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Neptunium Subcritical Observation (NeSO) Experiment Design

Nuclear Criticality Safety Program Technical Program Review

Alex McSpaden, Theresa Cutler, Jesson Hutchinson, Rian Bahran

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Outline

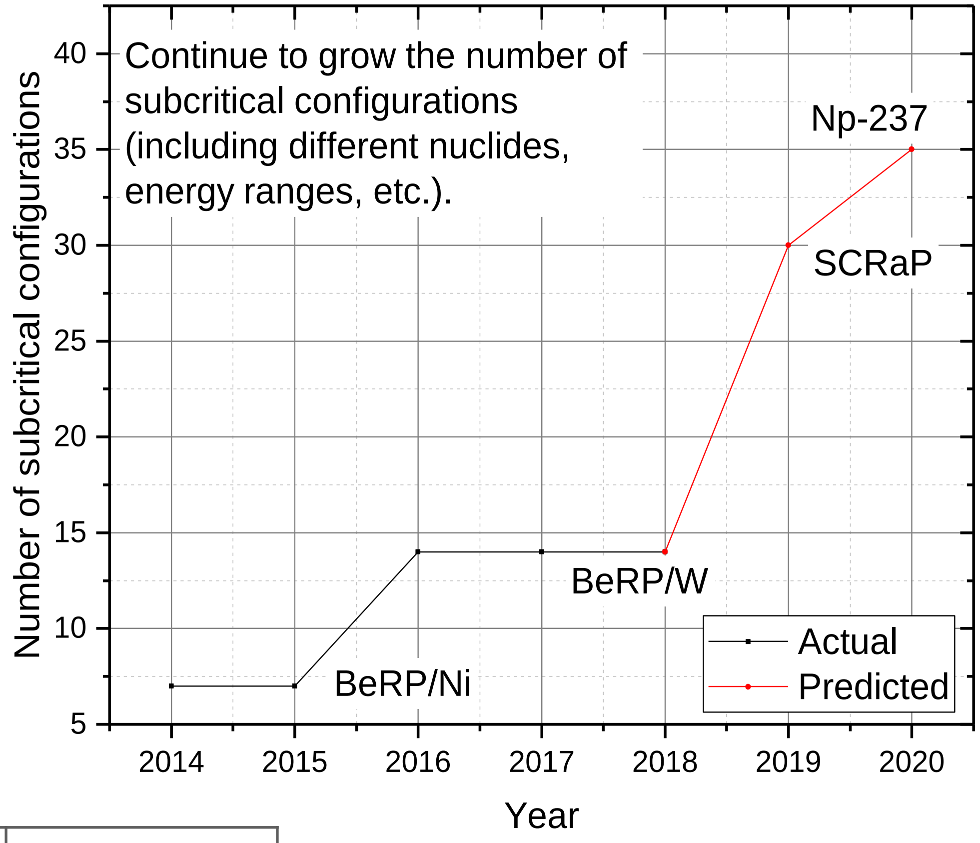
- **What is NeSO?**
- **Motivation**
- **The Sphere and Reflectors**
  - Material and configurations
- **Detectors and Analysis Method**
- **Monte Carlo Simulations**
  - Multiplication, Count Rates, Sensitivities, Uncertainties
- **Preliminary Measurements**
- **Composition Troubles**
- **Current and Future Work**

Overview of NeSO

- **Subcritical experiment with a 6kg sphere of Neptunium ("Np sphere")**
- **Includes configurations with both the bare sphere and varying amounts of nickel reflection**
  - Nickel increases multiplication of system, leading to configurations spanning a variety of multiplication levels
- **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

- **Np sphere exists to better understand ^{237}Np critical mass**
  - Subject of previous critical benchmarks
  - Difference in critical masses between data libraries
- **^{237}Np is a byproduct of power reactors**
  - (n,γ) reactions of ^{235}U or (n,2n) reactions involving ^{238}U
  - ^{241}Am α-decay
- **Help validate ^{237}Np nuclear data, and subcritical measurement methods**
  - Create a benchmark much more sensitive to ^{237}Np cross sections than any already in existence
- **Add to steadily growing group of NCERC subcritical benchmark measurements**



Library	ENDF/B-VIII.0	ENDF/B-VII.1	JENDL-4.0	JEFF-3.1
Critical Mass (kg)	58.59	58.7	58.7	63.8

