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Title:	Seeking Reproducibility in Fast Critical Assembly Experiments
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Seeking Reproducibility in Fast Critical Assembly Experiments

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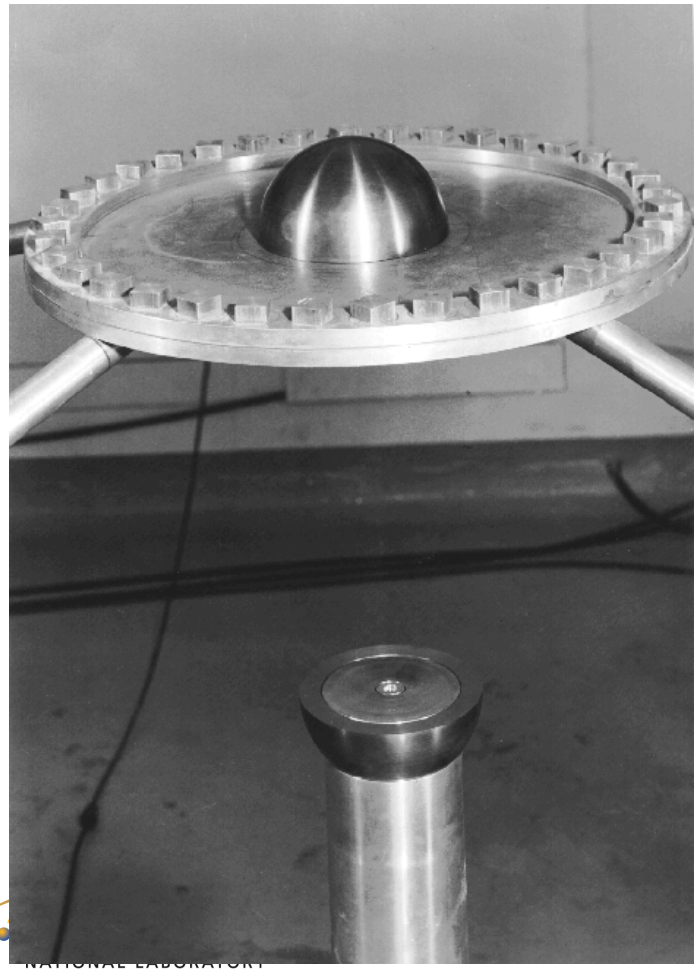
Presentation at the ND2013 Conference, New York, NY, March 4-8, 2013

Abstract

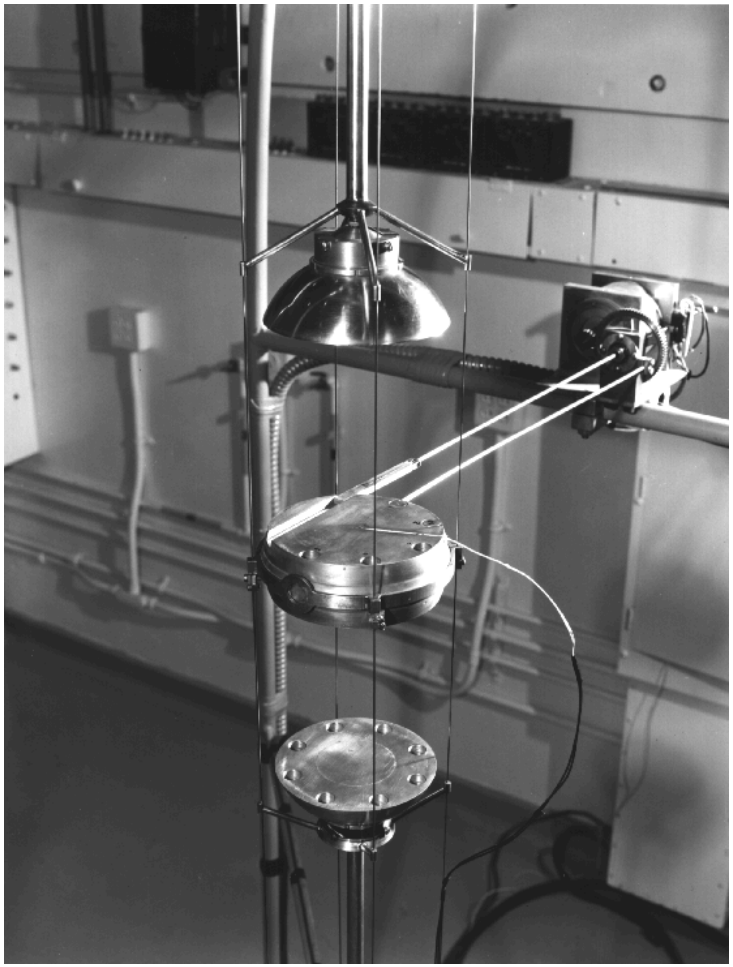
Critical assembly experiments have taken on a preeminent role in the understanding of nuclear data uncertainty quantification within simulations. Differential nuclear data, e.g. cross sections or emission spectra, often have uncertainties that lead to larger than desirable uncertainties in integral quantities in simulations, e.g. k-effective or activations. Further, correlations between differential data are difficult to establish and often unavailable. Critical assembly measurements typically provide much tighter constraints on the integral quantities of interest and add the missing correlations between the differential data. Given the importance of critical assembly measurements in providing the key constraints within many applications, it is vital to understand the uncertainties in these measurements. Unfortunately, many of the experiments were performed at a time when expectations were considerably lower then the goals of today, often 0.5% uncertainty in k-effective was adequate where 0.1-0.2% is now desired. Re-examination of articles and logbooks has shown the excellent work often done and led to modern benchmark evaluations near these desired accuracies. However, uncertain or even missing data have left questions whose time is gone. There are cases of remarkable consistency; the three key US, French and Russian bare plutonium assemblies provide confidence that we have a solid understanding of plutonium-239. It is thus more deeply troubling that the bare highly-enriched uranium (HEU) assemblies, where there are considerably more data, are discrepant substantially beyond the assigned uncertainties. This is most likely due to errors in accounting for or the reporting of experimental uncertainties but it raises the question of the overall reproducibility of the critical measurements. A proposal for a new high-precision HEU benchmark has been accepted and scheduled for completion in 2014 at the US National Critical Experiment Research Cernter (NCERC) with the design of this suite of experiments ongoing in 2013. These measurements will examine the reproducibility of the systematic uncertainties. Variations will attempt to examine systematic effects due to materials characterization, experimental repeatability, 1-D, 2-D and 3-D perturbations, and the influence of the experimental facility, e.g. assembly structure, detector systems and room return. A discussion of the planned experiments and analysis will be presented.

Fast Critical Assembly Experiments

Godiva



Jezebel

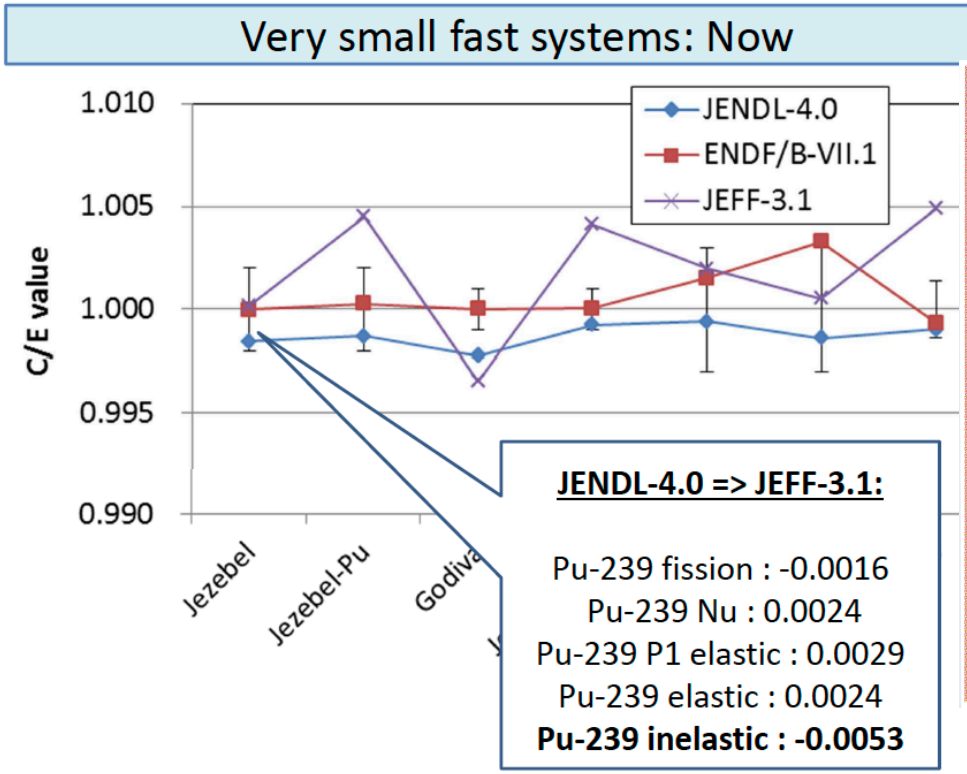


From the Draft "CIELO Paper"

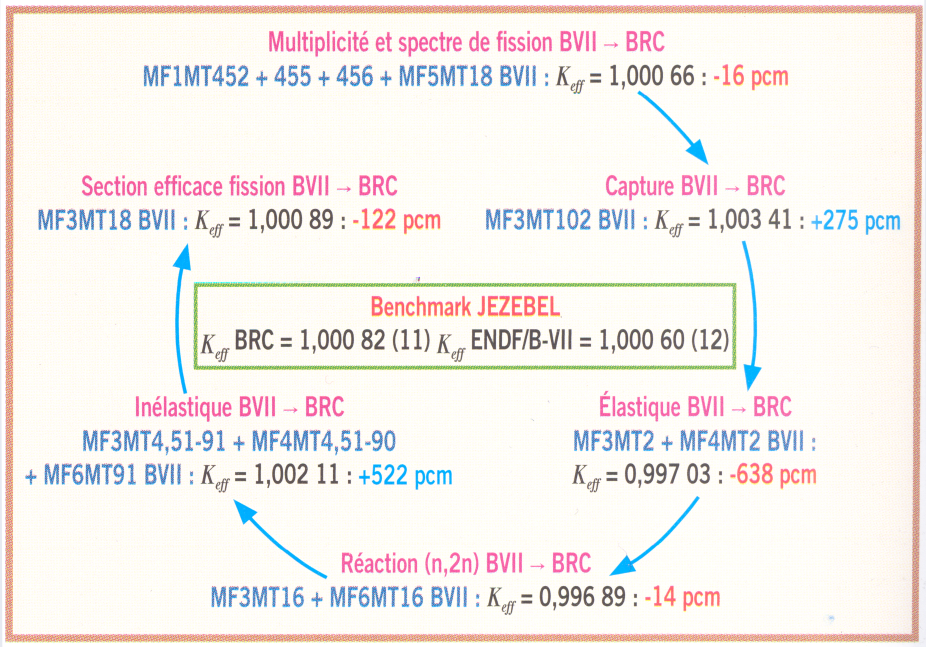
- **Compensating errors**
  - Significant compensating errors must be present in most, and ***likely all***, of the evaluations.
- **Calibration**
  - Calibration has been used in some cases in the evaluated databases to ***better match*** measured criticality of integral systems. Thus, agreement between simulated and measured criticality keff ***is not as impressive as it might seem***, though of course a common set of evaluated data were used for all the neutronics simulations of different critical assemblies (that is, calibration was not done on an assembly-by-assembly basis!). Where some calibration was done it usually involved some reasonable physics assumptions, ***and was not entirely ad-hoc***, and cross sections were ***usually*** adjusted within their uncertainty levels. Such a ***tiny calibration*** may also compensate some deficiencies in the data processing and transport calculations.

