Serpent Neutronic Calculations of Nuclear Thermal Propulsion Reactors

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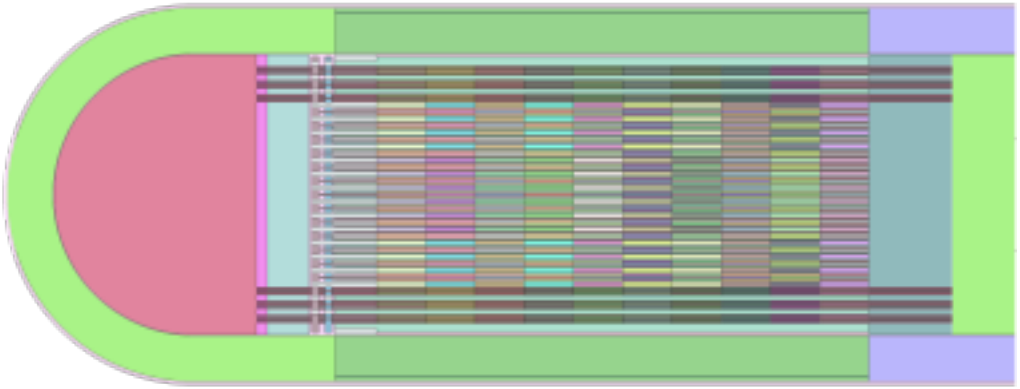
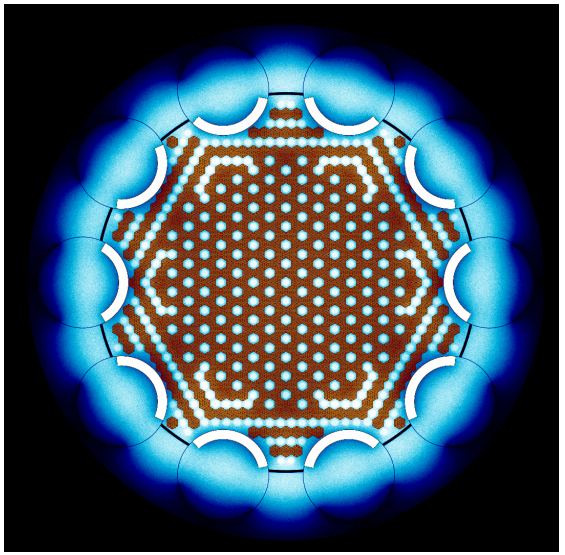
Overview

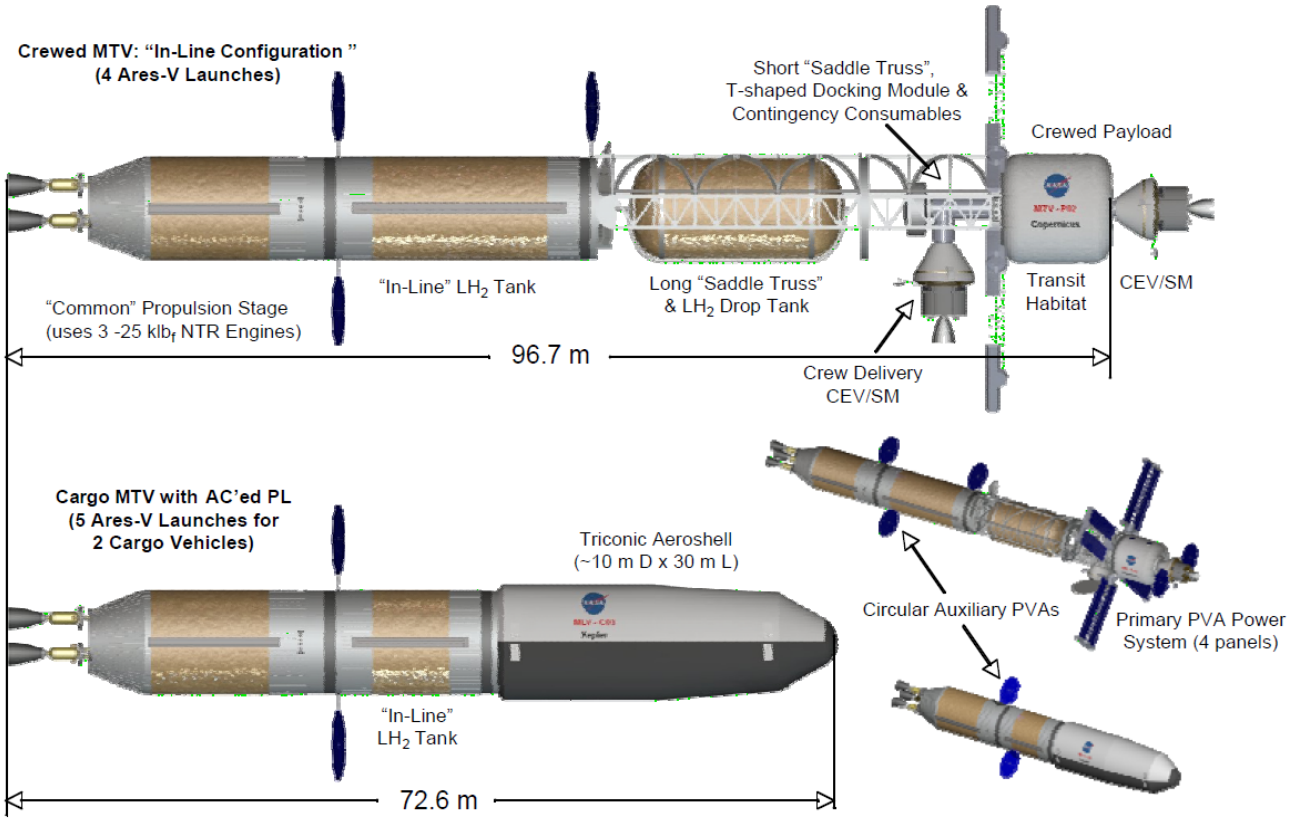
- **Nuclear Propulsion Overview**
- **Role of Serpent in NTP Research**
- **Examples of Analysis**
- **Future Implementations**
- **Conclusion**

Purpose

Introduce the application of Serpent to a reactor with advanced characteristics and novel operating conditions.



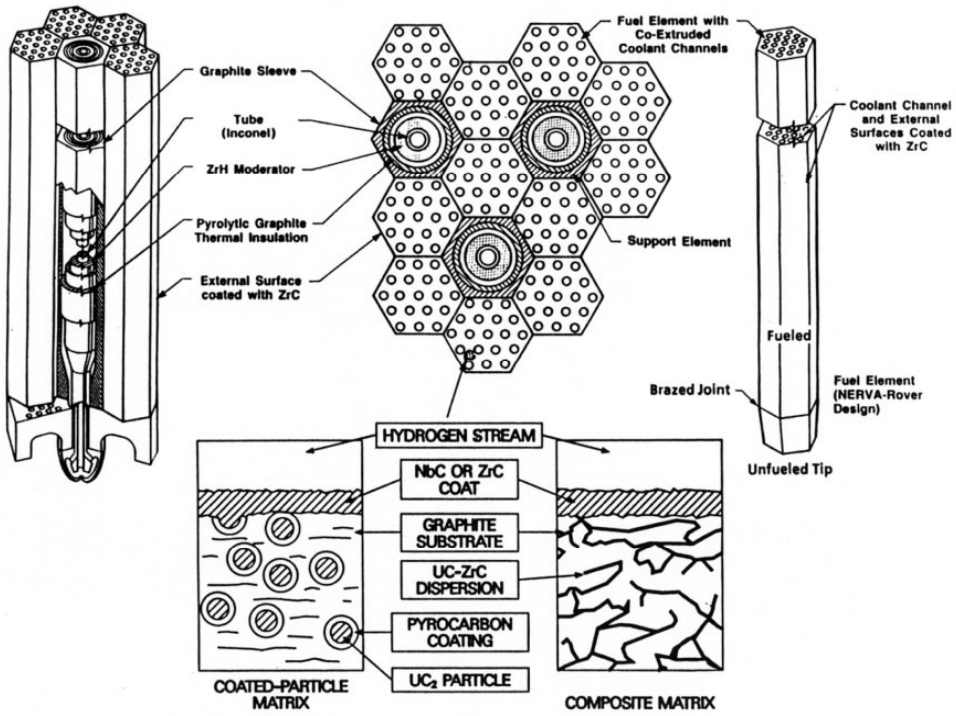


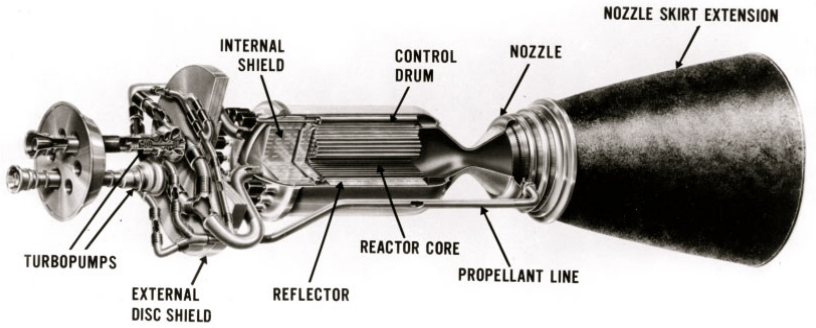


NUCLEAR THERMAL PROPULSION

Nuclear Thermal Propulsion Overview

- **Simple concept**
  - Extremely high temperature gas cooled reactor with a single pass open loop cooling cycle
  - Propellant heat is provided by nuclear reactor to provide thrust
- **Characteristic Operating Regime**
  - Hydrogen Coolant
  - Coolant outlet temperature > 2700 K
  - Coolant mass flow rate around 14 kg/s
  - Full power operation limited to 4 full power burns, each less than 30 min long
- **Critical for Human Exploration of the Solar System**
  - Minimize transit time
  - Maximize efficiency of propellant usage





Motivation:
Low Enriched Uranium Fuel is the Key to NTR Future

http://www.hq.nasa.gov/alsj/a17/ap17-KSC-72PC-589.jpg

HEU-NTR → LEU-NTR

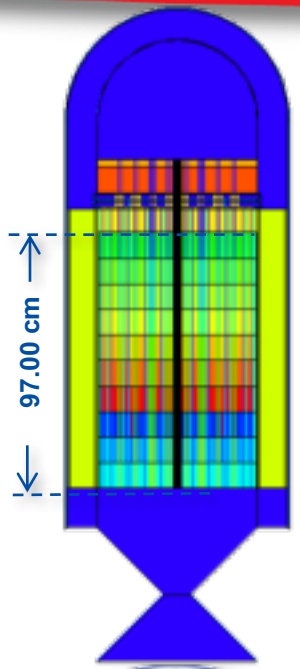
http://www.spaceref.com/news/viewpr.html?pid=27338

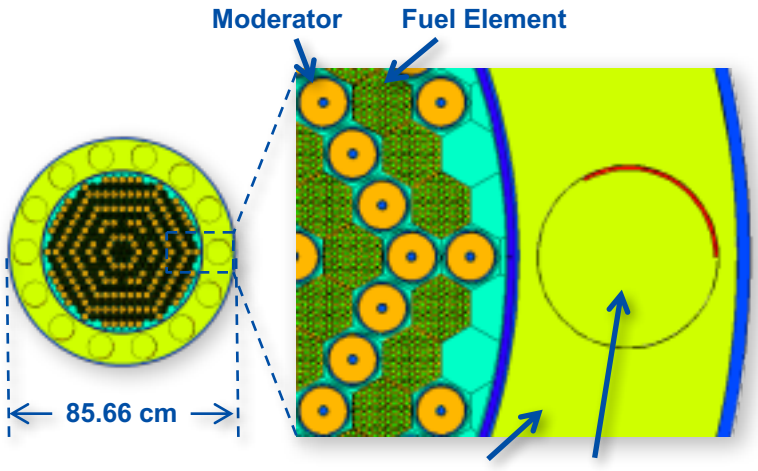
- Greatly lower costs of research and development
- Enable non nuclear weapon states to engage in serious R&D
- First concrete step towards eventual commercialization
- Enhances proliferation resistance

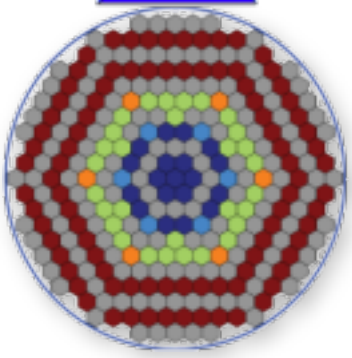
REFERENCE CORES:
TUNGSTEN CERMET AND GRAPHITE COMPOSITE

Space Capable Cryogenic Thermal Engine

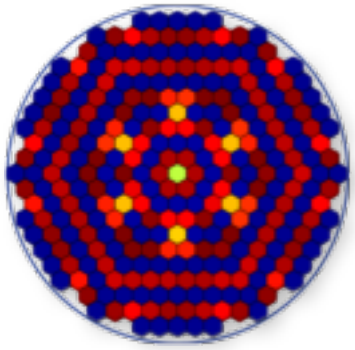
(Baseball Card as of 9/8/14, Rev. 1.0.1)



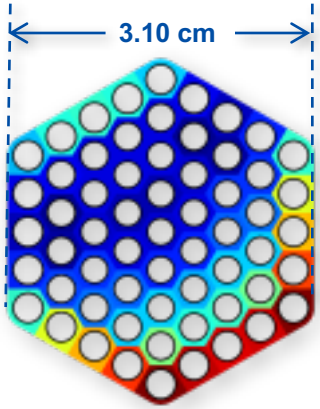




Radial Enrichment Zones (gray is moderator)



Core Power Deposition (Radial peaking factor of 1.089)

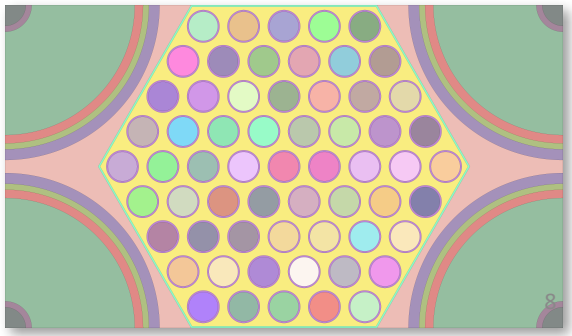


Channel by channel power deposition in a fuel element

General Description
SCCTE is a LEU W-UO_2 cermet fuel, $ZrH_{1.8}$ moderated nuclear thermal propulsion concept. SCCTE was produced with the Center for Space Nuclear Research's Space Propulsion Optimization Code (SPOC).

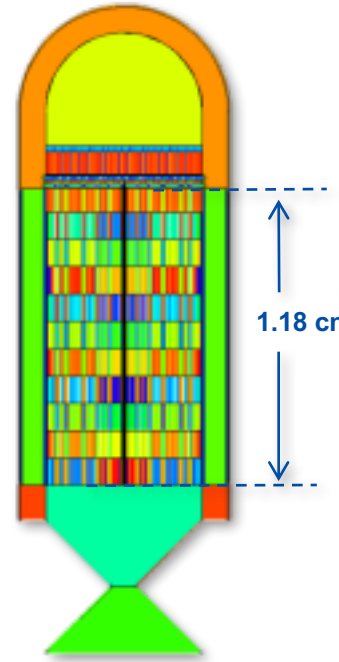
Key Performance Parameters	
Nominal Isp (150:1 Nozzle)	894
Nominal Thrust (kN)	157.3 (~35k lbsf)
Reactor Power (MW)	765.3
Fuel Temperature Max (K)	2850.0

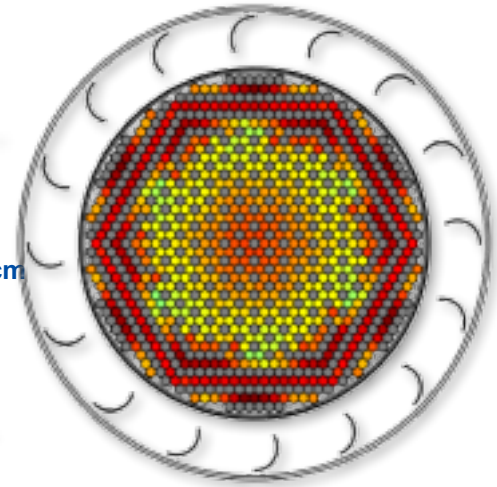
Fuel Details	
Fuel composition	W-UO_2-ThO_2
Volume loading of Oxide (% vol.)	60.0
ThO_2 in the Oxide (%mol.)	6.0
Enrichment of ^{184}W (% atom)	98.0
Enrichment of ^{235}U (% atom)	19.75 to 13.13
Total Enriched W (kg)	376.0
Total ^{235}U (kg)	45.9
Percent Theoretical Density (% TD)	97.0



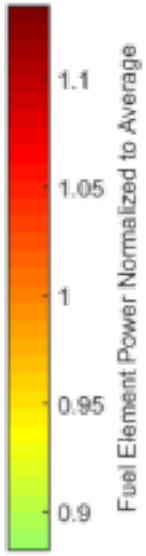
SULEU Baseball Card

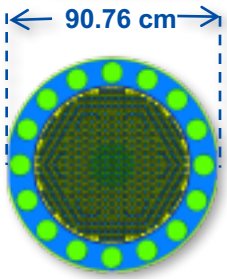
(Baseball Card as of 9/8/15, Rev 0.0.2)

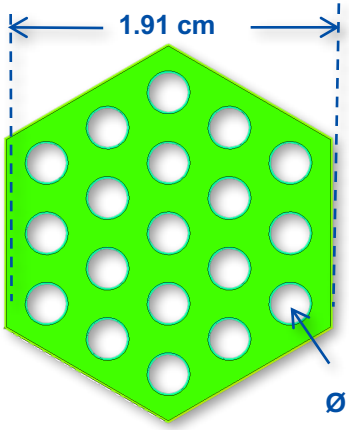


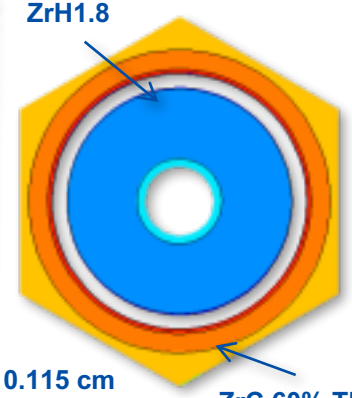


Fuel PPF 1.134







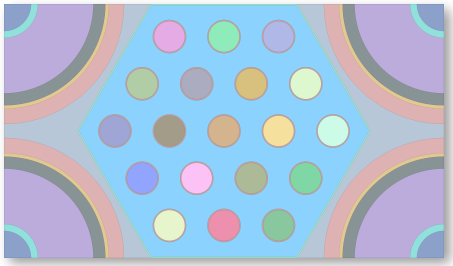


General Description
SULEU is a LEU Graphite Composite Fuel, $ZrH_{1.8}$ moderated nuclear thermal propulsion concept relying largely on heritage design.

Key Performance Parameters	
Nominal Isp (150:1 Nozzle)	897.7
Chamber Temperature (K)	2712.9
Nominal Thrust (kN)	155.7 (35k lbf)
Reactor Power(MW)	768.9
Fuel Temperature Max (K)	2850.0

Engine System Interface Information			
Interface Point	Flow Rate (kg/s)	Pressure (MPa)	Temp. (K)
Core inlet	17.68	8.0	300.0
Core outlet	17.68	5.0	2712.8

Fuel Details	
Carbide Fraction (% vol)	35
Uranium Loading (g/cm3)	0.64
Enrichment of ^{235}U (% atom)	19.75
Total ^{235}U (kg)	18.1
Fuel Coating	ZrC



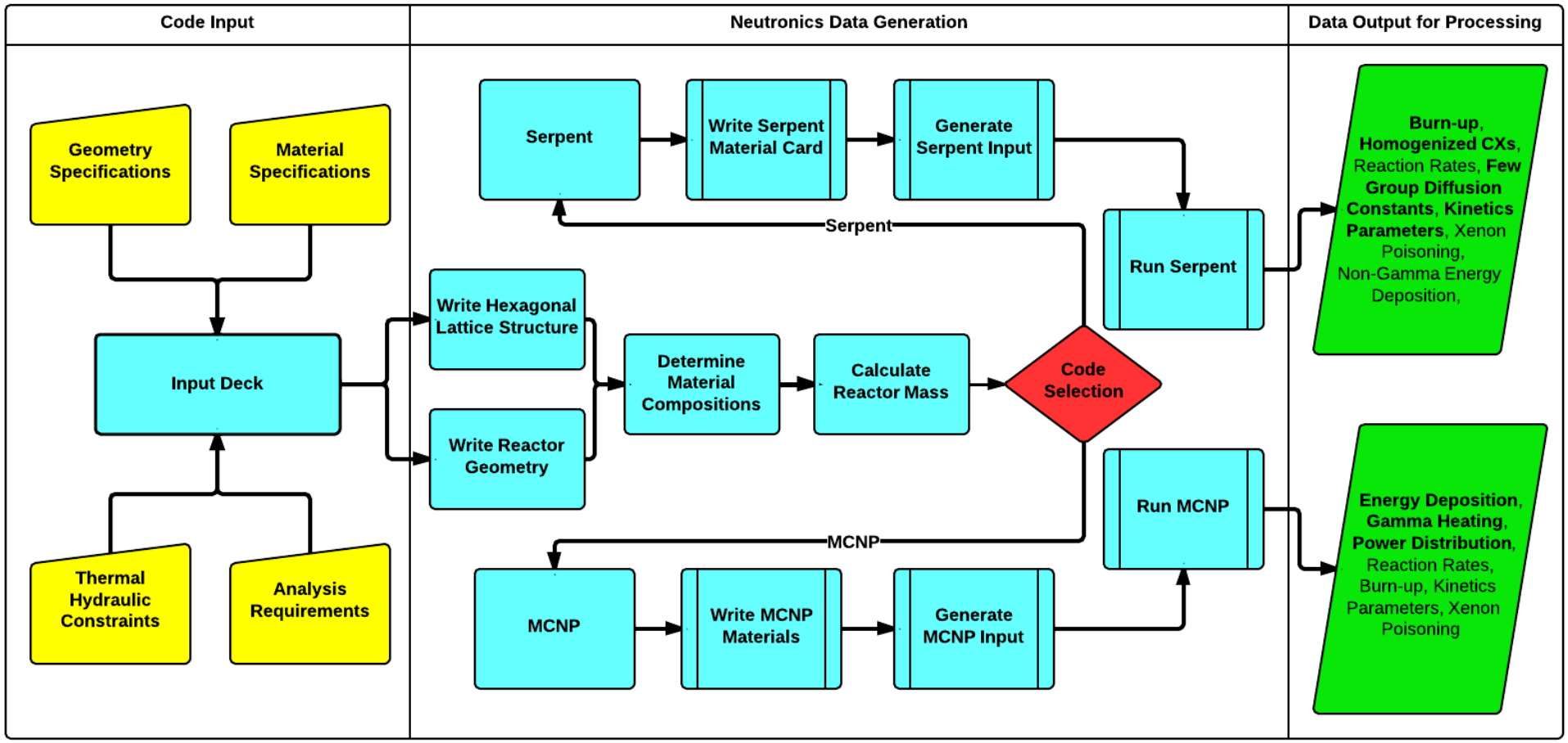
ROLE OF SERPENT IN NTP RESEARCH

Why Serpent?

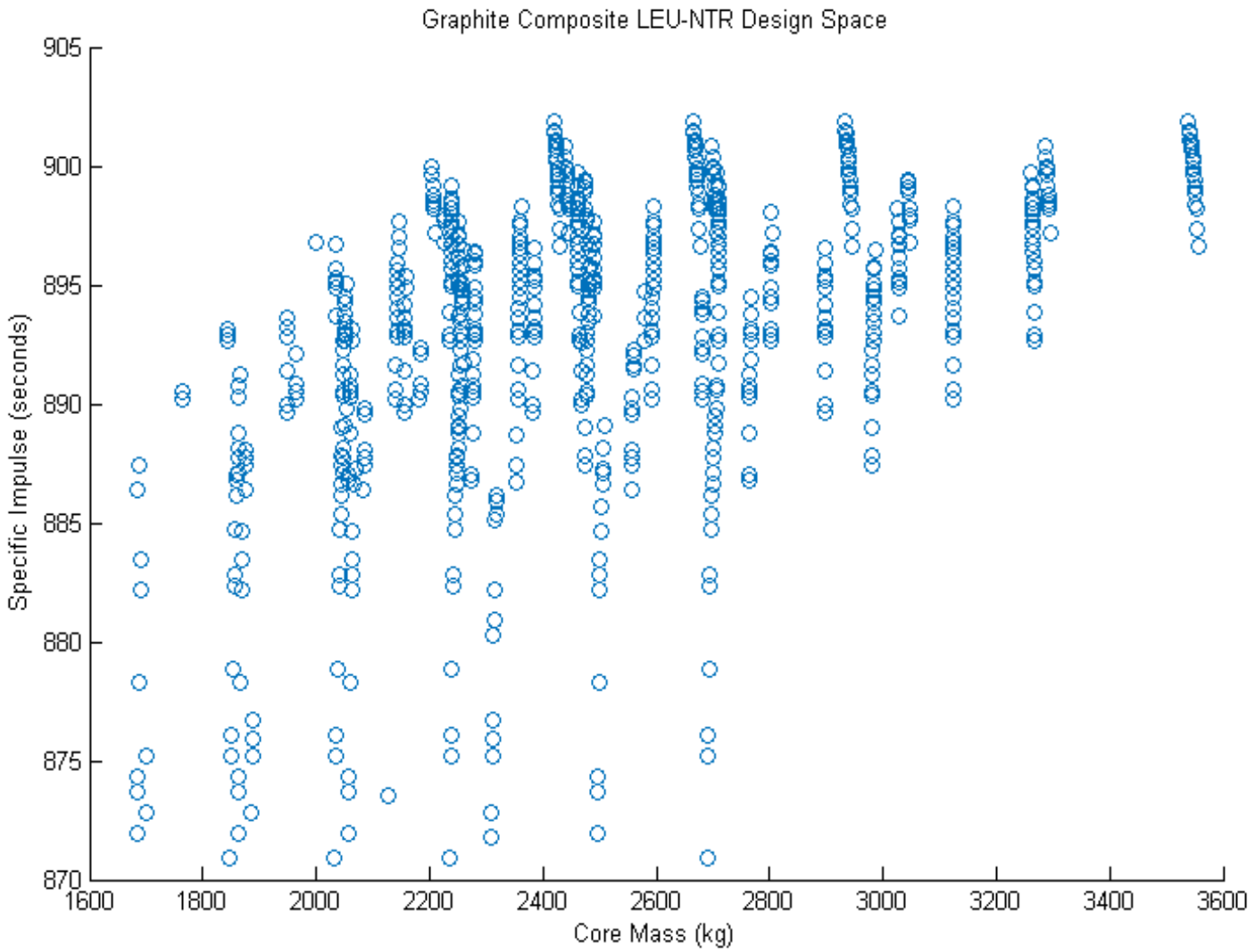
- **Lack of key tools**
  - Lattice code for NTP analysis
  - Fixed core design
  - Well documented criticality experiments
  - Recent operating experience
- **Limits Neutronic Analysis to Monte Carlo Codes**
  - MCNP Family
  - Serpent
- **Serpent Offers Key Advantages**
  - Rapid Burnup Calculations
  - Easily Accessible Outputs
    - Kinetic Parameters
    - Homogenized Cross-Sections
    - Reaction Rates
  - Easy to Work With
    - Modify key parameters
    - Material definitions
    - Output in MatLab/Python readable format

- **Promises:**
  - **Gamma transport**
  - **Easy integration of tallies to mesh format**
  - **Neutronic/Thermal coupling**

Serpent Integration

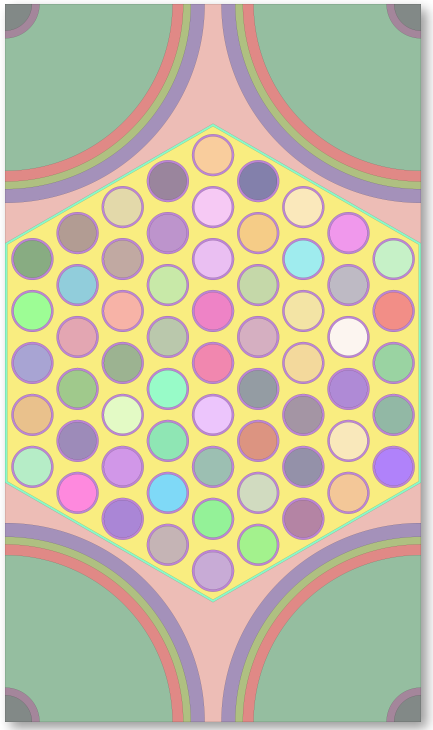


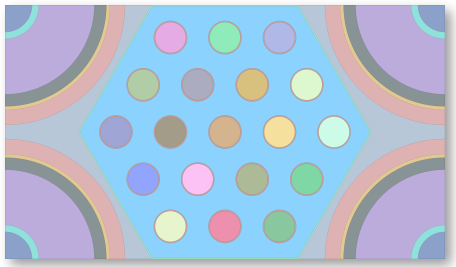
These are then Used to Generate Massive Studies



SSS Implementation

- **The Space Nuclear Industry Standard:**
  - MCNP
- **Serpent is a New Code for Space Nuclear**
  - We are the only ones who have used it
  - Some are skeptical that it works as promised
    - Massive time-savings for depletion calculations
- **Requires Comparison with MCNP at Every Step**
  - Infinite Lattice
  - Depletion
  - Finite Core
- **Current Application:**
  - Depletion
  - Component and Parameter Studies

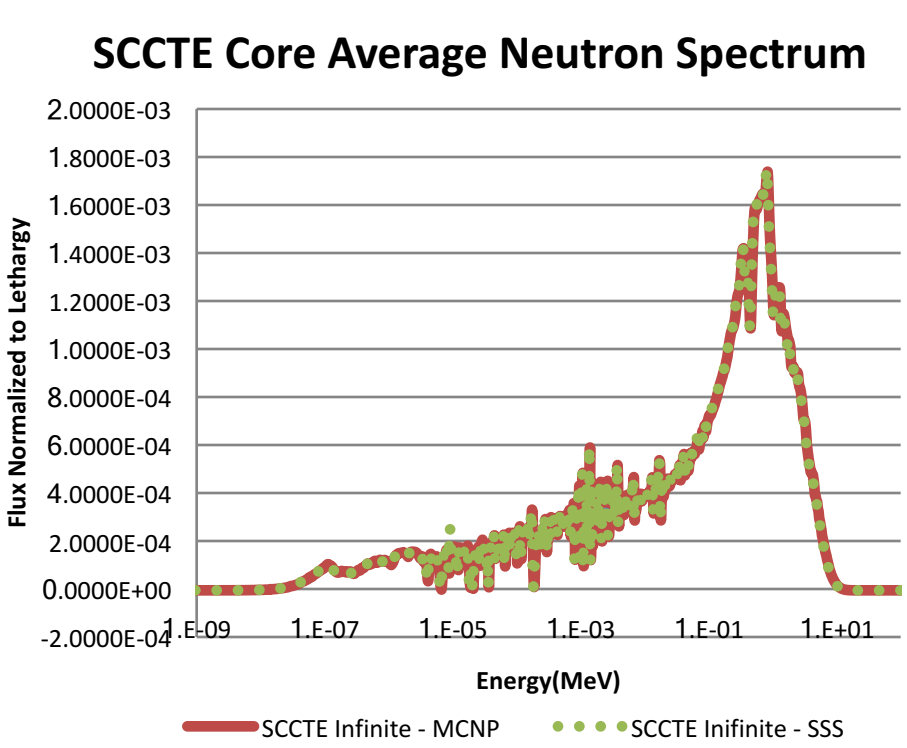


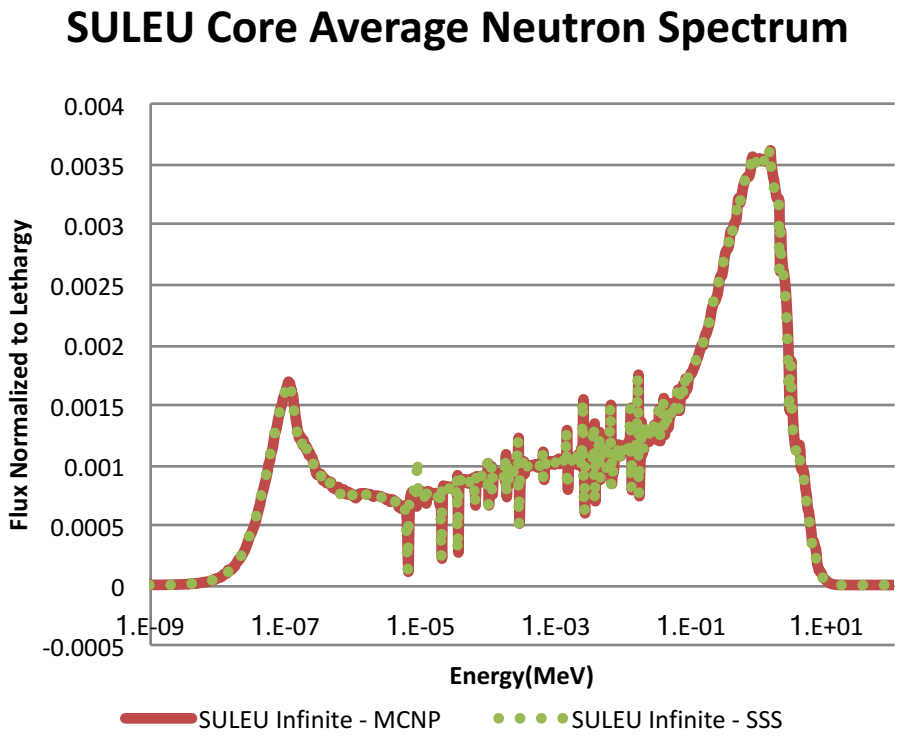


MANDATORY MCNP COMPARISON

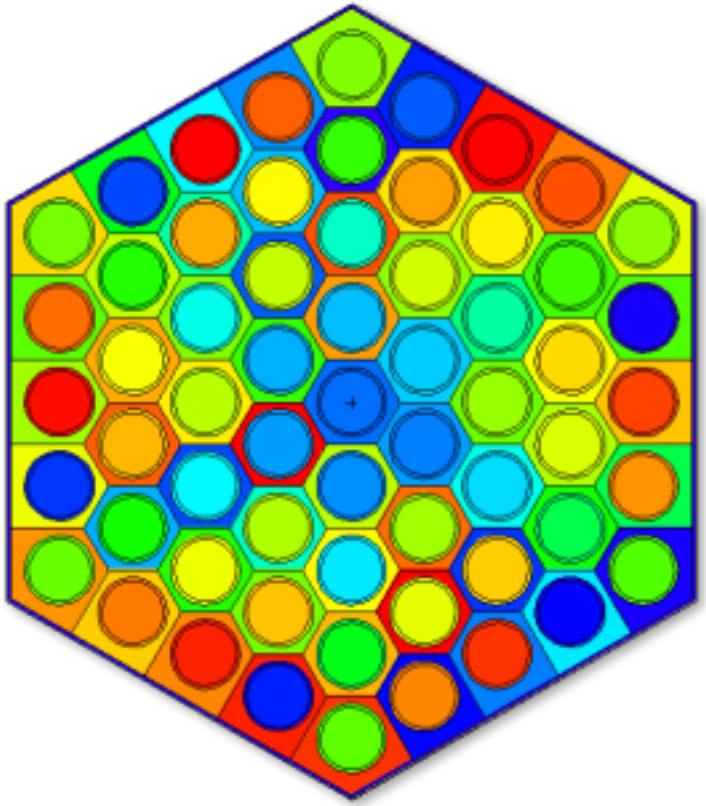
Infinite Lattice Comparison

	SSS2	Std. Dev	MCNP6 1.0	Std. Dev	Δρ (pcm)
SULEU	1.46939	0.00026	1.47232	0.00005	-135
SCCTE	1.16000	0.00023	1.15995	0.00006	5

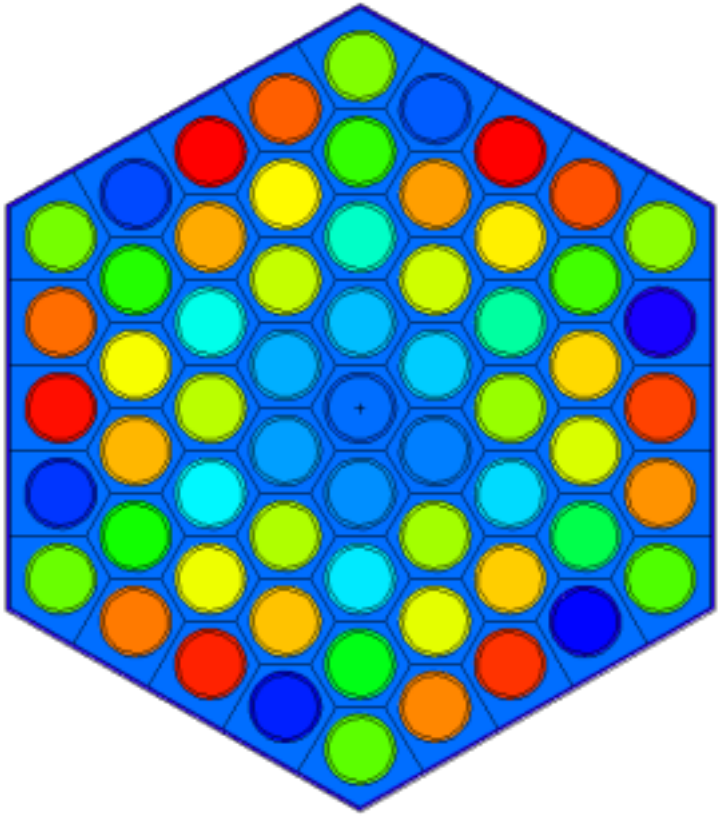




Self-Shielding Effects in Burnup

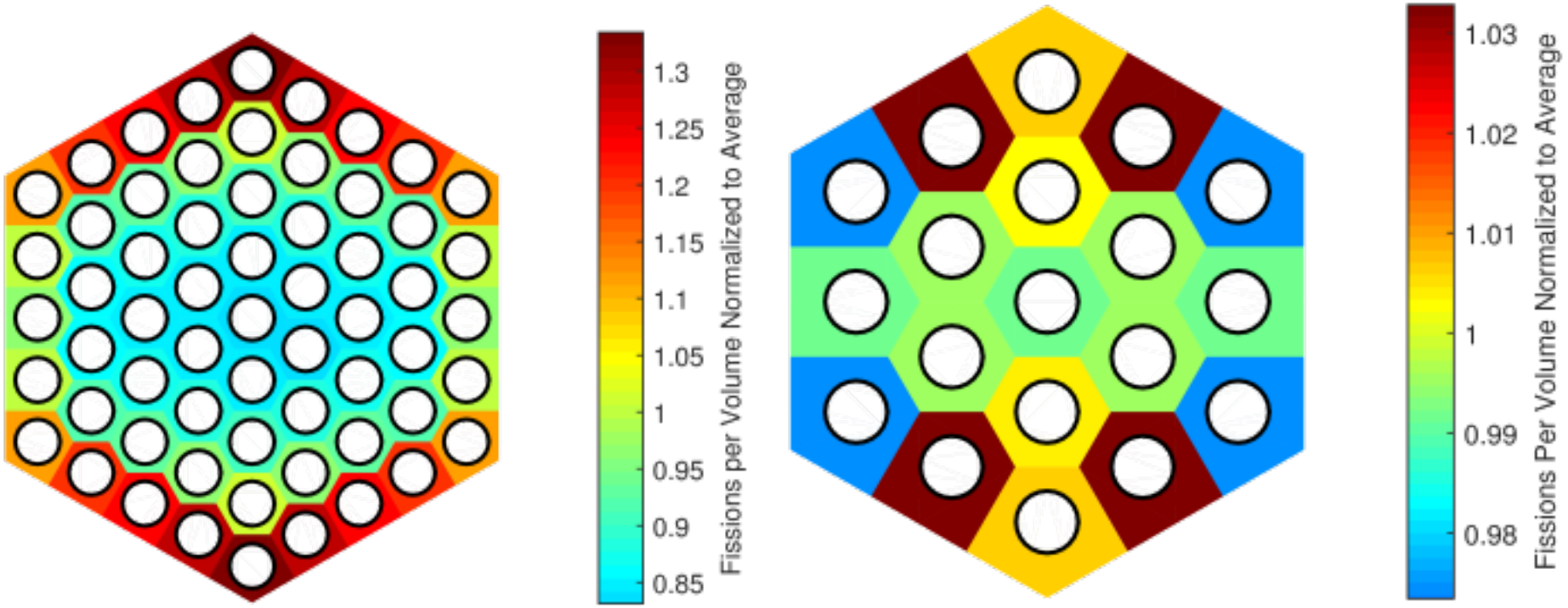


Channel by Channel (CBC)

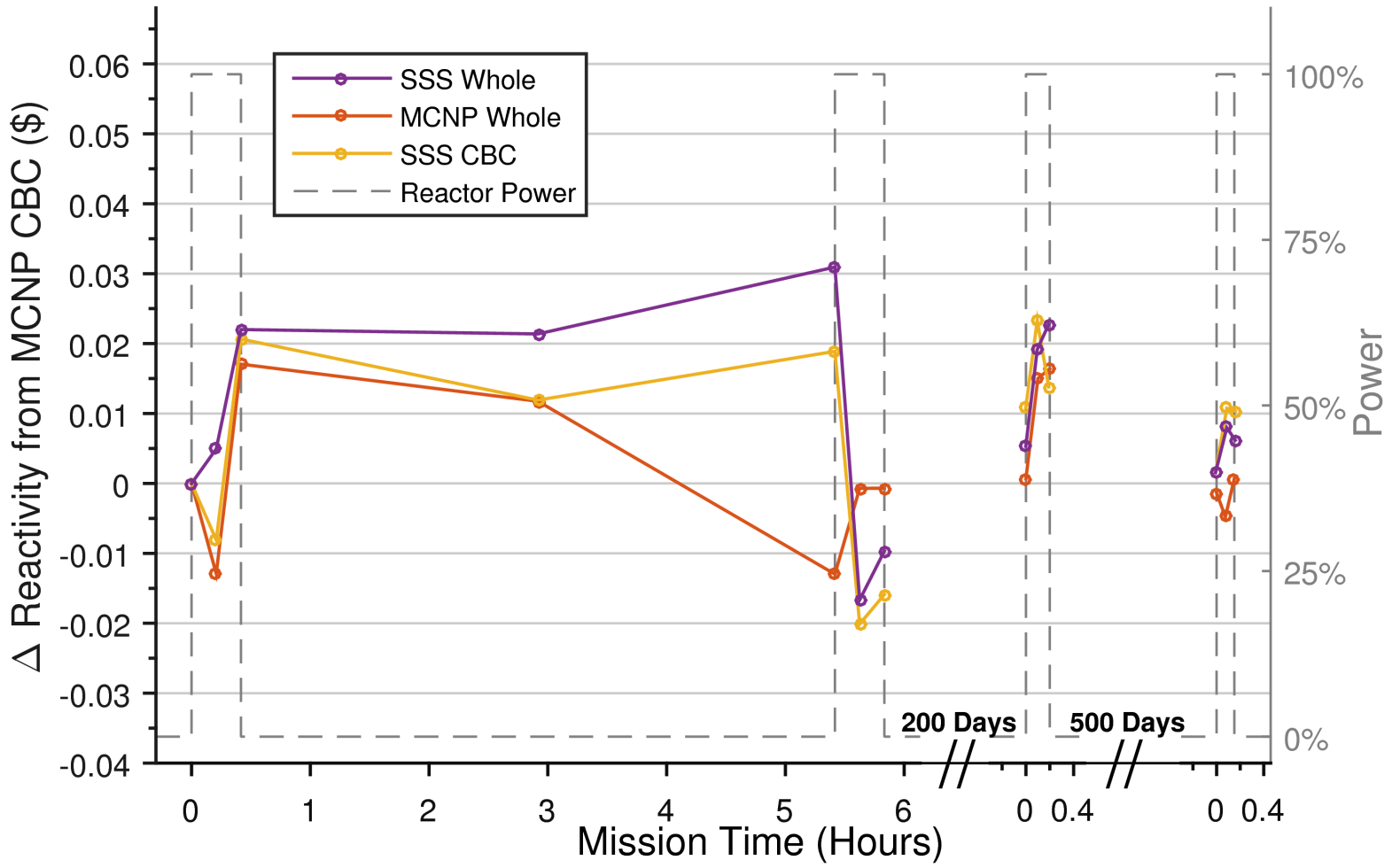


Whole

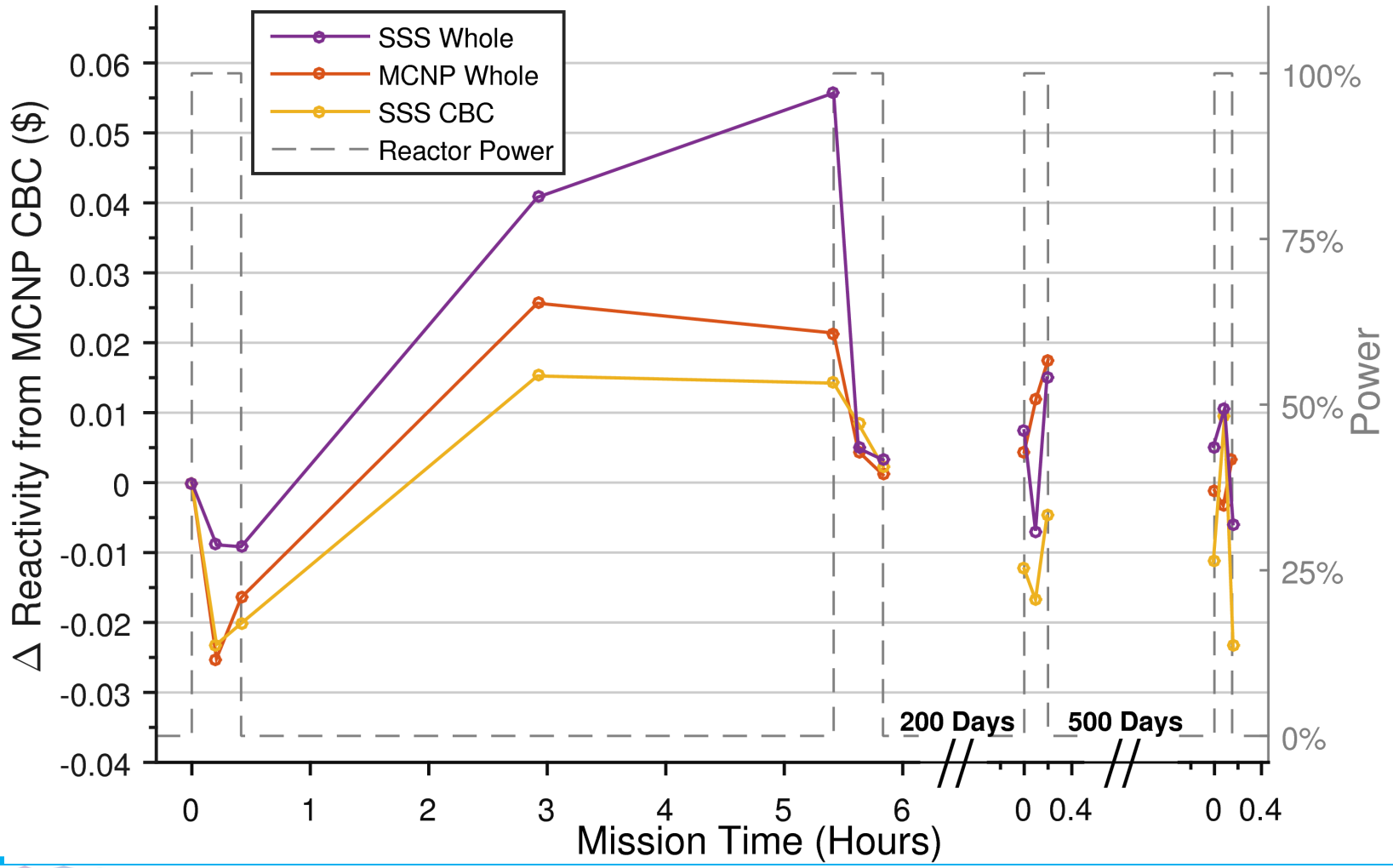
This is Why


1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
Fissions per Volume Normalized to Average
1.03
1.02
1.01
1
0.99
0.98
Fissions Per Volume Normalized to Average

SULEU MCNP vs Serpent Δ



SCCTE MCNP vs Serpent Δ



Finite Core

Case: ENDF VII.1 cross sections, ENDF-VII sab, 0 k cross-section, H at 300 K

SCCTE (CERMET)

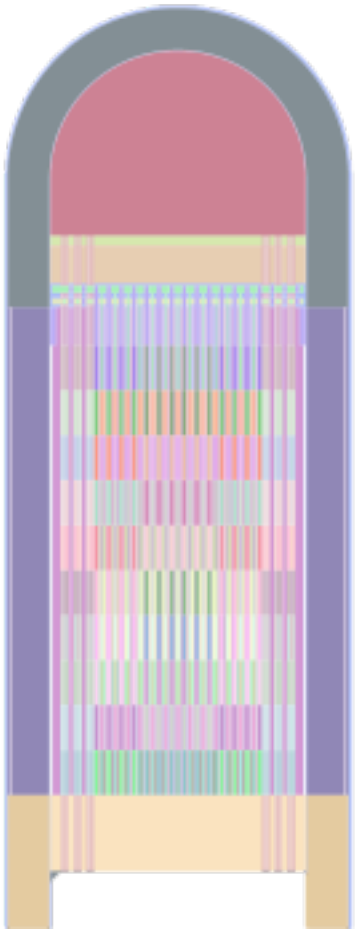
core temp (K)	MCNP6	std. dev.	SSS2	std. dev.	rho diff (pcm)
op temp	1.03678	0.00024	1.03624	0.00025	-50
300	1.05199	0.00025	1.05211	0.00024	11
600	1.04268	0.00023	1.04271	0.00025	3
900	1.03579	0.00021	1.03539	0.00024	-37
1200	1.0298	0.00023	1.03005	0.00025	24
2500	1.01342	0.00022	1.01356	0.00024	14

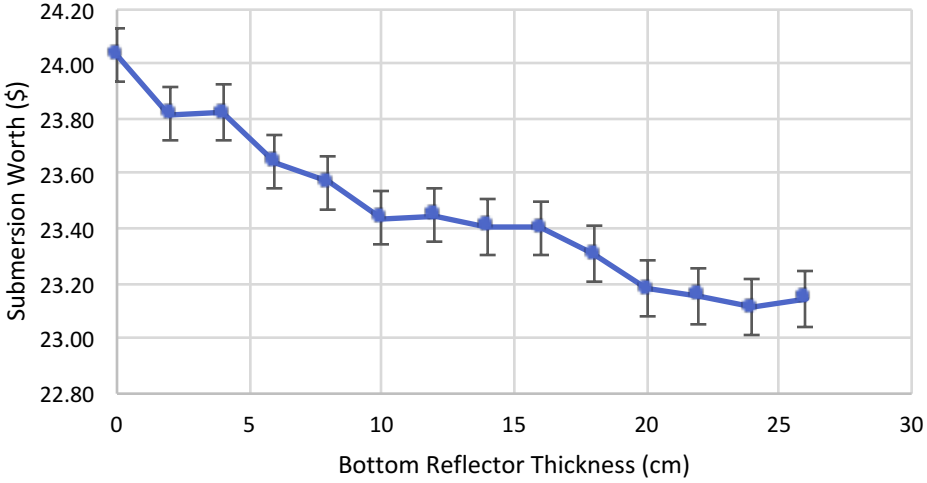
SULEU (Graphite Composite)

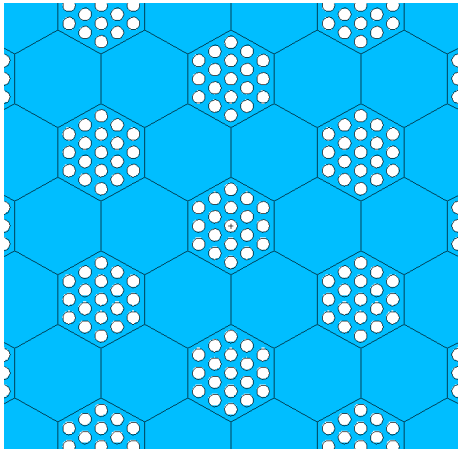
core temp (K)	MCNP6	std. dev.	SSS2	std. dev.	rho diff (pcm)
op temp	0.98381	0.00026	0.98585	0.00027	211
300	1.00970	0.00025	1.01403	0.00027	423
600	0.99660	0.00023	1.00031	0.00027	372
900	0.98747	0.00025	0.99088	0.00027	348
1200	0.97783	0.00025	0.98195	0.00026	429
2500	0.95218	0.00024	0.95611	0.00027	431

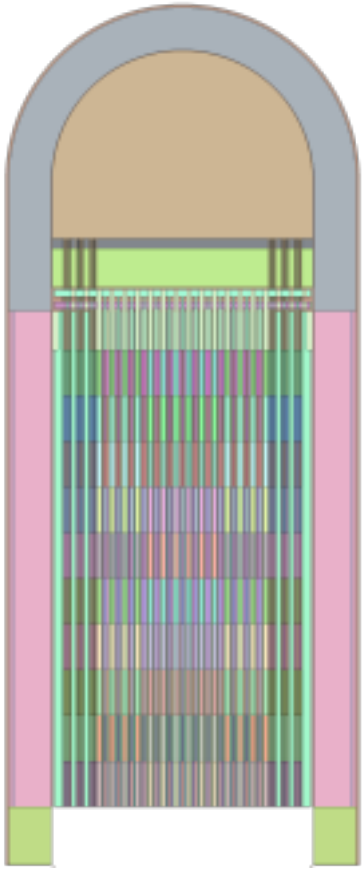
EXAMPLE IMPLEMENTATIONS

Axial Reflectors

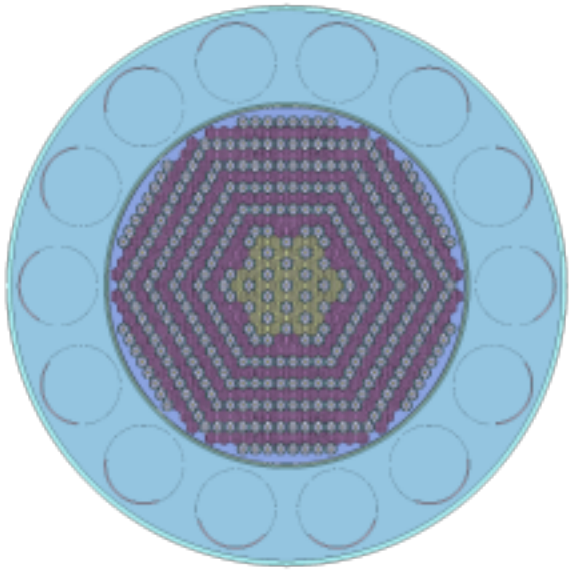
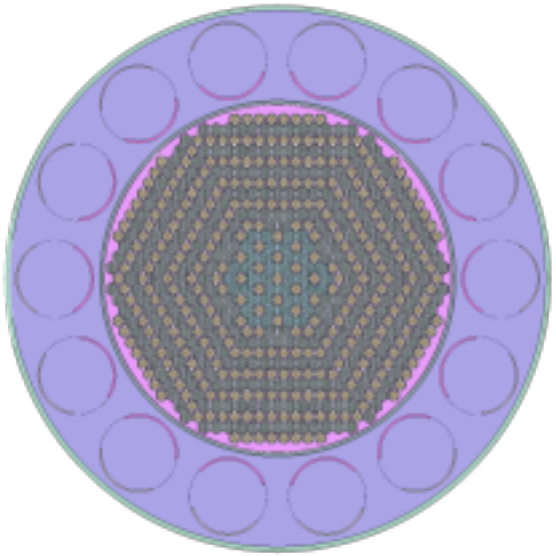
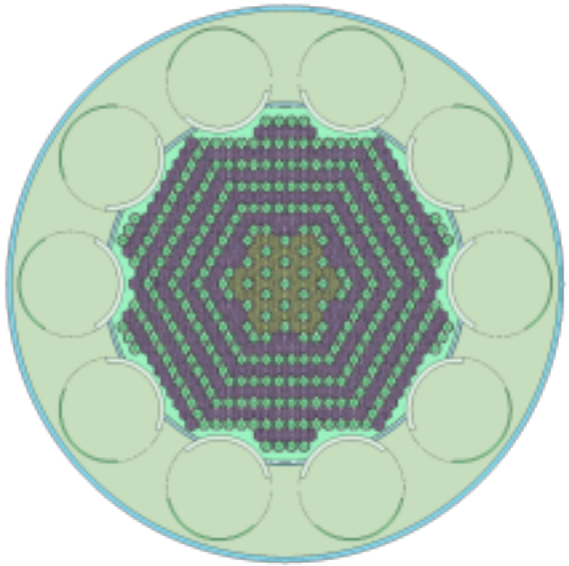
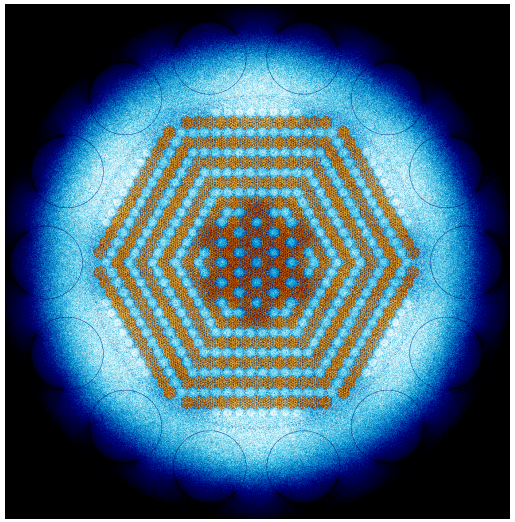
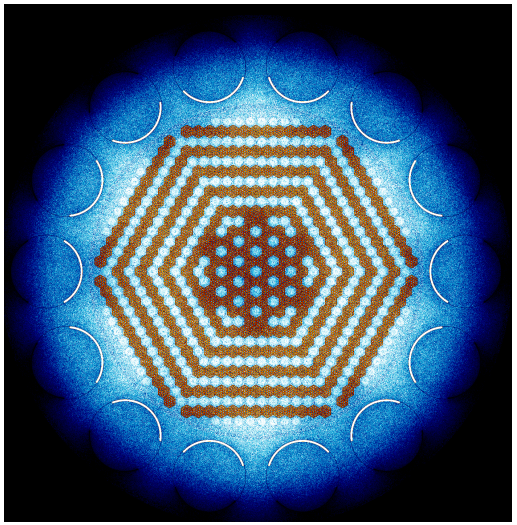
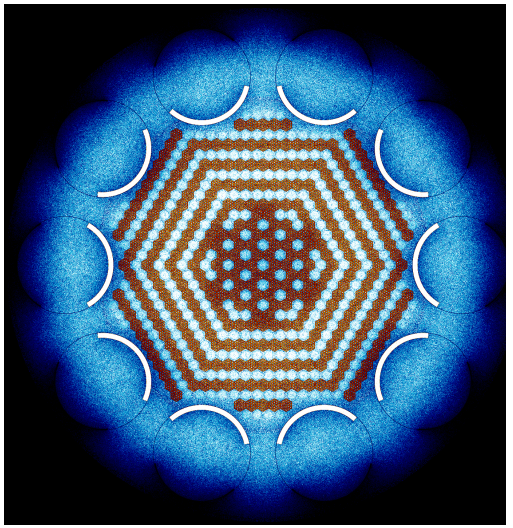




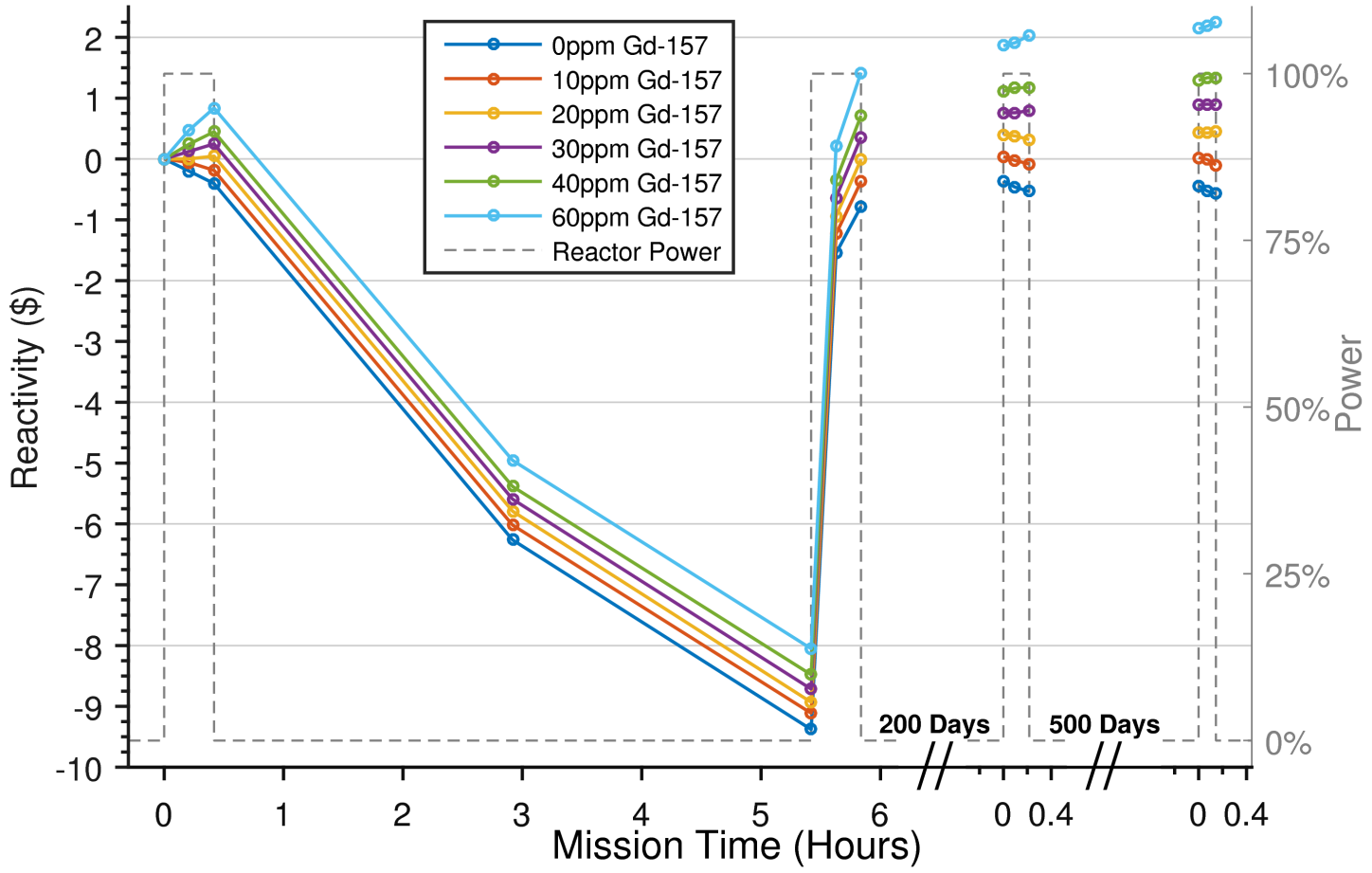




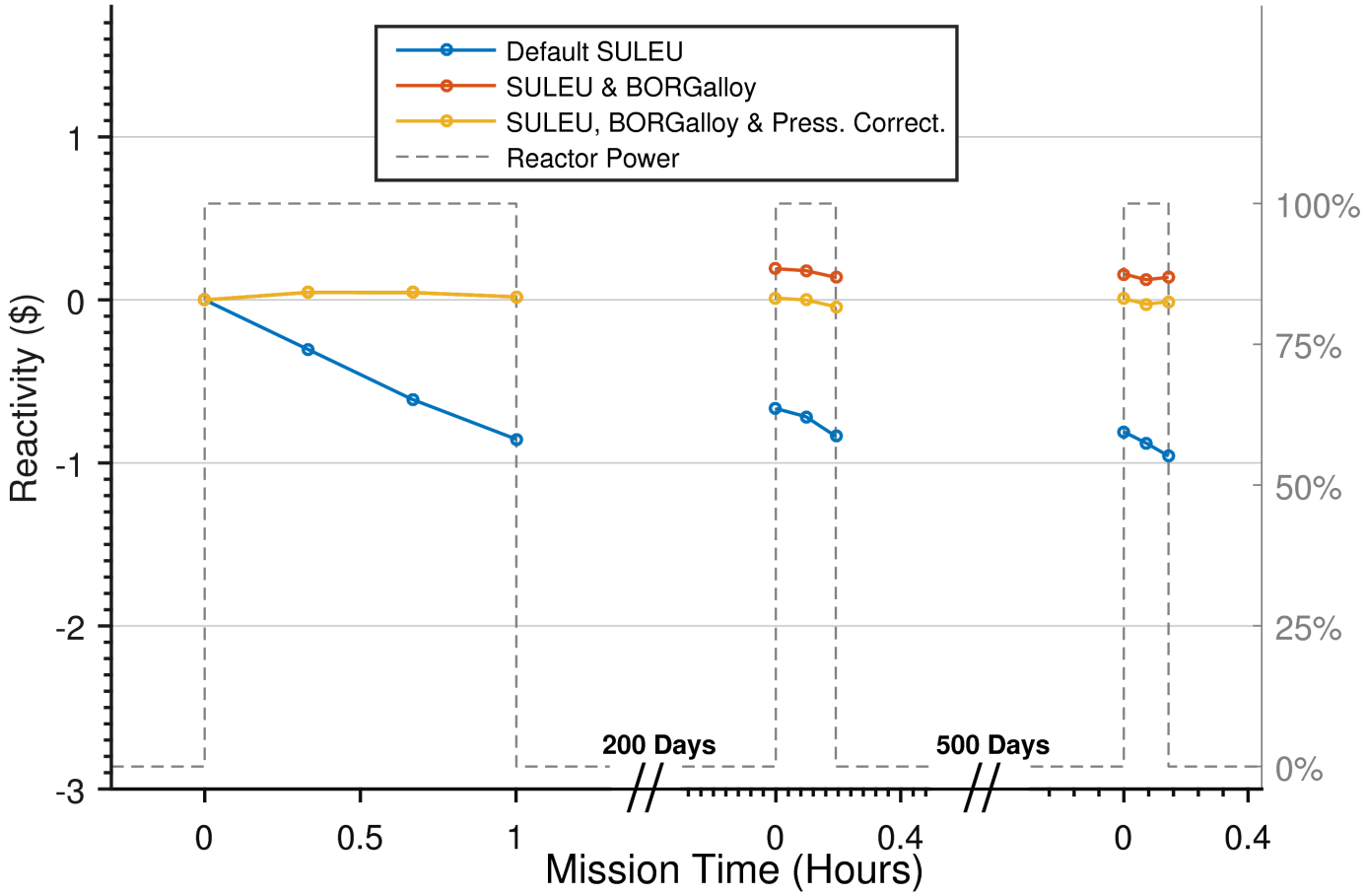
Alternative Control Drums

Finite Core Depletions



Which Finally Result In …



Dear Serpent Developer Team …

FUTURE SERPENT IMPLEMENTATIONS

Fully Implement TMP and Temp Dep. S(a,b)

Case: ENDF VII.1 cross sections, ENDF-VII sab, 0 k cross-section, H at 300 K

SCCTE (CERMET)

core temp (K)	No TMP	std. err.	Fuel TMP	std. err.	rho diff (pcm)
op temp	1.03636	0.00024	1.03836	0.00024	186
300	1.05205	0.00024	1.05406	0.00023	181
600	1.04210	0.00024	1.04484	0.00024	252
900	1.03619	0.00024	1.03826	0.00023	192
1200	1.03032	0.00024	1.03243	0.00024	198
2500	1.01358	0.00024	1.01642	0.00024	276

SULEU (Graphite Composite)

core temp (K)	No TMP	std. err.	Fuel TMP	std. err.	rho diff (pcm)
op temp	0.97671	0.00027	0.97615	0.00027	-58
300	1.00297	0.00026	1.00275	0.00026	-22
600	0.98956	0.00027	0.98992	0.00027	37
900	0.98120	0.00027	0.98141	0.00027	21
1200	0.97187	0.00027	0.97229	0.00027	45
2500	0.94701	0.00029	0.94698	0.00029	-4

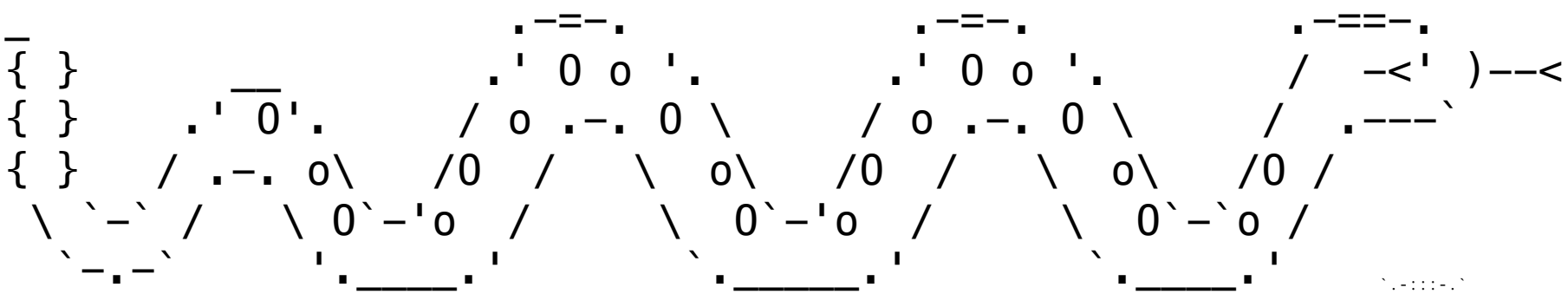
Neutronic/Thermal Coupled Simulations

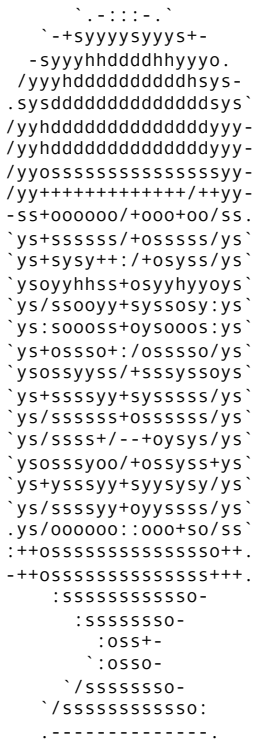
- **Current Couplings:**
  - Steady State
  - MCNP coupled to Channel Analysis or ANSYS
- **Our Objective:**
  - Remove the need for MCNP
  - Transient and Steady State
  - Serpent Enabled
    - Directly providing energy deposition
    - Cross-section and group constant generation
  - Coupling with a System Analysis Environment
    - MOOSE Framework?
      - MAMMOTH
      - BISON
      - RELAP etc.
- **What We Need in Serpent**
  - Gamma and Radiative Heat Transport

Conclusion

- **Nuclear Thermal Propulsion is Real**
  - Very good chance that we (NASA lead) will build a system in the next 5-10 years
- **Serpent has been an Enabling Code**
  - Speed of Calculation
  - Ease of Use
  - Developing Team Support
  - Active User Community
- **Only partial Implementation has been realized**
  - Used for k-eff parametric studies and component development
  - Depletion calculation
  - Energy tallies are waiting on gamma and heat transport functionality
  - Advanced features have been avoided in order to ensure MCNP equivalency

Credit Where It's Due





THANK YOU

QUESTIONS?