The Effects of Shim Arm Depletion and Xenon Buildup on Estimated Critical Positions in NBSR for New- and Mid-Cycle Startups

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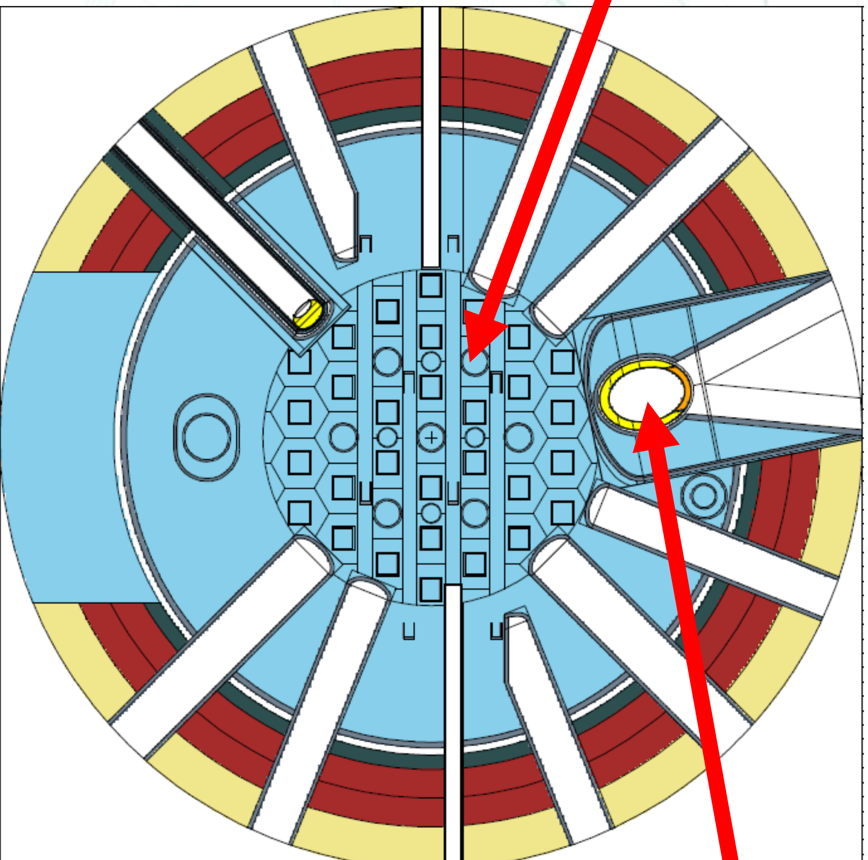
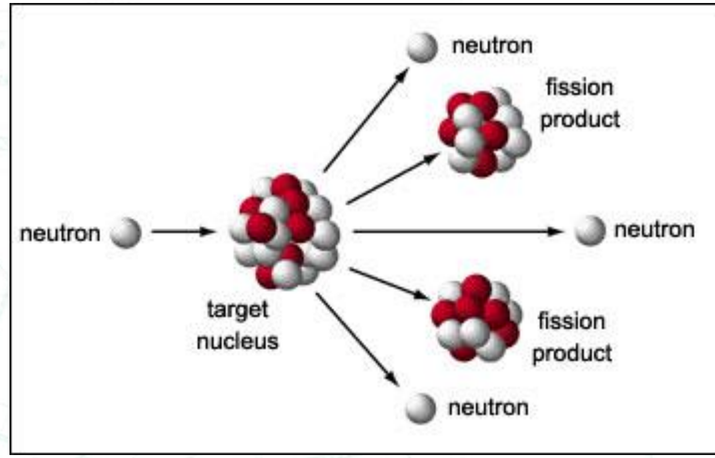
Project Objectives

- Develop a procedure for estimating critical positions.
- Quantify the duration of the Xenon-limited startup window.
- Improve management of fuel inventory and scheduled cycle length.
- Minimize obtrusiveness during “normal” operations.

U-235 Fuel Elements



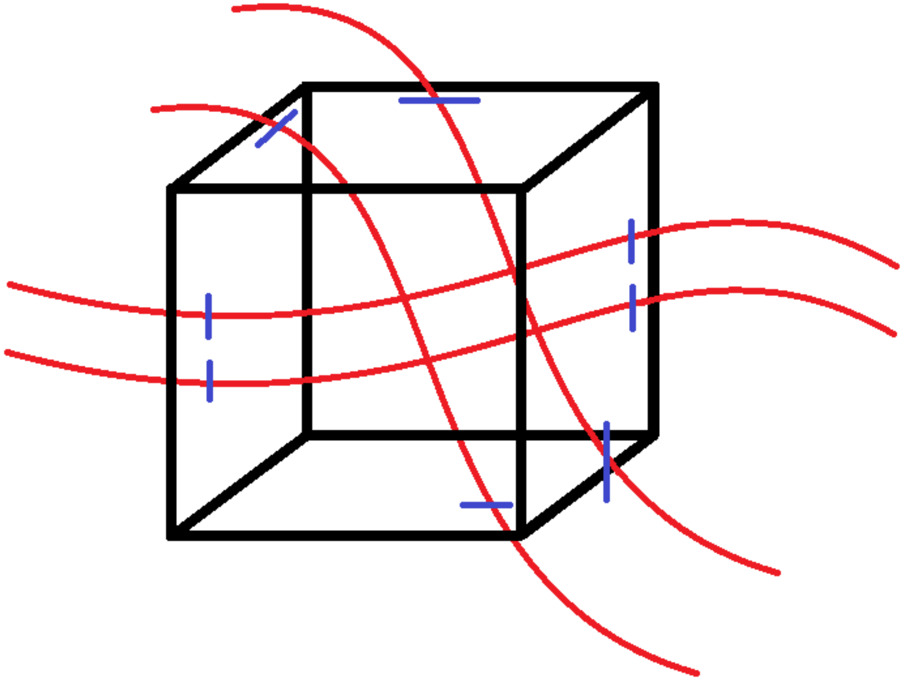
Cold Neutron Source

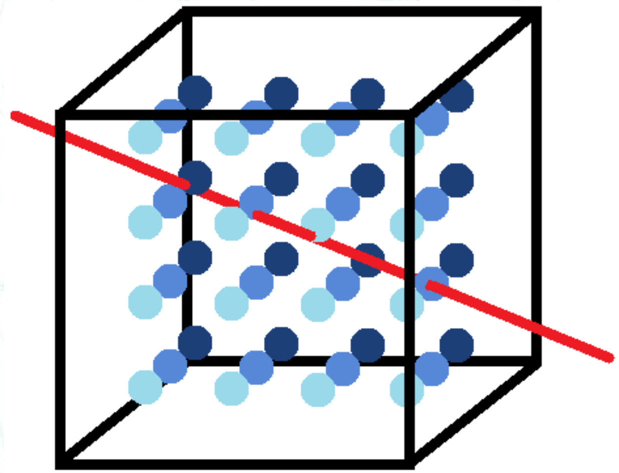


Graphic courtesy atomicarchive.com

Some Terminology

- Flux (φ) $\equiv$ *Total <u>path length</u> of all n's in a volume at one time* $\left(\frac{n}{cm^2 - s}\right)$.
- Cross Section (Σ) $\equiv$ *Cumulative <u>target size</u> per unit material* (cm^{-1}).
- Reaction Rate ($\varphi^*\Sigma$) $\equiv$ *Frequency of neutron interaction in a material.*





Neutron ~~Transport~~ Balance Equation

- Variant of Boltzman Equation (1872) – *Describes the statistical behavior of a thermodynamic system not in equilibrium.*

Neutron Losses | *Neutron Production*

$$(D\nabla\varphi_2 + \Sigma_a\varphi_2 + \Sigma_{1\to2}\varphi_2) = \frac{1}{k_{eff}} * (\nu\Sigma_f(\varphi_1 + \varphi_2) + \Sigma_{2\to1}\varphi_2)$$

Diffusion

Absorption

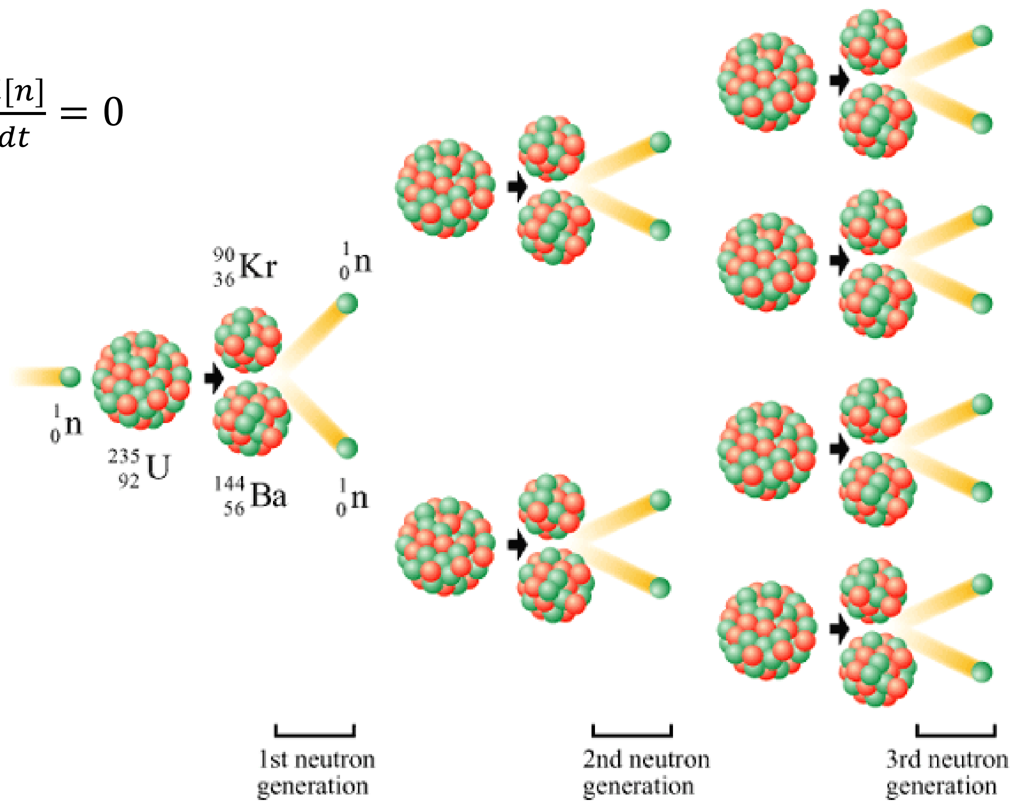
Down-scattering

Fission Source

Up-scattering

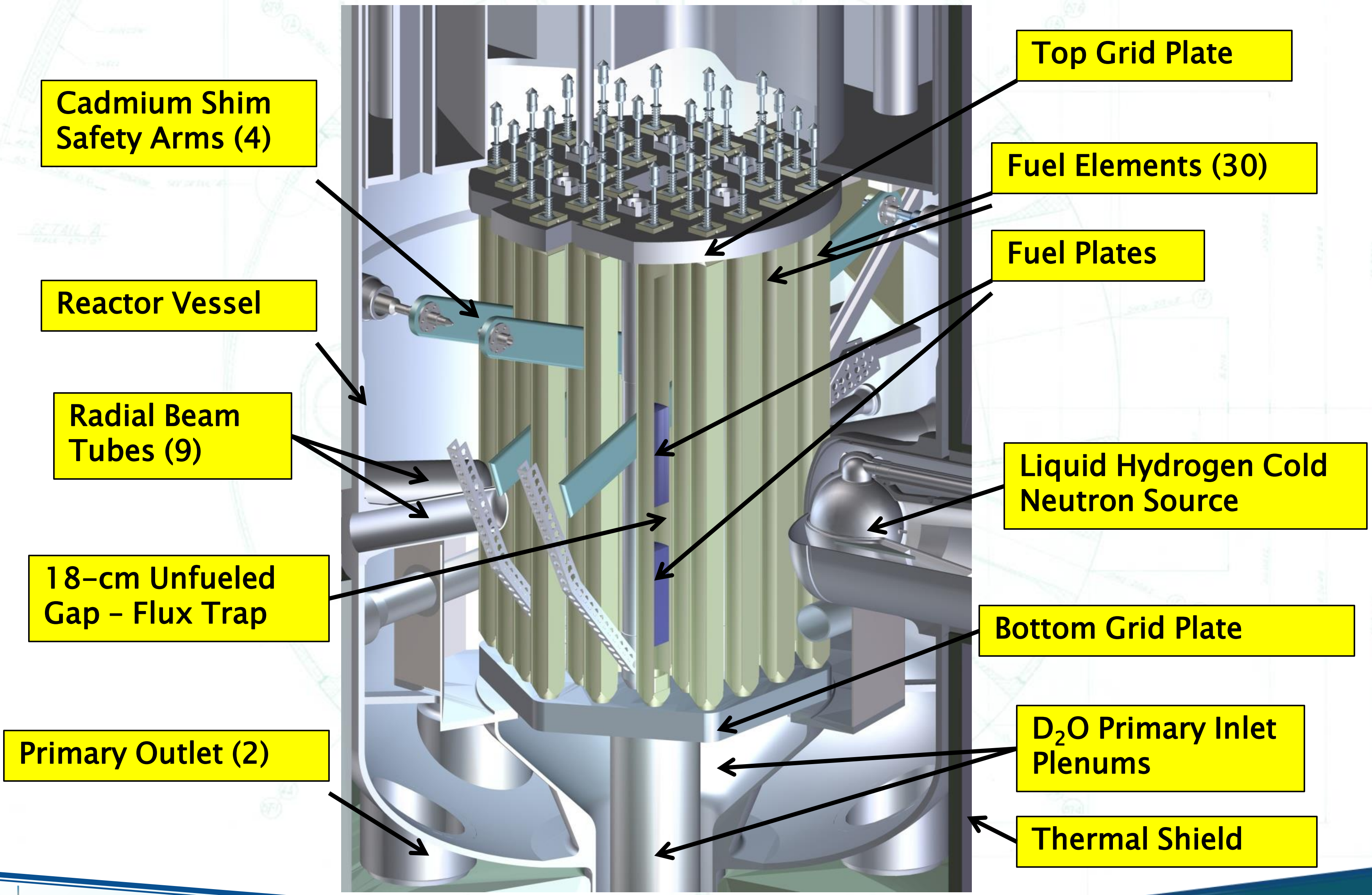
Measuring Criticality

- What is "criticality?"
  - Mathematically, $k_{eff} = 1$, or $\frac{d[n]}{dt} = 0$
- Why does it matter?
  - Nuclear Safety Analysis
  - Performance Benchmarking
- How do we observe it?
  - Operationally
    - Slowly increasing power
    - No shim arm movement
    - P_{Rx}~100kW
  - Computationally
    - Monte Carlo methods

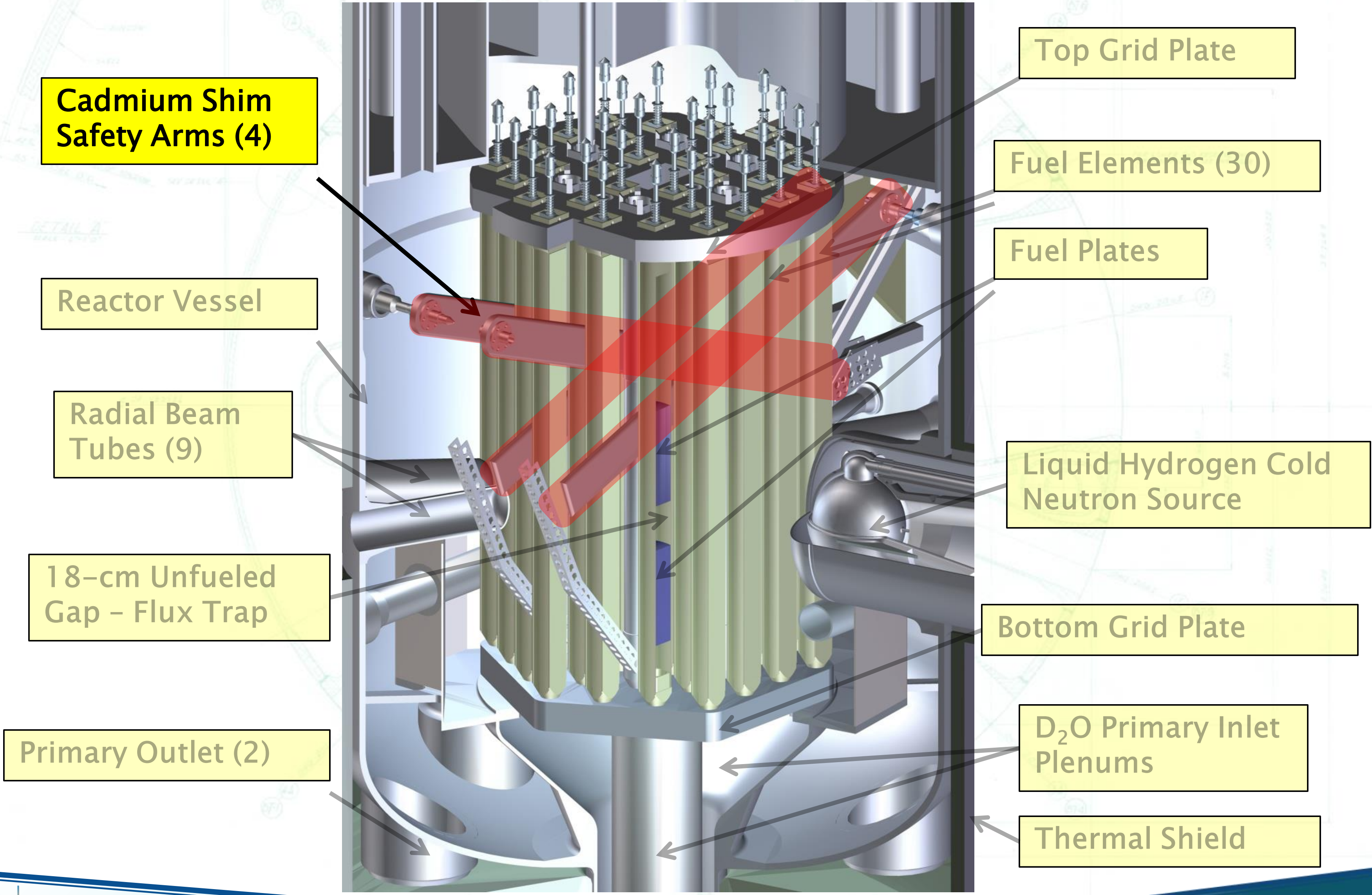


Graphic courtesy http://www.hk-phy.org

The Neutron Beam Split-Core Reactor (NBSR)



Controlling the NBSR

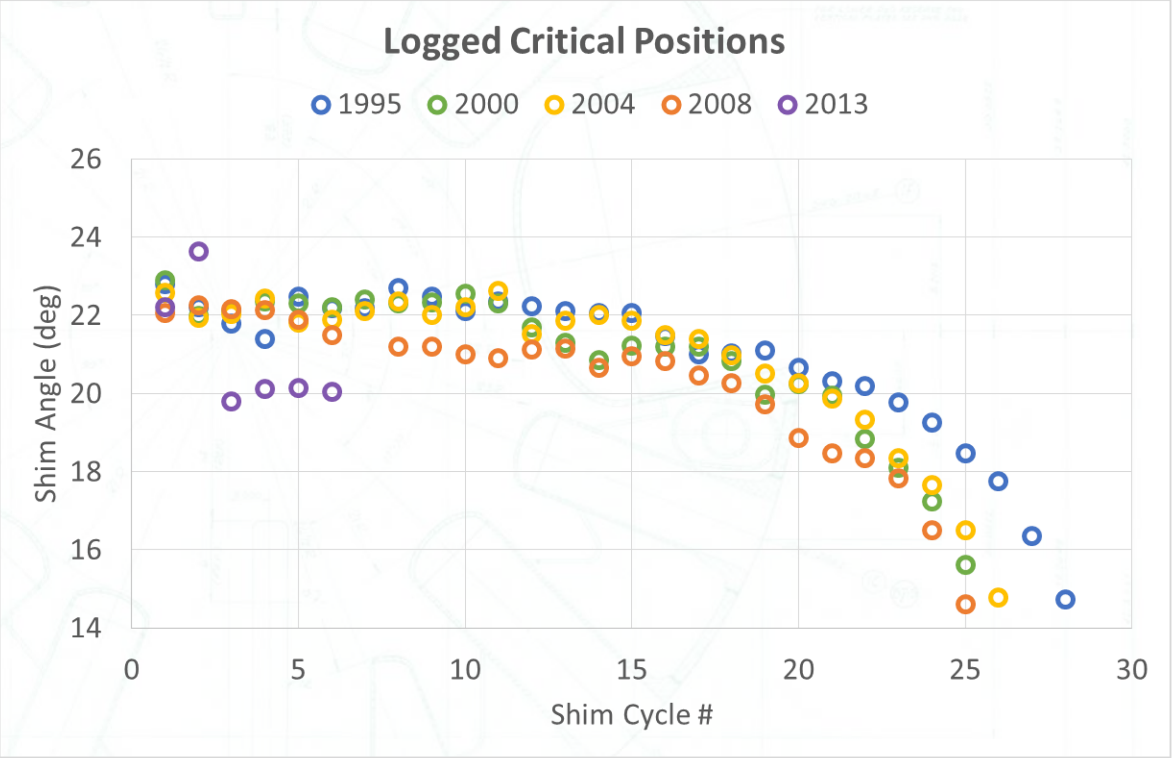


Cadmium Shim Arm Depletion

- NBSR typical fuel cycle: 38.5 days
- Shim arm lifetime: ~25 cycles

- Minimum Shutdown Reactivity: A reactor safety concern

- Must adjust for external variables
  - *Temperature*
  - *Fuel history*
  - *Extra fuel loading*
  - *Reg rod*



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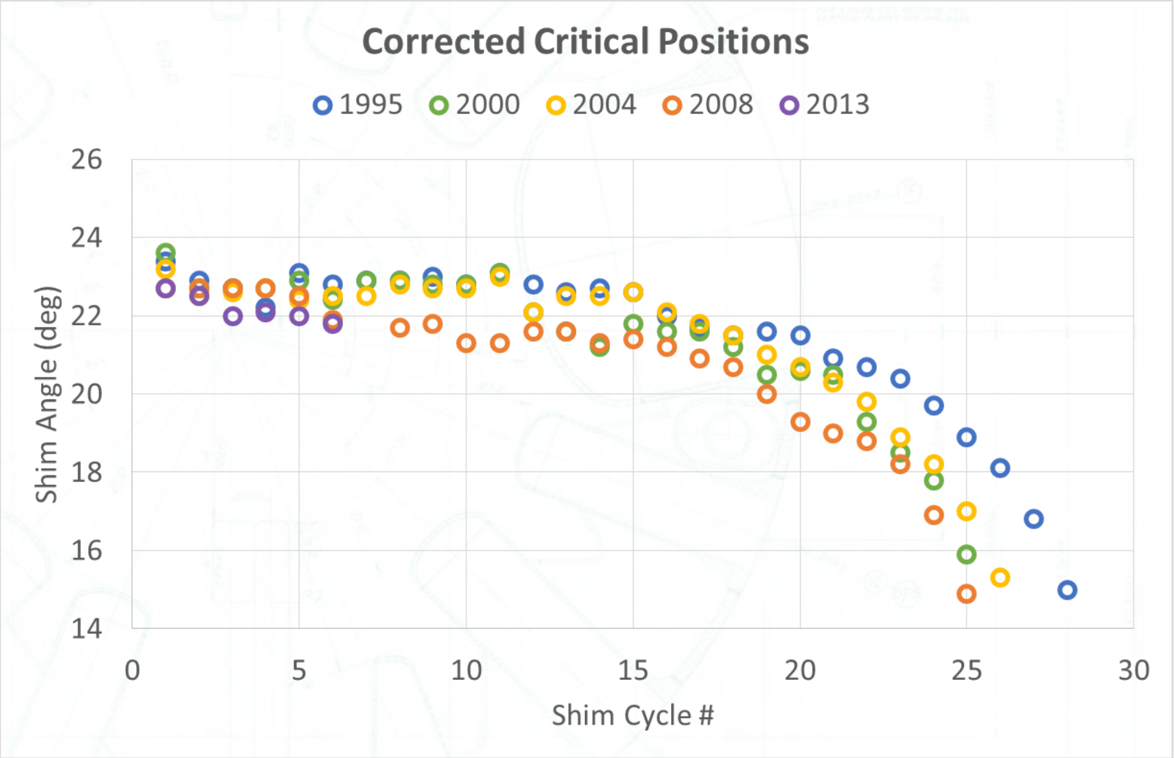
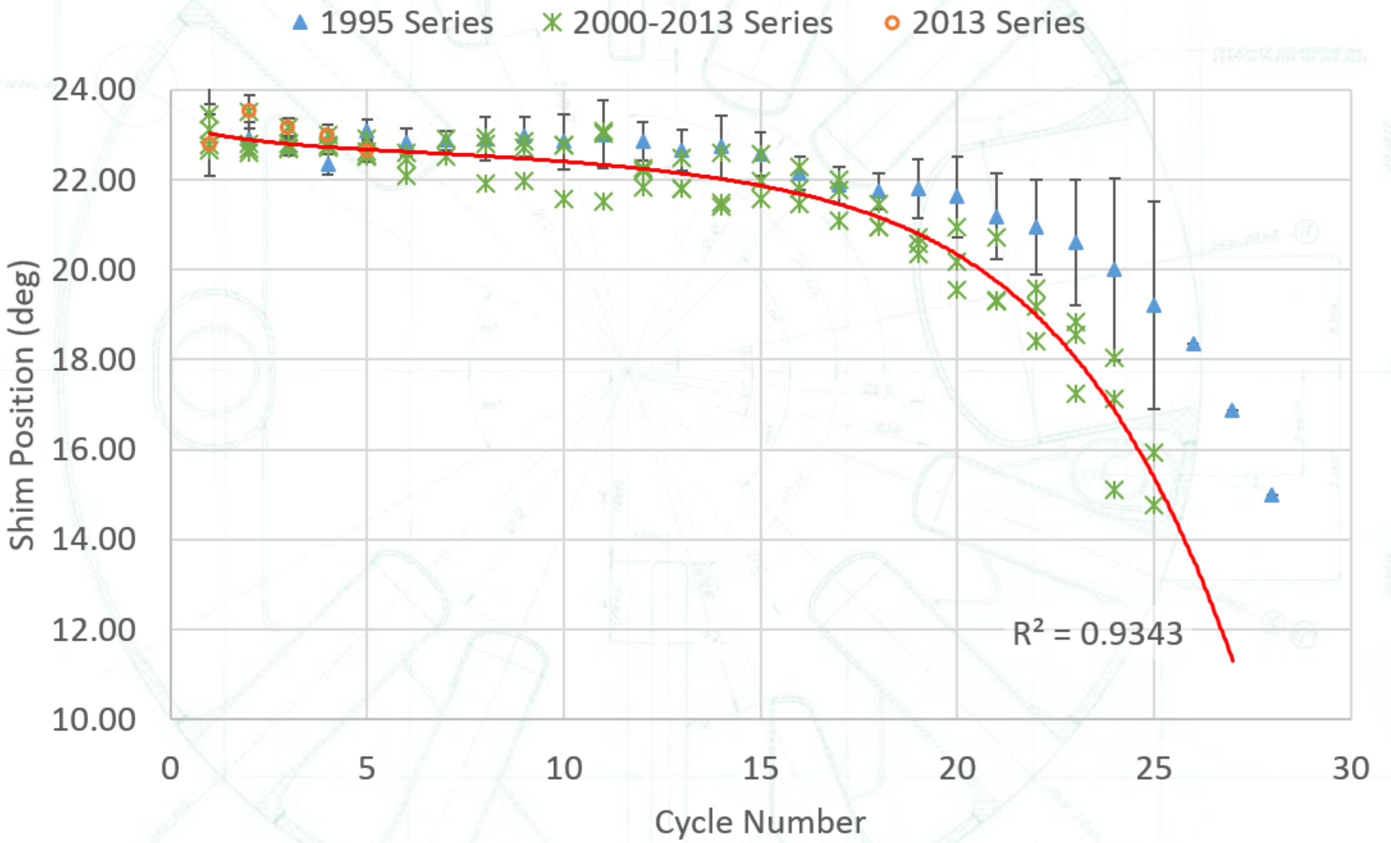
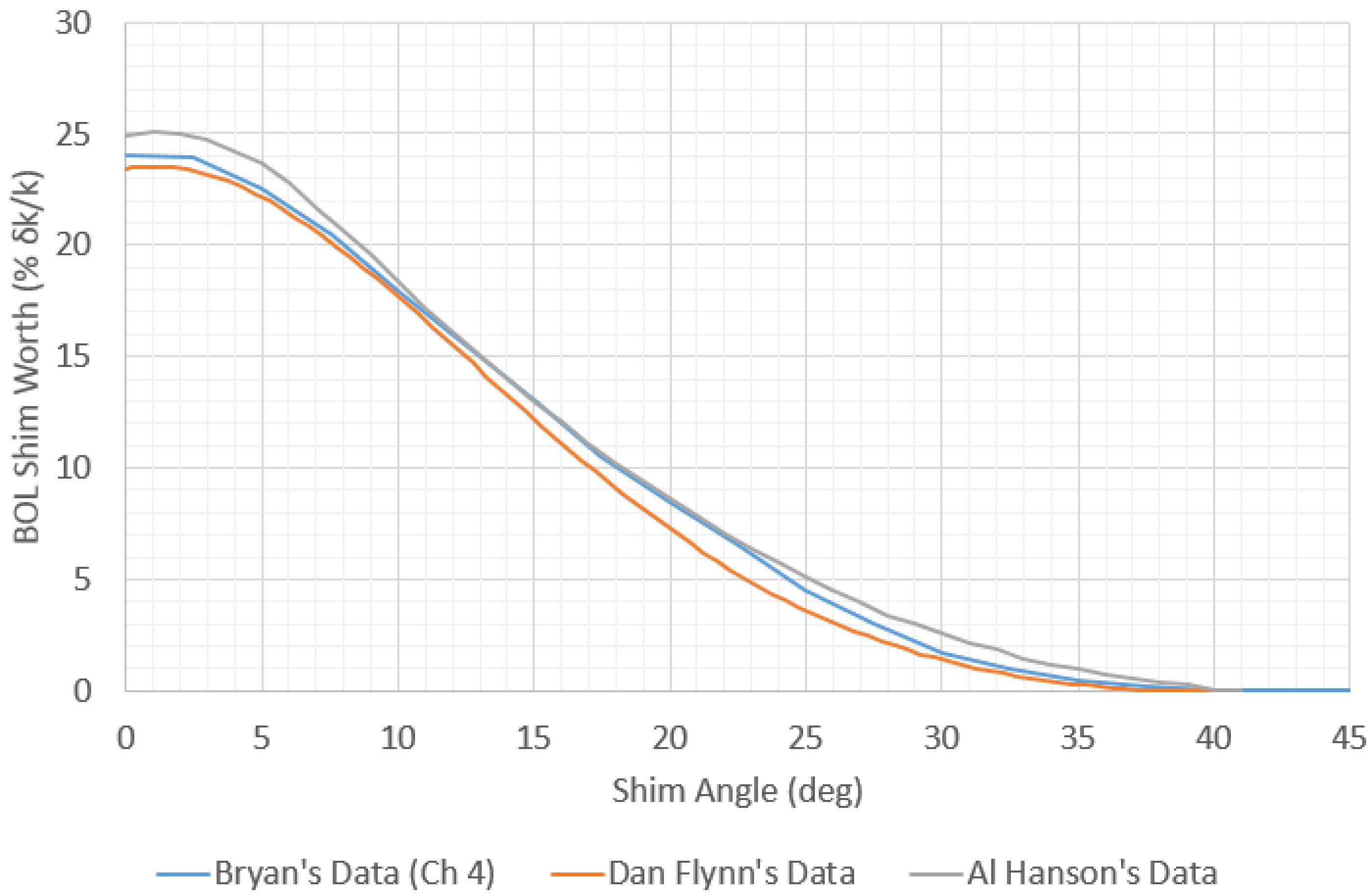


So, “Game, Set, Match.” …Right?

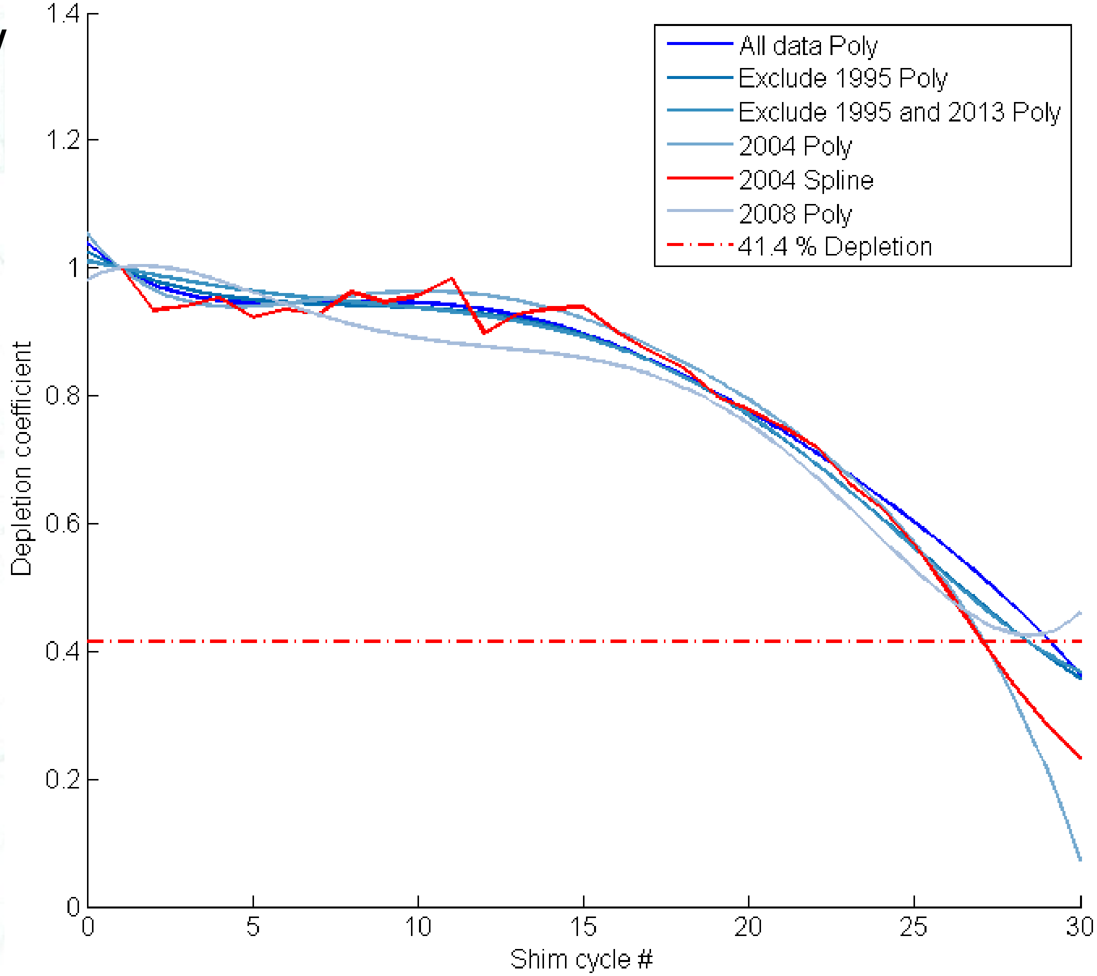


Shim Arm Reactivity: Not exactly linear.



Final Shim Depletion Estimate

- *Adjusted for temperature and reg rod position only.*
- Tech Spec Limit: 41.4% Loss
  - (That's 10.2% dk/k, or $13.5)
- "Reference core" – 68 F Req'd
- Searched for "most conservative" prediction
  - 2004 had erratic, sharp curve
  - 8/8/2004 cycle canceled due to insufficient reactivity
- Error difficult to quantify
  - Operator logging practices
  - Limited data available @ 20 MW



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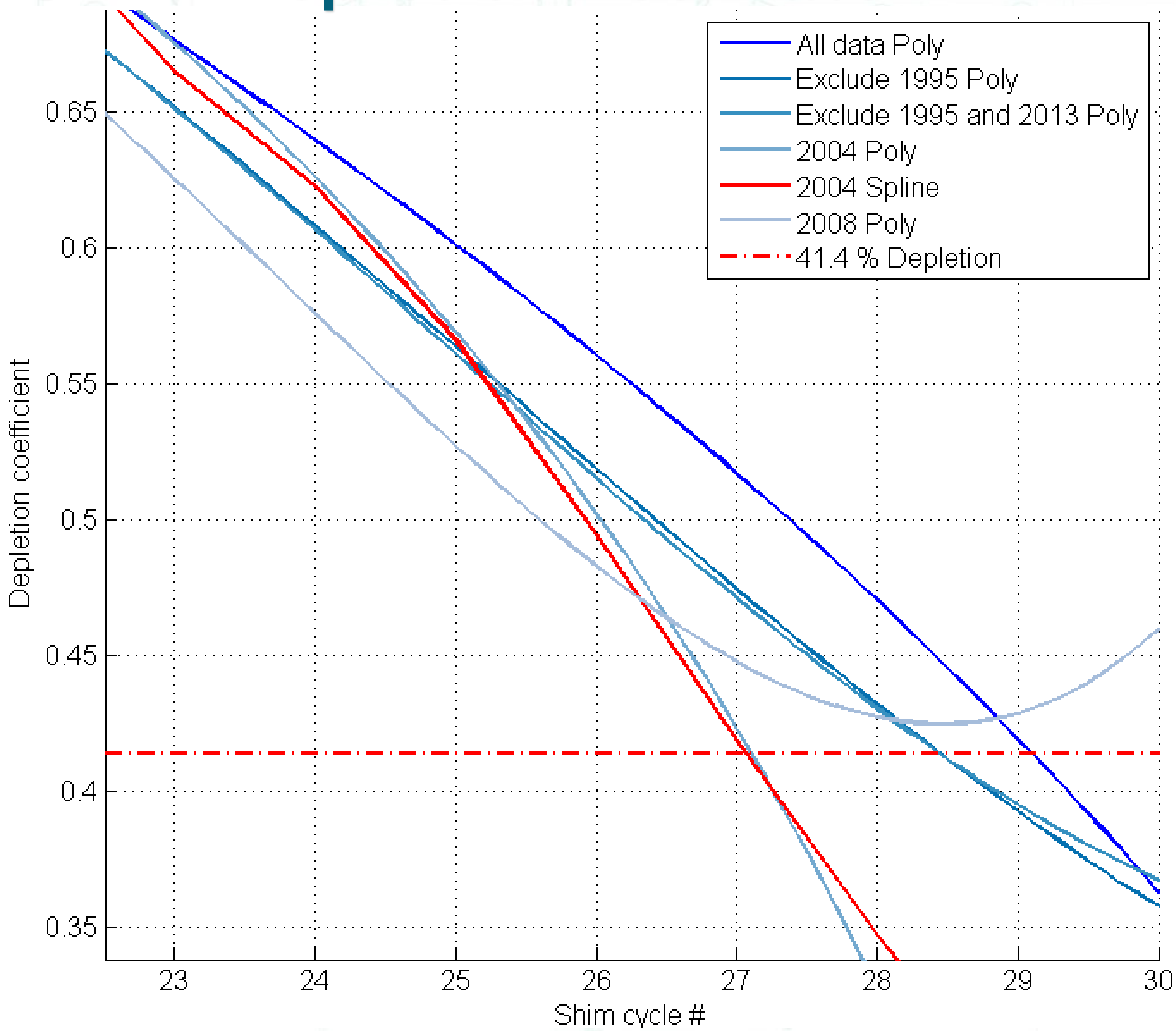

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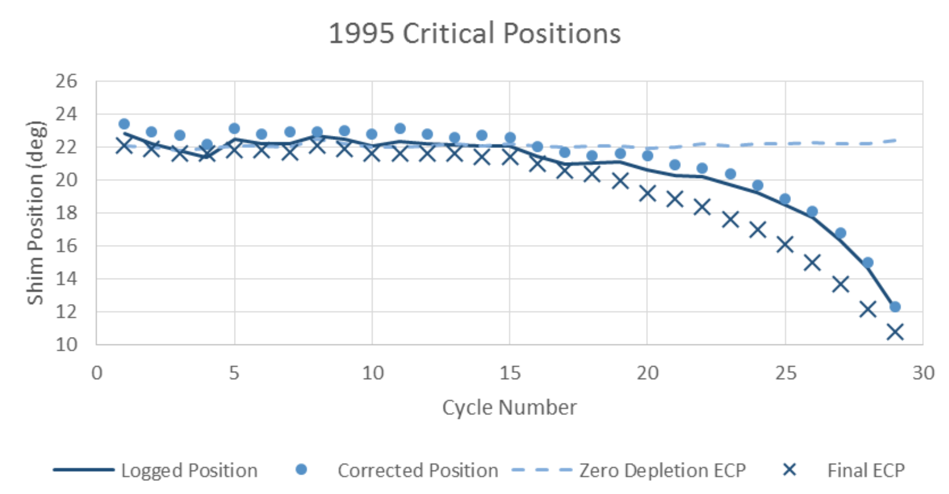
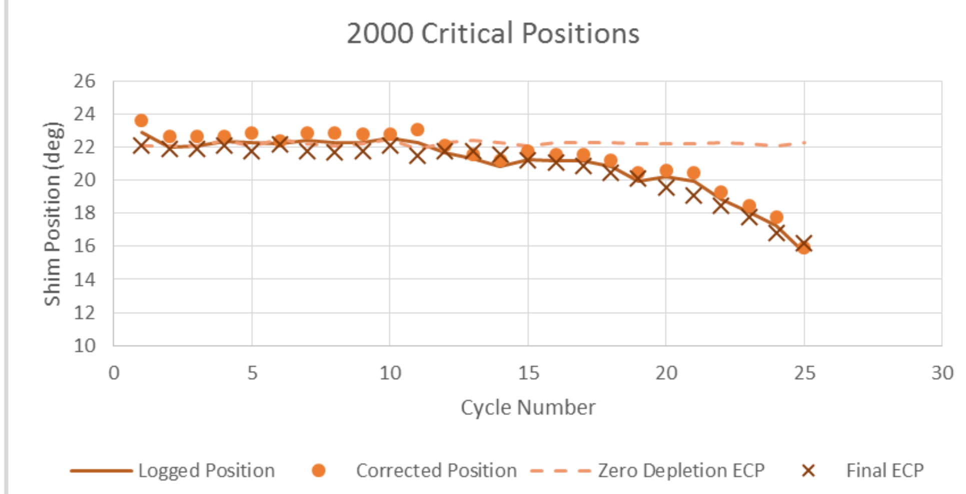
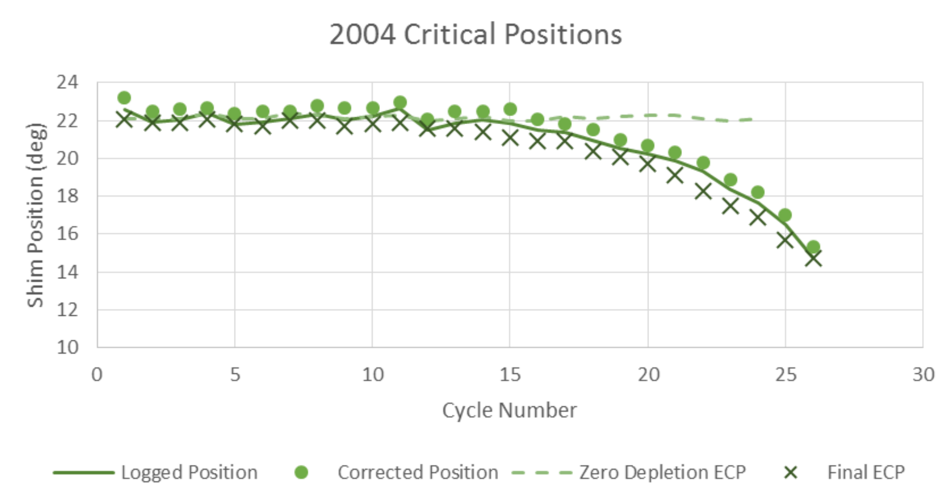
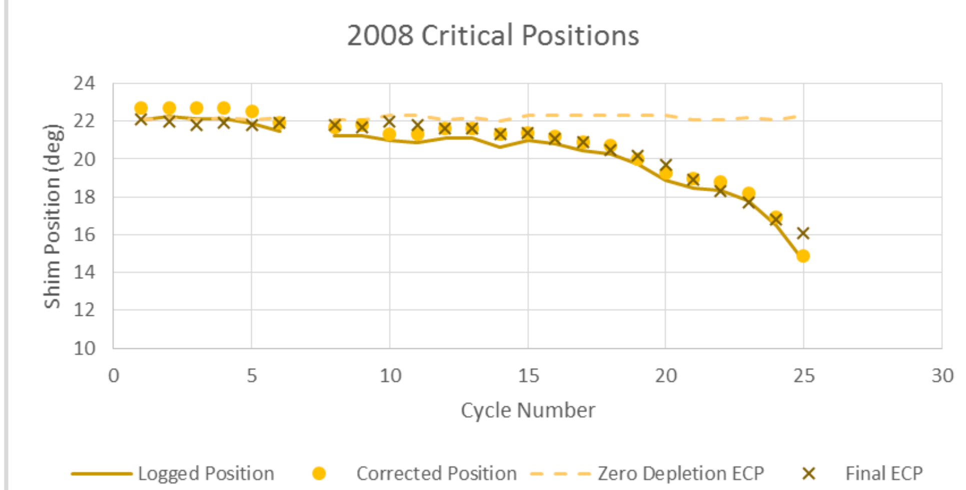
BOC Startup ECPs (1995–2013)









$$\bar{x} = 0.42°;\ \sigma = 0.29°$$

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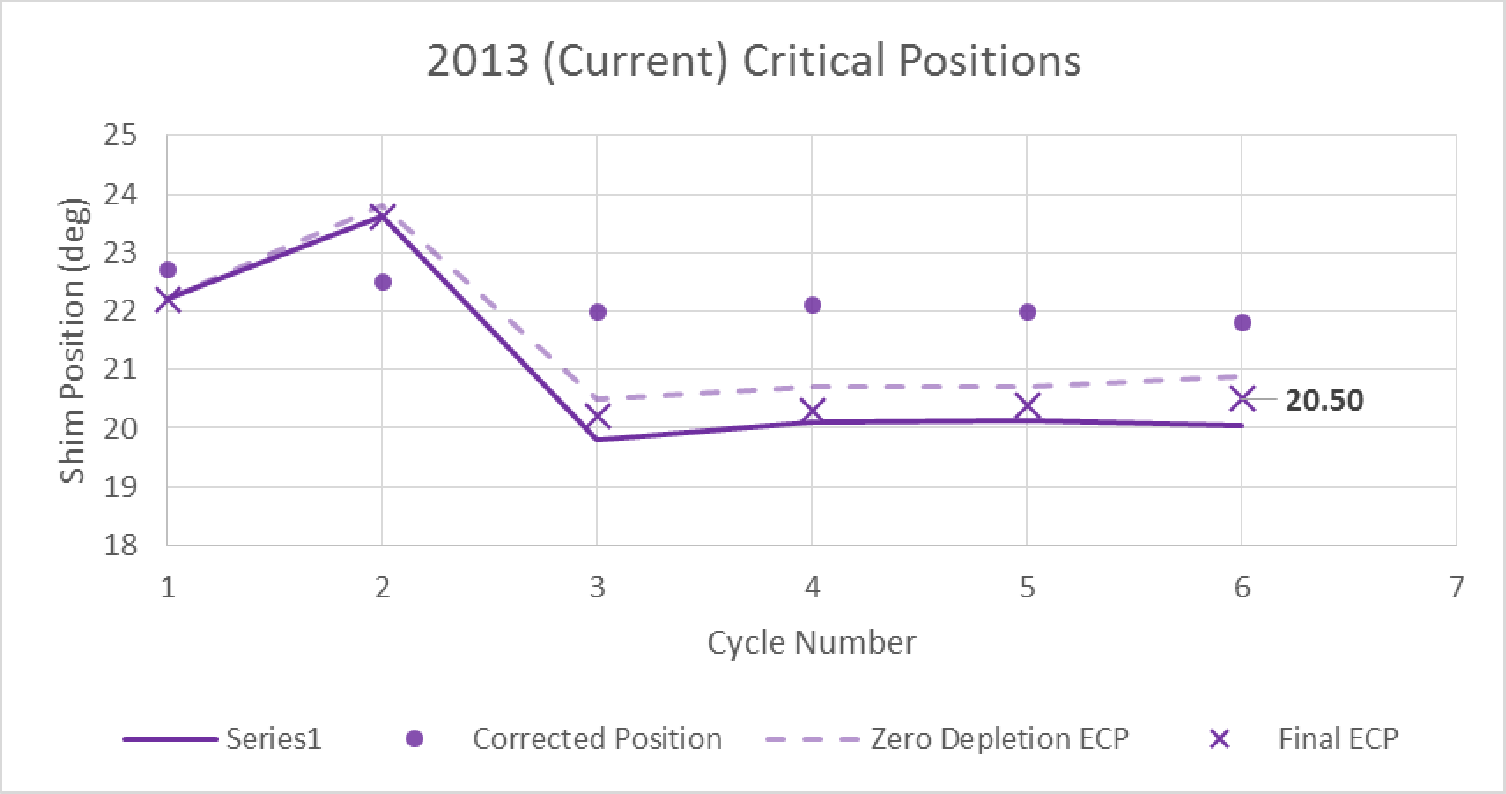
BOC Startup ECPs (2013–Present)

- Unique aspects of the 2013 cycle:
  - Loaded 3 (not 4) fuel elements for 2nd cycle
  - 2nd cycle was 10 days short
  - Loaded 5 (not 4) fuel elements for 3rd cycle



Part 2: Xenon Buildup & Mid-Cycle ECPs

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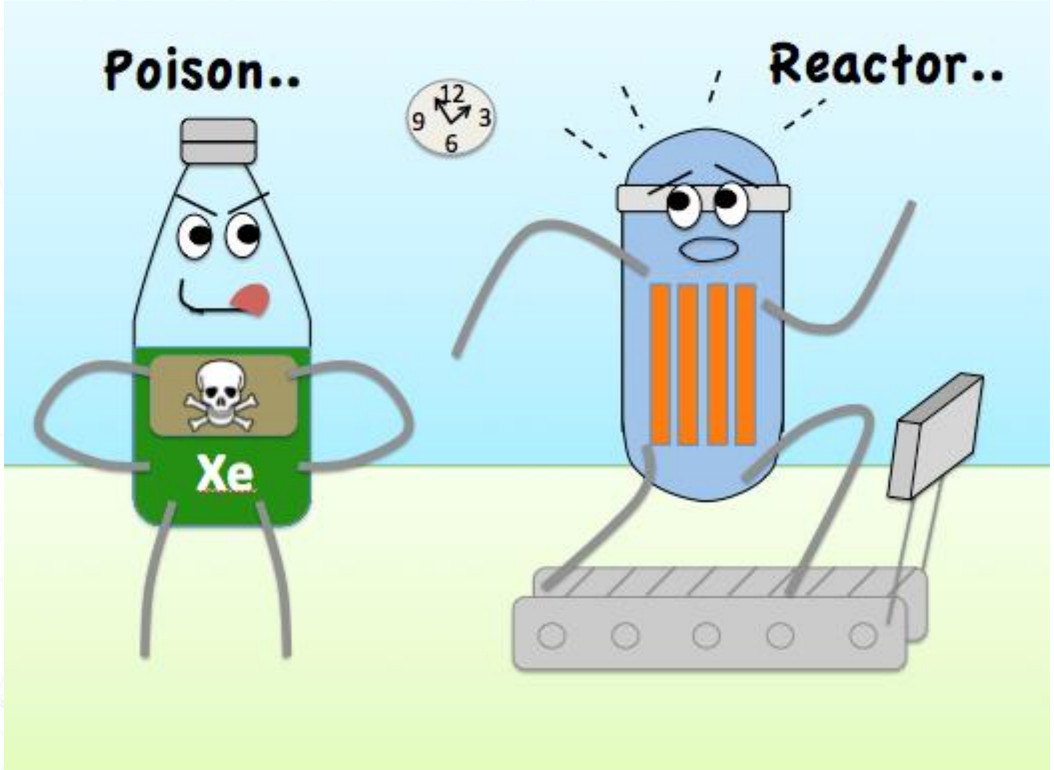
Xenon: A Powerful Neutron Poison

- Xe's cross section is VERY large (~2 million barns!!!)

- <u>Xe Sources</u>
  - Direct fission product (0.23%)
  - Radioactive decay of I-135
    - Also fission product (6.39%)
    - $t_{1/2}$=6.57 h

- <u>Xe Losses</u>
  - Radioactive decay
    - 6.39%
  - Burnup (fission capture)
    - $\sigma > 2e6$ b



Graphic courtesy http://www.stanford.edu

Xenon Analytic Solution

- Variation of Rutherford's equation for radioactive decay (1908):

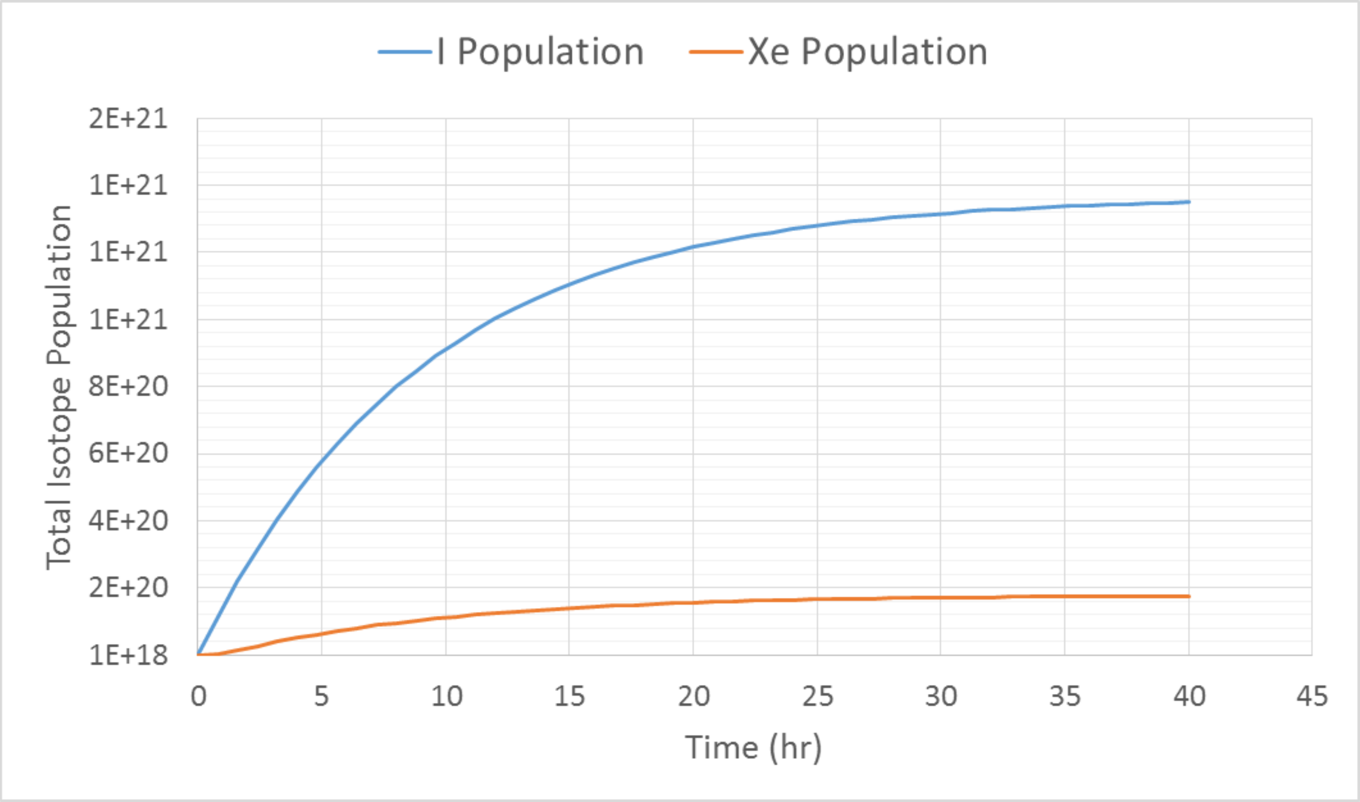
$$\frac{\delta I}{\delta t} = \gamma_I \Sigma_f \varphi(r,t) - \lambda_I \, I(r,t)$$

$$\frac{\delta Xe}{\delta t} = \gamma_{Xe} \, \Sigma_f \, \varphi(r,t) + \lambda_I \, I(r,t) - \lambda_{Xe} \, Xe(r,t) - \sigma_a^X \varphi(r,t) \, Xe(r,t)$$

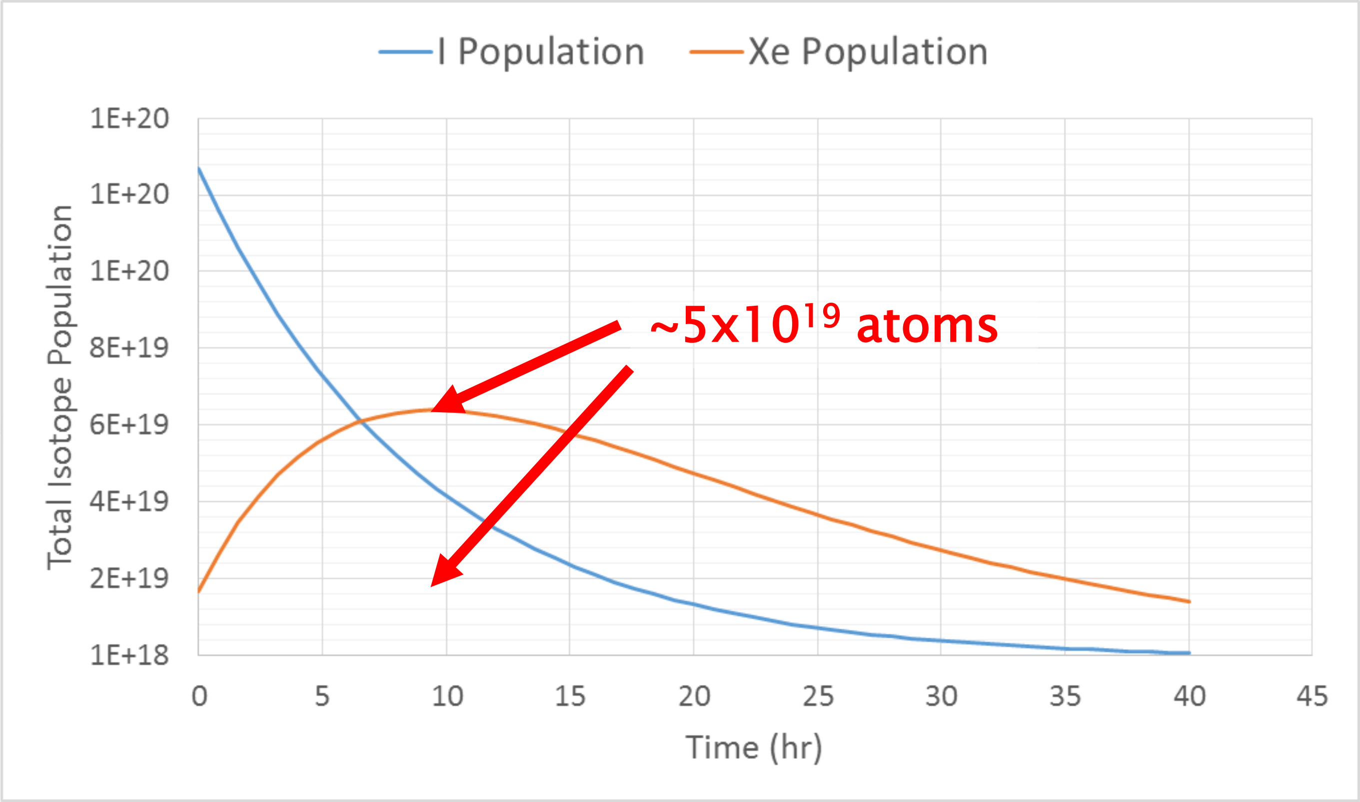
Fission Source — *Iodine Decay* — *Xenon Decay* — *Xenon Burnup*

- Solution known as the Bateman equation (1910).

Xenon Analytic Solution: Reactor Startup



Xenon Analytic Solution: Reactor Shutdown



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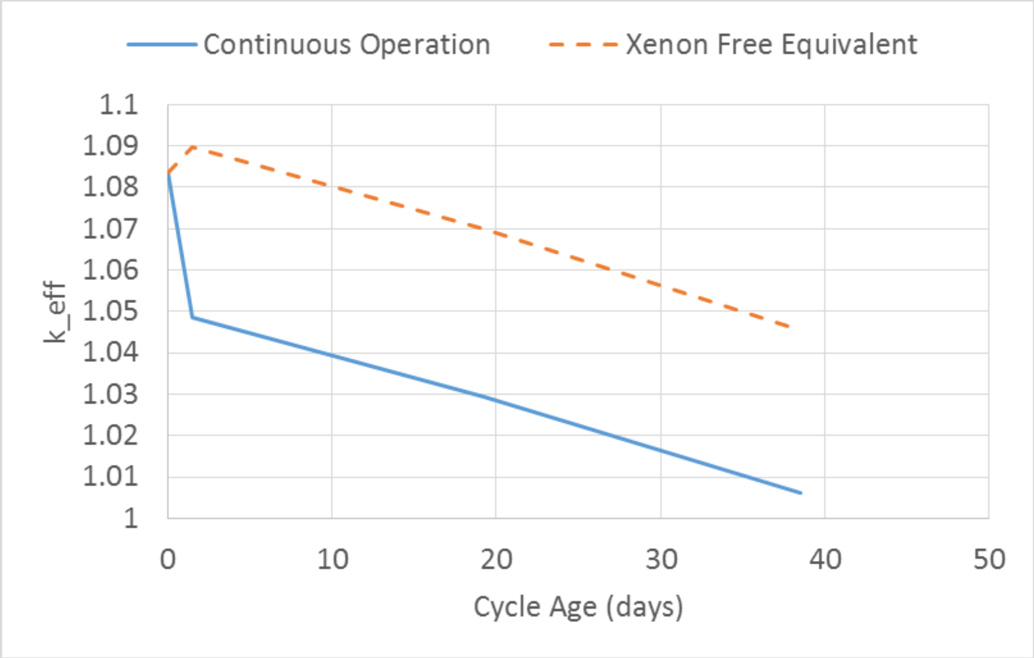
But how much is Xenon *worth?*

Problem

- Core population: ~1.7E18, but distribution is unknown
- $\varphi(\bar{r}, t)$ solution is formidable

Solution

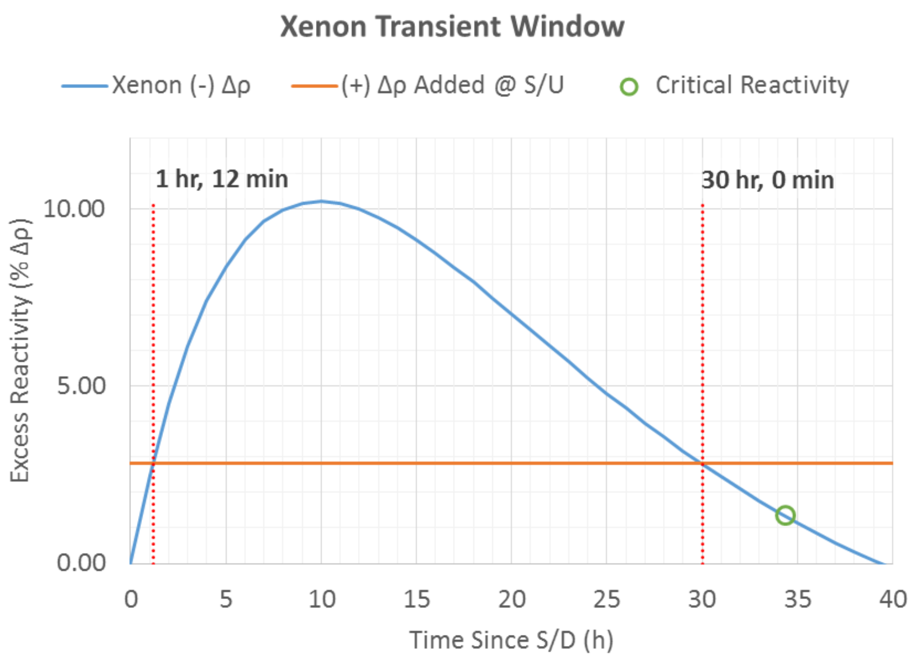
- Stick to "point kinetics" calculations
- Let MCNP handle the flux internally
  - LANL software: "Monte Carlo Neutron Gamma"
  - Returns k_{eff} for a given geometry
  - No time dependence

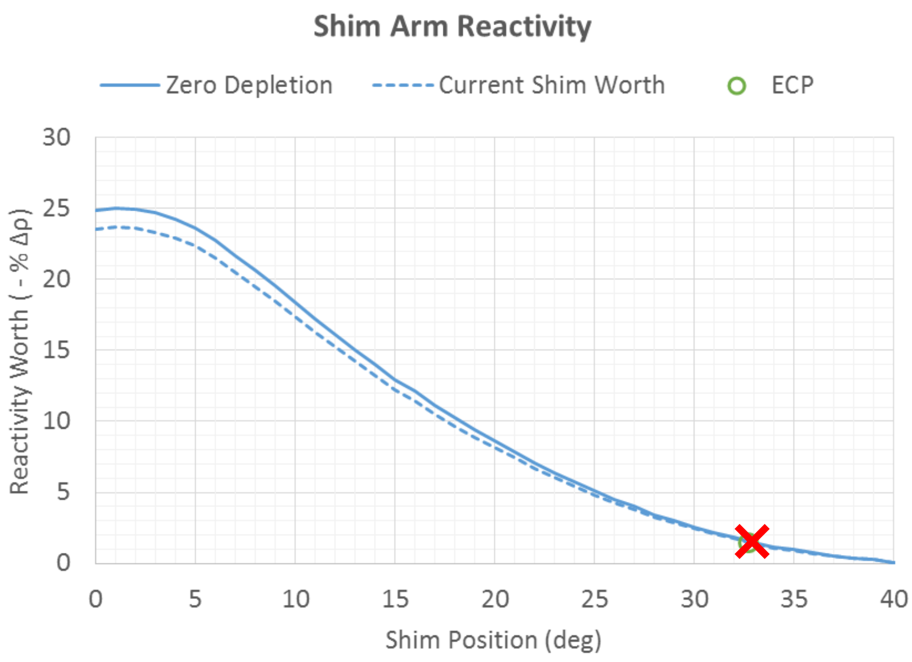


Xenon Worth Estimate (above)

- Used materials from BNL
- Removed all [Xe]
  - Kept Samarium content
- Total eq. Δρ: 3.68% dk/k
  - (or $4.86)

Thermal Column Cooling Repair (6/17/14)

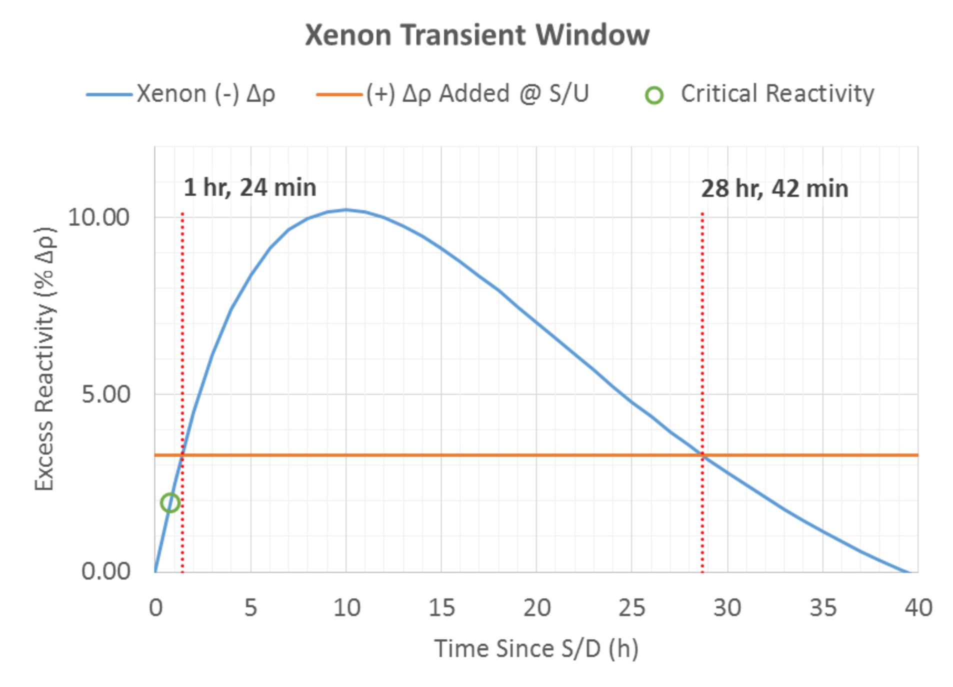


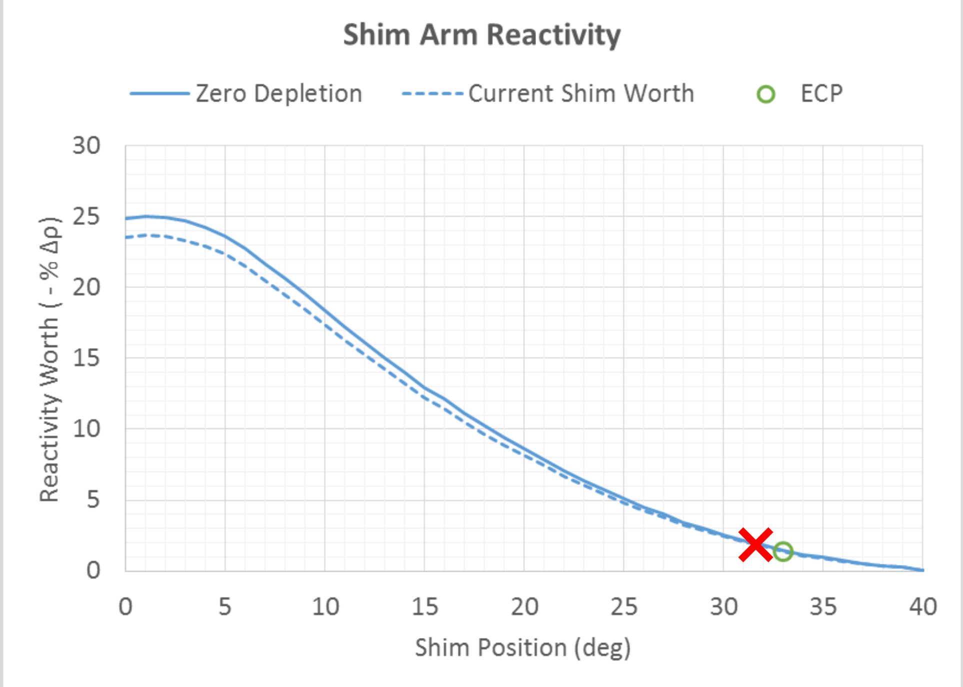


- Window limit error
  - ~10 mins (left)
  - ~1 hr (right)

Prediction: 32.70 deg
Observation: 32.60 deg

Loss of Site Power (3/12/13)



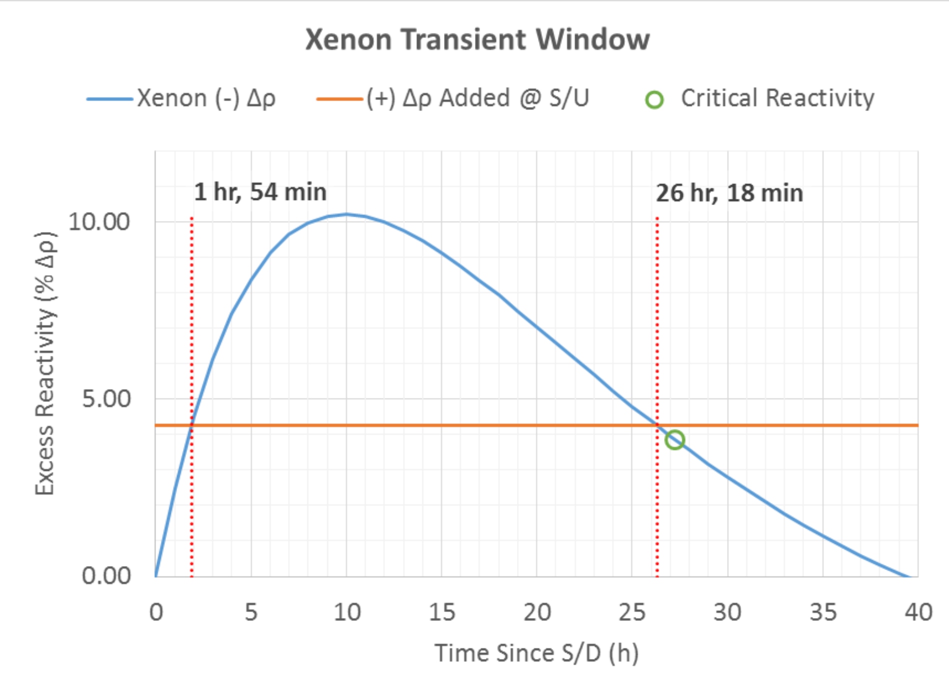


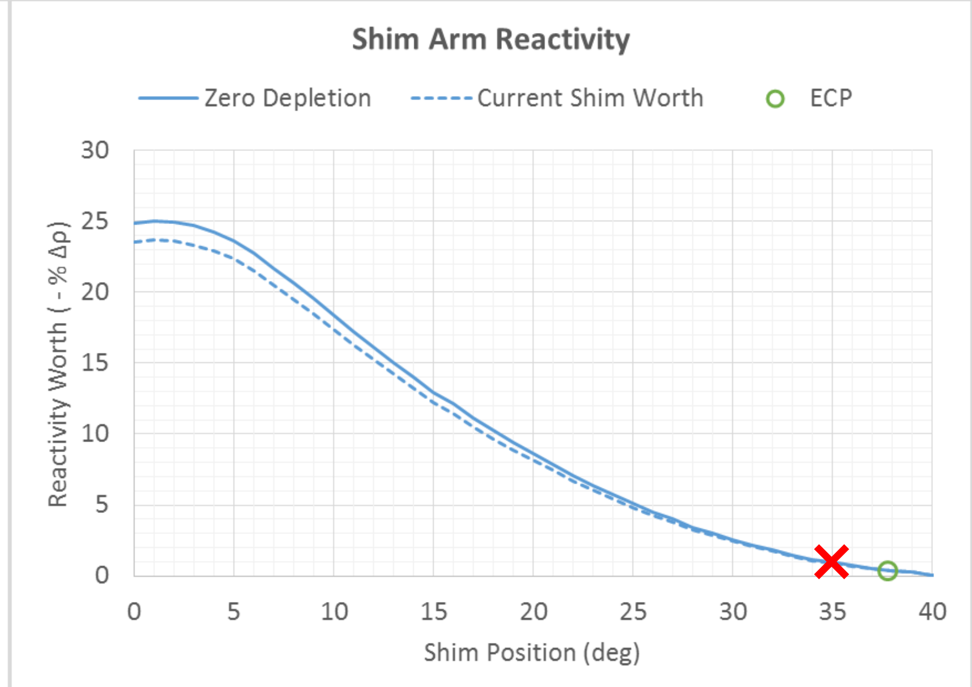
- Window limit error
  - ~10 mins (left)
  - ~1 hr (right)

**** Opposite side of the window*

Prediction: 33.00 deg
Observation: 31.60 deg

Cold Source PLC Replacement (7/29/14)





- Window limit error
  - ~10 mins (left)
  - ~1 hr (right)

Prediction: 37.80 deg
Observation: 35.00 deg

**** Much smaller $\Delta\rho/\Delta\theta$ at this height*

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Outliers

Incident	Date	Length (h)	Δρ shim (dk/k)	Angle Err (°)
Cold Source PLC Failure	7/29/2014	27.27	3.923	2.8
Thermal Column Failure	6/17/2014	34.35	2.808	0.1
PV-1003 Incident	6/11/2013	32.65	5.981	-2.3
Loss of Site Power	3/12/2013	0.77	3.272	1.4
Unexplained S/D	1/19/2013	36.48	1.842	0.7
Power Dip	9/29/2012	0.38	1.136	0.3
TS8 Rundown -> S/D	8/8/2012	43.98	0.836	-2.0
TS Rundown, NCS Alarm	5/10/2012	31.95	3.272	1.0
#3 Shim Failure	1/27/2011	34.05	2.426	1.4
XC H2O Low #	1/20/2011	0.85	3.216	-0.1

Conclusions

- BOC ECPs are ready for general use; $\bar{x} = 0.42°$; $\sigma = 0.29°$.
  - Operational procedure currently in development.
  - Potential error in current cycles due to poor data for extra fuel loading.
- Xenon-limited window tool is already in use
  - 7/30/14, Saved 3 hrs ($15k)
  - Room for improvement in rundown cases.
- Fuel reactivity measurements still in progress.
  - Need to develop more short-term models in MCNP – material extrapolation req'd.
- Recommend changing Console Log recording practices:
  - Need short cycle shutdown reactivity data!!!
  - Short cycle (or all?) startup reactivity data would be nice.