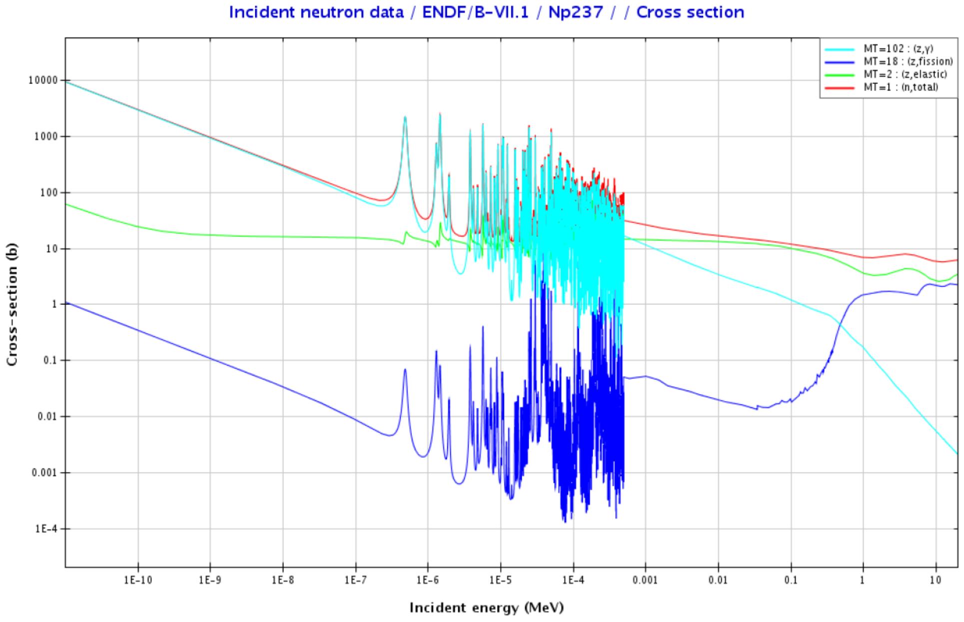
The Neptunium Sphere

- **Cast in 2001**
- **Total mass: 6070.4 grams**
  - ^{237}Np: 6060 grams
- **Radius: 4.149 centimeters**
- **Includes Tungsten and Nickel cladding**
  - Meant to decrease dose from ^{233}Pa γ-rays
  - Tungsten is 0.259 cm thick
  - Two layers of nickel, total 0.381 cm thick
- **Composition shown in table on right, from analysis of the surface**
  - Taken from previous critical benchmark
    - SPEC-MET-FAST-008, Np sphere surrounded by HEU
  - May not be representative of other parts of the sphere
  - Low emission rate
    - Spontaneous fission yield from PANDA Manual

