Antineutrino Data:
Reactor Operational Data Uncertainties

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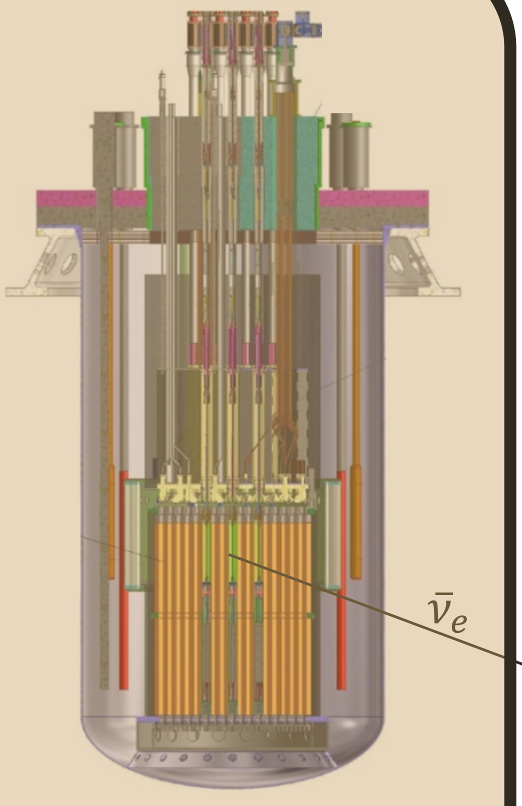
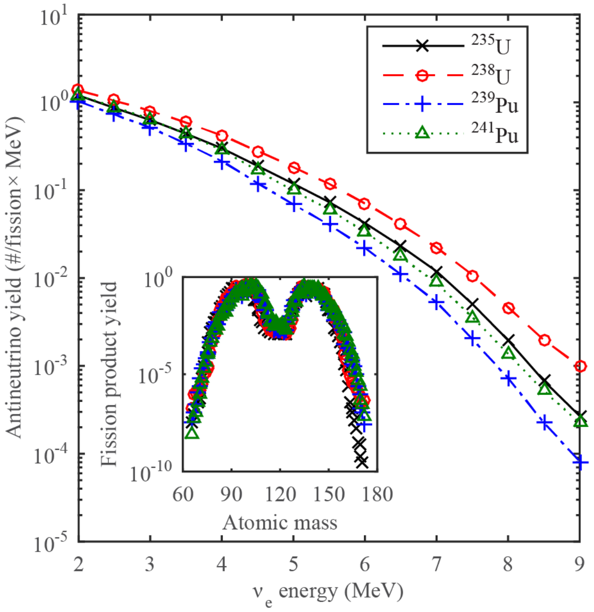
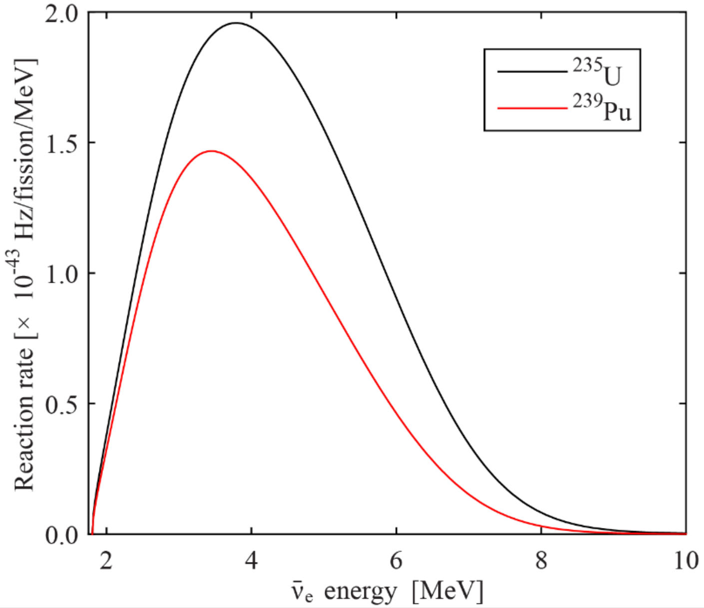
Reactor Evaluation Through Inspection of Near-field Antineutrinos (RETINA)

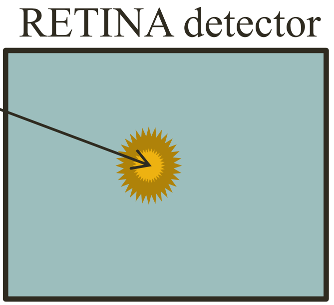


$${}^{A}_{Z}X \rightarrow {}_{Z+1}^{\;\;A}Y + \beta^- + \bar{\nu}_e$$

Reactor + Vessel + Shielding







Inverse beta decay: $\bar{\nu}_e + p \xrightarrow{-1.8\ MeV} n + e^+$

Neutron capture: $n + {}^6Li \xrightarrow{4.78\ MeV} \alpha + T$

Translating neutron-based fission into detector event rates

$$n_b(t) = \frac{N_d}{4\pi L^2}\sigma_b^{IBD}\epsilon_b S_b(t) + B_b$$

$S_b(t)$ = antineutrinos generated for given burnup and energy bin

$$\frac{dN(E,t)}{dEdt} = \frac{P_{th}(t)}{\overline{E_f}(t)}\sum_{i=1}^{4} f_i(t) s_i(E) c_i^{ne}(E)$$

- Uncertainties:
  - Thermal power + energy release per fission
  - Relative fission rate for each isotope
  - Fission product distribution
  - Neutron spectrum

Operational Uncertainties

- Initial reactor fuel loading: mass and enrichment
- Reactor geometry
- Total thermal power
- Effect of temperature and other operational parameters on XS and neutron flux
- Propagation of fuel burnup

Antineutrino analysis for continuous monitoring of nuclear reactors: Sensitivity study

