Current Status of the IRPhEP and ICSBEP (August 2014)

John D. Bess and J. Blair Briggs
Idaho National Laboratory (INL)

Jim Gulliford and Ian Hill
OECD Nuclear Energy Agency (OECD/NEA)

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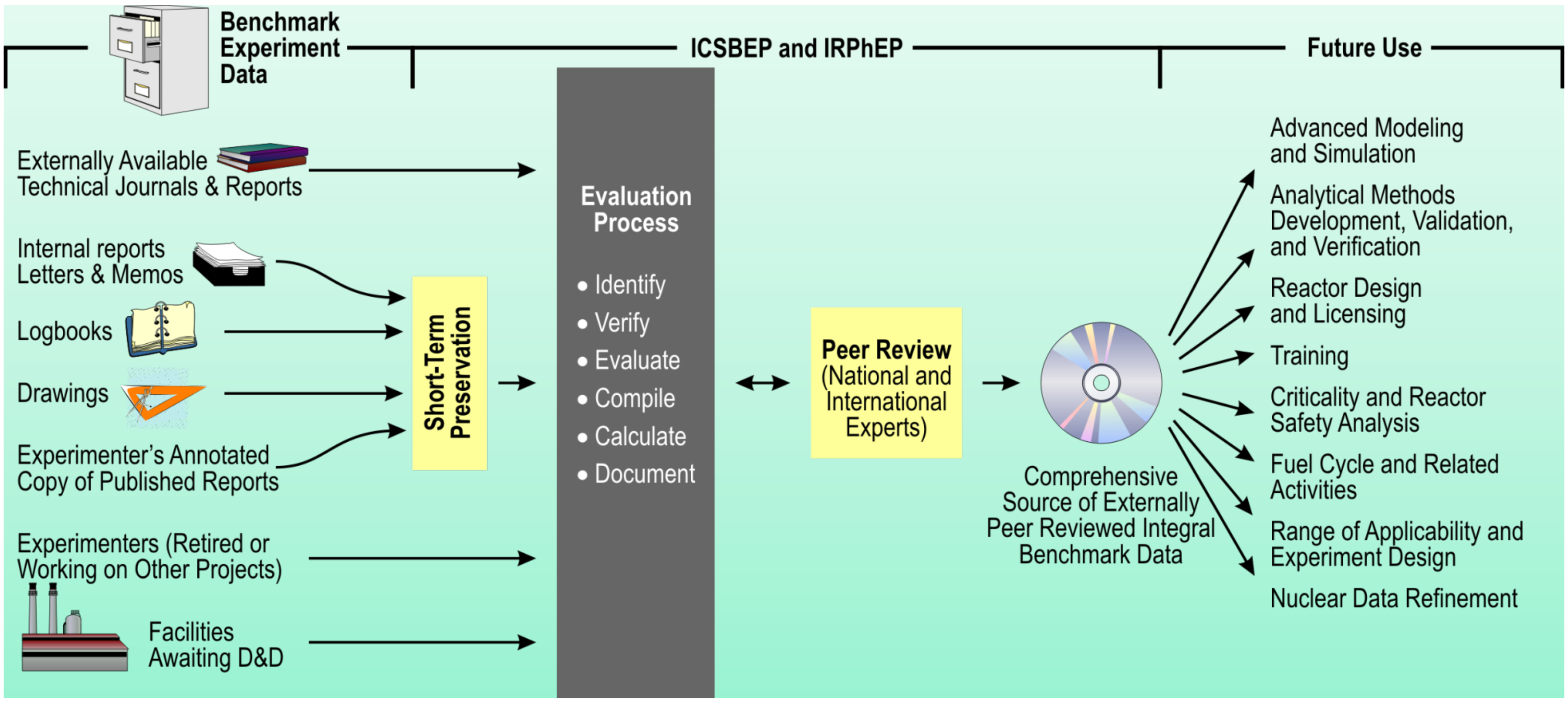
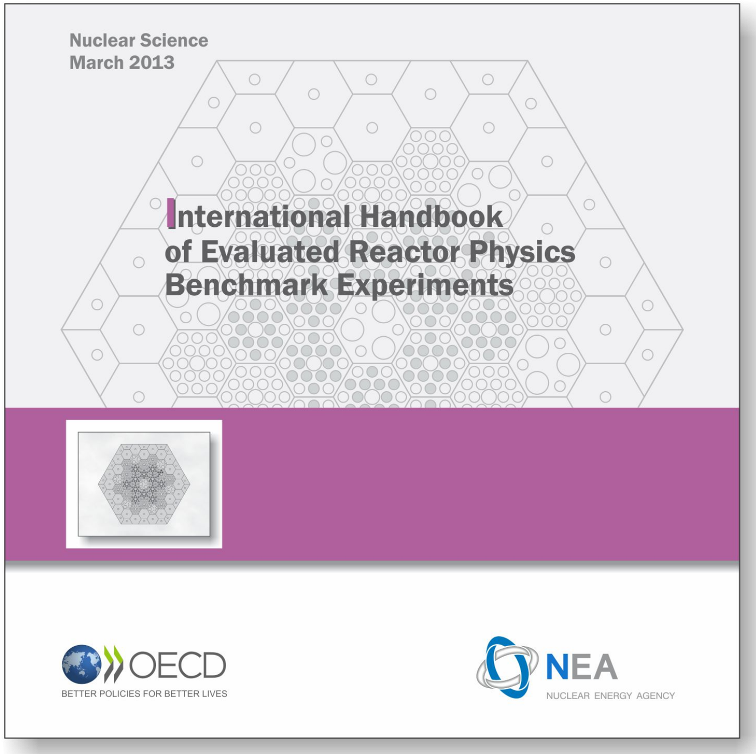
The Benchmark Evaluation Process



International Handbook of Evaluated Reactor Physics Benchmark Experiments

March 2014 Edition

- 20 Contributing Countries
- Data from 136 Experimental Series performed at 48 Reactor Facilities
- Data from 3 are published in DRAFT form
- Handbook available to OECD member countries, all contributing countries, and to others on a case-by-case basis



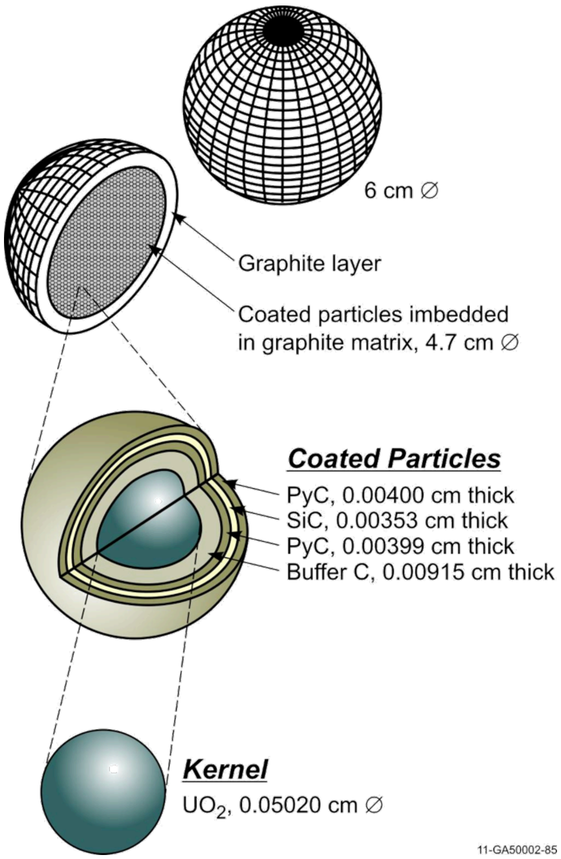
http://irphep.inl.gov/

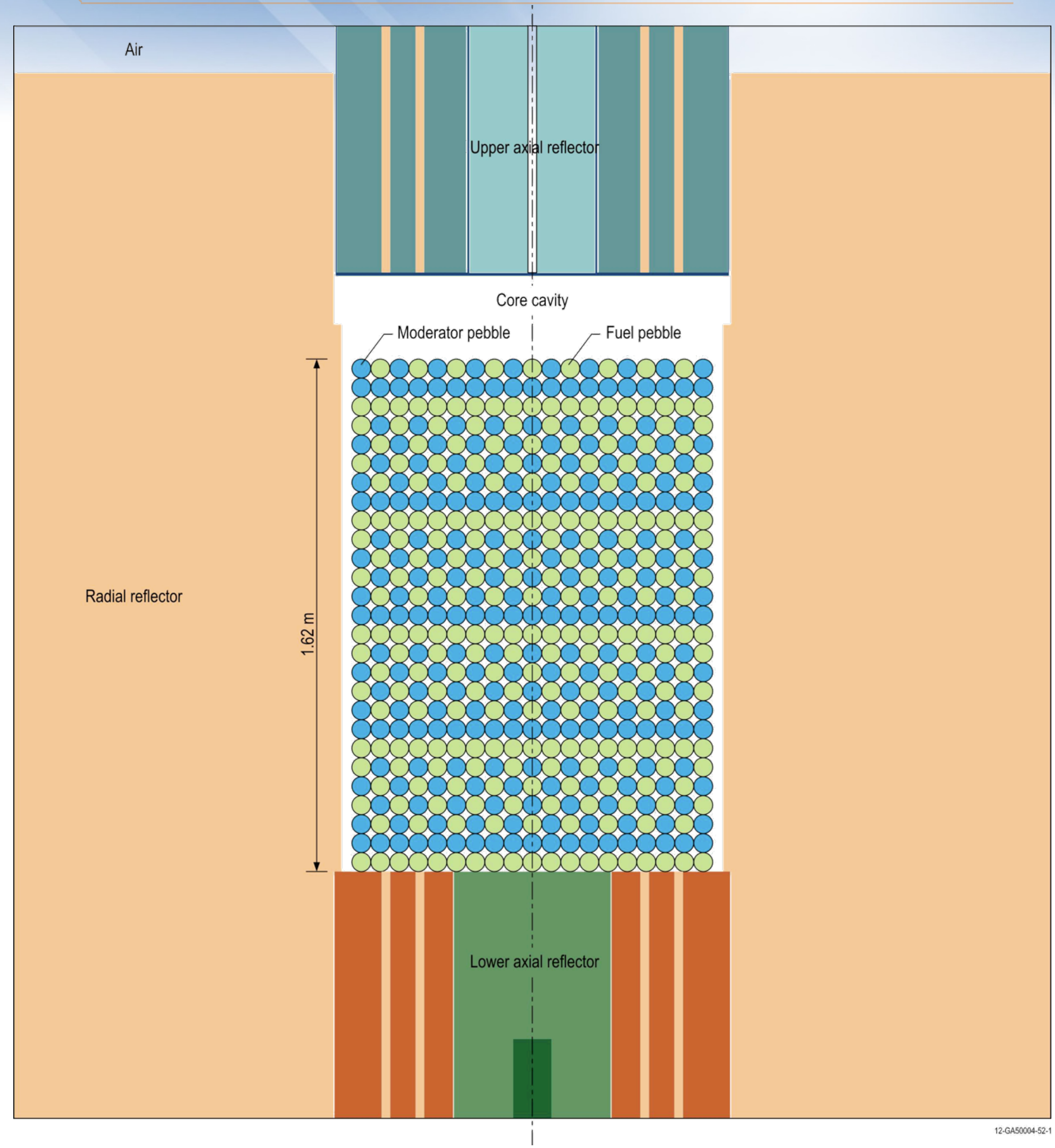
http://www.oecd-nea.org/science/wprs/irphe/

New/Revised Benchmarks in 2014 Handbook

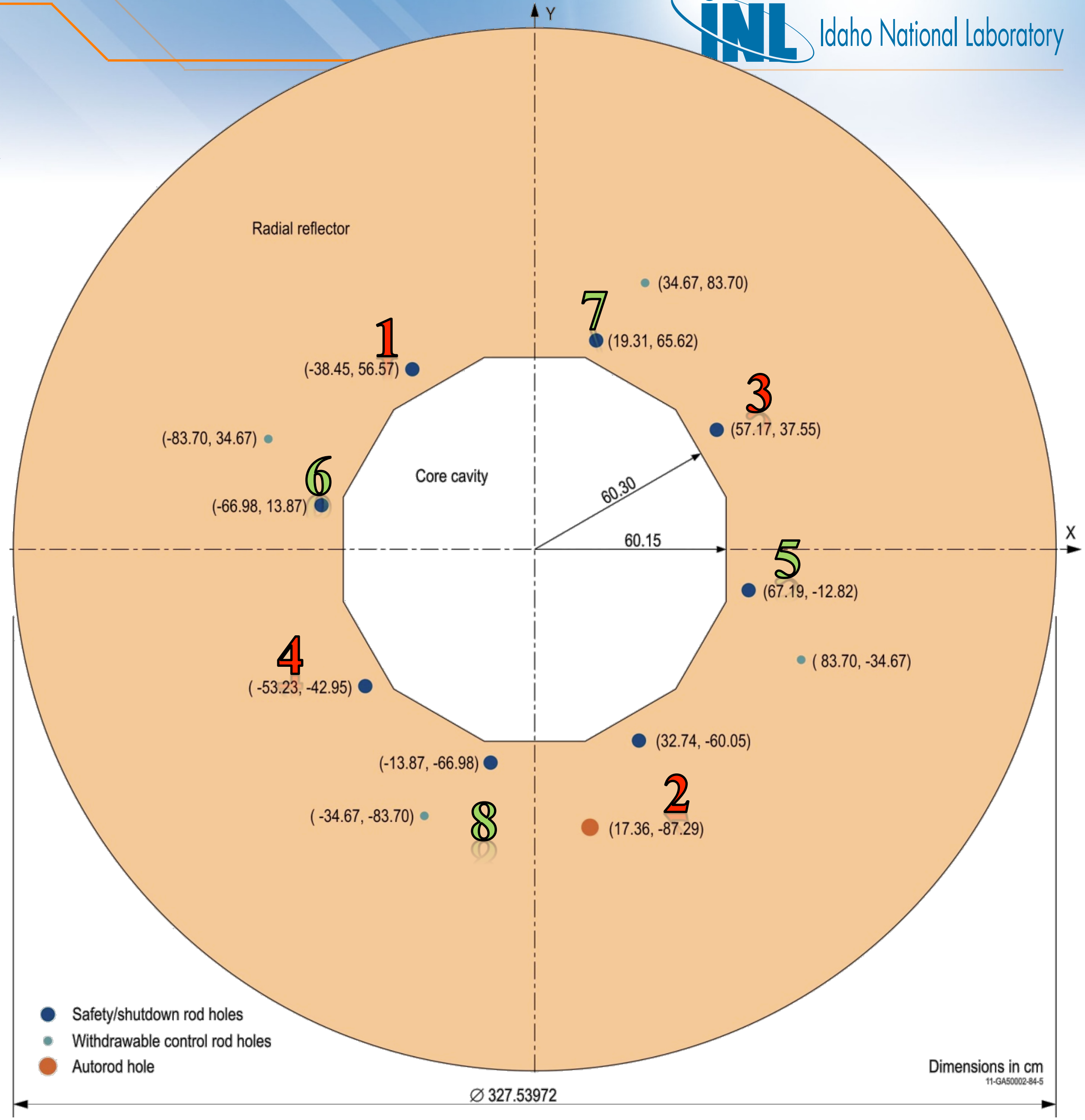
- **Gas-Cooled Reactor (GCR)**
  - HTR-PROTEUS Cores 4, 9+10
    - Absorber Rod Worth Measurements
- **Light Water Reactor (LWR)**
  - IPEN/MB-01 Research Reactor
    - Subcritical measurements
- **Space Reactor (SPACE)**
  - SCCA 3
    - Cadmium-Ratio and Reaction-Rate Distributions
- **Pressurized Water Reactor (PWR)**
  - VENUS 7
    - Criticality, Reactivity Effects Measurements, and Reaction Rate Distributions
  - B&W Spectral Shift Reactor Lattice Experiment
    - Criticality
- **Fundamental Physics Reactor (FUND)**
  - ORSphere
    - Reactivity Effects and Coefficient and β_{eff}
  - NRAD Reactor 64-Element Core Upgrade
    - Criticality, Absorber Rod Worth Measurements

HTR-PROTEUS Absorber Rod Worths





Rod Positions



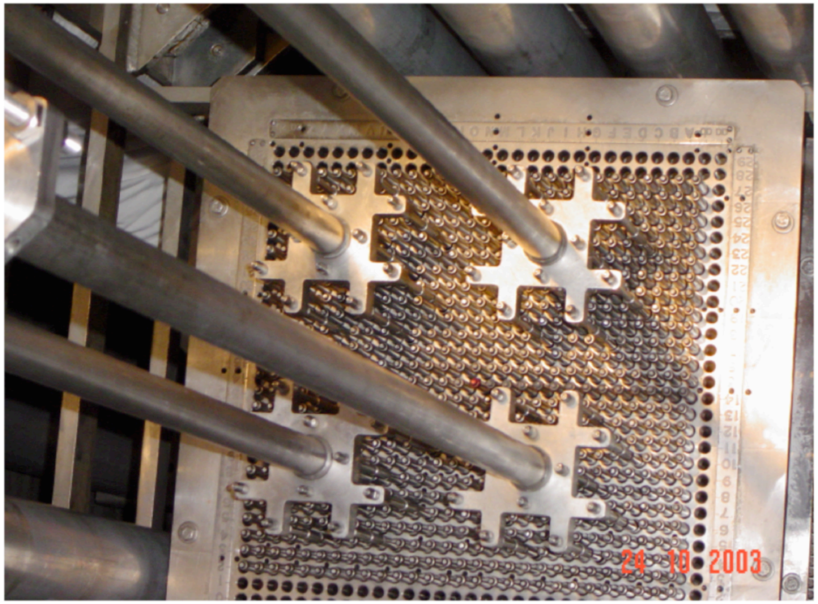
Core 10 Results (MCNP5 + ENDF/B-VII.0)

$\beta_{eff} = 685 \pm 34$ pcm

Absorber Rod	Calculated Worth ρ$	±	1σ	Benchmark Experiment ρ$	±	1σ	C/E	±	1σ
Control Rod 1	-0.29	±	0.02	-0.30	±	0.02	0.97	±	0.09
Control Rod 2	-0.28	±	0.02	-0.29	±	0.02	0.97	±	0.10
Control Rod 3	-0.25	±	0.02	-0.29	±	0.02	0.86	±	0.09
Control Rod 4	-0.28	±	0.02	-0.30	±	0.02	0.93	±	0.09
Control Rod Bank	-1.11	±	0.06	-1.15	±	0.07	0.97	±	0.08
Autorod	-0.08	±	0.01	-0.073	±	0.004	1.14	±	0.14
Autorod Rest Worth	-0.09	±	0.01	-0.081	±	0.005	1.13	±	0.19
Shutdown Rod 5	-2.73	±	0.14	-2.81	±	0.10	0.97	±	0.06
Shutdown Rod 6	-2.75	±	0.14	-2.82	±	0.09	0.98	±	0.06
Shutdown Rod 7	-2.73	±	0.14	-2.80	±	0.16	0.98	±	0.07
Shutdown Rod 8	-2.66	±	0.13	-2.72	±	0.15	0.98	±	0.07
Shutdown Rods 5+6	-5.70	±	0.29	-5.93	±	0.16	0.96	±	0.06
Shutdown Rods 5+7	-5.54	±	0.28	-5.73	±	0.32	0.97	±	0.07
Shutdown Rods 5+8	-5.49	±	0.27	-5.75	±	0.33	0.95	±	0.07
Shutdown Rods 5+6+7	-8.65	±	0.43	-9.29	±	0.20	0.93	±	0.05
Shutdown Rods 5+6+7+8	-11.81	±	0.59	-12.64	±	0.29	0.93	±	0.05

IPEN/MB-01 Reactor

- Measurement of reactivity levels of subcritical systems
- Gandini and Salvatores subcritical kinetics model
  - Based on APSD
- Performed at critical with all control rods out and then inserted control rods in steps



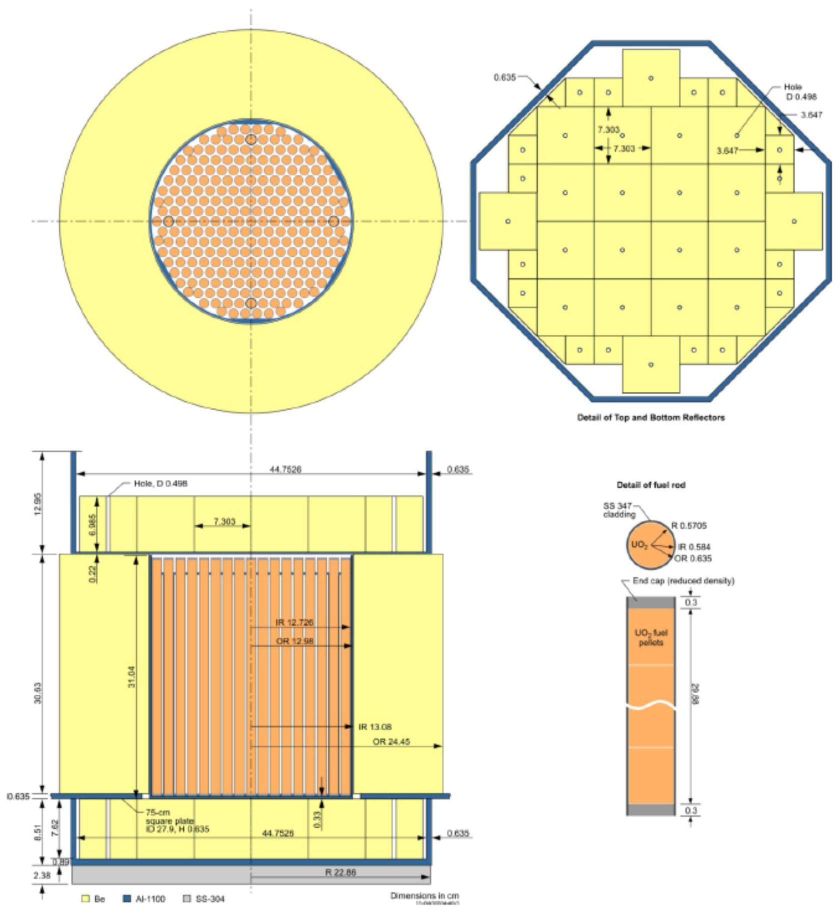
Calculation and Benchmark k_{eff} and $\Sigma\rho$

Code (Cross Section Set) → Case Number ↓	MCNP5 (Continuous Energy ENDF/B-VII.0)	Benchmark Value $k_{eff} \pm \sigma$	(C-E)/E[(a)] ± σ %
1	1.0007 ± 0.0002	1.0004 ± 0.0005	0.02 ± 0.02
2	0.9990 ± 0.0002	0.9992 ± 0.0005	-0.02 ± 0.02
3	0.9984 ± 0.0002	0.9984 ± 0.0006	0.00 ± 0.03
4	0.9977 ± 0.0002	0.9975 ± 0.0006	0.02 ± 0.03
5	0.9963 ± 0.0002	0.9964 ± 0.0006	-0.01 ± 0.03
6	0.9952 ± 0.0002	0.9955 ± 0.0006	-0.03 ± 0.03
7	0.9942 ± 0.0002	0.9942 ± 0.0006	0.01 ± 0.04
8	0.9923 ± 0.0002	0.9933 ± 0.0007	-0.11 ± 0.05
9	0.9910 ± 0.0002	0.9919 ± 0.0007	-0.09 ± 0.06
10	0.9896 ± 0.0002	0.9901 ± 0.0008	-0.07 ± 0.07
11	0.9875 ± 0.0002	0.9884 ± 0.0008	-0.09 ± 0.07
12	0.9860 ± 0.0002	0.9868 ± 0.0008	-0.09 ± 0.07
13	0.9836 ± 0.0002	0.9848 ± 0.0009	-0.13 ± 0.08
14	0.9814 ± 0.0002	0.9814 ± 0.0009	0.00 ± 0.08
15	0.9790 ± 0.0002	0.9786 ± 0.0010	0.04 ± 0.09
16	0.9764 ± 0.0002	0.9750 ± 0.0010	0.14 ± 0.10
17	0.9741 ± 0.0002	0.9717 ± 0.0011	0.25 ± 0.11
18	0.9711 ± 0.0002	0.9687 ± 0.0012	0.25 ± 0.12
19	0.9681 ± 0.0002	0.9651 ± 0.0013	0.31 ± 0.13
20	0.9653 ± 0.0002	0.9624 ± 0.0014	0.30 ± 0.15
21	0.9625 ± 0.0002	0.9597 ± 0.0016	0.29 ± 0.17
22	0.9592 ± 0.0002	0.9565 ± 0.0017	0.29 ± 0.19
23	0.9563 ± 0.0002	0.9542 ± 0.0020	0.23 ± 0.22

(a) C and E are, respectively, the calculated and benchmark experiment values.

Code (Cross Section Set) → Case Number ↓	MCNP5 (Continuous Energy ENDF/B-VII.0)	Benchmark Value $\Sigma\rho \pm \sigma$	(C-E)/E ± σ %
1	68 ± 24	10 ± 4	580.00 ± 313.67
2	-168 ± 24	-117 ± 12	43.59 ± 25.35
3	-226 ± 24	-196 ± 15	15.63 ± 15.23
4	-299 ± 24	-288 ± 18	3.67 ± 10.60
5	-440 ± 24	-397 ± 22	10.81 ± 8.59
6	-550 ± 24	-484 ± 26	13.67 ± 7.92
7	-649 ± 24	-621 ± 33	4.53 ± 6.71
8	-849 ± 24	-708 ± 41	19.91 ± 7.67
9	-974 ± 24	-851 ± 52	14.44 ± 7.51
10	-1,121 ± 24	-1,020 ± 65	9.86 ± 7.33
11	-1,335 ± 24	-1,210 ± 67	10.33 ± 6.38
12	-1,493 ± 24	-1,372 ± 69	8.82 ± 5.76
13	-1,735 ± 24	-1,573 ± 73	10.28 ± 5.33
14	-1,964 ± 24	-1,928 ± 78	1.89 ± 4.30
15	-2,216 ± 24	-2,226 ± 84	-0.46 ± 3.91
16	-2,488 ± 24	-2,595 ± 92	-4.12 ± 3.52
17	-2,723 ± 24	-2,951 ± 101	-7.73 ± 3.27
18	-3,041 ± 24	-3,267 ± 113	-6.92 ± 3.30
19	-3,368 ± 24	-3,653 ± 126	-7.80 ± 3.26
20	-3,660 ± 24	-3,940 ± 143	-7.10 ± 3.42
21	-3,966 ± 24	-4,239 ± 162	-6.45 ± 3.61
22	-4,322 ± 24	-4,588 ± 182	-5.80 ± 3.78
23	-4,633 ± 24	-4,838 ± 206	-4.24 ± 4.11

Small Compact Critical Assembly – III



- Critical assemblies to support space reactor power plant design
- HEU-O_2 fuel, SS-clad
- Beryllium reflected
- 1.506-cm pitch

SCCA-003 Results

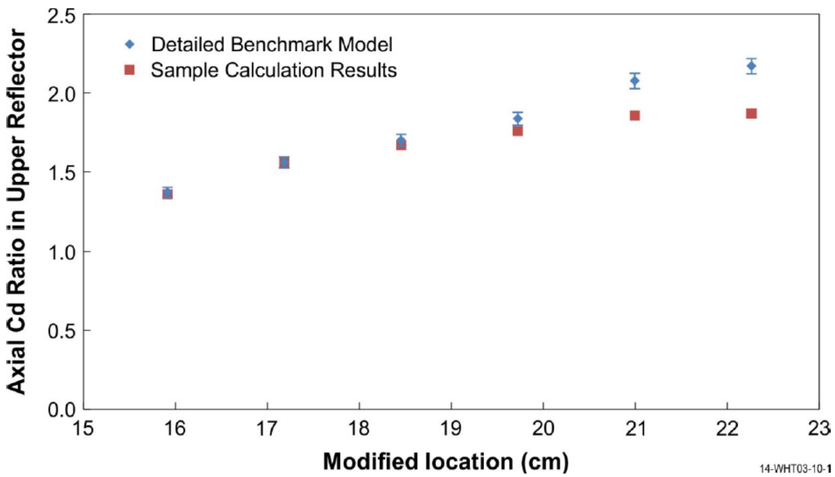


Figure 4.3-1. Benchmark and Calculated Results for Cadmium Ratio in Upper Reflector for Detailed Benchmark Model.

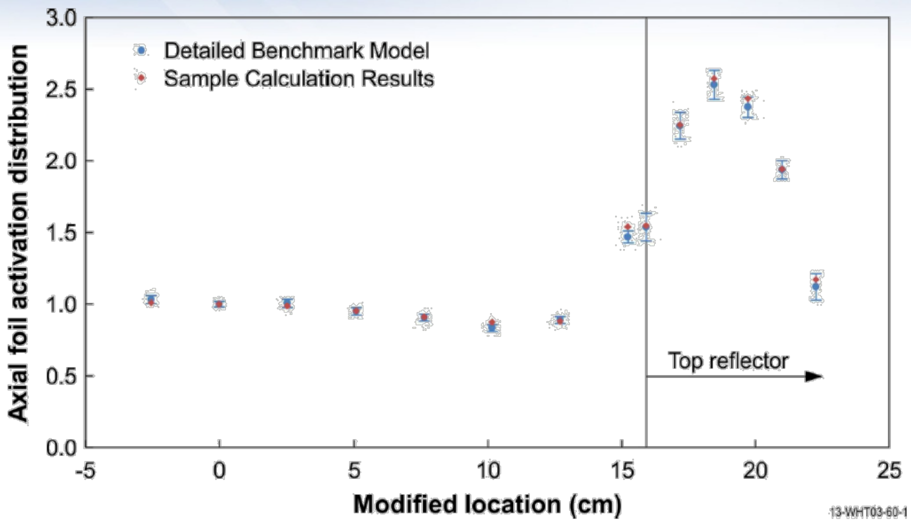


Figure 4.7-1. Benchmark and Calculated Results for Axial Foil Distribution for Detailed Benchmark Model.

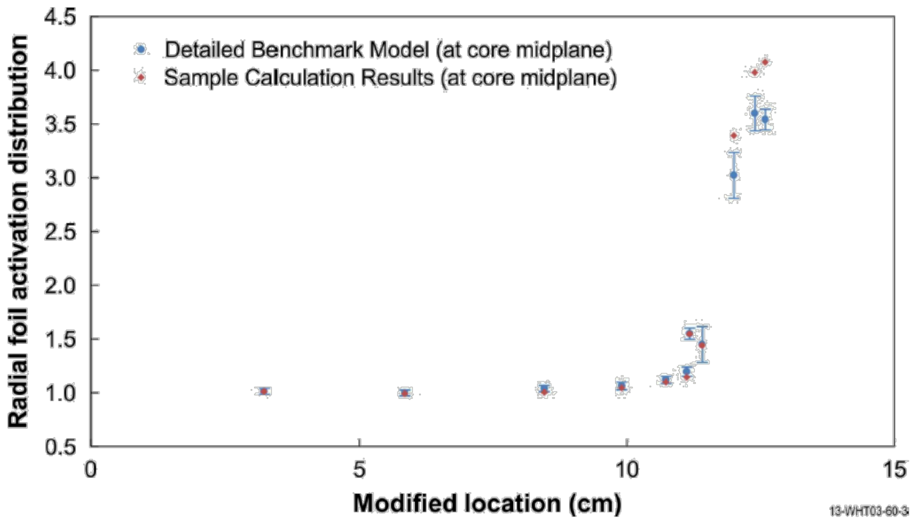
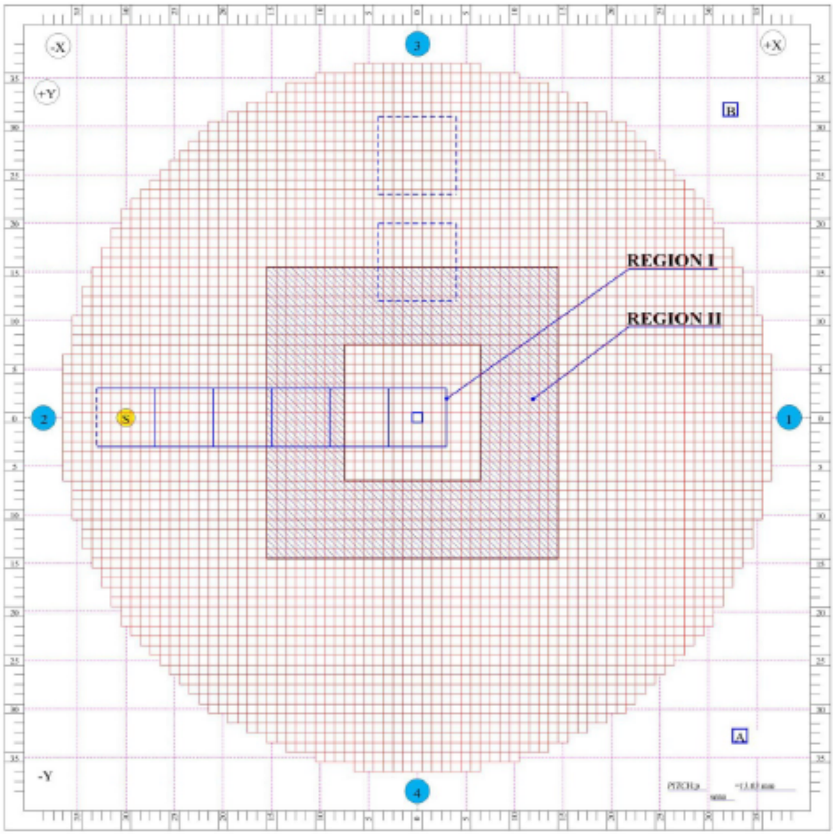


Figure 4.7-2. Benchmark and Calculated Results for Radial Foil Distribution for Detailed Model.

VENUS-7



- PWR with MOX and UO_2 fuel
- Part of VENUS-PRP (Plutonium Recycle Physics) Program
  - Main purpose was to improve/develop calculation methods for MOX power plants comparable with standard UO_2 fuel assemblies

VENUS-7 Results

Configuration no.	Benchmark case	k_{eff} (Benchmark model)	k_{eff} (MCNP5, ENDF/B-VII.0)	k_{eff} (MCNP5, JEFF-3.1.1)
7a	1	1.00075 ± 0.00163	0.99469	0.99449
7b	2	1.00117 ± 0.00163	0.99623	0.99595
7b subst. 3/1	3	1.00059 ± 0.00163	0.99535	0.99514
7b subst. 4/0	4	1.00211 ± 0.00163	0.99743	0.99727
7c	5	1.00067 ± 0.00163	0.99578	0.99557
7d	6	1.00105 ± 0.00163	0.99593	0.99577
7d subst. 2/2.7	7	1.00013 ± 0.00163	0.99527	0.99515
7/1a	8	0.99959 ± 0.00163	0.99576	0.99558
7/1b	9	1.00089 ± 0.00163	0.99699	0.99694
7/1c	10	1.00024 ± 0.00163	0.99637	0.99630
7/3	11	0.99830 ± 0.00163	0.99630	0.99621

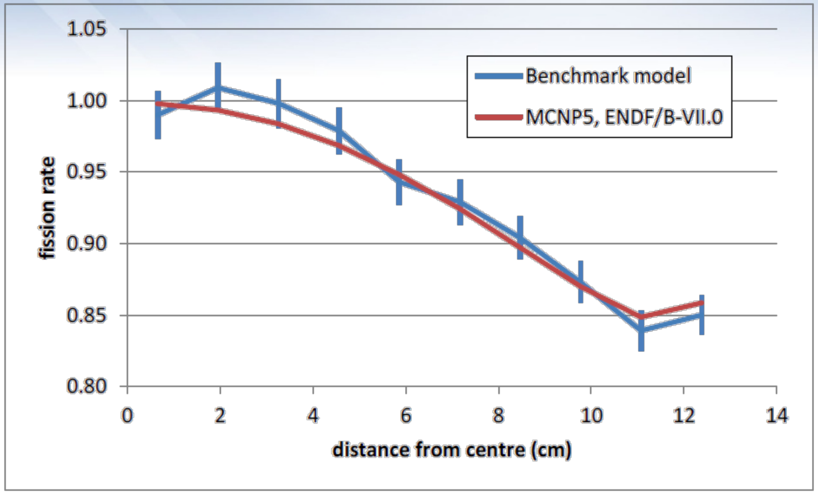


Figure 4-1. Fission Rate Distribution in Configuration 7/1b along the X Axis: Benchmark Model and Calculated Values (Benchmark Case 9).

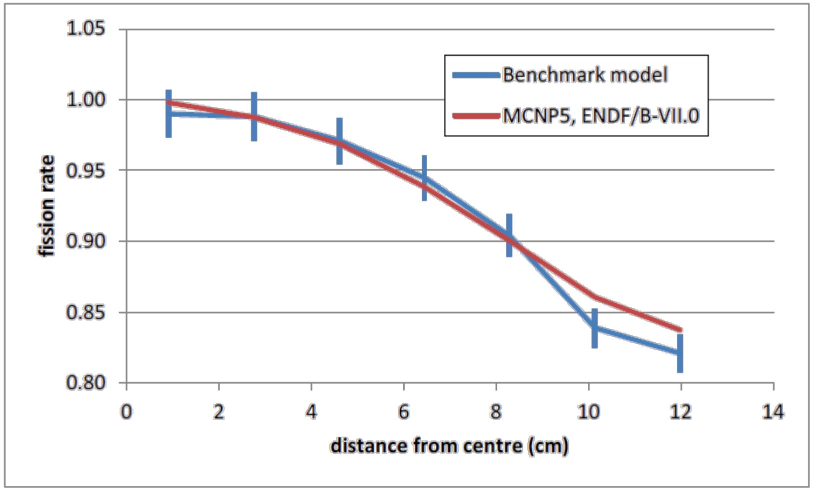
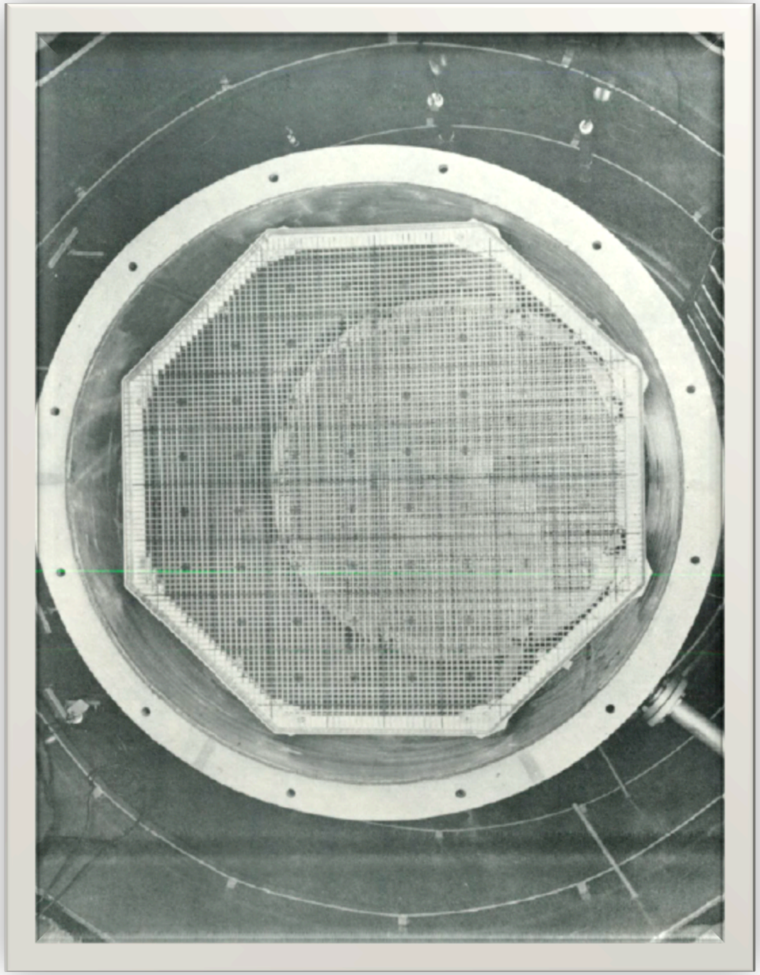


Figure 4-2. Fission Rate Distribution in Configuration 7/1b along the Diagonal: Benchmark Model and Calculated Values (Benchmark Case 9).

B&W Spectral Shift Control Reactor

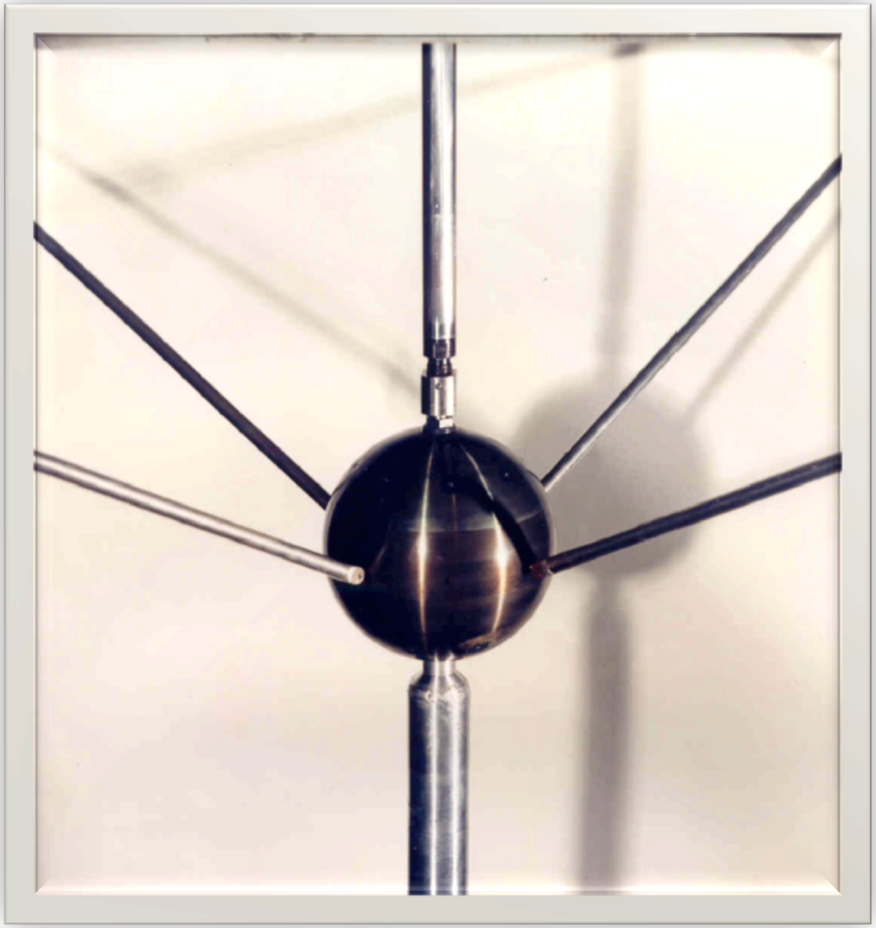
- Study nuclear properties of rod lattices moderated by D_2O-H_2O mixtures
- PWR design experiments
- UO_2-ThO_2 fuel rods
  - 93% ^{235}U enrichment
  - $N_{Th}/N_{25} = 15$
- 60.40 % (by mole) D_2O



B&W SSCR Criticality Results

Cross Section Library	Calculated Results	Benchmark Value	$\frac{C-E}{E}$ (%)
MCNP5 ENDF/B-VI.6	0.99270 ± 0.00009	0.9999 ± 0.0014	-0.72
MCNP5 ENDF/B-VII.0	1.00382 ± 0.00009		+0.39
MCNP6 ENDF/B-VII.1	1.00315 ± 0.00008		+0.32
MCNP5 JEFF 3.1.1	0.99152 ± 0.00009		-0.84

Oak Ridge Sphere (ORSphere)



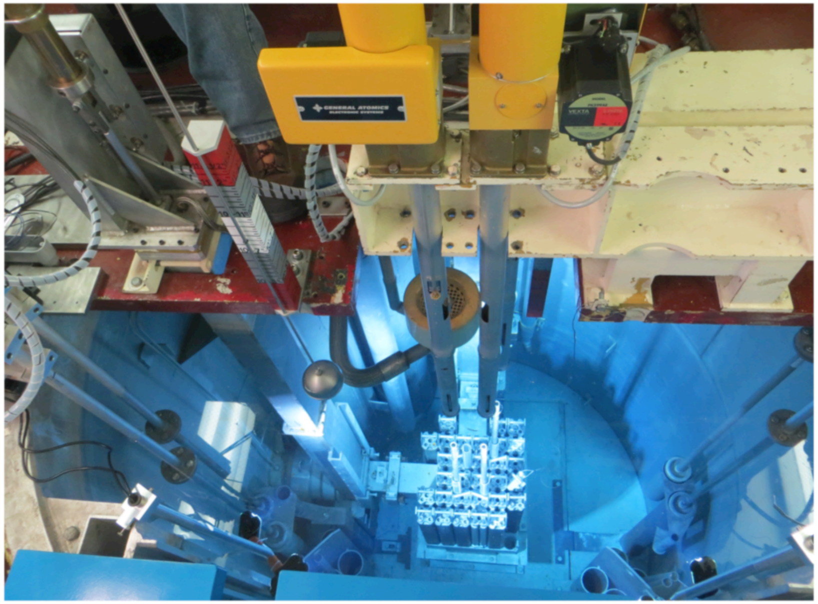
- Recreation of GODIVA sphere in 1970s @ ONRL
- More accurate measurement of critical mass
- Additional measurements of higher quality than those from 1950s

ORSphere Results

	MCNP5 ENDF/B-VII.0			Calculated System Reactivity			Mass		
8.80491-cm-Average-Radius Sphere	1.00411	±	0.00002	62.301	±	0.357	53,475.983	±	1.017 g
8.74268-cm-Average-Radius Sphere	0.99821	±	0.00002	-27.294	±	0.317	52,350.943	±	0.210 g
			Change	89.59	±	0.477	1,125.04	±	1.038 g
Benchmark Worth per Gram of Surface Material				0.086	±	0.003	¢ per gram		
Sample Calculation of Worth per Gram of Surface Material				0.0796	±	0.0004	¢ per gram		

- Benchmark βeff = 0.00657 ± 0.00009
- Most cross section libraries calculate high using Keepin-Inhour Point-Kinetics methods and low using MCNP analyses

Neutron Radiography (NRAD) Reactor



- 250 kW TRIGA Mark II
- Conversion-type
- Located at INL
- 64 U(30/20)ErZrH rods
- 12 graphite reflector blocks
- 4 graphite rods
- 3 B_4C control rods
- 2 beam lines
- Empty positions for in-core experimentation

NRAD Reactor Calculations

Analysis Code	Neutron Cross Section Library	Calculated k_{eff}	±	σ	Benchmark k_{eff}	±	σ	$\frac{C-E}{E}(\%)$
MCNP5	ENDF/B-VII.0	1.01479	±	0.00007	1.0012	±	0.0015	1.36
	JEFF-3.1	1.01281	±	0.00007				1.16
	JENDL-3.3[(a)]	1.01191	±	0.00007				1.07
	ENDF/B-VI.8[(b)]	1.01022	±	0.00007				0.90
KENO-VI	ENDF/B-VII.0 (238-group)	1.01528	±	0.00007				1.41
	ENDF/B-VII.0 (continuous energy)[(c)]	1.010205	±	0.0007				0.90
SERPENT	ENDF/B-VII.0 (v. 1.1.17)	1.01490	±	0.00008				1.37
	ENDF/B-VII.0 (v. 2.1.13)	1.01332	±	0.00008				1.21

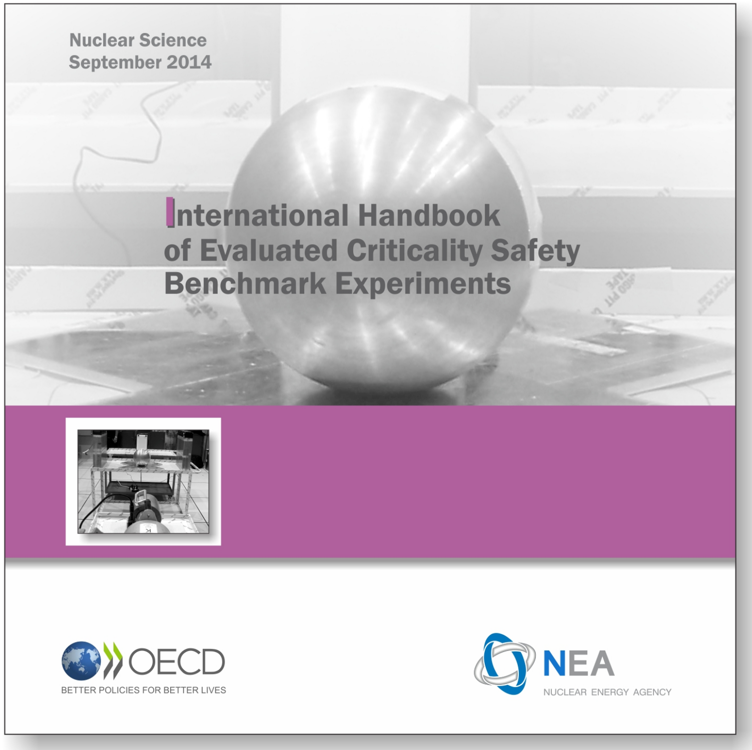
(a) $S(\alpha,\beta)$ data from the ENDF/B-VII.0 library were used with the JENDL-3.3 cross section data..
(b) ENDF/B-VII.0 cross section data for erbium isotopes were used.
(c) This value is calculated to be 1.01385 ± 0.00008 using updated thermal scattering data and treatments currently in the SCALE 6.2 software package (prerelease). Personal communication with B. J. Marshall at ORNL (July 3, 2013).

- Rod Worth Calculations in Good Agreement

International Handbook of Evaluated Criticality Safety Benchmark Experiments

September 2014 Edition

- 20 Contributing Countries
- Spans nearly 67,000 Pages
- Evaluation of 561 Experimental Series
- 4,839 Critical, Near Critical, Subcritical, or k_∞ Configurations
- 24 Criticality-Alarm/Shielding Benchmark Configuration
- 207 Fundamental Physics Measurements



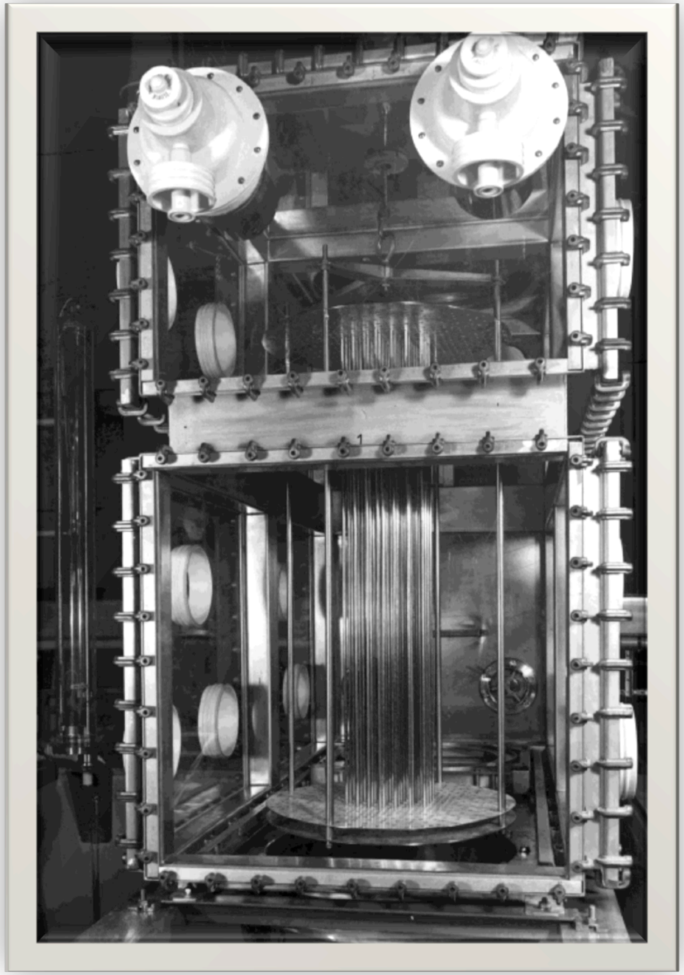
http://icsbep.inel.gov/

http://www.oecd-nea.org/science/wpncs/icsbep/

New/Revised Benchmarks in 2014 Handbook

- **MIX-MISC-THERM-007**
  - Assemblies of UO_2-PuO_2 PHENIX Pins in Pu Nitrate Solution
- **PU-MET-INTER-003**
  - ZPR-3 Assembly 58: Pu Metal and Graphite with Thick DU Reflector
- **PU-MET-INTER-004**
  - ZPR-3 Assembly 59: Pu Metal and Graphite with Thick Pb Reflector
- **SUB-LEU-COMP-THERM-002**
  - IPEN/MB-01 Research Reactor Subcritical Configurations
- **FUND-NCERC-PU-HE3-MULT-001**
  - Ni-Reflected Pu-Metal-Sphere Subcritical Measurements

MIX-MISC-THERM-007



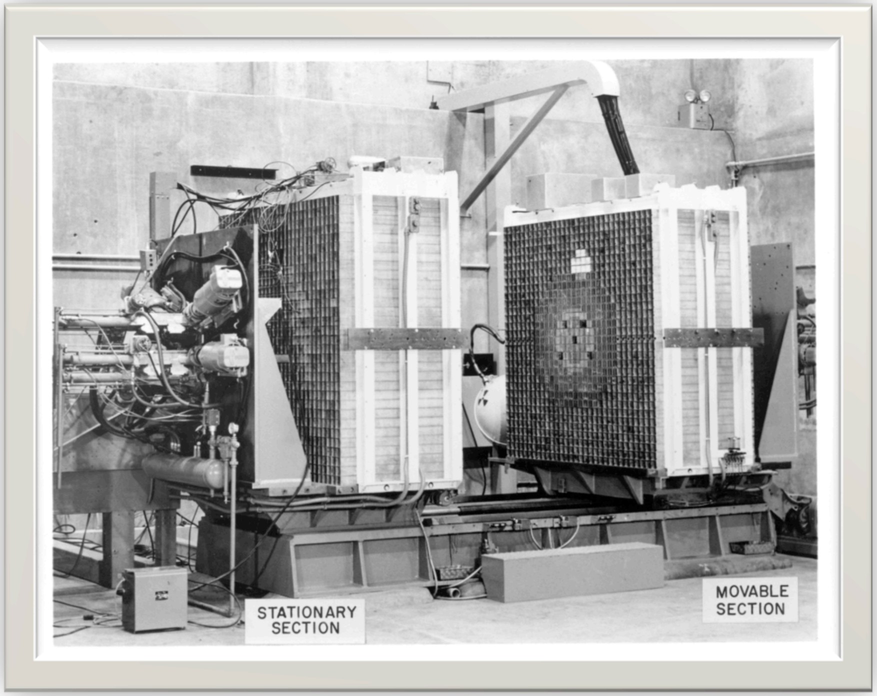
- UO_2-PuO_2 PHENIX pins in various arrays
  - 26 wt.% Pu
  - $^{240}Pu/Pu$ = 16 wt.%
- Pu-nitrate solution
  - $^{240}Pu/Pu$ = 19 wt.%
- Apparatus B @ French Valduc facility
  - 1974-1976

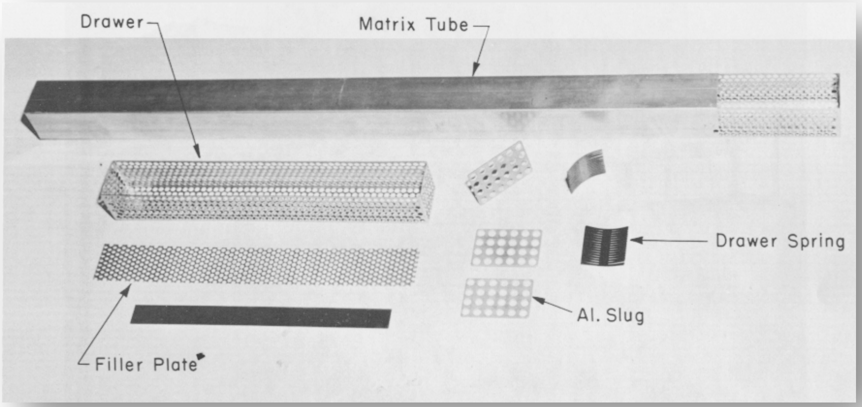
Results from PHENIX Pins in Pu-Nitrate Solution

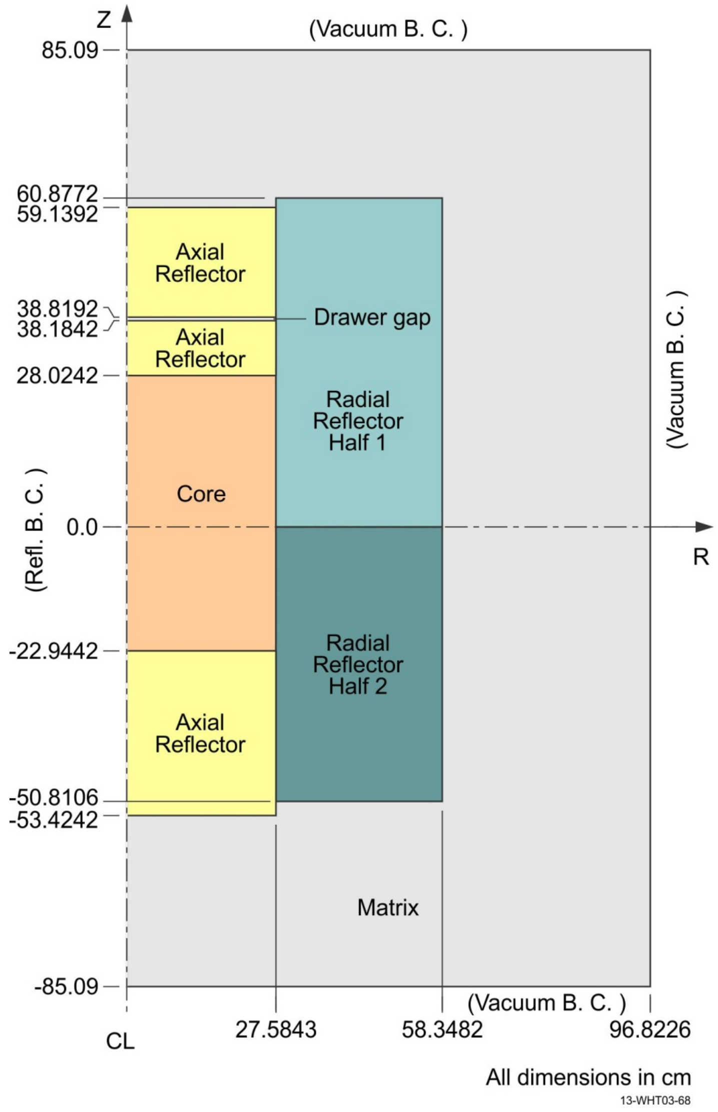
Case[a]	MORET 5 Continuous Energy JEF2.2 Library[b] (σ_{MC}= 0.00033)		MORET 5 Continuous Energy JEFF3.1 Library [b] (σ_{MC}= 0.00033)		MORET 5 Continuous Energy ENDF/VII.0 Library[b] (σ_{MC}= 0.00033)	
	k_{eff}	($k_{eff(cal)}$ - $k_{eff(exp)}$)/$k_{eff(exp)}$ (%)	k_{eff}	($k_{eff(cal)}$ - $k_{eff(exp)}$)/$k_{eff(exp)}$ (%)	k_{eff}	($k_{eff(cal)}$ - $k_{eff(exp)}$)/$k_{eff(exp)}$ (%)
1	1.01284	1.51	1.00768	0.99	1.00770	0.99
2	1.01333	1.49	1.00874	1.03	1.00869	1.02
3	**1.01472**	**1.59**	**1.00942**	**1.06**	**1.01023**	**1.14**
4	**1.01411**	**1.53**	**1.00906**	**1.03**	**1.00919**	**1.04**
5	**1.01410**	**1.46**	**1.01082**	**1.13**	**1.01048**	**1.10**
6	**1.01494**	**1.57**	**1.01150**	**1.22**	**1.01191**	**1.26**
7	**1.01098**	**1.20**	**1.00735**	**0.84**	**1.00699**	**0.80**
8	**1.01146**	**1.25**	**1.00743**	**0.84**	**1.00847**	**0.95**
9	**1.01100**	**1.30**	**1.00648**	**0.85**	**1.00607**	**0.81**
10	**1.01040**	**1.17**	**1.00646**	**0.78**	**1.00633**	**0.76**
11	1.01071	1.26	1.00539	0.73	1.00607	0.80
12	1.00951	1.15	1.00434	0.64	1.00402	0.60
13	1.01799	1.92	1.01323	1.44	1.01330	1.45
14	1.01866	2.05	1.01220	1.40	1.01251	1.43
15	1.01357	1.56	1.00939	1.14	1.00912	1.11
16	1.01446	1.47	1.00982	1.00	1.01078	1.10
17	1.01482	1.40	1.01043	0.96	1.01062	0.98
18	1.01325	1.40	1.00895	0.97	1.00933	1.00
19	1.01139	1.22	1.00712	0.79	1.00716	0.80
20	1.01183	1.08	1.00788	0.69	1.00868	0.77
21	**1.01172**	**0.99**	**1.00886**	**0.70**	**1.00952**	**0.77**
22	**1.01164**	**1.04**	**1.00783**	**0.66**	**1.00793**	**0.67**
23	**1.01204**	**1.08**	**1.01075**	**0.95**	**1.01040**	**0.92**
24	**1.01438**	**1.29**	**1.00996**	**0.84**	**1.01045**	**0.89**

a) In bold characters cases with Phenix pins.
b) Results provided by the evaluator Nicolas Leclaire (IRSN, France).

PU-MET-INTER-003 and -004







Idaho National Laboratory

ZPR-3 Results

- DU Reflected

	Case 1 – ZPR-3/58 Loading 12
Experimental k_{eff}	1.0002 ± 0.0012
Adjusted Experimental k_{eff}	1.0000 ± 0.0012
Monte Carlo Transformation	-0.0158 ± 0.0010
Benchmark Model k_{eff}	0.9842 ± 0.0016

	MCNP5 (Continuous Energy ENDF/B-VII.1)
Case 1	0.9878 ± 0.0001

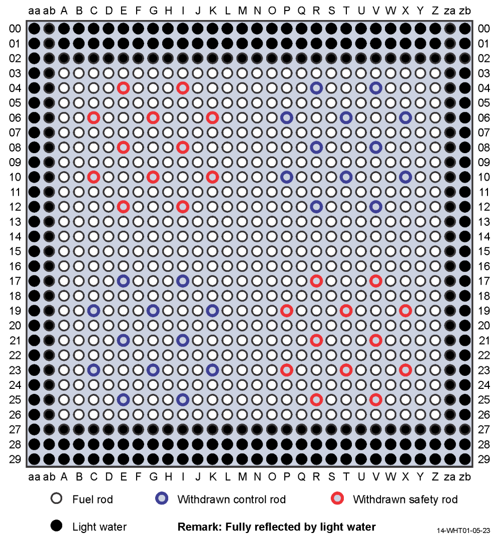
- Pb Reflected

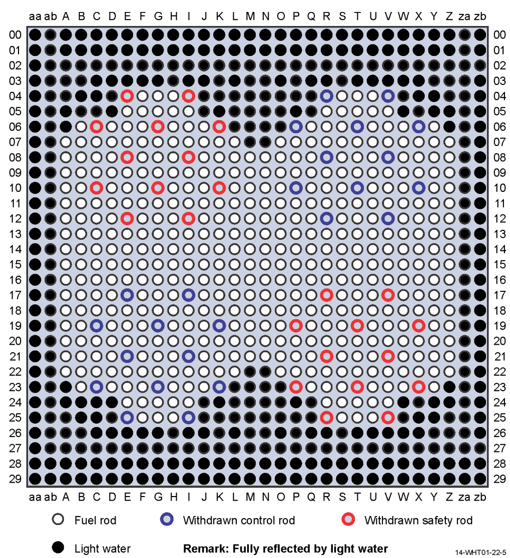
	Case 1 – ZPR-3/59 Loading 6
Experimental k_{eff}	1.0008 ± 0.0018
Adjusted Experimental k_{eff}	0.9944 ± 0.0023
Monte Carlo Transformation	-0.0221 ± 0.0001
Benchmark Model k_{eff}	0.9723 ± 0.0023

	MCNP5 (Continuous Energy ENDF/B-VII.1)
Case 1	0.97472 ± 0.0009

Idaho National Laboratory

SUB-LEU-COMP-THERM-002

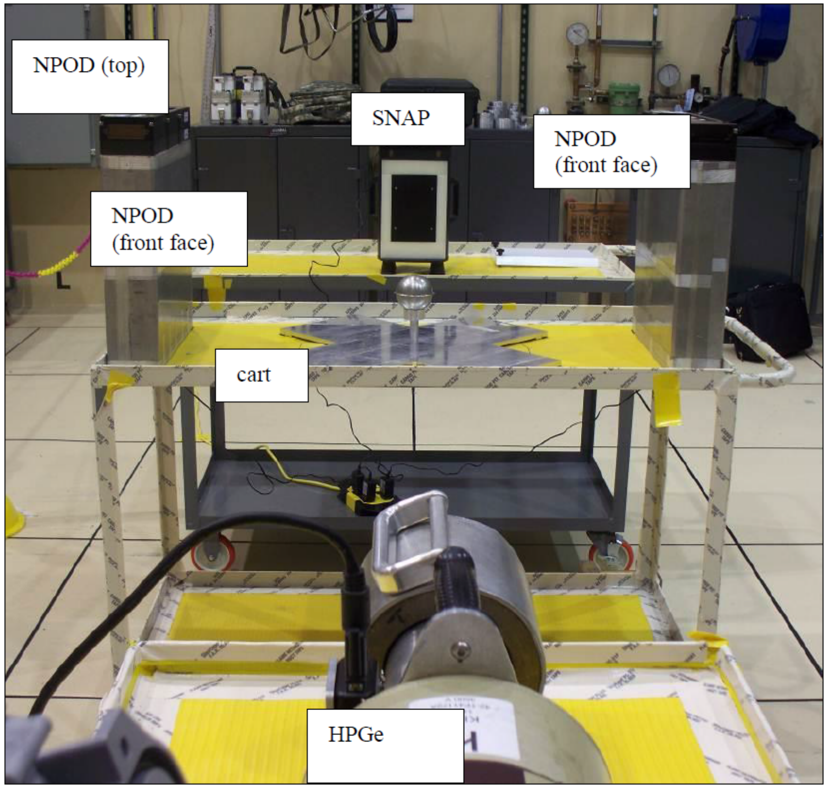




Case	$\Sigma\rho_{gen}$ Experimental **(pcm)**	$\Sigma\rho_{gen}$ Calculated **(pcm)**	(C-E)/E ± 1σ (pcm) %
1	10 ± 3	72 ± 16	619 ± 269
2	-159 ± 17	-161 ± 23	1 ± 18
3	-239 ± 19	-246 ± 23	3 ± 12
4	-309 ± 20	-310 ± 23	0 ± 10
5	-432 ± 21	-430 ± 23	0 ± 7
6	-545 ± 23	-550 ± 23	1 ± 6
7	-657 ± 24	-656 ± 23	0 ± 5
8	-780 ± 26	-836 ± 23	7 ± 5
9	-918 ± 29	-960 ± 23	5 ± 5
10	-1047 ± 33	-1108 ± 23	6 ± 4
11	-1270 ± 37	-1325 ± 23	4 ± 4
12	-1468 ± 43	-1497 ± 23	2 ± 3
13	-1654 ± 47	-1730 ± 23	5 ± 3
14	-1939 ± 53	-1970 ± 23	2 ± 3
15	-2181 ± 59	-2214 ± 23	2 ± 3
16	-2480 ± 61	-2507 ± 23	1 ± 3
17	-2650 ± 66	-2746 ± 23	4 ± 3
18	-3052 ± 68	-3042 ± 23	0 ± 2
19	-3579 ± 72	-3502 ± 23	-2 ± 2
20	-3960 ± 75	-3974 ± 24	0 ± 2
21	-4399 ± 81	-4478 ± 24	2 ± 2
22	-4782 ± 86	-5017 ± 24	5 ± 2
23	-5072 ± 93	-5618 ± 24	11 ± 2

FUND-NSERC-PU-HE3-MULT-001

- National Criticality Experiments Research Center
- BERP ball
  - α-phase Pu sphere
  - Steel clad
- Ni reflectors up to 3” thick
- Subcritical multiplication measurements



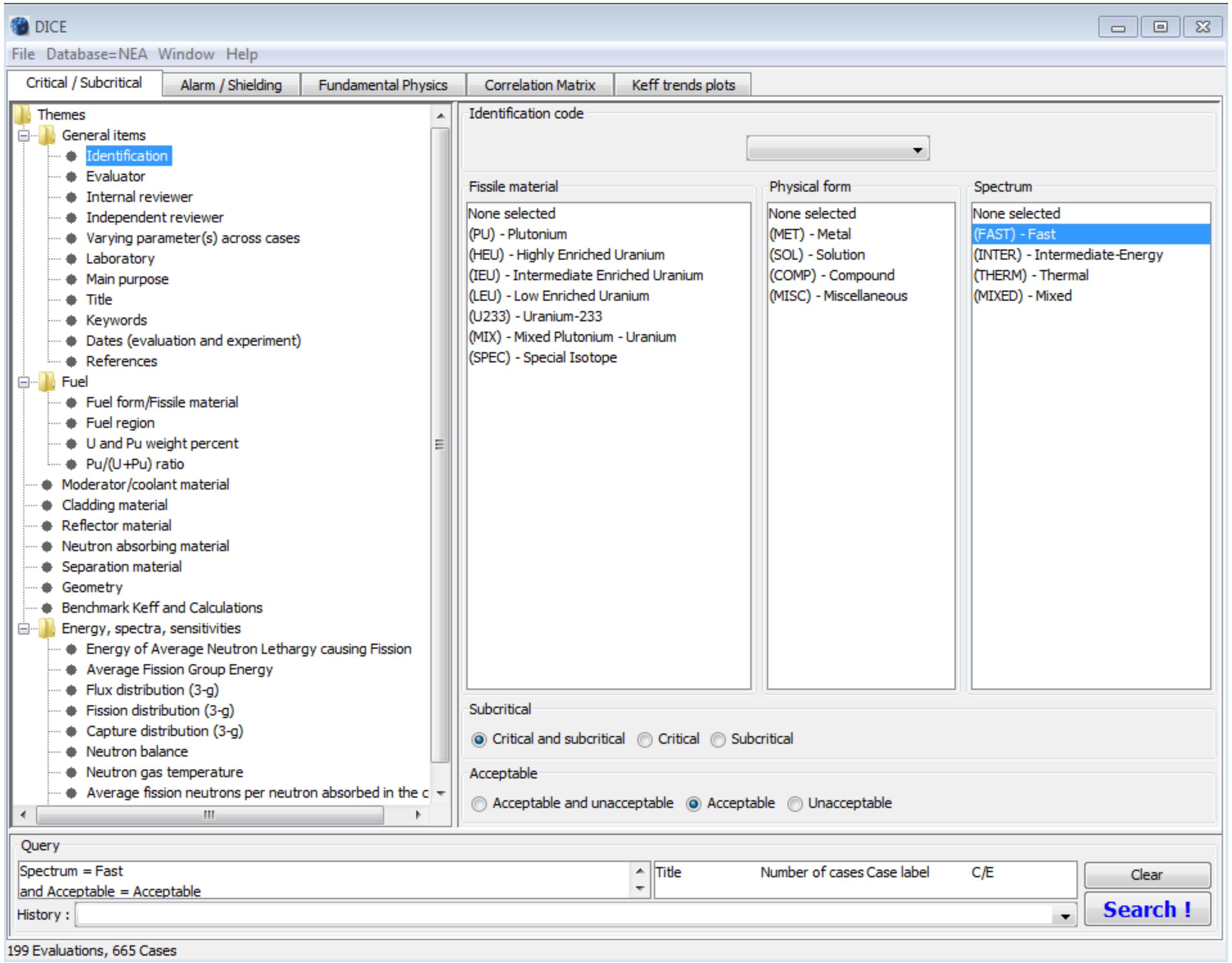
Ni-Reflected BERP Ball Measurements

Configuration	R1 (cts/s)	σ	(C-E)/E (%)	R2 (cts/s)	σ	(C-E)/E (%)	Ml	σ	(C-E)/E (%)
Bare	9165.22	3.08	2.7	1643.94	8.93	2.8	3.46	0.01	0.6
Threshold/0.5"	12279.05	3.84	3.5	3970.47	15.48	4.9	4.47	0.01	2.8
5"/1.0"	15108.29	4.59	3.7	7399.47	23.80	5.9	5.38	0.01	2.5
6"/1.5"	17874.68	5.36	4.4	12107.45	33.38	7.8	6.19	0.01	1.8
7"/2.0"	20515.21	6.14	5.3	18092.06	46.38	10.5	6.95	0.01	2.4
8"/2.5"	23062.18	6.94	5.6	25379.04	61.44	11.9	7.66	0.01	2.3
9"/3.0"	25538.92	7.74	7.0	33952.73	78.13	15.6	8.31	0.01	2.7

- R_1 = Singles Counting Rate
  - Neutron count rate in a single detector
- R_2 = Doubles Counting Rate
  - Rate at which two neutrons from a single fission chain are detected in a single detector
- M_L = Leakage Multiplication
  - Number of neutrons that escape the outer-most reflector per starter neutron

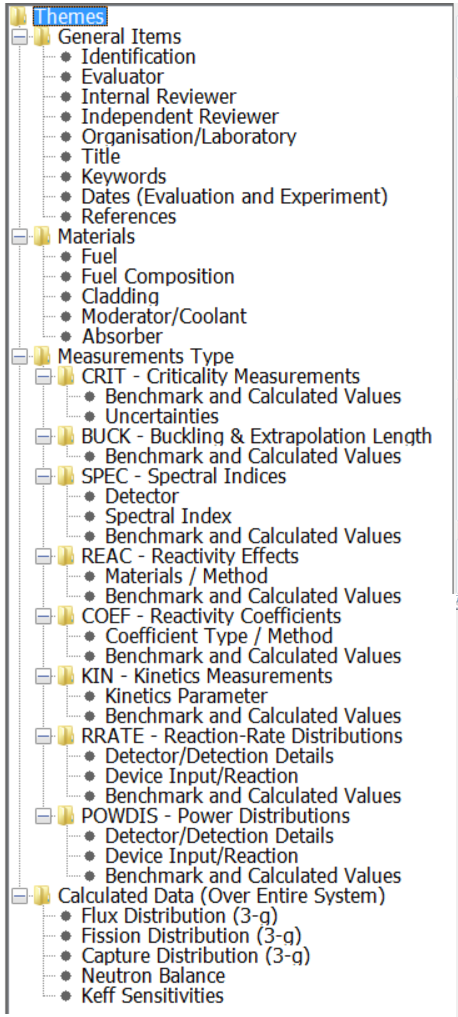
Database International Criticality Experiments (est. 2001)

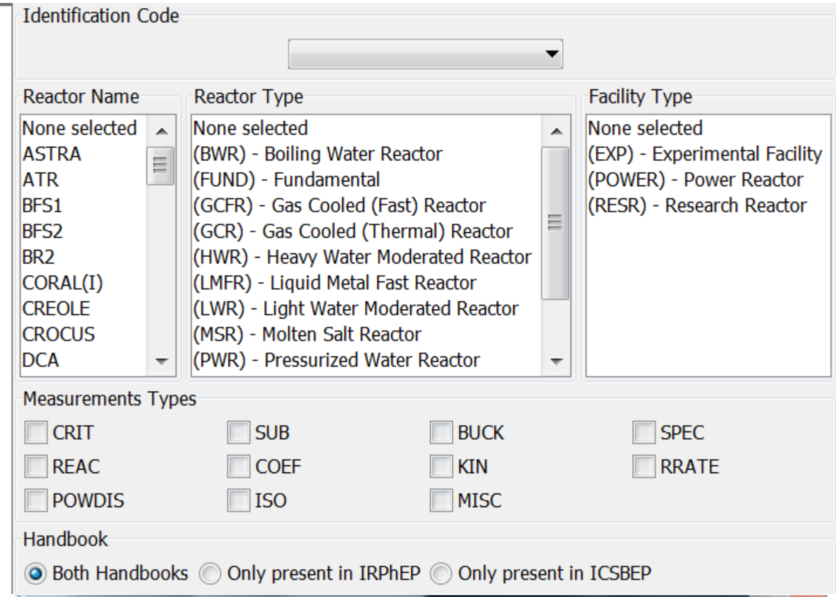
- ✓ **Relational Database**
- ✓ **Made available online 2013**
- ✓ **Search using sensitivity data 2013**

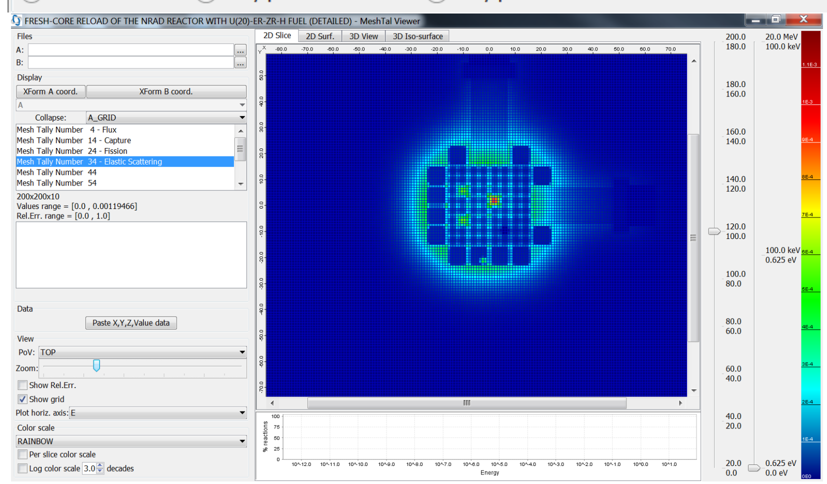


*IRPhEP **D**atabase and **A**nalysis **T**ool (est.2013)*

- ✓ **Made available online 2014**
- ✓ **Visualize fluxes and reaction rates**
- ✓ **Search by meas. type**
- ✓ **Trend C/E's by**

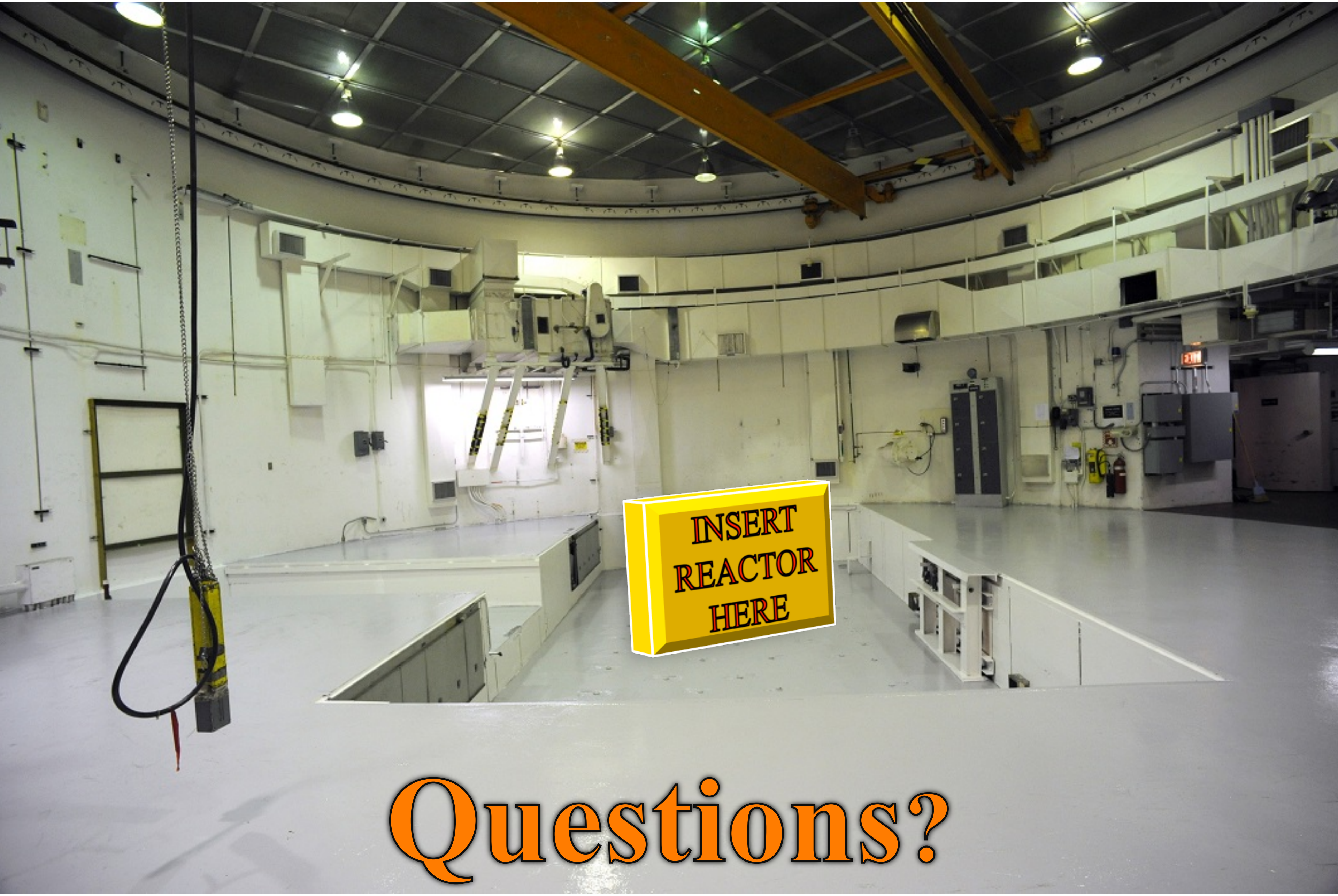






Summary and Conclusions

- ✓ The ICSBEP and IRPhEP are collaborative efforts that involve numerous scientists, engineers, administrative support personnel and program sponsors from 24 different countries and the OECD NEA. The authors would like to acknowledge the efforts of all of these dedicated individuals without whom those two projects would not be possible.
- ✓ Those two handbooks continue to grow and provide high-quality integral benchmark data that will be of use to the criticality safety, nuclear data, and reactor physics communities for future decades.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Questions?