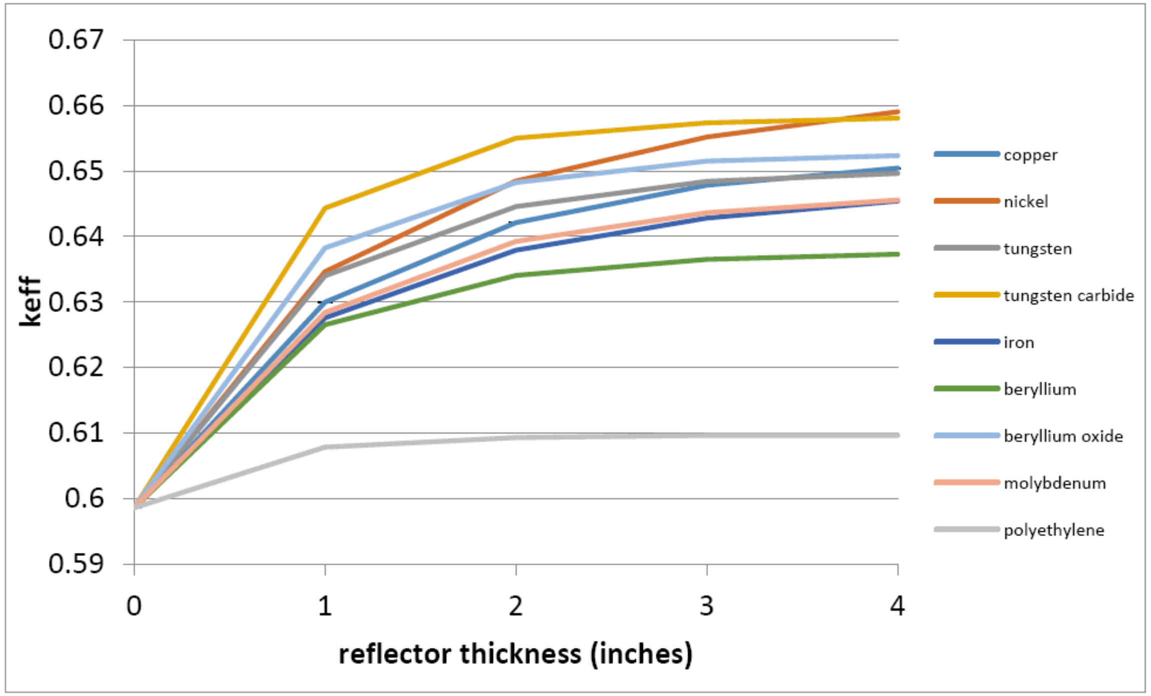
Nuclide	Mass (g)	S.F. yield (neutrons/s)
^{237}Np	6.06×10^{3}	6.90×10^{-1}
^{233}U	2.17×10^{-1}	1.87×10^{-4}
^{234}U	3.48×10^{-2}	1.75×10^{-4}
^{235}U	1.66	4.96×10^{-4}
^{236}U	9.28×10^{-3}	5.09×10^{-5}
^{238}U	1.87×10^{-1}	2.54×10^{-3}
^{238}Pu	9.83×10^{-2}	2.55×10^{2}
^{239}Pu	1.95	4.25×10^{-2}
^{240}Pu	1.40×10^{-1}	1.43×10^{2}
^{241}Pu	3.77×10^{-3}	1.88×10^{-4}
^{242}Pu	1.95×10^{-2}	3.35×10^{1}
^{241}Am	4.04×10^{-4}	4.76×10^{-4}
^{243}Am	1.12×10^{1}	-
Total	6.07×10^{3}	4.32×10^{2}

The Reflectors

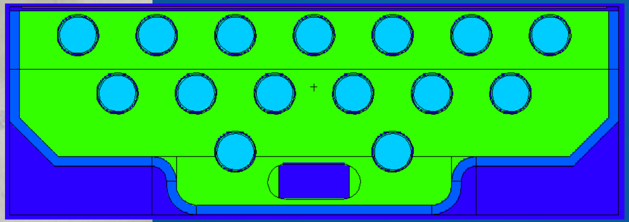
- ^{237}**Np is a threshold fissioner**
  - Reflecting materials such as polyethylene or graphite wouldn't increase multiplication as much
- **Simulations investigated a series of material choices**
  - Iron, tungsten, nickel, copper, beryllium, etc.
- **Nickel chosen due to larger range of multiplication factor values, and consistency with cladding**
  - Previous benchmark experience with Nickel 200, a high purity alloy



