Evaluation of the Pool Critical Assembly (PCA) Benchmark with ENDF/B-VIII.1beta1 using MCNP6

Greg Fischer

fischega@westinghouse.com

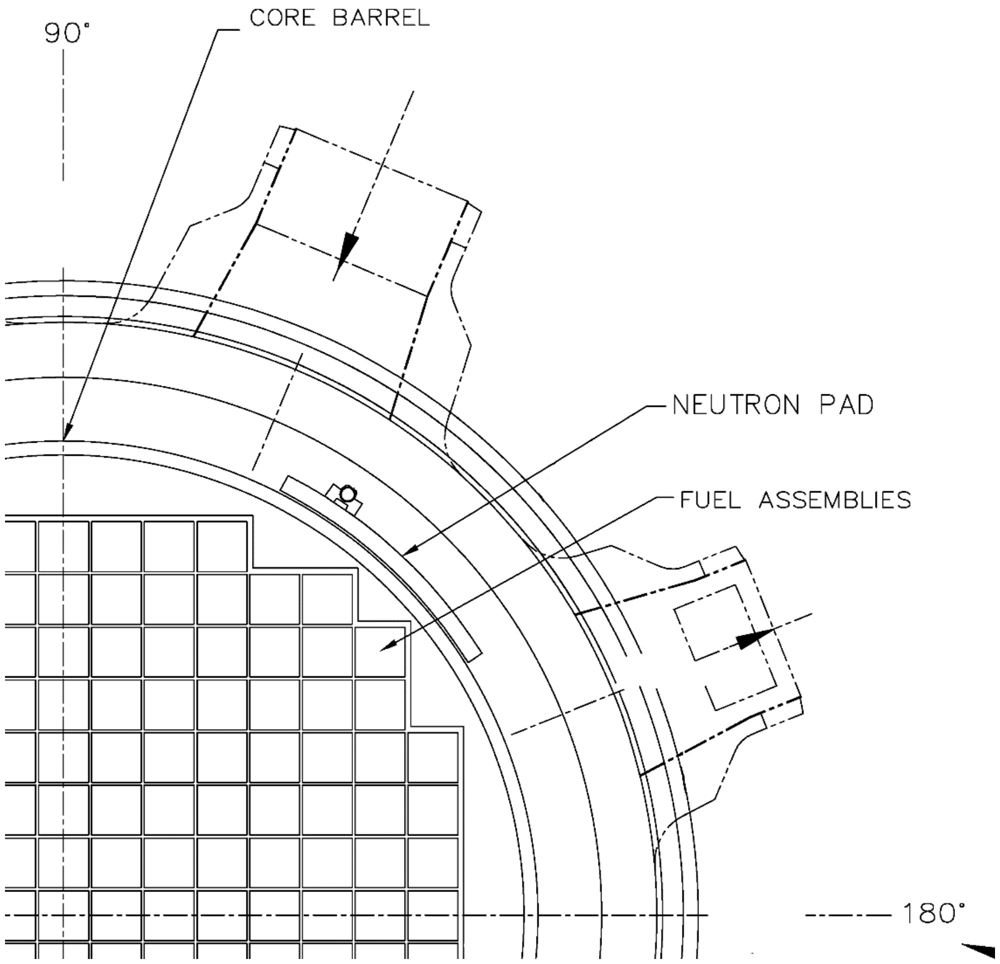
Overview

- Background on RPV fluence calculations for LWRs
- ENDF/B-VIII.1b1 Benchmarking
  - 1D PWR Comparison
  - Pool Critical Assembly

Background on Fluence Calculations

- Most fission neutrons remain inside the core, supporting the self-sustaining chain reaction

- We're interested in the relatively few neutrons that leak outside of the core and impinge upon the reactor vessel



