INL/CON-23-75079-Revision-0

Predicting Safety Rod Reactivity Insertion in the Advanced Test Reactor

November 2023

Changing the World's Energy Future

John Charles Tortorello

Idaho National Laboratory

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National Nuclear Security Administration
MATERIAL MANAGEMENT AND MINIMIZATION
CONVERT, REMOVE, DISPOSE
Idaho National Laboratory
MPR

National Nuclear Security Administration (NNSA)

Defense Nuclear Nonproliferation (DNN)

ATR Core Safety Assurance Package Modernization Efforts

John Tortorello, MPR Associates Inc.

ANS Winter Meeting
November 14, 2023

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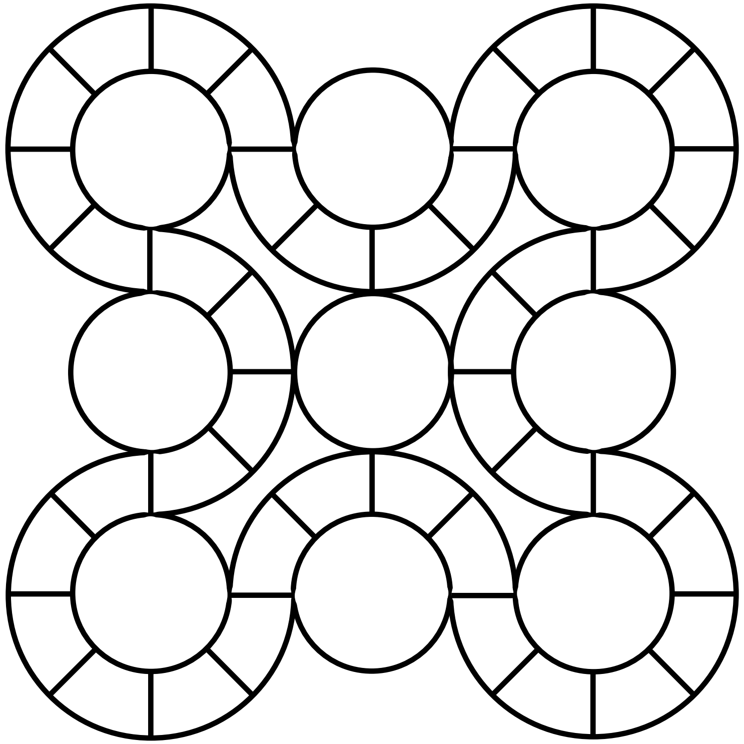
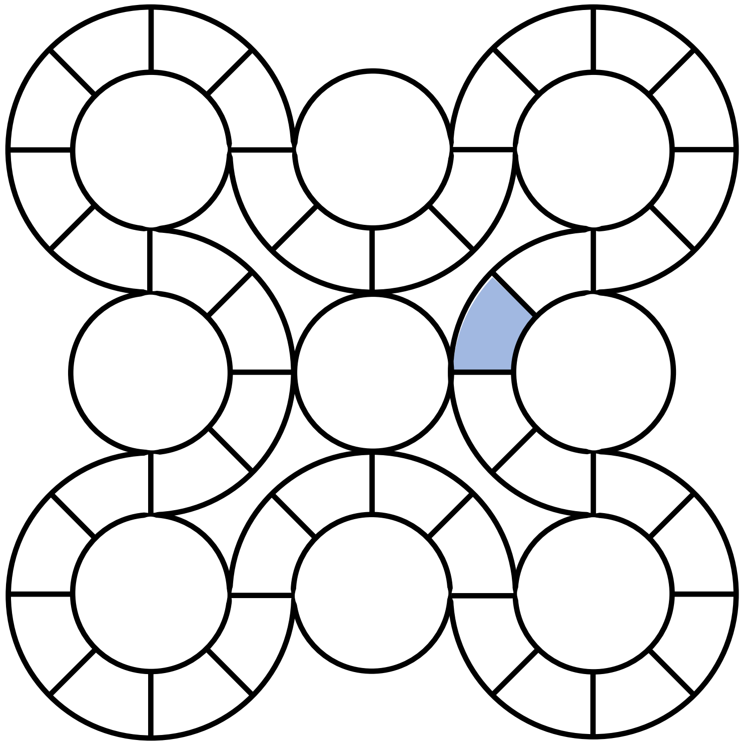
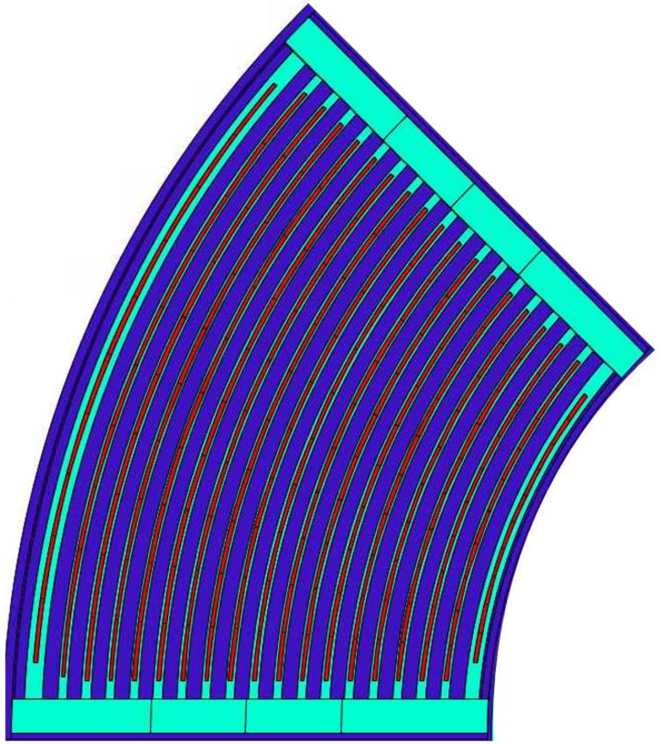
Unique Geometry of the ATR



Unique Geometry of the ATR



1 of 40 Fuel Elements

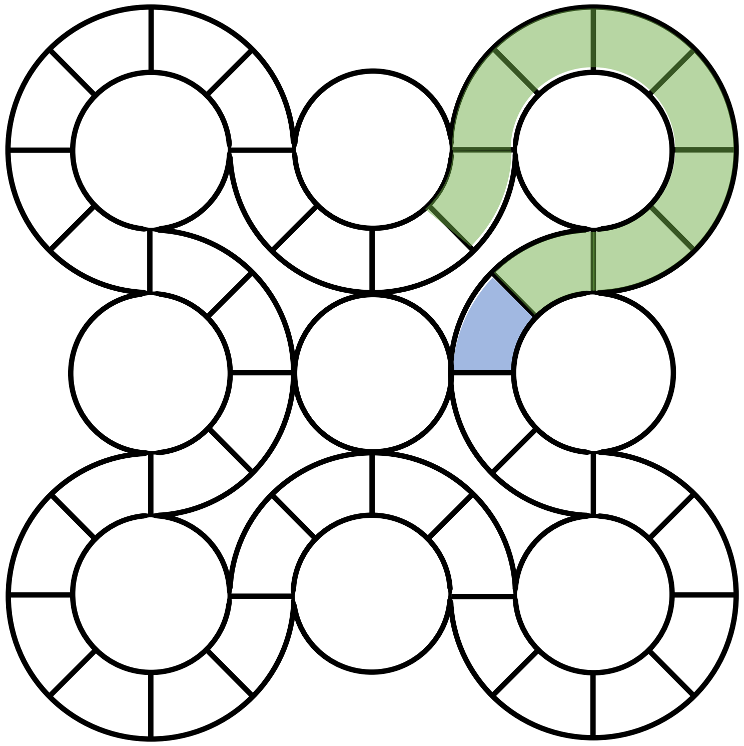


The mission to convert research reactors to LEU fuel is the inspiration to redesign these elements with a new fuel composition

