IER-183: Quantifying Uncertainties in Subcritical Neutron Multiplication Inference

Rian M. Bahran[1], Jesson Hutchinson[2], Mark Smith-Nelson[2] & Avneet Sood[1]

[1]Monte Carlo Methods, Codes and Applications (XCP-3)

[2]Advanced Nuclear Technology (NEN-2)

Los Alamos National Laboratory

Presented at the Nuclear Criticality Safety Program Technical Program Review

Wednesday March 26th, 2014

LA-UR-14-21889

General Overview

- **Monte Carlo simulations of an experimental subcritical benchmark were performed.**
  - Helps validate recent improvements in computational tools.
  - Provides better predictability and understanding in the sensitivities and uncertainties associated with subcritical systems.

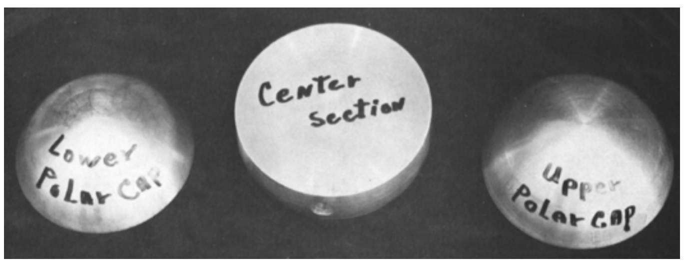
- **Experiments/simulations involved extensive mass and geometry perturbations.**
  - 40+ different configurations.
  - Detailed model of the system /associated perturbation configurations.
  - MCNP5 with list-mode patch used for simulations.

- **^{3}He neutron multiplicity detectors provided list-mode data in exp. & simulation.**
  - Time stamp (and location) of every registered event.

- **Data analyzed using the Feynman Variance-to-Mean method to obtain M_T.**

Subcritical System: Thor Pu-metal core

- **Three individual δ-phase plutonium components.**
  - Net masses 3273.9 g (Upper), 4158.2 g (Center) and 2216.9 (Lower).
  - Half-inch diameter glory hole in center.
- **Assembled pieces approximate a sphere ~10.6 cm in diameter.**
  - Total net mass (with inserts) 9649.0 g.



- **Isotopic composition similar to Jezebel/BeRP.**
  - 5.1% ^{240}Pu (alloyed with ~1.01 wt% gallium).
  - All components clad with~ 13 cm (5 mils) of nickel.

Several major Thor Core experiment and evaluation publications are available in the literature.

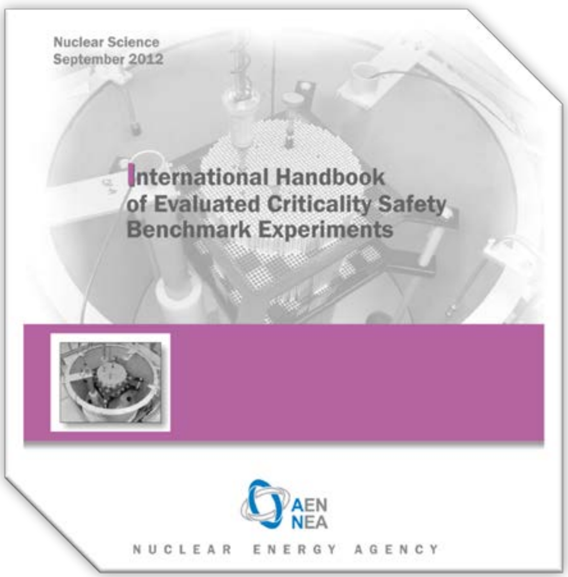
Several major Thor Core experiment and evaluation publications are available in the literature.

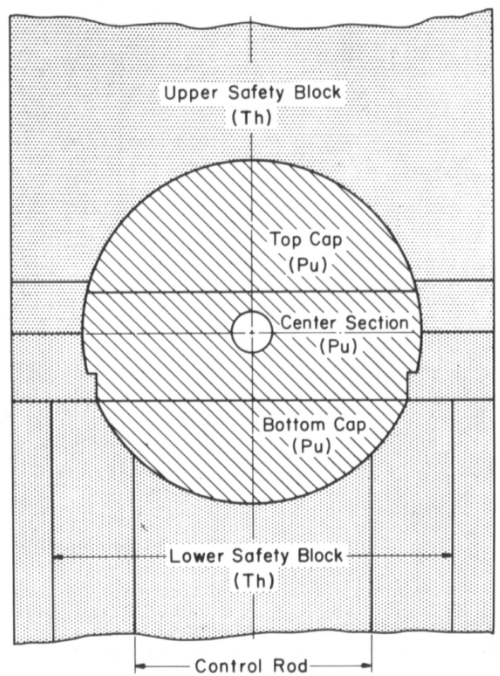
NUCLEAR SCIENCE AND ENGINEERING: **71**, 287-293 (1979)

Thor, A Thorium-Reflected Plutonium-Metal Critical Assembly

G. E. Hansen and H. C. Paxton

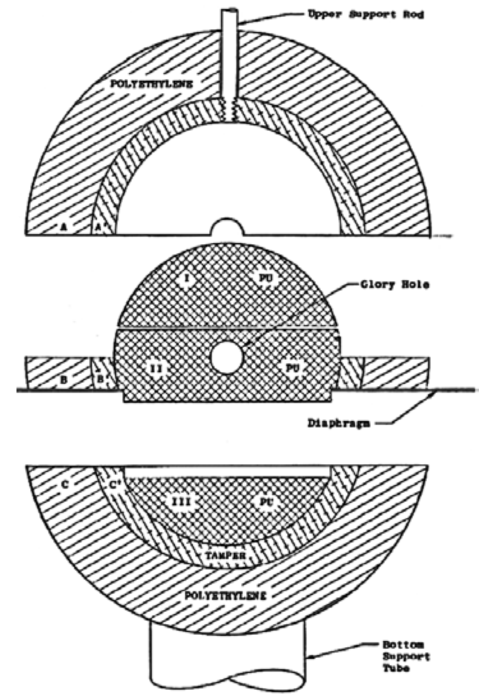
University of California, Los Alamos Scientific Laboratory, P.O. Box 1663 Los Alamos, New Mexico 87545





PU-MET-FAST-008

Benchmark Critical Experiment of a Thorium Reflected Pu Sphere

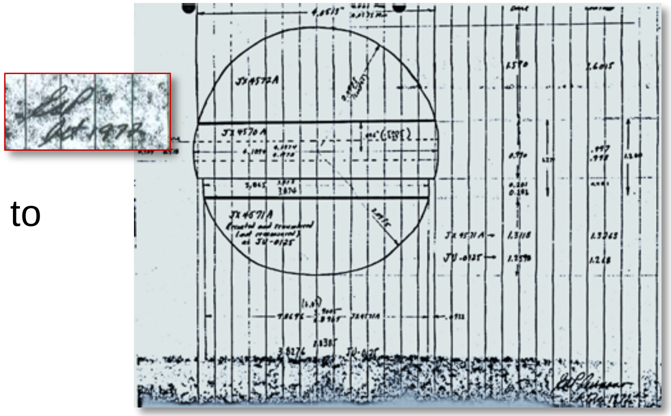


PU-MET-FAST-044

Pu Metal Sphere with Be, Graphite, Al, Fe and Mo Tampers and Polyethylene Reflectors

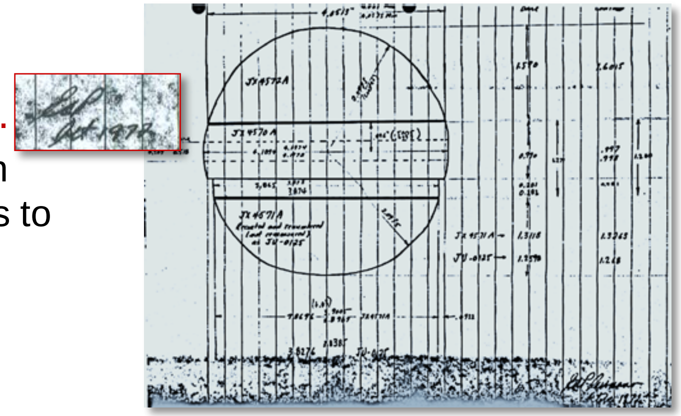
A geometry revaluation of the Thor core major components geometry was performed.

- **Updated dimensions determined from:**
  - Original unpublished drawings from 1972.
  - Unpublished documents from 2005 when material was transferred from Los Alamos to the Nevada National Security Site.

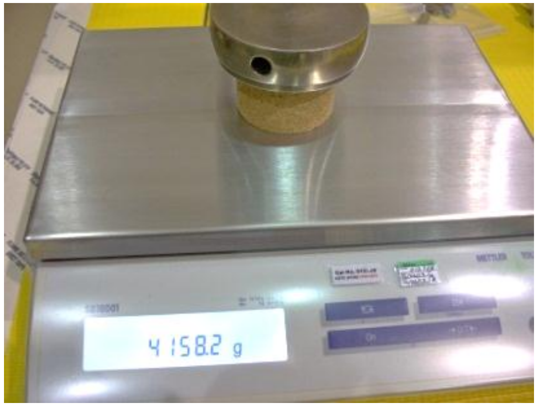


A geometry revaluation of the Thor core major components geometry was performed.

- **Updated dimensions determined from:**
  - Original unpublished drawings from 1972.
  - Unpublished documents from 2005 when material was transferred from Los Alamos to the Nevada National Security Site.

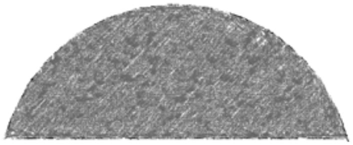


- **Updated mass and density values also obtained for the Thor components from:**
  - Mass measurements.
  - Stochastic volume ray-tracing estimation method with MCNP.
  - Analytical calculations.



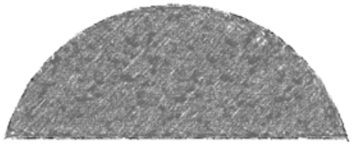
Updated Thor mass and volume from a recent geometry re-evaluation.

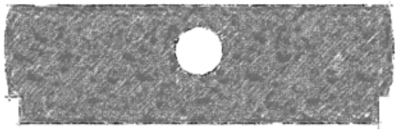
Upper Spherical Cap (JX-4572)				
Volume	**Coated [cm³]**	**Ni [cm³]**	**Pu-alloy [cm³]**	
present work: MCNP5	206.4 ± 0.1	2.67 ± 0.01	203.7 ± 0.12	
Mass	**Coated [g]**	**Ni [g]**	**Pu-alloy [g]**	**Pu [g]**
present work: measurement / MCNP5	3273.9 ± 0.1	23.78 ± 0.1	3249.2 ± 0.14	3216
unpublished work (2005)	3274.0	25.25	3249	3216.2
unpublished work (1972)			3225	3192.4
Robba et al. (1983)			3225	3193



Updated Thor mass and volume from a recent geometry re-evaluation.

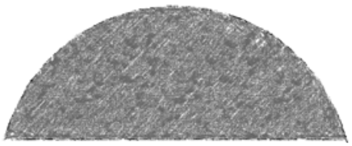
Upper Spherical Cap (JX-4572)				
Volume	**Coated [cm³]**	**Ni [cm³]**	**Pu-alloy [cm³]**	
present work: MCNP5	206.4 ± 0.1	2.67 ± 0.01	203.7 ± 0.12	
Mass	**Coated [g]**	**Ni [g]**	**Pu-alloy [g]**	**Pu [g]**
present work: measurement / MCNP5	3273.9 ± 0.1	23.78 ± 0.1	3249.2 ± 0.14	3216
unpublished work (2005)	3274.0	25.25	3249	3216.2
unpublished work (1972)			3225	3192.4
Robba et al. (1983)			3225	3193
Center Component (JX-4570)				
Volume	**Coated [cm³]**	**Ni [cm³]**	**Pu-alloy [cm³]**	
present work: MCNP5	262.4 ± 0.13	3.58 ± 0.01	258.8 ± 0.13	
Mass	**Coated [g]**	**Ni [g]**	**Pu-alloy [g]**	**Pu [g]**
present work: measurement / MCNP5	4158.2 ± 0.1	31.9 ± 0.1	4126.3 ± 0.14	4085
unpublished work (2005)	4158.3	33.71	4124.6	4083
unpublished work (1972)			4127	4085.3
Robba et al. (1983)			4127	4086

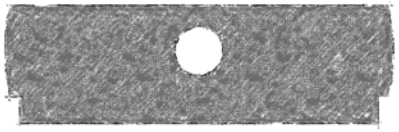


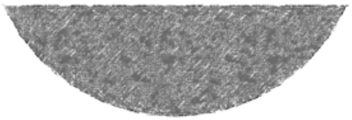


Updated Thor mass and volume from a recent geometry re-evaluation.

Upper Spherical Cap (JX-4572)				
Volume	**Coated [cm^3]**	**Ni [cm^3]**	**Pu-alloy [cm^3]**	
present work: MCNP5	206.4 ± 0.1	2.67 ± 0.01	203.7 ± 0.12	
Mass	**Coated [g]**	**Ni [g]**	**Pu-alloy [g]**	**Pu [g]**
present work: measurement / MCNP5	3273.9 ± 0.1	23.78 ± 0.1	3249.2 ± 0.14	3216
unpublished work (2005)	3274.0	25.25	3249	3216.2
unpublished work (1972)			3225	3192.4
Robba et al. (1983)			3225	3193
Center Component (JX-4570)				
Volume	**Coated [cm^3]**	**Ni [cm^3]**	**Pu-alloy [cm^3]**	
present work: MCNP5	262.4 ± 0.13	3.58 ± 0.01	258.8 ± 0.13	
Mass	**Coated [g]**	**Ni [g]**	**Pu-alloy [g]**	**Pu [g]**
present work: measurement / MCNP5	4158.2 ± 0.1	31.9 ± 0.1	4126.3 ± 0.14	4085
unpublished work (2005)	4158.3	33.71	4124.6	4083
unpublished work (1972)			4127	4085.3
Robba et al. (1983)			4127	4086
Lower Spherical Cap (JU-125)				
Volume	**Coated [cm^3]**	**Ni [cm^3]**	**Pu-alloy [cm^3]**	
present work: MCNP5	137.9 ± 0.1	2.22 ± 0.01	135.7 ± 0.1	
Mass	**Coated [g]**	**Ni [g]**	**Pu-alloy [g]**	**Pu [g]**
present work: measurement / MCNP5	2216.9 ± 0.1	19.7 ± 0.1	2197.2 ± 0.14	2175
unpublished work (2005)	2216.9	20.44	2196.5	2174.3
unpublished work (1972)	2216.75	20.85	2195.9	2173.7
Robba et al. (1983)			2196	2174



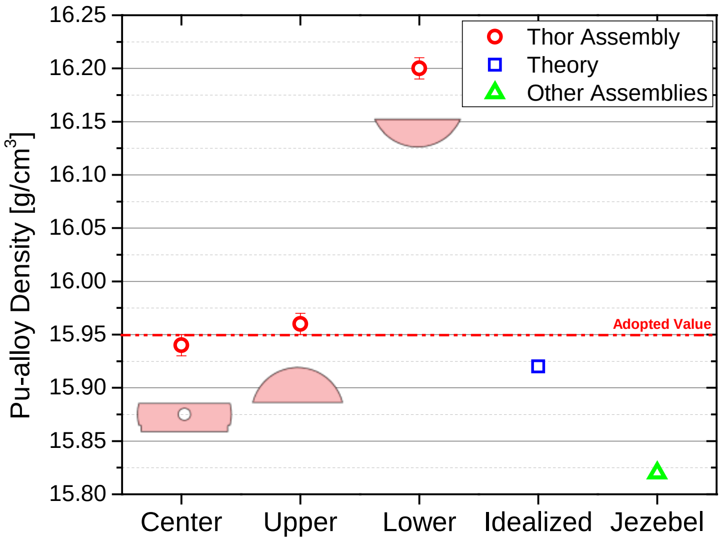




An updated Thor density of 15.95 g/cm^3 was obtained.

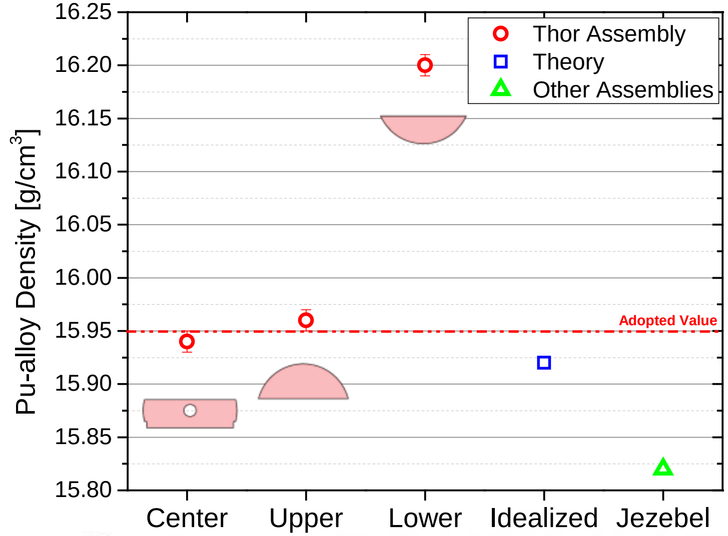
- **Calculated $\rho_{Pu\text{-}alloy}$ for Center/Upper components within statistical uncertainties.**
  - Mass-averaged value of 15.95 g/cm^3.

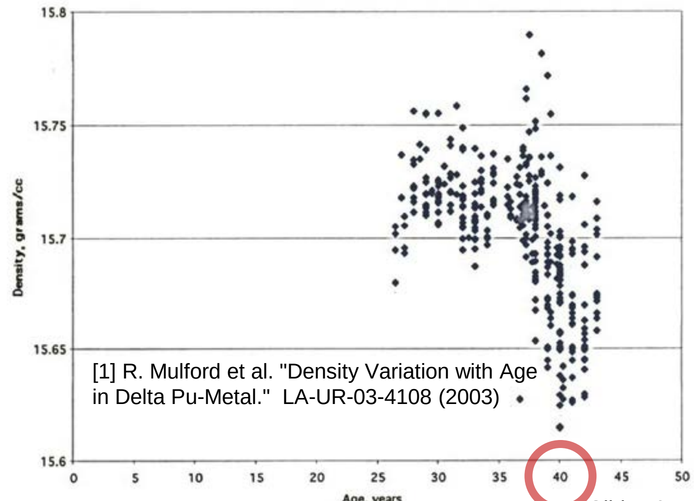
- **Discrepancy in Lower piece.**
  - Likely attributed to dimension inaccuracies.
  - Component was stripped of its original Ni cladding leading to material loss.



An updated Thor density of 15.95 g/cm³ was obtained.

- **Calculated $\rho_{Pu\text{-}alloy}$ for Center/Upper components within statistical uncertainties.**
  - Mass-averaged value of 15.95 g/cm³.
- **Discrepancy in Lower piece.**
  - Likely attributed to dimension inaccuracies.
  - Component was stripped of its original Ni cladding leading to material loss.
- **Density of δ-phase plutonium metal decreases as a function of time due to void swelling from helium buildup [1].**
  - Average rate of density loss after 35 years ~0.01 g/cm³ per year.
  - Can vary locally for a specific sample.
  - MISC [2] was used to decay initial Pu isotopes of the 40+ year old Thor core.

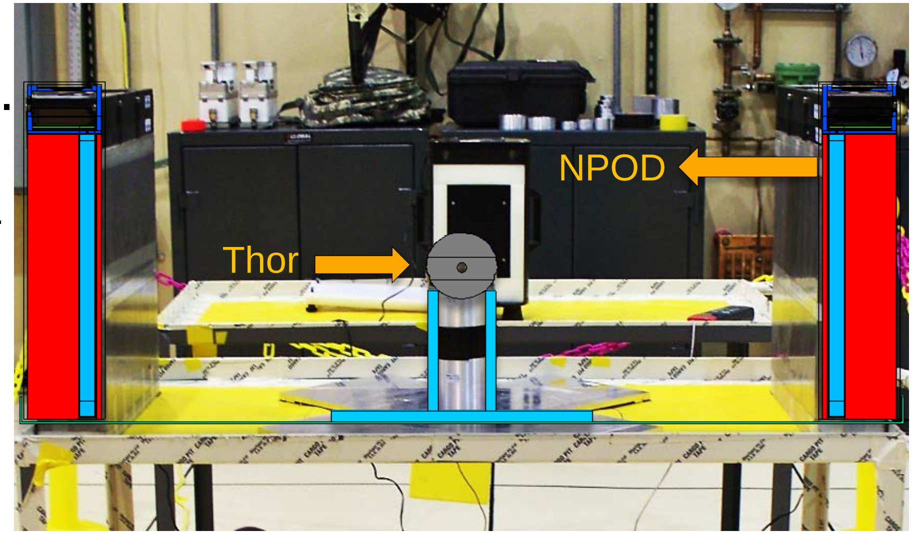




[1] R. Mulford et al. "Density Variation with Age in Delta Pu-Metal." LA-UR-03-4108 (2003)

[2] C. Solomon "MCNP Intrinsic Source Constructor (MISC):A User's Guide" LA-UR-12-20252 (2012)

Configuration of Thor Pu-metal core measurements.



- **14 main configurations were measured (various combinations of Thor core pieces).**
- **40+ perturbation configurations:**
  - Varying mass (different glory hole loadings).
  - Varying geometry (S-to-D distance).
  - Measurements with only 1 NPOD.
- **4 Detectors used:**
  - 2 x NPOD (LANL neutron multiplicity detector).
  - 1 x SNAP (LANL gross neutron counter).
  - 1 x HPGe (ORTEC gamma detector).
- **List-mode data obtained from NPOD measurements and simulations with MCNP**
  - Hage-Cifarelli formalism of the Feynman variance-to-mean method was used in analysis.
  - Single value for efficiency (all bare configurations).
    - Measured using a neutron source: 0.0091 +/- 0.0005
    - Validated using a combination of the SNAP/NPOD count rates for each configuration.

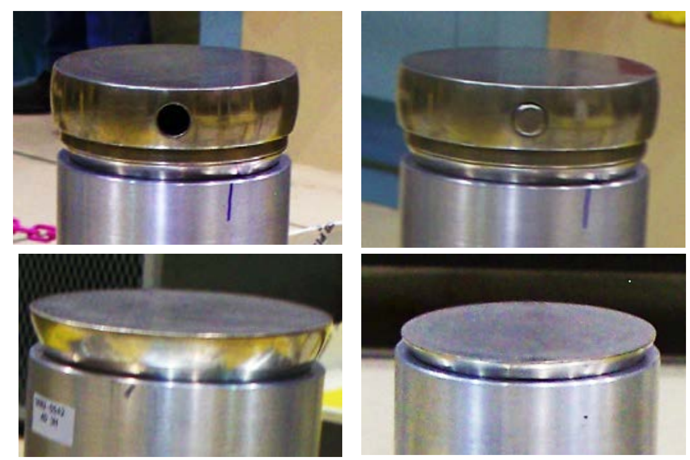
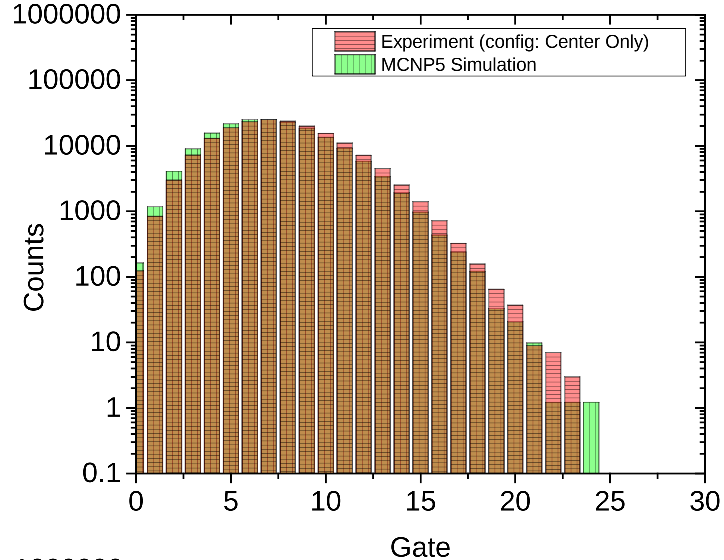
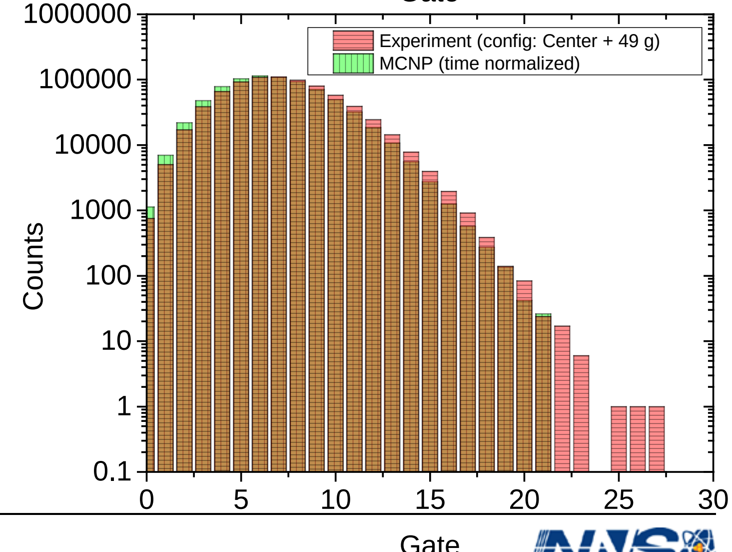


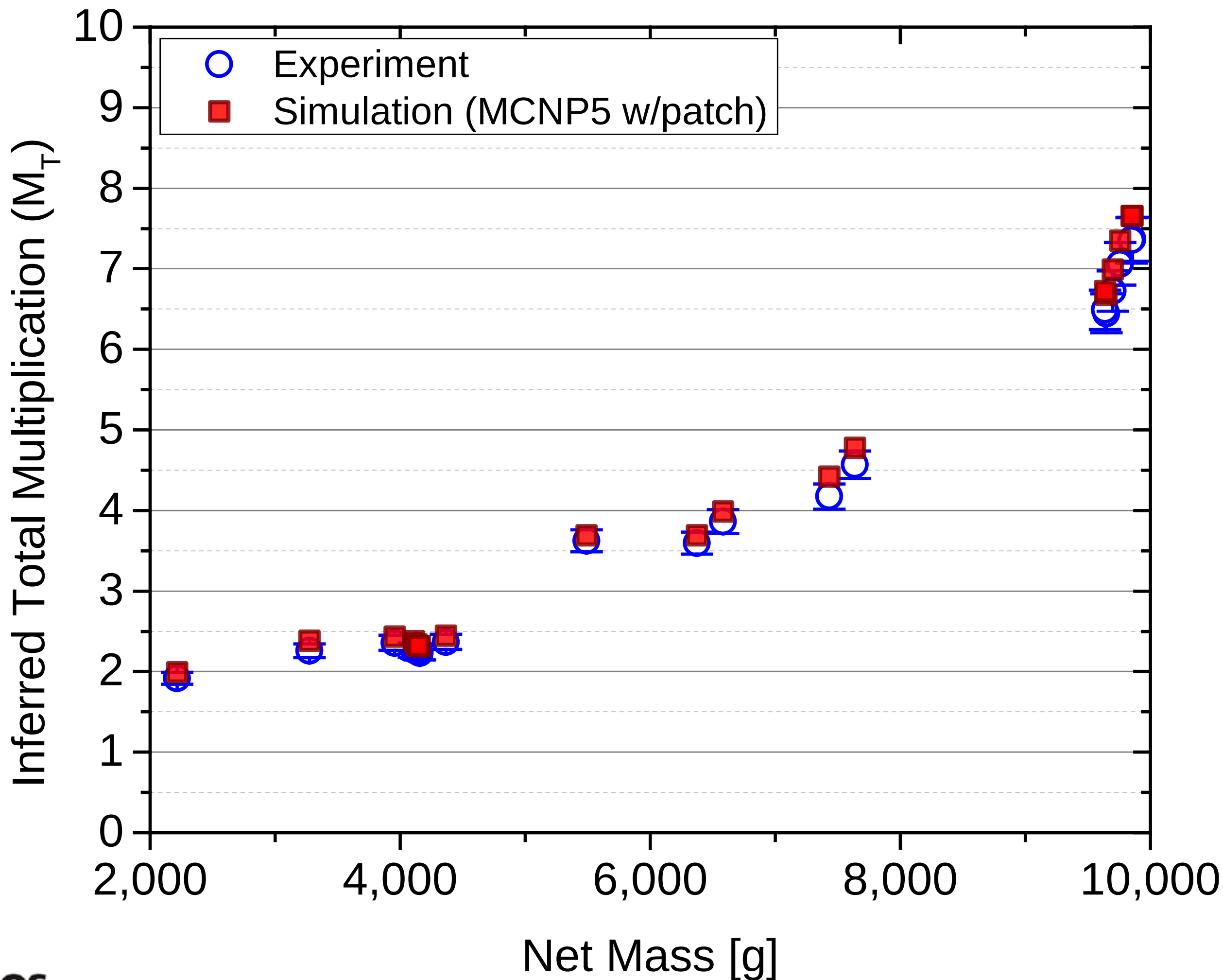
Table of the different configuration perturbations.

		Thor Core				Glory Hole			NPOD	
CONFIG. #	PERT.	Lower	Center	Upper	→	Loading	Mass [g]	Direction	S/D [cm]	#
1		+			def=vertical	None	0	def=NE-SW ↗	def=50	def=2
2			+		def=vertical	None	0	def=NE-SW ↗	def=50	def=2
3			+		def=vertical	Full	206.9	def=NE-SW ↗	def=50	def=2
	3p1		+		def=vertical	Full	206.9	N-S ↕	def=50	def=2
	3p2		+		def=vertical	Full	206.9	E-W ↔	def=50	def=2
	3p3		+		def=vertical	Full	206.9	def=NE-SW ↗	49.5	def=2
	3p4		+		def=vertical	Full	206.9	def=NE-SW ↗	49	def=2
	3p5		+		def=vertical	Full	206.9	def=NE-SW ↗	48	def=2
	3p6		+		def=vertical	Full	206.9	def=NE-SW ↗	45	def=2
	3p12		+		def=vertical	Quarter	49	def=NE-SW ↗	def=50	def=2
	3p13		+		def=vertical	Altern. Full	200.7	def=NE-SW ↗	def=50	def=2
	3p15		+		def=vertical	1/8th	24.7	def=NE-SW ↗	def=50	def=2
	3p16		+		def=vertical	1/16th	11.8	def=NE-SW ↗	def=50	def=2
	3p17		+		def=vertical	Full	206.9	E-W ↔	def=50	def=2
4				+	def=vertical	None	0	def=NE-SW ↗	def=50	def=2
5		+	+		def=vertical	None	0	def=NE-SW ↗	def=50	def=2
6		+	+		def=vertical	Full	206.9	def=NE-SW ↗	def=50	def=2
7		+		+	def=vertical	None	0	def=NE-SW ↗	def=50	def=2
	7p1	+		+	inverted ↓	None	0	def=NE-SW ↗	def=50	def=2
8			+	+	def=vertical	None	0	def=NE-SW ↗	def=50	def=2
9			+	+	def=vertical	Full	206.9	def=NE-SW ↗	def=50	def=2
10		+	+	+	def=vertical	None	0	def=NE-SW ↗	def=50	def=2
	10p1	+	+	+	def=vertical	None	0	E-W ↔	def=50	def=2
	10p2	+	+	+	def=vertical	None	0	N-S ↕	def=50	def=2
11		+	+	+	def=vertical	Full	206.9	def=NE-SW ↗	def=50	def=2
	11p2	+	+	+	def=vertical	1/16th	11.8	def=NE-SW ↗	def=50	def=2
	11p3	+	+	+	def=vertical	Alt. Full	200.7	def=NE-SW ↗	def=50	def=2
	11p4	+	+	+	def=vertical	Full	206.9	N-S ↕	def=50	def=2
	11p5	+	+	+	def=vertical	Full	206.9	E-W ↔	def=50	def=2
	11p6	+	+	+	def=vertical	Full	206.9	def=NE-SW ↗	49.5	def=2
	11p7	+	+	+	def=vertical	Full	206.9	def=NE-SW ↗	49	def=2
	11p8	+	+	+	def=vertical	Full	206.9	def=NE-SW ↗	48	def=2
	11p9	+	+	+	def=vertical	Full	206.9	def=NE-SW ↗	45	def=2
	11p14	+	+	+	inverted ↓	Full	206.9	def=NE-SW ↗	def=50	def=2
	11p15	+	+	+	def=vertical	Full	206.9	def=NE-SW ↗	def=50	1
12		+	+	+	def=vertical	Half	109.5	def=NE-SW ↗	def=50	def=2
13		+	+	+	def=vertical	Quarter	49	def=NE-SW ↗	def=50	def=2
14					def=vertical	Full	206.9	def=NE-SW ↗	def=50	def=2
	14p1				def=vertical	Full	206.9	N-S ↕	def=50	def=2
	14p2				def=vertical	Full	206.9	E-W ↔	def=50	def=2
	14p3				def=vertical	Half	109.5	def=NE-SW ↗	def=50	def=2
	14p4				def=vertical	Quarter	49	def=NE-SW ↗	def=50	def=2
	14p5				def=vertical	Altern. Full	200.7	def=NE-SW ↗	def=50	def=2

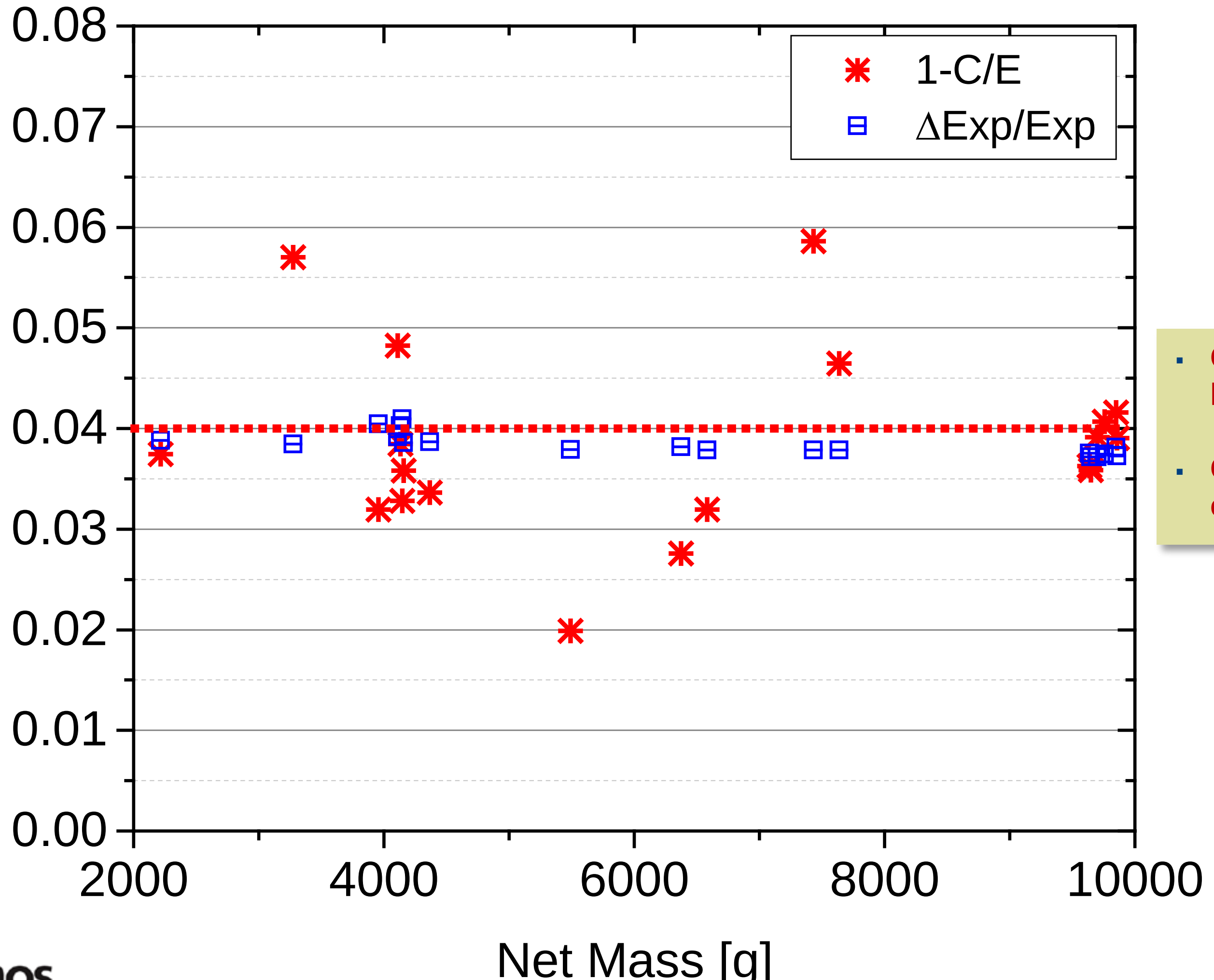




Total Neutron Multiplication (Inferred) vs System Mass

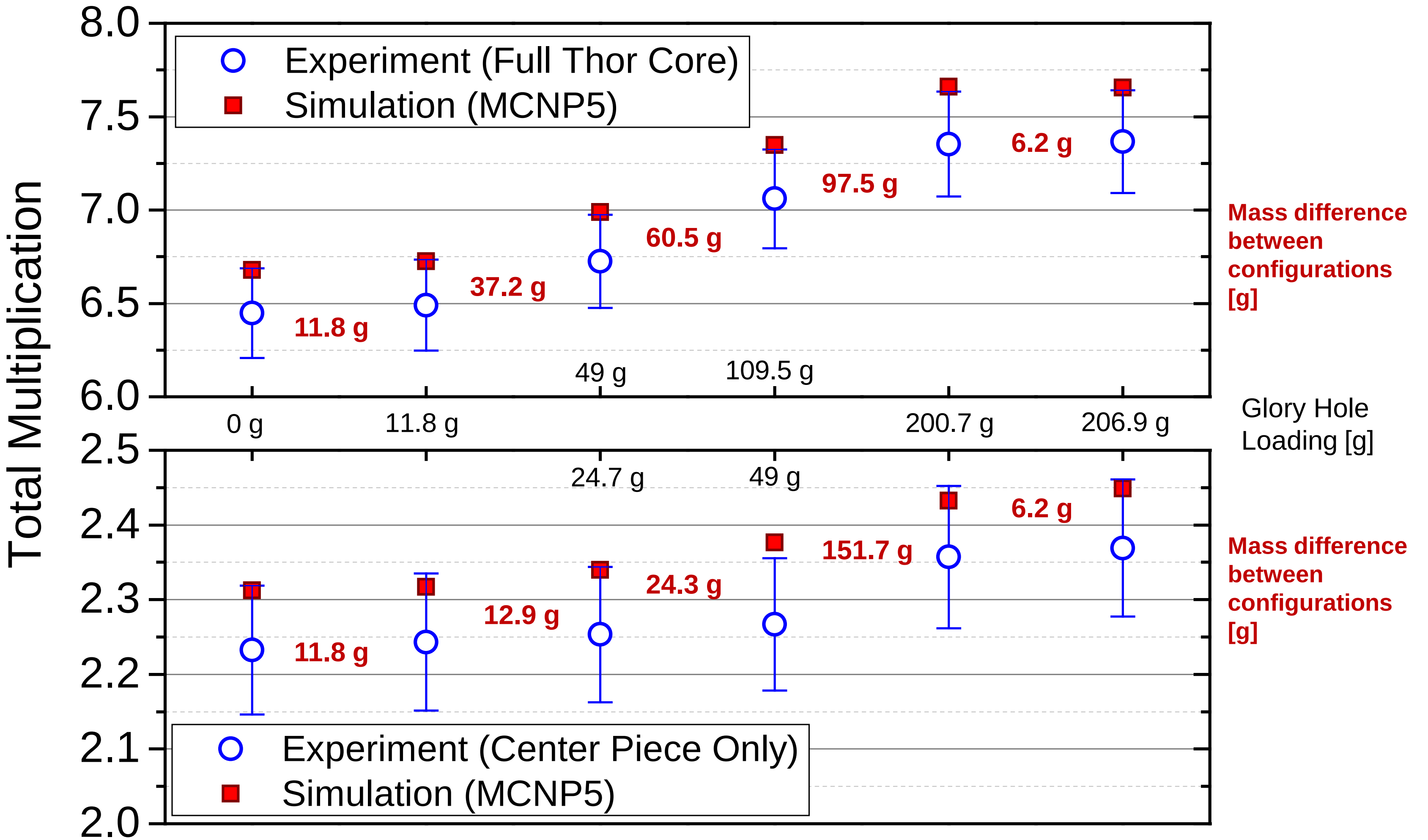


Calculation/Experiment for Total Multiplication



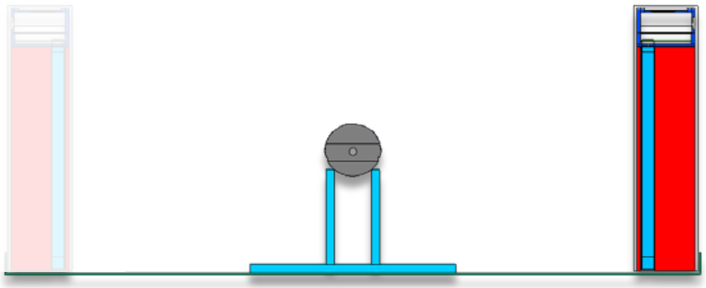
- **Calculation ~4% higher.**
- **Consistent with past experiences.**

Detectable mass threshold decreases as mass (and system multiplication) increases.



Varying NPOD position provides an observable effect on the inferred neuron multiplication.

- **Varying the Source-to-Detector distance.**
  - Efficiency of stationary NPOD increases as varying NPOD moves closer.
- **Shifted NPOD (5 cm):**
  - Simulation: **27%** ↑ in R1, **75%** ↑ in R2
  - Experiment: **25%** ↑ in R1, **41%** ↑ in R2
- **Stationary NPOD:**
  - Simulation: **0.85%** ↑ in R1, **2.5%** ↑ in R2
  - Experiment: **0.94%** ↑ in R1, **2.5%** ↑ in R2
- **Removing NPOD**
  - Presence of an NPOD adds reflection that another NPOD can see.
  - Simulation: **4.4%** ↑ in multiplication
  - Experiment: **3.9%** ↑ in multiplication



Deducing the possible sources of uncertainty/bias in the simulation results.

- **Nuclear data**
  - Ongoing assessment of underlying nuclear data effects for this application.
  - Pu: nubar, total, scattering fission, and capture neutron cross section [2-4].
- **Thor system specifications**
  - Geometry re-evaluation performed.
  - Isotopic composition

> - **Preliminary simulations with ^{239}Pu JEFF 3.1.2 cross sections provided multiplication results slightly closer to experimental values as compared to ENDF/B-VII.0.**
> - This is consistent with fast Pu benchmark integral data which shows eigenvalue [(k_{eff}) calculations 2].

- **Modeled NPOD efficiency**
  - Overestimate of gas pressure or active length could lead to higher inferred values*.
  - Improved efficiency measurements underway (for BeRP experiment with identical setup).
- **Radiation transport code**
  - Computational transport codes will always have some limitations.
  - MCNP6 expected to provide improved physics relative to this application.

[1] K. Clark et al., "Characterization of the NPOD3 Detectors in MCNP5 and MCNP6" LA-UR-14-20342 (2014)

[2] T. Kooyman et al., "Comparative sensitivity study of some criticality safety benchmark experiments using JEFF3.1.2, JEFF3.2T and ENDF/B-VII.1" NEMEA-7/CIELO International Collaboration on Nuclear Data (2013)

[3] S. Boldin, C. Solomon "Simulations of Multiplicity Distributions with Perturbations to Nuclear Data" Trans. ANS., Washington DC (2013)

[4] M. Chadwick et al. "The CIELO Collaboration Neutron Reactions on ^{1}H, ^{16}O, ^{56}Fe, ^{235,238}U and ^{239}Pu" Trans. ANS., Washington DC (2013)

Comparing experiments and simulations helps in assessing/reducing uncertainties in models and data.

- **Ongoing effort to accurately quantify uncertainty in neutron multiplication inference from measurements and calculations.**

- **Significant improvements will depend on:**
  - These types of measurements and their simulations.
  - Incremental improvements in computational tools.
  - Leveraging community-wide parallel efforts related to quantifying uncertainties and correlations for nuclear data.
  - Applying new analyses techniques.
    - e.g. Bayesian interpretation of historical benchmark data.

Related technical sessions organized by LANL scientists at upcoming American Nuclear Society (ANS) meetings.

ANS

2014 ANS Annual Meeting
June 15–19, 2014 • Reno, Nevada • Grand Sierra Resort
The U.S. Role in a Global Nuclear Energy Enterprise

Critical and Subcritical Experiments

Session Organizer: Jesson Hutchinson (LANL)

Session Chair: Richard Malenfant (LANL – retired)

ANS

2014 Winter Meeting and Technology Expo
November 9-13, 2014 • Anaheim, CA • Disneyland Hotel

"Nuclear: The Foundation of Clean Energy"
Deadline: June 13. 2014

Nuclear Data for Nonproliferation Applications

Session Organizer: Rian Bahran (LANL)

Acknowledgements

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

Thank you for your attention.