Advanced 3D Cross Section Generation for Axially Heterogeneous Cores (RBWR)

Andrew Hall
Michael Jarrett
Andrew Ward

9/17/2014

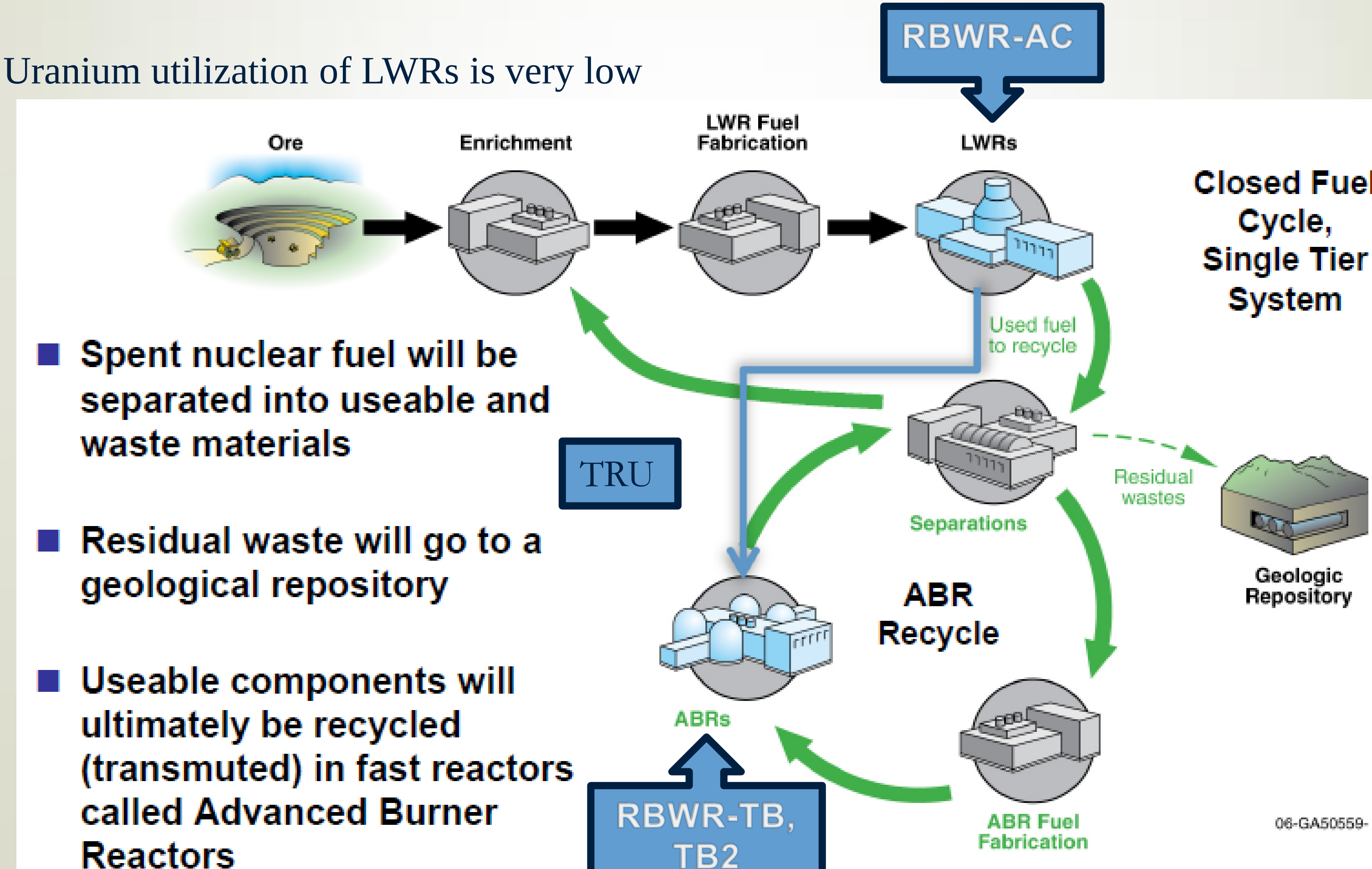
MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Outline

- RBWR Motivation and Design
- Code Suite for the RBWR
- Modeling the RBWR
- Generating an Equilibrium Cycle
- BWR Control Rod Study
- Conclusions

Motivation

- No current long term solution for the spent fuel issue
- Transuranic (TRU) production is higher in uranium based light water reactors (LWRs)
- Uranium utilization of LWRs is very low

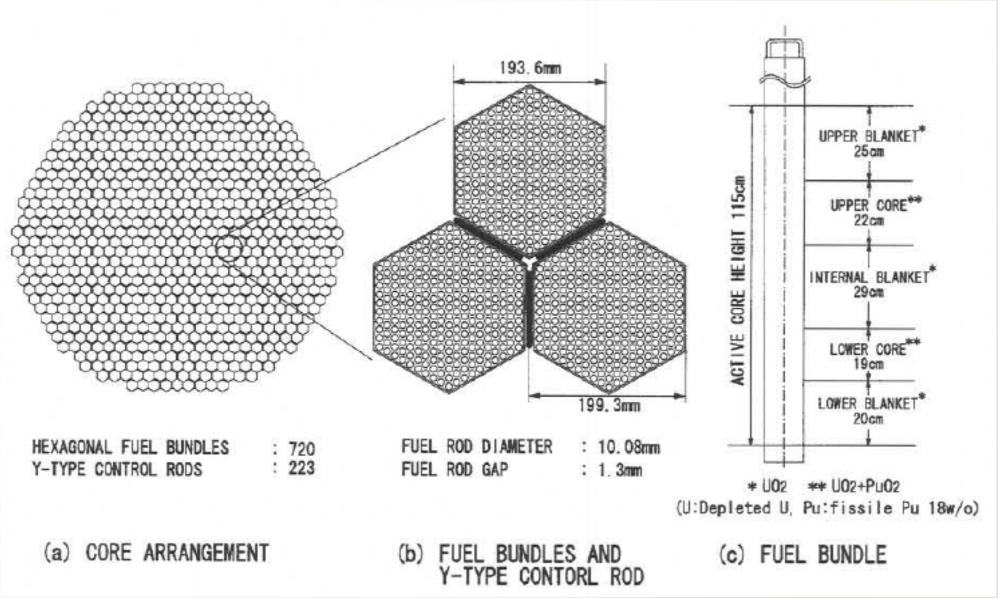


Introduction

- Advantages of Light Water Fast Reactors
  - Light water technology and infrastructure is well established
  - TRU burning is most efficient in fast spectrum reactors
- RBWR Advantages:
  - RBWR-AC (Breeder Reactor)
    - Conversion ratio of 1.0 (or 1-2% above 1.0)
  - RBWR-TB2 (Burner Reactor)
    - Low conversion ratio of ~0.5
  - Closed Fuel Cycle
  - Uses existing ABWR Technology

