

# Advanced Methods Development for Equilibrium Cycle Calculations of the RBWR

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# Outline

- RBWR Motivation and Design
- Why use Serpent Cross Sections?
- Modeling the RBWR
- Axial Discontinuity Factors
- Generating an Equilibrium Cycle
- Conclusions

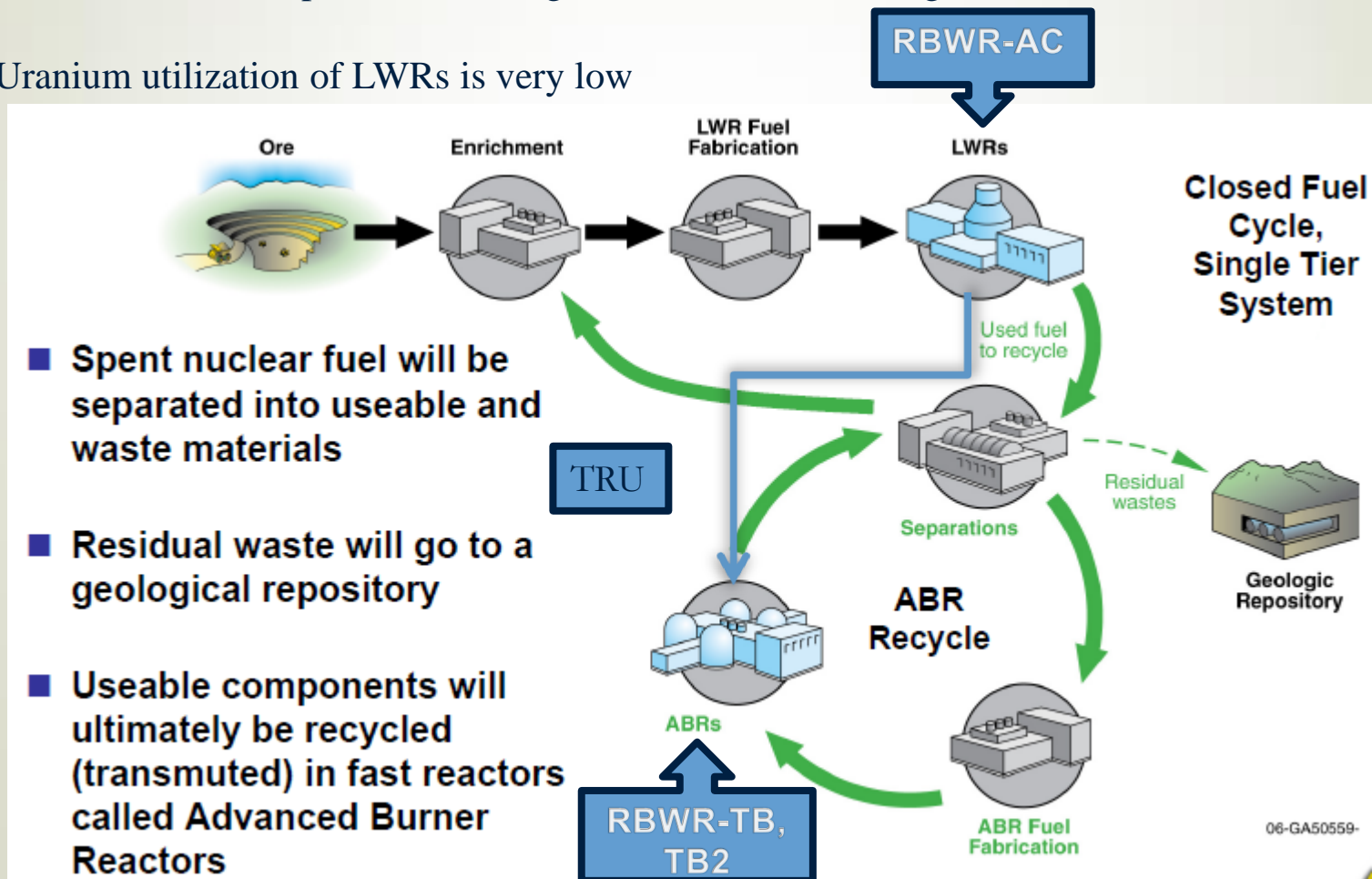


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# Motivation

- 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

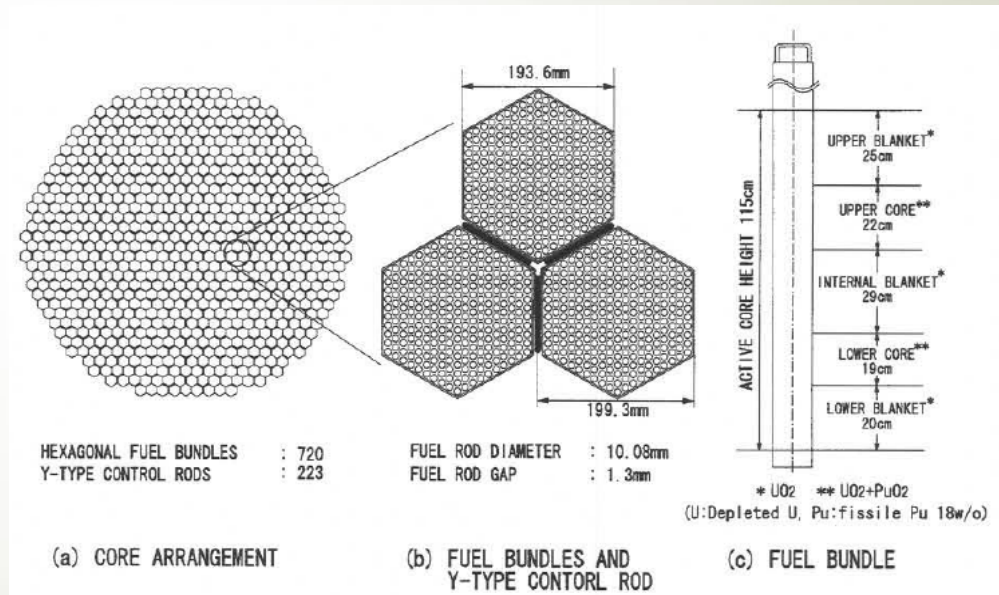


# DOE NEUP Projects Michigan/UCB/MIT

- Generate Equilibrium Cycle for both the RBWR-AC and RBWR-TB2
- Perform Reactivity Coefficient Analysis
  - Doppler Reactivity Coefficient
  - Void Reactivity Coefficient
- Stability and Transient Analysis for both cores
  - Recirculation Pump Failure is of interest since this could lead to an asymmetric reduction in cooling
  - Events such as Turbine Trips and Main Steam Isolation Valve Closures are not expected to be as significant due to a smaller void coefficient and larger Doppler coefficient

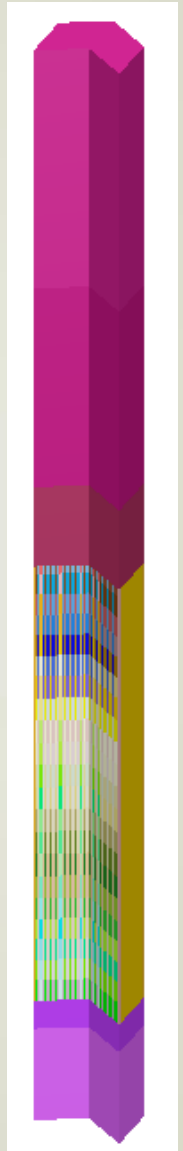
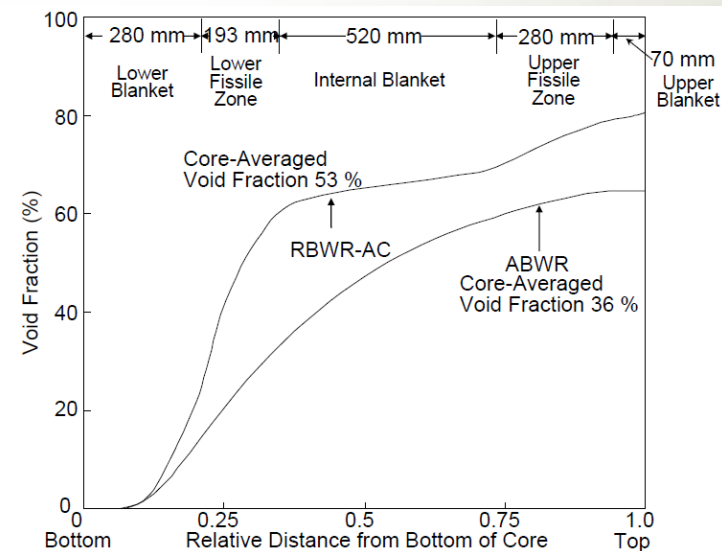
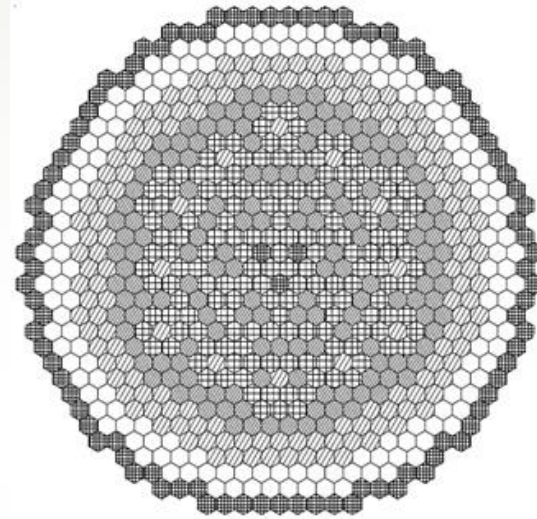
# Resource-Renewable Boiling Water Reactor (RBWR)

- 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-AC

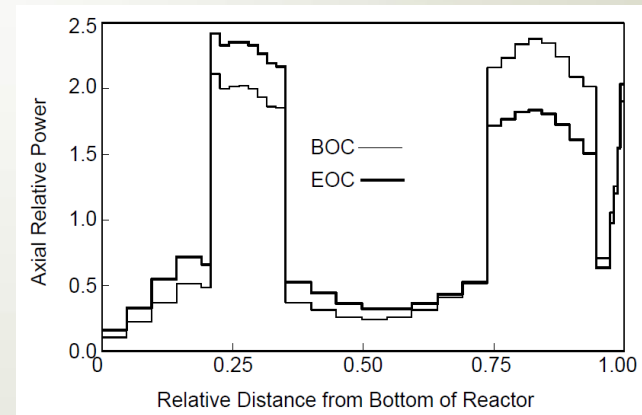
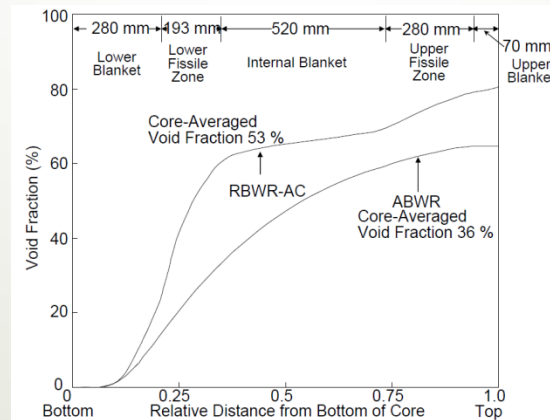
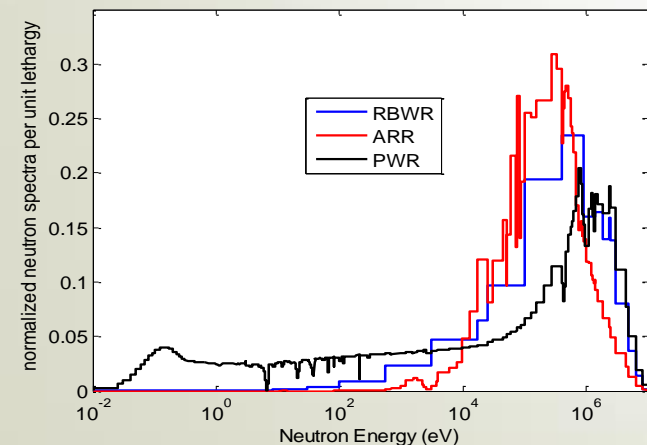
- The RBWR-AC is a tight pitch, boiling water reactor with a high core average void (~53%) / hard spectrum
- Parfait style assembly with internal blankets
- Features a conversion ratio of 1.0



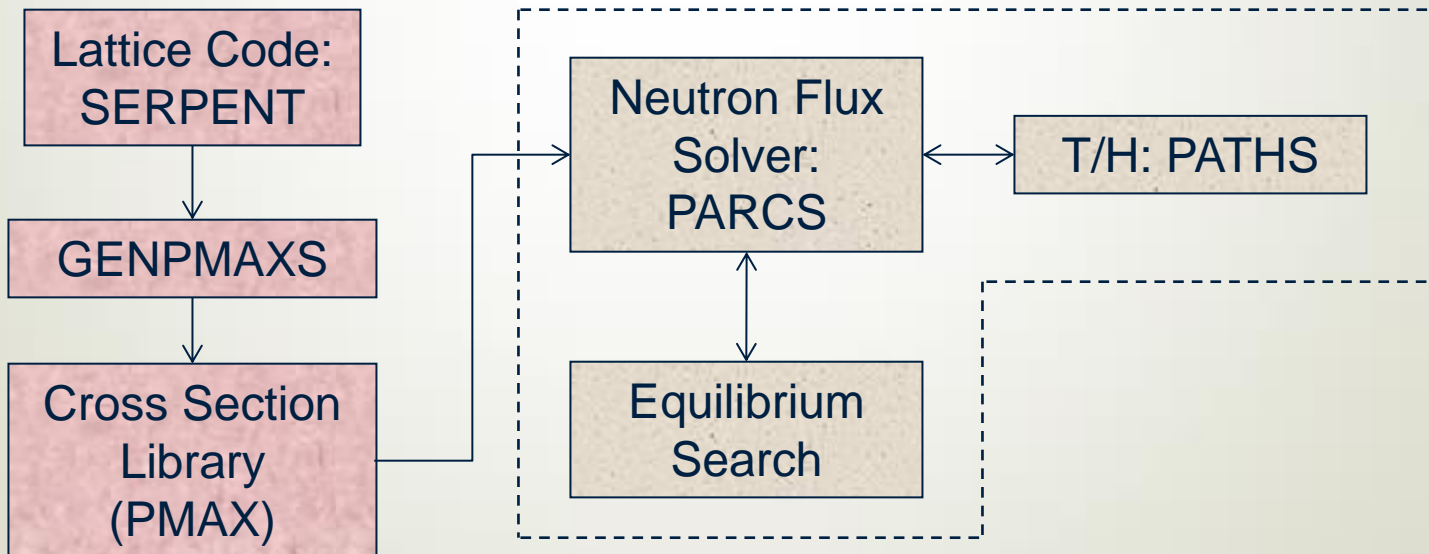
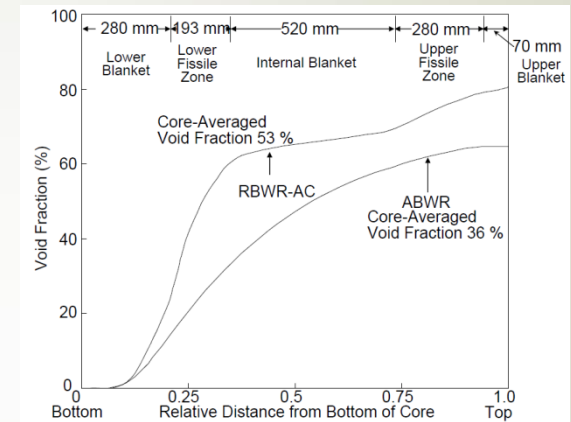
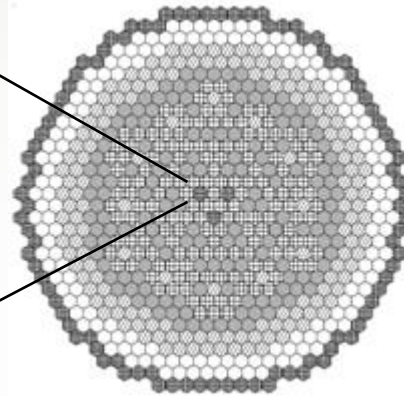
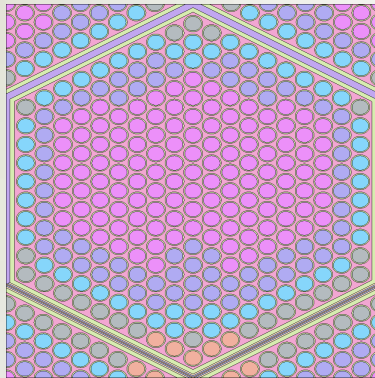


# RBWR Characteristics

- 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





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# Monte Carlo XSEC Generation

- Motivation:
  - Past methods used 12 group, homogenized cross sections from the 2-D lattice physics code HELIOS.
  - 3D Monte Carlo studies by MIT showed that there are some deficiencies in using this approach for the axially heterogeneous RBWR
- Challenges:
  - Computational burden due to multiple Monte Carlo calculations
    - 22 burnup steps x 20 branches x 6 histories
    - ~2,640 Serpent cases, take about 1-2 weeks to run
  - Large amount of memory required to store cross sections

# Cross Sections with SERPENT

- SERPENT – 3D Monte Carlo
  - Produces homogenized multi-group constants for deterministic reactor simulator calculations
  - Calculates ADFs for boundary surfaces and corners
  - Works for high void cases in RBWR where deterministic approaches break down
- Use SERPENT to generate 3D cross sections for PARCS (PMAXS)
- GenPMAXS code used to convert cross sections to PMAXS format along with calculation of the following:
  - Axial discontinuity factors
  - Zone-specific burnup



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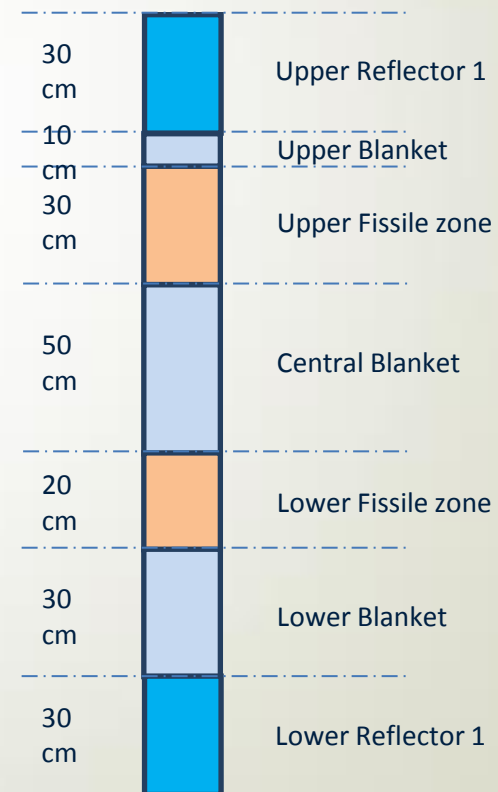
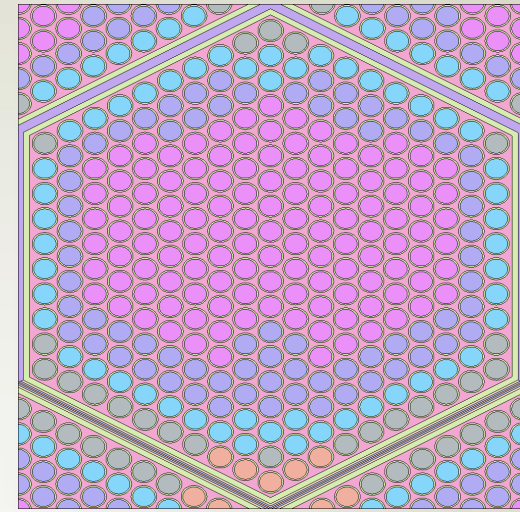


# Model Construction

- Generate benchmark assembly level models and 3D cross sections
- Comparison of 2D and 3D cross sections for assembly level analysis showed the need for axial discontinuity factors
- Generate 3D cross section libraries for depletion
- Perform Equilibrium Cycle Analysis using 3-D Serpent generated cross sections

# RBWR Benchmark 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 with 2D Serpent Cross Sections

- Generated 2D homogenized cross sections using Serpent
- A single assembly PARCS simulation with the 2D cross sections was used to check the solution
- Noticeable different between 3D Serpent assembly calculation and 2D cross sections
- Desire to use 3D cross sections to correct for differences

| Method                  | K       | Difference from Serpent (pcm) |
|-------------------------|---------|-------------------------------|
| 3D Serpent              | 1.09601 | -                             |
| 3D PARCS, 2D Serpent XS | 1.05422 | 4179                          |

# RBWR Assembly with 3D Serpent Cross Sections

- Generated 3D homogenized cross sections using Serpent
- A single assembly PARCS simulation with the 3D cross sections was used to check the solution
- There is still a difference seen between the 3D Monte Carlo solution and the 3D deterministic solution
- To correct for this, axial discontinuity factors were created

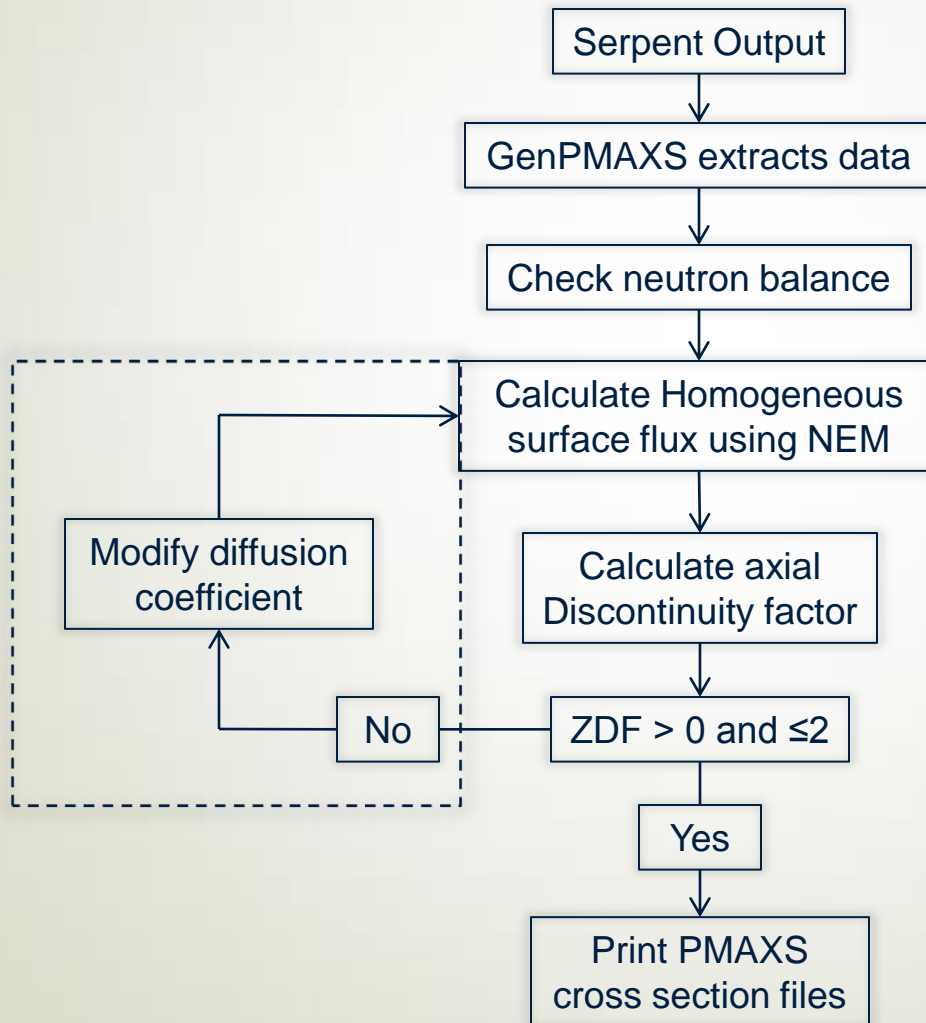
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| 3D Serpent              | 1.09601 | -                             |
| 3D PARCS, 2D Serpent XS | 1.05422 | 4179                          |
| 3D PARCS, 3D Serpent XS | 1.08772 | 829                           |



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# Axial Discontinuity Factor Generation Process



# Axial Discontinuity Factors

- Defined as the heterogeneous surface flux divided by the homogeneous surface flux
- The heterogeneous surface flux is calculated by using Serpent partial currents
- The homogeneous surface flux is generated by solving NEM in a single node
  - Discussed in more detail next slide

$$f_{i,g} = \frac{\phi_{i,g}^{het}}{\phi_{i,g}^{hom}}$$

$$\phi_{i,g}^{Het} = 2(J_{i,g}^{+} + J_{i,g}^{-})$$

$$J_{i,g}^{net} = -D_{i,g} \frac{d\phi_{i,g}}{dz}$$

# NEM Solver

- Start with transverse integrated 1D diffusion equation:

$$-D \frac{d^2 \phi_g(z)}{dz^2} + \Sigma_{t,g} \phi_g(z) - \frac{\chi_g}{k} \sum_{g'=1}^G \nu \Sigma_{fg'} \phi_{g'}(z) - \sum_{g'=1}^G \Sigma_{g,g'}^0 \phi_{g'}(z) = -L_{g,0}(z)$$

- Approximate the solution with 4<sup>th</sup> order Legendre polynomials:

$$\bar{\phi}(\xi) = \sum_{i=0}^4 \bar{a}_i P_i(\xi)$$

- Solve for the 5 coefficients using:

- Heterogeneous cell average flux

$$\bar{a}_0 = \bar{\phi}$$

- Net currents on left and right surfaces

$$\bar{a}_3 = -\frac{h}{12D} (\bar{J}^L + \bar{J}^R) - \frac{1}{6} \bar{a}_1$$

$$\bar{a}_4 = \frac{h}{20D} (\bar{J}^L - \bar{J}^R) - \frac{3}{10} \bar{a}_2$$

- Weighted residual equations

$$\left( \bar{A} + \frac{5\bar{D}}{2h^2} \right) \bar{a}_1 = -\frac{5}{4h} (\bar{J}^L + \bar{J}^R)$$

$$\left( \bar{A} + \frac{21\bar{D}}{2h^2} \right) \bar{a}_2 = -\frac{7}{4h} (\bar{J}^L - \bar{J}^R)$$

- Solve for the left and right surface fluxes:

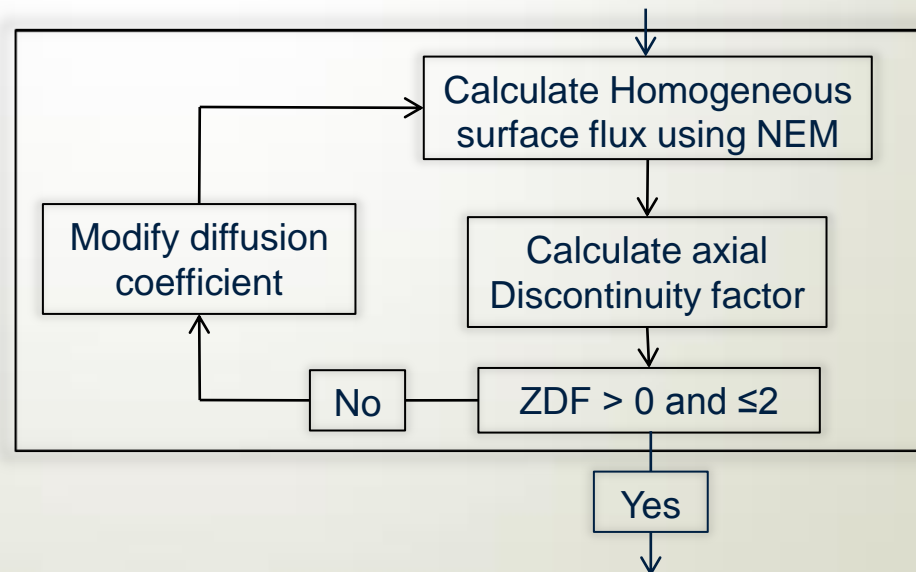
$$\bar{\phi}_{i,g}^{L,Hom} = \bar{a}_0 - \bar{a}_1 + \bar{a}_2 - \bar{a}_3 + \bar{a}_4$$

$$\bar{\phi}_{i,g}^{R,Hom} = \bar{a}_0 + \bar{a}_1 + \bar{a}_2 + \bar{a}_3 + \bar{a}_4$$

# Treatment of the Diffusion Coefficient

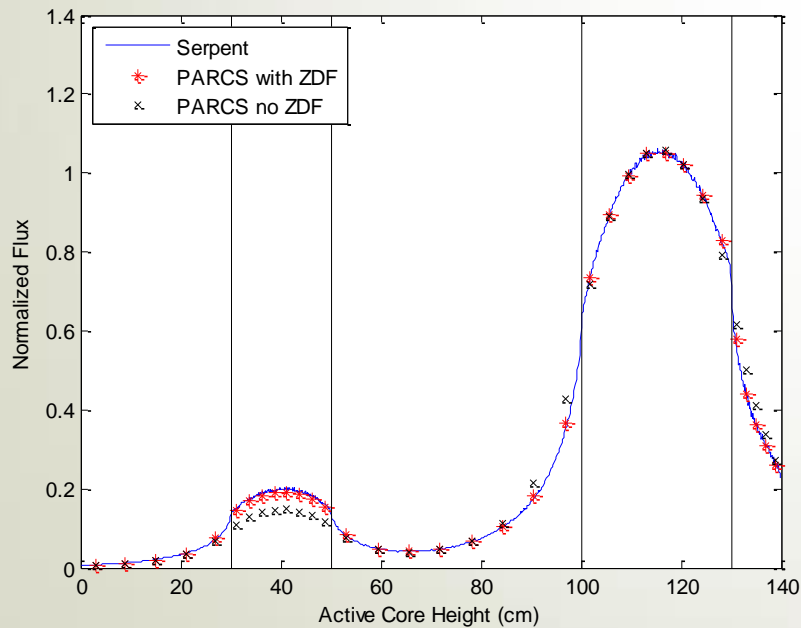
- Any discontinuity factor that is  $<0$  and  $>2$  is adjusted since this causes instabilities within PARCS
  - This occurs when the gradient on the boundary is large
  - Typically on the interface between blanket and fissile regions due to steep change in the flux
  - Diffusion coefficient is modified to preserve the net surface current
  - Iterative process until the axial discontinuity factor lies within the specified bounds

$$\tilde{D}_{i,g} = D_{i,g} \left( \frac{\bar{\phi}_{i,g} - \phi_{i,g}^{Hom}}{\bar{\phi}_{i,g} - \frac{1}{2} \phi_{i,g}^{Het}} \right)$$

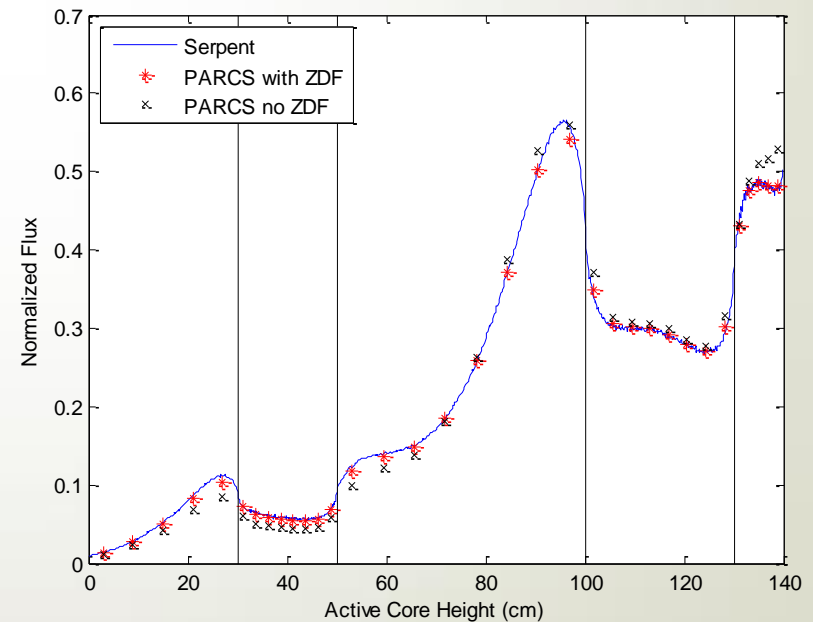


# RBWR Assembly Simulation

| Method                | K       | Difference from Serpent (pcm) |
|-----------------------|---------|-------------------------------|
| 3D Serpent            | 1.09601 | -                             |
| 3D PARCS without ZDFs | 1.08772 | 829                           |
| 3D PARCS with ZDFs    | 1.09601 | 0                             |



Fast (Group 1) Flux Comparison



Thermal (Group 9) Flux Comparison





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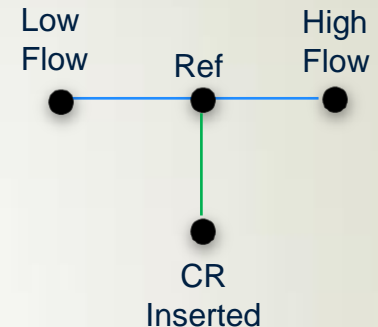


# Equilibrium Cycle Analysis

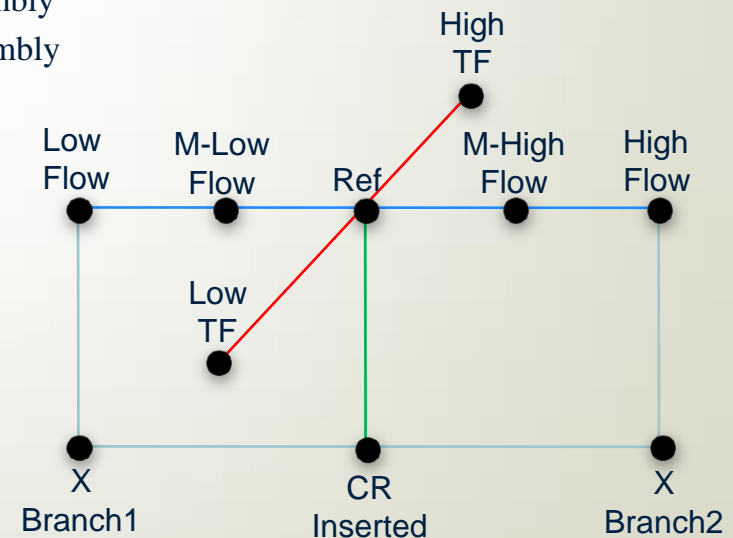
- Develop appropriate set of cross sections to capture core conditions
  - History and branch structure for the cross sections
- Process the cross sections using GenPMAXS code
  - Also calculate axial discontinuity factors and node burnups
- Perform coupled code analysis using PARCS-PATHS
  - PARCS is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

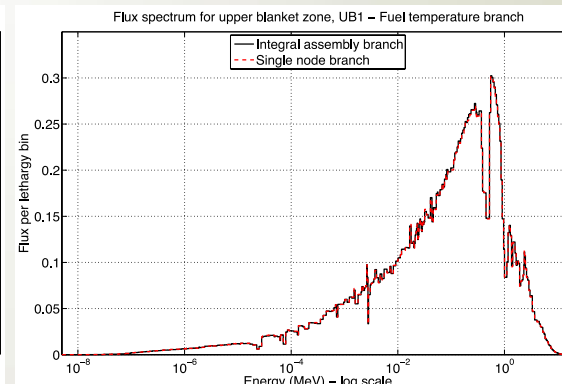
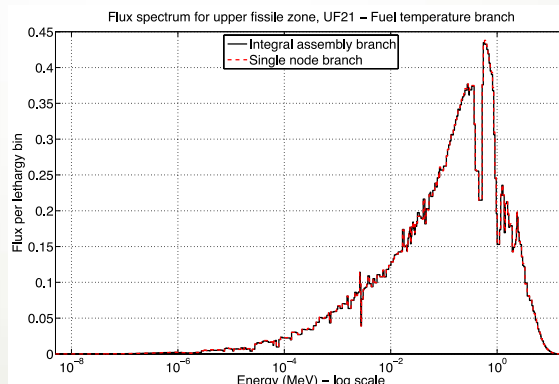
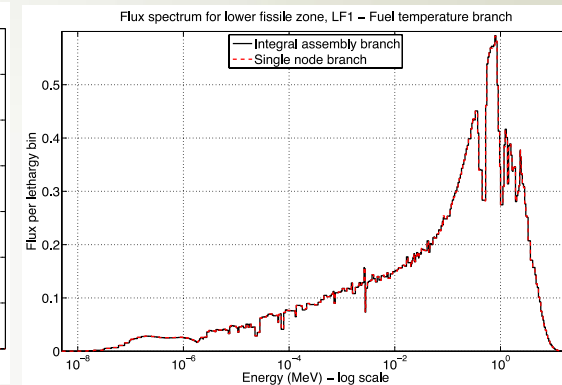
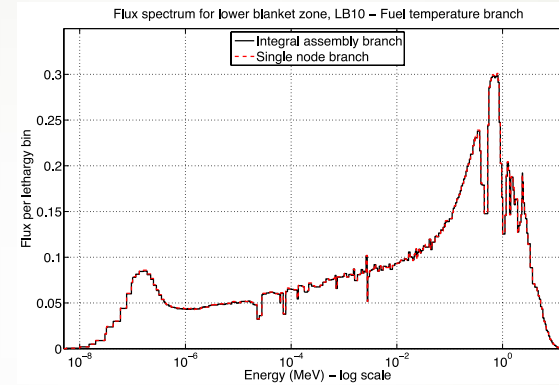


- 10 branch cases:
  - Reference branch
  - Low uniform fuel temperature perturbation over the whole assembly
  - High uniform fuel temperature perturbation over the whole assembly
  - Low flow void distribution (80% flow)
  - Medium-low flow void distribution (90% flow)
  - Medium-high flow void distribution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



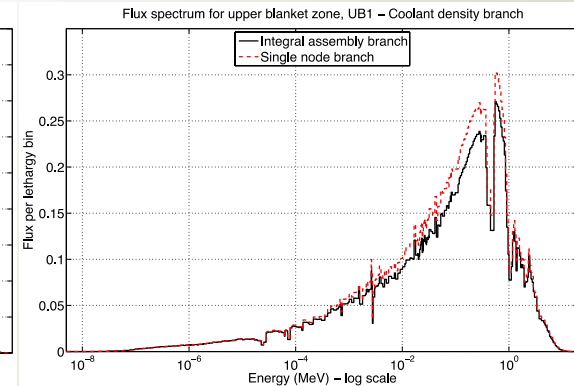
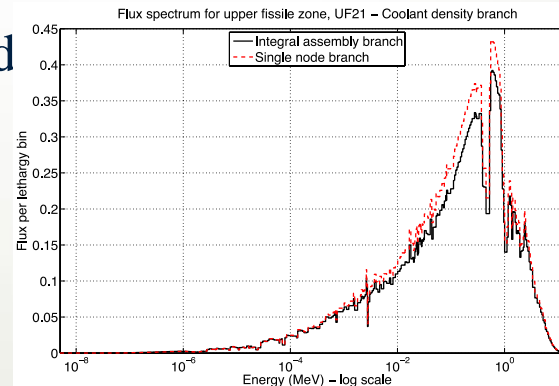
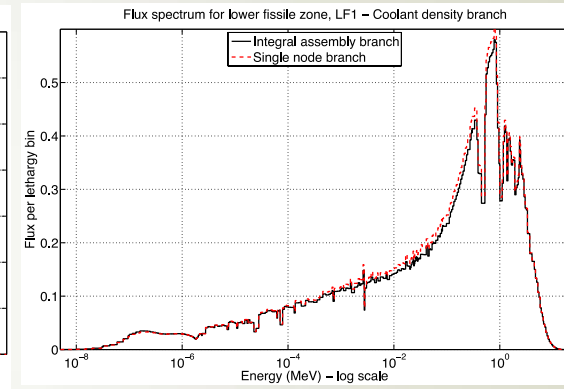
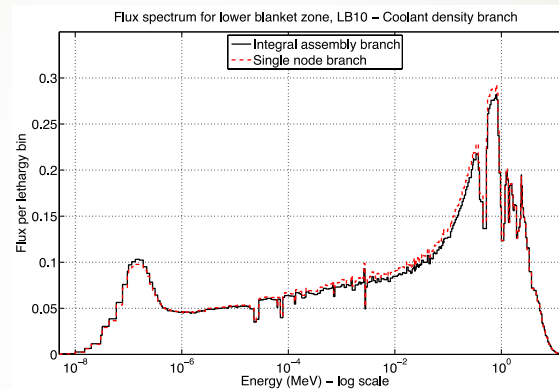
# Temperature Branches

- Nick Brown at BNL performed a parametric study: +300K fuel temp.
- Looked at perturbing single regions and the integral assembly
- No spectral variation seen
- Can perturb temperature simultaneously for entire assembly



# Void Branches

- Nick Brown also looked at this: +20% coolant density
- Looked at perturbing single regions and the integral assembly
- Spectral variation seen towards top of the assembly
- Must physically perturb void distribution
- Use Coupled PARCS/RELAP with 2D cross sections to develop void profiles for various flows



# CR Branches

- For first take at equilibrium cycle, generate cross sections for control rod fully inserted in assembly
- Second time, generate cross sections for control rod inserted at several different levels within the assembly
- Unrodded cross sections for regions towards the top of the assembly get complicated since there are second order effects from where exactly the rod is positioned

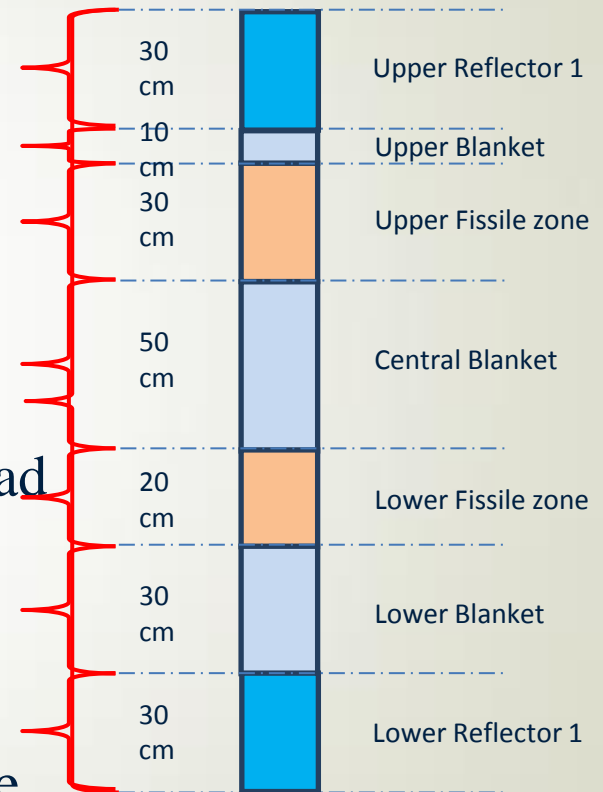


# GenPMAXS Capabilities

- Converts Serpent and Serpent2 cross sections to PMAXS format
- Node-wise burnup from 3D calculation
  - Previously calculated assembly averaged burnup
- ZDF Control
  - Bounds for ZDFs
  - Capability to set partial derivatives to zero (Reference only ZDFs)
- Set IHMD and cell volume
- Transport cross section treatment
- Absorption cross section adjustment for neutron balance

# Depletion Analysis

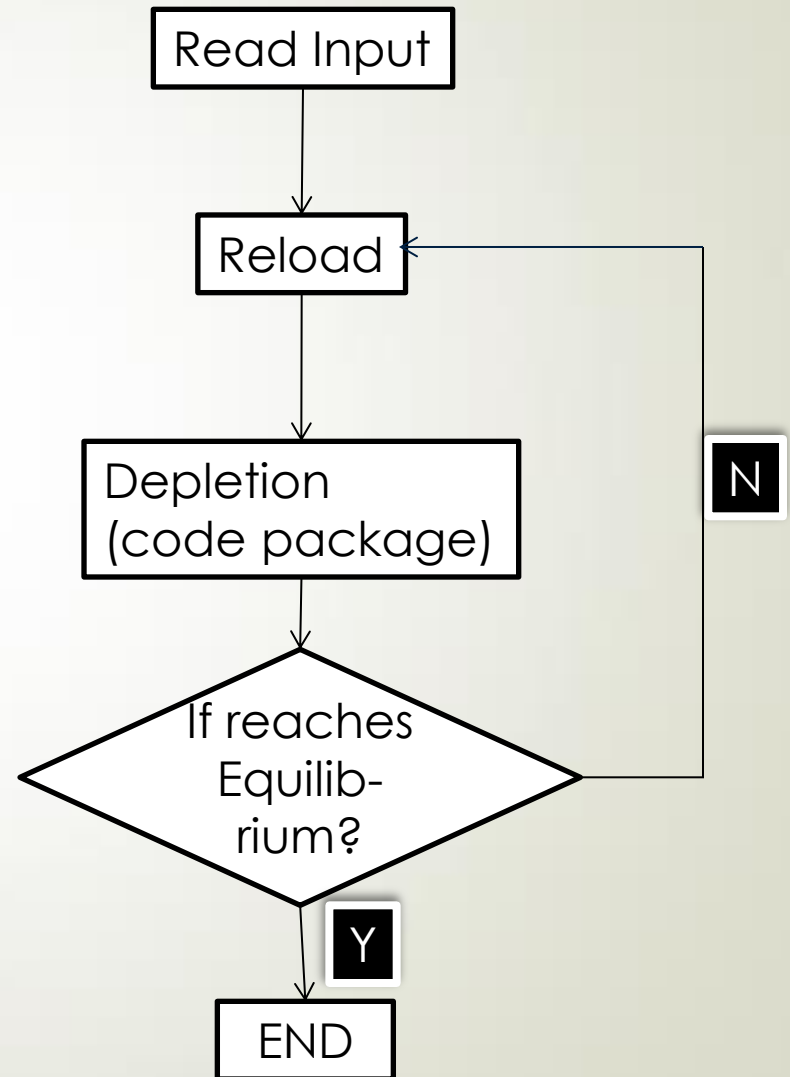
- PARCS and Serpent perform depletion two different ways:
  - Serpent depletes using an average assembly burnup
  - PARCS depletes based upon individual node burnups
- This is a problem when PARCS attempts to read cross sections based on a burnup other than 0 MWd/kgU
- One solution involves determining the individual node-wise burnups directly from the Serpent simulation





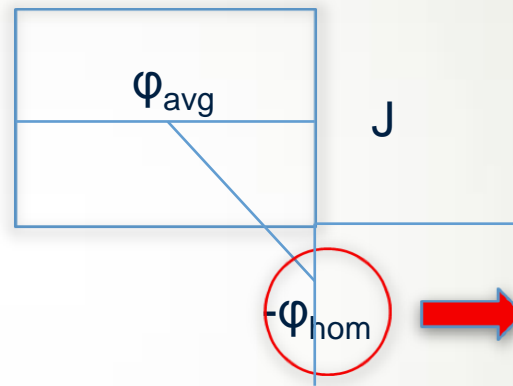
# Equilibrium cycle search flowchart

- **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**



# ZDF Generation

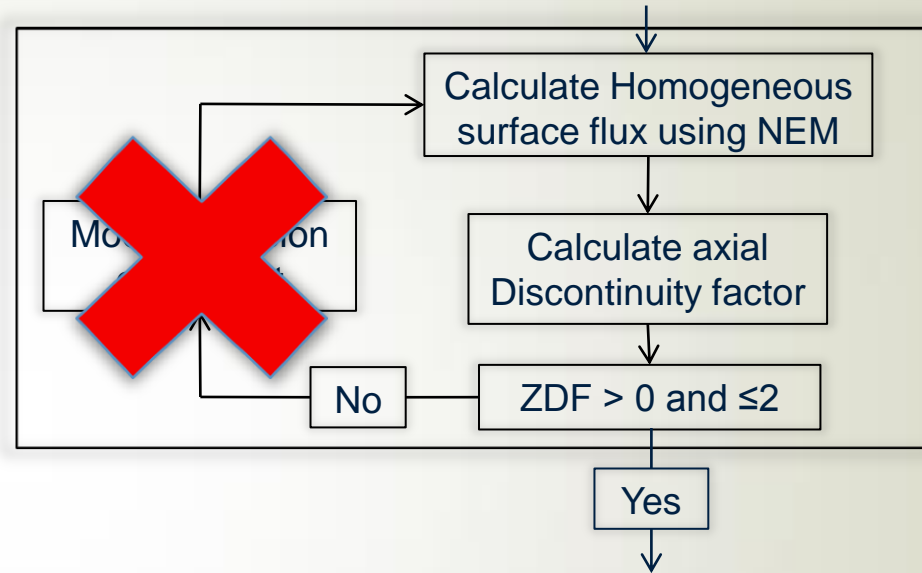
- On the interface, large currents can cause the homogeneous flux to become negative
  - This leads to negative ZDFs and negative fluxes in PARCS
- To address this issue, the ZDFs were adjusted by modifying the diffusion coefficient to fit within certain bounds (0.85-1.15)
- This works great for reference conditions but introduces another issue when dealing with multiple branches and histories



$$f = \frac{\phi_{i,g}^{het}}{-\phi_{i,g}^{hom}} = -f$$

# ZDF Bounding Treatment

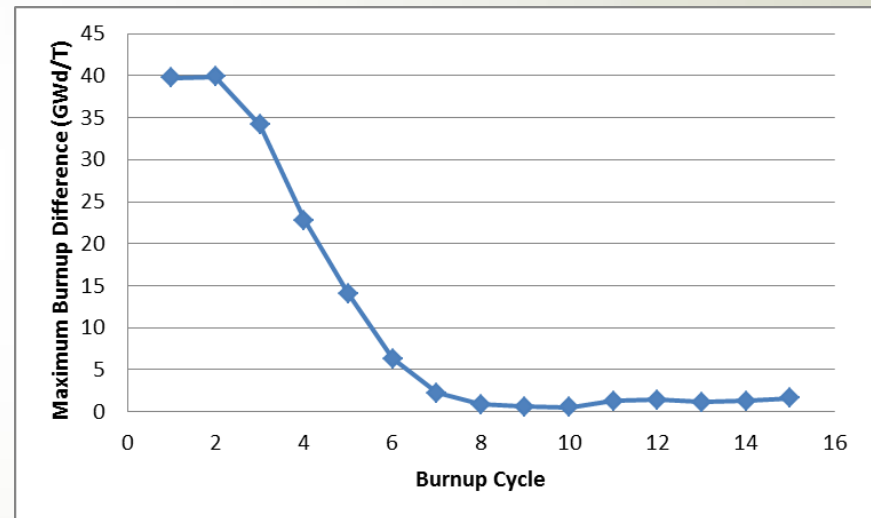
- Instead of adjusting the diffusion coefficient, a cap was placed on the ZDFs (0.85-1.15)
- Single assembly benchmark case was used to test this effect



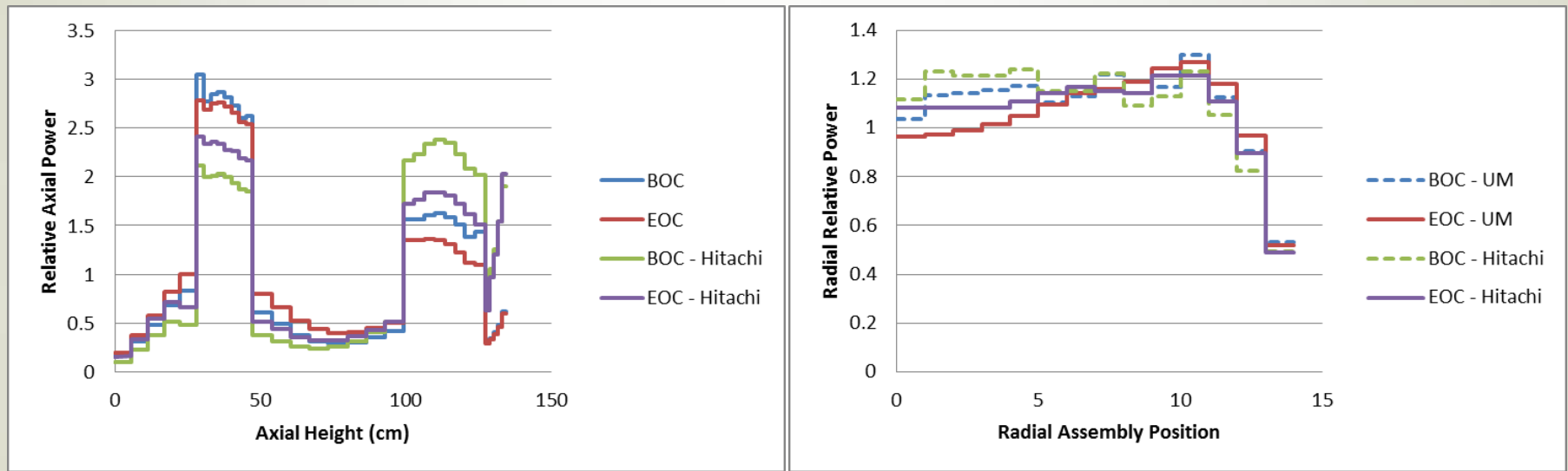
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|--|---------|-------------------------------|
| 3D Serpent   | 1.09601 | -                             |
| 3D PARCS without ZDFs                                  | 1.08772 | -829                          |
| 3D PARCS with ZDFs                                     | 1.09601 | 0                             |
| 3D PARCS with ZDFs no Diffusion coefficient adjustment | 1.09645 | 44                            |

# *Equilibrium Cycle*

- 3D Cross Sections
  - 1 history, 8 branches
- Bounded ZDFs (0.85 – 1.15)
- No iteration on the transport cross section
- Node-wise burnup from Serpent
- System is slightly subcritical over equilibrium cycle (0.996-0.994)



# Equilibrium Cycle





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# Summary/Conclusions

- PARCS with Serpent 3D cross sections for the RBWR
  - Successfully reproduced 3D Serpent solution for an assembly benchmark with PARCS using 3D Serpent cross sections with ZDFs
  - For 3D core Equilibrium Cycle calculation, encountered some numerical instabilities with using large ZDFs.
    - Imposed restriction on the magnitude of the ZDFs and eliminated the diffusion coefficient modification.
    - Successfully computed 3D equilibrium cycle
  - Continuing work
    - Expand cross section set to encompass a broader range of history and branch effects
    - Perform stability and transient analysis on equilibrium core
- Serpent
  - Possible inclusions/modifications to Serpent:
    - Calculate GCU based burnups as well as total averaged burnup
    - Output formatting modifications for post-processing



Thank you for your attention!

Questions?