Graphic from JANIS



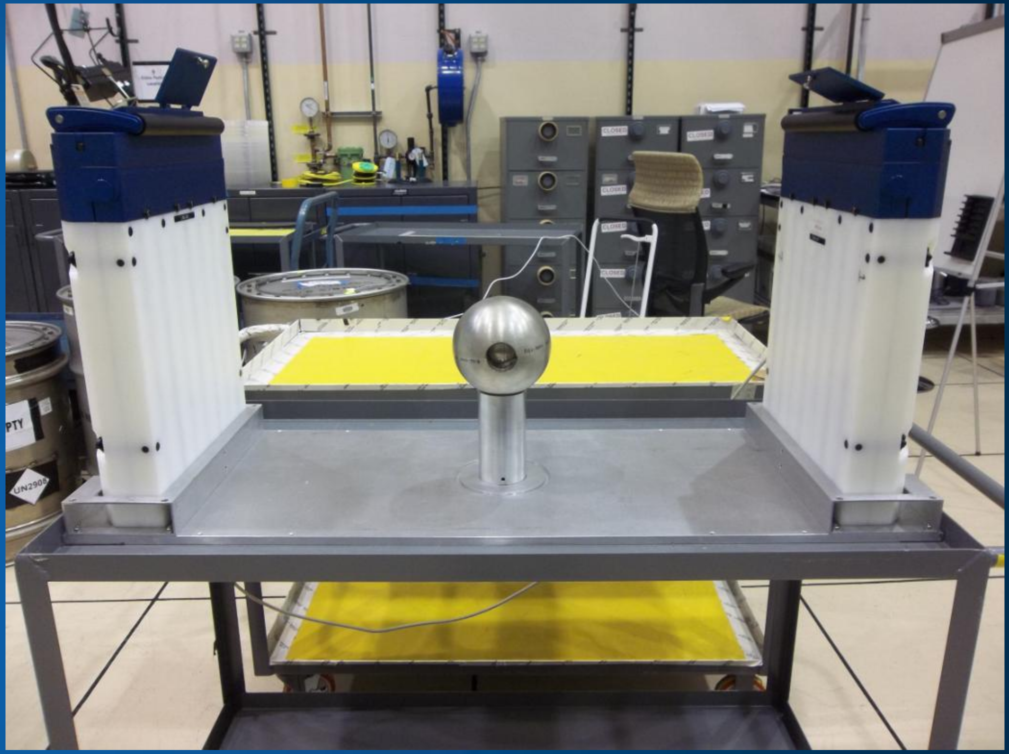
Detectors & Analysis Method



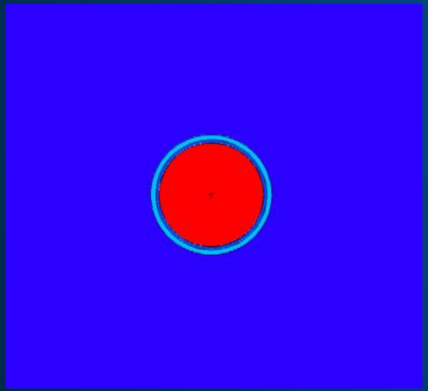
- **Neutron Multiplicity Array Detector (NoMAD)**
  - 15 ^{3}He tubes surrounded by polyethylene
  - Creates list-mode data
  - Two will be placed at 30 cm from the center of the sphere
- **Data will be analyzed with Hage-Cifarelli formalism of Feynman Variance-to-Mean technique**
  - Same as previous NCERC subcritical measurements
  - Allows to solve for leakage multiplication (M_L) from singles and doubles rates (R_1 and R_2)
    - M_L – number of neutrons that leave the system per starter neutron
    - R_1 – rate at which counts are recorded in the detector
    - R_2 – rate at which two neutrons from same fission chain are recorded in the detector

Final Configurations

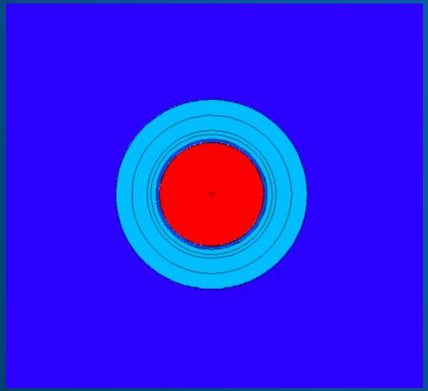
- **Bare (no added nickel), 0.6”, 1.1”, 2.1”, 3.6” Nickel**
  - A range of distinct M_L values
  - Smaller range than previous benchmarks, but still distinguishable
- **Nickel reflection from nesting spherical shells**
  - Similar in style to previous subcritical benchmarks



