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PARCS Applications – Core Depletion and Reactor Statics



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SCALE 6.3.1 last revision (May 2024)

Outline

- **Purposes of reactor design & analysis**
- **Introduction to our patient – Zora Unit 1**
- **Running PARCS core simulations for a realistic core**
  - Setting up a core model
  - Core depletion with DEPL
  - Equilibrium core iterations with MCYCLE
- **Restarting state points and pin power reconstruction**
- **Reactor statics**
  - Reactivity coefficients
  - Shutdown margin/stuck control rod worth
  - Ejected control rod worth

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Purposes of nuclear design & analysis



Purposes of nuclear design & analysis

- LWR cores are a mix of fresh (feed) and exposed (burned) fuel assemblies arranged to:
  - Generate required energy over the course of the operating cycle
  - Utilize fuel efficiently such that costs are controlled
  - Maintain power distribution comfortably within failure limits
  - Ensure "safe" reactivity characteristics
    - Inherent feedback mechanisms shut fission reaction down upon power increases (i.e., negative total power feedback coefficient)
    - Safety-related means of reactivity control shut fission reaction down upon demand
- Regulatory criteria spelled out in NUREG-0800, Section 4.3 (Nuclear Design) and Section 15.4 (Reactivity-initiated Events)

“Observables” for PWRs

- Cycle energy
  - End of cycle critical boron concentration should be near zero
- Fuel efficiency
  - Fuel assembly burnup at discharge should be close to, but not past, fuel burnup limits
  - Burnup limits usually established at a local or pin-averaged level
- Power distribution
  - Peak axially-integrated pin relative power (FΔh) should be less than fuel design limit
    - protect against departure from nucleate boiling (DNB) (AOO criteria)
  - Peak local pin power (Fq) should be less than design limit
    - protect against fuel centerline melt (AOO criteria)
  - Other bases within safety analysis (LOCA, etc.)

"Observables" for PWRs

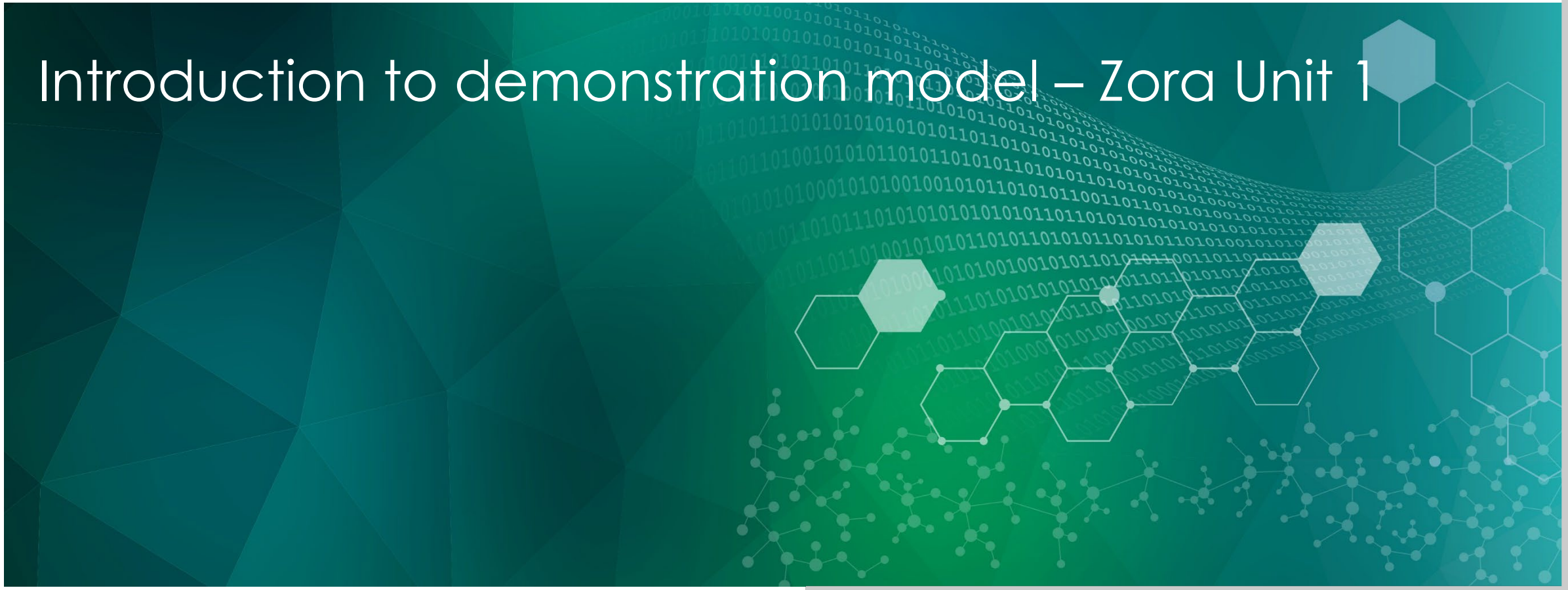
- Reactivity characteristics
  - Doppler feedback is always negative for LEU cores – need to make sure moderator/coolant temperature feedback is either negative or only slightly positive
    - Sets upper limit on critical boron concentration – usually ~1500 ppm at hot full power (plant dependent)
  - Control rod worth is sufficiently large to instantaneously shut fission reaction down
  - Potential ejected rod worth is sufficiently low to ensure fuel stays coolable if there is a rod ejection

Methods of nuclear design & analysis

- Design & safety criteria are demonstrated through use of core simulator software
  - Few-group nuclear data for each distinct fuel assembly segment generated with a lattice physics code (e.g., Polaris, CASMO, PARAGON2)
  - 3D nodal simulator code is used to arrange fuel segments into assemblies, place assemblies within the core, and simulate core behavior (reactivity, power distribution, etc.) throughout operating cycle, under any configuration allowed by plant technical specifications (TS) (e.g., PARCS, SIMULATE, ANC)
  - High-fidelity options like ORNL's VERA combine lattice physics and core simulator into a single package to do full-core, pin-by-pin transport/depletion – at the cost of lots of cpu-hours for the solution
  - Every fuel vendor and many utilities have NRC-approved core design and analysis methodologies that evaluate all the relevant criteria
    - Ensure reloads fit within operational envelope established in safety analysis
- Later – walk through an example of how to accomplish elements of these processes with PARCS

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Introduction to demonstration model – Zora Unit 1



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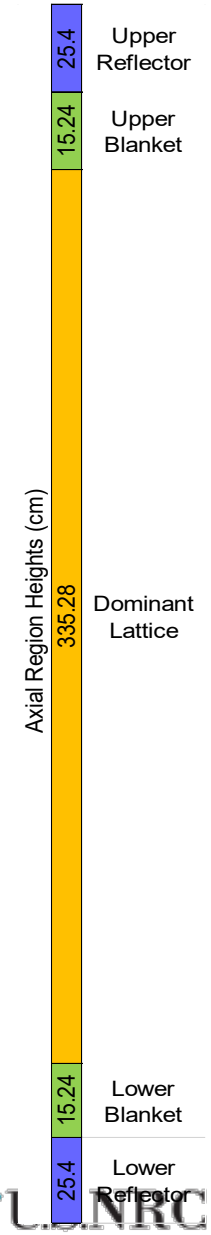
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Zora Unit 1

- Westinghouse 3-loop plant
  - 17x17 fuel design
  - 157 fuel assemblies
  - 12 foot active fuel length
  - Rated power 2940 MWth
- 69 feed assemblies
  - 1 2.0 wt %
  - 32 4.7 wt %
  - 36 4.95 wt %
- Gadolinia (Gd_2O_3) used for early-cycle critical boron and power distribution control

row \ column	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							4.95 wt/o 16@4 wt/o N-09	4.95 wt/o 16@4 wt/o K-06	4.95 wt/o 16@4 wt/o C-09						
2					4.70 wt/o 24@8 wt/o L-09	4.70 wt/o 24@8 wt/o M-09	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o FEED	4.70 wt/o 24@8 wt/o D-09	4.70 wt/o 24@8 wt/o E-09				
3				4.70 wt/o 24@8 wt/o F-14	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o N-11	4.95 wt/o 24@8 wt/o FEED	4.95 wt/o 16@4 wt/o C-11	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o FEED	4.70 wt/o 24@8 wt/o K-14			
4			4.70 wt/o 24@8 wt/o B-10	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 16@4 wt/o J-02	4.95 wt/o 20@4 wt/o N-10	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o H-10	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 20@4 wt/o C-10	4.95 wt/o 16@4 wt/o G-02	4.95 wt/o 16@4 wt/o FEED	4.70 wt/o 24@8 wt/o P-10		
5		4.70 wt/o 24@8 wt/o G-05	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 16@4 wt/o P-07	4.70 wt/o 24@8 wt/o G-09	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 24@8 wt/o H-14	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o J-09	4.95 wt/o 16@4 wt/o B-07	4.95 wt/o 16@4 wt/o FEED	4.70 wt/o 24@8 wt/o J-05	
6		4.70 wt/o 24@8 wt/o G-04	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 20@4 wt/o F-03	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 16@4 wt/o D-12	4.70 wt/o 24@8 wt/o K-05	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o F-05	4.95 wt/o 16@4 wt/o M-12	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 20@4 wt/o K-03	4.95 wt/o 20@4 wt/o FEED	4.70 wt/o 24@8 wt/o J-04	
7	4.95 wt/o 16@4 wt/o G-03	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 16@4 wt/o E-03	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o L-06	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 24@8 wt/o H-13	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o E-06	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 16@4 wt/o L-03	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 16@4 wt/o J-03
8	4.95 wt/o 16@4 wt/o K-10	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o F-08	4.95 wt/o 20@4 wt/o B-08	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 24@8 wt/o C-08	2.00 wt/o - FEED	4.95 wt/o 24@8 wt/o N-08	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 20@4 wt/o P-08	4.70 wt/o 24@8 wt/o K-08	4.95 wt/o 24@8 wt/o FEED	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o F-06
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12			4.70 wt/o 24@8 wt/o B-06	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 16@4 wt/o J-14	4.95 wt/o 20@4 wt/o N-06	4.70 wt/o 24@8 wt/o FEED	4.70 wt/o 24@8 wt/o H-06	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 20@4 wt/o C-06	4.95 wt/o 16@4 wt/o G-14	4.95 wt/o 16@4 wt/o FEED	4.70 wt/o 24@8 wt/o P-06		
13				4.70 wt/o 24@8 wt/o F-02	4.95 wt/o 16@4 wt/o FEED	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o N-05	4.95 wt/o 24@8 wt/o FEED	4.95 wt/o 16@4 wt/o C-05	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o FEED	4.70 wt/o 24@8 wt/o K-02			
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15							4.95 wt/o 16@4 wt/o N-07	4.95 wt/o 16@4 wt/o F-10	4.95 wt/o 16@4 wt/o C-07						

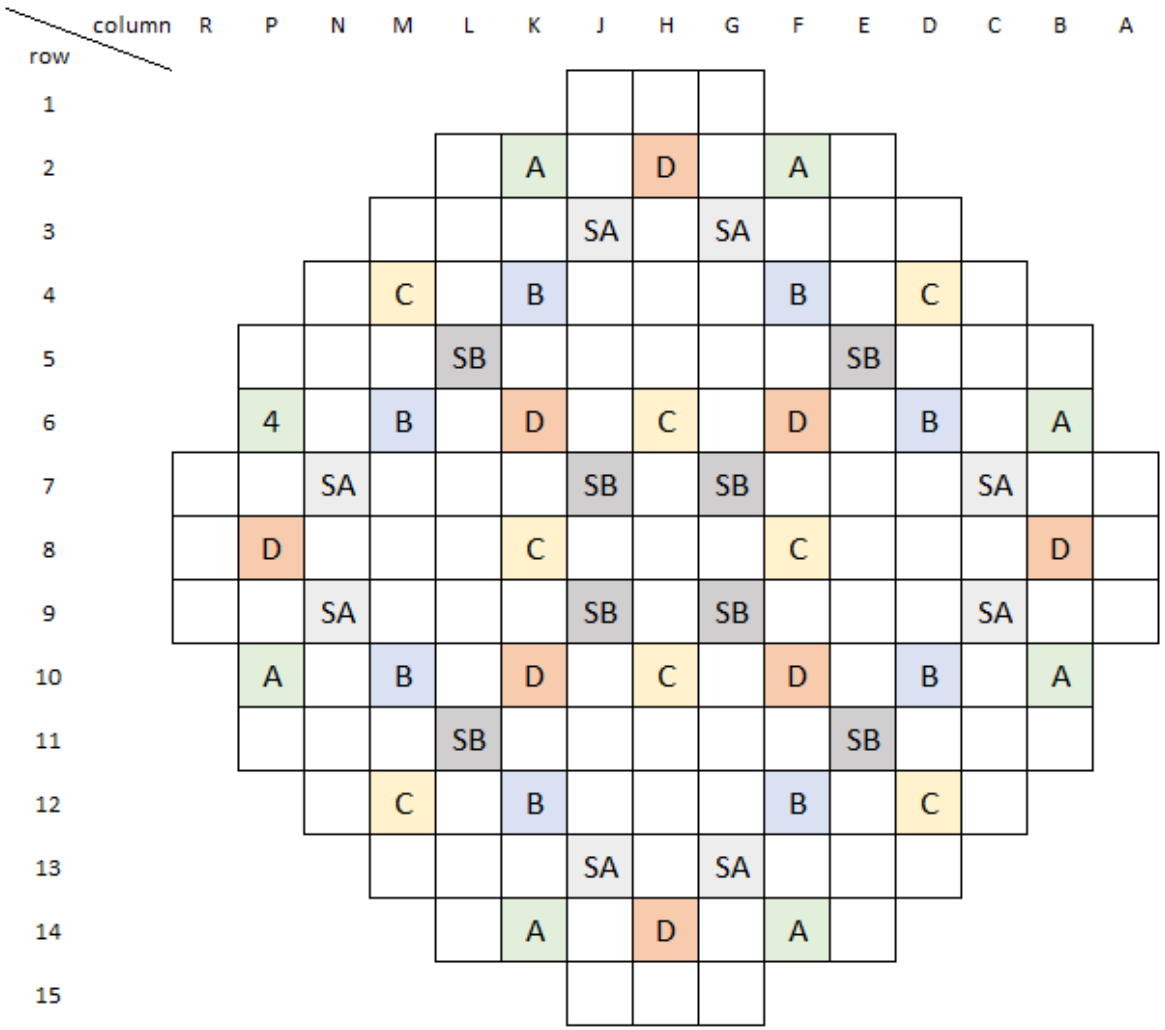
Enrichment
Gad loading
Prior Cycle Location



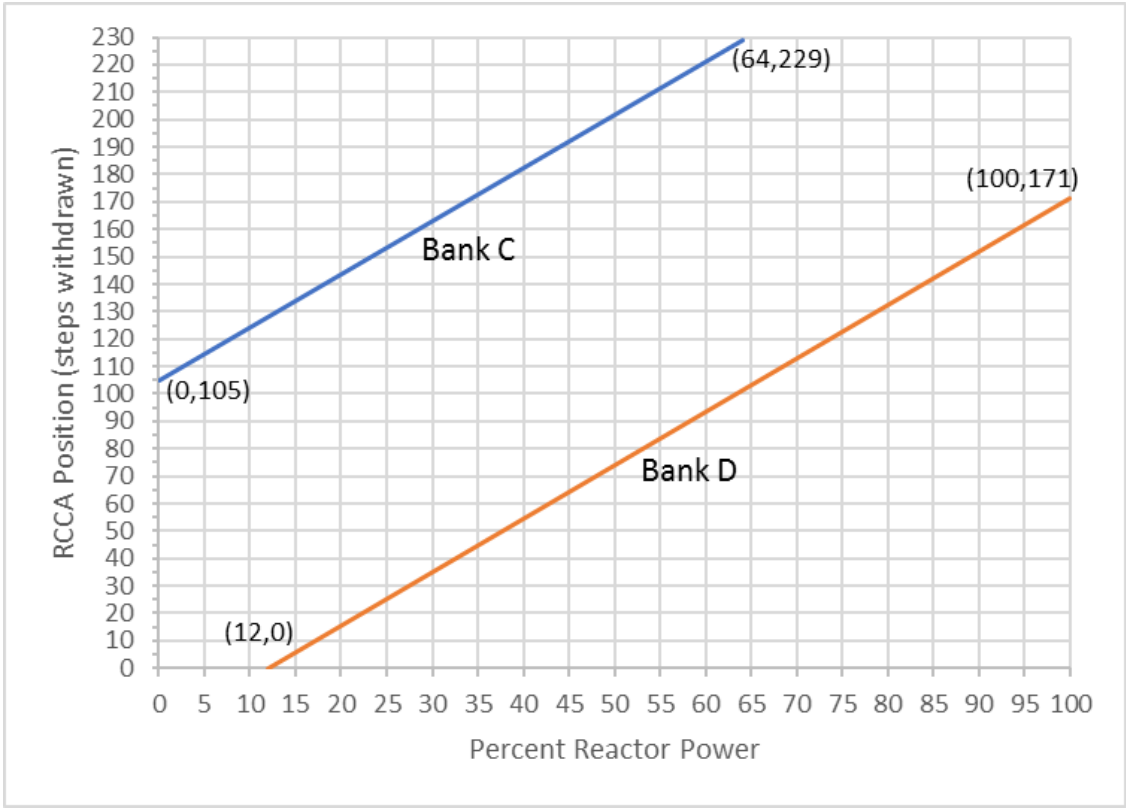
Equilibrium Cycle Loading Pattern (LP)

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Control rod layout



Control Rod Locations



Rod Insertion Limits (RILs)

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Setting up a core model and getting to equilibrium



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Plan of attack

- MCYCLE examples will be performed in quarter-core symmetry with coarse axial discretization to save run time
- Switch to full core, nominal axial discretization for subsequent calculations
- Sequence of events:
  - Set up assembly input, load core & run single, all-fresh statepoint
  - Use MCYCLE to:
    - Deplete all-fresh core for single cycle
    - Iterate loading pattern to equilibrium core
- Once we get through this – move to full core simulations for safety checks (today) and transient simulations (tomorrow)

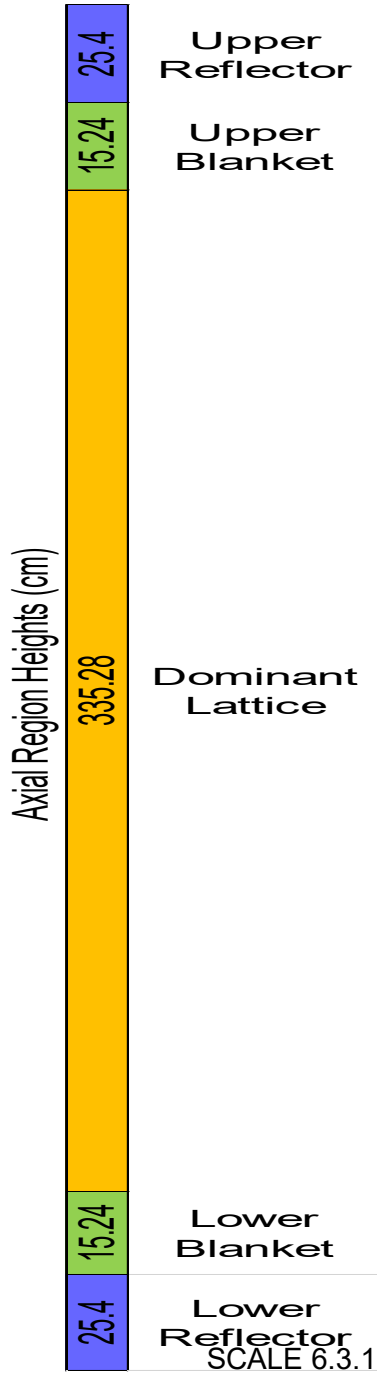
Quarter-core version of Zora-1

	H	G	F	E	D	C	B	A
8	2.00 wt/o FEED	4.95 wt/o 24@8 wt/o C-08	4.70 wt/o 24@8 wt/o FEED	4.95 wt/o 20@4 wt/o B-08	4.70 wt/o 24@8 wt/o F-08	4.95 wt/o 24@8 wt/o FEED	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o F-10
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14	4.95 wt/o 20@4 wt/o FEED	4.95 wt/o 16@4 wt/o FEED	4.70 wt/o 24@8 wt/o G-12	4.70 wt/o 24@8 wt/o G-11				
15	4.95 wt/o 16@4 wt/o F-10	4.95 wt/o 16@4 wt/o G-13						

Enrichment

Gad loading

Prior Cycle Location



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Exercise 1: Building quarter-core models with GEOM:RAD_CONF

- Open `exercise1.parcs_inp`
- Goal:
  - Add references to lattice cross sections with `DEPL: PMAX_F` (step 1)
  - Add necessary assembly types to `GEOM: ASSY_TYPE` (step 2)
  - Insert assemblies according to loading pattern in `GEOM: RAD_CONF` (step 3)
  - Run a critical boron search
- Key tips:
  - Available lattice cross sections are in XSEC directory
  - There are 15 axial levels – build the assemblies bottom to top
  - All assembly types use the same blanket lattice at the top and bottom six inches of active fuel (2.5 wt %)

Exercise 2: Adding depletion via DEPL:TIME_STP

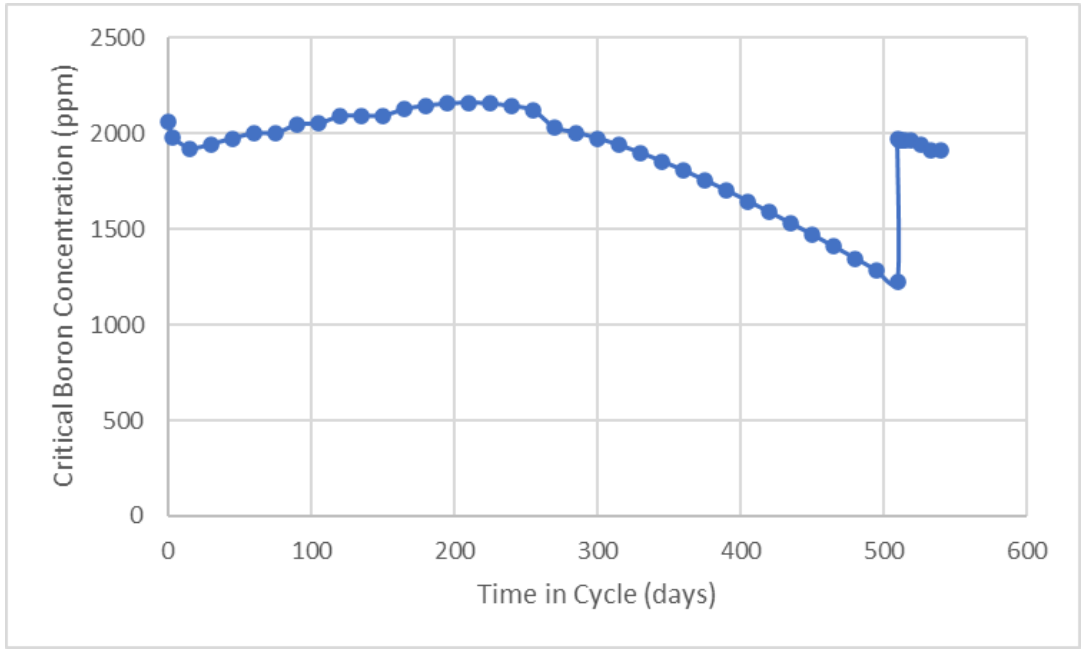
- **Exercise 1** – check `parcs_dpl` file for summary results:
  - Critical boron concentration (CBC) - 2063.9 ppm
  - Pxy (max assembly relative power) – 1.294
  - Pxyz (max nodal relative power) – 1.791
  - a single, all-fresh statepoint
- **Exercise 2**, we want to add in a cycle's worth of depletion
- Zora Unit 1 operates on 18-month cycles
  - Translates to 510 effective full power days (EFPDs) (i.e., 100% power)
  - 30 day between-cycle cooling time for xenon decay and samarium build-in

Exercise 2: Adding depletion via DEPL:TIME_STP

- Zora Unit 1 operates on 18 month cycles
  - Translates to 510 effective full power days (EFPDs) (i.e., 100% power)
  - 30 day between-cycle cooling time for xenon decay and samarium build-in
- Use `MCYCLE:DEPL_STEP` and `POWER_LEV` input to deplete fully-fresh core for one cycle
  - Start with 3 day, then 12 day, then 15 day depletion steps to 510 EFPD - want to be careful modeling gadolinia burnout
  - For 30 day cooling period, use very low power timesteps (1E-4%) for 1, 2, 2, 4, 7, 7, 7, 7 day increments
  - Remember that `DEPL_STEP` specifies *intervals* whereas `POWER_LEV` is *state points* – there is one more state point than interval

Exercise 2 results

- What happened here?
- Loaded a completely fresh core chock full of gadolinia – Gad initially holds excess reactivity down, but as it starts burning out, CBC increases
- After 510 days, switch to very low power outage period – PARCS stays in critical boron search mode
  - Effect of samarium build-in is evident
- We want to get this model into a more realistic condition – mix of fresh, once-, and twice-burned fuel



Equilibrium cycle simulation

- In the real world, first cores are specially designed
  - Each subsequent reload cycle must meet cycle-specific constraints related to available burned fuel inventory (among many other things)
- In our world, we want to generate a core that is "representative" of one in the fleet as they are designed/operated today, without needing to explicitly do core follow (i.e., model every cycle a reactor has ever had to get to the present moment)
- We do this using the equilibrium cycle approach
  - Run a sequence of cycles until an equilibrium cycle is simulated.
  - Apply the same fuel management between each cycle – feed inventory, shuffling, loading pattern, and discharged assemblies remain identical
  - Iteration sequence kicks off with depletion of a completely fresh core
  - Equilibrium cycle is reached when cycle-to-cycle burnup distribution converges

Core design criteria for equilibrium cycle

- For Zora-1, the following constraints were set for `MCYCLE` to ensure core performed like operating fleet reference plants:
  - EOC boron concentration at or near 0 ppm (cycle energy)
  - Cycle maximum boron concentration ~1400 ppm (moderator reactivity)
  - Maximum assembly relative power Pxy < 1.4
    - This is a surrogate for maximum pin relative power FΔh < 1.583
    - FΔh limit will be confirmed in subsequent full-core calculations
  - Maximum EOC assembly average burnup < 57 GWd/MTU
    - This is a surrogate for maximum rod average burnup < 62 GWd/MTU
    - PARCS does not have a pin burnup reconstruction algorithm – need offline fuel performance calculations to rigorously confirm

Exercise 3: MCYCLE for equilibrium cycle generation

- Open `exercise3.parcs_inp`
- Following `DEPL` block, edit `MCYCLE:SHUF_MAP` block
  - `MCYCLE:LOCATION` provides PARCS the string name of each assembly in the core
  - `MCYCLE:SHUF_MAP` allows users to move assemblies around between depletion cycles
  - `MCYCLE:CYCLE_IND` and `CONV_EC` control equilibrium cycle iteration
- Key task here is to define `MCYCLE:SHUF_MAP`
  - Load feed assemblies by type (according to `ASSY_TYPE`) with negative number
  - Load burned fuel back in by previous cycle location index (shown in `LOCATION`)
  - As PARCS iterates on the shuffling, it tracks the feed assemblies as they move around the core – `RAD_CONF` is only adhered to for the first iteration

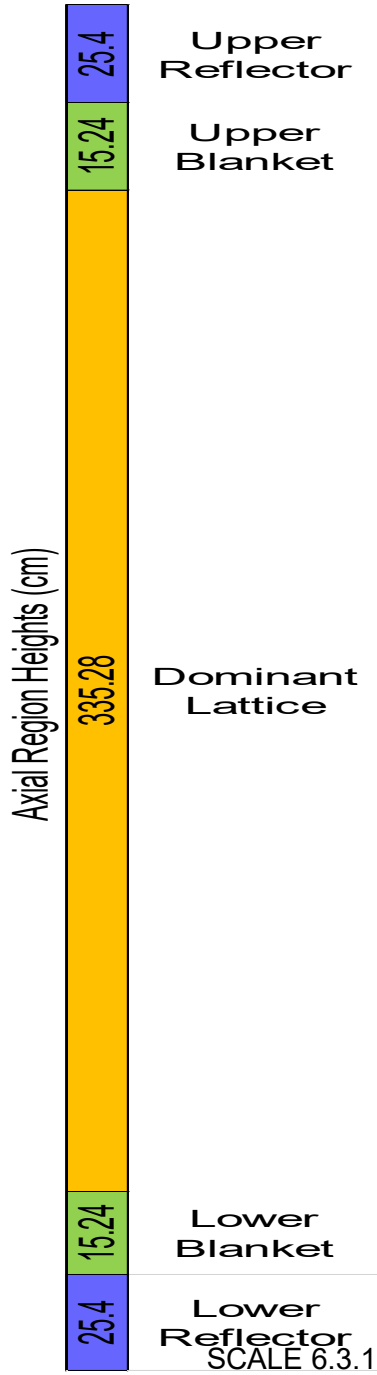
Quarter-core version of Zora-1

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Enrichment

Gad loading

Prior Cycle Location



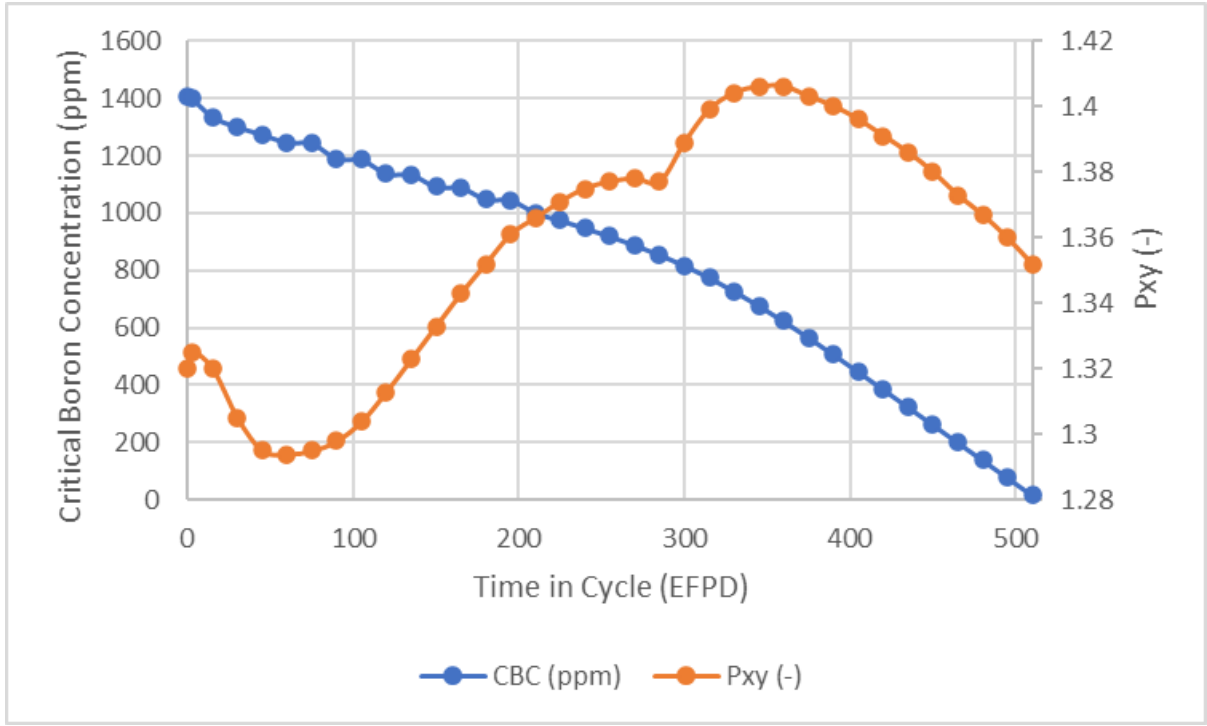
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Exercise 3 Results

- PARCS took 8 shuffle iterations to converge EOC nodal burnup <0.1 GWd/MTU
- Open `example3.parcs_dpl`
  - See how peaking factors and critical boron change with each iteration
- Cycle 8 is our "equilibrium cycle" – screen for design criteria
  - Max CBC is 1406.1 ppm ~ 1400 ppm constraint
  - EOC CBC is 16.5 ppm – pretty close to 0 ppm
  - Max Pxy ~1.4 – will verify that pin level FΔh constraint of 1.583 is met in next step
- Open `example3.parcs_cyc-08`
  - Search backwards for `EXP 2D MAP` – axially averaged assembly BU
  - Max BU < 57 GWd/MTU



This design works!

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Riffs on core design

- Before moving on – spend some time playing with `SHUF_MAP`
- Try loading different feed types (see `XSEC` directory for available options)
- Try shuffling fuel to different locations
- Try changing the batch maps
- Standard practice is quarter core, rotational symmetry
- Remember conservation of fuel assemblies –
  - Consider shuffling fuel between axes/diagonals and the 8th core locations
  - PARCS *will* let you do illegal shuffles ☺
- See if you can optimize this design any further!

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Evaluating safety criteria using full core models



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We have our cycle – what now?

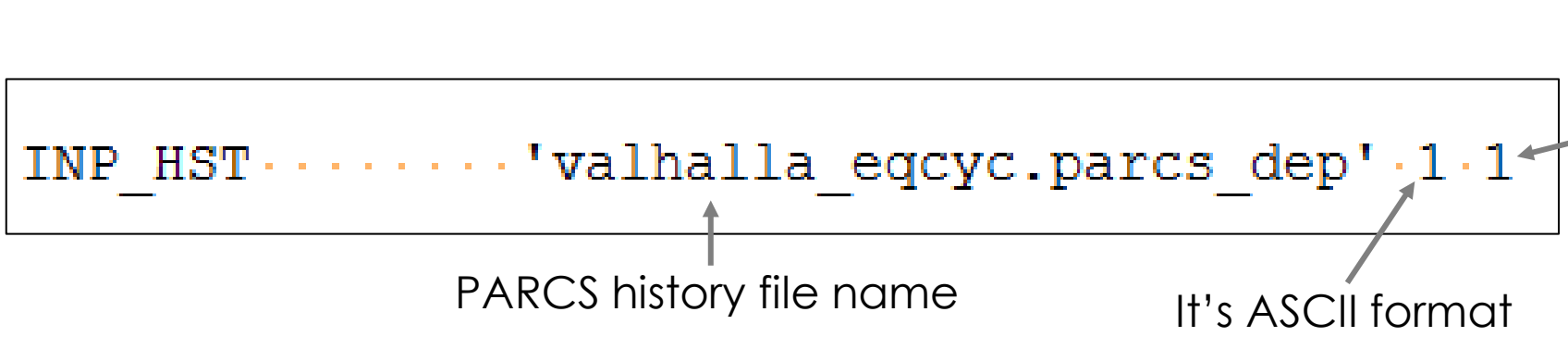
- We used `MCYCLE` to generate an equilibrium cycle
- Next step – do some checks on that cycle to ensure adequate safety performance at points of interest within that cycle
- Requires two features of PARCS:
  - Restarting statepoint calculations from a PARCS history file allows us to look at what happens at specific points in the cycle, at conditions different than the base depletion, without having to re-run the entire depletion
    - Note – history file type is `parcs_cyc-NN` (when PARCS uses `MCYCLE`) or `parcs_dep` (otherwise)
  - Activating pin power reconstruction (PPR) allows us to see power response at the pin-resolved level – recall peaking limits are based on pin, rather than node, resolution

Restarting a simulation from a history file

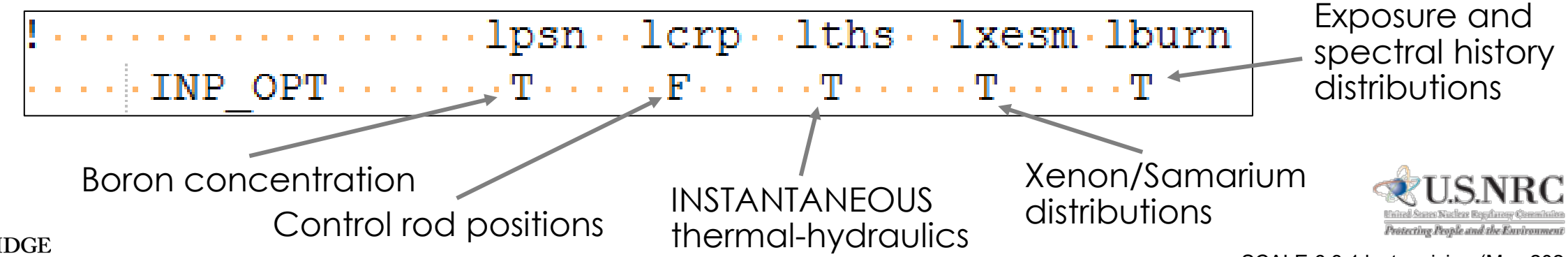
- Once we have an equilibrium cycle, we don't need to re-run the full iteration every time we change something
  - After equilibrium cycle iteration, we have the equilibrium core loading in a `parcs_cyc` file
  - Many safety checks are performed at specific times in life, not the entire cycle – it's useful to be able to perturb specific statepoints
- We can restart individual statepoints and instantaneously perturb model to see reactivity effect
  - Insert controls rods
  - Modify T/H conditions
  - Change boron concentration or xenon/samarium option
- We can also restart a depletion from BOC and turn on PPR

Using INP_HST and INP_OPT

- DEPL:INP_HST is how we tell PARCS to start its calculation from a history file:



- DEPL:INP_OPT is how we tell PARCS which parameters we want to read in from the history file:



Using Pin Power Reconstruction (PPR)

- PARCS typically calculates the neutron flux/power solution at the *nodal* level – i.e., fuel lattice is smeared into a neutronically equivalent lump
- To see what's happening at the *pin* level, need to combine nodal flux solution with pre-computed pin power factors included within the PMAXS libraries
- Accomplished via turning on a couple input options in PARCS
- PPR slows down solution considerably, so we only turn it on when we've got depletion models up and running
  - Acceptance criteria are at the pin level, so it is very important to use this capability
- PPR data of interest were recently included in `parcs_dpl` depletion summary – can directly check there

Plan of attack – pin power reconstruction

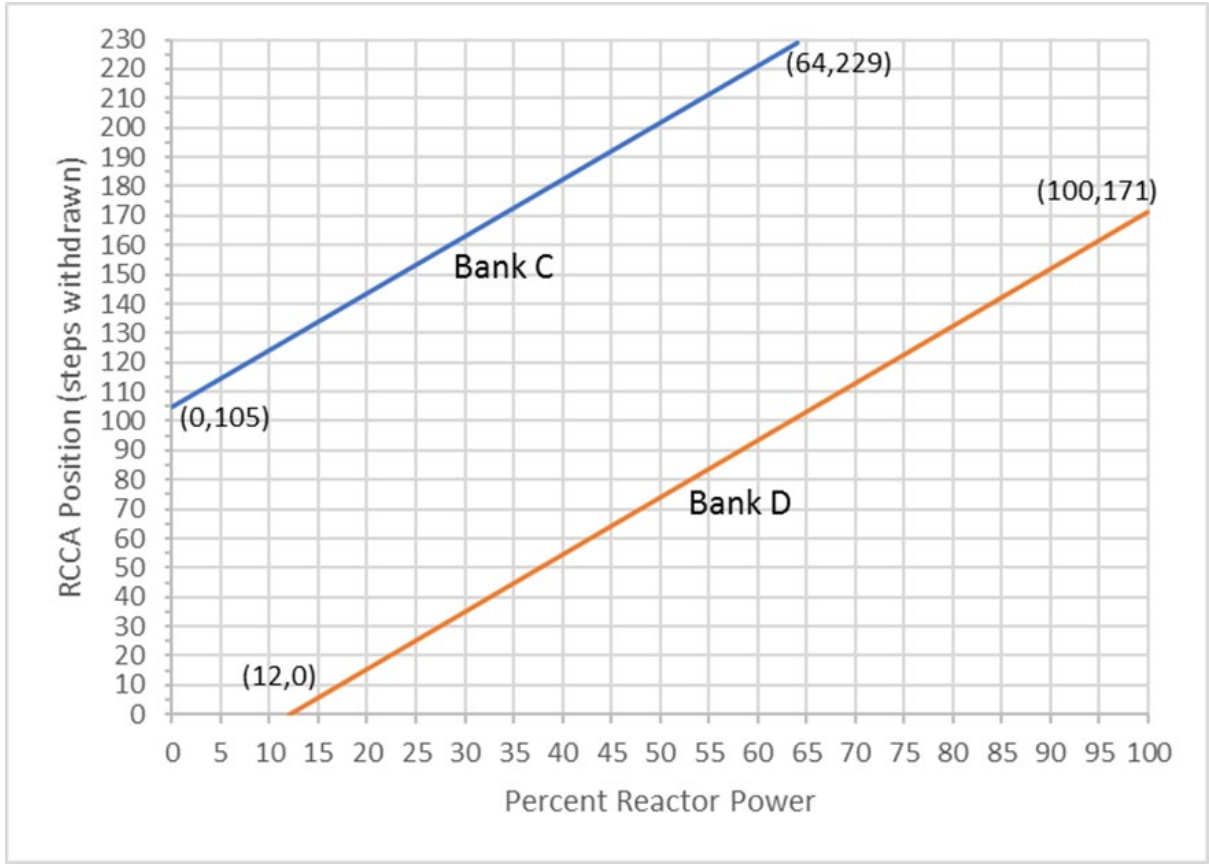
- We have switched from quarter-core, coarse axial nodalization (12 inch node height) to full-core, "production" axial nodalization (6 inch node height)
- First – restarting from a history file, deplete equilibrium cycle with PPR active so we can confirm $F\Delta h$ and Fq limits are met
  - For this design, $F\Delta h < 1.583$ and $Fq < 2.50$ at hot full power (HFP)
- Then – put Bank D at RIL and deplete equilibrium cycle with PPR
  - PWRs mostly operate with their control rods almost completely withdrawn, but plant technical specifications (TSs) allow some degree of rod insertion – can affect power peaking
  - Check "rodded" peaking factors – same criteria as unrodded
  - For transient analysis (especially rod ejection), control rod worths are higher if upper part of fuel is shadowed by rod insertion during depletion – rodded depletions usually make for more interesting/limiting transient simulations

Exercise 4: Activating pin power reconstruction

- Open "`exercise4\exercise4.parcs_inp`"
- Notice this is now the full core, with "normal" axial discretization
- Equilibrium core history file: "`zora_eqcyc.parcs_dep`"
- Changes:
  - Turn `CNTL:PIN_POWER` on
  - Set `CNTL:PLOT_OPTS`(6) = 2
  - Add `GEOM:PINCAL_LOC` input – put 1's where there are fuel assemblies
  - Add `DEPL:INP_HST` to read in beginning of equilibrium cycle
- Execute case

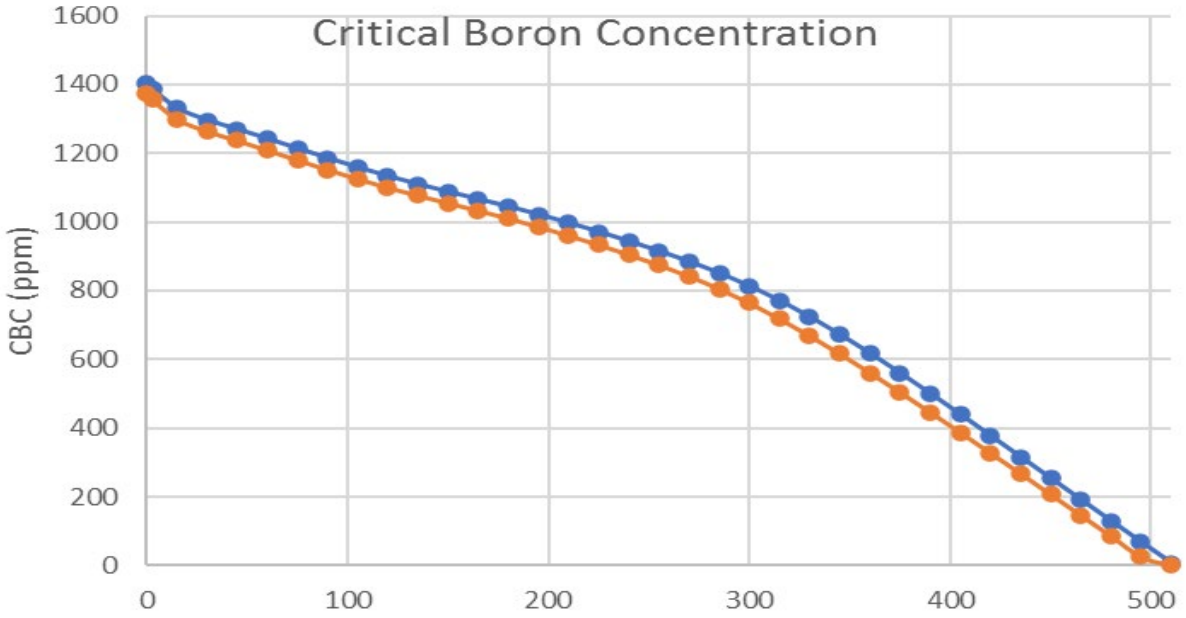
Exercise 5: Rodded depletion with PPR

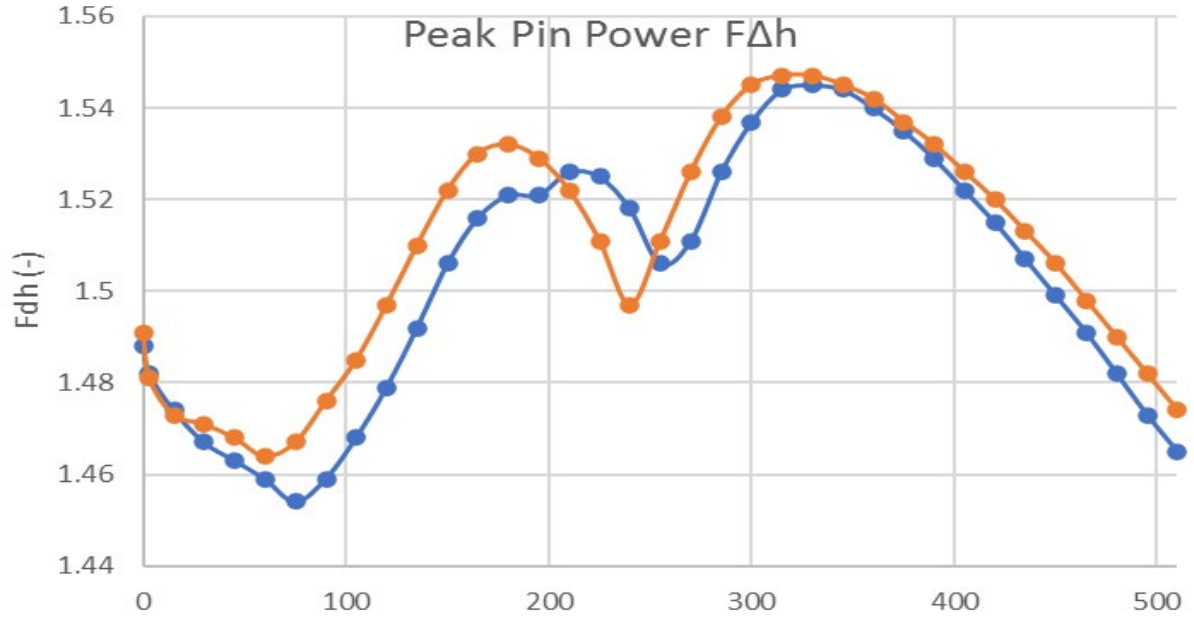
- Open "`exercise5\exercise5.parcs_inp`" (or copy and rename your `exercise4.parcs_inp`, make sure to change `CASEID` at top of the input)
- Modify `CNTL:BANK_POS` *and* `MCYCLE:BANK_DEF` to hot full power with rods at rod insertion limits (RILs)
- Execute "`run_exercise5.bat`"
- Using EXCEL, plot CBC, axial offset, FΔh and Fq as a function of time in cycle for all rods out (ARO) and rodded depletion cases

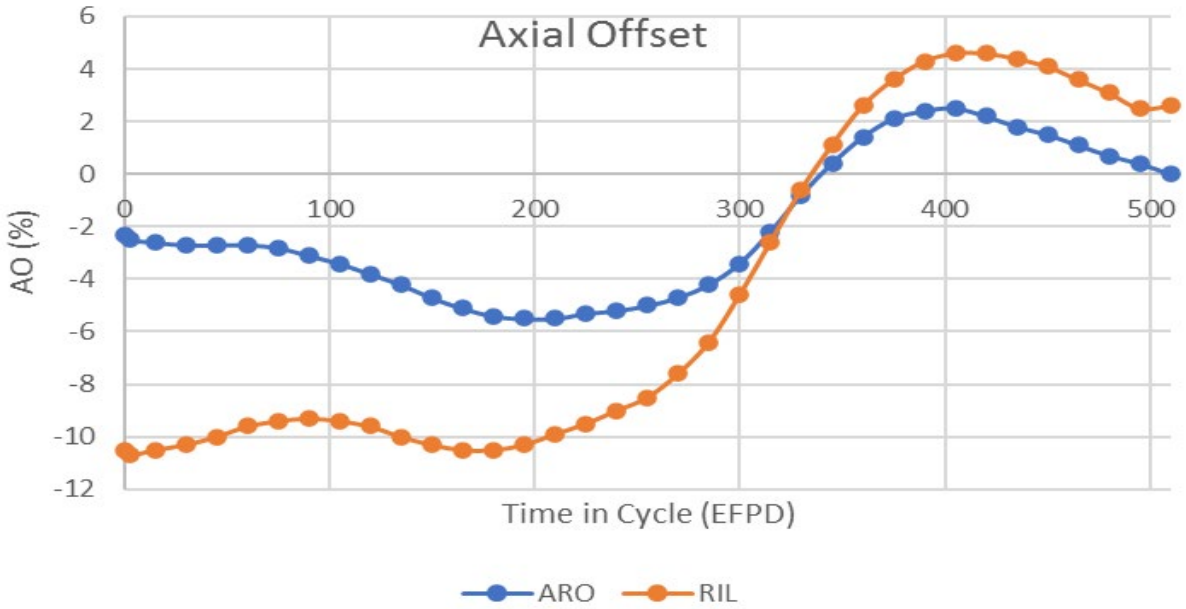


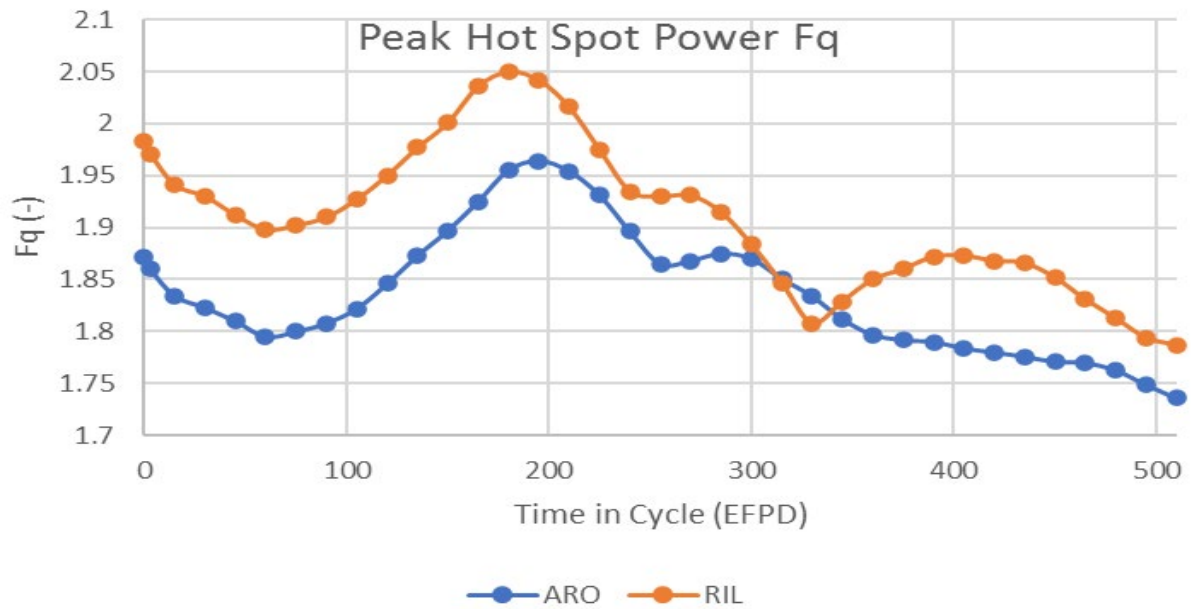
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All rods out vs. rodded depletion









Safety checks for reactivity parameters

- We've now verified our design meets power shape limits
- Next step is to evaluate reactivity behavior
  - Inherent reactivity feedback – make sure power increases are suppressed by negative feedback
  - Control rod characteristics
    - Enough available worth to shut down fission reaction
    - Not *too* much worth in any one control rod to blow apart the core (too much)
- We'll employ `INP_HST` and `INP_OPT` for this
- We're not depleting, so we remove `MCYCLE` block
  - Move rods with `CNTL:bank_pos`
  - Change inlet thermal-hydraulics with `TH:flow_cond`
- Also: PARCS's *stacked cases* feature can significantly streamline input specification

Plan of attack – additional safety checks

- Statepoint-dependent analyses – verify assumptions in safety analysis
  - Reactivity coefficients (no exercise)
  - BOC shutdown margin (SDM) (exercise 6)
    - Power defect
    - Total available rod worth
    - Worst rod stuck out
  - EOC HZP ejected rod worth from RIL (exercise 7)
- This is *not* the exhaustive list – this is a subset which we tend to focus on for our purposes

Why do we look at multiple statepoints?

- Reactivity feedback characteristics and relative control rod absorption depend on the amount of soluble boron in the core
  - High boron (i.e., at or near BOC) – relatively lower moderator temperature feedback and control rod worth
  - Low boron (i.e., at or near EOC) – vice versa
- For BOC calculations, want to push CBC high to minimize moderator feedback
  - ARO, zero Xenon/Samarium condition (non-physical, but "conservative")
- For EOC calculations, want to do the opposite
  - RIL, equilibrium Xenon/Samarium condition
- In safety analysis calculations:
  - Heat up events tend to be worse with minimal moderator feedback
  - Cooldown events tend to be worse with maximal moderator feedback

Evaluating Reactivity Coefficients

- One method: direct perturbations of state variable around a reference critical state (e.g., coolant temperature, power, boron concentration)
  - Very straightforward for isothermal (i.e., zero-power) core states
  - Do not have direct access to state variable distributions for at-power states
- Alternatively, PARCS provides an adjoint-based method to calculate feedback coefficients for each state variable in the cross section functionalization
  - Fuel temperature is straightforward – everyone uses temperature for fuel feedback
  - Coolant is less so
    - We functionalize based on physical parameter of importance (i.e., density)
    - Vendors often express coolant feedback characteristics in terms of *temperature*
    - We do not currently have a straightforward method to convert our coolant density coefficients into temperature coefficients
  - Enabling PARCS to print out feedback coefficients is easy – just involves turning on some switches in `CNTL:KIN_OPT` (see input manual)

Shutdown margin

- Reactor cores are *required* to be able to shut down instantaneously and be held sufficiently subcritical in the immediate aftermath of a disturbance
  - PWRs use control rods for prompt shutdown
  - Can rely on safety-related boron injection to stay shutdown
- A key piece of safety checks is to ensure there is sufficient control rod worth to counteract the positive reactivity insertion from cooling down from at-power conditions, while accounting for the highest worth control rod remaining fully out of the core
- The degree to which the core is shutdown, given the above accounting, is referred to as *shutdown margin* (SDM)
- An actual SDM calculation includes considerations for uncertainties in the various components, along with some additional factors (e.g., axial power shape manipulation)
- We use PARCS to evaluate the major pieces of SDM - the "rack up" (i.e., summing of constituent parts) is its own methodology

Evaluating shutdown margin

- Cover the full range of moderator reactivity effect
  - BOC case with ARO, no xenon/samarium to push reference CBC up
  - EOC case at RIL, equilibrium xenon/samarium to push it down
- We're going to walk through the BOC case – similar process for EOC
  - Establish initial (reference) state
  - Fix boron concentration and:
    - Bring core down to HZP, calculate k_{eff} to figure out total power defect
    - Insert all control rods into HZP core, calculate all rods in (ARI) rod worth
    - Perform a series of simulations with candidate stuck rods from each bank – the stuck rod that results in highest k_{eff} increase relative to ARI configuration is worst rod stuck out (WRSO)

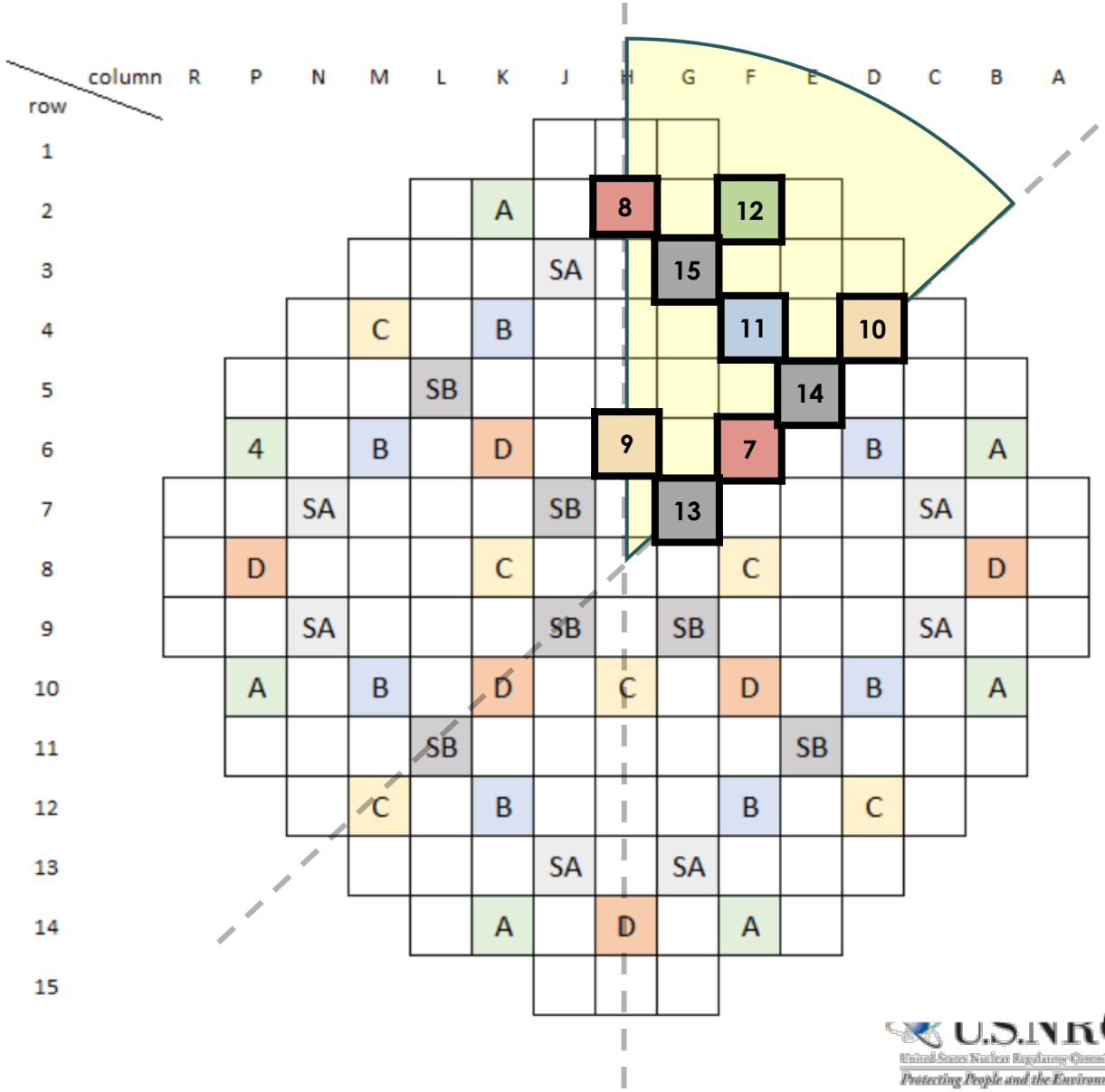
Exercise 6: BOC SDM – reactivity defect

- Run a BOC case from equilibrium cycle depletion
  - Open `exercise6.parcs_inp`, save as `exercise6_ref.parcs_inp`
  - Set samarium and xenon to zero
  - Split out rods to be stuck in control rod input (next slide)
  - Add `DEPL:INP_HST` and `INP_OPT` to read first statepoint from equilibrium cycle
  - Change `CASEID` to `exercise6_ref` and run it

- Copy reference case and rename `exercise6_hzp.parcs_inp`
  - Change `CASEID`
  - Change `CNTL:search` to do a k_{eff} search and `CNTL:core_power` to 1e-4
  - Change `DEPL:INP_HST` and `INP_OPT` to read in reference case boron concentration and history state (NOT TH state)
  - This case will give us the power defect (i.e., the reactivity insertion from cooling the fuel and coolant down to the inlet temperature)

Exercise 6 – splitting stuck rods into their own bank

- PARCS requires any rod that will be independently manipulated to be split into its own bank
- Our core has the control rods in 1/8th symmetry, and the LP is (basically) 1/8th symmetric – we only have to test stuck rods within 1/8th of the core
- Remember in PARCS model, rod banks have integer indexes (A = 4, B = 3, C = 2, D = 1, SB = 5, SA = 6)
- Each unique rod location within shaded region will need to be assigned to a unique bank so we can test that rod
- This results in 15 banks, of which 9 are individual rods that will be stuck out of the core



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Exercise 6: BOC SDM – Control Rod Manipulations

- Copy HZP case and rename exercise6_rods.parcs_inp – make sure to change CASEID
- This step is going to:
  - Run an ARI case – get us our total available rod worth
  - Use PARCS's stacked cases to alternate sticking a control rod from each symmetrical position within each bank
  - We can then evaluate the resulting differences in k_{eff} to figure out which individual rod is of the highest worth
  - We need to manipulate both `GEOM:bank_conf` and `CNTL:bank_pos` to achieve this

Exercise 6: Splitting out stuck control rods

- In `CNTL:bank_pos`, set all 15 banks to ARI position
- In `GEOM:crb_type`, set all 15 banks to type 1
- In `GEOM:bank_conf`, re-index one rod from each bank, in each 1/8th symmetrical position, to allow all possibilities to be accounted for (use figure on previous slide as guide)
- Add 9 stacked cases to the bottom of the input, separated by /
  - Repeat `CNTL:bank_pos` to remove one of the stuck rods for each case
  - Include `DEPL:INP_HST` and `INP_OPT` from HZP case for all cases – needs to be re-read in (read in boron and history)

Exercise 6 results

- Reactivity difference between State A and State B calculated as:

$$\Delta\rho_{AB}\ (pcm) = \left(\frac{1}{k_A} - \frac{1}{k_B}\right) \times 10^5$$

State	Configuration	keff
1	HFP ARO	0.999991
2	HZP ARO	1.013715
3	HZP ARI	0.942598
4	HZP Stuck D1	0.947944
5	HZP Stuck D2	0.944224
6	HZP Stuck C1	0.947325
7	HZP Stuck C2	0.944554
8	HZP Stuck B	0.948238
9	HZP Stuck A	0.943187
10	HZP Stuck SB1	0.945305
11	HZP Stuck SB2	0.945551
12	HZP Stuck SA	0.948455

	State A	State B	dk/k (pcm)
Power Defect	1	2	1354
Total Rod Worth	2	3	-7443
Stuck D1 Worth	3	4	598
Stuck D2 Worth	3	5	183
Stuck C1 Worth	3	6	529
Stuck C2 Worth	3	7	220
Stuck B Worth	3	8	631
Stuck A Worth	3	9	66
Stuck SB1 Worth	3	10	304
Stuck SB2 Worth	3	11	331
Stuck SA worth	3	12	655
WSR	SA		655
Raw N-1 Worth	-6788		

Notes on SDM

- "Real" SDM rack-ups include consideration for uncertainties
  - Usually ~7-10% on total rod worth, somewhat higher for individual rods
  - Might be a couple extra terms to consider
    - Void collapse
    - Axial re-distribution
    - RILs
- After incorporating the proper uncertainties, available SDM must be greater in magnitude than that assumed in the safety analysis
  - Plant and event specific, but decent rule of thumb is > 5% (i.e., 5000 pcm)
  - Westinghouse 2-loop core designs can be challenged
  - Most other cores – plenty of available worth

Static ejected rod worth

- SDM is necessary to demonstrate there's *enough* worth to shut down the core
- Static ejected rod worth (ERW) is necessary to demonstrate that *any one rod* doesn't have enough worth to severely damage the core (recall: SL1)
- Tomorrow: transient rod ejection accident (REA) simulations
- Today: figure out which rod(s) to eject

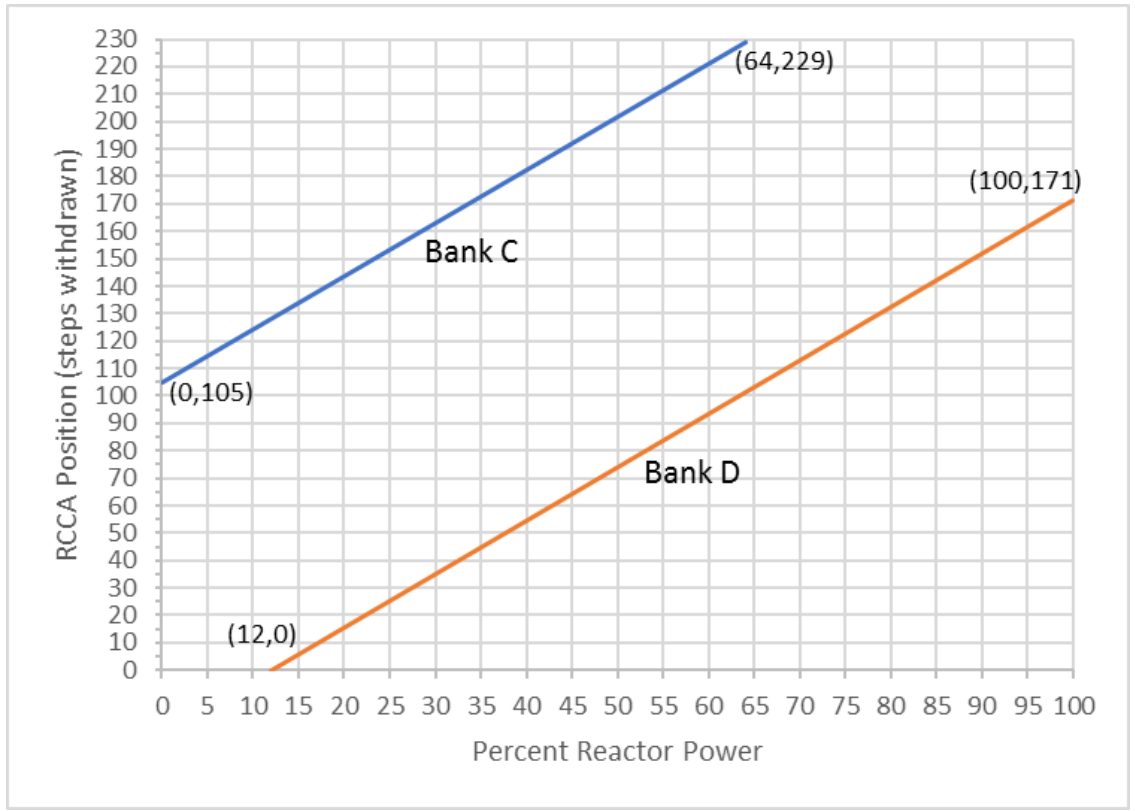
Calculating ERW with PARCS

- Input/approach is like stuck rods for SDM calculation
- Steps:
  - Choose initial condition, set rods to RILs and calculate CBC
  - Split candidate rods into their own banks
  - Run k_{eff} searches with each rod removed from the core in turn
  - Highest change in reactivity is the limiting ERW
- ERW has first-order influence over energy deposited in the fuel resulting from REAs – highest worth rods (often) lead to highest enthalpy deposition, which is a primary figure of merit (see Regulatory Guide 1.236)

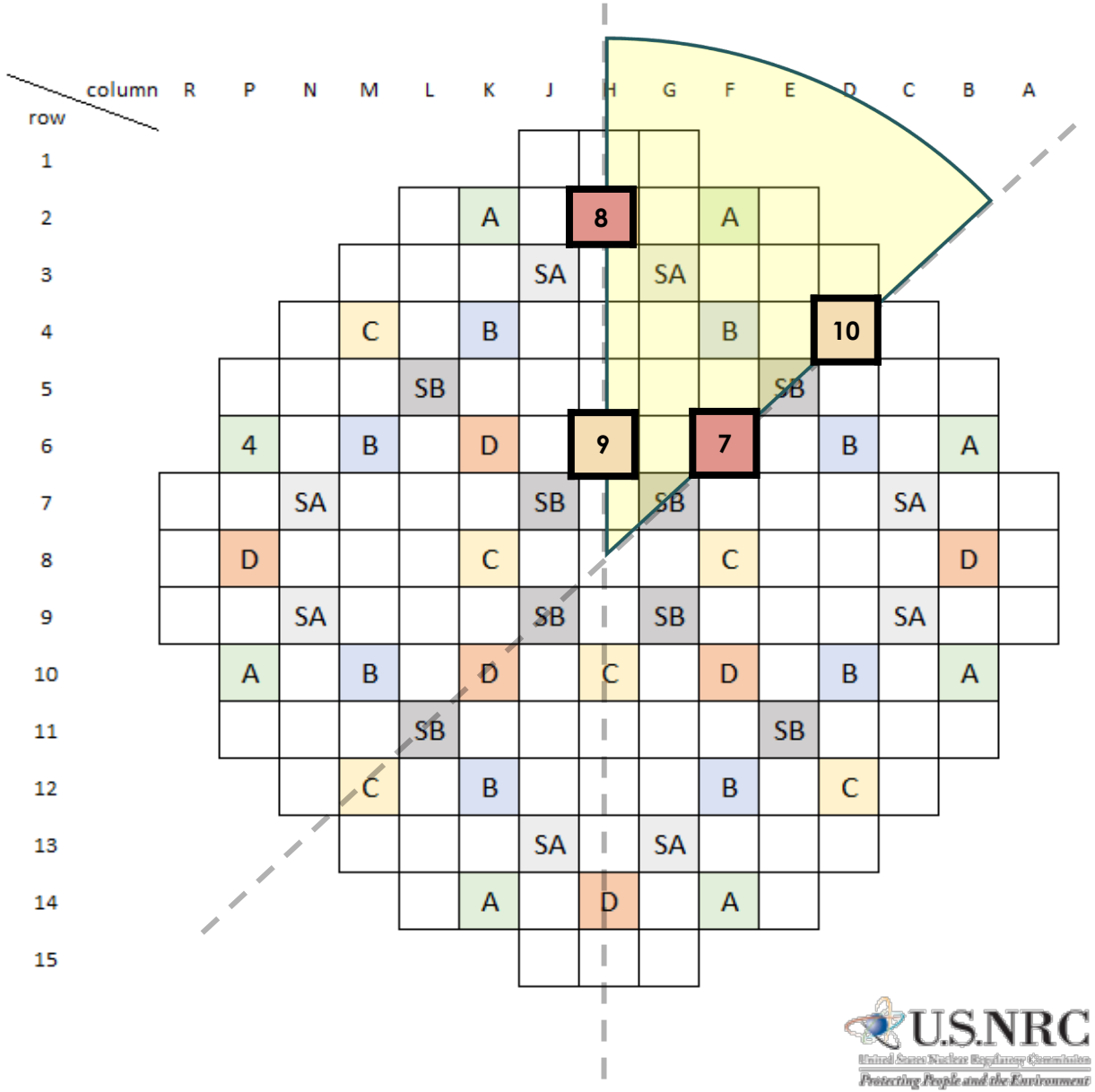
Exercise 7: Calculating ERW

- Open `exercise7.parcs_inp`, save as `exercise7_hzp.parcs_inp`
- Run two cases from EOC HZP RIL configuration – generate reference statepoint models for each
  - Read one case from ARO depletion
  - Read a stacked case from the RIL depletion (recall exercise 5)
  - Note that **both** reference cases will be run from HZP RILs – it's the *input history file* that is different
  - In both cases, read Xe/Sm in from history file
  - Modify control rod maps and bank positions to reflect candidate ejected rods from banks D and C (next slide)
- New consideration for this analysis:
  - Want to isolate instantaneous reactivity effect ONLY of removing control rod, without incorporating thermal feedback
  - Therefore, we will "freeze" TH relative to the base case and read it in from the history file
    - Note at HZP the core is basically isothermal – this approach is most important for at-power evaluations

Control rod configurations



Rod Insertion Limits (RILs)



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Exercise 7 – Calculating ERW

- Copy resulting input into new input file `exercise7_ejr.parcs_inp`
  - Change `CASEID`, switch `CNTL:search` to keff, switch `CNTL:INT_TH` to `F`, turn on pin power reconstruction
  - Change `INP_HST` to read from reference state, `INP_OPT` to read in CBC, instantaneous TH state, and Xenon/Samarium
  - Set up stacked cases to pull out each candidate ejected rod in turn
    - First 4 cases will be with ARO depletion, second 4 with RIL depletion
  - Run model – compare ERW for unrodded vs. rodded depletions

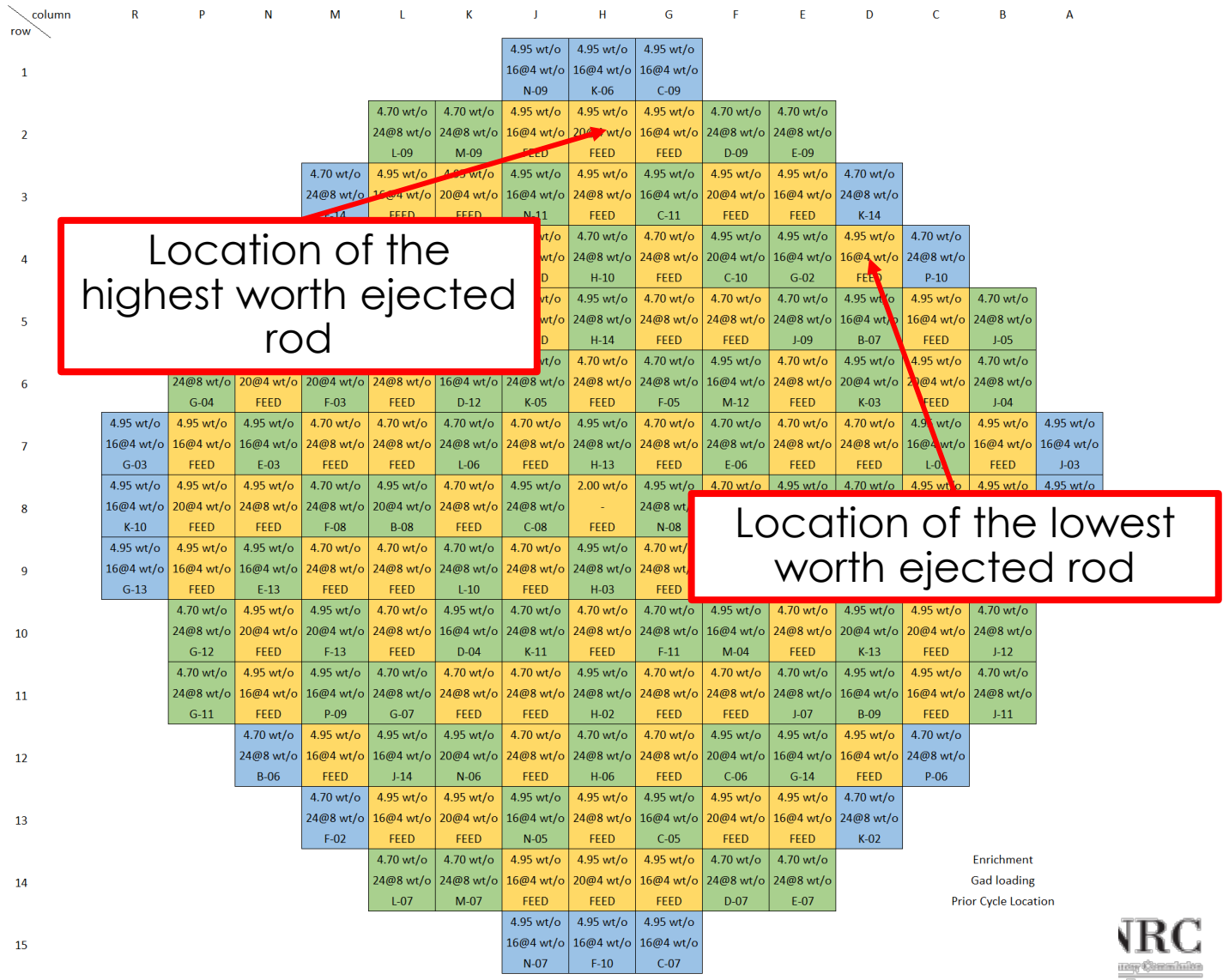
Exercise 7 - Results

- The bank D rod to the northeast of the core center has by far the highest worth, regardless of irradiation conditions
- As expected, inserting Bank D to its RIL during depletion significantly increases its ERW from HZP RIL conditions
  - In both cases, an REA from the HZP RIL would lead to a prompt-critical reactivity excursion ($\beta = 501\ pcm$)
- Bank C rods are also affected

Ejected Rod	ARO Δρ (pcm)	RIL Δρ (pcm)	ARO Δρ ($)	RIL Δρ ($)	Difference (%)
Bank D NE	244	299	0.49	0.59	21.0
Bank D N	507	631	1.02	1.25	22.9
Bank C N	201	212	0.40	0.42	4.2
Bank C NE	186	156	0.37	0.31	-17.3

Some physical insights, based on the core design

- The highest worth rod is inserted into a feed bundle surrounded by feed fuel on three sides
- At EOC, the gad has burned out, so they are quite reactive – removing absorber material in their vicinity will pull the power distribution strongly into this region of the core
- In contrast, the lowest-worth rod is in a low-flux region of the core surrounded by once- and twice-burned assemblies
- By EOC, there isn't nearly as much juice left in this region – rod worths are relatively low



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Wrapping up ejected rod worth calculations

- As with other elements of core design, a "real" analysis package would include disposition of uncertainties within this analysis to ensure it remains bounded by the safety analysis of record
- In addition to rod worth, it is also important to consider resulting increases in pin peaking
  - Usually the two are well-correlated
  - Vendors may use change in peaking resulting from the rod ejection to help them determine whether the loading pattern stays within its licensing basis
  - A more rigorous analysis will include PPR as part of this evaluation
- We will use the results of these calculations to do ***terrible*** things to this core in our transients session

Wrapping up depletion and statics

- This session's goal was ambitious:
  - Learn about modeling equilibrium cycles with PARCS
  - Learn how to read in history files and use pin power reconstruction
  - Learn how to use stacked cases
  - Learn examples/subsets of the types of analyses necessary to demonstrate the safety of a PWR reload core
- Tomorrow, we will move towards some typical transient simulations

Thank you for your attention!

Acknowledgement

Dr. Andrew Bielen from the US Nuclear Regulatory Commission is the primary author of this presentation, with ORNL staff contributing.