Differences in Reasons for Fast Plutonium Criticality

Japanese analysis



CEA analysis



Inelastic & elastic are modeled very differently. (PFNS effect would be larger except all evaluations use a similar approach)

Systematic What?

We tend to use uncertainty and error interchangeably.

This is not quite right.

- **Systematic Uncertainty**
  - If we measure a metric many times, we will obtain an uncertainty about a mean.
  - The uncorrelated nature allows their reduction by making more measurements.

- **Systematic Error**
  - If the calibration of our measurement is incorrect, the error is a constant bias.
    - It is the same error throughout the measurements in which it is present.
    - The correlated nature propagates its effect unchanged.
  - But, a breakthrough in understanding of the error can be used to remove it.

Physics

Physics is an observational science.

D.L. Smith and N. Otuka, Experimental Nuclear Reaction Data Uncertainties: Basic Concepts and Documentation, Nuclear Data Sheets 113 (2012) 3006–3053.

1-D Spherical Cow

When working toward the solution of a problem, it always helps if you know the answer.

Engineering

If it doesn’t work, hit it.

If it still doesn’t work, hit it with a bigger hammer.

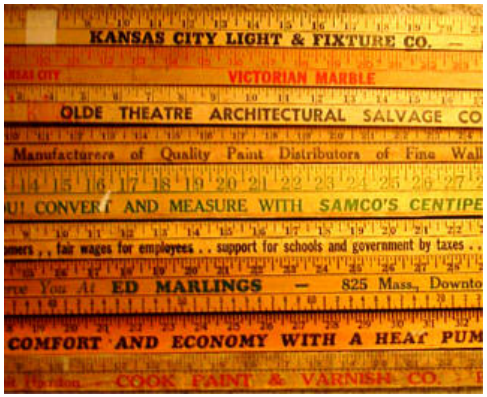
Engineering is the art of making science practical.

Duct tape is not a *perfect* solution to *anything*. But in a pinch, it's an *adequate* solution to just about everything.

Statistics

A branch of applied mathematics concerned with the collection and interpretation of quantitative data and the use of probability theory to estimate population parameters

- **Everyone lies**
  - Politicians make a career of it
  - Statisticians make a science of it



STATISTICS2013.ORG
INTERNATIONAL YEAR OF STATISTICS

There are lies. There are damn lies. And then, there are statistics.

Left to themselves, things tend to go from bad to worse.

Language and Arts

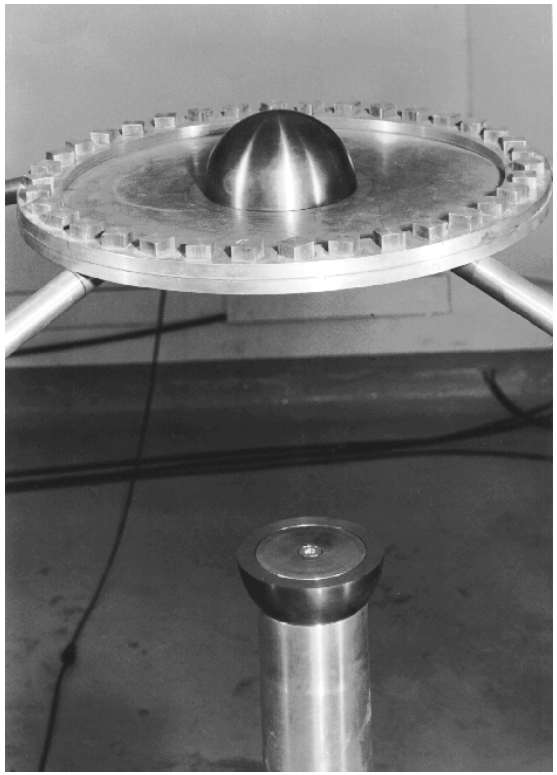
Information decays over time.

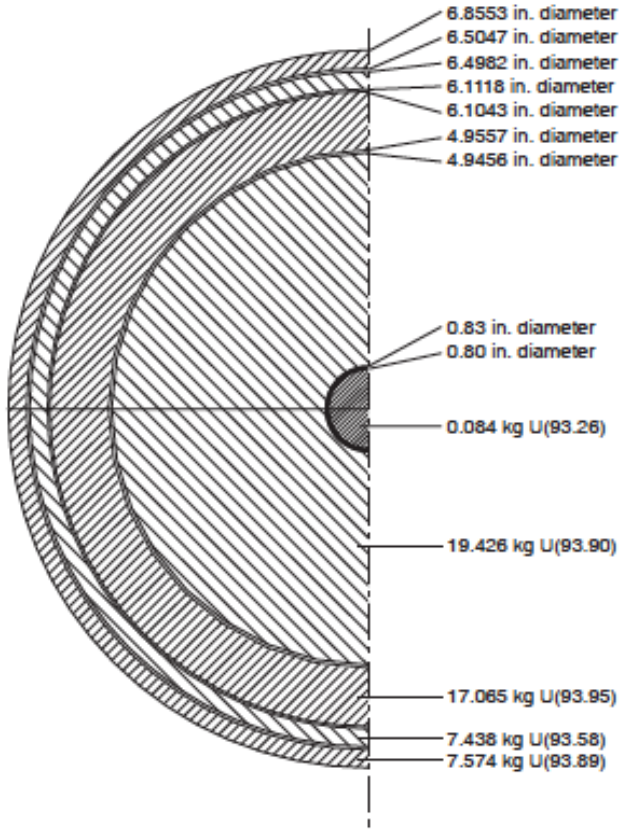
- **We focus on STEM (science, technology, engineering and mathematics)**
  - Few of us enjoy the process of documentation
  - Few of us focus on the art of documentation
- **The goals of a journal article are not those benchmark documentation**

Hubbel eXtreme Deep Field

Van Gogh Starry Night

Reality Meets Modeling

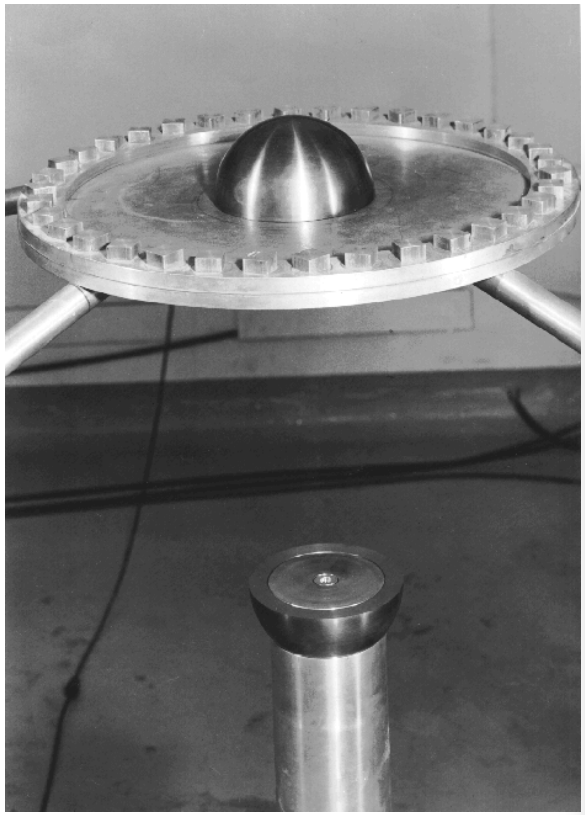




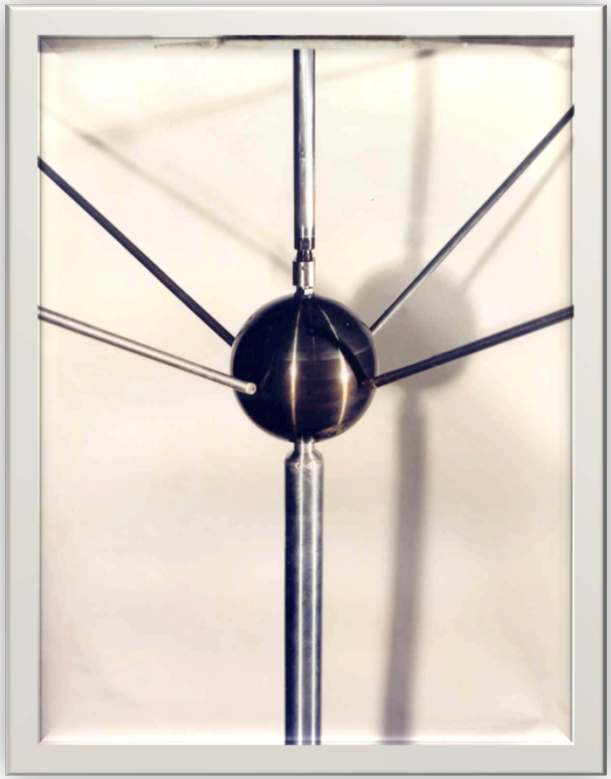
We need to take advantage of reality rather than try to model it away.

Fast Critical Assembly Experiments Overly Simplified?

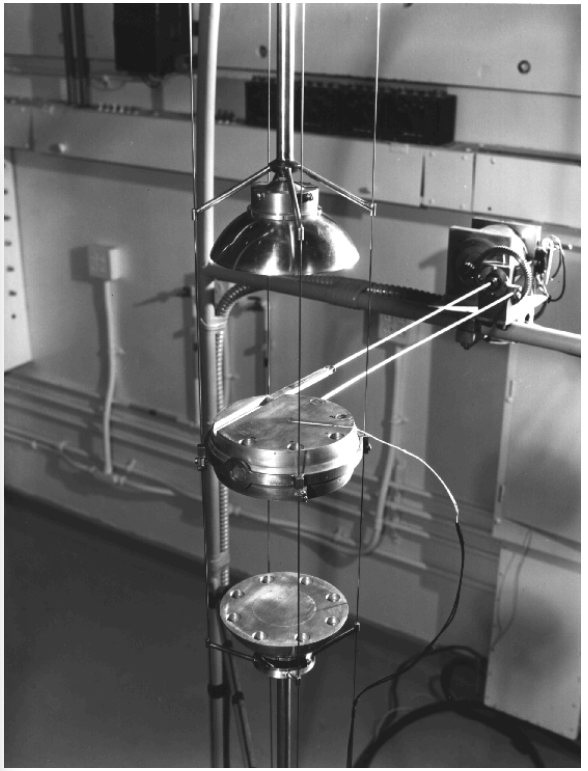
Godiva



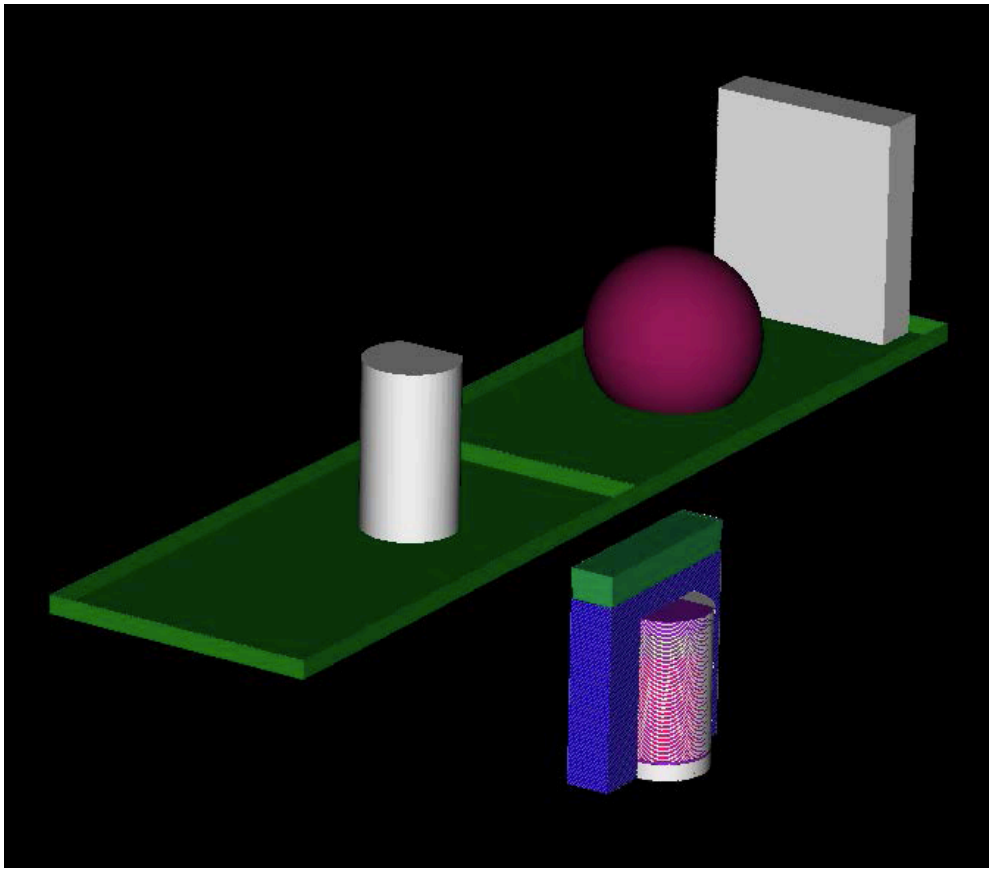
ORNL Sphere



Jezebel

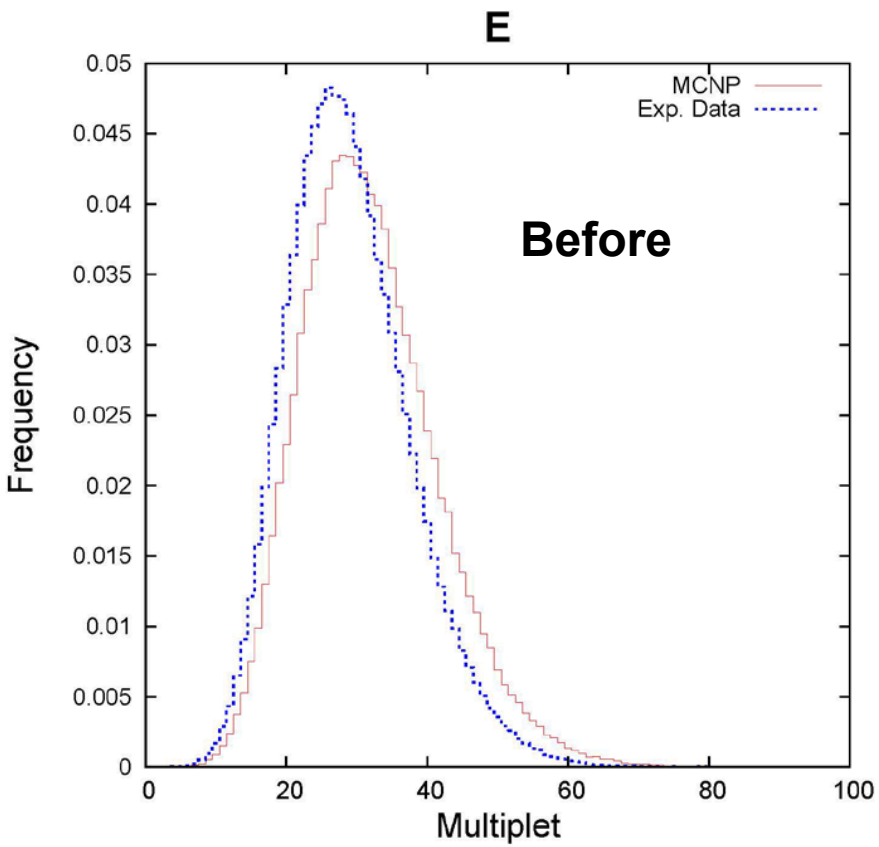


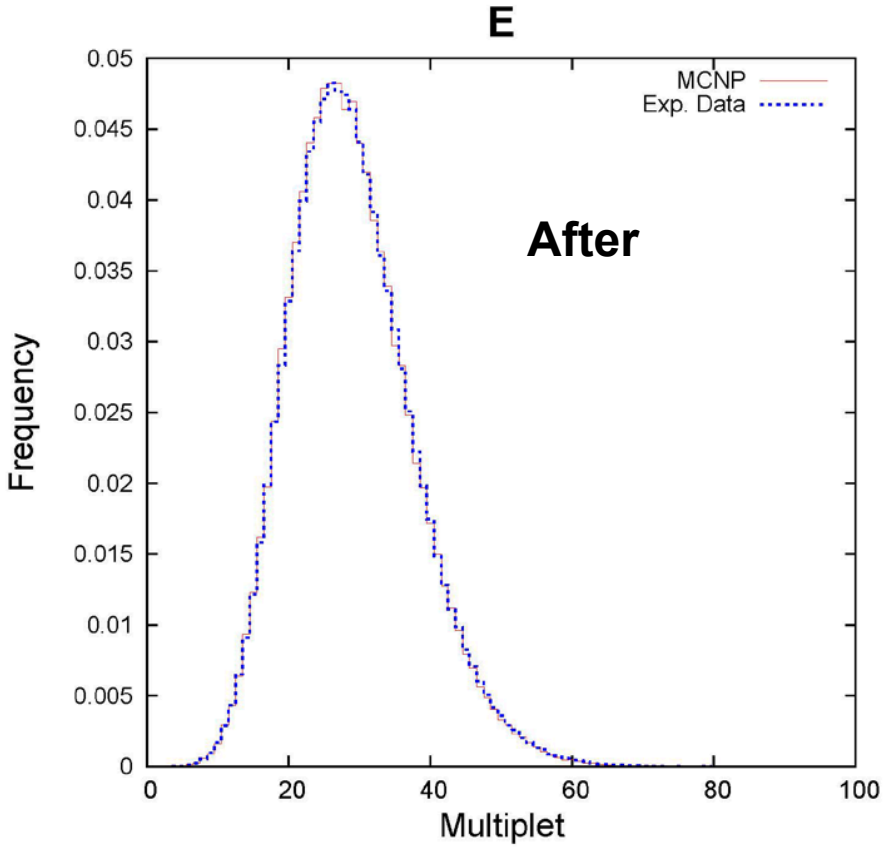
Subcritical Experiments Isolating nubar?



- **Nuetron multiplicity distribution measurements**
- **Pu-239 sub-critical sphere**
- **Fixed source**
- **NPOD detector**
  - 15 helium-3 tubes encased in polyethylene moderator
- **Five (5) thicknesses of polyethylene moderation**
  - Surrounding plutonium sphere
  - Increasingly poor fit for thicker reflectors

“A Tiny Calibration”
Adjusting nubar





Thanks to CJ Solomon and S Bolding.

Attacking Systematic Errors Through Systematic Variations

- **Systematic errors are among the hardest to discover and correct**
  - However, the fact that the error is constant provides a lever arm to root it out
- **We need to take advantage of reality rather than try to model it away**
  - Detailed modeling of a suite of systematic variations may allow us to isolate issues
- **There are multiple avenues that should be explored**
  - One-dimensional variations – simple changes with symmetry
  - Changes in geometry – spherical versus cylindrical versus cartesian …
  - Three-dimensional variations – putting ears on the spherical cow
  - Material composition – sources, manufacturing, characterization
  - Structural, safety/control, and facility environments

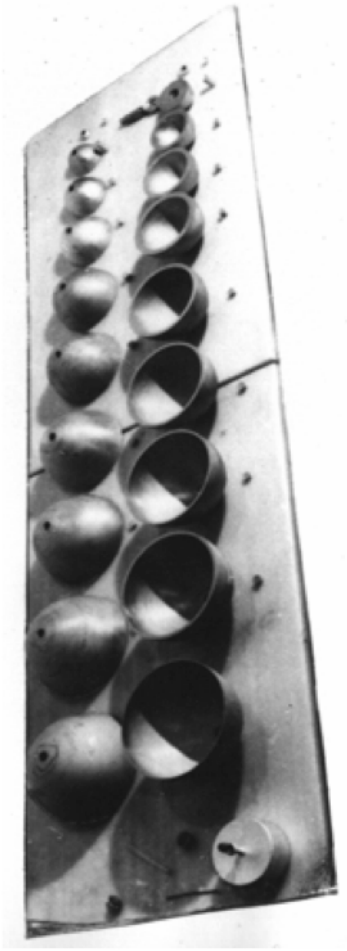
One-Dimensional Spherical Variations
Material Composition Variations

US Rocky Flats Shells

Part #	Ri (in)	Ro (in)	M (g)	
1		0.7870	296.283	
3	0.7926	0.9203	175.579	
5	0.9243	1.0511	233.235	
7	1.0550	1.1824	302.372	
9	1.1861	1.3131	376.526	
11	1.3165	1.4449	465.252	
13	1.4486	1.5757	555.101	
15	1.5813	1.7078	652.839	
17	1.7107	1.8382	766.981	
19	1.8420	1.9703	890.183	
21	1.9753	2.1013	1005.152	
23	2.1050	2.2321	1147.338	
25	2.2358	2.3631	1287.900	
27	2.3668	2.4941	1444.597	
29	2.4981	2.6263	1612.157	
31	2.6294	2.7570	1778.835	
33	2.7603	2.8877	1949.018	
35	2.8908	3.0184	2133.652	
37	3.0220	3.1506	2349.234	
39	3.1546	3.2820	2527.271	
41	3.2861	3.4129	2721.604	
43	3.4186	3.5452	2945.429	
45	3.5467	3.6740	3188.373	
47	3.6782	3.8061	3441.567	Ri & Ro (b)
49	3.8102	3.9373	3656.427	
51	3.9419	4.0687	3912.002	
53	4.0727	4.2007	4206.810	
55	4.2028	4.3314	4463.913	
57	4.3350	4.4623	4733.285	
59	4.4666	4.5934	5003.286	
61	4.5974	4.7243	5322.672	
63	4.7288	4.8568	5659.972	
65	4.8620	4.9803	5509.053	
67	4.9869	5.1191	6495.490	
69	5.1220	5.2494	6599.798	
71	5.2534	5.3816	6981.928	
73	5.3857	5.5126	7261.688	
75	5.5157	5.6430	7619.006	
77	5.6466	5.7739	7983.804	Ro (b)
79	5.7796	5.9072	8414.934	