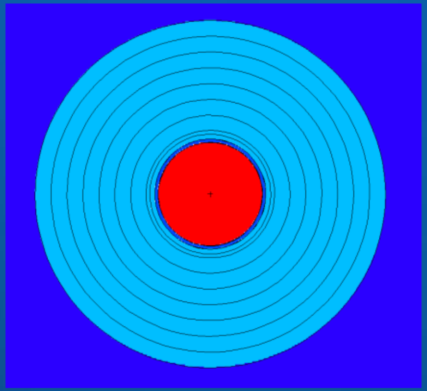
Bare – M_L 1.94



1.1” Ni – M_L 2.10



3.6” Ni – M_L 2.21



Statistical uncertainties $\leq$ 0.0005

Monte Carlo Simulations

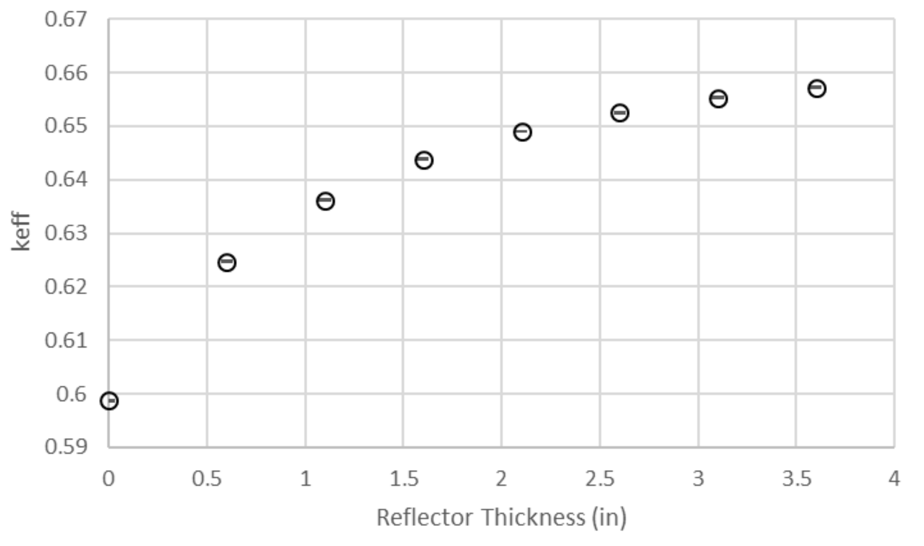
- **MCNP® version 6.2 KCODE criticality source computations, with ENDF/B-VII.1 cross sections**
  - Used to determine the effective multiplication factor k_{eff} for each experimental configuration
  - 5,000 active cycles, 10,000 neutrons per cycle
- **Can estimate total multiplication and leakage multiplication from k_{eff}**

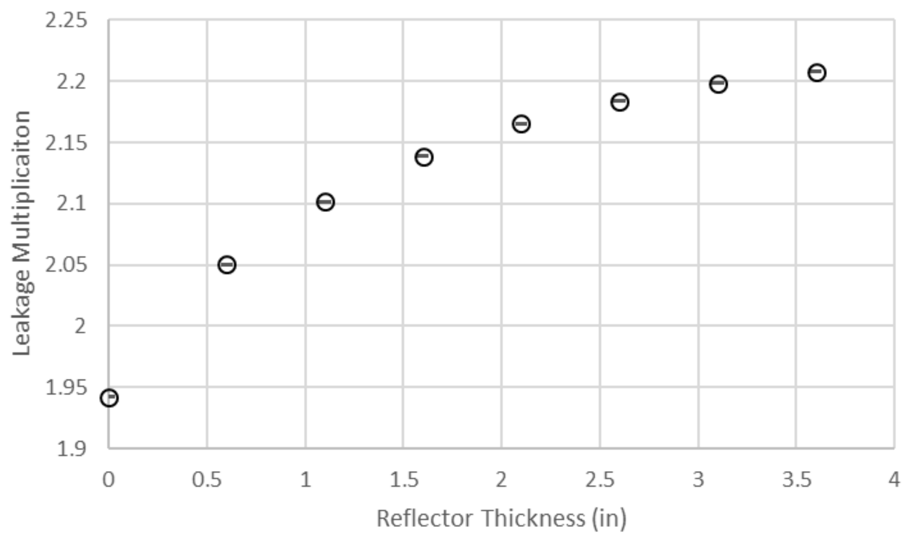
$$k_{eff} = \frac{k_p}{1-\beta_{eff}} \qquad M_T = \frac{1}{1-k_p}$$

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

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

- **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**





Estimation of Count Rates

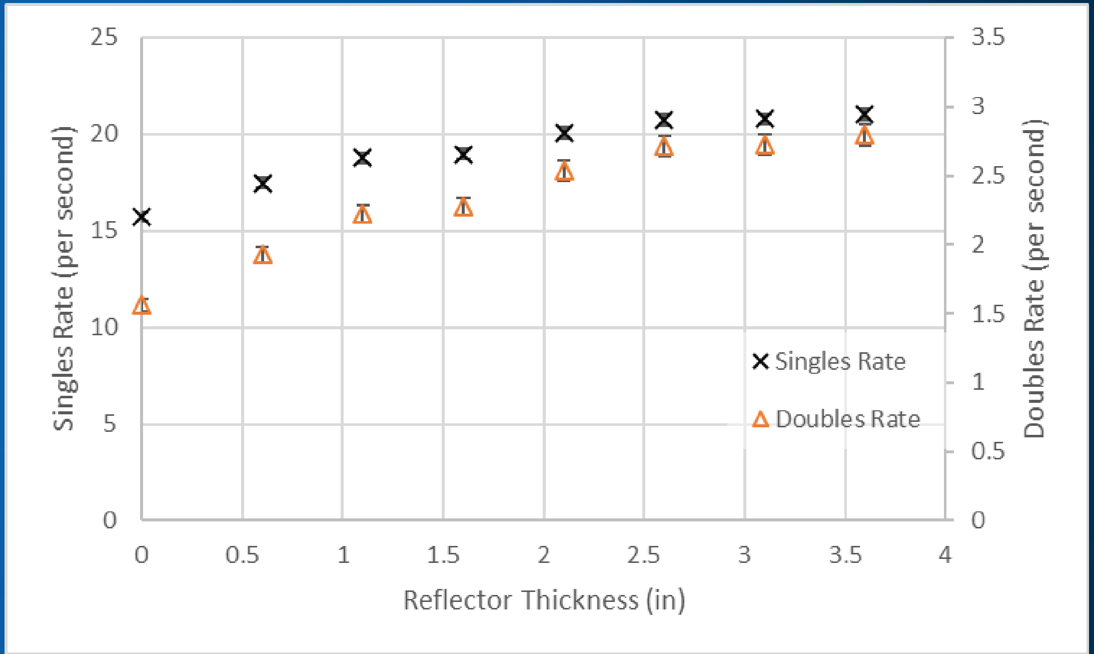
- **Can further estimate singles and doubles rates from leakage multiplication**

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

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

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

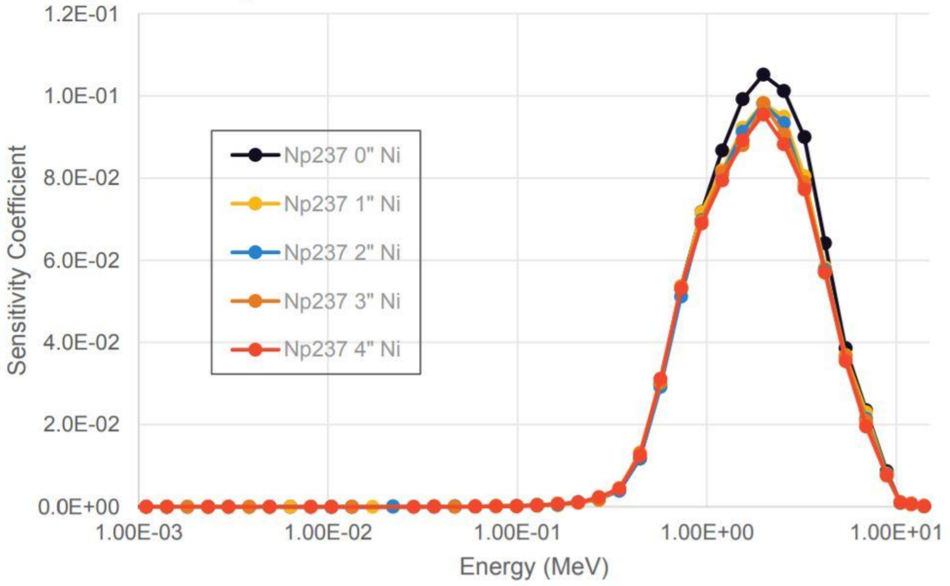
- ε – **detector efficiency**
- F_S **- spontaneous fission rate**
- $\overline{\nu_{In}}$ – n**th reduced factorial moment of the induced fission neutron multiplicity distribution**
- $\overline{\nu_{Sn}}$ – n**th reduced factorial moment of the spontaneous fission neutron multiplicity distribution**



Cross Section Sensitivities

- Integral and continuous energy cross section sensitivity coefficients were also calculated for various thicknesses of nickel
- Much more sensitive to ^{237}Np than previous benchmarks
- Fast system, fast sensitivities
- Sensitivity coefficients to Plutonium isotopes are very small (<4.8E-4)

Nickel Thickness	^{237}Np Total XS Sensitivity
0.0	7.94E-01 ± 1.91E-3
1.0	7.52E-01 ± 2.03E-3
2.0	7.37E-01 ± 2.06E-3
3.0	7.37E-01 ± 2.14E-3
4.0	7.26E-01 ± 2.11E-3



