Impact of Recent U.S. Nuclear Data on Graphite Reactor Benchmark Calculations

John D. Bess

Idaho National Laboratory

Nuclear Data Week
BNL, NY
November 14-18, 2016

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

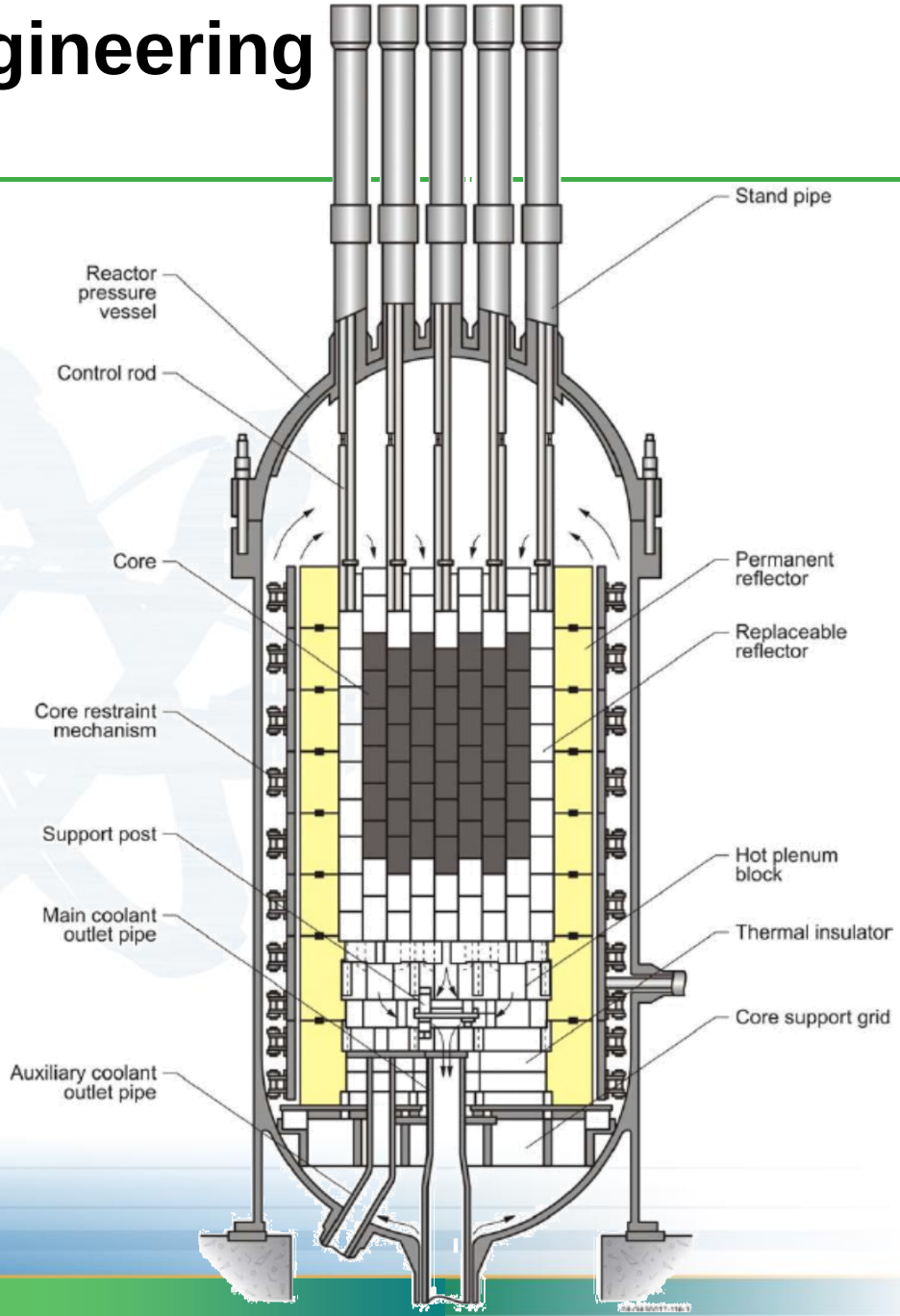
Available Thermal-Spectrum Graphite Reactors on IRPhEP Handbook

- **Pebble-Bed**
  - **ASTRA**
    - Kurchatov, Russia
    - 1 evaluation
    - 5 configurations
  - **HTR-10**
    - China
    - 1 evaluation
    - 1 configuration
  - **HTR-PROTEUS**
    - PSI, Switzerland
    - 4 evaluations
    - <u>11 configurations</u>
      - 10 hand-stacked
- **Prismatic**
  - **HTTR**
    - Oarai, Japan
    - 3 evaluations
    - 9 configurations
      - <u>7 room temperature</u>
  - **VHTRC**
    - Tokai, Japan
    - 1 evaluation
    - 7 configurations
      - 1 room temperature

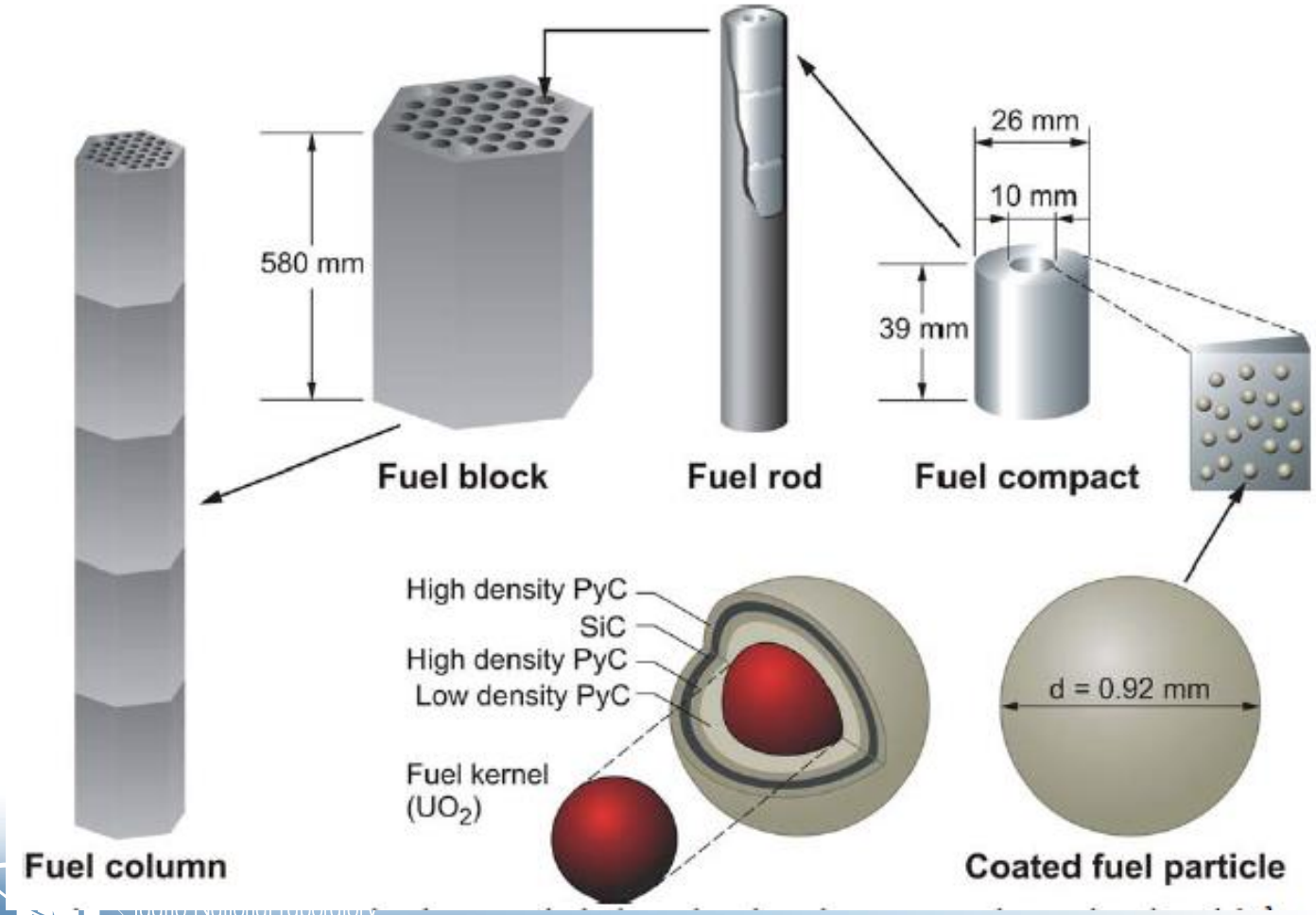
Underlined Models Available in MCNP at Room Temperature

High Temperature Engineering Test Reactor (HTTR)

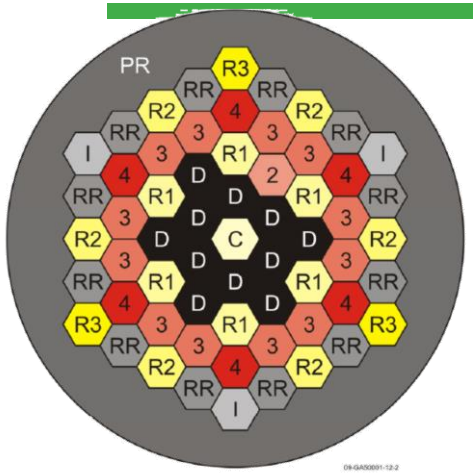
- 30 MWth
- Graphite-moderated
- Helium-cooled
- Engineering (not benchmark) reactor
  - Establish and upgrade technological basis for advanced HTGRs
- Core Height 2.9 m
- Core Diameter 2.3 m
- Reflector Thickness ~ 1 m

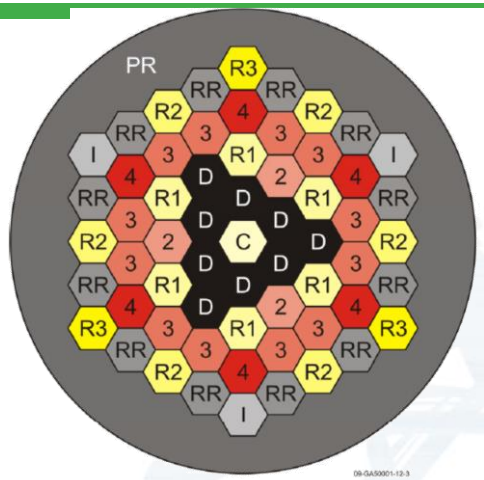


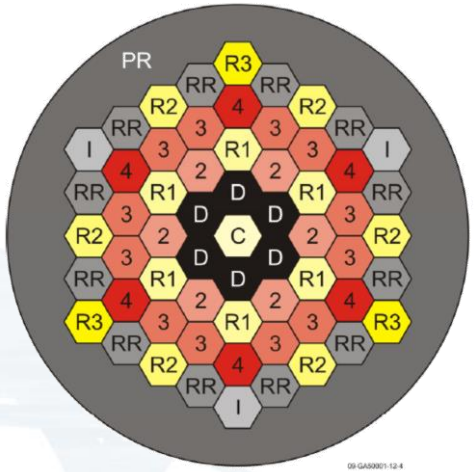
TRISO Fuel in Graphite System

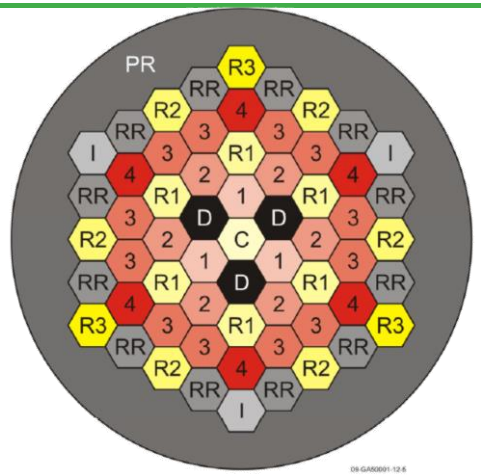


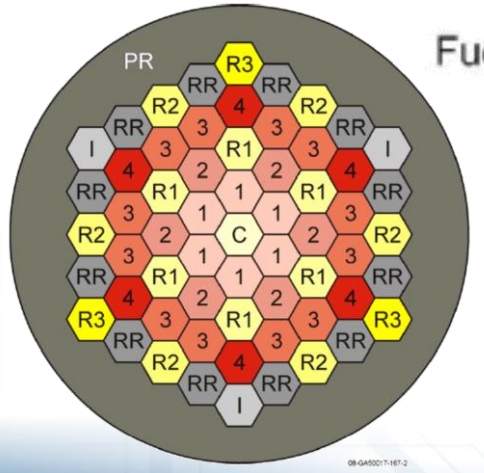
Various Core Loadings at Start-Up











Fuel zones: 1, 2, 3, 4

Control rods: C, R1, R2, R3

Dummy zone: D

Instrumentation: I

Replaceable reflectors: RR

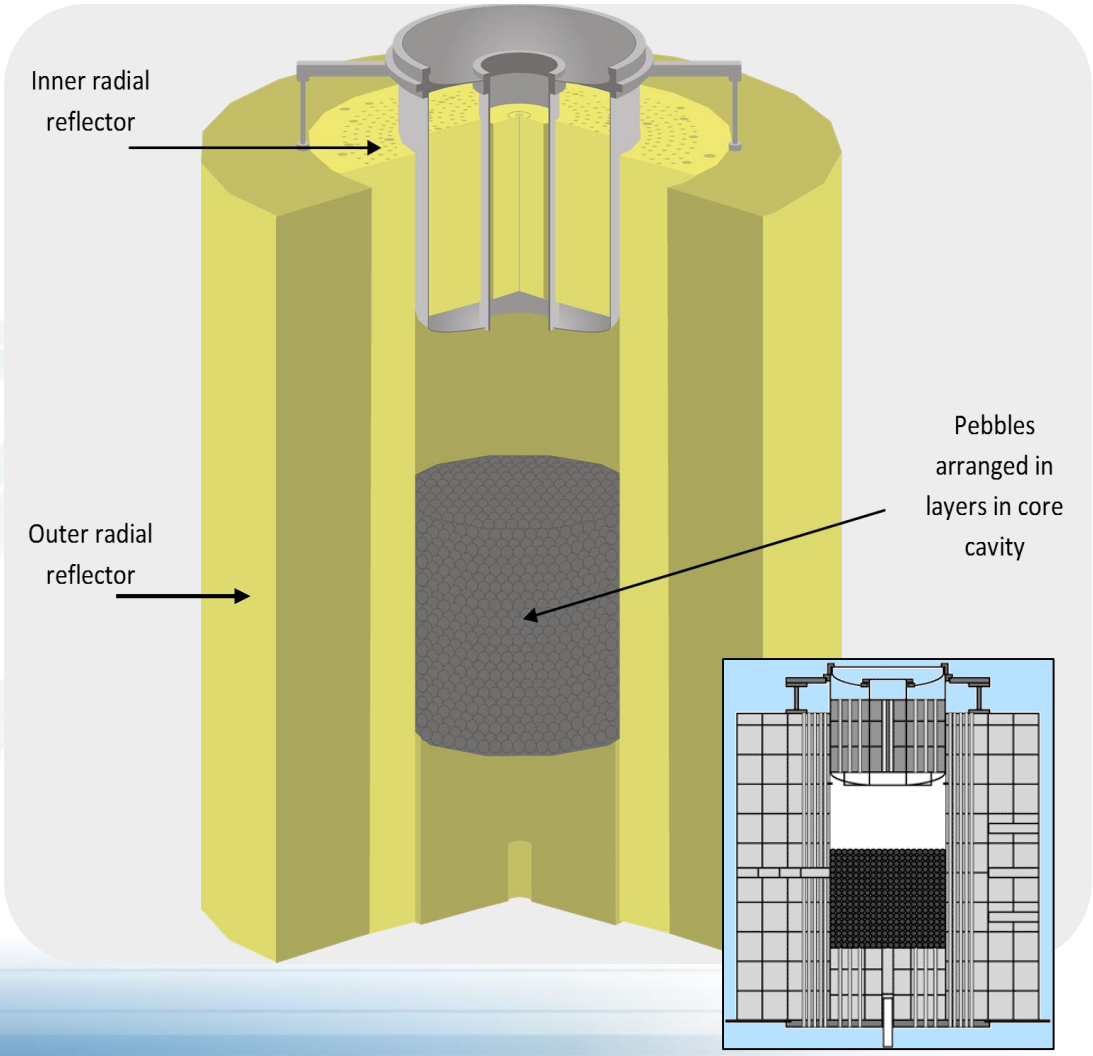
Permanent reflector: PR

HTTR – Known Issues

- First prismatic HTGR benchmark for IRPhEP
- Evaluation process identified key issues
  - Engineering test reactor, not a benchmark validation design reactor (like VHTRC)
- Insufficient publicly available information to support evaluation of simplification biases
  - Likely underestimation of benchmark model keff
- Significant benchmark uncertainty due to graphite block impurities
  - Between approximately 600 and 1000 pcm