Part #	Ri (in)	Ro (in)	M (g)	
2		0.7873	296.066	
4	0.7921	0.9205	176.008	Ri (b)
6	0.9242	1.0511	234.068	
8	1.0550	1.1824	301.792	Ri & Ro (b)
10	1.1861	1.3132	375.840	
12	1.3167	1.4449	465.569	
14	1.4488	1.5757	554.457	
16	1.5812	1.7077	651.868	
18	1.7112	1.8385	766.461	
20	1.8421	1.9703	890.197	
22	1.9738	2.1009	1012.648	
24	2.1048	2.2321	1150.275	
26	2.2360	2.3629	1285.889	
28	2.3671	2.4940	1440.437	
30	2.4977	2.6259	1611.533	
32	2.6298	2.7573	1777.389	
34	2.7601	2.8876	1950.943	
36	2.8912	3.0186	2130.469	
38	3.0224	3.1506	2342.362	
40	3.1535	3.2802	2511.390	
42	3.2852	3.4127	2740.764	
44	3.4186	3.5458	2953.071	
46	3.5477	3.6747	3179.244	
48	3.6812	3.8092	3449.984	
50	3.8104	3.9374	3658.146	
52	3.9414	4.0686	3917.948	
54	4.0721	4.2004	4208.395	
56	4.2039	4.3314	4461.288	
58	4.3351	4.4624	4728.704	
60	4.4669	4.5939	5024.960	
62	4.5979	4.7250	5326.166	
64	4.7289	4.8569	5650.004	
66	4.8626	4.9806	5495.230	
68	4.9862	5.1183	6491.830	
70	5.1221	5.2491	6597.668	
72	5.2535	5.3820	6972.764	
74	5.3856	5.5125	7244.404	
76	5.5162	5.6432	7613.166	
78	5.6462	5.7743	7951.602	Ri (b)
80	5.7782	5.9067	8413.208	

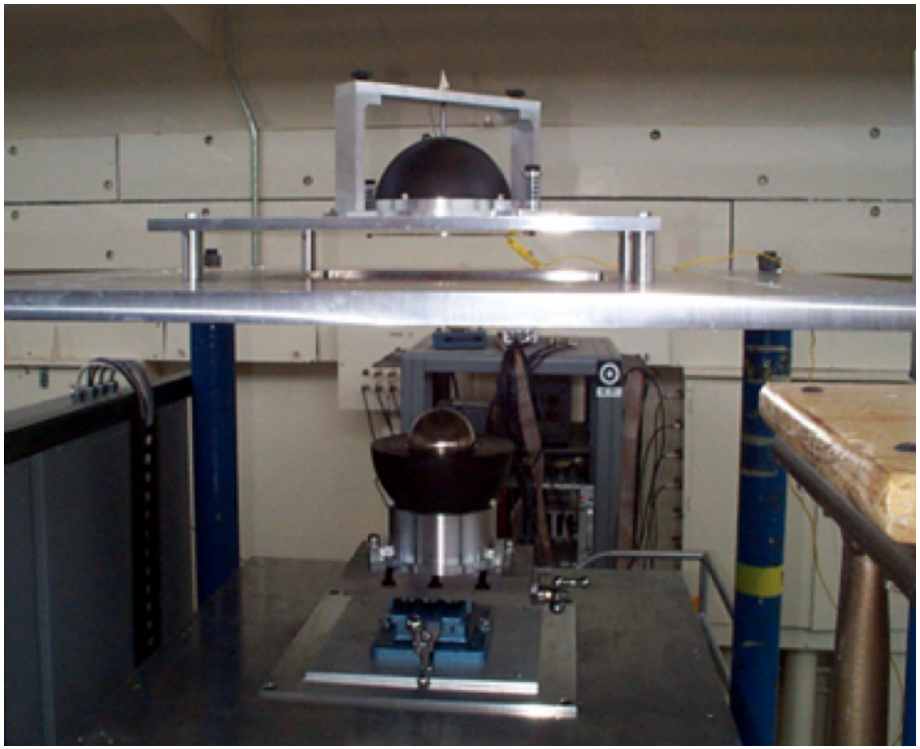
Russian VNIIEF Shells



HEU-MET-FAST-048 Table 3. 80 shells, 256 kg.