Sensitivity Analysis and Uncertainty Quantification

- **Perturb certain parameters by multiple times their uncertainty in each direction, treat difference in results as a derivative**
  - This is the sensitivity
- **To obtain uncertainty due to a parameter, multiply this derivative by the uncertainty in the parameter**
- **From table below, can see that count rates are very sensitive to plutonium content**
  - Leakage multiplication is less sensitive

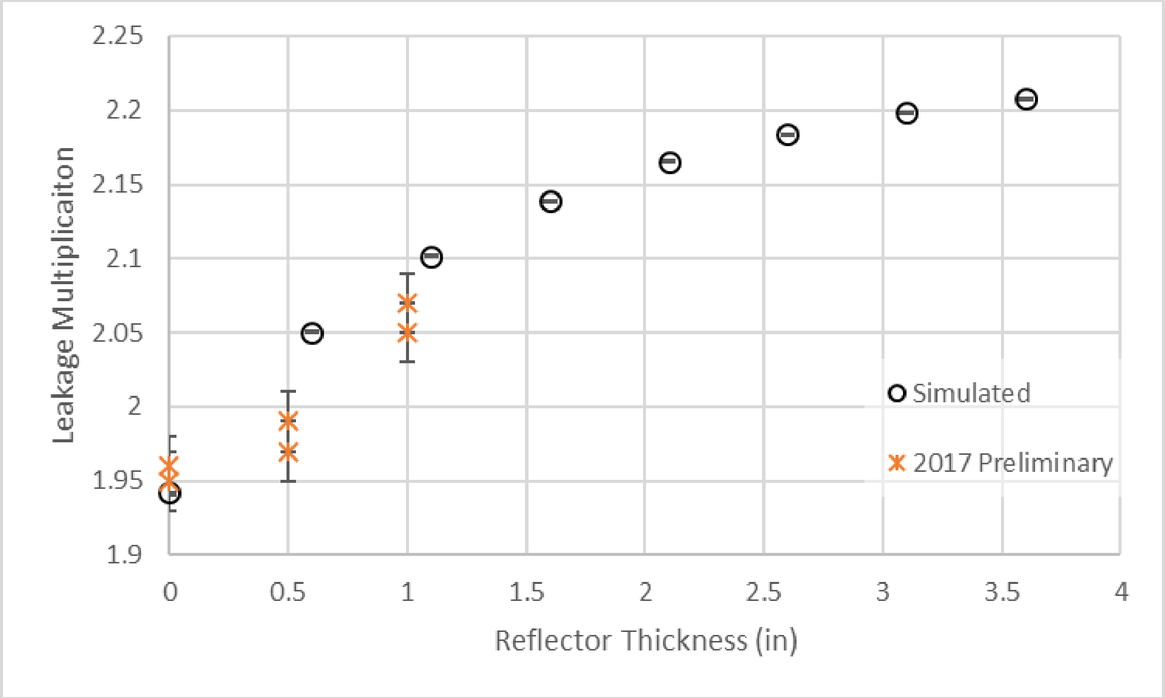
$$S_{k,x} = \frac{k_P - k_R}{P_x}$$

$$\delta k_x = u_x S_{k,x}$$

- **$S_{k,x}$ - sensitivity of benchmark parameter k to experimental parameter perturbation x**
- **P – Perturbation**
- **R – Reference**
- **δk_x - Uncertainty in k due to uncertainty in x**
- **u_x - uncertainty in x**

	M_L Sensitivity	**M_L Uncertainty**	**R_1 Sensitivity**	**R_1 Uncertainty**	**R_2 Sensitivity**	**R_2 Uncertainty**
Np Radius $\pm$ 2.74 mils	-0.6462	0.004497	0	0	0	0
Ni Cladding Thickness $\pm$ 2 mils	0.1029	0.001046	0	0	0	0
Ni Mass $\pm$ 0.5%	0.0008057	0.0008057	0	0	0	0
Pu Content +61g/–2g	0.0002269	0.014298	7.141	449.9	0.7139	44.97

Preliminary Measurements

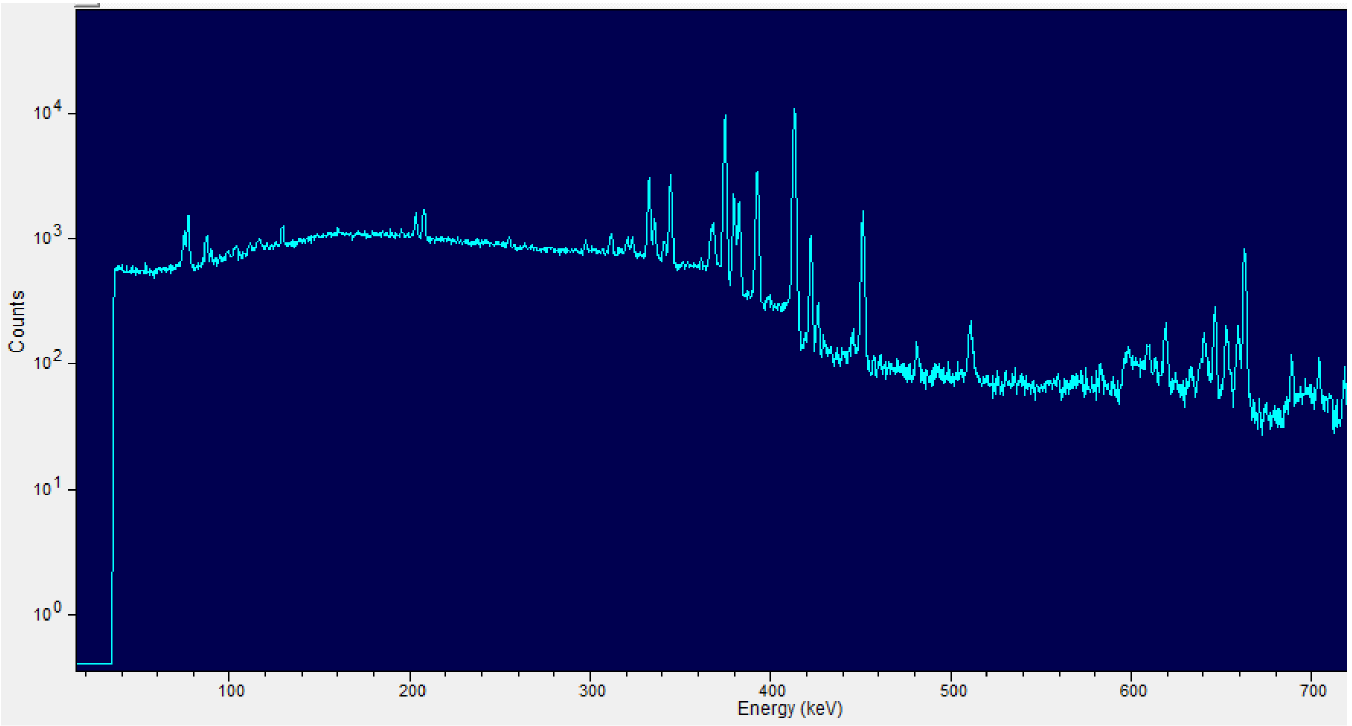


Case	R_1	R_2	M_L
Bare	174.95 ± 0.36	17.753 ± 0.351	1.95 ± 0.02

- **Performed in Feb 2017 with 2 NoMAD systems at 47cm from center of sphere**
  - 30 minute measurements, much shorter than benchmark
- **Measured M_L matches with simulated data for non-reflected case**
  - Reflected shows right shape, but not exactly representative of benchmark shells
    - Current shells not made to fit Np sphere, some gaps present
    - Leftover from BeRP-Ni benchmark
- **Count rates do not agree**
  - Over an order of magnitude higher

Composition Uncertainty

- **2002 LANL report estimated 63 grams of Pu based on emission rate**
  - SPEC-MET-FAST-008 has 2 grams
- **2002 Estimated emission rate: 12,000 n/s**
  - 2017: 8,700 n/s
  - 2018: 8,400 n/s
  - Simulation Model: 400 n/s
- **Unsure if extra neutrons are from plutonium, curium, or something else entirely**
- **Gamma spectroscopy difficult due to shielding**
  - Lower energy peaks are suppressed



Current and Future work

- **Continue investigation of neutron emission rate issue**
  - Could further analysis be performed on the sprue material?
  - Continue to analyze gamma spectroscopy data
- **Determine the effect of ENDF/B-VIII.0 vs ENDF/B-VII.1**
  - Updated nickel reaction cross sections
- **Purchase Nickel reflector shells**
- **Execute the experiment**
  - Expected this year

Thank you!

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