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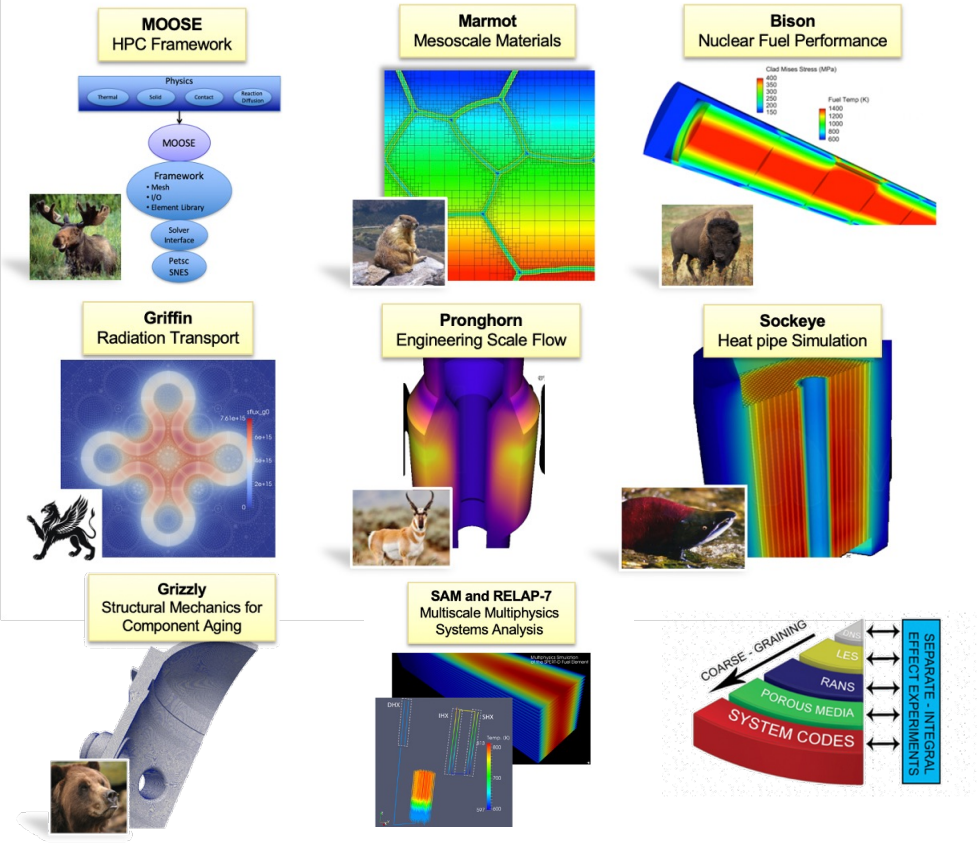
Reduced Order Model Generation for Fast Running Equilibrium Core Calculations.

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

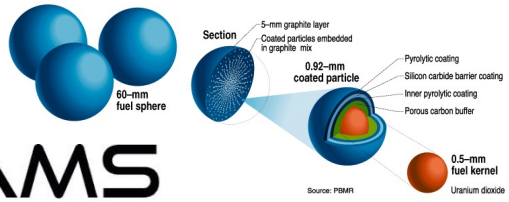
DOE NEAMS MOOSE Based Applications



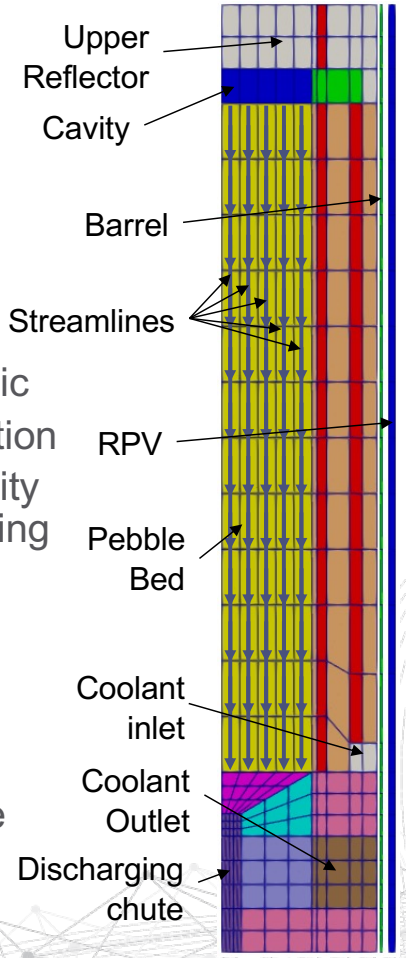
- **NEAMS**: The Nuclear Energy Advanced Modeling and Simulation Program
- **MOOSE**: Multiphysics Object Oriented Simulation Environment
- **Flexible**
  - 1D, 1DR, 2D, 2DRZ, 3D,
  - Huge variety of physics
  - Adaptive time stepping and sub cycling
  - Multiscale through Multiapp system
  - Easily Extendible to new physics and sales
- **Tunable fidelity**
  - 0D scalar lumped parameters problem
  - 1D systems models
  - Multi D Intermediate “homogenized” geometry
  - High-fidelity “explicit” Geometry
- **Scalable**
  - MOOSE supports hybrid parallelism
  - Scales well on workstation and HPC
  - 2D/RZ models execute in minutes
  - High-fidelity 3D models execute on HPC

NEAMS Base Reactor Design

- Physical Characteristics
  - Total Power: 200 MW
  - Core height/radius: 8.93/1.20 m
  - Fuel type: Pebble
    - # of TRISO per Pebble: 18687
  - Fuel material: 15.5% enriched UO_2 TRISO particles
  - Coolant: Helium
  - Inlet temperature: 533 K
  - Outlet pressure: 5.8 MPa
  - Burnup limit: 147,600 MWd/t_{HM}
  - Pebble unloading rate = ~1 pebble/min



- Multiphysics coupled simulations
  - Codes:
    - **Griffin** for neutronics and depletion
    - **Pronghorn** for thermal-hydraulic
    - **BISON** for pebble heat conduction
  - Where: Nuclear Science User Facility (NSUF) High Performance Computing (HPC) at INL
  - Mesh Type: Mesh generator and/or mesh data from a file
  - Geometry type: RZ geometry (axisymmetric)
  - Equilibrium core under steady-state condition



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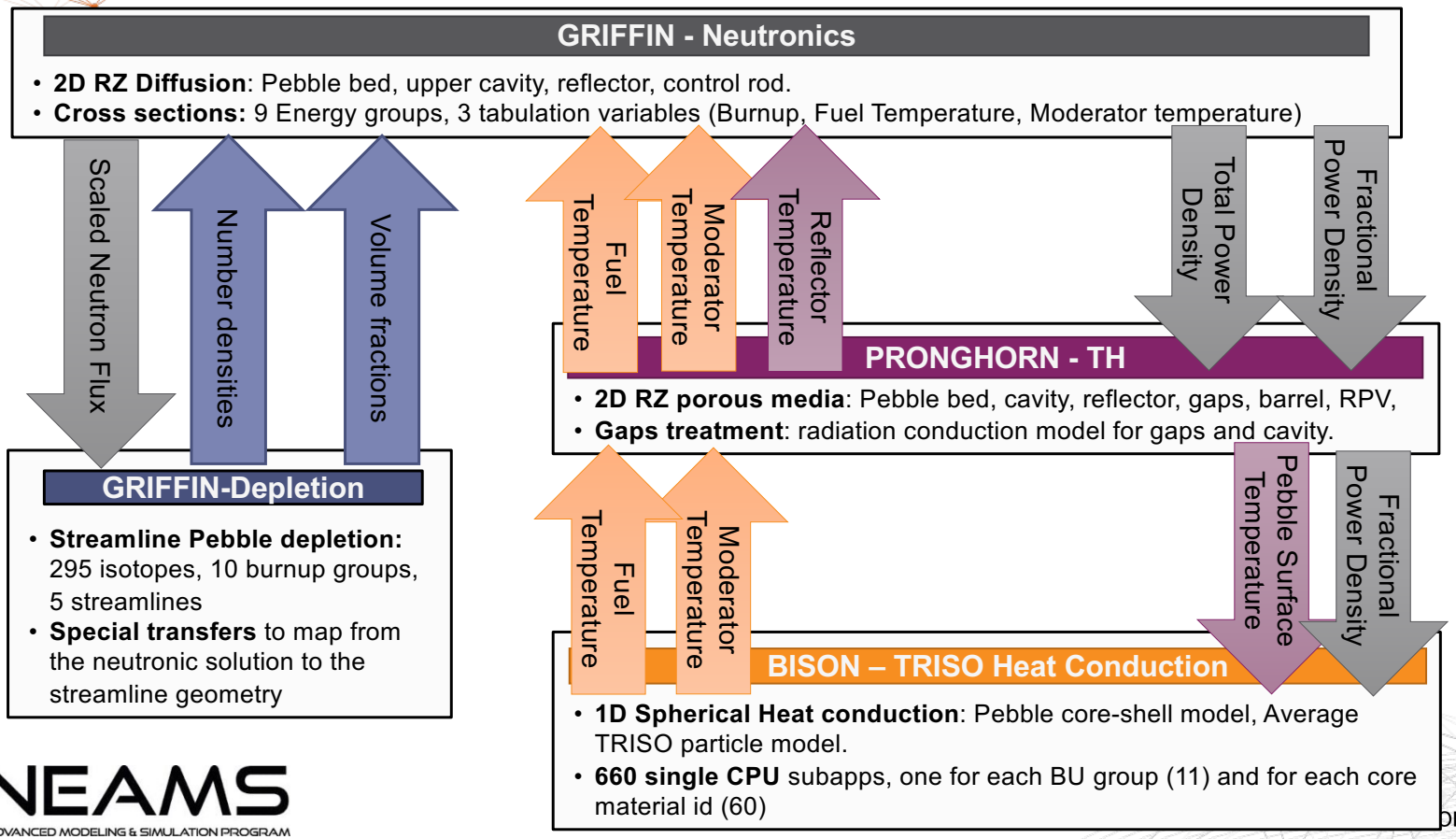
Multiphysics Coupling



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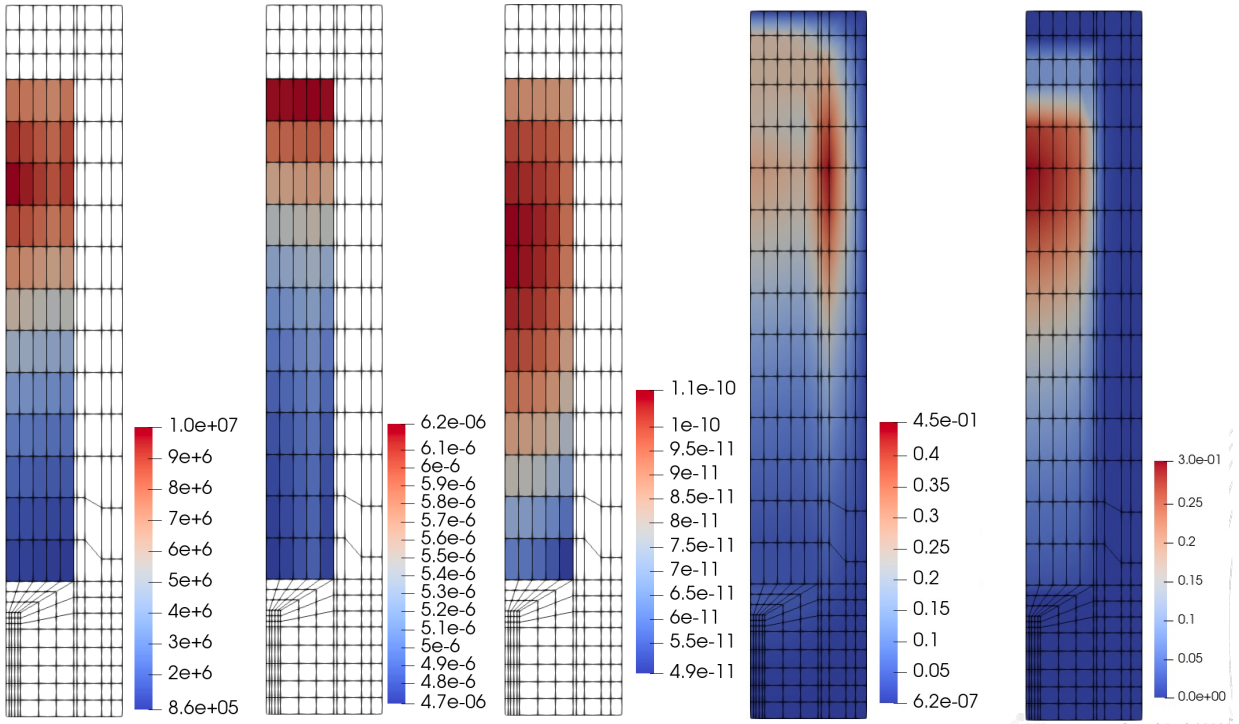
OLOGIES

Simulation Results for Base Reactor

- $k_{eff} = 1.012124$
- Power density is maximum near top because of fresh pebbles (see U^{235} density)
- As the pebbles move from top through the bottom, power density decreases substantially
- Xe^{135} concentration profile is shifted downward from power density smoother



Power density [W/m^3] | U^{235} density [1/m-barn] | Xe^{135} density [1/m-barn] | Normalized Thermal flux | Normalized Fast flux

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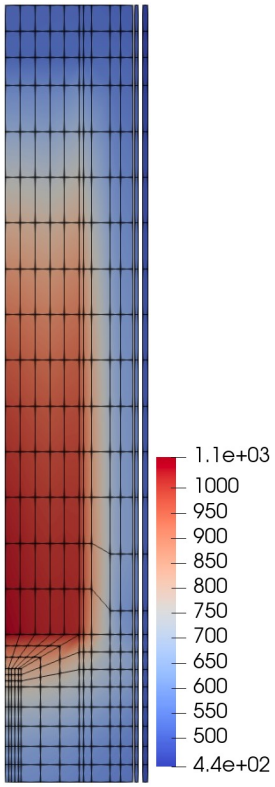
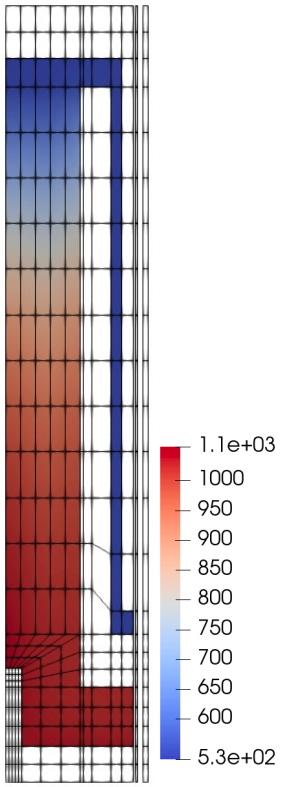
Simulation Results for Base Reactor

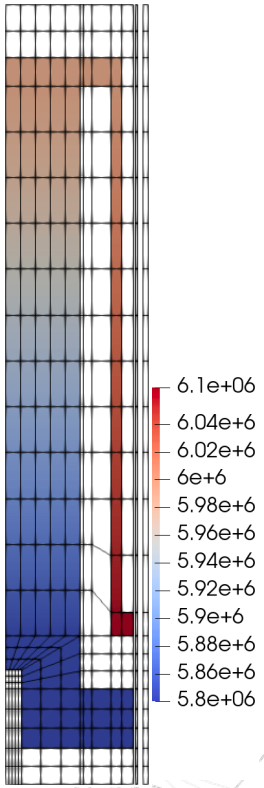
- Max pebble surface temperature: 1061 K
- Fluid temperature increase: 524 K
- Pressure drop: 226 kPa



Pebble surface temp. [K]



Helium temp. [K]



Pressure [Pa]

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ADVANCED REACTOR TECHNOLOGIES

Search for Optimized Reactor Parameters

- Sensitivity Analysis:
  i. To explore the impact of perturbations in input parameters on quantities of interest (QOIs)
  ii. To filter parameters that are unimportant to QoIs
  iii. To reveal high-impact parameters affecting uncertainty of QoIs
- Sampling-based and variance-based methods
- Perturbation based on random sampling (Monte Carlo) or sparse quadrature (Smolyak) methods
- Design/uncertainty space based on distributions:
  - Equal parameter probability defining lower and upper bound (uniform distribution)
  - Defining parameter mean and variance (normal distribution)

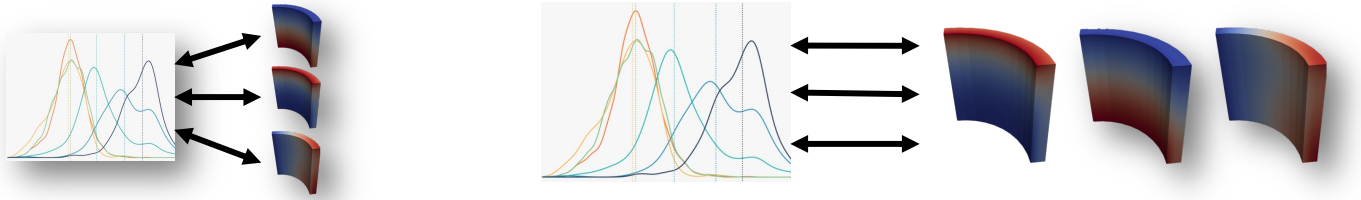
Search for Optimized Reactor Parameters

- PBMR input parameters:
  - Pebble TRISO parameters
    - *Fuel enrichment*
    - *TRISO kernel size*
  - Core wide shuffling parameters
    - Pebble unloading rate
    - Limit on discharge burnup
  - Core wide thermal-hydraulics parameters:
    - Outlet pressure
    - Inlet temperature
    - Mass flow rate
    - Reactor power

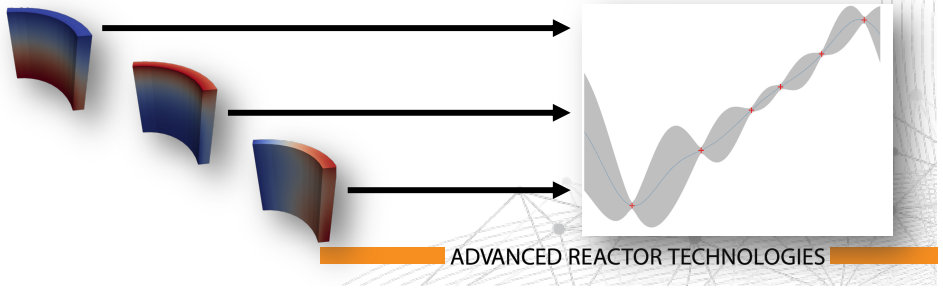
- PBMR quantities of interest (QoI):
  - k_{eff}
  - Max TRISO power
  - Max TRISO/pebble/reflector temperature
  - Power/Xenon peaking factor
  - Axial power/Xenon offset
  - Radial power/Xenon offset
  - Max/average fuel/reflector fast flux

Methods

- Tools for sensitivity analysis: MOOSE stochastic tools module (STM)
  - Open-source MOOSE module available to all MOOSE-based applications
  - Provides a **MOOSE-like interface** for performing stochastic analysis
  - **Efficiently** and **scalably** samples parameters, runs applications, and gathers data
  - Performs UQ and sensitivity analysis with **distributed data**



  - Trains meta-models to develop fast-evaluating **surrogates** of the high-fidelity multiphysics model
  - Provides a **pluggable** interface for these surrogates
- Sensitivity analysis methods:
  - Sobol sampling
  - Morris screening
  - **Polynomial expansion**



Initial Sensitivity Study: Parameter and output space

Parameter	Symbol	Lower Bound	Upper Bound	Units
Pebble unloading rate	v_p	0.5	2	pebbles/ min
Burnup limit	Bu^{max}	131,200	164,000	MWd/t_{HM}
Mass flow rate	$\dot{m}$	74.7	82.5	kg/s
Inlet Temperature	T_{in}	506.6	559.9	K
Outlet Pressure	P_{out}	5.55	6.13	MPa
Reactor Power	P	180	220	MW

QoI	Symbol	Units
k_{eff}	k_{eff}	—
TRISO Power	P_k^{max}	W
Max temperature	$T_k^{max}, T_m^{max}, T_{ref}^{max}$	K
Power peaking factor	f_P, f_P^z, f_P^r	—
Xenon peaking factor	$f_{Xe}, f_{Xe}^z, f_{Xe}^r$	—
Fast flux (group 1)	$\phi_{1,k}^{max}, \phi_{1,ref}^{max}$ $\bar{\phi}_{1,k}, \bar{\phi}_{1,ref}$	1/cm^2-s

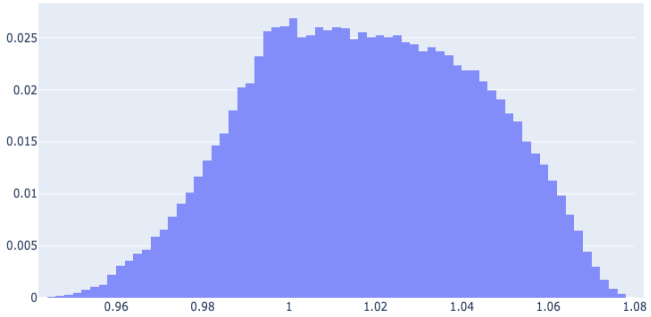
Initial Sensitivity Study: Results

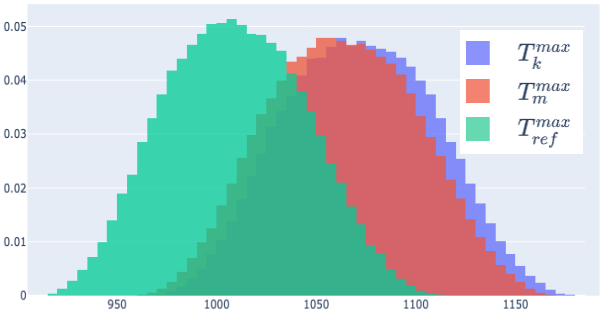
QoI	Mean	Standard Deviation (%)
$\mathbf{k_{eff}}$	**1.018**	**2.54 (~2,500 pcm)**
$\boldsymbol{P_k^{max}}$	**3,017**	**13.9**
T_k^{max}	1,072	3.45
T_m^{max}	1,063	3.47
T_{ref}^{max}	1,009	3.47
$\mathbf{f_P}$	**1.973**	**10.0**
$\mathbf{f_P^z}$	**1.825**	**9.90**
f_P^r	1.081	0.591

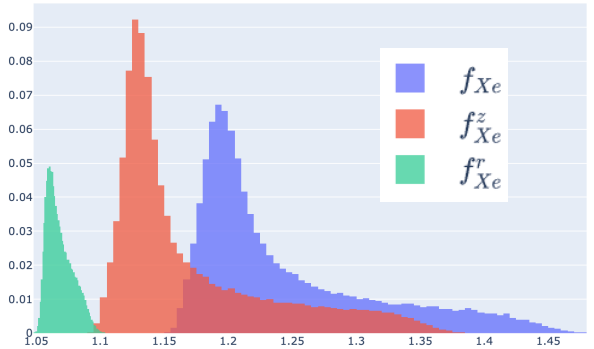
QoI	Mean	Standard Deviation (%)
f_{Xe}	1.245	5.65
f_{Xe}^z	1.171	5.32
f_{Xe}^r	1.069	0.954
$\boldsymbol{\Phi_{1,k}^{max}}$	**7.07e12**	**15.8**
$\boldsymbol{\Phi_{1,ref}^{max}}$	**2.91e12**	**14.3**
$\bar{\phi}_{1,k}$	3.03e+12	6.61
$\bar{\phi}_{1,ref}$	1.11e+11	7.32

Initial Sensitivity Study: Results cont.

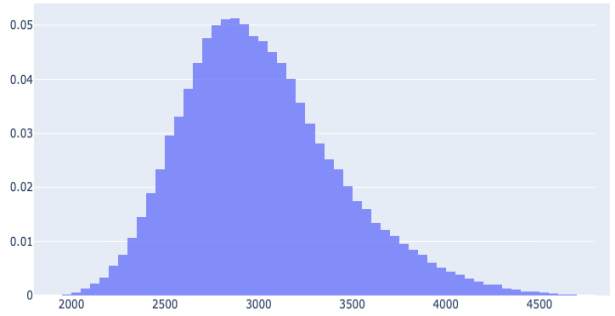
k_{eff}

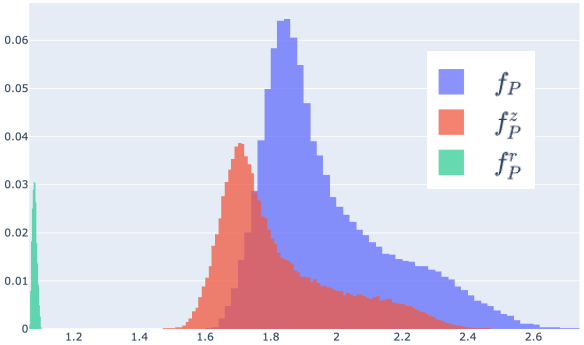


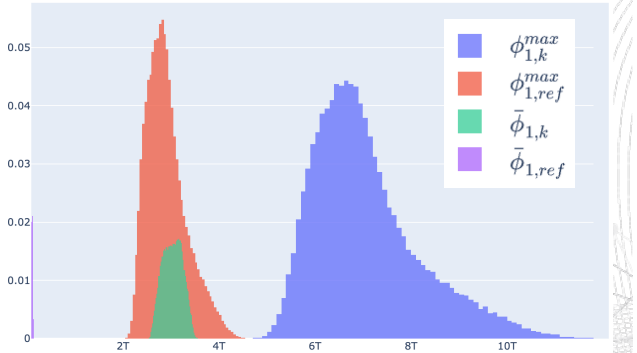




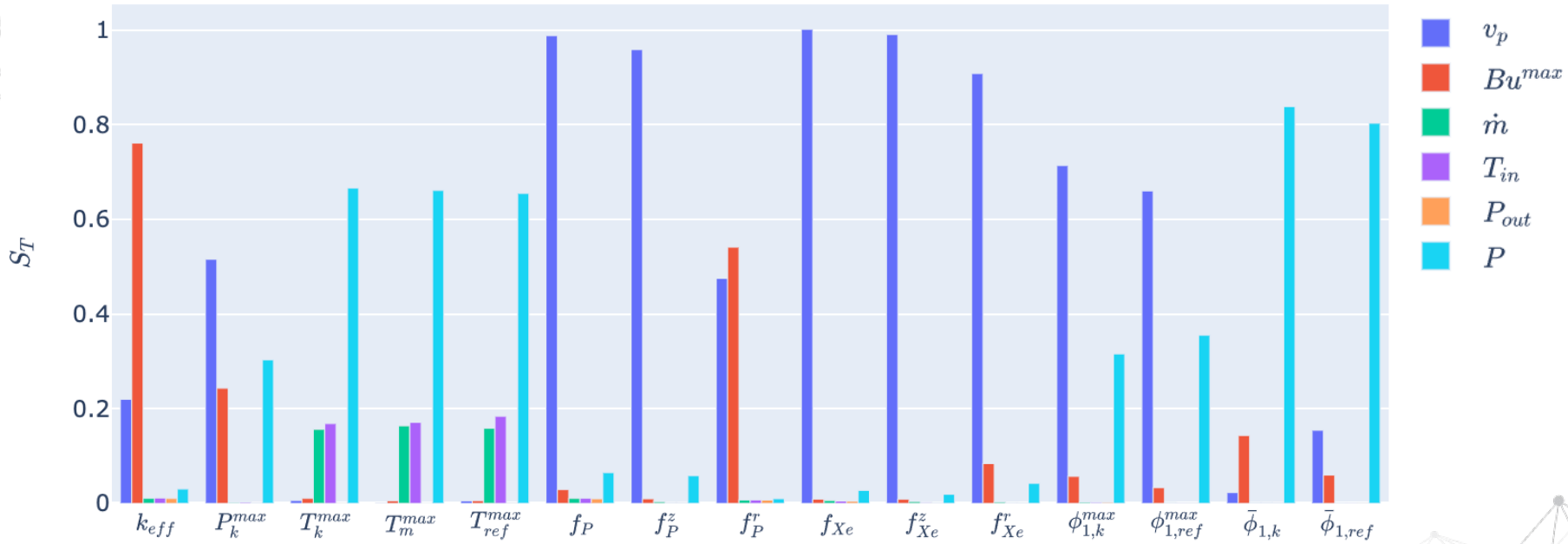
P_k^{max}







Initial Sensitivity Study: Sensitivity Results



Initial Sensitivity Study: Analysis

- Temperature quantities have little variation compared to other QoIs
- Power and Xenon shape is flat radially with little variation

- Burnup limit and pebble unloading rate has the most significant impact on QoIs
  - Separation of these parameters is a unique Griffin capability
- 5% perturbation of thermal hydraulics parameters have small impact on neutronics QoIs
  - But important for temperature-related QoIs
- Power has little impact on unitless quantities

Moving Forward

- **Ongoing Work (FY22)**
  - Include other design parameters in sensitivity study
    - Fuel enrichment
    - Kernel and pebble sizes
    - Reactor dimensions
  - Include fuel performance physics
  - Investigate reduced order modeling methods

- **Future Work (FY23+)**
  - Build transient model
    - Design relevant input/output space
    - Perform sensitivity study on new model
  - Investigate ROMs for transient model
  - Create optimization workflow using ROMs