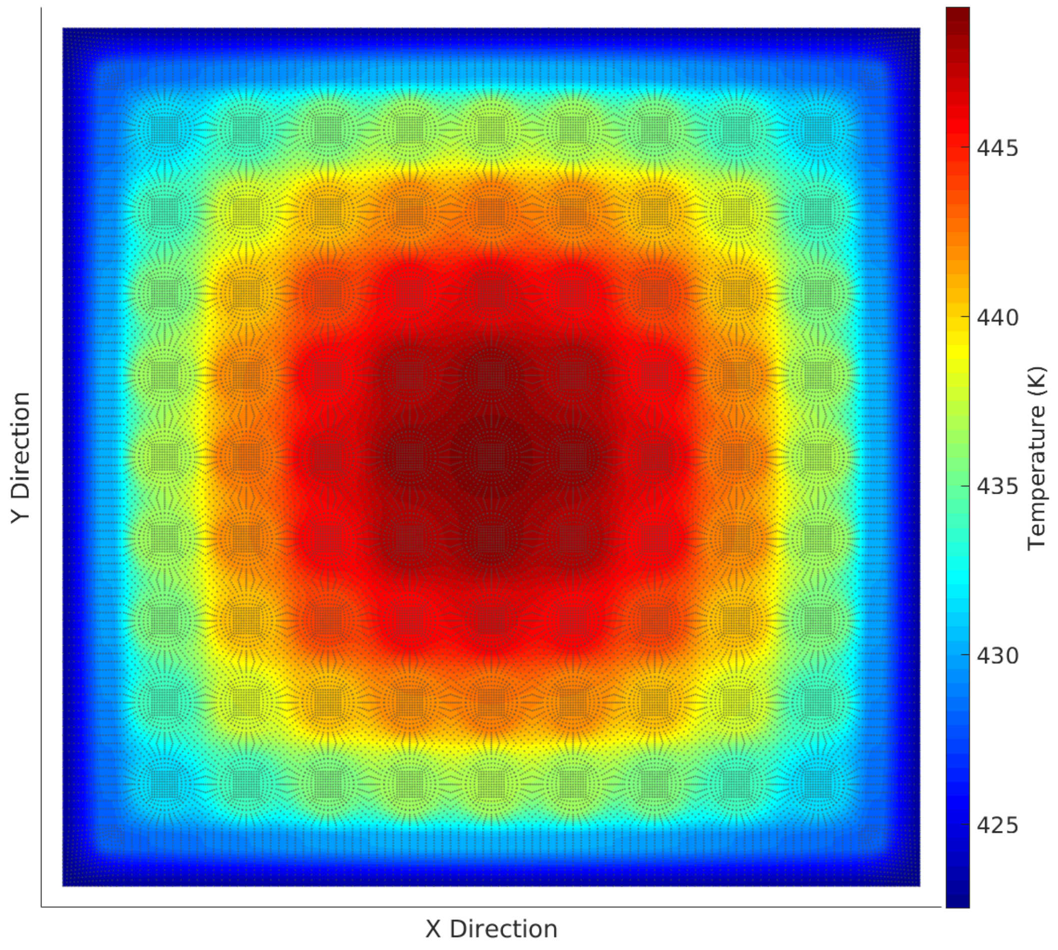
MATLAB
The Language of Technical Computing

- Using user-input, MATLAB can create arbitrarily complex journal files based on a custom dictionary of FLUENT text user-interface commands
- These journal files are sent to the ANSYS - FLUENT environment where they are used to modify model parameters based on their uncertainty
- Solution data is exported after each simulation, these files are then collected by MATLAB and used for UQ data analysis

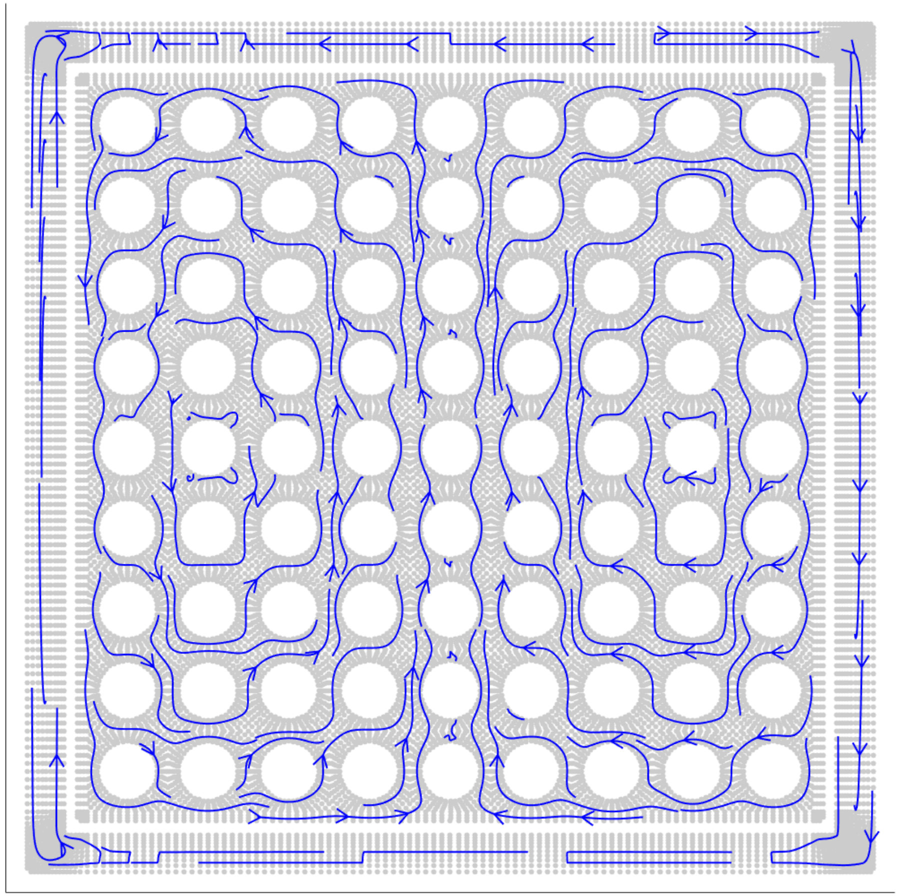
PDF of the Center Temperature Distribution



Mean Temperature Distribution

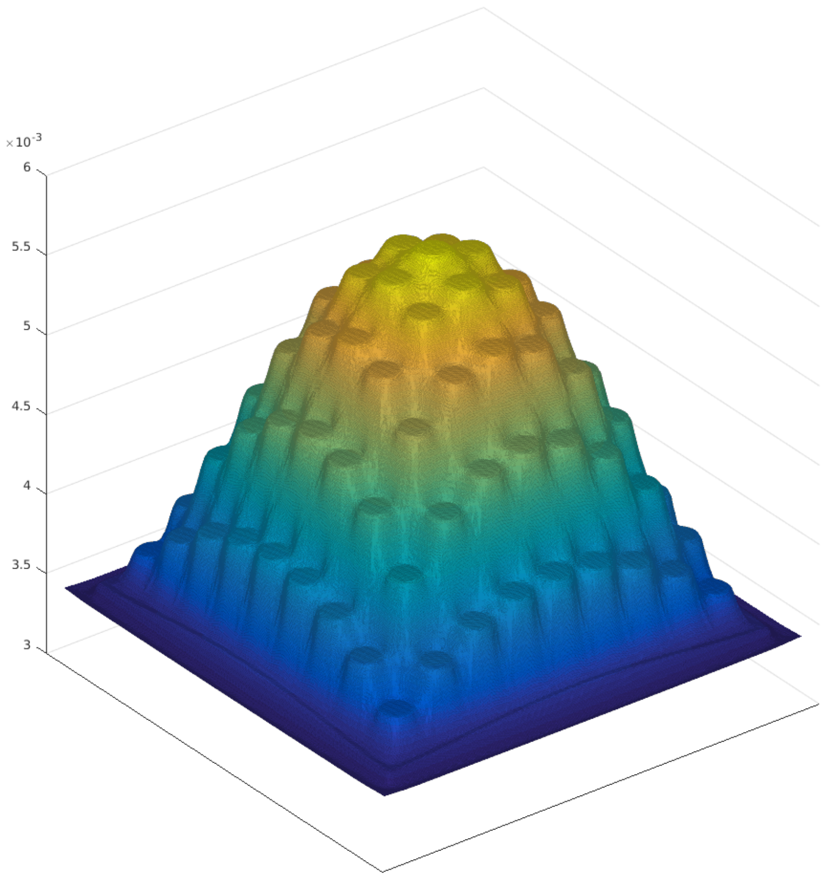


Average Velocity Distribution



Max velocity = 0.23 cm/sec

Coefficient of Variance (COV)

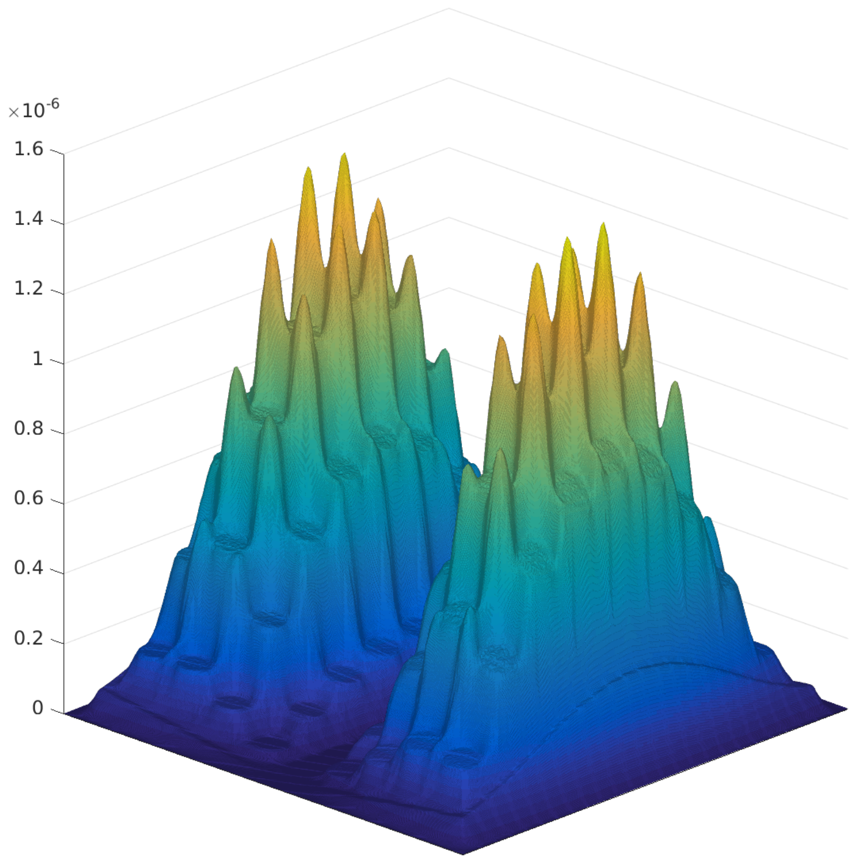


- COV for temperature was calculated at each point in the mesh to determine areas sensitive to variation in input model parameters

- the center of the fuel assembly has the highest coefficient of variation, and thus the largest sensitivity to uncertainty