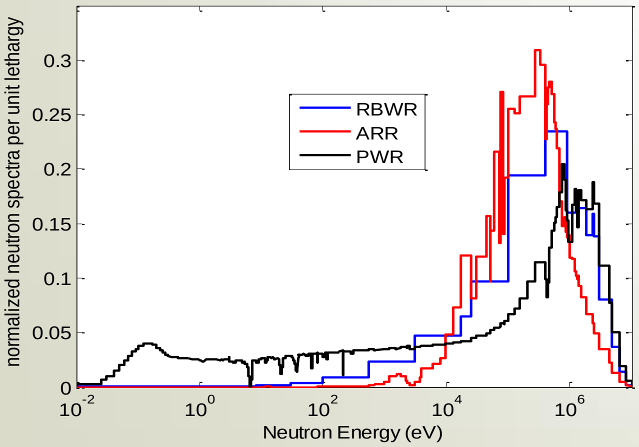
Resource-Renewable Boiling Water Reactor (RBWR)

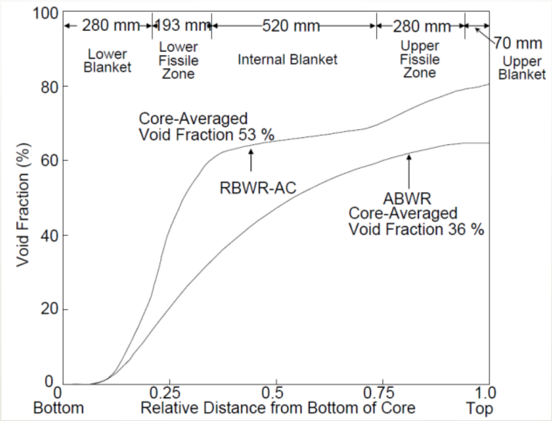
- The RBWR is a reactor design originally proposed by Hitachi which is capable of achieving a conversion ratio of 1.0
- Design features include:
  - Short, parfait style core
  - Tight pitch fuel lattice
  - Smaller coolant mass flow-rate
  - Large exit void fraction
  - Less negative core void reactivity coefficient
  - Y-shaped control blades

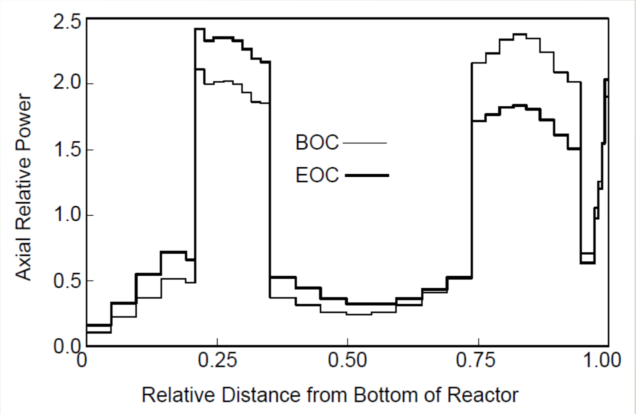


RBWR Characteristics

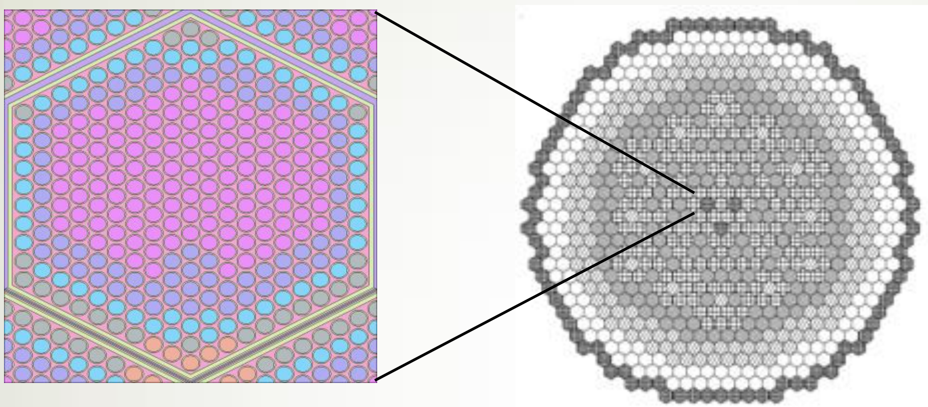
- Hard neutron spectrum compared to typical LWRs
- Average core void fraction of 53% compared to 36% for the ABWR
- Double peaked axial power distribution provides large axial heterogeneity
- RBWR requires 3D cross sections and axial discontinuity factors

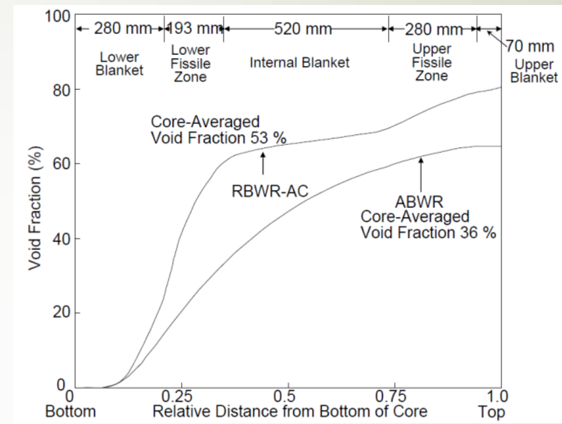






Coupled Code System for RBWR Simulation





Lattice Code: SERPENT

GENPMAXS

Cross Section Library (PMAX)

