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Title: Validation of Dosimetry Data Using Historic and Recent Measurements on the Flattop Critical Assembly

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Validation of Dosimetry Data Using Historic and Recent Measurements on the Flattop Critical Assembly

Morgan C. White

ND2016 International Conference on Nuclear Data for Science and Technology
September 11-16, 2016, Bruges, Belgium

Many shall pass too and fro and knowledge shall be increased

Francis Bacon's Novum Organum (1620): Straits of Gibraltar flanked by the colossal pillars of Hercules.

Plus Ultra

there is more beyond

(motto of the great scientific pioneers of the 16th & 17th Century)

*Slide thanks to Mark Chadwick (LANL)

Acknowledgements

- Advanced Nuclear Technology – Rian Bahran, John Bounds, Theresa Cutler, Derek Dinwiddie, Joetta Goda, Travis Grove, Dave Hayes, Jesson Hutchinson, Bob Margevicius, Bill Myers, Rene Sanchez
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- Theory – Skip Kahler, Toshihiko Kawano, Bob MacFarlane, Patrick Talou, Phil Young
- X-Computation Physics – Mark Chadwick, Jeremy Conlin, Jeff Favorite, Stephanie Frankle, Greg Hutchens, Pete Jaegers, Paul Mendoza, Russ Mosteller, Denise Neudecker, Chuck Wilkerson

Abstract

First assembled in March 1958, the Flattop critical assembly remains one of the mainstays of critical assembly experiments today. As such, it is likely the longest running suite of critical experiments ever fielded on the same machine. A nearly infinitely thick, spherical natural uranium reflector surrounds a central cavity where various fissile cores can be placed. Flattop-25 (or just Flattop) is the most well-known configuration using a highly enriched uranium-235 core; Flattop-Pu and Flattop-23 use plutonium (6% Pu-240) and uranium-233 cores. Three large control rods and multiple mass adjustment buttons allow for substantial variation in reactivity control. A glory hole traversing one side of the reflector and the full width of each core enables access to many neutron spectra. One of its primary roles of this assembly has been to provide standard neutron fields for activation irradiations. The first irradiation performed using Flattop, similar to many recent measurements, was a set of actinide irradiations to study cumulative fission product yields. Activation measurements of standard dosimetry reactions have also been taken at many times over the years. These measurements have influenced decades of nuclear data evaluations, particularly the ENDF/B libraries, and have been used for validation of, among others, the IRDFF international dosimetry libraries. In this study we explore the rich history of the measurements and modeling of this assembly to see what new lessons we can learn from this unique resource. In particular, we examine the consistency of measurement results over the years and aspects of the uncertainties of the measurement and modeling techniques used for these comparisons.

The Nuclear Data Pipeline.

Differential Experiments

Compilation

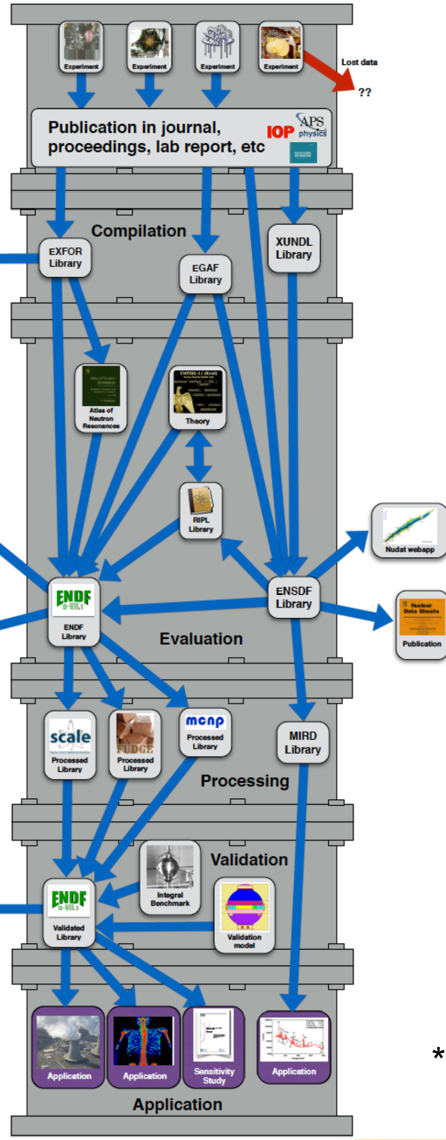
Nuclear Theory

Evaluation

Processing

Validation

Applications



The pipeline is long, complex and has *feedback loops* that are not always evident.

*Graphic D. Brown (BNL)

Applications rule the day.

Making a *general purpose* nuclear data library is difficult.

- The ENDF/B nuclear data library is intended to be valid for use in a wide range of applications.
- Nuclear data evaluation adapts the best experimental data and theory.
  - This includes both differential and ***integral*** data.
- Evaluated data survive in a Darwinian-like competition of the *fittest**. (**Best fit is subjective*.)
- Nuclear data's *dirty secret* is that we allow key data from integral benchmarks and applications to strongly influence this process.

Applications

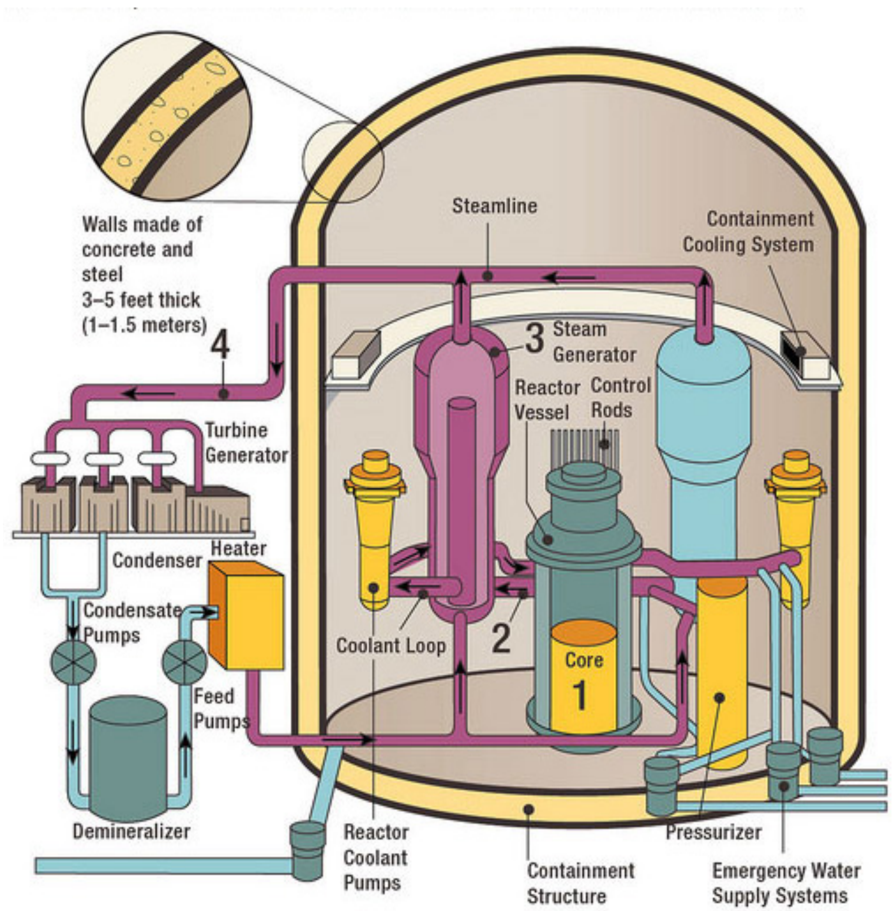
Nuclear Energy

Nuclear Astrophysics

Nuclear Medicine

Nuclear Security

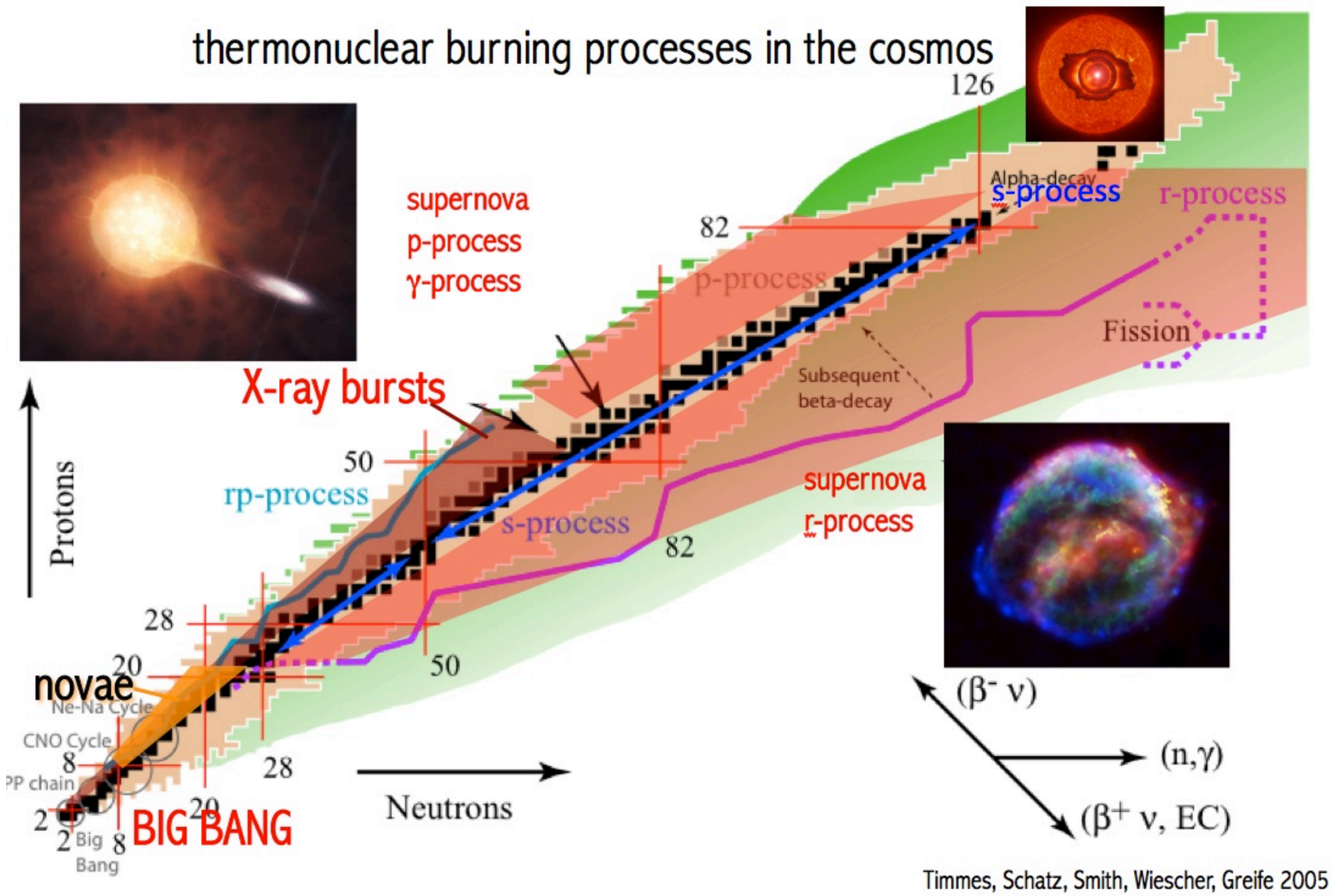
Nuclear data are essential to nuclear reactor design, fabrication, operation and disposal.



Nuclear energy is a key component of many nations energy security plans. It is also a low carbon alternative.

*Graphics US NRC and the Simpsons.

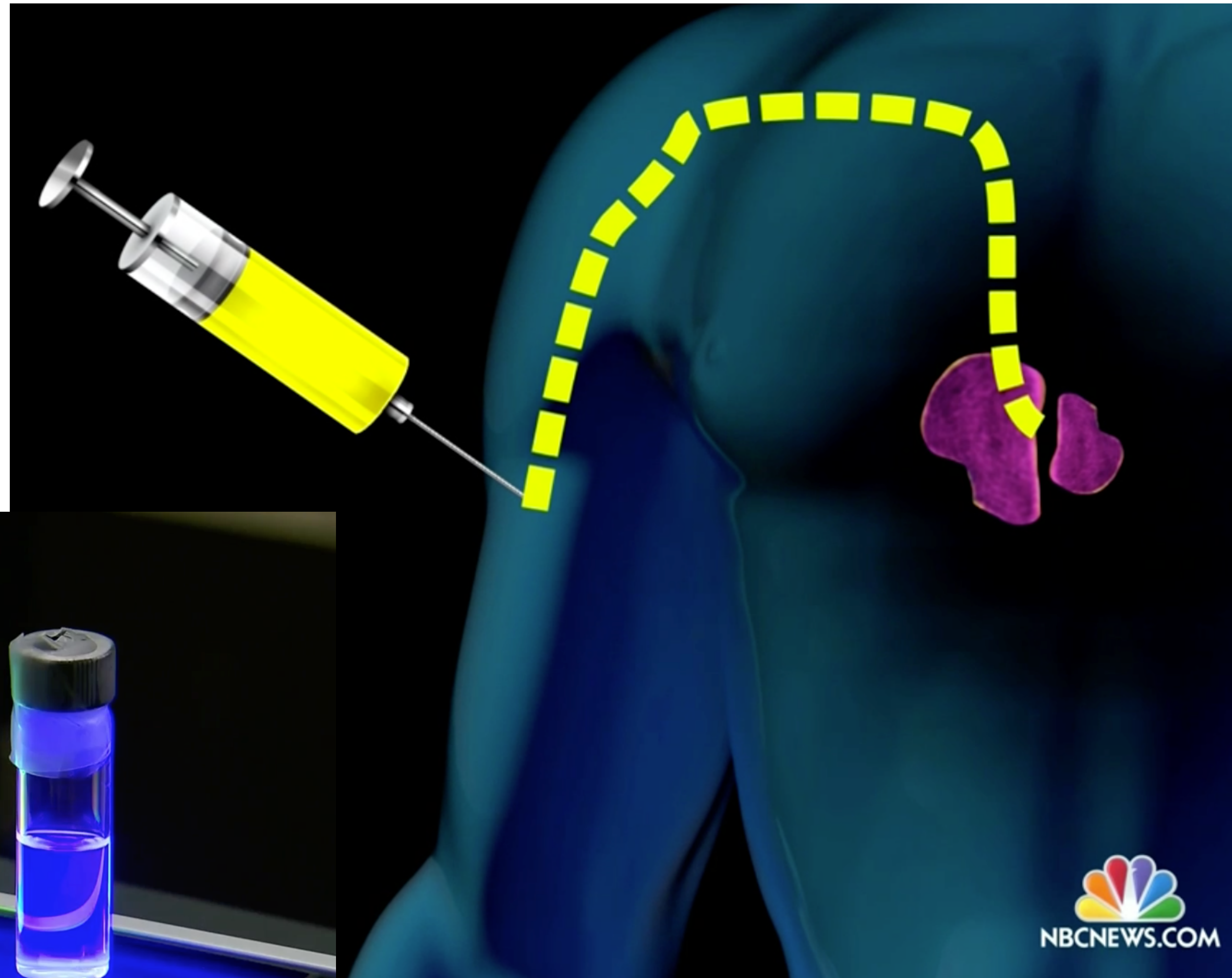
Nuclear data are essential to our understand the origins of the universe.



*Graphics ORNL Astrophysics Group.

Nuclear data are essential to develop, produce and use nuclear medicines.

10s of millions of patients undergo treatment involving nuclear medicine every year. And that number is growing.



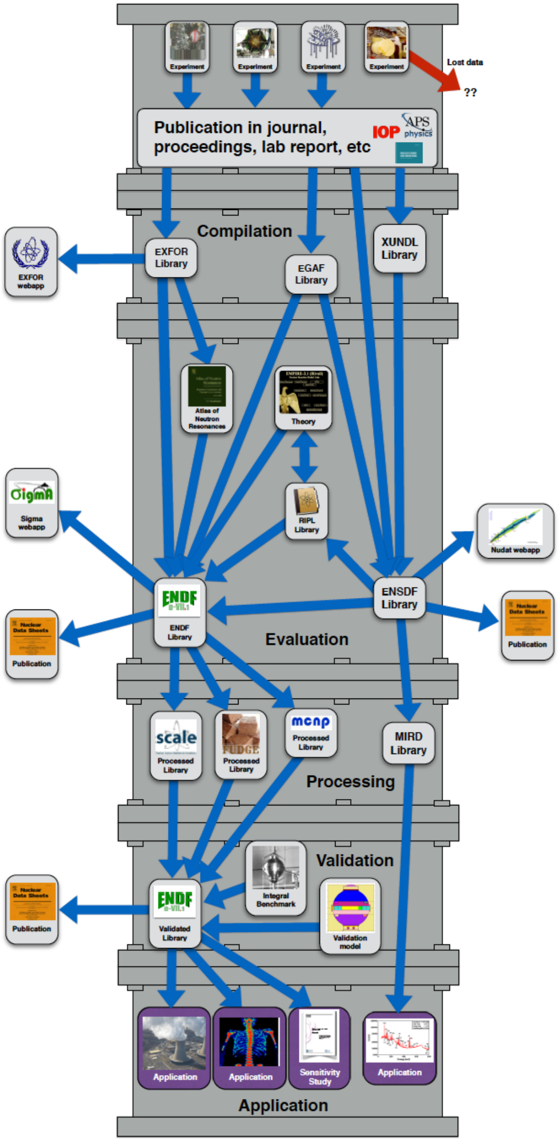
*Graphics LANL Isotope Program & NBC.

Nuclear data are essential to detect, develop, maintain and dispose of nuclear weapons.

- As long as there are nuclear weapons in the world, the U.S. is committed to sustaining a safe, secure, and effective nuclear deterrent.
- Proliferation poses a great risk. In a world with nuclear weapons, safeguards, non-proliferation treaty verification and counter-proliferation are essential.

Many of our experimental techniques and neutronics capabilities trace their origins to the Manhattan project.

- In the 1950s, it was decided that fundamental nuclear data should be placed in the public domain.



*Graphic D. Brown (BNL)

Common goals:

Boltzmann Equation

neutron reactivity
criticality safety
radiation shielding

Bateman Equation

isotopic transmutation
waste disposal
dosimetry

How critical assembly influence nuclear data library…

First, do no harm.
-- Mark Chadwick, ENDF/B Evaluation Chairman

Stephanie Frankle's 119 benchmark suite…

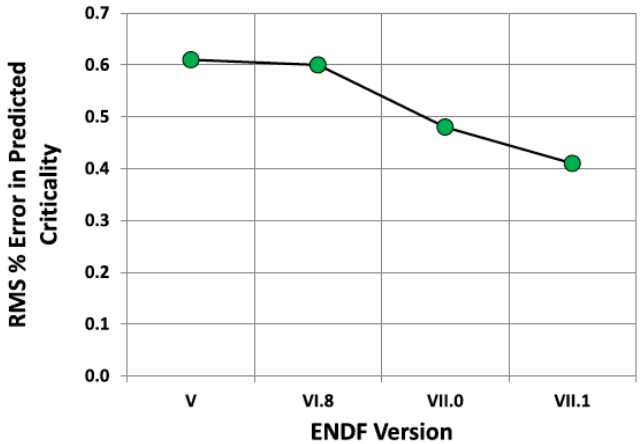
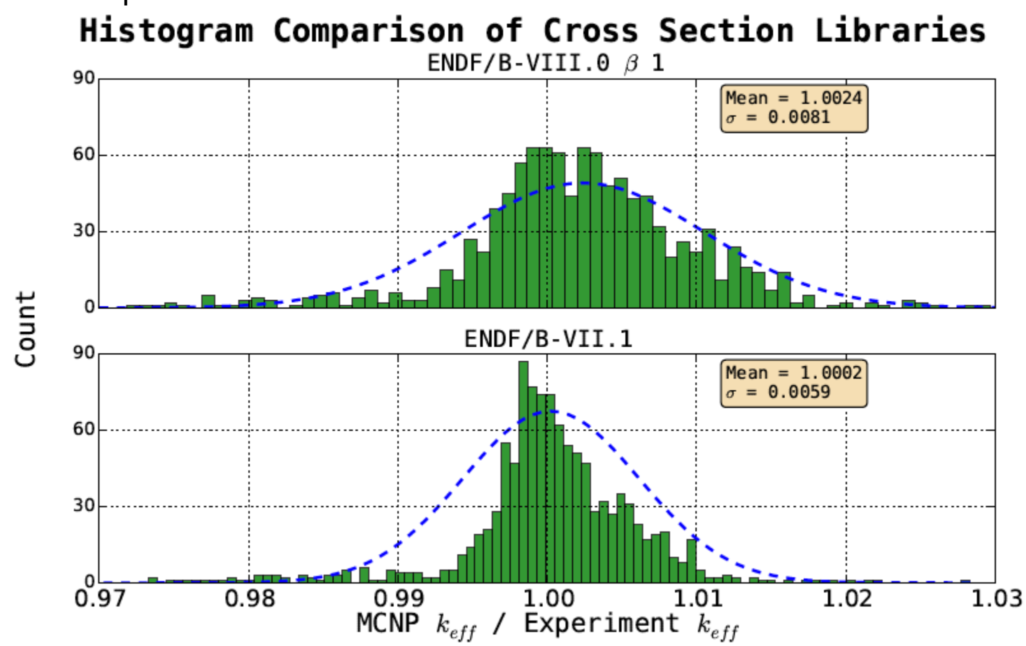


FIG. 1. Calculated/measured root mean square deviation (in %) from unity for nuclear criticality, k_{eff}, for a suite of 119 critical assemblies, as a function of ENDF library version number.

CIELO paper (DOI: 10.1016/j.nds.2014.04.002)

Skip Kahler's 1187 benchmark suite…

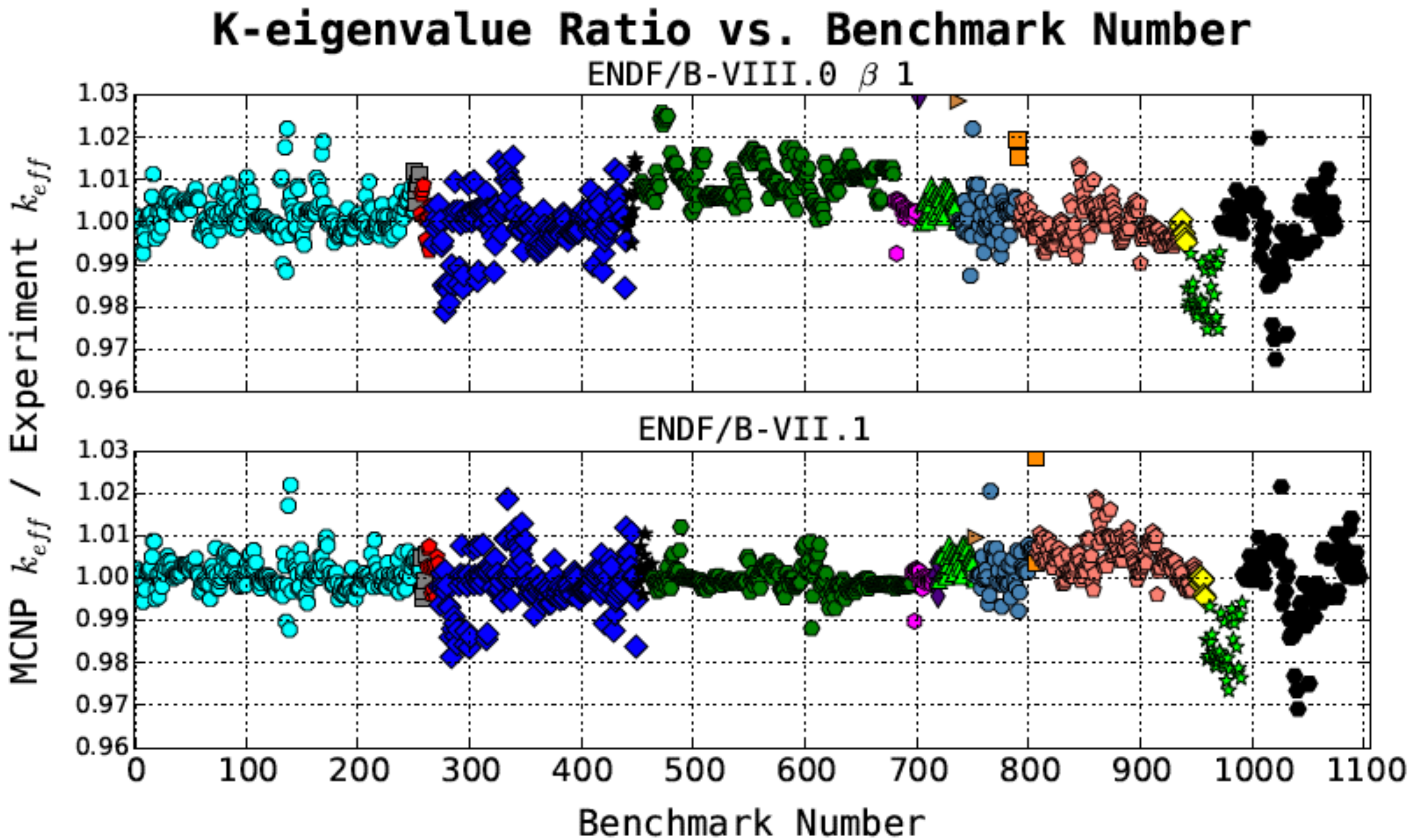


Paul Mendoza (Texas A&M, 2016 summer student LANL)

ENDF/B-VIII.0 Beta 1 shows a clear bias to over estimate neutron reactivity. More work to do.

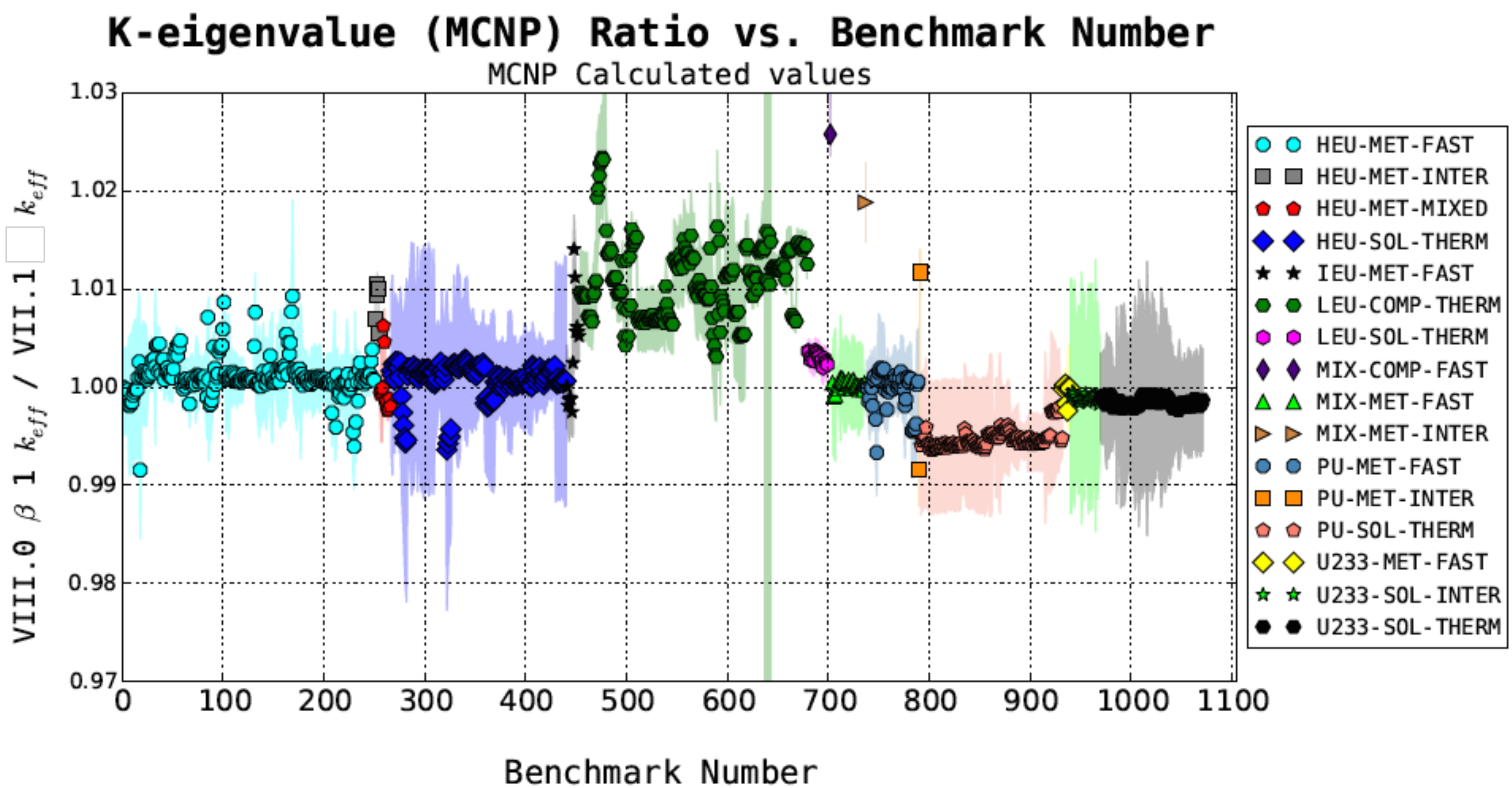
* So does ENDF/B-VII.1, though it is better.

The broad view…



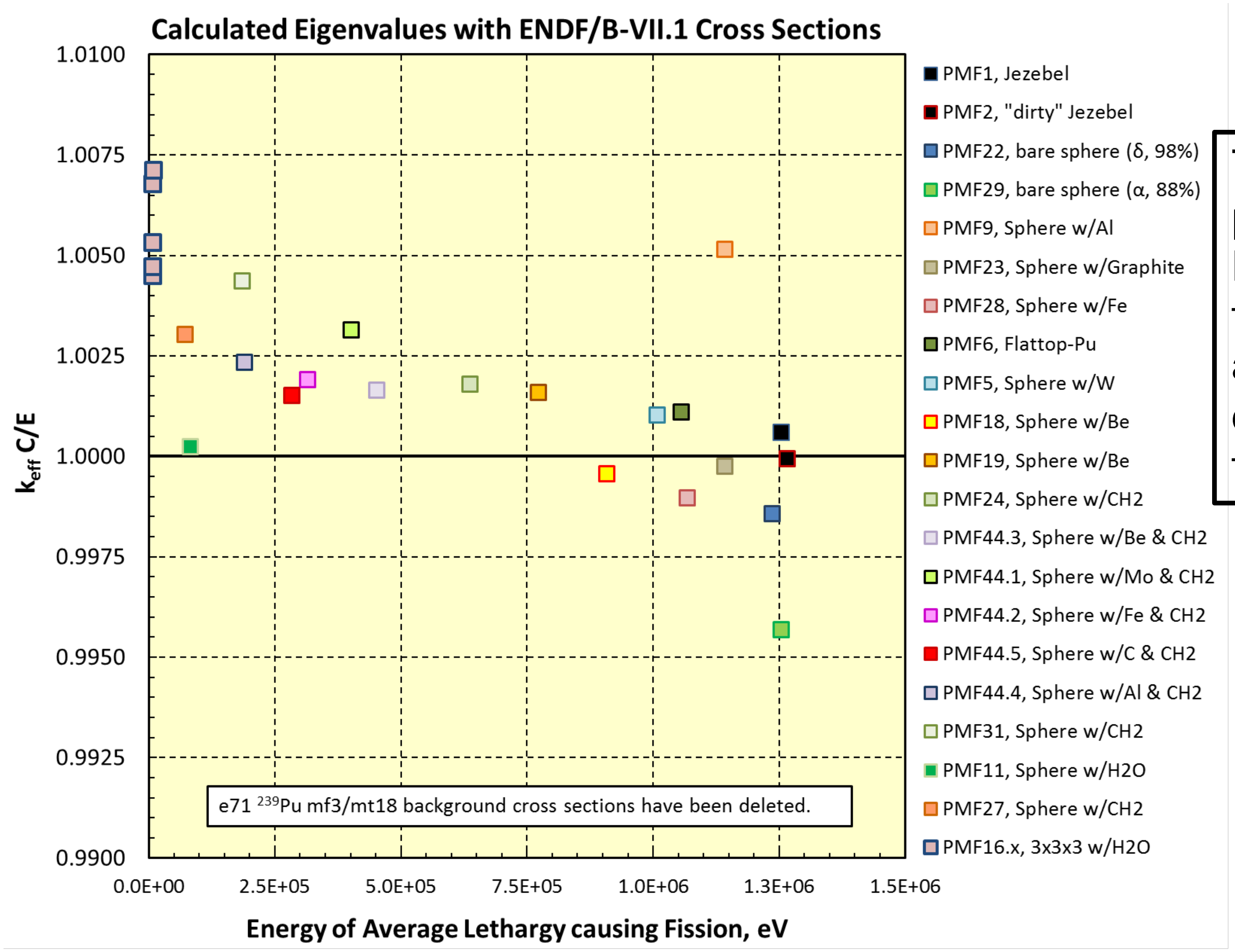
* From Paul Mendoza report LA-UR-16-26595 & -26661

What has changed…



* From Paul Mendoza report LA-UR-16-26595 & -26661

Are there trends… Yes.

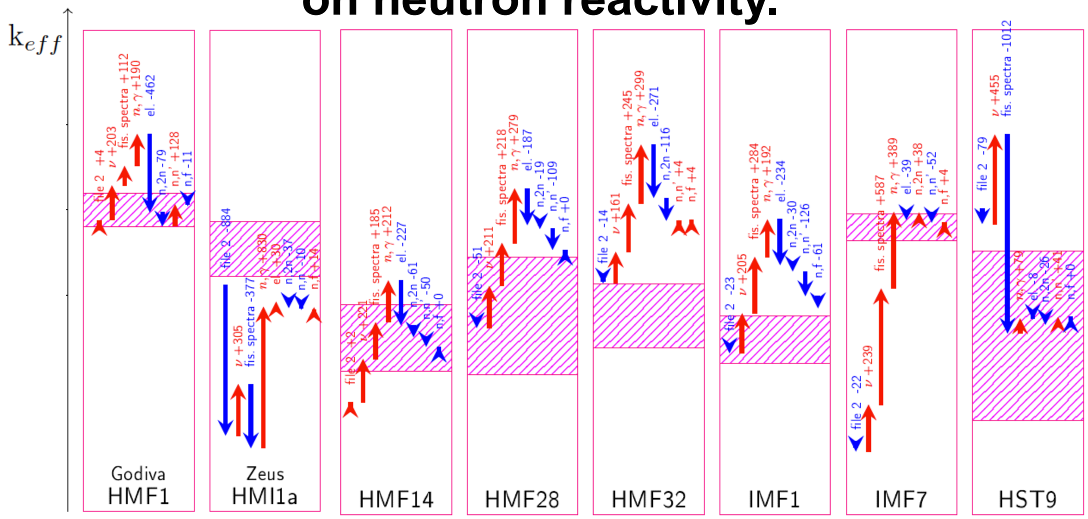


There is an obvious positive bias in ENDF/B-VII.1 k_{calc} for the PMF class as a function of decreasing average fission energy.

* From Skip Kahler report LA-UR-16-23419

Key calibrations introduce compensating errors that are hiding non-unique solutions. No one seems to have “the answer”.

Impact of nuclear data components on neutron reactivity.



B. Morillon et al. (CEA,DAM,DIF), Status of 235U CIELO Evaluation, from presentation to SG40 at the May 2015 WPEC meeting.

- Critical assembly benchmarks provide very tight integral constraints
- Examining the difference in how two nuclear data evaluations perform in such validation exposes differences in the underlying differential data

- **There are many ways to match the constraints we have.**
- **Discrepancies in the data allow for subjective expert judgments that often result in solutions that are themselves discrepant.**
- **Untangling this requires the creation of advanced techniques to measure data in new ways and the study of historic measurements to illuminate and understand previously undiagnosed errors.**

Can activation data be used to help?

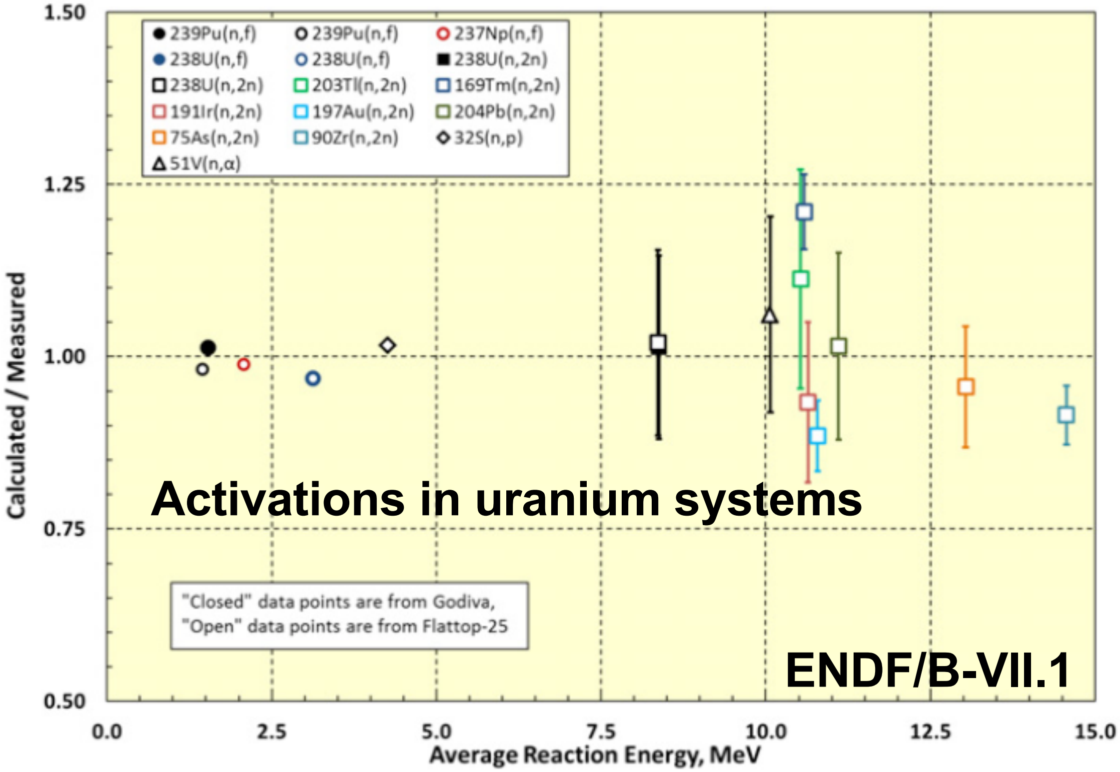


Figure 4, Kahler ISRD2015 (DOI: 10.1051/epjconf/201610604007)

Reaction	Assembly Calculation	Experiment
	GODIVA	
^{238}U(n,2n)	7.84E-3 ± 13%	7.73E-3 ± 4%
	Flattop-25	
^{238}U(n,2n)	7.08E-3 ± 13%	6.94E-3 ± 4%
^{203}Tl(n,2n)	1.70E-3 ± 13%	1.52E-3 ± 6%
^{169}Tm(n,2n)	1.78E-3 ± 3%	1.47E-3 ± 4%
^{191}Ir(n,2n)	1.76E-3 ± 12%	1.89E-3 ± 4%
^{197}Au(n,2n)	1.43E-3 ± 5%	1.61E-3 ± 3%
^{204}Pb(n,2n)	1.66E-5 ± 12%	1.64E-5 ± 6%
^{75}As(n,2n)	1.43E-4 ± 7%	1.50E-4 ± 6%
^{90}Zr(n,2n)	4.40E-5 ± 3%	4.85E-5 ± 3%
^{32}S(n,p)	3.11E-2	3.06E-2 ± 6%
^{51}V(n,α)	1.18E-5 ± 12%	1.11E-5 ± 6%
	Jezebel	
^{238}U(n,2n)	1.32E-2 ± 12%	1.06E-2 ± 4%
^{169}Tm(n,2n)	3.72E-3 ± 3%	3.13E-3 ± 3%
^{191}Ir(n,2n)	3.76E-3 ± 11%	3.21E-3 ± 4%
	Flattop-Pu	
^{238}U(n,2n)	1.10E-2 ± 12%	9.02E-3 ± 4%
^{203}Tl(n,2n)	2.92E-3 ± 13%	2.27E-3 ± 6%
^{169}Tm(n,2n)	3.05E-3 ± 3%	2.43E-3 ± 3%
^{191}Ir(n,2n)	3.08E-3 ± 11%	2.83E-3 ± 4%

Table 1 from CIELO paper (DOI: 10.1016/j.nds.2014.04.002)

Nuclear Data Sheets ENDF/B-VII.0, ENDF/B-VII.1, CIELO and many other articles show many examples of diving into these data.

Should we change Pu239 PFNS or scattering?

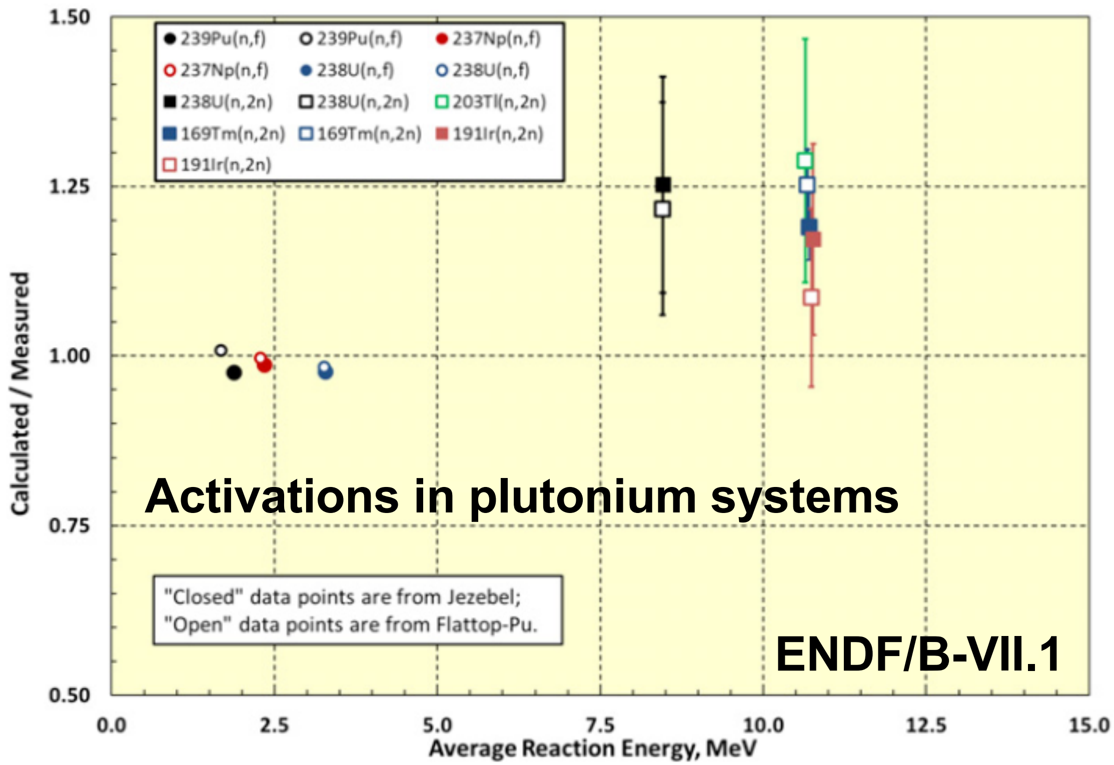


Figure 3, Kahler ISRD2015 (DOI: 10.1051/epjconf/201610604007)

Reaction	Assembly Calculation	Experiment
	GODIVA	
^{238}U(n,2n)	7.84E-3 ± 13%	7.73E-3 ± 4%
	Flattop-25	
^{238}U(n,2n)	7.08E-3 ± 13%	6.94E-3 ± 4%
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Nuclear Data Sheets ENDF/B-VII.0, ENDF/B-VII.1, CIELO and many other articles show many examples of diving into these data.

- Is it fair to tune our nuclear data libraries to these data?
- Is so, when we show such a match, ***is that really validation***?
  - If the data are tuned to achieve these results, it is not a prediction.
- How do we play this game fairly?

Diving deeper, where did the reaction rate data come from?

Recent reports on reaction rates

(Not complete, but gives you a flavor…)

ENDF-202 1974 CSEWG Benchmark Specifications

-> ICSBEP Supplemental Info

ENDF/B-VII.0 NDS V107 (10.1016/j.nds.2006.11.001) pp. 3017-3021

Young, U Evaluations NDS V108 (10.1016/j.nds.2007.11.002) Tables 8-14

Reaction Rates ND2007 (10.1051/ndata:07332)

ENDF/B-VII.1 NDS V112 (10.1016/j.nds.2011.11.002) pp. 2970-2971

Integral Testing ENDF/B-VII.1 NDS V112 (10.1016/j.nds.2011.11.003)

The most complete listing to date is given in…

CIELO NDS V118 (10.1016/j.nds.2014.04.002) Appendix A

Where are the original data recorded…

In a box or drawer, somewhere…

*Thanks to Indiana Jones
Raiders of the Lost Ark

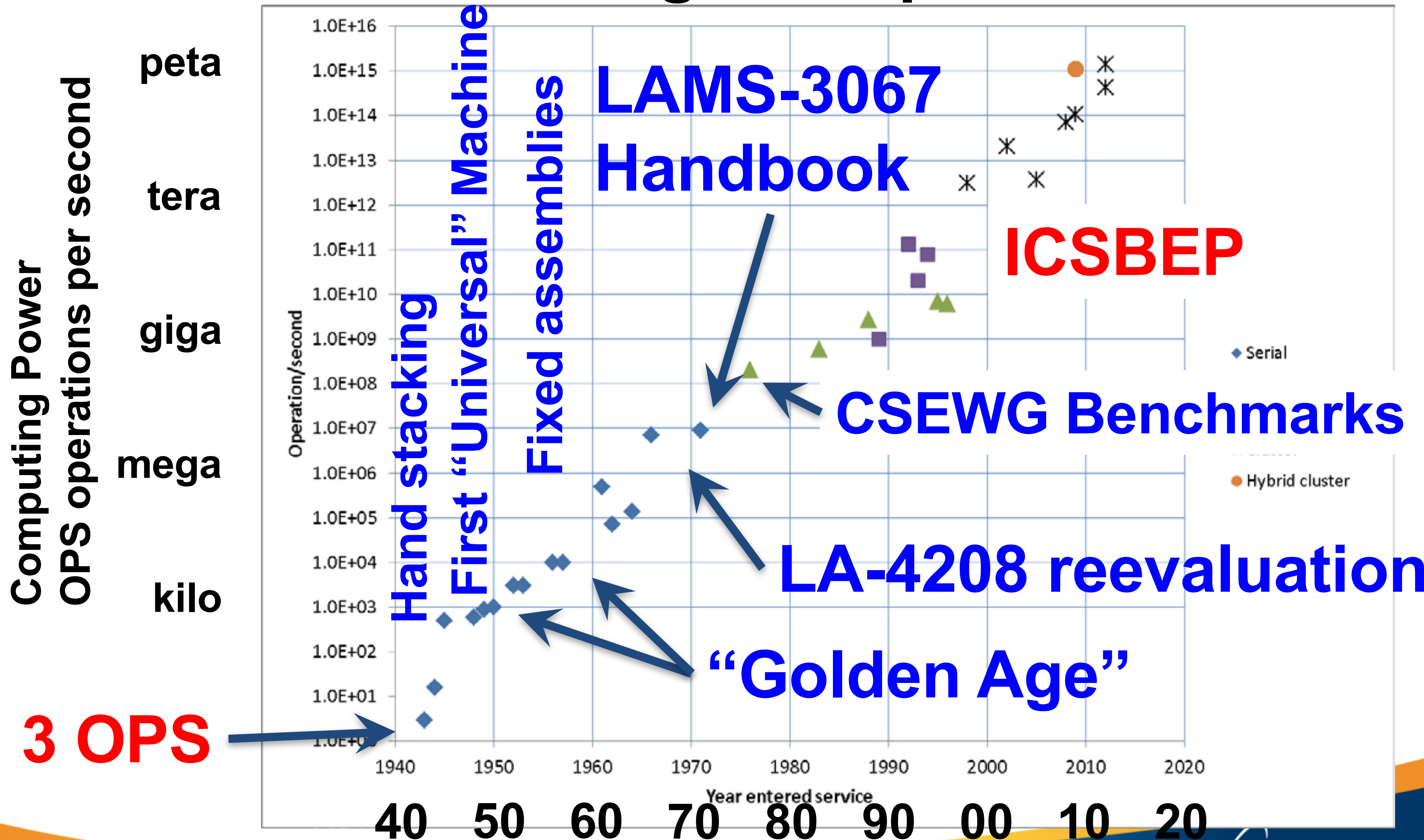
Critical assembly data

The US nuclear data and neutronic simulation capabilities originated in the Manhattan project.

- The first priority was to measure the fundamental data – fission cross sections, nubar, and the fission emission distribution*.
  - Given the time pressures, the Illinois Cockcroft-Walton accelerator, Wisconsin Long Tank (Van de Graff) and the Harvard Cyclotron were moved to Los Alamos in the summer of 1943 to make differential measurements.
- As larger quantities of material became available critical experiments were performed (1940s – 1950s) to provide determine "truth".

* For example, the very first informal report – LAMS-1, Bennett and Richards, A Discussion of the Fission Neutron Spectrum.

Our concept of simulations is dramatically different from the original experimentalists.



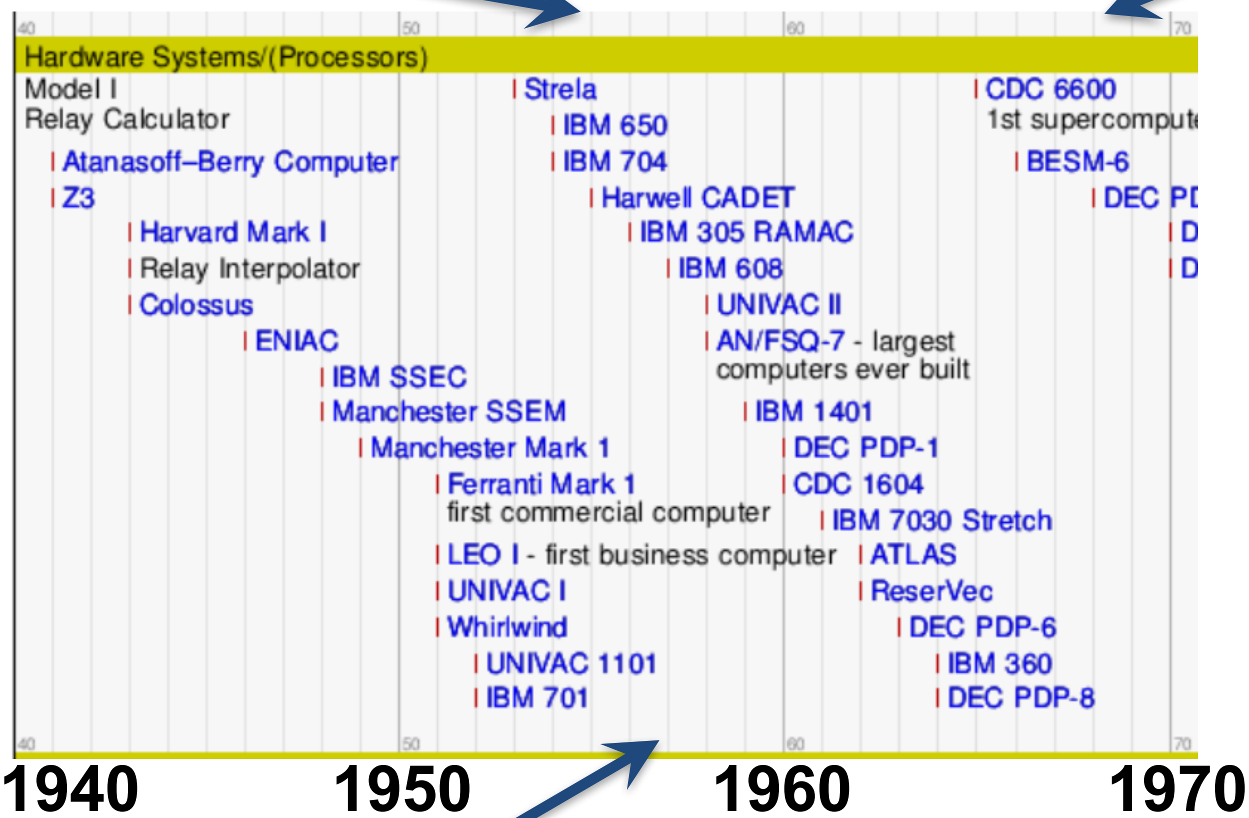
NNSA National Nuclear Security Administration

Los Alamos NATIONAL LABORATORY EST. 1943

Data libraries came late in this process.

1955 First Edition
BNL-325 Barn Book

1968 ENDF/B-I



1957 Fortran-1

During the development of the bare critical assemblies, experiments ruled the day.

- Early experiments hand stacked simple shapes – plates, shells and cubes – until 1945-6 criticality accidents prompted move to remote operations.
- First general purpose machine TOPSY ~1947
  - Followed quickly by ELSIE, COMET and PLANET
  - TOPSY/ELSIE used cubes with/without thick reflectors
  - COMET/PLANET were lift assemblies with *materials to order*
  - Established criticality safety limits for other operations
  - Used to establish trends (and ***tune*** simulations)
- Development of dedicated assemblies 1950s
  - Established bare critical mass of HEU (1951), PU (1954) and U233
  - Established (near-)infinite natural uranium reflector (1955)

Basic experimental measurement techniques were still being actively developed…

Early days experimentalists depended on radiochemistry with alpha and beta counting using scintillators and ionization chambers.

PMTs
1930s

Rossi Alpha
LA-744 1949

HPGe(Li)
1963

1940 **1950** **1960** **1970**

Early days experimentalists were building their own electronics

EG&G 1947

NIM 1968
Nuclear Instrumentation Module

CAMAC 1972
Computer-Aided Measurement And Control

*VME 1979

Isotope identification by gamma-rays without radiochemistry is hard…

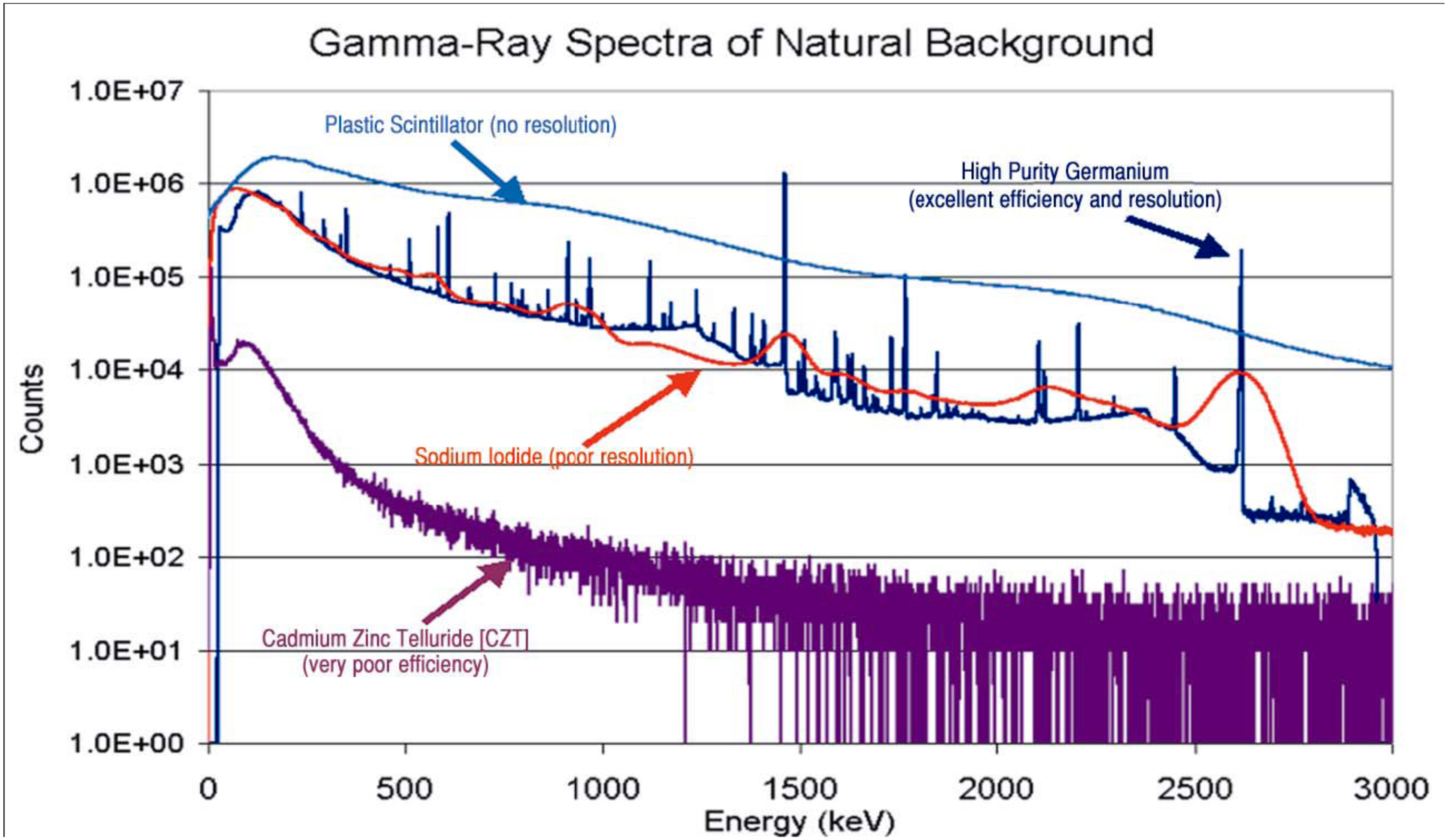
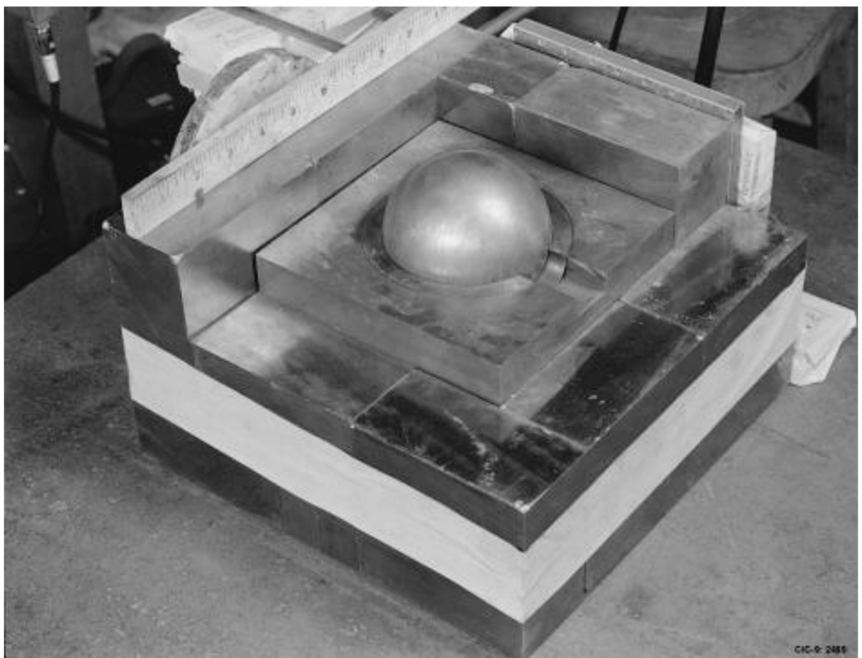
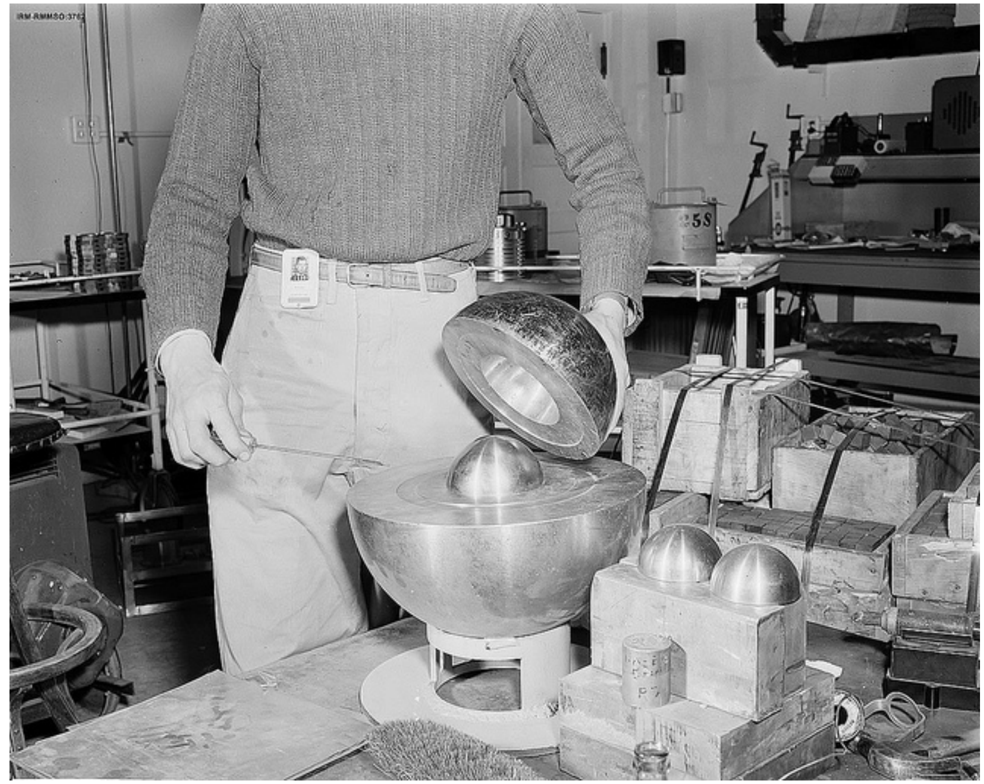


*Figure from ORTEC (www.ortec-online.com)

During early experiments, scientists would hand stack materials…

Configuration of the assembly at the time of the August 21, 1945 accident that killed Harry Daghlian.





Configuration of the assembly at the time the May 21, 1946 accident that killed Louis Slotin.

TOPSY (~1947) First *universal*, remote operated critical assembly machine.

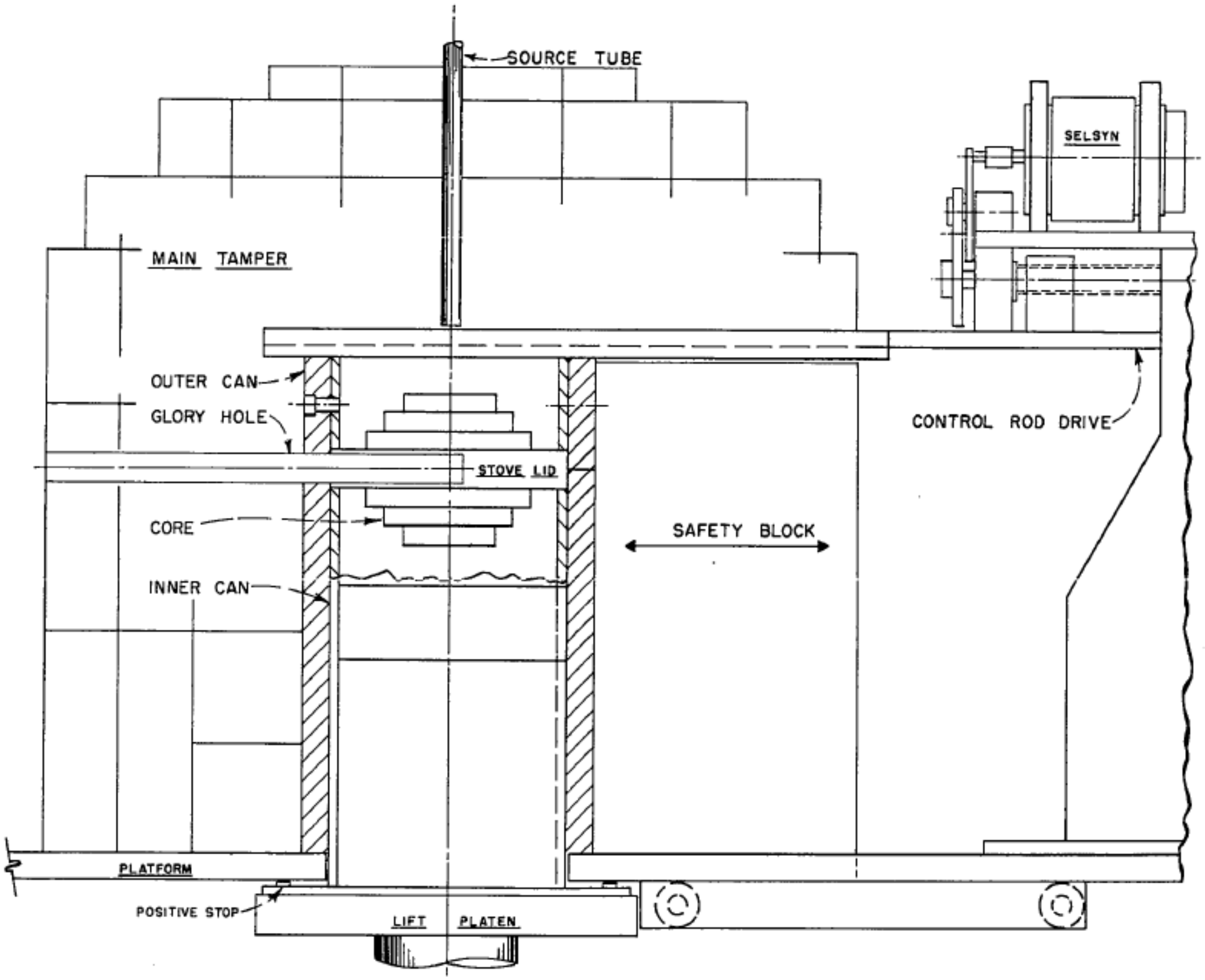
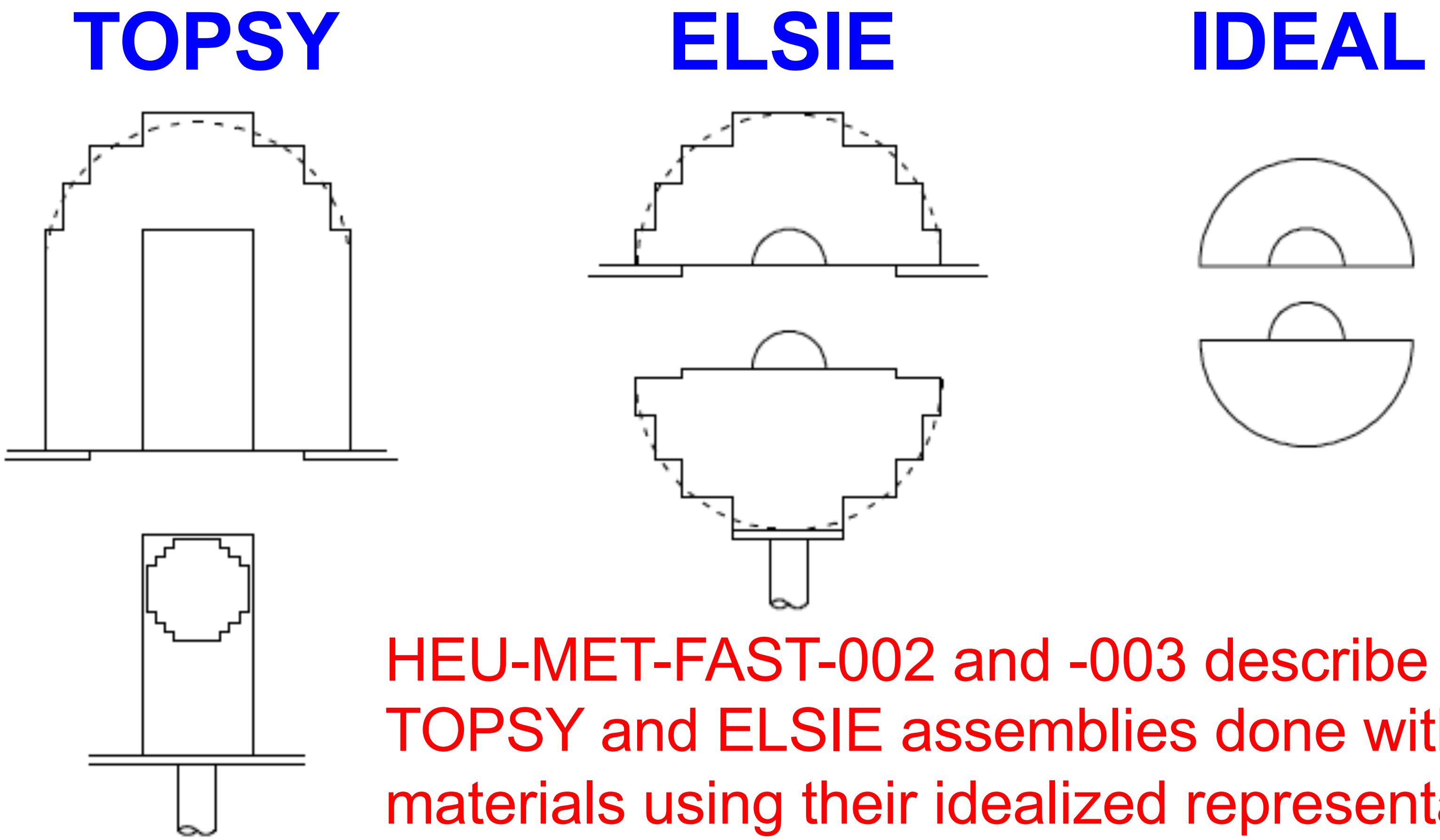


Fig. 10. Sectional view of a typical assembly operating at delayed critical.

ELSIE (~1948) Split-core *universal*, remote operated critical assembly machine.



HEU-MET-FAST-002 and -003 describe TOPSY and ELSIE assemblies done with cube materials using their idealized representations.

Do we trust “shape factors”? (LA-1155)

Figure 1. Types of Reflector Assemblies Used in Critical Mass Studies.

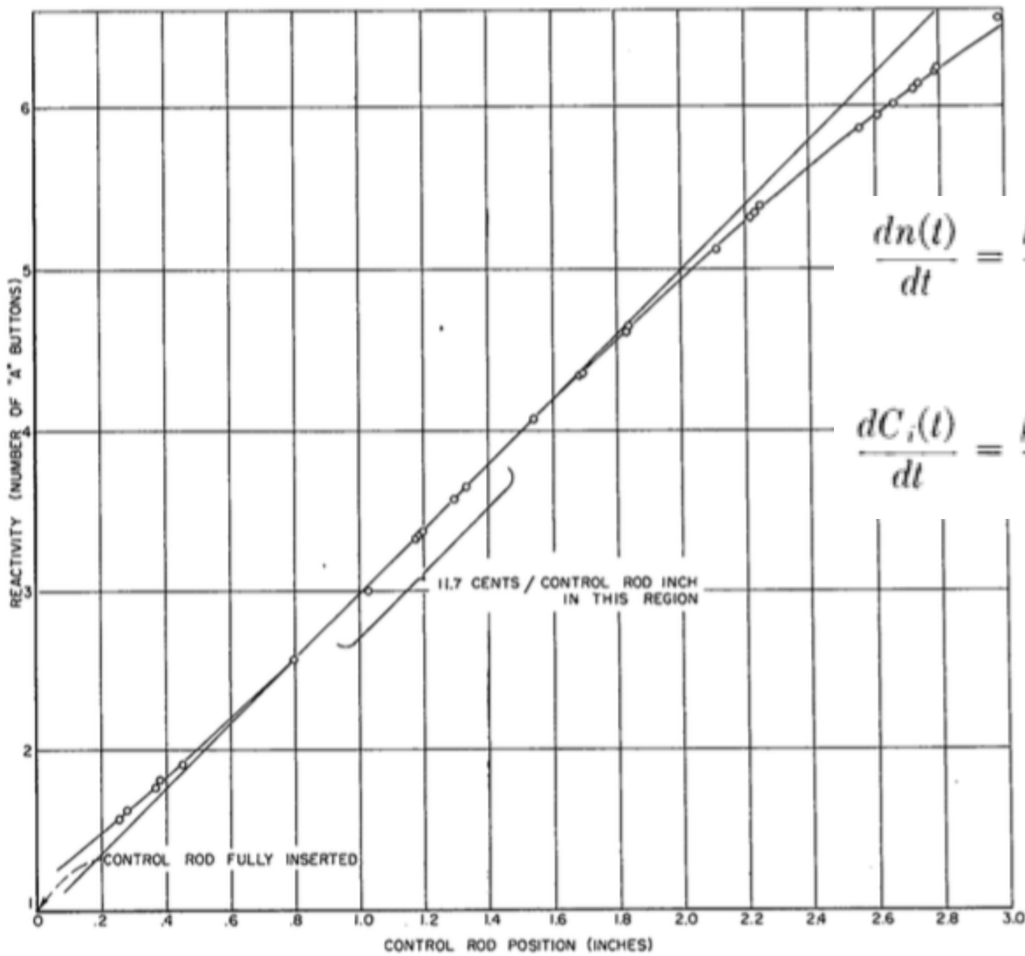
TOPSY (~1947) Design Requirements
From LA-1579 June 1953 Review Document

- The design of TOPSY was governed by two requirements
  - Protection of personnel and equipment via remote assembly
  - Precision – i.e. accurate, reproducible alignment and positioning
- A basic experimental program consisted of…
  - Time behavior (Rossi alpha) measurements of neutron lifetime
  - Neutron distribution by various detection schemes
  - Material replacement studies
- Measurements were a function of control rod calibration with control rods and mass buttons allowing reasonable $ delta-k
- Measurement campaign was extensive covering a huge range of nuclear material and reflector combinations

We can measure reactivity in a critical assembly with incredible precision.

- The Inhour equation is so named because it was only required to discern whether a reactor increased power x2.71 over an hour (much longer than the longest delayed neutron group) and this gives a precision on k-effective of a few pcm (that is, we can measure criticality to **1 part in 100,000**)
- First reference to the Inhour equation was published in 1947 as part of a measurement technique for absorption cross sections http://dx.doi.org/10.1103/PhysRev.72.16
- The early (and modern) logbooks, reports and articles are full of discussions of critical assembly measurements using control rod positions, dollars and cents or similar units

This methodology requires understanding the delayed neutron response…



Need precise Beta-effective

$$\frac{dn(t)}{dt} = \frac{k(t)(1 - \bar{\gamma}\beta) - 1}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i \gamma_i C_i(t) + \gamma_s S(t) \quad (1a)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i k(t)}{\Lambda} n(t) - \lambda_i C_i(t) \qquad i = 1, 2 \cdots 6 \quad (1b)$$

NSE Vol. 8 pp. 670-690 (1960)
Keepin and Cox,
General Solution of the Reactor Kinetic Equations
(Published version of LA-1033)

LA-1614 Figure 6. Control rod worth for Lady Godiva.

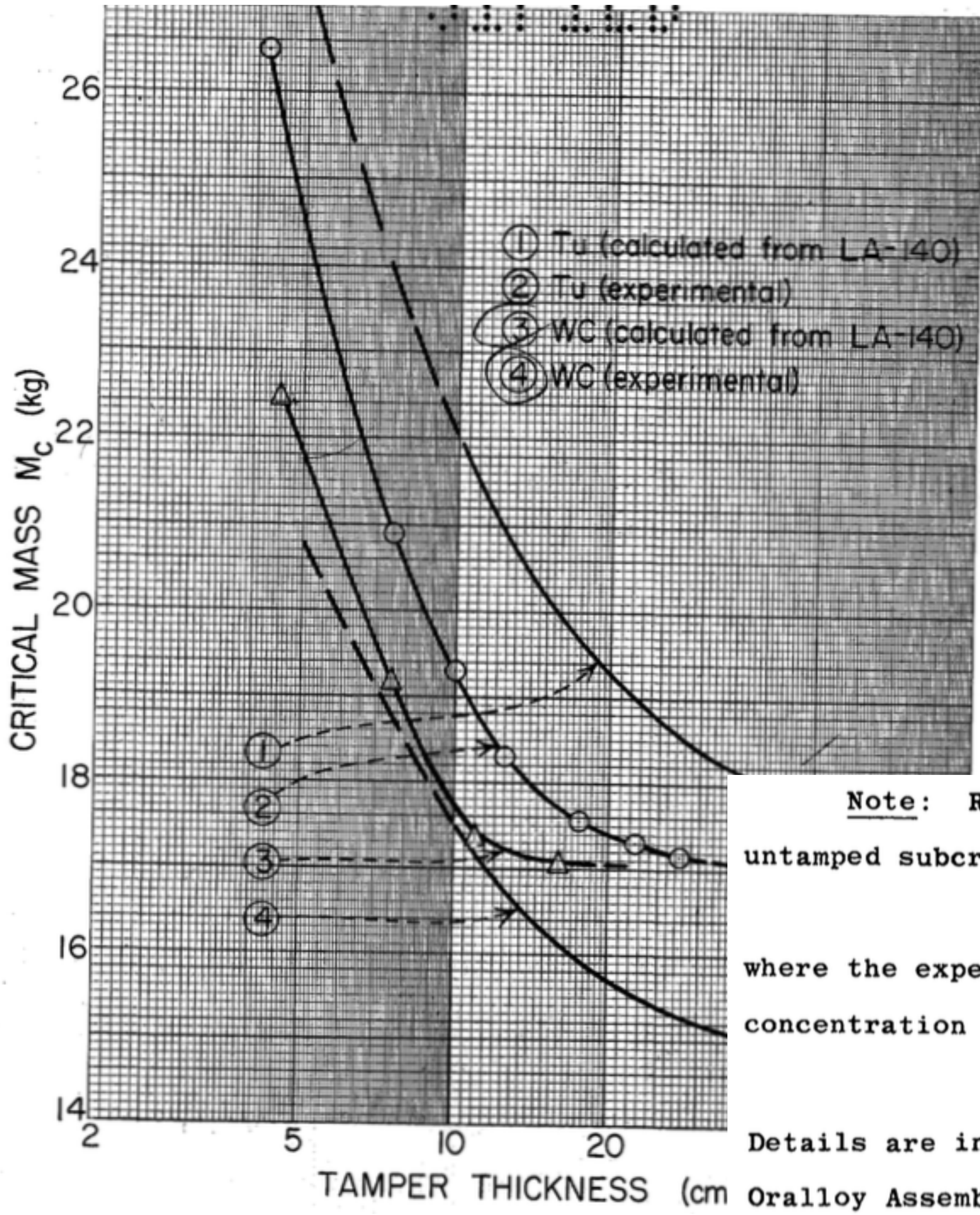
Possibly the earliest Criticality Handbook

LA-1579 June 1953

TABLE 1

TOPSY DELAYED CRITICAL MASS DATA

	Core			Tamper			
Reference	Material	ρ(gm/cm^3)	Shape	Material	ρ(gm/cm^3)	Shape	Critical mass(kg)
LA-1114 (1950)	Oy(94%)	18.7	pseudosphere	Tu	~ 19.0	pseudosphere ~ 11" thick	17.2
LA-1251 (1951)	Oy(67.6%)	18.75	"	"	"	pseudosphere 8½" thick	30.73
"	Oy(47.3%)	18.8	"	"	"	pseudosphere 7-3/4" thick	57.28
"	Oy(94%)	15.8 ½" cubes at 18.7	"	"	"	pseudosphere ~ 8-3/4" thick	21.34
"	Oy(94%)	9.35 ½" cubes at 18.7	"	"	"	pseudosphere 7-1/4" thick	39.34
LA-1114 (1950)	Oy(94%)	18.7	"	Ni	8.35	pseudosphere ~ 8-3/4" thick	21.20
Not yet reported	Pu alloy	15.7	sphere (central source cavity-0.4" diam.)	Tu	~ 19.0	pseudosphere ~ 9½" thick	5.81



LA-1114 Figure 8.

The primary goal was not simulation benchmarks.

Rather, experimentalists sought functional forms relating critical mass to, e.g., reflector thickness, fuel density, fuel concentration, etc.

From LA-1251…

Note: Recent material replacement measurements on an untamped subcritical assembly lead to the relation

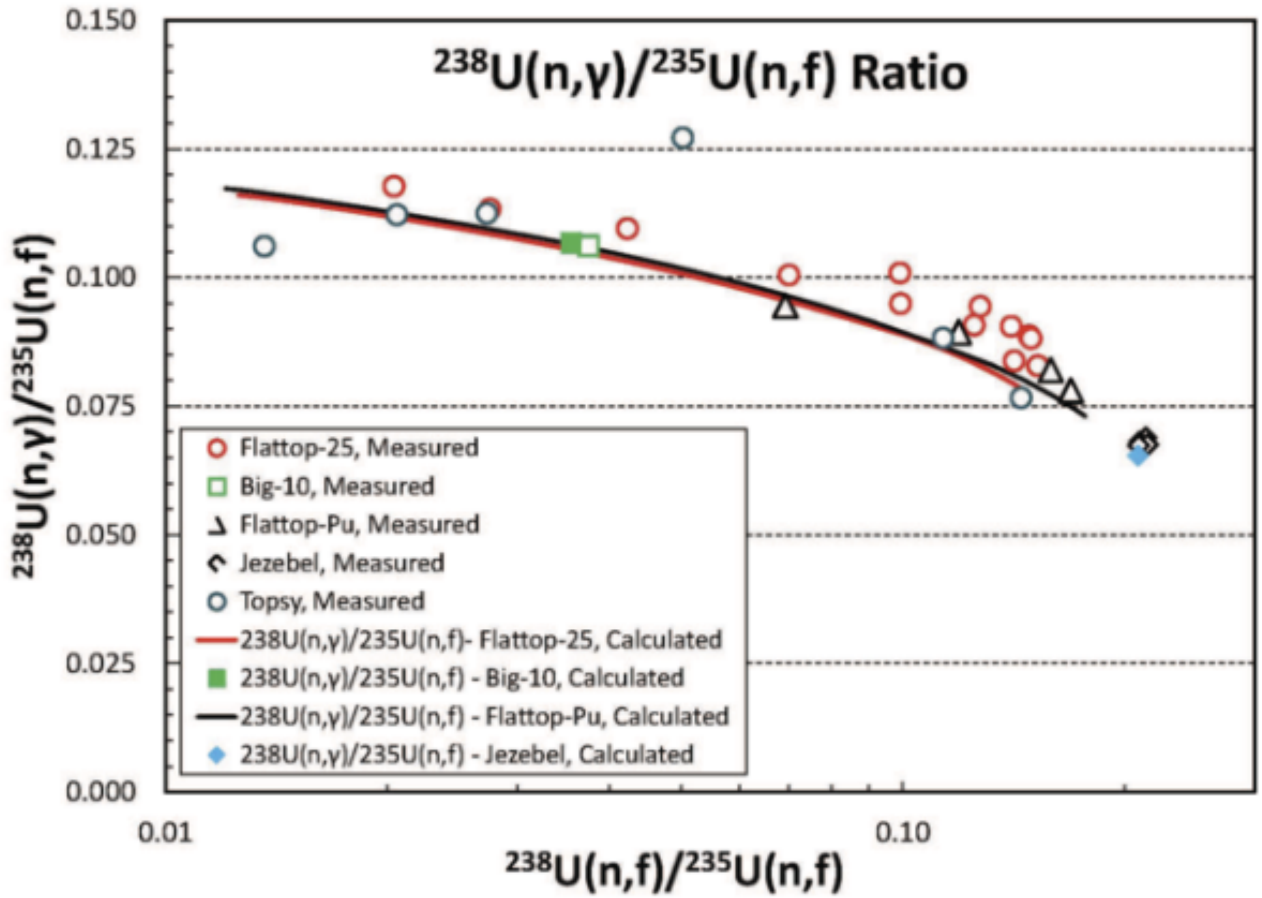
$$M_c = \text{const } \rho^{-2.07\pm0.15} ,$$

where the expected power of ρ is -2.00. The corresponding concentration relation is

$$M_c = \text{const } \rho^{-1.78\pm0.15} .$$

Details are included in LA-1209 ("Measurements on Untamped Oralloy Assembly", Orndoff and Paxton, February 8, 1951).

Relationships for radiochemistry measurements were also developed for diagnostics…



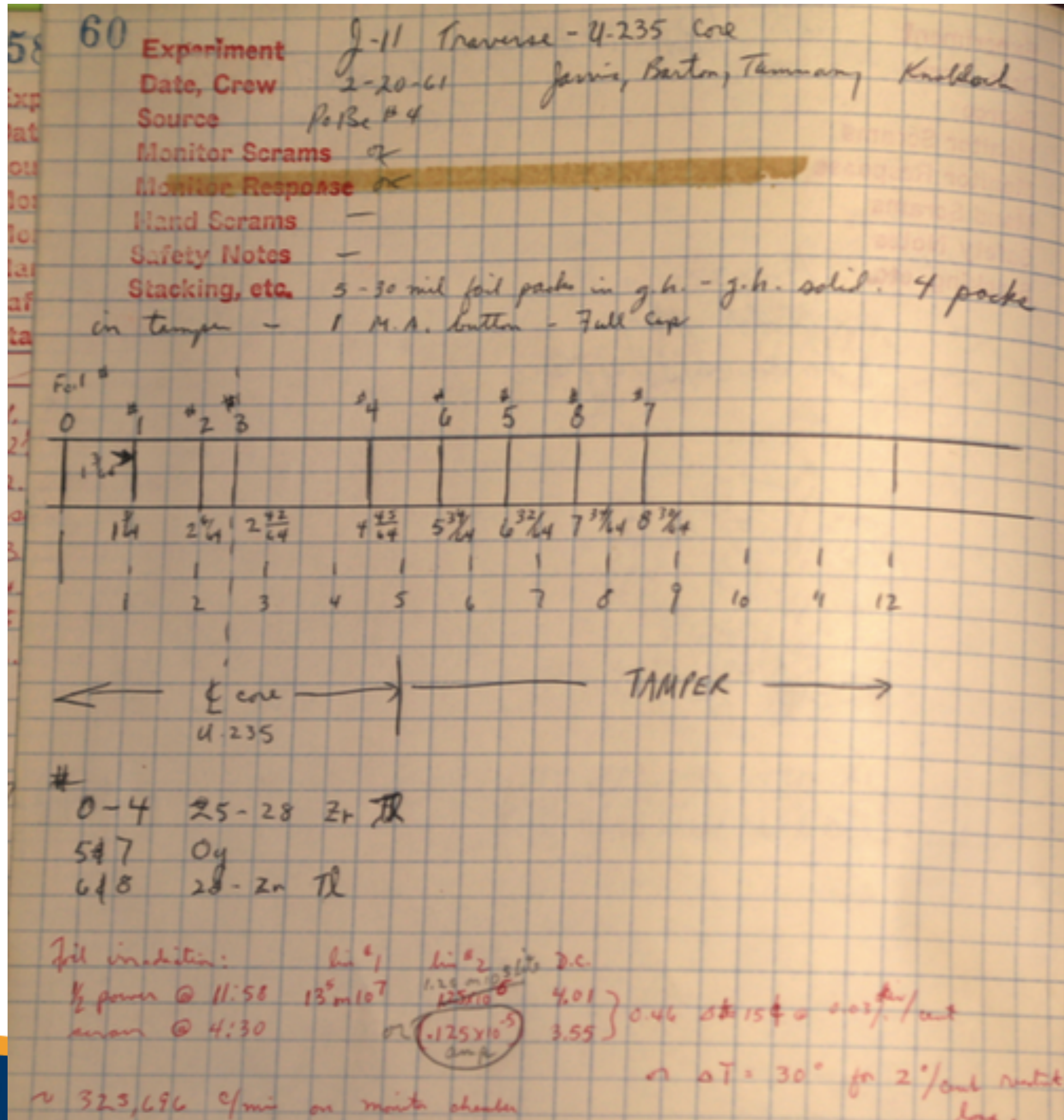
NDS Vol. 112 p. 2887 "ENDF/B-VII.1 Big Paper" Figure 58
See also Figure 93 and many others

Details are hard to find, most of the documentation found is previous summaries.

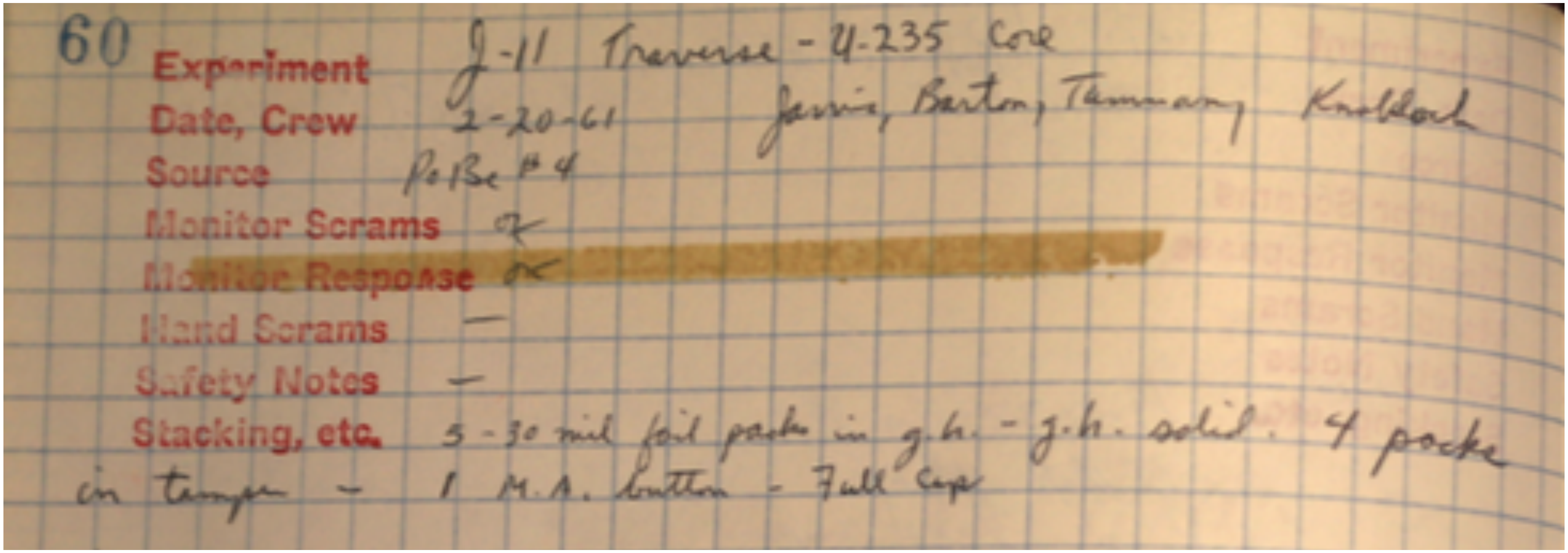
On February 20 and March 13, 1961, experiments were performed on the Flattop assembly (U^{235} with U^{238} tamper) which involved the irradiation of foil packets located at various radial positions in the assembly. The foils used were of the same material and thickness as those described in J-11 Memo "Radiochemical Experiments on the U^{233} Jezebel Assembly" Sept. 5, 1961. For brevity in the following discussion the run of February 20, on which Flattop was operated for 270 minutes at an extimated power level of 200 W, is designated as Run 94, and the run of March 13, for 309 minutes at 200 W, is designated as Run 95.

Browne. J-11, March 7, 1962, Radiochemical Experiments on the Flattop Assembly.

Flattop Logbooks are all accounted for. But the details available are scarce…

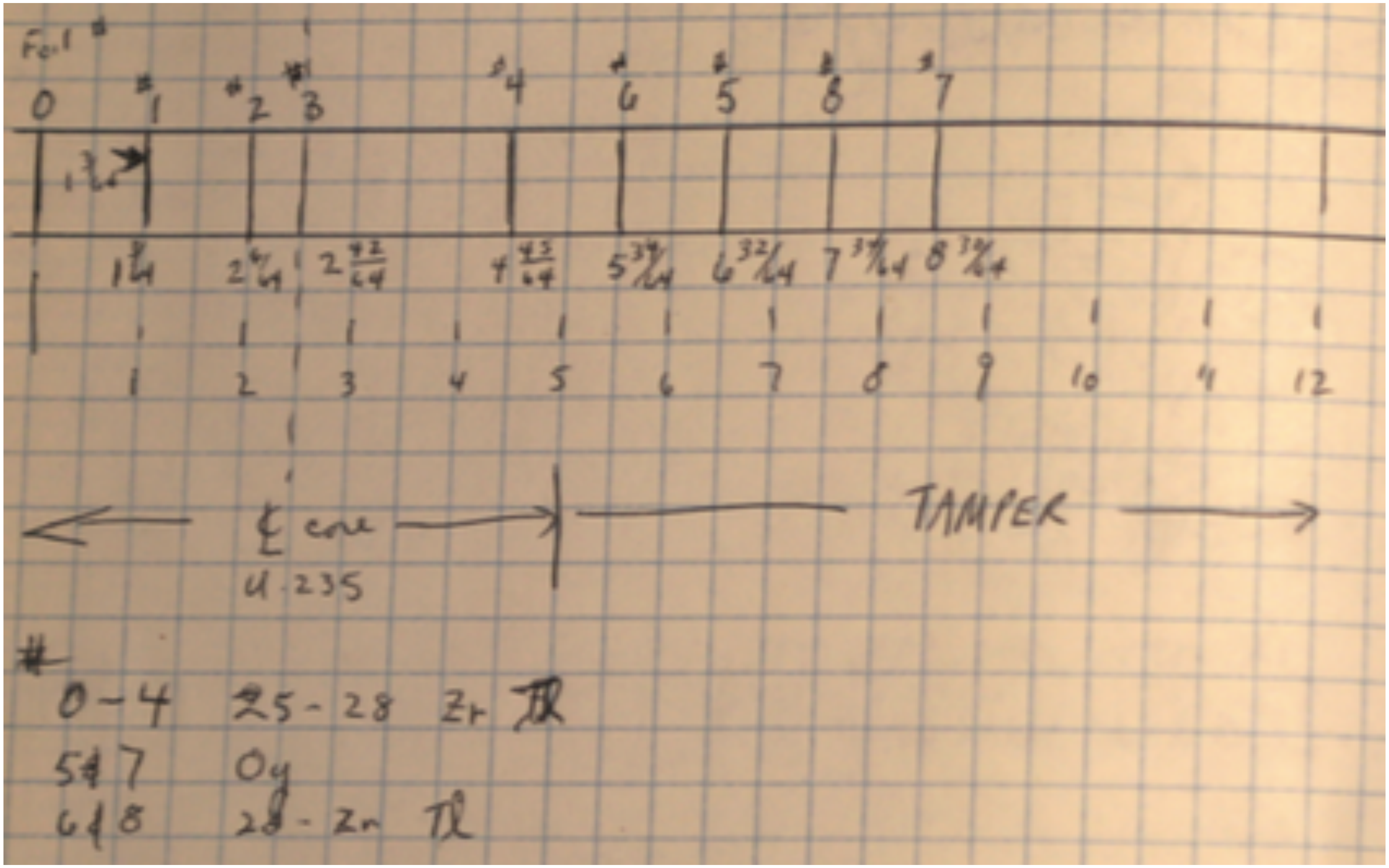


Flattop Logbook Vol. 1 p. 60



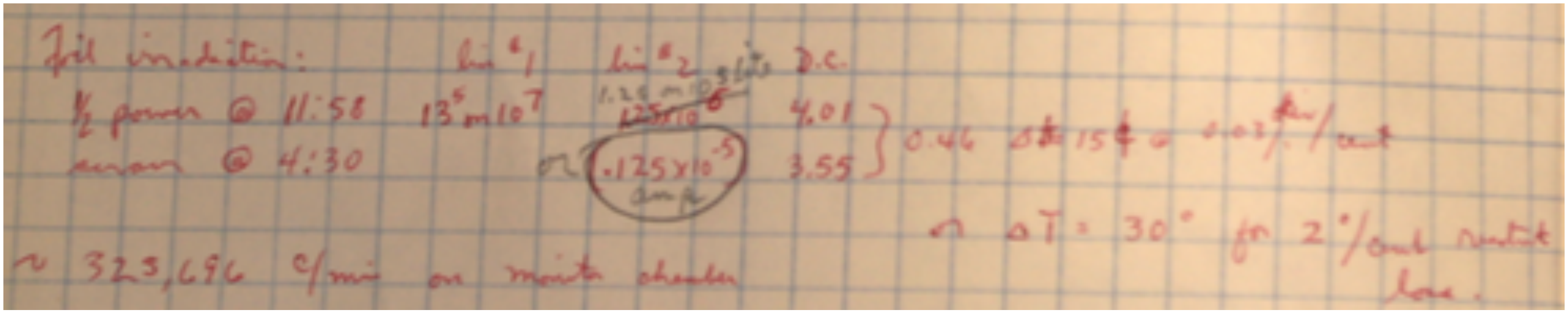
Useful notes "g.h. solid… 1 M.A. button – Full Cap"

Flattop Logbook Vol. 1 p. 60



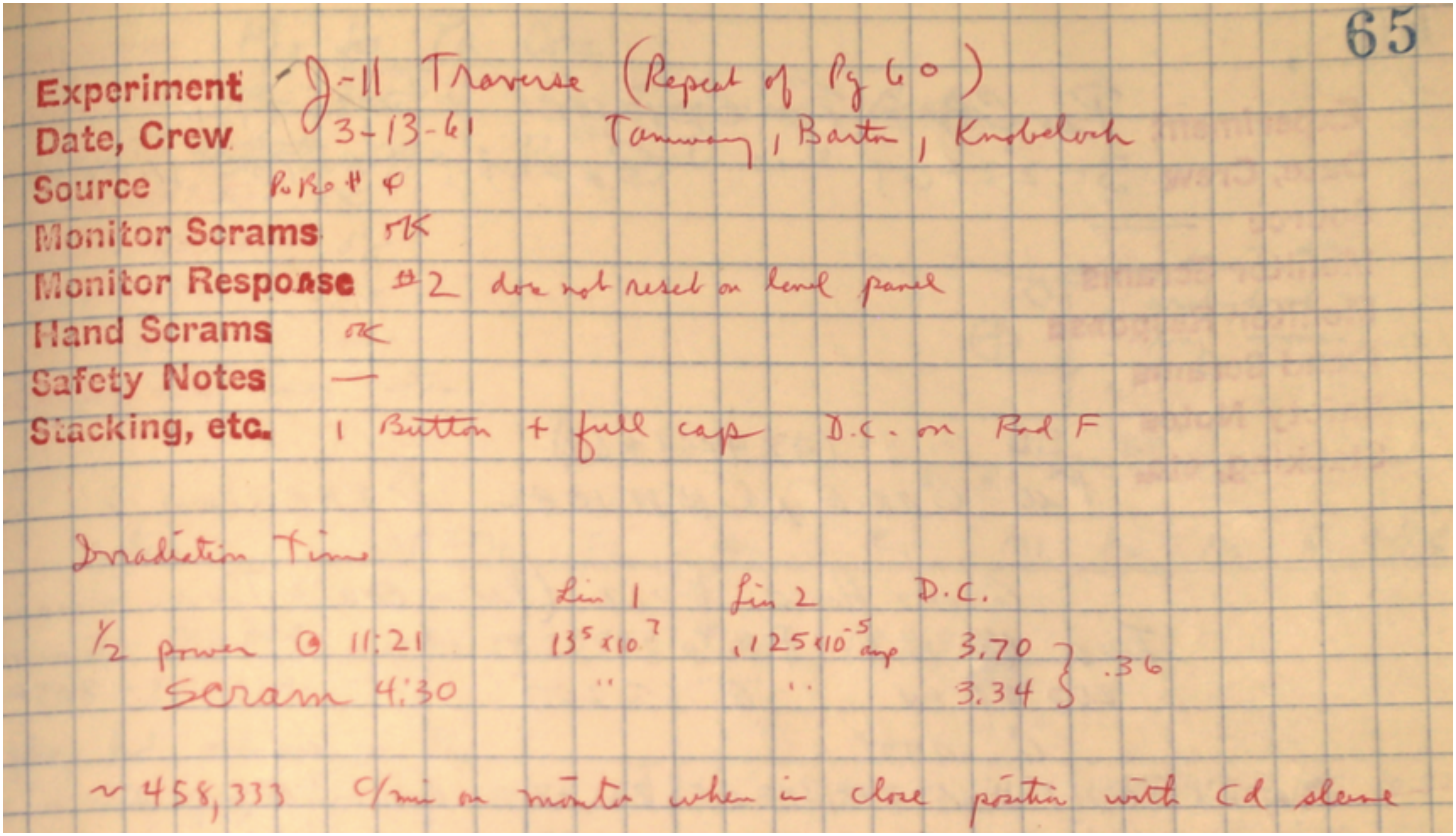
Useful notes foil positions and stacking order.

Flattop Logbook Vol. 1 p. 60



Useful notes "1/2 power", irradiation start and stop time, "D.C." with control rod positions (but not which one) and total temperature rise during irradiation .

Flattop Logbook Vol. 1 p. 60


65

Experiment: J-11 Traverse (Repeat of Pg 60)
Date, Crew: 3-13-61 Tammany, Barton, Knobeloch
Source: Po Be # 4
Monitor Scrams: OK
Monitor Response: #2 does not reset on level panel
Hand Scrams: OK
Safety Notes: —
Stacking, etc.: 1 Button + full cap D.C. on Rod F

Irradiation Time

	Lin 1	Lin 2	D.C.	
1/2 power @ 11:21	1.35 x 10^-7	.125 x 10^-5 amp	3.70	.36
Scram 4:30	"	"	3.34	

~ 458,333 c/min on monitor when in close position with Cd sleeve

Probably used "Rod F" for control of both irradiations.

Flattop Logbook Vol. 1 p. 65

Can cross check the positions of the foils…

a. Run 94.

TABLE 1 - Run 94 Foil Locations

Sample	Radius (cm)	Foils in Packet
943	0.40	Oy, D-38, Zr, Tl
942	1.03	Oy, D-38, Zr, Tl
941	3.69	Oy, D-38, Zr, Tl
944	5.60	Oy, D-38, Zr, Tl
940	6.32	Oy, D-38, Zr, Tl
945	7.70	D-38, Zr, Tl
946	10.16	Oy
947	12.78	D-38, Zr, Tl
948	15.16	Oy

Foil composition in "Sept 5, 1961" memo. Not found yet.

TABLE 2 - Foil Weights

Sample	Oy (mg)	D-38 (mg)	Zr (mg)	Tl (mg)
943	49.9	101.6	70.2	113.7
942	46.0	99.7	68.7	146.3
941	46.8	109.2	70.5	138.2
944	46.3	99.0	70.0	129.2
940	44.0	93.7	69.1	147.3
945	----	91.3	68.5	134.8
946	41.6	----	----	----
947	----	90.7	70.0	148.1
948	46.0	----	----	----

Browne. J-11, March 7, 1962, Radiochemical Experiments on the Flattop Assembly.

And here is the "full" summary of the radiochemistry…

2. Run 94.

TABLE 6 - Fission Data - Run 94

Sample	Mo^{99} c/m/mg Oy x 10^{-4}	Mo^{99} c/m/mg D-38 x 10^{-3}	$(nvt\ \sigma_F)_{25}$ x 10^{8}	$(nvt\ \sigma_F)_{28}$ x 10^{10}	$\sigma_F^{25}/\sigma_F^{28}$
943	3.26_2	5.42_3	3.20_2	4.92_3	6.50_4
942	3.19_8	5.37_6	3.13_9	4.58_0	6.43_2
941	2.84_1	4.39_7	2.79_1	3.99_0	6.99_5
944	2.00_4	2.74_1	1.97_1	2.45_3	7.92_8
940	1.84_3	2.00_9	1.81_7	1.82_0	9.98_4
945	(1.30)	1.00_5	(1.28)	(0.906)	(14.14)
946	0.849_8	(0.390)	(0.841)	(0.350)	(24.04)
947	(0.58)	0.179_6	(0.575)	(0.160)	(35.92)
948	0.421_7	(0.100)	(0.416)	(0.083)	(47.51)

Browne. J-11, March 7, 1962, Radiochemical Experiments on the Flattop Assembly.

We have made minor updates (0.3% below) based on updated K-factors…

Location, cm (blank = center)		Reaction	Measured (original)	Measured (revised)
	20-Feb-61			
0.4		$^{238}U(n,f)$ / $^{235}U(n,f)$	0.1537	0.1543
1.03		$^{238}U(n,f)$ / $^{235}U(n,f)$	0.1555	0.1560
3.69		$^{238}U(n,f)$ / $^{235}U(n,f)$	0.1430	0.1435
5.6		$^{238}U(n,f)$ / $^{235}U(n,f)$	0.1261	0.1266
6.32		$^{238}U(n,f)$ / $^{235}U(n,f)$	0.1002	0.1005
7.7		$^{238}U(n,f)$ / $^{235}U(n,f)$	0.0707	0.0710
12.78		$^{238}U(n,f)$ / $^{235}U(n,f)$	0.0278	0.0279

NDS Vol. 111 (2010) p. 2904 – K-factor measurements

And we can assign some systematic errors to the radiochemistry…

LA-1721 Collected Radiochemistry Procedures (multiple editions from 1954 – 1990) Defined standard procedures to separate elements for individual analysis.

LAMS-2342 Standard Deviations of Radiochemical Analysis Provides analysis of precision during the 1959 timeframe.

TABLE I

Standard Deviations of Radiochemical Analyses

A. Fission Products

Nuclide	Cases Studied	Average Standard Deviation (per cent)
Mo^{99}	348	0.962
Ce^{144}	219	1.22
Nd^{147}	43	2.34

B. Heavy Elements

Nuclide	Cases Studied	Average Standard Deviation (per cent)
U^{235}	191	0.775
Pu^{239}	116	0.632
Np^{239}	264	0.948

PU-MET-FAST-001 rev 4

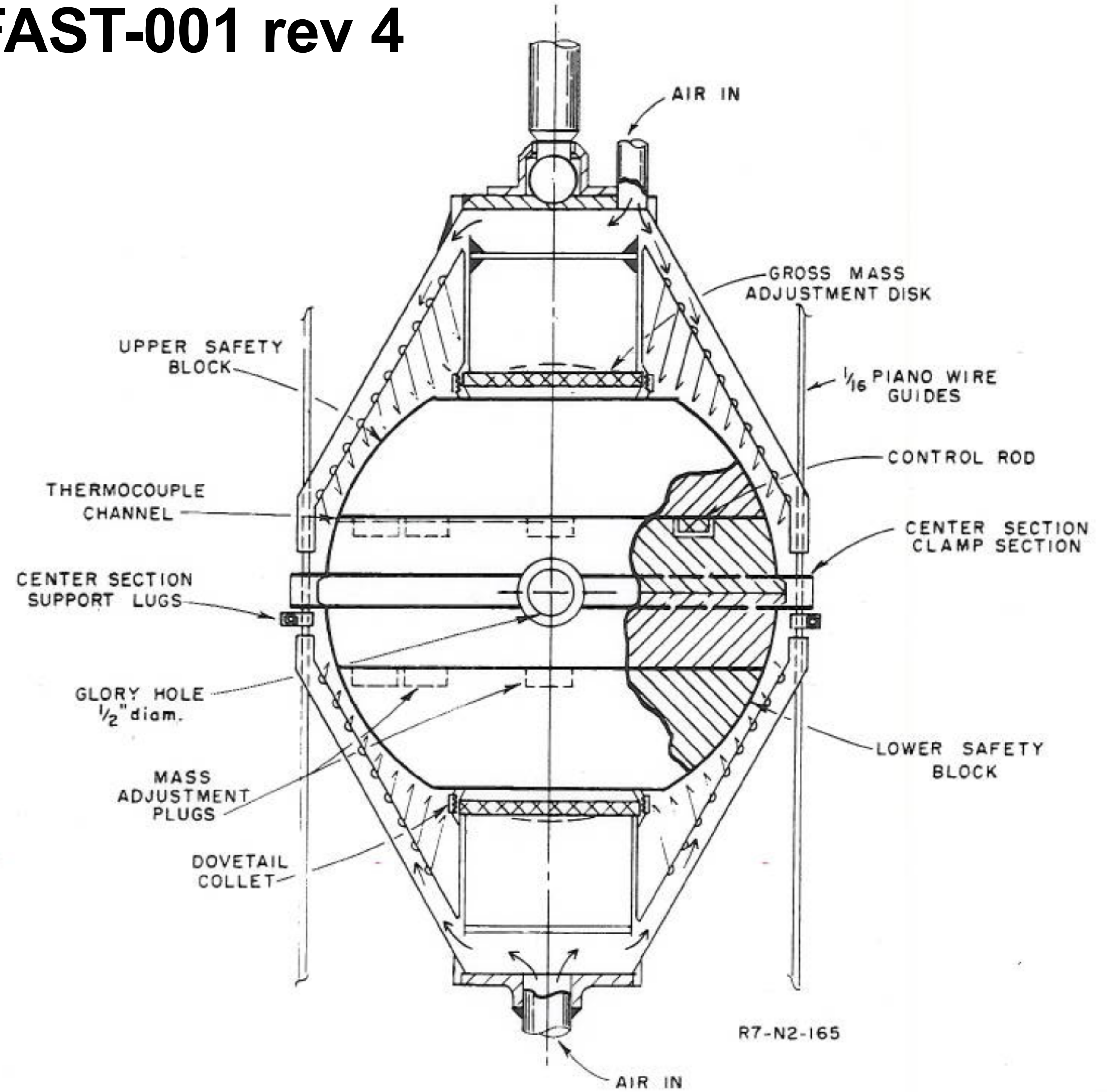


Figure 3. Proposed Jezebel Assembly (Reference 1).[a]

PU-MET-FAST-001 rev 4

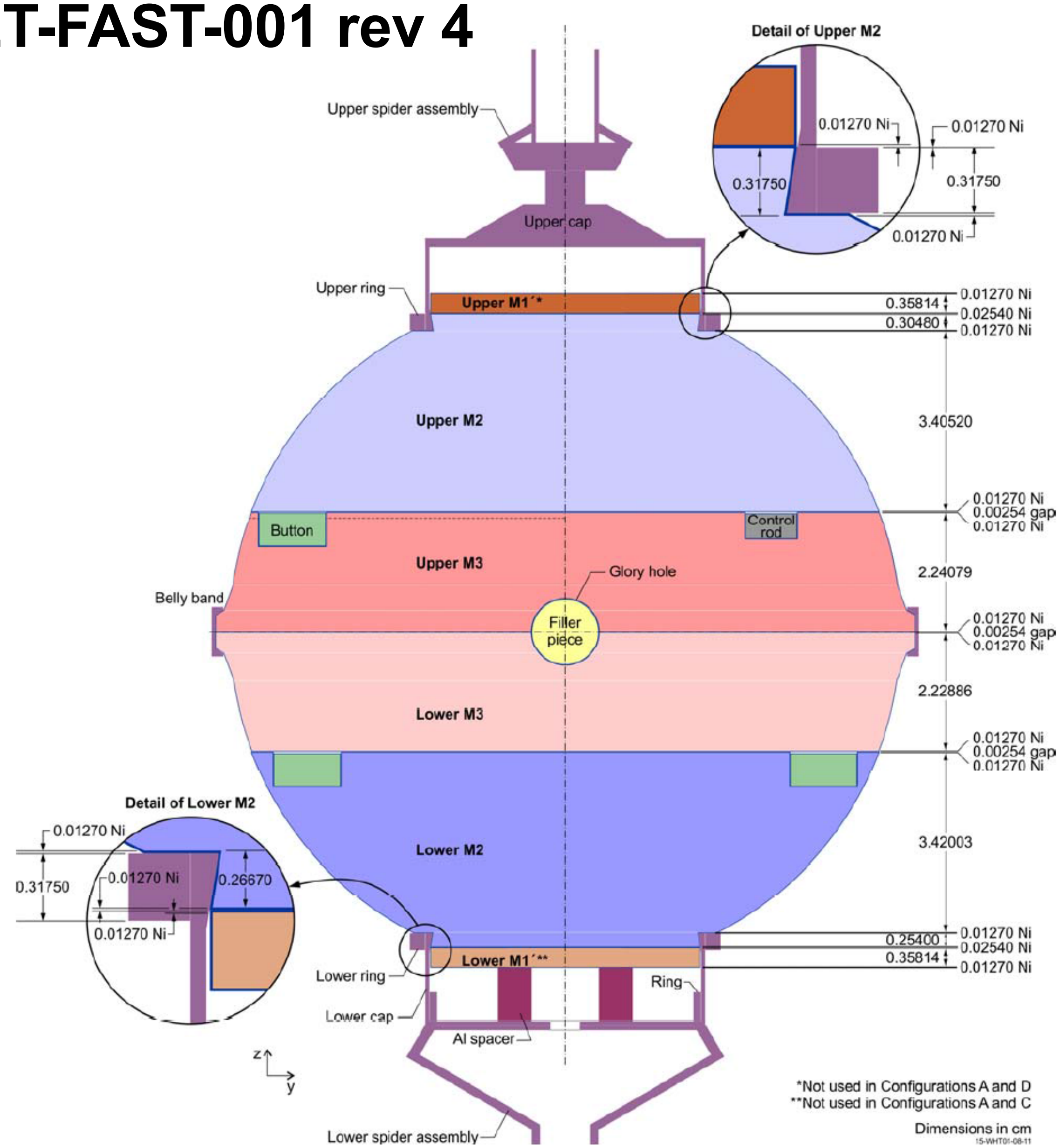
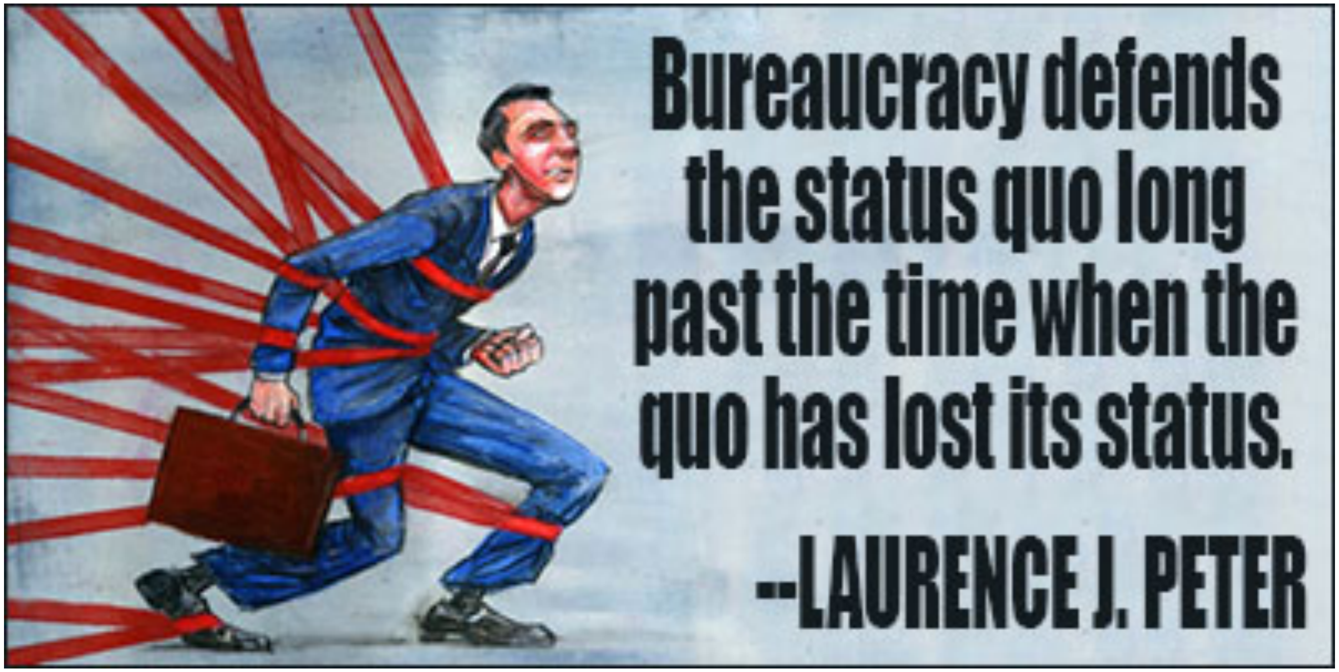


Figure 30. Assembly of Parts; View Plane Perpendicular to Glory Hole.
(Dimensions are in centimeters.)

Modern measurements are …



Bureaucracy, the rule of no one,
has become the modern form of despotism.

Mary McCarthy, "The Vita Activa,"
The New Yorker, Oct. 18, 1958

The current critical experiment measurement campaigns have minimal new value* unless we can address the following issues…

- Lack of verifiable characterization for existing materials
  - Need modern assessments of mass, elemental analysis, isotopic analysis, dimensions, **gaps** and most importantly **density**
- Lack of fabrication stream for new parts, particularly SNM
  - With full material characterization
- Poor supporting infrastructure
  - Must modernize measurement equipment and add count rooms
- Inability to perform experiment variations in a timely manner
  - Early measurement campaigns did hundreds of variations
  - Modern measurements are only getting a few variations often separated by months of waiting

*as nuclear data benchmarks.

Summary

- Garbage in (*still gives*) garbage out (GIGO).
  Faster, bigger computers make more garbage faster.
  We must have good data.

- There is great value in tuning our nuclear data libraries based on high-quality differential *and integral* data.

- There is still much that can be learned, and fit, from examination of past measurements.

- Modern attempts to reproduce and extend key measurements must be designed to assess – and document – the relevant systematic uncertainties.

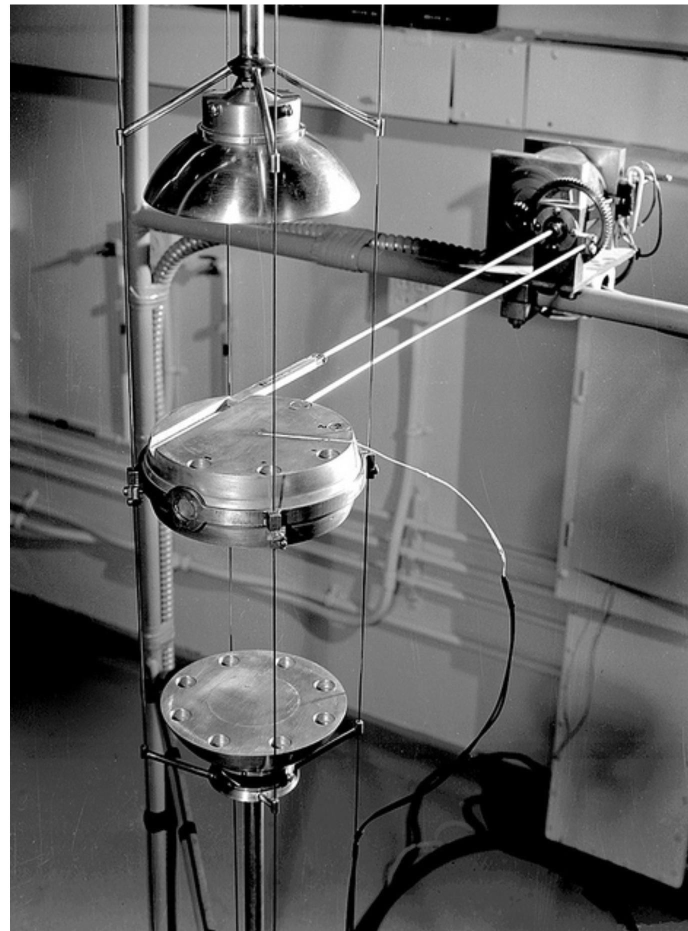
Final bare critical mass experiments were a testament to "getting it right".

"Lady Godiva"

LA-1614 first critical in August 1951

*Damaged beyond repair in February 1954

"Jezebel"



*Trouble.

CIELO paper (DOI: 10.1016/j.nds.2014.04.002)

TABLE VII. Reaction rate measurements in the HEU Godiva critical assembly.

Assembly/date	Reaction	Measurement	
Godiva	$^{238}U(n,2n)/^{235}U(n,f)$	7.729E-03	
6/30/1959	$^{238}U(n,f)/^{235}U(n,f)$	1.629E-01	0.1629
	$^{239}Pu(n,f)/^{235}U(n,f)$	1.365	

"Lady Godiva" did not exist in 1959. This is a measurement using Godiva-II, a 7" diameter right cylindrical assembly.

There is a 3% disagreement between values in CIELO paper and LA-1614.

LA-1614 TABLE III.

Variation of the ratio of fission cross sections of U-235 and U-238 with radial position of these detectors in Godiva. Data are based on radio-chemical analysis of foils irradiated in the critical assembly.

Detector Position: Inches from center of Godiva	Ratio: $\sigma_f(U\text{-}235)/\sigma_f(U\text{-}238)$	
0.02	6.32	1 / 0.158
0.50	6.23	1 / 0.161

No details beyond LA-1614 have been found (yet) on the chemistry, counting, foil masses, decay constants, ???

Table XXXVII ENDF/B-VII.1 paper (NDS V112 p. 2971) propogates the same values as HEU-MET-FAST-001 which quotes the values given in ENDF-202

ENDF-202 (1974) Benchmark specification gives a value of 0.1643 +/- 1% and cites Nuc. Sci. & Eng. Vol. 8 pp. 608-614 which contains no fission data.

By coincidence, ENDF/B-VII.1 calculates 0.1579

Dosimetry data calculations for ENDF/B-VII.1

TABLE XXXVII: Comparison of calculated spectra indices for ENDF/B-VII.1 with measured values in the center of various Los Alamos critical assemblies. U238*f*/U235*f* refers to the ^{238}U fission rate divided by the ^{235}U fission rate, *etc.* Because ^{238}U and ^{237}Np are threshold fissioners, the spectral indices for these isotopes (in ratio to ^{235}U) measure the hardness of the neutron spectrum in the assembly Exp-A refers to experimental data as documented in the CSEWG Fast Reactor Benchmark Compilation, BNL 19302 (June 1973); Exp-B refers to the same measurements, but as reanalyzed by G. Hansen, one of the lead experimentalists, and transmitted to R. MacFarlane in 1984. The C/E ratios are based on the Hansen values where available.

Assembly	Quantity	U238*f*/U235*f*	Np237*f*/U235*f*	U233*f*/U235*f*	Pu239*f*/U235*f*
Godiva	Calc	0.1579	0.8301	1.5687	1.3823
(HMF001)	Exp-B	0.1643 ±0.0018	0.8516±0.012		1.4152 ± 0.014
	Exp-A	0.1642 ±0.0018	0.837 ±0.013	1.59±0.03	1.402±0.025
	Calc/Exp	C/E=0.9610	C/E=0.9747	C/E=0.9866	C/E=0.9768
Jezebel	Calc	0.2085	0.9708	1.5561	1.4242
(PMF001)	Exp-B	0.2133 ±0.0023	0.9835 ±0.014		1.4609 ± 0.013
	Exp-A	0.2137 ±0.0023	0.962 ±0.016	1.578 ±0.027	1.448 ±0.029
	Calc/Exp	C/E=0.9775	C/E=0.9871	C/E=0.9861	C/E=0.9749
Jezebel-23	Calc	0.2111	0.9970		
(UMF001)	Exp-B	0.2131 ±0.0026	0.9970 ±0.015		
	Exp-A	0.2131 ±0.0023	0.977 ±0.016		
	Calc/Exp	C/E=0.9906	C/E=1.000		
Flattop-25	Calc	0.1438	0.7693	1.5674	1.3586
(HMF028)	Exp-B	0.1492 ±0.0016	0.7804 ±0.01	1.608 ±0.003	1.3847 ±0.012
	Exp-A	0.149 ±0.002	0.76 ±0.01	1.60 ±0.003	1.37 ±0.02
	Calc/Exp	C/E=0.9638	C/E=0.9858	C/E=0.9748	C/E=0.9812
Flattop-Pu	Calc	0.1767	0.8521		
(PMF006)	Exp-B	0.1799 ±0.002	0.8561 ±0.012		
	Exp-A	0.180 ±0.003	0.84 ±0.01		
	Calc/Exp	C/E=0.9822	C/E=0.9953		
Flattop-23	Calc	0.1882	0.9128		
(UMF006)	Exp-B	0.1916 ±0.0021	0.9103 ±0.013		
	Exp-A	0.191 ±0.003	0.89 ±0.01		
	Calc/Exp	C/E=0.9823	C/E=1.0027		

ENDF/B-VII.1 paper (NDS V112 p. 2971)

Uranium reflected experiments leading to final FLATTOP design.

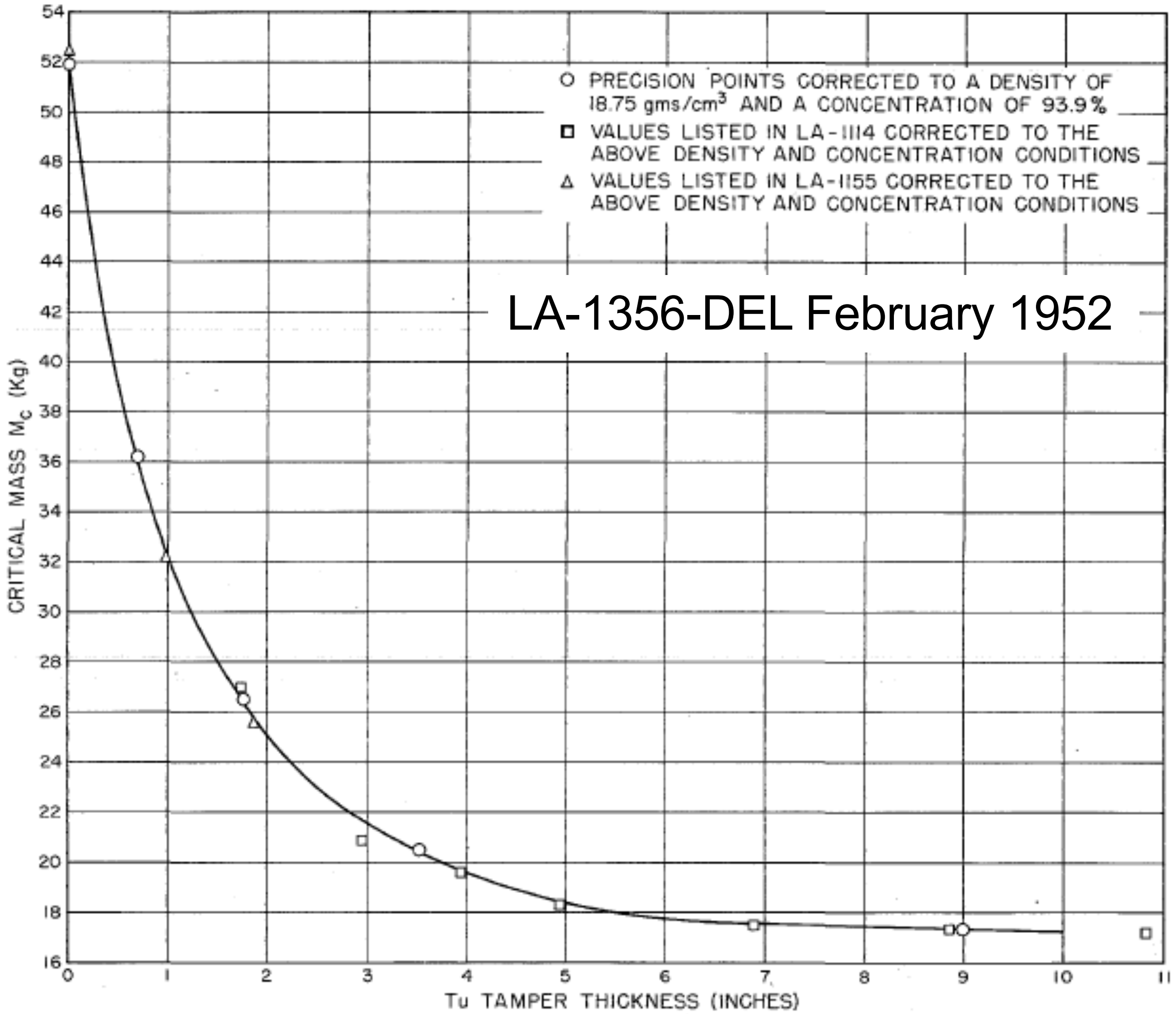


FIG. 3. Oy critical mass as a function of tamper thickness for Tu.