Los Alamos
NATIONAL LABORATORY

EST. 1943

Finalization of the IER 488 (MUSIC) Experiment Design

NCSP Technical Program Review

Alex McSpaden, Theresa Cutler, Jesson Hutchinson, Geordie McKenzie

March 26th, 2019

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

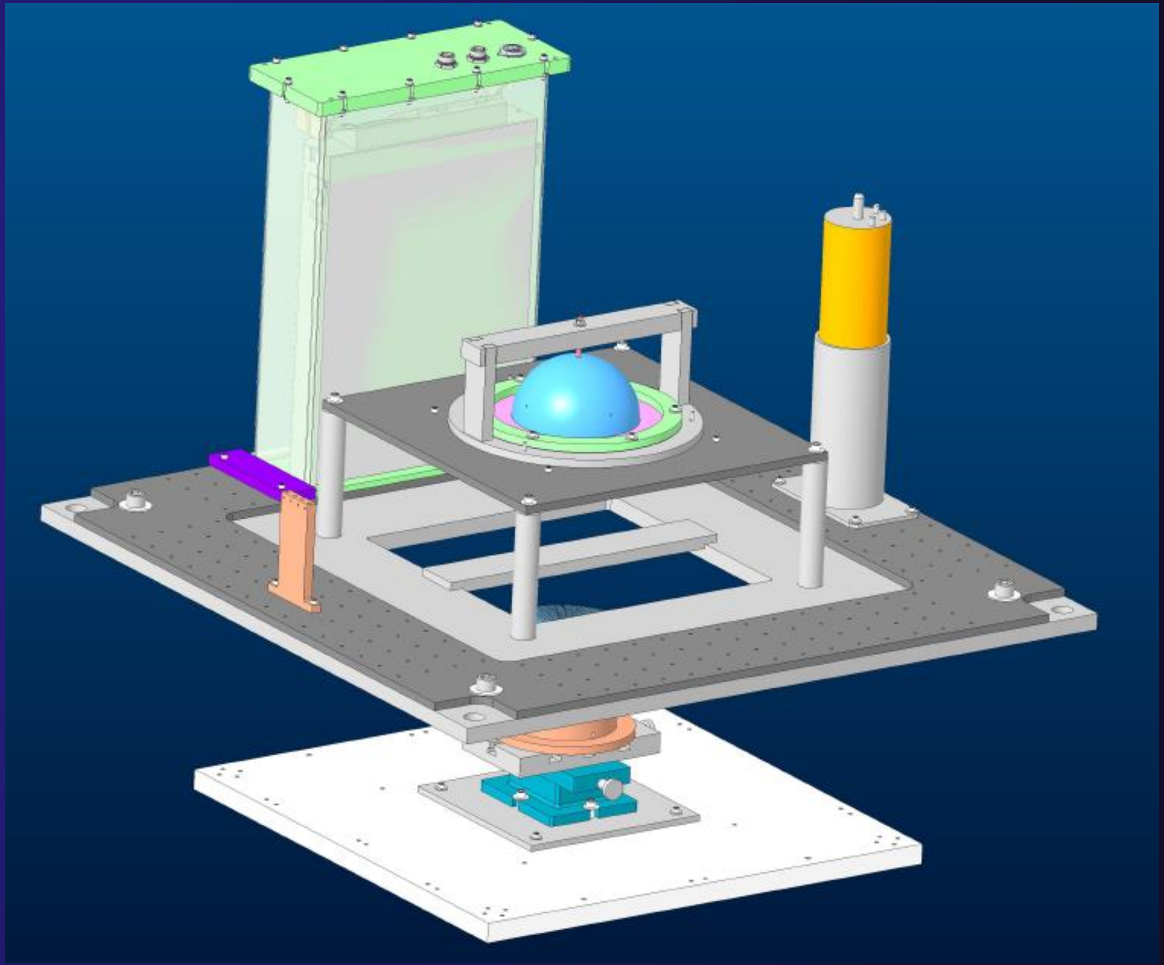
LA-UR-19-22235

Outline

- Experiment Overview
- Motivation
- Experiment Components & Configurations
- Simulation Results
  - k_{eff} and Cross Section Sensitivity
  - Count Rate and Leakage Multiplication
  - Sensitivity and Uncertainty Analysis
  - Measurement Time Determination
- Current and Future Work

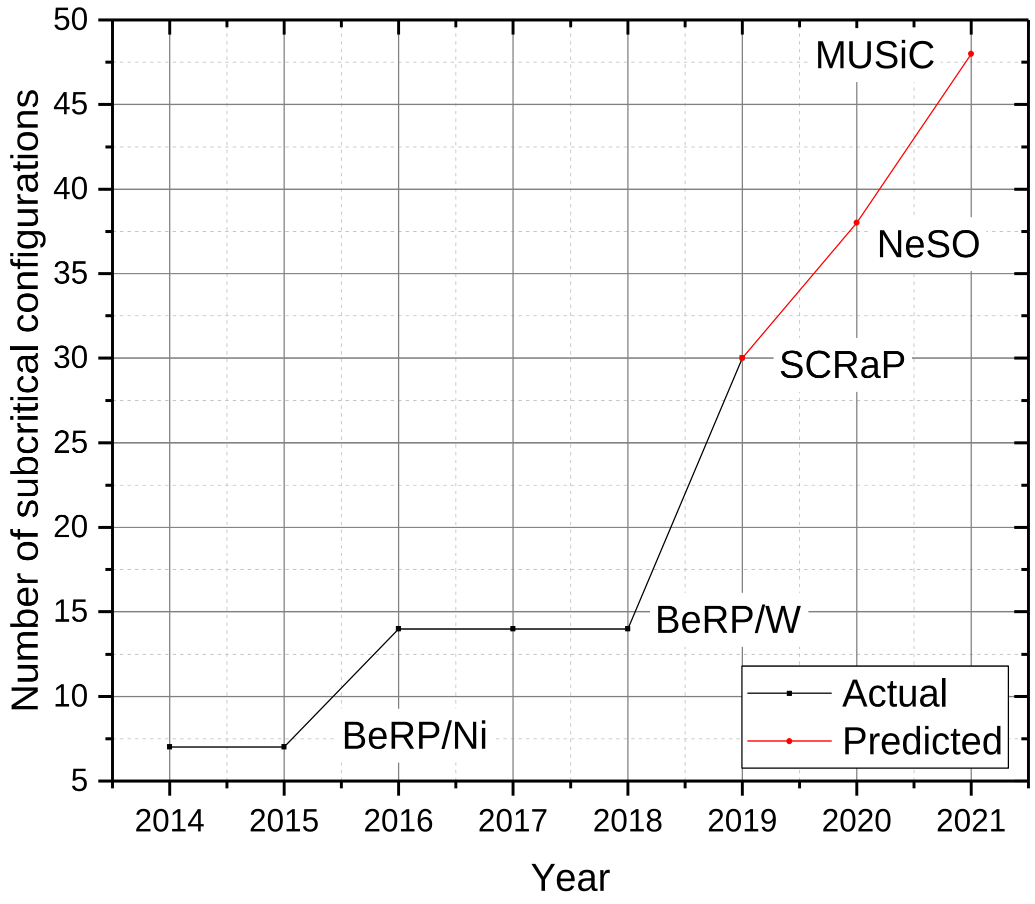
Experiment Overview

- 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



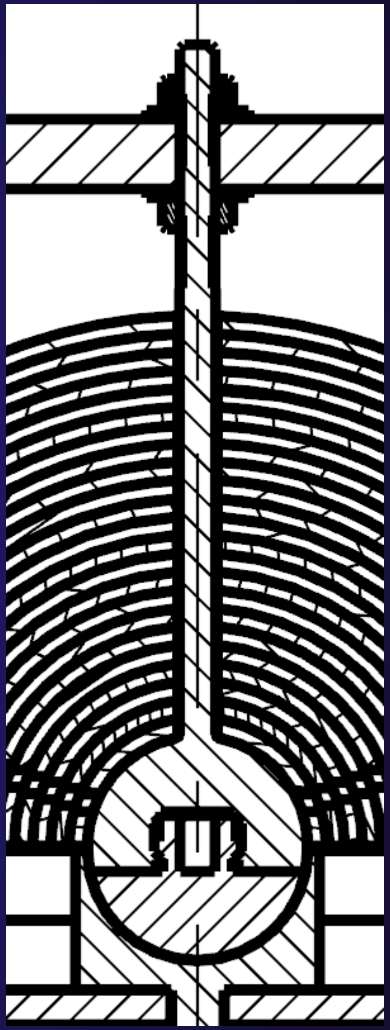
Experimental Components – Rocky Flats Shells

