Conceptual Nuclear Design of Innovative Liquid HALEU-loaded Thermal Propulsion Reactor

액체 고순도저농축우라늄(HALEU) 연료를 사용하는 열추진 원자로 핵설계 개념 연구

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Presentation Outline

- **Introduction**
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  2. Historical Perspective
- **Objectives**
- **Reactor Concept and Methods**
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  2. Fuel
  3. Moderator
  4. Reactor Mass
- **Results and Analysis**
  1. Neutronics
  2. Power Distributions
  3. Reactivity Coefficients
- **Summary and Future Work**
- **References**

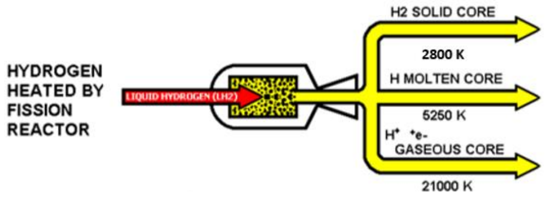
Introduction

1. Principles of Nuclear Rocket Propulsion

Chemical Engine

Fuel = *Propellant*

Nuclear Engine



Fuel ≠ *Propellant*

U ≠ H_2

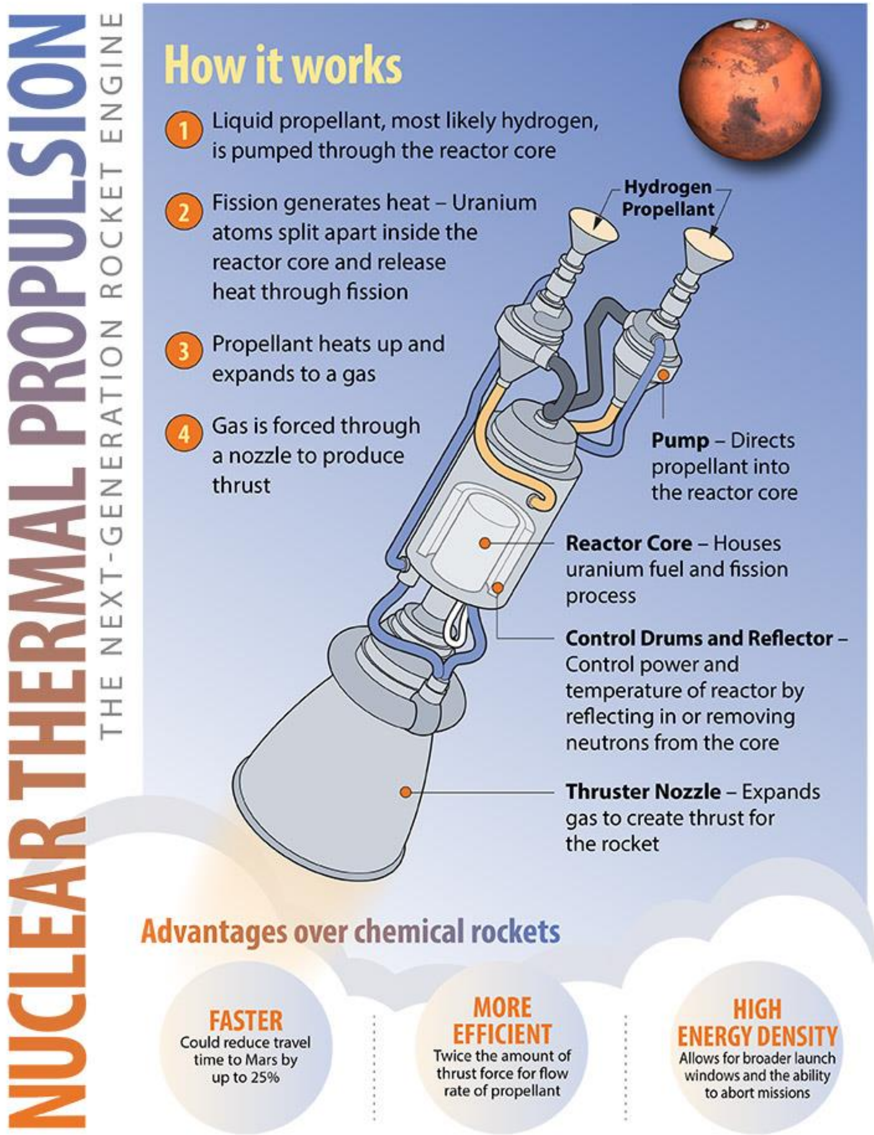
→ **Why Nuclear ?**

$I_{sp,\ \mathrm{Nuclear}} = 2\sim3\ I_{sp,\ \mathrm{Chemical}}$

Rocket efficiency ∝ I_{sp} (Specific impulse) ∝ $T_{\text{exhaust gas}}$

Energy-limited

Power density-limited T_{max}



2. Historical Perspective

Nuclear Engine for Rocket Vehicle Applications (NERVA)

- *Prismatic fuel elements*

• Late 1950s (US)

Fuel Design Development

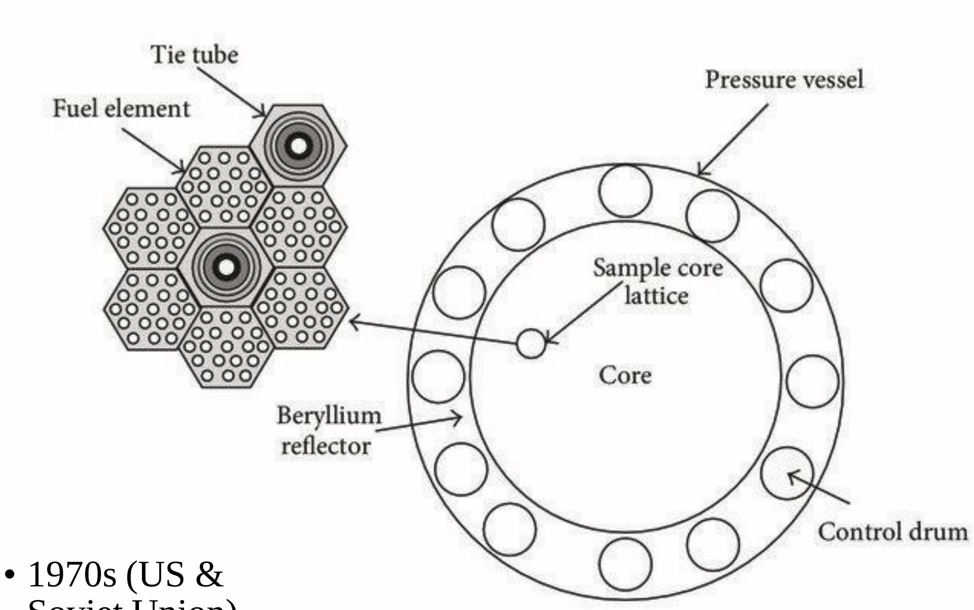
- *Cermets (Ceramic Metals)*

• 1970s (US & Soviet Union)

Timberwind Program

- *Particle bed reactor*

• Until 1990s (US Air Force)



Solid-core reactors fueled with highly enriched uranium.

Introduction

Specific Impulse:
A measure of the efficiency of a rocket or jet engine.

$$I_{sp} = \frac{v_e}{g_c} = \frac{F}{g_c \dot{m}} = \frac{1}{g_c}\sqrt{\frac{2\gamma}{\gamma - 1}\frac{R_u}{mw}T_c\left(1 - \frac{T_e}{T_c}\right)}$$

2. Historical Perspective

Program	NERVA	CERMET	Particle Bed Reactor
	Graphite Composite	*Refractory Metal Composite*	*Monolithic Carbide*
Fuel Compound	UC_2	UO_2 UN	(U, Zr)C (U, Nb)C
Matrix Material	Graphite	Tungsten	N/A
Geometry	Solid block w/coolant channels		Particle Bed
$T_{fuel, exit}$ (K)	2750	**2900**	2800
I_{sp} (s)	890	**945**	915

- **Higher Specific Impulse (I_{sp}):**
Shortens human missions to Mars compared to chemical propulsion.

