The Collaborative International Benchmark Evaluation for the SILENE Solution Critical Experiment – A Shielding Benchmark

Presented by:

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I must recognize the contributions of my collaborators

- Oak Ridge National Laboratory
  - Design, measurements, documentation, and evaluation
  - T. M. Miller, C. Celik, M. E. Dunn, J. C. Wagner, and K. L. McMahan
- CEA Valduc
  - Design, irradiation, measurements, and documentation
  - N. Authier, X. Jacquet, G. Rousseau, H. Wolff, J. Piot, L. Savanier and N. Baclet
- CEA Saclay
  - Shielding materials and evaluation
  - Y. K. Lee, V. Masse, J. C. Trama, and E. Gagnier
- Lawrence Livermore National Laboratory
  - Rocky Flats CAAS
  - S. Kim and G. M. Dulik
- Babcock International Group, now Cavendish Nuclear
  - CIDAS CAAS
  - R. Hunter
- Y-12 National Security Complex
  - BoroBond shielding materials
  - K. H. Reynolds
- IRSN France
  - ICSBEP external reviewers
  - P1-3: M. Duluc, F. Trompier, M. A. Chevallier
  - P1: S. Beytout (MILLENNIUM)
  - P2-3: M. Troisne (Contractor)
- Slovakia
  - ICSBEP external reviewer
  - L. Snoj

Outline

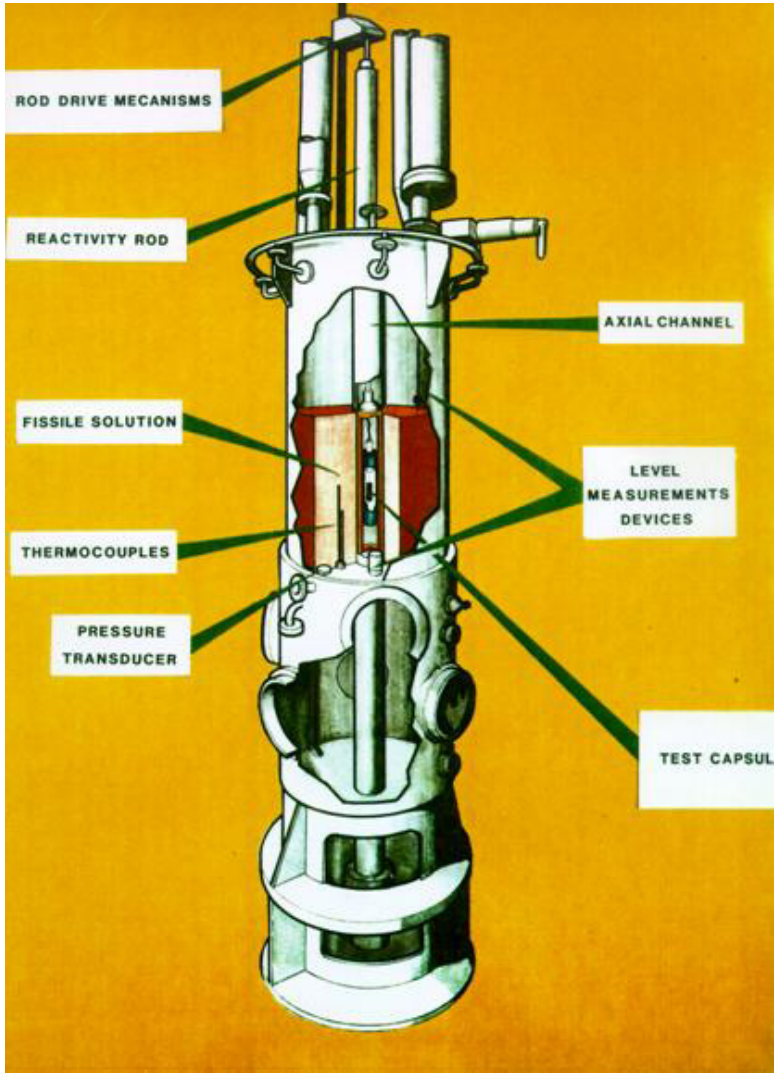
- BRIEF overview of experiment
  - Description of SILENE
  - Description of detectors and shielding materials
  - Description of benchmark experiments configurations
- Review evaluated results for pulse 1
  - Data needs
- Review available evaluated results for pulses 2 and 3
  - Data needs
- Summary and Conclusions

References (for more details)

- ICNC 2011 paper discussing the first experiment (pulse 1)
- NCSD 2013 paper discussing the second and third experiments (pulses 2 and 3)
- ICNC 2015 paper discussing concrete compositions
- ICSBEP evaluation of the first experiment was published at the end of 2015
- Evaluations of the second and third experiments will be presented to the ICSBEP in 2016

Introduction to SILENE

- Annular core
  - Internal cavity diameter 7 cm
  - Outer fuel diameter 36 cm
  - Typical critical height ~35 – 45 cm
- Uranyl Nitrate fuel Solution
  - ~93% ^{235}U
  - ~71 g of uranium per L
- Power level ranges from 10 mW to 1000 MW
- Three operating modes
  - Single pulse
  - Free evolution
  - Steady State



Background: neutron and photon detectors

- Neutron activation foils: Au, In, Fe, Ni, Co, Mg
- Valduc provided Al_2O_3 TLDs and ORNL provided ^6LiF and ^7LiF TLDs
- CAAS Detectors present, but no benchmark quality data generated. The CAAS detectors either alarmed or did not alarm (they alarmed as expected)
  - Rocky Flats CAAS
  - CIDAS CAAS

Background: shielding materials

- Shield materials, collimators, and stands
  - 2 collimators filled with borated plaster and polyethylene beads
  - 17 concrete slabs (1m x 1m x 20cm)
    - Standard ~2.3 g/cc
    - Barite ~3.25 g/cc
    - Magnetite ~3.9 g/cc
  - 3 core shields (reflectors)
    - Pulse 2 Lead, 10 cm thick
    - ~~Iron, 10 cm thick~~
    - Pulse 3 Cadmium lined polyethylene (0.7 mm Cd, 13 cm poly, 0.7 mm Cd)
  - 5 BoroBond slabs (1m x 1m x , 2 1-inch, 3 2-inch)

Experimental configurations (1)

- Pulse 1
  - SILENE bare (no reflector)
  - Collimator A – unshielded
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats CAAS
  - Collimator B – 20 cm barite concrete
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats & CIDAS CAAS
  - Free-field location
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
  - Scattering Box (2 magnetite & 4 standard concrete shields)
    - Full set of neutron activation foils
    - 3 partial sets of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - 2 additional HBG and DXT TLDs
    - 4 additional Valduc Al_2O_3 TLDs
    - Rocky Flats & CIDAS CAAS

Photographs of bare SILENE and pulse 1 cell configuration

Experimental configurations (2)

- Pulse 1
  - SILENE bare (no reflector)
  - Collimator A – unshielded
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats CAAS
  - Collimator B – 20 cm barite concrete
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats & CIDAS CAAS
  - Free-field location
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
  - Scattering Box (2 magnetite & 4 standard concrete shields)
    - Full set of neutron activation foils
    - 3 partial sets of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
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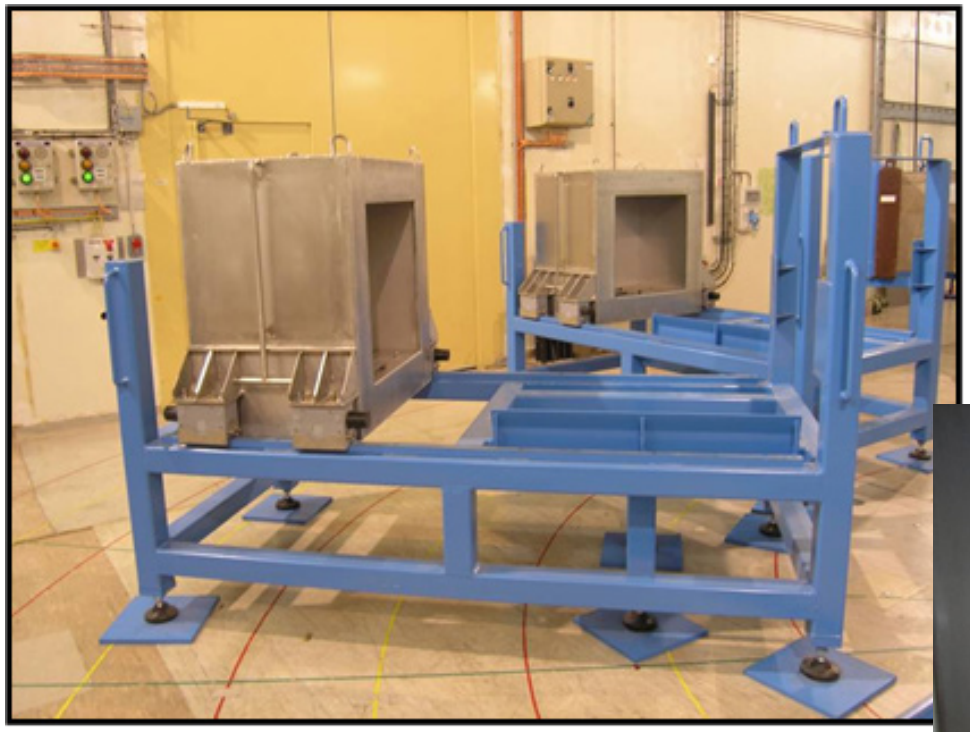
    - 4 additional Valduc Al_2O_3 TLDs
    - Rocky Flats & CIDAS CAAS

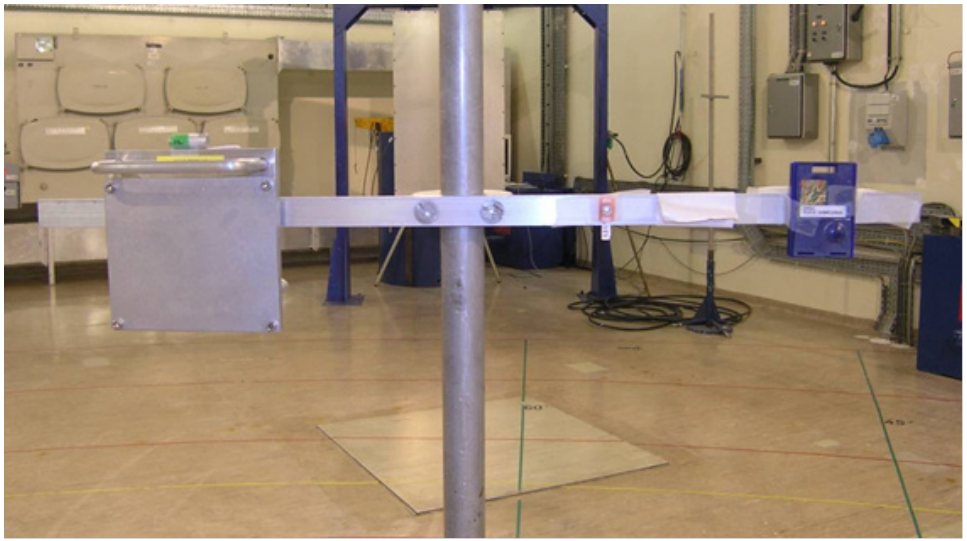
Photographs of collimators and detectors



Experimental configurations (3)

- Pulse 1
  - SILENE bare (no reflector)
  - Collimator A – unshielded
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats CAAS
  - Collimator B – 20 cm barite concrete
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats & CIDAS CAAS
  - Free-field location
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
  - Scattering Box (2 magnetite & 4 standard concrete shields)
    - Full set of neutron activation foils
    - 3 partial sets of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - 2 additional HBG and DXT TLDs
    - 4 additional Valduc Al_2O_3 TLDs
    - Rocky Flats & CIDAS CAAS

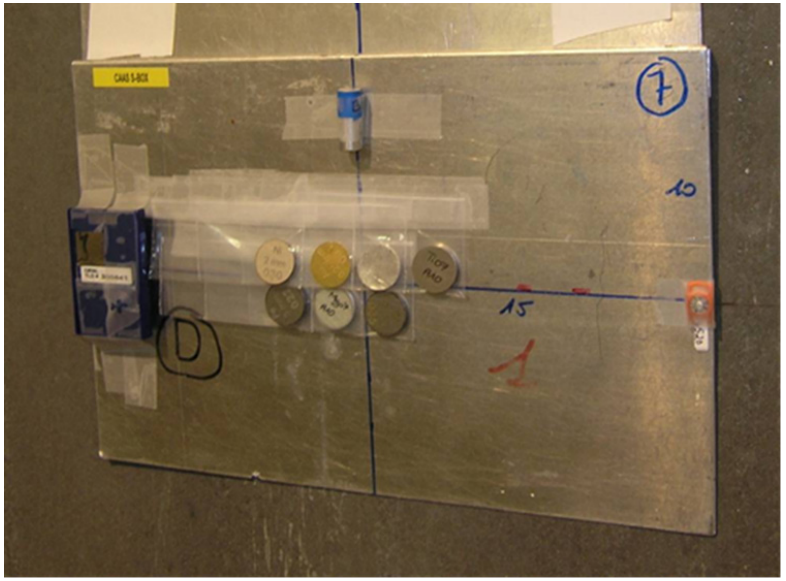
Photographs of the free-field location and neutron activation foils



Experimental configurations (4)

- Pulse 1
  - SILENE bare (no reflector)
  - Collimator A – unshielded
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats CAAS
  - Collimator B – 20 cm barite concrete
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - Rocky Flats & CIDAS CAAS
  - Free-field location
    - Full set of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
  - Scattering Box (2 magnetite & 4 standard concrete shields)
    - Full set of neutron activation foils
    - 3 partial sets of neutron activation foils
    - Valduc Al_2O_3, ORNL HBG & DXT TLDs
    - 2 additional HBG and DXT TLDs
    - 4 additional Valduc Al_2O_3 TLDs
    - Rocky Flats & CIDAS CAAS

Photographs of scattering box and detectors



Experimental configurations (5)

- Differences for pulse 2
  - SILENE lead reflector
  - Collimator B – 20 cm standard concrete

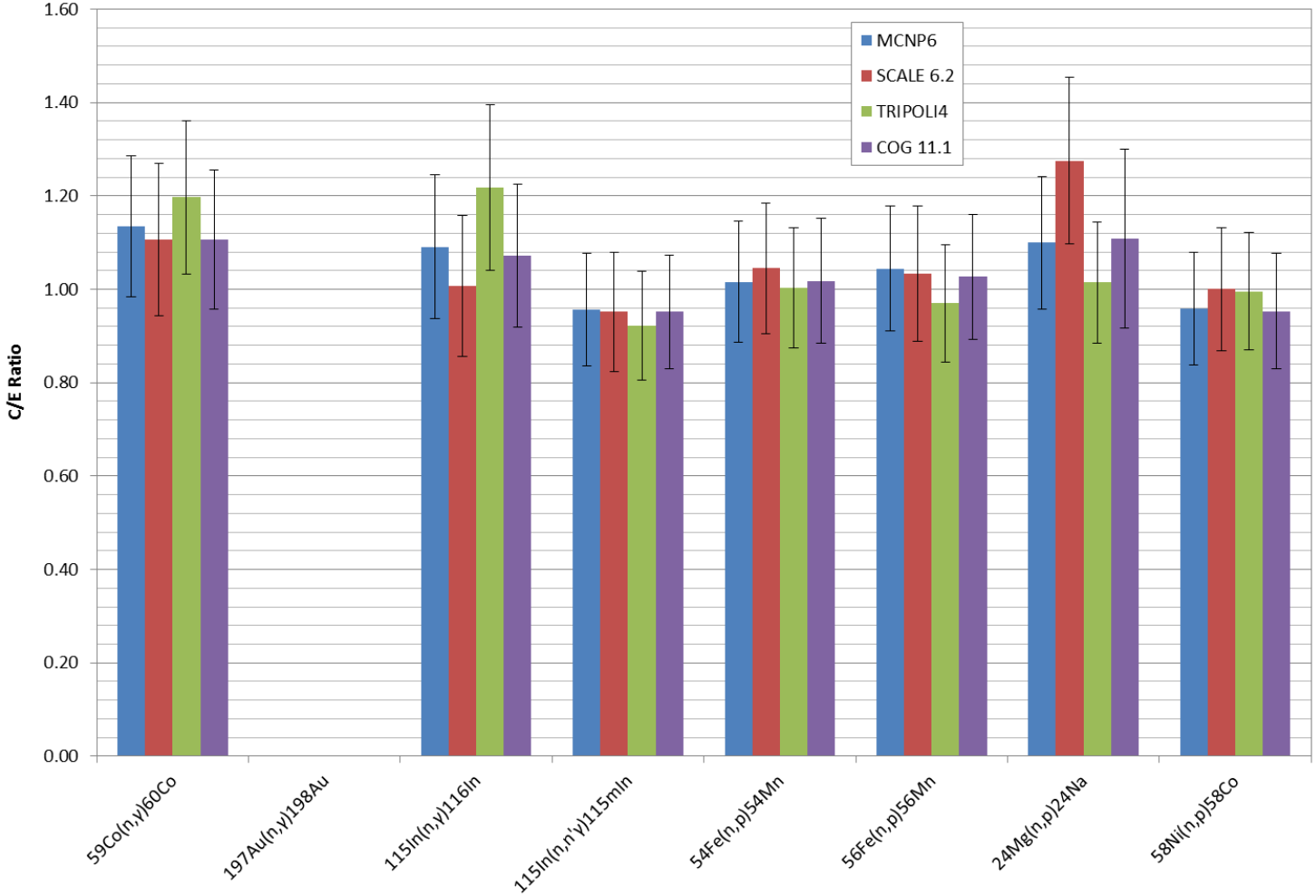
Experimental configurations (6)

- Differences for pulse 3
  - SILENE polyethylene reflector
  - Collimator B – ~3 in. BoroBond

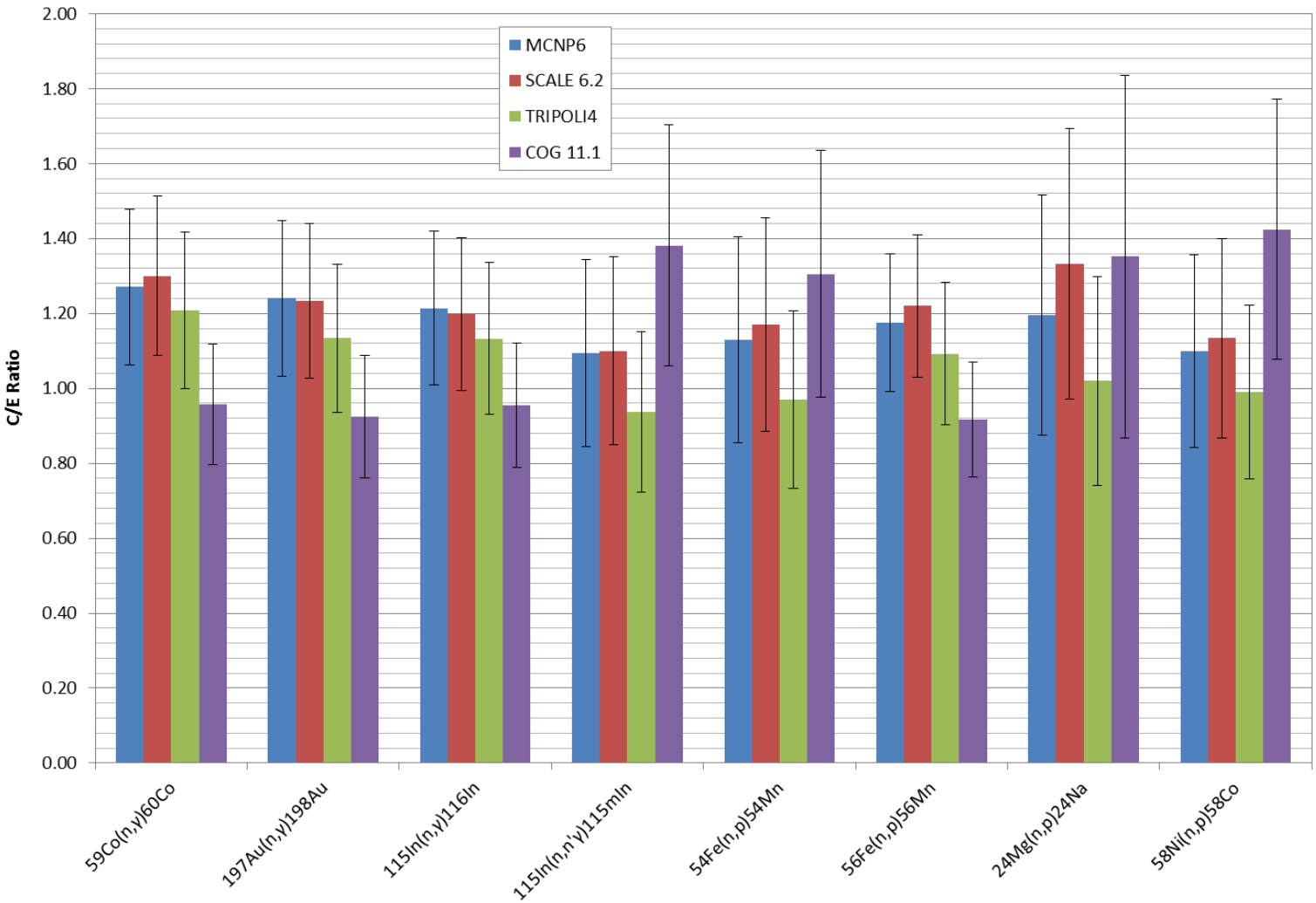
Summary of pulse 1 evaluated results

- Neutron activation results
  - Thermal reactions – the calculated results are generally overestimated by less than 30% (most less than 20%)
  - Threshold reactions – the calculated results are mixed
    - Unshielded (CA, FF, SB3, and SB4) within a few percent
    - Shielded (CB, SB1, and SB2) over estimated by a few to 50%
  - The concrete shields introduce some of the largest uncertainties for this benchmark
    - SB2 is the worst case – dependent on 2 concrete shield blocks
- Photon dose results
  - The calculated results are generally underestimated by 20 – 30%
  - Exception: free field location (slight overestimate)

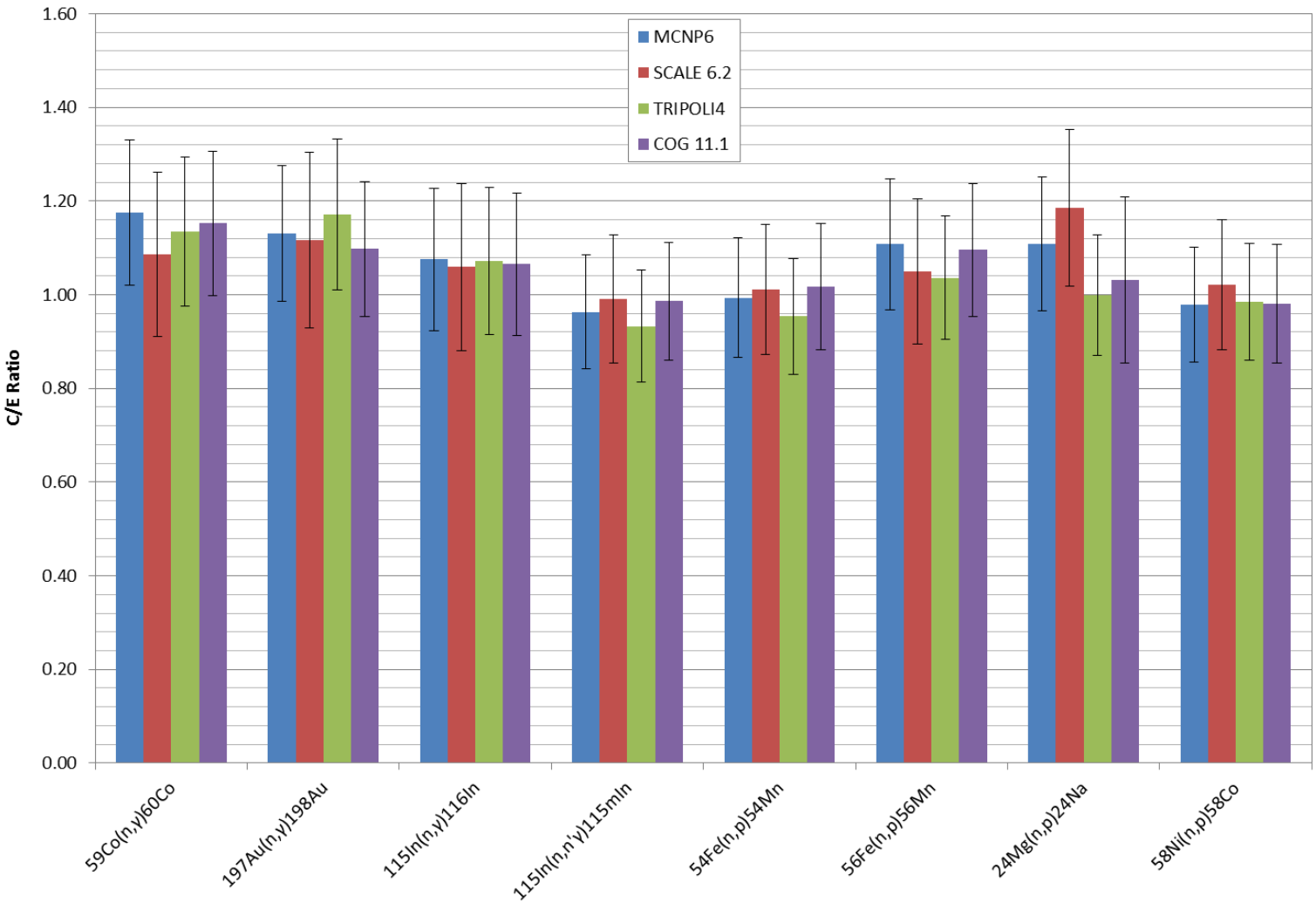
Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 CA neutron



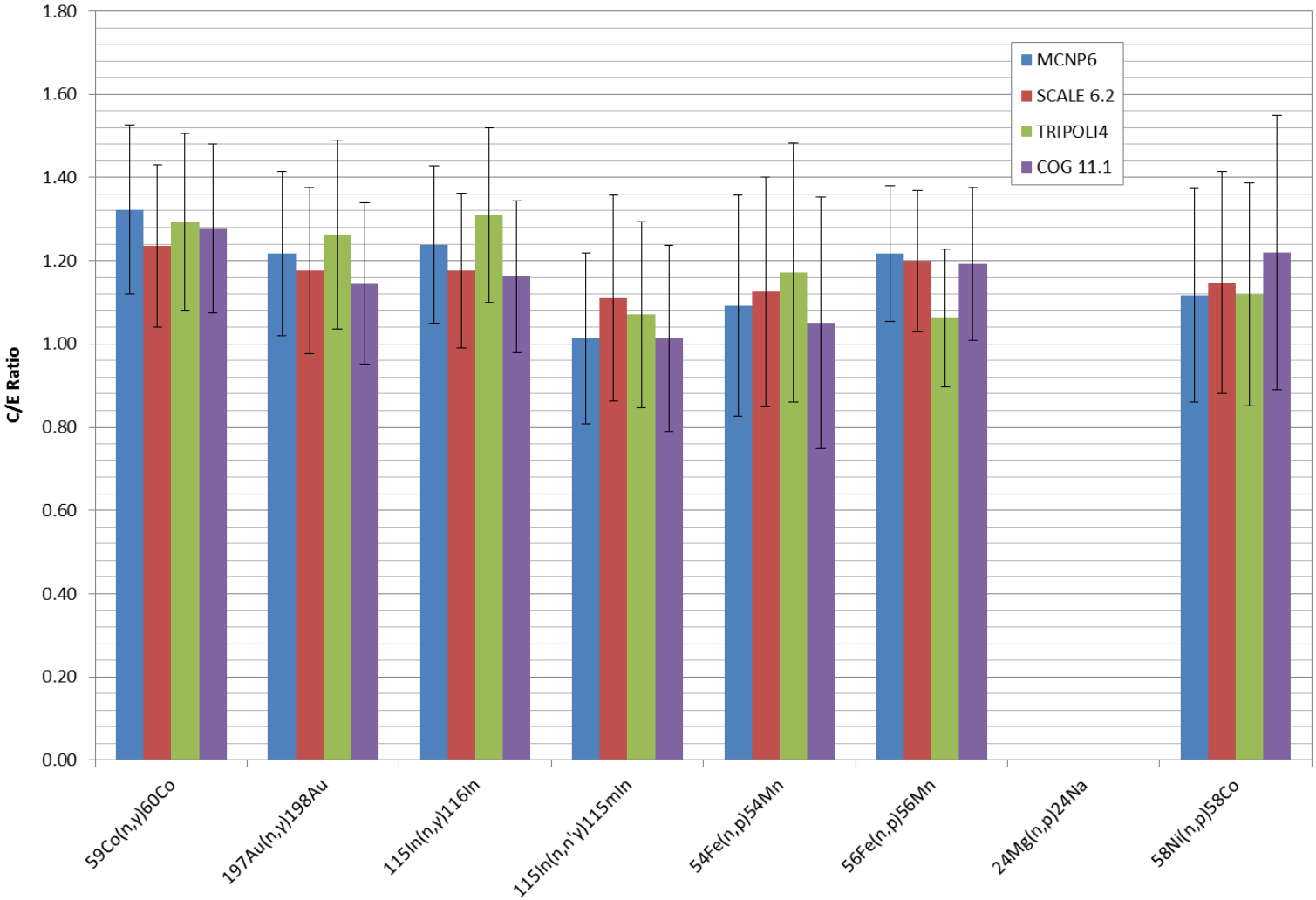
Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 CB neutron



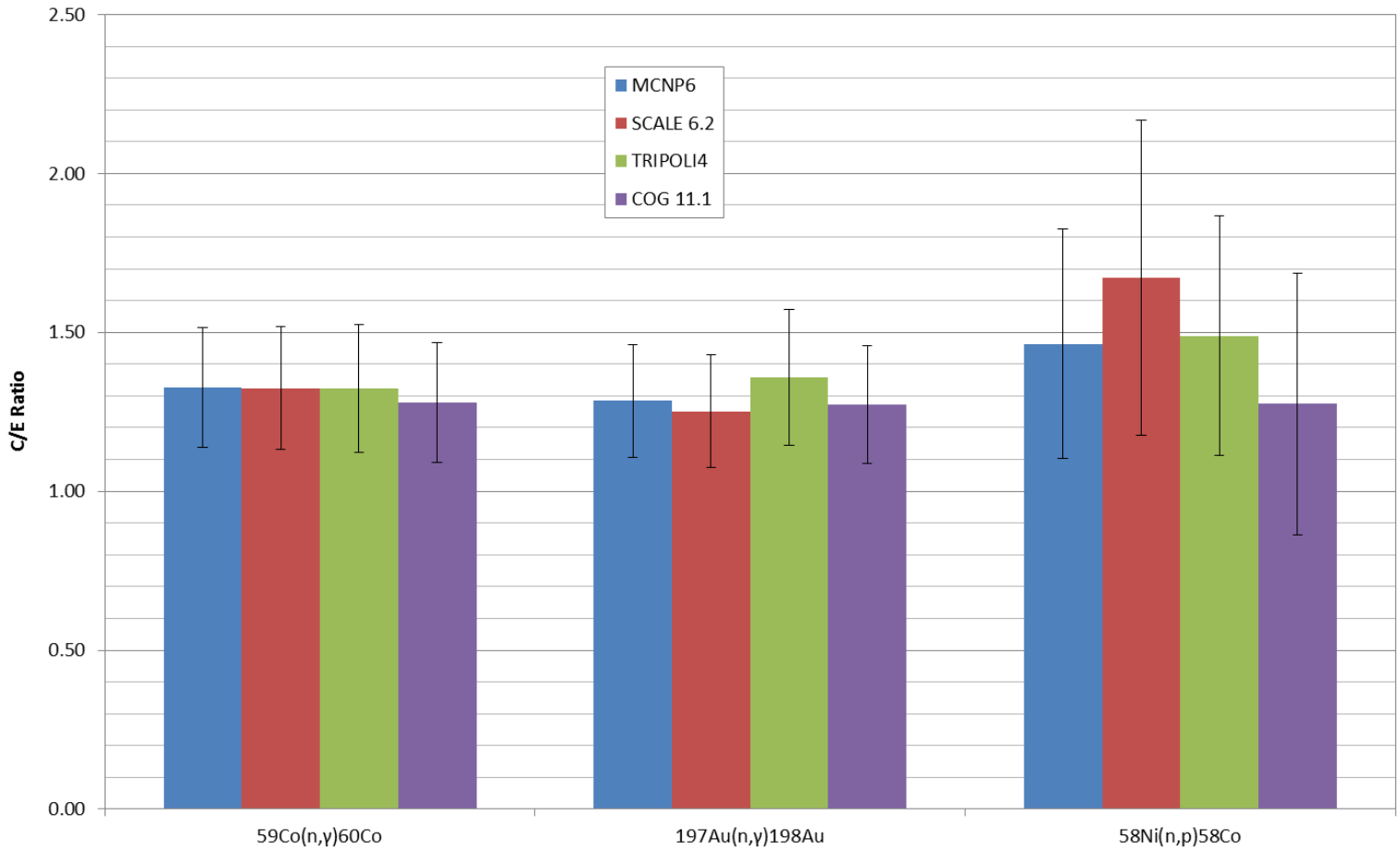
Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 FF neutron



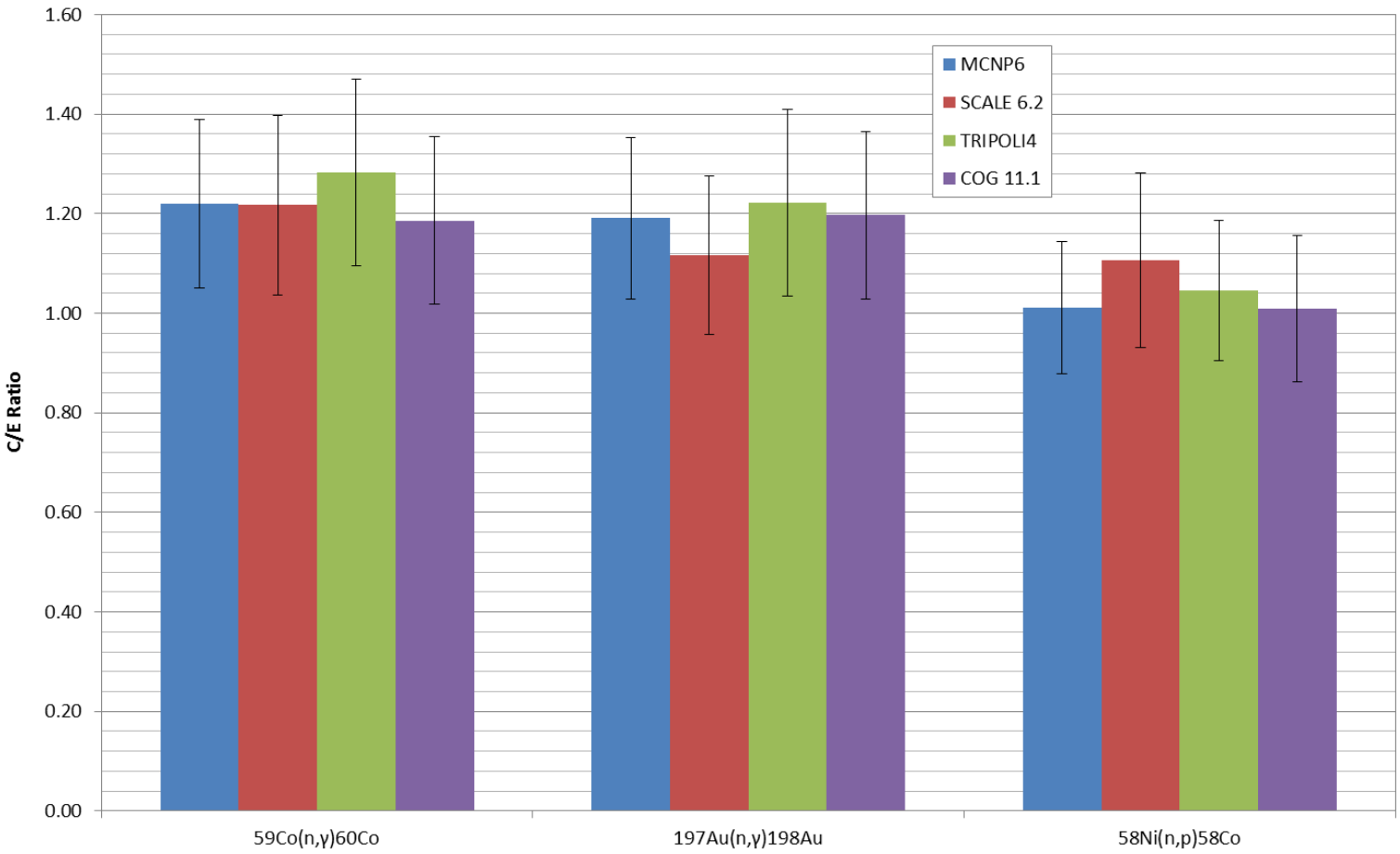
Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 SB1 neutron



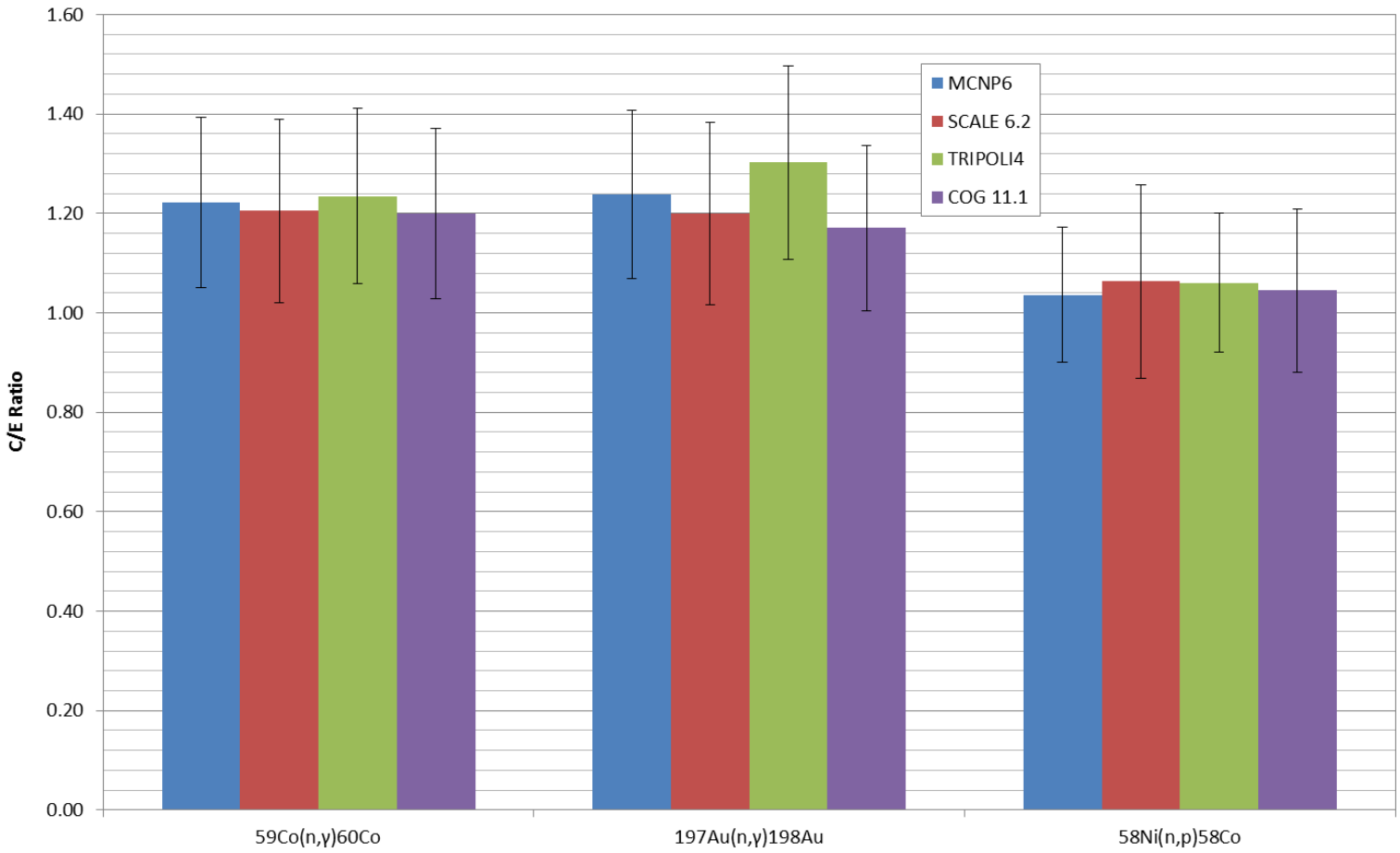
Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 SB2 neutron



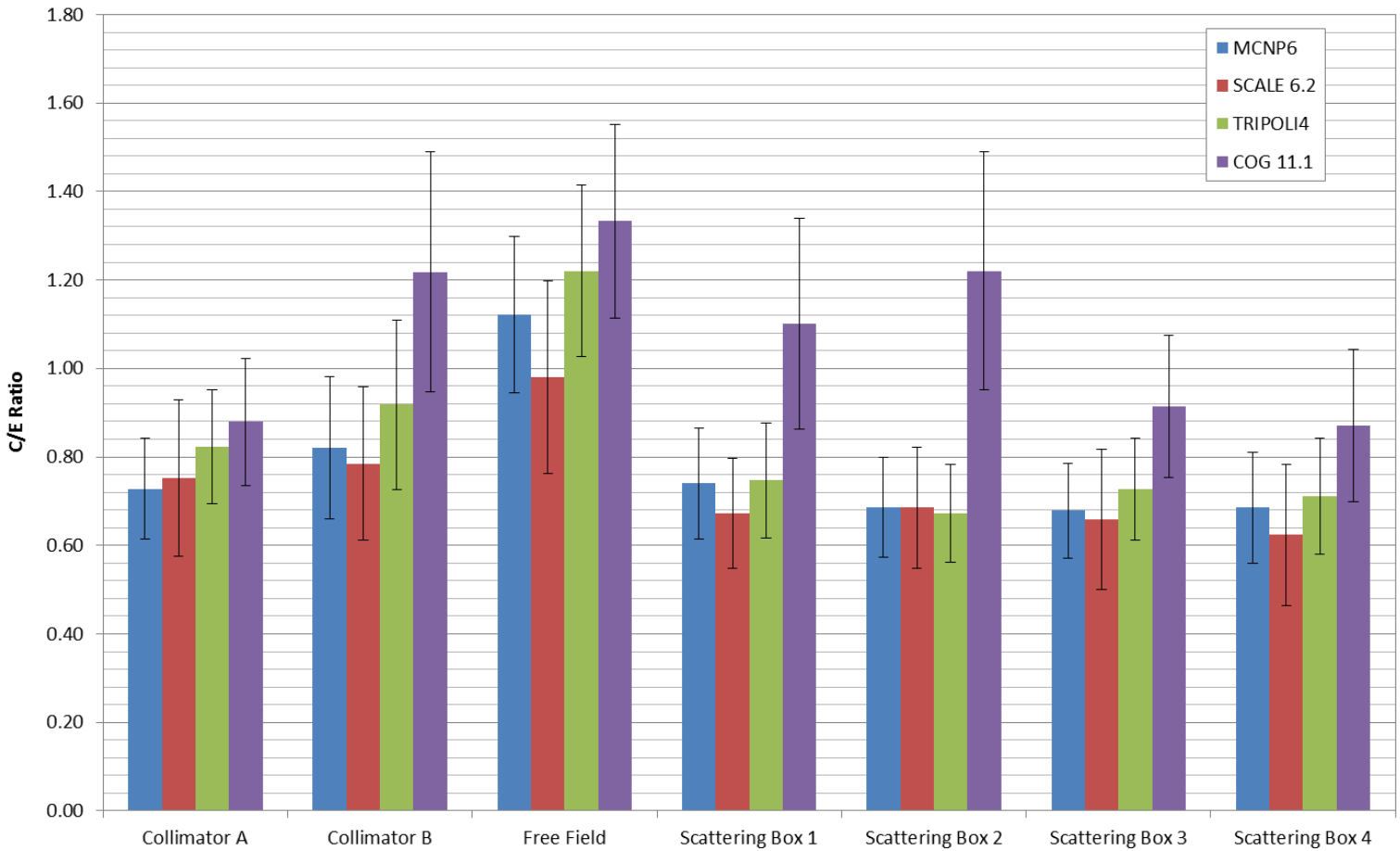
Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 SB3 neutron



Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 SB4 neutron



Calculated to experiment ratio with 2 sigma benchmark uncertainties – P1 all photon

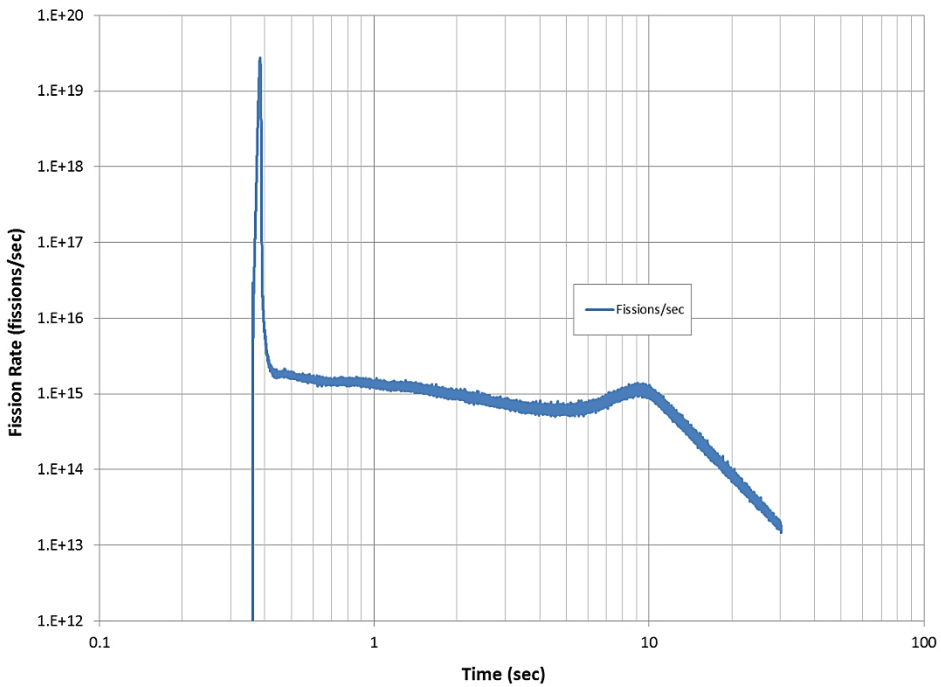


Delayed gamma contributions to TLD dose (1/3)

- The calculated TLD doses include prompt fission gammas and secondary gammas from neutron capture and inelastic scattering
  - Missing gammas from the decay of fission and activation products
- ORNL used ORIGEN to estimate the contribution of delayed gammas to the collimator A TLD dose
- LLNL used the delayed gamma feature in COG to estimate the contribution of <u>fission product gammas</u> to all the TLDs
- These are estimates because the details about the solution draining from SILENE are not available
  - When did the solution start to drain and at what rate?

Delayed gamma contributions to TLD dose (2/3)

- The ORIGEN and COG estimates of fission product gamma doses assumed all the fuel was present for 30 seconds and then all drained immediately (a step function)
- MCNP6 ACT card shows promise, but not operational for this scenario
  - Critical system requires the NONU card to suppress multiplication (already included in source)
  - ACT card cannot produce fission product gammas with NONU card



Delayed gamma contributions to TLD dose (3/3)

- Collimator A delayed gamma doses using ORIGEN

	Dose (Gy)	Rel. Unc.	Dose (Gy)	Rel. Unc.	Dose (Gy)	Rel. Unc.
Time (sec)	30.3		149		3600	
Fuel	9.500E-01	0.0043	0.000E+00	0.0000	0.000E+00	0.0000
Foils	2.120E-05	0.0062	5.270E-06	0.0026	2.500E-06	0.0021
Other	7.650E-04	0.0101	4.190E-04	0.0116	2.440E-06	0.0167
Total	9.508E-01	0.0043	4.243E-04	0.0115	4.940E-06	0.0083
Time (sec)	7200		10800		**Total**	
Fuel	0.000E+00	0.0000	0.000E+00	0.0000	**9.500E-01**	**0.0043**
Foils	1.170E-06	0.0021	5.470E-07	0.0021	**3.069E-05**	**0.0043**
Other	1.830E-06	0.0176	1.430E-06	0.0186	**1.190E-03**	**0.0077**
Total	3.000E-06	0.0108	1.977E-06	0.0135	**9.512E-01**	**0.0043**

  - 0.951 Gy from delayed gammas, mostly fission products, which is a 20% increase over no delayed gammas
  - 27% under prediction of dose without delayed gammas, 13% with

- Doses using COG delayed gamma (fission product) source

Location	Dose (Gy)	Rel. Unc.	Ratio: with delayed / without delayed	Ratio Rel. Unc.
Collimator A	5.810	0.0221	1.10	0.0304
Collimator B	0.999	0.0523	1.09	0.0728
Free Field	4.960	0.0236	1.16	0.0327
Scattering Box 1	0.639	0.0676	1.10	0.0934
Scattering Box 2	0.537	0.0743	1.01	0.1020
Scattering Box 3	1.610	0.0397	1.17	0.0547
Scattering Box 4	1.630	0.0393	1.13	0.0542

Barium gamma production data

- ENDF, JENDL, and CENDL do not contain any gamma production data for the naturally occurring isotopes of barium
  - ENDF does contain gamma production data for Ba-133
- JEFF contains gamma production data for Ba-134
- Collimator B shield for pulse 1 is barite concrete, which is ~32wt% barium
- The TENDL library based on models does contain gamma production data for barium
- Replacing the ENDF barium neutron cross sections with the TENDL neutron cross sections increases the calculated TLD dose in collimator B 7.6%

Summary of preliminary pulse 2 and 3 evaluated results – MCNP

- Neutron activation results
  - Pulse 2 – the calculated results are generally overestimated by less than 30%, most between 10 – 20%
  - Pulse 3 – everything within ±20%, most within ±10%
- Photon dose results
  - Pulse 2 – most of the calculated results are underestimated by 20%
  - Pulse 3 – Using ENDF The calculated results are generally underestimated by 30 – 40%

Cadmium gamma production data (1/2)

- Most of the evaluated data libraries based on measurements do not contain gamma production data for <u>all</u> cadmium isotopes
  - CENDL contains an elemental evaluation
- The polyethylene reflector / shield for pulse 3 has 0.7 mm of cadmium on the inner and outer surface
- Available gamma production data by cadmium isotope
  - Cd-106 (1.25 atom%): ENDF, JENDL, TENDL
  - Cd-108 (0.89 atom%): JENDL, TENDL
  - Cd-110 (12.49 atom%): JEFF, JENDL, TENDL
  - Cd-111 (12.8 atom%): ENDF, JEFF, JENDL, TENDL
  - Cd-112 (24.13 atom%): JENDL, TENDL
  - Cd-113 (12.22 atom%): JEFF, JENDL, TENDL
  - Cd-114 (28.73 atom%): JENDL, TENDL
  - Cd-116 (7.49 atom%): JENDL, TENDL

Cadmium gamma production data (2/2)

- When using cadmium neutron cross sections available in ENDF pulse 3 TLD doses underestimated by 30 – 40%
  - Cd-106, Cd-111 (14.05 atom%)
- When adding JEFF cadmium neutron cross sections pulse 3 TLD doses underestimated by 10 – 20%
  - ENDF + Cd-110, Cd-113 (38.76 atom%)
- Adding the remaining isotope evaluations from JENDL and TENDL with gamma production data does not significantly change the calculated doses

Summary and Conclusions

- The SILENE pulse 1 evaluation has been published and is publicly available
- The pulse 2 and 3 evaluations will be published later this year, if accepted by the ICSBEP
- We have identified a couple of data needs
  - Delayed fission product gammas within the available transport codes (to simplify the life of criticality safety analyst)
  - Improved gamma production data – lots of isotopes have none
  - The most egregious example is Cd-113

Thanks again to all of my collaborators

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