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Finalization of the IER 488 (MUSIC) Experiment Design

NCSP Technical Program Review



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Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

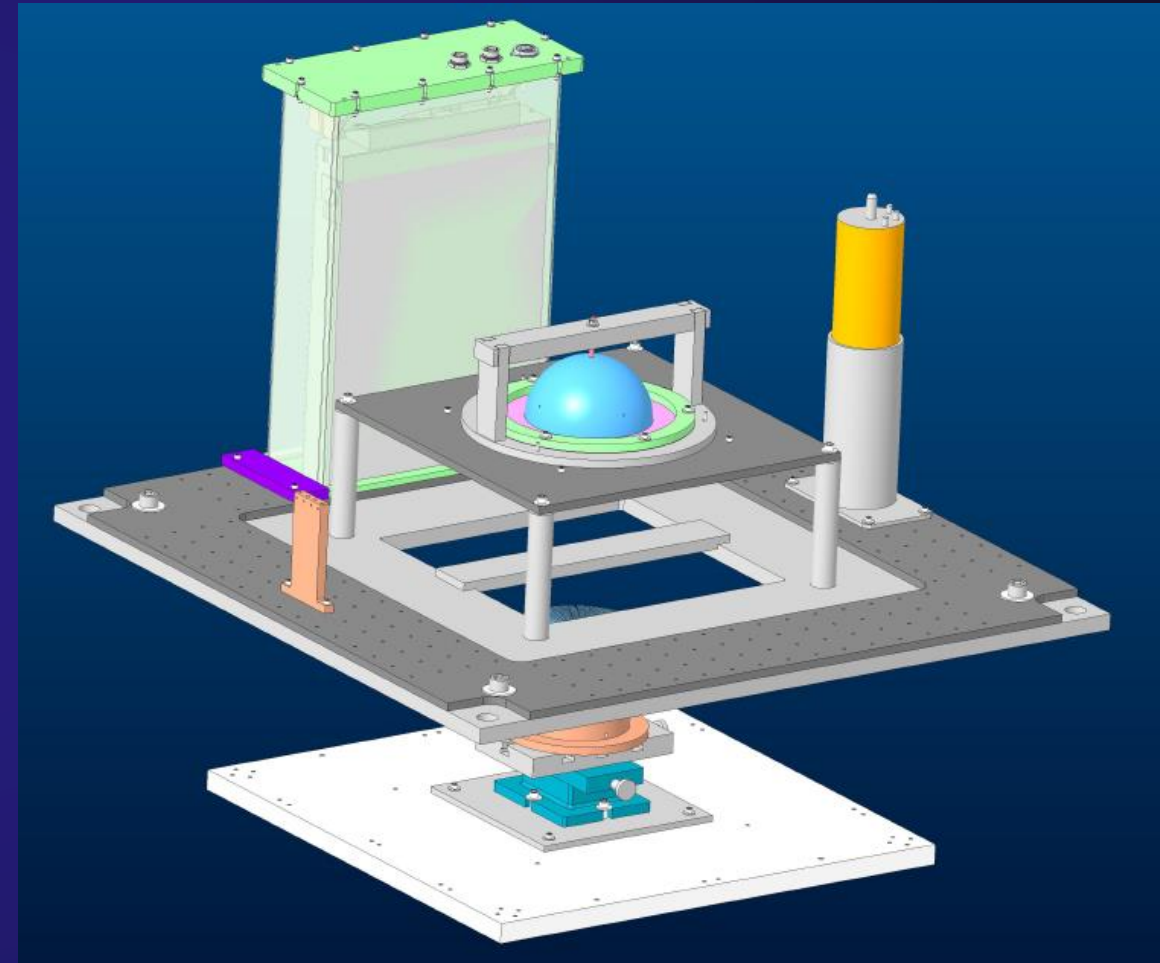
Outline



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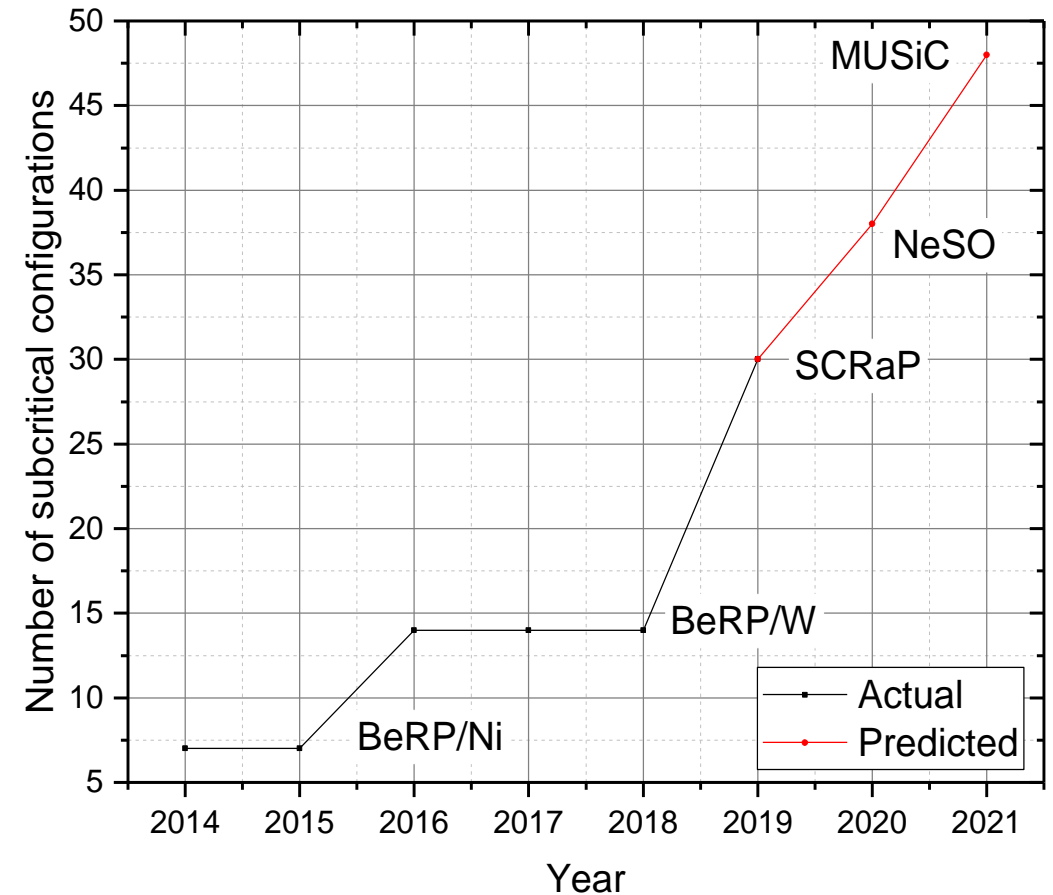
Experiment Overview

- Subcritical and critical experiment with high-enriched uranium (HEU)
 - Configurations will use varying numbers of the Rocky Flats nesting shells
 - Large range of neutron multiplication values, all the way from deeply subcritical to critical
 - Will use a variety of external sources and analysis methods
- To be performed at National Criticality Experiments Research Center (NCERC) at the Nevada National Security Site (NNSS)
- Goal is inclusion in International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook



Motivation

- ICSBEP has a growing suite of subcritical benchmarks