Neutron Flux Solver: PARCS

T/H: PATHS

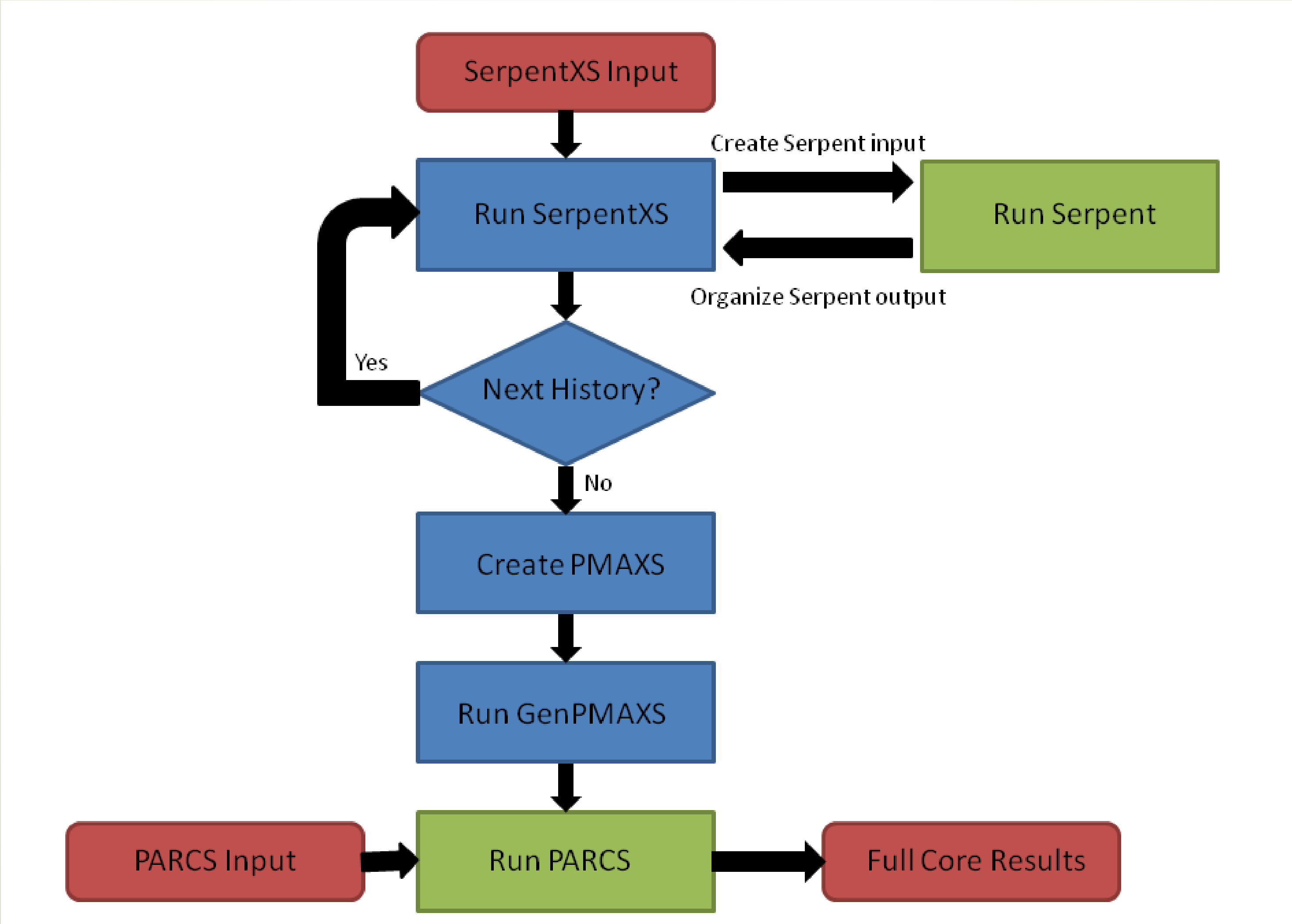
Equilibrium Search

SerpentXS

- SerpentXS was developed by Bryan Herman at MIT and provides a tool to run history and branch cases with SERPENT[1]
- Consists of two inputs
  - Branch file – Run parameters, state information, burnable materials
  - Geometry file – Geometry specifications, detectors, etc.
- Advantages
  - No changes to the SERPENT source
  - Parallel run capabilities with restart options
  - Change state conditions, materials, perform cross branches (based on GCU)
- Disadvantages
  - Independent code not maintained by SERPENT staff
  - Generates input files and separate folders for each branch case
  - Parallel only works with Torque job scheduler

1. B. Herman, *Cross Section Generation Strategy for High Conversion Light Water Reactors*, Masters Thesis, MIT (2011)

SerpentXS



From: B. Herman, *Cross Section Generation Strategy for High Conversion Light Water Reactors*, Masters Thesis, MIT (2011)

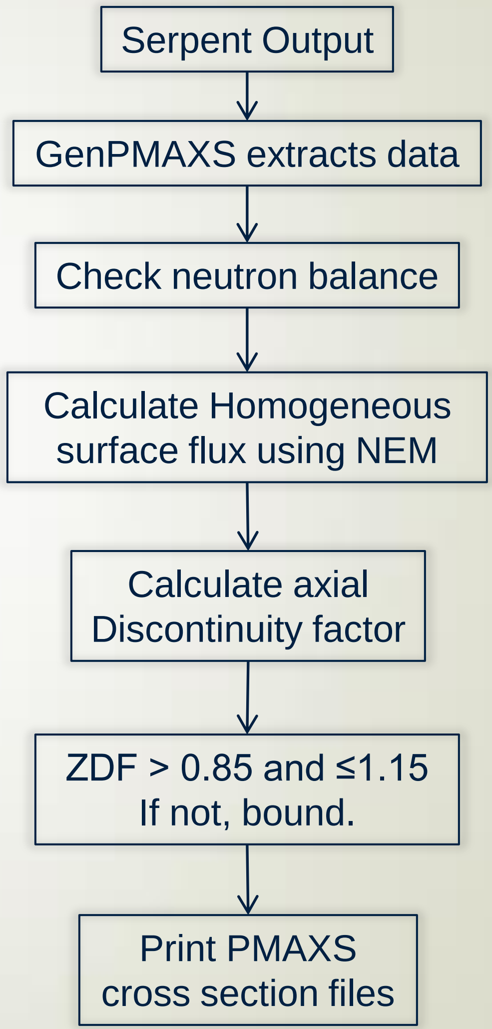
GenPMAXS

- GenPMAXS is a code capable of converting lattice physics data into the PMAXS format for use in the PARCS core simulator
- GenPMAXS supports the following lattice codes:
  - HELIOS
  - CASMO
  - TRITON
  - WIMS
  - CONDOR
  - SERPENT (1 and 2)
- Data the code processes:
  - Chi, Chid, inV
  - Fission yield
  - Beta, Lambda
  - Decay heat data
  - Σ_{tr}, Σ_a, $\nu\Sigma_f$, $\kappa\Sigma_f$, σ_{Xe}, σ_{Sm}, Σ_f, Det
  - Scattering cross sections
  - ADF, ZDF, CDF, GFF
  - Direct energy deposition and J1 factors

MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

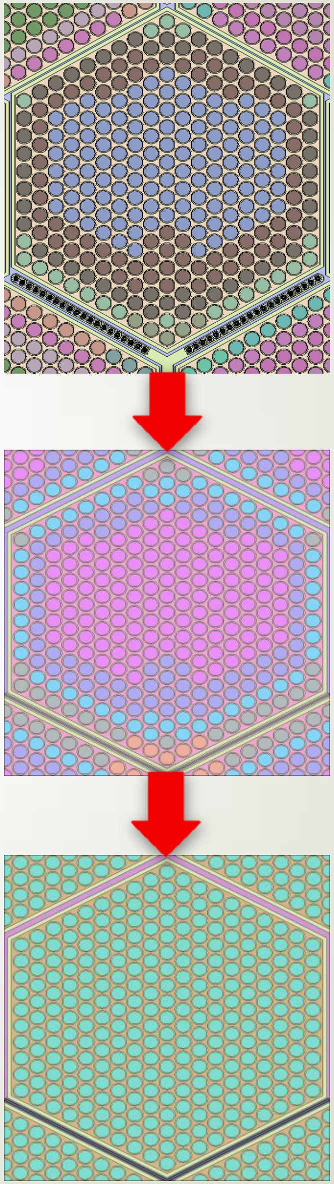
GenPMAXS 3D XS

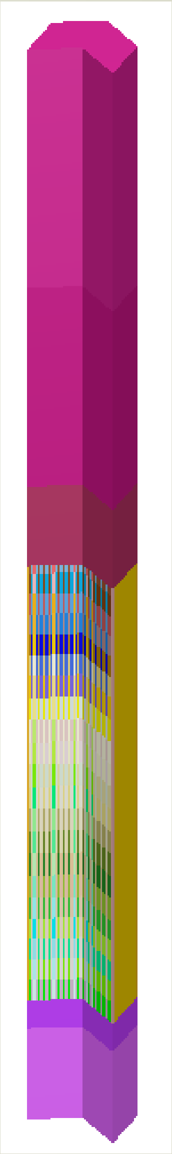
- In order to process 3D cross sections, 3 separate files are used:
  - _res.m File (2D and 3D)
    - Provides principal cross sections and most of the data needed
  - _dep.m File (3D only)
    - Contains a list of the node-wise burnup for cases with multiple GCUs when performing depletion
  - _det.m File (3D only)
    - List of detector currents used for ZDF calculations
- GenPMAXS is also used to calculated axial discontinuity factors (ZDFs)



RBWR Model

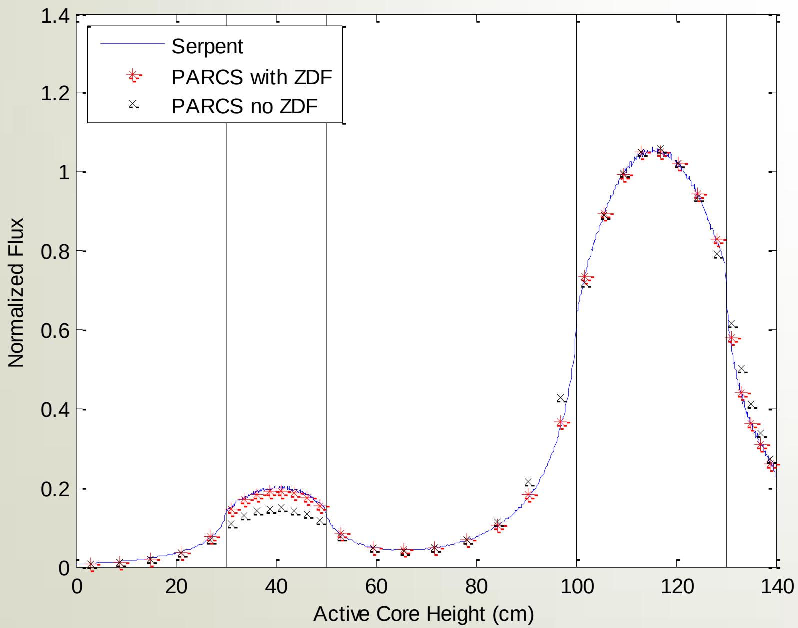
- Single assembly model
- Fissile zones composed of enriched plutonium and TRU
- 5 fuel pin types with varying enrichments
- Blanket regions composed of depleted uranium
- 12 energy groups
- Reflective boundary conditions
- Assembly is modified to fit within a regular hex geometry



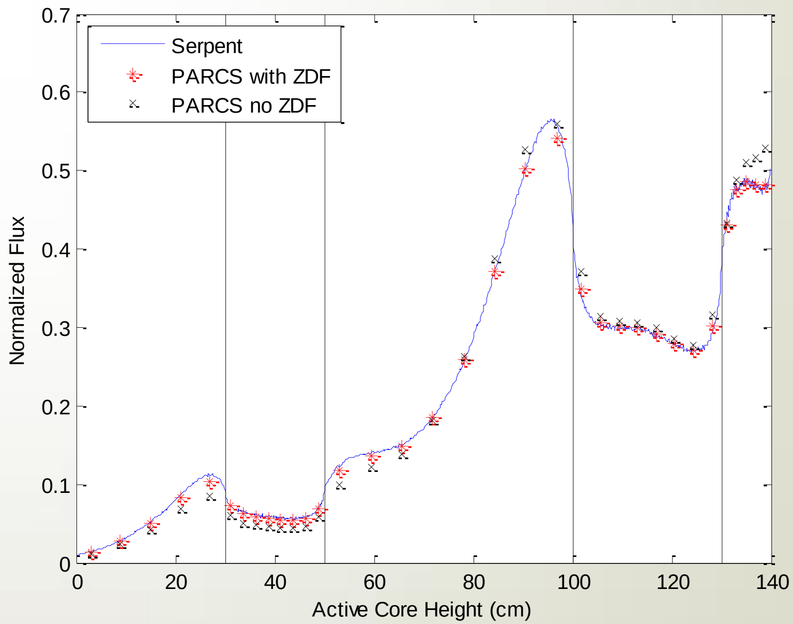


RBWR Assembly Simulation

Method	K	Difference from Serpent (pcm)
3D Serpent	1.09601	-
3D PARCS, 3D Serpent XS, no ZDFs	1.08772	829
3D PARCS, 3D Serpent XS, ZDFs	1.09601	0



Fast (Group 1) Flux Comparison



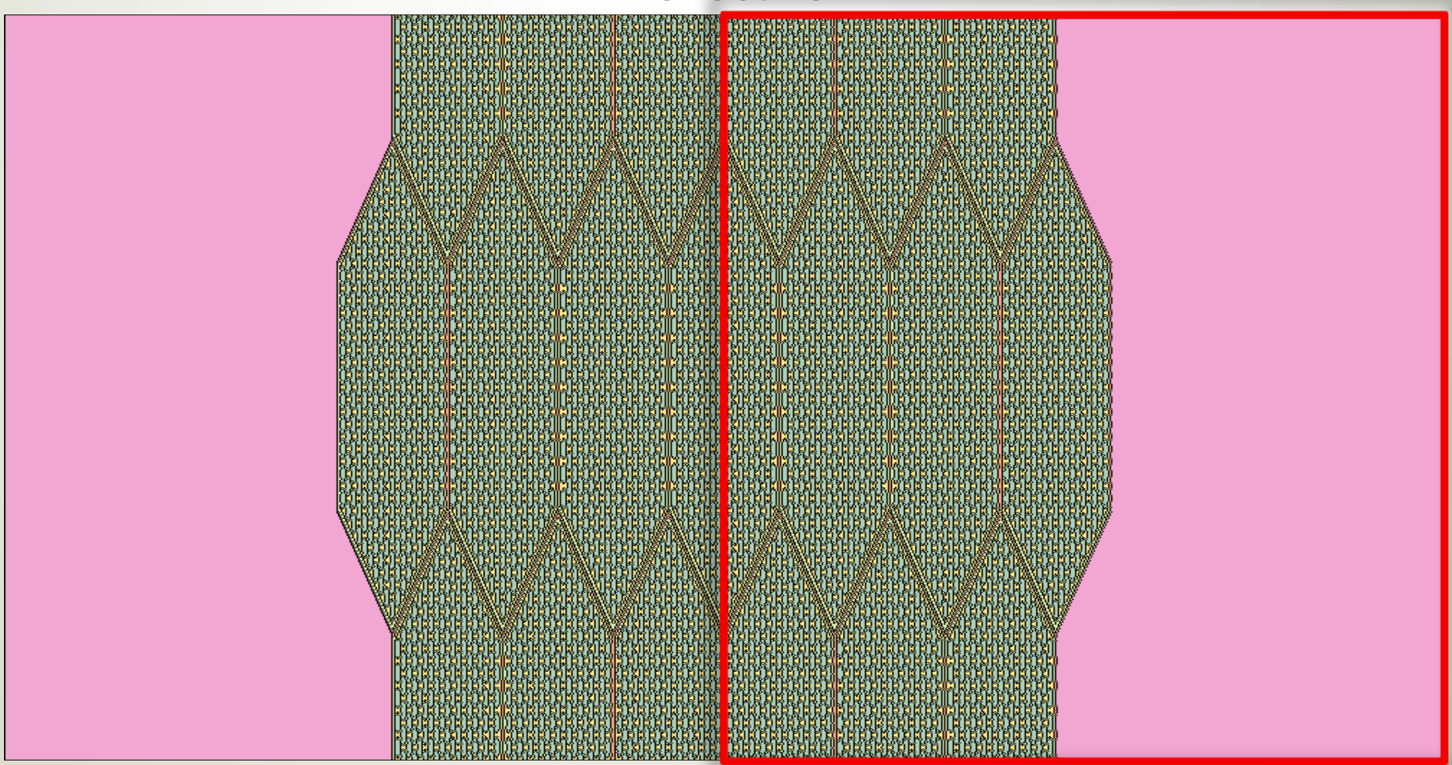
Thermal (Group 9) Flux Comparison

RBWR Radial Reflectors

- Reflector model used in Serpent (red box indicates typical fuel-reflector problem)
- Use 5 separate 2D Serpent models for each of the main regions in the RBWR-AC (LB, LF, IB, UF, UB)

Reflective

Vacuum



Vacuum

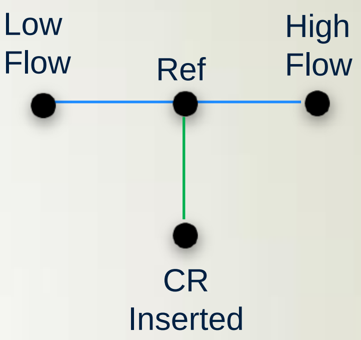
Reflective

Equilibrium Cycle Analysis

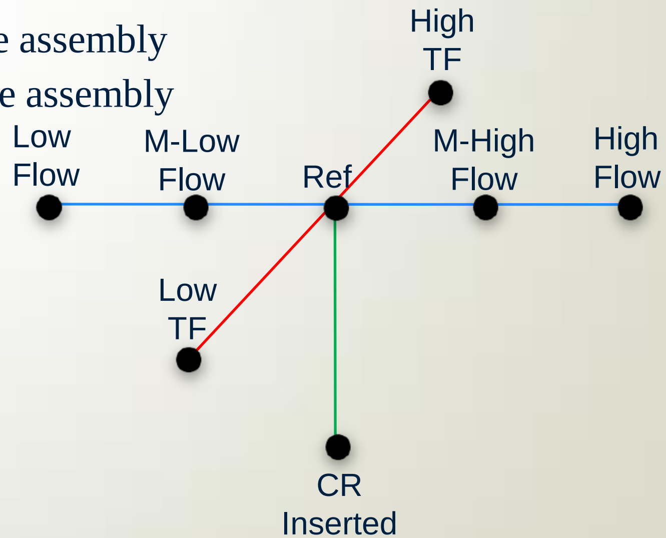
- Develop appropriate set of cross sections to capture core conditions
  - History and branch structure for the cross sections
- Process the cross sections using GenPMAXS code
  - Also calculate axial discontinuity factors
- Perform coupled code analysis using PARCS-PATHS
  - PARCS is a nodal diffusion code
  - PATHS is a drift flux thermal-hydraulics code
- Equilibrium Cycle results

Branching Methodology for RBWR

- 4 history cases:
  - Reference history case – reference void and temp. distribution, CR out
  - Low flow history case – low flow void distribution, ref. temp., CR out
  - High flow history case – high flow void distribution, ref. temp., CR out
  - 1 CR history case:
    - CR inserted through upper blanket, remaining reference conditions

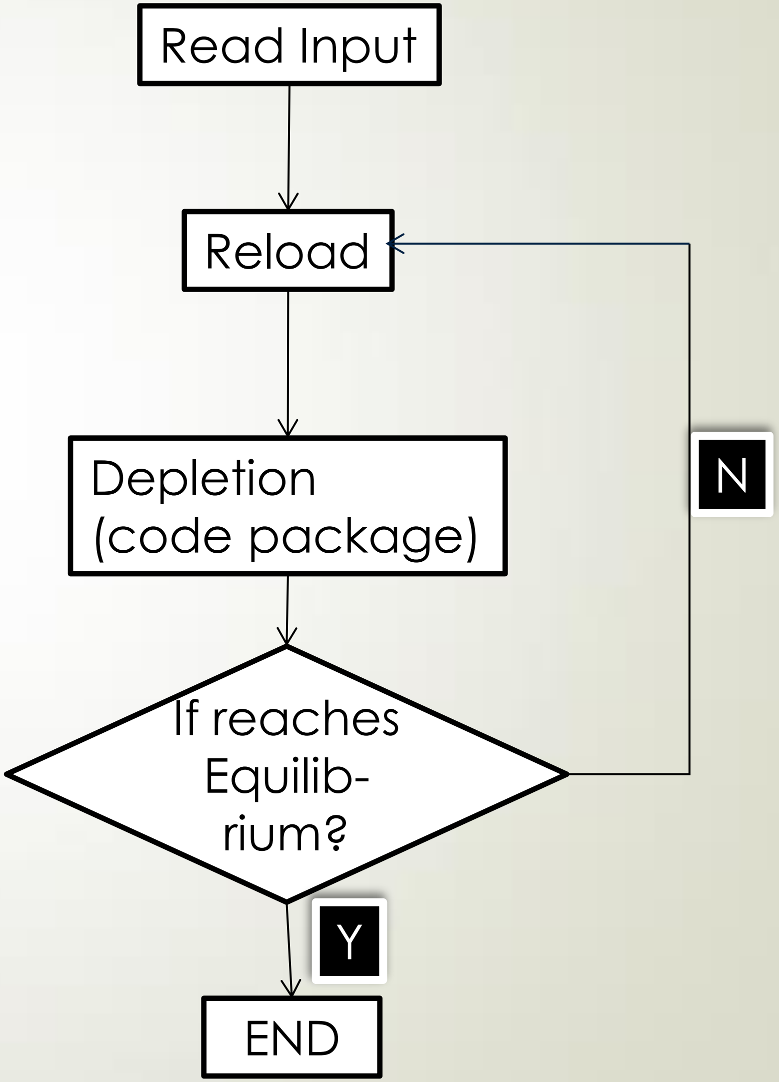


- 8 branch cases:
  - Reference branch
  - Low uniform fuel temperature perturbation over the whole assembly
  - High uniform fuel temperature perturbation over the whole assembly
  - Low flow void distribution (80% flow)
  - Medium-low flow void distribution (90% flow)
  - Medium-high flow void distribution (110% flow)
  - High flow void distribution (120% flow)
  - CR inserted at reference conditions

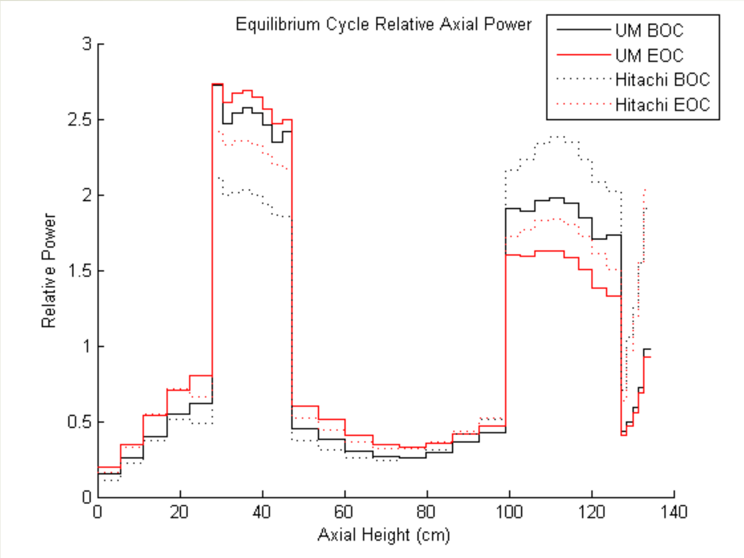


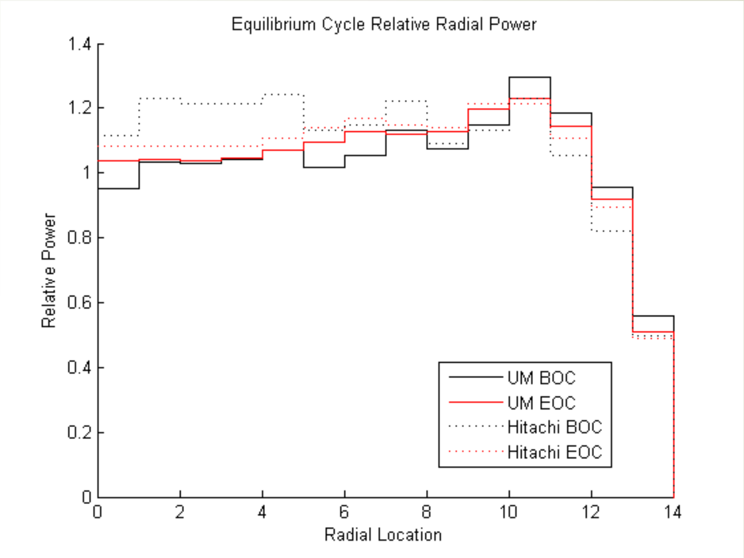
Equilibrium cycle search flowchart

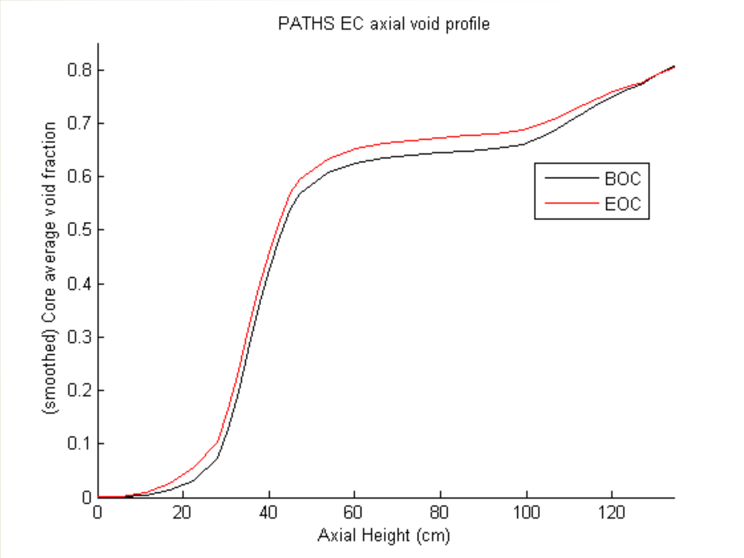
- **Begin with fresh core and load fuel after each burnup cycle using Hitachi specified loading pattern**
- **Explicitly model control rod pattern at each time step of depletion**
- **Convergence criterion: 0.1 GWD/T for Infinite norm of node-wise burnup matrix at EOC**

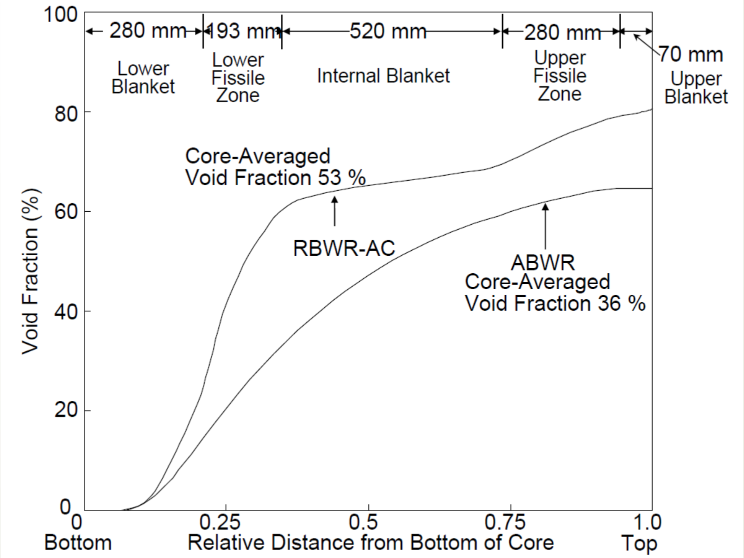


RBWR-AC Equilibrium Cycle Results







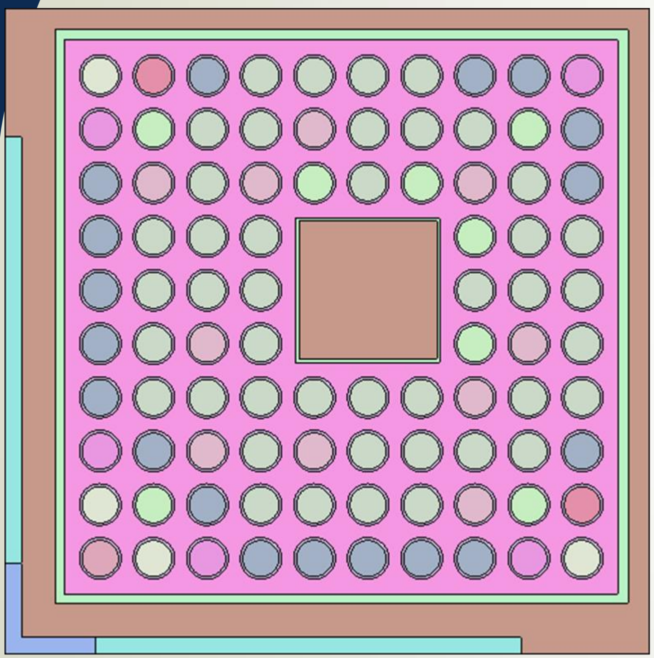


Control Rod Insertion for 3D XS

- The goal of this study was to assess the accuracy of 2D vs. 3D cross section generation for advanced fuel designs, specifically for control blade insertion
- Developed 2D and 3D cross sections using SERPENT for a BWR design with varying control blade positions
- Model consists of 8 different pin enrichments with 5 distinct axial layers (24 total axial regions)
- Compared relative power shapes, eigenvalue and peak axial planar powers for 2D, 3D and 3D with ZDF cross sections using PARCS to SERPENT at HZP

MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

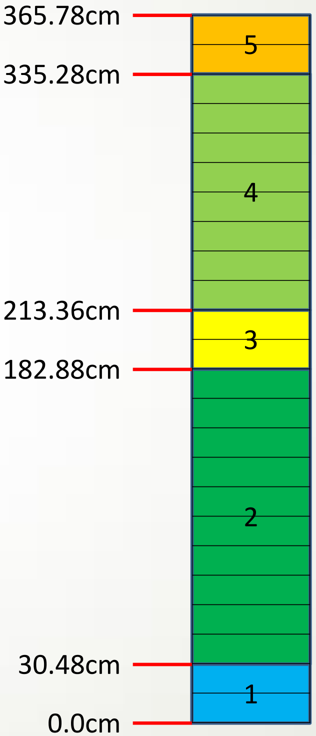
BWR Model



2	4	5	6	6	6	6	5	5	3
3	8	6	6	7	6	6	6	8	5
5	7	6	7	8	6	8	7	6	5
5	6	6	6	W	W	W	8	6	6
5	6	6	6	W	W	W	6	6	6
5	6	7	6	W	W	W	8	7	6
5	6	6	6	6	6	6	7	6	6
3	5	7	6	7	6	6	6	6	5
2	8	5	6	6	6	6	7	8	4
1	2	3	5	5	5	5	5	3	2

1) 1.8 w/o U-235
2) 2.1 w/o U-235
3) 2.6 w/o U-235
4) 3.0 w/o U-235
5) 3.4 w/o U-235
6) 3.7 w/o U-235
7) 3.7 w/o U-235+Gd
8) 3.4 w/o U-235*

* Part Length

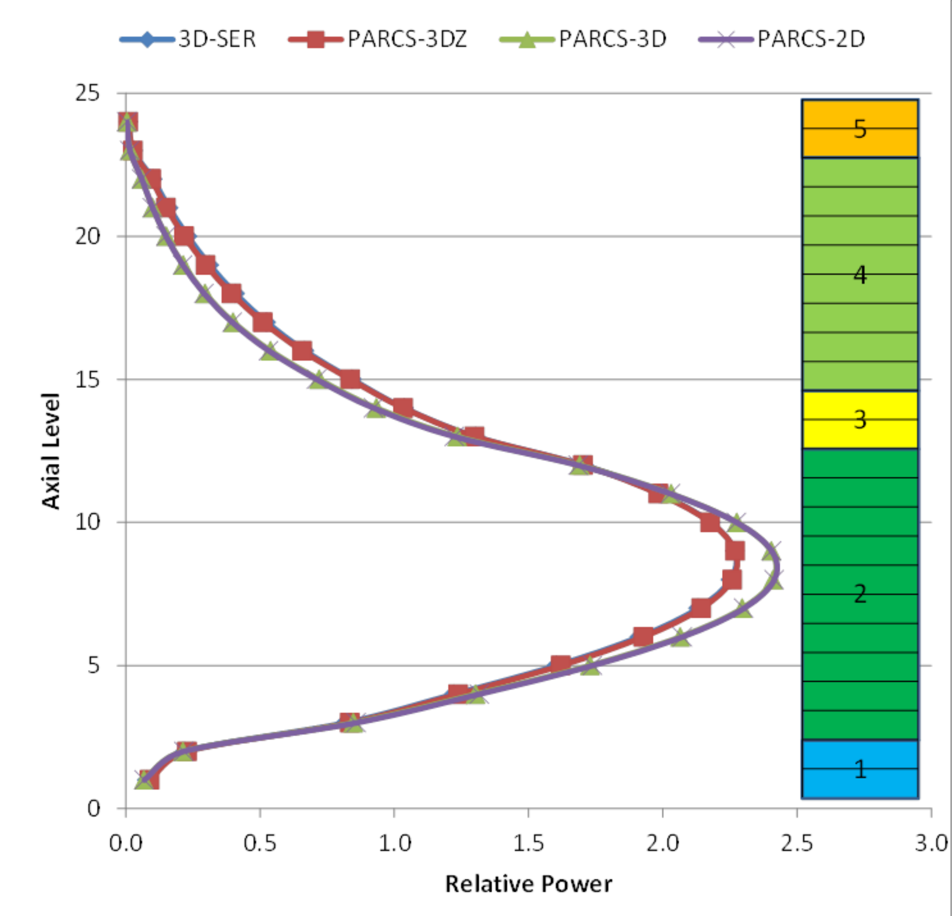


Axial Layers
5) Nat Uran, Part Length Vanished
4) Enriched Fuel, Part Length Vanished
3) Enriched Fuel, Part Length Empty
2) Enriched Fuel, Part Length Fueled
1) Nat Uran, Part Length Empty

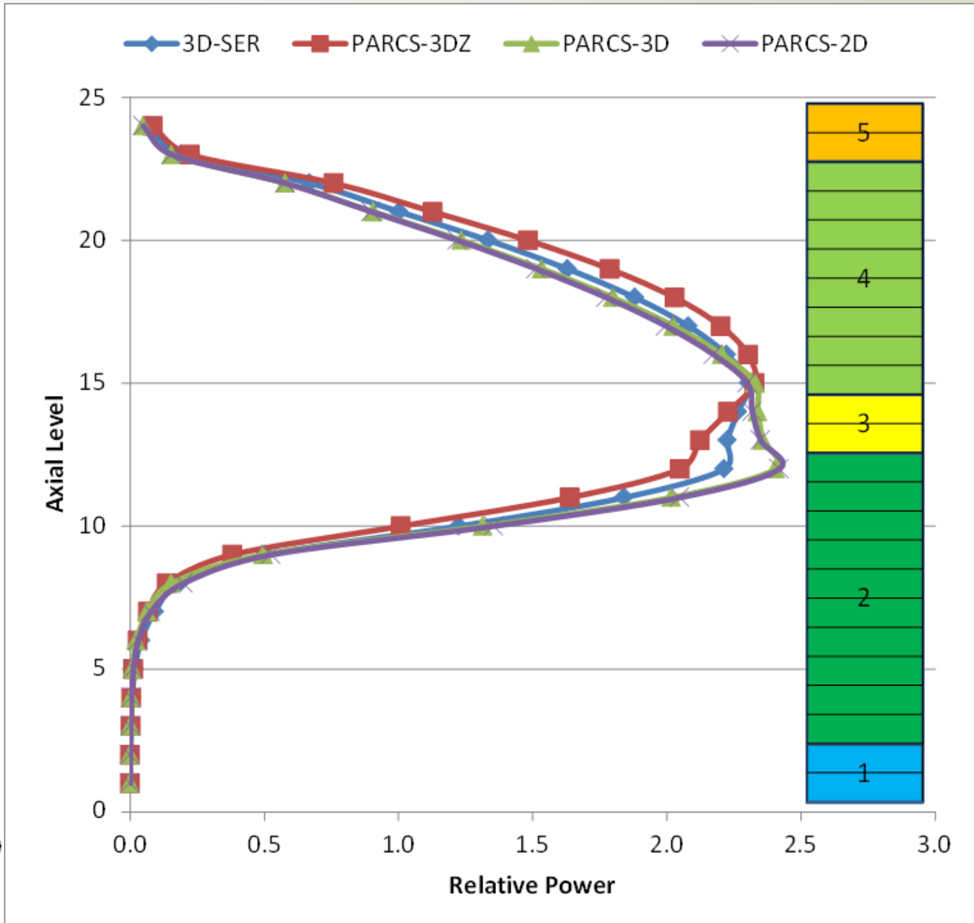
Boundary Conditions
Top and Bottom = Black
Radial = Reflective

Lines through each region indicate PARCS node boundaries

Relative Power Shape Comparison



Unrodded



Rodded Plane 9

MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Eigenvalue Comparison

Insertion	SERPENT	PARCS	PARCS	PARCS	P - ZDF	P- 3DXS	P-2DXS
	3D	3D-ZDF	3D -XS	2D -XS	Diff-SER.	Diff-SER.	Diff-SER.
[24=full]	[-]	[-]	[-]	[-]	[pcm]	[pcm]	[pcm]
0	1.07164	1.07163	1.07390	1.07406	-1	226	242
1	1.07146	1.07157	1.07383	1.07399	11	237	253
2	1.07102	1.07116	1.07334	1.07354	14	232	252
3	1.06953	1.06993	1.07197	1.07217	39	244	264
4	1.06721	1.06794	1.06992	1.07015	73	270	294
5	1.06445	1.06535	1.06732	1.06758	90	287	313
6	1.06133	1.06214	1.06412	1.06440	81	279	307
7	1.05744	1.05828	1.06027	1.06056	84	283	312
8	1.05346	1.05428	1.05630	1.05616	82	284	270
9	1.04885	1.04965	1.05146	1.05168	80	260	283
10	1.04497	1.04584	1.04756	1.04778	87	259	281
11	1.04142	1.04269	1.04446	1.04467	127	304	325
12	1.03838	1.03984	1.04180	1.04203	146	342	365
13	1.03504	1.03669	1.03902	1.03931	165	398	427
14	1.03072	1.03270	1.03551	1.03590	198	479	518
15	1.02510	1.02729	1.03076	1.03129	219	566	619
16	1.01741	1.01980	1.02418	1.02490	239	677	749
17	1.00665	1.00912	1.01477	1.01577	247	812	912
18	0.99060	0.99320	1.00066	1.00212	260	1007	1152
19	0.96591	0.96819	0.97833	0.98063	228	1242	1471
20	0.92641	0.92722	0.94108	0.94478	81	1467	1837

Summary/Conclusions

- PARCS with Serpent 3D cross sections for the RBWR
  - Developed a full set of 3D cross sections encompassing a wide range of operating conditions
  - Successfully reproduced 3D Serpent solution with PARCS using 3D Serpent cross sections with ZDFs
  - Completed equilibrium cycle calculation
- BWR control blade study
  - Tested the use of various cross section methodologies for axially heterogeneous BWR design with varying control blade positions
  - 3D cross sections with ZDFs provide the most accurate solution
  - In general, the error in the eigenvalue increased with control blade insertion
- Future studies:
  - Safety and stability analysis of the RBWR using PARCS/TRACE
  - Tallying of surface flux moments for higher order axial nodal solvers

MICHIGAN ENGINEERING

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Thank you for your attention!

Questions?

MICHIGAN ENGINEERING

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING