Computational design of an Ultra-Small Modular Reactor based on coupled Serpent sequences

Georgia Tech
CREATING THE NEXT

Georgia Institute of Technology

10/15/2019

Naiki Kaffezakis, Stefano Terlizzi, Corey Smith,

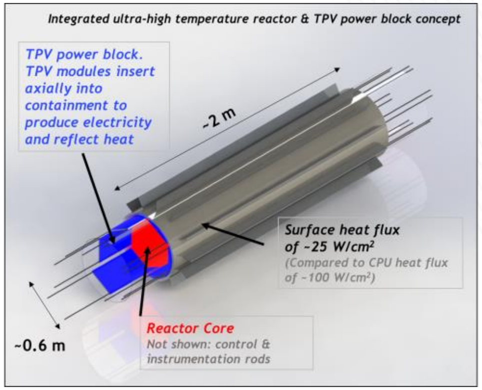
Ian Miner, Andrew Nelson, Dan Kotlyar

Outline

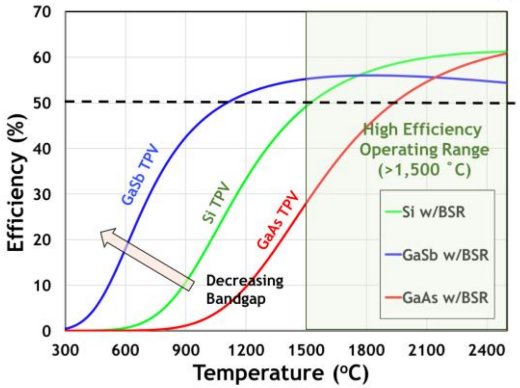
- The USMR Project
- Computational Methods
- Preliminary Design Studies
- Economic Analysis
- Secondary Design Analysis
- Ongoing Studies and Future Work

Objectives

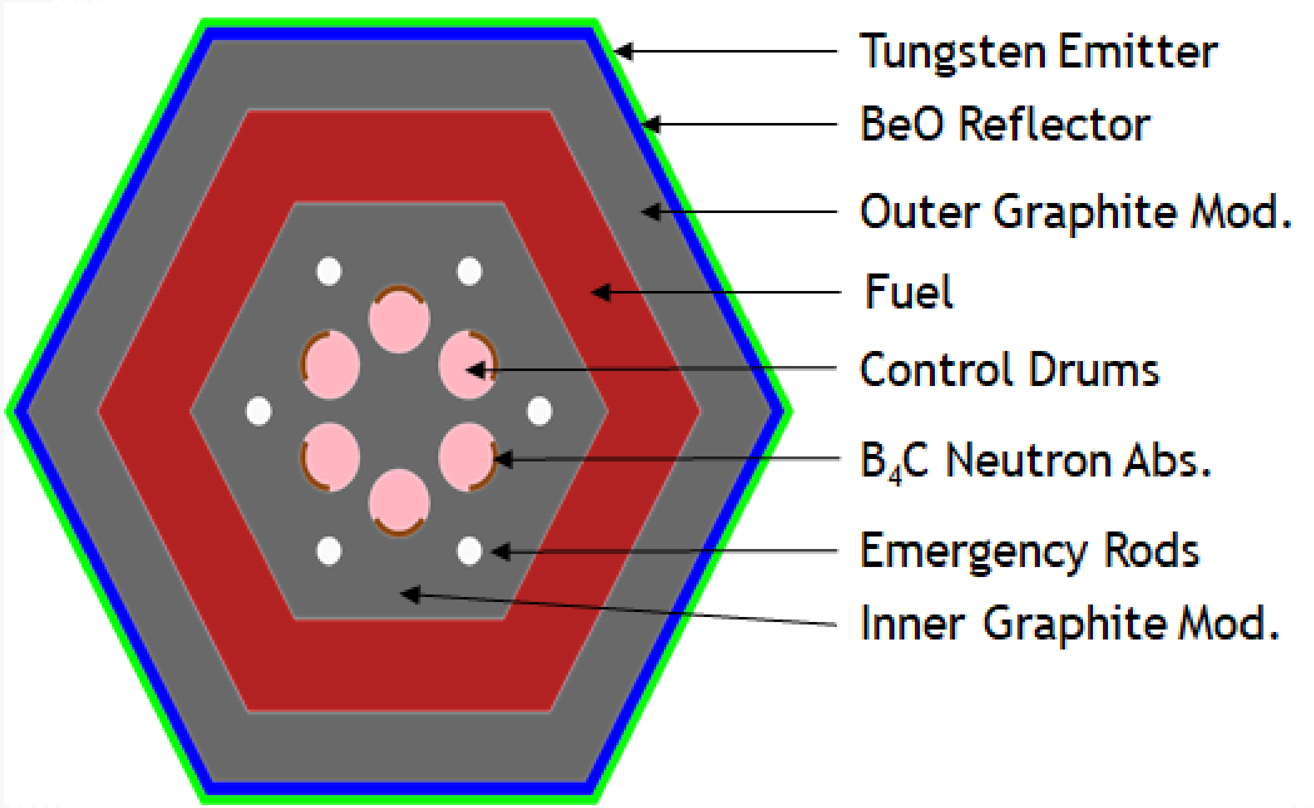
- Ultra-Small Modular Reactor (***USMR***)
  - Siting flexibility
    - – no need of large cooling water volume
  - Modularity
    - – add power in small unit increments
  - Factory production
    - – potential lower costs and higher quality



- Thermophotovoltaic (***TPV***) power-block
  - High-efficiency
  - Low-cost

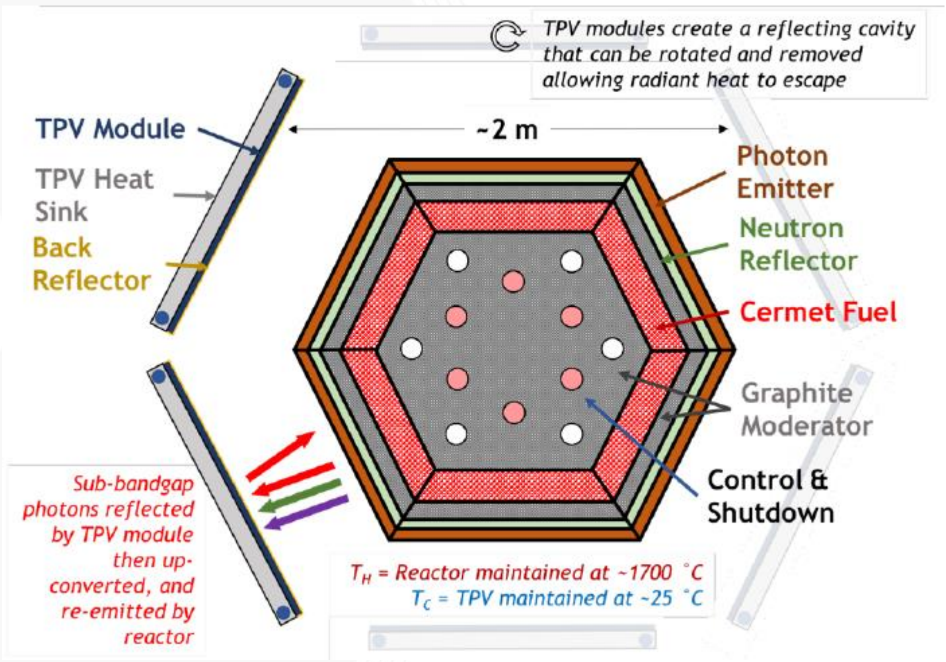


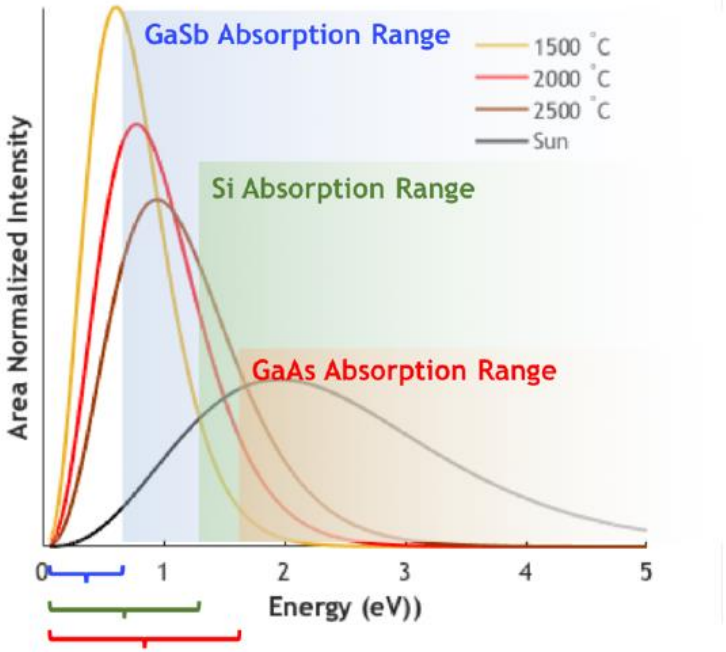
USMR Core Design



Georgia Tech
CREATING THE NEXT

USMR Physics

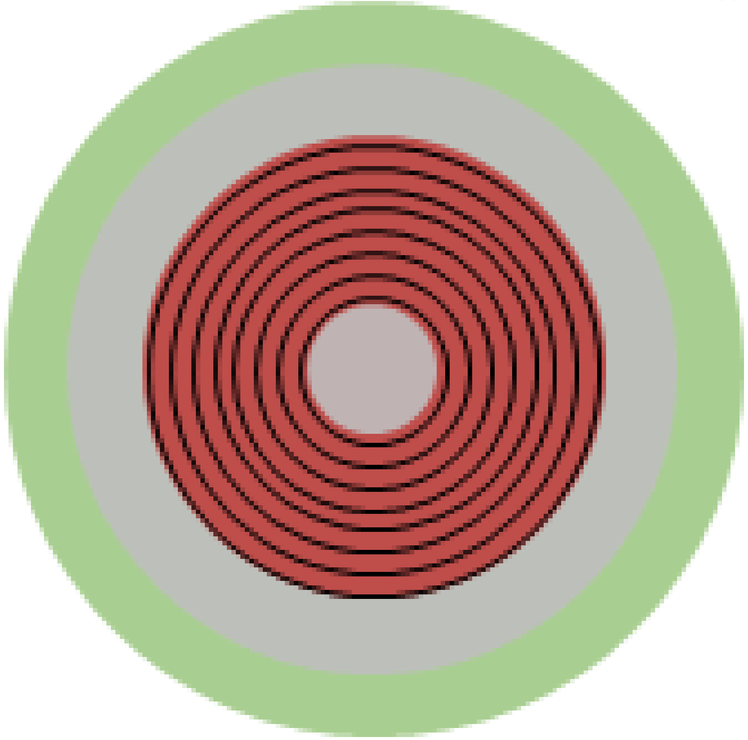




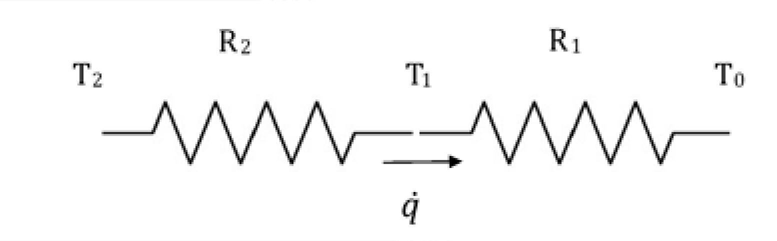
Georgia Tech
CREATING THE NEXT

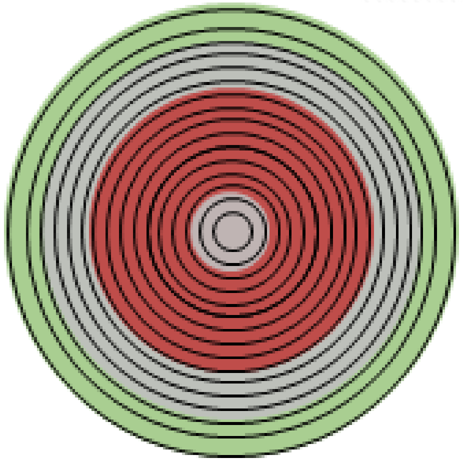
Serpent Models

- 2D Multiple concentric cylinders
- Uniquely defined materials with temperature dependent densities
- Fission rate detectors attached to regions with fissile isotopes
- 50,000 histories, 150 active cycles, 50 inactive cycles
- 1 MWd/kgU burn steps

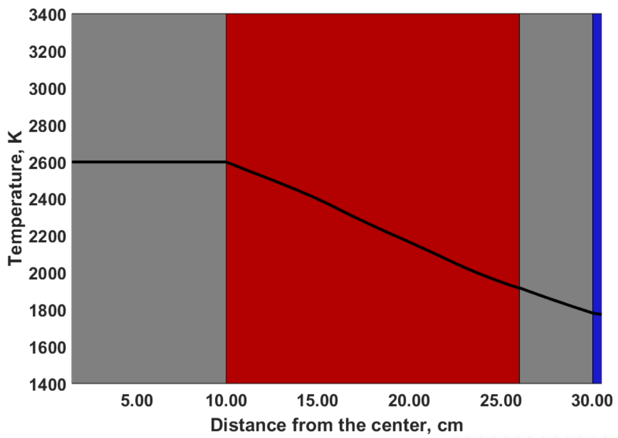


Finite Element Conduction Solver

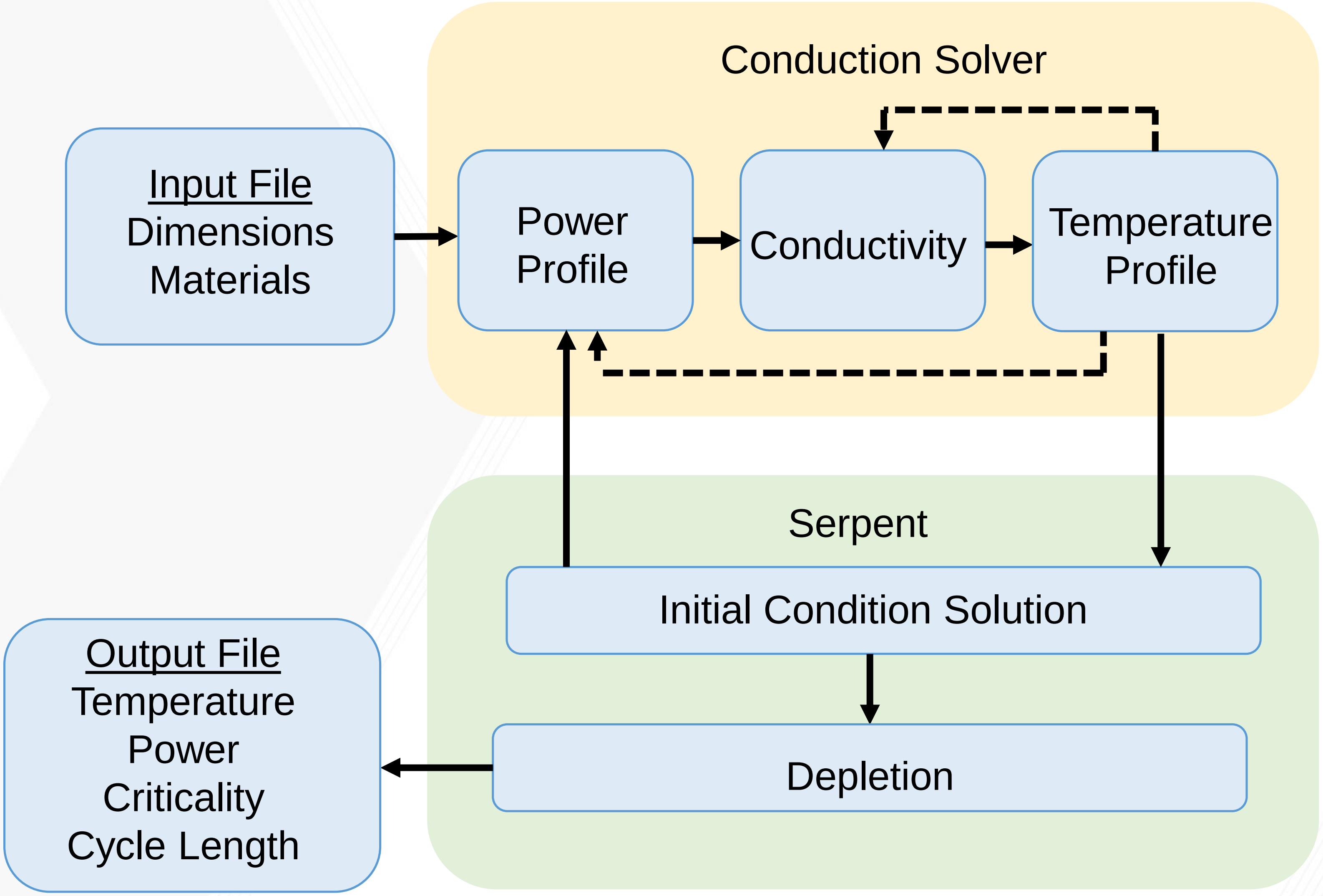




$$R_{i\pm} = \frac{\triangle r_i}{\left(r_m \pm \frac{\triangle r_i}{2}\right) \triangle \phi \triangle z} \frac{1}{k_{i\pm}}$$



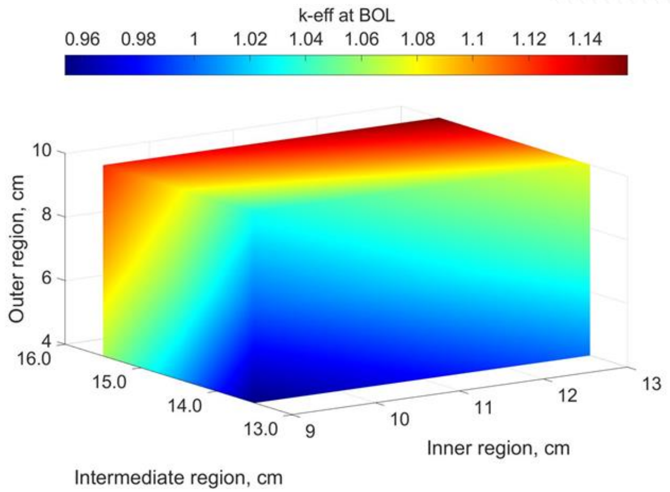
Computational Sequence

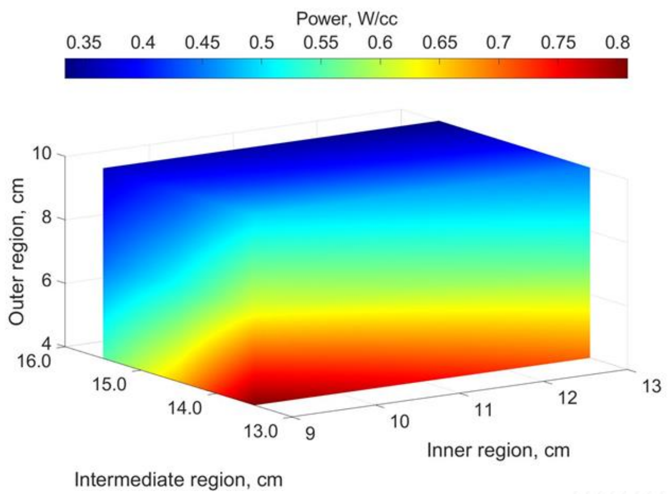


Georgia Tech CREATING THE NEXT

Initial Exploration of the Design

- Utilizing simplified 4-ring design
- Examined Variables:
  - Fuel Material
  - Outer Wall Temperature
  - Temperature Safety Margin
  - Ring Dimensions

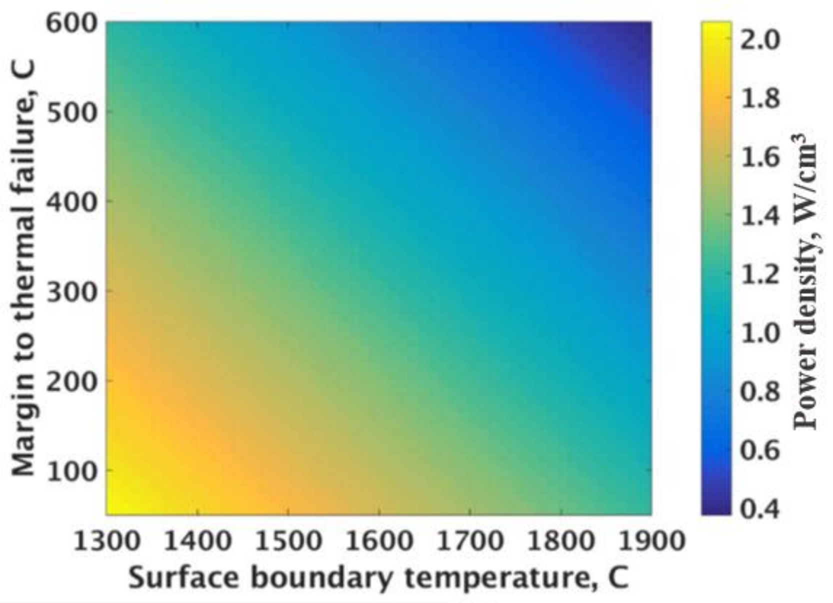




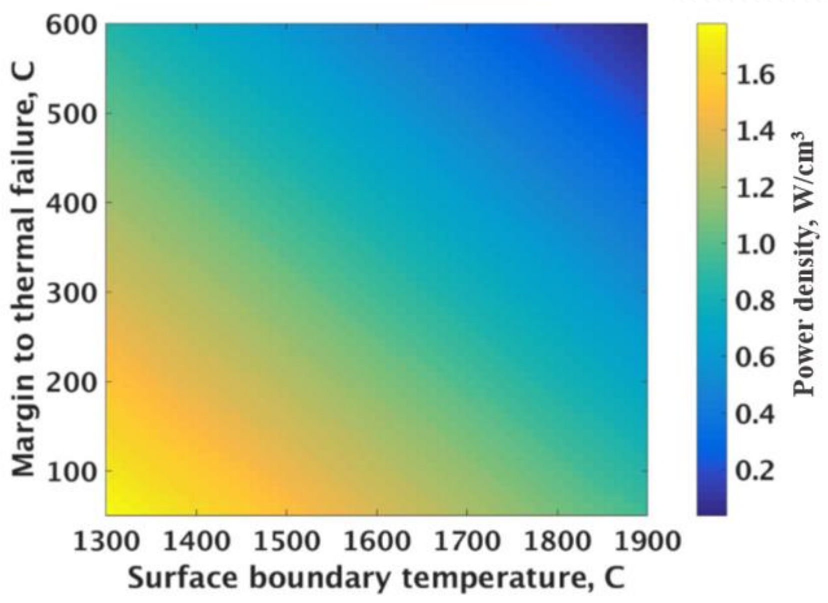
UC_2 fuel element with 1500˚C outer temperature and 200˚C safety margin

Georgia Tech CREATING THE NEXT

Results of the Preliminary Study



UN fuel



UC fuel

Georgia Tech CREATING THE NEXT

Conclusions of the Preliminary Study

- Maximum Power Density for a critical Geometry:
  - UN 2.00 W/cm^3
  - UC 1.60 W/cm^3
  - UC_2 1.00 W/cm^3
  - CERMET (U/W) 0.15 W/cm^3
- Preferred Design using UN fuel:
  - 6.5 kW/cm, 59 year operation, 7.5 MWd/kgU

Parameter	Value
Inner Graphite Radius, cm	17.5
Fuel Radius, cm	26.5
Outer Graphite Radius, cm	33.5
Beryllium Reflector Radius, cm	34.0
Tungsten Filament Radius, cm	34.5
Initial Criticality for 200K Margin	1.0135

Georgia Tech CREATING THE NEXT

Top-Down Economic Approach

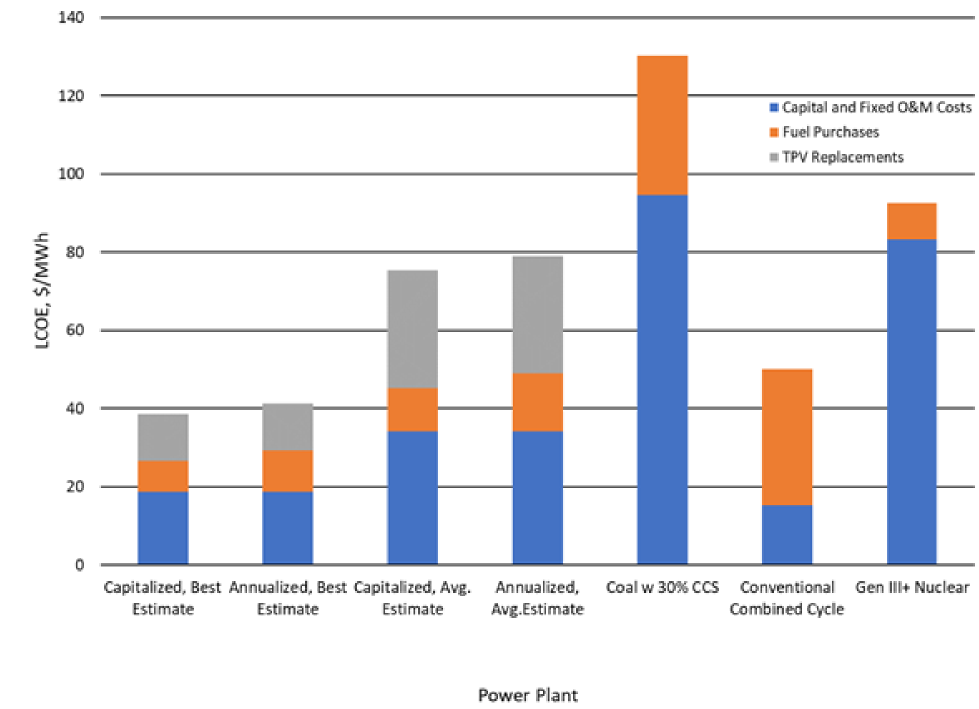
- Top-down differential economics approach
- Gen IV international forum code of accounts
- 10’s, 20’s, 30’s, 40’s, 70’s are drawn from EEDB and scaled to output,
- 50’s, 80’s are calculated using material and manufacturing costs
- 60’s, 90’s are pulled from the licensing costs for PWR

Account Codes	Account Description
10	Capitalized Preconstruction Costs
20	Capitalized Direct Costs
30	Capitalized Indirect Services Costs
40	Capitalized Owner's Costs
50	Capitalized Supplementary Costs
60	Capitalized Financial Costs
70	Annualized O&M Cost
80	Annualized Fuel Cost
90	Annualized Financial Cost

Georgia Tech CREATING THE NEXT

Deterministic

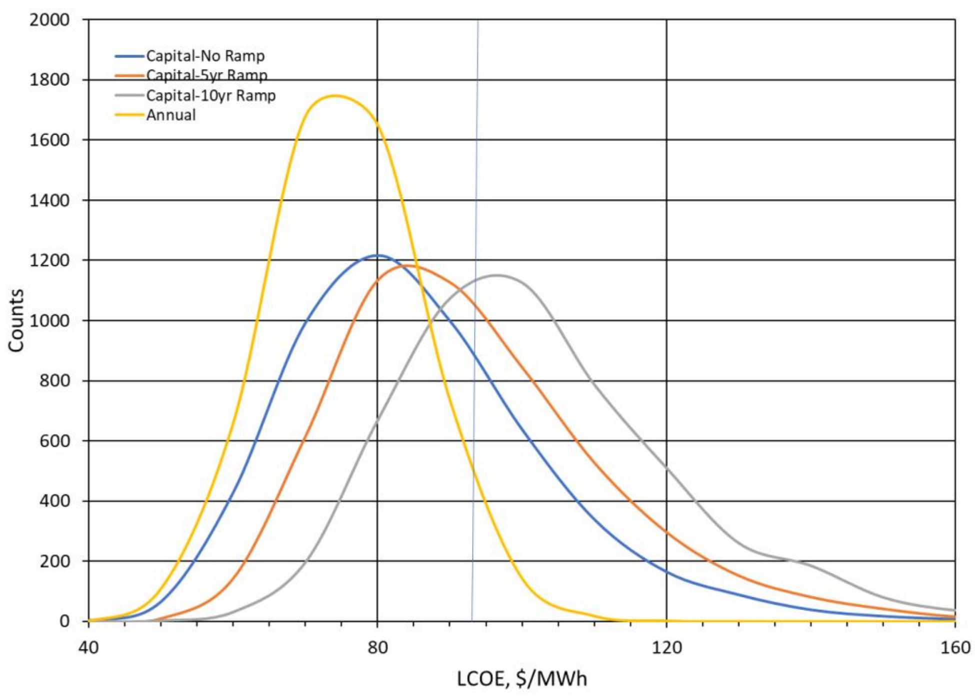
- Focusing on a single promising case
- Utilizing both the average and lowest costs from each account
- Examining both battery and multi-batch operation



Georgia Tech
CREATING THE NEXT

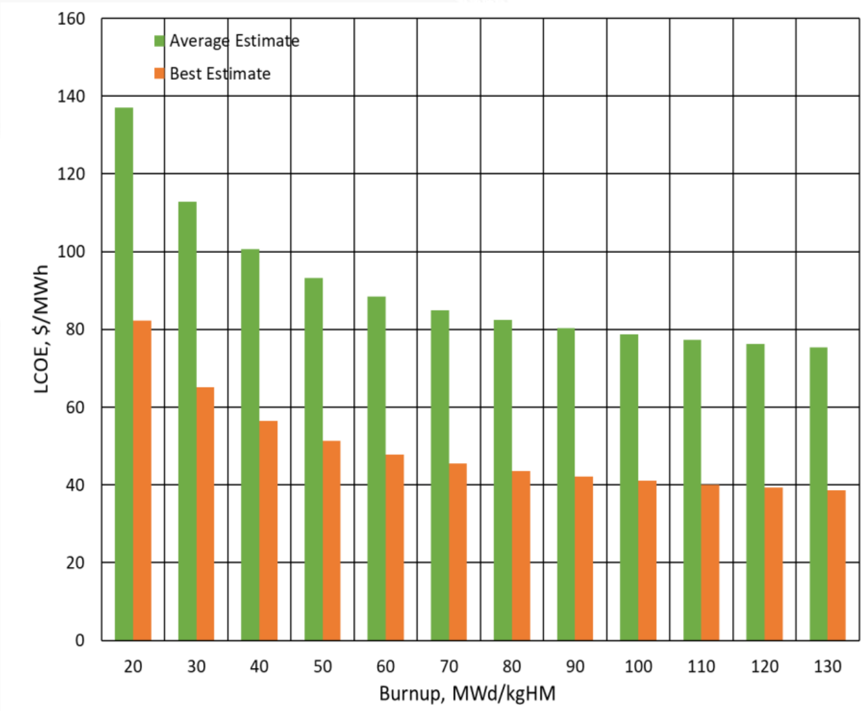
Stochastic

- Assumed normal distribution of account costs
- Assumed uniform distribution across design space
- Made 5000 random samples of designs and costs



Major Economic Factors

$$Relative\ Differential \equiv \frac{\frac{\partial y}{y}}{\frac{\partial x}{x}} \cong \frac{1}{N}\sum_{i=1}^{N}\frac{\frac{(y_i-y_{i-1})}{y_{i-1}}}{\frac{(x_i-x_{i-1})}{x_{i-1}}}$$



The relative differential of LCOE based on changing design parameters	
Parameter	LCOE Relative Differential
Capacity	-0.85
Plant Size	-0.30
Construction Period	0.24
Discharge Burnup	-0.23
Plant Efficiency	-0.15
Plant Lifetime	0.10
Ramp Period	0.10
Power Density	-0.002
Enrichment	0.08

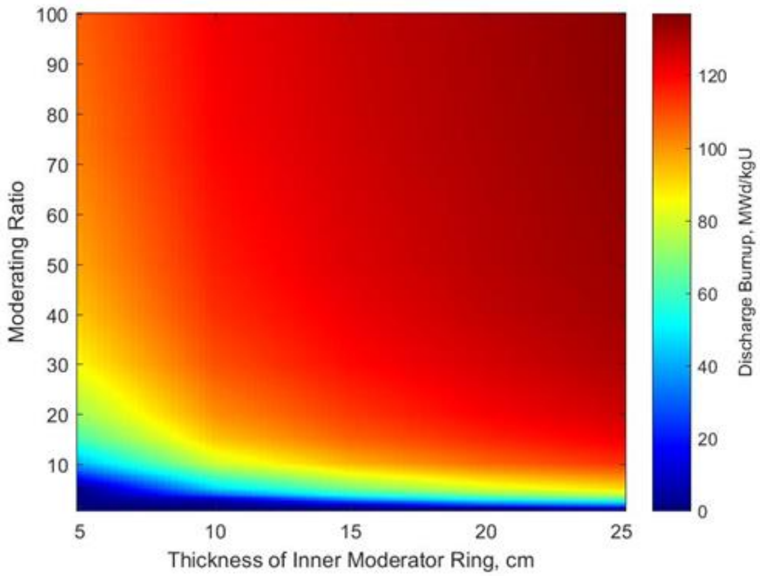
Georgia Tech CREATING THE NEXT

Moderating Ratio and Depletion Analysis

- Additional Analysis on Tuning the Moderator Ratio
- Interested in finding the optimal burnup to improve economics

Max Burnup MWd/kg

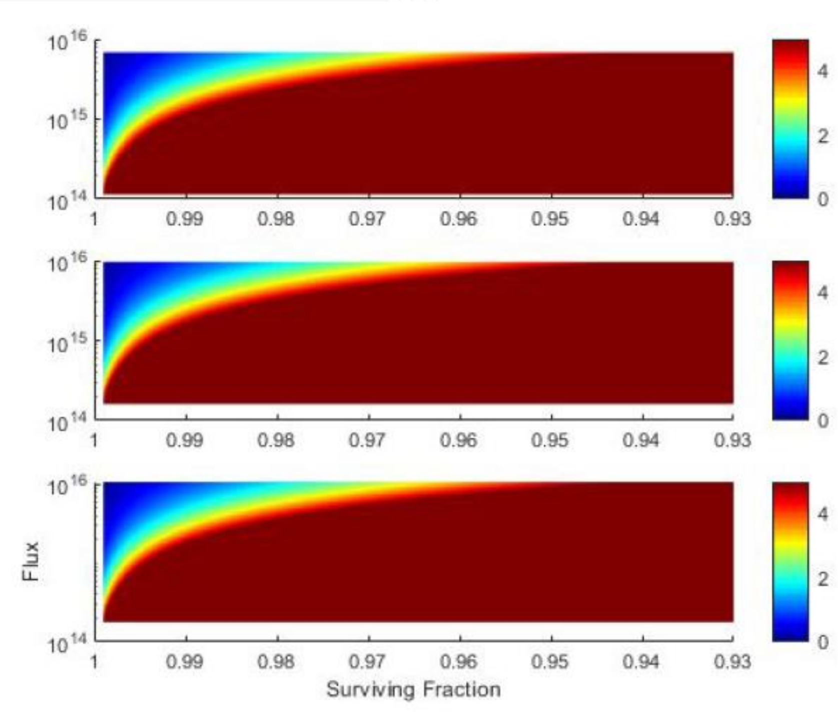
V_m/V_f	25	100
8%	15	24
12%	55	65
19.75%	130	137



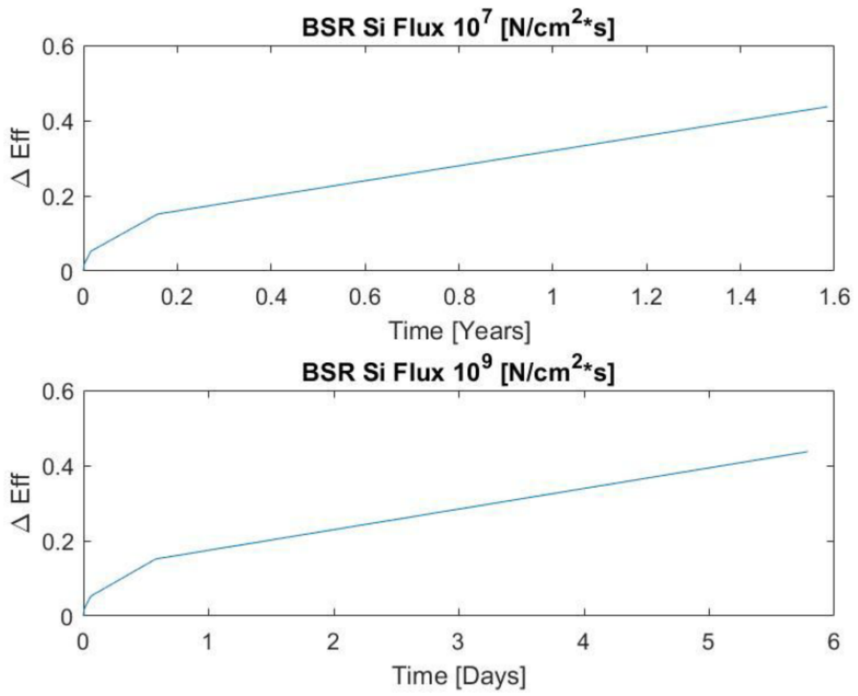
Georgia Tech CREATING THE NEXT

TPV Survivability

Silicon Transmutation



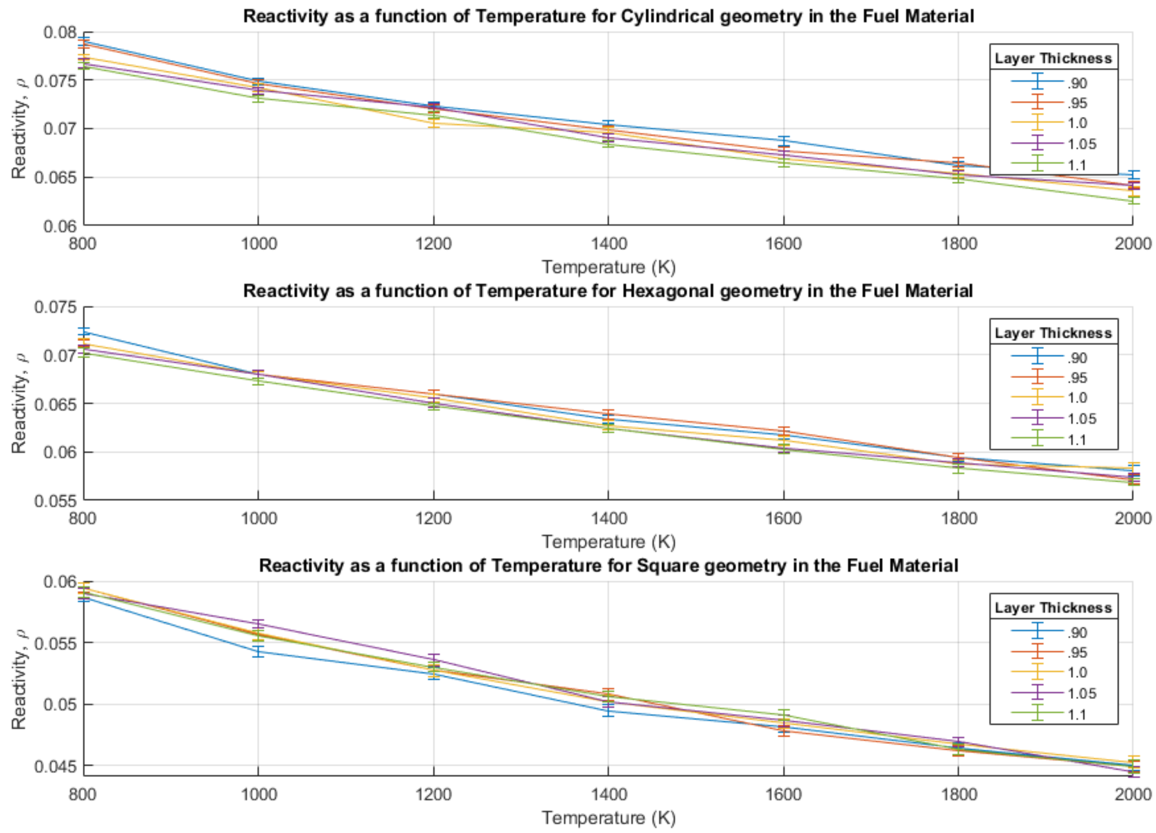
Fast Flux Damage



Georgia Tech
CREATING THE NEXT

Ongoing Work

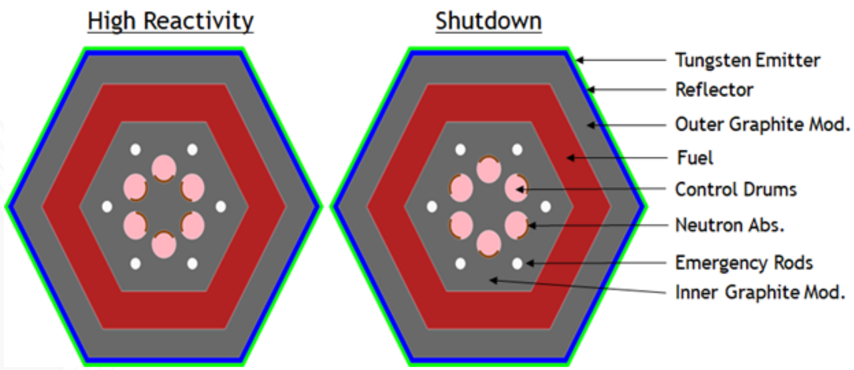
Reactivity Coefficients for Transient Conduction Solver



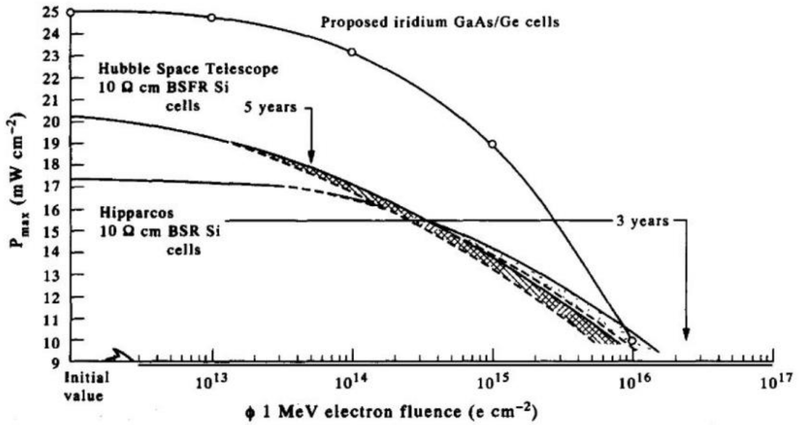
Georgia Tech CREATING THE NEXT

Future Work

Reactivity Controls



Experimental Validation

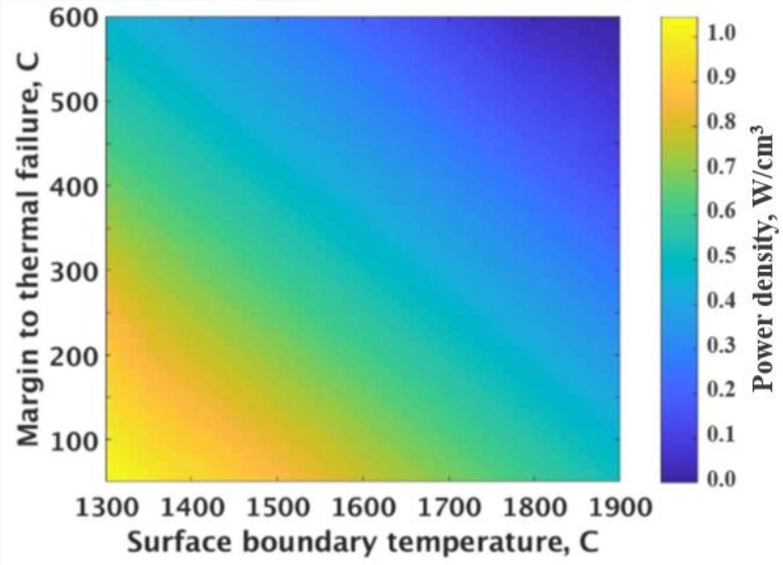


Georgia Tech
CREATING THE NEXT

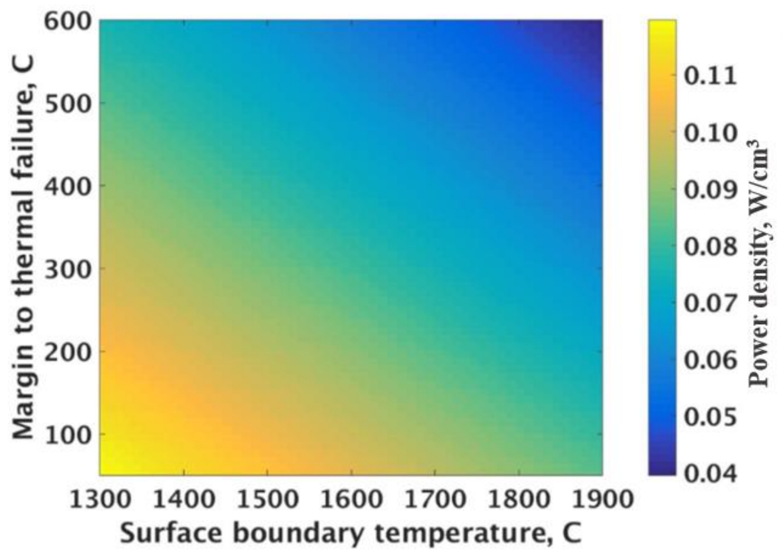
Questions?

Extra Slide (1)

Additional Preliminary Results



UC$_2$ fuel

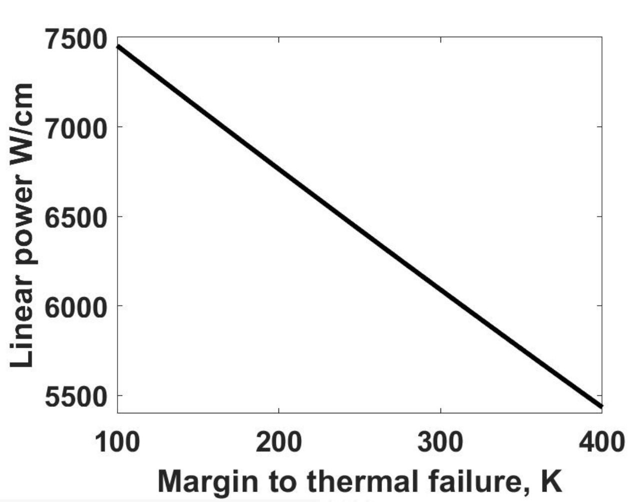


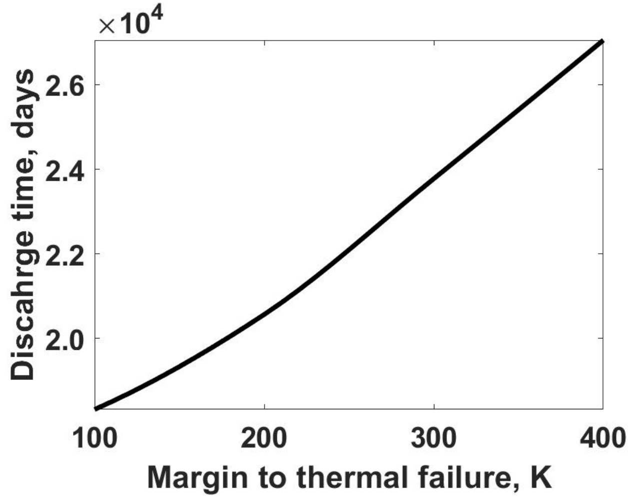
CERMET fuel

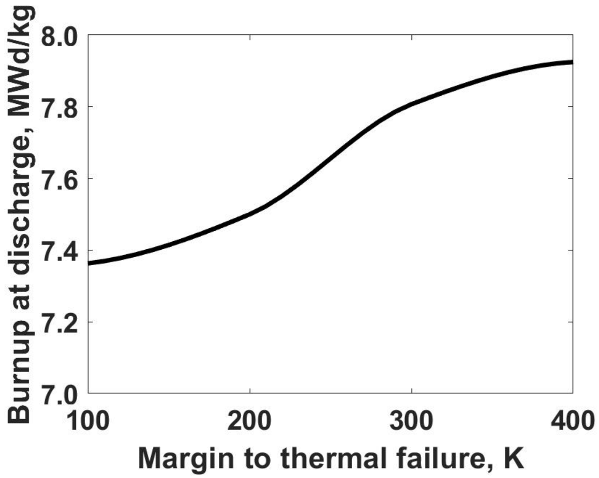
Georgia Tech
CREATING THE NEXT

Extra Slide (2)

Depletion of first converged case







Georgia Tech
CREATING THE NEXT

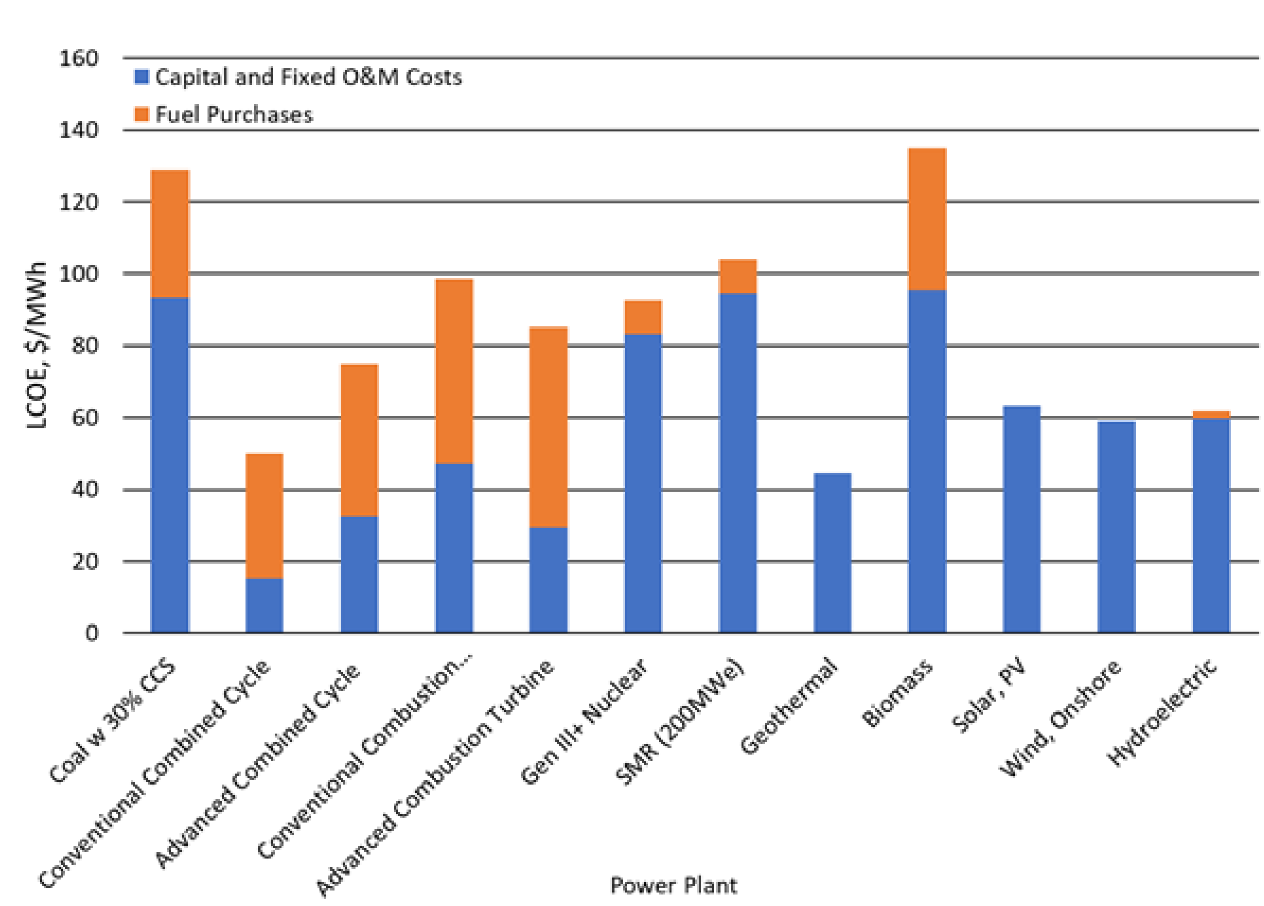
Extra Slide (3)

Economic Inputs for most promising design

Parameter	Value
Plant Parameters	
Capacity Factor (%)	95
Plant Output (MW)	1000
Plant Efficiency (%)	60
Total Lifetime (yr)	60
Ramp Period (yr)	5
Construction Period (yr)	1
Fuel Purchasing Plan	Capitalized
Fuel Parameters	
Burnup (MWd/kgU)	130
Fuel Enrichment (%)	19.75
Total Power Density (W/cm^3)	0.05
Fuel Material	UN

Extra Slide (4)

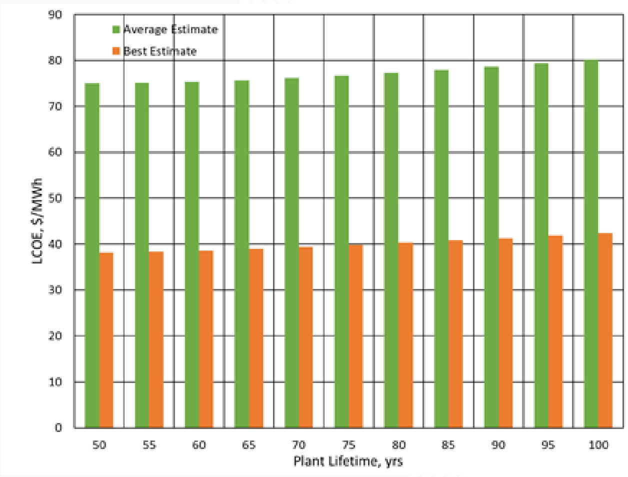
The LCOE breakdown for various other power sources

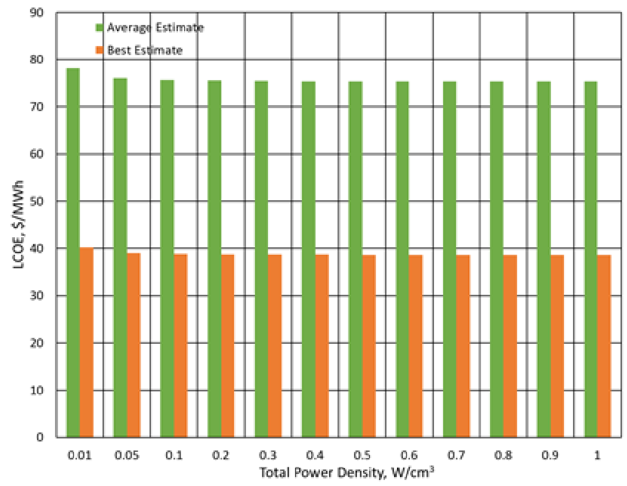


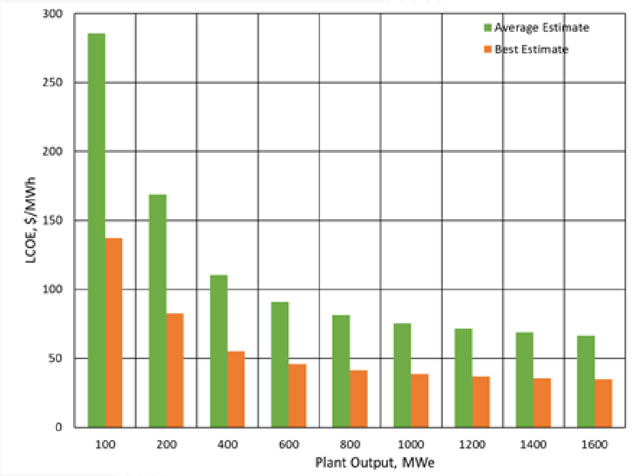
Georgia Tech
CREATING THE NEXT

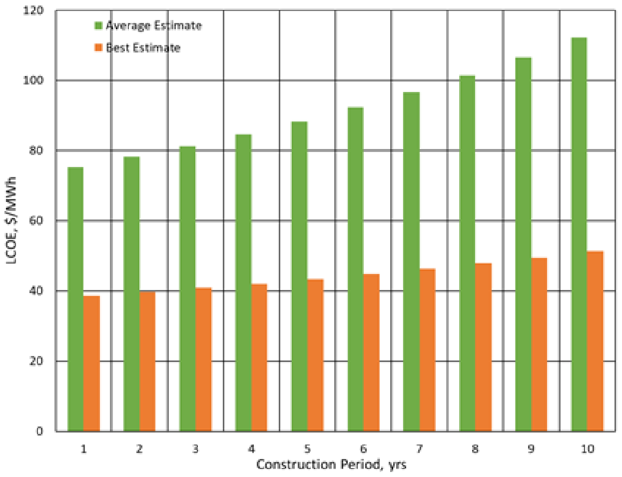
Extra Slide (5)

Additional Economic Sensitivity Figures





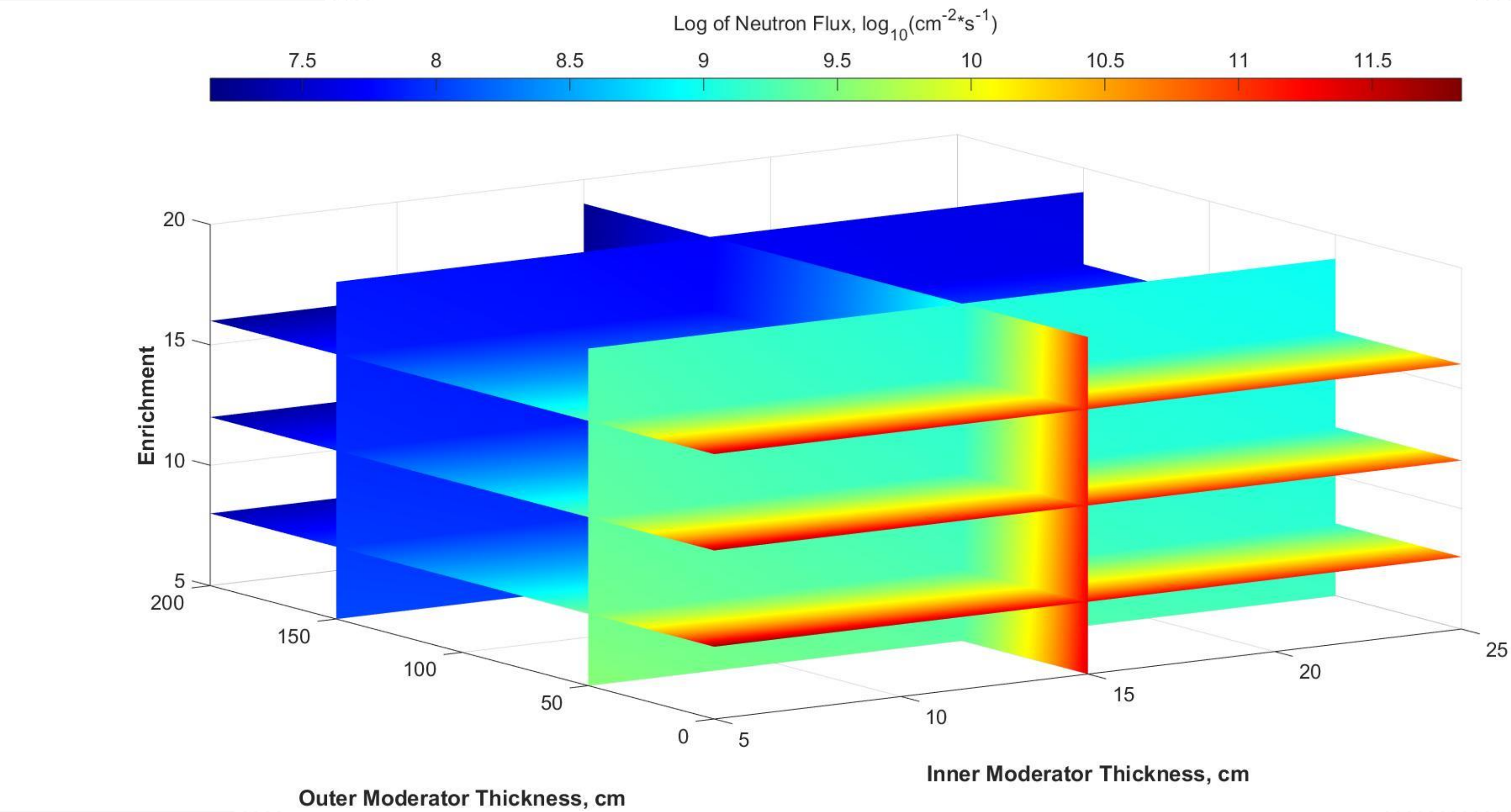




Georgia Tech
CREATING THE NEXT

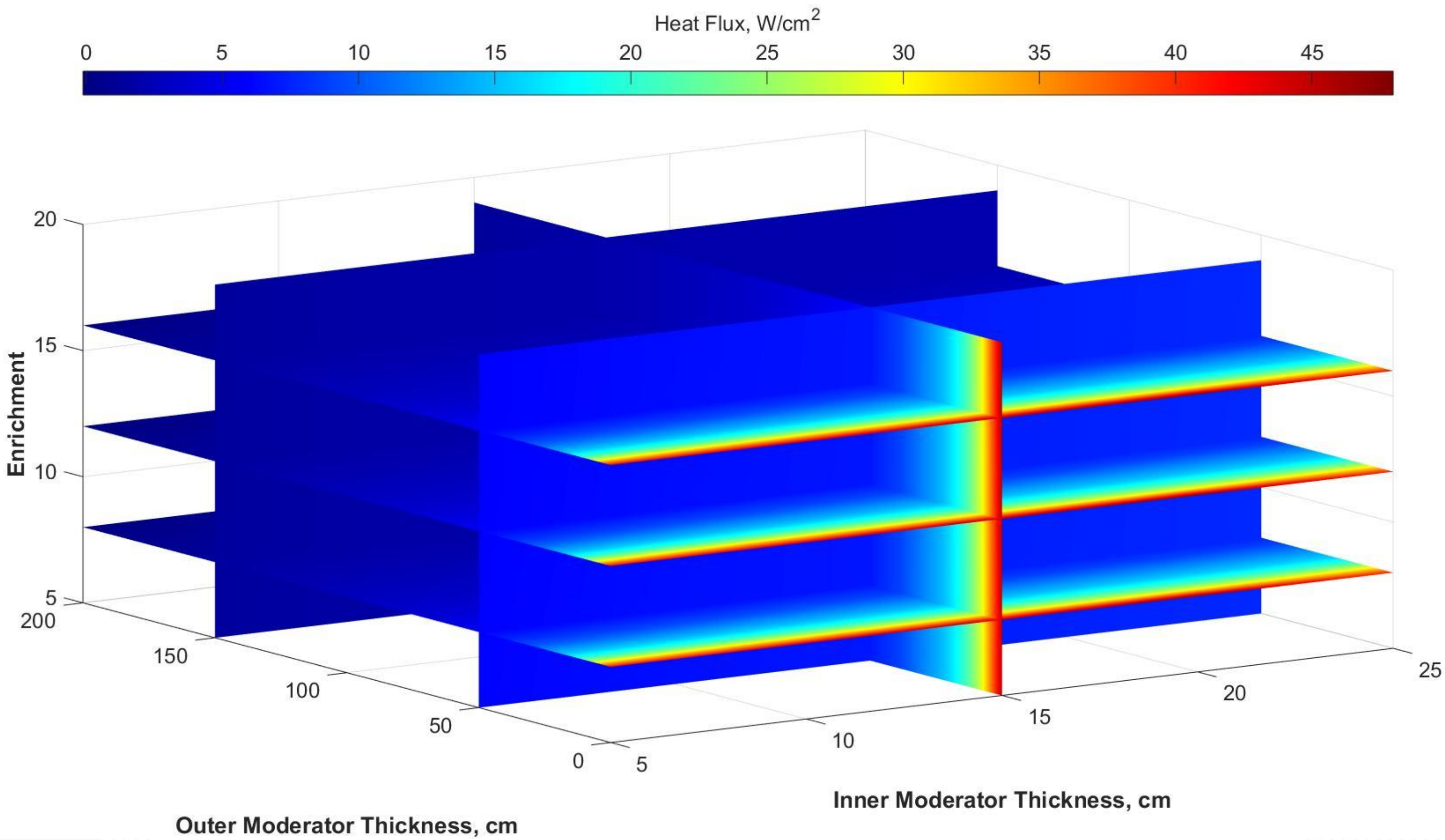
Extra Slide (6a)

Even More Moderating Ratio Tradeoffs



Extra Slide (6b)

Even More Moderating Ratio Tradeoffs



Georgia Tech
CREATING THE NEXT

Extra Slide (6c)

Even More Moderating Ratio Tradeoffs