- 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

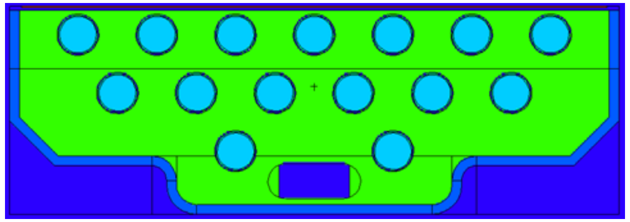
Experimental Components – Aluminum Pieces

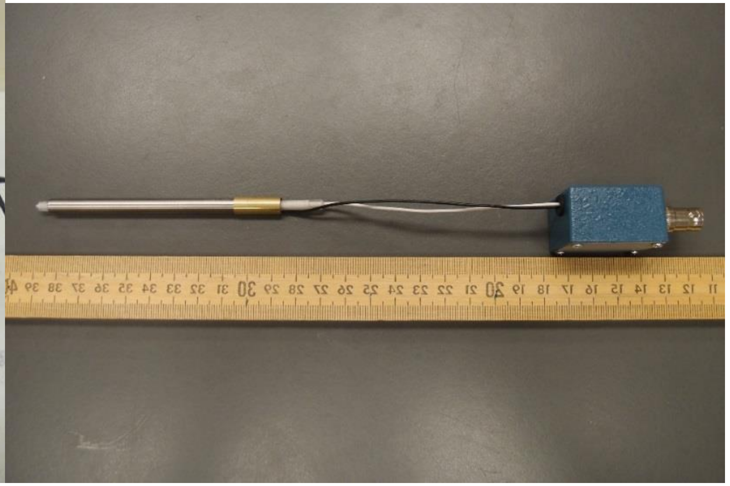
- Some of the inner shells will be replaced by aluminum mock shells
  - – NCERC already possesses pieces to replace shells 1-10
  - – Shells 1 and 2 will be replaced by a custom source holder for the ^{252}Cf
  - – Will also help with upper/lower stack alignment
- Also have spacers to put in between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



Experimental Components - Neutron Detectors

- Two separate list-mode neutron detectors
  - – NoMAD
    - Used for many previous subcritical measurements
    - 15 ^{3}He tubes embedded in high-density polyethylene
  - – Smaller ^{3}He 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

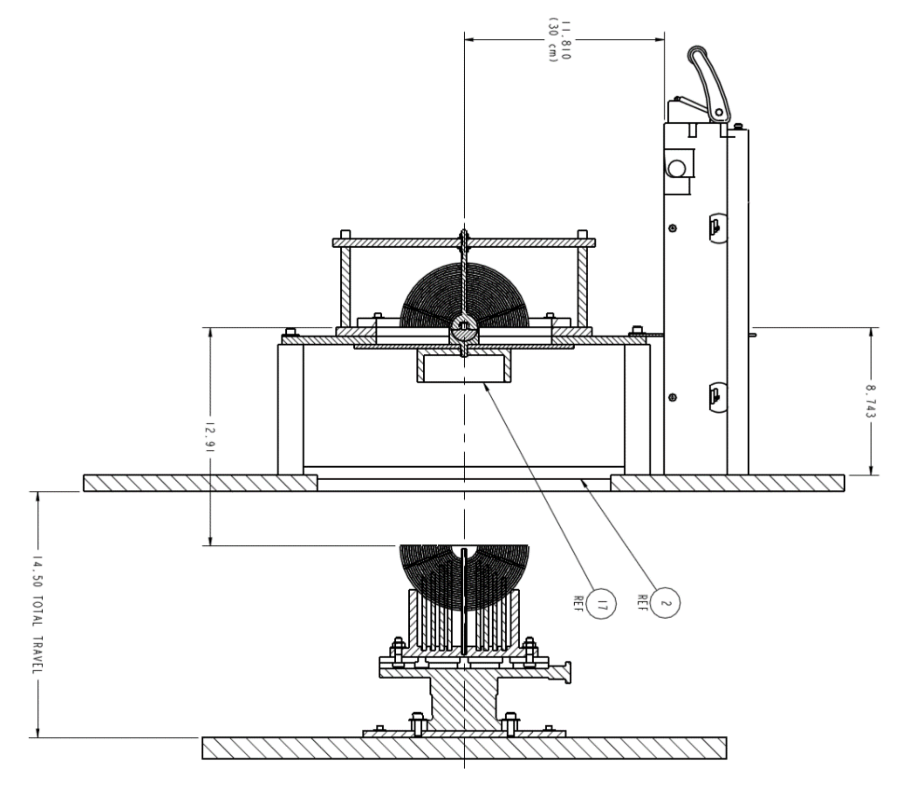




Experimental Configurations

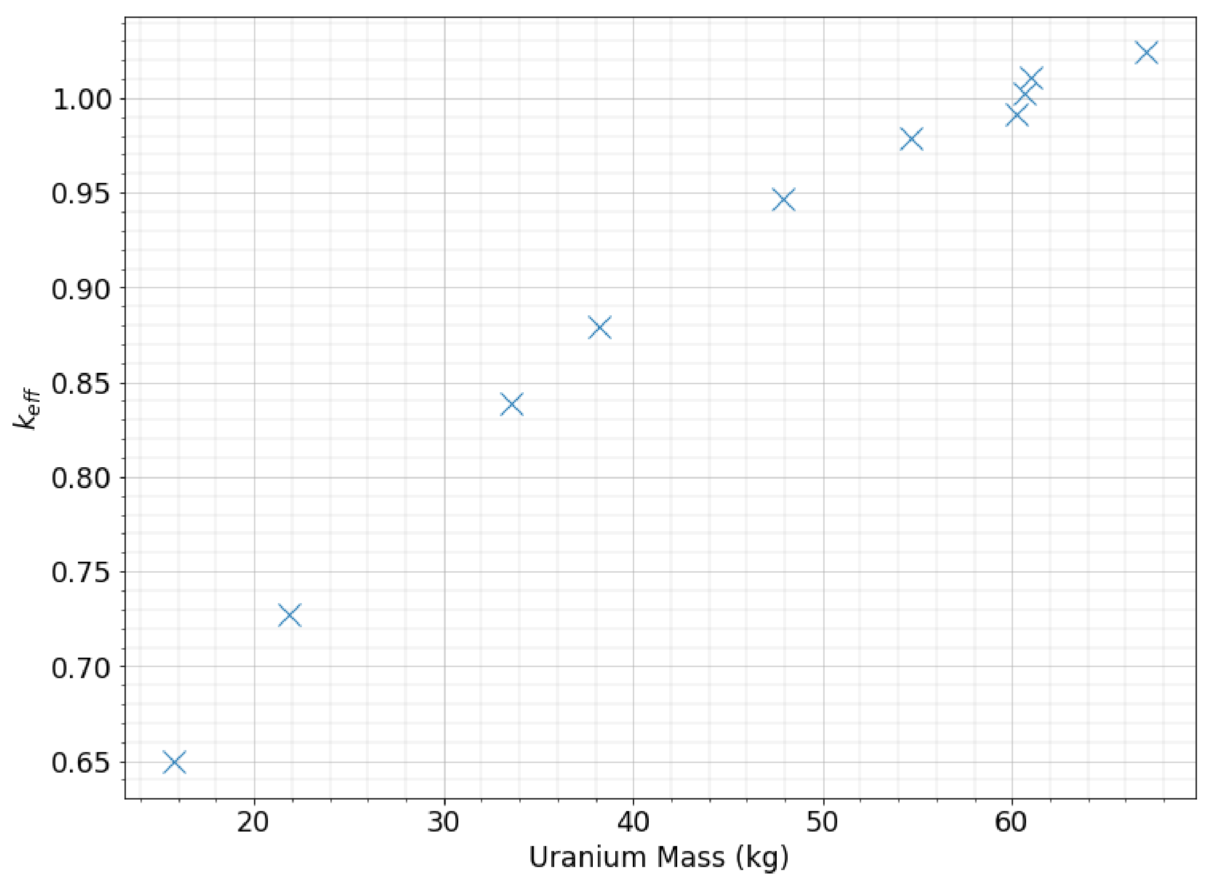
- Ten primary configurations assembled on the Planet vertical lift machine
  - Various numbers of the Rocky Flats shells with some inner shells replaced by aluminum
  - Additional configurations may be constructed during experiment, but will not be the focus

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



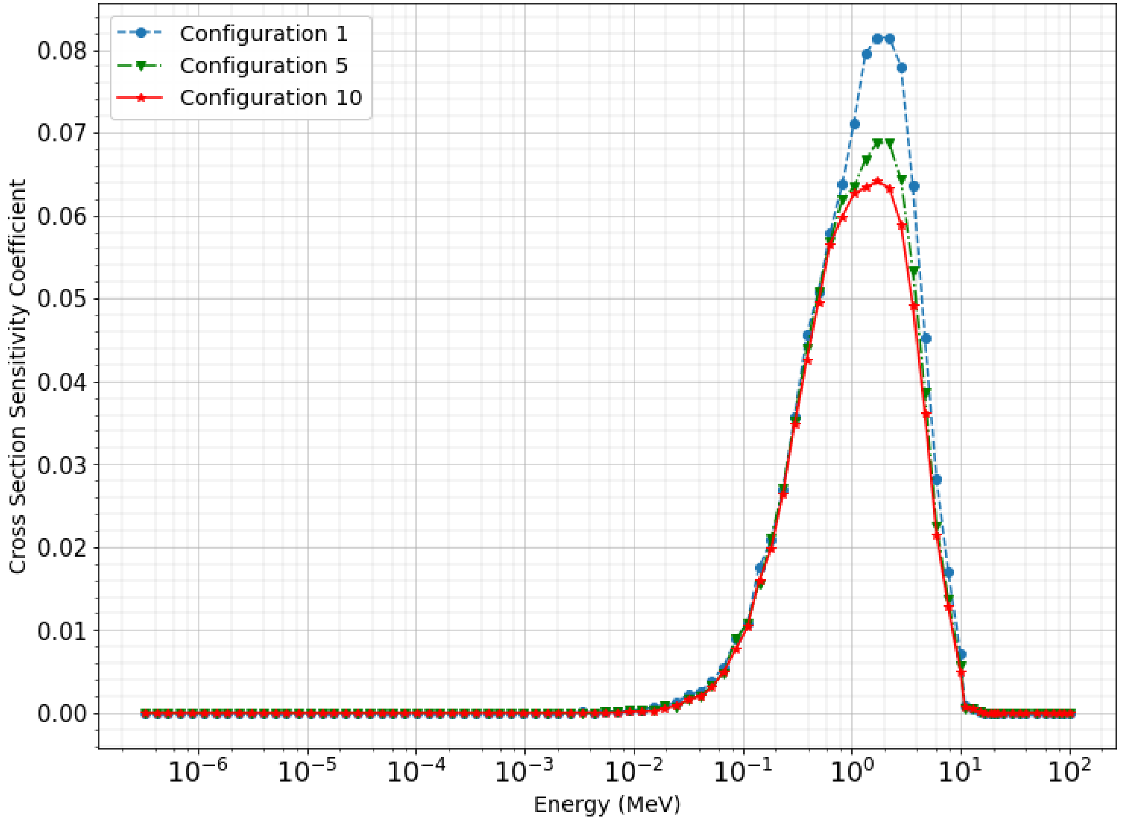
Simulation Results - k_{eff}

- 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

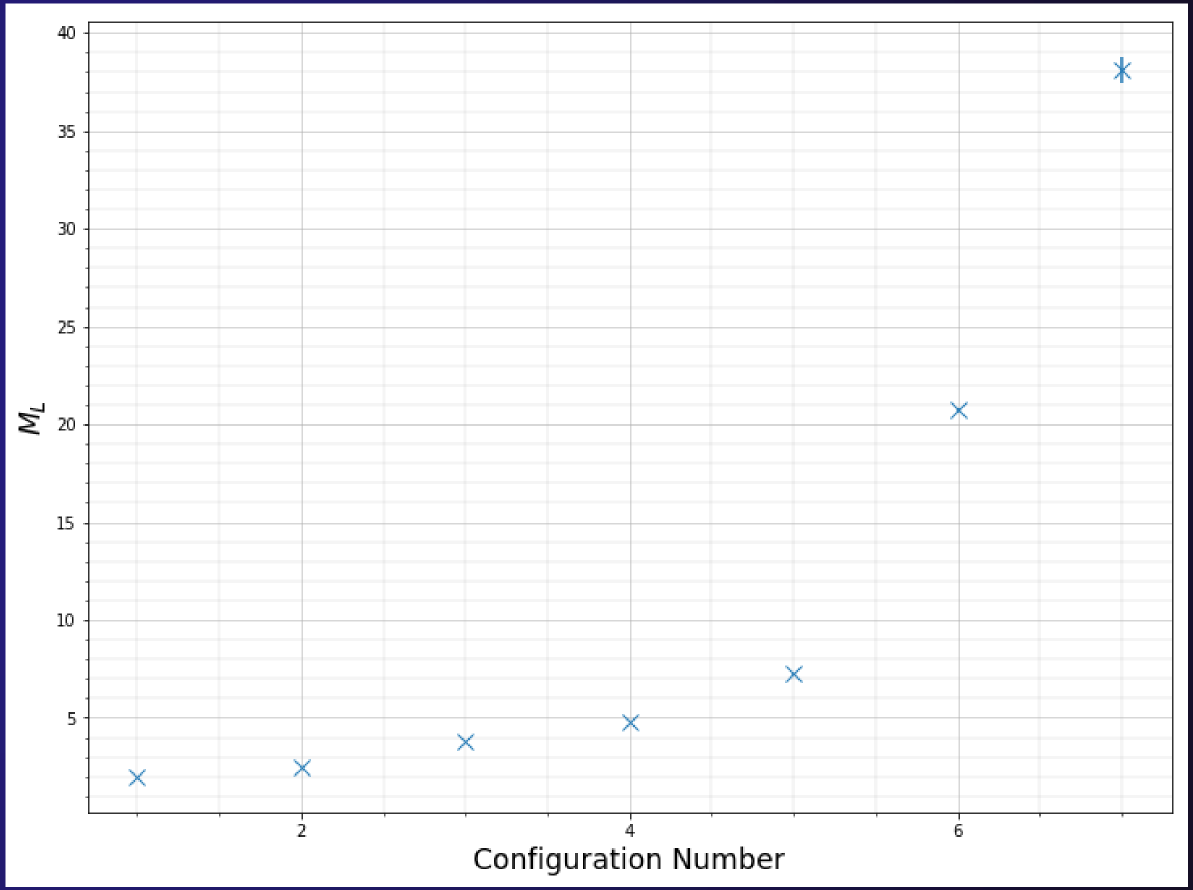
- Can convert k_{eff} to leakage multiplication M_L (average number of neutrons that leave the system per starter neutron) through

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

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

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

- 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

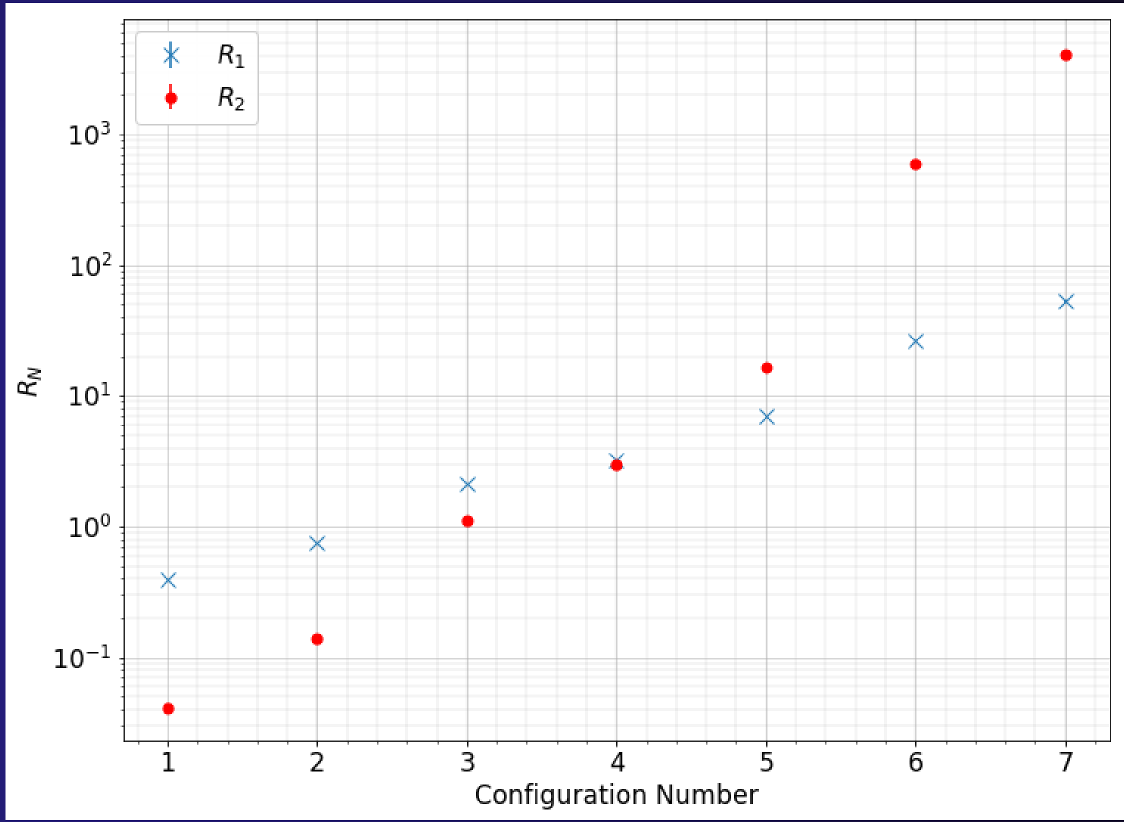
- M_L can be further converted to the count rates R_1 (the rate of neutron detection, or singles rate) and R_2 (the rate at which two neutrons from the same fission chain are detected)

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

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

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

- ε – detector efficiency
- F_S - spontaneous fission rate
- $\overline{\nu_{In}}$ – nth reduced factorial moment of the induced fission neutron multiplicity distribution
- $\overline{\nu_{Sn}}$ – nth 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 ± 2.4413g	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.

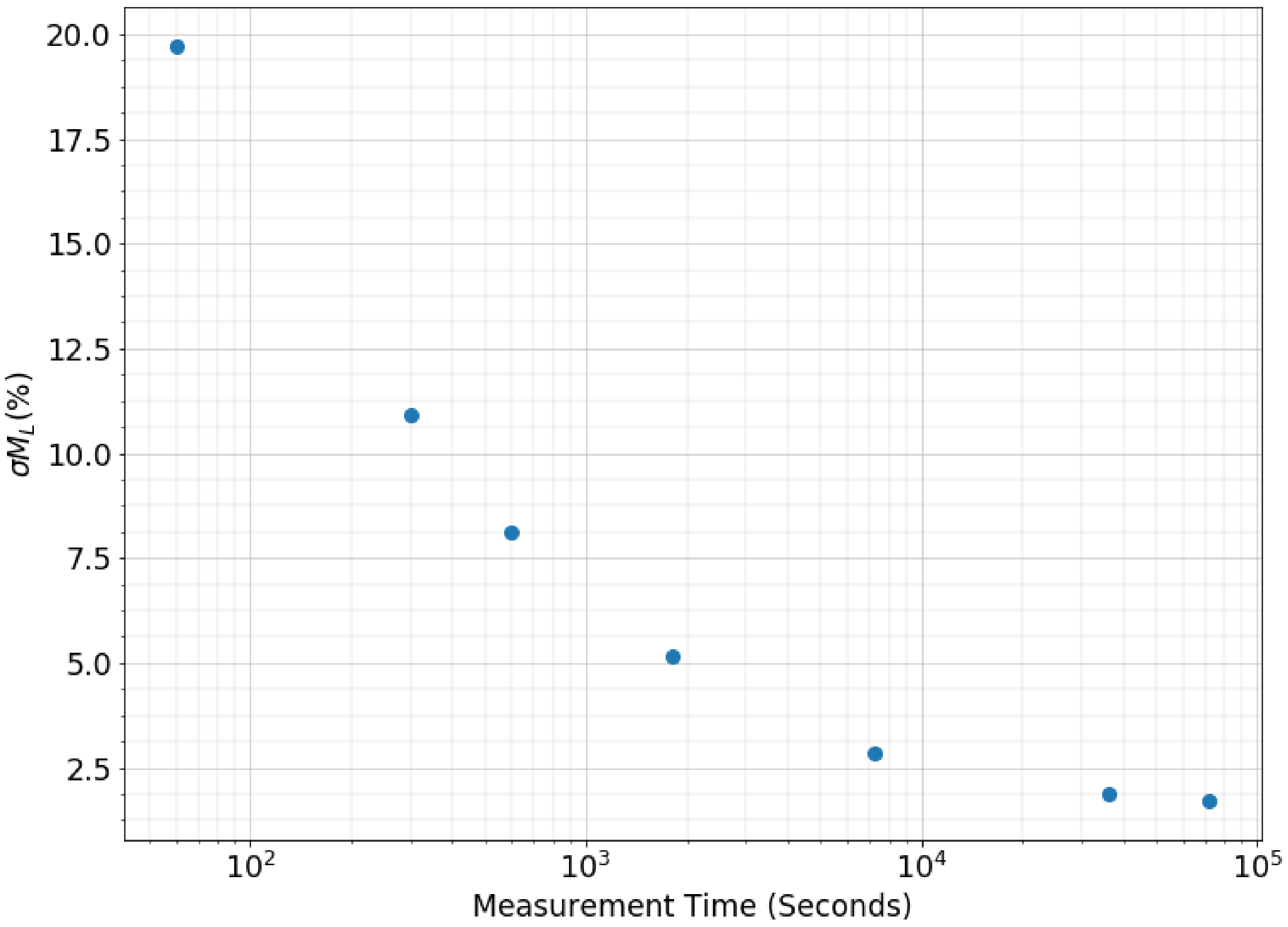
- Can see from these tables that only some parameters are significant to some of the configurations
  - The radius of the uranium shells is significant for all configurations
  - Indicates that either the uncertainty needs to be better assessed, or that the sensitivity treatment needs to be reviewed
- 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 ± 2.4413g	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

