OAK RIDGE National Laboratory

2020 SCALE Users Group Meeting

Back of the envelope PWR studies: Increased enrichment and burnup using SCALE tools

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U.S. DEPARTMENT OF ENERGY

Presentation objectives

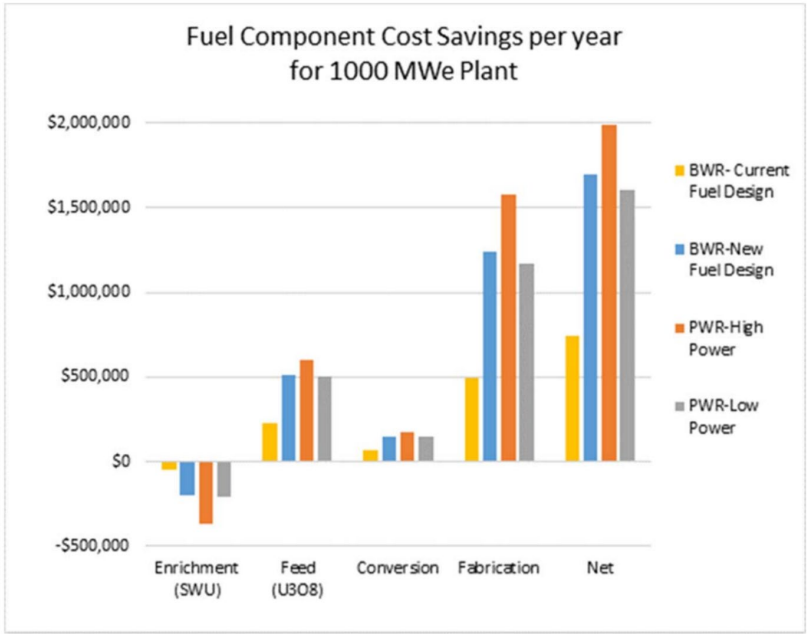
By the time we finish, you may:

- Have a greater appreciation of what a pin cell model can do for you
- Know the one key trick to building a proper pin cell model
- Know what information can be quickly and easily extracted from a Polaris output
- Be able to quickly answer questions about transitioning a PWR to higher enrichment, such as
  - How many fuel assemblies will we need? How much will discharge burnup increase?
  - What will happen to reactivity coefficients? How high do we expect the soluble boron to be?
  - Will we need more burnable absorber? What about the pellet rim effect? Pressure vessel fluence? Delayed neutron fraction?

All of this hangs on one fundamental truth of PWR physics: "PWRs are boring" (Ugur Mertyurek, 2020)

Extended Enrichment (EE) and High Burnup (HBU)

- **Commercial LWR Interest in EE and HBU**
  - **IAEA-TECDOC-1918**
  - **NEI White Paper**
  - **Two main drivers**
    - Potential economic benefit
    - Offset parasitic absorption of Accident Tolerant Fuel concepts



IAEA International Atomic Energy Agency

IAEA-TECDOC-1918

Light Water Reactor Fuel Enrichment beyond the Five Per Cent Limit: Perspectives and Challenges

NEI White Paper

The Economic Benefits and Challenges with Utilizing Increased Enrichment and Fuel Burnup for Light-Water Reactors

Prepared by the Nuclear Energy Institute
February 2019

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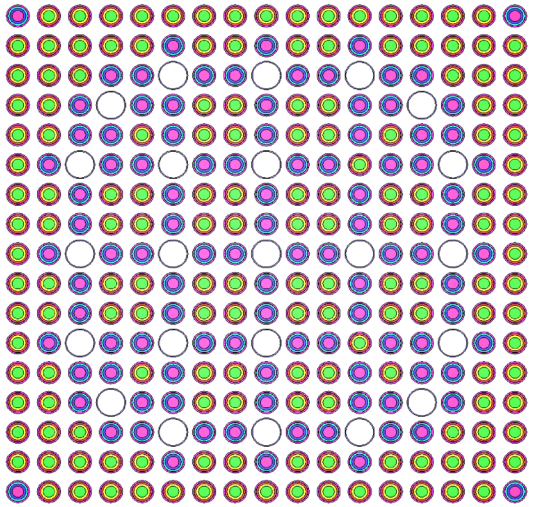
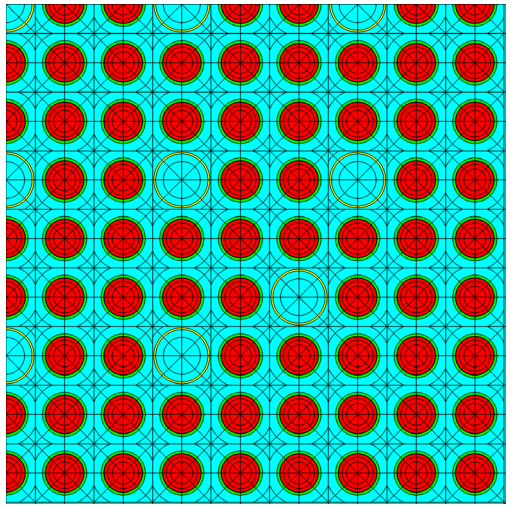
Some key questions

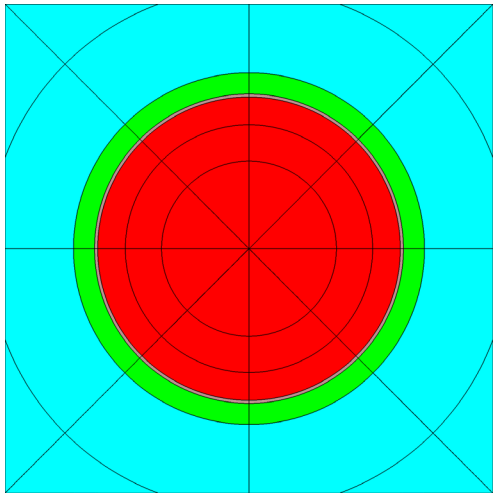
- How much does batch size and discharge burnup change with increased enrichment?
- How high do we need to go in enrichment?
- What about soluble boron worth and other key core parameters (MTC, DTC, B_{eff})?
- What about the "rim effect"?
- What kind of impact on vessel fluence?
- How much enrichment is needed for ATF cladding?

A Polaris pin cell model can provide back of the envelope answers to these questions

Run time – full lattice vs pin cell







Run time: **Polaris 56 group cross section depletion with branch cases (128 cases)**

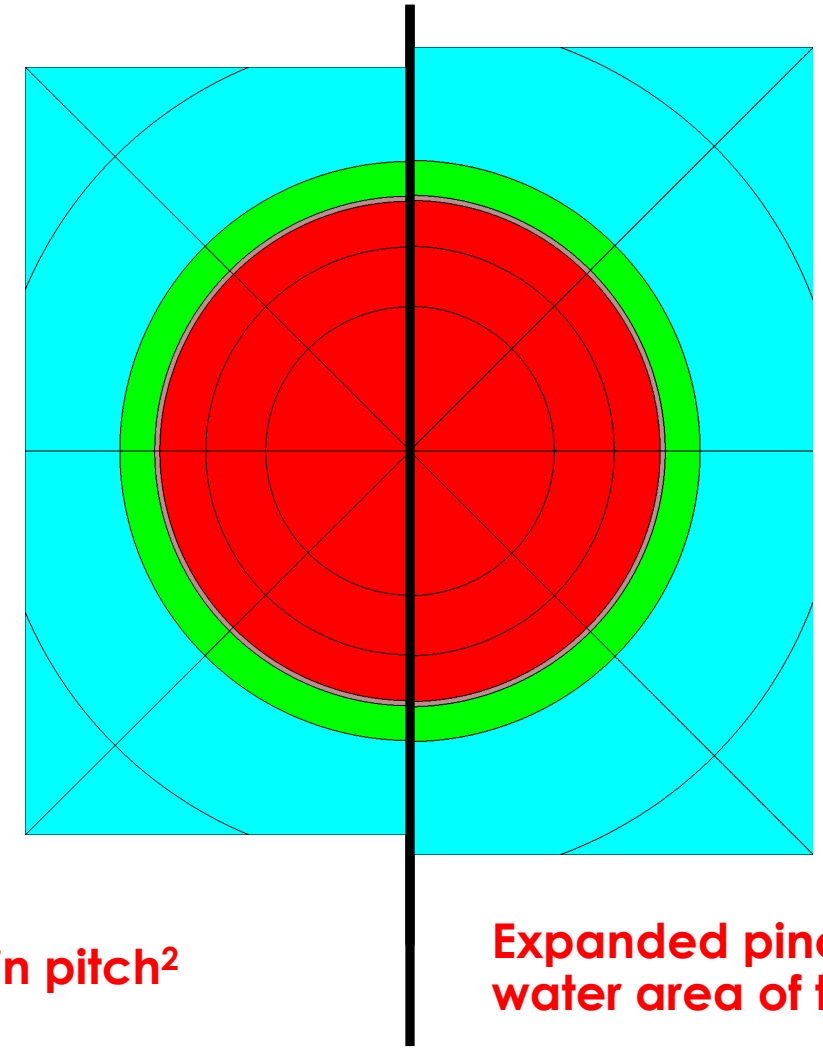
Full lattice: 15 hours **Pin cell: 7 minutes**

What you lose:

Control rods (need a little bigger model for that, maybe 3x3 or 5x5)

IFBA, WABA (not important for middle or end of cycle questions)

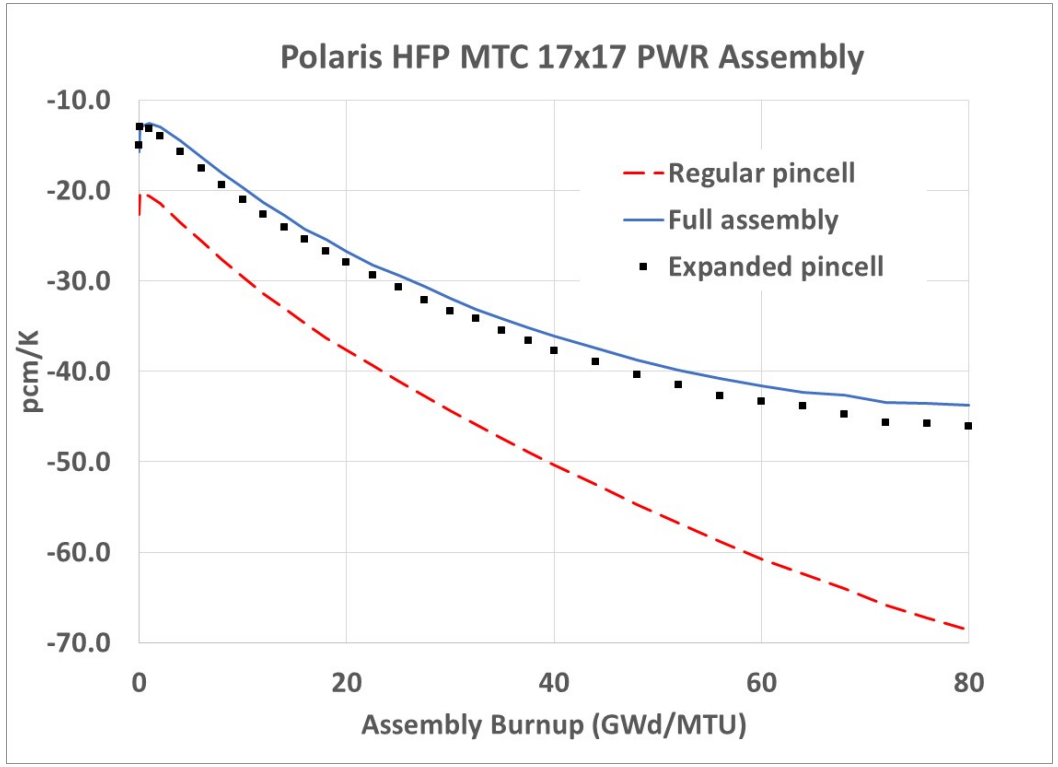
Building a pin cell – what's the difference?

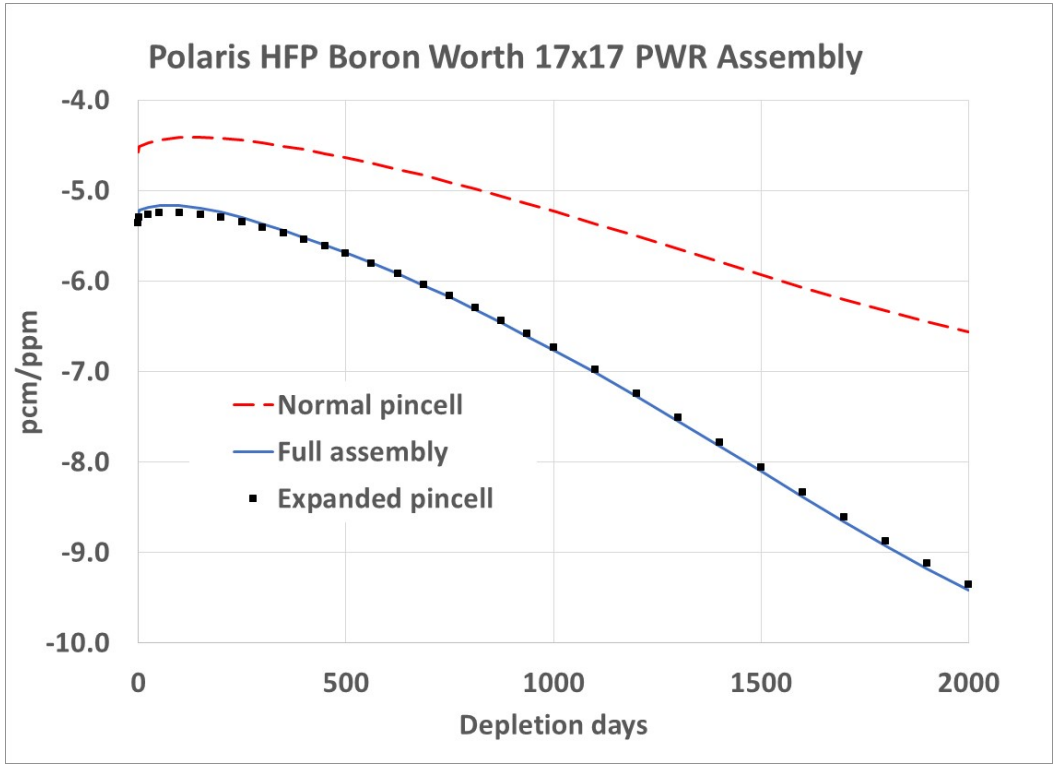


Normal pincell area = pin pitch^2

Expanded pincell area adds per-fuel-pin water area of the GT, IT, and assembly gap

Building a pin cell – what's the difference?

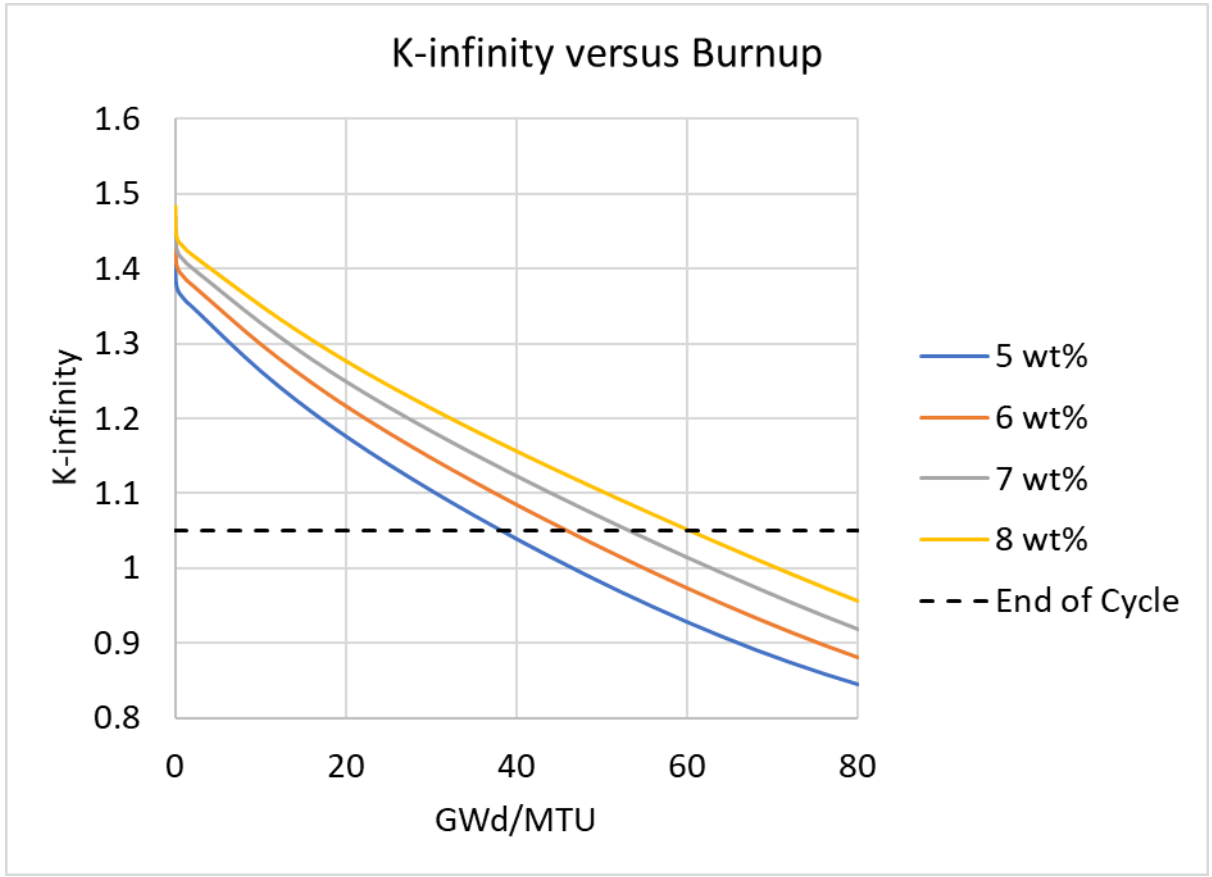




Expanded pin cell MTC at 1000 ppm boron matches full lattice model. Regular pincell does not.

Expanded pin cell boron worth matches full lattice model. Regular pincell does not.

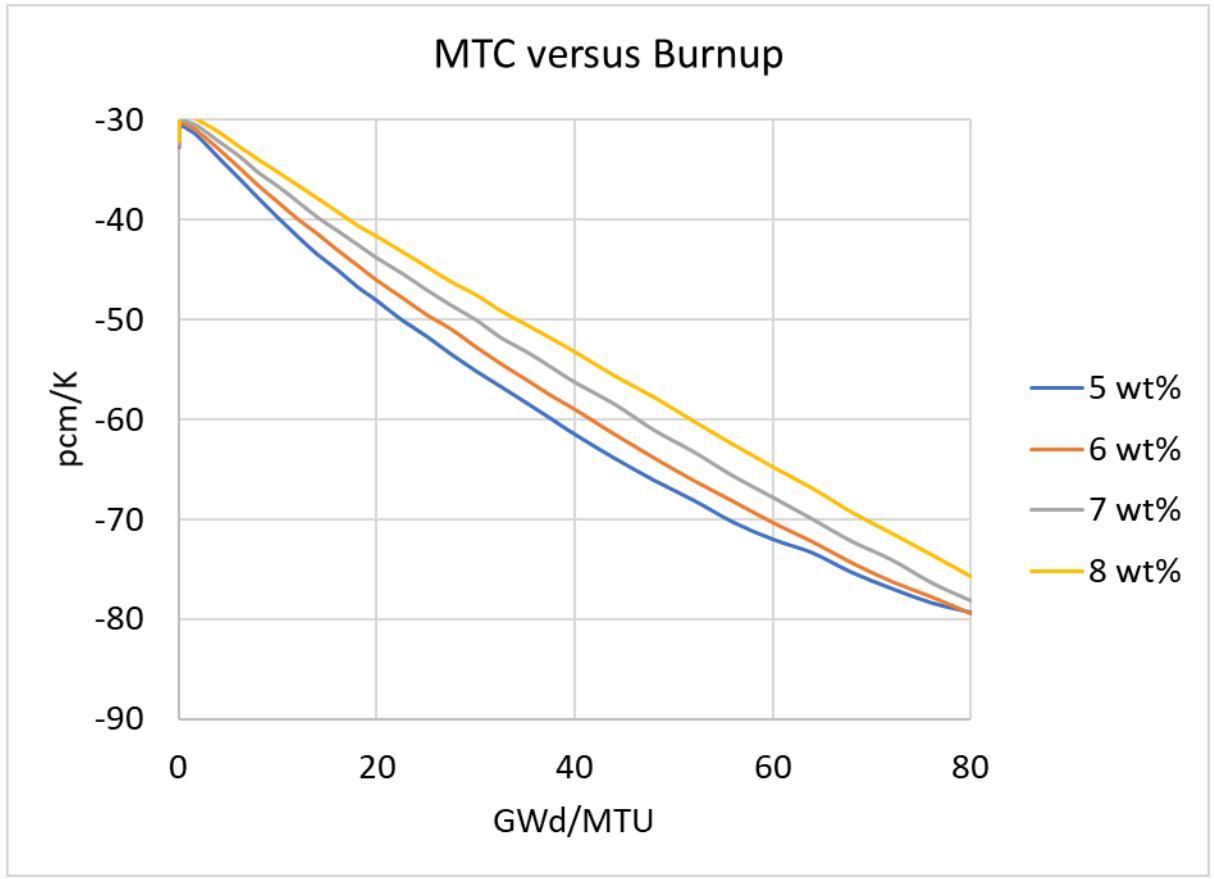
Pin cell results – increased enrichment and burnup



- Core average EOC k-inf ~ 1.05
- Intersection of 1.05 with each curve yields EOC core average burnup
- Curves are HFP, no soluble boron, equilibrium ^{135}Xe

Enrichment (wt% ^{235}U)	EOC Burnup (GWd/MTU)
5	38.2
6	45.9
7	53.3
8	60.4

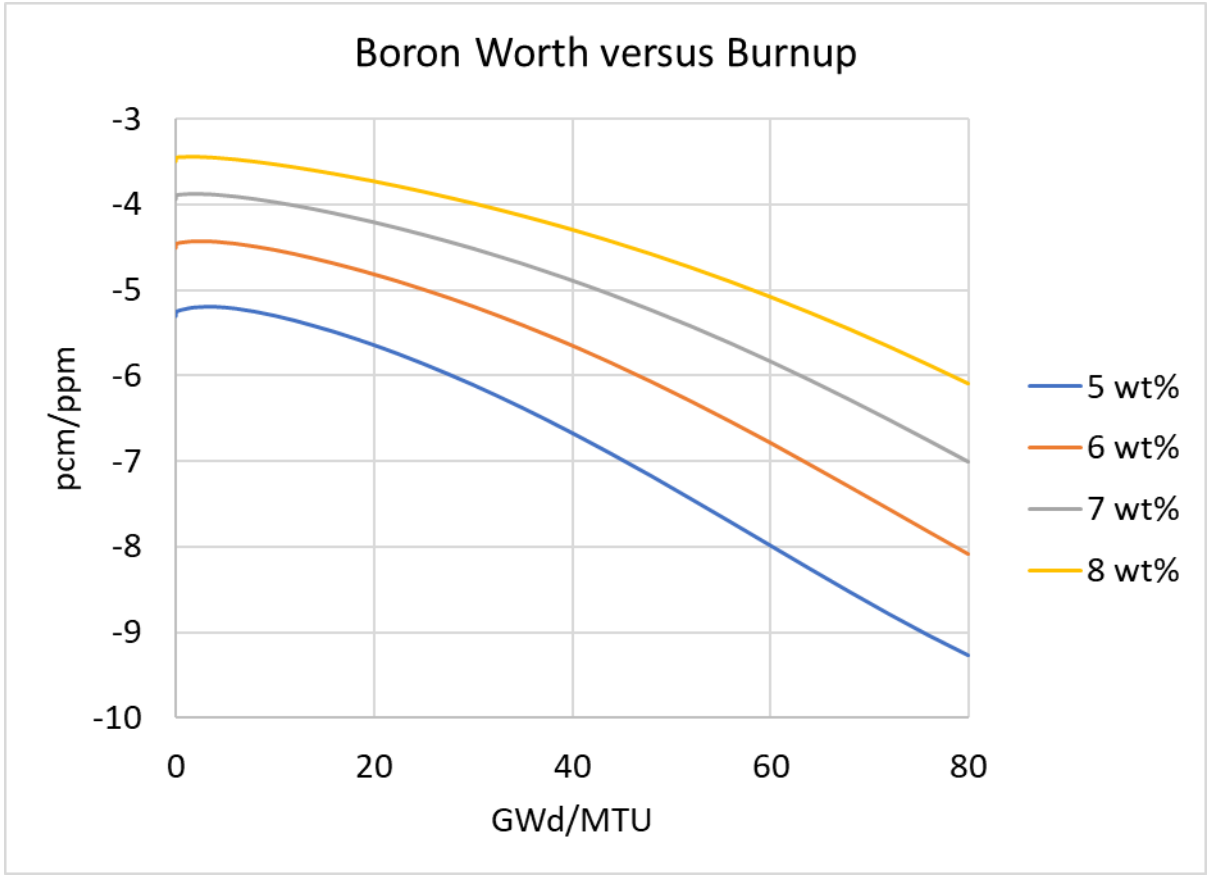
Pin cell results – core average EOC MTC estimate



- Polaris branch cases for boron worth, MTC, DTC, etc.
- Use core average burnup versus enrichment to estimate EOC MTC trend
- Slightly more negative with increased enrichment

Enrichment (wt% 235U)	EOC Core Avg. Burnup (GWd/MTU)	EOC MTC (pcm/K)
5	38.2	-60.4
6	45.9	-62.6
7	53.3	-64.0
8	60.4	-64.9

Pin cell results – mid-cycle (MC) soluble boron worth



- Use core average burnup versus enrichment to estimate MC boron worth
- MC burnup = EOC burnup – 10 GWd/MTU

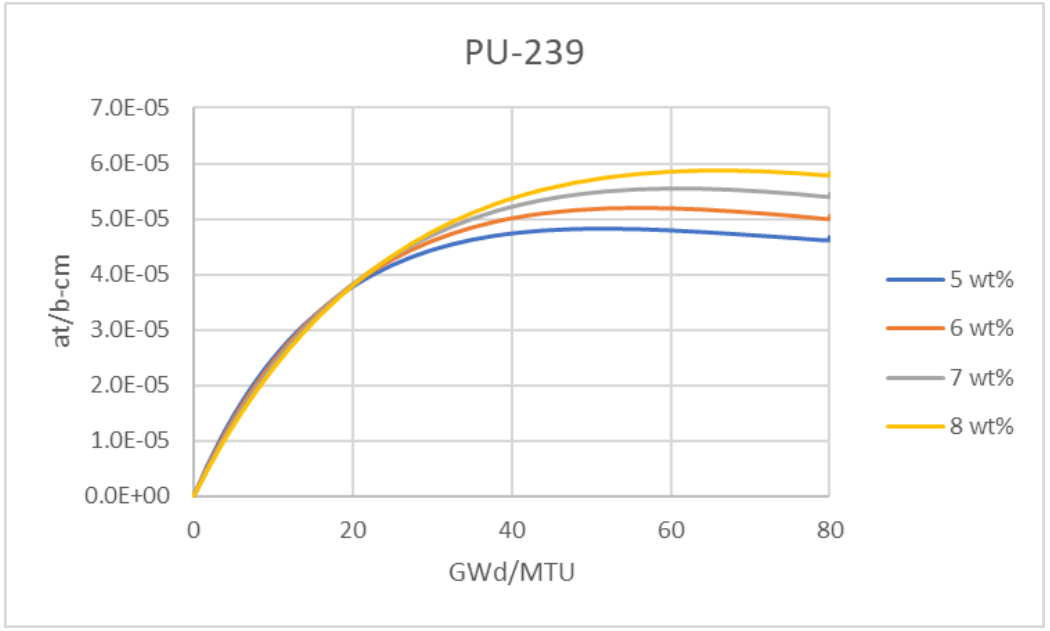
Enrichment (wt% 235U)	MC Burnup (GWd/MTU)	MC Boron Worth (pcm/ppm)
5	28.2	-6.0
6	35.9	-5.5
7	43.3	-5.0
8	50.4	-4.7

Pin cell results – other things you can get via simple script

- Basic isotopic data

I-135 Concentration = 7.3972E-09
Xe-135 Concentration = 3.5592E-09
Pm-149 Concentration = 1.5375E-08
Sm-149 Concentration = 4.1033E-08

U-235 Concentration = 1.5186E-04
U-238 Concentration = 6.5050E-03
Pu-239 Concentration = 4.5737E-05
Pu-241 Concentration = 8.6927E-06

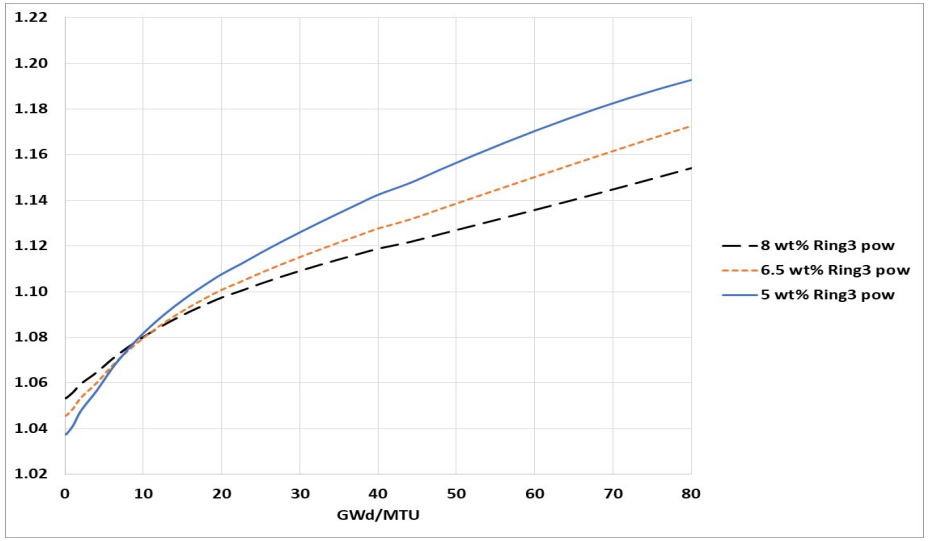


- Flux and power

```
-------------------------------------------------------
 Material Flux and Power Levels over Burnup Step
-------------------------------------------------------

 FUEL.1.p1.s1            |  3.7045E+14 |  1.2133E+01 |
 FUEL.1.p1.s2            |  3.7038E+14 |  1.2674E+01 |
 FUEL.1.p1.s3            |  3.7082E+14 |  1.5067E+01 |
 CLAD.1                  |  3.7138E+14 |  2.7637E-02 |
 COOL.1                  |  3.7114E+14 |  9.8203E-02 |
 GAP.1                   |  3.7155E+14 |  1.0830E-08 |
```

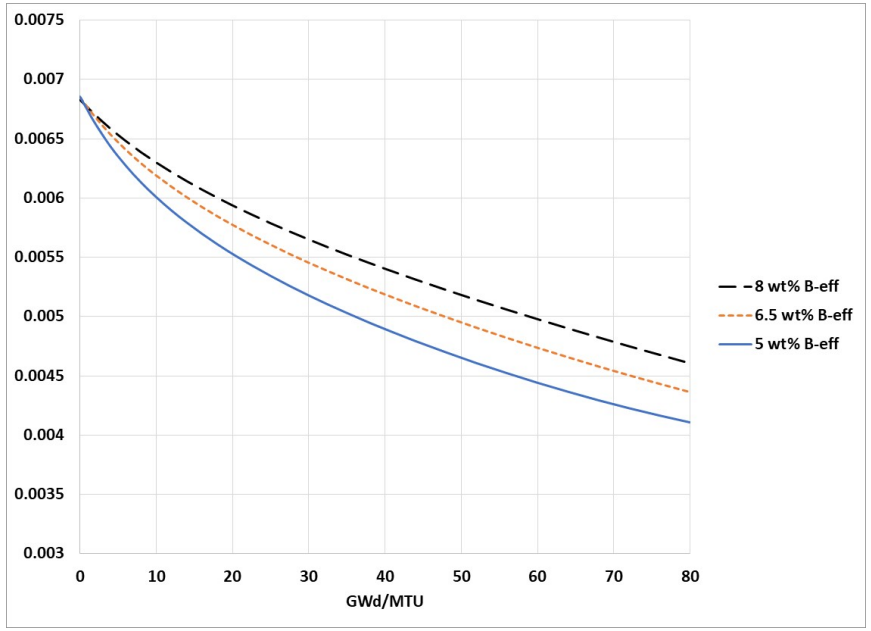
  - Integrate power over depletion steps to get ring burnups for "rim effect" estimate



Pin cell results – other things you can get via simple script

- Kinetics parameters

Decay Group	Beta	Lambda	Beta Eff.	Lambda Eff.
1	1.469E-04	1.264E-02	1.390E-04	1.264E-02
2	1.131E-03	3.076E-02	1.070E-03	3.076E-02
3	9.995E-04	1.208E-01	9.458E-04	1.208E-01
4	2.037E-03	3.213E-01	1.927E-03	3.213E-01
5	7.602E-04	1.268E+00	7.194E-04	1.268E+00
6	2.446E-04	3.409E+00	2.314E-04	3.409E+00
Sum	5.319E-03	8.352E-02	5.033E-03	8.353E-02



- Anything reactivity related that a branch case will allow
  - Set up branch cases

```
read branch basic
  add COOL : dens=0.6929 temp=588.15
```

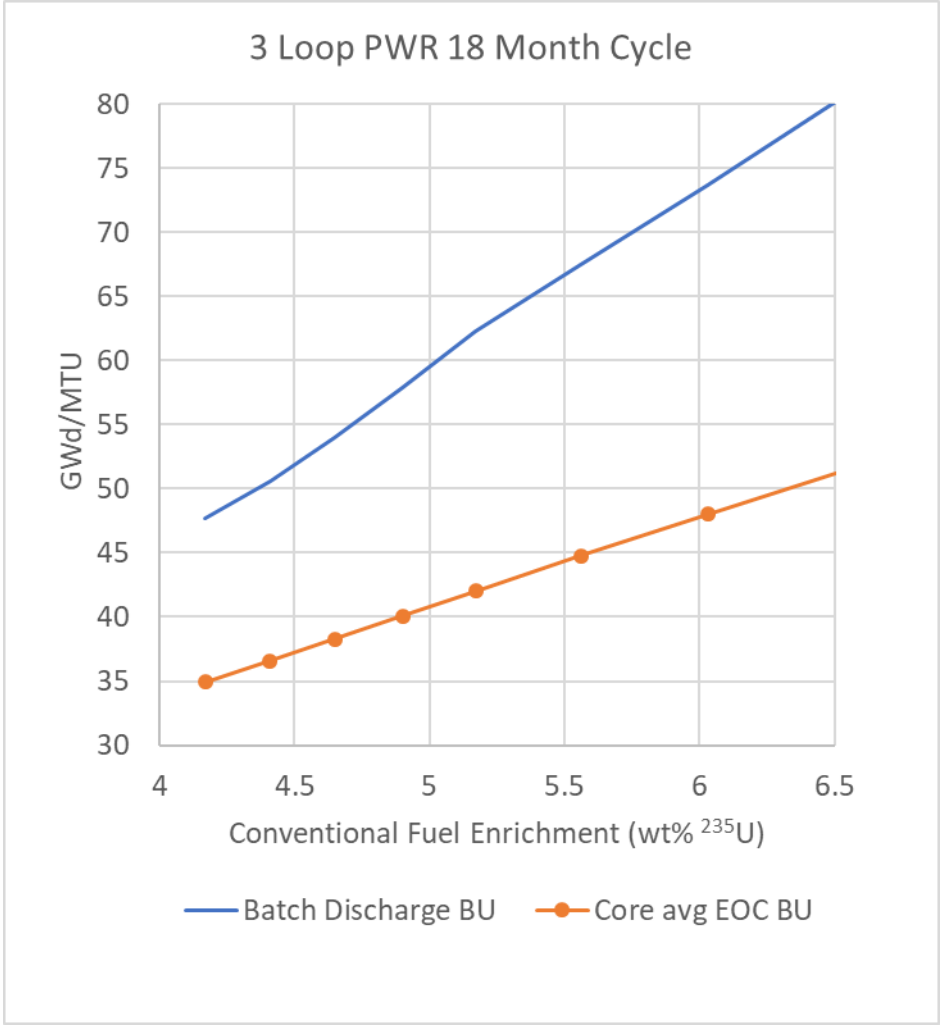
  - Use a simple script to pull the values

```
find "Transport: k-eff" *.out > test.txt
```

  - Drop it into a spreadsheet

Pin cell results – squeezing more from the spreadsheet

- Use the same k-infinity data (HFP, no soluble boron) to get batch discharge burnup estimates
  - Assume batch relative power is proportional to k-infinity
  - Batch powers sum to core power
  - Power and batch size weighted k-infinity at EOC is about 1.05



Batch size	Enrichment wt% ^{235}U	Discharge BU	Core Avg BU
68	4.17	47.7	34.9
64	4.41	50.6	36.6
60	4.65	54.0	38.3
56	4.9	57.9	40.1
52	5.17	62.3	42.0
48	5.56	67.5	44.8
44	6.03	73.6	48.0
40	6.56	81.0	51.6

Pin cell results – squeezing more from the spreadsheet

- Spreadsheet mechanics not covered here
- Important idea is batch enrichment and burnups can be estimated simply and quickly with Polaris pin cell data
  - NEI study discharge burnup increase per wt% increase: **12.8** GWd/MTU DBU/wt%
  - Westinghouse data, IAEA report: **15.0** GWd/MTU DBU/wt%
  - Polaris pin cell + spreadsheet: **14.7** GWd/MTU DBU/wt%

FA in core	157														
Rated power	2900	MW													
MTU/assembly	0.46	MTU													
Batch size	48														
Enrichment	5.56	wt%													
Cycle length	549	days													
Outage + maint	35	days	**1st estimate**			**2nd estimate**				**3rd estimate**				**Discharged**	
Low power core locations	28														
Low pwr loc power penalty	0.5														
		Low power	Rel power	BU	k	Rel power	Norm pwr	BU	k	Rel power	Norm pwr	BU	k		
Batches	4														
Avg Specific power	40.2			0				0							
Batch 1	48		1	20640	1.194	1.281	1.245	25688	1.164	1.258	1.253	25860	1.163	0	
Batch 2	48	0	1	41279	1.057	1.122	1.090	48191	1.030	1.084	1.080	48143	1.030	0	
Batch 3	48	15	1	61919	0.944	0.842	0.818	65076	0.928	0.819	0.816	64982	0.929	35	
Batch 4	13	13	1	82559	0.854	0.448	0.435	74059	0.875	0.454	0.452	74312	0.873	13	
Core avg				44697	1.048	1.029	1.000	44784	1.050	1.004	1.000	**44787**	**1.0499**		
Discharge burnup	**67509**														

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Other ideas for Polaris pin cell models

- Use Sampler perturbed cross section capability to determine isotope uncertainty
  - 1000 perturbed cross section libraries
  - Get hundreds of depletions with unique k-infinity and isotopic content versus burnup

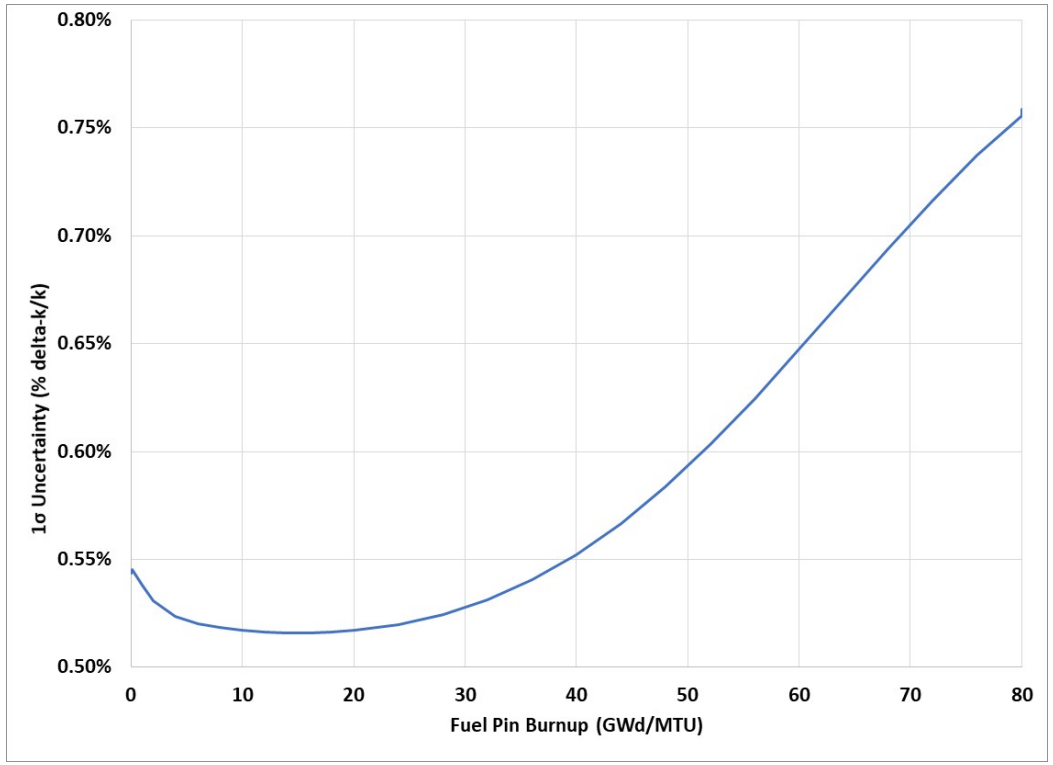

Table 5. Sampler isotopic content uncertainty*.

Isotope	60 GWd/MTU	80 GWd/MTU
^{239}Pu	2.0%	2.4%
^{238}U	0.0%	0.1%
^{241}Pu	1.9%	2.3%
^{240}Pu	2.1%	2.3%
^{235}U	1.8%	3.4%
^{135}Xe	3.6%	4.1%
^{103}Rh	1.9%	2.4%
^{143}Nd	2.1%	3.0%
^{16}O	0.0%	0.0%
^{237}Np	3.6%	3.9%
^{133}Cs	1.0%	1.4%
^{242}Pu	4.4%	5.2%
^{131}Xe	6.1%	8.2%
^{149}Sm	3.0%	3.7%

What about control rods, IFBA, WABA, Cr coated clad?

- Cr coated clad
  - Model the clad and calculate a k-infinity penalty
  - Change the target k-infinity for end of cycle in the spreadsheets
  - Re-calculate the required batch size / enrichment / burnup combinations
- IFBA
  - Expand the model to the minimum necessary size (2x2 pins)
  - 0 to 4 IFBA rods represents 0 to 100% IFBA in the fuel assembly
  - Model runs much faster than full lattice
  - Make sure to preserve assembly fuel/water ratio
- Control rods
  - 3x3 with a central guide tube
  - 1 out of 9 locations vs 24 out of 289 in a Westinghouse 17x17 assembly
  - Good enough for apples vs apples comparisons to a base case
  - Make sure to preserve the assembly fuel/water ratio

Polaris / pin cell / Sampler + spreadsheet

- Quick estimates of core parameters
- Changes due to enrichment and burnup
- Boron worth
- MTC
- DTC
- Rim effect
- Flux magnitude
- Isotopic content and uncertainty
- Build a “proper” pin cell!

Back of the envelope PWR studies

Questions?

Alternative titles

“When you’re too far behind to build a real core model”

“How to give your boss talking points without working that hard”

“No, commercial PWRs won’t need 8 wt% ^{235}U”

“Fun with Polaris (and maybe Sampler too)”

“C’mon! I’m an engineer, not a physicist”