Westinghouse

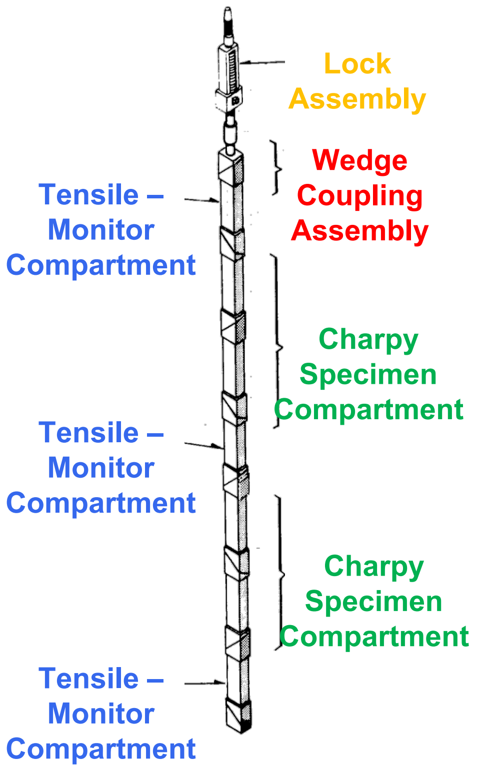
Background on Fluence Calculations

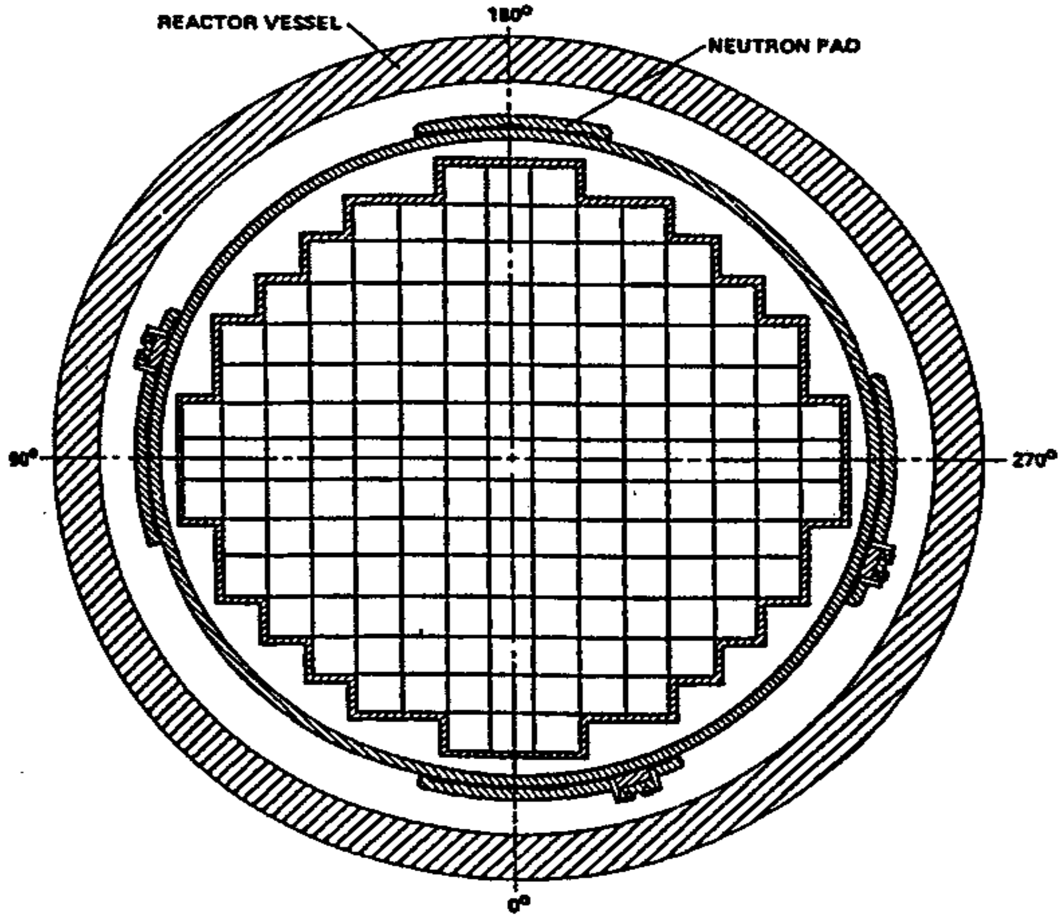
- The reactor pressure vessel and internals components are susceptible to irradiation-induced degradation of material properties

- These changes are manifested as:
  - Reduction in the toughness during ductile fracture
  - Tendency for brittle fracture to onset at increasing temperatures

- All reactors are required to have a materials surveillance program to monitor changes in reactor vessel materials properties

Background on Fluence Calculations





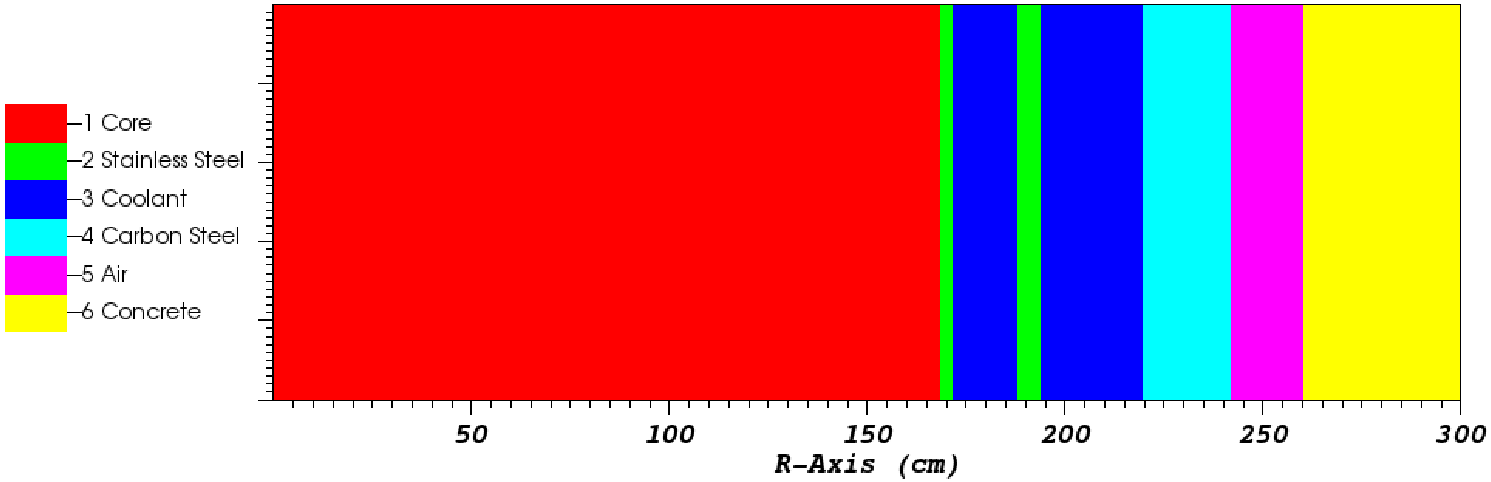
Westinghouse

Background on Fluence Calculations

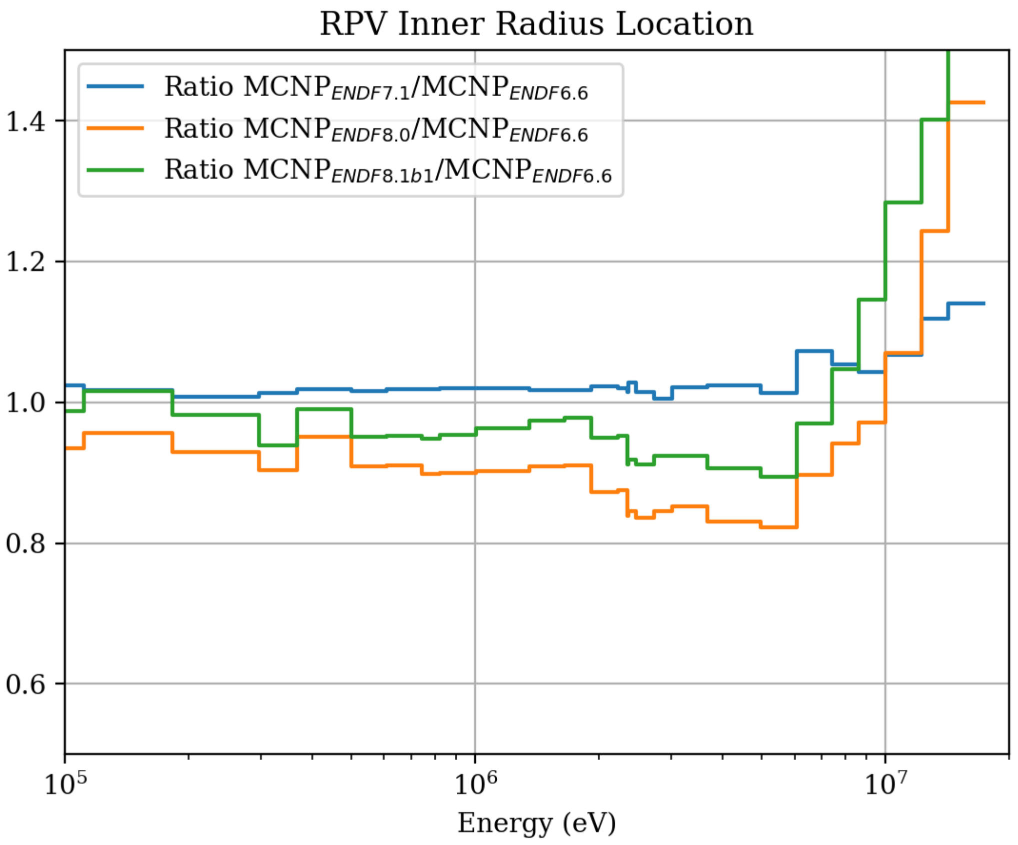
- Beginning in the 1980s, the NRC began to be concerned about the possibility of pressurized thermal shock (PTS) events
  - Postulated accident causes safety injection of cold coolant, placing severe thermal stresses on the (hot) reactor vessel
  - Event is followed by re-pressurization of the reactor vessel
  - This sequence of events could challenge the structural integrity of the reactor vessel
- Reactor vessel neutron exposure (especially for P's) is carefully tracked and monitored

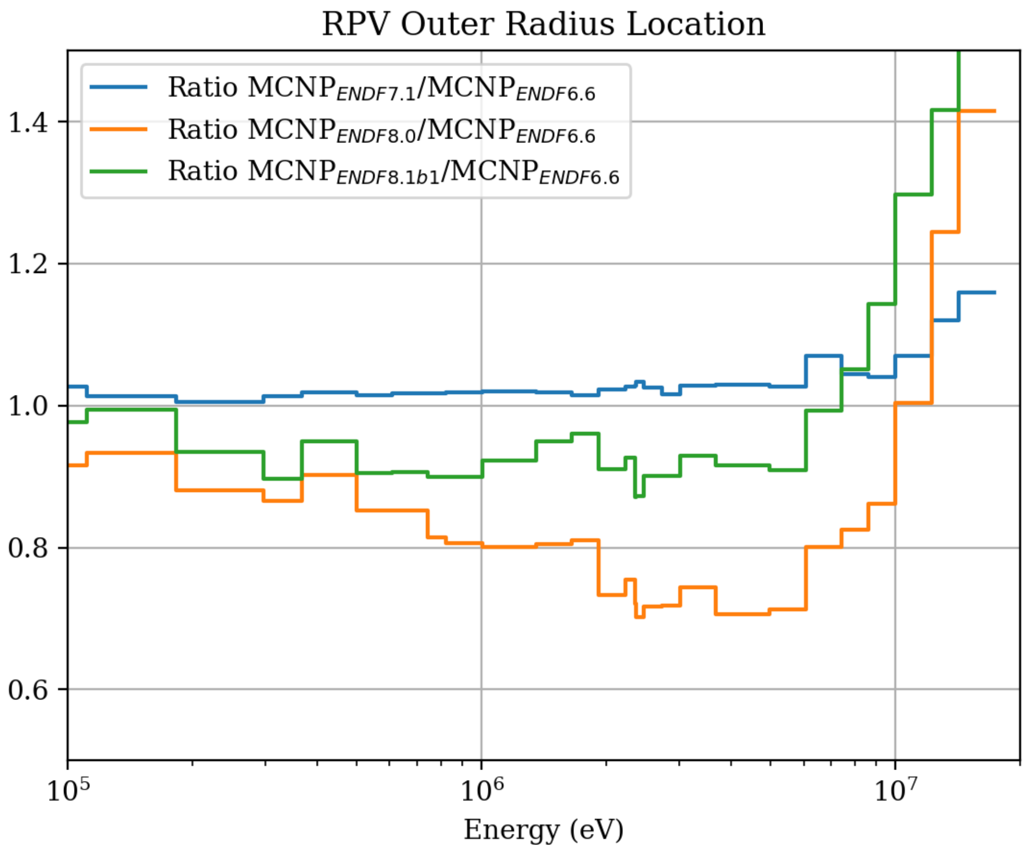
1D PWR Benchmarking

- A 1-D Monte Carlo model of a PWR was constructed to benchmark the cross sections:
  - Similar to the model used to generate the "fine group" weighting spectra for the BUGLE-96 library
  - Tallies were recorded at the inside surface and outside surface of the reactor pressure vessel



1D PWR Benchmarking



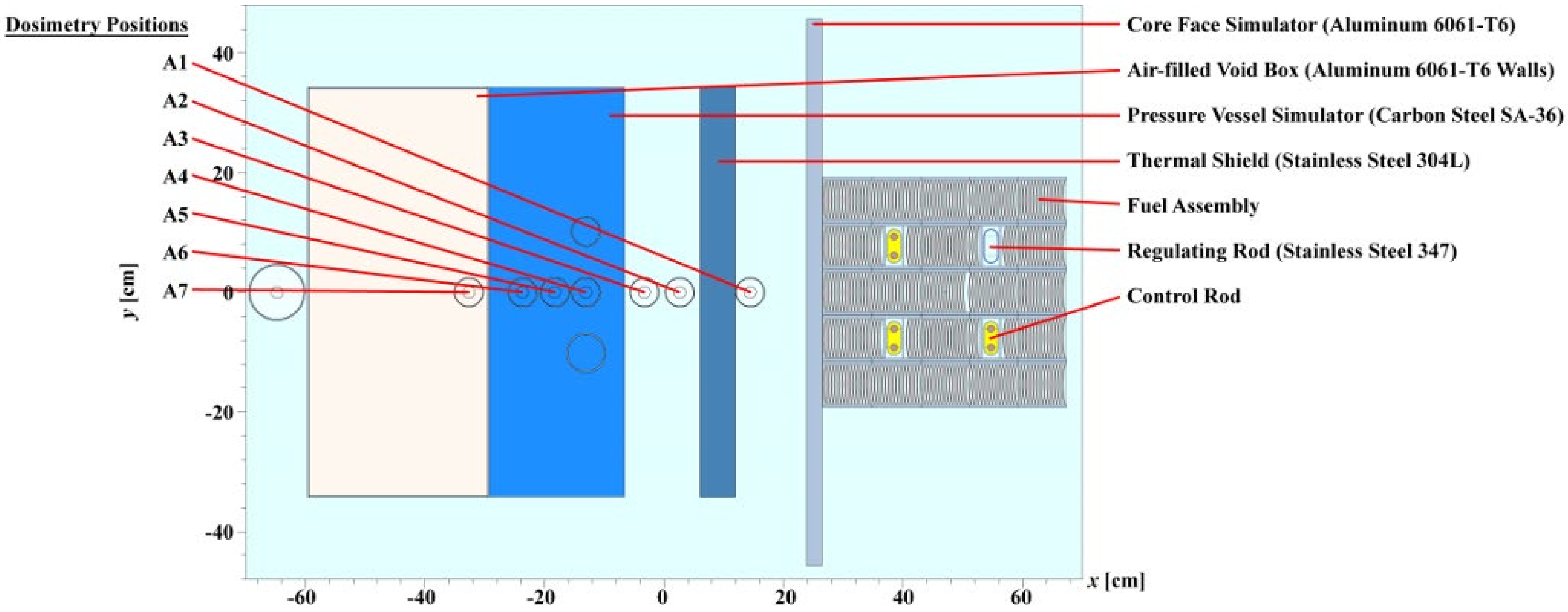


Pool Critical Assembly Benchmarking

- The Pool Critical Assembly (PCA) Pressure Vessel Simulator experiment was performed in the early 1980s as part of the NRC's LWR Pressure Vessel Surveillance Dosimetry Improvement Program (LWR-PV-SDIP)
  - Core region consists of high-enriched U-235 plates in a water pool with simulated reactor internals structural materials
  - Measurements: Al-27, Ni-58, Rh-103, In-115, U-238, and Np-237 sensor materials
  - Still widely-used as a methodology benchmark today

- Benchmark was recently re-analyzed with exact geometry by Dr. Kulesza (LANL/X-5), and MCNP inputs were published and available for use:
  - NUCLEAR TECHNOLOGY · VOLUME 197 · 284–295 · MARCH 2017
  - Paper: https://doi.org/10.1080/00295450.2016.1273711
  - MCNP Inputs: https://doi.org/10.2172/1601379

Pool Critical Assembly Benchmarking



Ref: Kulesza, Martz

Pool Critical Assembly Benchmarking

- MCNP workflow:
  - Step 1: KCODE calculation
  - Step 2: SSW (volumetric) – record fission source
  - Step 3: SSR - neutron transport to sensor locations

- Other notes:
  - Dosimetry cross sections used IRDFF-II data: https://www-nds.iaea.org/IRDFF/
  - Weight windows generated with ADVANTG
    - High-energy weight windows for Al-27 (tricky)
    - Lower-energy weight windows for the other sensors

Pool Critical Assembly Benchmarking

- Measurements:

	Reaction Rate (rps per source neutron) ($\pm 1\sigma$ Uncertainty)					
Location	$^{27}Al(n, \alpha)$		$^{58}Ni(n, p)$		$^{103}Rh(n, n')$	
A1	5.55E−33	(1.0%)	6.35E−31	(1.4%)	4.06E−30	(1.0%)
A2	7.19E−34	(2.0%)	6.74E−32	(2.0%)	—	—
A3	3.16E−34	(1.0%)	2.52E−32	(1.4%)	—	—
A4	7.19E−35	(2.0%)	5.78E−33	(1.0%)	5.67E−32	(1.5%)
A5	2.89E−35	(2.2%)	2.28E−33	(1.8%)	3.19E−32	(5.0%)
A6	1.09E−35	(2.2%)	8.10E−34	(2.2%)	1.61E−32	(5.0%)
A7	—	—	—	—	—	—
Location	$^{115}In(n, n')$		$^{238}U(n, f)$		$^{237}Np(n, f)$	
A1	1.06E−30	(1.0%)	—	—	8.71E−30	(6.2%)
A2	1.15E−31	(2.0%)	—	—	—	—
A3	3.76E−32	(1.0%)	—	—	2.98E−31	(6.3%)
A4	1.11E−32	(0.7%)	1.86E−32	(6.9%)	1.22E−31	(5.5%)
A5	5.22E−33	(1.5%)	8.36E−33	(6.8%)	6.80E−32	(5.7%)
A6	2.21E−33	(3.0%)	3.42E−33	(7.1%)	3.54E−32	(5.8%)
A7	—	—	—	—	9.51E−33	(9.2%)

Westinghouse

Pool Critical Assembly Benchmarking

- C/E Results (ENDF/B-VII.1):
  - MC uncertainty ~= 1%

	al27a	ni48p	rh103n	in115n	u238f	np237f	**avg**	**std dev**
	0.99	1.00	1.07	1.03			**1.02**	**3.7%**
	1.00	1.05	1.14	1.06			**1.06**	**5.3%**
	1.01	1.06	1.12	1.11			**1.08**	**4.6%**
	0.98	1.01	1.06	1.07	1.04	1.08	**1.04**	**3.7%**
	0.98	1.03	1.00	1.07	1.04	1.10	**1.04**	**4.4%**
	0.99	1.09	0.98	1.09	1.04	1.08	**1.04**	**5.0%**
			1.02	1.05	1.05	1.20	**1.08**	**7.6%**
avg	**0.99**	**1.04**	**1.05**	**1.07**	**1.04**	**1.11**	1.05	
std dev	**1.4%**	**3.3%**	**6.1%**	**2.4%**	**0.2%**	**1.1%**		**4.8%**

Pool Critical Assembly Benchmarking

- C/E Results (ENDF/B-VIII.0):
  - MC uncertainty ~= 1%

	al27a	ni48p	rh103n	in115n	u238f	np237f	**avg**	**std dev**
	0.96	0.96	1.04	1.00			**0.99**	**3.9%**
	0.95	0.93	1.05	0.97			**0.97**	**5.4%**
	0.98	0.95	1.03	1.01			**0.99**	**3.3%**
	0.94	0.86	0.94	0.92	0.90	0.97	**0.92**	**4.3%**
	0.89	0.83	0.87	0.90	0.87	0.97	**0.89**	**5.3%**
	0.88	0.85	0.85	0.90	0.84	0.95	**0.88**	**4.7%**
			0.88	0.86	0.84	1.05	**0.91**	**10.5%**
avg	**0.93**	**0.90**	**0.95**	**0.94**	**0.86**	**0.98**	**0.93**	
std dev	**4.1%**	**6.3%**	**9.3%**	**5.2%**	**3.1%**	**1.3%**		**6.9%**

Westinghouse

Pool Critical Assembly Benchmarking

- C/E Results (ENDF/B-VIII.1b1):
  - MC uncertainty ~= 1%

	al27a	ni48p	rh103n	in115n	u238f	np237f	**avg**	**std dev**
	0.97	0.96	1.04	1.00			**0.99**	**3.9%**
	1.02	0.98	1.08	1.01			**1.02**	**4.3%**
	1.05	1.01	1.07	1.06			**1.05**	**2.5%**
	1.03	0.96	1.00	1.01	0.98	1.03	**1.00**	**2.7%**
	1.03	0.96	0.95	1.00	0.98	1.05	**0.99**	**4.0%**
	1.04	1.02	0.93	1.03	0.98	1.03	**1.00**	**4.1%**
			0.96	0.99	0.99	1.13	**1.02**	**7.6%**
avg	**1.02**	**0.98**	**1.01**	**1.01**	**0.98**	**1.06**	**1.01**	
std dev	**2.8%**	**2.9%**	**6.4%**	**2.1%**	**0.1%**	**1.0%**		**4.2%**

Westinghouse

Conclusions

- ENDF/B-VIII.1b1 reduces the magnitude of the differences observed with ENDF/B-VIII.0 as compared to current cross section data.

- PCA comparisons with ENDF/B-VIII.1b1 seem to show better agreement with the measured data than ENDF/B-VII.1 or ENDF/B-VIII.0.