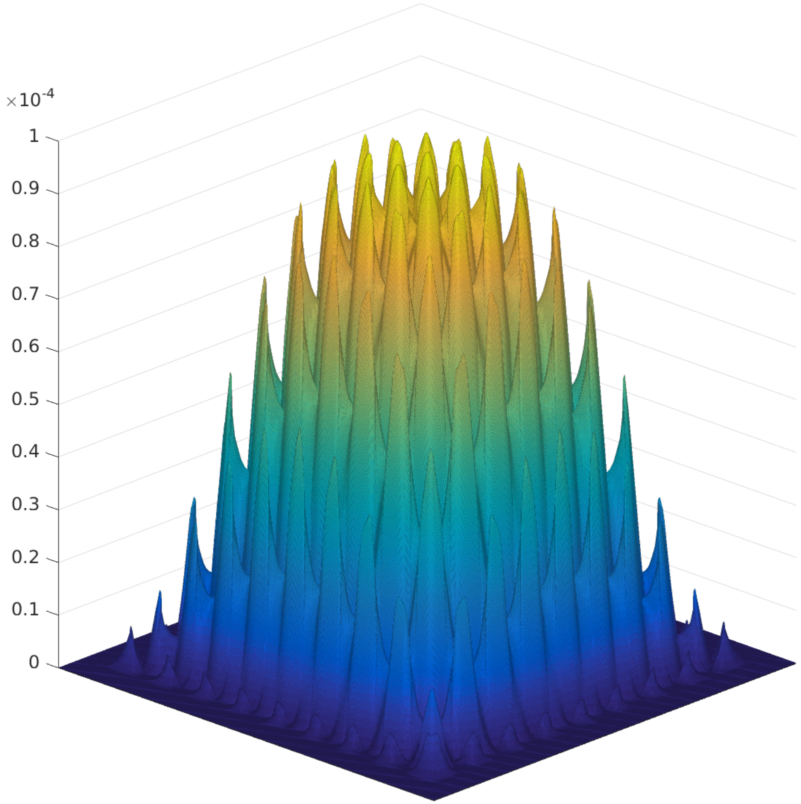
COV = mean /standard deviation

Sensitivity of the Temperature with respect to Variations of Specific Heat of He



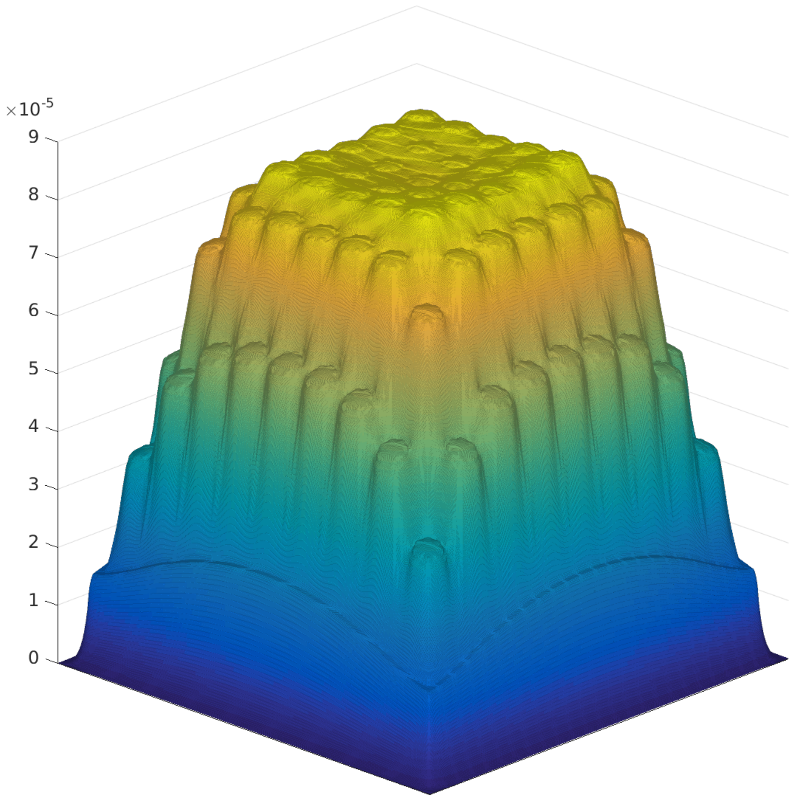
- The large spikes are indicative of the helium convection cells which facilitate natural-convective heat transfer
- The two clusters of spikes show that in the locations where the buffer gas is moving the least, it is the most sensitive to uncertainty in the specific heat
- The clusters of spikes are in accordance with the two convection loops shown in velocity profile

Sensitivity of the Temperature with respect to thermal conductivity of UO_2



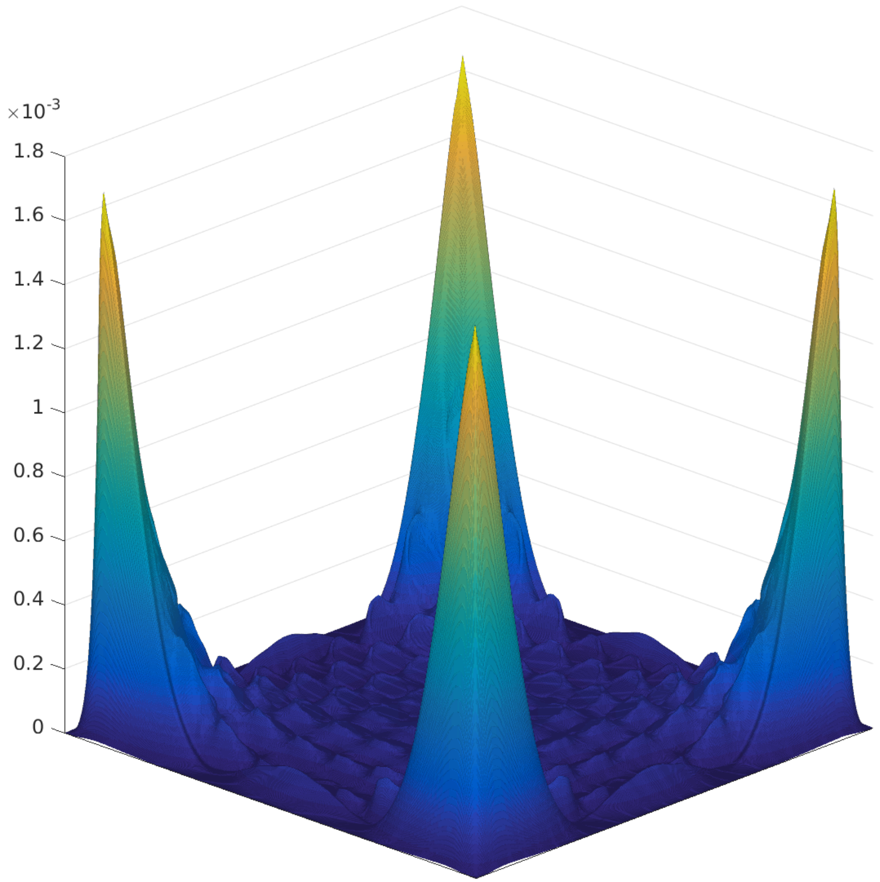
- pointing inward toward the center of the assembly with the highest value at the edge
- demonstrates the direction of heat transfer by conduction inside fuel rods from the center of the assembly to the outside wall
- the hotter fuel rods at the center of the assembly display the largest sensitivity

Sensitivity of the Temperature with respect to thermal conductivity of UO_2



- the flat top for the center fuel rods indicates a dominant radiation heat transfer mode at the center of the assembly
- radiation mode drops abruptly near the boundary wall where the radiation effect is lower as the temperature goes down

Sensitivity of the Temperature with respect to thermal conductivity of Zr



the location of the corners of the zircaloy channel are the most sensitive to uncertainty

Conclusion

- The implementation of the uncertainty quantification method and sensitivity analysis indicated that variation in the specific heats of He, Zr, and UO_2 have no significant impact on the peak temperature at the center of the assembly

- The analysis indicated that variation in the boundary wall temperature and the heat generation released by UO_2 have the largest effect on the peak temperature inside the assembly

Future Work

- Building 3D models of the assemblies
- HPC - run larger, more complex models
- This developed methodology can be applied to other complex systems of heat transfer that are currently solved numerically