Unique Geometry of the ATR

1 of 40 Fuel Elements

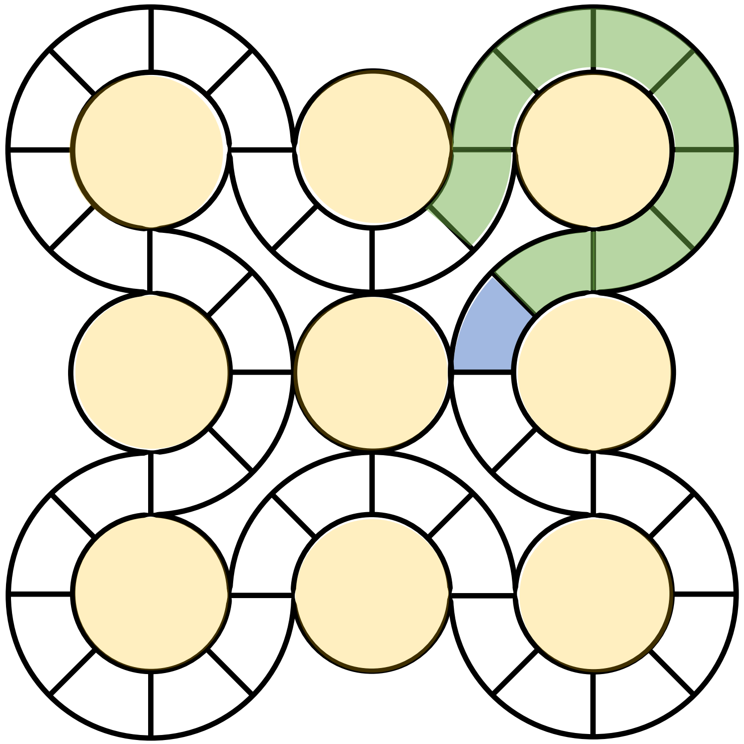
NE Lobe – 8 fuel elements



- The 5 lobes are referred to as NW, NE, C, SW, SE

- ATR fuel cycles have limiting requirements on the lobe powers

Unique Geometry of the ATR



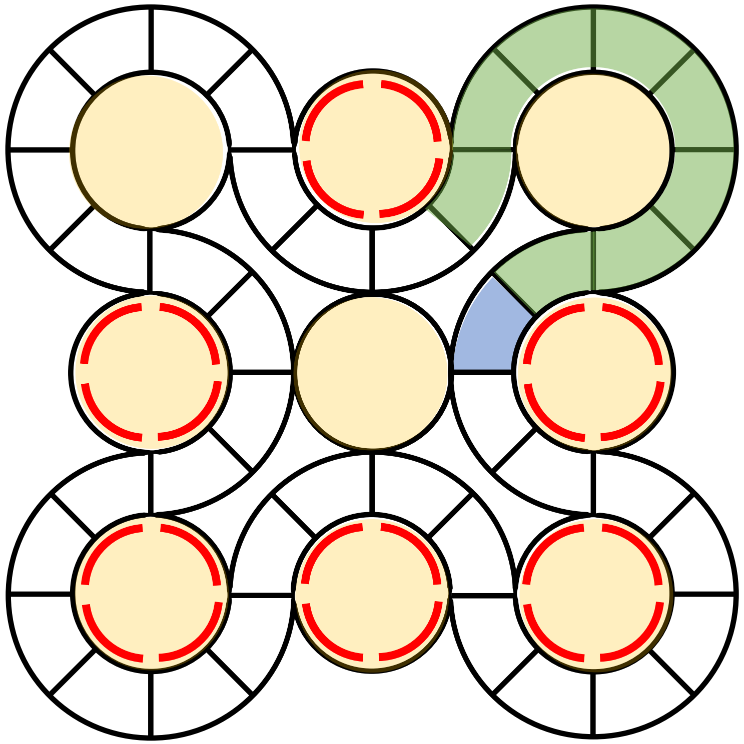
1 of 40 Fuel Elements

NE Lobe – 8 fuel elements

9 Flux Traps (experiment locations)

- The 9 flux traps are referred to as NW, N, NE, W, C, E, SW, S, SE
- The neutron flux may vary considerably from one flux trap to another to meet the needs of different experiments

Unique Geometry of the ATR



1 of 40 Fuel Elements

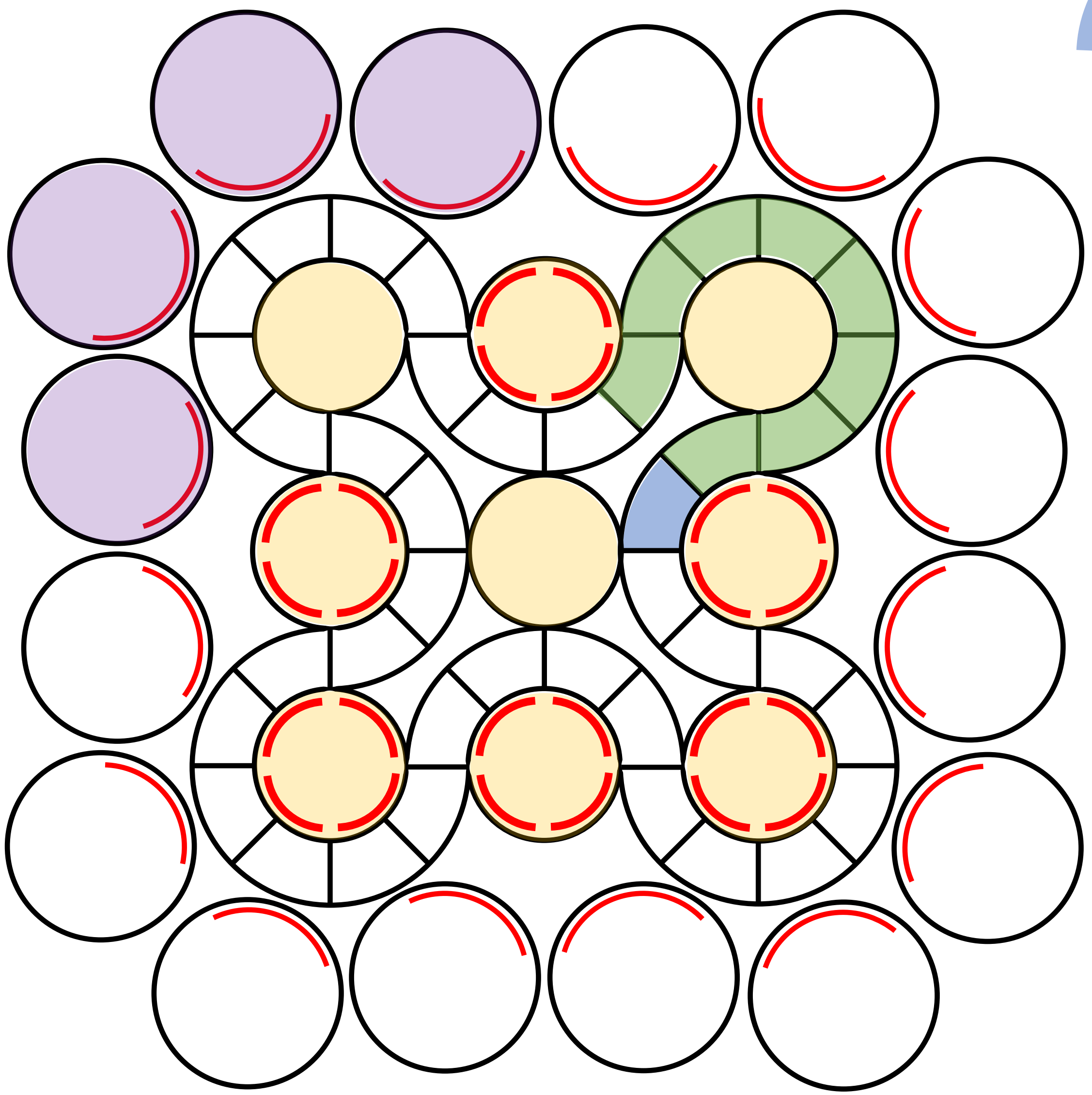
NE Lobe – 8 fuel elements

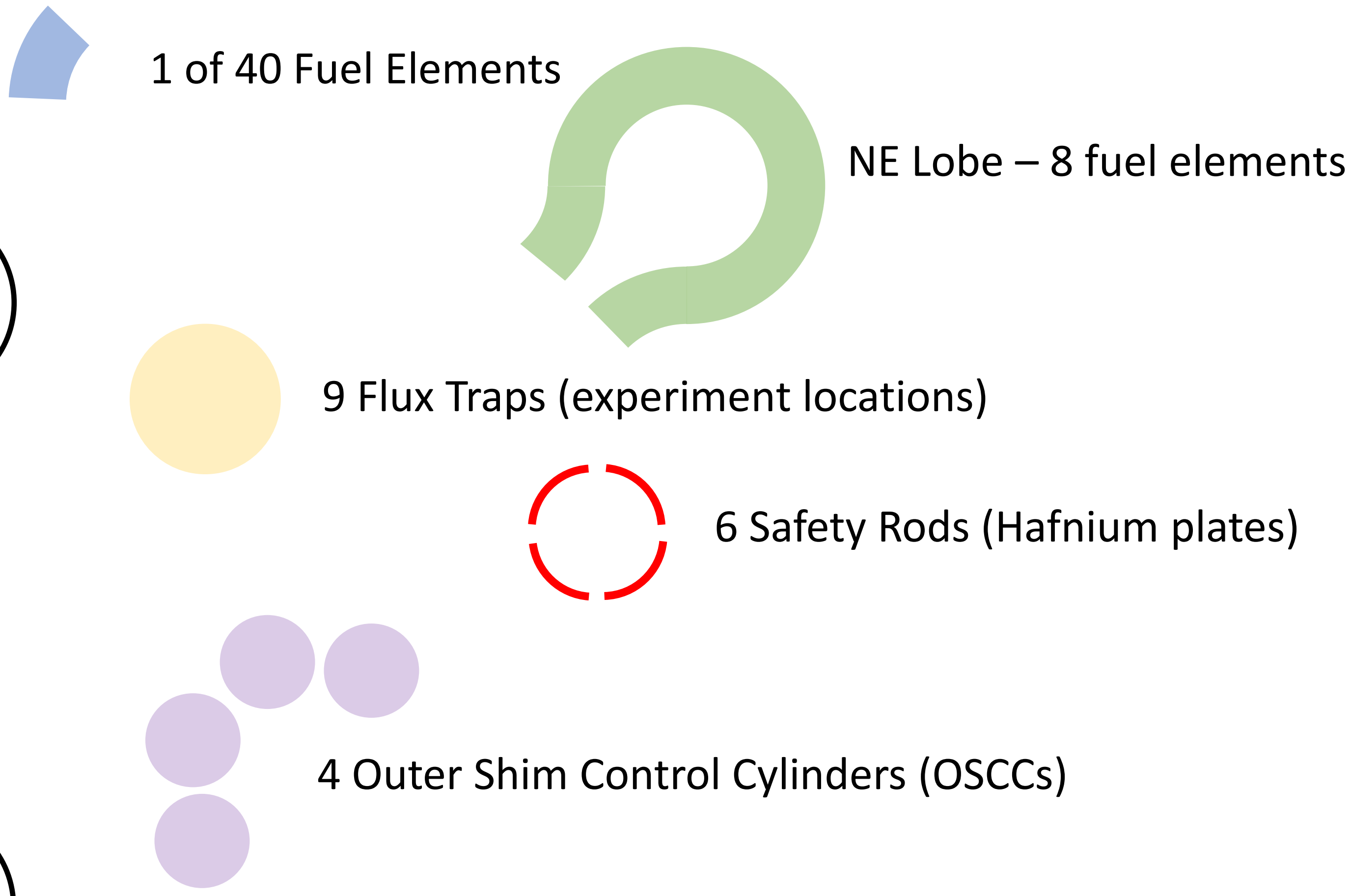
9 Flux Traps (experiment locations)

6 Safety Rods (Hafnium plates)

Certain criteria require a SCRAM to be possible assuming only the **five least reactive safety rods** are operable.

Unique Geometry of the ATR

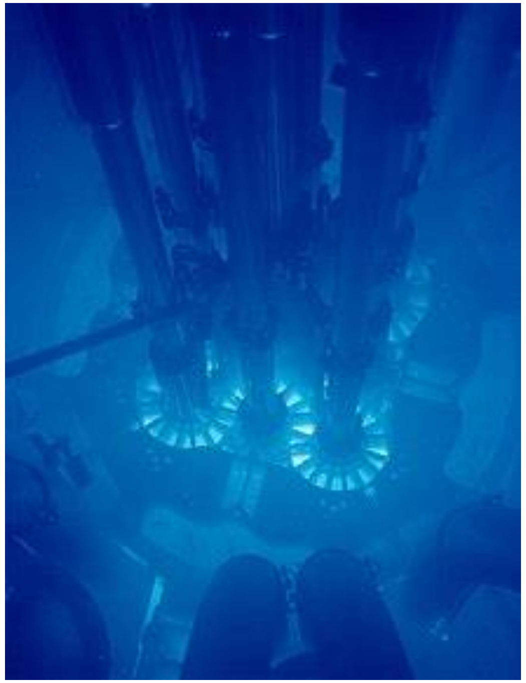




- Power & criticality is in part controlled by the OSCCs
- A hafnium absorber in the OSCC can insert & withdraw reactivity

CSAP (Core Safety Assurance Package)

- Purpose of the CSAP is to verify that the selected fuel loading meets the following criteria:
  - **operational**
    - Example: Ensure use of 3 primary coolant pumps
  - **experimental**
    - Example: Experiment power exposure limits
  - **safety**
    - Example: Reactivity margin (safety rod worth)

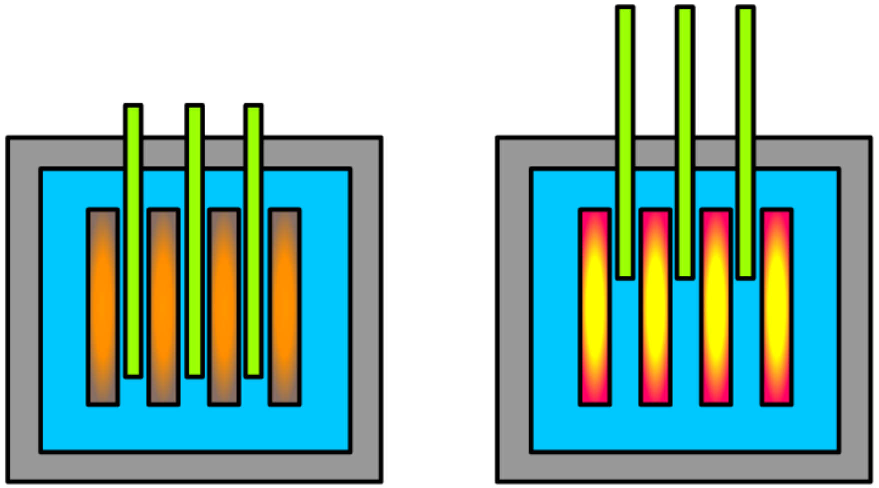


Reactivity Worth Calculation

$$\rho = \frac{\left(\frac{k_2 - k_1}{k_1 * k_2}\right)}{\beta_{eff}}$$

Where:

ρ	=	Reactivity worth (\$)
k_1, k_2	=	Final k-effective before the control element insertion and after, respectively
β_{eff}	=	The delayed neutron fraction (approximately 0.007)

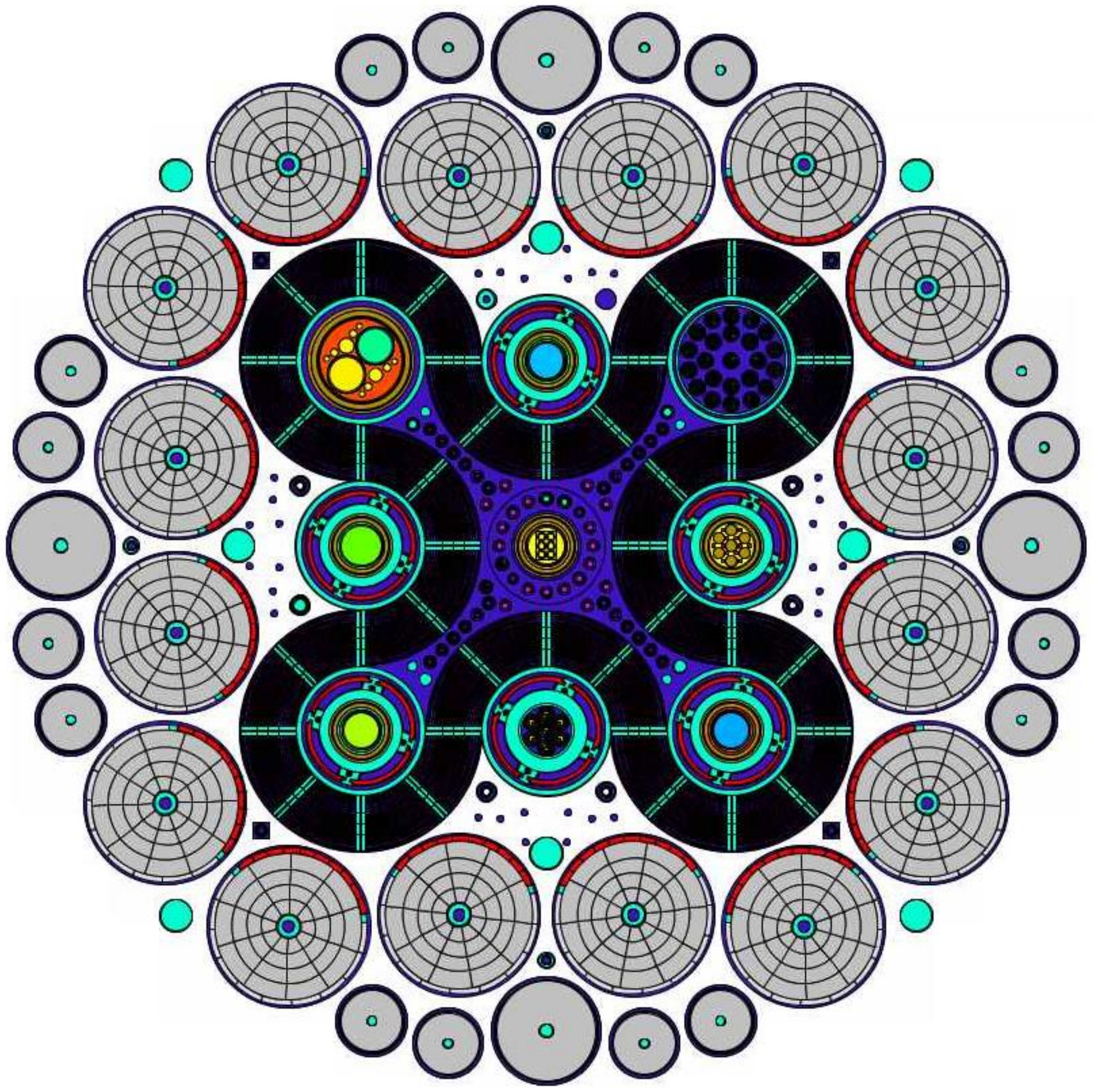


MC21 Model of ATR

- Detailed MC21 model created with the Physics Unified Modeling and Analysis (PUMA) system - Naval Nuclear Laboratory code

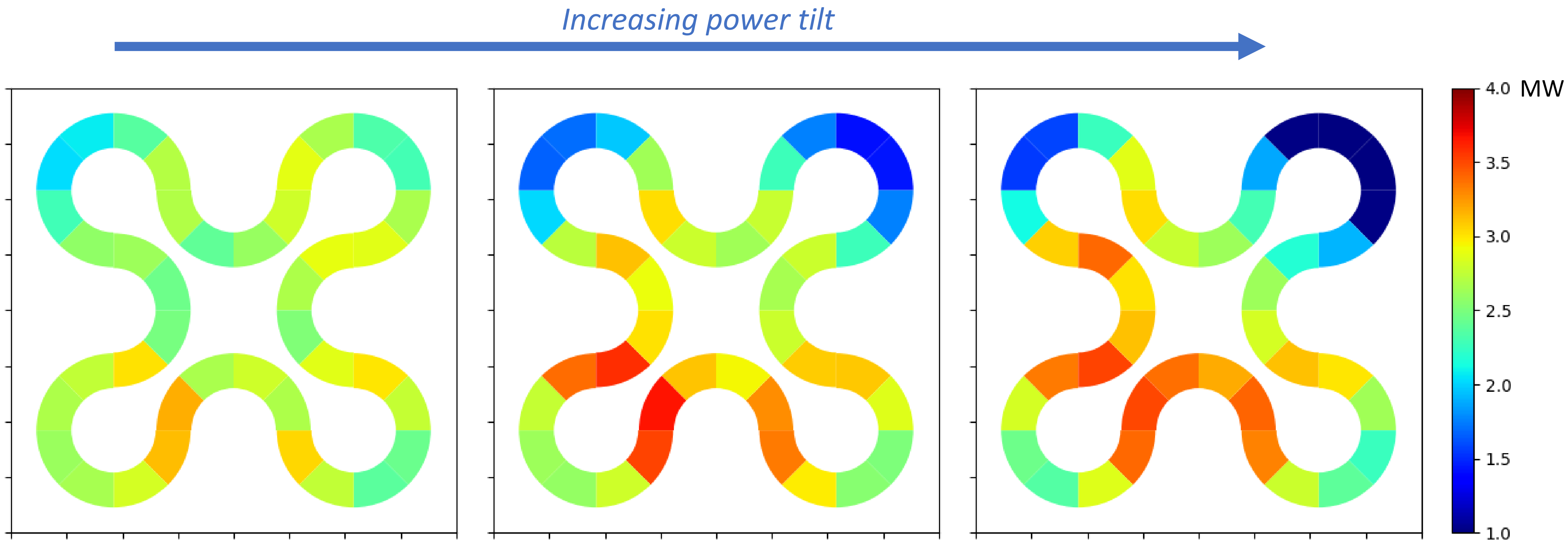
- Used for reactivity worth calculations

- One low uncertainty reactivity worth calculation can take ~1 hour of HPC time



ATR is Designed for Varied Conditions

- Test reactor contains varied experiments – no two cycles or timesteps are identical
- High power "tilt" – the plot of flux versus distance across the core has a large slope



Each power distribution is called a **power split**

Varied Conditions Cause Varied Reactivity Worth

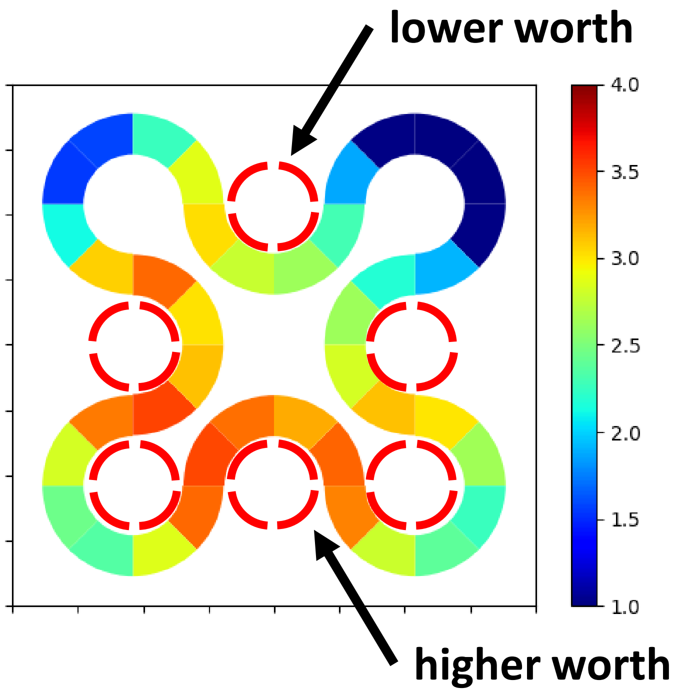
To a first order approximation, **reactivity insertion is proportional to the square of the neutron flux** at the position of the geometry change

$$\rho \propto \Phi^2$$

Where:

ρ = Reactivity worth ($)

Φ = Neutron Flux



- Safety rod worth is dependent on local flux trap power
- The minimum safety rod worth is dependent on specific cycle conditions

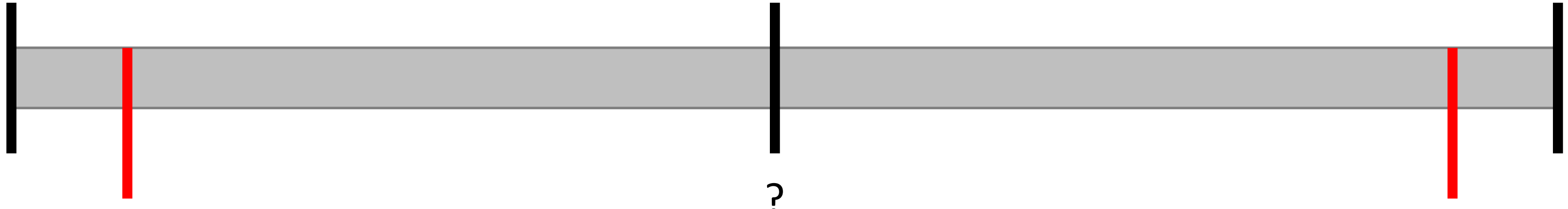
Historical Methodology to Predict Minimum Safety Rod Worth

- Five lobe powers for each cycle have required **nominal**, **minimum**, and **maximum**
- All permutations of the max and min: $2^5 = 32$ power splits
- Each power split has unique **restart** and **delayed restart** conditions (64 additional power splits)
- Powers in startup, nominal operation, restart, and delayed restart (4 additional power splits)
- $32 \times 3 + 4 =$ **100 power splits**
- With brute force computation on MC21, this could be 600 hours of HPC time

Problem Statement

Heavy use of engineering assumptions and ***operational experience (not yet available with LEU)***

Heavy use of computational time



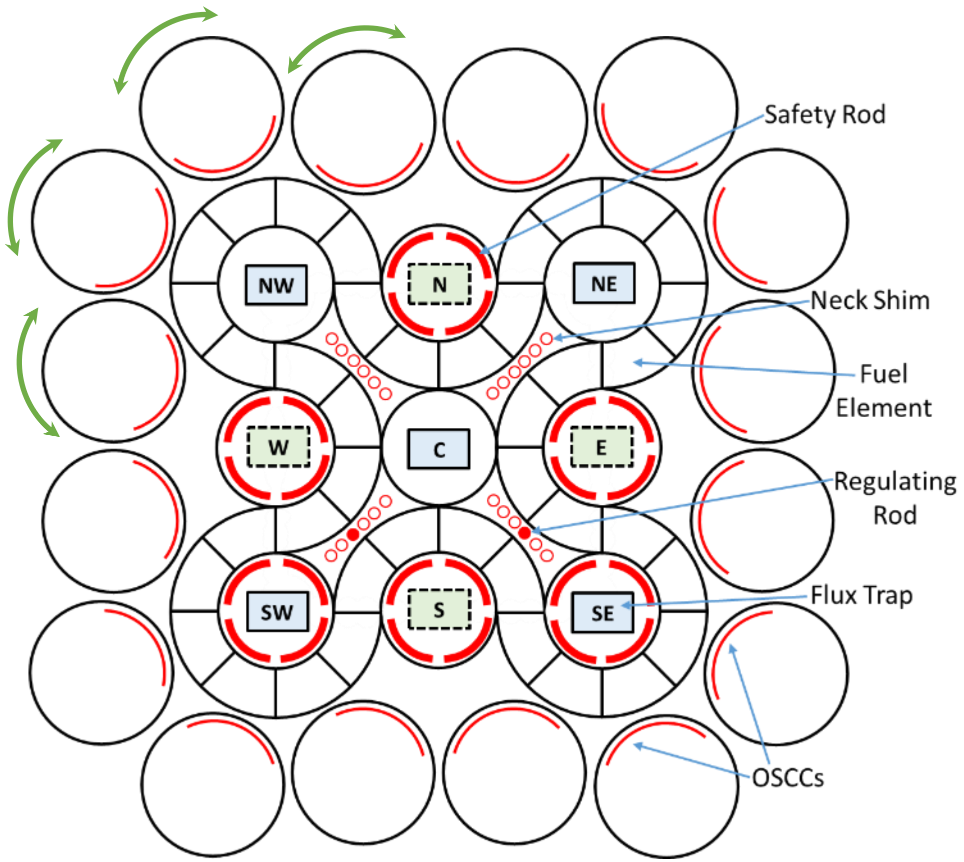
Flux squared weighting or other empirical relationships

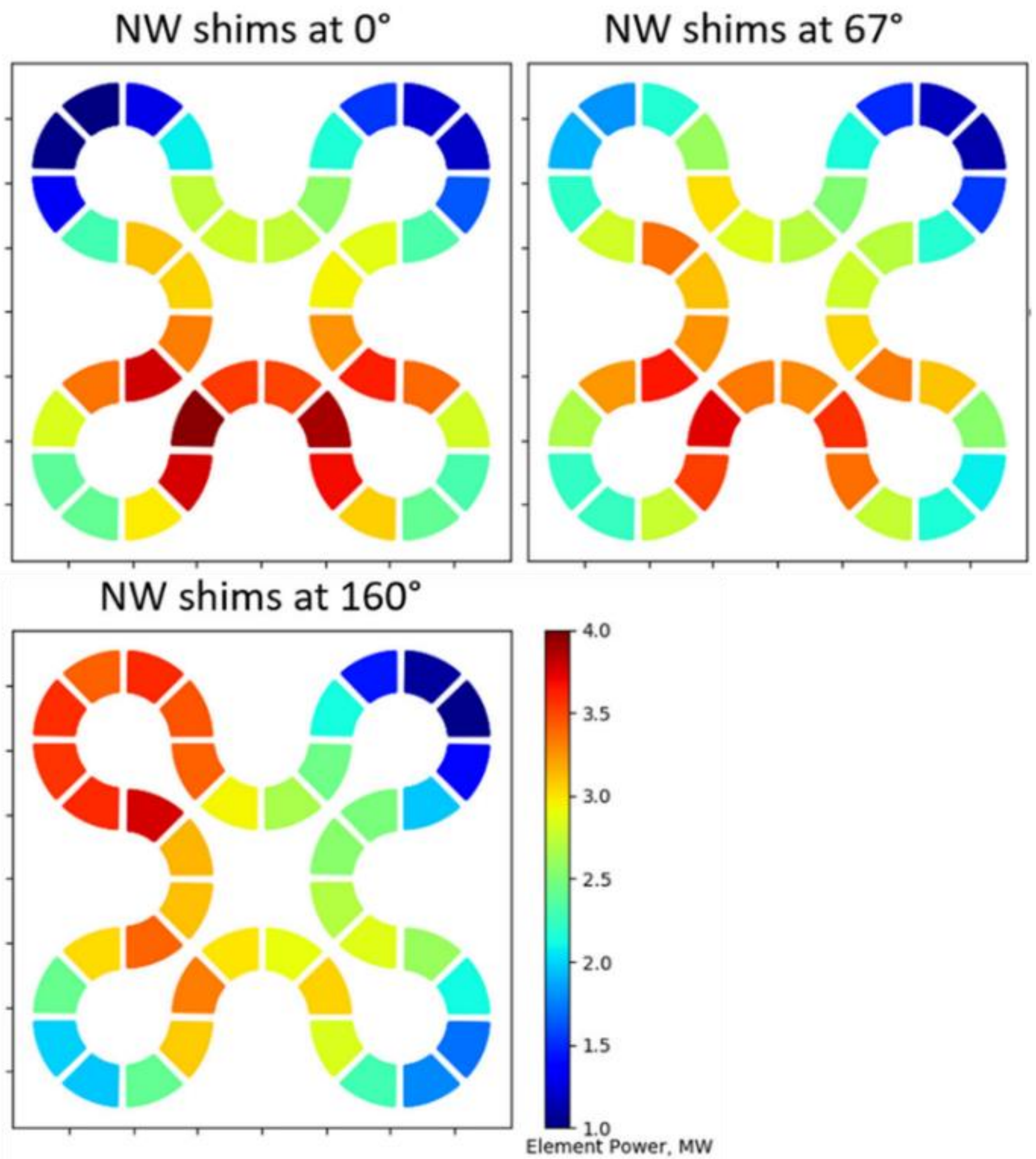
?

Use MC21 to find the worth in every possible power configuration

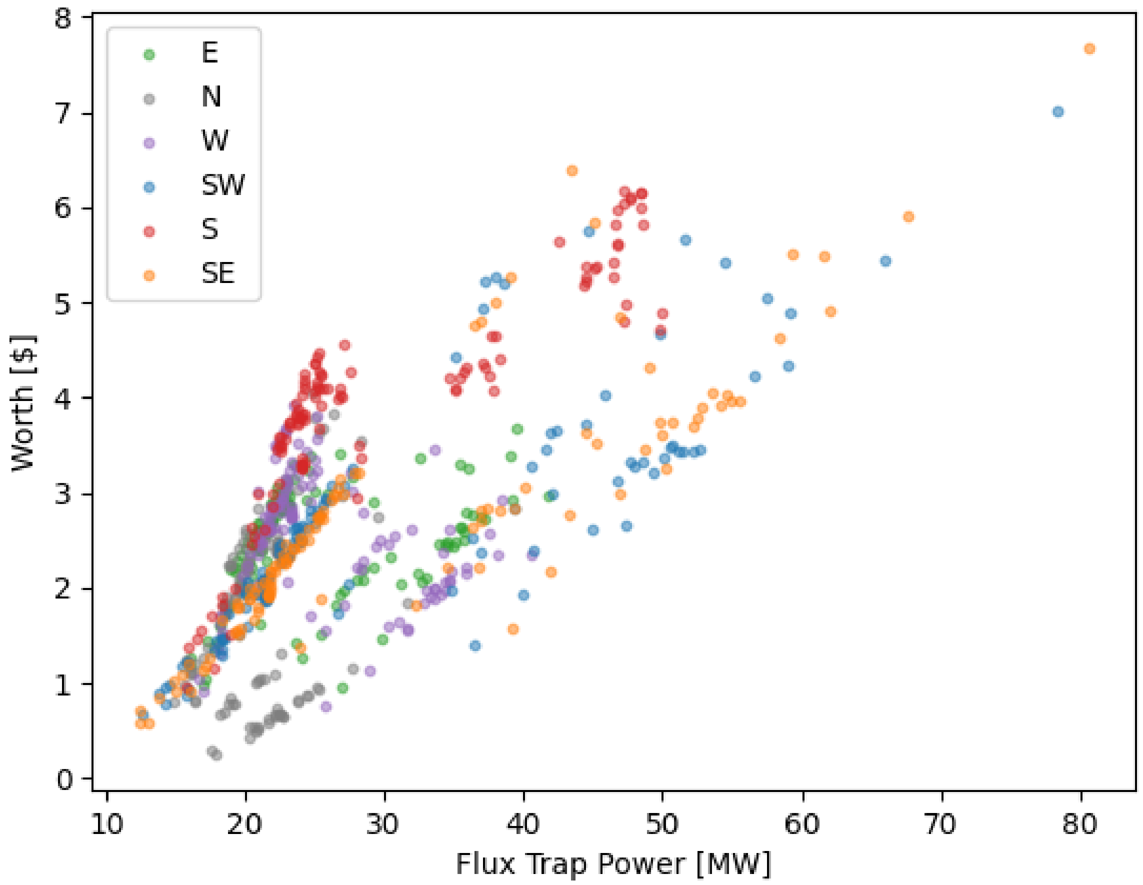
Our solution: Use MC21 as a data collection tool and run a regression on the outputs

Shim Movement to Change Power



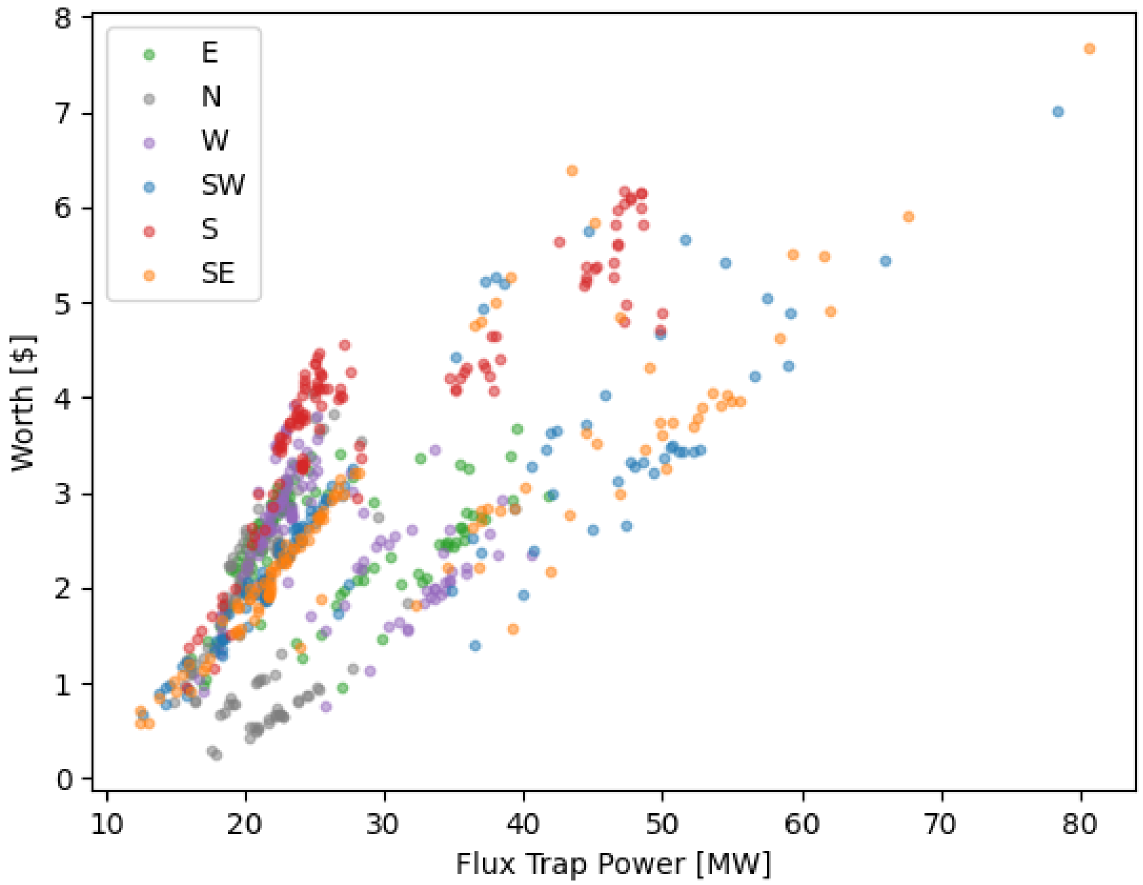


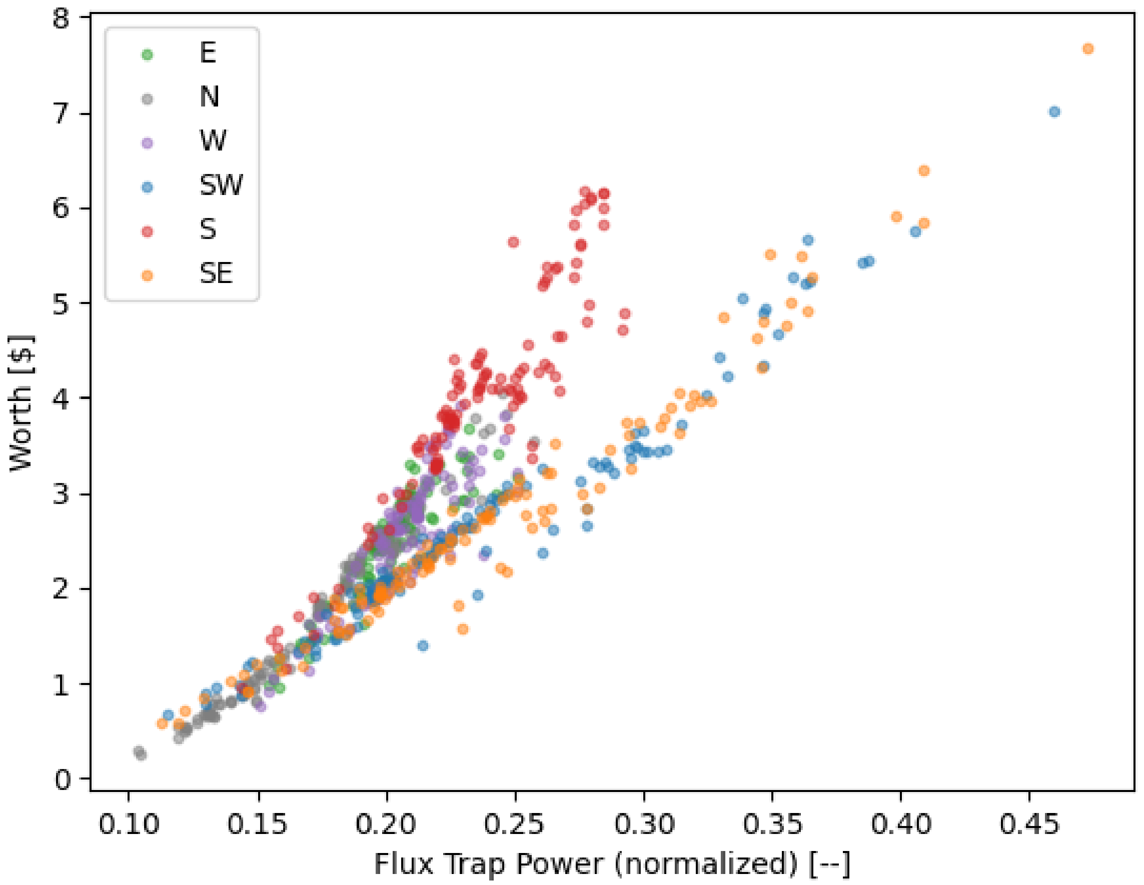
Reactivity Worth Dataset



- Expected positive correlation between power and reactivity worth
- Monte Carlo uncertainty is kept very low, approximately the width of the shown dots

Reactivity Worth Dataset





Improved correlation when normalizing – reactivity worth a function of relative flux

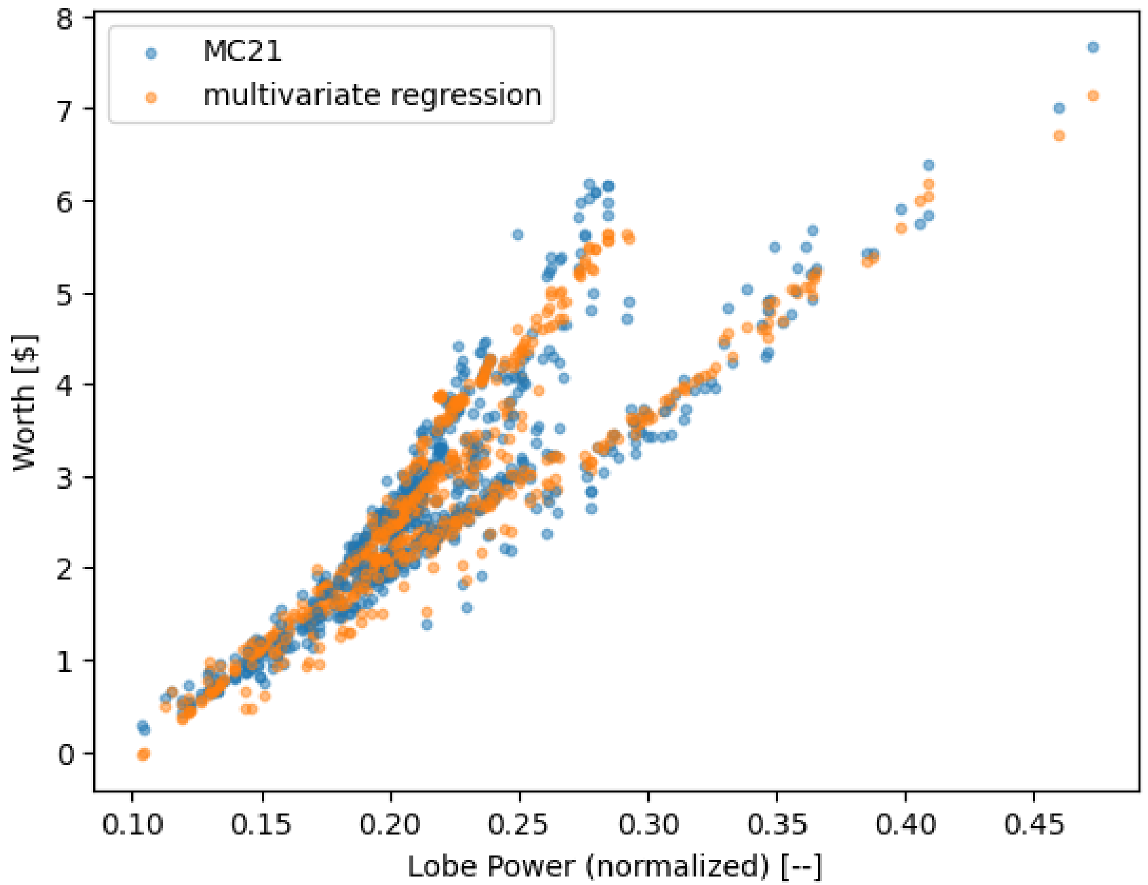
Reactivity Worth Multivariate Regression

$$\boxed{CP = \rho}$$

$$\begin{bmatrix} -7.003 & 2.598 & 11.292 & -6.727 & 1.712 & 1.873 \\ 4.420 & 3.406 & 3.372 & -4.590 & -4.575 & 2.033 \\ 3.425 & -6.760 & 10.744 & 1.455 & -6.976 & 1.889 \\ -3.633 & -3.045 & -0.976 & 15.217 & -5.87 & 1.676 \\ -8.848 & -8.044 & 13.222 & 2.832 & 2.966 & 2.129 \\ -3.631 & -3.332 & -1.257 & -5.951 & 15.815 & 1.644 \end{bmatrix} \begin{bmatrix} P_{NW} \\ P_{NE} \\ P_C \\ P_{SW} \\ P_{SE} \\ 1 \end{bmatrix} = \begin{bmatrix} \rho_E \\ \rho_N \\ \rho_W \\ \rho_{SW} \\ \rho_S \\ \rho_{SE} \end{bmatrix}$$

Where:

C	=	A matrix of coefficients
P	=	The normalized lobe powers, such that the sum of the lobe powers is unity. The vector of P also includes a constant value
ρ	=	The worth of the safety rods in units of \$



Conclusions

- This methodology has the potential to be used to predict many different in-core parameters
- It is important to look for trends that are backed by a first-principled explanation
- Computational methods can shine when perturbing one variable at a time for many iterations – this can reveal general trends that would otherwise be impossible to visualize

Questions/Discussion

$$CP = \rho \qquad \text{Equation 2}$$

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