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An Evaluation of Monte Carlo Simulations of Neutron Multiplicity Measurements of Plutonium Metal

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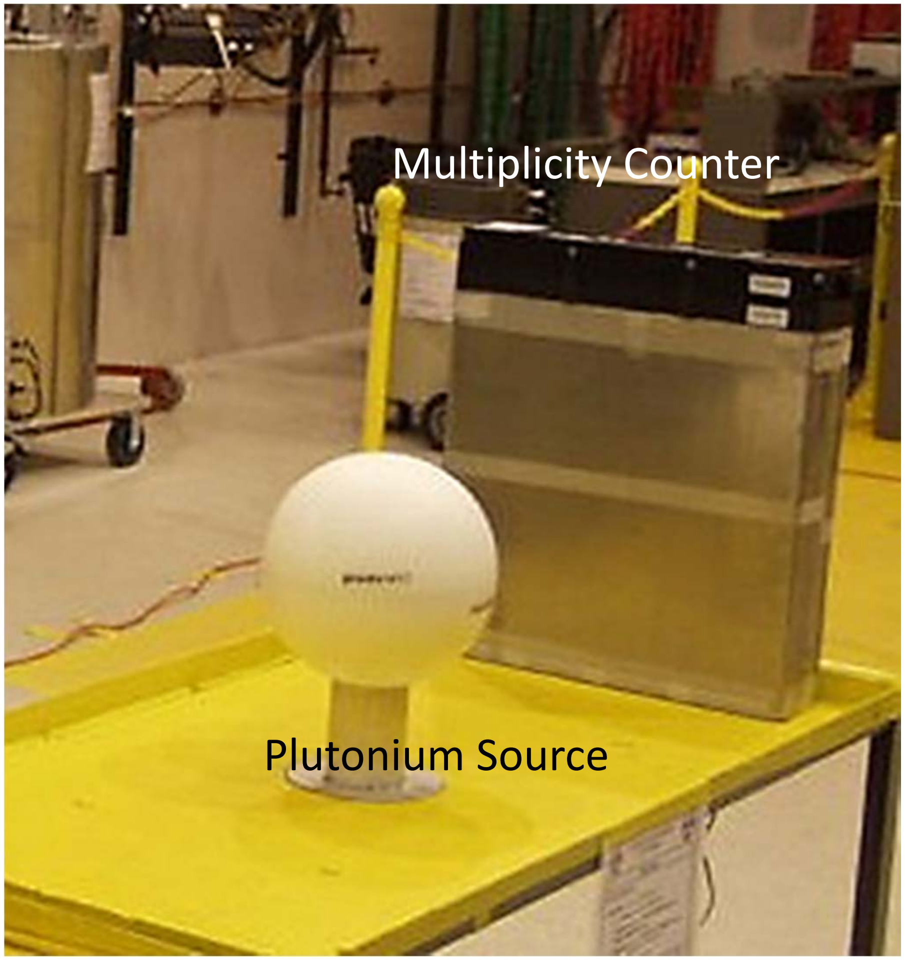
Introduction

- In January 2009, Sandia National Laboratories conducted neutron multiplicity measurements of a polyethylene-reflected plutonium metal sphere
- Over the past 3 years, those experiments have been collaboratively analyzed using Monte Carlo simulations conducted by
  - University of Michigan (UM)
  - Los Alamos National Laboratory (LANL)
  - Sandia National Laboratories (SNL)
  - North Carolina State University (NCSU)
- Monte Carlo simulations of the experiments consistently over-predict the mean and variance of the measured neutron multiplicity distribution
- This paper presents a sensitivity study conducted to evaluate the potential sources of the observed errors

Experiments

- The measurements were conducted at the Nevada National Security Site (NNSS) Device Assembly Facility (DAF)
- The source was a plutonium metal sphere surrounded by polyethylene spherical shells with varying thickness
- The detector was a portable neutron multiplicity counter

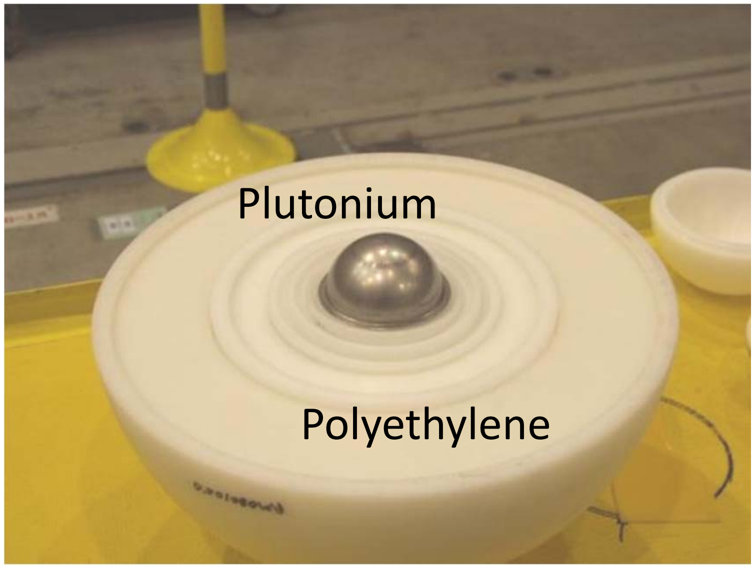


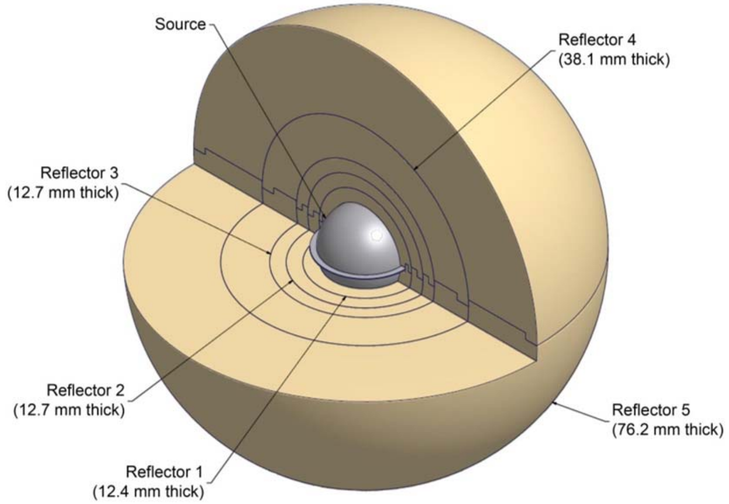
Plutonium source

- The source was the "BeRP ball" (Brandon 1980)
  - 4484 g plutonium (99.5% pure)
  - 19.6 g/cm^3 plutonium metal (α-phase)
  - 93.3% Pu-239 / 5.9% Pu-240
  - 0.3 mm steel cladding

- The source was reflected by nesting polyethylene shells
  - 0.95 – 0.96 g/cm^3
  - Thicknesses (mm): 12.4, 25.1, 37.8, 75.9, 152.1

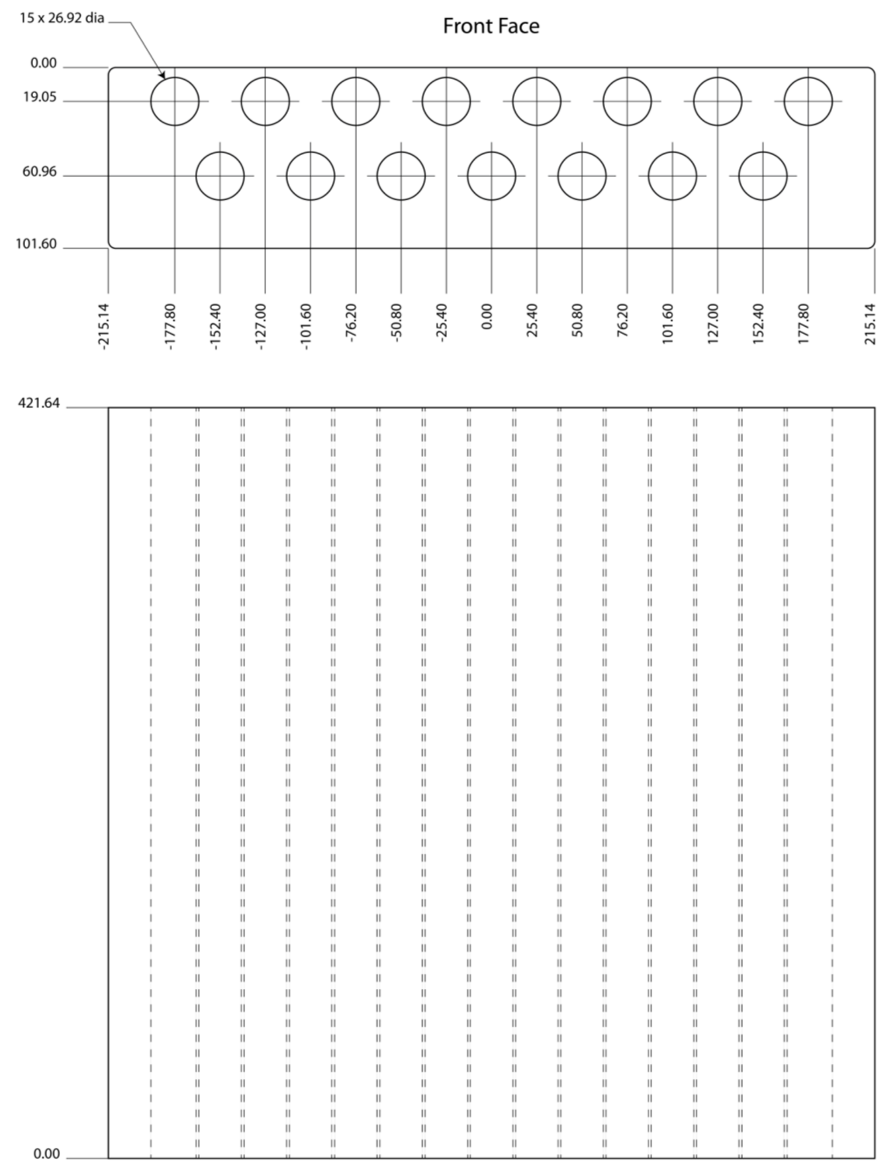
- Neutron multiplication $M = 1/(1-k)$ranged between 4.5 and 16.7





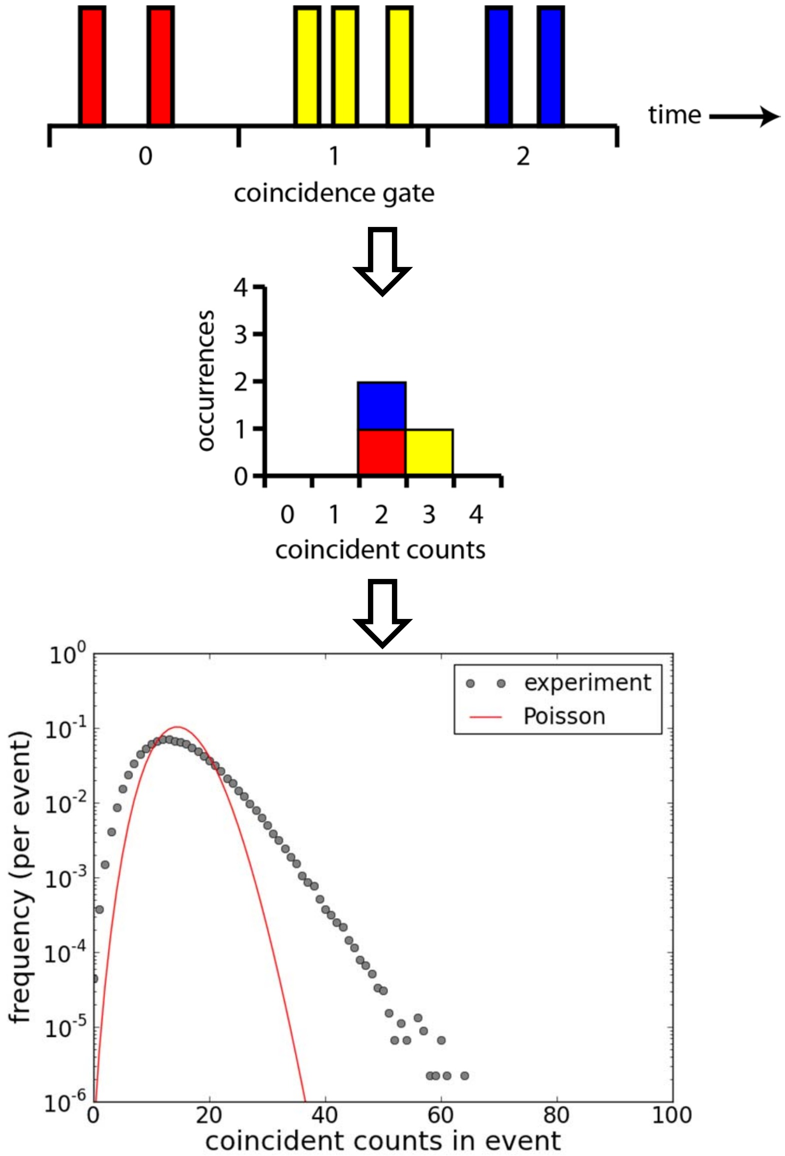
Multiplicity counter

- The detector was an “nPod” portable multiplicity counter developed by LANL
- 15 He-3 proportional counters
  - 10 atm He-3 pressure
  - 25.4 mm diameter
  - 381 mm sensitive length
  - Aluminum housing
- Polyethylene moderator
  - Nominally 0.95 g/cm^3
  - 430 mm wide × 422 mm tall × 102 mm deep
  - Wrapped in cadmium 0.8 mm thick
- The detector was located 500 mm from the source



Data acquisition

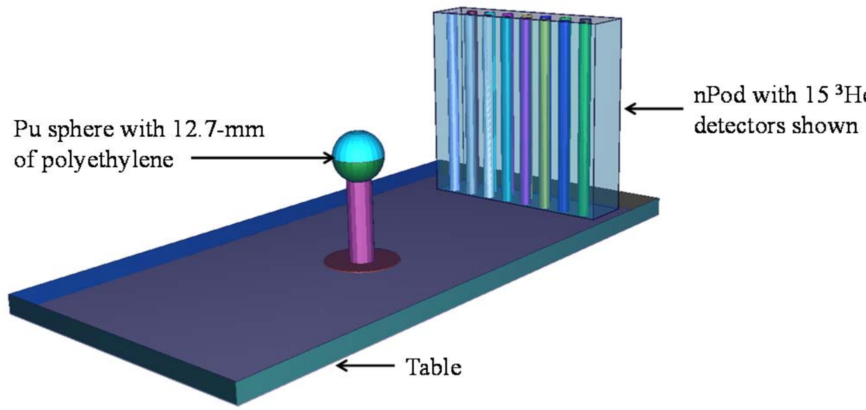
- The nPod records detection events in list-mode
  - Each list-mode "event" records the channels registering counts
  - Events are time-stamped with 1 μs resolution
- The multiplicity distribution was accumulated from the list-mode event stream
  - The event stream was segmented into a series of non-overlapping coincidence gates
  - Gate width is variable; in this paper a 4096 μs gate width was used
  - The frequency of events vs. the number of coincident counts in the event was accumulated



Simulations

- The experiments were simulated using two Monte Carlo codes
  - MCNPX-PoliMi (a patch to MCNPX2.7.0) developed by the Polytechnic of Milan and UM
  - A multiplicity patch to MCNP5 (developed by LANL)
  - Both codes implement extensive modifications to simulate the variable multiplicity of neutrons from spontaneous and induced fission
  - Both codes record detection events in list-mode
- All models contain the plutonium source, multiplicity counter, the iron table, and the floor

MCNPX-PoliMi Model



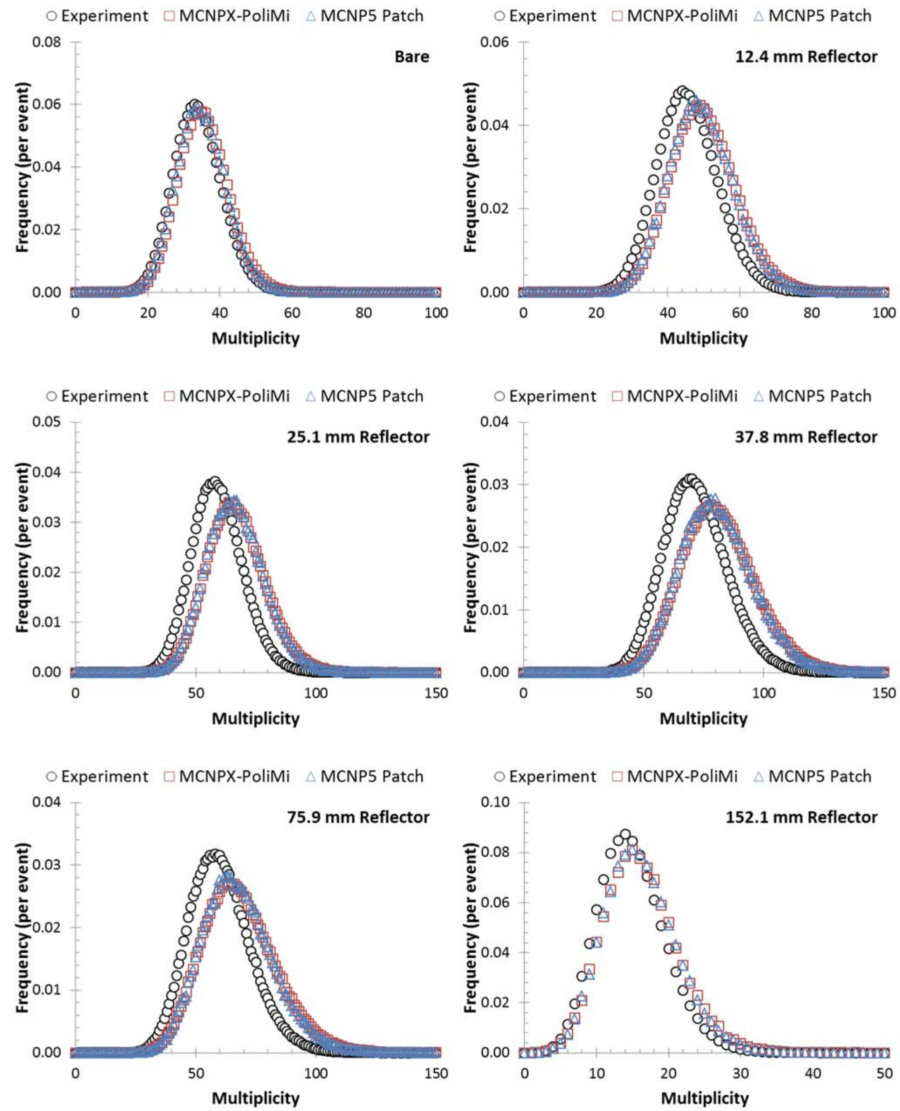
(floor not shown)

Initial results

- Simulations of the experiments significantly over-predict the measured multiplicity distribution
  - Mean (centroid)
  - Variance (width)

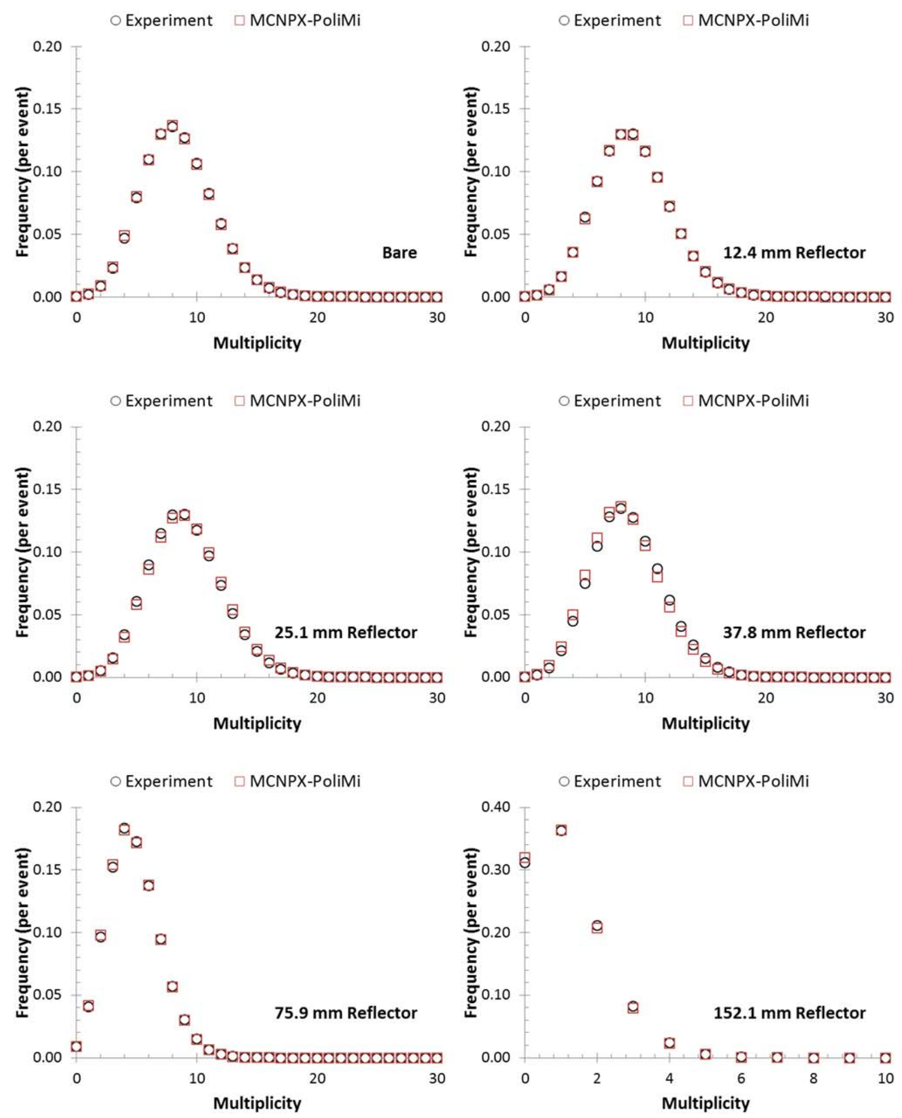
- The errors tend to grow with increasing neutron multiplication

- Nearly identical results were obtained by MCNPX-PoliMi and the MCNP5 patch
  - Consequently, it's unlikely that the logic to simulate neutron transport is incorrect in either code
  - It's more likely that one or more of the model parameters is incorrect



Cf-252 source measurements and simulations

- Measurements were also performed with a Cf-252 point source at the center of each reflector assembly
- MCNPX-PoliMi simulations match the Cf-252 experiments very closely
- Consequently, it is unlikely there are significant errors in the geometry or material models of the reflectors and multiplicity counter
- Instead, it's more likely that one or more parameters of the plutonium source model are incorrect



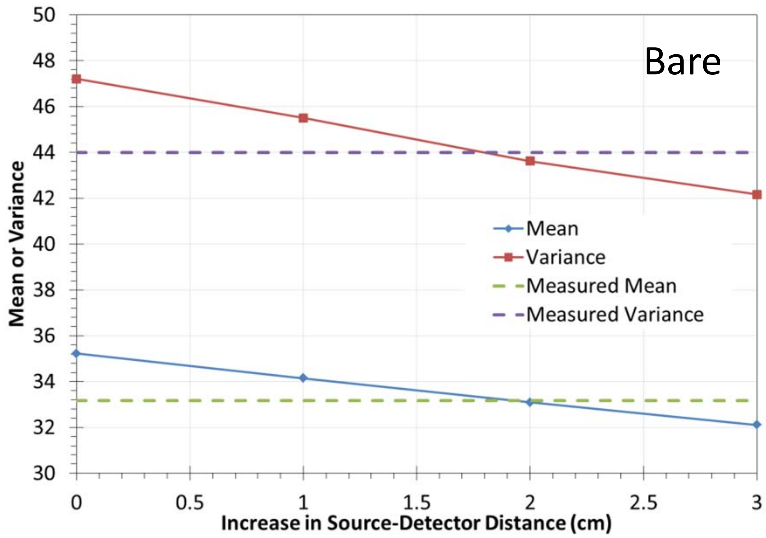
Analysis

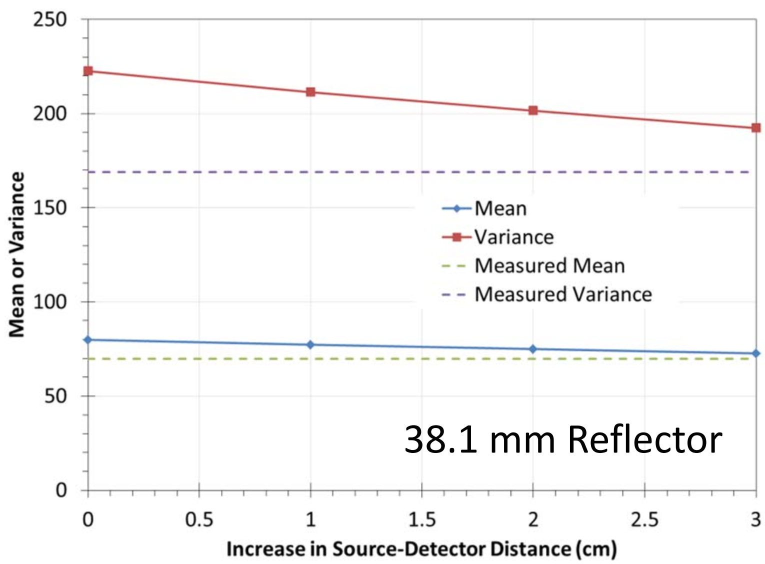
- A sensitivity study was conducted to attempt to isolate the potential cause(s) of the errors in the simulations

- MCNPX-PoliMi simulations were performed to evaluate the effect of varying:
  - Source-detector distance
  - Detector dead-time
  - Plutonium cross sections
  - Plutonium composition
  - Plutonium density
  - Pu-239 induced fission neutron multiplicity ($\bar{\nu}$)

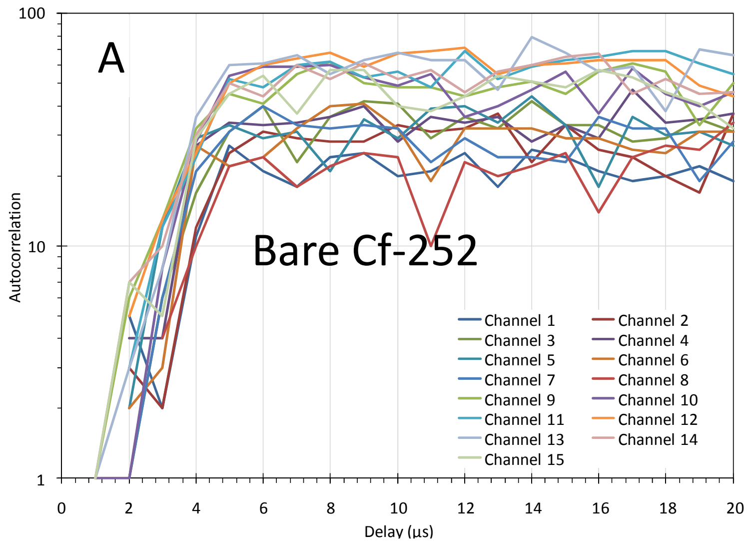
Sensitivity to source-detector distance

- The uncertainty in the source-detector distance (nominally 500 mm) was approximately ±5 mm
- The modeled source-detector distance was increased by up to 3 cm
  - No single reduction of the distance consistently corrected all the simulations
  - In several cases, the distance had to be increased by more than 3 cm to correct the simulation
- Incorrect source-detector distance did not cause the observed simulation errors

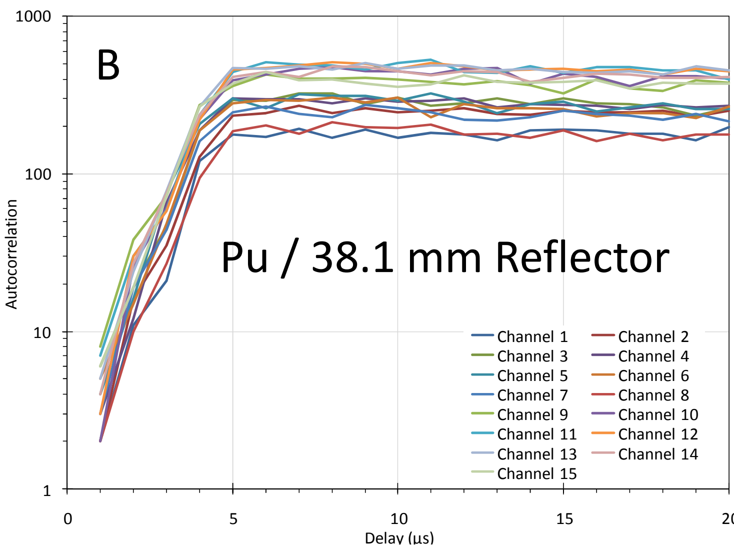


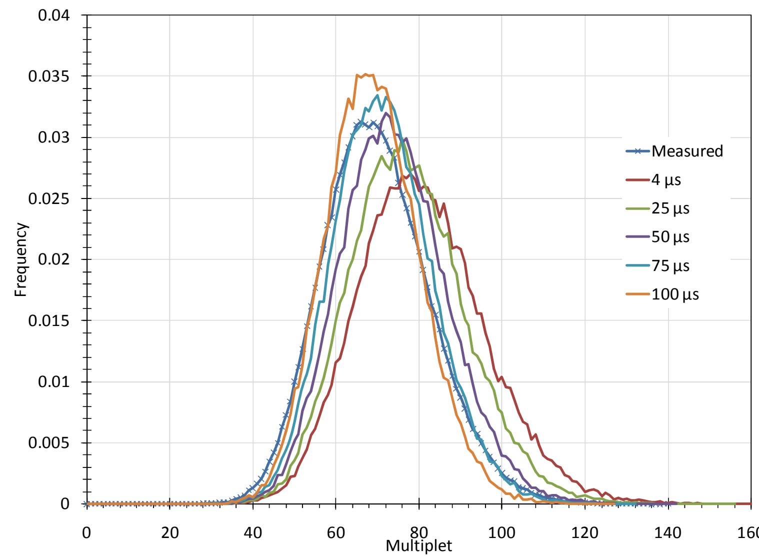


Sensitivity to detector dead-time



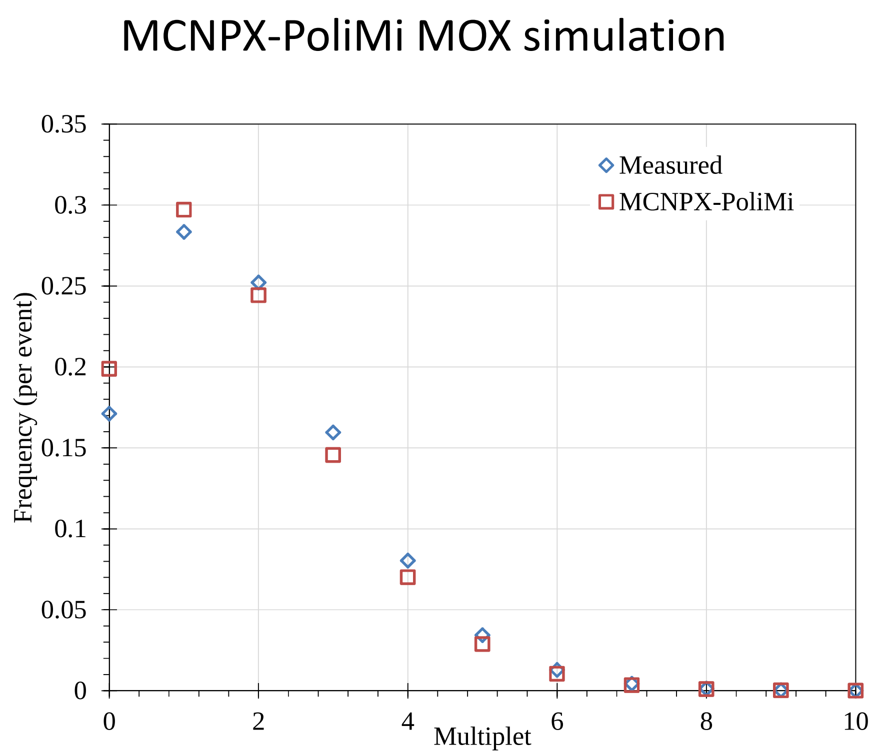
- The detector dead-time was measured to be 4 – 5 µs independent of count rate
- The simulated dead-time had to be increased to 40 – 80 µs to correct the simulations
- No consistent increase in the simulated dead-time corrected all the simulations
- Incorrect modeling of dead-time did not cause the observed simulation errors





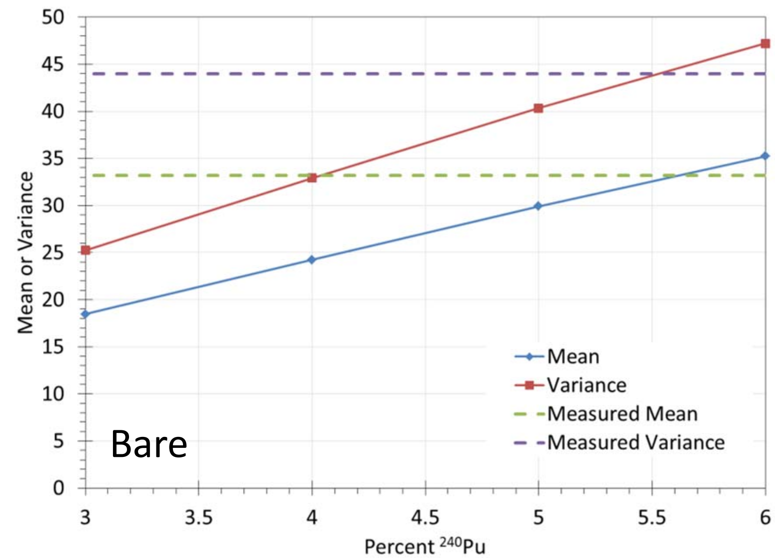
Plutonium cross sections

- MCNPX-PoliMi was previously validated against ESARDA benchmark measurements of MOX (Peerani 2009)
- Consequently, it seems unlikely that the plutonium cross sections caused the simulation errors
- However, note that the MOX samples had low mass and the multiplication was close to 1 (unlike the SNL experiments)

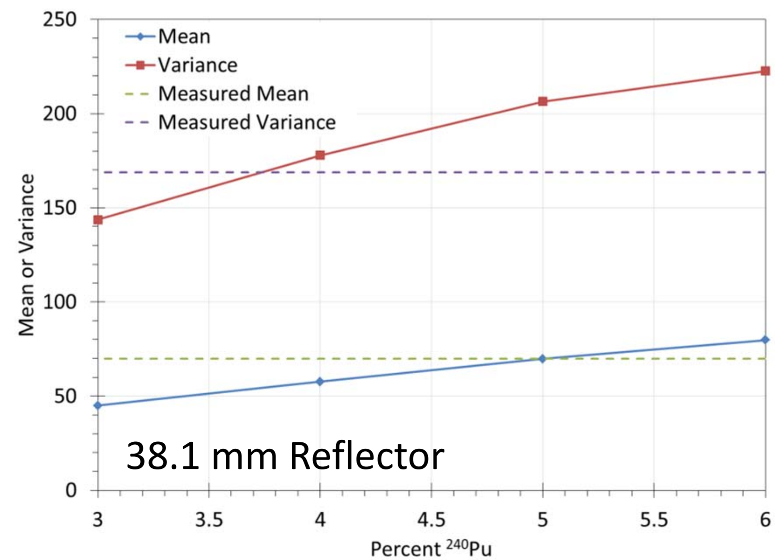


Sensitivity to plutonium composition

- The plutonium isotopic composition was measured in 1980 using radioanalytic chemistry
- The "baseline" Monte Carlo models used plutonium isotopics corrected to January 2009



- The modeled Pu-240 content was varied between 3% and 6%
  - No single change to the Pu-240 content consistently corrected all the simulations
  - Consequently, it's unlikely that the modeled plutonium composition caused the simulation errors



Sensitivity to plutonium density

- The radius of the plutonium sphere was measured in 1980 to be 37.94 mm
  - However, the sphere may have expanded slightly due to internal heating by alpha-decay
  - The maximum possible sphere radius is 38.28 mm (the inner radius of the steel clad)
- The effective sphere radius necessary to correct the simulations was estimated by reducing the plutonium density
  - In nearly every case, the sphere radius necessary to correct the simulations exceeded the maximum possible radius
  - Consequently, it's unlikely that the modeled plutonium density caused the simulation errors

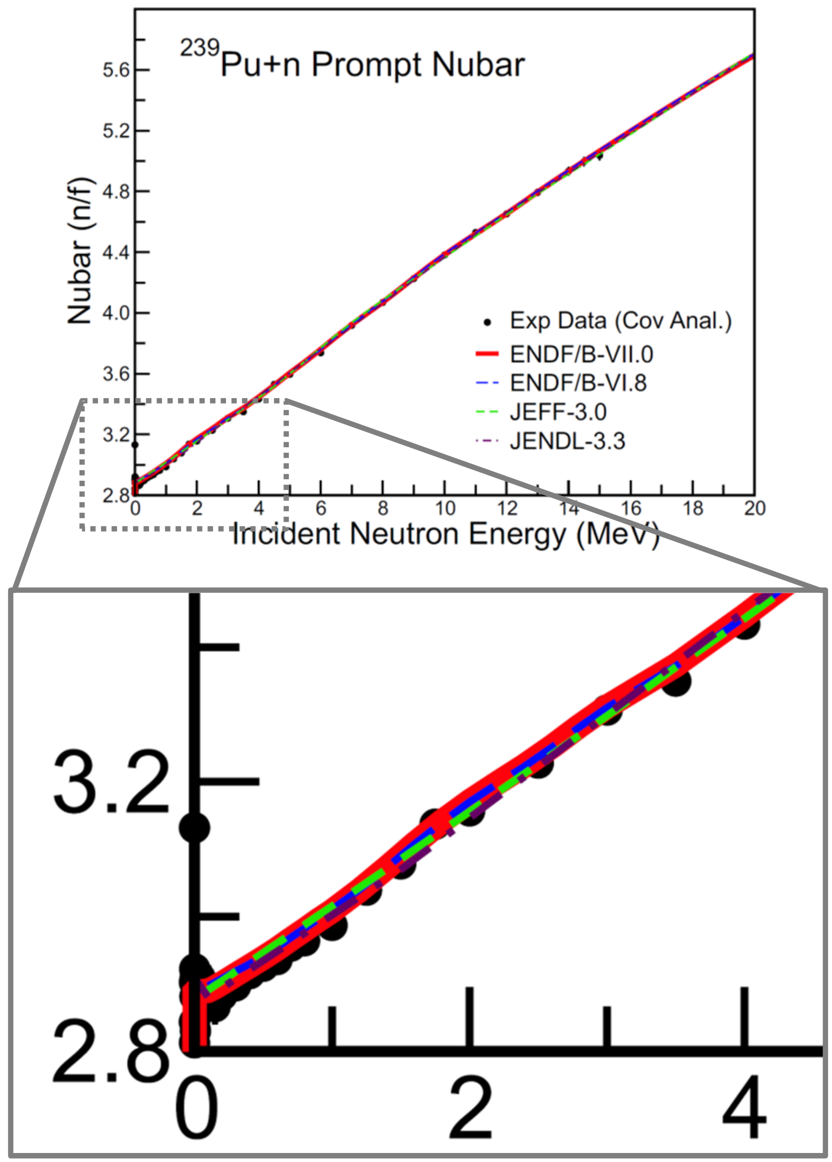
Reported Radius (mm)	37.94	
Max Radius (mm)	38.28	
Radius required to correct simulation (mm)		
Reflector Thickness (mm)	Mean	Variance
0.0	38.47	38.34
12.4	38.73	38.56
25.1	38.72	38.57
37.8	38.55	38.48
75.9	38.26	38.31
152.1	38.17	38.22

Pu-239 $\bar{\nu}$

- There are discrepancies between the ENDF/B-VII evaluation of Pu-239 $\bar{\nu}$ and experimental data below 2 MeV

- This discrepancy was noted in the original *Nuclear Data Sheets* article on the ENDF/B-VII evaluation of Pu-239 (Young 2007)

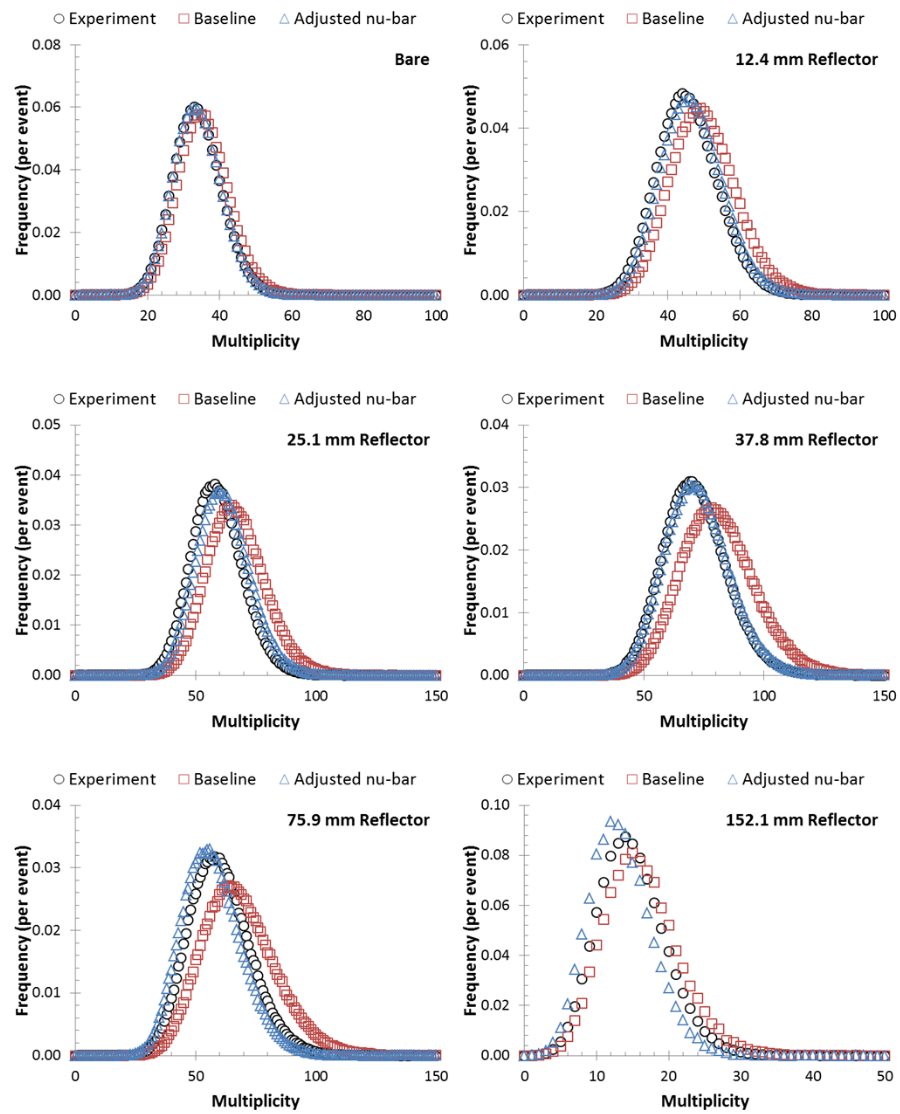
- In particular, the evaluated value of $\bar{\nu}(E)$ exceeds experimental data by about 2 standard deviations below 2 MeV



Young et al. (2007)

Sensitivity to Pu-239 $\bar{\nu}$

- The simulations were repeated with the value of Pu-239 $\bar{\nu}$ reduced by 1%, 2%, and 3% (for all neutron energies)
- An adjustment of $\bar{\nu}$ by -1.1% (relative to the ENDF/B-VII evaluation) was found to substantially improve the accuracy of *all* the simulations
- Consequently, over-estimation of the value of Pu-239 $\bar{\nu}$ in the ENDF/B-VII *may* have caused the observed simulation errors



Conclusions and future work

- MCNPX-PoliMi simulations of plutonium neutron multiplicity measurements exhibited systematic over-prediction of the neutron multiplicity distribution
  - The over-prediction tended to increase with increasing multiplication
  - MCNPX-PoliMi had previously been validated against only very low multiplication benchmarks
- We conducted sensitivity studies to try to identify the cause(s) of the simulation errors; we eliminated the potential causes we identified, except for Pu-239 $\bar{\nu}$
  - A very small change (-1.1%) in the Pu-239 $\bar{\nu}$ dramatically improved the accuracy of the MCNPX-PoliMi simulation for all 6 measurements
  - This observation is consistent with the trend observed in the bias exhibited by the MCNPX-PoliMi simulations: a very small error in $\bar{\nu}$ is "magnified" by increasing multiplication
- We applied a scalar adjustment to Pu-239 $\bar{\nu}$ (independent of neutron energy); an adjustment that depends on energy is probably more appropriate

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P. PEERANI, M. SWINHOE, A-L. WEBER, and L. G. EVANS, “ESARDA Multiplicity Benchmark Exercise - Phases III and IV,” ESARDA Bulletin No. 42 (2009).

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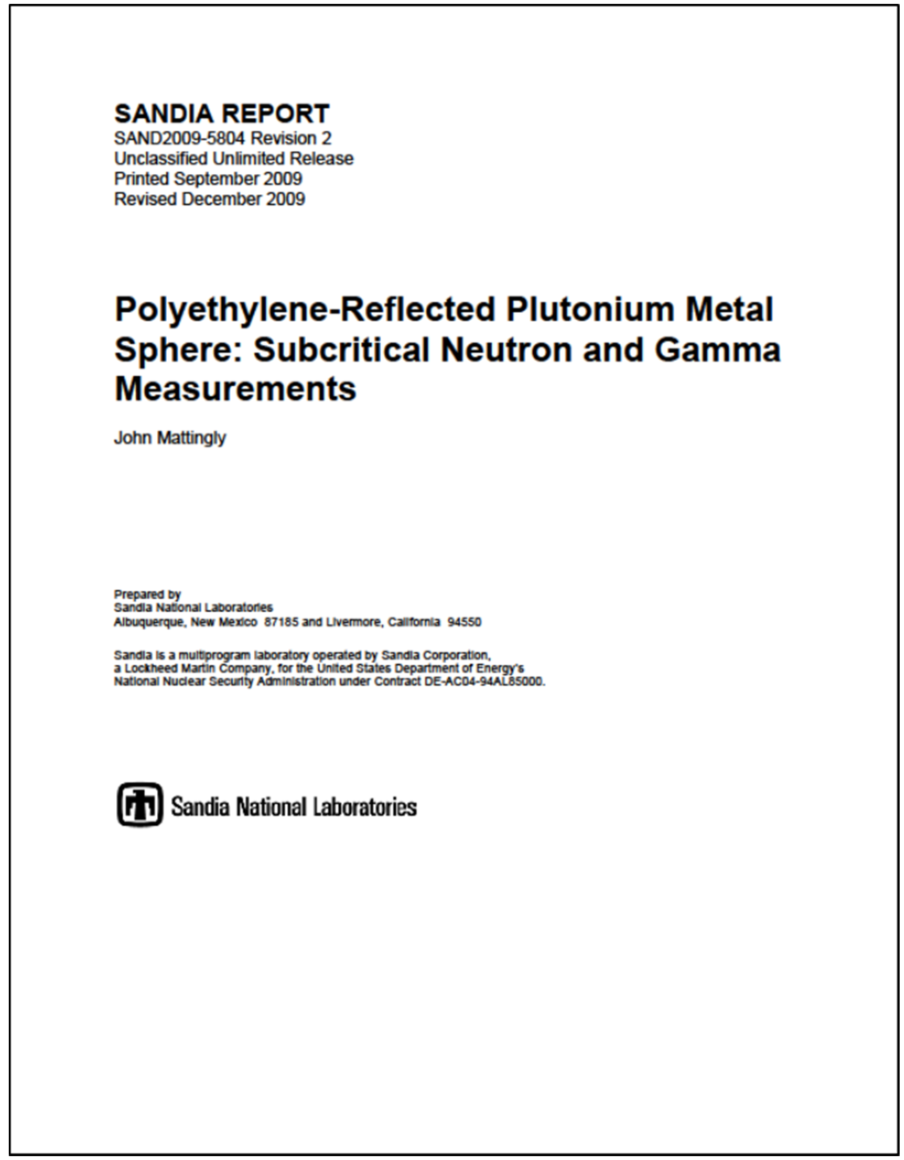
Benchmark data

- The experimental data analyzed in this paper is available in the SINBAD 2010.05 shielding and integral benchmark database

- SINBAD 2010.05 can be requested from the Radiation Safety Information Computational Center (RSICC) at http://rsicc.ornl.gov



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