- **Limitation:**
Still insufficient for longer missions, such as journeys to Jupiter's moon Europa.

If nuclear thermal rockets are assumed to be the baseline for nuclear propulsion systems

→

Increasing I_{sp} will require that structural or thermodynamic limitations be overcome or bypassed

T_{max}

Objectives

Objectives

To design an NTP that can achieve high propellant temperature > 3000 K.

nuclear power reactors. Standard reactors have a solid "core" made of an assembly of bars containing nuclear "fuel." The most common isotope nuclei capable of fissioning are Uranium and Plutonium, but others exist: these isotopes may be in the form of alloys, of ceramics, in pellets, or in the liquid/gaseous state. For instance, in most commercial reactors, solid ^{235}U-enriched fuel inside bars fissions, releases heat to a coolant flowing through the bar channels and is expanded in a turbine producing electricity. In a space reactor, the coolant (for instance, hydrogen) is ejected from a nozzle; so in a NTR, the coolant is also the propellant. In NTR fission, heat release occurs inside solid bars, limiting temperature to what the bar can tolerate without cracking, corroding, or melting. More advanced concepts to bypass the melting point of Uranium-based fuels include liquid and gaseous fuel cores. The issue of high-temperature materials is critical in all thermal rocket engines, because it controls and limits the I_{sp} that can be obtained.

Until recently, solid fuel temperatures above 2500–3000 K were thought unrealistic: UO_2 melts at 2800 °C, UC at 2400 °C and UN at 2630 °C.

T_{max}

Liquid Fuel Core

- ❑ $\uparrow I_{sp}$
- ❑ $\uparrow T_{exhaust}$
- ❑ $\downarrow t_{travel}$
- ❑ $\downarrow dose = \varphi_{radiation} \times t_{exposure}$

Objectives

- **Motivation for using liquid fuel:**

Bypassing the melting temperature of fuel	• Higher T_{fuel} up to the boiling point ~3500˚C. T_{max}
Homogeneous fuel composition	• Fuel burnup is relatively uniform in the axial direction.
Enables for noble gas diffusion "Xe-135"	• Simplifying reactivity control and extending core lifetime.

- **Optimization goals:**

Reactor Mass < 2500 kg	**$T_{exhaust} \geq 3000$ K**	**Thermal Spectrum**	**Thermal Power**
↓	↓	↓	↓
To not waste thrust	To improve I_{sp}	↑ neutron economy and proliferation resistance	To keep the fuel in liquid state

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Reactor Concept and Methods

Reactor Concept and Methods

1. Baseline Core:

- **Conceptual Core Design**
- **Baseline Core**
- Core Description
- Fuel
- Moderator
- Reactor Mass
- Simulation

Superb Use of Low Enriched Uranium (SULEU)

SULEU is a graphite composite fuel, $ZrH_{1.8}$ moderated LEU nuclear thermal propulsion concept relying largely on heritage design.

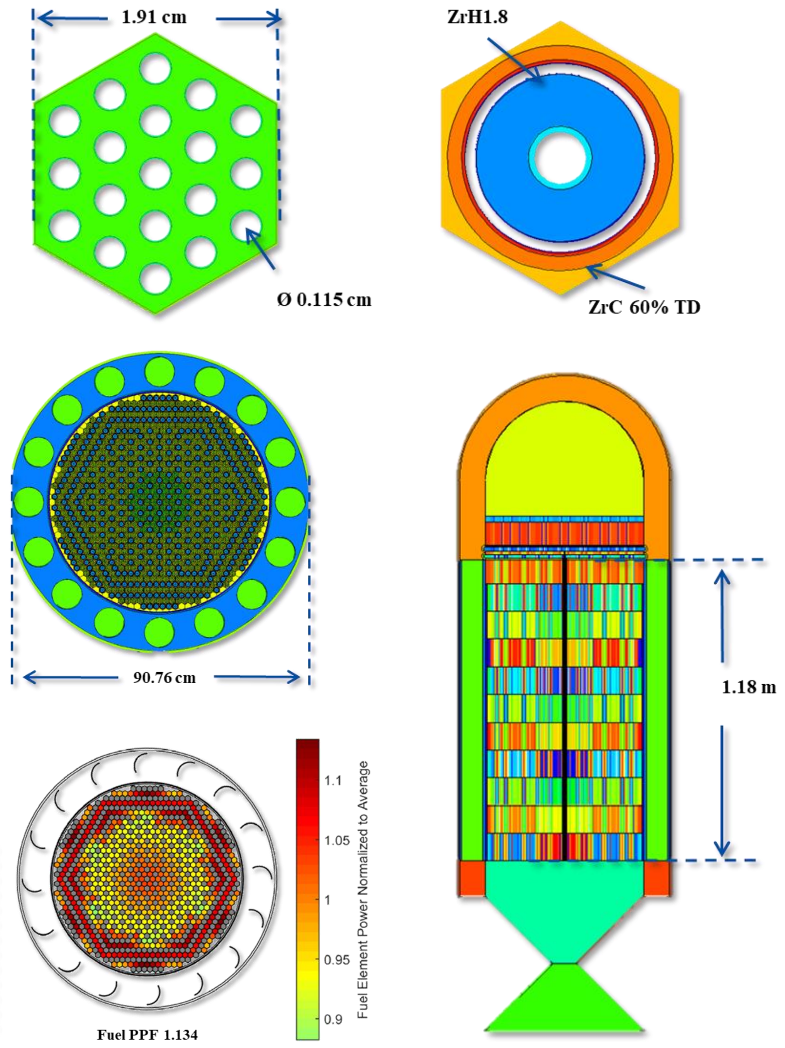
Reactor System Mass	
Fuel mass (600 elements) (kg)	800.1
Total mass (excluding shield) (kg)	2498.0

Key Performance Parameters	
Nominal I_{sp} (s)	897.9
Nominal thrust (kN)	155.7
Whole reactor power (MW)	768.9
Fuel temperature maximum (K)	2850

Engine System Interface Information			
Interface Point	Flow Rate (kg/s)	Pressure (MPa)	Temperature (K)
Core inlet	17.68	8	300.0
Core outlet	17.68	5	2712.8

Fuel Details	
Fuel composition	(U, Zr)C
Enrichment of ^{235}U (at. %)	19.75
Total ^{235}U (kg)	18.1
Fuel cladding	ZrC

Dr. Paolo Venneri's NERVA-derived NTP design which demonstrated the feasibility of using LEU fuel.



