Neutronics of a Liquid Salt Cooled, Very High Temperature Reactor

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Overview

- AHTR Design and the Core Modeling (MCNP)
- Fuels and Molten Salts Properties
- Moderation State
- Total Void Worth
- Moderator and Fuel Temperature Reactivity Coefficient
- Conclusions

AHTR Design

Molten Salt Reactors (1950-70's) ⇒ coolant

Gas Cooled HTRs ⇒ fuel (TRISO)

S-PRISM ⇒ decay heat removal system

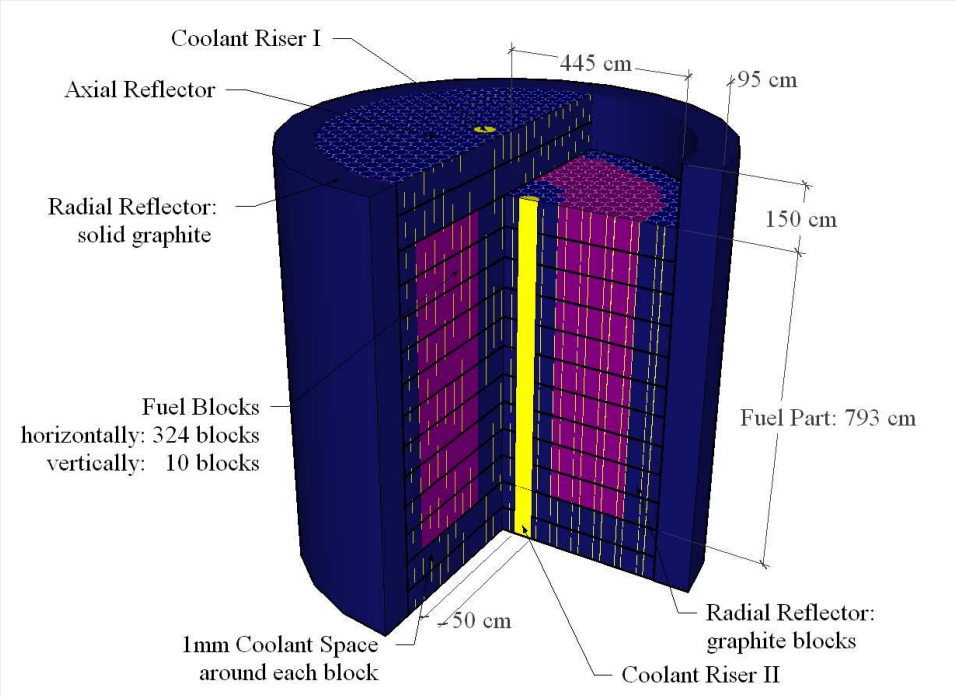
⇓

Advanced High Temperature Reactor (AHTR)

Also Liquid Salt Cooled, Very High Temperature Reactor (LS-VHTR)

AHTR Core Modeling (MCNP)

CORE



Power: 2400 MW_{th}

Coolant Temperature: 900/1000 °C

Active Core Height: 793 cm

Active Core Radius: ±390 cm

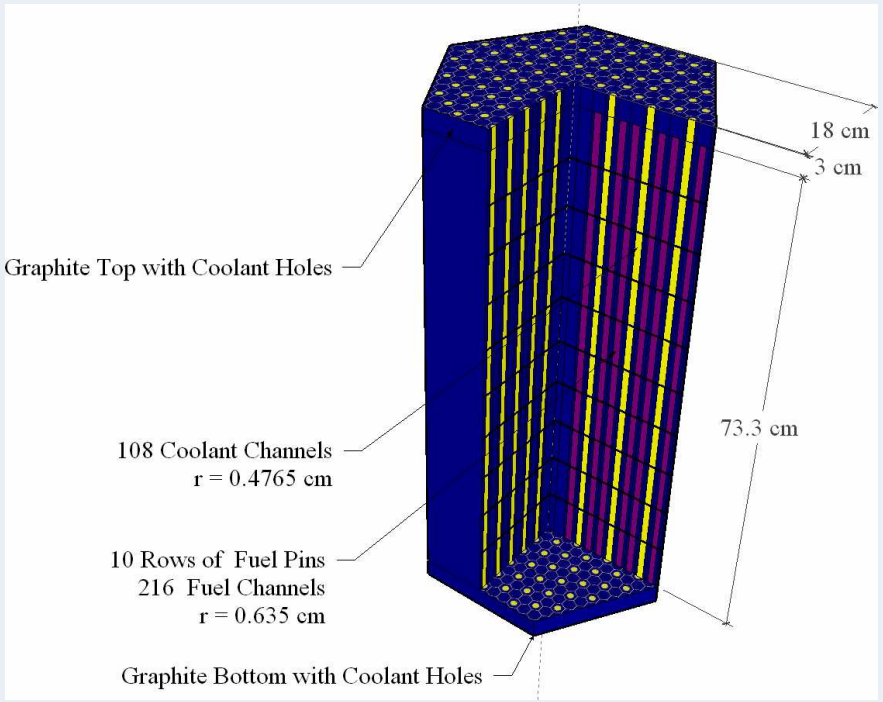
324x10 hexagonal fuel blocks

MCNP Simulation:

Fuel Temperature: 1500 K
Coolant Temperature: 1200 K
Graphite Temperature: 1200 K

AHTR Core Modeling

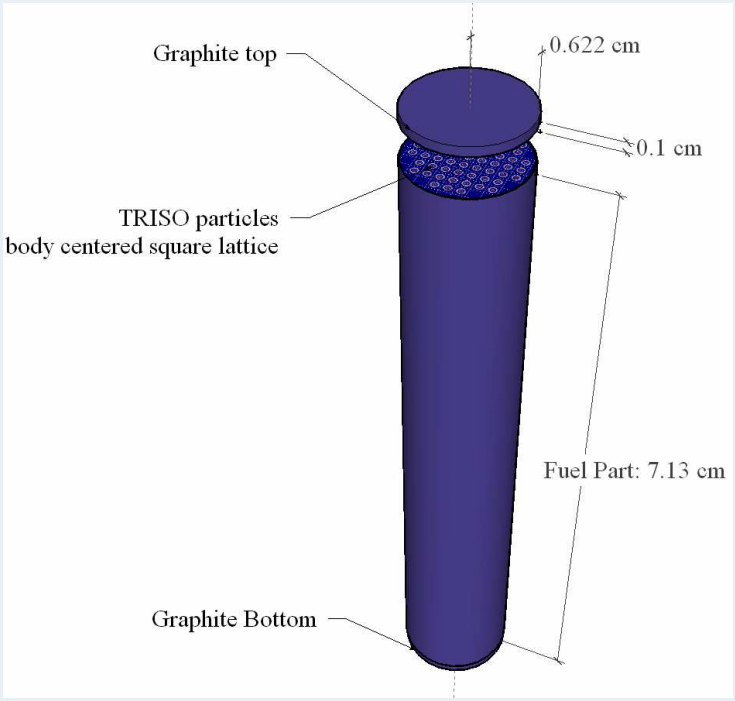
FUEL BLOCK



Apothem:	18 cm
Height:	79.3 cm
Axial Reflectors Height:	3 cm
Fuel Pins in the xy Plane	216
Fuel Pins along the z Axis	10
Radius of the Fuel Holes	0.635 cm
Coolant Channels	108
Radius of the Coolant Channel	0.4765 cm

AHTR Core Modeling

FUEL PIN



Radius:	0.622 cm
Height:	7.33 cm
Graphite Top/Bottom:	0.1 cm

Pu: TRISO packing fraction: 14.53%

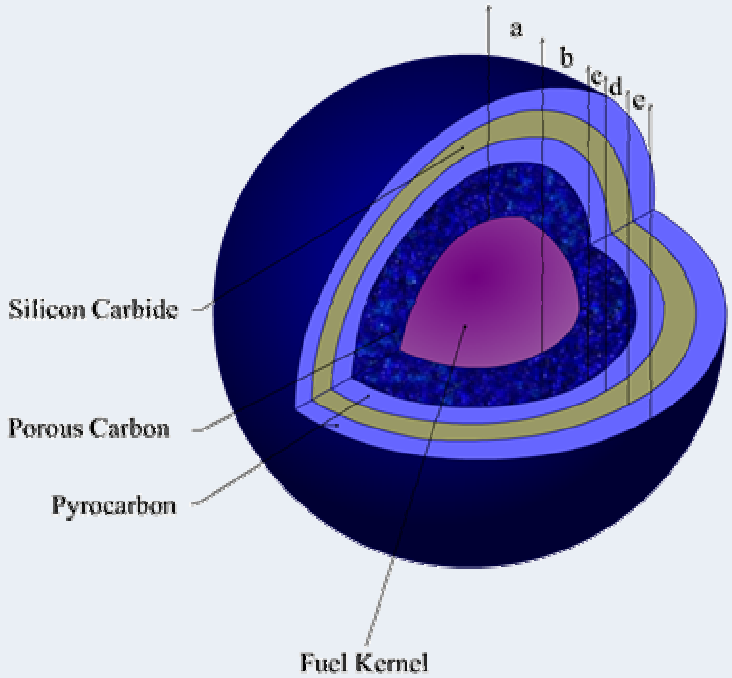
U: TRISO packing fraction: 24.83%

No TRISO particle was cut by any surface

Note: TRISO pf = TRISO particles volume/fuel pin volume

AHTR Core Modeling

TRISO PARTICLE



TRISO kernel contains either $NpPuO_{1.7}$ or $UO_{1.7}$. Density of the fuel was fixed to 10.2 gcm^{-3}.

Plutonium Fuel

^{237}Np	1.91 %
^{238}Pu	0.56 %
^{239}Pu	21.11%
^{240}Pu	8.5 %
^{241}Pu	3.09 %
^{242}Pu	1.87 %
^{16}O	62.96%

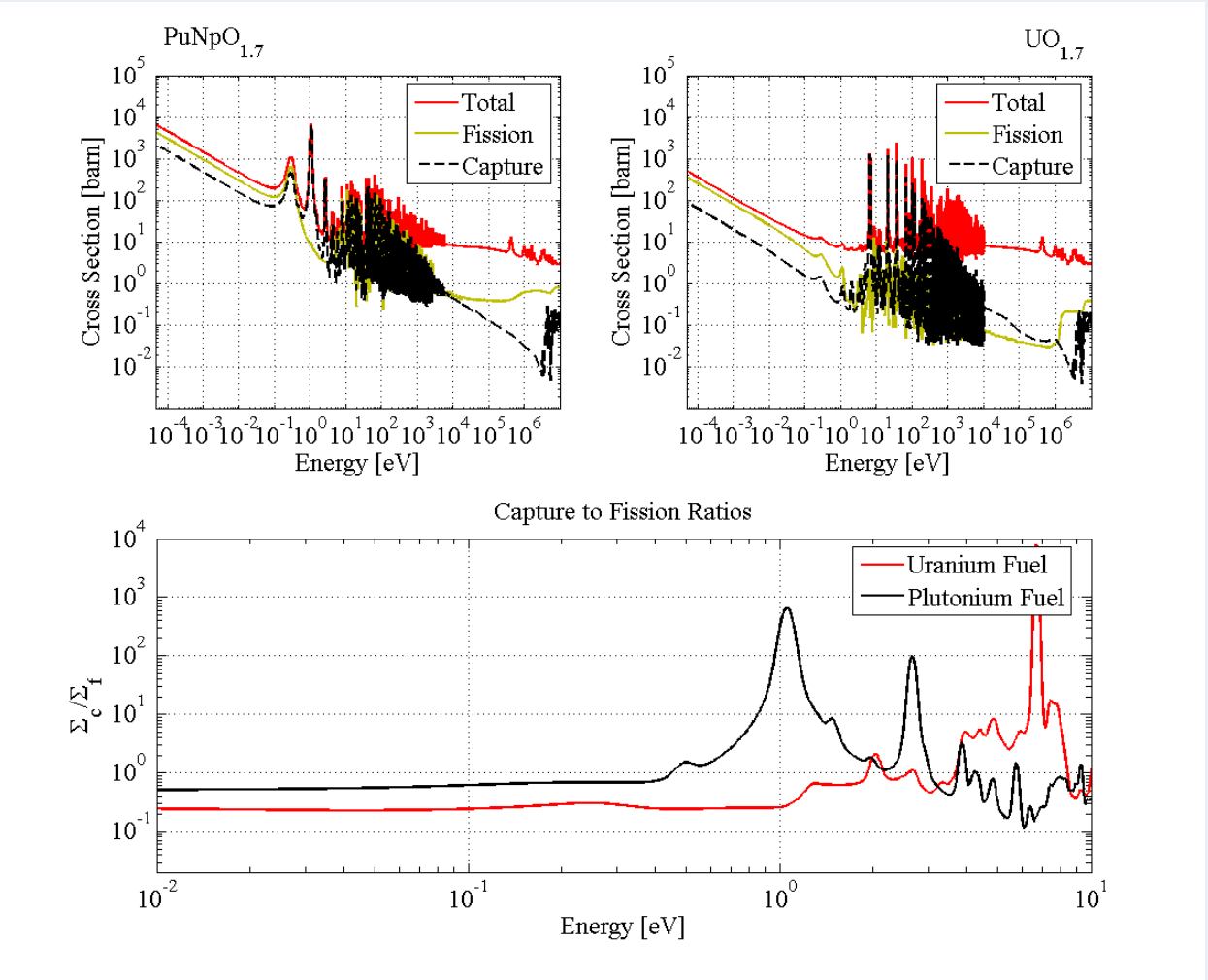
Uranium Fuel

^{235}U	2.58 → 5.56 %
^{238}U	34.46 → 31.15 %
^{16}O	62.96 %

Fuel Properties

Neutronic properties of the fuels

Nuclear data:
JEFF 3.0



Fuel Properties

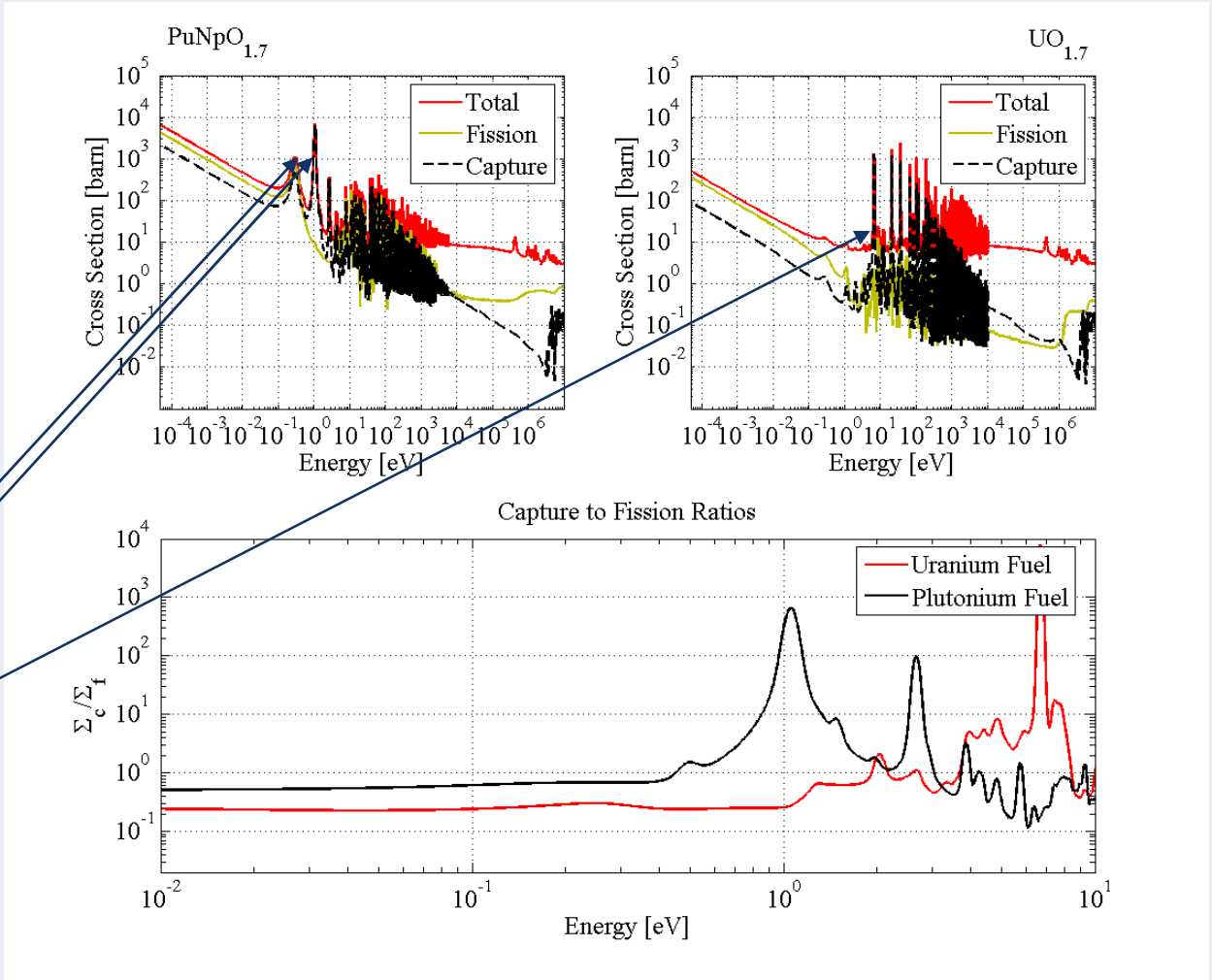
Neutronic properties of the fuels

Nuclear data:
JEFF 3.0

Peaks:
0.25 – 0.3 eV ^{239}Pu

1.056 eV ^{240}Pu

6.67 eV ^{238}U



Molten Salts Properties

Thermochemical properties of the molten salt

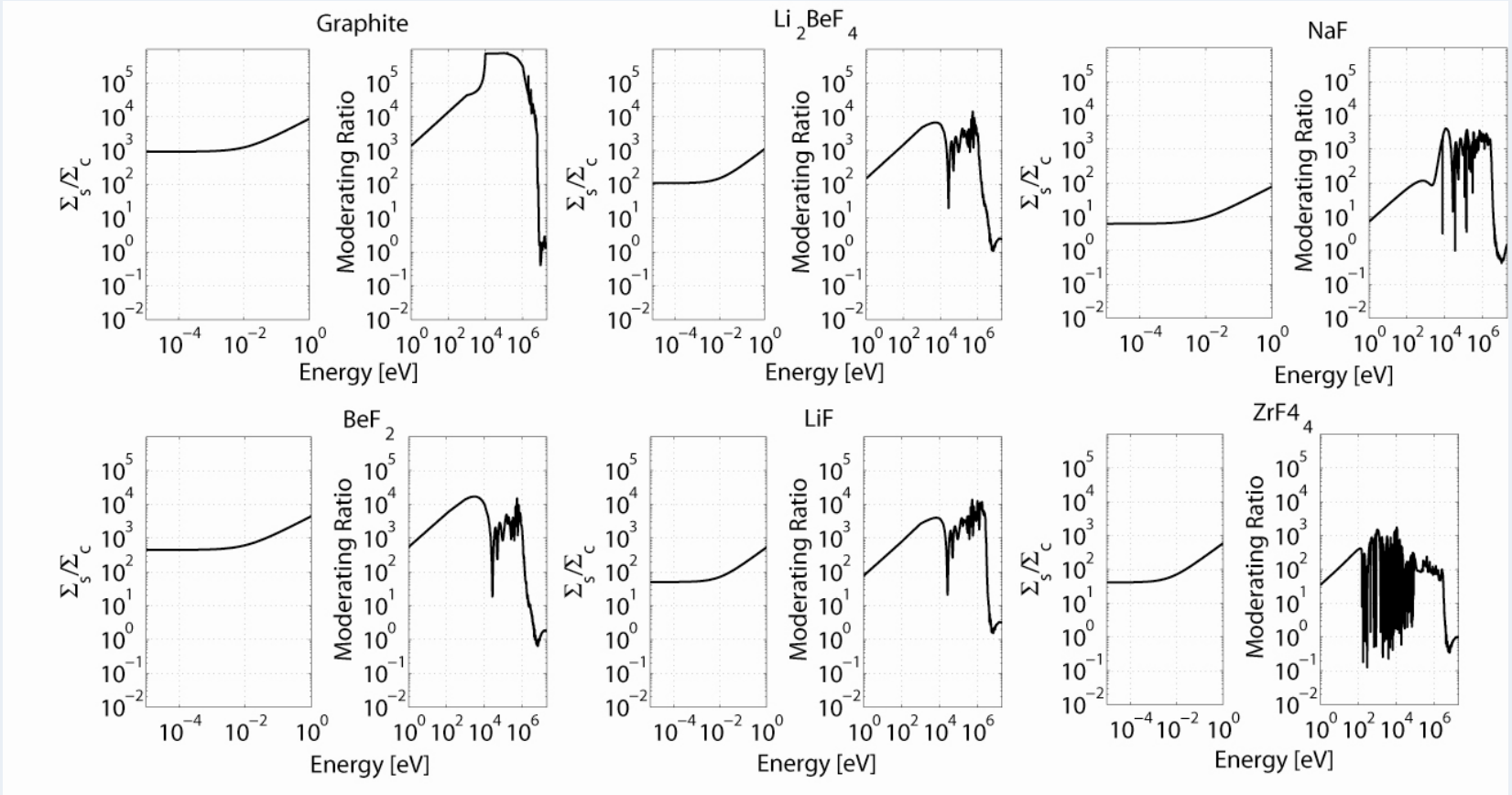
- No single-component molten salt has sufficiently low freezing point.
- Reference salt FLiBe: 66% LiF, 34% BeF_2 (used in all calculations)
- Table: Temperatures - atmospheric pressure (0.1 MPa), densities – 1200 K
- only ^7Li considered

	Li_2BeF_4	BeF_2	LiF	NaF	ZrF_4
ρ [kg·m^{-3}]	1827	1885	1765	2000	3209
t_{melt} [°C]	459	552	848	996	--- (1)
t_{boil} [°C]	1430	1169	1673	1704	912
C_p [kJ kg^{-1}°C^{-1}]	2.371	2.138	2.583	1.595	1.002

(1) ZrF_4 sublimes at atmospheric pressure.

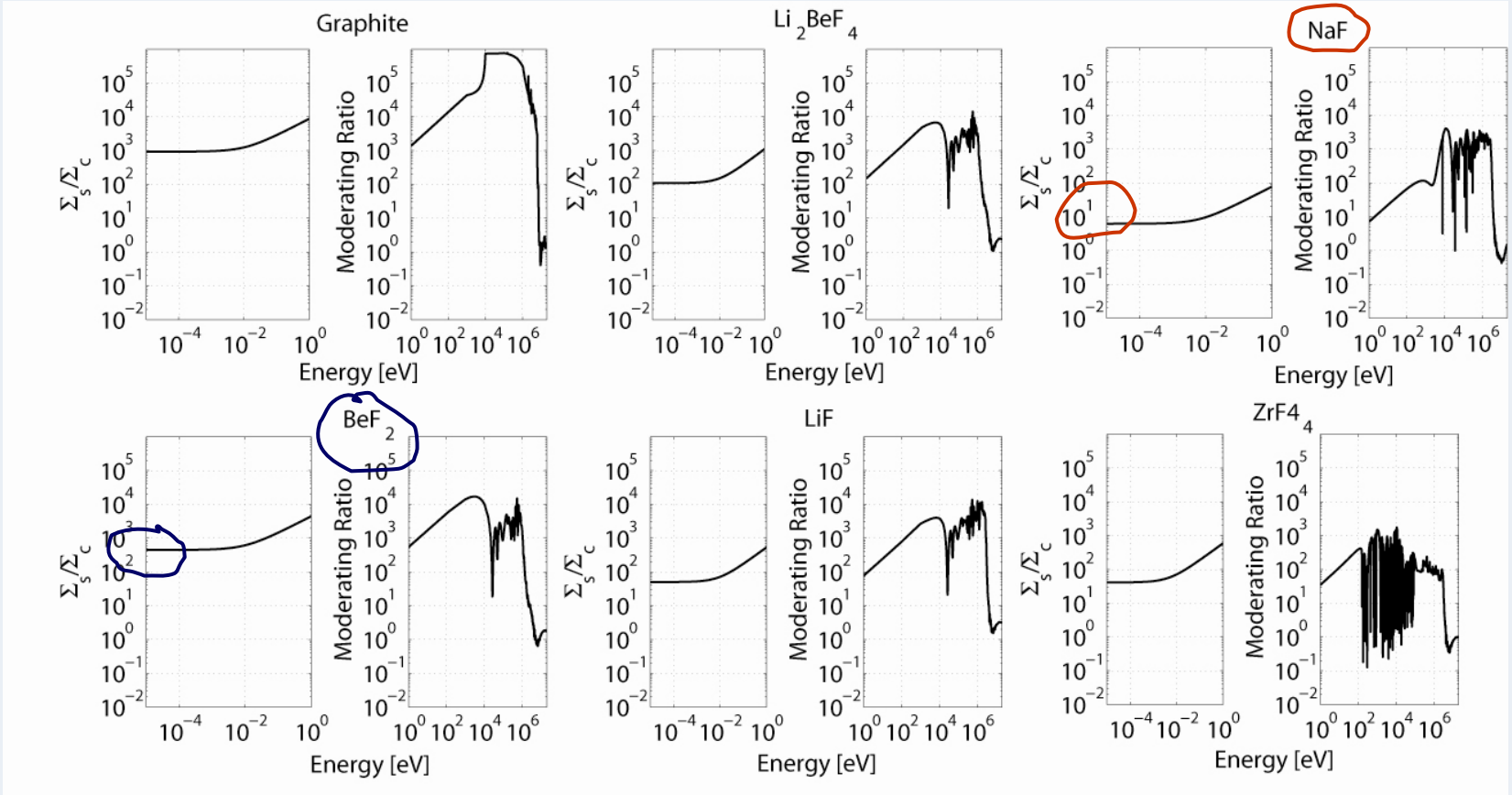
Molten Salts Properties

Neutronic properties of the molten salt



Molten Salts Properties

Neutronic properties of the molten salt



RESULTS

Coolant Void Reactivity Coefficient

Density decrease

1. Moderation $\rightarrow$ decreases $\Rightarrow$ Overmoderated core: **+**, Undermoderated: Core **-**

Coolant Void Reactivity Coefficient

Density decrease

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2. Capture $\rightarrow$ decreases $\Rightarrow$ always **+**

Coolant Void Reactivity Coefficient

Density decrease

1. Moderation → decreases ⇒ Overmoderated core: **+**, Undermoderated: Core **-**
2. Capture → decreases ⇒ always **+**
3. Leakage → increases ⇒ always **-**

Coolant Void Reactivity Coefficient

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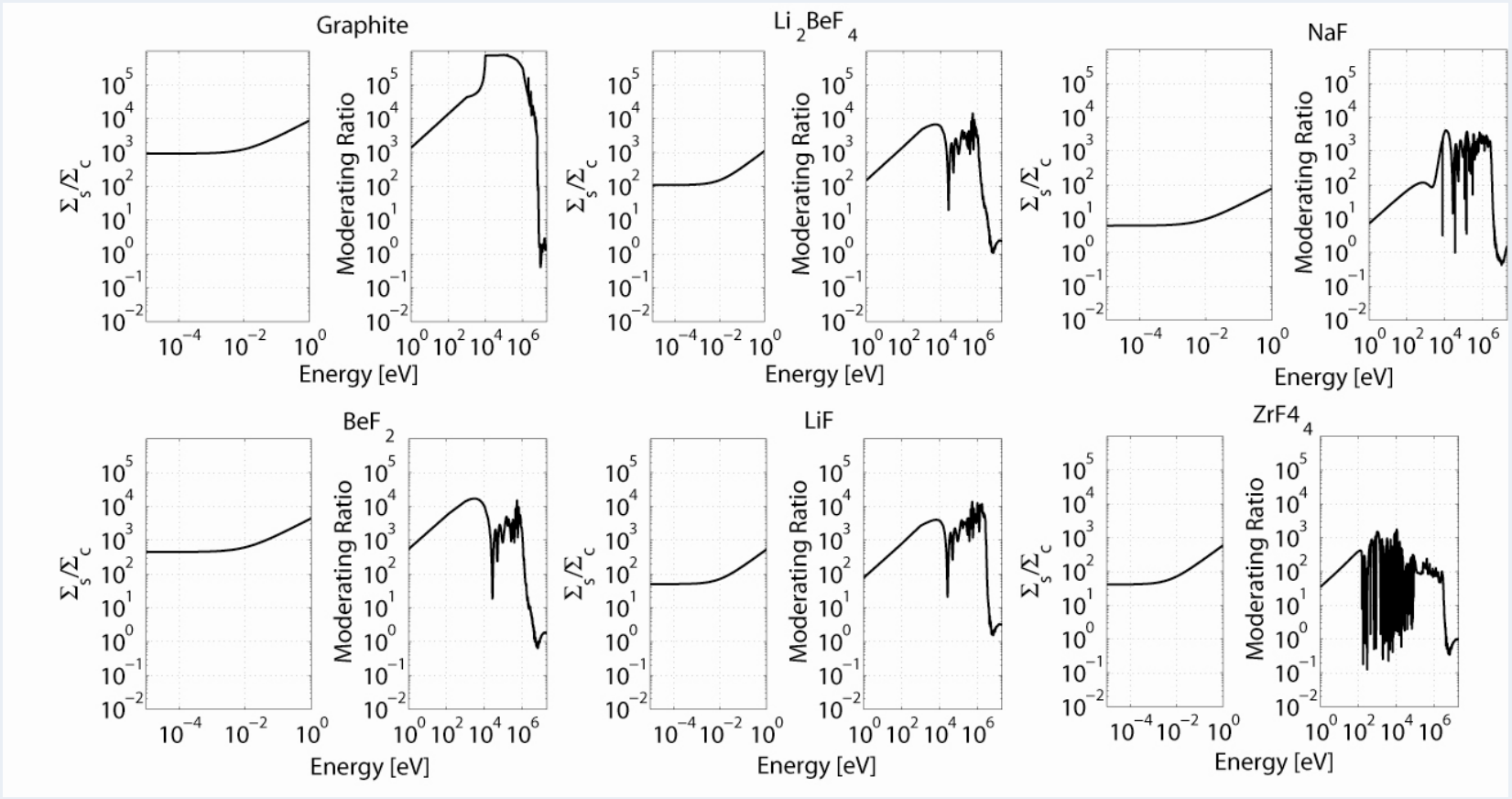
Which effect prevails depends on moderating abilities of the salt!

GO BACK TO…

Molten Salts Properties



Coolant Void Reactivity Coefficient

Density decrease

1. Moderation → decreases ⇒ Overmoderated core: **+**, Undermoderated: Core **-**
2. Capture → decreases ⇒ always **+**
3. Leakage → increases ⇒ always **-**

Which effect prevails depends on moderating abilities of the salt!

Limit case of Total Void investigated, ($\rho \rightarrow 0$)

Total Void Worth

Is the core configuration undermoderated or overmoderated at given F/M?

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Undermoderated: adding fuel (F/M↑) leads to a reactivity ….. ?

Total Void Worth

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Undermoderated: adding fuel (F/M↑) leads to a reactivity decrease!

Total Void Worth

Is the core configuration undermoderated or overmoderated at given F/M?

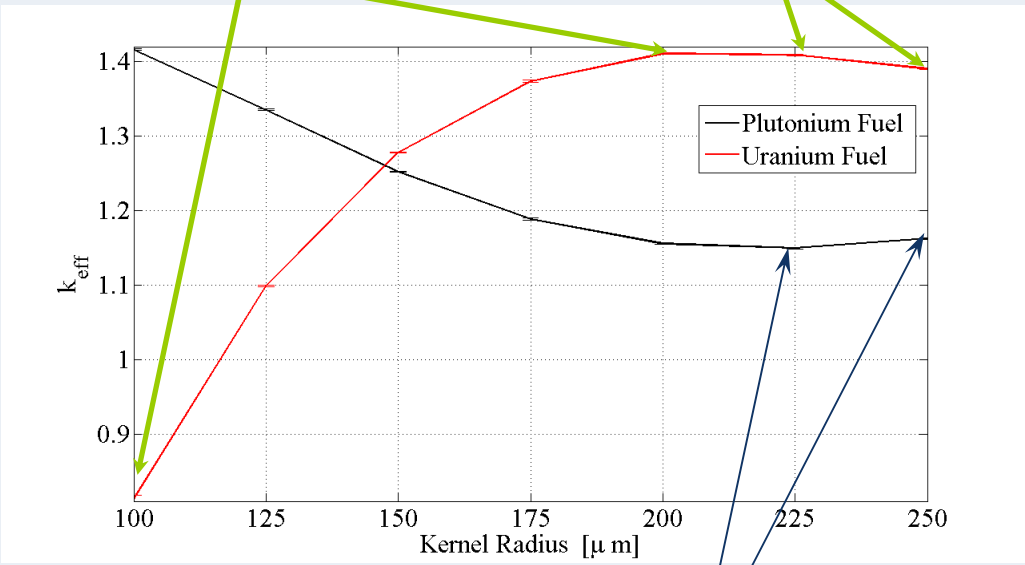
Undermoderated: adding fuel (F/M↑) leads to a reactivity decrease!
Overmoderated: adding fuel (F/M↑) leads to a reactivity increase!

F/M ratio is ruled by the TRISO particles kernel radius

Total Void Worth

k_{eff} as function of the kernel radius

U core:
overmoderated → undermoderated

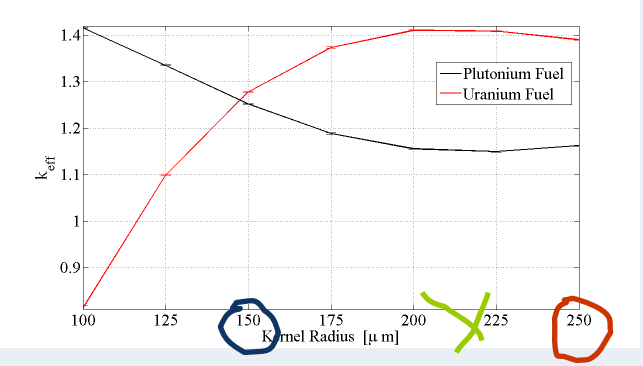


Pu core:
undermoderated → locally overmoderated

Local overmoderation:
Spectral peak passing over a c/f peak

Total Void Worth

Core configuration	1	2	3
Kernel size [μm]	150	250	215
TRISO pf [%]	14.53	17.48	24.32
^{235}U Enrichment [%]	6.965	6.965	15
FM Ratio [%]			
- Uranium Fuel	0.53	2.93	2.42
- Plutonium Fuel	0.44	2.44	2.01
β_{eff} [pcm]			
- Uranium Fuel	659	674	741
- Plutonium Fuel	267	225	303



Total Void Worth

1. Pu core Undermoderated, U core Overmoderated

TRISO kernel packing fraction of 14.53 % and a radius of 150 μm.

Molten Salt	Plutonium Fuel		Uranium Fuel	
	[$]	[pcm]	[$]	[pcm]
Li_2BeF_4	-2.40	-641 ± 60	+5.95	+3920 ± 48
BeF_2	-5.26	-1405 ± 52	+0. 43	+280 ± 40
LiF	+0. 31	+83 ± 52	+10.51	+6920 ± 38
NaF	+9.48	+2530 ± 51	+74.66(1)	+49170(1) ± 33
ZrF_4	+4.61	+1230 ± 50	+13.80	+9090 ± 37

(1) The core was subcritical

Total Void Worth

2. Pu core Locally Overmoderated, U core Undermoderated

TRISO kernel packing fraction of 18.56 % and a radius of 250 μm.

Molten Salt	Plutonium Fuel		Uranium Fuel	
	[$]	[pcm]	[$]	[pcm]
Li_2BeF_4	+2.31	+520 ± 90	-0.19	-129 ± 111
BeF_2	+0.68	+152 ± 111	-1.97	-1327 ± 114
LiF	+4.02	+904 ± 81	+1.64	+1105 ± 143
NaF	+7.60	+1708 ± 89	+15.18	+10234 ± 88
ZrF_4	+7.49	+1685 ± 85	+3.56	+2402 ± 109

Total Void Worth

3. Pu core Undermoderated, U core Undermoderated

TRISO kernel packing fraction of 24.83 % and a radius of 215 μm.

Molten Salt	Plutonium Fuel		Uranium Fuel	
	[$]	[pcm]	[$]	[pcm]
Li_2BeF_4	+1.40	+423 ± 44	-0.42	-308 ± 56
BeF_2	-1.99	-60 ± 38	-0.61	-1194 ± 57
LiF	+2.70	+816 ± 39	+0.61	+449 ± 58
NaF	+5.64	+1707 ± 37	+7.50	+5545 ± 49
ZrF_4	+5.43	+1642 ± 39	+2.09	+1551 ± 53

Total Void Worth

⇒ **Reference core configurations**

Pu fueled core

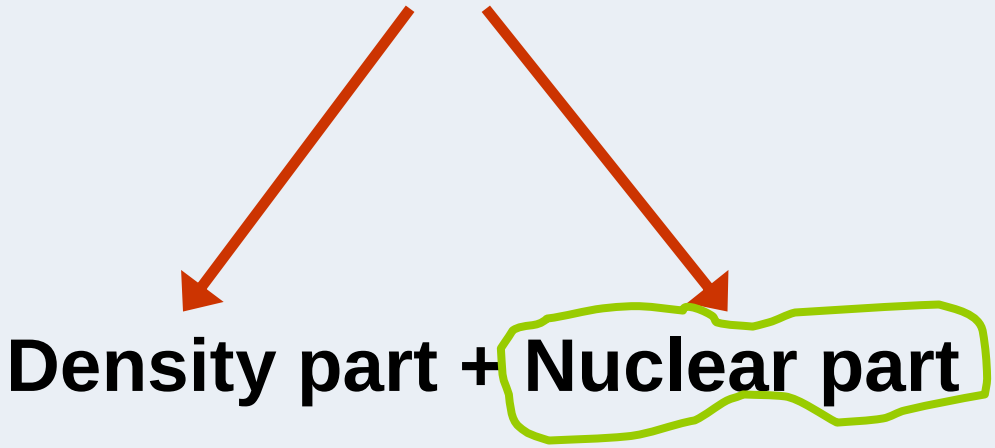
U fueled core

Core configuration	1	2	3
Kernel size [μm]	150	250	215
TRISO pf [%]	14.53	17.48	24.32
235U Enrichment [%]	6.965	6.965	15
FM Ratio [%]			
- Uranium Fuel	0.53	2.93	2.42
- Plutonium Fuel	0.44	2.44	2.01

Note: These configuration are used in the rest of the work

Moderator and Fuel Temperature Reactivity Coefficient

Temperature Reactivity Coefficient

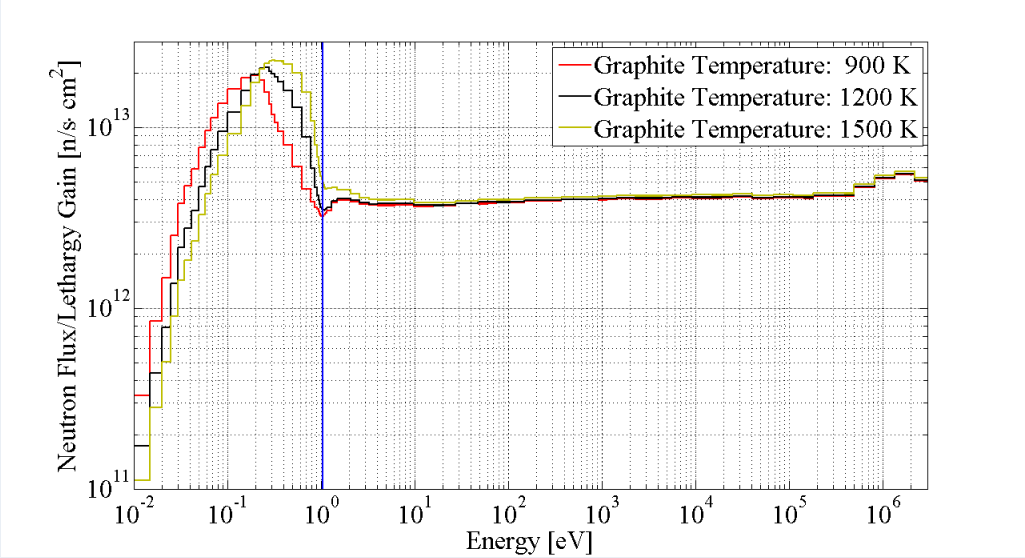


- Bigger effect on reactivity
- More funny!

Moderator Temperature Reactivity Coefficient

Nuclear Part

U fueled core: TRISO pf 24.83 % and a radius of 215 μm, 15% enrichment
Pu fueled core: TRISO pf 14.53 % and a radius of 150 μm

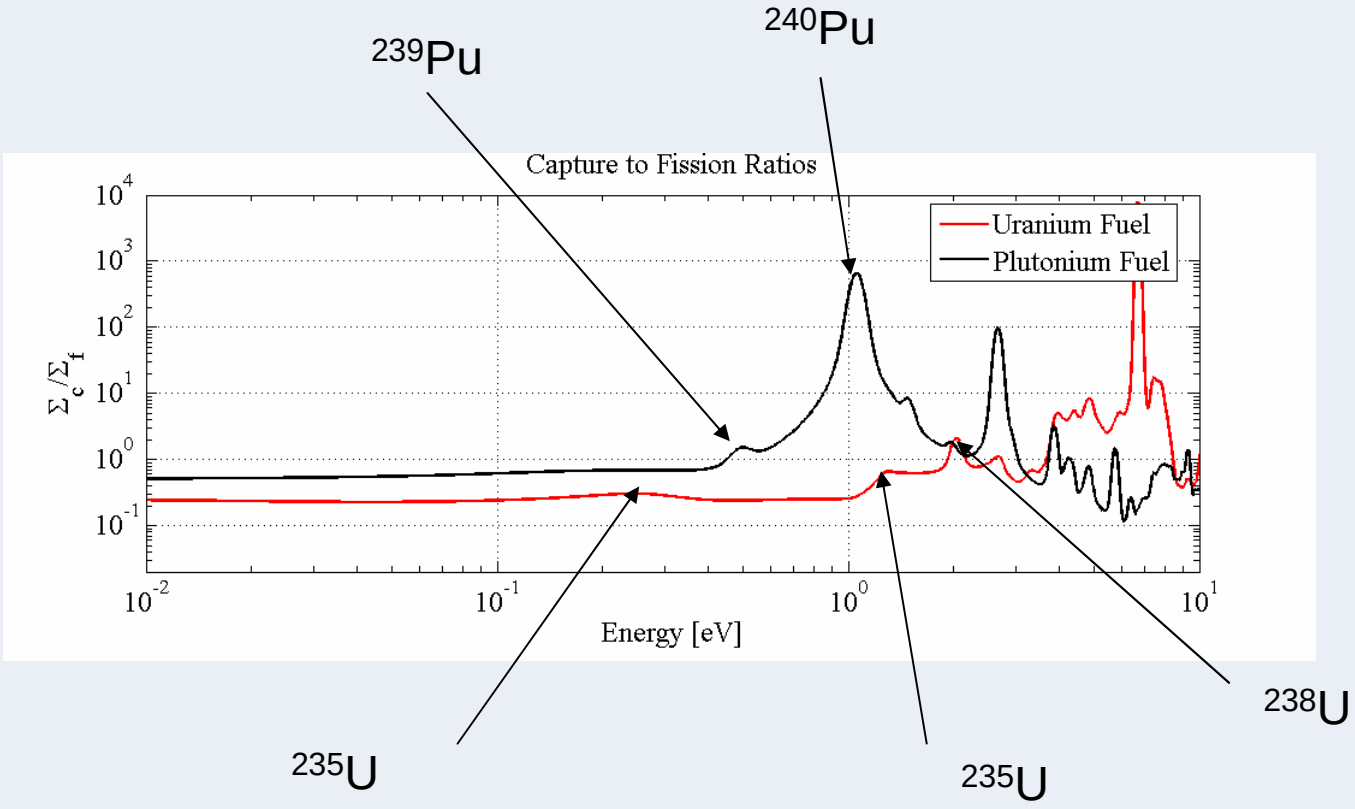


Increasing the graphite temperature causes a spectral shift to the higher energies.

At 1200 K spectral shift passes through, the peak of the cf ratio of ^{240}Pu.

Operational tmp (1200 K)
Pu: **- 6.53 ± 0.12 pcm/K**
U: **-0.21 ± 0.08 pcm/K**

Reminder

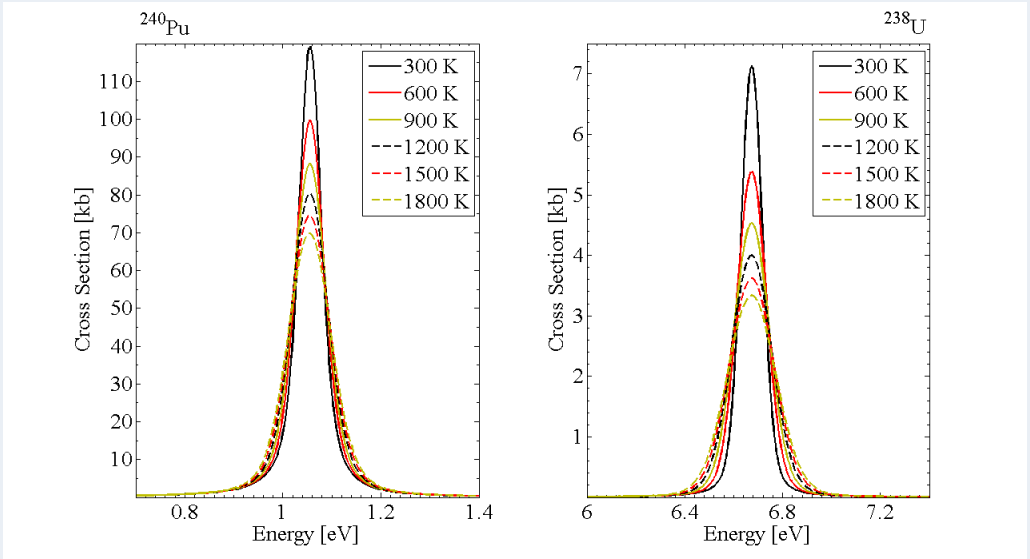

239Pu
240Pu
Capture to Fission Ratios
Uranium Fuel
Plutonium Fuel
Σ_c/Σ_f
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1
Energy [eV]
238U
235U
235U

Fuel Temperature Reactivity Coefficient

Nuclear Part

U fueled core: TRISO pf 24.83 % and a radius of 215 μm, 15% enrichment
Pu fueled core: TRISO pf 14.53 % and a radius of 150 μm

92% to the total ^{240}Pu capture



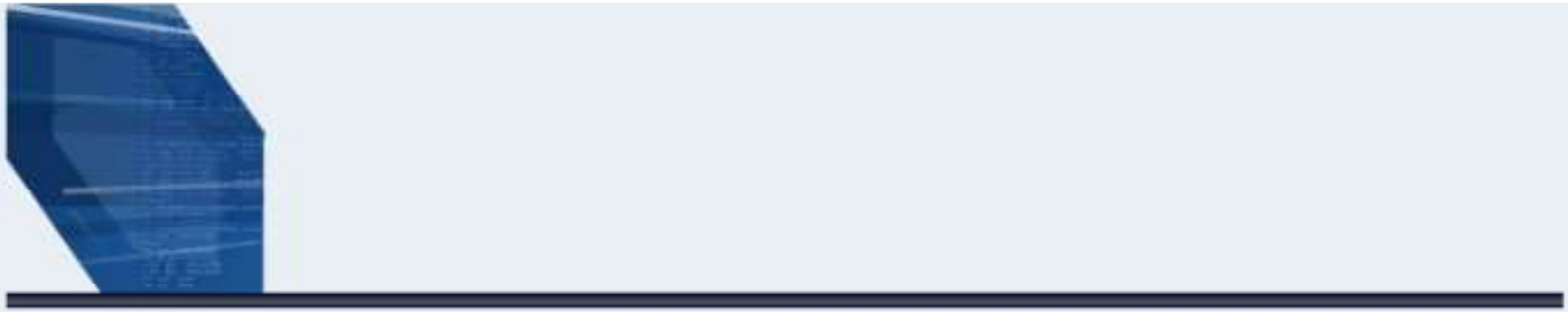
Doppler broadening:
Broader peaks are "visible" to more neutrons

Operational tmp (1500 K)
Pu: **- 1.24 ± 0.12 pcm/K**
U: **-2.26 ± 0.08 pcm/K**

Conclusions

- Negative total void worth coefficient can be reached for both U and Pu fueled core, with the reference salt (FLiBe) and appropriate F/M.

- At the operational temperatures, the total negative feedback from moderator and fuel is -7.82 pcm/K, for the plutonium fueled core and -2.47 pcm/K for the uranium fueled core.



Thank you for your attention!