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Title: Neutron Spectrum Measurements from Irradiations at NCERC

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Neutron Spectrum Measurements from Irradiations at NCERC

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Introduction

- Several irradiations have been conducted on assemblies at the National Criticality Experiments Research Center (NCERC) located at the Nevada National Security Site (NNSS)
- Configurations of the assemblies and irradiated materials changed between experiments
- Different metallic foils were analyzed using the radioactivation method by gamma-ray spectrometry to understand / characterize the neutron spectra

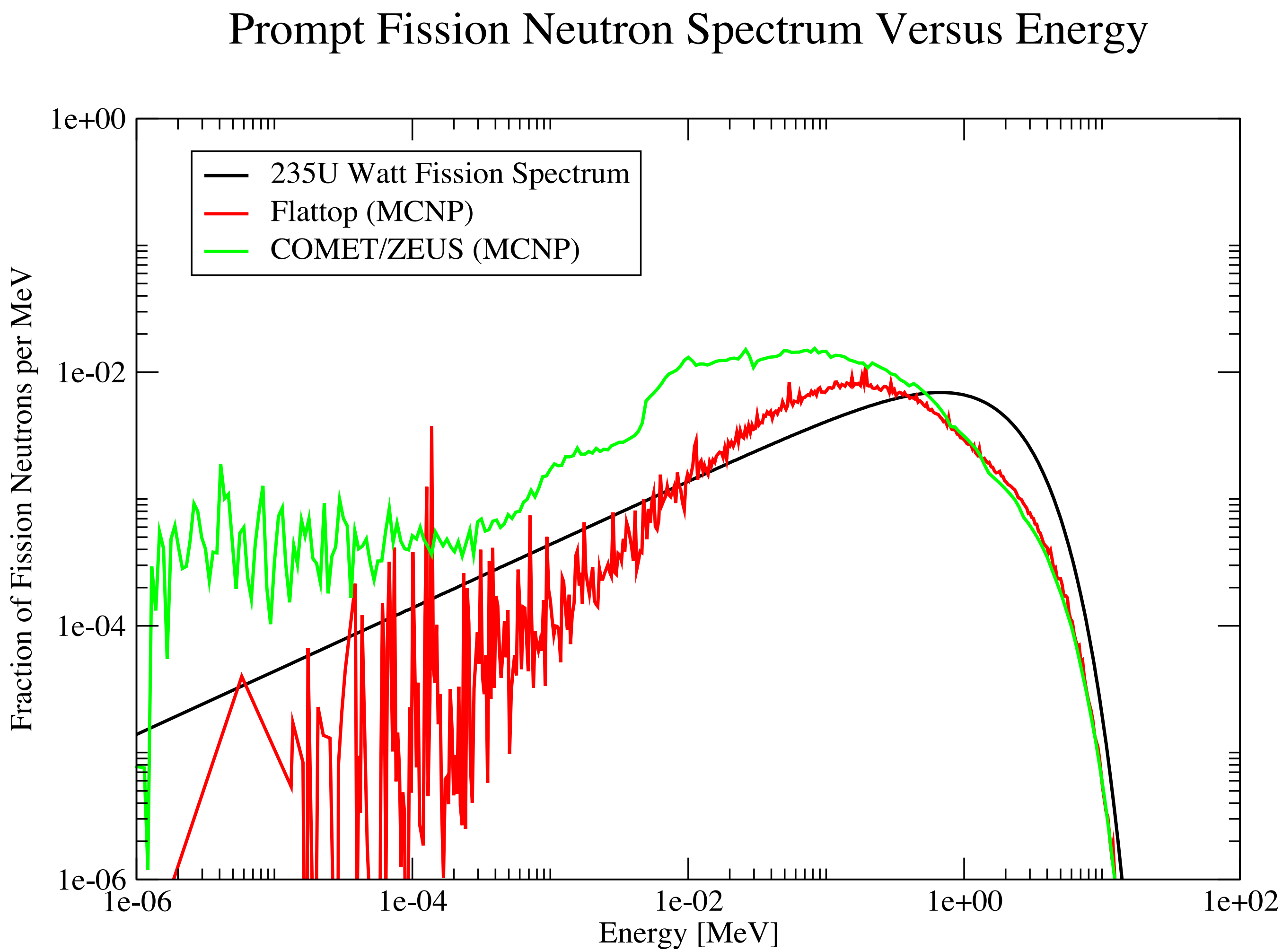
COMET/ZEUS

- Epithermal/Fission-spectrum (peaked ~500 keV)
- HEU rings raised by hydraulic lift
- Copper reflector (from ZEUS Experiments)
- First critical: August 11th, 2011
- Sample trays (16 foils at reflector; 24 foils in fuel)
- ~10^{12} fissions/gram (high-power)

Flattop

- Fast/Fission-spectrum
- HEU and Pu cores with Natural U reflector
- Reactivity increases as parts of spheres brought together and control rods inserted
- Foils inserted in the traverse or glory holes
- ~10^{13} fissions/gram (high power)

Fission Neutrons



Ref's: Int'l Handbook of Evaluated Critical Safety Benchmark Experiments (2009), M. White (LANL), and UCRL-AR-228518.

Activation Foils Used

Element	Shieldwerx Sets	Reaction(s)	Half-life	Cross-section(s)	Res/Thresh
Al	Fast/Broad	27Al(n,α)24Na	14.95 h	σ ~ 0.15 b	Thresh ~ 4 MeV
Au	Thermal/Broad	197Au(n,γ)198Au	2.6952 d	σ_t = 98.7 b; R.I. = 1550 b	4.9 eV
Au	Thermal/Broad	197Au(n,2n)196Au	6.617 d	σ ~ 2.2 b	Thresh ~ 8.5 MeV
Co	Thermal	59Co(n,γ)60Co	5.271 y	σ_t = 37 b; R.I. = 74 b	132 eV
Co	Thermal	59Co(n,2n)58Co	70.88 d	σ ~ 0.8 b	Thresh ~ 13 MeV
Co	Thermal	59Co(n,p)59Fe	44.50 d	σ ~ 0.05 b	Thresh ~ 3 MeV
Cu	Thermal/Fast/Broad	63Cu(n,γ)64Cu	12.701 h	σ_t = 4.5 b; R.I. = 5.0 b	401 eV; 579 eV
Cu	Thermal/Fast/Broad	63Cu(n,α)60Co	5.271 y	σ ~ 0.045 b	Thresh ~ 4 MeV
Fe	Thermal/Fast/Broad	54Fe(n,p)54Mn	312.1 d	σ ~ 0.48 b	Thresh ~ 2 MeV
Fe	Thermal/Fast/Broad	56Fe(n,p)56Mn	2.578 h	σ ~ 0.11 b	Thresh ~ 5 MeV
Fe	Thermal/Fast/Broad	58Fe(n,γ)59Fe	44.50 d	σ_t = 1.3 b; R.I. = 1.2 b	230 eV, 359 eV
Mn-Cu	Fast	55Mn(n,γ)56Mn	2.578 h	σ_t = 13.3 b; R.I. = 14 b	341 eV
Mn-Cu	Fast	55Mn(n,2n)54Mn	312.1 d	σ ~ 0.9 b	Thresh ~ 10 MeV
Mo	Thermal	98Mo(n,γ)99Mo	2.7476 d	σ_t = 0.13 b; R.I. = 7.2 b	12 eV; 470 eV
Nb	-	93Nb(n,n')93mNb	16.1 y	σ ~ 1.8 b	Thresh ~ 2.5 MeV
Nb	-	93Nb(n,2n)92Nb	10.13 d	σ ~ 1.3 b	Thresh ~ 9 MeV
Ni	Fast/Broad	58Ni(n,2n)57Ni	35.6 h	σ ~ 0.08 b	Thresh ~ 13 MeV
Ni	Fast/Broad	58Ni(n,p)58Co	70.88 d	σ ~ 0.6 b	Thresh ~ 2 MeV
Ni	Fast/Broad	60Ni(n,p)60Co	5.271 y	σ ~ 0.15 b	Thresh ~ 4 MeV
Sc	Thermal/Broad	45Sc(n,γ)46Sc	83.81 d	σ_t = 17 b; R.I. = 12 b	460; 3.3e3 eV
Ti	Fast/Broad	46Ti(n,p)46Sc	83.81 d	σ ~ 0.3 b	Thresh ~ 4 MeV
Ti	Fast/Broad	47Ti(n,p)47Sc	3.349 d	σ ~ 0.15 b	Thresh ~ 1 MeV
Ti	Fast/Broad	48Ti(n,p)48Sc	43.7 h	σ ~ 0.06 b	Thresh ~ 5 MeV
V	Fast/Broad	51V(n,α)48Sc	43.7 h	σ ~ 0.02 b	Thresh ~ 7 MeV
W	Thermal	186W(n,γ)187W	23.9 h	σ_t = 38 b; R.I. = 490 b	18.8 eV

Ref's: ASTM Standards E261 thru E266, ASTM E844 Foil Guide

Background (SAND-II-SNL)

- SAND-II-SNL Spectrum Unfolding / Iterative Perturbation Method
  1. Activities are calculated based on current iteration of neutron spectrum (flux) using cross-section libraries in code
  2. Calculated activities are compared with measured activities to provide correction factors for each foil
  3. Weighting function (as a function of energy) is obtained for each foil based on sensitivity (differential cross-section times differential flux)
  4. Foil weighting functions are applied to an averaging procedure to obtain average correction factors at each energy (based on calculated/measured activity and relative contribution to flux at given energy)
  5. Average correction factors are applied to current iteration of neutron spectrum (flux) to obtain the next iterative spectrum

Note: flux for steady-state, fluence for pulsed reactors

Ref's: AFWL-TR-67-41 (1967), SAND93-3957 (1994).

Background (SAND-II-SNL)

$$A_i^{[k]} = \sum_{j=1}^{m} \bar{\sigma}_{i,j}^{[k]} \Phi_j^{[k]} \prod_{r=1}^{3} e^{-N_r * X_r * \bar{\sigma}_{r,j}}$$

→

j is energy index
i is foil index
k is iteration index
N is foil cover nuclei density
X is foil cover thickness
σ_r is foil cover removal cross-section
σ_i is foil reaction cross-section
Φ is integral flux
bar above means energy averaged

$$w_{i,j}^{[k]} = \frac{\frac{1}{2}\left(A_{i,j}^{[k]} + A_{i,j-1}^{[k]}\right)}{A_i^{[k]}}$$

→ $j = 2, 3, \ldots, m$

$$C_j^{[k]} = \frac{\sum_{j=1}^{n} w_{i,j}^{[k]} \ln\left(\frac{A_i}{A_i^{[k]}}\right)}{\sum_{j=1}^{n} w_{i,j}^{[k]}}$$

→ $$\varphi_i^{[k+1]} = \varphi_i^{[k]} \mathrm{e}^{\left(C_j^{[k]}\right)}$$

Ref's: AFWL-TR-67-41 (1967), SAND93-3957 (1994).

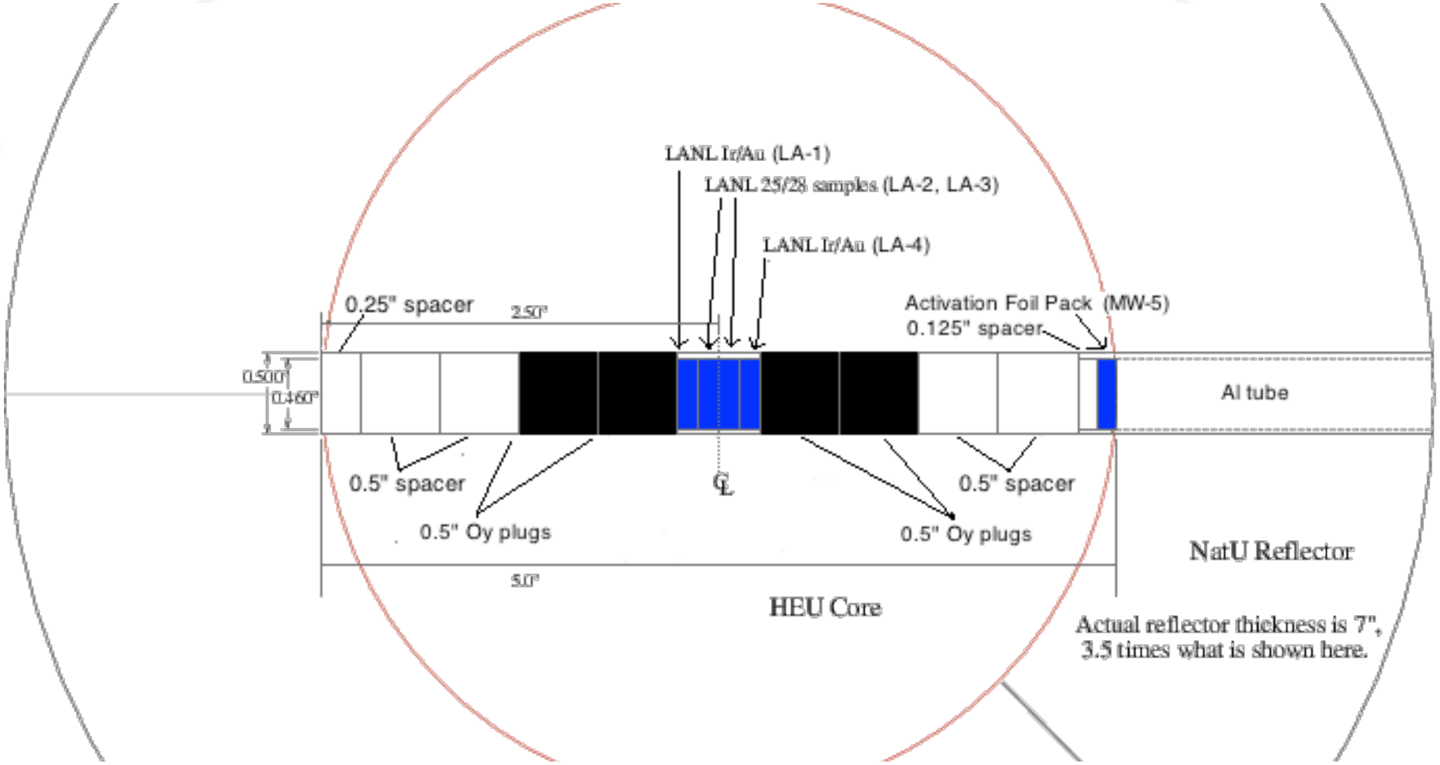
COMET/ZEUS Experiments

- Four irradiations on COMET/ZEUS
  - SEP 2011 targets at bottom reflector
    - Au
  - SEP 2012 – targets at bottom reflector
    - Al-Au (0.67% + 1 Cd covered), Cu, Co, Mn-Cu, Nb, and Ti
  - DEC 2012 – targets near center of core
    - Al-Au (0.67% + 1 Cd covered), Mo, W, Sc, Ni, Fe, V, and Ti
  - AUG 2013 – targets near center of core
    - Al-Au (0.67% + 1 Cd covered), Cu, W, Sc, Ni, Fe, and Ti

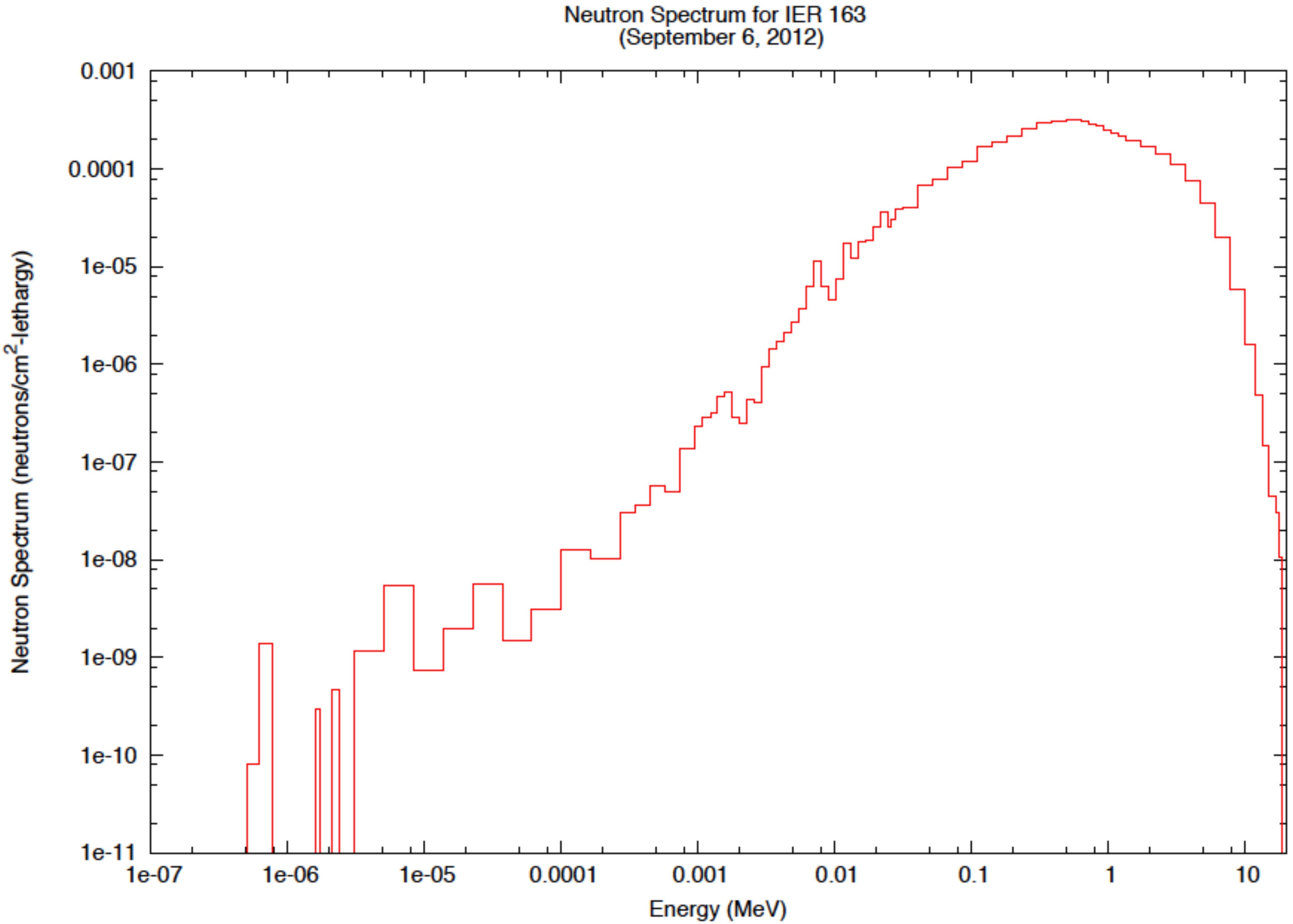
Flattop Experiments

- Three irradiations on Flattop
  - JUN 2013 – fuel plugs on one side
    - Sc, Ti, Ni, and Cu at core / reflector interface
  - JUL 2014 – fuel plugs symmetric
    - Sc, Ti, Ni, and Cu at core / reflector interface
  - AUG 2014 – fuel plugs on one side
    - Sc, Ti, Ni, and Cu at core / reflector interface

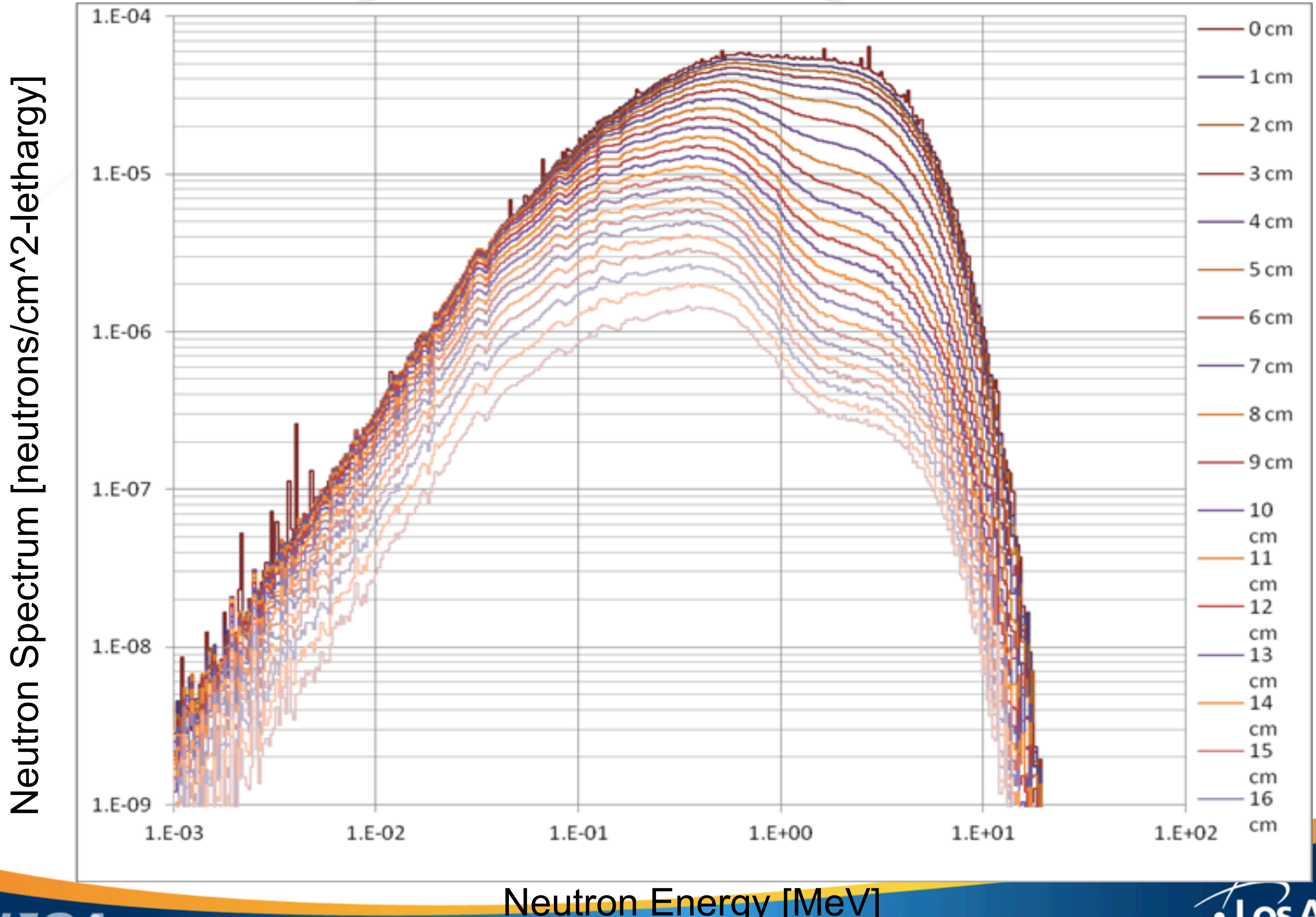
Flattop Irradiation – JUL 2014



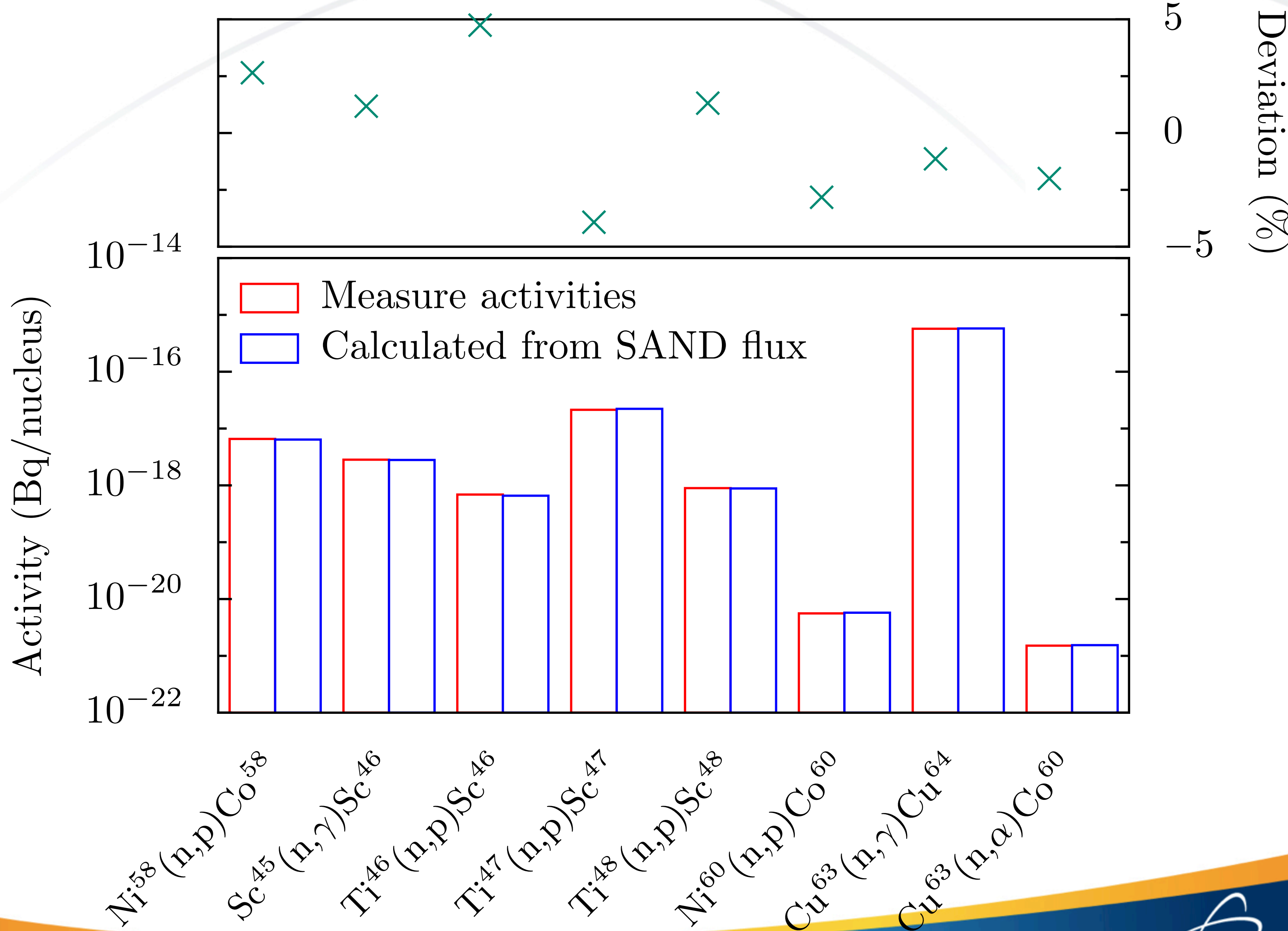
MCNP Calculations for COMET/ZEUS



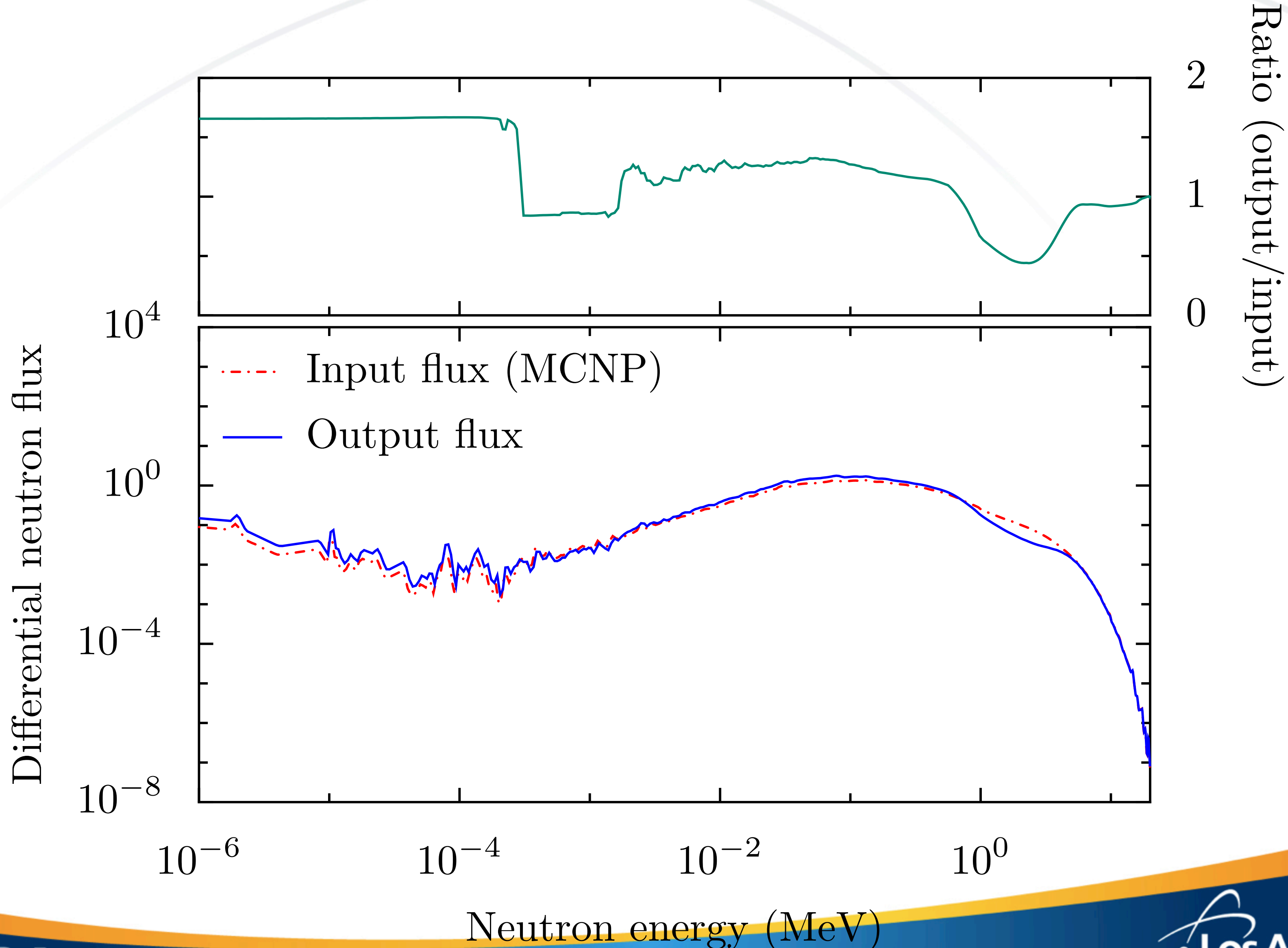
MCNP Calculations for Flattop



Results for Flattop



Results for Flattop (cont'd)



Improvements

- Incorporate IRDF 2002 cross-section library into SANDII-SNL (update SNL library) and potentially IRDFF library (up to 60 MeV)
- Incorporate > 20 MeV reactions using data from TALYS / TENDL for LANL Isotope Production Facility (IPF) neutron spectrum characterization (100 MeV)
- Evaluate use of alternate statistical techniques (e.g. maximum likelihood) and least-squares adjustment codes (LSL-M2, STAY'SL) for neutron spectrum unfolding / adjustment

Conclusions

- MCNP simulated spectra agree with experimental measurements
  - Limited by statistics at low-energies
  - Some activation foils have low activities
- Experiments will continue to be conducted to understand / characterize the neutron spectra of assemblies at NCERC

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