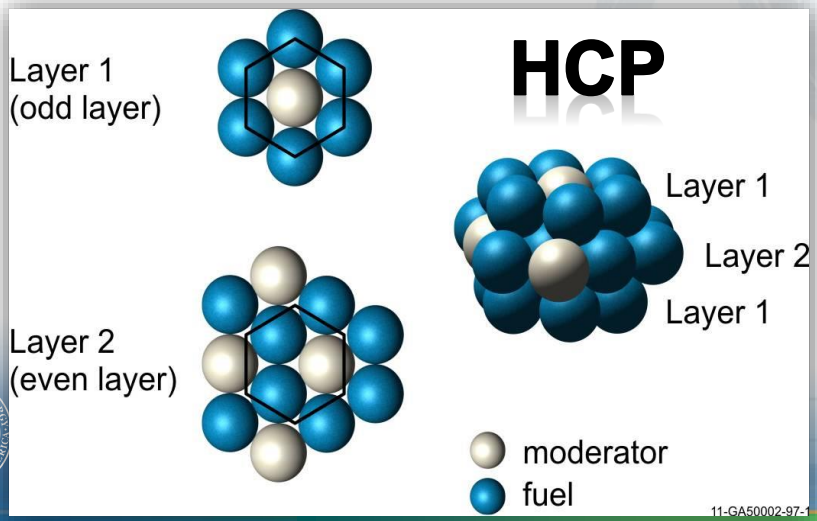
HTR-PROTEUS (1992-1996)

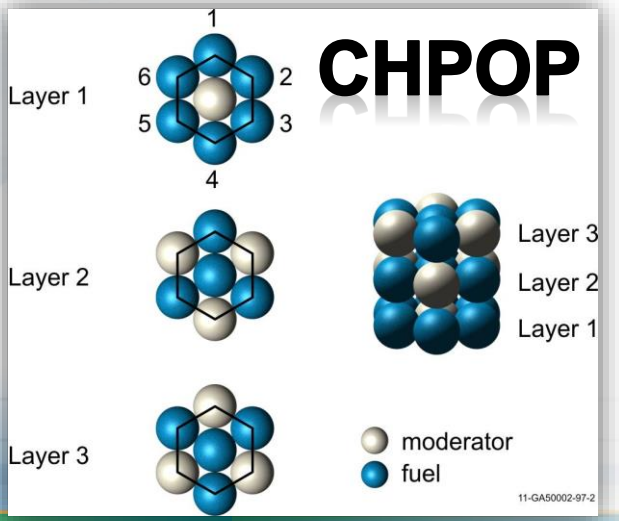
- Comprehensive <u>benchmark</u> program to support HTGR development
- 17 critical configurations
  - 10 core designs
- Reactor physics measurements
  - Control rod worth
  - Kinetics
  - Reaction rates
  - Water ingress effects
  - Small sample reactivity



Primary Core Configurations

Cores	Pebble Packing	Moderator-to-Fuel Pebble Ratio
1, 1A, 2, and 3	Hexagonal Close Packing	1:2
4	Random Packing	1:1
5, 6, 7, and 8	Columnar Hexagonal Point-On-Point Packing	1:2
9 and 10	Columnar Hexagonal Point-On-Point Packing	1:1





Key Core Parameters

FR = Fueled Region
UR = Unfueled Region

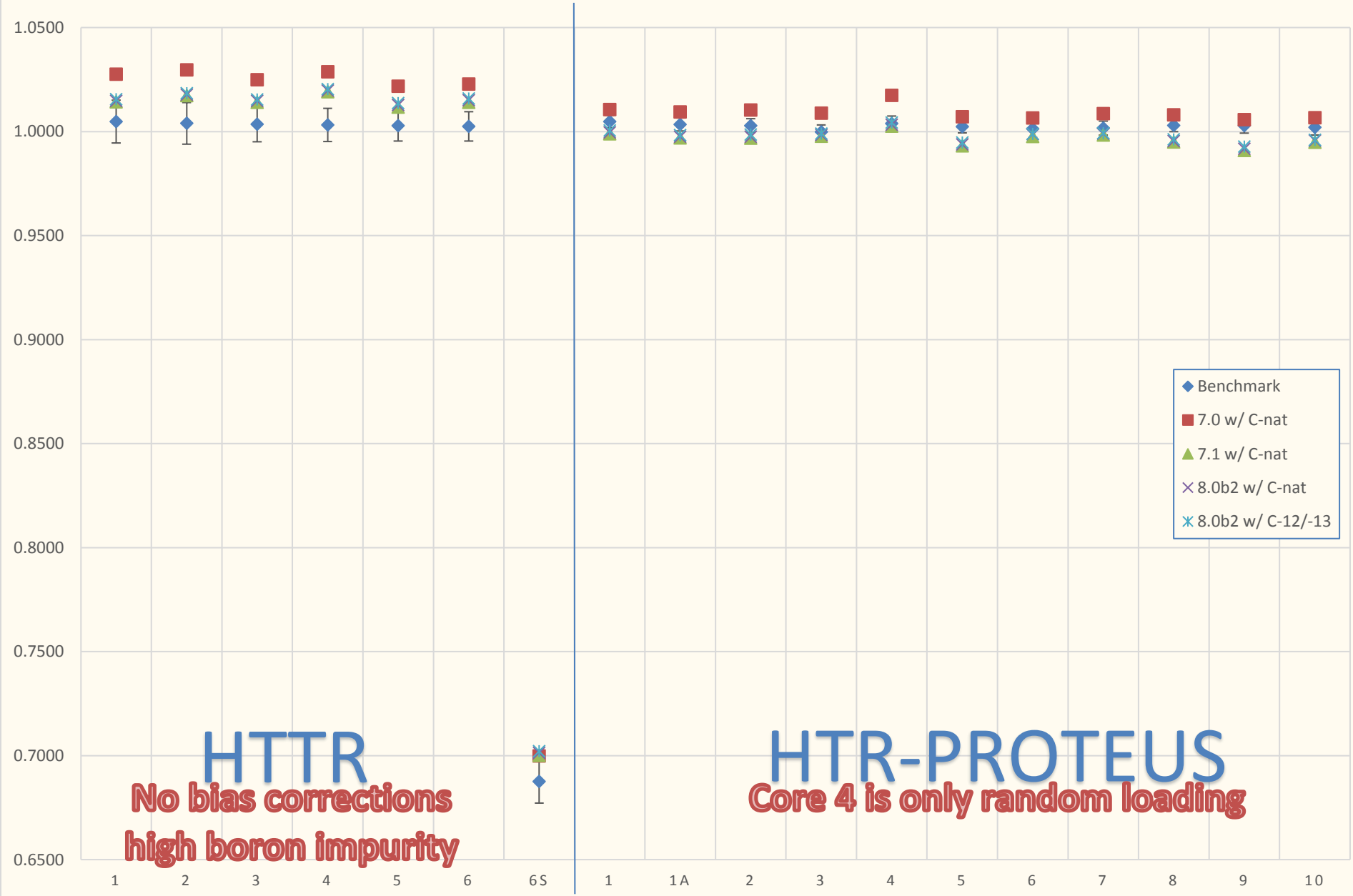
Core	# Fuel Pebbles	# Moderator Pebbles	# Pebble Layers	Core Height (m)	# Poly Rods
1	5181	2585	22	1.0888	--
1A	4951	2470	21	1.0398	--
2	3768 (FR) 0 (UR)	1880 (FR) 6009 (UR)	16 (FR) 17 (UR)	1.6277	--
3	4009	2000	17	0.8438	327
4	4920	4920	--	1.51	--
5	5433	2870	23	1.38	--
6	5184	2758	22	1.32	654
7	4221	2277	18	1.08	654
8	5433	2870	23	1.38	654
9	4870	4877	27	1.62	--
10	4332	4332	24	1.44	654

Comparison of Primary Uncertainties

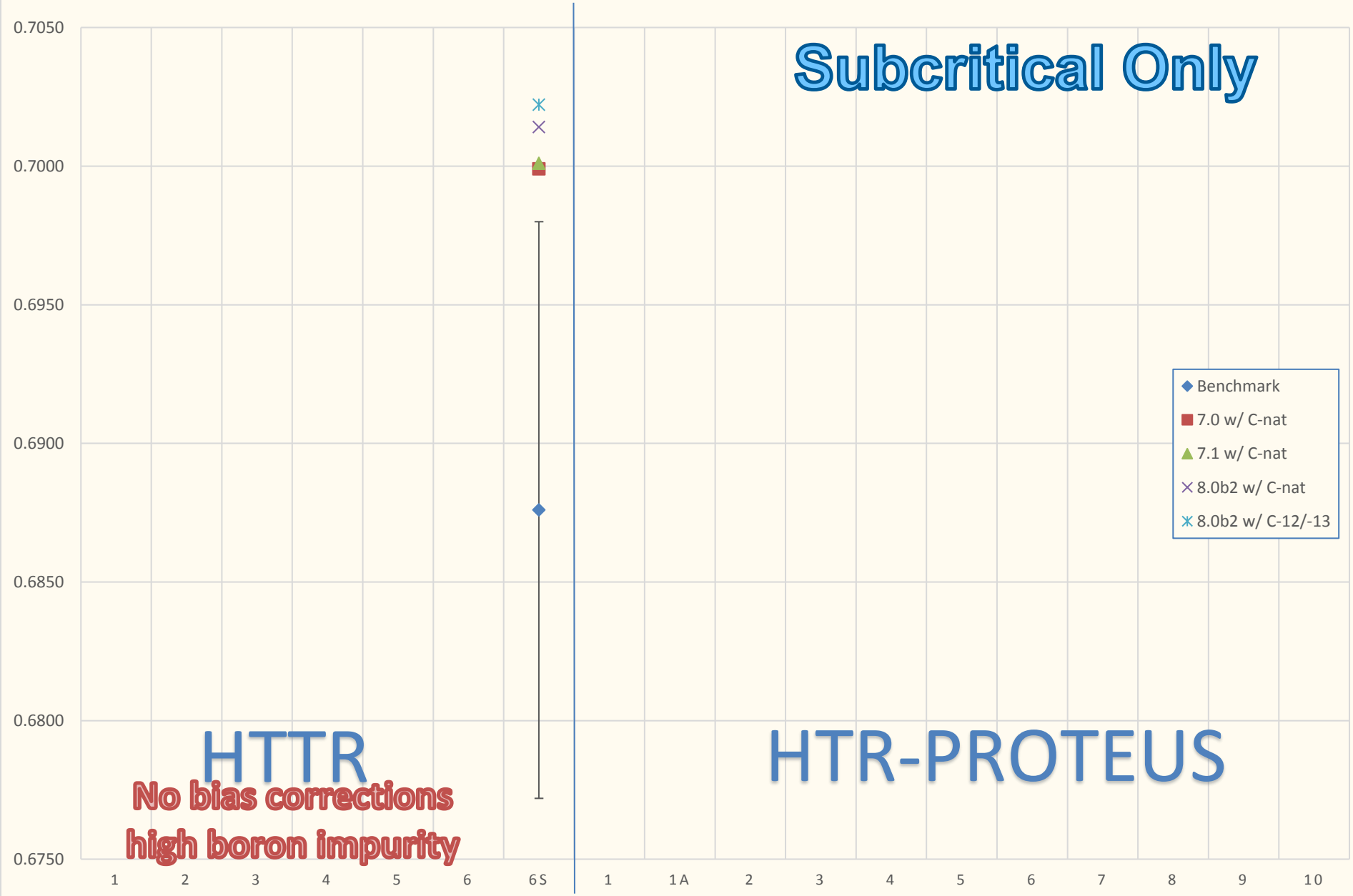
Uncertainty (Δk_{eff} in pcm) \\ Core	1	1A	2	3	4	5	6	7	8	9	10
Radial Reflector Density	97	89	91	76	104	108	61	74	102	102	81
Radial Reflector Impurities	69	78	78	62	104	103	52	66	96	113	80
Location of Upper Axial Reflector	98	110	11	104	13	11	<10	<10	<11	15	<10
Upper Axial Reflector Housing Dimensions	36	35	<10	33	68	60	26	36	53	72	46
Aluminum Composition in Upper Axial Reflector	19	31	<10	28	38	34	12	22	31	37	24
^{235}U Isotopic Content	223	226	227	267	252	233	334	305	245	262	312
Fuel Pebble Uranium Mass	27	25	26	35	31	28	46	41	30	34	42
Moderator Pebble Impurities	100	108	192	90	173	87	76	77	81	166	154
Polyethylene Rod Linear Density	--	--	--	11	--	--	190	<10	17	--	<10
Polyethylene Rod H:C Ratio	--	--	--	34	--	--	40	<10	<10	--	12
Pebble Random Packing	--	--	--	--	45	--	--	--	--	--	--
Total Experimental Uncertainty (Δk_{eff} in pcm)	**301**	**309**	**329**	**327**	**354**	**301**	**406**	**335**	**303**	**359**	**374**

Well Characterized Biases and Uncertainties

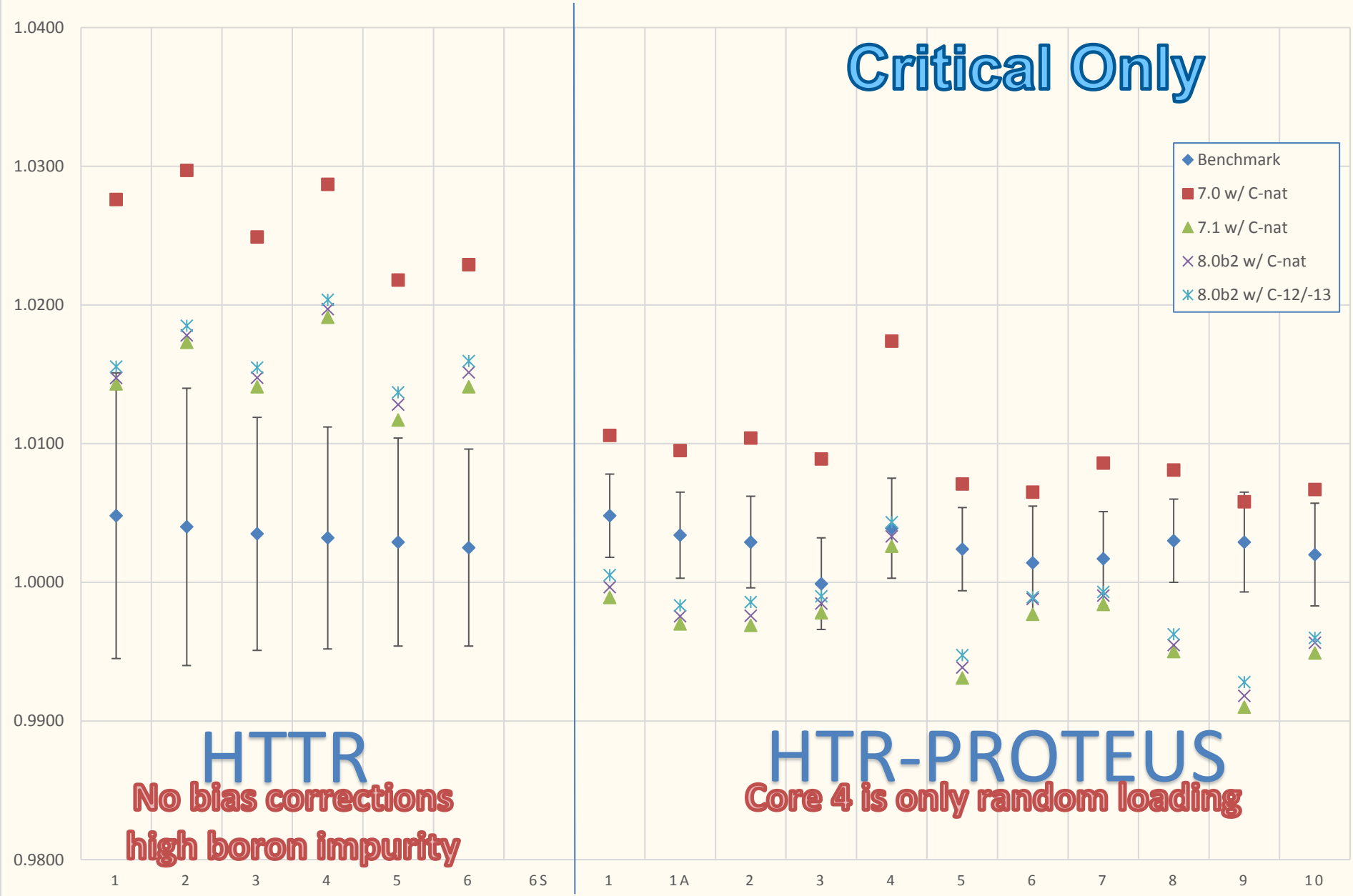
EIGENVALUE CALCULATIONS FOR HTTR AND HTR-PROTEUS BENCHMARK EXPERIMENTS



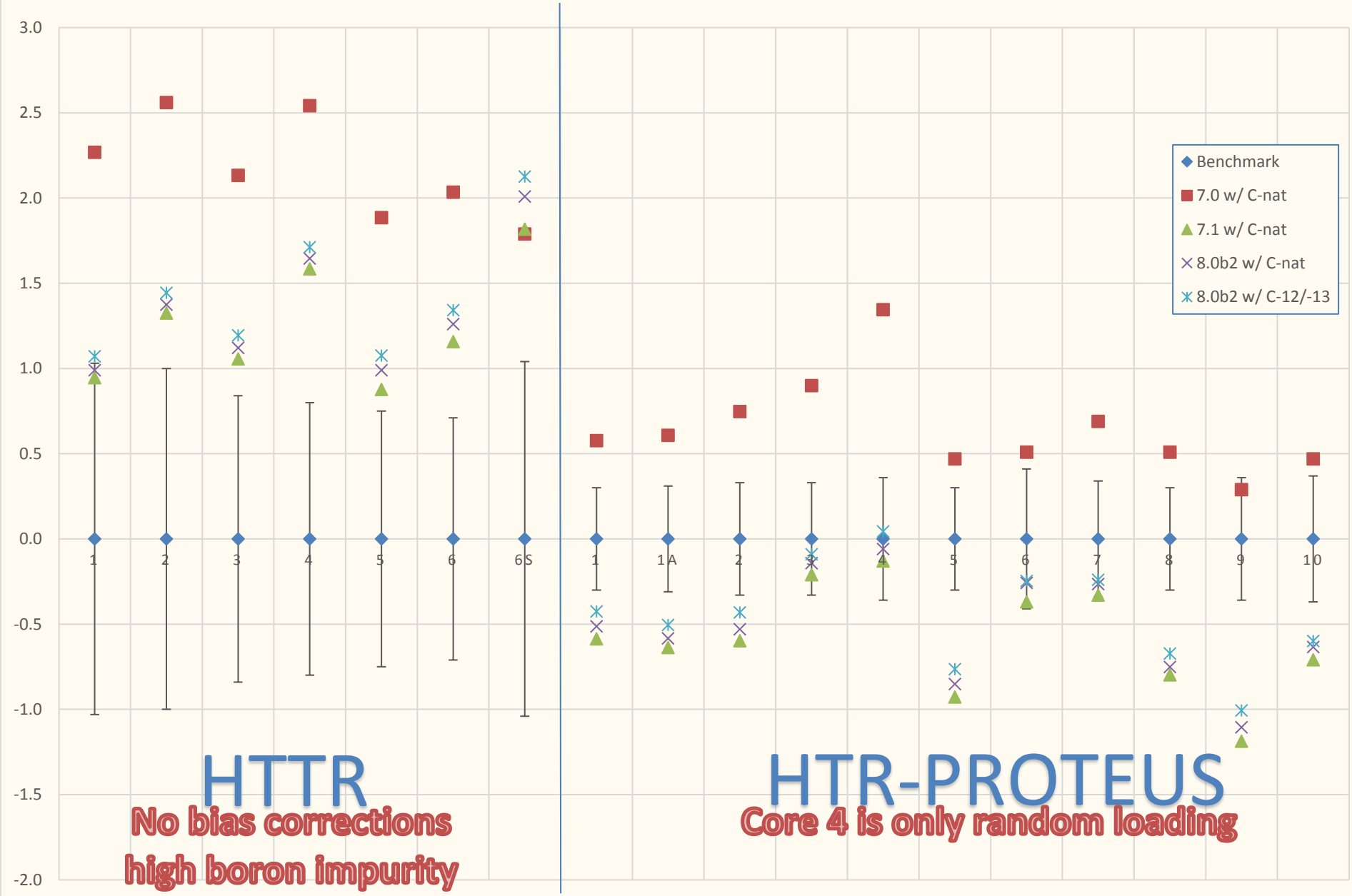
EIGENVALUE CALCULATIONS FOR HTTR AND HTR-PROTEUS BENCHMARK EXPERIMENTS



EIGENVALUE CALCULATIONS FOR HTTR AND HTR-PROTEUS BENCHMARK EXPERIMENTS

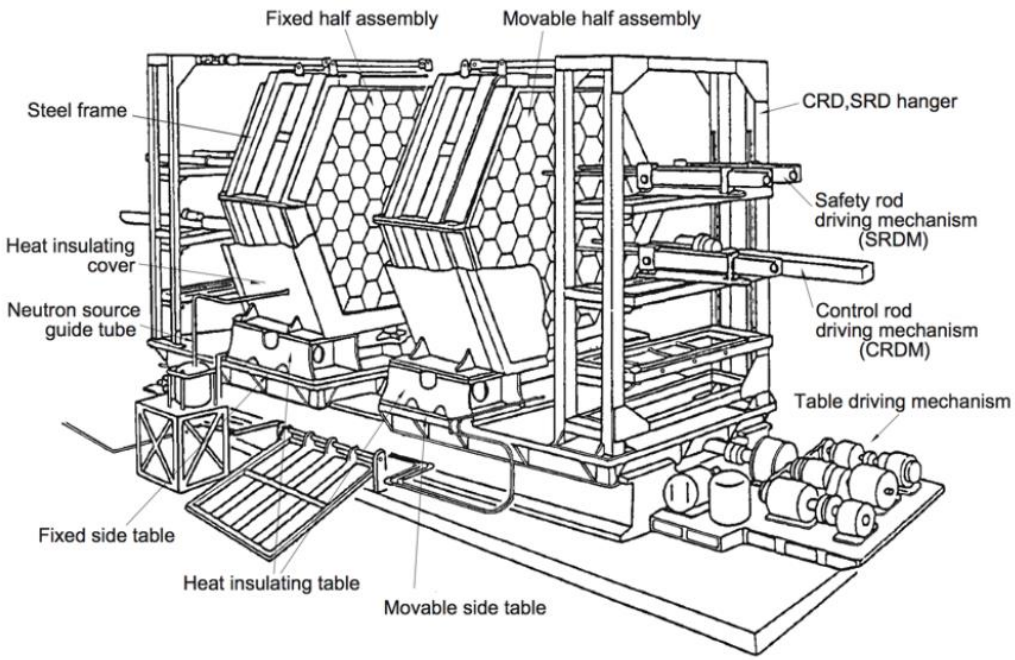


(C-E)/E [%] CALCULATIONS FOR HTTR AND HTR-PROTEUS BENCHMARK EXPERIMENTS



Very High Temperature Reactor Critical (VHTRC)

- Critical assembly constructed to verify accuracy of HTTR neutronic design
- Biases quantified and smaller total uncertainty
  - ~ 300 – 370 pcm
- Only MVP-II and JENDL-4.0 results available



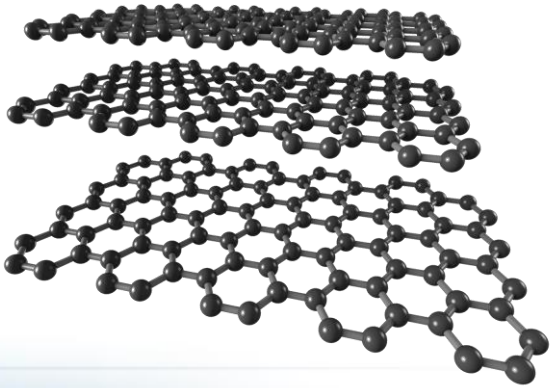
VHTRC MVP-II with JENDL-4.0 Results

Case	Core	Temperature (°C)	k_{eff}		(C-E)/E (%)
			Benchmark[a]	Calculation	
1	HP	25.5	1.0115 ± 0.0032	1.00706 ± 0.00006	-0.44
2		71.2	1.0046 ± 0.0033	0.99998 ± 0.00006	-0.46
3		100.9	0.9994 ± 0.0035	0.99527 ± 0.00006	-0.41
4		150.5	0.9906 ± 0.0035	0.98700 ± 0.00006	-0.36
5		199.6	0.9820 ± 0.0037	0.97893 ± 0.00006	-0.31
6	HC-1	8.0	1.0121 ± 0.0034	1.00524 ± 0.00006	-0.68
7	HC-2	200.3	1.0086 ± 0.0031	1.00426 ± 0.00006	-0.43

Comparable with HTR-PROTEUS ENDF/B-VII.1

Conclusions

- **HTTR benchmark evaluation not very useful for validation of integral data measurements at criticality**
  - **Recommend building MCNP model for VHTRC for results more comparable with HTR-PROTEUS**
- **HTR-PROTEUS results demonstrate that the computational bias after adopting JENDL-4.0 graphite absorption cross section data might be too large**
  - **Other factors might contribute to this discrepancy such as S(α,β)**
  - **C-12/-13 = slight improvement**



Questions?

Extra Slides

Calculated Results (i.e. the Numbers)

Benchmark Evaluation	Case	Core	Label	Benchmark Experiment Eigenvalue	±1σ	Calculated Eigenvalue ENDF/B-VII.0 C-nat	(C-E)/E %	Calculated Eigenvalue ENDF/B-VII.1 C-nat	(C-E)/E %	Calculated Eigenvalue ENDF/B-VIII.0b2 C-nat	(C-E)/E %	Calculated Eigenvalue ENDF/B-VIII.0b2 C-12/C-13	(C-E)/E %
HTTR-GCR-RESR-002	-001	19-column	1	1.0048	0.0103	1.0276	2.27	1.0143	0.95	1.0147	0.99	1.0156	1.07
	-002	21-column	2	1.0040	0.0100	1.0297	2.56	1.0173	1.32	1.0178	1.37	1.0185	1.44
	-003	24-column	3	1.0035	0.0084	1.0249	2.13	1.0141	1.06	1.0148	1.12	1.0155	1.19
	-004	24b-column	4	1.0032	0.0080	1.0287	2.54	1.0191	1.58	1.0197	1.64	1.0204	1.71
	-005	27-column	5	1.0029	0.0075	1.0218	1.88	1.0117	0.88	1.0128	0.99	1.0137	1.08
HTTR-GCR-RESR-001	-001	30-column	6	1.0025	0.0071	1.0229	2.03	1.0141	1.16	1.0151	1.26	1.0160	1.34
	-002	subcritical	6s	0.6876	0.0104	0.6999	1.79	0.7001	1.82	0.7014	2.01	0.7022	2.13
PROTEUS-GCR-RESR-001	-001	1	1	1.0048	0.0030	1.0106	0.58	0.9989	-0.59	0.9997	-0.51	1.0005	-0.43
	-002	1a	1a	1.0034	0.0031	1.0095	0.61	0.9970	-0.64	0.9976	-0.58	0.9983	-0.51
	-003	2	2	1.0029	0.0033	1.0104	0.75	0.9969	-0.60	0.9976	-0.53	0.9986	-0.43
	-004	3	3	0.9999	0.0033	1.0089	0.90	0.9978	-0.21	0.9985	-0.14	0.9990	-0.09
PROTEUS-GCR-RESR-002	-001	4 (random)	4	1.0039	0.0036	1.0174	1.34	1.0026	-0.13	1.0033	-0.06	1.0043	0.04
PROTEUS-GCR-RESR-003	-001	5	5	1.0024	0.0030	1.0071	0.47	0.9931	-0.93	0.9939	-0.85	0.9947	-0.76
	-002	6	6	1.0014	0.0041	1.0065	0.51	0.9977	-0.37	0.9988	-0.26	0.9989	-0.25
	-003	7	7	1.0017	0.0034	1.0086	0.69	0.9984	-0.33	0.9990	-0.27	0.9993	-0.24
	-004	8	8	1.0030	0.0030	1.0081	0.51	0.9950	-0.80	0.9955	-0.75	0.9963	-0.67
PROTEUS-GCR-RESR-004	-001	9	9	1.0029	0.0036	1.0058	0.29	0.9910	-1.19	0.9918	-1.11	0.9928	-1.01
	-002	10	10	1.0020	0.0037	1.0067	0.47	0.9949	-0.71	0.9957	-0.63	0.9960	-0.60

Note: MCNP6.1.1 uncertainties are approximately ≤ 0.0001.