2. Core Description:

- **Conceptual Core Design**
- Baseline Core
- **Core Description**
- Fuel
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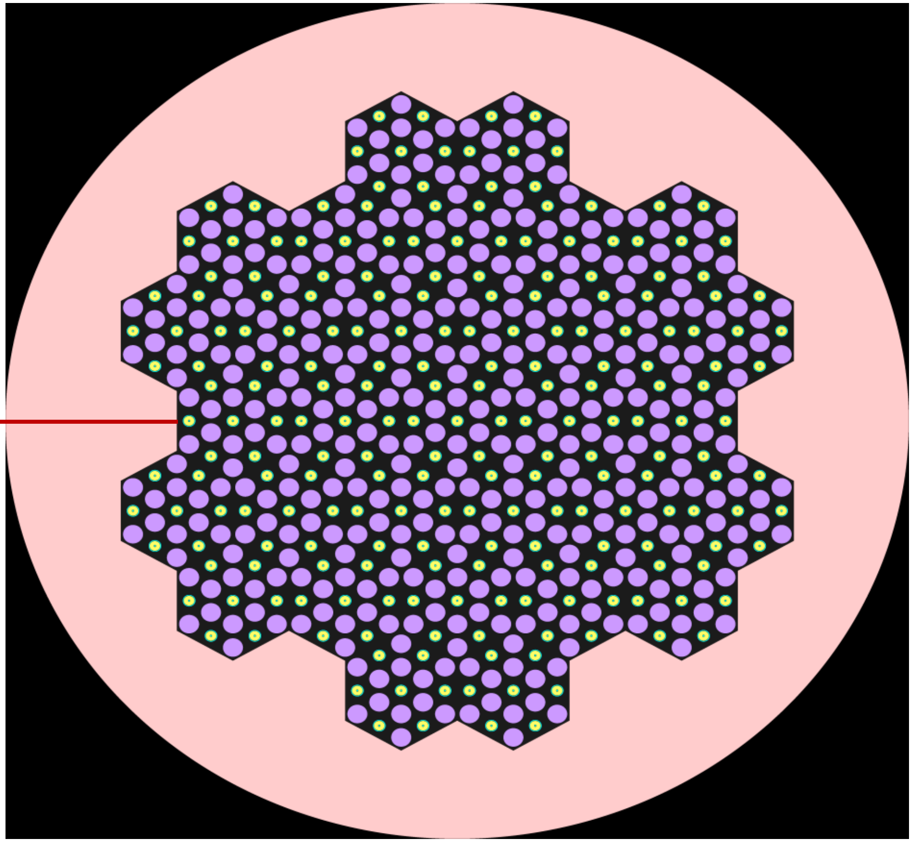

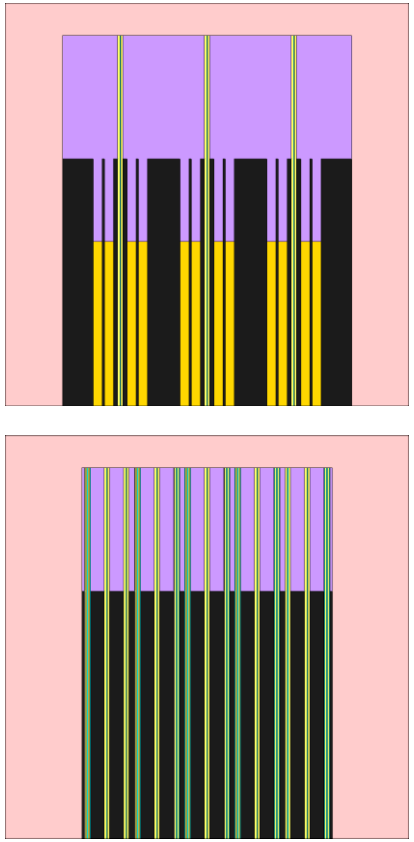

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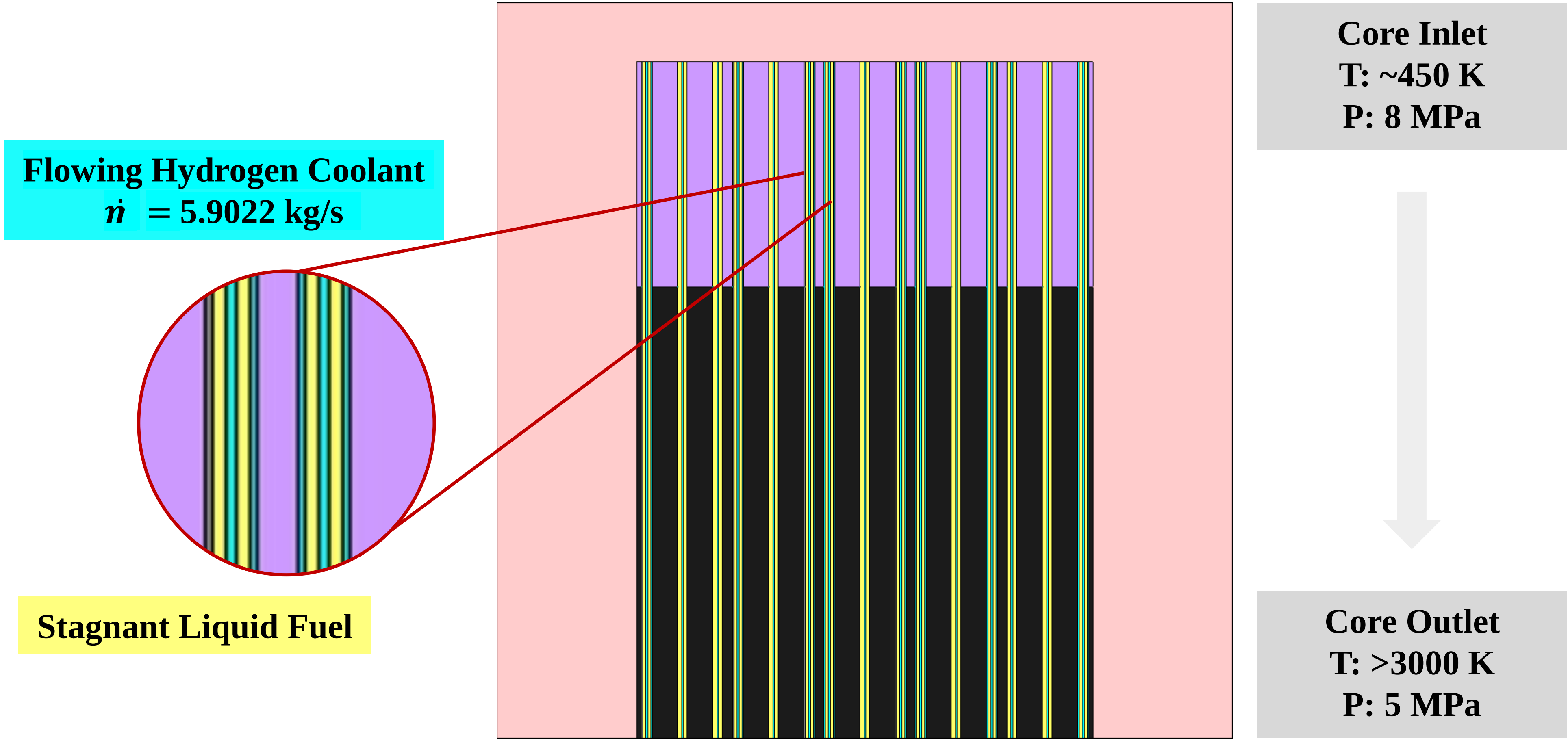


Reactor Concept and Methods

3. Fuel:

- **Conceptual Core Design**
- Baseline Core
- Core Description
- **Fuel**
- Moderator
- Reactor Mass
- Simulation

Enrichment

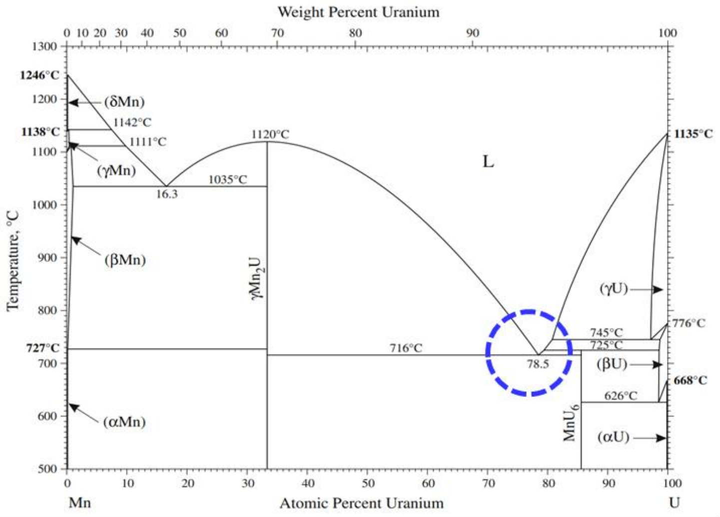
- HALEU 19.75%

Material Options:

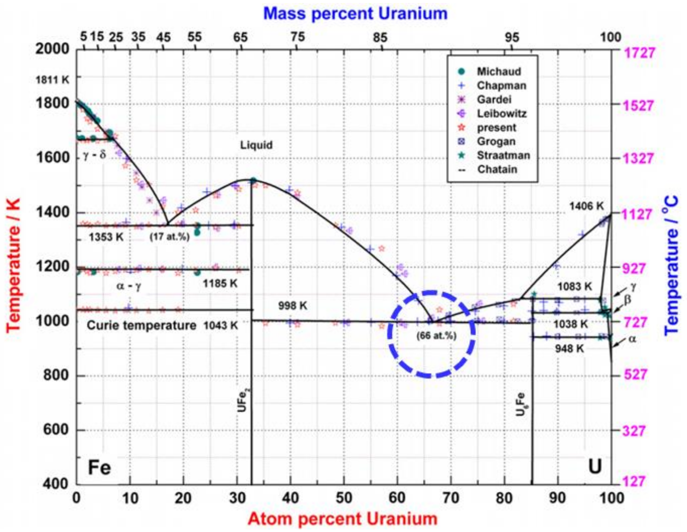
1. U-Only
2. Liquid metal eutectic

Liquid Fuel Candidate	U mass fraction %	$T_{melting}$ (K)
U	100%	1405
U-Mn	94.05%	989
U-Fe	89.22%	998

→ *For today's preliminary results*



a. U-Mn



b. U-Fe

3. Fuel:

Conceptual Core Design

Baseline Core

Core Description

Fuel

Moderator

Reactor Mass

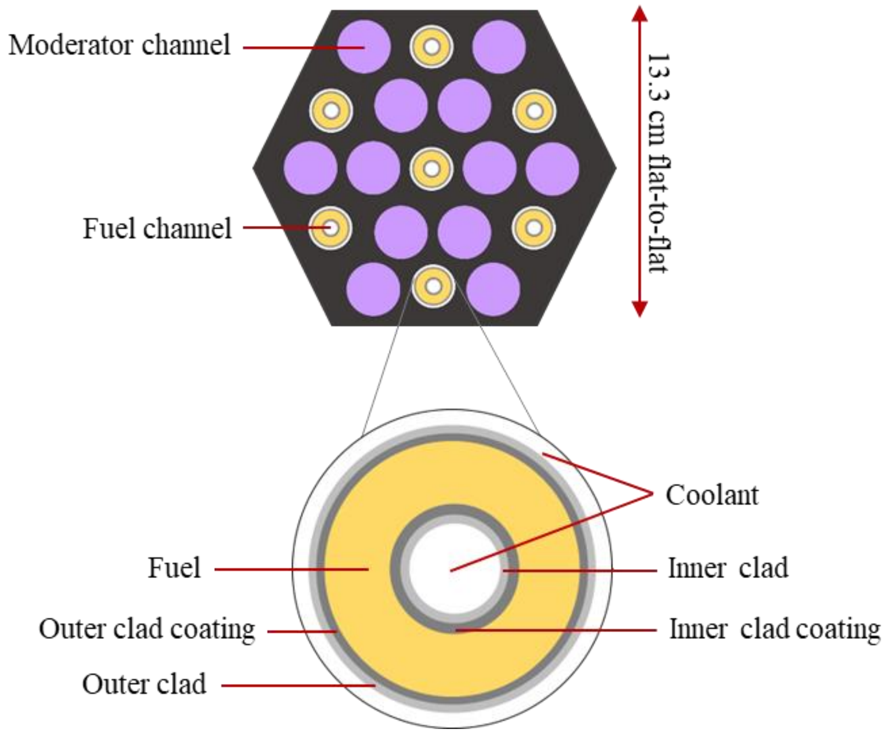
Simulation

Fuel Assembly

- Hexagonal block with a flat-to-flat distance of 13.3 cm.
- Upper 1/3 is filled with BeO, and remainder with graphite.
- 19 channels (7 fuel/12 moderator).

Annular Fuel Channel

Layer	Material	Density (g/cm^3)	Outer Radius (cm)
Coolant	H_2	8.40E-5	0.118
Inner Clad	Ta	16.40	0.126
Clad Coating	ZrC (100% TD)	6.730	0.131
Fuel	UMn (Liquid)	15.29	0.631
Clad Coating	ZrC (100% TD)	6.730	0.636
Outer Clad	Ta	16.40	0.644
Coolant	H_2	8.40E-5	0.762



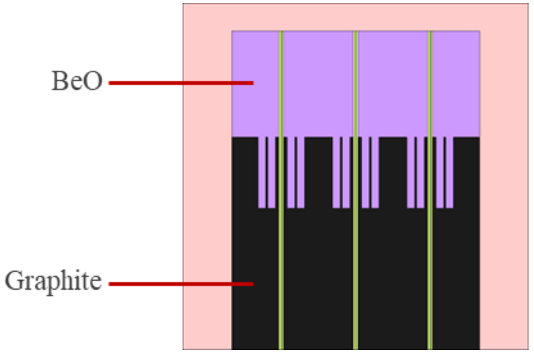
4. Moderator:

- **Conceptual Core Design**
- Baseline Core
- Core Description
- Fuel
- **Moderator**
- Reactor Mass
- Simulation

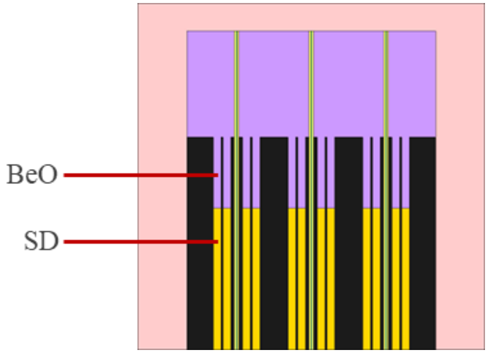
3-Moderator Model

- Hexagonal block filled with:
  1. BeO
  2. Graphite
- Moderator channels (r = 1.20 cm) filled with:
  1. BeO
  2. Synthetic Diamond (SD) “70-85% packing factors”

Material	Density (g/cm^3)
Graphite	1.700
SD (100%)	3.500
SD (70%)	2.450
SD (75%)	2.625
SD (80%)	2.800
SD (85%)	2.975



Hexagonal Block



Moderator Channels

4. Moderator:

Conceptual Core Design

Baseline Core

Core Description

Fuel

Moderator

Reactor Mass

Simulation

Synthetic Diamond (SD) as a novel moderator material:

1. It offers **good stability** at high temperatures up to 3500°C.

1. Lab-grown diamonds are typically **less expensive** than natural diamonds.

1. It has a **higher mass density** of 3.5 g/cm^3 compared to 1.7 g/cm^3 of nuclear-grade graphite.

1. It offers **superior neutron slowing down power and moderating ratio**.

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Growth of diamond in liquid metal at 1 atm pressure

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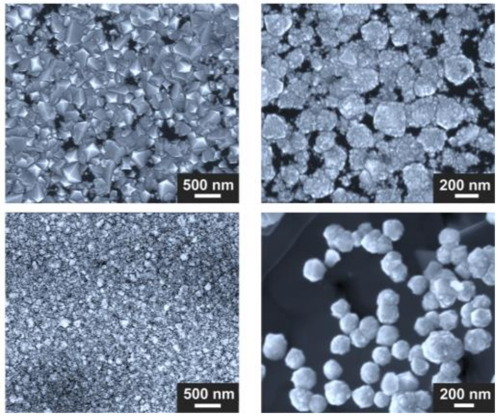

5. Reactor Mass:

- **Conceptual Core Design**
- Baseline Core
- Core Description
- Fuel
- Moderator
- **Reactor Mass**
- Simulation