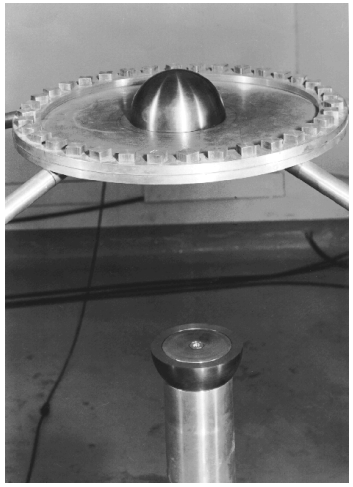
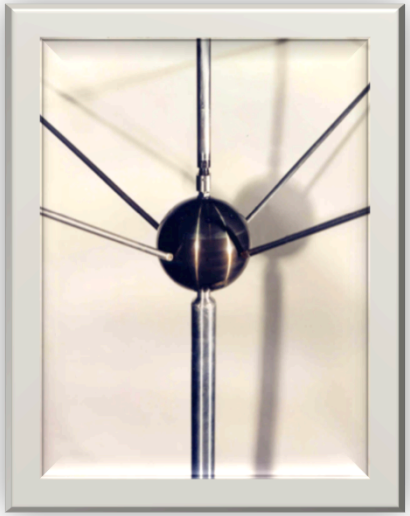
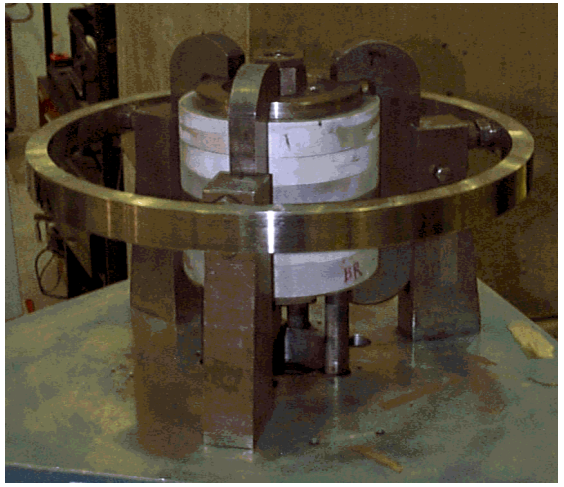
Critical Experiments Facilities
FKBN-2M at VNIIEF, Russia

Critical Experiments Facilities
PLANET (Now) at NCERC, Nevada, USA



What If Lady GODIVA Was Wrong?
(Thanks to John Bess for his great title.)

Reality was there. Physics was there. Our interpretation is questionable.

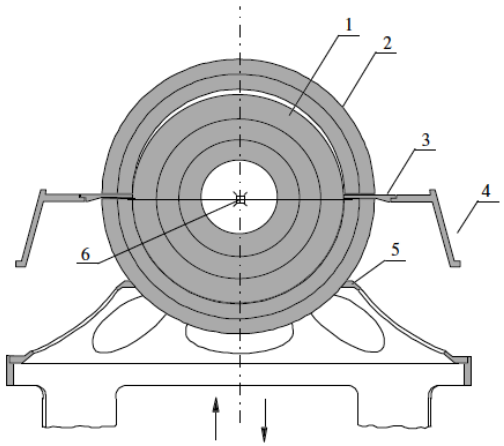
GODIVA 1950s	ORNL Sphere 1970s	GODIVA-IV 2000s
		
C/E = 1.0000	C/E = 0.9912	C/E = 0.9984
	Thanks to Marshall, Bess and Murray ND2013.	Thanks to Mosteller (HEU-MET-FAST-086).

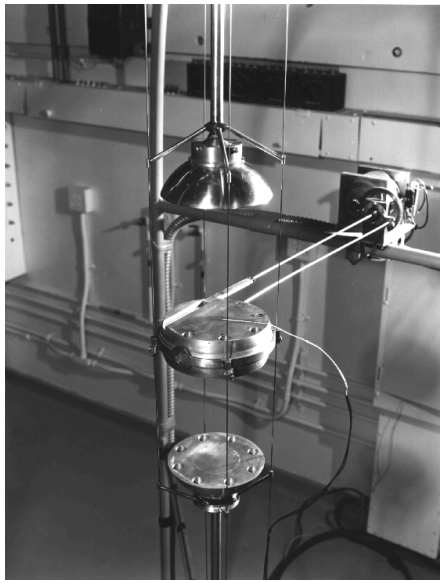
Selected Bare HEU Systems

		Exp		C/E	
HEU-MET-FAST-001	1	1.0000	100	0.9998	-0.2
HEU-MET-FAST-001	2	1.0000	100	0.9999	-0.1
HEU-MET-FAST-008		0.9989	160	0.9971	-1.8
HEU-MET-FAST-018		1.0000	140	1.0004	0.3
HEU-MET-FAST-015		0.9997	170	0.9947	-3.1
HEU-MET-FAST-065		0.9985	130	0.9995	-0.4
HEU-MET-FAST-051	14	0.9996	20	0.9992	-4
HEU-MET-FAST-051	15	0.9998	10	0.9983	-17
HEU-MET-FAST-051	16	0.9981	10	0.9984	-16
HEU-MET-FAST-051	17	0.9969	10	0.9986	-14
HEU-MET-FAST-051	18	0.9984	10	0.9959	-41
HEU-MET-FAST-007	1	0.9950	240	0.9981	-0.8
HEU-MET-FAST-007	19	0.9956	150	1.0011	0.7

Selected Bare Plutonium Systems

	C/E			
PU-MET-FAST-022:	0.99843 210	RU	1.8% Pu240	(d)
PU-MET-FAST-001:	0.99992 200	US	4.5% Pu240	(d)
PU-MET-FAST-029:	0.99559 200	RU	9.9% Pu240	(a)
PU-MET-FAST-002:	0.99992 200	US	20.1% Pu240	(d)





Summary

- **We are in the opening stages of designing the next series of critical assembly experiments**
  - We need to take advantage of reality rather than try to model it away
  - We need simulations to help learn where the sensitivities are and focus the experiments on exploring these regions of phase-space
- **We must understand how to integrate multiple integral experiments**
  - Little work has been done to establish and understand covariance data
  - This analysis must include metrics beyond multiplicity, i.e. activation, …
- **We must address the question, when is it good enough?**