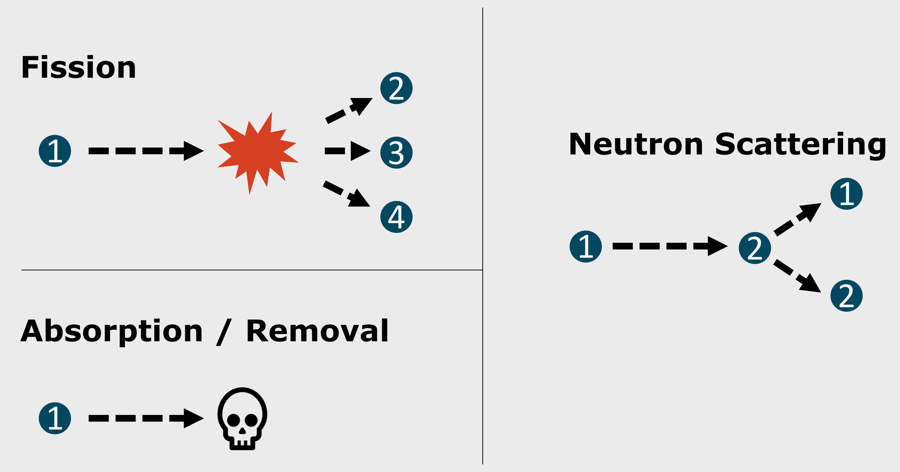
REDUCED ORDER MODELING OF NUCLEAR REACTOR CORE KINETICS

Anthony L. Alberti and Todd S. Palmer
albertia@oregonstate.edu

Modeling and Simulation of a Nuclear Reactor Core

- For all space and time, we must consider **several coupled physics phenomena**: 1) neutron population, 2) material concentration, 3) material/fluid properties.



- Developing digital models of such complex systems often suffer from the **"curse of dimensionality"**.
- In this work, we aim to **overcome this curse** through a novel **reduced order modeling** technique known as ***proper generalized decomposition***.

Nuclear Reactor Kinetics

- Accounts for **time dependent behavior** of **neutron population** and **fission product creation/decay**.

$$\underbrace{\frac{1}{v_g}\frac{\partial \phi_g}{\partial t}}_{\text{time rate of change}} - \underbrace{\nabla \cdot D_g(\boldsymbol{r})\nabla\phi_g(\boldsymbol{r},t)}_{\text{diffusivity/leakage}} + \underbrace{\Sigma_{r,g}(\boldsymbol{r},t)\phi_g(\boldsymbol{r},t)}_{\text{removal}}$$

$$= \underbrace{(1-\beta)\chi_g^p \sum_{g'=1}^{G} \nu_{g'}\Sigma_{f,g'}(\boldsymbol{r})\phi_{g'}(\boldsymbol{r},t)}_{\text{fission source}} + \underbrace{\sum_{\substack{g'=1 \\ g'\neq g}}^{G} \Sigma_s^{g\leftarrow g'}(\boldsymbol{r})\phi_{g'}(\boldsymbol{r},t)}_{\text{scattering source}} + \underbrace{\sum_{k=1}^{K} \lambda_k \chi_g^k C_k(\boldsymbol{r},t)}_{\text{precursor source}}$$

$$\underbrace{\frac{\partial C_k}{\partial t}}_{\text{time rate of change}} = -\underbrace{\lambda_k C_k(\boldsymbol{r},t)}_{\text{precursor decay}} + \underbrace{\beta_k \sum_{g=1}^{G} \nu\Sigma_{f,g}\phi_g(\boldsymbol{r},t)}_{\text{production from fission}}$$

Oregon State University | ARCS Advancing Science in America

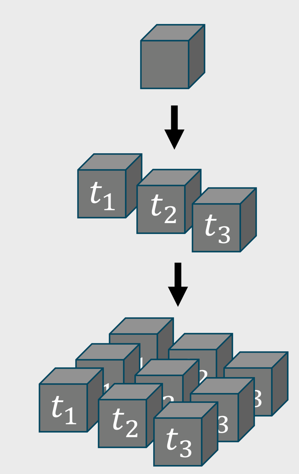
Curse of Dimensionality

- Reactor core kinetics problems exhibit **high computational demand** and often require large, complex, expensive computing resources (**i.e. *supercomputers***)

Space
$100 \times 100 \times 100 = 10^6$

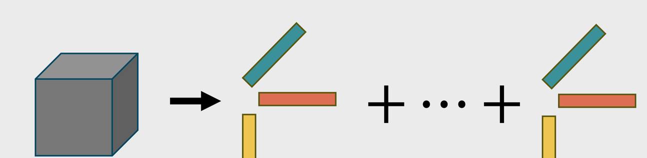
Time
$10^6 \times 100 = 10^8$

Energy
$10^8 \times 10 = 10^9$



Proper Generalized Decomposition (PGD)

- Reduced order modeling method which **does not rely on any previous knowledge** and **overcomes the curse of dimensionality** through a **linear relationship.**

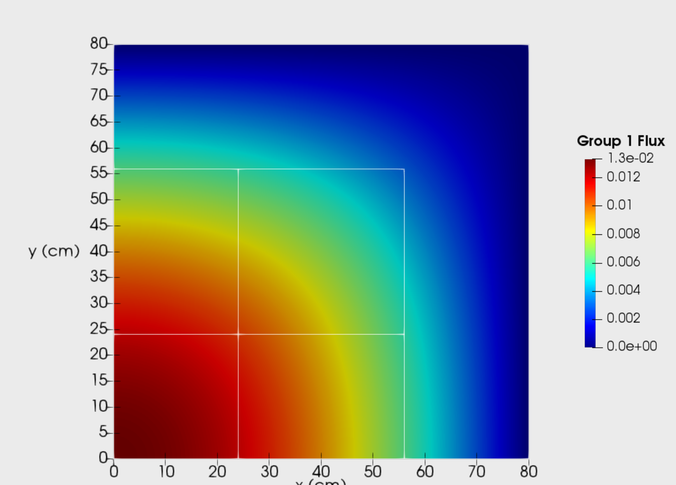


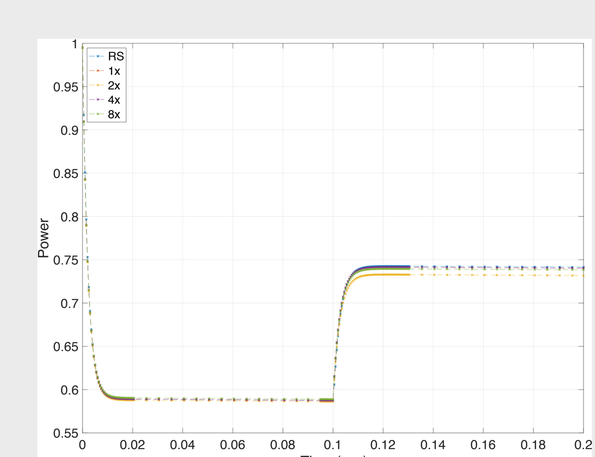
$$(100 + 100 + 100) + (100) + (10) << 10^9$$

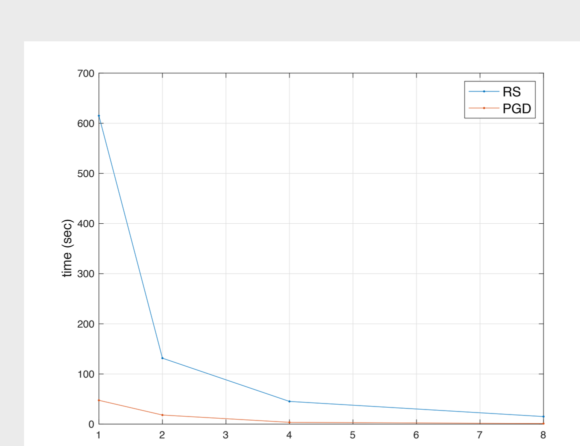
- Differential equations are **decomposed in space and time** and **computed with a nonlinear algorithm.**
- Spatial dimensions are solved via **continuous finite elements**; time dimension is solved with an **adaptive BDF method.**

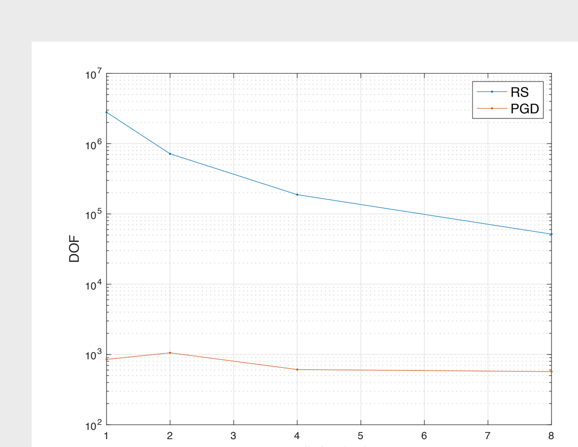
Results

- **For idealized problems** (that exhibit smooth spatial solutions), **PGD accurately computes the power profile using less time and fewer unknowns**

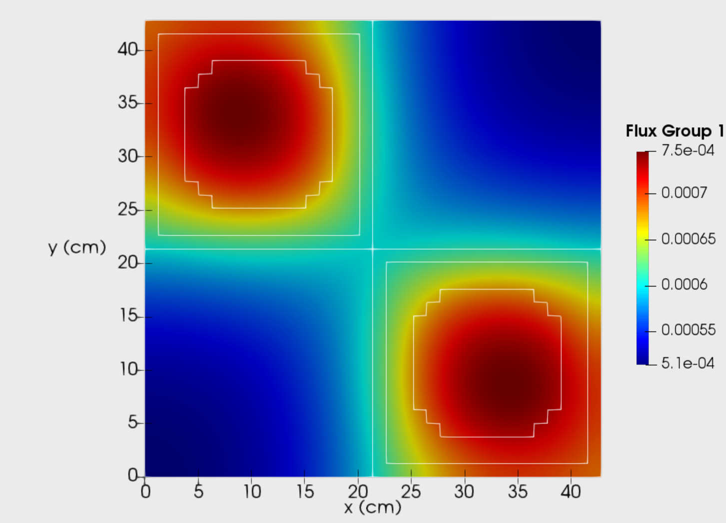


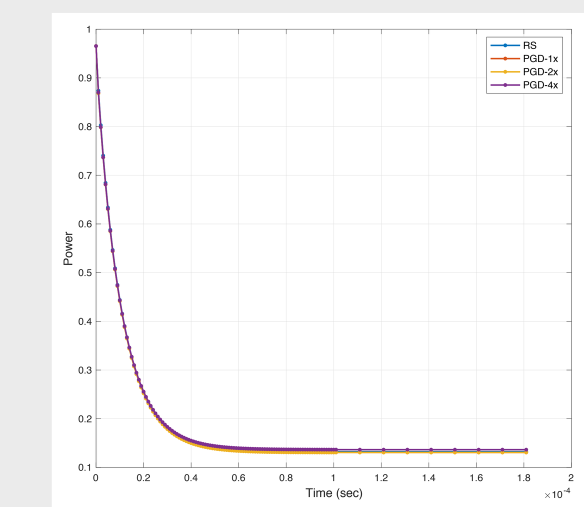


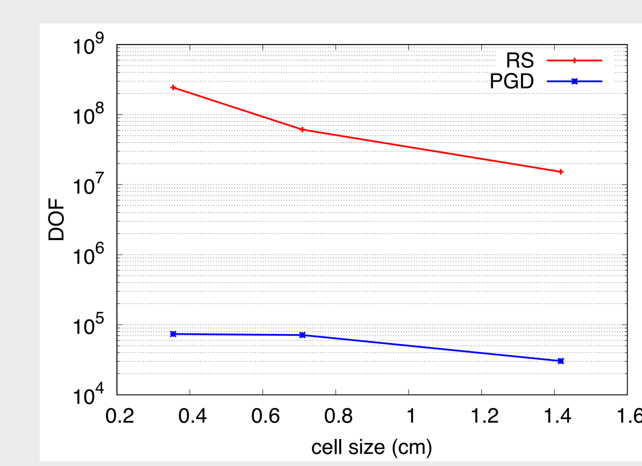


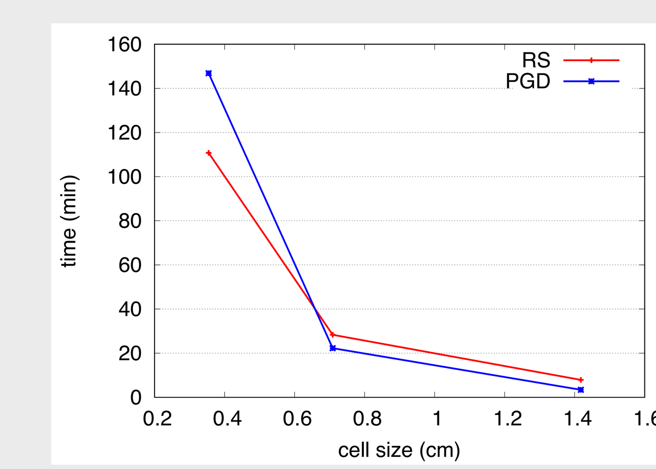


- **PGD accurately computes power profile** for **multi-material problems** with **fewer unknowns**.
- The combination of **large linear systems and solver selection** leads to **increased computation time**.

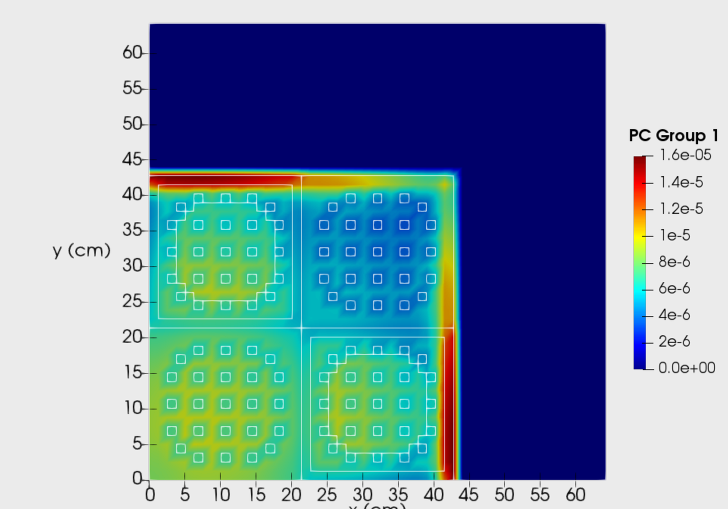


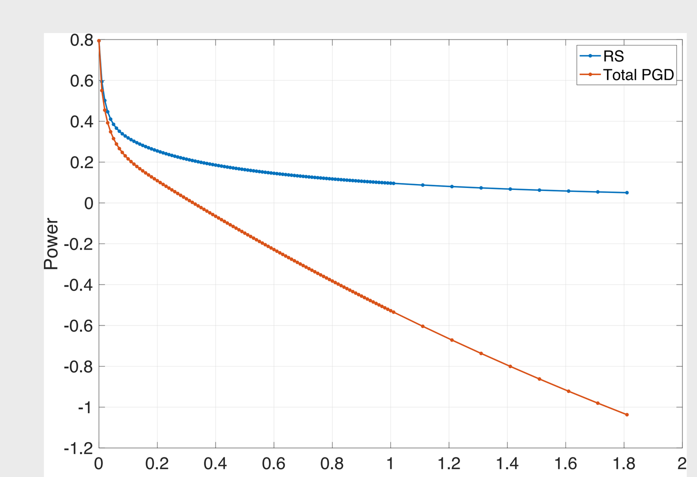


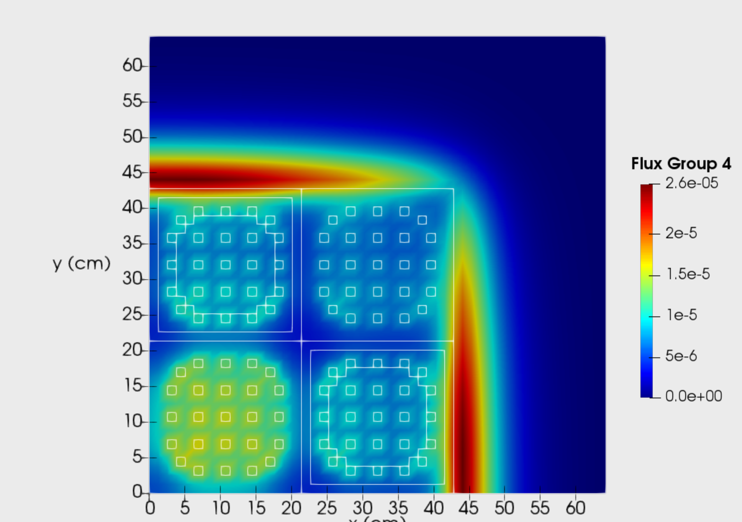




- **Realistic reactor problems** exhibit **significant spatial heterogeneity.**
- **Proposed PGD algorithm/solvers compute incorrect results;** negative neutron population -> negative reactor power







Conclusions

- **Nuclear reactor core kinetics calculations** suffer from the **"curse of dimensionality"**
- PGD has been shown to be **an effective reduced order modeling technique** for reactor kinetics problems that are **sufficiently smooth in space**
- **Algorithm/solver setup presented** produces **incorrect results** for **realistic reactor kinetics benchmarks**.
- **Discontinuous finite elements** are expected to alleviate observed issues.