Material	Mass (kg)	
Fuel	U: 347.71 Mn: 21.99 Total: 369.70	
Graphite	Without SD	400.11
	With SD	281.74
Be (Reflector)	866.09	
Hydrogen (Coolant)	9.587E-04	
ZrC (Clad Coating)	3.25	
Ta (Clad)	12.69	
BeO	511.42	

SD Packing Factor	Total SD mass (kg)	Total mass of reactor (kg)
Without SD	-	2163.29
70%	170.60	2215.52
75%	182.78	2227.70
80%	194.97	2239.89
85%	207.16	2252.08

Reactor Concept and Methods

5. Reactor Mass:

- **Conceptual Core Design**
- Baseline Core
- Core Description
- Fuel
- Moderator
- Reactor Mass
- **Simulation**

Simulation code	Serpent 2.20 Continuous-Energy Monte Carlo code	
Neutron histories	*Neutronics*	100,000 (50 inactive, 200 active cycles)
	Reactivity Coefficients	6,000,000 (100 inactive, 500 active cycles)
Cross-section library	ENDF/B-VIII.0 [T = 2500 K]	
S(α,β) data library	ENDF/B-VII.0 [$T_{Graphite}$ = 2000 K, $T_{Be/BeO}$ = 1200 K]	
Boundary conditions	Vacuum on both radial and axial directions	

Results and Analysis

1. Neutronics:

Preliminary Results

Neutronics

Power Distributions

Reactivity Coefficients

Criticality and Fission Reaction Rate:

- ***Design constraint: without SD loading → excess reactivity < 1000 pcm.***

Energy Distribution Grid (MeV)

- Thermal: $1.03 \times 10^{-11} < E < 1.02 \times 10^{-6}$
- Epithermal: $1.07 \times 10^{-6} < E < 0.10021$
- Fast: $0.106051 < E < 19.4493$

SD Loading	k_{eff}	$\pm\sigma$ (pcm)	Thermal RR%	Epithermal RR%	Fast RR%	Reactor Mass (kg)
Without SD	1.00697	69	46.20%	45.87%	7.92%	2163.29
70% SD	1.01449	64	46.22%	45.94%	7.82%	2215.52
75% SD	1.01344	73	46.30%	45.89%	7.80%	2227.70
80% SD	1.01553	69	46.30%	45.91%	7.77%	2239.89
85% SD	1.01776	69	46.37%	45.87%	7.75%	2252.08

347.71 kg of uranium is needed to achieve criticality.

Fission reaction rates in the thermal and epithermal regions are **92%**.

Synthetic diamond offers **1052 pcm** enhancement in reactivity.

1. Neutronics:

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Criticality and Fission Reaction Rate:

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- Thermal: $1.03 \times 10^{-11} < E < 1.02 \times 10^{-6}$
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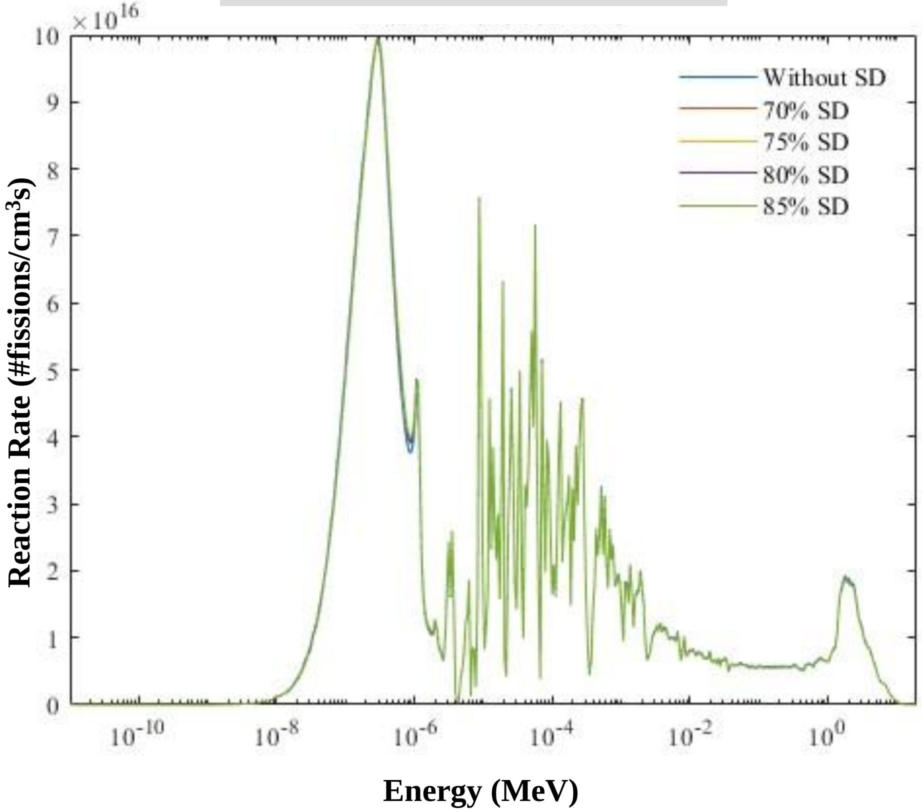
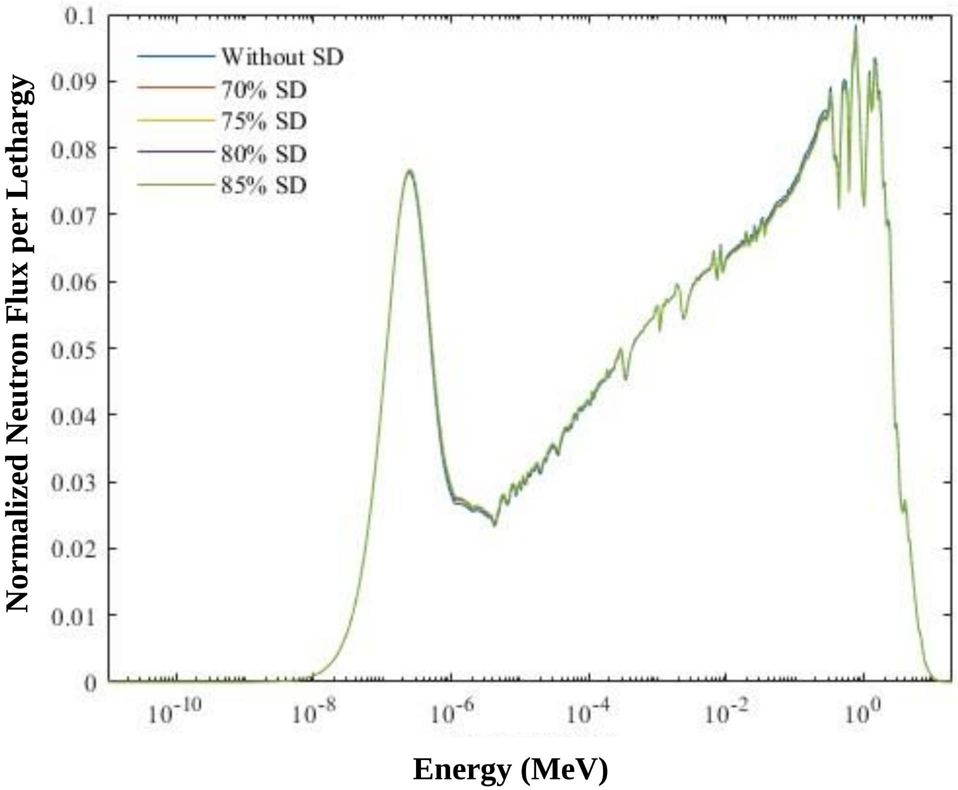
Fission Reaction Rate



Neutron Spectrum



2. Power Distributions:

Thermal Power = 250 MWth

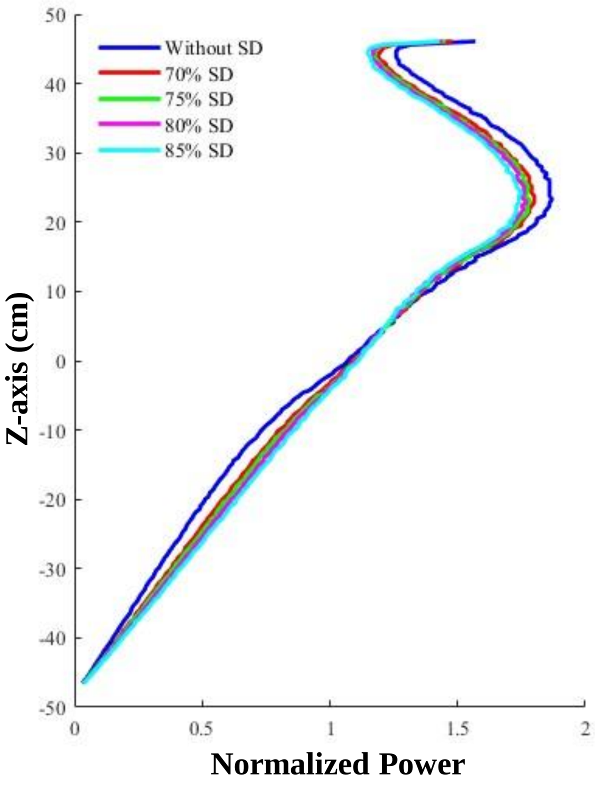
- *PPF: Power Peaking Factor*
- *FP: Fission Power*

Preliminary Results → Neutronics → **Power Distributions** → Reactivity Coefficients

Axially:

- ***Design constraint: fuel in liquid state at the core inlet.***

Axial Power Distribution



SD Loading	NO SD	70% SD	75% SD	80% SD	85% SD
$Power_{max}$ (W)	2.33E+06	2.25E+06	2.23E+06	2.21E+06	2.18E+06
$Power_{avg}$ (W)	1.25E+06	1.25E+06	1.25E+06	1.25E+06	1.25E+06
PPF	1.87	1.80	1.78	1.77	1.75
FP in BeO region	54.77%	52.45%	51.92%	51.39%	50.79%

Top-skewed axial power shape.

Synthetic diamond reduced PPF from **1.87** to **1.75**

3% less fission power is produced in the BeO region when 85% SD is loaded.

2. Power Distributions:

Thermal Power = 250 MWth

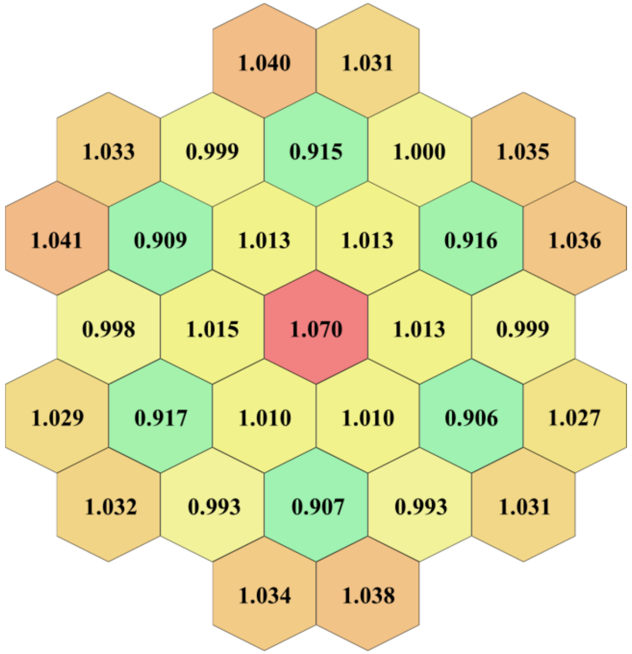
- *PPF: Power Peaking Factor*

Preliminary Results → Neutronics → **Power Distributions** → Reactivity Coefficients

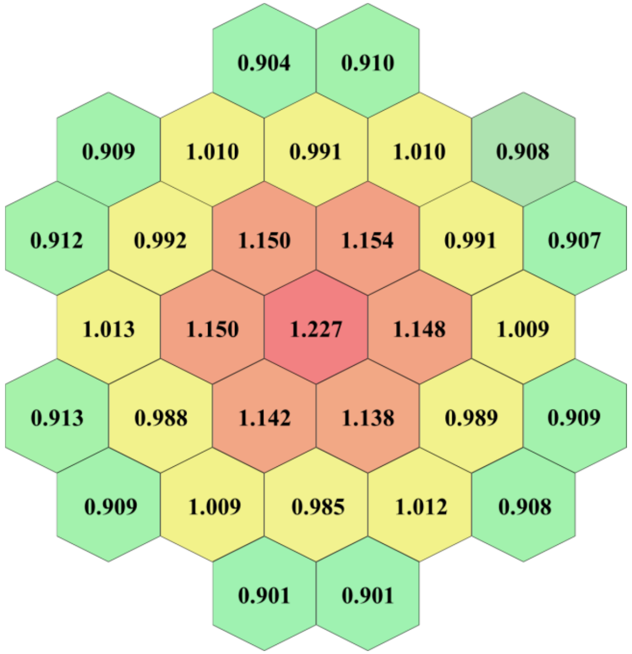
Radially:

- ***Design constraint: axially integrated PPF~1.1.***

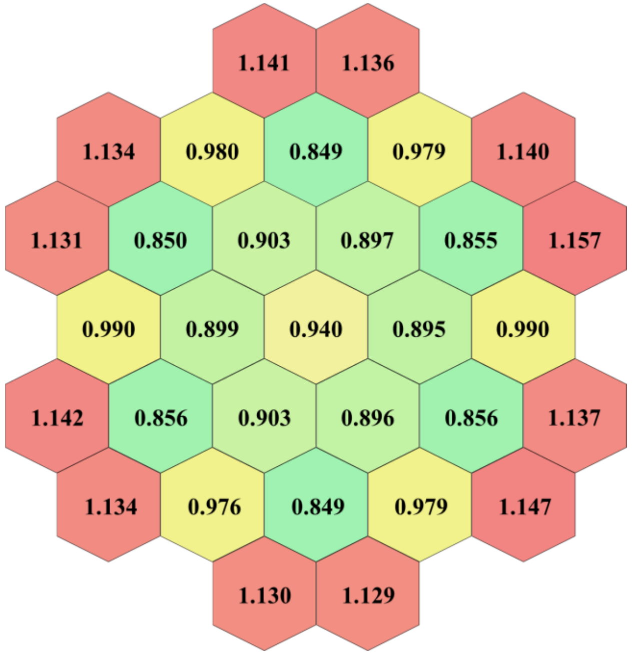
Normalized Radial Power Distribution (NO SD)



BeO



BeO + Graphite



Graphite

2. Power Distributions:

Thermal Power = 250 MWth

- *PPF: Power Peaking Factor*

Preliminary Results

Neutronics

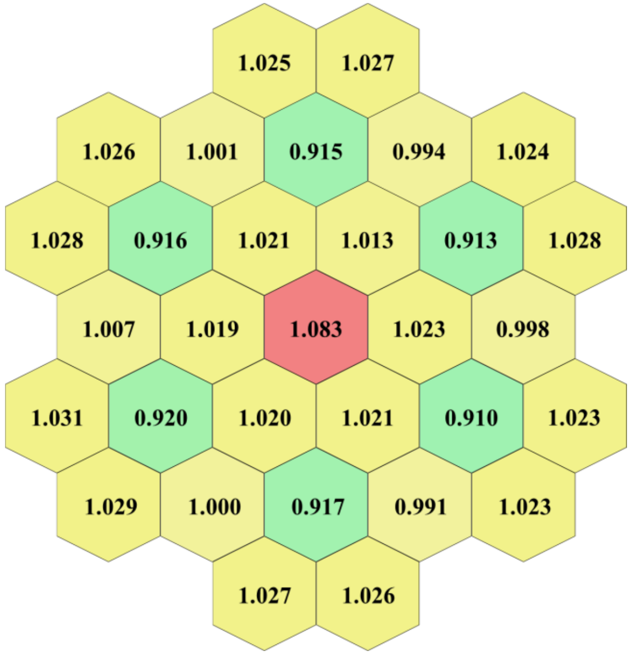
Power Distributions

Reactivity Coefficients

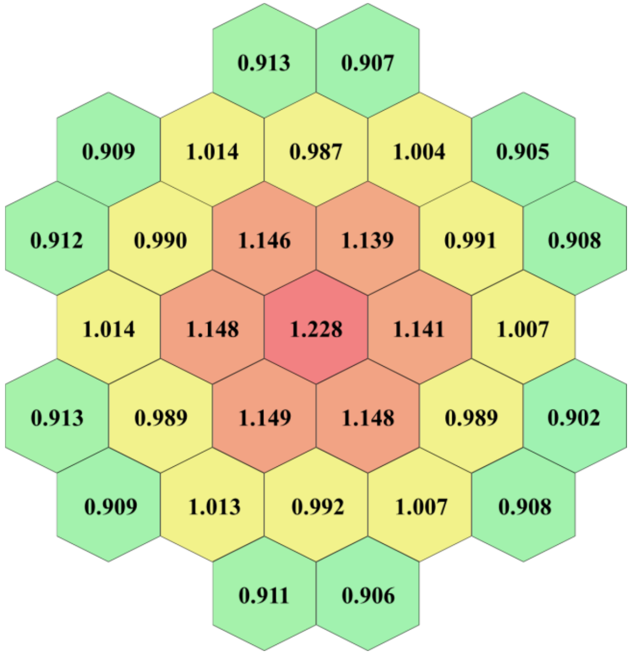
Radially:

- *Design constraint: axially integrated PPF~1.1.*

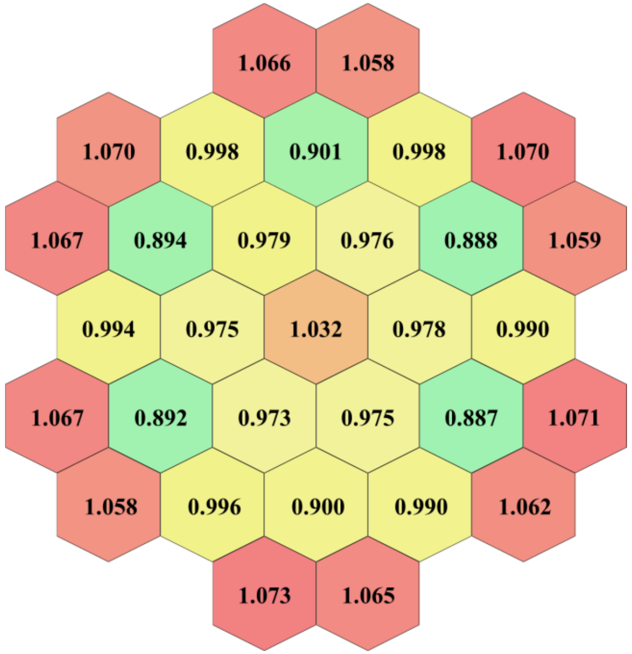
Normalized Radial Power Distribution (85% SD)



BeO



BeO + Graphite



Graphite + SD

2. Power Distributions:

Thermal Power = 250 MWth

- *PPF: Power Peaking Factor*

Preliminary Results → Neutronics → **Power Distributions** → Reactivity Coefficients

Radially:

- ***Design constraint: axially integrated PPF~1.1.***

Region	BeO		BeO + Graphite		Graphite	
SD Loading	*NO SD*	*85% SD*	*NO SD*	*85% SD*	*NO SD*	*85% SD*
$Power_{max}$ (W)	2.35E+06	2.38E+06	5.39E+06	5.00E+06	1.71E+06	1.92E+06
$Power_{avg}$ (W)	2.19E+06	2.20E+06	4.40E+06	4.08E+06	1.48E+06	1.79E+06
PPF	1.07	1.08	1.22	1.22	1.15	1.07
Fission Power	27.19%	27.23%	54.50%	50.54%	18.30%	22.23%

The **middle** region produces the majority of fission power.

The introduction of synthetic diamond boosts the lower region's fission power production by **4%**.

Results and Analysis

2. Power Distributions:

Thermal Power = 250 MWth

- *PPF: Power Peaking Factor*

Preliminary Results

Neutronics

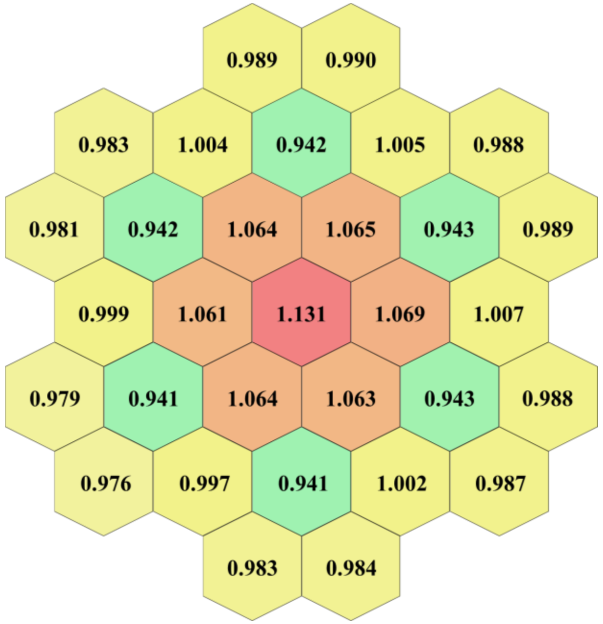
Power Distributions

Reactivity Coefficients

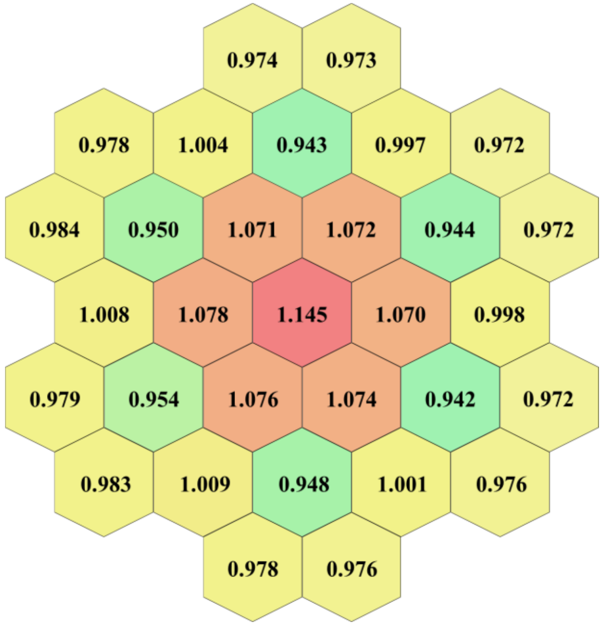
Radially:

- ***Design constraint: axially integrated PPF~1.1.***

Axially Integrated Normalized Radial Power Distribution



NO SD



85% SD

SD Loading	NO SD	85% SD
$Power_{max}$ (W)	9.12E+06	9.23E+06
$Power_{avg}$ (W)	8.06E+06	8.06E+06
PPF	1.13	1.14

3. Reactivity Coefficients:

Preliminary Results

Neutronics

Power Distributions

Reactivity Coefficients

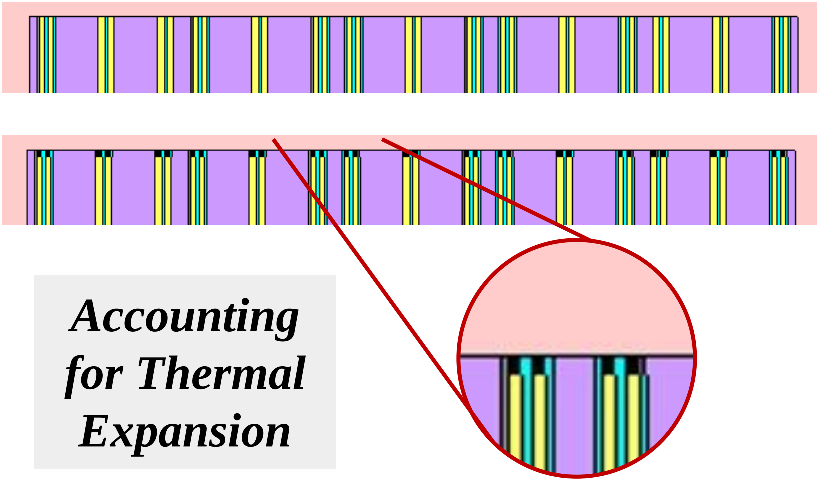
Evaluation Temperature = 2250 K

- ***Design constraints: Zero MTC / Slightly Negative FTC / Near Zero RTC.***

	MTC [pcm/K]		FTC [pcm/K]		RTC [pcm/K]		ITC [pcm/K]	
	NO SD	*85% SD*	*NO SD*	*85% SD*	*NO SD*	*85% SD*	*NO SD*	*85% SD*
Reactivity Coefficient	-0.09843	-0.03854	-0.75504	-0.73910	-0.06889	0.03854	-0.82356	-0.69114
2σ	0.11224	0.11106	0.11203	0.11084	0.11223	0.14157	0.11202	0.11084

$T_{reference}$ = 2500 K

$T_{evaluation}$ = 2250 K



Accounting for Thermal Expansion

Improving **accuracy** is needed.

Calculation of **Temperature-dependent** reactivity coefficients.

Summary and Future Work

Summary and Future Work

This research introduced a novel concept for NTR technology, addressing limitations of solid-core designs.

- ❑Nuclear design **optimization** and **burnup** calculations.
- ❑Modeling the entire reactor, including **control mechanisms** and **shielding**.
- ❑Thermal analysis and **temperature distributions**.
- Rocket performance calculation of **thrust** and **specific impulse**.

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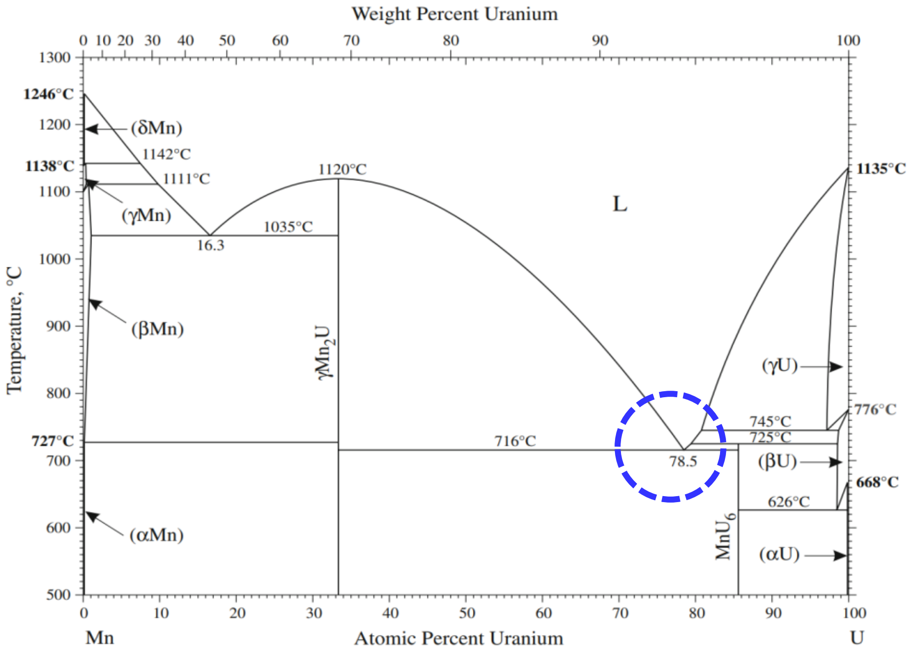
Supplementary Slide

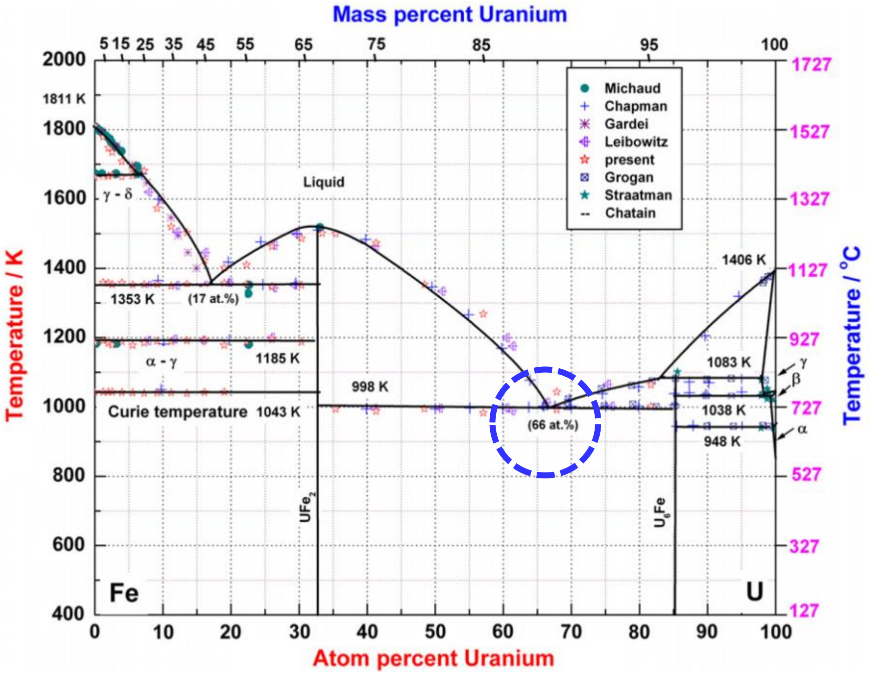
Melting and Boiling Temperature of Core Materials:

Material	Classification	$T_{melting}$ (K)	$T_{boiling}$ (K)
U	Fuel	1405	4404
U-Mn		989	N/A
U-Fe		998	N/A
ZrC	Clad coating / Clad	3805	5373
TaC		4153	5053
Ta		3293	5730
BeO	Moderator	2851	4173
Graphite		3873	4473
Synthetic Diamond		3823	5103
Be	Reflector	1560	3043

Fuel Material:

Liquid metal eutectic phase diagram(U-Mn, U-Fe alloy)





U-Mn (mass fraction: 94.05%)

U-Fe (mass fraction: 89.22%)

Metal	$U_6Mn : UMn_2$	$U_6Fe : UFe_2$
Atomic ratio (solid)	12.3182 : 4.5909	8.9091 : 12.5455

Space model U enrichment: 19.75 wt.%

Supplementary Slide

Fuel Composition:

U-Mn (U mass fraction: 94.05%)

Density of mixture	15.31739
W-U-235	0.185749
W-U-238	0.754751
W-Mn-55	0.0595
Sum	1

U-Fe (U mass fraction: 89.22%)

Density of mixture	14.66997257
W-U-235	0.175766164
W-U-238	0.714188922
W-Fe-54	0.006434626
W-Fe-56	0.100970456
W-Fe-57	0.00233187
W-Fe-58	0.000307962
Sum	1

W: Weight fraction

Proposed Core Loading Patterns: