Recent Progress in Validating POLARIS for USNRC Use

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Outline

- Regulatory purpose of confirmatory analysis
- Role of code assessment in confirmatory analysis
- Recent integral validation and assessment of POLARIS/PARCS
    - DIMPLE
    - Otto Hahn
    - TMI1 Cycles 1 and 2
    - Hatch
- Conclusions

Regulatory Purpose and Confirmatory Analysis

- Confirmatory analyses are performed by the USNRC staff to aid in regulatory decision making by providing an independent analysis of safety related issues.
- The Office of Nuclear Regulatory Research (RES) is often tasked to perform confirmatory analysis for new reactor designs (e.g., NuScale) or proposed license amendments (e.g., Extended Power Uprate) using our suite of reactor systems analysis tools.
- RES maintains a suite of codes for this purpose, such as SCALE, PARCS, FRAPCON, TRACE, MELCOR, etc.

Role of Assessment

- RES systems analysis tools must be assessed before being applied to analyze specific transient events for specific reactor types.
- RES relies on a process of phenomena identification and ranking to determine the key phenomena that affect analysis of a given event.
- All highly important phenomena must be represented by models that are validated against experimental data over the full range of application.
- The code models must represent the associated phenomena with reasonable accuracy.

Recent Progress in Assessment of POLARIS with PARCS

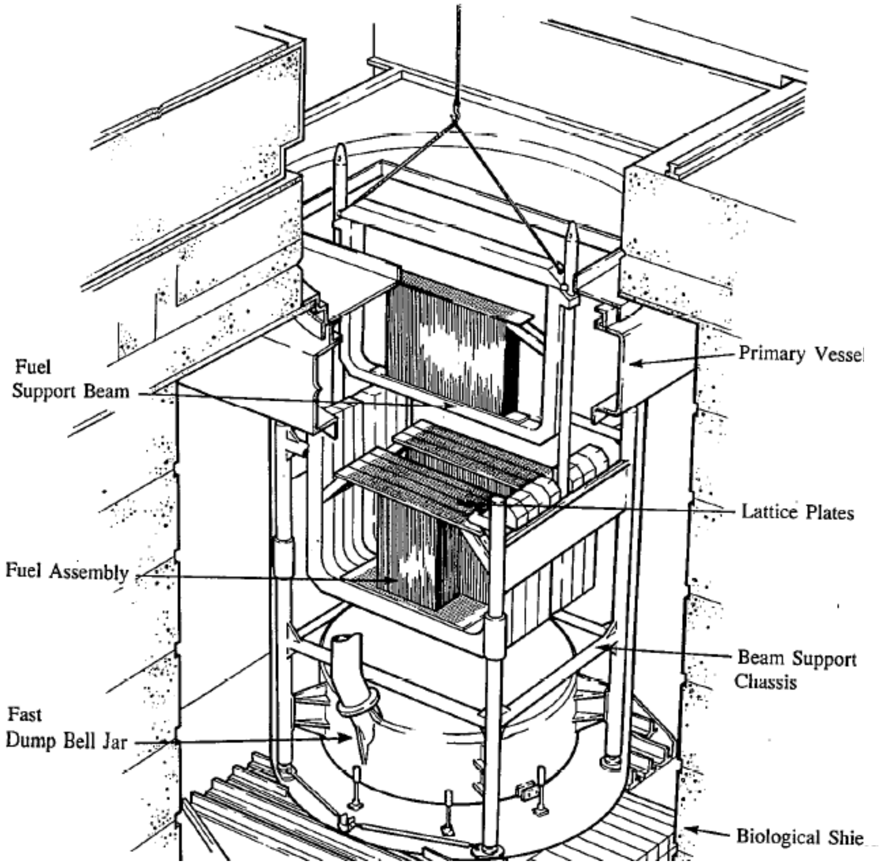
- Application to Small Modular Reactors
  - DIMPLE and Otto Hahn small critical experiments
- Application to PWR depletion (including control rod history effects)
  - Three Mile Island Unit 1 (TMI1) Cycles 1 and 2
- Application to BWR depletion
  - Hatch Unit 1 Cycles 1, 2 and 3 (IN PROGRESS)

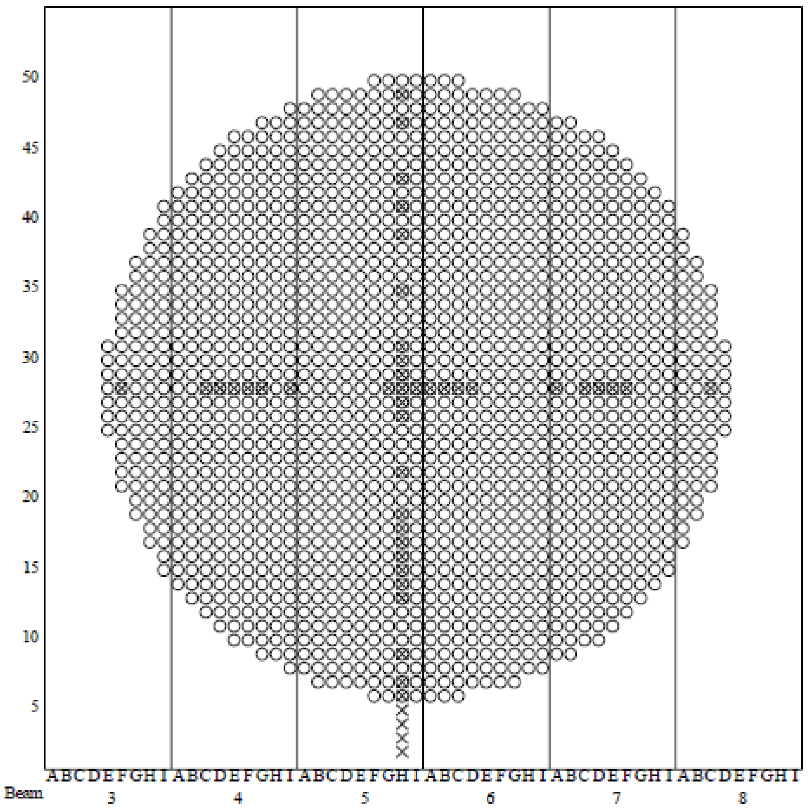
DIMPLE

Background

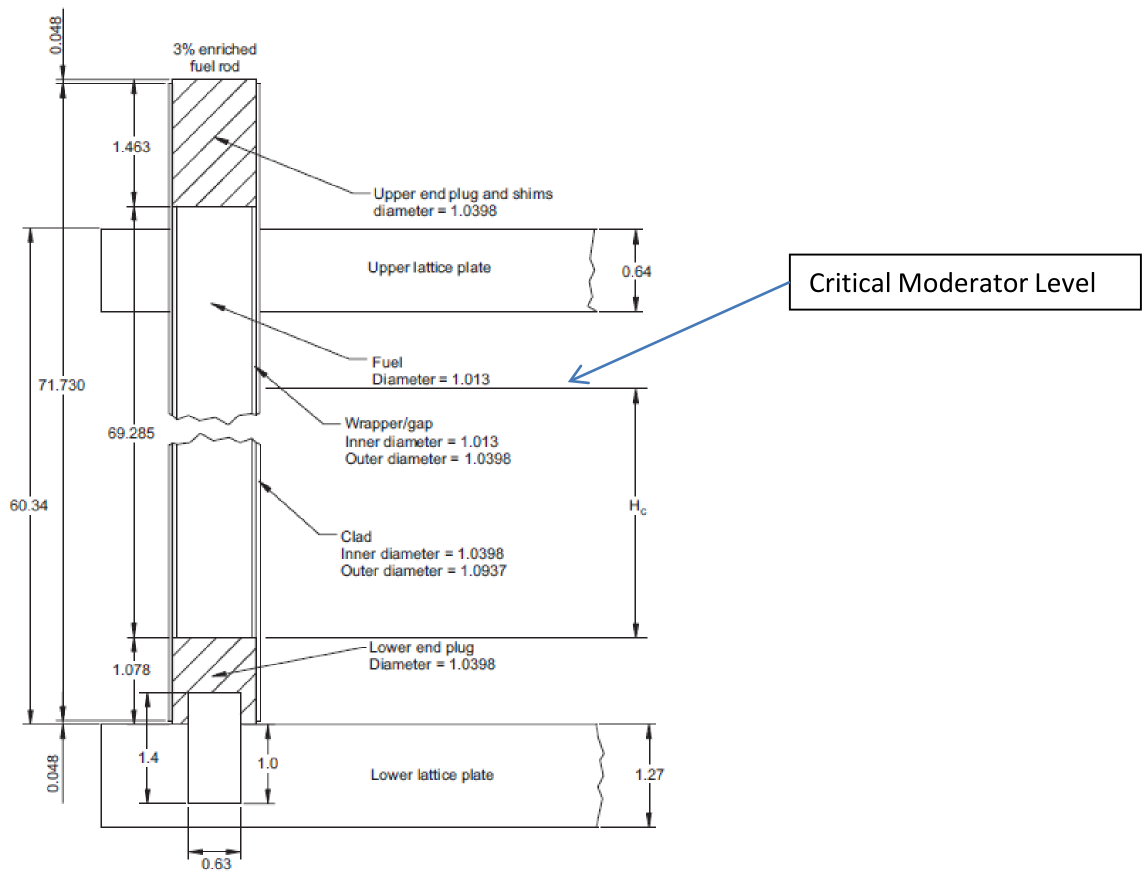
- The DIMPLE facility, located in the UK, was originally constructed to study heavy-water moderated lattices in 1960s, but was repurposed for light water in 1983. S01A was the first of the series.
- The Facility consisted of a large aluminum primary vessel where a wide range of experimental core arrangements could be easily assembled. The reactor control was via varying water level height, allowing criticality experiments without presence of control media.
- Core fuel pins were arranged in an open pool at atmospheric conditions.

DIMPLE Facility and Test S01A Configuration





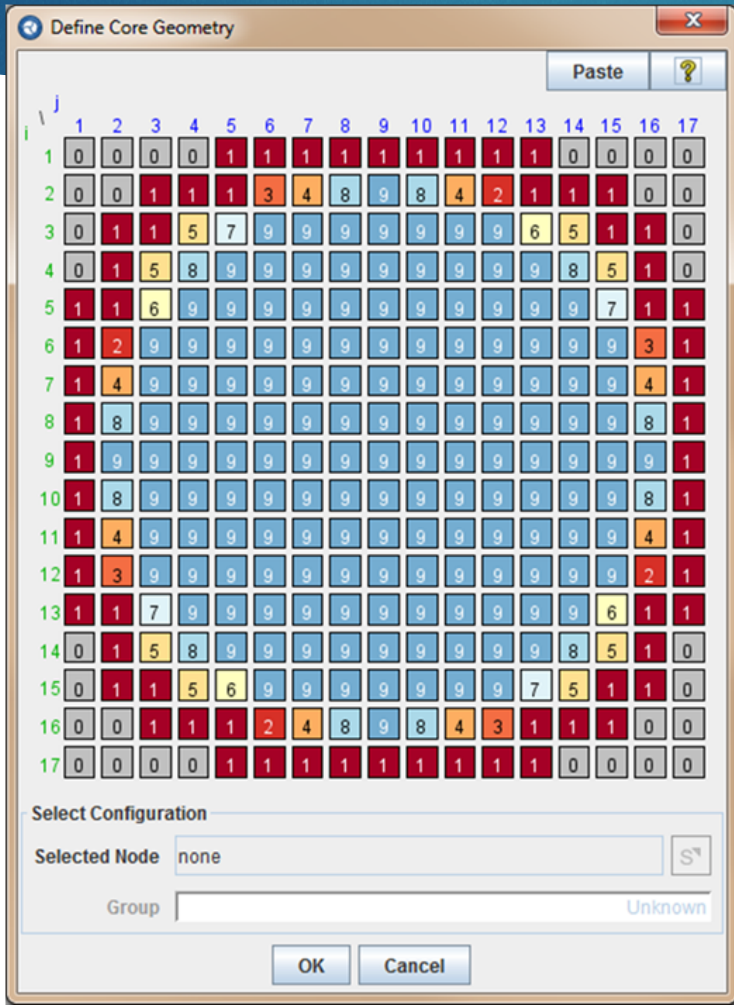
Test S01A Fuel Pin



TRACE/PARCS modeling for DIMPLE S01A

- POLARIS used to perform lattice physics calculations.
- GENPMAXS used to convert to PMAXS format.
- PARCS used to construct a 3D geometric representation of the core, and its computational nodes are interfaced with TRACE via a MAPTAB file.
- A 3x3 pin array arrangement was used to define the radial core layout.
- Layout resulted in 193 assembly arrays configured with 149 full arrays with 9 pins, and the remaining partially filled arrays.

PARCS Layout Configuration



i \ j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0
2	0	0	1	1	1	3	4	8	9	8	4	2	1	1	1	0	0
3	0	1	1	5	7	9	9	9	9	9	9	9	6	5	1	1	0
4	0	1	5	8	9	9	9	9	9	9	9	9	9	8	5	1	0
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6	1	2	9	9	9	9	9	9	9	9	9	9	9	9	9	3	1
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15	0	1	1	5	6	9	9	9	9	9	9	9	7	5	1	1	0
16	0	0	1	1	1	2	4	8	9	8	4	3	1	1	1	0	0
17	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0

Where:
[9] – Full array
[2-8] – Partial filled array
[1] – radial reflector

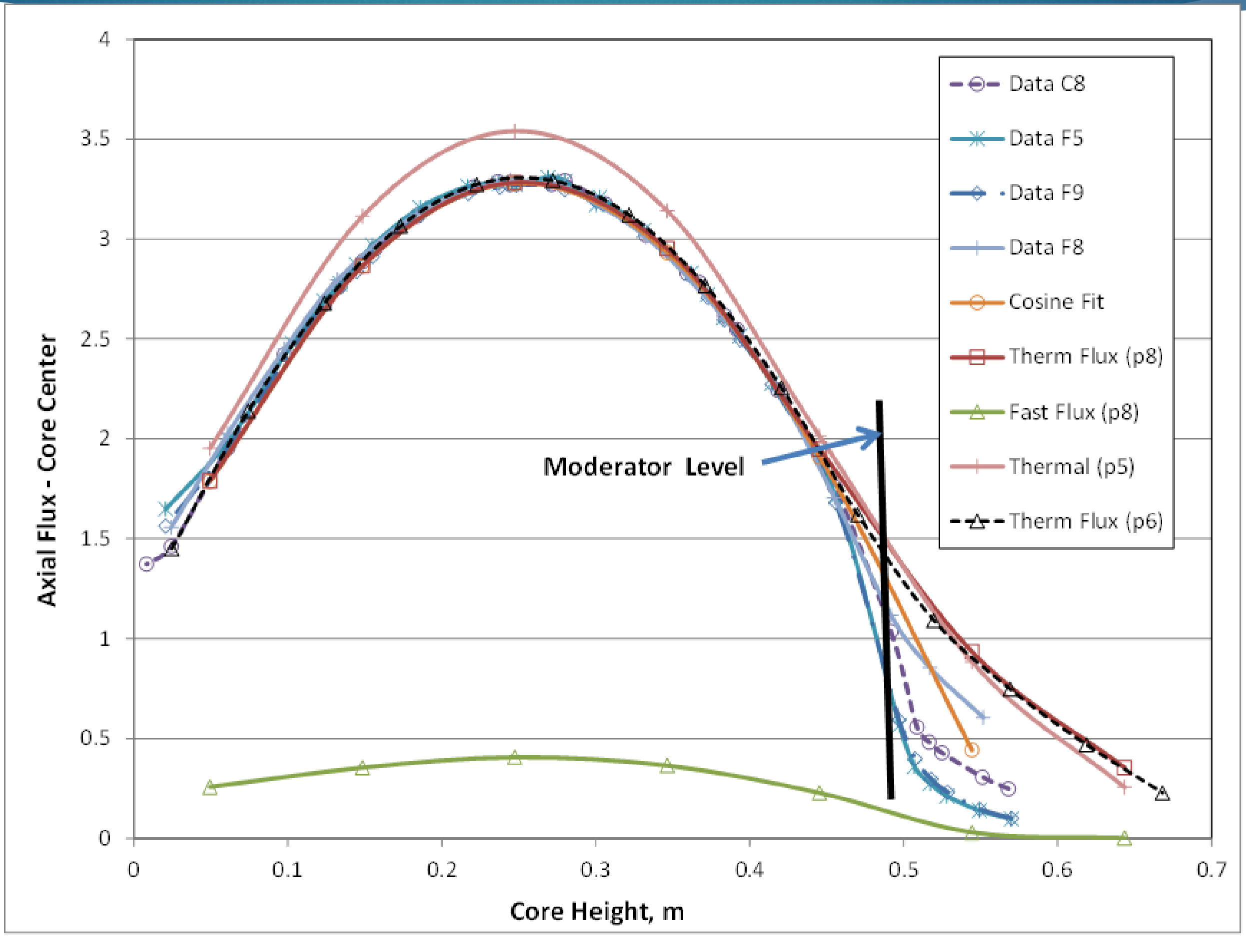
Multiplication Factor Results

- k_{eff} results for cases run are:

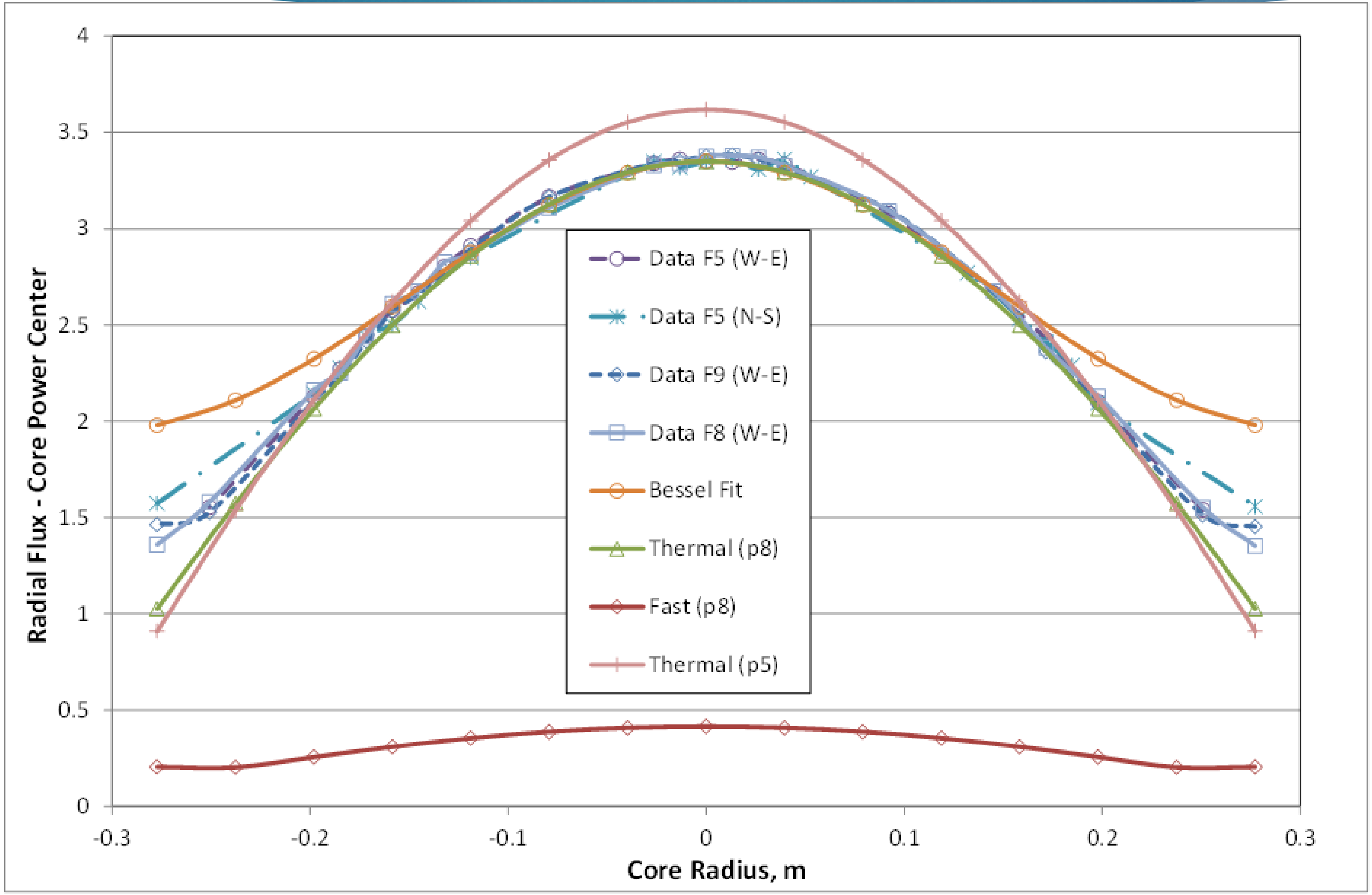
Run	PARCS Boundary Condition	#Core Nodes	Peak Radial Power	Peak Axial Power	Keff
p6	zero current	14	1.697	1.741	0.9908
p5	zero flux	7	1.820	1.755	0.9767
p8	**zero current**	**7**	**1.697**	**1.735**	**0.9910**
p9	reflective	7	1.231	1.547	1.0675

Note: p6 indicates axial noding is adequate

Axial Flux Comparison



Radial Flux Comparison



Buckling Comparison

- Buckling Results are:

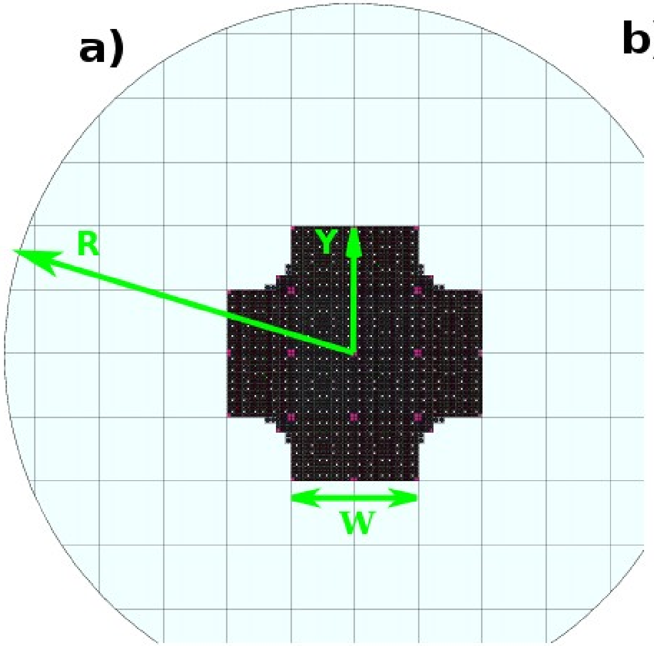
Run	PARCS Boundary Condition	Keff	**Buckling Computation ($-m^2$) (ax/rad)**	**Percent Difference (%)**
p5	zero flux	0.9767	**24.7 / 47.0**	**2.5 / 13.3**
p8	**zero current**	**0.9910**	**24.2 / 43.3**	**0.4 / 4.3**
Test	-	1.0000	**24.1 / 41.5**	**-**

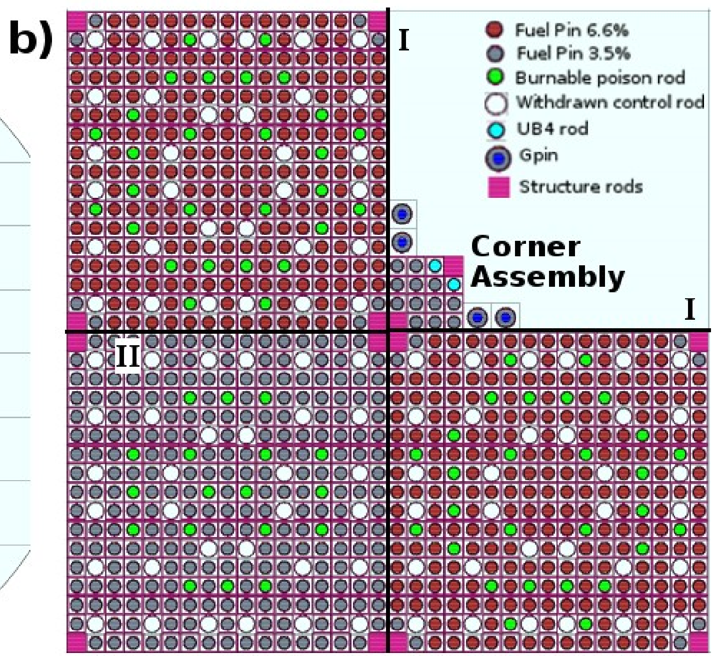
Otto Hahn

Background

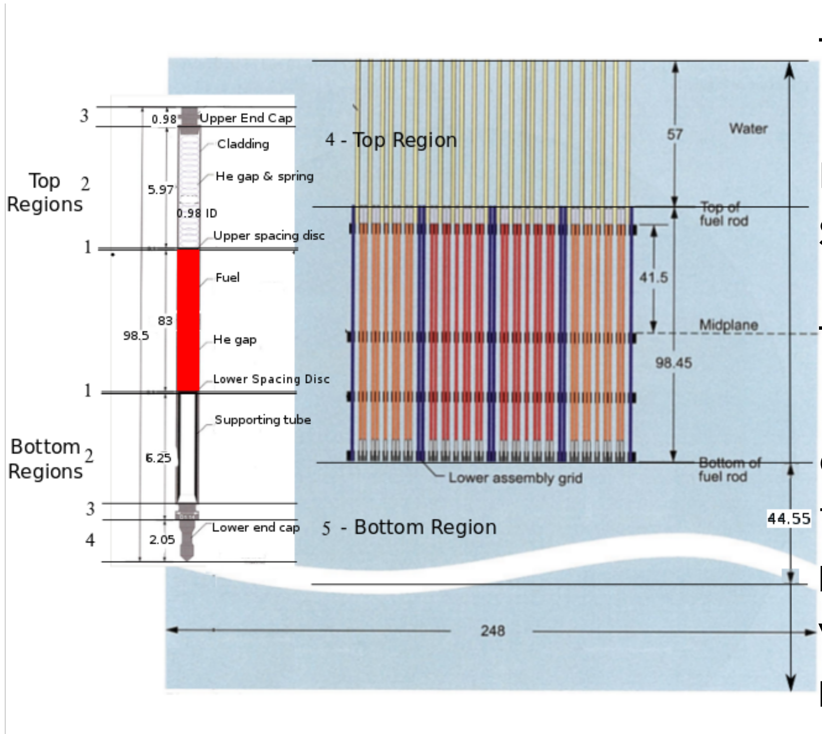
- The Otto Hahn (OH) second core zero power experiment was identified as a test that could be used to examine the applicability of POLARIS/PARCS to a SMR core because of its small size, small number of assemblies, and light-water-reflected boundaries.

Otto Hahn Core Description





Fuel Rod and Core Description



(Modified from Rogan et al., 2007)

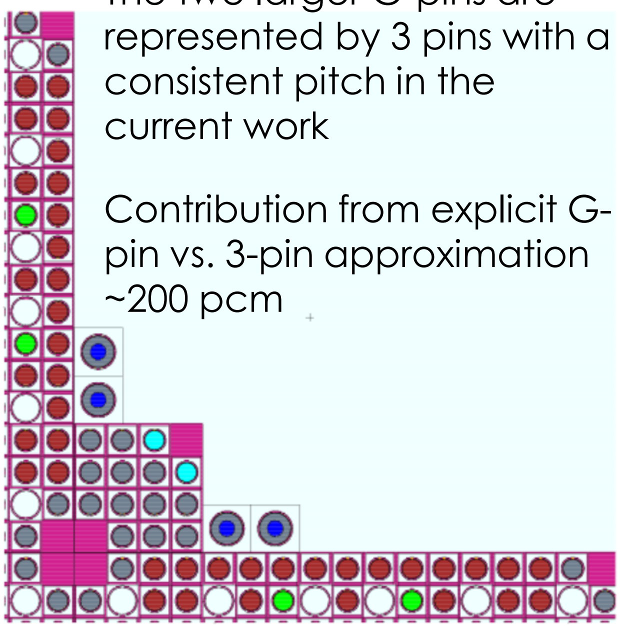
The core top and bottom reflectors are modeled with 4 and 5 slabs, respectively.

The core is surrounded by light water in a cylindrical reflector tank. The radial reflector consists of the water outside the core region.

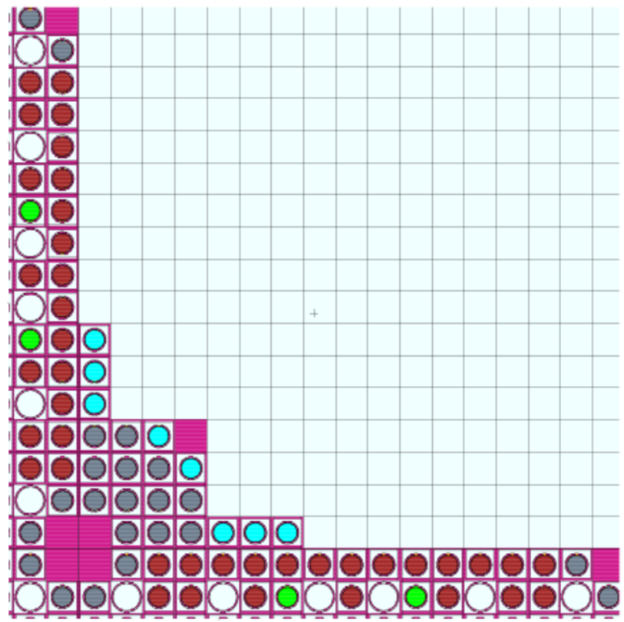
Corner Assembly Representation

The two larger G-pins are represented by 3 pins with a consistent pitch in the current work

Contribution from explicit G-pin vs. 3-pin approximation ~200 pcm

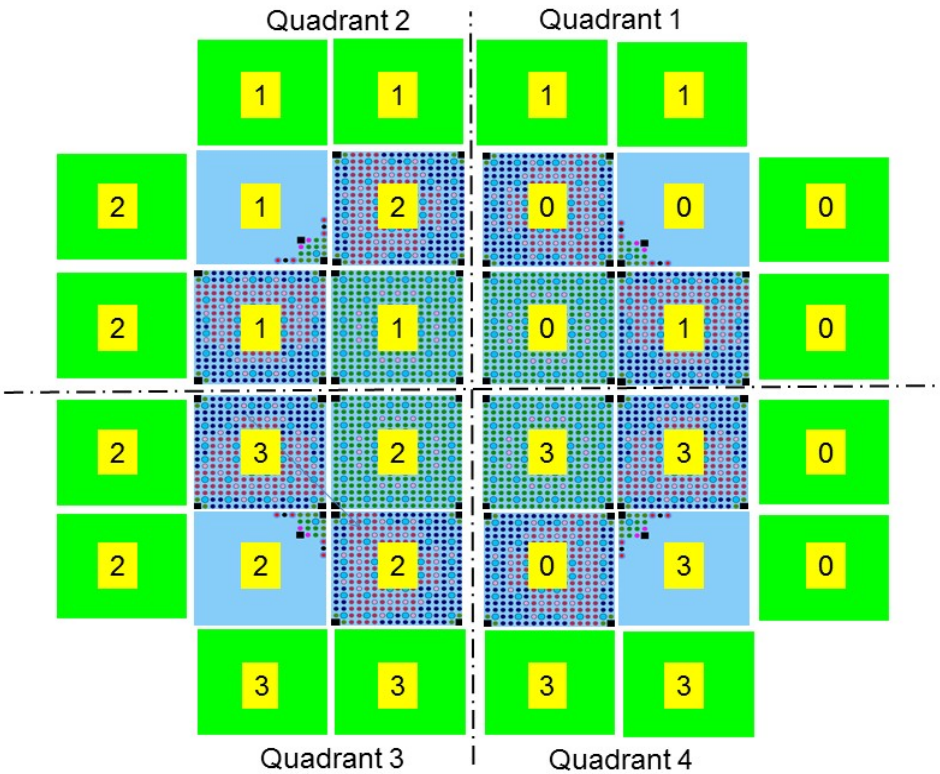


a) MCNP model of corner lattice with oversized UO_2-B_4C Fuel Pins



b) MCNP model of corner lattice with three pin representation of oversized UO_2-B_4C Fuel Pins

PARCS Model



- A two-group model, typical for light water reactor analysis, was used.
- The core consists of 16 radial nodes with three unique PMAX files to represent the core nuclear nodes. Assembly rotation is used.
- The reflectors are modeled with three unique PMAX files (top, bottom, and radial).

PARCS k_{eff} Results

Run	Boundary Conditions	XS library	keff (PARCS)
p1	0 Incoming Current	P, C-C	0.99088
p2	Top & Bot Reflective	P, C-C	1.03022
p3	Radially Reflective	P, C-C	1.04031
p4	All BCs Reflective	P, C-C	1.08308
p5§	0 Incoming Current	P	0.99169
p6	0 Incoming Current	C	0.99964
p7	0 Incoming Current No Corner Lattices	P	0.98637

§Cross-section libraries for corner assemblies generated with POLARIS for geometry and conditions generally outside POLARIS's range of applicability.

Buckling Results

Comparison of PARCS and MNCP buckling ratios indicates reasonable agreement (less than ~5% difference)

Boundary Conditions	L^2B^2 PARCS	L^2B^2 MCNP	% error wrt MCNP
0 Incoming Current BCs	0.093049	0.089787	3.63
Reflective Top & Bot.	0.051309	0.048935	4.85
Reflective Radial	0.041113	0.041036	0.19
All Reflective Boundaries	0.000000	0.000000	-----

Three Mile Island Unit 1

Background

- During cycles 1 and 2 of Three Mile Island Unit 1 (TMI1 C1-C2), the plant operated with burnable poison rod assemblies (BPRAs) and heavily inserted rod control cluster assembly (RCCA) banks.
- Operating data, core design information, and in-core detector measurements are publicly available in Electric Power Research Institute (EPRI) reports.
  - EPRI NP-1410, Volume 1, "Reactor Core Physics Design and Operating Data for Cycles 1 and 2 of TMI Unit 1 PWR Power Plant," August 1980.
  - EPRI NP-1410, Volume 2: Appendices A and B, "Reactor Core Physics Design and Operating Data for Cycles 1 and 2 of Three Mile Island Unit 1 PWR Power Plant," August 1980.

TMI1 C1 and C2 Operation

- TMI1 Cycle 1 operated with several burnable poison rod assemblies (BPRAs) inserted into assemblies that were not below rod control cluster assembly (RCCA) locations. These include three different loadings of burnable absorber.
- During Cycle 1 the 6th, 7th, and 8th rod banks were inserted.
- The 8th bank is comprised of axial power shaping rods (APSRs) that are part length.
- Part way through Cycle 1, after ~250 effective full power days (EPFDs), the banks were reconfigured so that some shutdown rods became part of the 7th bank and vice-versa.
- At the end of Cycle 1, the BPRAs were withdrawn. No assembly with a BPRA previously inserted was loaded beneath a RCCA in Cycle 2. No additional BPRAs were inserted in Cycle 2.

Description of TMI1 C1-C2 Control Elements

- TMI1 C1-C2 includes three distinct types of control elements: RCCAs, APSRs, and BPRAs.

Rod Type	Absorber Material	Pellet OR [cm]	Cladding	Active Length [cm]
RCCA	AIC	0.498	Stainless Steel	340
APSR	AIC	0.476	Stainless Steel	91.4
BPRA1	1.43 w/o B_4C in Alumina	0.432	Zircaloy	320
BPRA2	1.26 w/o B_4C in Alumina	0.432	Zircaloy	320
BPRA3	1.09 w/o B_4C in Alumina	0.432	Zircaloy	320

Control Rod Banks C1A (First ~250 EFPDs)

					0	0	0	0	0					
			0	0	7	9	4	9	7	0	0			
		0	10	5	10	3	10	3	10	5	10	0		
	0	10	4	11	8	10	6	10	8	11	4	10	0	
	0	5	11	6	11	1	10	1	11	6	11	5	0	
0	7	10	8	11	2	9	2	9	2	11	8	10	7	0
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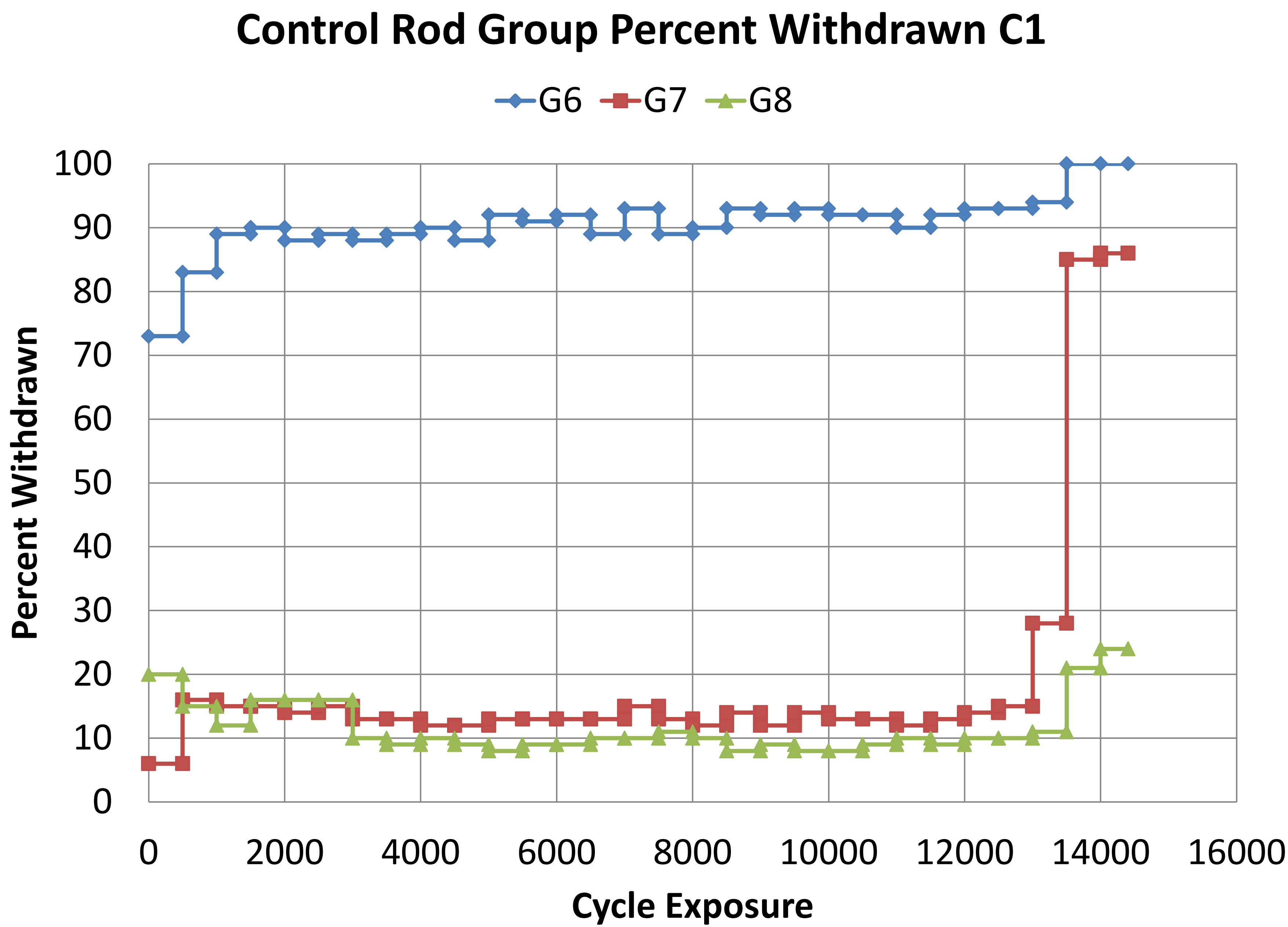
0	4	10	6	10	2	9	7	9	2	10	6	10	4	0
0	9	3	10	1	9	5	9	5	9	1	10	3	9	0
0	7	10	8	11	2	9	2	9	2	11	8	10	7	0
	0	5	11	6	11	1	10	1	11	6	11	5	0	
	0	10	4	11	8	10	6	10	8	11	4	10	0	
		0	10	5	10	3	10	3	10	5	10	0		
			0	0	7	9	4	9	7	0	0			
					0	0	0	0	0					

Legend	
BPRA1	
BPRA2	
BPRA3	
RCCA G6	
RCCA G7	
APSR G8	

Control Rod Banks C1B (After ~250 EFPDs)

					0	0	0	0	0					
			0	0	4	9	7	9	4	0	0			
		0	10	5	10	3	10	3	10	5	10	0		
	0	10	7	11	8	10	6	10	8	11	7	10	0	
	0	5	11	6	11	1	10	1	11	6	11	5	0	
0	4	10	8	11	2	9	2	9	2	11	8	10	4	0
0	9	3	10	1	9	5	9	5	9	1	10	3	9	0
0	7	10	6	10	2	9	7	9	2	10	6	10	7	0
0	9	3	10	1	9	5	9	5	9	1	10	3	9	0
0	4	10	8	11	2	9	2	9	2	11	8	10	4	0
	0	5	11	6	11	1	10	1	11	6	11	5	0	
	0	10	7	11	8	10	6	10	8	11	7	10	0	
		0	10	5	10	3	10	3	10	5	10	0		
			0	0	4	9	7	9	4	0	0			
					0	0	0	0	0					

Legend	
BPRA1	
BPRA2	
BPRA3	
RCCA G6	
RCCA G7	
APSR G8	


Control Rod Group Percent Withdrawn C1
G6
G7
G8
Percent Withdrawn
100
90
80
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
12000
14000
16000
Cycle Exposure

Control Rod Banks C2

					0	0	0	0	0					
			0	0	4	9	5	9	4	0	0			
		0	10	2	10	7	10	7	10	2	10	0		
	0	10	6	11	8	10	3	10	8	11	6	10	0	
	0	2	11	3	11	1	10	1	11	3	11	2	0	
0	4	10	8	11	5	9	6	9	5	11	8	10	4	0
0	9	7	10	1	9	3	9	3	9	1	10	7	9	0
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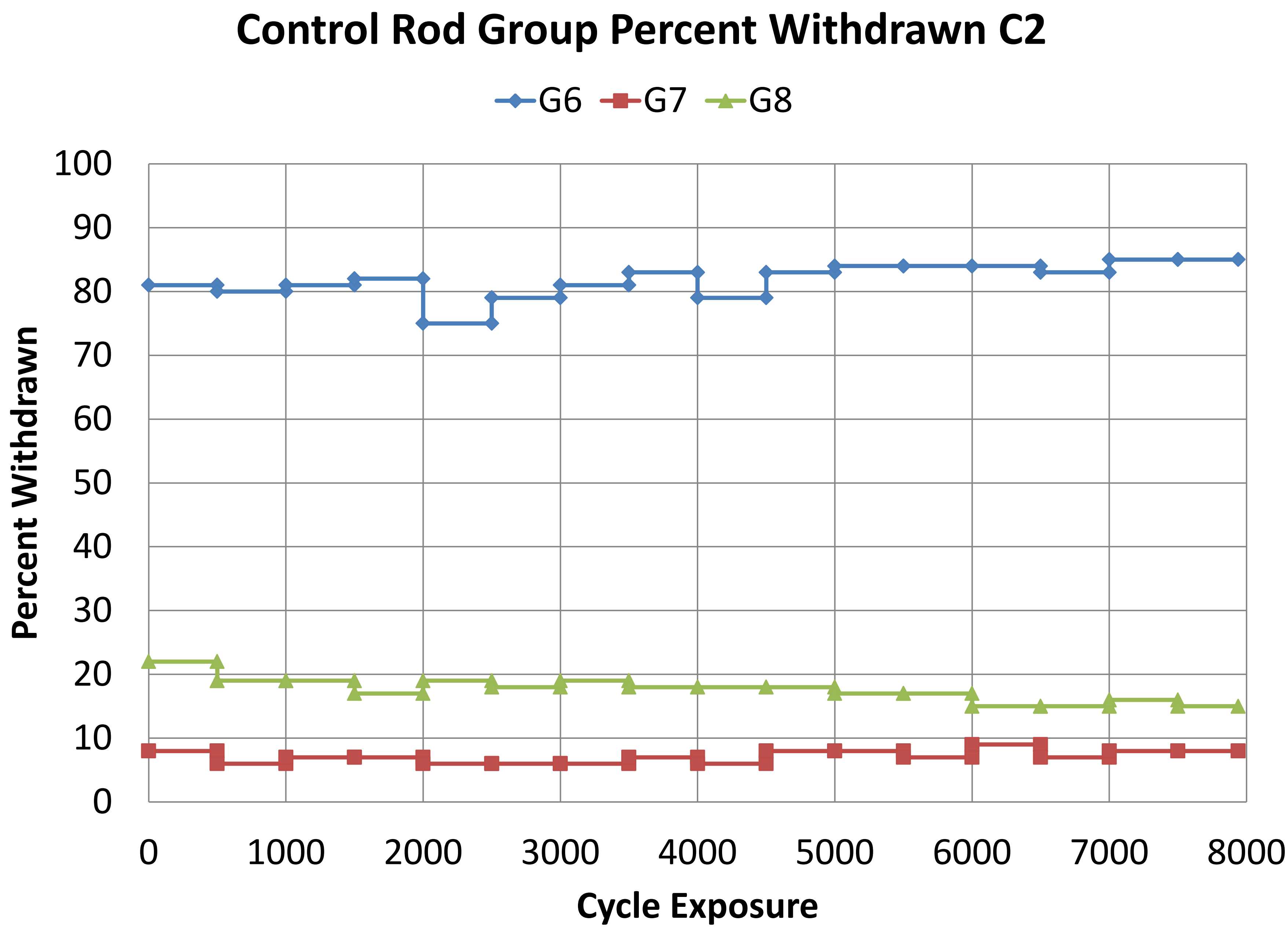
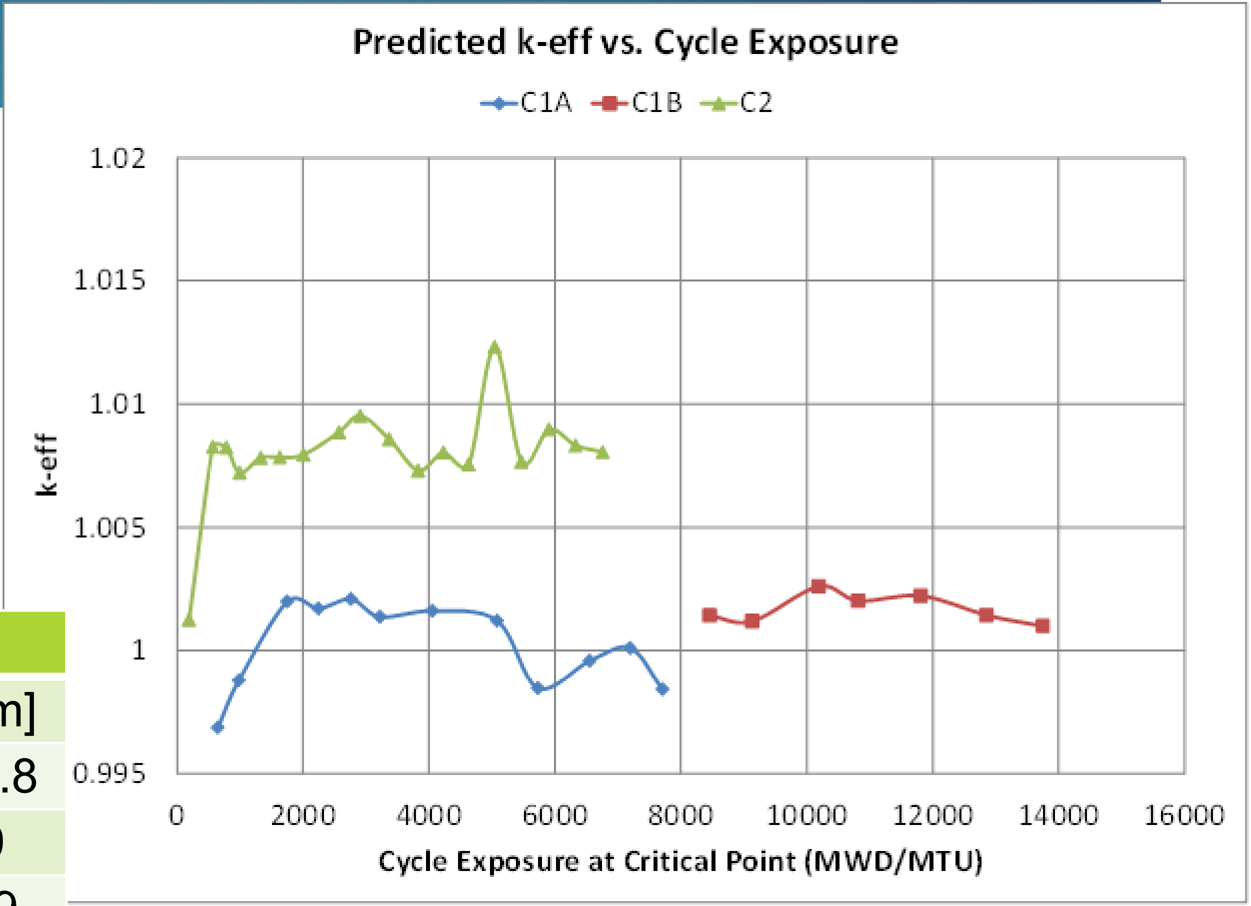
0	9	7	10	1	9	3	9	3	9	1	10	7	9	0
0	4	10	8	11	5	9	6	9	5	11	8	10	4	0
	0	2	11	3	11	1	10	1	11	3	11	2	0	
	0	10	6	11	8	10	3	10	8	11	6	10	0	
		0	10	2	10	7	10	7	10	2	10	0		
			0	0	4	9	5	9	4	0	0			
					0	0	0	0	0					

Legend	
BPRA1	
BPRA2	
BPRA3	
RCCA G6	
RCCA G7	
APSR G8	


Control Rod Group Percent Withdrawn C2
G6
G7
G8
Percent Withdrawn
100
90
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Cycle Exposure

Base Case

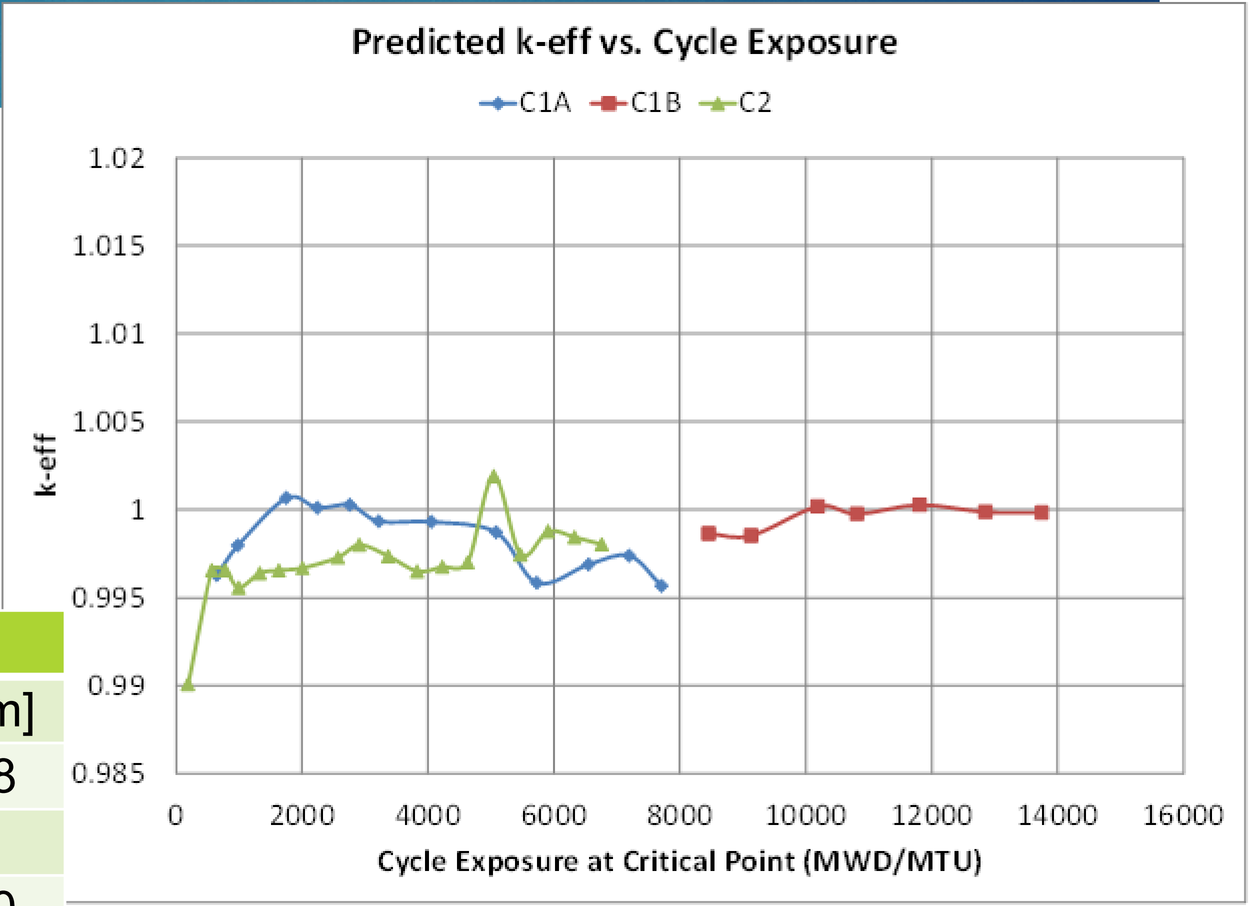
- C1A performance is good, low bias and uncertainty within 200 pcm.
- C1B seems to show a shift in k_{eff} bias.
- C2 shows a large shift in k_{eff} bias to quite a large value (~800pcm).



Case	K-eff Bias	σ
	[pcm]	[pcm]
C1A	18.5	173.8
C1B	170	59
C1	74	159
C2	799	203

No History Tracking (NHT)

- NHT case offers much more consistent performance in terms of k_{eff} bias and uncertainty across both cycles.
- Much smaller magnitude of bias in Cycle 2.



Case	K-eff Bias	σ
	[pcm]	[pcm]
C1A	-179	178
C1B	-41	71
C1	-128	160
C2	-300	221

Hatch Unit 1 Cycles 1-3 (In Progress)

Background

- Hatch Unit 1 Cycles 1-3 fuel design, core design, and operational data including TIP measurements are available in the public domain in a series of EPRI reports (EPRI NP-562 and EPRI NP-2106).
- Three 7X7 fuel types loaded in initial core.
- Second cycle core includes a new fuel type (8X8).
- Third cycle includes another new 8X8 fuel type with a new water rod design.
- Work is in-progress to perform assessment with POLARIS/PARCS – results presented here are for HELIOS lattice physics instead of POLARIS

Hatch Unit 1 Cycle 3 Core

								10	20	30	20	20	20	20	30	20	10								
							20	1	5	1	5	3	3	5	1	5	1	20							
				10	20	10	3	5	3	5	4	5	5	4	5	3	5	3	10	20	10				
			10	1	5	4	5	4	5	2	5	3	3	5	2	5	4	5	4	5	1	10			
		10	1	3	3	5	4	5	3	5	3	5	5	3	5	3	5	4	5	3	3	1	10		
		20	5	3	4	2	5	2	5	2	5	3	3	5	2	5	2	5	2	4	3	5	20		
		10	4	5	2	5	3	4	1	4	2	4	4	2	4	1	4	3	5	2	5	4	10		
	20	3	5	4	5	3	5	2	5	3	5	1	1	5	3	5	2	5	3	5	4	5	3	20	
10	1	5	4	5	2	4	2	4	2	4	1	4	4	1	4	2	4	2	4	2	5	4	5	1	10
20	5	3	5	3	5	1	5	2	5	1	5	1	1	5	1	5	2	5	1	5	3	5	3	5	20
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20	5	4	5	3	5	2	5	1	5	1	5	1	1	5	1	5	1	5	2	5	3	5	4	5	20
20	3	5	3	5	3	4	1	4	1	4	1	2	2	1	4	1	4	1	4	3	5	3	5	3	20
20	3	5	3	5	3	4	1	4	1	4	1	2	2	1	4	1	4	1	4	3	5	3	5	3	20
20	5	4	5	3	5	2	5	1	5	1	5	1	1	5	1	5	1	5	2	5	3	5	4	5	20
30	1	5	2	5	2	4	3	4	1	4	1	4	4	1	4	1	4	3	4	2	5	2	5	1	30
20	5	3	5	3	5	1	5	2	5	1	5	1	1	5	1	5	2	5	1	5	3	5	3	5	20
10	1	5	4	5	2	4	2	4	2	4	1	4	4	1	4	2	4	2	4	2	5	4	5	1	10
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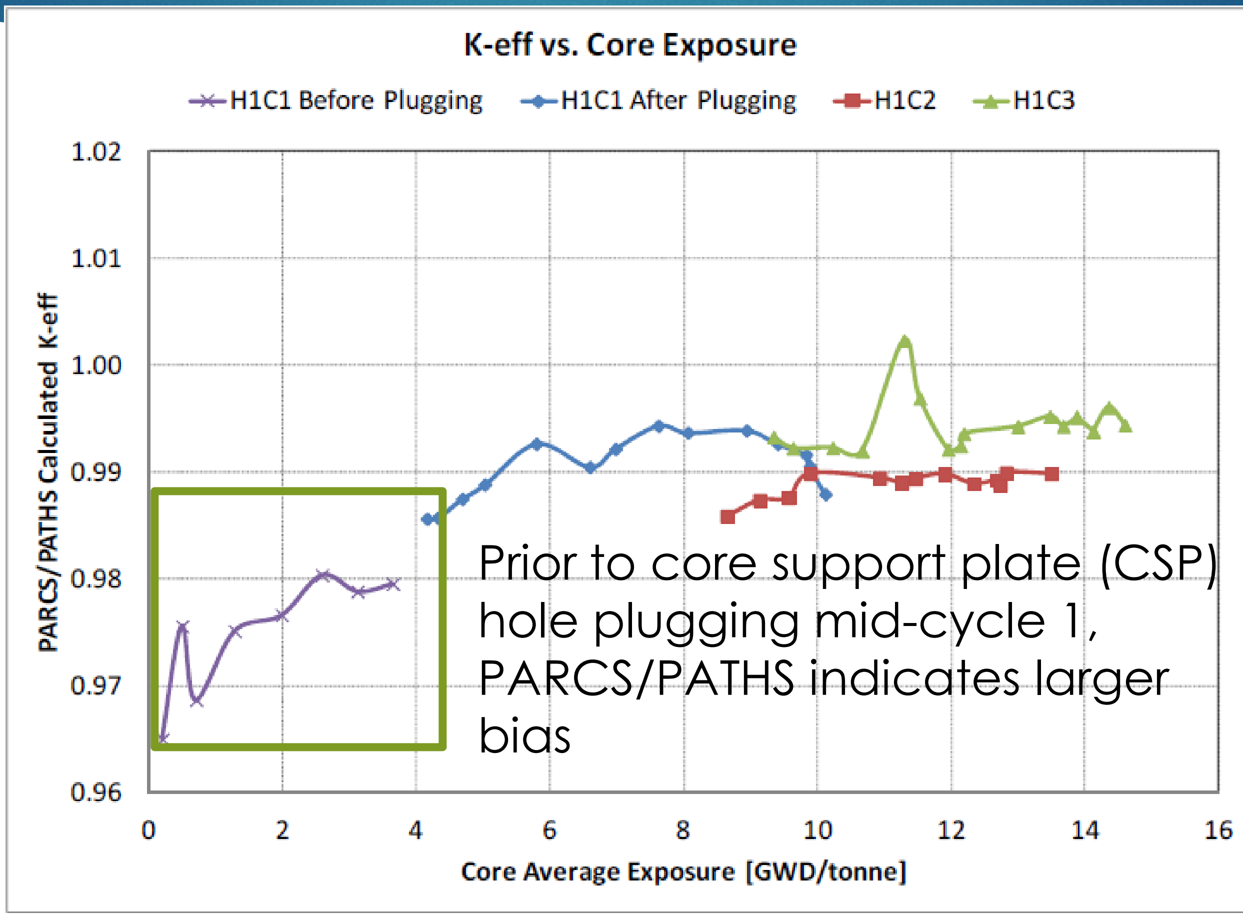
		20	5	3	4	2	5	2	5	2	5	3	3	5	2	5	2	5	2	4	3	5	20		
		10	1	3	3	5	4	5	3	5	3	5	5	3	5	3	5	4	5	3	3	1	10		
			10	1	5	4	5	4	5	2	5	3	3	5	2	5	4	5	4	5	1	10			
				10	20	10	3	5	3	5	4	5	5	4	5	3	5	3	10	20	10				
							20	1	5	1	5	3	3	5	1	5	1	20							
								10	20	30	20	20	20	20	30	20	10								

Figure based on EPRI NP-2106

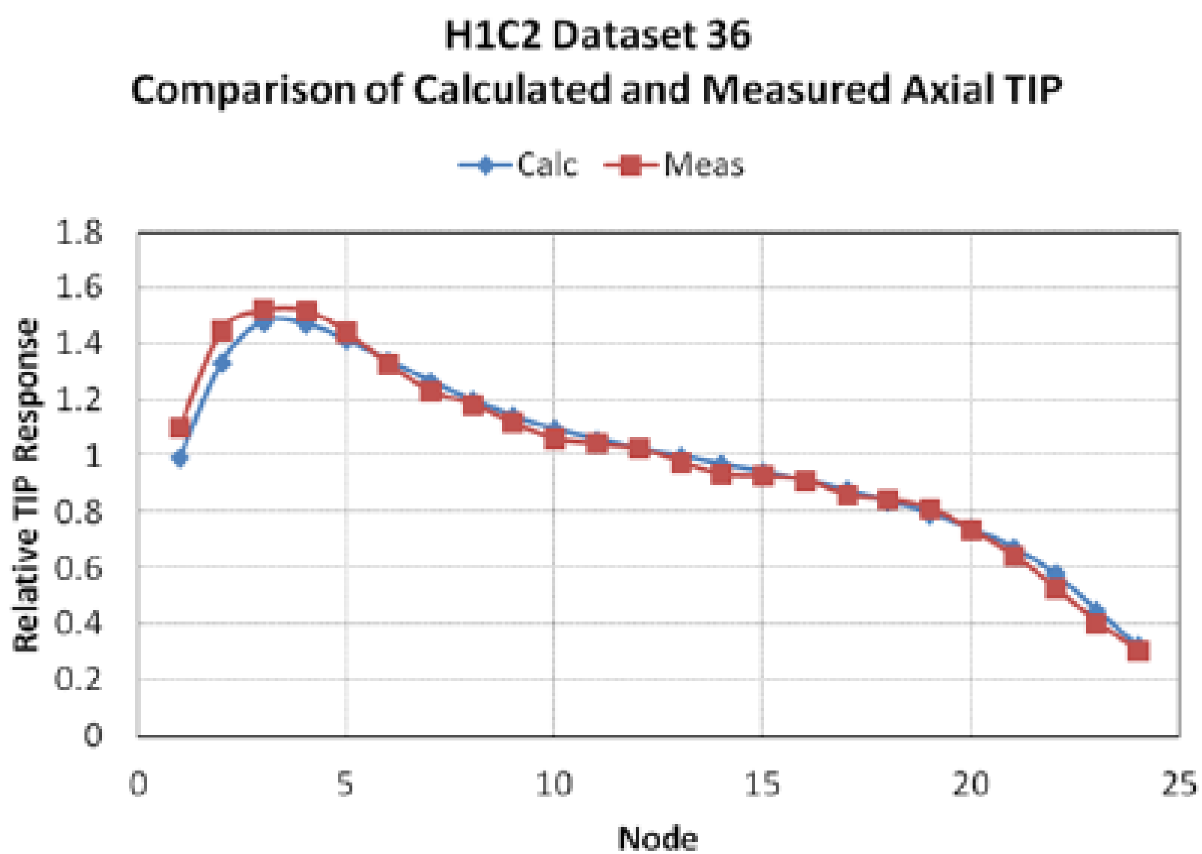
Sample HELIOS/PARCS/PATHS Multiplication Factor Calculations



Sample HELIOS/PARCS/PATHS Axial Shape Comparison (H1C2 Near End of Cycle)

Blue is PARCS/PATHS calculated average axial TIP response.

Red is the average axial TIP response from EPRI NP-2106.



Conclusions

- POLARIS/PARCS has been validated for application to small modular reactor cores.
- The TMI1 C1-C2 assessment indicates that there are some issues with calculating the effects of rodded-history. This is currently being addressed by PARCS methods improvements.
- POLARIS/PARCS is currently being assessed against the H1 C1-C3 data to determine the applicability to BWR cores.

References

- Thurston, C. and Yarsky, P., "Validation of POLARIS, PARCS, and TRACE against DIMPLE S01A Benchmark," Proc. PHYSOR2016, May 2016.
- Skarda, R., Yarsky, P., and Boyle, T., "Validation of POLARIS and PARCS against Otto Hahn Second Core Zero Power Experiment Benchmark," Proc. PHYSOR2016, May 2016.
- Yarsky, P., "Use of POLARIS and PARCS to Predict Cycle Depletion for Three Mile Island Unit One Cycles One and Two," Proc. PHYSOR2016, May 2016.
- Yarsky, P., Ward, A., Xu, Y., Downar, T., and Hudson, N., "The Application of PARCS/PATHS to Depletion of Hatch Cycles 1-3." *Proc. NURETH-15*, May 2013.

References

- Jesse, M., Jarrell, W., Wiesselquist, M., Williams, K., Kim, T., and Evans, T., "POLARIS- 2D Light Water Reactor Lattice Physics Module."
- T. Downar, et al., "PARCS: Purdue Advanced Reactor Core Simulator," Proceedings of Reactor Physics Topical Meeting (PHYSOR 2002), Seoul, Korea, October 7-10, 2002 (2002).
- B. Collins, et al. "PATHS: a Steady State Two-Phase Thermalhydraulics Solver for PARCS Depletion," Proceedings of NURETH-14, Toronto, Canada, September 25-30, 2011 (2011).

References

- W. A. V. Brown, W. N. Fox, D. J. Skillings, C. F. George, and G. D. Burholt, "Measurements of Material Buckling and Detailed Reaction Rates in a Series of Low Enrichment UO2 Fueled Cores Moderated by Light Water", AEEW- R 502 (1967).
- A. D. Knipe, "Specification of the DIMPLE S01 Benchmark Assemblies", AEA TSD 0375, JEF/DOC-504, OECD NEA Data Bank, Paris (1994).
- NEA/INS/DOE(2006)1, "Light Water Moderated and Reflected Low Enriched Uranium (3 wt% 235U) Dioxide Rod Lattices DIMPLE S01"DIMPLE-LWR-EXP-001,
- CRIT-BUCKSPEC-REAC-COEF-RRATE ", March 31, 2006 (ML14259A284)
- Rogan, P., Ravnik, M., Snoj, L., Lengar,I., "PWR Type UO2 Fuel Rods With Enrichments of 3.5 and 6.6 WT% With Burnable Absorber ("Otto Hahn" Nuclear Ship Program, Second Core)," Jozef Stefan Institute, NEA/NSC/DOC/(95)03 IV, Volume IV, LEUCOMP-THERM- 081, September 30, 2007.

References

- EPRI NP-1410, Volume 1, "Reactor Core Physics Design and Operating Data for Cycles 1 and 2 of TMI Unit 1 PWR Power Plant," August 1980.
- EPRI NP-1410, Volume 2: Appendices A and B, "Reactor Core Physics Design and Operating Data for Cycles 1 and 2 of Three Mile Island Unit 1 PWR Power Plant," August 1980.
- EPRI NP-562, "Core Design and Operating Data for Cycle 1 of Hatch 1," January 1979.
- EPRI NP-2106, "Core Design and Operating Data for Cycles 2 and 3 of Hatch 1," February 1984.
- EPRI NP-1235, "Core Performance Benchmarking Edwin I. Hatch Nuclear Plant Unit 1, Cycle 1," November 1979.

Backup Slides

DIMPLE

Regulatory Purpose

- The goal is to apply PARCS to confirmatory analysis supporting regulatory decision making.
- DIMPLE S01A was selected for PARCS validation to support application to analysis of small modular reactors (SMRs) due to larger leakage fraction.
- The current work provides comparisons of code predictions to critical measurements of radial and axial buckling to infer capability to compute leakage for SMRs.

Background

- The DIMPLE facility, located in the UK, was originally constructed to study heavy-water moderated lattices in 1960s, but was repurposed for light water in 1983. S01A was the first of the series.
- The Facility consisted of a large aluminum primary vessel where a wide range of experimental core arrangements could be easily assembled. The reactor control was via varying water level height, allowing criticality experiments without presence of control media.
- Core fuel pins were arranged in an open pool at atmospheric conditions.

Previous Assessments of Methodology

- Applicability for neutronic assessments are based on a number of recent studies with PARCS coupled with TRACE or RELAP5.
- POLARIS is a recent SCALE sequence that performs lattice physics calculations for LWR lattices (replaces TRITON).
- Recent benchmarks to plant data include:
  - Ringhals-3 PWR Cycles 10, 19, and 22
  - St. Laurent PWR Cycle 10
  - Trillo PWR Feedwater Transient (yr 2000)
  - Hatch BWR Cycles 1, 2 and 3.

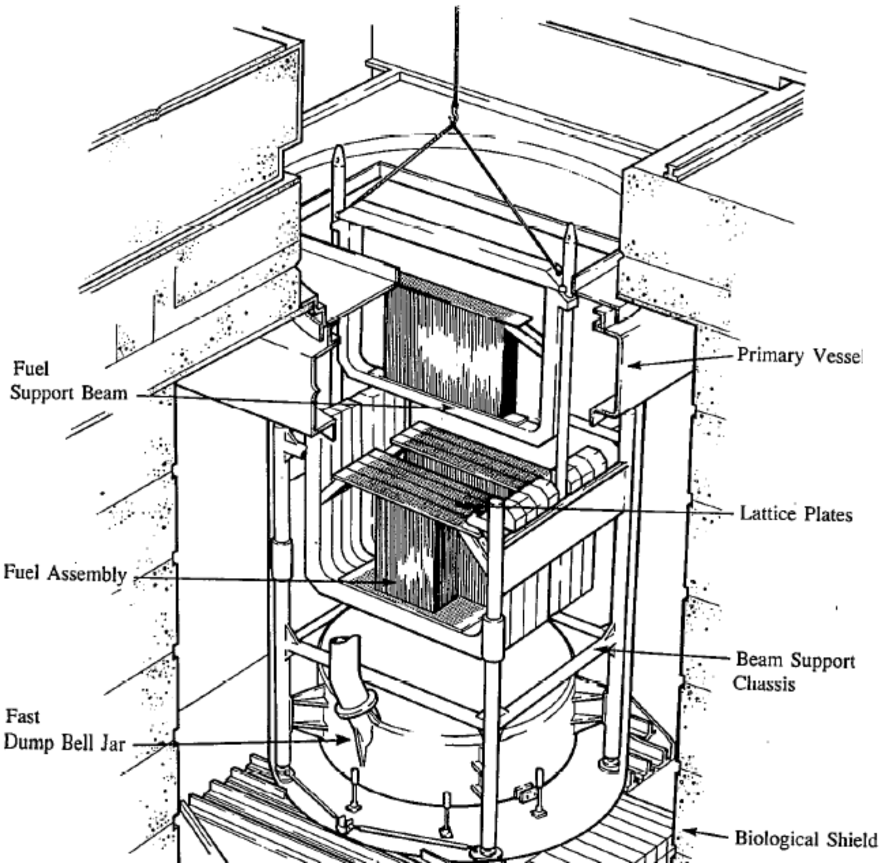
Previous Assessments of Methodology (continued)

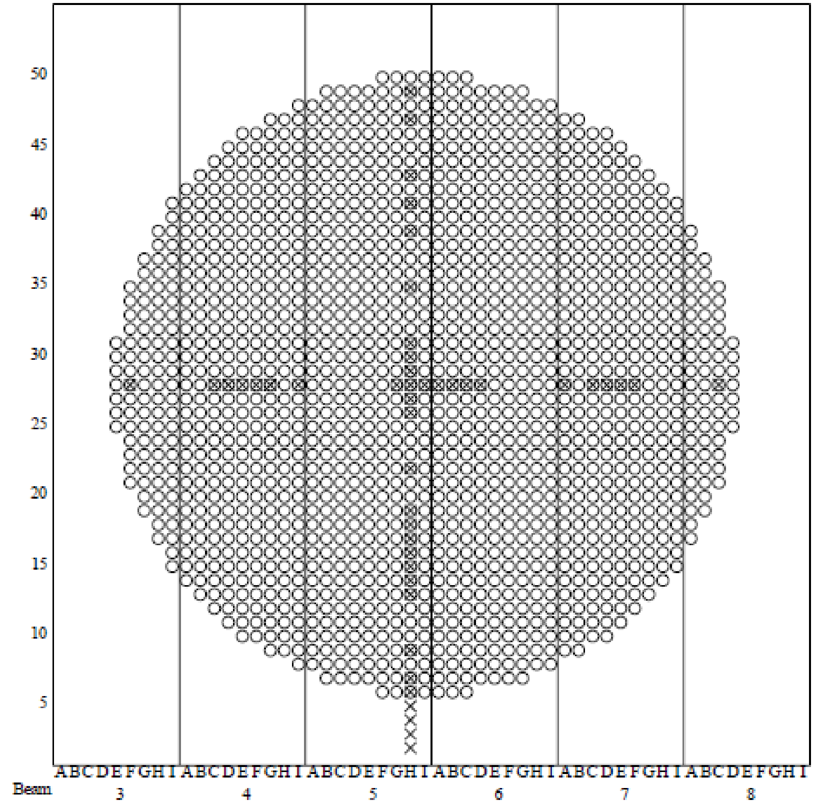
- Plant benchmarks indicated that PARCS is capable of predicting axial and radial power profiles in PWRs
- Tendency was noted for BWR applications to show lower multiplication factor results which appear attributable to density changes, i.e., voiding in the core.

Assembly Test S01A Configuration

- The primary vessel was 2.6 m in diameter and 4 m high.
- Test S01A was a high leakage core comprised of 1565 low enriched uranium (3%) dioxide fuel pins arranged on a square pitch.
- The core support included a lower support assembly with dowels holding each pin individually and an upper drilled support plate. The support system included 6 changeable mounting plates.
- A select number of fuel pins contained 0.25mm reaction rate measurement foils inserted in between pellets of one of three types: U-235 (F5), Pu-239 (F9), and U-238 (F8 and C8) .
- The reaction-rate foils were located in two pins in the center for axial measurements, and at axial power center (~25cm from bottom of fuel) in N-S and W-E orientations for radial measurements.
- Test S01A core rods were subjected to a critical height of ~50 cm of water above the base of the active fuel (~69cm).

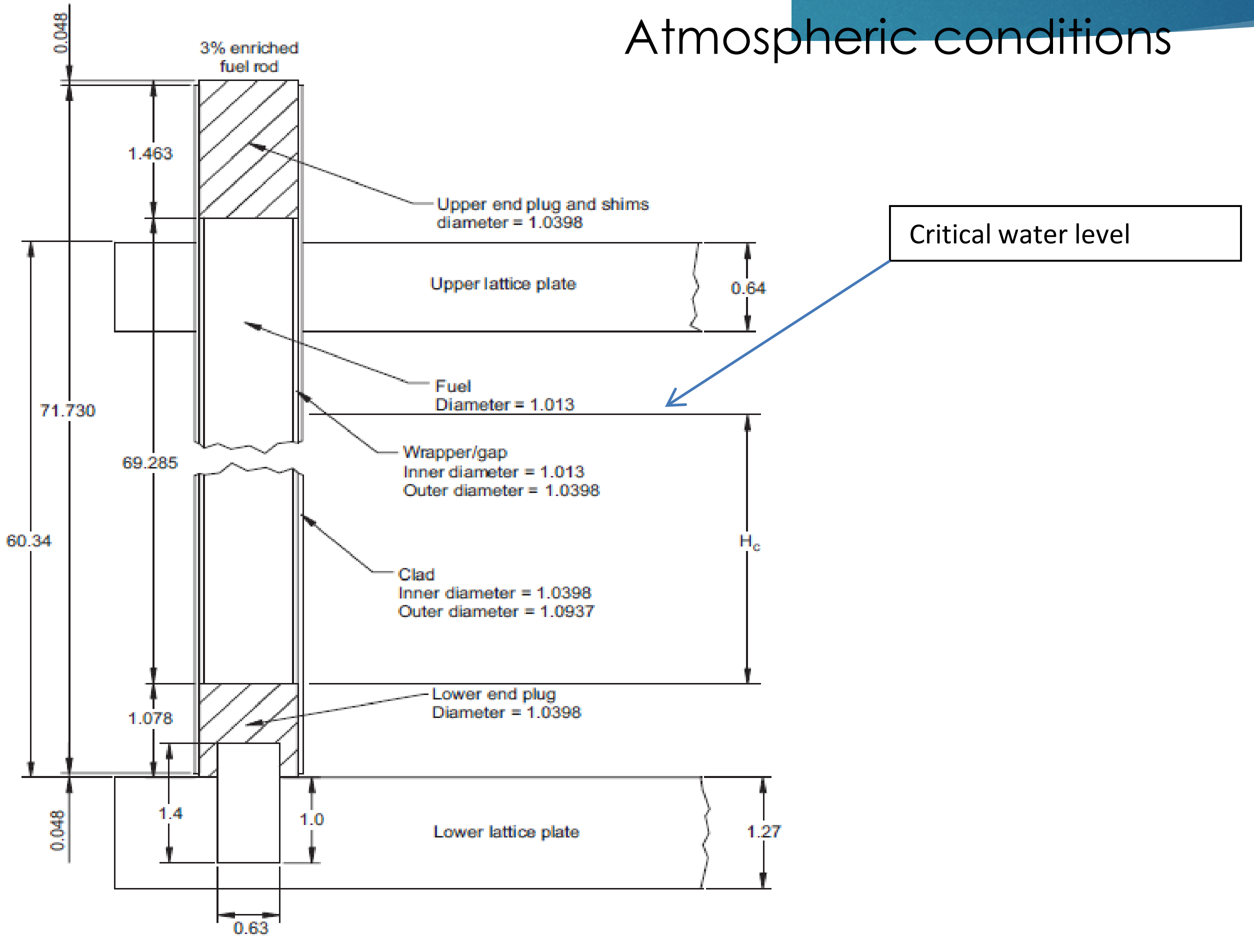
Facility and Test S01A Configuration





Test S01A Fuel Pin Setup (axial view)

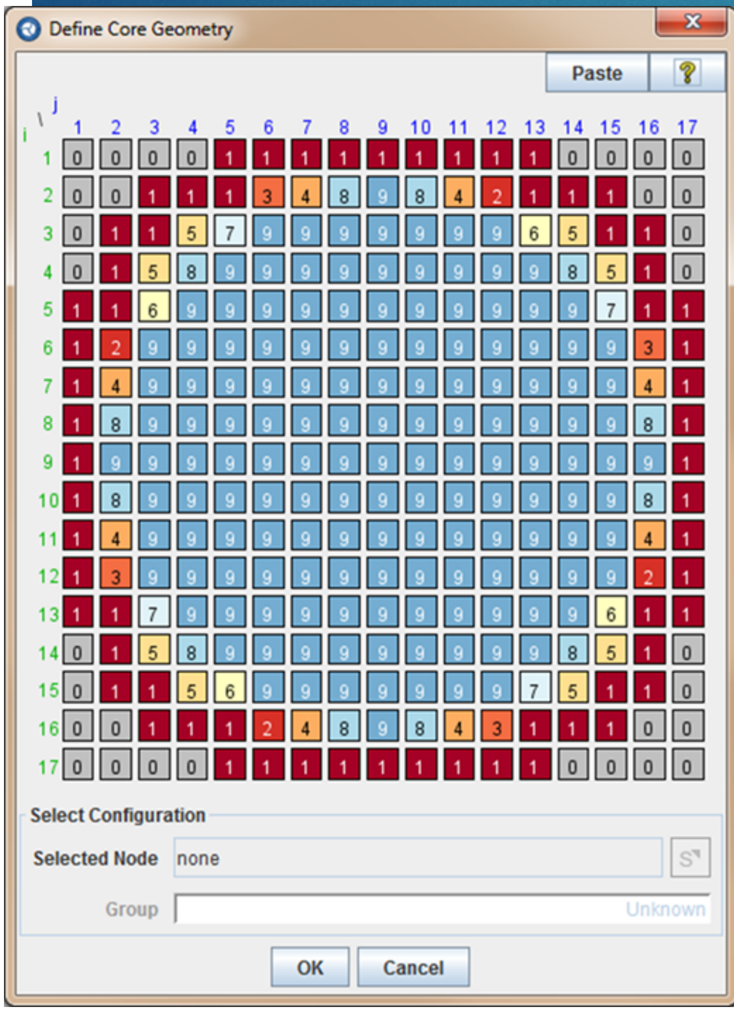
Atmospheric conditions



TRACE/PARCS modeling for DIMPLE S01A

- POLARIS used to perform lattice physics calculations.
- GENPMAXS used to convert to PMAXS format.
- PARCS used to construct a 3D geometric representation of the core, and its computational nodes are interfaced with TRACE via a MAPTAB file.
- A 3x3 pin array arrangement was used to define the radial core layout.
- Layout resulted in 193 assembly arrays configured with 149 full arrays with 9 pins, and the remaining partially filled arrays.

PARCS Layout Configuration



Where:
[9] – Full array
[2-8] – Partial filled array
[1] – radial reflector

POLARIS/PARCS inputs

- Fuel and reflector lattices computed with POLARIS. Branching was added for density since fuel is exposed to both water and air. No burn up history or fuel temperature branching were needed.
- Eleven (11) lattice configurations needed to physically represent the DIMPLE S01A core in PARCS.
- All 3 PARCS boundary condition types are modeled, zero flux, zero incoming current, and reflective. Neither zero flux, nor zero incoming current conditions are ideal because of expected relatively large thermal fluxes and return currents a short distance from outer row of fuel pins.

TRACE inputs

- The core is modeled as VESSEL with two fluid nodes radially, one for fuel region and one for reflector, and axially with 10 nodes in active fuel region.
- Explicit coupling between PARCS and TRACE is defined in a MAPTAB file, allowing calculated power in PARCS to be reflected in corresponding heat structures in TRACE.
- The TRACE model is relatively simple with a FILL and BREAK for the input and outlet boundaries. The flow is stagnant and the water level is set to the test condition. Level control is not needed.

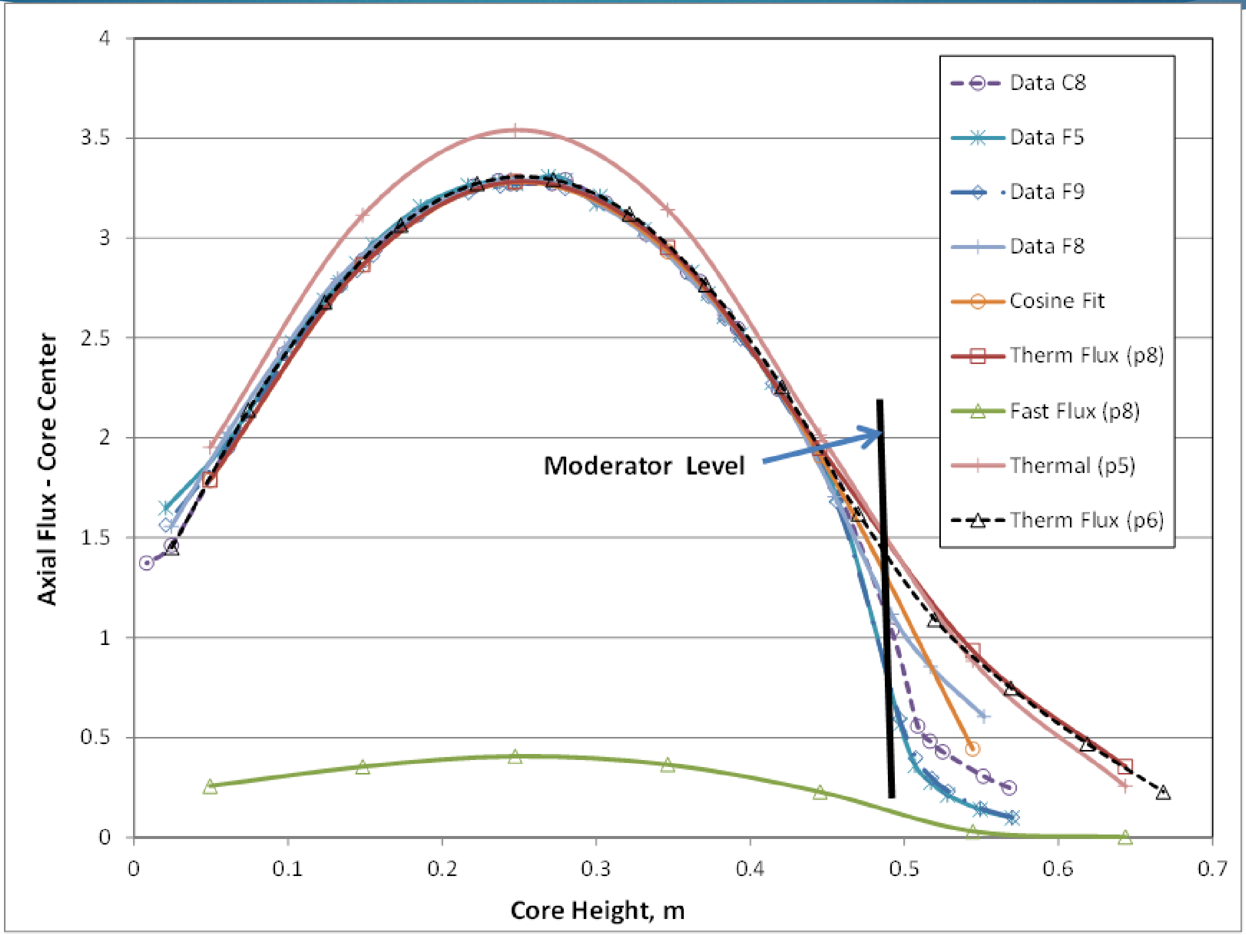
PARCS results

- PARCS results for cases run are:

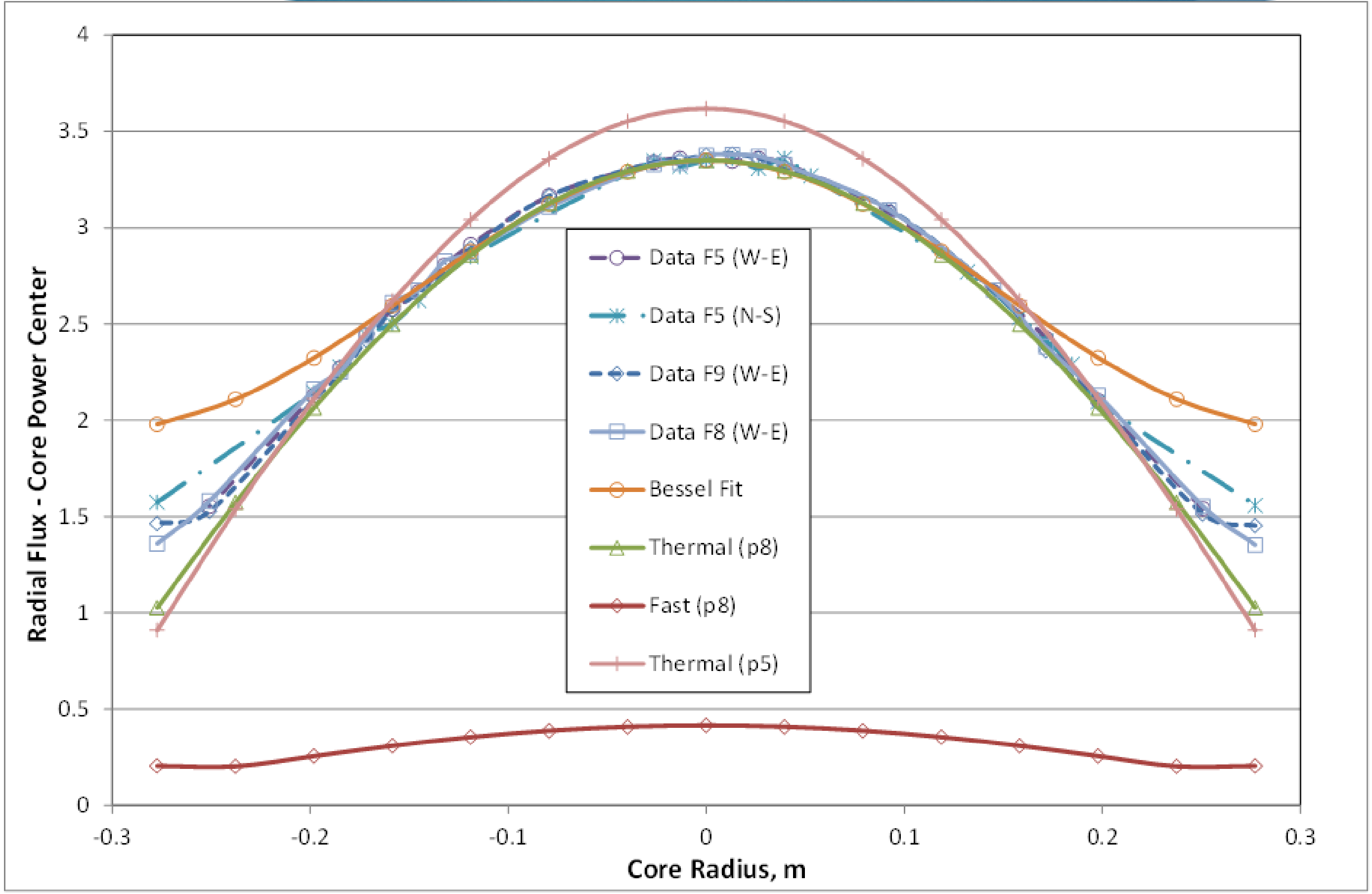
Run	PARCS Boundary Condition	#Core Nodes	Peak Radial Power	Peak Axial Power	Keff
p6	zero current	14	1.697	1.741	0.9908
p5	zero flux	7	1.820	1.755	0.9767
p8	**zero current**	**7**	**1.697**	**1.735**	**0.9910**
p9	reflective	7	1.231	1.547	1.0675

Note: p6 indicates axial noding is adequate

PARCS results



PARCS results



PARCS results

- Axial and Radial Buckling results are:

Run	PARCS Boundary Condition	Keff	**Buckling Computation ($-m^2$) (ax/rad)**	**Percent Difference (%)**
p5	zero flux	0.9767	**24.7 / 47.0**	**2.5 / 13.3**
p8	**zero current**	**0.9910**	**24.2 / 43.3**	**0.4 / 4.3**
Test	-	1.0000	**24.1 / 41.5**	**-**

Conclusions and Future Work

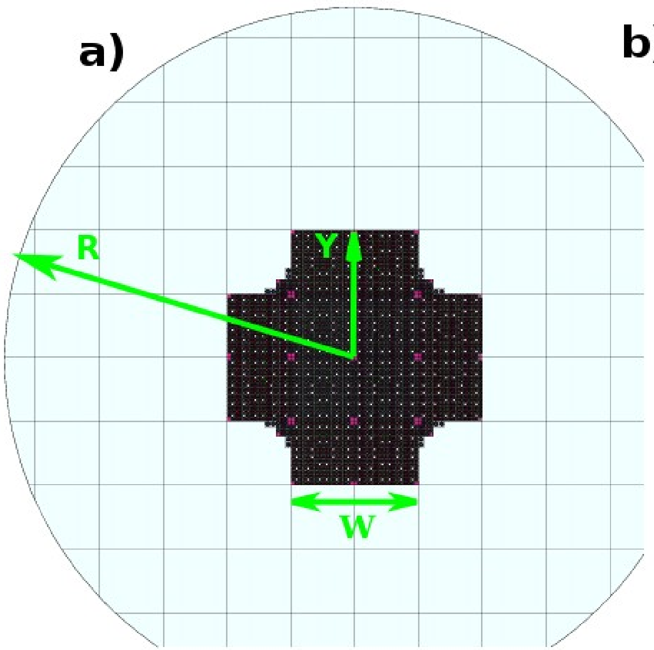
- PARCS axial and radial power profiles showed reasonably good overall agreement to DIMPLE S01A.
- The axial buckling results are much better than radial.
- POLARIS/PARCS predicted Keff is low but consistent with other benchmark where there is large density gradient in moderator, i.e., BWRs.
- Future work:
  - Rerun with latest release of POLARIS,
  - Consider different treatment of radial reflectors

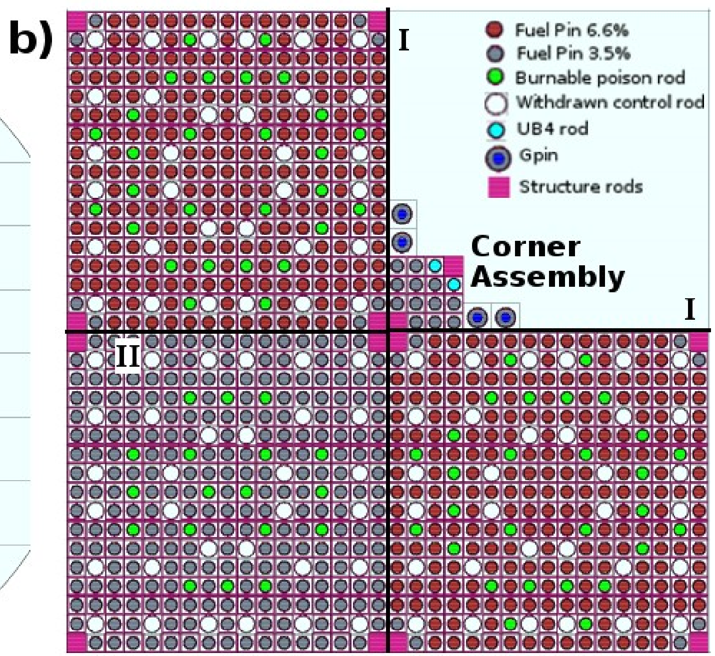
Otto Hahn

Regulatory Purpose

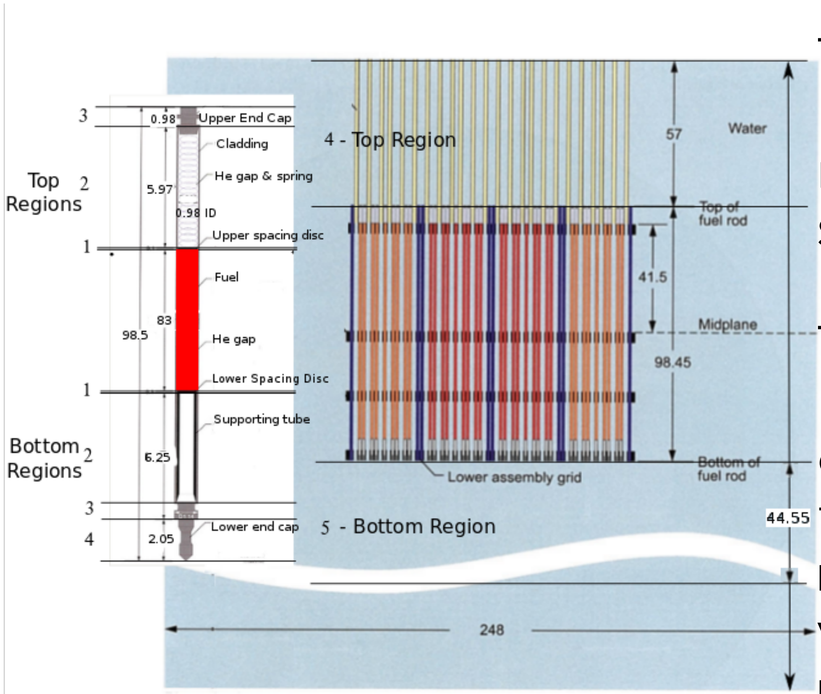
- The goal is to apply POLARIS and PARCS for confirmatory analysis supporting regulatory decision making.
- The NRC anticipates licensing submittals for small modular reactors (SMRs).
- Current work is aimed at assessing the capability of POLARIS and PARCS to simulate small cores.
- The Otto Hahn (OH) second core zero power experiment was identified as a test that could be used to examine the applicability of POLARIS/PARCS to a SMR core because of its small size, small number of assemblies, and light-water-reflected boundaries.

Core Description





Fuel Rod and Core Description



(Modified from Rogan et al., 2007)

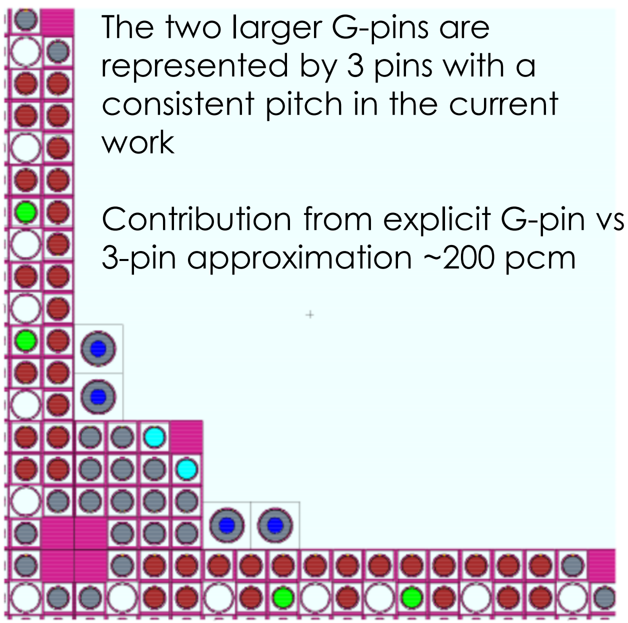
The core top and bottom reflectors are modeled with 4 and 5 slabs, respectively.

The core is surrounded by light water in a cylindrical reflector tank. The radial reflector consists of the water outside the core region.

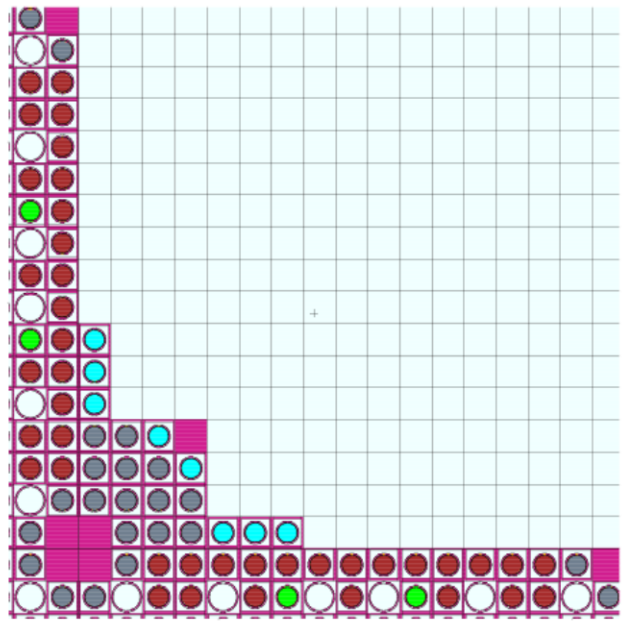
Corner Assembly Representation

The two larger G-pins are represented by 3 pins with a consistent pitch in the current work

Contribution from explicit G-pin vs. 3-pin approximation ~200 pcm

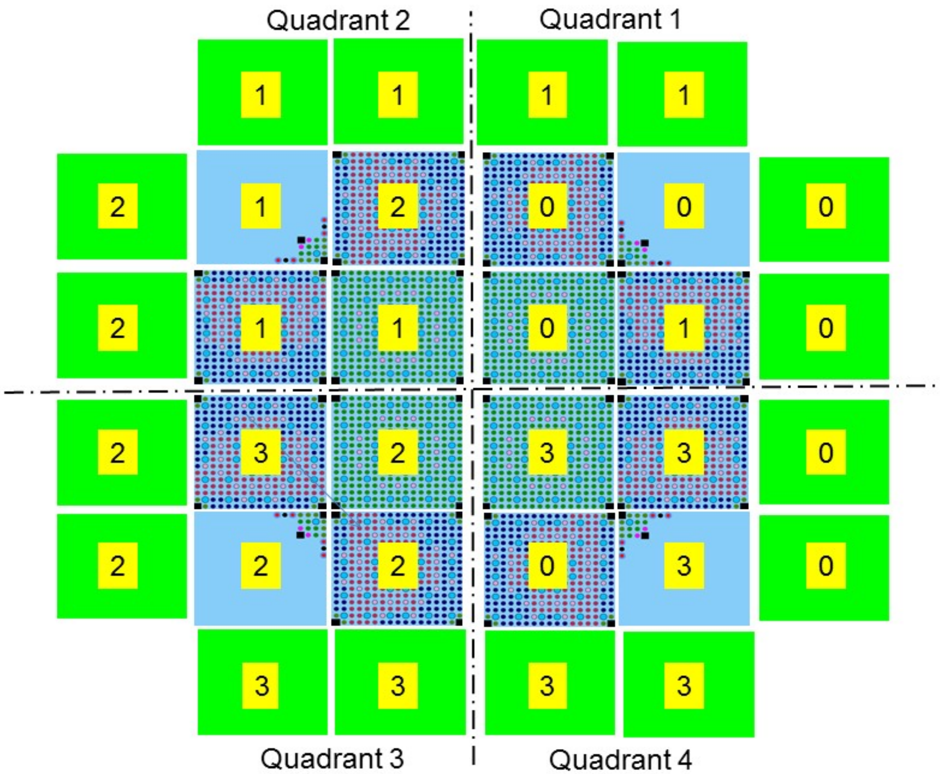


a) MCNP model of corner lattice with oversized UO_2-B_4C Fuel Pins



b) MCNP model of corner lattice with three pin representation of oversized UO_2-B_4C Fuel Pins

PARCS Model



- A two-group model, typical for light water reactor analysis, was used.
- The core consists of 16 radial nodes with three unique PMAX files to represent the core nuclear nodes. Assembly rotation is used.
- The reflectors are modeled with three unique PMAX files (top, bottom, and radial).

PARCS k_{eff} Results

Run	Boundary Conditions	XS library	keff (PARCS)
p1	0 Incoming Current	P, C-C	0.99088
p2	Top & Bot Reflective	P, C-C	1.03022
p3	Radially Reflective	P, C-C	1.04031
p4	All BCs Reflective	P, C-C	1.08308
p5§	0 Incoming Current	P	0.99169
p6	0 Incoming Current	C	0.99964
p7	0 Incoming Current No Corner Lattices	P	0.98637

§Cross-section libraries for corner assemblies generated with POLARIS for geometry and conditions generally outside POLARIS's range of applicability.

PARCS Results Summary

- POLARIS/PARCS with CASMO5 Corner Assemblies (p1 case) k_{eff} is low 0.99088
- CASMO5/PARCS (p6 case) compares well with experiment; k_{eff} is 0.99964, but this is likely an over-prediction because of the G-pin vs. 3-pin approximation.
- Corner assemblies contribute ~1300 pcm. Difference between using CASMO5 MxN approach vs. POLARIS is ~80 pcm.

MCNP k_{eff} Results

Run	Boundary Conditions	Bottom Supports	Corner G-pin approx	keff (MCNP)	Std Dev MCNP
m1	0 Incoming Current	included	3 pin approx.	0.99447	0.00060
m2	Top & Bot Reflective	included	3 pin approx.	1.03320	0.00052
m3	Radially Reflective	included	3 pin approx.	1.04104	0.00056
m4	All BCs Reflective	included	3 pin approx.	1.08376	0.00054
m5	0 Incoming Current	included	2 pin actual	0.99686	0.00085
m6	0 Incoming Current	excluded	3 pin approx.	0.99308	0.00059
m7	0 Incoming Current No Corner Lattices	included	-------	0.99185	0.00083

Analysis of Results and Comparison to Experiment

- Experimental uncertainty is ~510 pcm.
- MCNP (m5 case) is 314 pcm low, but within the uncertainty.
- 3-pin MCNP (m1 case) is 553 pcm low (outside of the uncertainty) but this is because of the contribution of the approximation of the G-pins.
- POLARICS/PARCS result (p1 case), corrected for G-pin vs. 3-pin, is 0.99327; or 673 pcm low. This result is slightly outside the uncertainty range.
- CASMO5/PARCS result (p6 case), corrected for G-pin vs. 3-pin, is 1.00203; or 203 pcm high. This is inside the uncertainty range.

Axial and Radial Buckling

- Buckling is approximated by calculation of the worth of leakage (total, radial, and axial). The error is approximated by comparison of the PARCS results to MCNP results on the basis of calculating the reactivity effect of leakage:

$$Error = \frac{(L^2B^2)_{PARCS}}{(L^2B^2)_{MCNP}} - 1 \approx \frac{(B^2)_{PARCS}}{(B^2)_{MCNP}} - 1$$

Buckling Results

Comparison of PARCS and MNCP buckling ratios indicates reasonable agreement (less than ~5% difference)

Boundary Conditions	L^2B^2 **PARCS**	L^2B^2 **MCNP**	**% error wrt MCNP**
0 Incoming Current BCs	0.093049	0.089787	3.63
Reflective Top & Bot.	0.051309	0.048935	4.85
Reflective Radial	0.041113	0.041036	0.19
All Reflective Boundaries	0.000000	0.000000	-----

Conclusions

- An assessment of the PARCS/POLARIS models has been carried out against the Otto Hahn zero power second core experiment.
- The PARCS/POLARIS k_{eff} was ~900 pcm lower than the experiment and benchmark result. Applying the ~240 pcm approximation correction improves agreement with the benchmark. However, results remained outside the estimated benchmark uncertainty (510 pcm).
- The results of the current benchmark are fairly reasonable and similar biases have been observed in other PARCS assessments. Therefore, the staff has concluded that PARCS can be used to analyze SMR cores.

Future Work

- At present, POLARIS is not intended for modeling non-square lattices, differing pin pitches, or significantly differing lattice boundary flux conditions, all of which are present in the corner elements of the OH core.
- Future POLARIS capabilities might include:
  - the ability to perform MxN lattice calculations, which may improve PARCS/POLARIS model accuracy especially for small-sized cores proposed for small modular reactors, and
  - the capability to model fuel assemblies containing oversized fuel pins or pin pitches of different sizes, which would improve fidelity and accuracy of OH-type models.

TMI1 C1-C2

Regulatory Purpose

- The goal is to apply PARCS for confirmatory analysis supporting regulatory decision making.
- Control rod history effects were identified as a phenomenon lacking in existing PARCS assessment.
- Current work is aimed at assessing the capability of PARCS to simulate pressurized water reactor depletion problems with heavy control rod insertion.

Background

- During cycles 1 and 2 of Three Mile Island Unit 1 (TMI1 C1-C2), the plant operated with burnable poison rod assemblies (BPRAs) and heavily inserted rod control cluster assembly (RCCA) banks.
- Operating data, core design information, and in-core detector measurements are publicly available in Electric Power Research Institute (EPRI) reports.
  - EPRI NP-1410, Volume 1, "Reactor Core Physics Design and Operating Data for Cycles 1 and 2 of TMI Unit 1 PWR Power Plant," August 1980.
  - EPRI NP-1410, Volume 2: Appendices A and B, "Reactor Core Physics Design and Operating Data for Cycles 1 and 2 of Three Mile Island Unit 1 PWR Power Plant," August 1980.

TMI1 C1 and C2 Operation

- TMI1 Cycle 1 operated with several burnable poison rod assemblies (BPRAs) inserted into assemblies that were not below rod control cluster assembly (RCCA) locations. These include three different loadings of burnable absorber.
- During Cycle 1 the 6^{th}, 7^{th}, and 8^{th} rod banks were inserted.
- The 8^{th} bank is comprised of axial power shaping rods (APSRs) that are part length.
- Part way through Cycle 1, after ~250 effective full power days (EPFDs), the banks were reconfigured so that some shutdown rods became part of the 7^{th} bank and vice-versa.
- At the end of Cycle 1, the BPRAs were withdrawn. No assembly with a BPRA previously inserted was loaded beneath a RCCA in Cycle 2. No additional BPRAs were inserted in Cycle 2.

Description of TMI1 C1-C2 Control Elements

- TMI1 C1-C2 includes three distinct types of control elements: RCCAs, APSRs, and BPRAs.

Rod Type	Absorber Material	Pellet OR [cm]	Cladding	Active Length [cm]
RCCA	AIC	0.498	Stainless Steel	340
APSR	AIC	0.476	Stainless Steel	91.4
BPRA1	1.43 w/o B_4C in Alumina	0.432	Zircaloy	320
BPRA2	1.26 w/o B_4C in Alumina	0.432	Zircaloy	320
BPRA3	1.09 w/o B_4C in Alumina	0.432	Zircaloy	320

Control Rod Banks C1A (First ~250 EFPDs)

					0	0	0	0	0					
			0	0	7	9	4	9	7	0	0			
		0	10	5	10	3	10	3	10	5	10	0		
	0	10	4	11	8	10	6	10	8	11	4	10	0	
	0	5	11	6	11	1	10	1	11	6	11	5	0	
0	7	10	8	11	2	9	2	9	2	11	8	10	7	0
0	9	3	10	1	9	5	9	5	9	1	10	3	9	0
0	4	10	6	10	2	9	7	9	2	10	6	10	4	0
0	9	3	10	1	9	5	9	5	9	1	10	3	9	0
0	7	10	8	11	2	9	2	9	2	11	8	10	7	0
	0	5	11	6	11	1	10	1	11	6	11	5	0	
	0	10	4	11	8	10	6	10	8	11	4	10	0	
		0	10	5	10	3	10	3	10	5	10	0		
			0	0	7	9	4	9	7	0	0			
					0	0	0	0	0					

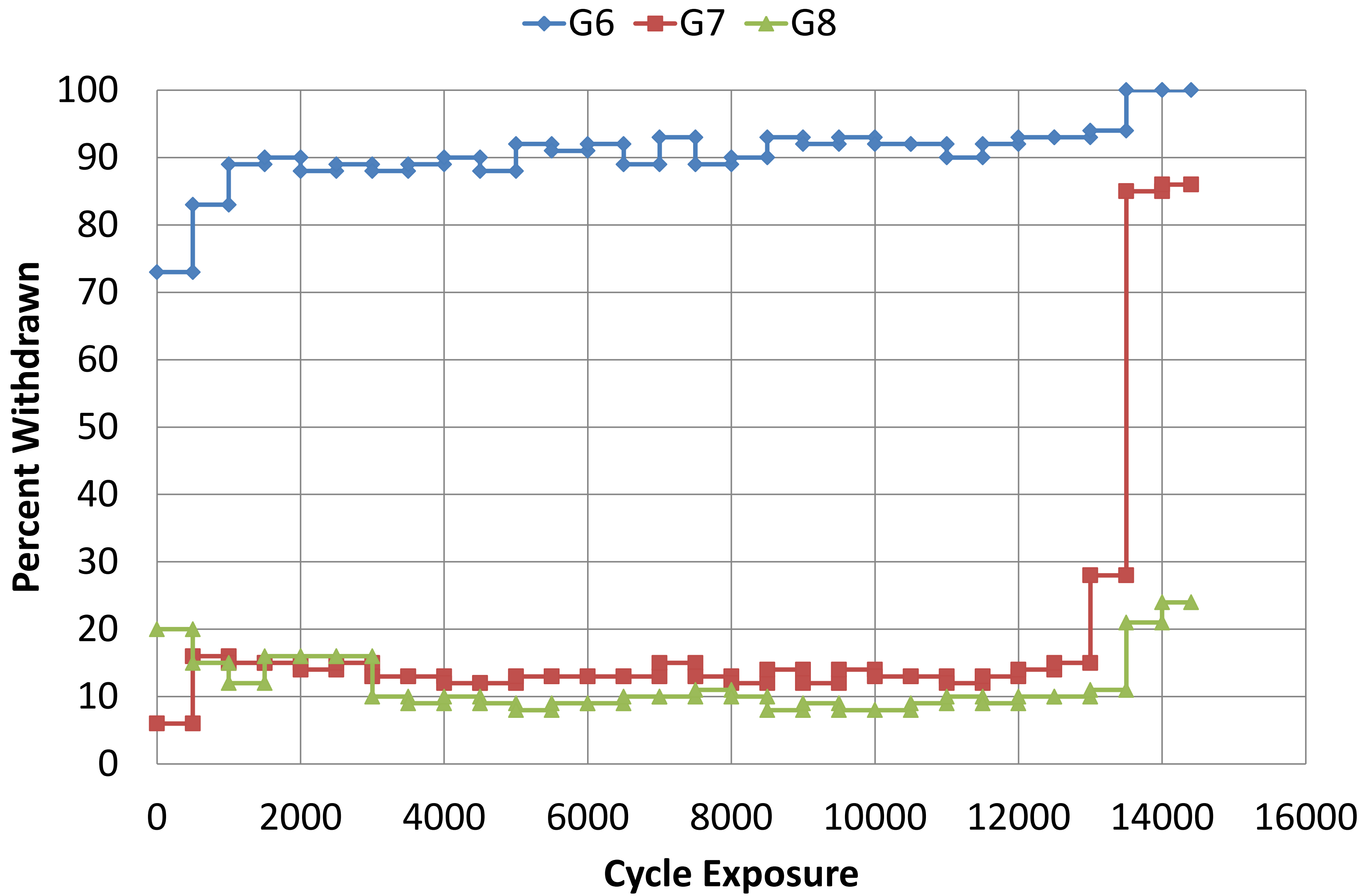
Legend	
BPRA1	
BPRA2	
BPRA3	
RCCA G6	
RCCA G7	
APSR G8	

Control Rod Banks C1B (After ~250 EFPDs)

					0	0	0	0	0					
			0	0	4	9	7	9	4	0	0			
		0	10	5	10	3	10	3	10	5	10	0		
	0	10	7	11	8	10	6	10	8	11	7	10	0	
	0	5	11	6	11	1	10	1	11	6	11	5	0	
0	4	10	8	11	2	9	2	9	2	11	8	10	4	0
0	9	3	10	1	9	5	9	5	9	1	10	3	9	0
0	7	10	6	10	2	9	7	9	2	10	6	10	7	0
0	9	3	10	1	9	5	9	5	9	1	10	3	9	0
0	4	10	8	11	2	9	2	9	2	11	8	10	4	0
	0	5	11	6	11	1	10	1	11	6	11	5	0	
	0	10	7	11	8	10	6	10	8	11	7	10	0	
		0	10	5	10	3	10	3	10	5	10	0		
			0	0	4	9	7	9	4	0	0			
					0	0	0	0	0					

Legend	
BPRA1	
BPRA2	
BPRA3	
RCCA G6	
RCCA G7	
APSR G8	

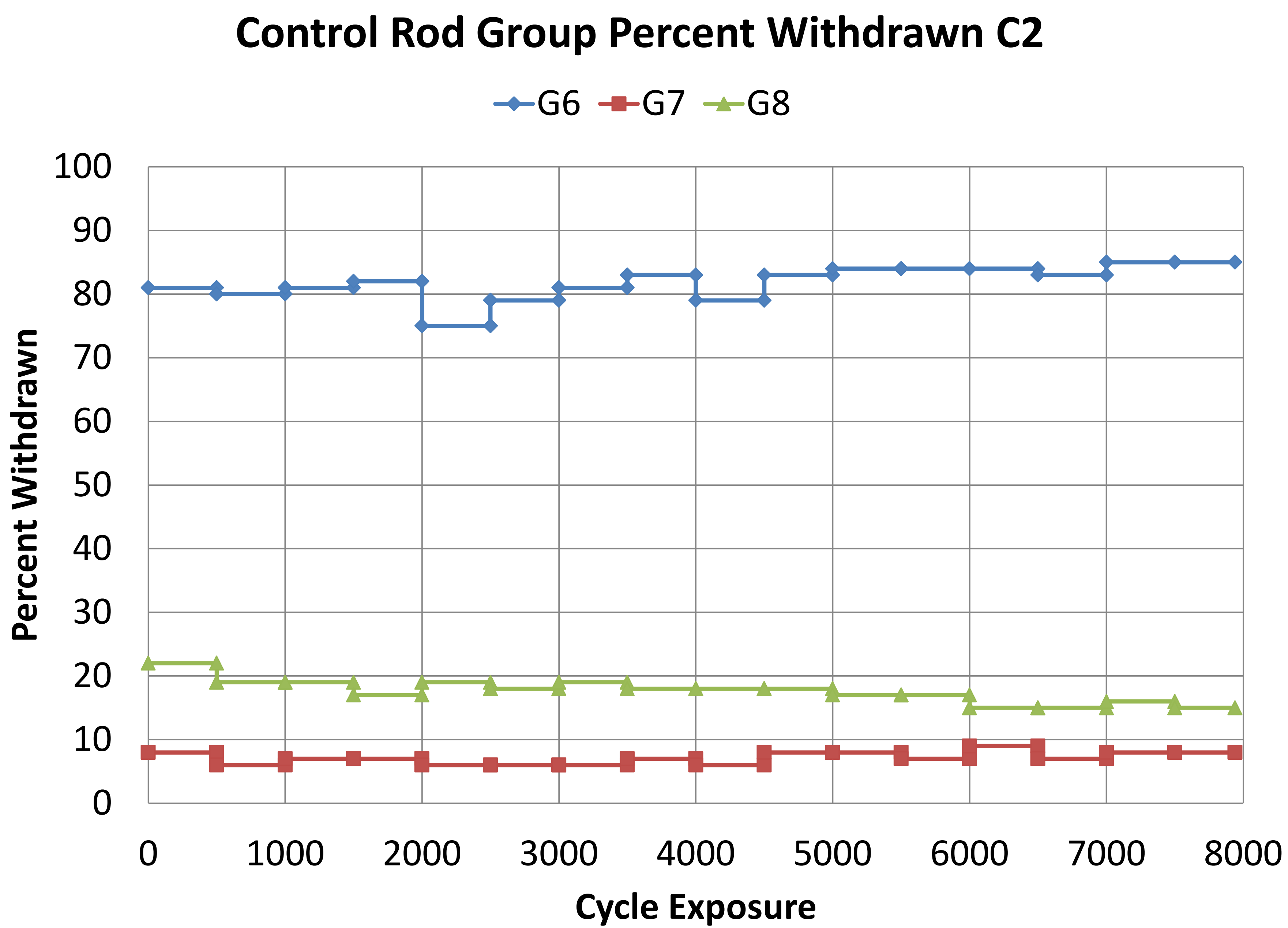
Control Rod Group Percent Withdrawn C1



Control Rod Banks C2

					0	0	0	0	0					
			0	0	4	9	5	9	4	0	0			
		0	10	2	10	7	10	7	10	2	10	0		
	0	10	6	11	8	10	3	10	8	11	6	10	0	
	0	2	11	3	11	1	10	1	11	3	11	2	0	
0	4	10	8	11	5	9	6	9	5	11	8	10	4	0
0	9	7	10	1	9	3	9	3	9	1	10	7	9	0
0	5	10	3	10	6	9	4	9	6	10	3	10	5	0
0	9	7	10	1	9	3	9	3	9	1	10	7	9	0
0	4	10	8	11	5	9	6	9	5	11	8	10	4	0
	0	2	11	3	11	1	10	1	11	3	11	2	0	
	0	10	6	11	8	10	3	10	8	11	6	10	0	
		0	10	2	10	7	10	7	10	2	10	0		
			0	0	4	9	5	9	4	0	0			
					0	0	0	0	0					

Legend	
BPRA1	
BPRA2	
BPRA3	
RCCA G6	
RCCA G7	
APSR G8	



Control Rod Group Percent Withdrawn C2
G6
G7
G8
Percent Withdrawn
100
90
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Cycle Exposure

First Deployment of SCALE/POLARIS

- POLARIS is a SCALE sequence that performs lattice physics calculations for LWR lattices.
  - Based on Method of Characteristics transport solution.
  - Self shielding calculations are embedded in the method, simplifying the overall calculation method compared to the TRITON sequence.
  - Catered for LWR lattice applications with greatly simplified user input.

```
% definition of pin types

pin F : 0.470   0.479   0.546
      : FUEL.1  GAP     CLAD.1
pin I : 0.560   0.626   0.638   0.704
      : COOL    CLAD.2  COOL    CLAD.2
pin G : 0.632   0.673
      : COOL    CLAD.2

pinmap
I
F F
F F G
F F F F
F F F F G
F F G F F F
F F F F F F F
F F F F F F F F
```

Capturing History Effects

- One POLARIS calculation can consider only one state condition for depletion. All branches in one calculation are derived from one set of historical conditions.
- Eight calculations are required to account for coolant density history, fuel temperature history, boron history, and control rod history.
  - Nominal history conditions
  - High and low coolant density
  - High and low fuel temperature
  - High and low boron concentration
  - Type “1” control state
- GenPMAXS is used to combine the eight POLARIS output files into one PMAX file for each lattice.

Branch Structure

BPRA assemblies reference condition is controlled

```
!        CR  MD     B      TF       ID
 1       1.0 0.7143 600.0  966.7  ! 'Nominal'
 2       1.0 0.7143 600.0  550.0  ! 'LoTF'
 3       1.0 0.7143 600.0  2200.0 ! 'HiTF'
 4       1.0 0.6    600.0  966.7  ! 'LoMD'
 5       1.0 0.8    600.0  966.7  ! 'HiMD'
 6       1.0 0.7143 0.0    966.7  ! 'LoB'
 7       1.0 0.7143 1200.0 966.7  ! 'HiB'
 8       0.0 0.7143 600.0  966.7  ! 'BankB'
 9       3.0 0.7173 600.0  966.7  ! 'BankR'
 10      0.0 0.7143 600.0  550.0  ! 'LoTF-U'
 11      0.0 0.7143 600.0  2200.0 ! 'HiTF-U'
 12      0.0 0.6    600.0  966.7  ! 'LoMD-U'
 13      0.0 0.8    600.0  966.7  ! 'HiMD-U'
 14      0.0 0.7143 0.0    966.7  ! 'LoB-U'
 15      0.0 0.7143 1200.0 966.7  ! 'HiB-U'
```

Non-BPRA assemblies have CR types for APSR and RCCA active zones and APSR follower (not all are used)

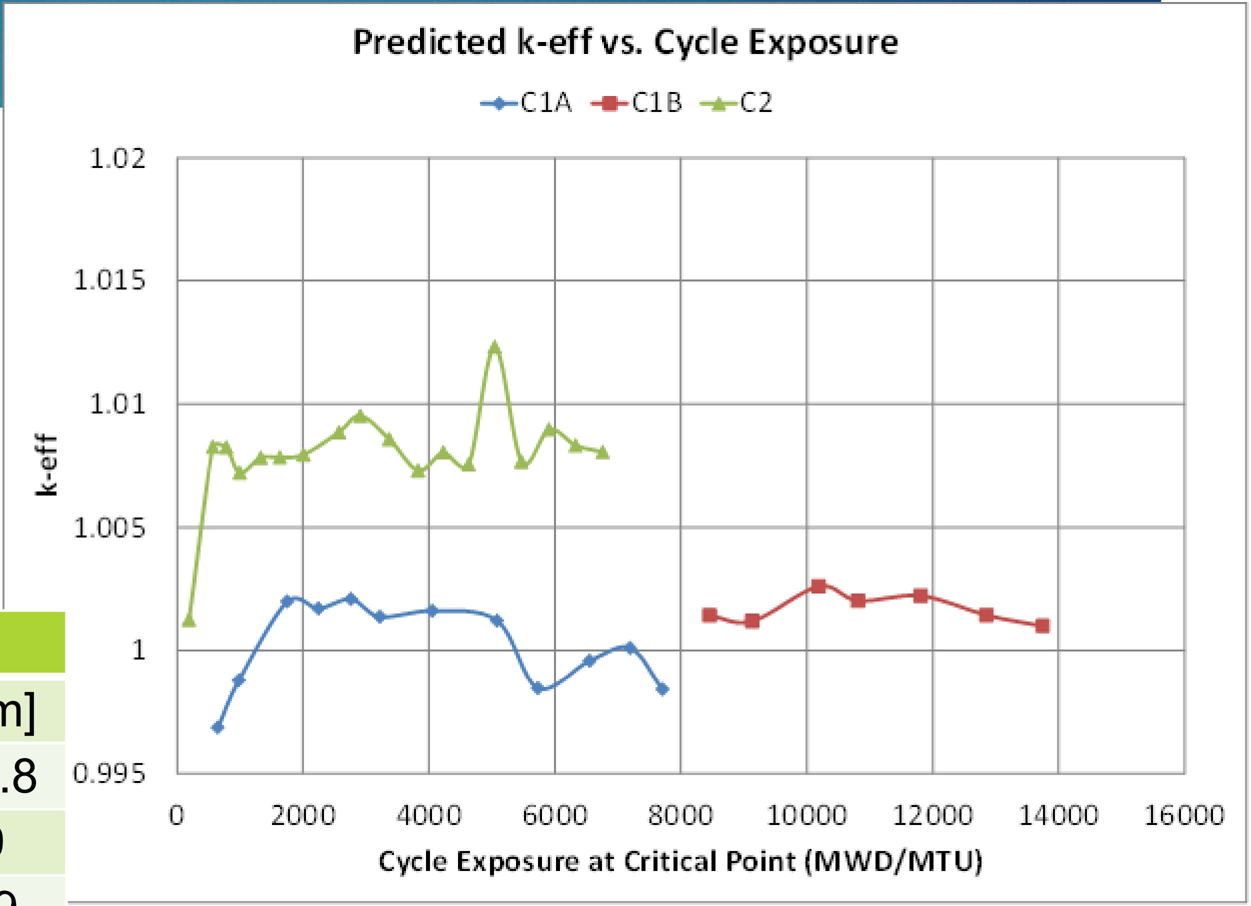
```
!        CR  MD     B      TF       ID
 1       0.0 0.7143 600.0  966.7  ! 'Nominal'
 2       0.0 0.7143 600.0  550.0  ! 'LoTF'
 3       0.0 0.7143 600.0  2200.0 ! 'HiTF'
 4       0.0 0.6    600.0  966.7  ! 'LoMD'
 5       0.0 0.8    600.0  966.7  ! 'HiMD'
 6       0.0 0.7143 0.0    966.7  ! 'LoB'
 7       0.0 0.7143 1200.0 966.7  ! 'HiB'
 8       1.0 0.7143 600.0  966.7  ! 'BankP'
 9       2.0 0.7173 600.0  966.7  ! 'BankO'
 10      3.0 0.7173 600.0  966.7  ! 'BankR'
 11      1.0 0.7143 600.0  550.0  ! 'LoTF-C'
 12      1.0 0.7143 600.0  2200.0 ! 'HiTF-C'
 13      1.0 0.6    600.0  966.7  ! 'LoMD-C'
 14      1.0 0.8    600.0  966.7  ! 'HiMD-C'
 15      1.0 0.7143 0.0    966.7  ! 'LoB-C'
 16      1.0 0.7143 1200.0 966.7  ! 'HiB-C'
```

Coping with the 1CRH Limitation in PARCS

- PARCS is currently limited in that it can only account for control rod history (CRH) effects for one control rod "type."
- In PMAX files, control rod branches and histories are labeled with a numerical index, so "type" refers to one of these indices.
- PARCS can simulate axial variation of the contents of a control rod by assigning "type" indices to axial spans of a control rod.
- For BPRA loaded assemblies in Cycle 1, the 1CRH available is used to track history for branch/history "1." Branch/history 1 is the BPRA withdrawn. The BPRAs are then withdrawn after Cycle 1.
- For assemblies beneath RCCA locations, the RCCA active region is approximated as being the same as the APSR active region, noted as branch/history "1" for those PMAX files.

Base Case

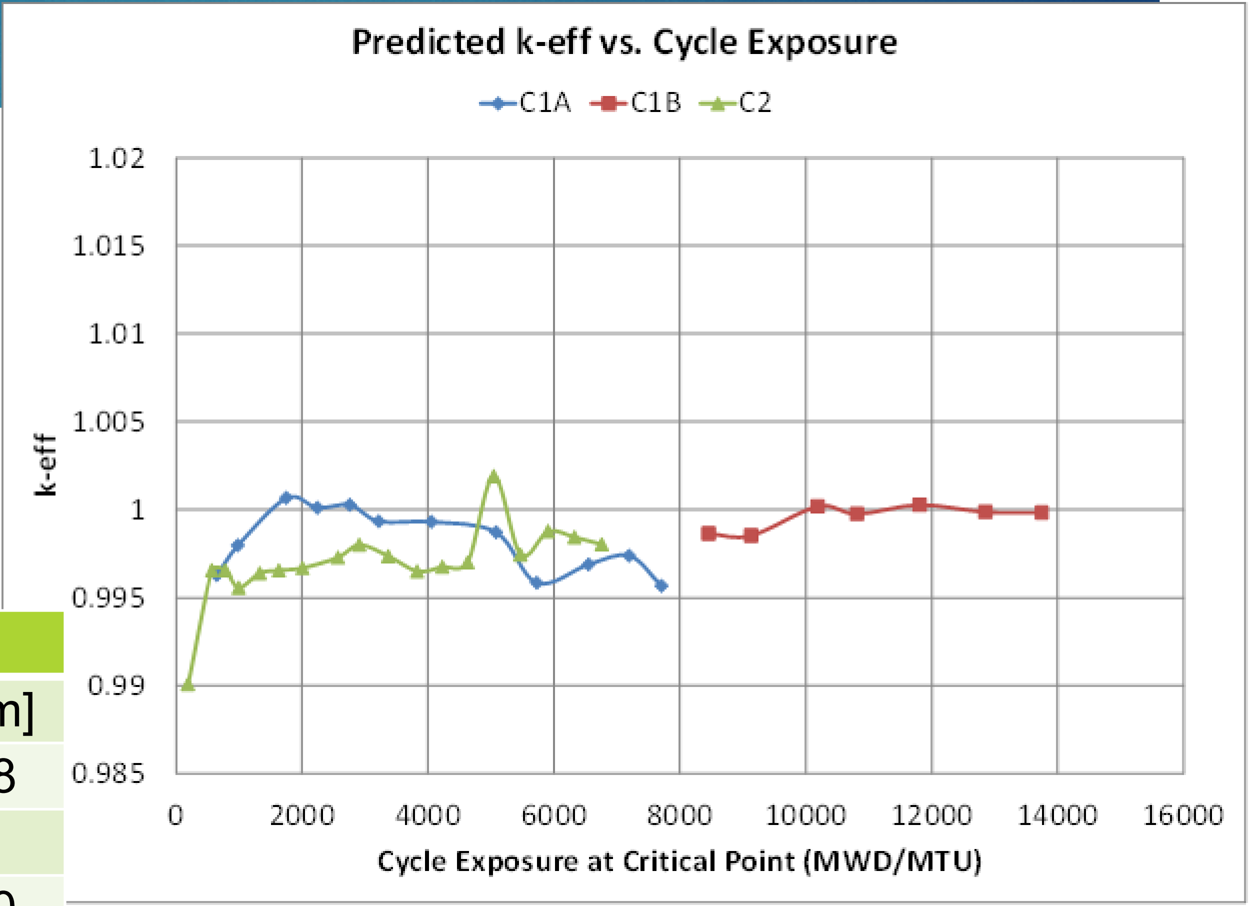
- C1A performance is good, low bias and uncertainty within 200 pcm.
- C1B seems to show a shift in k_{eff} bias.
- C2 shows a large shift in k_{eff} bias to quite a large value (~800pcm).



Case	K-eff Bias	σ
	[pcm]	[pcm]
C1A	18.5	173.8
C1B	170	59
C1	74	159
C2	799	203

No History Tracking (NHT)

- NHT case offers much more consistent performance in terms of k_{eff} bias and uncertainty across both cycles.



Case	K-eff Bias	σ
	[pcm]	[pcm]
C1A	-179	178
C1B	-41	71
C1	-128	160
C2	-300	221

Conclusions

- Preliminary assessment indicates that use of control rod history tracking in PARCS for PWR depletion problems degrades calculation performance with respect to eigenvalue calculation.
- At the current time, PARCS is not recommended to analyze PWR depletion problems that include significant control rod shim during cycle depletion. As many modern PWR cores operate with primarily chemical shim, PARCS can still be applied to a wide variety of confirmatory analyses.

Future Work

- Develop detector response model in POLARIS to assess against local power measurement data in TMI1 C1-C2. This would form a more complete assessment and assist in diagnosing causes for the eigenvalue biases.
- Evaluate alternatives to linear CRH weighting, for example, exponential weighting of history data to determine cross-sections. An exponential weighting scheme is a more intuitive scheme for combining history data that would account for the asymptotic behavior of isotopics under changing spectral conditions.

Hatch 1 C1-C3

Outline

- Introduction
- Overview of PARCS/PATHS
- Modeling
- Multiplication factor calculations and assessment
- Hatch Unit 1 Cycles 1-3 (H1C1-3) operation history
- Traversing in-core probe (TIP) assessment
- Summary of power distribution uncertainties
- Conclusions

Introduction: Motivation

- It is desirable to be able to simulate BWR cycle depletion as a means for developing input conditions for transient calculations at various points in cycle to support independent confirmatory analyses.
- PARCS/PATHS is a tool with significant speed advantages relative to using PARCS/TRACE for depletion calculations.

Introduction: Assessment

- Evaluation models must be assessed against applicable data to estimate the model's accuracy.
- Operational data were available for Hatch Unit 1 Cycles 1-3 for assessment in terms of multiplication factor and power distribution in the public domain:
  - EPRI NP-562, "Core Design and Operating Data for Cycle 1 of Hatch 1," January 1979
  - EPRI NP-2106, "Core Design and Operating Data for Cycles 2 and 3 of Hatch 1," February 1984
  - EPRI NP-1235, "Core Performance Benchmarking Edwin I. Hatch Nuclear Plant Unit 1, Cycle 1," November 1979

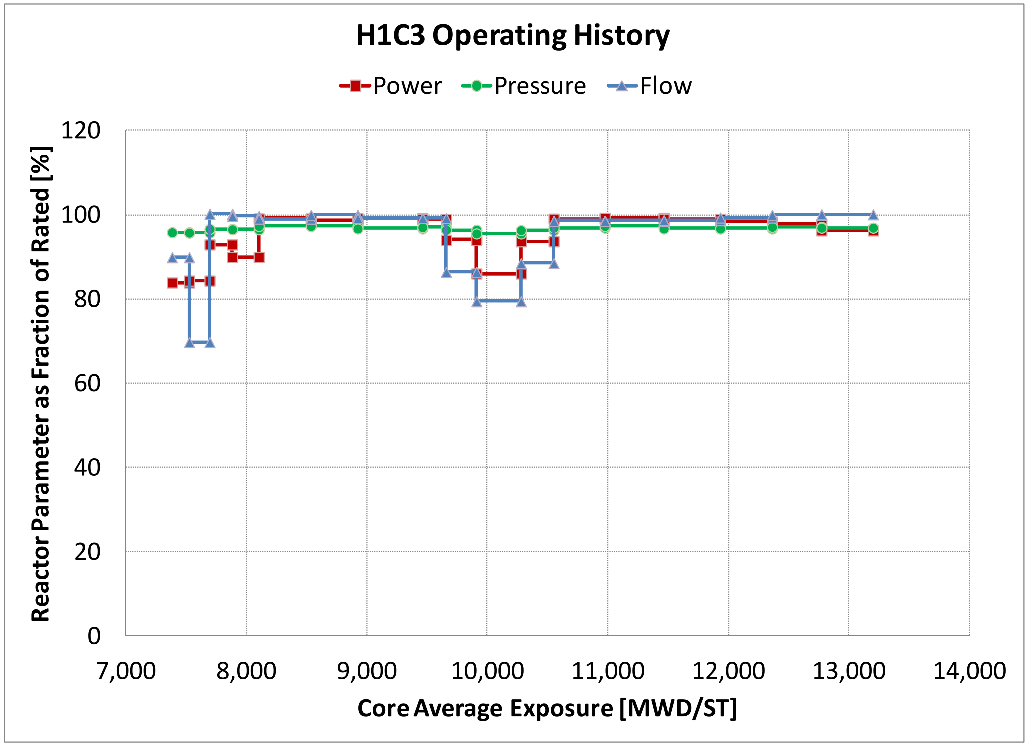
PARCS/PATHS Overview

- PARCS is a three-dimensional nodal diffusion code applicable to pressurized and boiling water reactors (PWR and BWR).
- PATHS is a simplified, three-equation thermal-hydraulic code that simulates conditions in the parallel fuel channels of a BWR core.
- PARCS/PATHS are coupled to iteratively calculate thermal-hydraulic state and power distribution
- Depletion calculations are performed using "step-like" updates to exposure history and thermal-hydraulic boundary conditions.

Modeling with a Step-like Approach

- Power, flow, and pressure assumed to be constant and steady between exposure points in the calculation.
- Exposure points selected to ensure < 0.7 GWD/T steps between points.
- Exposure points added to coincide with dataset points from EPRI NP-562.
- Step-like approach similar to industry approach discussed in EPRI NP-1235.

Sample Step-like Operating History Plotted for H1C3



Between exposure points, the power, pressure, and flow are held constant in the calculation, but undergo step changes at fixed points.

This approach is typical and a good approximation for normal cycle operation.

Limitations of Step-like Approach

During the first several months of operation at Hatch, the plant experienced several operational transients – this was approximated with "step-like" depletion in the PARCS/PATHS calculation.

Since H1C1 operation is atypical, this presents a challenge to the current method.

Operational Parameters During a Typical Month Early in H1C1

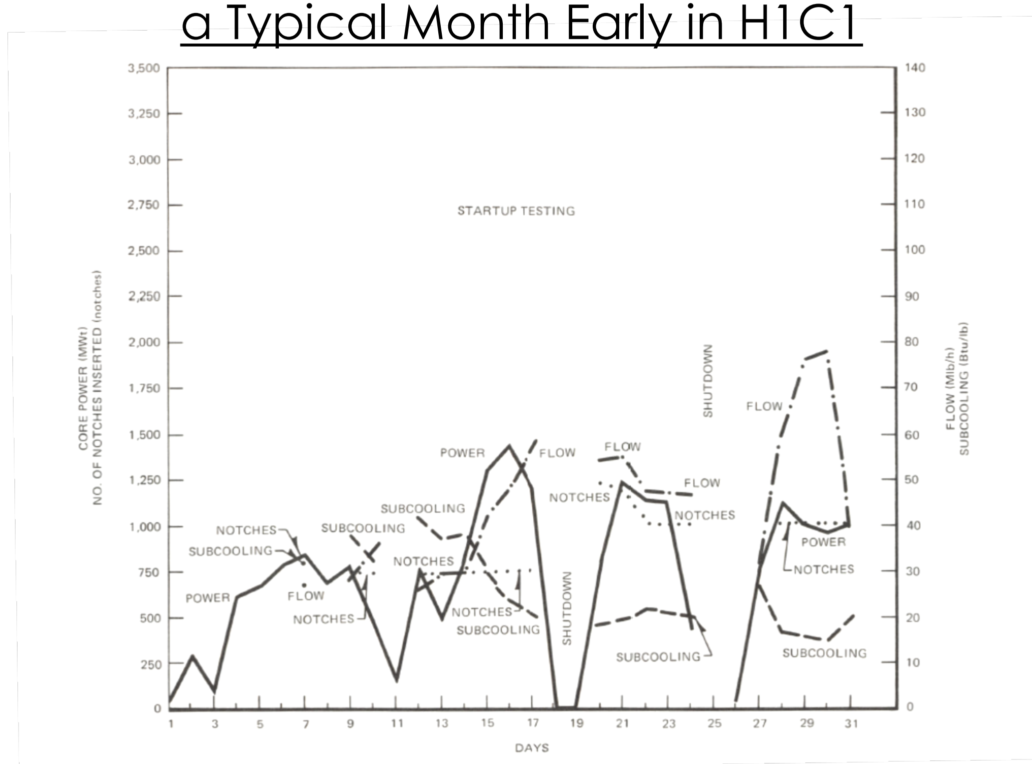


Figure from EPRI NP-562

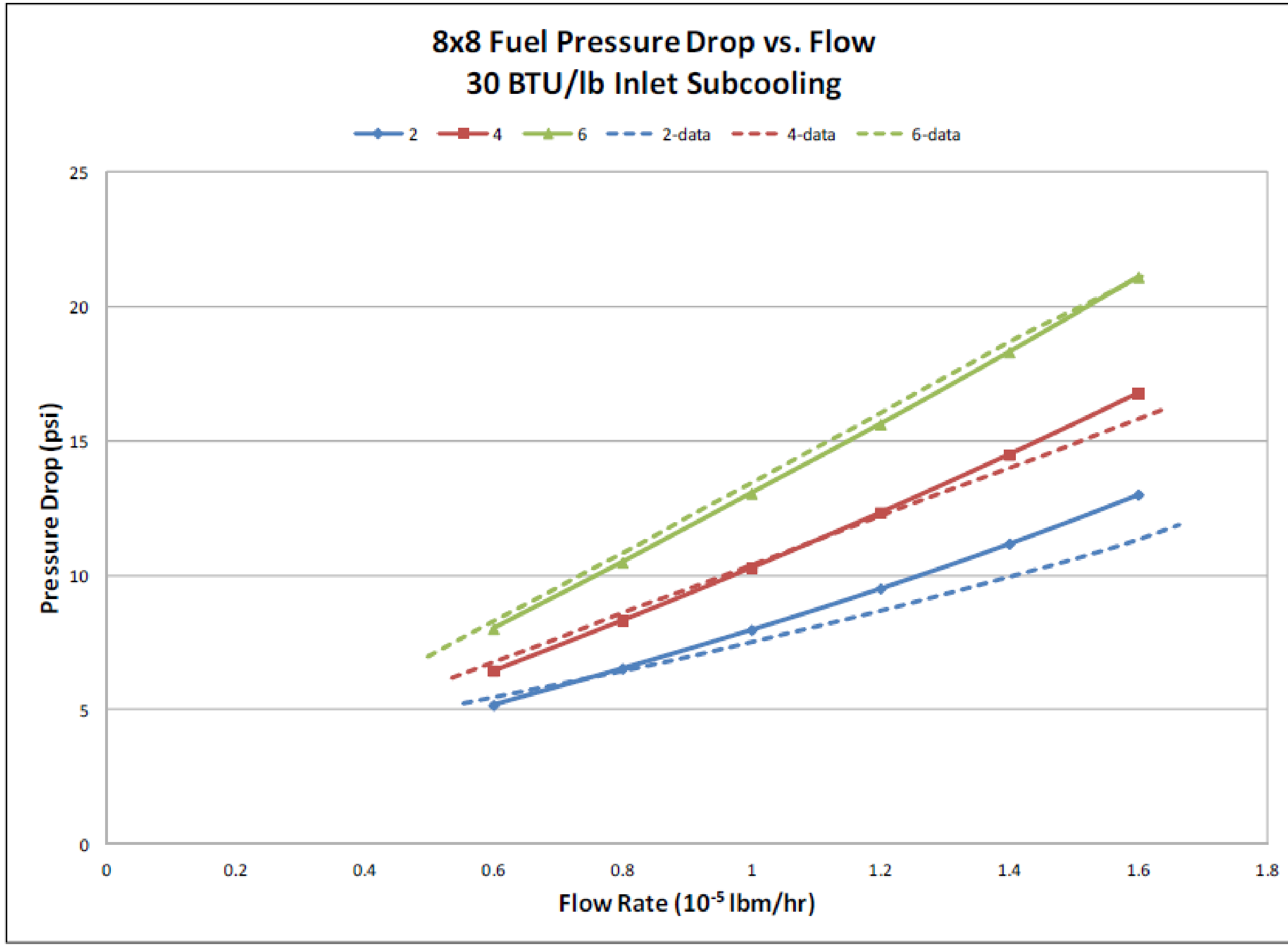
Thermal-Hydraulic Models in PATHS

- The thermal-hydraulic closure models were selected as PATHS defaults based on comparisons to TRACE for Peach Bottom Cycles 1 and 2 fuel.
  - Electric Power Research Institute (EPRI) void-quality correlation
  - EPRI sub-cooled boiling model
  - Smooth-fit of Blasius and Churchill wall friction factor correlations
  - Martinelli-Nelson-Jones two-phase friction multiplier
- Loss coefficients based on thermal-hydraulic data and were tuned using TRACE calculations

Pressure Drop Calibration with TRACE

Loss coefficients were tuned based on comparison of EPRI NP-562 and EPRI NP-2106 hydraulic data to TRACE.

Results are very good except for high flow / low power bundles, which generally are not in-core due to orificing peripheral fuel.



Detector Response Model

- PARCS uses lattice cross-section data in PMAX format, functionalized with respect to nodal parameters.
- Neutron detector response kernels are calculated according to lattice corner flux and Uranium-235 cross-sections.
- The neutron detector response is functionalized like a cross-section in the PMAX data file.
- Currently the method is limited to neutron detectors.

Hatch Unit 1 Cycles 1-3 Core Designs

- Fuel design, core design, and operational data including TIP measurements are available in the public domain in a series of EPRI reports (EPRI NP-562 and EPRI NP-2106).
- Three 7X7 fuel types loaded in initial core.
- Second cycle core includes a new fuel type (8X8).
- Third cycle includes another new 8X8 fuel type with a new water rod design.

Sample: Hatch Unit 1 Cycle 3 Core

								10	20	30	20	20	20	20	30	20	10								
							20	1	5	1	5	3	3	5	1	5	1	20							
				10	20	10	3	5	3	5	4	5	5	4	5	3	5	3	10	20	10				
			10	1	5	4	5	4	5	2	5	3	3	5	2	5	4	5	4	5	1	10			
		10	1	3	3	5	4	5	3	5	3	5	5	3	5	3	5	4	5	3	3	1	10		
		20	5	3	4	2	5	2	5	2	5	3	3	5	2	5	2	5	2	4	3	5	20		
		10	4	5	2	5	3	4	1	4	2	4	4	2	4	1	4	3	5	2	5	4	10		
	20	3	5	4	5	3	5	2	5	3	5	1	1	5	3	5	2	5	3	5	4	5	3	20	
10	1	5	4	5	2	4	2	4	2	4	1	4	4	1	4	2	4	2	4	2	5	4	5	1	10
20	5	3	5	3	5	1	5	2	5	1	5	1	1	5	1	5	2	5	1	5	3	5	3	5	20
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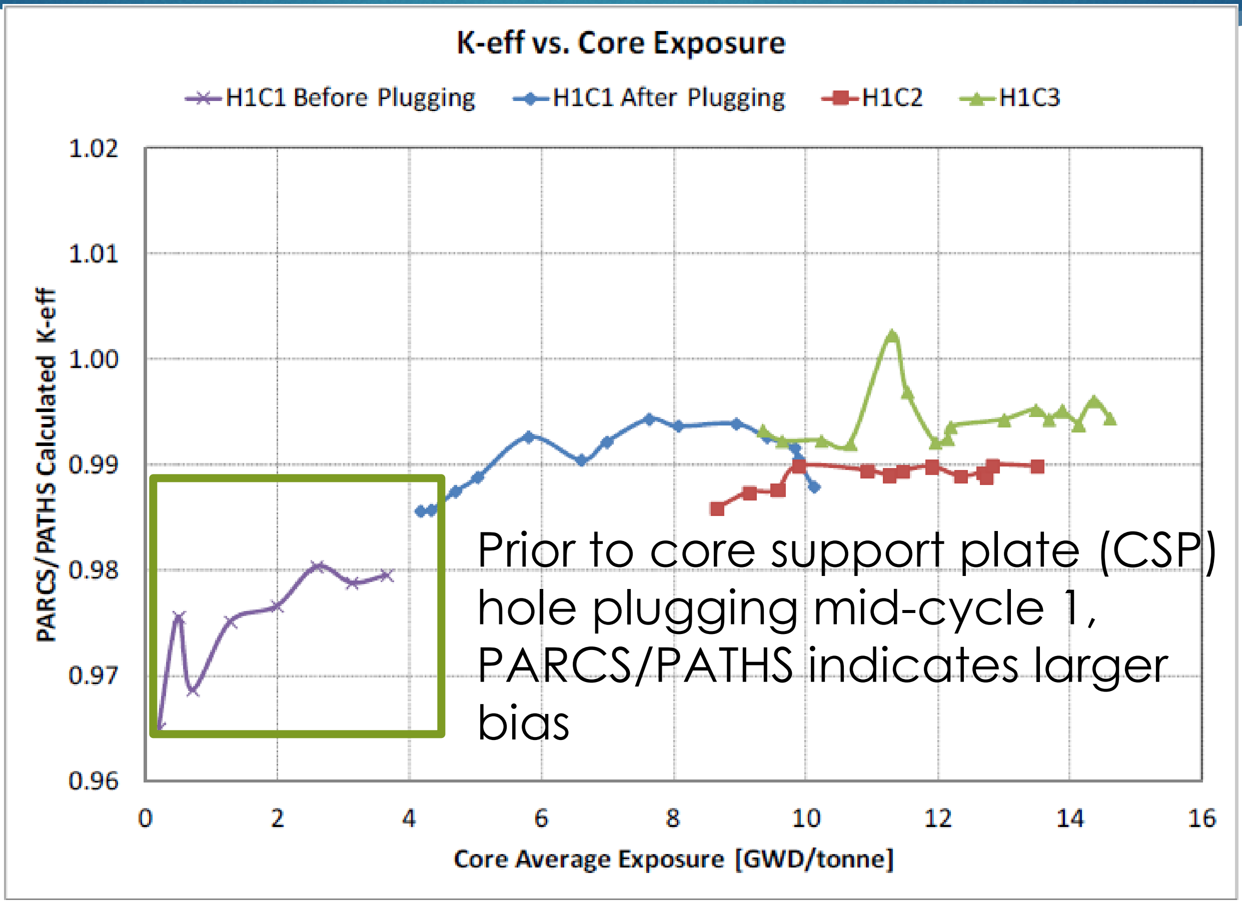
30	1	5	2	5	2	4	3	4	1	4	1	4	4	1	4	1	4	3	4	2	5	2	5	1	30
20	5	3	5	3	5	1	5	2	5	1	5	1	1	5	1	5	2	5	1	5	3	5	3	5	20
10	1	5	4	5	2	4	2	4	2	4	1	4	4	1	4	2	4	2	4	2	5	4	5	1	10
	20	3	5	4	5	3	5	2	5	3	5	1	1	5	3	5	2	5	3	5	4	5	3	20	
		10	4	5	2	5	3	4	1	4	2	4	4	2	4	1	4	3	5	2	5	4	10		
		20	5	3	4	2	5	2	5	2	5	3	3	5	2	5	2	5	2	4	3	5	20		
		10	1	3	3	5	4	5	3	5	3	5	5	3	5	3	5	4	5	3	3	1	10		
			10	1	5	4	5	4	5	2	5	3	3	5	2	5	4	5	4	5	1	10			
				10	20	10	3	5	3	5	4	5	5	4	5	3	5	3	10	20	10				
							20	1	5	1	5	3	3	5	1	5	1	20							
								10	20	30	20	20	20	20	30	20	10								

Figure based on EPRI NP-2106

PARCS/PATHS Multiplication Factor Calculations



Multiplication Factor Results

- PARCS/PATHS bias for H1C1 is highest (~ -1500 pcm) but this includes the early cycle data.
  - Early cycle operation is more sporadic with several periods of shutdown and is modeled with a step-like approach.
  - The effect of bypass flow is not explicitly captured in PARCS/PATHS. Before CSP hole plugging bypass flow in the plant is high.
- Considering only the data after plugging, the bias is -873 pcm with a standard deviation of 332 pcm.

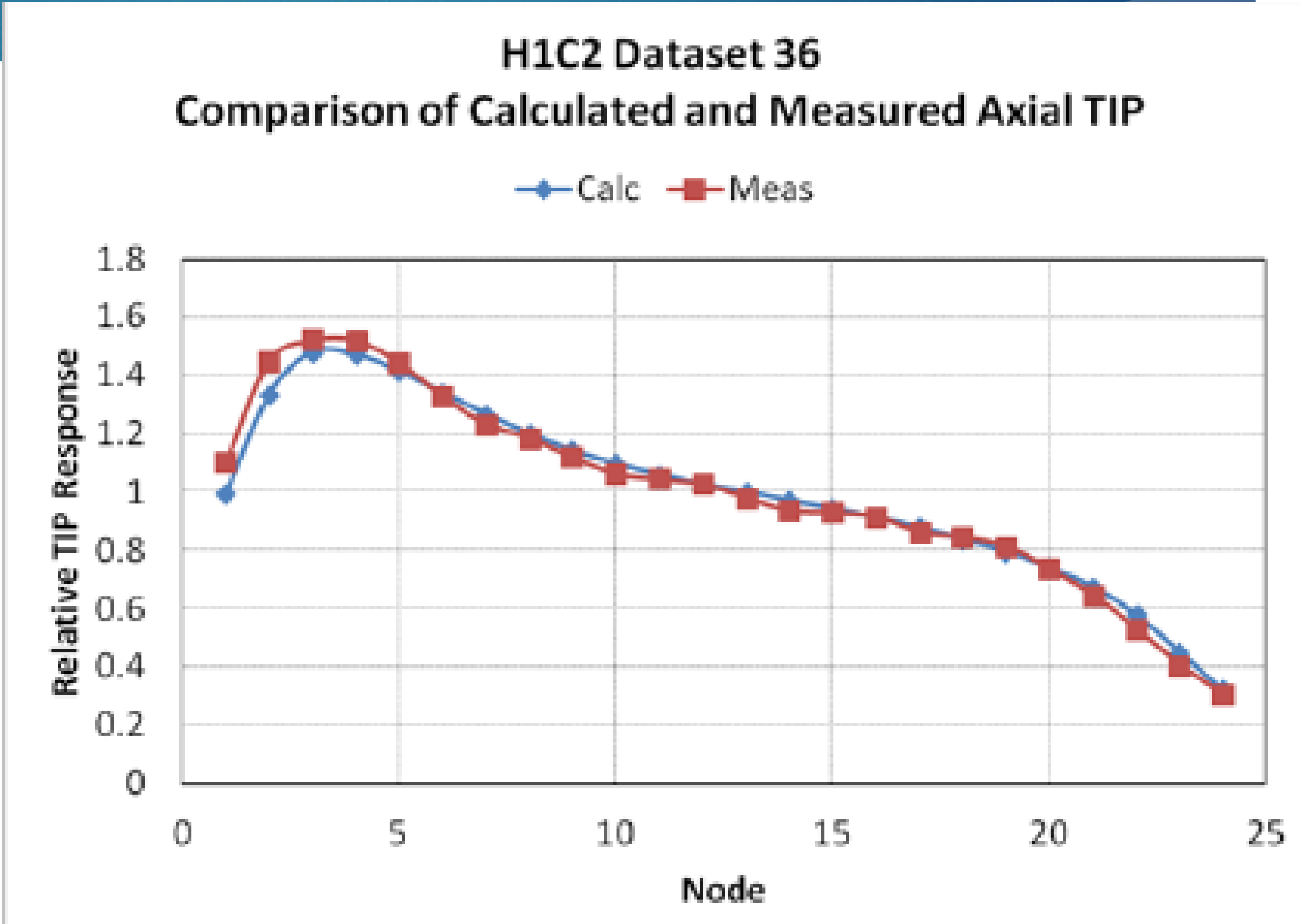
Power Distribution Assessment

- Power distribution is inferred from thermal TIP measurements performed during H1C1 and H1C2.
- Thermal TIPs were replaced with gamma TIPs in H1C3. PARCS/PATHS currently does not currently support calculation of gamma TIP response, so H1C3 TIP data were not considered.
- The focus is H1C2 because of the indicated k-eff biases in early H1C1 operation, but H1C1 still considered in the paper.

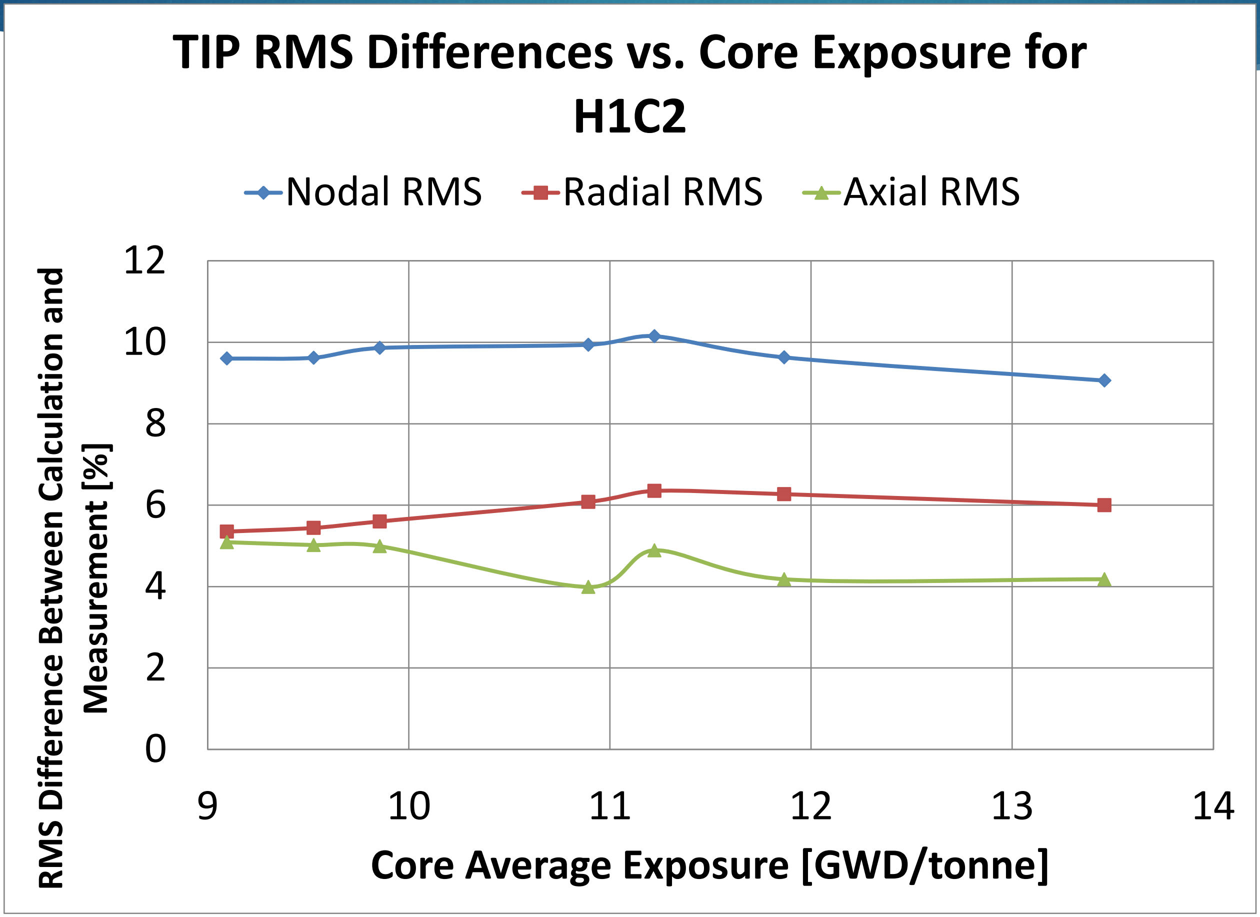
Sample Axial Shape Comparison (H1C2 Near End of Cycle)

Blue is PARCS/PATHS calculated average axial TIP response.

Red is the average axial TIP response from EPRI NP-2106.



TIP Statistics Summary for H1C2



PARCS/PATHS differences to EPRI NP-2106 measurement data for nodal, radial, and axial TIP are plotted.

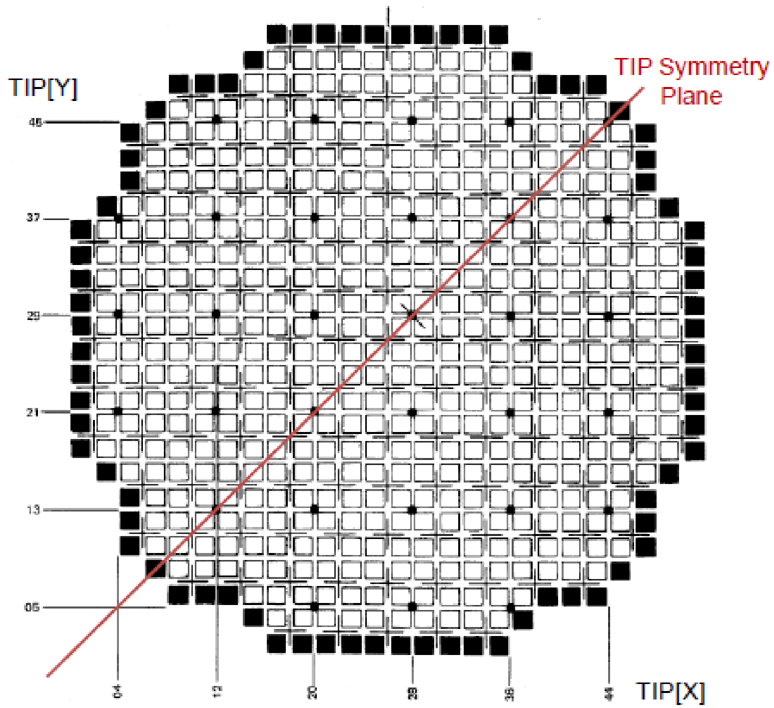
No exposure dependence indicated.

Calculation Uncertainty

- Total uncertainty is a combination of measurement and calculation uncertainty.
- Total uncertainty inferred by comparing calculation to measurement data using root-mean-square (RMS) differences.
- Calculation uncertainty approximated by subtracting the measurement uncertainty.

$$\sigma_{CALC} \approx \sqrt{(\sigma_{TOT})^2 - (\sigma_{MEAS})^2}$$

Measurement Uncertainty



Measurement uncertainty is approximated by RMS differences in symmetric TIP responses for points in H1C1 where the core loading and operational histories are symmetric.

Summary of Calculation Comparisons to H1C2 TIP Data

PARCS/PATHS compared to TIP measurements from EPRI NP-2106 over H1C2. Uncertainties approximated based on RMS differences in calculations and measurements, adjusted by the measurement uncertainty

	Nodal RMS Difference	Radial RMS Difference	Axial RMS Difference
Average over H1C2	9.69%	5.87%	4.62%
Standard Deviation	0.35%	0.40%	0.48%
Measurement Uncertainty	5.87%	3.68%	2.46%
Calculation Uncertainty	7.72%	4.57%	3.91%

Summary and Conclusions

- Multiplication factor bias and uncertainty are about -870 pcm and 330 pcm, respectively
- Power calculation uncertainties for nodal, radial, and axial shape are about 8%, 4.5%, and 4%, respectively
- Use of PARCS/PATHS to simulate BWR cycle depletion has been demonstrated to predict reasonable results

Hatch Unit 1 Cycle 1 Design

								30	30	30	30	30	30	30	30	30	30								
							30	3	3	2	1	2	1	2	1	3	3	30							
				30	30	30	3	1	2	1	2	1	2	1	2	1	2	3	30	30	30				
			30	3	3	2	1	2	1	2	1	2	1	2	1	2	1	2	1	3	3	30			
		30	3	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	30		
		30	3	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	3	30		
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			30	3	3	1	2	1	2	1	2	1	2	1	2	1	2	1	2	3	3	30			
				30	30	30	3	2	1	2	1	2	1	2	1	2	1	3	30	30	30				
							30	3	3	1	2	1	2	1	2	3	3	30							
								30	30	30	30	30	30	30	30	30	30								

Figure based on EPRI NP-2106

Hatch Unit 1 Cycle 2 Design

								10	20	10	20	10	10	20	10	20	10								
							10	2	3	1	3	2	2	3	1	3	2	10							
				20	10	20	1	3	1	3	2	4	4	2	3	1	3	1	20	10	20				
			10	2	4	3	4	1	4	2	4	1	1	4	2	4	1	4	3	4	2	10			
		20	2	3	1	4	2	4	2	4	2	3	3	2	4	2	4	2	4	1	3	2	20		
		10	4	1	4	1	3	2	3	1	3	2	2	3	1	3	2	3	1	4	1	4	10		
		20	3	4	1	4	3	4	2	1	2	1	1	2	1	2	4	3	4	1	4	3	20		
	10	1	4	2	3	3	1	1	3	1	1	3	3	1	1	3	1	1	3	3	2	4	1	10	
10	2	3	1	4	2	4	1	2	2	1	4	2	2	4	1	2	2	1	4	2	4	1	3	2	10
20	3	1	4	2	3	2	3	2	1	1	2	2	2	2	1	1	2	3	2	3	2	4	1	3	20
10	1	3	2	4	1	1	1	1	1	3	1	3	3	1	3	1	1	1	1	1	4	2	3	1	10
20	3	2	4	2	3	2	1	4	2	1	4	2	2	4	1	2	4	1	2	3	2	4	2	3	20
10	2	4	1	3	2	1	3	2	2	3	2	3	3	2	3	2	2	3	1	2	3	1	4	2	10
10	2	4	1	3	2	1	3	2	2	3	2	3	3	2	3	2	2	3	1	2	3	1	4	2	10
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10	1	3	2	4	1	1	1	1	1	3	1	3	3	1	3	1	1	1	1	1	4	2	3	1	10
20	3	1	4	2	3	2	3	2	1	1	2	2	2	2	1	1	2	3	2	3	2	4	1	3	20
10	2	3	1	4	2	4	1	2	2	1	4	2	2	4	1	2	2	1	4	2	4	1	3	2	10
	10	1	4	2	3	3	1	1	3	1	1	3	3	1	1	3	1	1	3	3	2	4	1	10	
		20	3	4	1	4	3	4	2	1	2	1	1	2	1	2	4	3	4	1	4	3	20		
		10	4	1	4	1	3	2	3	1	3	2	2	3	1	3	2	3	1	4	1	4	10		
		20	2	3	1	4	2	4	2	4	2	3	3	2	4	2	4	2	4	1	3	2	20		
			10	2	4	3	4	1	4	2	4	1	1	4	2	4	1	4	3	4	2	10			
				20	10	20	1	3	1	3	2	4	4	2	3	1	3	1	20	10	20				
							10	2	3	1	3	2	2	3	1	3	2	10							
								10	20	10	20	10	10	20	10	20	10								

Figure based on EPRI NP-2106