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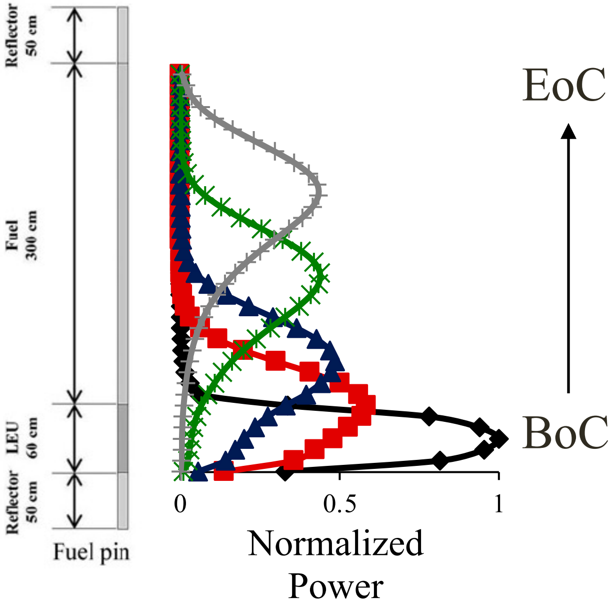
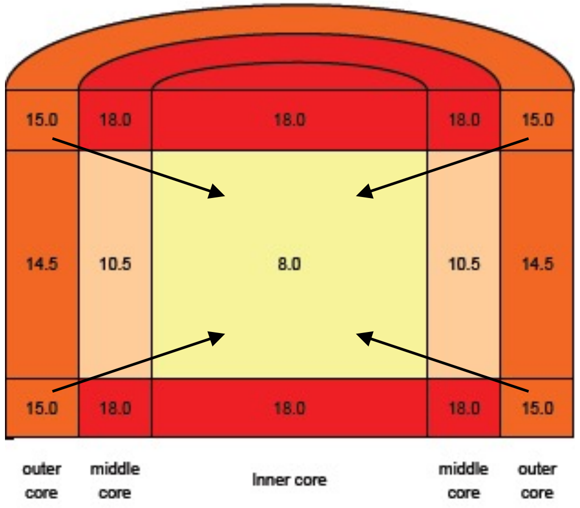
Comparison of reactor antineutrino sources

<table>
<tr><th>High-power core: UCFR-1000</th><th>Low-power core: AFR-100</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>3D source</td><td>Point source</td></tr>
<tr><td>Good counting statistics</td><td>Poor counting statistics</td></tr>
<tr><td>SQ ~ 0.1%</td><td>SQ ~ 1%</td></tr>
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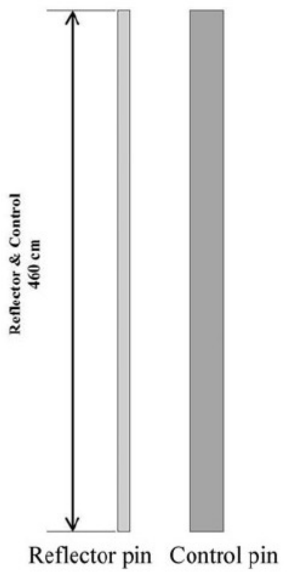
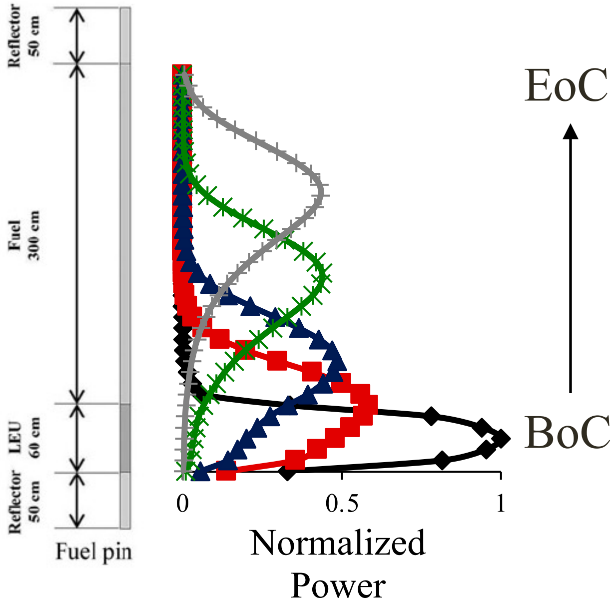
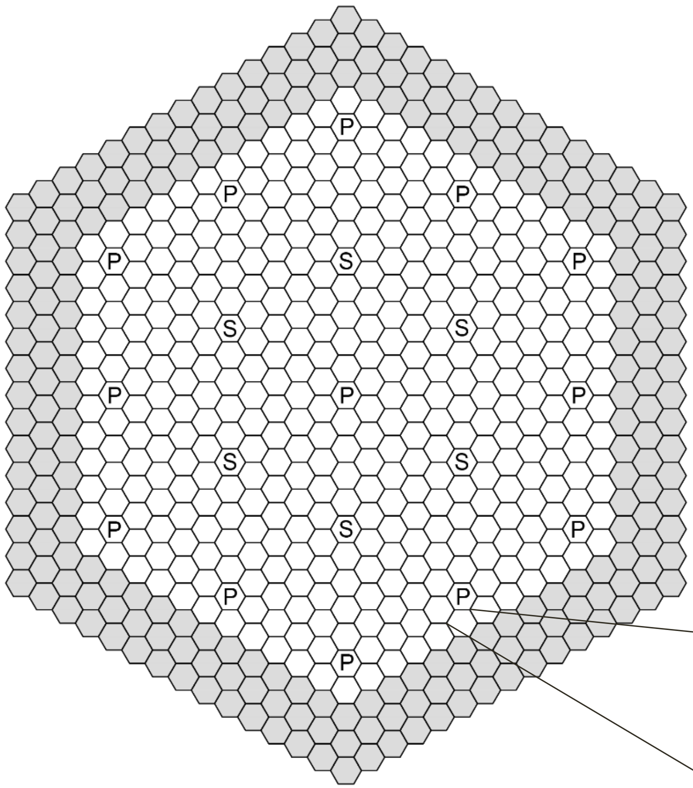
High-power core: UCFR-1000

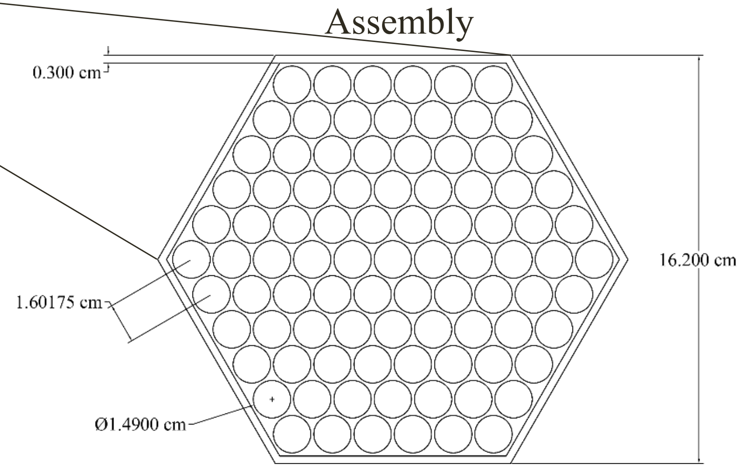






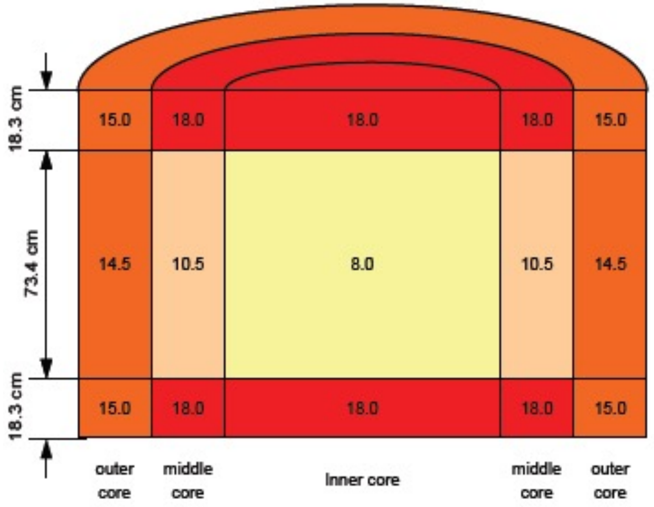
Core layout

Parameter	Value (293 K)
Power (MW_t/MW_e)	2600/1000
Cycle length	60 EFPY
Active core height	360 cm
No. fuel assemblies	378
Initial HM inventory	201 t
Fuel form	U-10Zr
Uranium enrichment	12.3% / natural
Volumetric power density	81.0 kW/L

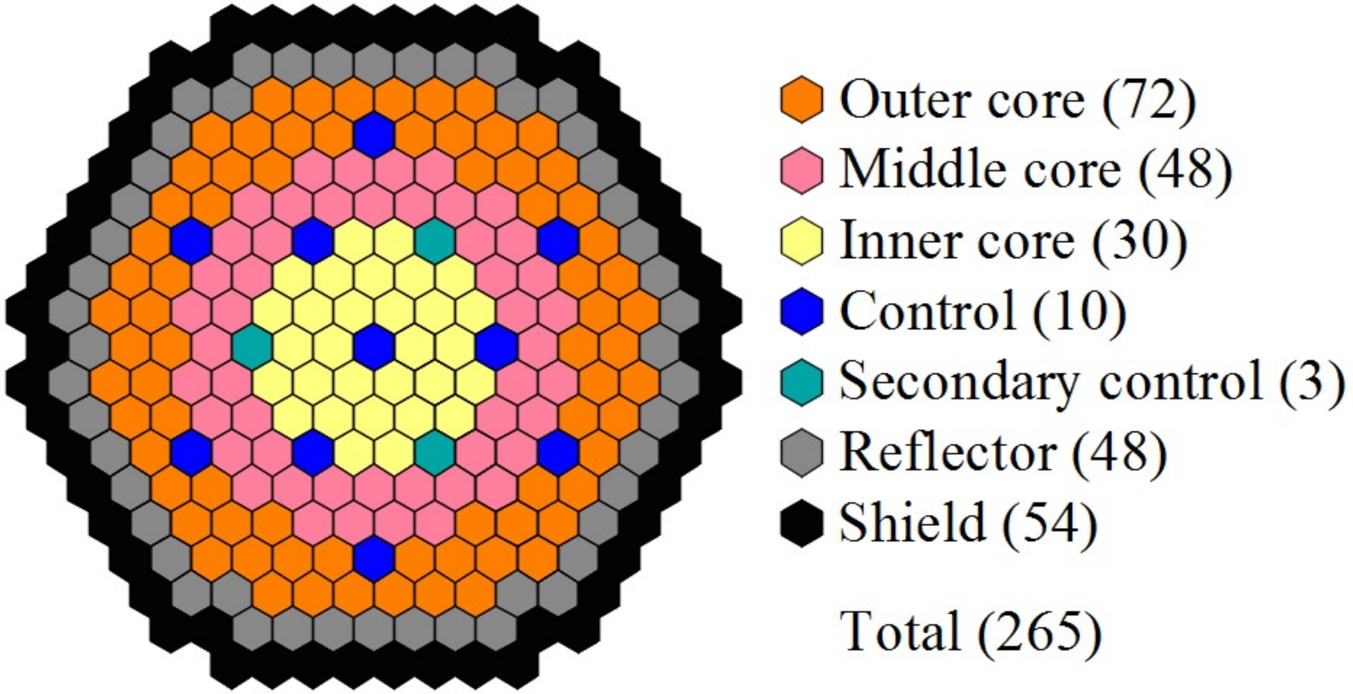


Low-power core: AFR-100

Parameter	Value (293 K)
Power (MW_t/MW_e)	250/100
Cycle length	30 EFPY
Capacity factor	90%
Active core height	110 cm
No. fuel assemblies	150
Initial HM inventory	24.64 t
Fuel form	U-10Zr
Core average enrichment	13.47%
Volumetric power density	58.2 kW/L

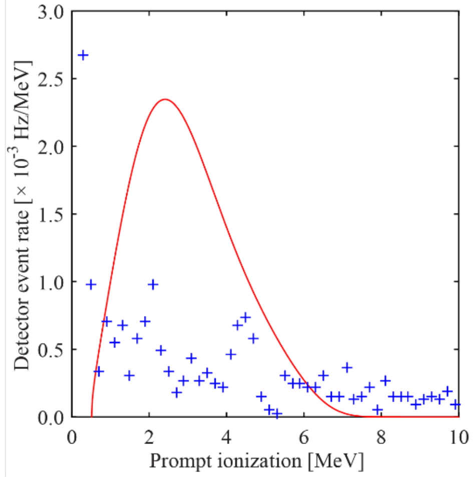


C. Grandy. "An Overview of U.S. SFR Design Concepts", GIF/INPRO Workshop on SFR Safety, December, 2011.

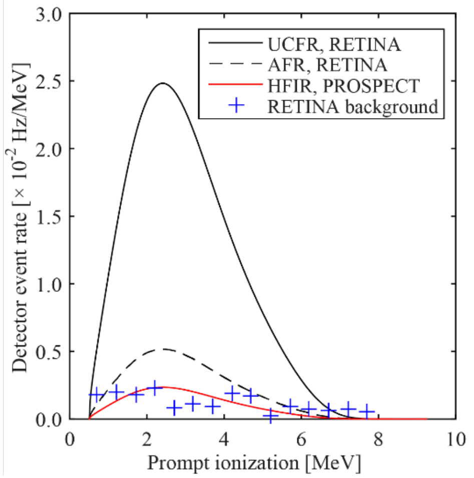


The RETINA detector suite is based on current-generation antineutrino detectors

Parameter	PROSPECT AD-I	PROSPECT AD-II (est.)	RETINA (each)
Scintillator	EJ-309	EJ-309	EJ-309
Proton density	$5.5 \times 10^{28}/m^3$	N/A	$5.5 \times 10^{28}/m^3$
Neutron capture dopant	^6Li	^6Li	^6Li
Target mass (total)	2940 kg	10 t	< 10 t
Target mass (fiducial)	1480 kg	~ 7 t	5 t
Efficiency in fiducial vol.	42%	N/A	42%
Reactor source power	85 MW	85 MW	2600 MW / 250 MW
Core-detector standoff	6.9 m / 9.4 m	15 m	25 m / 17 m
S:B ratio	3.1 / 1.8	3.0	~ 8.0 / 1.5

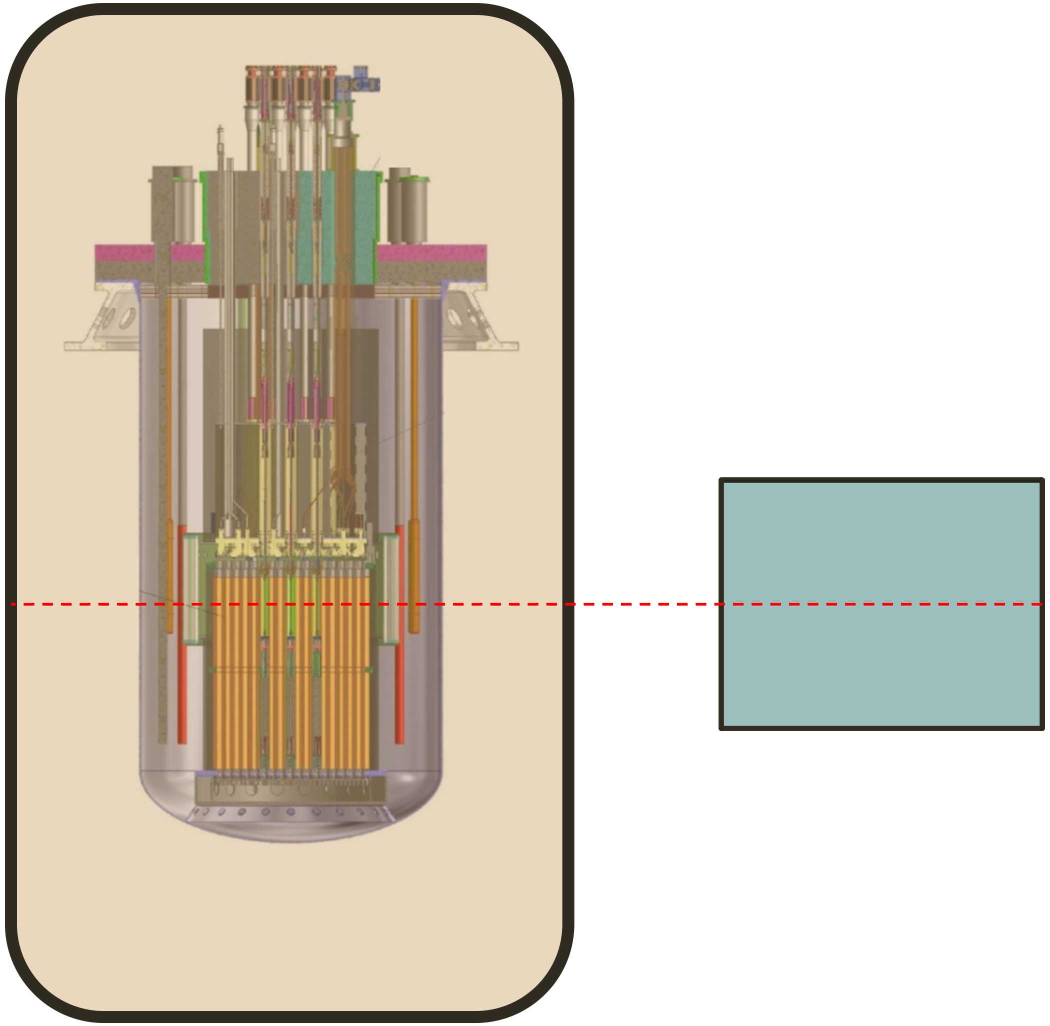


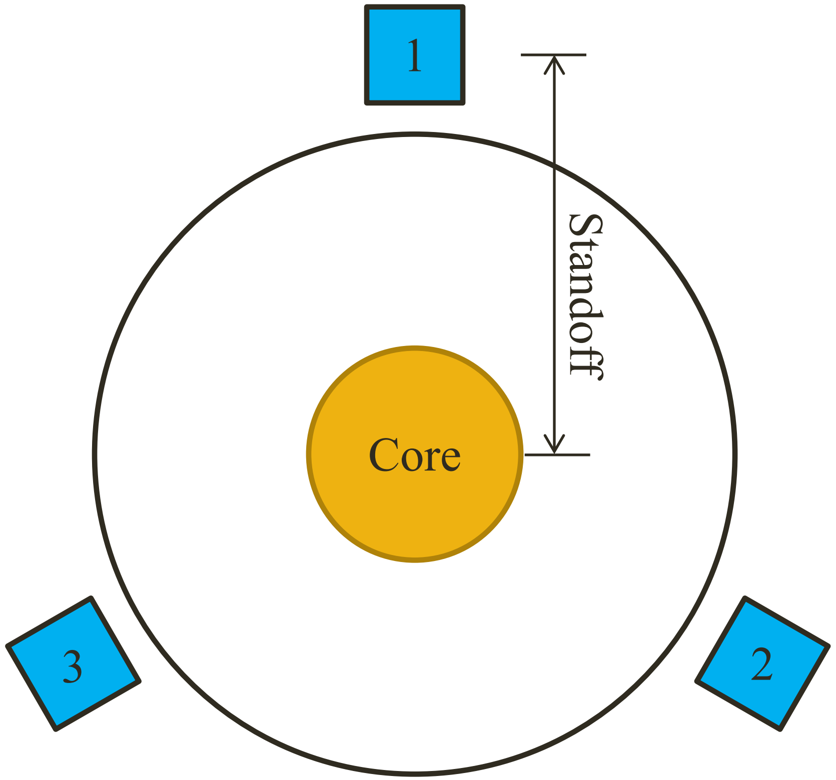
PROSPECT
+
HFIR



RETINA
+
UCFR/AFR

Detector suite configuration



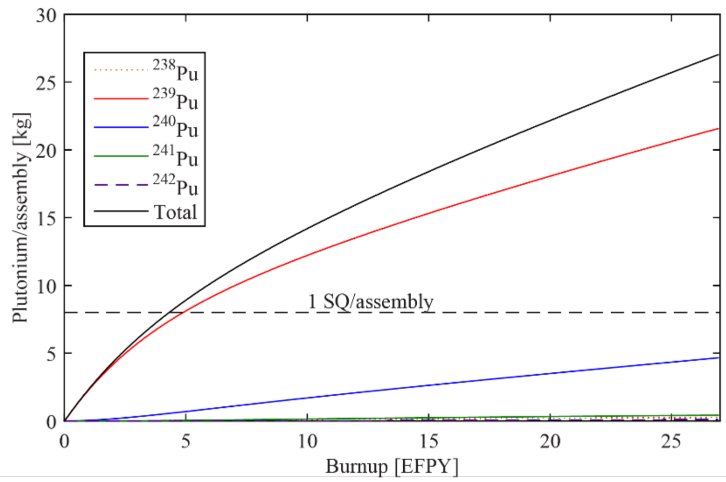


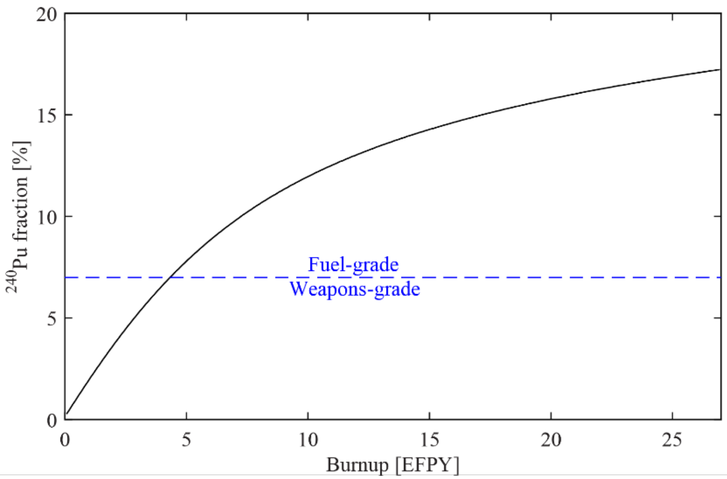
The UCFR yields multiple SQ of plutonium per assembly, but its purity is compromised

- The UCFR breeds plutonium above the burn zone, depletes it as the burn zone moves upward, and leaves relatively unusable plutonium behind.

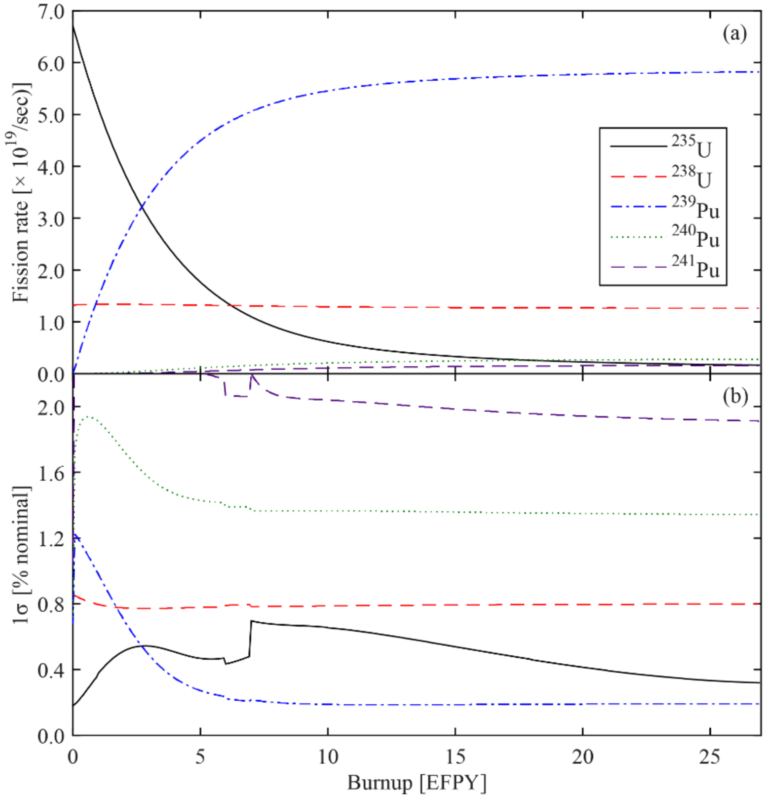
- Once steady-state burn zone propagation begins, the amount of weapons-grade plutonium remains relatively constant

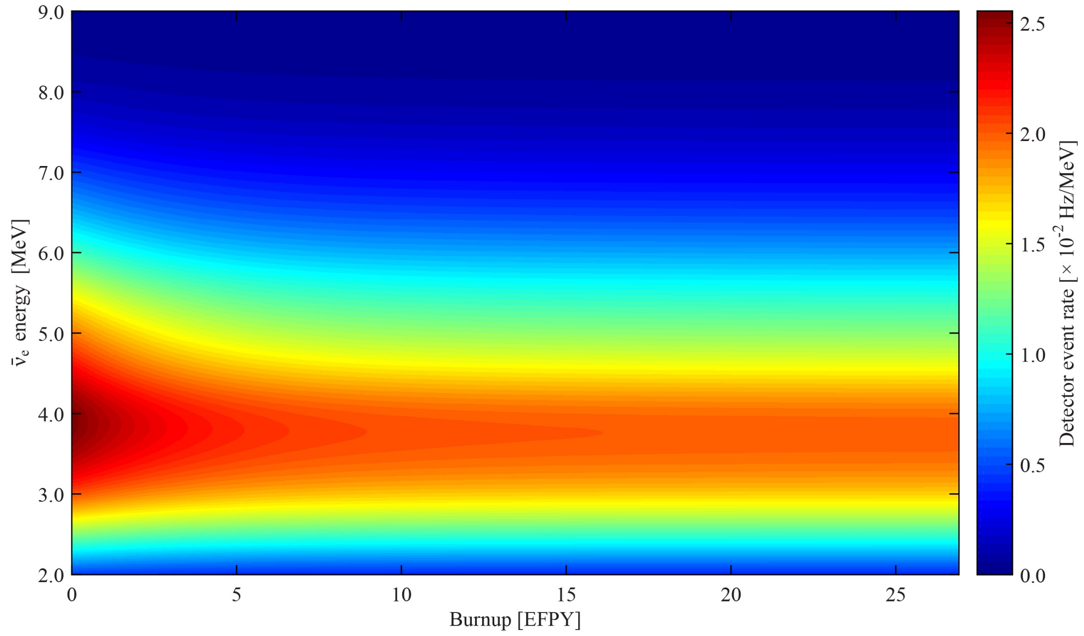
- Depleted plutonium below the burn zone is contaminated with both ^{240}Pu and many fission products.





The UCFR-1000 antineutrino signal evolves quickly, then enters a steady state

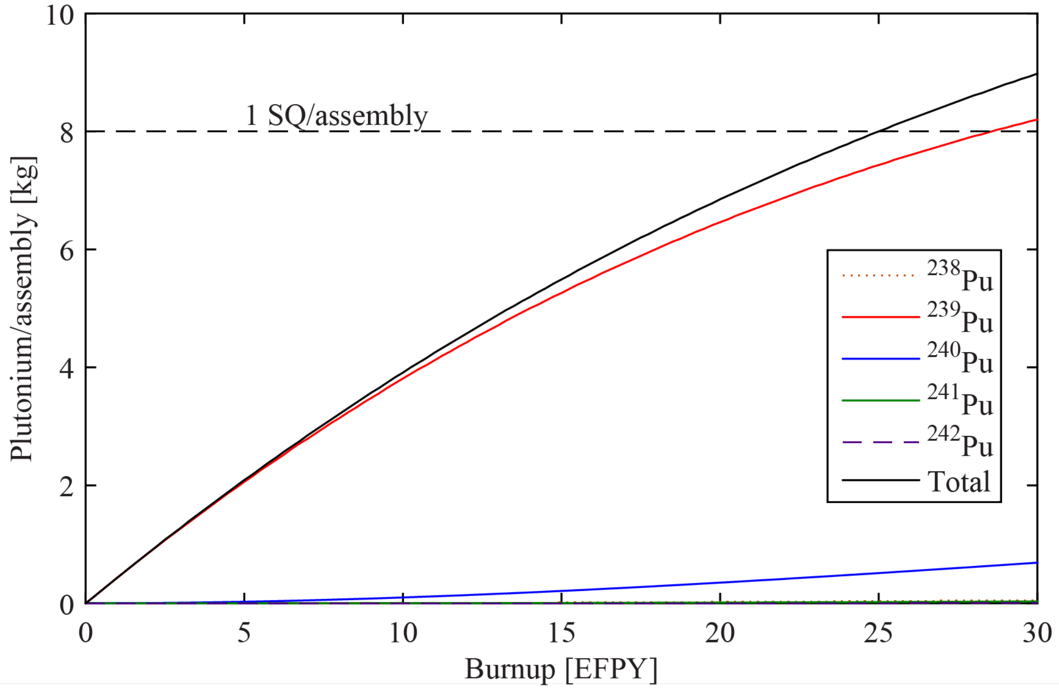




The AFR-100 yields little plutonium per assembly

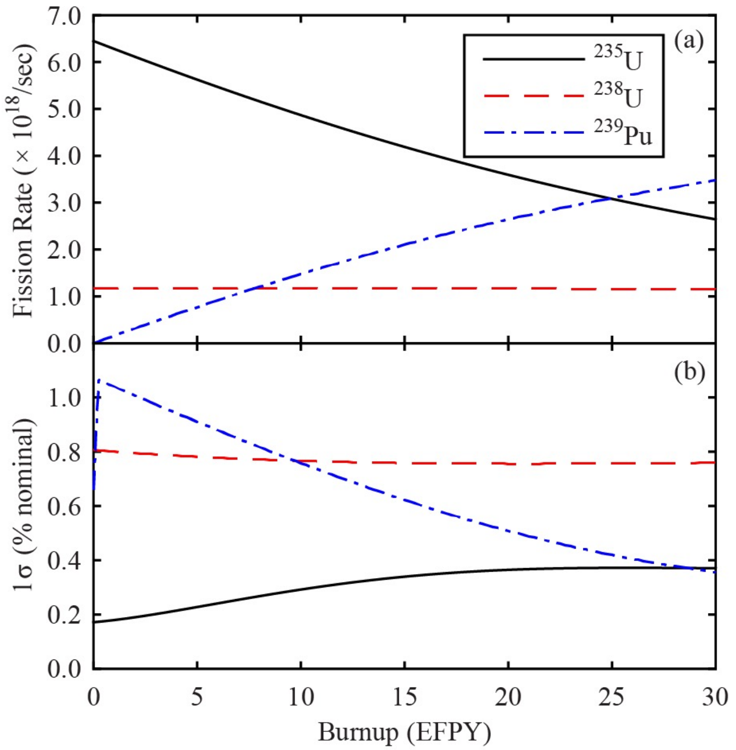
- The AFR's low power density (~20% of traditional SFR designs) keeps the average plutonium content per assembly below 8 kg for nearly the entire cycle.

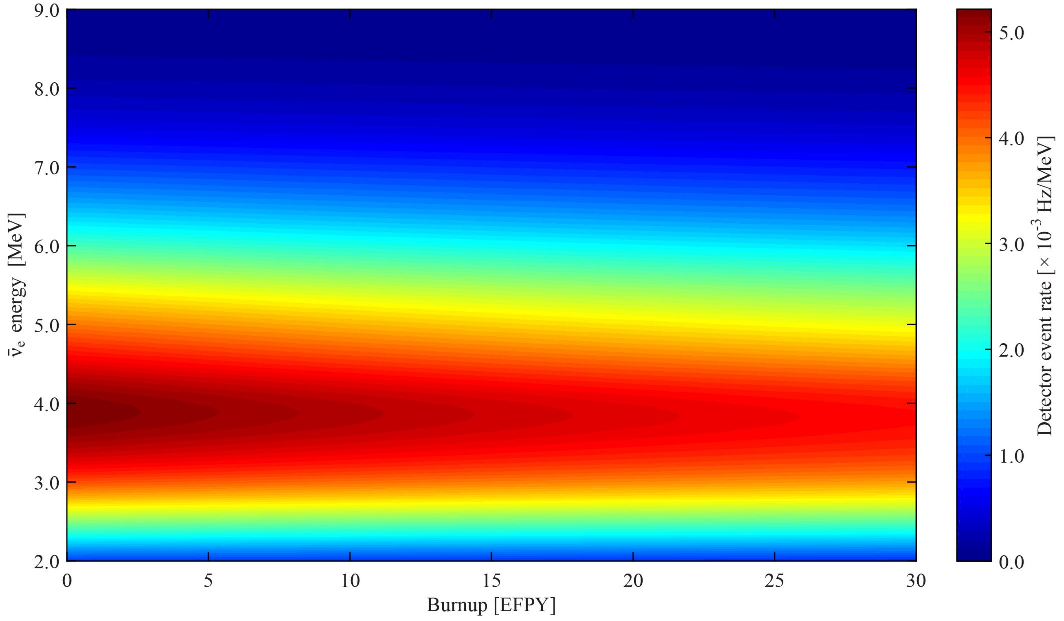
- Plutonium breeding is concentrated in the inner assemblies near the core midplane as part of the effort to offset increased neutron absorption in the late cycle.



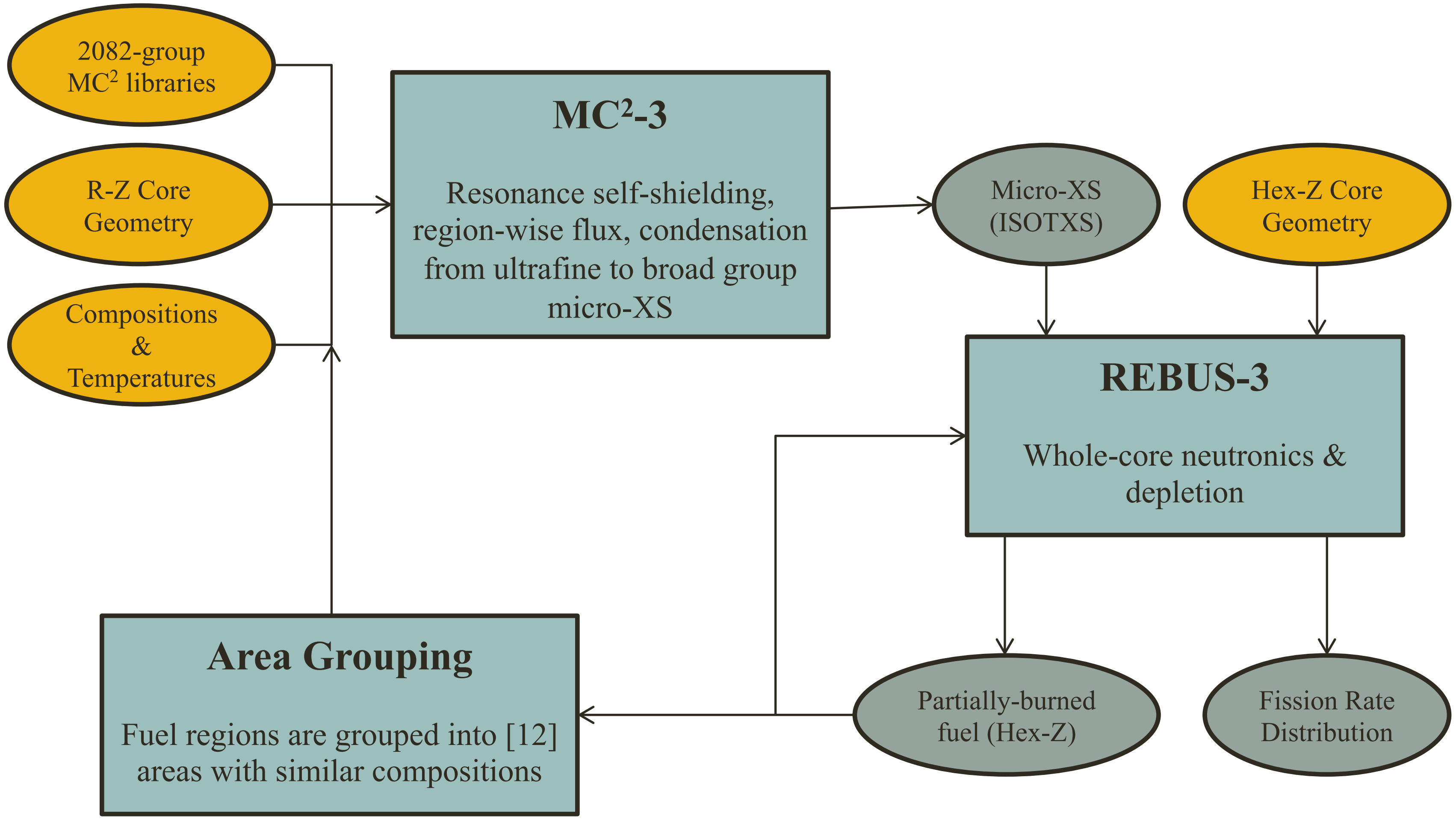
- Core-edge plutonium is ultra-pure due to cross section dominance by uranium isotopes (~15% ^{235}U enrichment), but one SQ cannot be obtained from fewer than two (late-cycle) or three (mid-cycle) assemblies.

The AFR-100 antineutrino signal evolves gradually over the entire burnup cycle

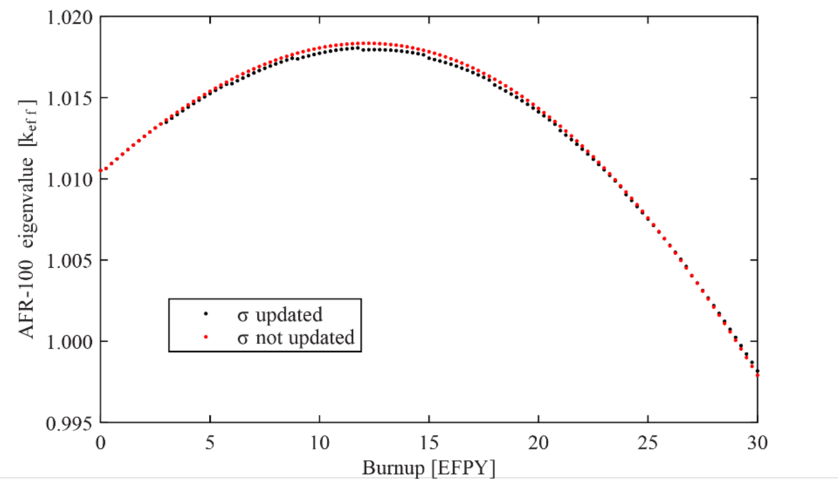


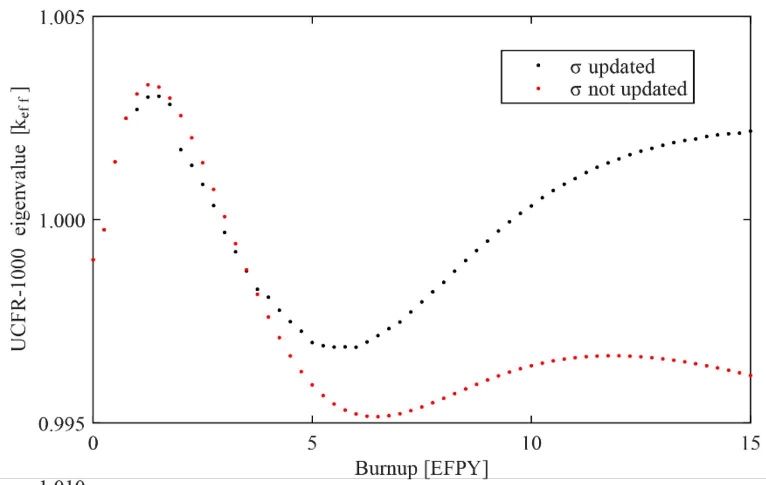


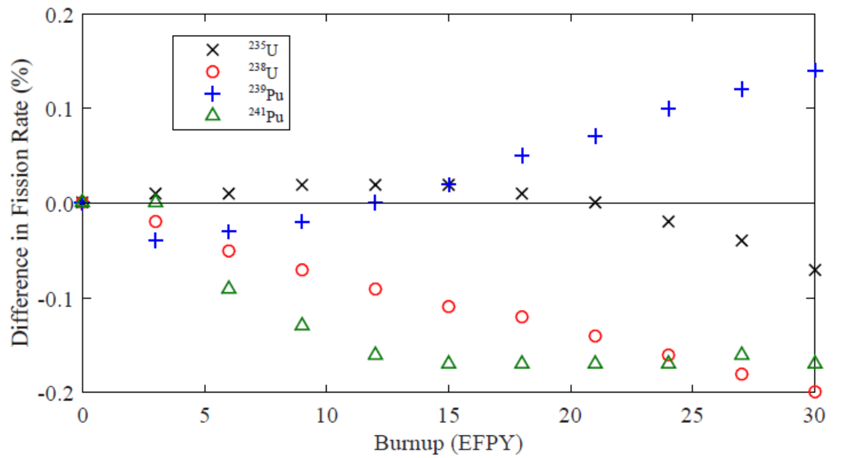
Fuel Cross Section Update Scheme

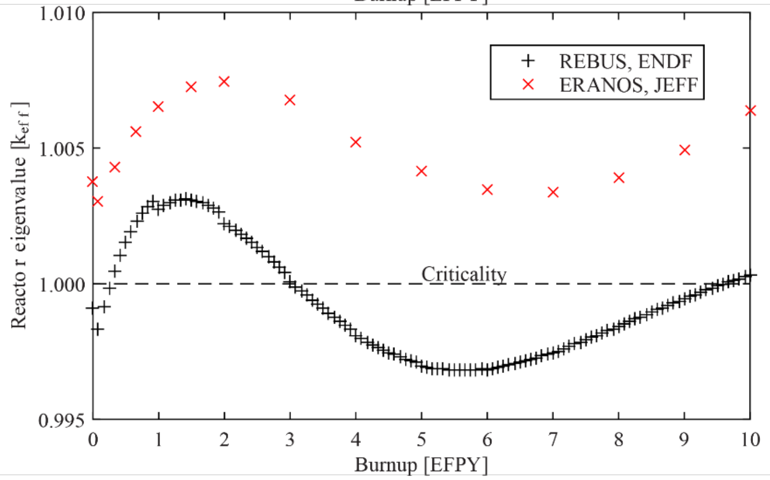


Effects of XS updates









Summary

- The uncertainty on the reactor antineutrino source arising from the model of the reactor and its burnup cycle is propagated through the calculated isotopic fission rates, determined by:
  - the initial-state reactor compositions,
  - the microscopic cross sections for each interaction, and
  - the operating history of the reactor.
- The approach to propagating uncertainty on each of these becomes complex due to the significant correlation and anti-correlation introduced through the imposition of a total thermal power output for the reactor.
- Question: what effect covariances will have on uncertainty quantification of antineutrino rate and spectrum?

0 EFPY	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
^{235}U	2.95×10^{-6}	-1.20×10^{-5}	-7.23×10^{-7}	1.13×10^{-7}	-2.87×10^{-7}
^{238}U	-1.20×10^{-5}	6.49×10^{-5}	9.95×10^{-7}	-2.86×10^{-6}	-2.06×10^{-6}
^{239}Pu	-7.23×10^{-7}	9.95×10^{-7}	4.33×10^{-5}	1.23×10^{-5}	1.83×10^{-5}
^{240}Pu	1.13×10^{-7}	-2.86×10^{-6}	1.23×10^{-5}	5.09×10^{-5}	1.14×10^{-5}
^{241}Pu	-2.87×10^{-7}	-2.06×10^{-6}	1.83×10^{-5}	1.14×10^{-5}	1.16×10^{-4}

1 EFPY	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
^{235}U	3.23×10^{-6}	-1.22×10^{-5}	-4.91×10^{-6}	-5.07×10^{-6}	-5.97×10^{-6}
^{238}U	-1.22×10^{-5}	6.41×10^{-5}	3.65×10^{-6}	-8.37×10^{-7}	-2.81×10^{-6}
^{239}Pu	-4.91×10^{-6}	3.65×10^{-6}	1.08×10^{-4}	1.16×10^{-4}	1.34×10^{-4}
^{240}Pu	-5.07×10^{-6}	-8.37×10^{-7}	1.16×10^{-4}	3.28×10^{-4}	3.01×10^{-4}

15 EFPY	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
^{235}U	1.15×10^{-5}	-8.11×10^{-6}	-1.56×10^{-5}	-1.80×10^{-5}	-2.45×10^{-5}
^{238}U	-8.11×10^{-6}	5.75×10^{-5}	-1.39×10^{-5}	-1.80×10^{-5}	-2.47×10^{-5}
^{239}Pu	-1.56×10^{-5}	-1.39×10^{-5}	3.87×10^{-5}	3.91×10^{-5}	5.21×10^{-5}
^{240}Pu	-1.80×10^{-5}	-1.80×10^{-5}	3.91×10^{-5}	2.55×10^{-4}	2.41×10^{-4}
^{241}Pu	-2.45×10^{-5}	-2.47×10^{-5}	5.21×10^{-5}	2.41×10^{-4}	7.18×10^{-4}

30 EFPY	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
^{235}U	1.37×10^{-5}	-8.12×10^{-7}	-8.38×10^{-6}	-9.28×10^{-6}	-1.49×10^{-5}
^{238}U	-8.12×10^{-7}	5.77×10^{-5}	-1.63×10^{-5}	-1.93×10^{-5}	-2.48×10^{-5}
^{239}Pu	-8.38×10^{-6}	-1.63×10^{-5}	1.26×10^{-5}	5.22×10^{-6}	7.38×10^{-6}
^{240}Pu	-9.28×10^{-6}	-1.93×10^{-5}	5.22×10^{-6}	2.07×10^{-4}	1.64×10^{-4}
^{241}Pu	-1.49×10^{-5}	-2.48×10^{-5}	7.38×10^{-6}	1.64×10^{-4}	5.86×10^{-4}

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Questions