 - A few experiments with plutonium, but no multiplication experiments have been accepted with bare HEU
 - These experiments help validate data such as $\bar{\nu}$ and reaction cross sections
 - Test subcritical measurement, simulation, and analysis methods
- Variety of external neutron sources used (^{252}Cf and a Deuterium-Tritium neutron generator) will also help validate associated analysis methods
- Also interest in helping predict criticality accidents



Experimental Components – Rocky Flats Shells

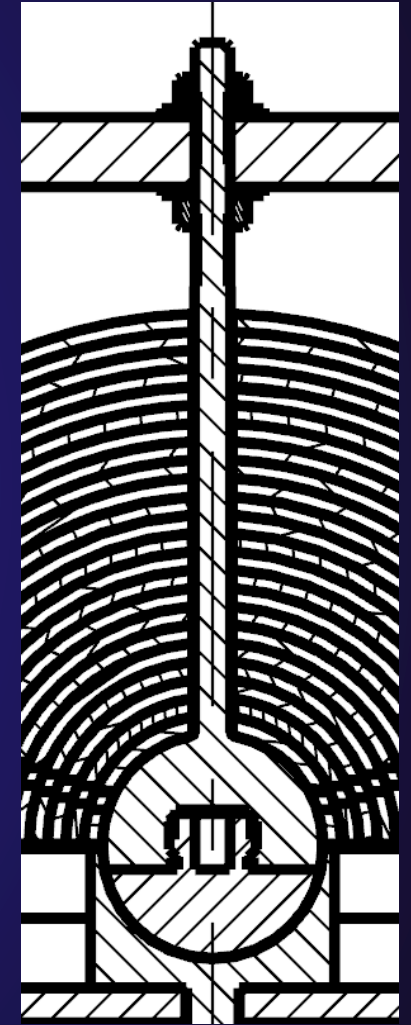
- Used in the 1960's for experiments at the Rocky Flats Critical Mass Laboratory
- Series of nesting hemishells (except shells 1 and 2, which are solid hemispheres)
 - Each approximately 0.3 cm thick
 - Outer radii range from 2 cm to 10 cm
 - Mass range from ~300 g to ~3600 g

Uranium Nuclide	1973 Weight Percent
234	1.02
235	93.16
236	0.47
238	5.35



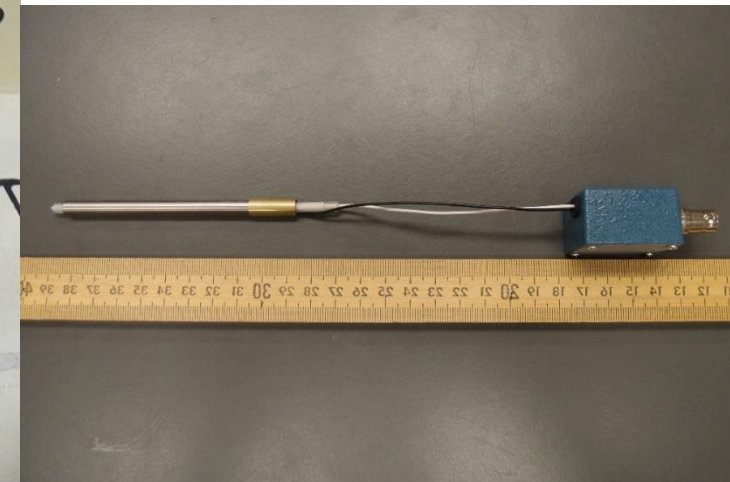
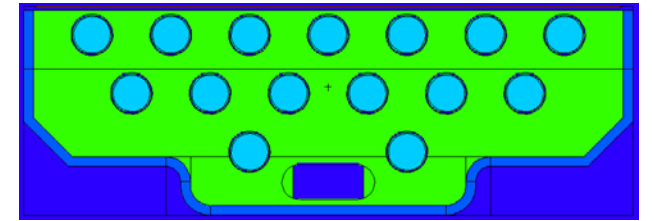
Experimental Components – Aluminum Pieces

- Some of the inner shells will be replaced by aluminum mock shells
 - NCERC already possesses pieces to replace shells 1-10
 - Shells 1 and 2 will be replaced by a custom source holder for the ^{252}Cf
 - Will also help with upper/lower stack alignment
- Also have spacers to put in between the two stacks for finer reactivity control
 - Preliminary simulations show 1.5-1.75 ϕ /mil of spacer



Experimental Components - Neutron Detectors

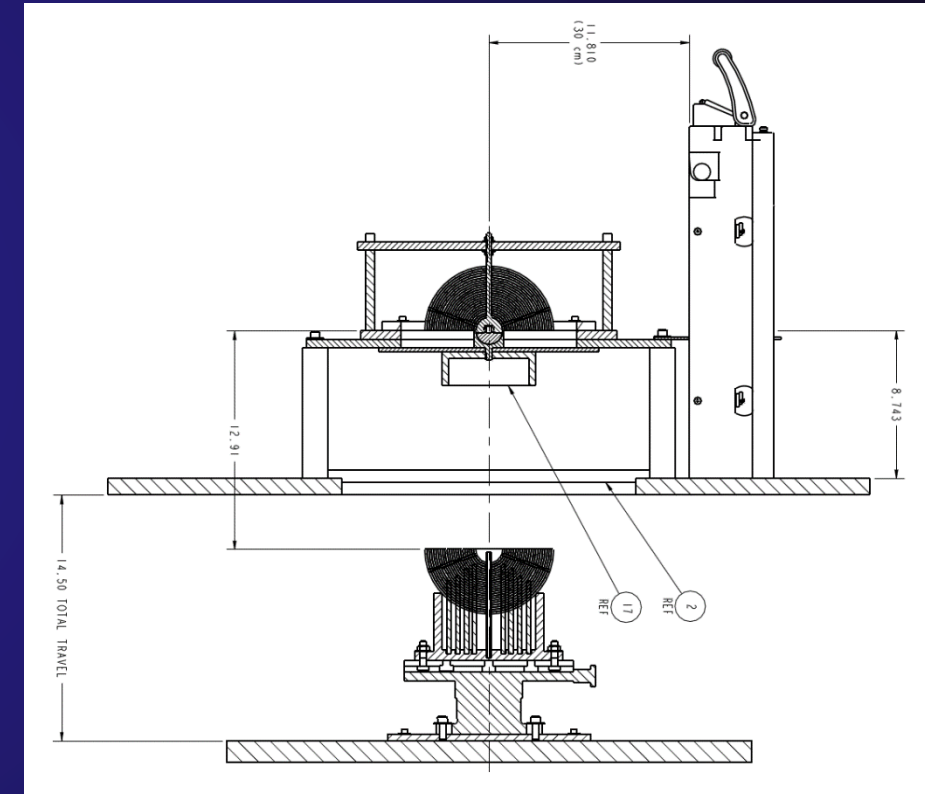
- Two separate list-mode neutron detectors
 - NoMAD
 - Used for many previous subcritical measurements
 - 15 ^3He tubes embedded in high-density polyethylene
 - Smaller ^3He Tube
 - Much smaller, but higher gas pressure
 - 40 atm vs 10 atm in the NoMAD
 - Can place in more locations
 - Smaller Efficiency means smaller chance of saturation
 - Four will likely be used
- Potential for Additional Detector from IRSN



Experimental Configurations

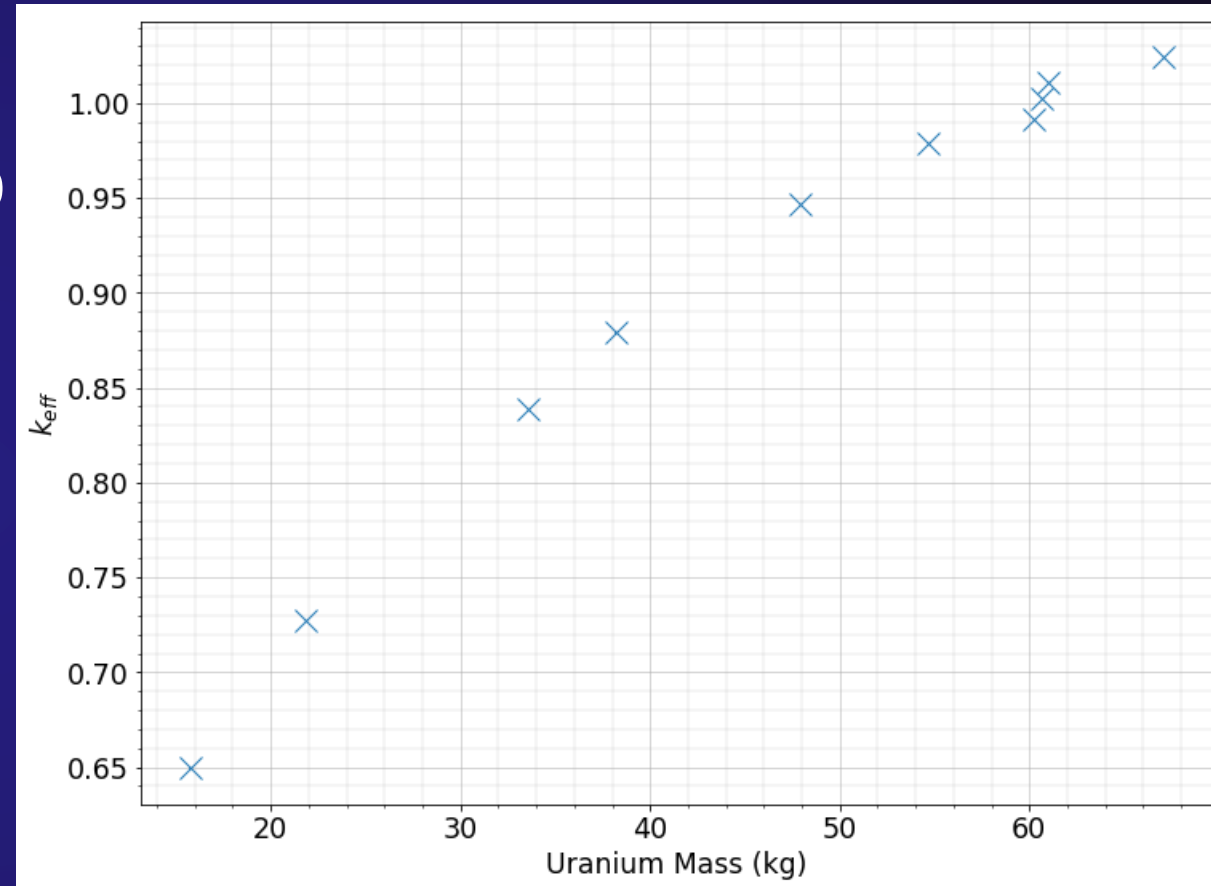
- Ten primary configurations assembled on the Planet vertical lift machine
 - Various numbers of the Rocky Flats shells with some inner shells replaced by aluminum
 - Additional configurations may be constructed during experiment, but will not be the focus

Configuration	Outer Aluminum Shell	Outer Uranium Shell	Uranium Mass (kg)	k_{eff}
1	1,2	25	15.723	0.64925
2	1,2	29	21.832	0.72715
3	1,2	35	33.552	0.83854
4	1,2	37	38.243	0.87888
5	5,6	41	47.925	0.92428
6	1,2	43	54.642	0.97914
7	5,6	45	60.190	0.99179
8	3,4	45	60.657	1.00228
9	1,2	45	61.009	1.01077
10	5,6	47	67.082	1.02448



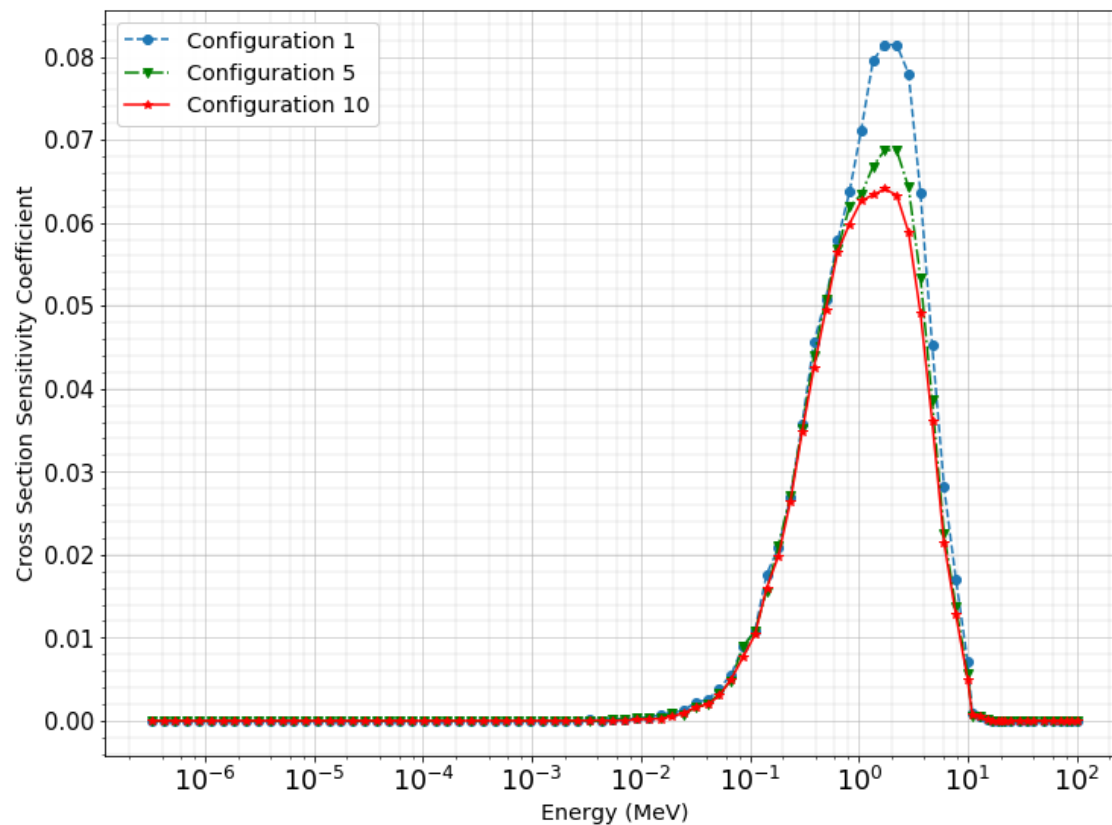
Simulation Results - k_{eff}

- Simulations performed with MCNP version 6.2, ENDF/B-VII.1 cross sections
 - KCODE eigenvalue mode, 5,100 cycles of 10,000 neutrons each
- Largest effective multiplication factor range of any potential benchmark
 - Deeply subcritical (0.64925) to above critical (1.02448)



Simulation Results – Cross Section Sensitivity

- Calculated with MCNP KSEN card, which outputs adjoint-based sensitivity coefficients for all isotopes in the problem
 - Outputs both energy-sensitive and energy-integrated coefficients
- Given lack of moderators, system sensitivity is dominated by ^{235}U in the fast region



Configuration	^{235}U	^{238}U	^{27}Al
1	9.14E-01	1.93E-02	1.42E-02
2	8.89E-01	1.84E-02	1.09E-02
3	8.58E-01	1.87E-02	9.89E-03
4	8.36E-01	1.91E-02	1.13E-02
5	8.14E-01	1.89E-02	1.04E-02
6	7.92E-01	1.79E-02	9.01E-03
7	7.95E-01	1.83E-02	1.07E-02
8	7.90E-01	1.68E-02	1.04E-02
9	7.88E-01	1.76E-02	9.73E-03
10	7.75E-01	1.75E-02	1.01E-02

Simulation Results – Leakage Multiplication

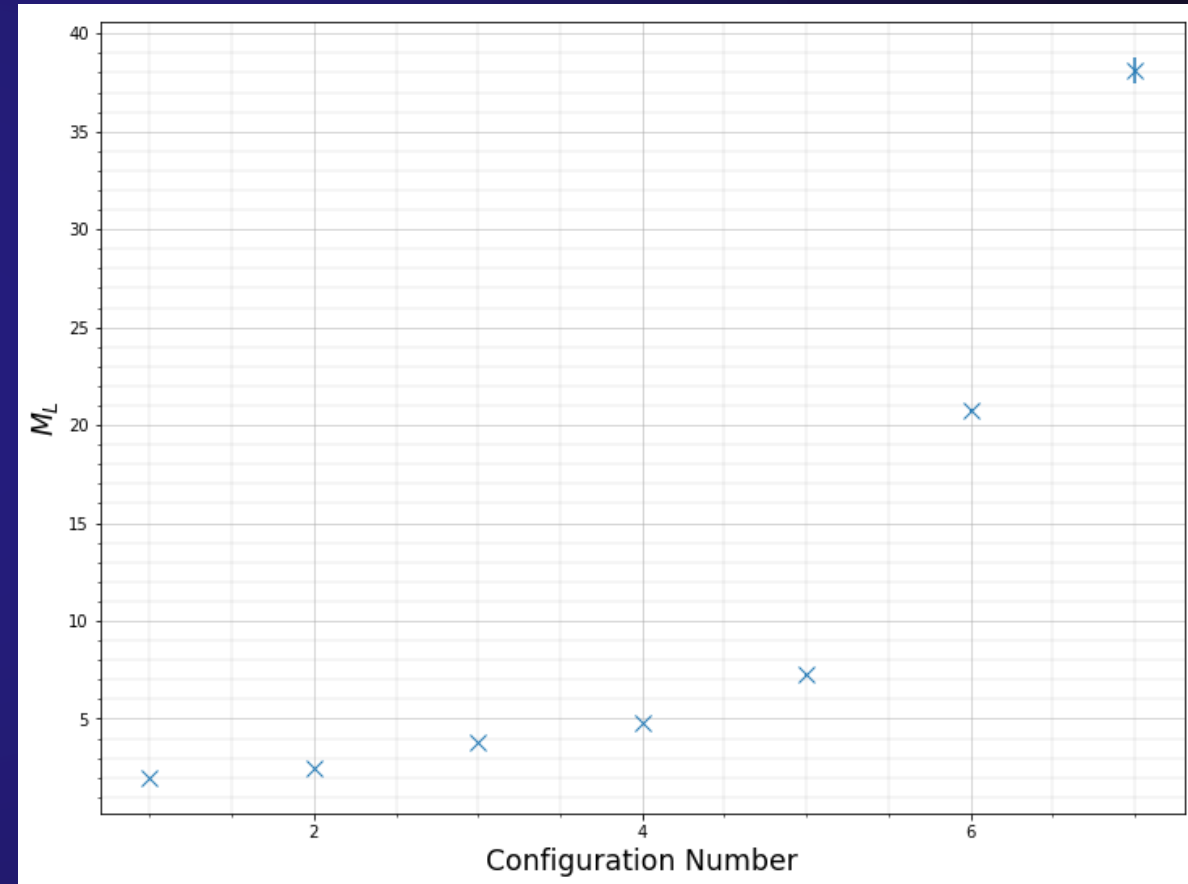
- Can convert k_{eff} to leakage multiplication M_L (average number of neutrons that leave the system per starter neutron) through

$$k_{eff} = \frac{k_p}{1 - \beta_{eff}} \quad M_T = \frac{1}{1 - k_p}$$

$$M_L = \frac{1}{\bar{\nu}} [(\bar{\nu} - 1 - \alpha)M_T + 1 + \alpha]$$

$$\alpha = \frac{\Sigma_c}{\Sigma_f}$$

- β_{eff} - effective delayed neutron fraction
- k_p - prompt multiplication factor
- M_T – total multiplication, the number of neutrons produced per starter neutron
- $\bar{\nu}$ - average number of neutrons produced in fission
- Again, the large multiplication range is highlighted here



Simulation Results – Count Rate Estimations

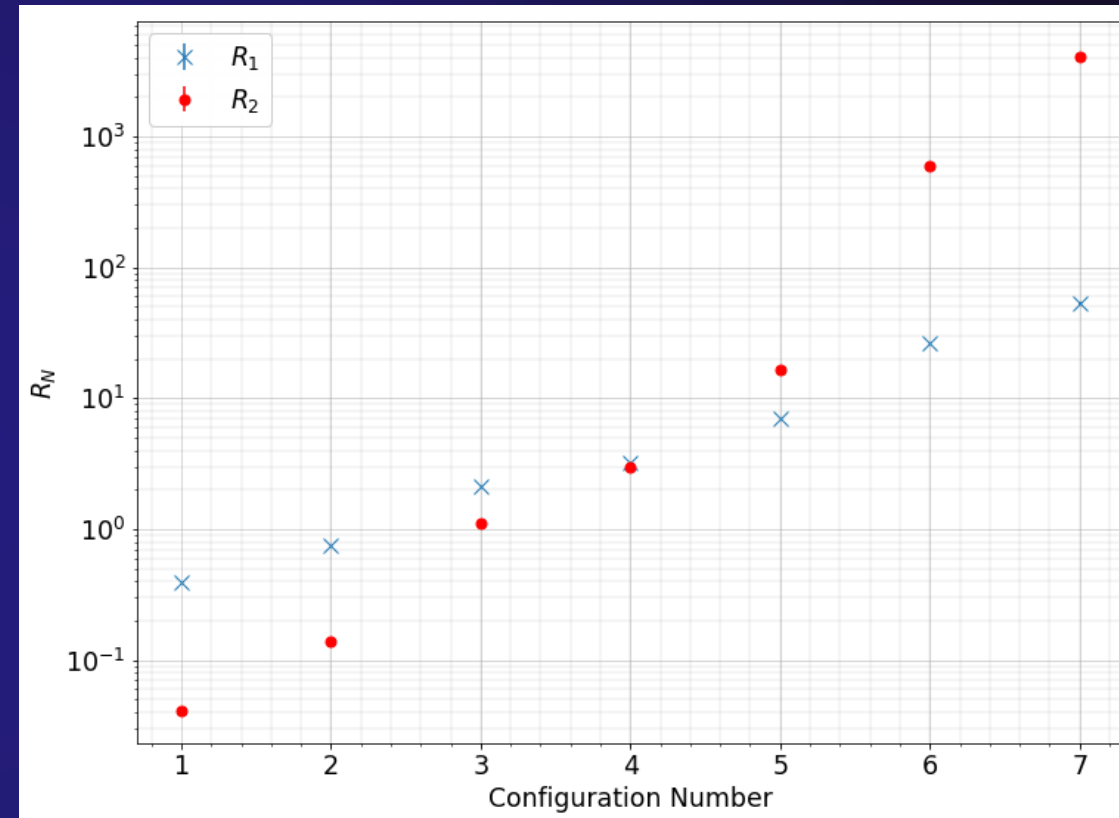
- M_L can be further converted to the count rates R_1 (the rate of neutron detection, or singles rate) and R_2 (the rate at which two neutrons from the same fission chain are detected)

$$R_1 = \varepsilon b_{11} F_S \quad R_2 = \varepsilon^2 b_{21} F_S$$

$$b_{11} = M_L \overline{\nu_{S1}}$$

$$b_{21} = M_L^2 \left[\overline{\nu_{S2}} + \frac{M_L - 1}{\overline{\nu_{I1}} - 1} \overline{\nu_{S1} \nu_{I2}} \right]$$

- ε – detector efficiency
- F_S - spontaneous fission rate
- $\overline{\nu_{In}}$ – n th reduced factorial moment of the induced fission neutron multiplicity distribution
- $\overline{\nu_{Sn}}$ – n th reduced factorial moment of the spontaneous fission neutron multiplicity distribution



Note: values in this plot are without an external source

Sensitivity and Uncertainty Analysis

- Predict the sensitivity of the experiment (and the resultant uncertainty) due to certain parameters
 - E.g. uncertainty in uranium mass, aluminum mass, uranium shell radius, etc.
- Estimated by either adjoint-based sensitivity coefficients (KSEN card) or by perturbing the parameter in the simulation by multiples of the uncertainty

	M_L Sensitivity	M_L Uncertainty	R_1 Sensitivity	R_1 Uncertainty	R_2 Sensitivity	R_2 Uncertainty
Al Mass $\pm 0.5\%$	0	0	0	0	0	0
U Radius ± 0.005 cm	1.085	0.005423	-0.7795	0.003898	-1.008	0.005041
U Mass ± 2.4413 g	0.00017	0.000395	0	0	0.000010	0.000025
U Enrichment $\pm 0.05\%$	0.02587	0.000388	0	0	0	0

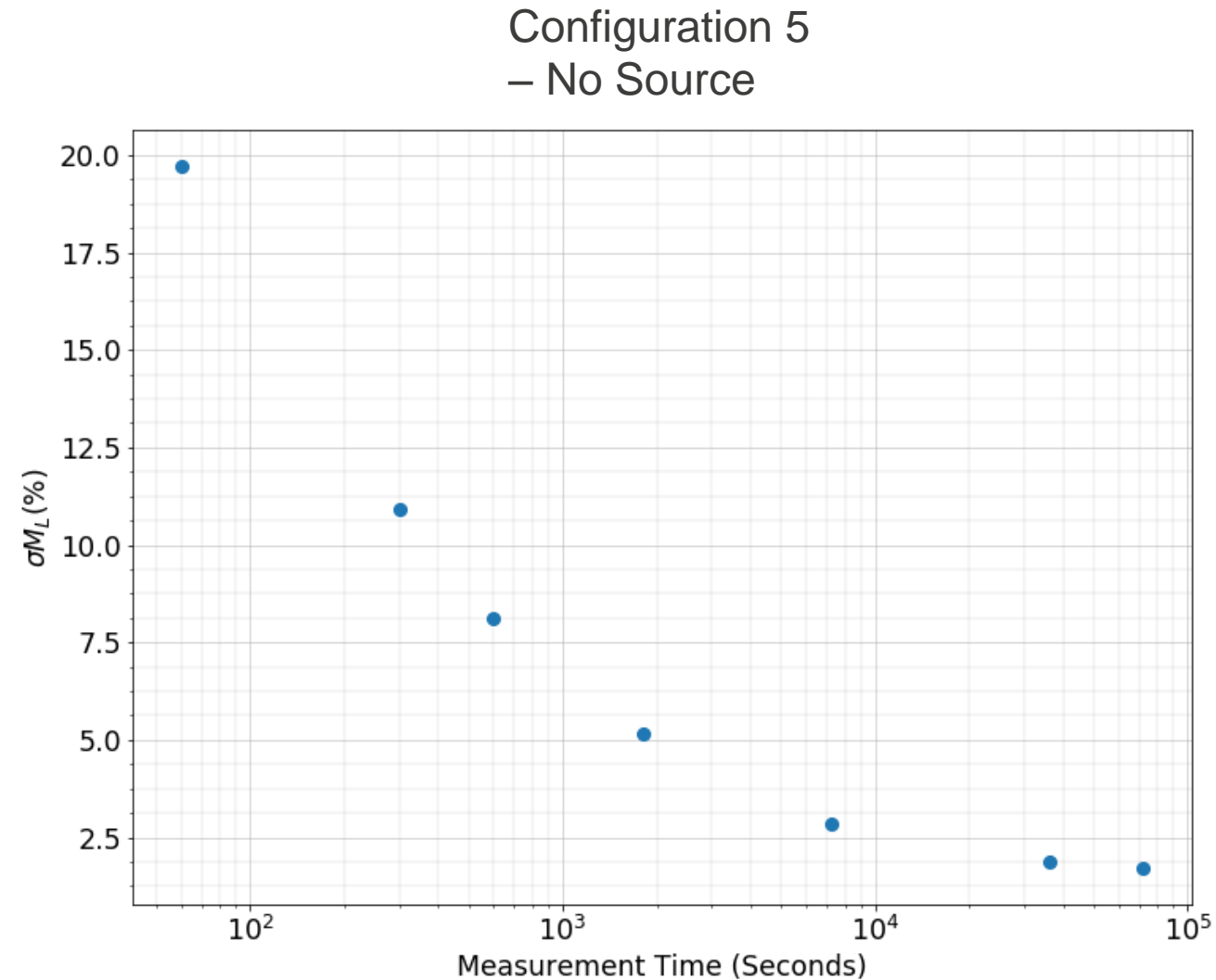
Sensitivity and Uncertainty Analysis cont.

- Can see from these tables that only some parameters are significant to some of the configurations
 - The radius of the uranium shells is significant for all configurations
 - Indicates that either the uncertainty needs to be better assessed, or that the sensitivity treatment needs to be reviewed
- Also repeated analysis accounting for the presence of the californium source

	M_L Sensitivity	M_L Uncertainty	R_1 Sensitivity	R_1 Uncertainty	R_2 Sensitivity	R_2 Uncertainty
Al Mass $\pm 0.5\%$	0.000353	0.000176	0	0	0	0
U Radius ± 0.005 cm	1.061	0.005307	-27560	137.8	-9759	48.80
U Mass ± 2.4413 g	0.000185	0.000451	0	0	1.617	3.949
U Enrichment $\pm 0.05\%$	0	0	0	0	0	0

Measurement Time Determination

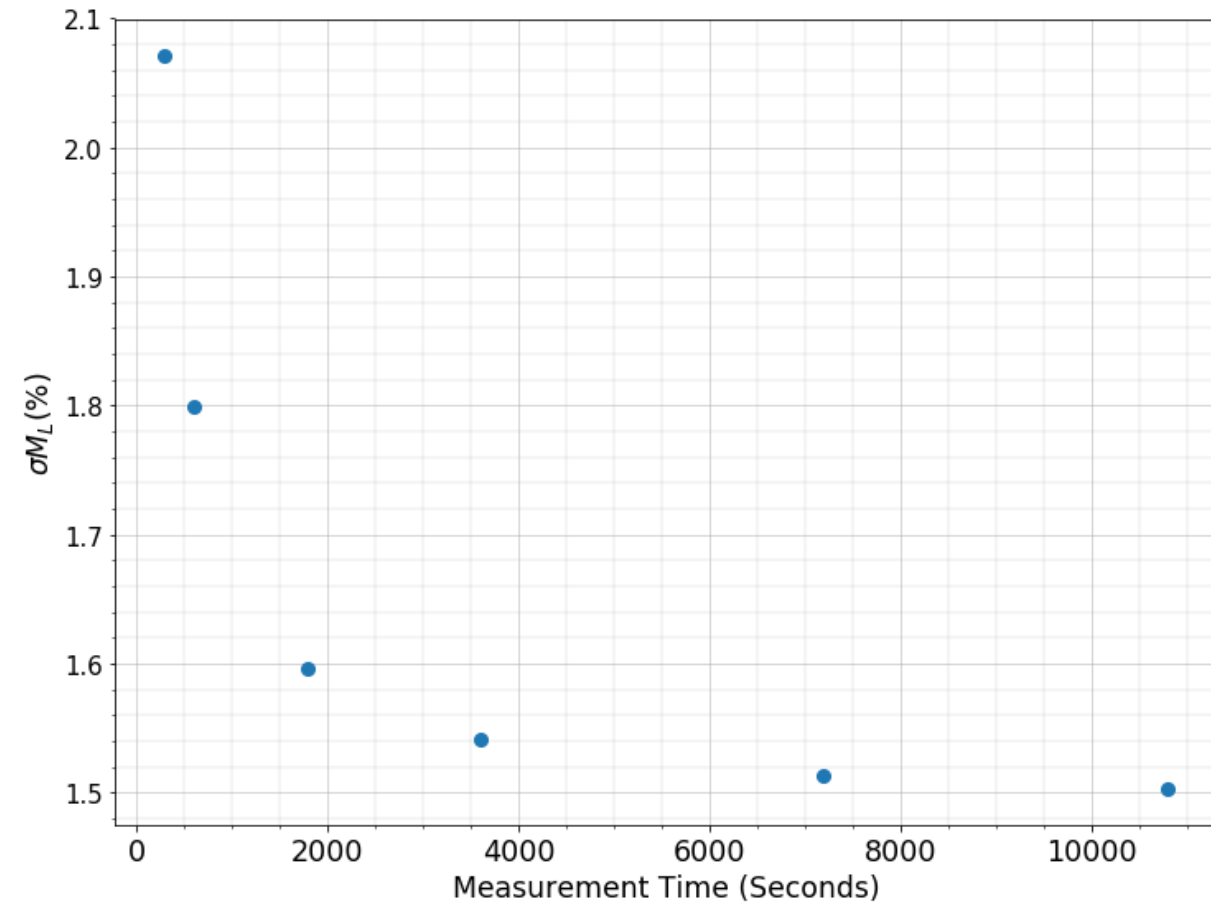
- Need to know how long to measure subcritical configurations to get desired precision
- Many simulations performed with 1-D code called Neutron Generator
 - Creates list-mode data files that are analyzed to determine count rates and uncertainties
 - Results fit to determine uncertainty as a function of time
- Since the goal is inclusion in ICSBEP, want uncertainties very close to the theoretical minimum (within 1-2%)
- Looked at Configuration 5 without the californium, and configuration 1 with the source
 - Extremes in count rates meant to highlight difference in needed measurement times



Measurement Time Determination cont.

- Estimated how much time was needed for uncertainties to be within 2% of theoretical minimum
 - With the source, Configuration 1 needs around ninety minutes
 - Any other configuration will have a higher count rate, and therefore take even less time
 - Without the source however, Configuration 5 will need over 20 hours of measurement time
 - Uncertainty still 13% above theoretical minimum
 - Other subcritical configurations will have a lower count rate, and therefore will take longer to measure
- Will need to take into account during planning, as a no-source measurement will be desired for the experiment.

Configuration 1
– With Source



Current and Future Work

- Procure remaining aluminum pieces
 - Source holder, structural components, spacers, and detector containers
- Look at simulation of D-T neutron generator measurements
 - Large number of neutrons, pulsing emissions make it more challenging
- NCSP Deliverable Due Dates
 - CED-3a due Q2 2019
 - CED-3b Q4
 - CED-4a Q2 2020
- Execute experiment
 - Planned for August-September of 2019
- ICSBEP Benchmark
 - Submit in 2020 or 2021

Thank you!

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