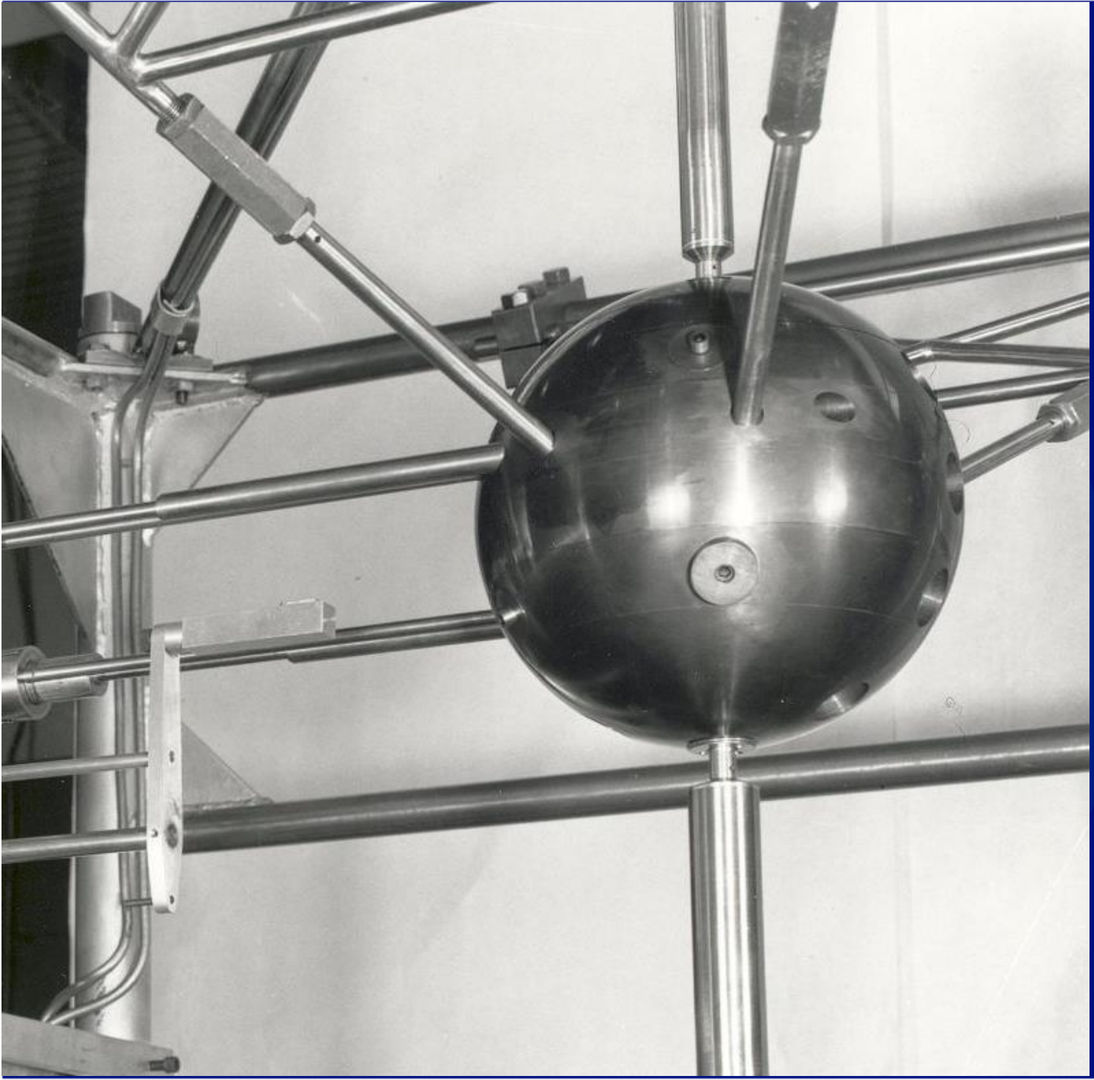

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IER 551: EUROPA
Intermediate Pu and Be Experiment

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NCSP TPR 2024

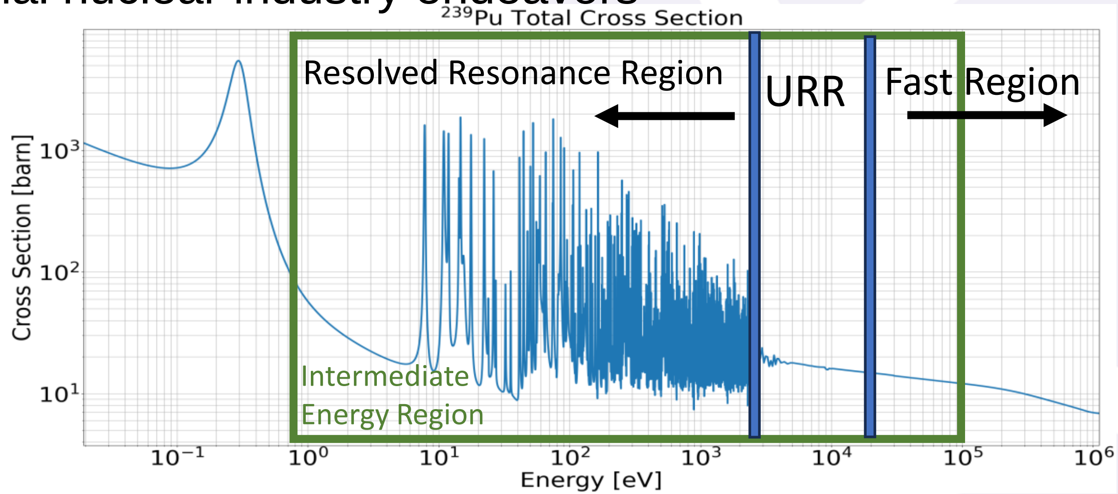
LA-UR-24-21076

Overview

1. Introduction
   1. Validation of Pu Cross Sections
   2. Plutonium Benchmarks
2. Experiment for Unresolved Resonance Of Plutonium Actinides (EUROPA)
   1. Creation of series of true intermediate benchmarks via Particle Swarm Optimization (PSO)
3. Summary
   1. Preliminary Design and Secondary Considerations

Nuclear Data
Connecting the RRR, URR, and Fast Regions of Pu

- Intermediate Energy Region (0.65 eV to 100 keV) contains all three evaluation methods of Pu
- Due to limitations of theory and differential data, there’s always a need to validate the cross sections using integral experiments
- Pu isotopes are critical to the national stockpile stewardship, non-proliferation, and commercial nuclear industry endeavors



Summary of Current ICSBEP Benchmarks

- Currently around 48 cases of (near) intermediate configurations.
  - PU_MET_INTER(PMI) 02-04 are ZPPR assemblies at ANL (1980s)
  - PU_MET_MIXED(PMM)-01 are BFS critical assemblies (1960s)
  - PMM-02 is TEX-Pu done at NCERC (2017/8)
  - PU_COMP_MIXED(PCM)-02 are assemblies from Hanford crit mass lab (1960s)
  - PU_COMP_INTER(PCI)-01 is a k-infinity benchmark done at HECTOR in UK (1960s)

Benchmark	C/E $k_{eff} \pm 1\sigma$	Main Moderator(s)	Intermediate Fissions
PMI-02	0.997 ± 0.0023	Graphite/Stainless Steel	66.38%
PMM-01	1.01 ± 0.0037	Polyethylene	61.55%
PMM-02	1.002 ± 0.00260	Polyethylene	42.76%
PCM-02	1.04 ± 0.0046	Polystyrene	19.39%
PCI-01 (k infinity)	1.001 ± 0.0110	Graphite/Boron	88.36%

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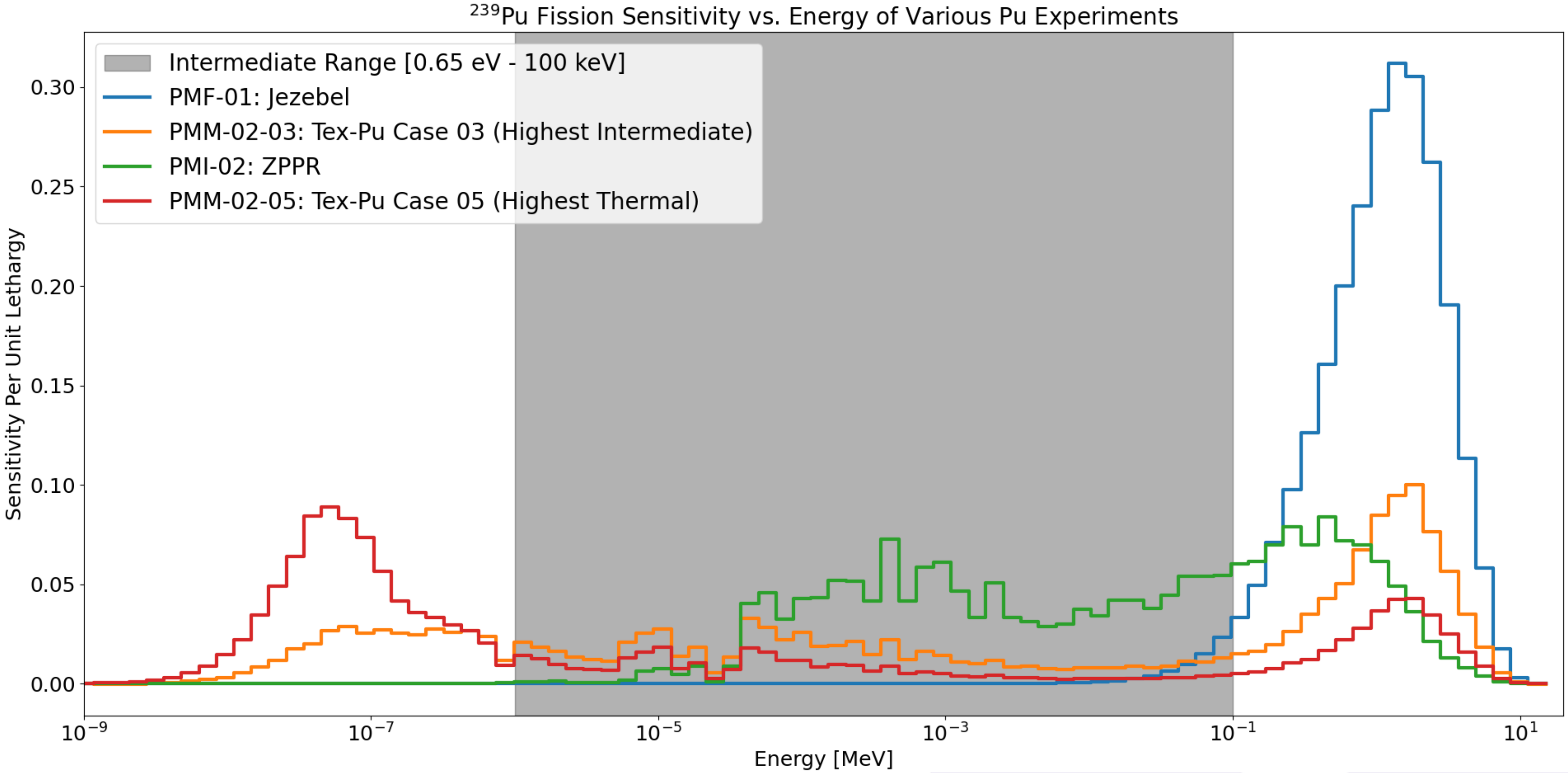
There are no modern Pu system that are truly intermediate and reliable enough for ND validation.

Targets for Intermediate Pu Systems

Cross Section Sensitivities for Pu Intermediate for 0.65 eV to 100 keV

- Besides PCI-01, all systems are below 0.19%/% for fission sensitivity
- Similarly, capture sensitivity does not exceed -0.13%/%

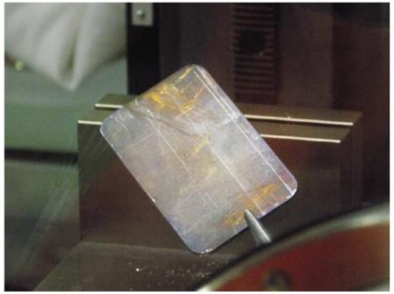
Benchmark	Capture Sensitivity (%/%)	Fission Sensitivity (%/%)
PMI-02	-1.3035E-01	1.9083E-01
PMM-01	-9.8473E-02	1.5946E-01
PMM-02	-8.5911E-02	1.4758E-01
PCM-02	-2.1148E-02	3.6065E-02
PCI-01 (k-infinity)	-1.6520E-01	5.2318E-01


^{239}Pu Fission Sensitivity vs. Energy of Various Pu Experiments
Intermediate Range [0.65 eV - 100 keV]
PMF-01: Jezebel
PMM-02-03: Tex-Pu Case 03 (Highest Intermediate)
PMI-02: ZPPR
PMM-02-05: Tex-Pu Case 05 (Highest Thermal)
Sensitivity Per Unit Lethargy
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
Energy [MeV]

Experiment for Unresolved Resonance Of Plutonium Actinides (EUROPA)

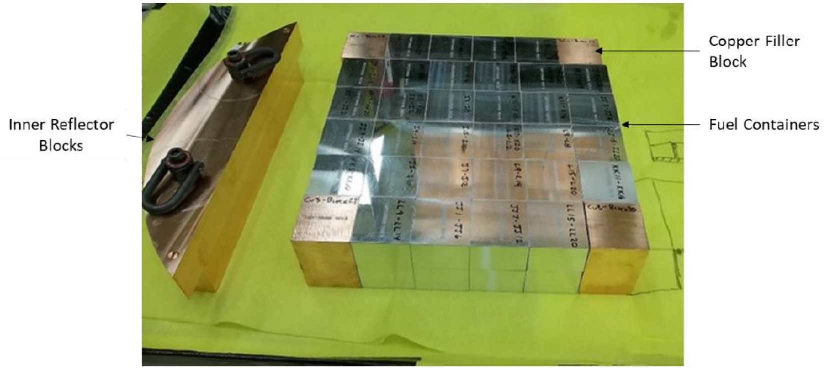
IER 551 True Intermediate Plutonium

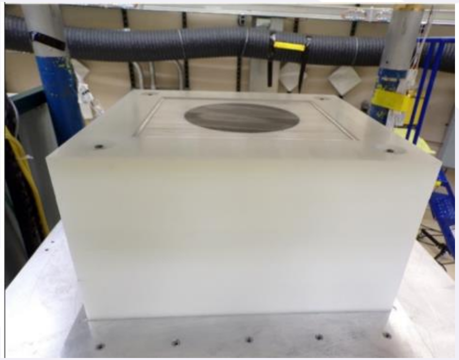
- Energy gap in available Pu benchmarks for intermediate energies
  - 0.65 eV – 100 keV includes resolved, unresolved, and fast regions
- **GOAL**
  - **1) Maximum % of fissions caused by intermediate neutrons**
  - **2) sensitivities to Pu-239 fission > 0.2 %/%**
  - **3) and experimental uncertainties below 300 pcm**
- Use ZPPR PANN and PAHN (high Pu-240 content) plates to develop a series of true intermediate benchmarks, to validate current and future Pu evaluations

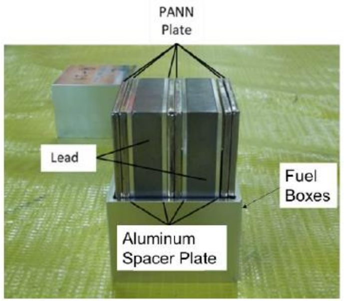


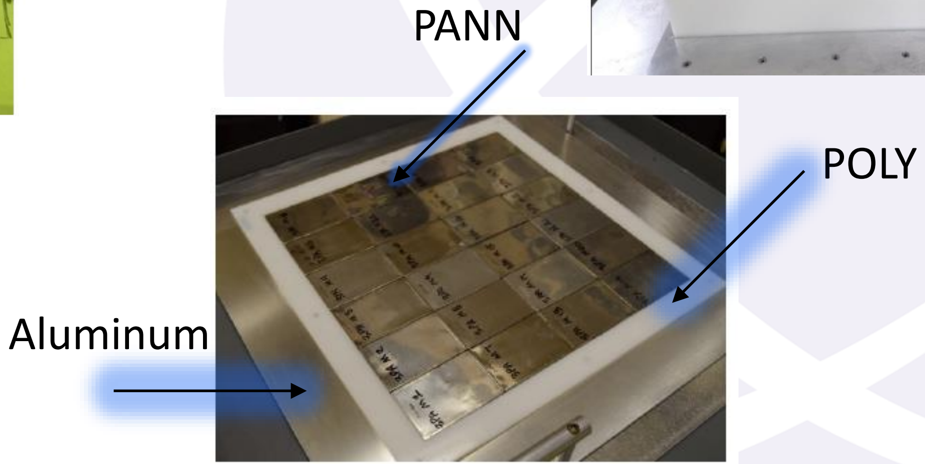
Geometries, Materials, and Permutations

- Jupiter fuel block style vs. CWS/TEX layers
- Layer-style (CWS/TEX) designs win out due to ease of optimization



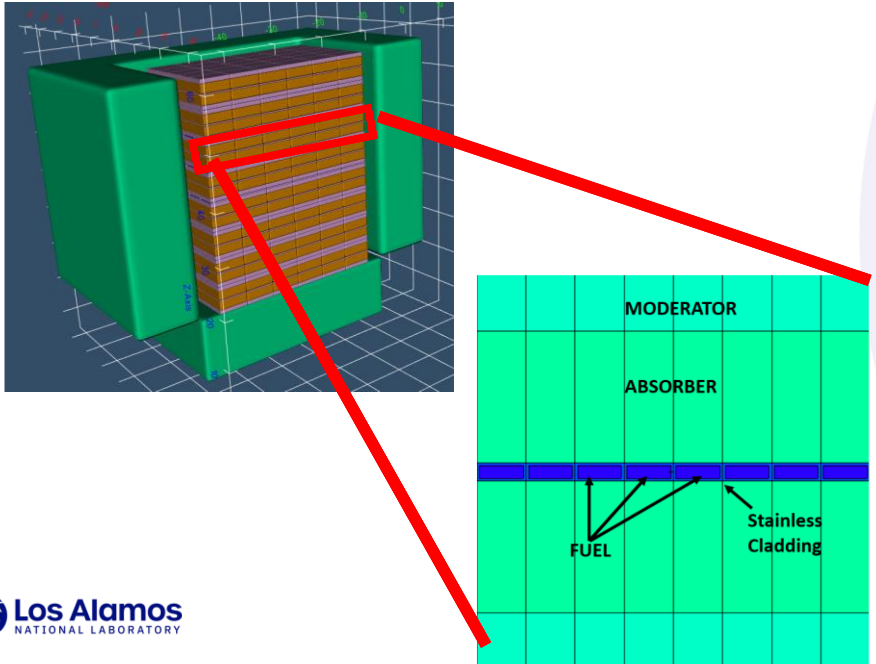






Particle Swarm Optimization (PSO) for Material Selection

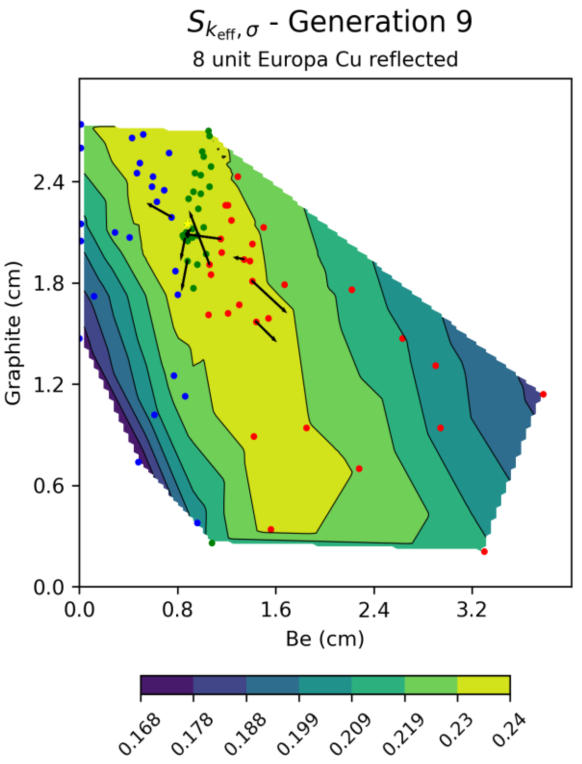
- An “optimized” design has high sensitivities and high percent of intermediate neutrons causing fission
- Need to perform an exhaustive material search to say that this is in fact optimized for intermediate

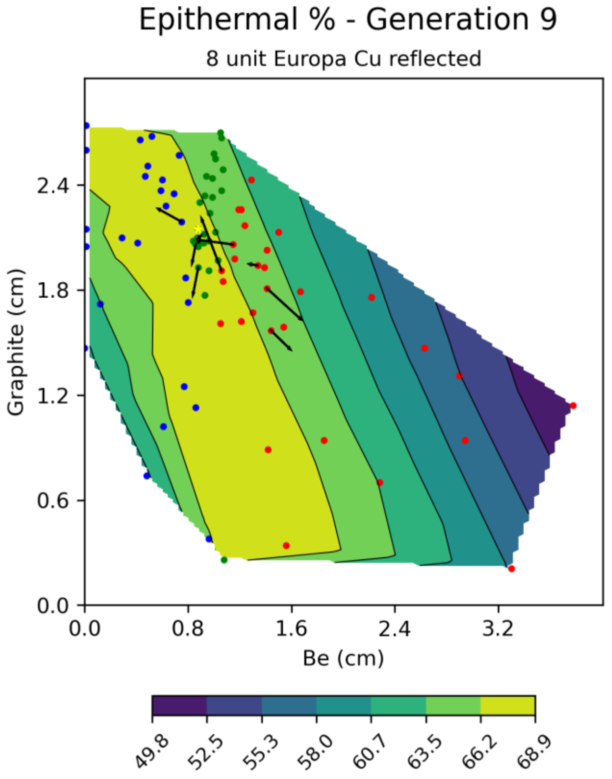


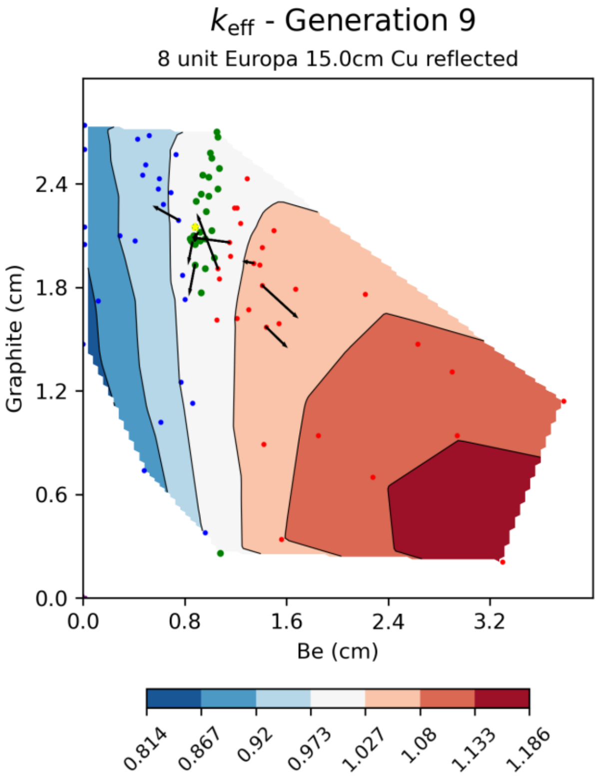
TYPE	Material	Nominal Density $[\frac{g}{cm^3}]$
MOD / IR	HDPE	0.96
MOD / ABS	*Borated*[a] HDPE	1.04
MOD	Lucite	1.18
MOD / IR	Be	1.848
MOD	BeO	3.02
MOD / IR	Graphite	2.266
MOD / IR	Alumina	3.95
ABS	Cadmium	8.96
ABS	Gadolinium	7.90
IR	Stainless Steel - 304	7.5
IR	Copper	8.96
IR	Lead	11.37
IR	None (Air)	1.25×10^{-3}

[a] Borated polyethylene is 5% boron by weight and enriched to 90% ^{10}B

While PSO searches for intermediate fissions it also must be constrained to look for critical configurations







Results

Beryllium material combinations take 8 out of 10 spots for highest intermediate neutrons with 8 fuel layers

- Look for additional high sensitivity and intermediate fissions as reactivity can be controlled orthogonally

Materials	Mod.	Abs.	K_{eff}	EALF	T %	I %	F %	Sens. ^{239}Pu (n,f)
BeO-Cd	3.19	0.01	0.99694	0.000509	6.35	73.03	20.62	0.31092
BeO-Gd	2.73	0.01	0.99134	0.000774	5.62	72.11	22.27	0.29581
Be-Cd	2.99	0.01	1.00095	0.000378	8	72.05	19.95	0.31683
Be-Gd	2.76	0.01	0.99011	0.00048	8.05	71.03	20.92	0.30839
Teflon-Graphite	3.64	1.29	0.73795	0.001753	3.83	70.73	25.44	0.25627
Graphite-Cd	3.35	0.01	0.86086	0.001648	2.96	69.89	27.16	0.27047
BeO-BHDPE	1.77	0.04	0.99869	0.001337	4.57	69.76	25.67	0.26556
Be-BHDPE	1.45	0.04	1.00335	0.001387	4.74	68.68	26.58	0.26985
Be-Cu	1.59	0.36	0.99351	0.001306	5.53	68.54	25.93	0.24239
BeO-Pb	2.26	0.63	1.0139	0.000711	8.8	68.06	23.15	0.23724
BeO-Graphite	1.25	2.02	0.99727	0.000518	10.52	67.33	22.14	0.24268
Graphite-BHDPE	3.29	0.08	0.80033	0.001154	5.98	67.21	26.81	0.29641
Teflon-Pb	3.17	0.78	0.67017	0.009289	0.4	67.12	32.47	0.18869
Graphite-Gd	3.97	0.06	0.68703	0.003171	1.7	67.02	31.28	0.29239
Be-Graphite	0.88	2.15	0.99387	0.000591	10.02	66.91	23.07	0.23932
Teflon-Gd	3.89	0.06	0.60972	0.011328	0.1	66.82	33.08	0.21661
Be-Pb	1.91	0.93	0.99803	0.000634	10.35	65.83	23.82	0.23387
Teflon-Cd	2.67	0.05	0.69425	0.014751	0.04	65.4	34.57	0.17028
BeO-Cu	3.12	0.48	0.99043	0.000287	14.77	65.08	20.15	0.25279
Graphite-Cu	2.79	1.38	0.69062	0.003158	3.28	64.86	31.86	0.24655
Cu-Graphite	0.07	2.07	0.85518	0.005552	1.33	64.52	34.16	0.19827
Alumina-Cd	3.64	0.06	0.6696	0.013079	0.07	63.26	36.67	0.18282
Cu-BHDPE	2.59	0.28	0.55907	0.004819	1.95	60.78	37.27	0.28903
Alumina-BHDPE	2.46	0.66	0.44649	0.003291	3.01	60.67	36.32	0.32683
Alumina-Pb	3.9	1.69	0.54587	0.015946	0.5	58.72	40.78	0.17359
Pb-BHDPE	3.55	0.4	0.50544	0.005099	2.41	58.02	39.57	0.2928
Teflon-BHDPE	3.76	1.07	0.32557	0.004612	2.93	57.01	40.06	0.31367
HDPE-Cd	0.59	0.01	0.79909	0.00036	15.47	56.94	27.59	0.28733
Lucite-Gd	1.91	0.06	0.43969	0.001016	9.35	56.73	33.92	0.33063
Lucite-Cd	0.98	0.01	0.75957	0.000251	18.09	55.76	26.15	0.29023
Graphite-Graphite	0.62	0.66	0.7955	0.026035	0.14	53.54	46.32	0.13174

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Preliminary Design Concepts

Achieved: Exceed 68% intermediate fissions and 0.2 Pu-239 fission sensitivity
How feasible are these designs?

- Is it better to lose a larger fission sensitivity for a better benchmark experiment?
- Is 0.1 mm of Cd a realistic material dimension to incorporate into a design?
- Maybe other moderator/interstitials will yield similar sensitivities and avoid both Be hazards and thin pieces
- Minimize number of reflector and moderating elements to highlight Pu isotopes

[a] Teflon-Graphite combination has been loaded with three additional fuel plates to bring predicted k_{eff} to critical.

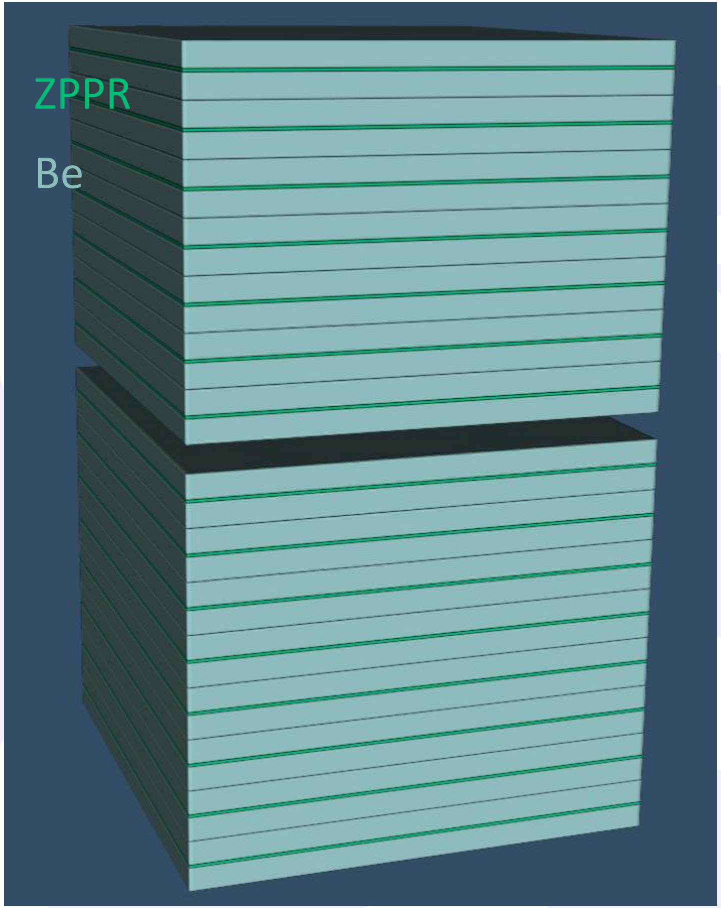
Material	Mod.	Abs.	K_{eff}	EALF	T%	I%	F%	$S^{239Pu}_{(n,f)}$
Teflon_Graphite[a]:	3.64	1.29	1.00978	0.0043445	1.45	68.39	30.16	0.3190
HDPE_Pb:	0.32	0.45	1.01195	0.000229	25.22	46.92	27.87	0.16545
Be_Cu:	1.59	0.36	0.99351	0.001306	5.53	68.54	25.93	0.2423
Be_Cd:	2.99	0.01	1.00095	0.000378	8	72.05	19.95	0.31683
BeO_Cd:	3.19	0.01	0.99694	0.000509	6.35	73.03	20.62	0.31092

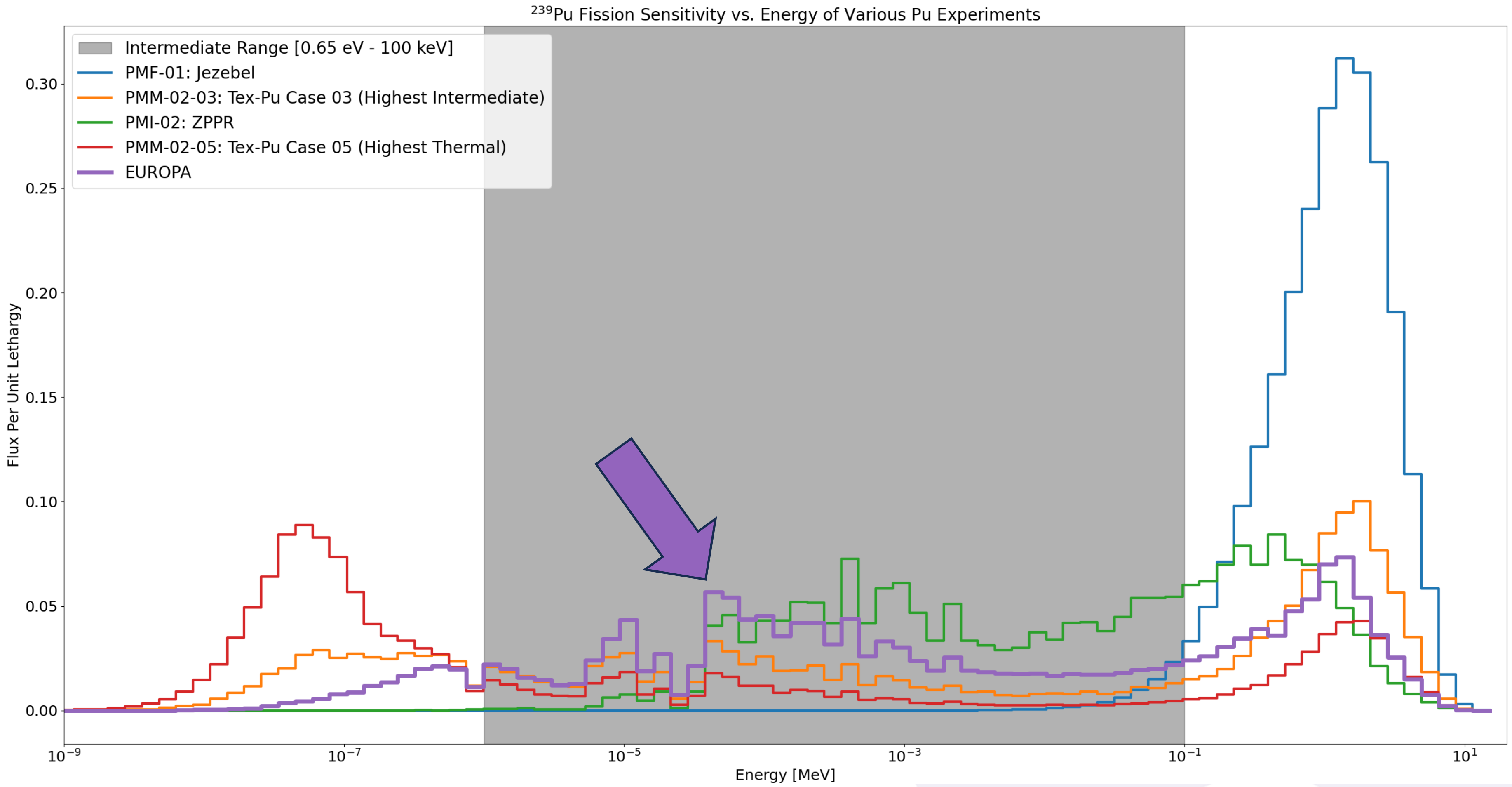
Final CED-01 Design of EUROPA

Minimize materials other than Pu

- 16 - 7 x 5 fuel layers of ZPPR sandwiched between 1.8 cm of Be-metal
- More fuel layers and (n,2n) from Be allow for no reflector to be used

Model	Fission Sensitivity	Capture Sensitivity	Intermediate %
EUROPA	**0.3021**	**-0.1610**	**67.89**
PMI-02	0.1902	-0.1304	66.38
PMM-01	0.1594	-0.0980	61.55
PMM-02	0.1476	-0.0861	42.76
Jupiter	0.0127	-0.0054	16.07

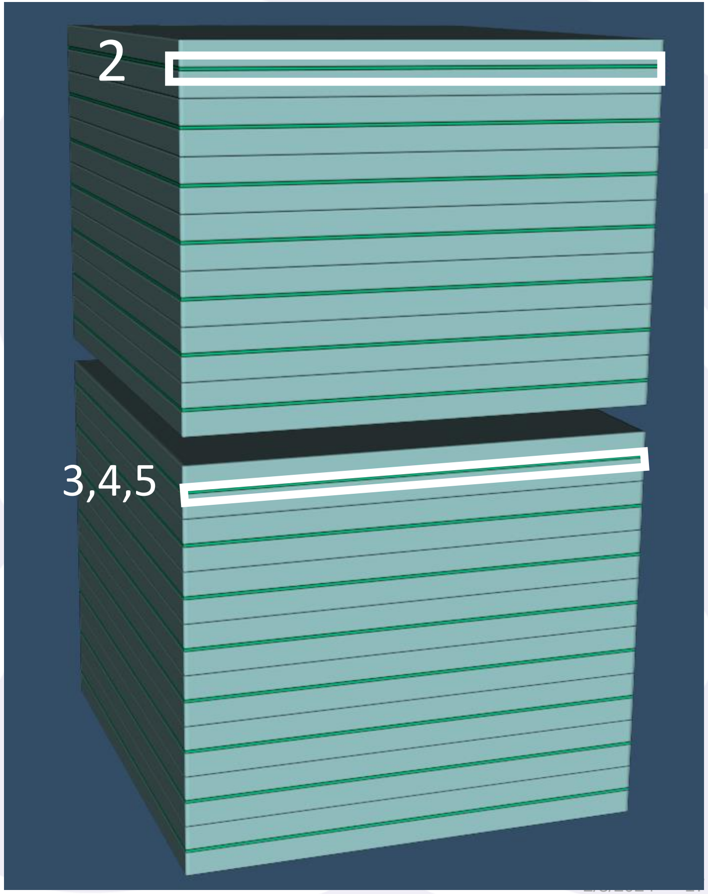



^{239}Pu Fission Sensitivity vs. Energy of Various Pu Experiments
Intermediate Range [0.65 eV - 100 keV]
PMF-01: Jezebel
PMM-02-03: Tex-Pu Case 03 (Highest Intermediate)
PMI-02: ZPPR
PMM-02-05: Tex-Pu Case 05 (Highest Thermal)
EUROPA
Flux Per Unit Lethargy
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
Energy [MeV]

Series of Critical Configurations

Validate Pu-239 and Pu-240

- PAHN plates will be used to add high Pu-240 content into system
- Pu-240 has higher capture cross section than Pu-239, needs to be varied throughout in the system
- 39 PAHN plates in inventory and each layer has 35 plates currently



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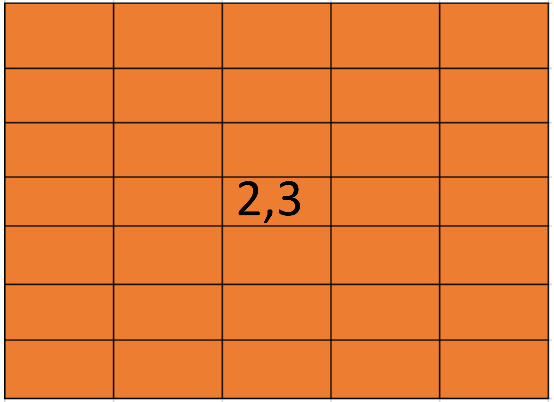
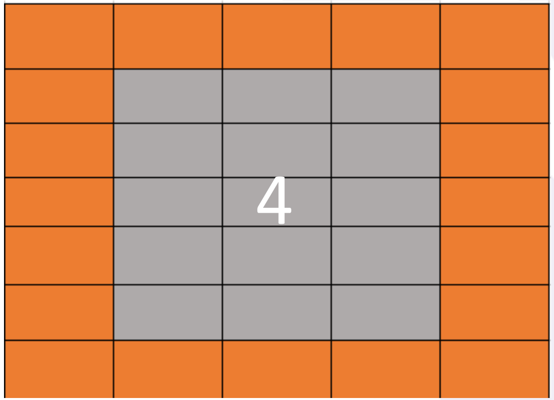
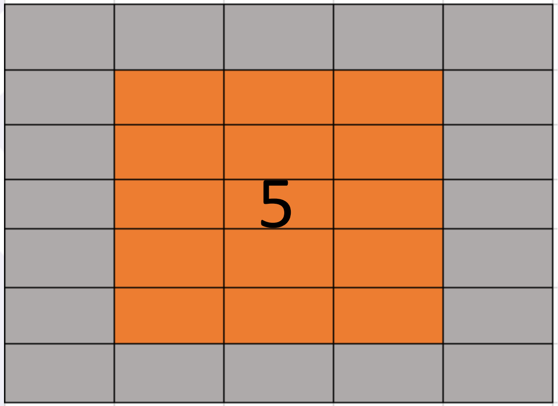
PAHN Experiment Layers

Need to introduce high Pu-240 plates into design to validate cross sections

- 1 is all PANN, nominal structure setup
- 2 is maximum PAHN on top of uppermost layer, 3 is top of bottom stack
- 4 is outer ring on top of bottom stack, 5 is center on top of bottom stack







CED – 2 Discussions

Looking ahead

- Is a thin graphite or aluminum reflector preferred to remove room return?
- If beryllium isn't available in the quantities, can Alumina/Graphite with Cu-reflector prove to be a suitable alternative?
- Sensitivities to Pu-240 calculations and final PAHN experiments

Summary

Experiment for Unresolved Resonance Of Plutonium Actinides

- Motivation of validating end of RRR, whole URR, and beginning of fast region of Pu isotopes with new targeted integral measurement.
- Experiment design using ZPPR plates layered between moderators and absorbers optimized using PSO.
- Be-Cd interstitial combination proved to yield highest sensitivity to fission/capture cross sections with 8 fuel layers.
- Sole Be metal and ZPPR plate design chosen to move forward as it achieves design criteria with highest ND constraints

Acknowledgements

- This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.

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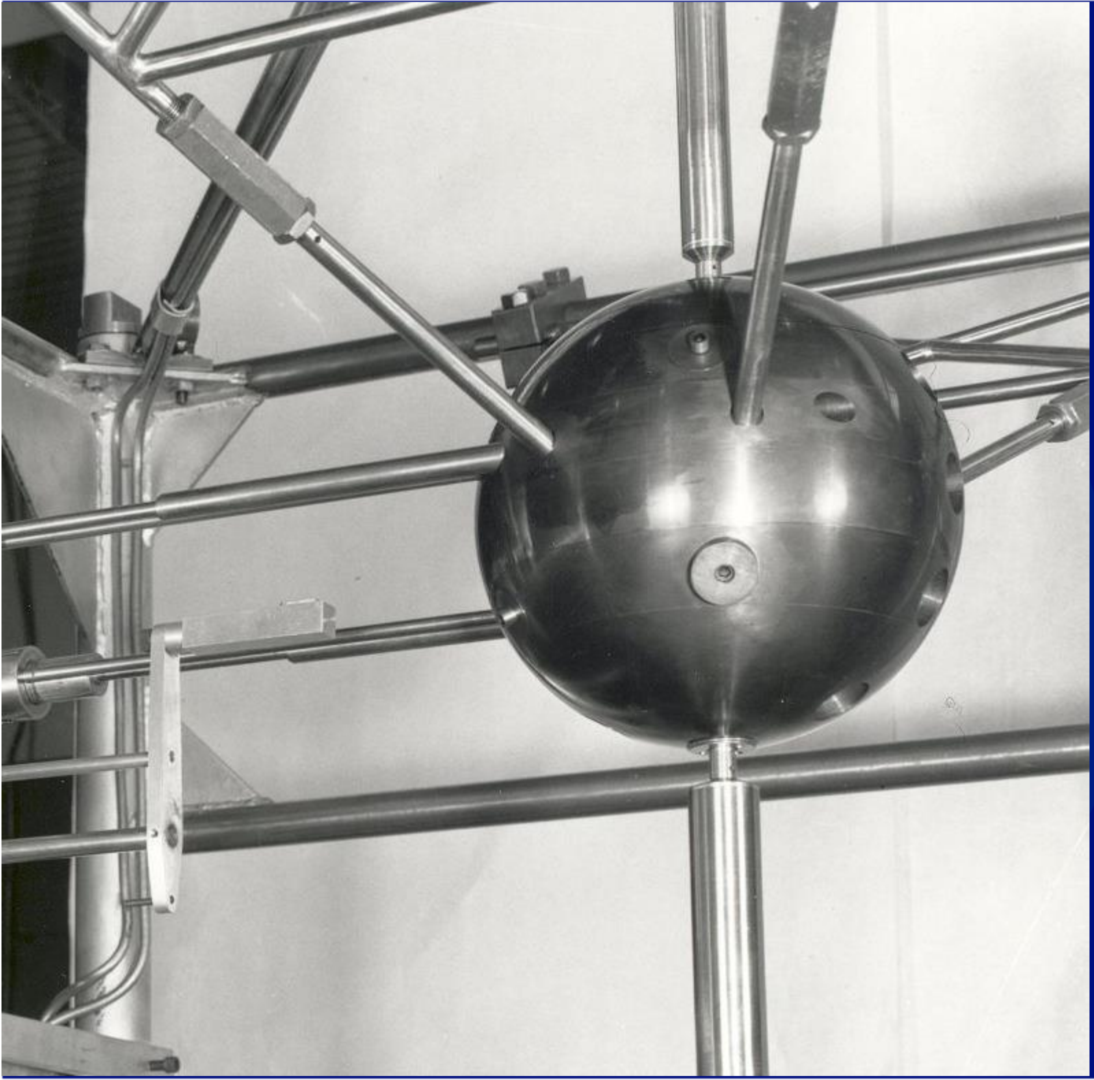

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Particle Swarm Optimization

Gradient free optimization for Monte Carlo simulations by C. Kostelac

- Particle swarm optimization built on the premise of a swarm of particles traveling through a design space, position represented as design parameters

$$\vec{x}_i^k = \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_n \end{bmatrix}$$

- Each particle updates its position in time with weighted knowledge of swarm best (φ), personal best (ρ), and current velocity (ω)

$$\vec{v}_i^{k+1} = \omega \vec{v}_i^k + \phi r_1 (\vec{p}_i^k - \vec{x}_i^k) + \rho r_2 (\vec{g}^k - \vec{x}_i^k)$$

- Swarm set to optimize for high intermediate fissions and fission sensitivities