The ORSphere Benchmark Evaluation and Its Potential Impact on Nuclear Criticality Safety

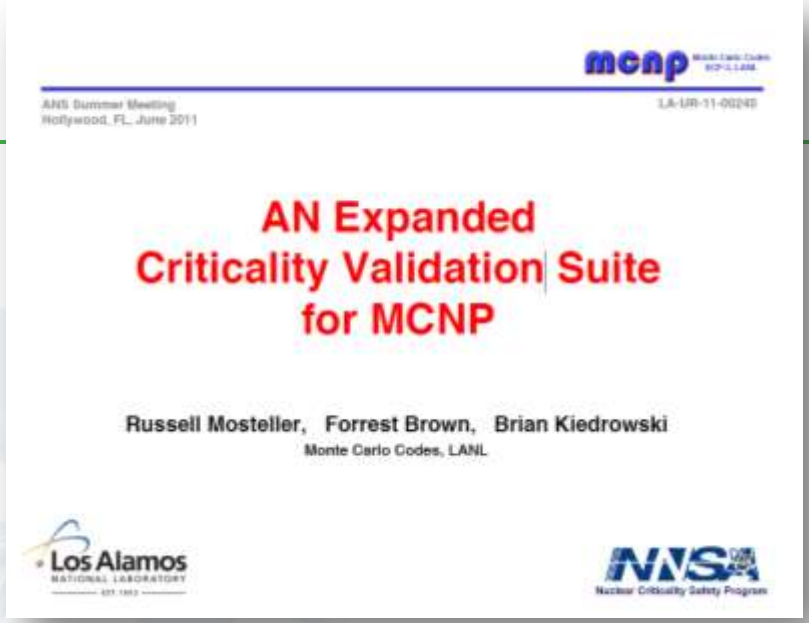
John D. Bess
Margaret A. Marshall
J. Blair Briggs
Idaho National Laboratory

NCSD 2013
Wilmington, NC
September 29 – October 3, 2013

This paper was prepared at Idaho National Laboratory for the U.S. Department of Energy under Contract Number (DE-AC07-05ID14517)

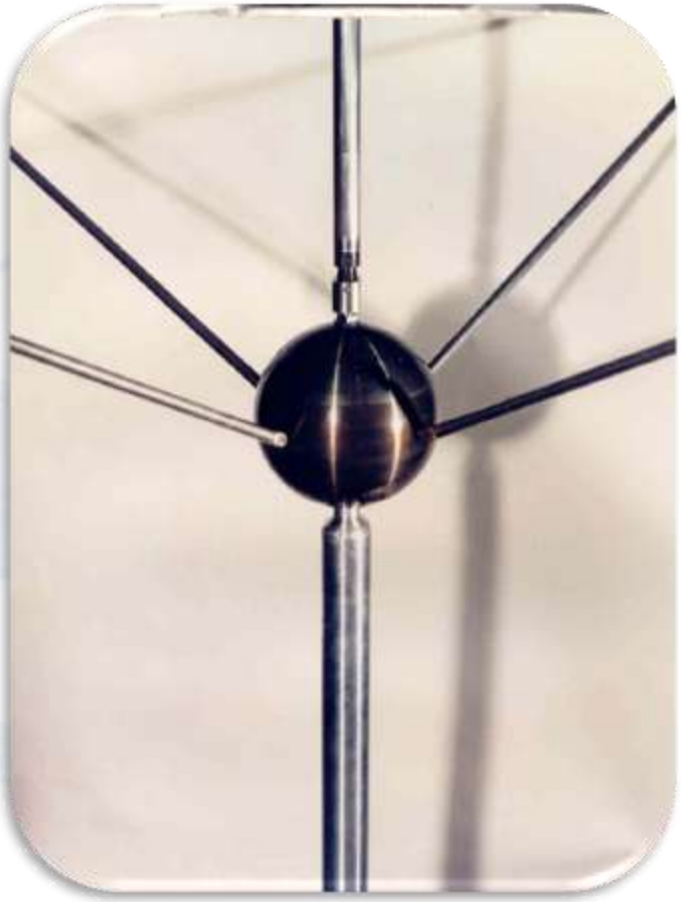
Introduction

- ORSphere critical configurations evaluated
- Compared with existing bare HEU metal benchmark data
- What is the impact on Nuclear Criticality Safety?

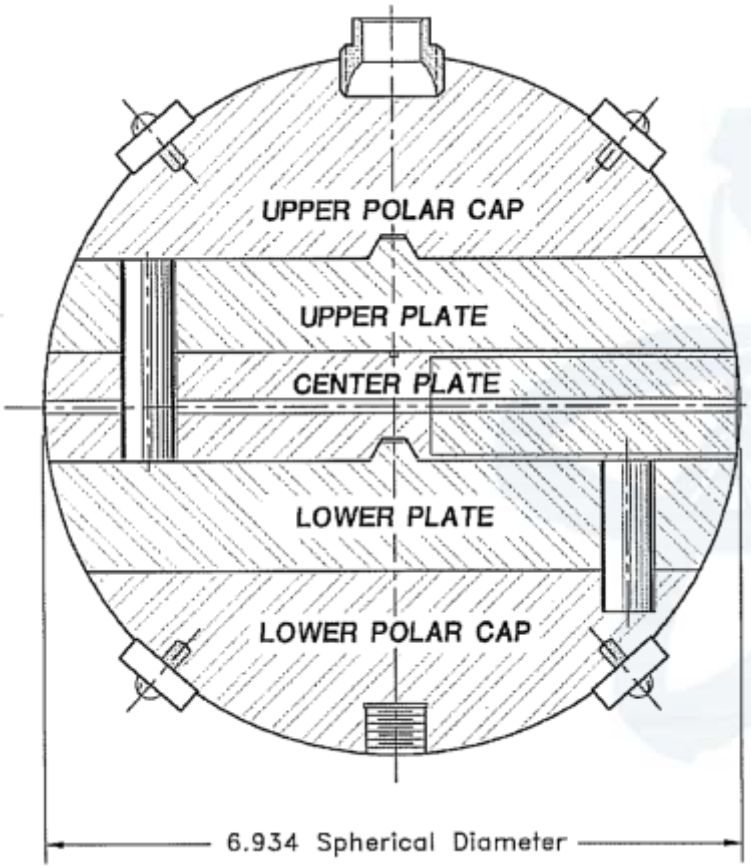


ORCEF Sphere (ORSphere) Experiments

- 1971
- Two spheres
  - One slightly supercritical
  - Machined radius
  - One slightly subcritical
- Experimentally measured corrections
- More accurate than GODIVA critical mass
  - ~60% reduction in uncertainty



ORCEF Sphere Experiments



- Radii of 8.80618 and 8.74395 cm
- Density of 18.74 g/cm^3
- 93.2 wt.% ^{235}U
- Additional physics measurements
  - Void worth
  - Button worths
  - Prompt neutron decay
  - Delayed neutron fraction
  - Fission rate distribution

ORCEF Measurement Uncertainties

- Very precise measurement capabilities at Y-12
  - Dimensions
    - ±0.0001 in.
  - Mass
    - ±0.01 g
  - Isotopics
    - ±1% ^{234}U
    - < ±0.02 wt.% ^{235}U & ^{236}U
  - Impurities
    - ~500 ppm average content
- John T. Mihalczo
  - Experimenter still available for collaboration
- Further information available
  - ORNL/TM-2012/32

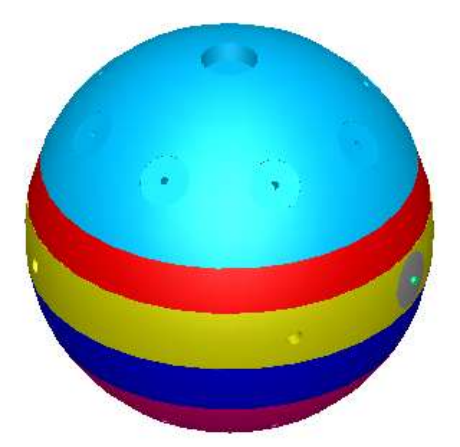
Parameter	Perturbation ±1σ	Case 1 $\pm\Delta k_{eff}$ (1σ)	Case 2 $\pm\Delta k_{eff}$ (1σ)
Reactivity Measurement[(a)]	2.0 ¢	0.00013	0.00013
Radius	2.54×10^{-4} cm	0.00005	0.00005
Curve of Ellipsoidal Parts	0.12 % (volume)	0.00066	0.00066
Lower Polar Cap/Lower Plate Gap	2.54×10^{-4} cm	0.00004	0.00004
Lower Plate/Center Plate Gap	2.54×10^{-4} cm	0.00007	0.00011
Center Plate/Upper Plate Gap	2.54×10^{-4} cm	0.00009	0.00008
Upper Plate/Upper Plate Cap Gap	2.54×10^{-4} cm	0.00006	0.00005
Tilt Angle	Effect of No Gap ÷ 2√3	-0.00011	NA
Diametral Hole Diameter	2.54×10^{-4} cm	<0.00001	<0.00001
Diametral Rod Diameter	2.54×10^{-4} cm	<0.00001	<0.00001
Diametral Rod Length	2.54×10^{-4} cm	<0.00001	<0.00001
Brass Bolt Diameter	0.033274 ÷ 2√3 cm	<0.00001	<0.00001
Brass Bolt Height	2.54×10^{-4} cm	0.00001	0.00001
Bottom Section Mass	1 g (Case 1) 0.01 g (Case 2)	0.00006	<0.00001
Center Section Mass	0.01 g	<0.00001	<0.00001
Top Section Mass	0.01 g	<0.00001	<0.00001
Diametral Filler Rod Mass	0.014 g	<0.00001	<0.00001
Parts and Voids within Sphere	2.54×10^{-4} cm	<0.00001	<0.00001
Uranium Fraction	0.0005 gU/g Total	0.00003	0.00003
Silicon	20% ÷ √3	0.00001	0.00001
Boron	70% ÷ √3	0.00002	0.00002
Carbon	20% ÷ √3	-0.00003	-0.00003
Other Impurities	70% ÷ (√11 × √3)	-0.00004	-0.00004
^{234}U Content	1%	-0.00004	-0.00004
^{235}U Content	0.0177 wt.%	-0.00009	-0.00009
^{236}U Content	0.0130 wt.%	0.00002	0.00002
Brass Density	0.2 g/cm^3	0.00006	0.00006
Brass Composition	Red vs. Yellow Brass	0.00001	0.00001
Temperature	2 °C	0.00004	0.00004
Total Experimental Uncertainty		**0.00071**	**0.00070**

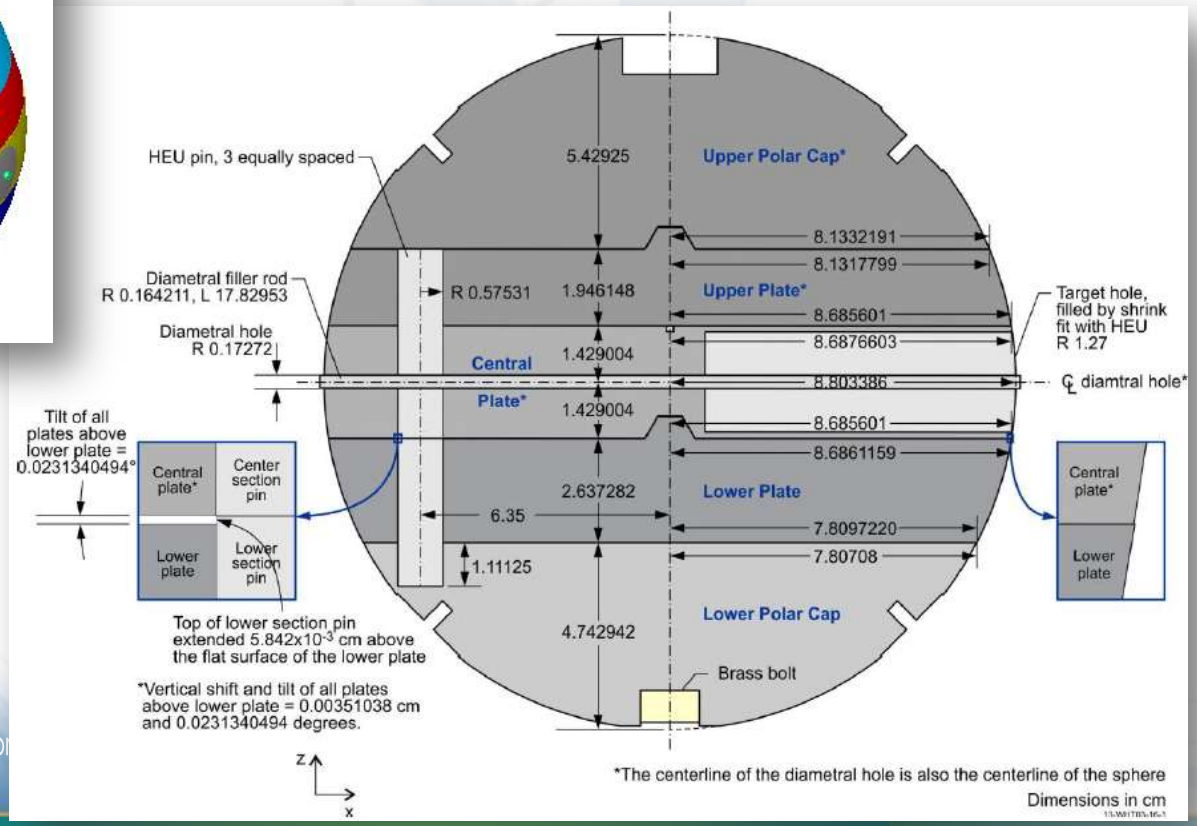
(a) Reactivity uncertainty includes reproducibility, reactor period measurement, and delayed neutron parameter uncertainties.

Benchmark Results

Case	Model	Benchmark Experiment k_{eff}	±	σ	Calculated[a] k_{eff}	±	σ	$\frac{C-E}{E}$ %
1	Detailed	1.0026	±	0.0007	1.00385	±	0.00002	0.13
	Simple	1.0031	±	0.0007	1.00441	±	0.00002	0.18
2	Detailed	0.9966	±	0.0007	0.99821	±	0.00002	0.17
	Simple	0.9966	±	0.0007	0.99826	±	0.00002	0.17

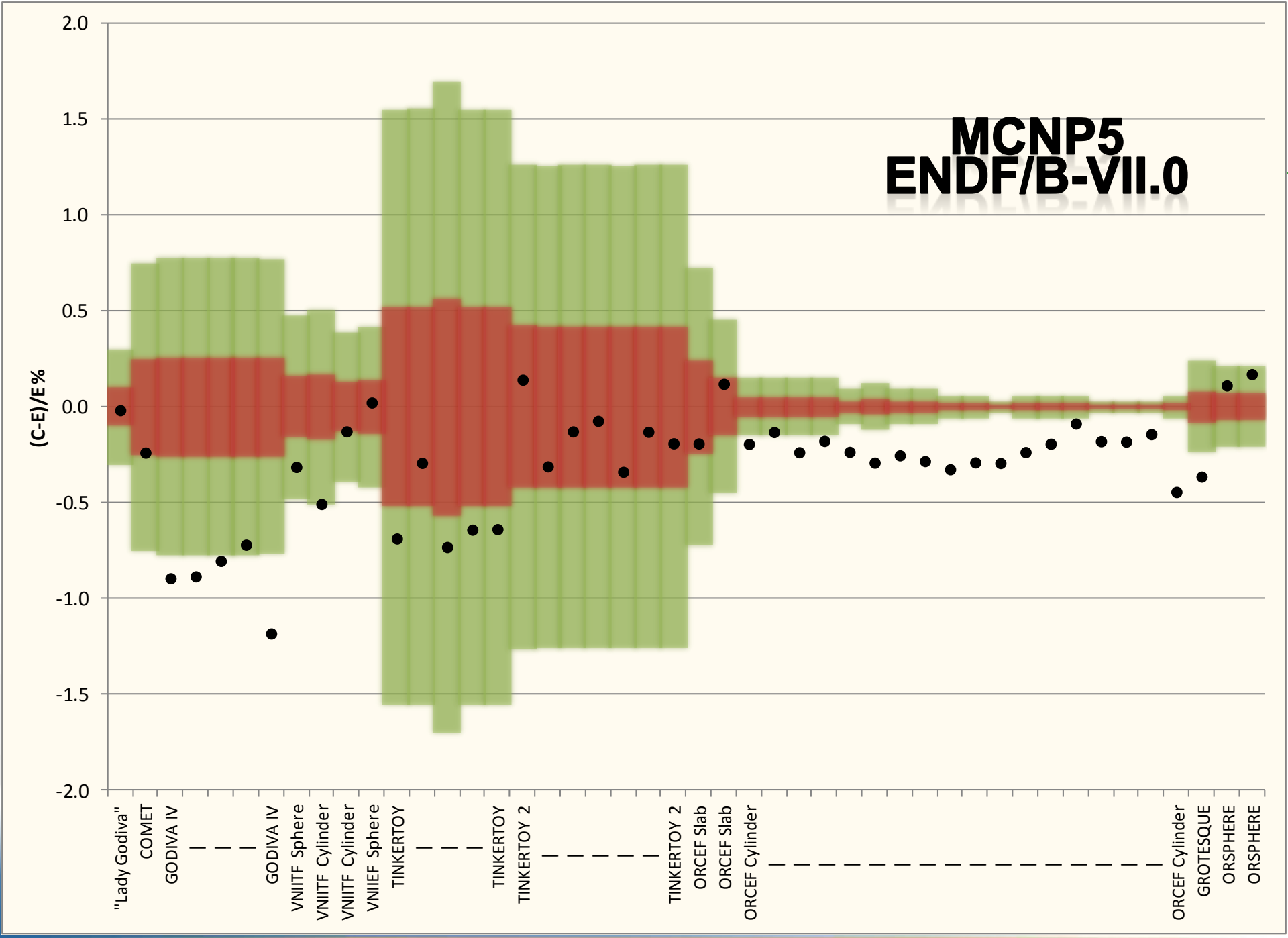
(a) Results obtained using 500,000 histories for 2650 cycles, skipping the first 150 cycles using MCNP5-1.60 [5] and ENDF/B-VII.0 neutron cross section libraries [6].





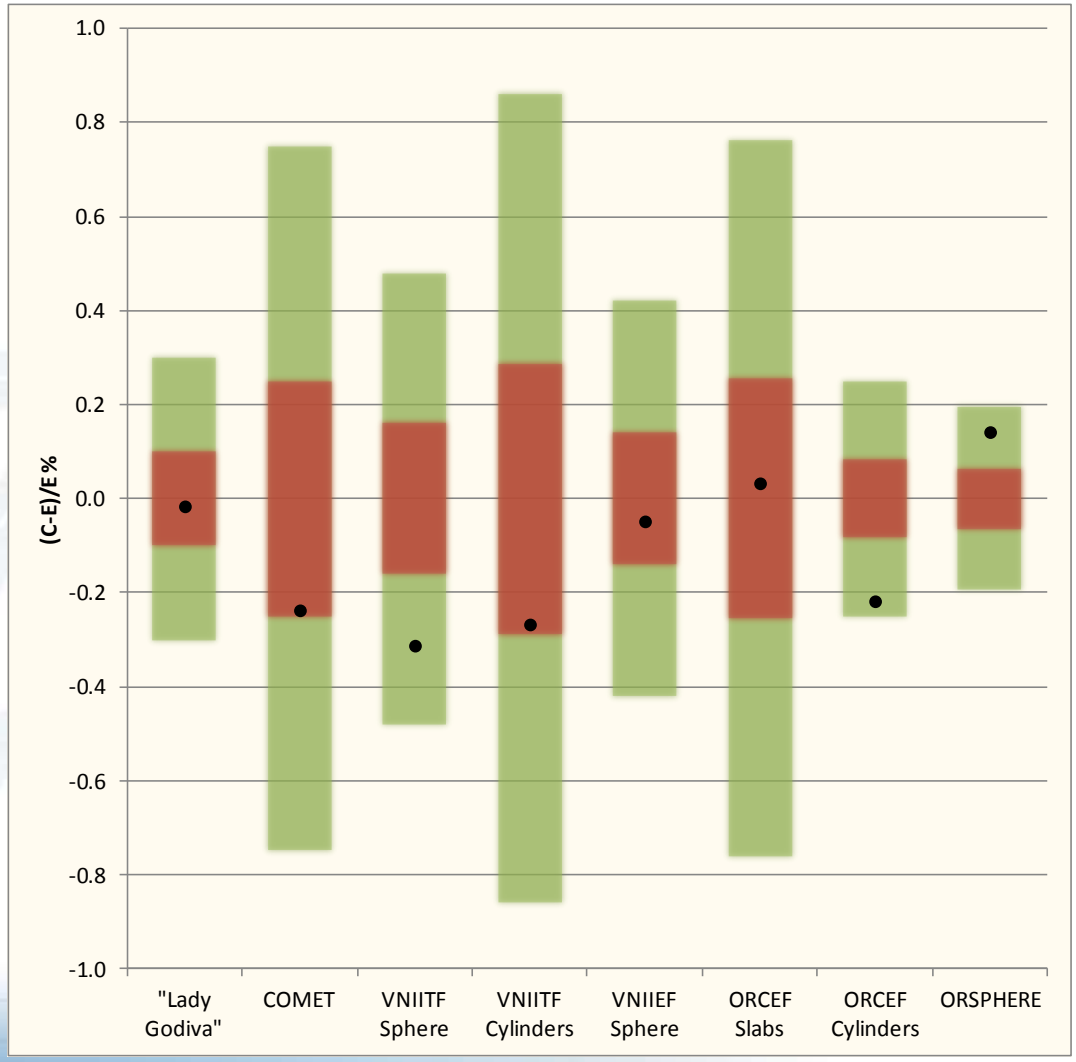
Bare HEU Benchmark Experiment Comparison

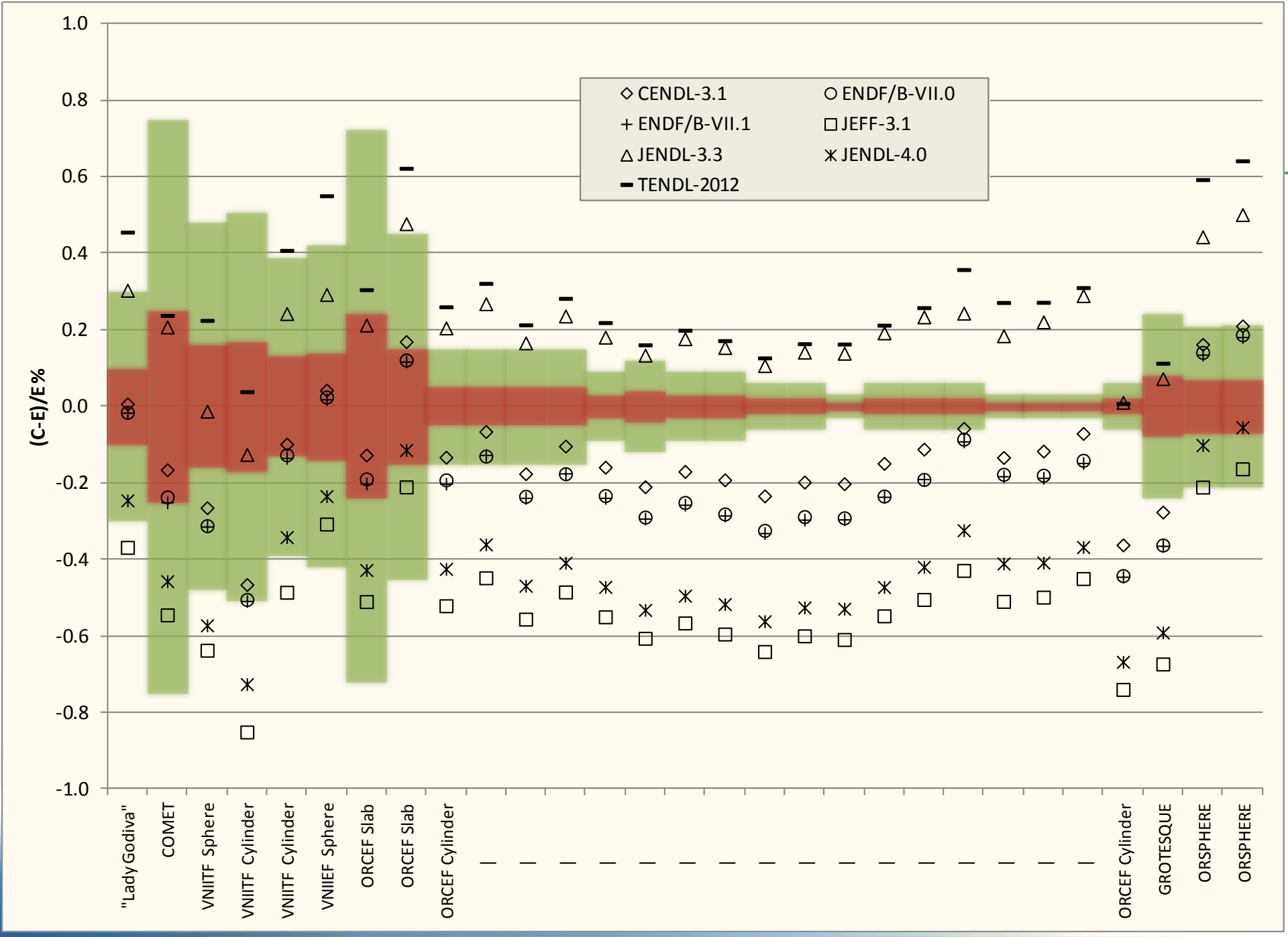
- 46 Experiments
- ^{235}U Enrichment
  - "Lady Godiva"
    - ~94 wt.% (no ^{236}U)
  - RFNC Spheres
    - ~90 wt.% (no ^{236}U)
  - VNITF Cylinders
    - ~96 wt.% (no ^{236}U)
  - LANL and ORNL
    - ~93 wt.%
    - (no ^{236}U in COMET)
    - Oralloy
- Primary Uncertainty Sources
  - Fuel mass
  - Fuel dimensions
  - Measured distances
- High-Precision-Experiment Uncertainty Sources
  - Experimental methods or measurement
  - Limitations on "minimum" measurable quantities
  - Placement between components


MCNP5
ENDF/B-VII.0
(C-E)/E%
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
"Lady Godiva"
COMET
GODIVA IV
GODIVA IV
VNIITF Sphere
VNIITF Cylinder
VNIITF Cylinder
VNIIEF Sphere
TINKERTOY
TINKERTOY
TINKERTOY 2
TINKERTOY 2
ORCEF Slab
ORCEF Slab
ORCEF Cylinder
ORCEF Cylinder
GROTESQUE
ORSPHERE
ORSPHERE

Spheres, Slabs, and Cylinders

- Consolidate data for basic geometries
- Combined correlated experiments
  - Variance-weighted average
  - Standard deviation




1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
(C-E)/E%
CENDL-3.1
ENDF/B-VII.0
ENDF/B-VII.1
JEFF-3.1
JENDL-3.3
JENDL-4.0
TENDL-2012
"Lady Godiva"
COMET
VNIITF Sphere
VNIITF Cylinder
VNIITF Cylinder
VNIIEF Sphere
ORCEF Slab
ORCEF Slab
ORCEF Cylinder
ORCEF Cylinder
GROTESQUE
ORSPHERE
ORSPHERE

Conclusions – I

- **ORSphere critical experiments evaluated**
  - **Additional measurements being evaluated for inclusion within IRPhEP Handbook**
  - **~70 pcm uncertainty**
  - **ENDF/B-VII calculations within 0.2% (3σ)**
  - **Higher precision experiments than GODIVA**
    - **MCNP + ENDF/B-VII tailored to fit to GODIVA**
    - **Revision of HEU-MET-FAST-001 uncertainties might be necessary**
      - **Currently ~100 pcm**
      - **Expect ~180 pcm**

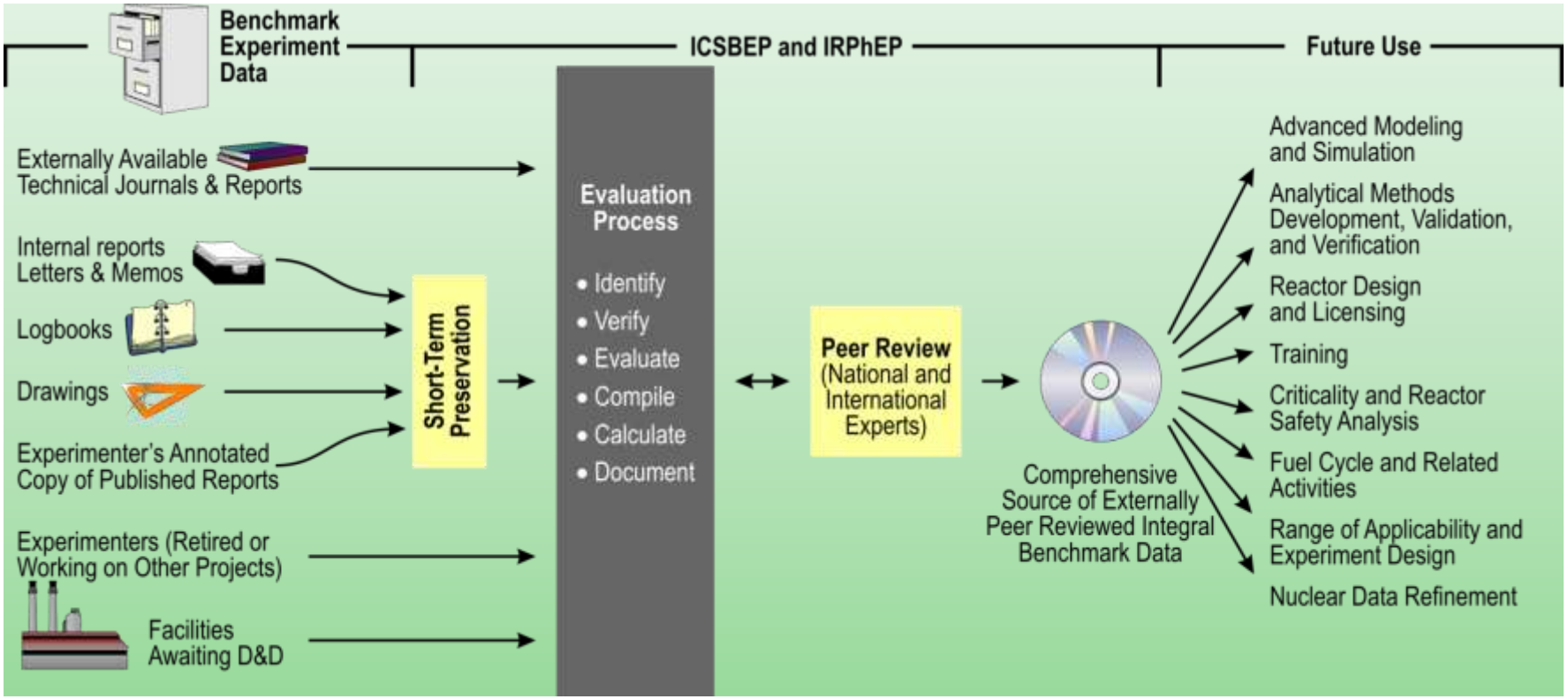
Conclusions – II

- Comparison of 46 bare HEU benchmark experiments
  - Basic spherical, slab, and cylindrical geometries are within 3σ of the benchmark values
    - When accounting for variations in correlated experiments with increased uncertainties
  - Reasonable results for spheres and slabs
  - Cylindrical system calculations appear low
    - Even for complex systems with cylinders
    - Need to investigate scatter in ORCEF cylinders
  - Selection of nuclear data library has larger impact on calculated results than variations within a given experimental series

Questions?

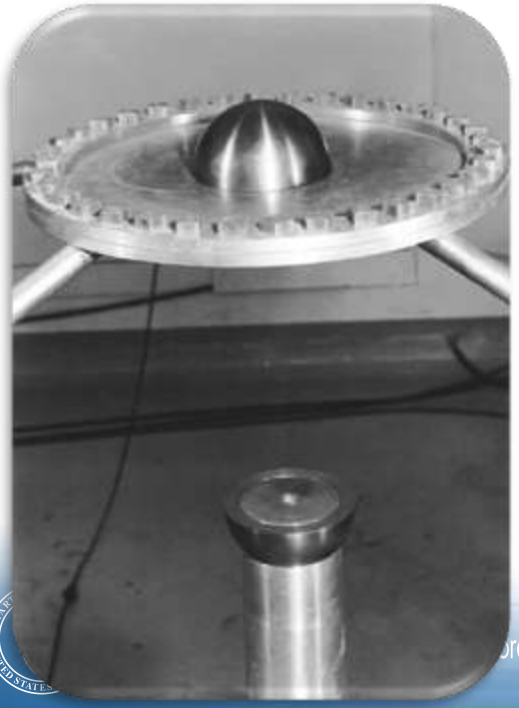
Extra Slides

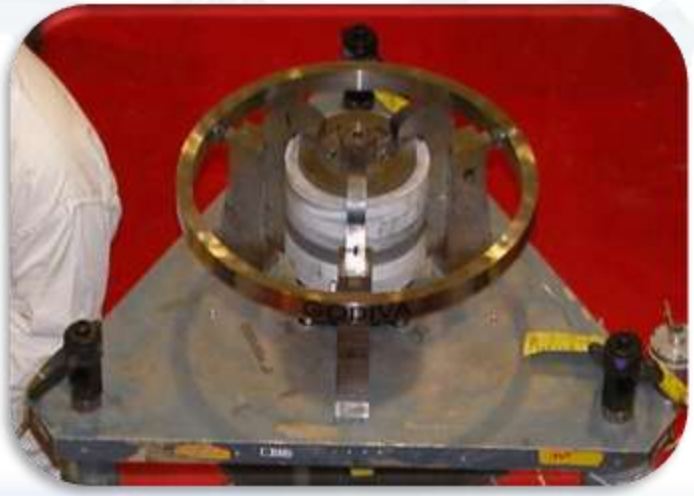
The Benchmark Evaluation Process



Bare HEU Benchmark Experiments – LANL

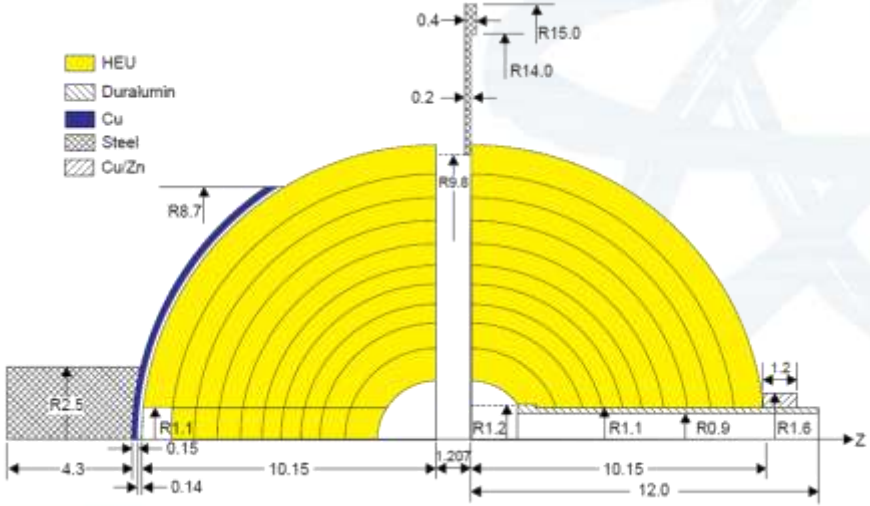
- **Los Alamos National Laboratory**
  - **GODIVA (1) : HMF-001**
  - **COMET (1) : HMF-078**
  - **GODIVA IV (5) : HMF-086**

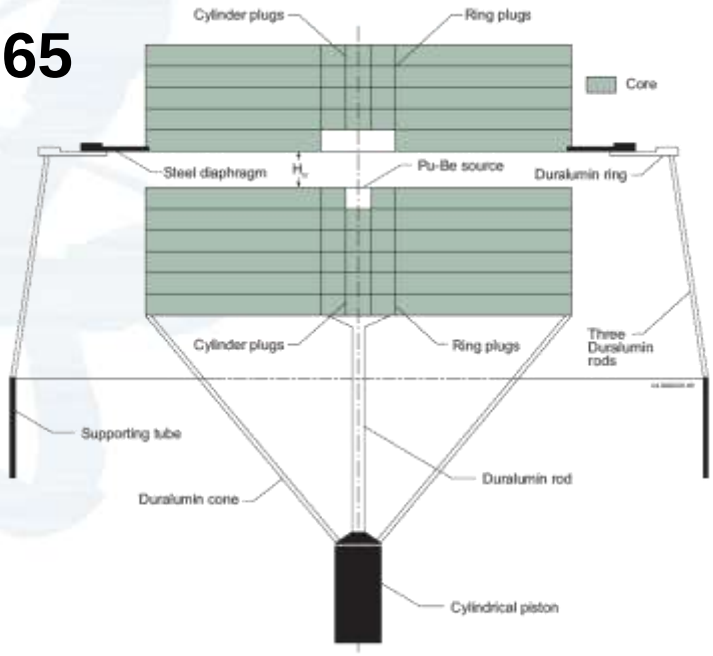




Bare HEU Benchmark Experiments – VNIITF

- **Russian Federal Nuclear Center – Institute of Technical Physics (RFNC-VNIITF)**
  - **Sphere (1) : HMF-008**
  - **Cylinders (2) : HMF-015, -065**

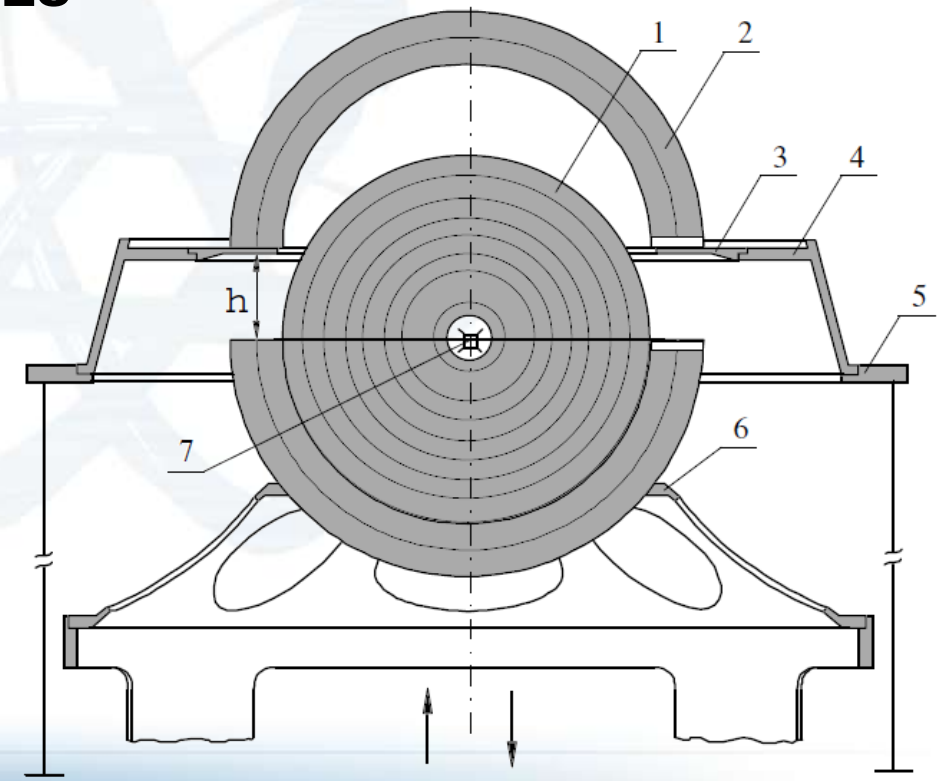




Bare HEU Benchmark Experiments – VNIIEF

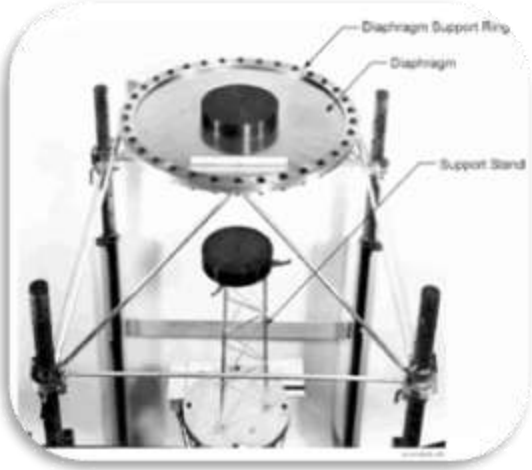
- **Russian Federal Nuclear Center – Institute of Experimental Physics (RFNC-VNIIEF)**
  - **Sphere (1) : HMF-018**

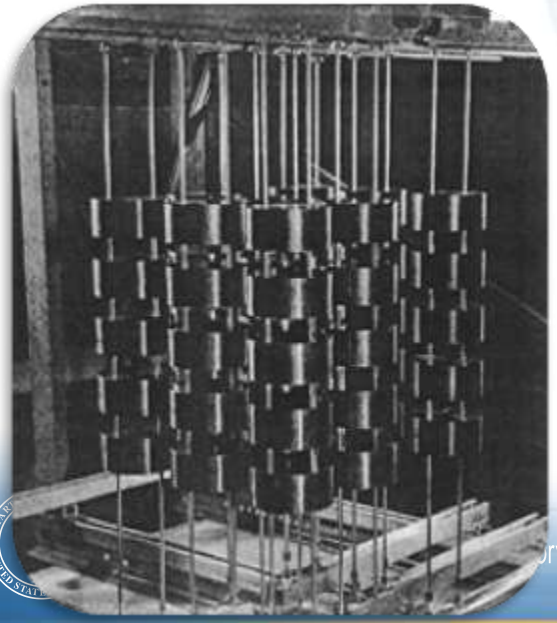
1 – lower core unit
2 – upper core unit
3 – steel diaphragm
4 – upper support
5 – attachment
6 – lower support
7 – neutron source

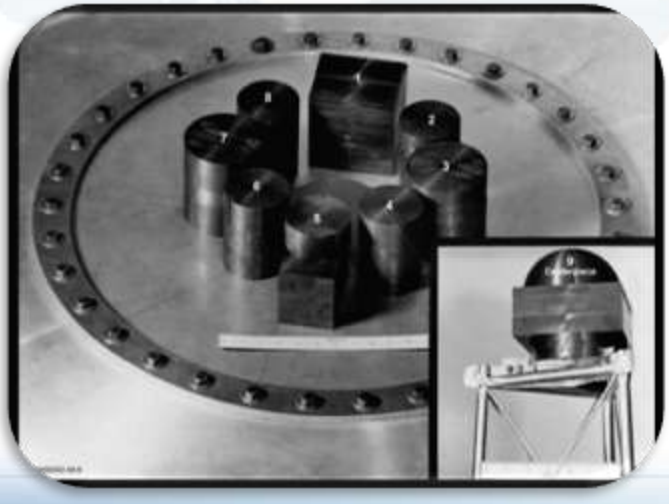


Bare HEU Benchmark Experiments – ORCEF

- **Oak Ridge Critical Experiments Facility**
  - **Slabs (2) : HMF-007**
  - **TINKERTOY (12) : HMF-023, -026**
  - **Cylinders (18) : HMF-051**
  - **GROTESQUE : HMF-081**







Eigenvalue Calculations

- Monte-Carlo N-Particle (MCNP) 5-1.60
  - 1050 cycles, skipped 50, 1E6 histories/cycle =1E9
  - Statistical uncertainty 0.00002 Δk
- ENDF/B-VII.0 neutron data
  - ENDF/B-VII.1 has ENDF/B-VI.8 delayed neutron data for uranium isotopes and covariance data
    - Negligible impact on k_{eff}
- Compared against benchmark experiment eigenvalue and uncertainty

HEU-MET-FAST-001 Uncertainty

- **Original uncertainty:**
  - **0.3 % corrected mass uncertainty**
  - **Perturbation of radius, conserving density**
  - **Δk of 0.001 (1σ)**
    - **ONEDANT**
    - **27-g ENDF/B-IV**

Correction	Percent Change		
Critical Extrapolation	+2.00	±	0.20
Diaphragm Correction	-0.58	±	0.06
Incidental Reflection	+0.29	±	0.15
Model Defect	-0.21	±	0.07
Filling Voids (inc. Shell Dimensions)	-0.87	±	0.17
Impurity Removal	+0.04	±	0.00
Total	**+0.67**	**±**	**0.32**

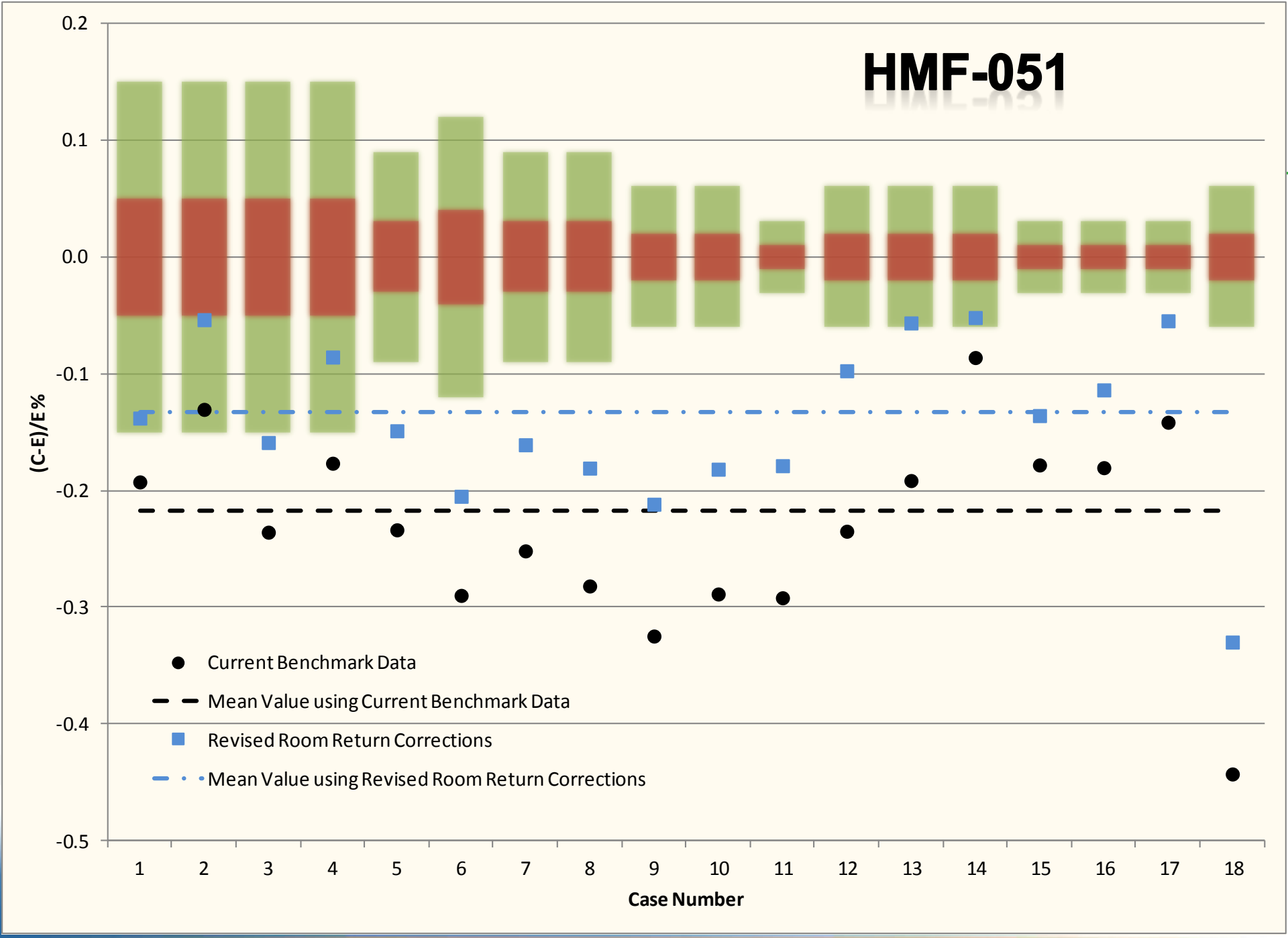
HEU-MET-FAST-001 Uncertainty Investigation

- Significant details regarding uncertainty analysis not available
- Repetition of uncertainty
  - ±0.32% in surface mass
  - Δk of 0.00089 (1σ)
    - MCN5
    - ENDF/B-VII.0
- However…
- Perturbation of mass density while retaining constant radius
  - Δk of 0.00265 (1σ)
  - Factor of ~3×

HEU-MET-FAST-001 Uncertainty Reevaluation

- Divided original mass uncertainty into components
  - Mass
    - Extrapolation
    - Room return
    - Impurity
  - Dimensions
    - Support structure
    - Model defect
    - Filling voids
- Scaled evaluated uncertainties for density and radius perturbations
  - 0.25 % mass uncertainty
  - 0.19 % radius uncertainty
  - Δk of 0.00213 (1σ)
    - Comparable to other LANL experimental uncertainties

Note: Isotopic uncertainty was also calculated, and is negligible


HMF-051
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
(C-E)/E %
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Case Number
Current Benchmark Data
Mean Value using Current Benchmark Data
Revised Room Return Corrections
Mean Value using Revised Room Return Corrections