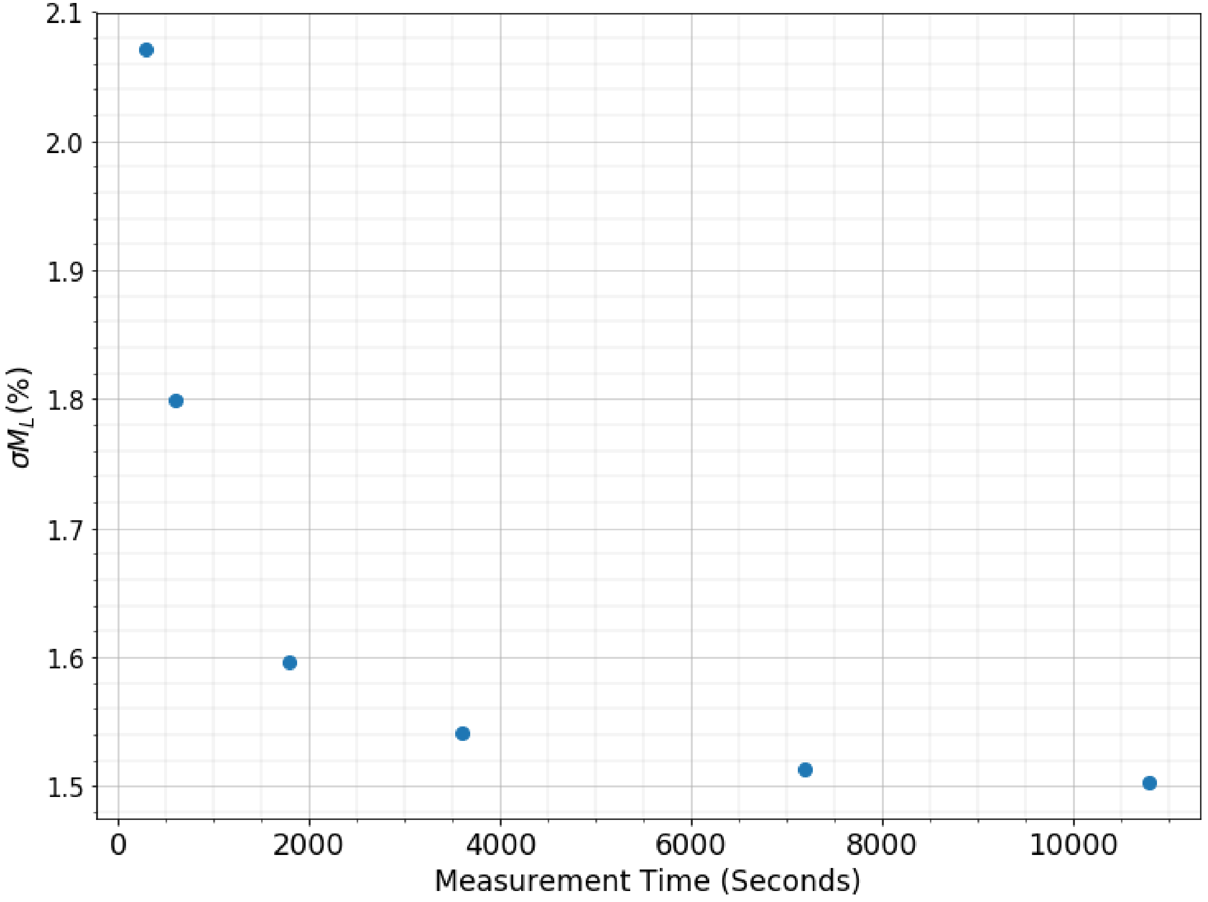
Configuration 5 – No Source



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!

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

NCERC

NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER