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Changing the World's Energy Future

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Predicting Safety Rod Reactivity Insertion in the Advanced Test Reactor

John Tortorello[1], Curt Brown[1], Ryanne Kennedy[1], Nathan Manwaring[2], Derreck Blight[2]

[1]MPR Associates, 320 King Street, Alexandria VA 22314, jtortorello@mpr.com
[2] Idaho National Laboratory, 1955 Freemont Ave, Idaho Falls, ID, 83415

INTRODUCTION

Background

The Advanced Test Reactor (ATR), and complimentary zero-power ATR Critical (ATRC) reactor, located at Idaho National Labs (INL), are undergoing conversion from Highly Enriched Uranium (HEU) to Low Enriched Uranium (LEU). Both have a variety of testing locations that can receive large variations in flux due to its unique serpentine design, consisting of five lobes surrounding nine flux traps (see Figure 1). Initial criticality and power distribution throughout the core are controlled by core-external outer shim control cylinders (OSCCs). Distinct test loops allow for testing at specific temperatures, pressures, and irradiation conditions such as flux and fission density. The ATR is one of the key nuclear engineering research and testing facilities within the DOE National Laboratory Complex, and the ATRC supports its operation [1].

Currently, the Office of Material Management and Minimization (M^3) within the National Nuclear Security Administration of the DOE is working to convert the remaining research reactors, including the ATR, from 93% HEU fuel to 19.75% LEU fuel (LEU) to support non-proliferation [2]. Extensive materials testing at INL and internationally has demonstrated that a high-density uranium molybdenum (U-10Mo) alloy can meet the performance requirements of the remaining high powered research reactors. The current LEU fuel element design is named the LOWE element. However, there are many technical challenges to address before the conversion to LEU can be successful, including the accurate characterization of the reactor core physics with LEU fuel.

To ensure safe operation of the ATR, reactor engineers prepare a CSAP (Core Safety Assurance Package) before each cycle. The purpose of the CSAP is to verify the reactor performance calculation used to determine if the selected fuel loading meets operational, experimental, and safety criteria. Many of the criteria in the CSAP are limits on reactivity insertion in various accident scenarios.

It is therefore necessary to have the capability to predict reactivity change due to a safety rod insertion, shim insertion, or moderator voiding. This is a particular challenge in a research reactor such as the ATR because by its nature, no two cycles are identical. Even within a single cycle at a particular moment in time, there can be significant spatial variation in core conditions. High "tilt" is commonly used to describe a cycle in which the plot of flux versus distance across the core has a large slope. In one cycle, the flux tilt may be aligned such that the Southwest lobe has the highest power, and in the next cycle, the Southeast lobe is the highest power.

In addition to the mid-cycle power tilt, the power distribution may be different in startup or restart conditions due to the necessary shim positions at startup and the presence of xenon in the core following a SCRAM and restart.

This variation in power tilt directly leads to variation in reactivity insertion from safety rods and control elements. The extent to which a new fuel type, LEU, will change the reactivity insertion must be calculated before this fuel is inserted into the reactor. The purpose of this paper is to discuss how reactivity insertion can be predicted in an accurate and cost-effective method using Monte Carlo simulation and linear regression. The focus will be on using this methodology to quantify safety rod worth.

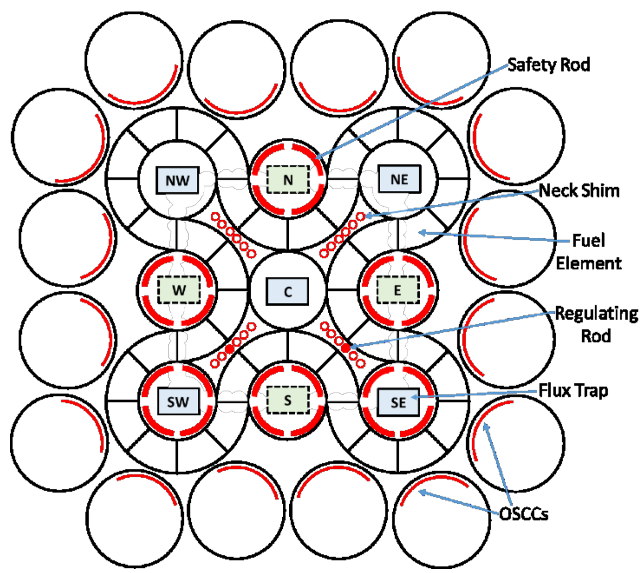

Fig. 1. Simplified core geometry of the ATR indicating key components including shims and safety rods.

Figure 1 illustrates the unique geometry of the ATR. There are 40 fuel elements. In the four corners, 8 fuel elements encircle each corner flux trap. The final 8 elements surround the central flux trap. These five groups of 8 elements are referred to as the five lobes of the ATR: NW, NE, C, SW, and SE. The power drawn to each flux trap is proportional to the power drawn to the lobe it is enclosed within. ATR power is measured by N16 detectors that correspond to lobe power. Due to this direct experimental measurement of lobe power, the flux traps that are not enclosed within a lobe (i.e., the "cardinal" flux traps – N, W, E, and S) are assumed to have a power equal to the average of the three adjacent lobes.

Reactivity Worth Calculation

Many codes have been used to model the ATR behavior since the reactor's inception. Reactor physics safety evaluations currently use Monte Carlo for the 21st Century (MC21), a continuous-energy Monte Carlo radiation transport code [3]. Existing MC21 models of the ATR and ATRC cores have a validation basis for use in neutronics analyses with HEU fuel. The models are used to support safety analyses that include comparisons to the safety requirements for the reactors. Validation of LOWE element behavior in the ATR model is an ongoing effort for deploying this new fuel.

Monte Carlo codes such as MC21 can be used to calculate reactivity insertion with Equation 1. These codes are designed to calculate the effective multiplication factor, k_{eff} (often referred to as eigenvalue), as a measurement of criticality. Notably, Equation 1 assumes that two models are run with two unique geometries. Using the example of a safety rod: in first case (k_1), the safety rod is not inserted into the core. In the second case (k_2), the safety rod is fully inserted. This change in geometry of the safety rod position causes a change in core criticality from which the reactivity worth of the safety rod can be calculated.

Equation 1

Where:

	=	Reactivity worth ($)
	=	Final k-effective before the control element insertion and after, respectively
	=	The delayed neutron fraction (approximately 0.007)

While these high-fidelity Monte Carlo methods are accurate, this methodology is time consuming. To achieve low uncertainty, a single reactivity worth calculation will take approximately one hour with moderate memory use on a high-performance computer. There are six safety rods and two regulating rods in the ATR. Pre-existing CSAP preparation codes consider 100 different power distributions when calculating the limiting safety and regulating rod worth [4]. Devoting approximately 800 hours of high-performance compute time to calculate limiting reactivity worth before every ATR cycle is an overly expensive and impractical method.

Due to this challenge, the ATR CSAP has relied on first principles and operational experience to quantify linear relationships between reactor power distribution and reactivity insertion. To a first order approximation, reactivity insertion is proportional to the square of the neutron flux at the position of the geometry change [5]. While first principles are a useful guide, in a reactor as complicated as the ATR, experimental or computational methods offer necessary support to paint the full picture.

REGRESSION METHODOLOGY

Changing Power Distribution in the ATR

First principles in cooperation with operational experience allowed ATR reactor engineers to quantify reactivity insertion in the presence of HEU fuel. However, with the new fuel type, operational experience can no longer be entirely relied upon. This is where computational methods, like MC21, can bridge the gap.

MC21 can be used to simulate many different power distributions in the ATR. At each unique power distribution, the reactivity insertion of each safety rod and regulating rod can be measured.

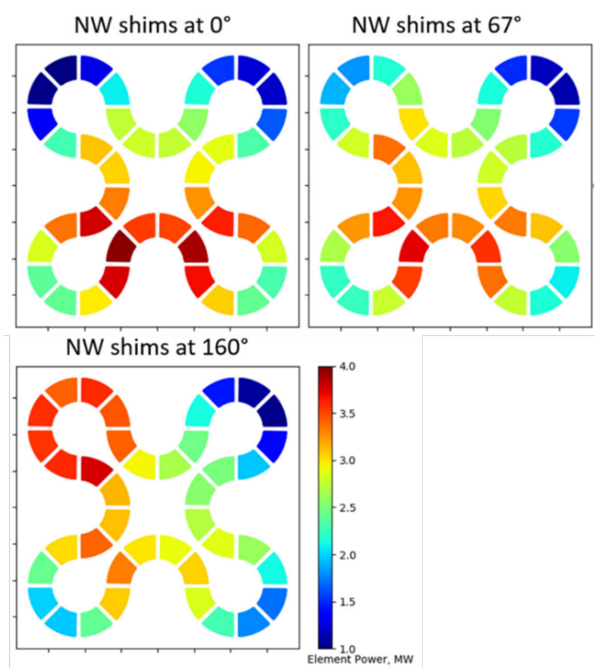

Fig. 2. Effect of NW OSCC rotation on element power for a simulated ATR cycle.

The simplest way to manipulate power distribution in the ATR is with the OSCCs. These shims are specifically designed to pull or push power into or away from a corner (lobe) of the ATR. Figure 2 illustrates how the power distribution can change due to the motion of the OSCCs in the northwest corner.

Core Power and Reactivity Worth Correlation

MC21 movable groups allows the user to simulate many core geometries in a single run. The OSCCs are moved, an initial k_{eff} is calculated in MC21, a safety rod is inserted, and a final k_{eff} is calculated. The change in k_{eff} is used in Equation 1 to calculate reactivity insertion. This process is repeated until the simulated power distributions span all probable power tilts that may occur throughout a cycle. These power tilts include startup conditions, restart conditions, nominal conditions, and off-nominal conditions due to approximate power uncertainty in each lobe.

Recall from Figure 1 that each safety rod resides within a flux trap, and the power of a flux trap corresponds to the local lobe power, which is an experimentally measurable quantity that can be extracted from the MC21 simulation. Using this methodology, safety rod worth can be plotted directly against power at the position of the safety rod (Figure 3).

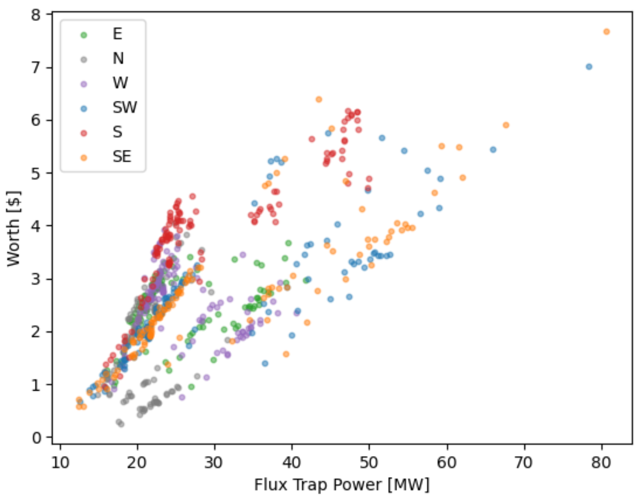

Fig. 3. Safety Rod reactivity worth as a function of Flux Trap Power

Because reactivity worth is a function of local neutron flux and local power is a function of neutron flux, there is an expected positive correlation between power and reactivity worth in Figure 3. Figure 3 is generated by simulating nine ATR cycles with different total core powers. The correlation between reactivity worth and power is more apparent when the core power is normalized such that the power in all five lobes sums to 1. Figure 4 illustrates the normalized power correlation with reactivity worth.

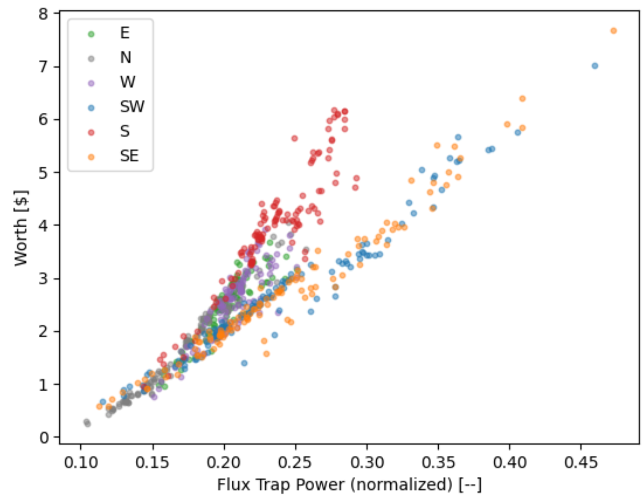

Fig. 4. Safety Rod reactivity worth as a function of normalized Flux Trap Power

Multivariate Regression

Figure 4 illustrates a correlation that appears closer to linear than Figure 3, but there still appears to be at least three separate trend lines in the data. While the correlations appear to be somewhat unique for each safety rod, all data are related. Due to the interconnectedness of the data, a multivariate regression has been run, shown in Equation 2.

Equation 2

Where:

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

Figure 5 illustrates the regression overlayed onto the data, independent of which safety rod worth is plotted. The overall R^2 of the correlation is 0.96.

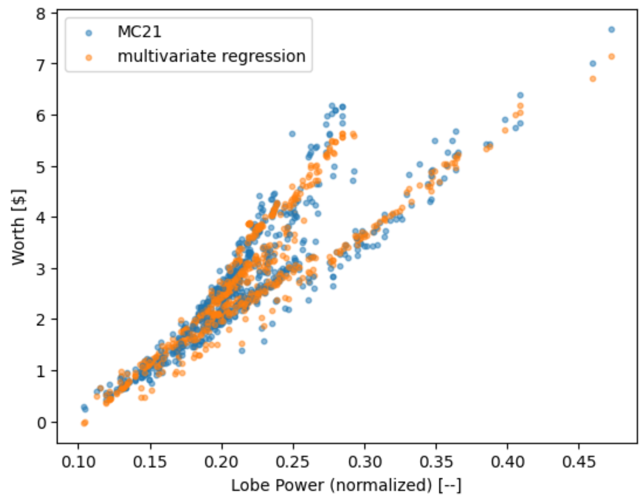

Fig. 5. Safety Rod reactivity worth multivariate regression

CONCLUSIONS

At the ATR or any research reactor, there are three tools that can help in quantifying safety basis values: experimentation, reactor theory, and computational simulation. Experimentation is the most valuable input, but due to the important safety processes in place in reactor operation, experimental data is the most expensive and difficult to produce.

Reactor theory and computational simulation work best hand in hand. It is important not to rely on simulation too heavily, not only because high power computing resources are a valuable commodity, but because model results must be in balance with engineering judgment.

In the case of reactivity insertion, the expectation that worth is positively correlated with local power acted as the guiding principle. There are many reactor parameters that could be correlated with worth: shim position, fission density, or fuel depletion are a few examples. However, local power is both measurable and has a connection to first principles. By being easily measured, the connection between local core power and reactivity insertion can be experimentally validated in time.

In this example, linear regression based on simulated outputs is performed to calculate safety rod reactivity worth. However, this methodology could be applied in many situations in which fully simulating all possibilities is unreasonable. Void worth, shim worth, or even fuel temperature could all be predicted with this methodology. While there is considerable computational effort in defining the initial regression, it only requires setup once. Subsequent reactivity worth calculations are nearly instantaneous as they only require matrix multiplication. As time goes on, data from new core configurations and even experimental measurement can be added to the regression dataset, improving and self-checking the reactivity worth calculation.

Reactivity worth calculations are complicated yet imperative for operational safety. In the case of the ATR, there are hundreds of variables that contribute to the reactivity worth of the safety rods and control elements. To simulate or measure every possible scenario would be costly, slow, and impractical.

It is crucial to recognize where a significant increase in time and effort in calculating a safety pertinent quantity leads to an insignificant increase in accuracy. Due to the safety margin deliberately designed into the safety rods, a more accurate reactivity worth estimate is not more valuable than the quick approximation. There is a non-negligible risk that costly, slow methods can inhibit the progress of the LEU conversion project and ultimately the nuclear industry at large. This simple and effective reactivity worth calculation has been developed by considering the bigger picture of progress goals, how much accuracy is needed to meet requirements, and how modern methods of data insights can be applied to nuclear reactor behavior.

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