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Optimization of Pu-238 Production in the Advanced Test Reactor

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Outline

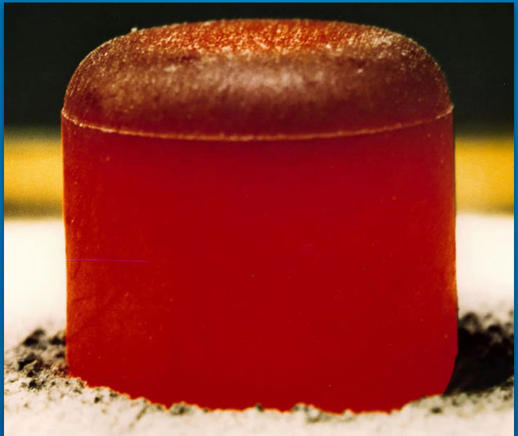
- Objectives & Background
- Design Specifications & Geometry
- Methodology
- Results
- Analysis & Recommendations
- Future Work

Objective & Background

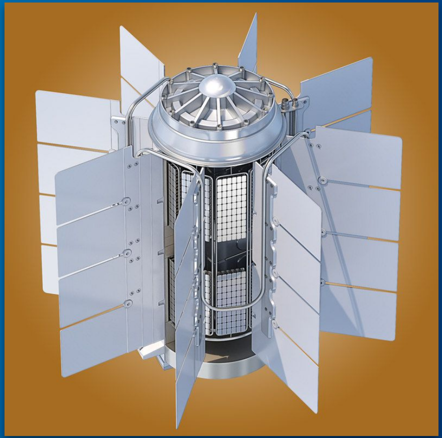
Objective

Create an ATR irradiation design meeting radiological exposure and safety standards which, with HFIR, can produce 1.5 kg Pu-238 annually by 2025.

Credit: Argonne Nat. Lab



Credit: Los Alamos Nat. Lab

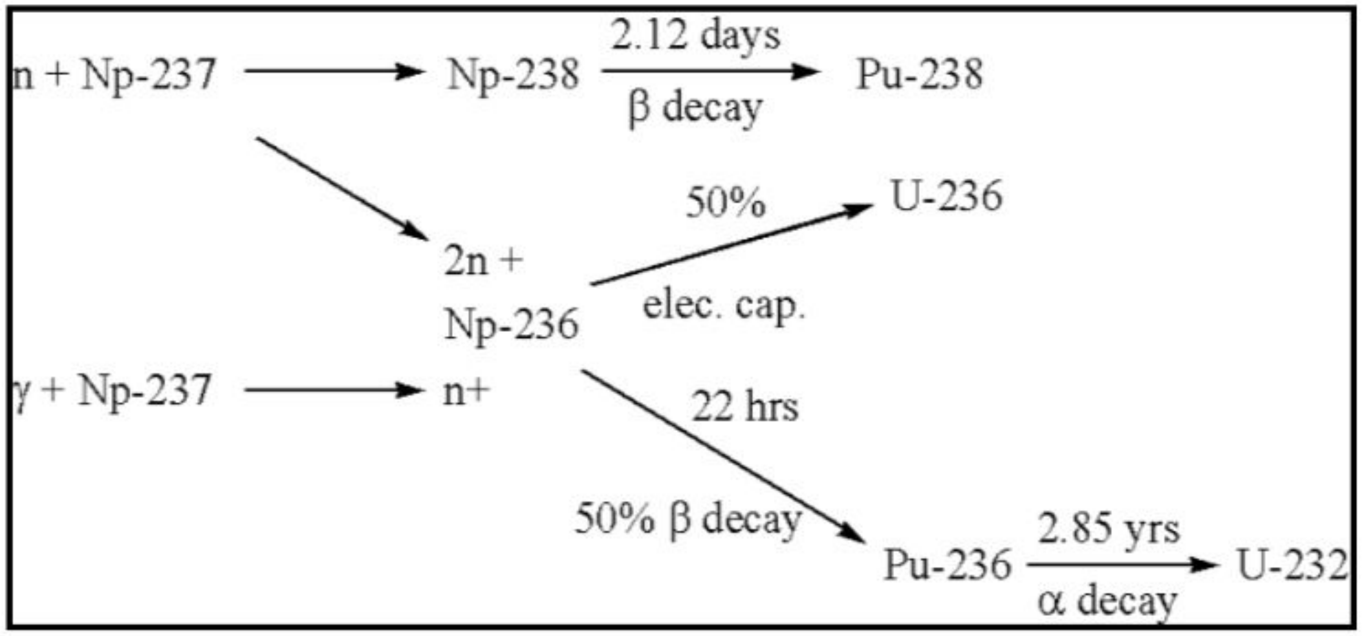


Credit: Brian Haeger

Commonly Used Terms

- ATR - Advanced Test Reactor at Idaho Natl. Lab
- HFIR - High Flux Isotope Reactor at Oak Ridge Natl. Lab
- MMRTG - Multi-Mission Radioisotope Thermoelectric Generator
- Target Rod - Pellet stack assembly with cladding, plenum, and spacers
- Pellet - NpO_2- Al powder mixed and pressed together
- Plenum - Space for fission gases to go during irradiation
- Cladding - Outer aluminum coating of pellet stack
- Basket - Aluminum casing that holds targets in place
- Irradiation Facility - Aluminum container holding target baskets
- I-Position/Channel - Where target rods are placed on ATR periphery
- B-Position/Channel - Where target rods are placed closer to ATR fuel lobes
- Np-237 - Neptunium isotope that decays into plutonium when irradiated
- Pu-238 - Plutonium isotope used in RTGs for spacecraft missions
- Pu-236 - Plutonium isotope, decay daughters include 2.62 MeV gammas

Pu-238 Reaction Scheme



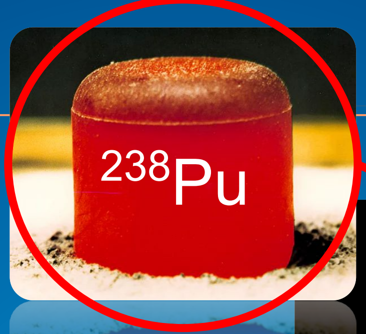
Reaction schemes for transmuting Np into Pu (Credit: Patent US 6896716 B1 (2005))

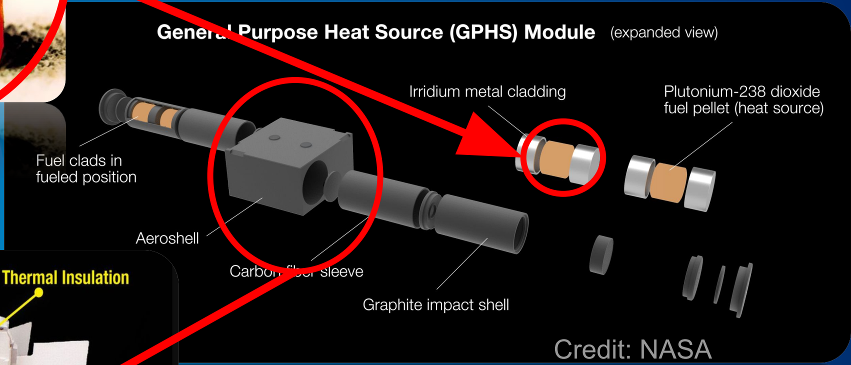
MMRTGs

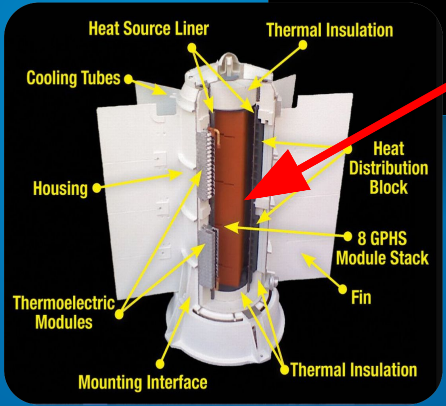
Multi-**M**ission **R**adioisotope **T**hermoelectric **G**enerators

Generator running on heat produced from radioactive decay of ^{238}Pu

Missions are typically labeled in required W_e(electric watts)







Credit: NASA

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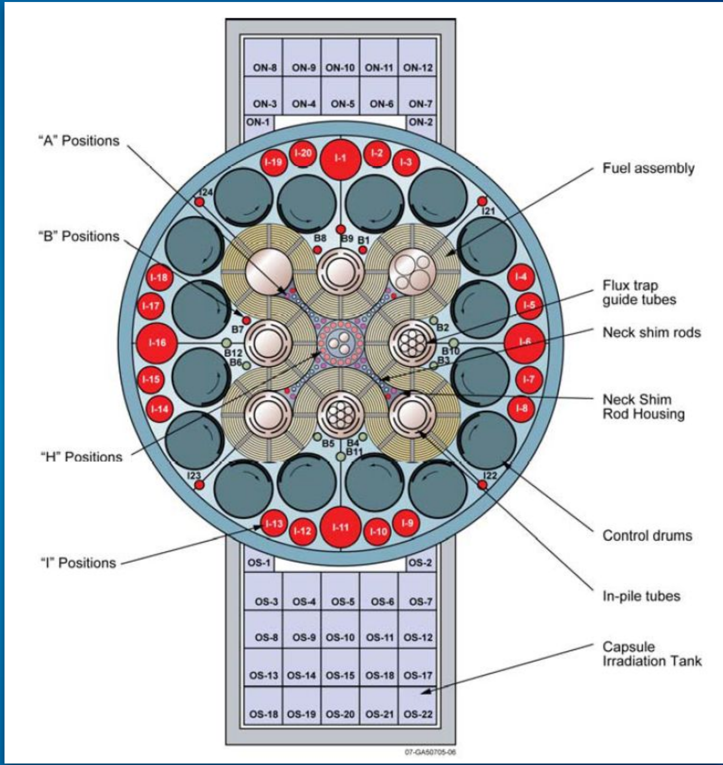
The ATR

- Irradiation of Np-237 at ATR & HFIR
- HFIR limited to 300-500g (using all positions)
- ATR I and B positions most readily available



Credit: Idaho Nat. Lab

Design Specs & Geometry

Design Positions

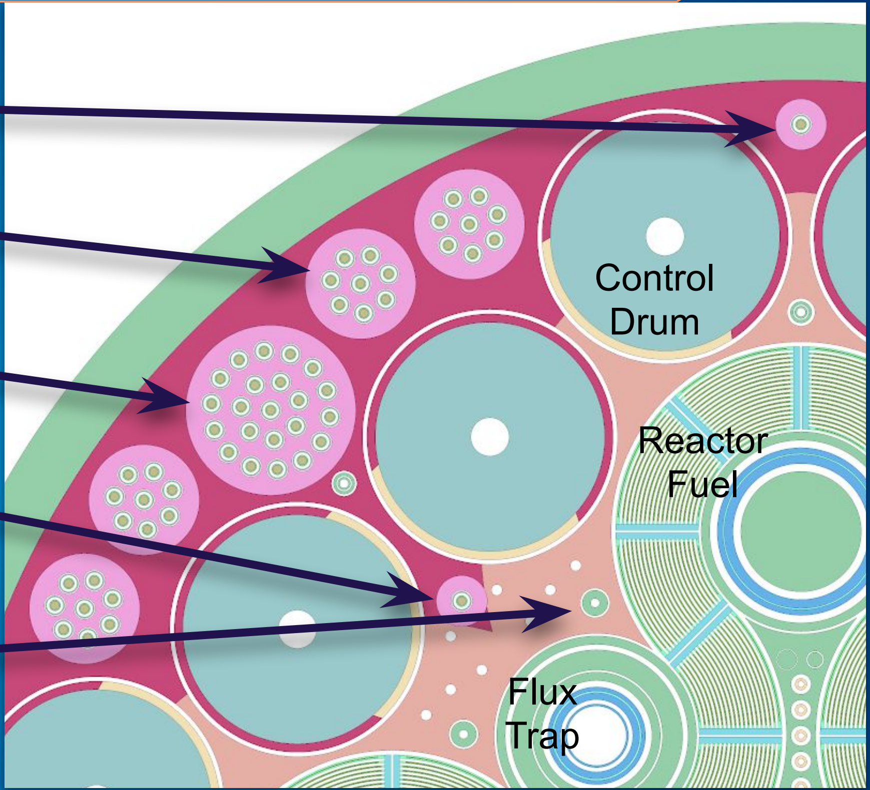
Small I: 4 Positions, 4 Targets

Medium I: 16 Positions, 128 Targets

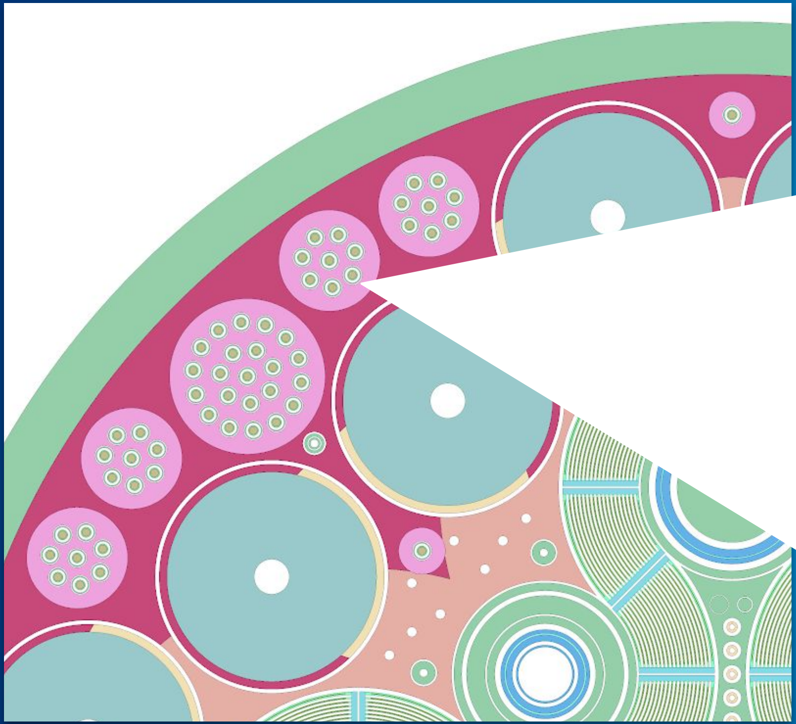
Large I: 4 Positions, 88 Targets

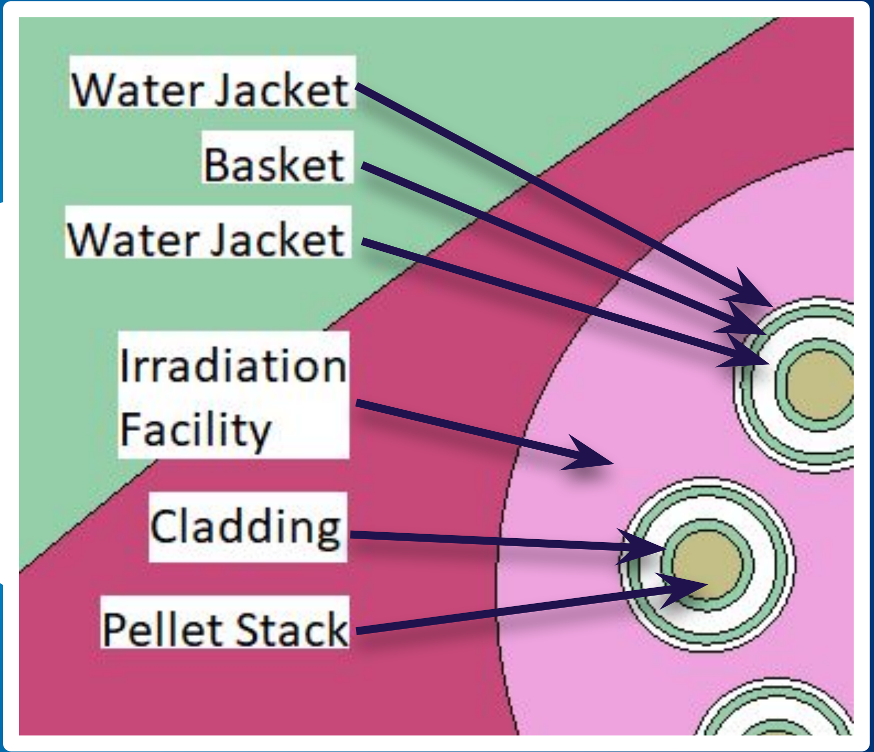
Large B: 4 Positions, 4 Targets

Small B: 7 Positions, 7 Targets



Design Positions Cont.





Design Parameters

Parameter	Limit
Target Rod Length	40 inches MAX
Pu-236 Concentration	2 ppm MAX
NpO_2- Al Pellet Concentration (volumetric)	30% MAX
Pu-238 Quality	87% MIN
Pu-238 Conversion Ratio	10% MIN

Methodology

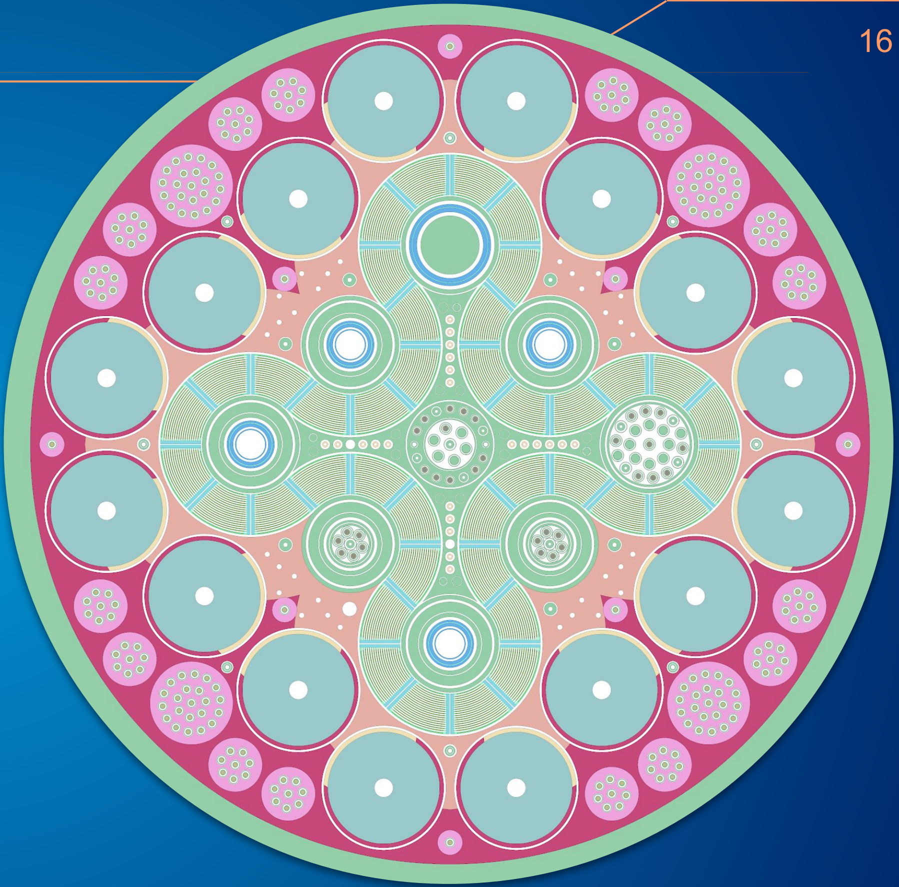
Method

- Used previous results to define optimization scope
- Modeled in Serpent
  - Used depletion analysis to observe material levels
  - Simplified lattice structures for ease of editing
- Advantages of Serpent over MCNP
  - Runs faster
  - Advanced lattice types
- Idaho National Laboratory’s High Performance Computing system used for modeling

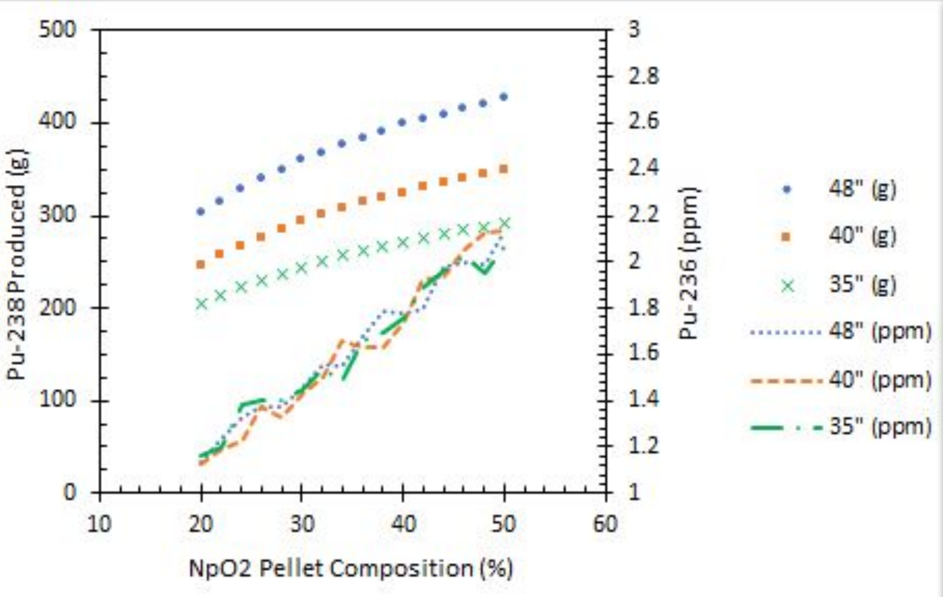
Results

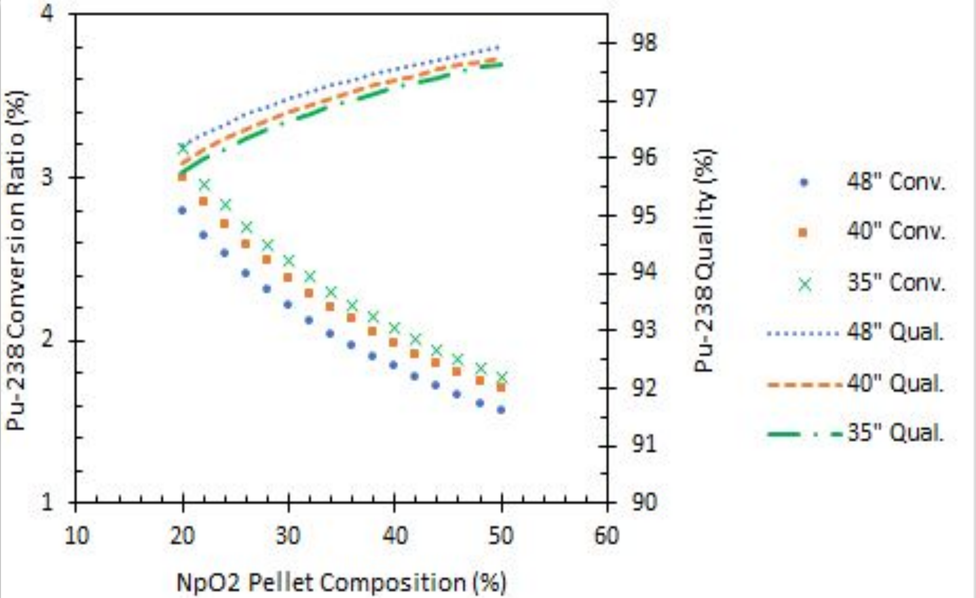
Range of Analysis

- Varied target length from 35”, 40”, and 48”
- Increased initial NpO_2 conc. from 20% to 50%
  - 2% step increments
- Added targets in alternative positions in ATR
  - Small and Large B-Positions
  - Small I-Positions



Large/Medium I-Positions

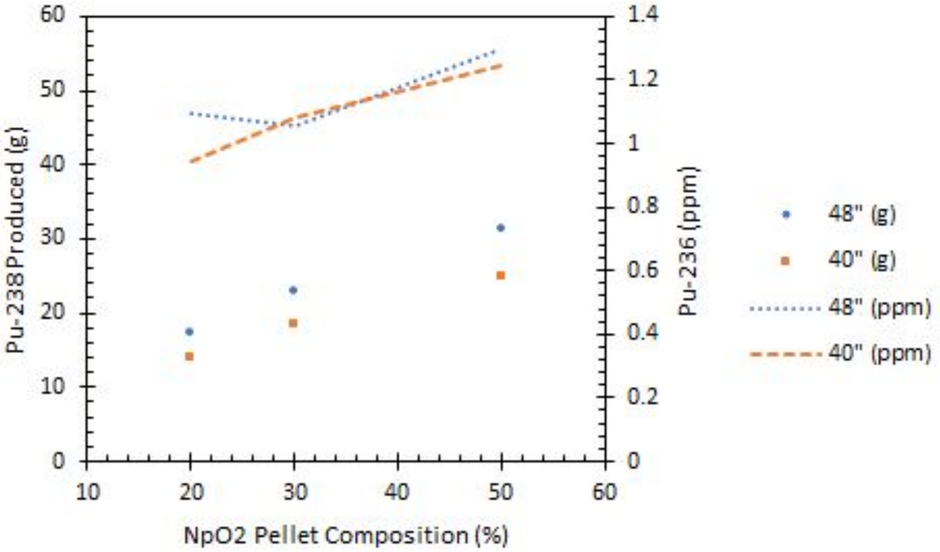


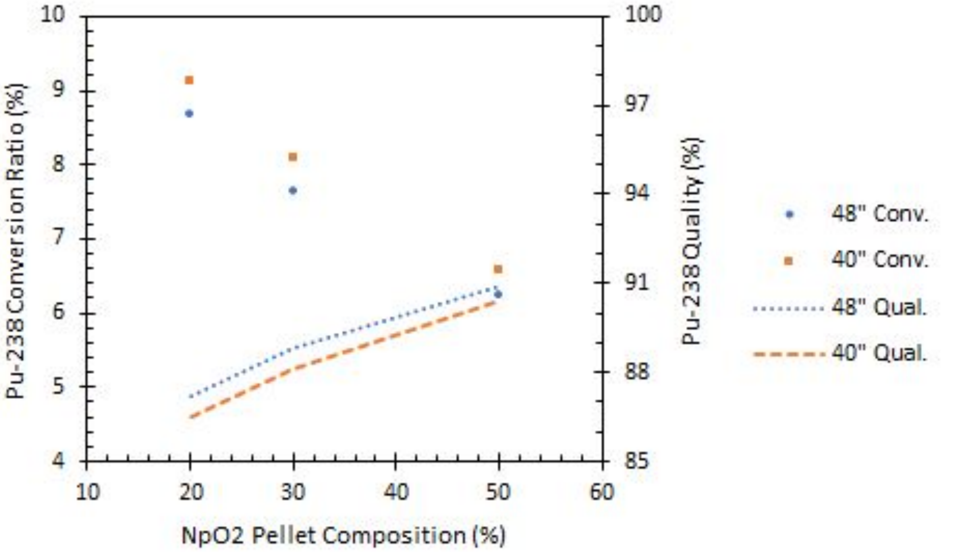


Longer targets have superior:

- Annual Pu-238 Yield (200-300 g), Pu-236 Concentration (<2 ppm), and Pu Quality (96-98%)

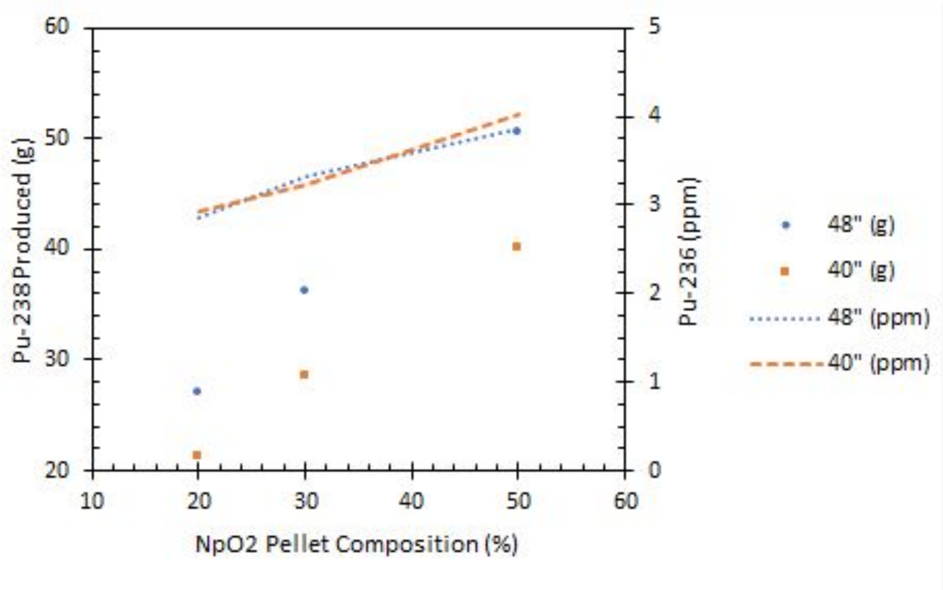
Small I-Positions

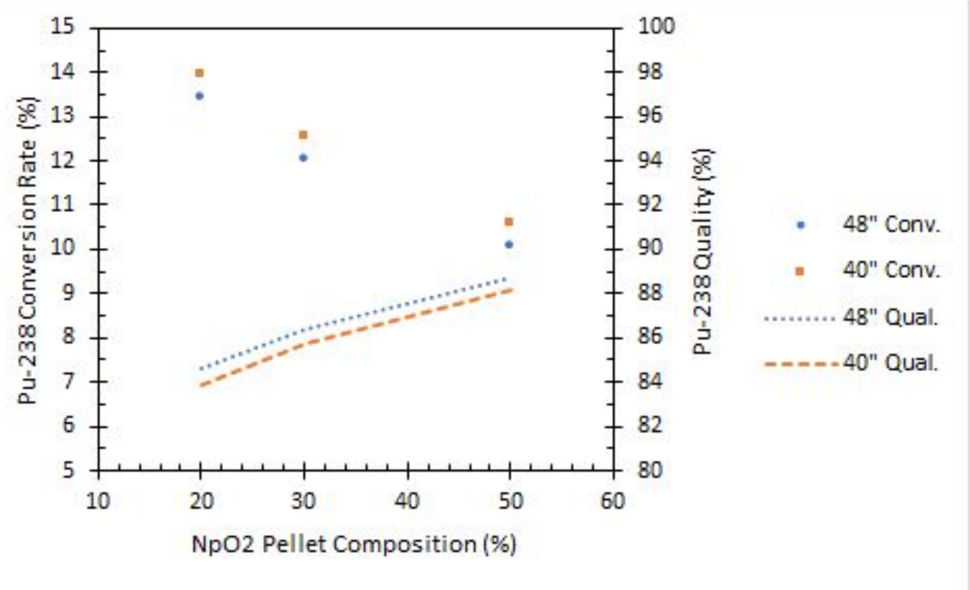




- Low annual Pu-238 production
- 6-9% Conversion ratio
- 87-91% Quality

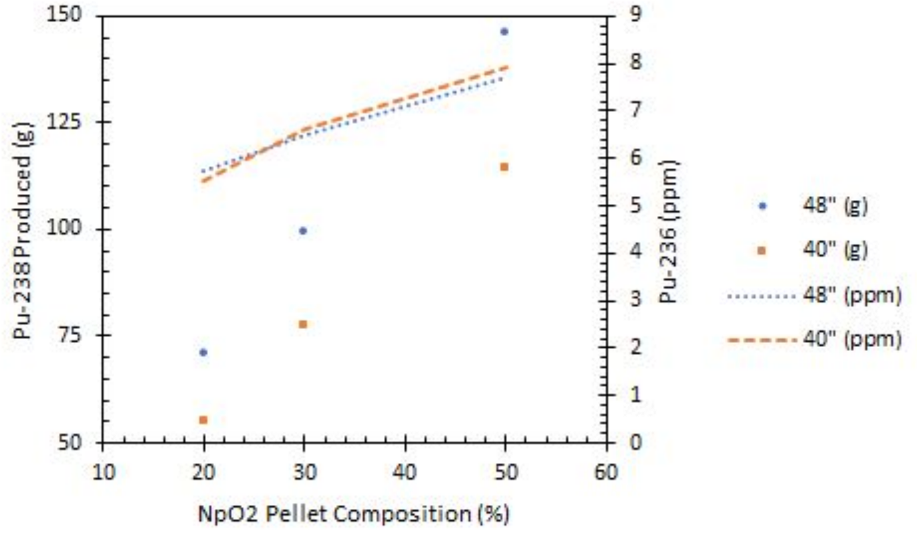
Large B-Positions

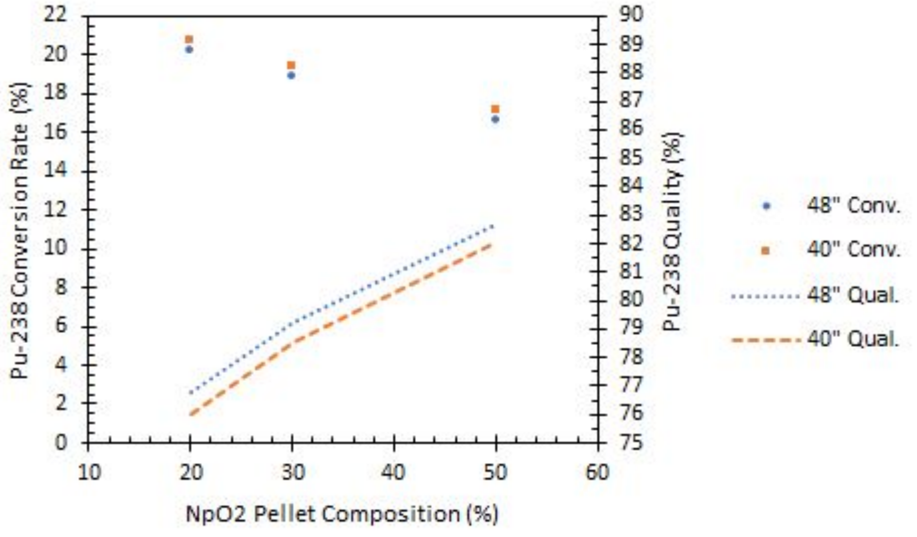




- Higher annual Pu-238 production than small I-positions
- Pu-236 concentration increase to 3-4 ppm, closer to reactor fuel
- 10-14% conversion ratio, Quality only acceptable at high pellet conc.

Small B-Positions

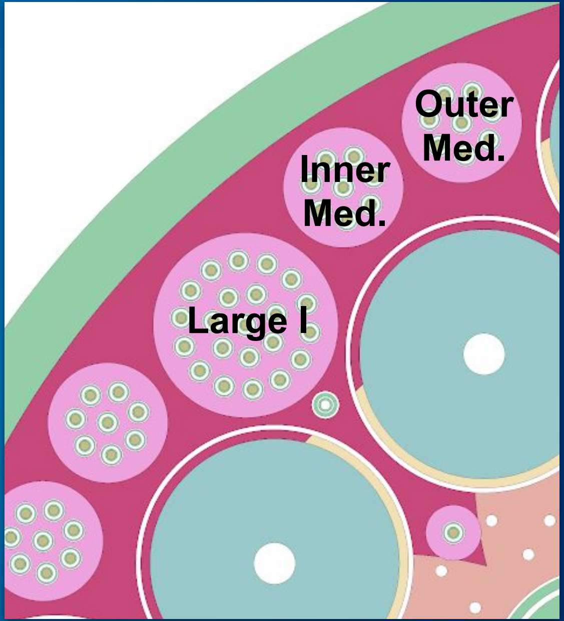




- Significant annual Pu-238 production from only 7 rods
- Pu-236 concentration unacceptable at 6-8 ppm
- 16-20% Conversion Ratio, but <83% Quality Unacceptable

Individual Position Yield

40” Rod, 30% NpO_2

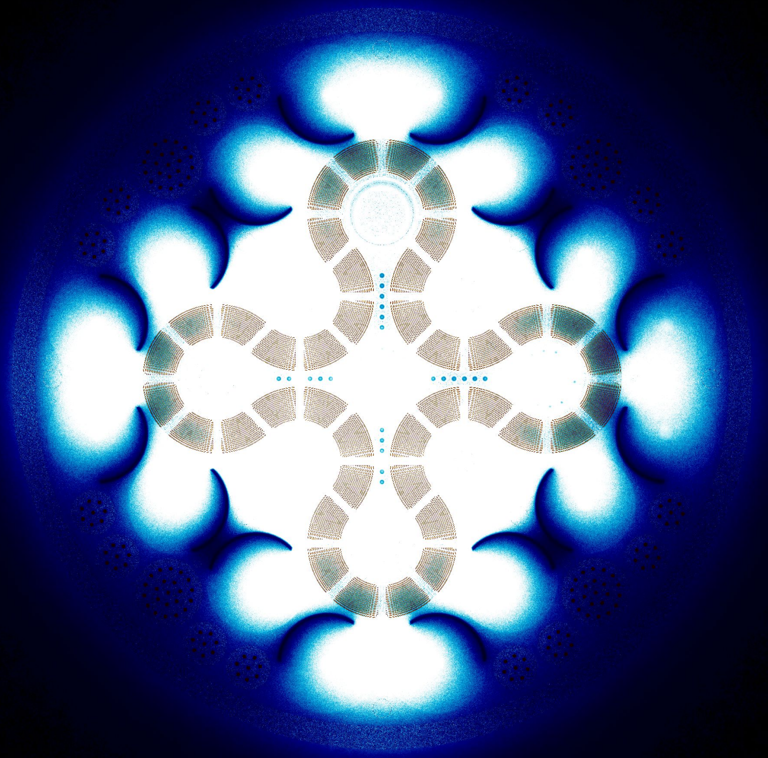


Note: Large I positions have 22 rods per position and medium I positions have 8. All other positions have 1 rod/position. Production increases as positions are used together.

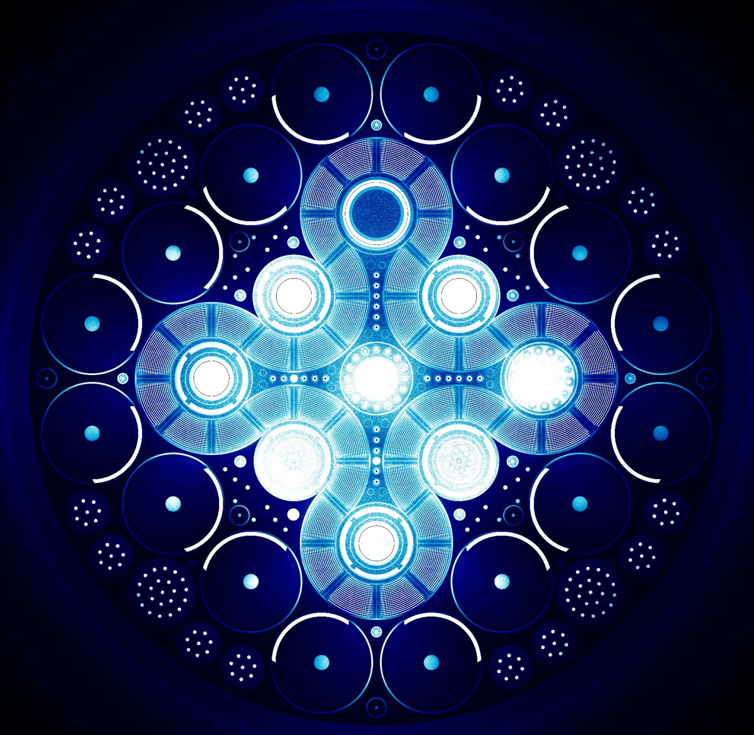
Pu-238 Production/Position

(40" Rod, 30% NpO_2)

Position	Target Quantity	^{238}Pu Production (g)	^{236}Pu Conc. (ppm)	^{238}Pu Quality (%)	^{238}Pu Conversion Ratio (%)
Large I	22	27.05	1.50	97.01	2.16
Medium I, inner	8	12.19	1.33	96.07	2.68
Medium I, outer	8	12.80	1.39	96.09	2.81
Small I	1	3.86	1.54	90.07	6.79
Large B	1	6.55	3.43	86.94	11.50
Small B	1	10.34	6.46	80.01	18.15



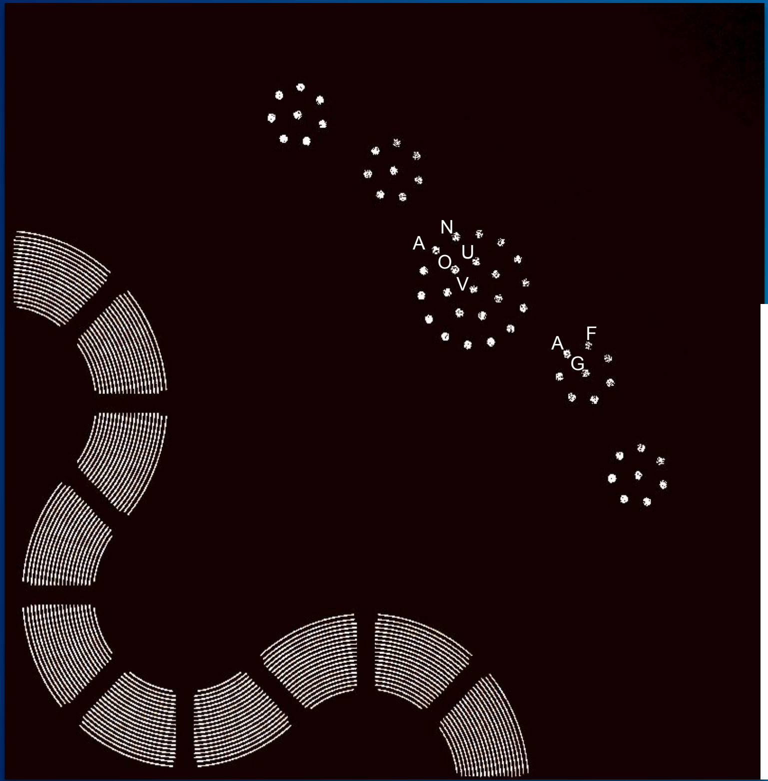
Fission Rate/Thermal Flux

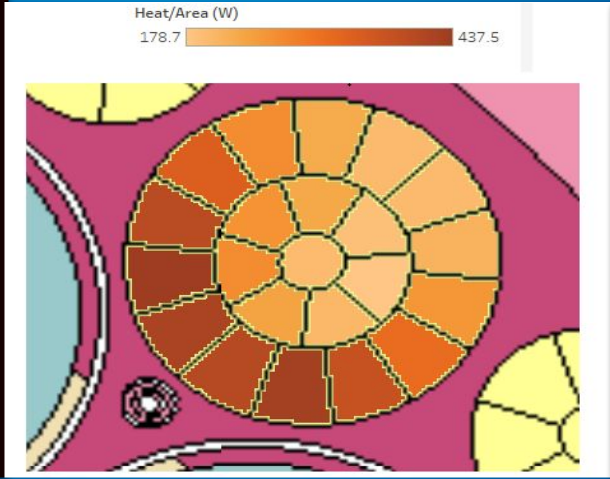


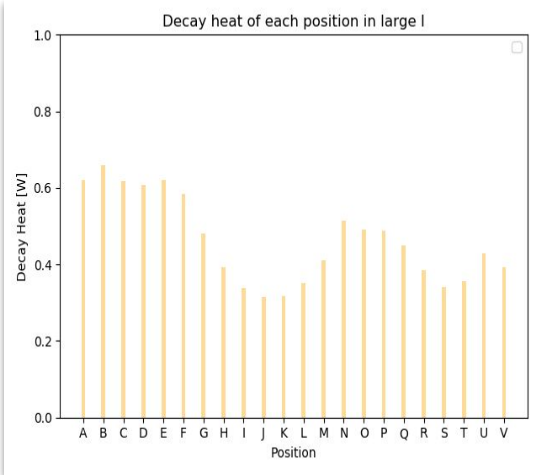
Neutron Capture

Heat distribution from Serpent

- Track total heating deposition for each target rod
- Calculate decay heat in each target rod







Analysis & Recommendations

Design Recommendations

Max Yield Design:

778.04 g of Pu-238 @ 96.72%, 3.34 ppm (Pu-236)

- 48” Rods, 50% NpO_2, All I and B positions
- Ran full core instead summing individual positions; interactions are significant

Conservative Yield Design:

350.58 g of Pu-238 @ 96.32%, 1.63 ppm (Pu-236)

- 40” Rods, 30% NpO_2, All I and Large B positions (no Small B)

Stockpile Enrichment

Assuming 16 kg of usable 78% Pu available in current stockpile:

Design	Annual 87% Pu-238 (kg)	Pu to Add from Stockpile (kg)	Stockpile Gone (years)
All I and B Positions 48” Rods, 50% NpO_2	1.456	0.869	18
I and Large B Positions 40” Rods, 30% NpO_2	0.6445	0.377	42

Conclusion

Conclusion & Future Work

ATR/HFIR production can meet NASA's goal, but with serious concessions in quality and ^{236}Pu. In addition, ATR/HFIR positions are not always available.

1. Flux Traps and other High-Priority positions
   a. Deal with high Pu-236 levels, low Pu-238 quality
2. Pure Np-237 Pellets
   a. Deal with high Pu-236 levels, low conversion ratio

Acknowledgements

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- Previous project members have made invaluable contributions: Ashoak Nagarajan, Dominik Fritz, Grace Marcantel, Lucas Beveridge, Joshua Rhodes, Tyler Gates, and John Kuczek.

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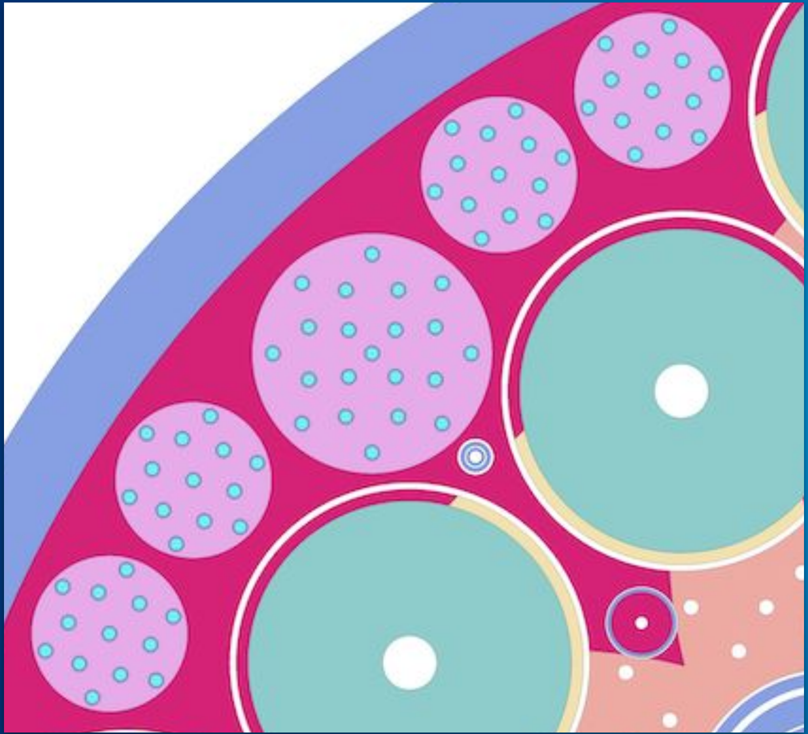
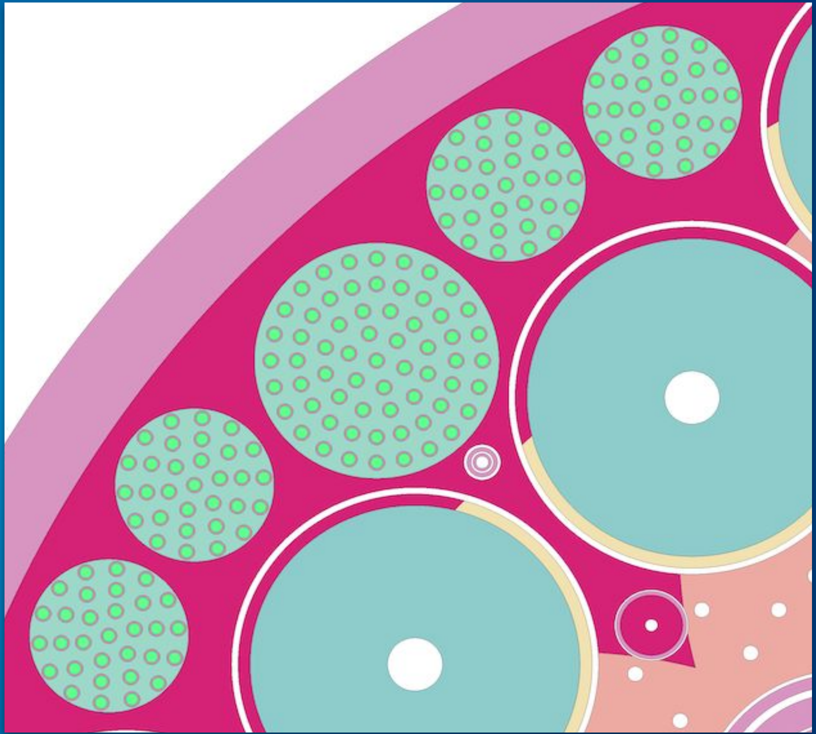
Questions?



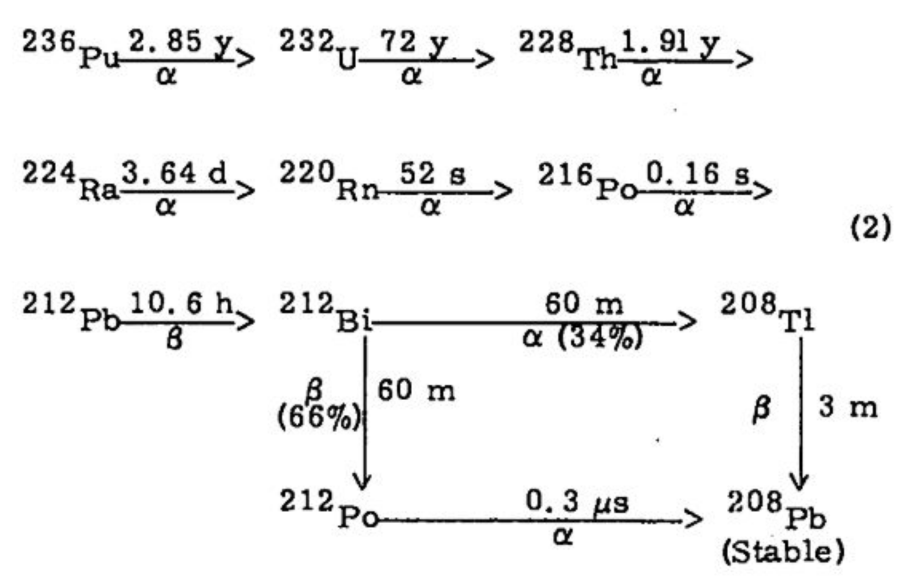
Scrapped Design 5



Scrapped Design 6

Extra Slides

Pu-236 Daughters

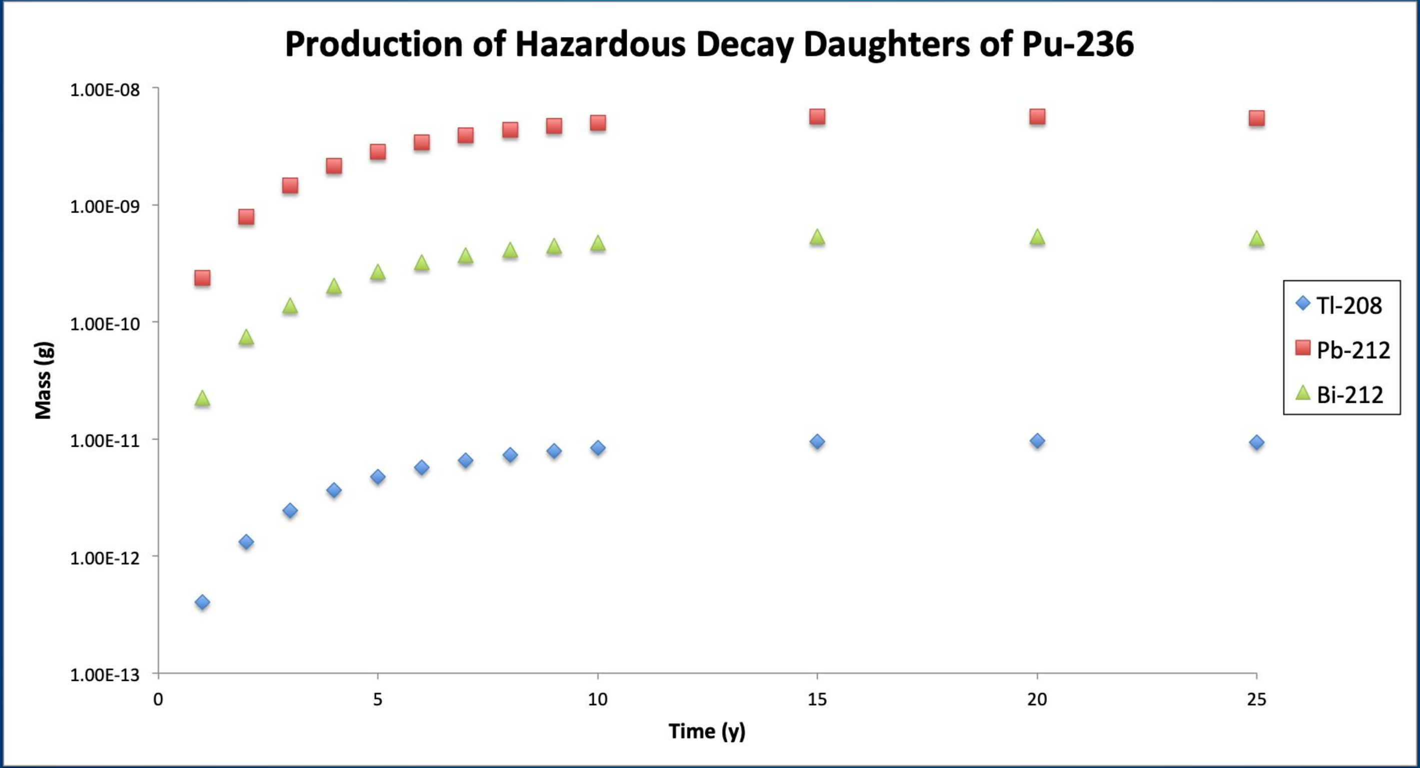


Principal Gamma Ray Abundances From ^{236}Pu Daughters

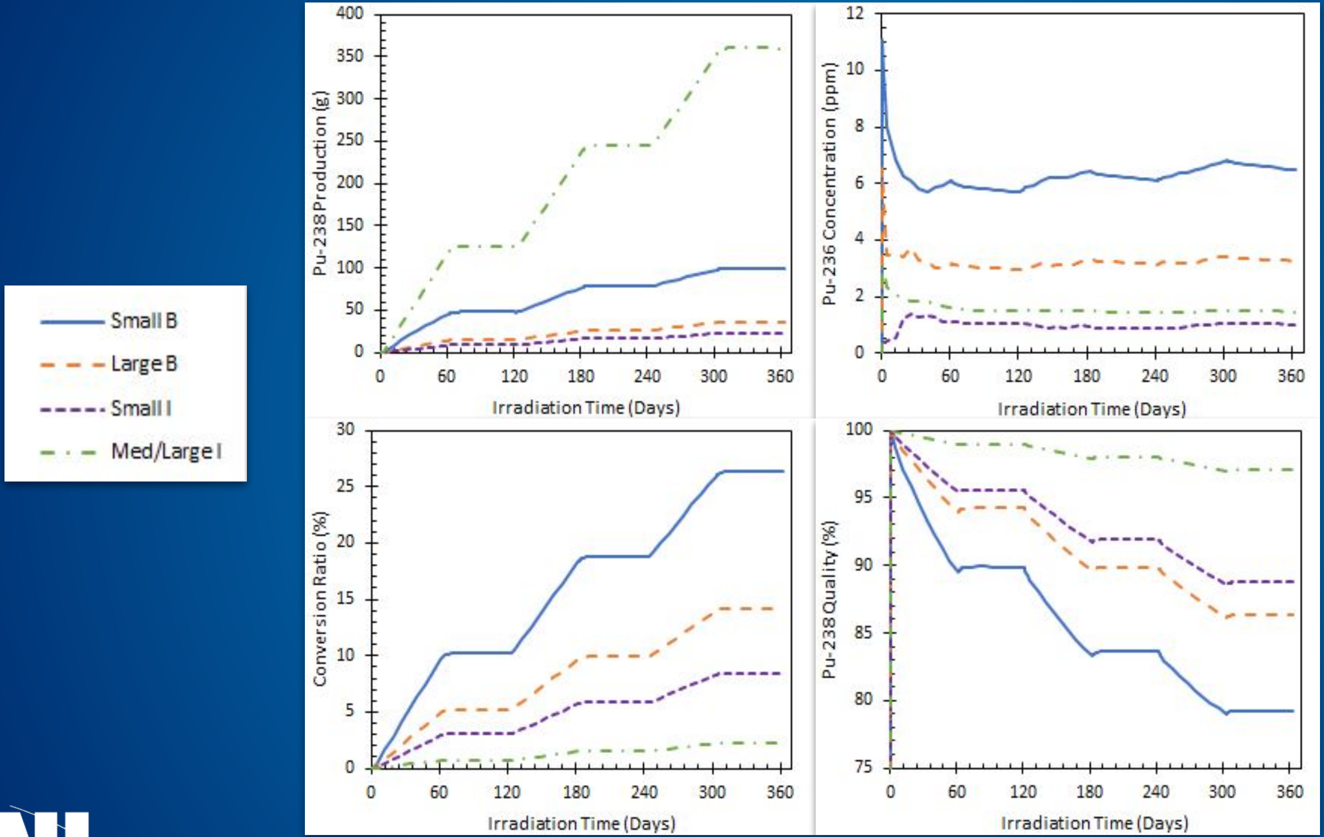
Nuclide	Gamma, Mev.	% Abundance
^{212}Pb	0.239	82
^{212}Bi	0.727	6
^{208}Tl	0.277	3
	0.511	8
	0.583	30
	0.860	3
	2.62	34

Matlack, G., and Metz, F. “Radiation Characteristics of Plutonium-238,” 1967. Los Alamos Scientific Laboratory.

Pu-236 Daughters Cont.



Pu Trends Over Cycle Length



48" Rod, 30% NpO_2

Note: Small B positions do not include B7 (for HSIS).

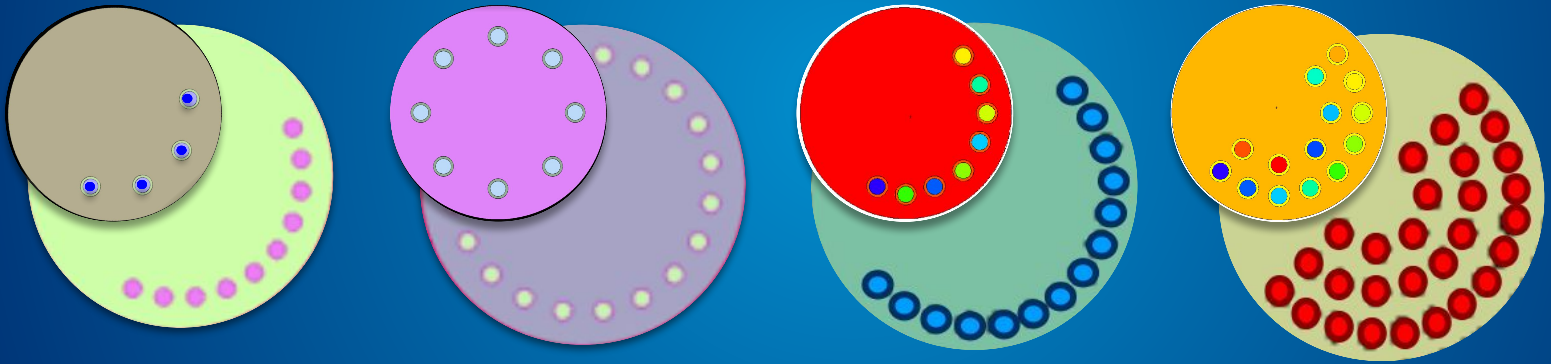
What about the 1993 study*?

	1993 Study	2019 Analysis
ATR Positions Utilized	3 modified Flux Traps, Large B, Small B, Small I	Large I, Medium I, Small I, Large B
Operational Cycle	288 days at power, 72 day shutdown (24/6)	186 days at power, 180 day shutdown (62/60)
Power Level	200 MW	105 MW
237Np Irradiated	102.1 kg	12.76 kg
238Pu Produced	11.35 kg	350 g
238Pu < 2 ppm	1.07 kg	~315 g

*B. G. SCHNITZLER, "INEL Advanced Test Reactor Plutonium-238 Production Feasibility Assessment," in "AIP Conference Proceedings," (1993), vol. 271.

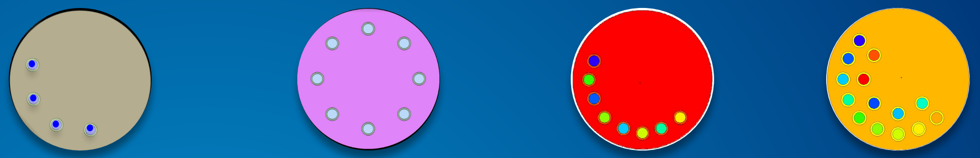
Previous Designs

- PFS-3 Design Specification for ATR not incorporated in previous designs. Increases target size by 90%.
- Only Design 2 from previous year runs successfully.
- MCNP did not include $^{237}Np(\gamma,n)^{236}Np \rightarrow ^{236}Pu + \beta^-$ process.



Design 1 Design 2 Design 3 Design 4

2018 Results



Design	#1	#2	#3	#4
Conversion Ratio	0.038	0.030	0.033	0.025
Pu-238 (g)	129	204	193	267
Quality (%)	0.95	0.96	0.96	0.97
Pu 236 (ppm)	1.17	1.08	1.28	1.65
Number of rods	104	208	184	332
Analysis Factor	1.0000	0.6001	0.6783	0.3088