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CONTROL ROD REACTIVITY CURVES FOR THE ANNULAR CORE RESEARCH REACTOR*

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Experiments were conducted at the Annular Core Research Reactor (ACRR) to increase the fidelity of the control rod integral reactivity worth curve. This experiment series was designed to refine the integral reactivity curve used for pulse yield prediction and eliminate the need for operator compensation in the pulse setup. The experiment series consisted of delayed critical and positive period measurements with various ACRR cavity configurations. An improved integral reactivity worth curve for the ACRR control rods has been constructed using the positive period measurements, the delayed critical measurements, and radiation transport modeling of the reactor. A series of prompt period measurements is used to validate that the new control rod curve more accurately predicts the energy yield of the pulse operations. The new reactivity worth curve is compared with the current curve that was developed using traditional approaches.

1 Introduction

The Annular Core Research Reactor (ACRR) is a water-moderated pool-type reactor designed for testing many types of objects in the pulse and steady-state modes of operation. One of the distinguishing features of the ACRR is the large (22.86 cm diameter) dry central irradiation cavity. The cavity permits the fielding of large experiments and allows the radiation environment to be tailored using spectrum modifying cavity inserts (buckets). This feature also requires that the ACRR has more

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excess reactivity in the control elements than is typical for a research reactor of this design type (i.e., the excess reactivity in the control rod bank of 6 elements for an empty central irradiation cavity is ~\$10.00). A recent analytic construction of an integral reactivity worth curve for the control rods highlighted the discrepancies produced by the bootstrap experimental technique that was used to construct the current reactivity worth curve [1]. By bootstrap technique, we mean that the integral and differential reactivity as a function of control rod position was measured during initial critical loading of the core.

The current integral reactivity tables used by the reactor operators consistently overestimate the yield of a pulse, so experienced operators and supervisors adjust the pulse setup reactivity to compensate for this phenomenon. This adjustment can vary between operators and cannot be reliably extrapolated to new test configurations and large negative reactivity worth test packages. Experimenters depend on operations to be able to provide reproducible pulses for their experiments. Experimenters routinely use passive dosimeters, such as the activity from a ^{58}Ni(n,p) monitor foil, as a metric to evaluate the consistency of a series of pulses and the linearity of the radiation environment at different power levels. Differences between the experimenter dosimetry at the test location and the operations measure of reactor power, typically traceable to an increase in the fuel temperature, are a matter of continuing confusion. Experiment planning in research reactors typically requires a calculation of the reactivity worth of an experiment before the experiment is fielded. The worth of the experiment package is always validated with a delayed critical measurement before performing a pulse operation. When there is a large difference between the delayed critical measurement of the experiment worth and the calculated value, it reflects poorly on the state of today’s radiation transport methods. It can also lead reactor safety review committees to doubt the ability of analysts to model the expected radiation environments.

Experiments were conducted at the ACRR to increase the fidelity of the control rod integral reactivity worth curve. This experiment series was design to refine the integral reactivity curve used for pulse yield prediction and eliminate the need for operator compensation in the pulse setup. The experiment series consisted of delayed critical and positive period measurements with various ACRR cavity configurations. An improved integral reactivity worth curve for the ACRR control rods has been constructed using the positive period measurements, the delayed critical measurements, and radiation transport modelling of the reactor. A series of prompt period measurements is used to validate that the new control rod curve more accurately predicts the energy yield of the pulse operations. The new reactivity worth curve is compared with the current curve that was developed using traditional approaches.

2 Experimental Setup and Procedures

2.1 Spectrum Modifying Cavity Inserts (Buckets)

The ACRR facility has several spectrum modifying cavity inserts (buckets) of varying combinations of materials. The experiment series utilized the lead boron and the lead polyethylene buckets as well as an empty central irradiation cavity. The lead boron bucket (Pb-B_4C) is a spectrum modifying insert designed to remove thermal neutrons from the neutron spectrum while reducing the level of gamma dose inside the bucket. The Pb-B_4C bucket has a reactivity worth of approximately -$6.00 when compared to an empty central cavity. The lead polyethylene bucket (LP-1) is a spectrum modifying bucket designed to increase the thermal-to-fast neutron ratio while decreasing the gamma dose inside the bucket. The LP-1 bucket has a reactivity worth of approximately -$2.60 when compared to an empty central cavity.

The control rod bank at the ACRR has the ability to move a range of 55.0 cm (5500 rod units). The fully inserted control rod bank is located at 0 rod units while a fully withdrawn control rod bank is positioned at 5500 rod units. If the transient (pulse) elements are used as a poison shim on the control rod reactivity, then the reactor with the Pb-B_4C bucket in the central cavity can be placed in a delayed critical configuration with the control rod bank at positions varying from approximately 3200 rod units to 5500 rod units (fully withdrawn). The range of critical positions for the LP-1 bucket is approximately 2250 - 3500 rod units while an empty central cavity has a range of critical positions from approximately 1500 - 2800 rod units. The overlapping regions of critical positions created by using the buckets allow one to construct a control rod bank integral reactivity curve with the fully assembled reactor rather than having to rely on bootstrap (load to critical) techniques for the measurement.

2.2 Delayed Critical and Positive Period Measurements

Starting with the Pb-B_4C bucket in the central cavity and the transient rod bank inserted, a delayed critical core configuration was obtained with the control rod bank fully withdrawn. When the delayed critical configuration was established and verified, the poison transient rod banks were removed by a fixed number of rod units starting the reactor on a positive period. The doubling time of reactor power was measured. Using Eq. (1), the reactor period (T) was calculated from the doubling time:

$$T = \frac{\text{Doubling Time}}{\ln 2}. \tag{1}$$

After the doubling time was measured, the control rod bank was inserted to establish a delayed critical configuration again. Using the results from Eq. (1) and Eq. (2) (the Inhour equation), the reactivity of the power excursion is calculated:

$$\rho = \frac{l_p}{T + l_p} + \frac{T}{T + l_p} \cdot \sum_i \frac{\beta_i}{1 + \lambda_i T} \tag{2}$$

where ρ is the reactivity, l_p is prompt neutron lifetime in the ACRR, β_i is the delayed neutron fraction of the i^{th} delayed neutron group, and λ_i is the decay constant for the i^{th} delayed neutron group. The differential reactivity worth of the control rod bank is equivalent to the positive reactivity measured by the doubling time. The positive period and delayed critical measurements continued until the Pb-B_4C bucket configuration could no longer establish a delayed critical configuration. The process was repeated for both the LP-1 bucket cavity configuration and the empty central cavity configuration. The differential reactivity worth and integral reactivity worth values obtained from the measurements are found in Table 1. The shaded regions in the table identify where the control rod bank positions are covered by two central cavity configurations.

Table 1. Differential and integral reactivity worth values determined from the delayed critical and positive period measurements with various central irradiation cavity configurations.

Control Rod Bank Position (Rod Units)	**Δρ (Cents)**	**Integral ρ (Cents)**	**Cavity Configuration**
5500	0.0	0.0	Pb-B_4C Bucket in Central Cavity
4840	27.8	27.8	
4504	36.8	64.6	
4355	20.9	85.5	
4075	57.5	143.0	
3875	40.2	183.2	
3695	39.0	222.2	
3530	40.5	262.7	
3520	2.5	265.2	Pb-B_4C Bucket or LP-1 Bucket in the Central Cavity
3457	15.7	280.9	
3385	17.3	298.2	
3328	14.6	312.8	
3275	13.3	326.1	
3183	20.6	346.7	
3174	11.1	357.8	
3080	35.6	393.3	LP-1 Bucket in the Central Cavity
3004	25.4	418.8	
2925	27.3	446.1	
2844	28.2	474.3	
2799	16.1	490.4	
2770	10.3	500.7	LP-1 Bucket in the Central Cavity or Empty Central Cavity
2652	34.4	535.1	
2600	15.5	550.6	
2555	29.1	579.7	
2495	21.7	601.4	
2375	40.2	641.6	
2284	18.1	659.7	
2232	16.0	675.6	
2160	27.7	703.3	Empty Central Cavity
2087	25.0	728.3	
1954	43.2	771.5	
1830	38.6	810.1	
1765	22.8	832.9	
1707	15.6	848.5	
1635	23.9	872.4	
1494*	40.3	912.7	
***Typically, the ACRR cannot obtain a critical configuration below this control rod bank position without adding fuel elements.**			

3 Control Rod Integral Reactivity Curves

Using the perturbation theory methodology described by Duderstadt and Hamilton [2], the data from Table 1 was used to construct an integral reactivity worth curve for the ACRR control rods. The results obtained from the perturbation fit to the positive period measurements are found in Figure 1 along with a MCNP5 [3] calculated integral worth curve. The MCNP5 curve was constructed by calculating the reactivity derived from k_{eff} values at incremental locations for the control rod bank. The k_{eff} calculations for the MCNP5 curve were performed using a previously described model of the ACRR [4].

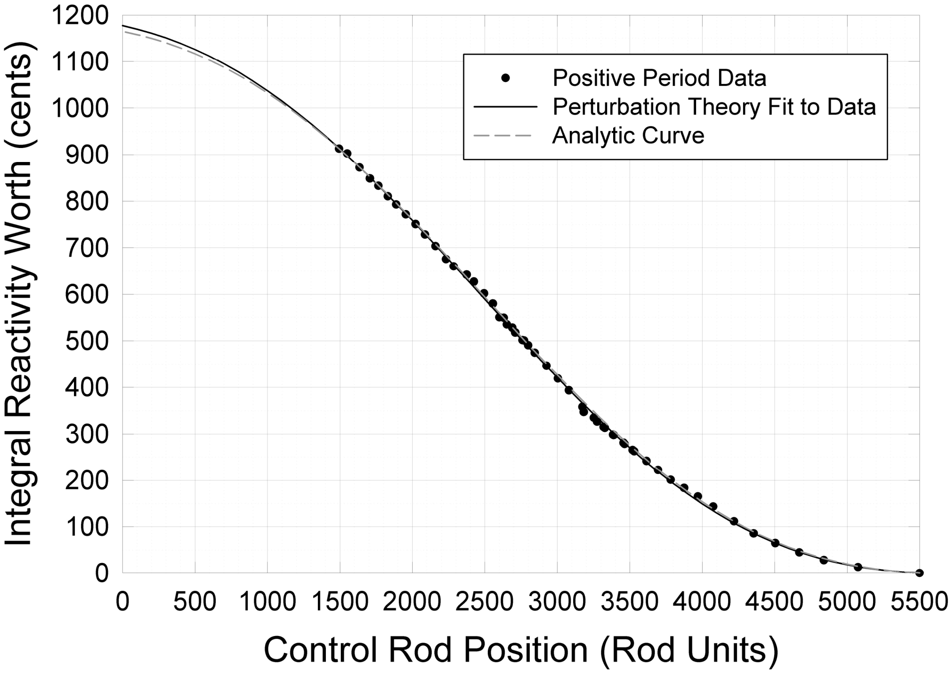

Figure 1. Integral reactivity curves obtained from (1) a perturbation theory fit to positive period data and (2) an analytic calculation of the reactivity of the control rod bank.

There is close agreement between the integrals of the MCNP5 calculated curve and the perturbation fit. The difference is \$0.13 over the entire curve while the statistical uncertainty in the MCNP5 curve is ~\$0.08. There is also a high level of qualitative agreement between the two curves over the entire stroke of the control rod bank. The high level of quantitative and qualitative agreement in addition to the lack of the ability to obtain positive period measurements for control rod bank positions between 0 and 1500 rod units were the foundation for the recommendation that the curve derived from the MCNP5 calculations be implemented as the control rod bank integral reactivity worth curve for the ACRR.

Figure 2 presents a comparison of the recommended integral reactivity curve for the ACRR control rods with the curve constructed using the bootstrap experimental method described previously [1]. The figure demonstrates that the MCNP5 calculations (validated using the positive period measurements) result in an integral reactivity worth curve that is less than the curve obtained by bootstrap experiments by approximately \$1.15. We theorize that the adjustments required by the operations staff for pulse operations are based in the differences between the integral reactivity curve that they currently use and the recommended curve that more closely matches the actual control rod bank reactivity worth.

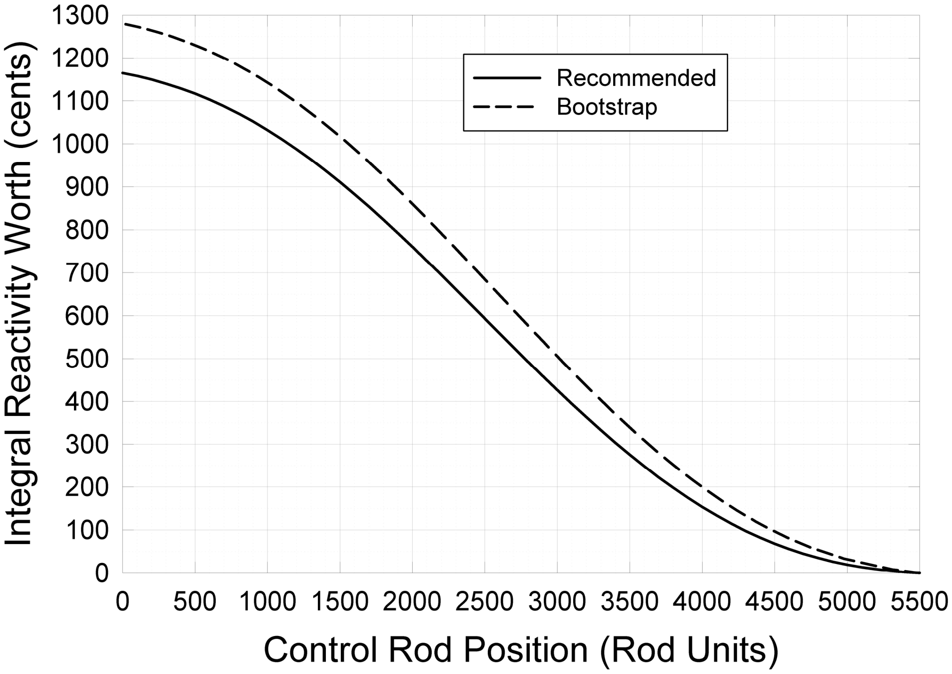

Figure 2. The recommended integral reactivity curve based on this work is compared with the previously obtained reactivity curve based upon a bootstrap experimental technique.

4 Prompt (Pulse) Period Measurement Comparisons

Each year, the operations staff at the ACRR performs calibration prompt period measurements (pulses) to comply with facility safety basis requirements. The pulses are performed for nominal reactivity insertions of \$1.50, \$2.00, \$2.50, and \$3.00 (maximum pulse). The minimum stable reactor period for each pulse is determined from the pulse diagnostics system and used to calculate a reactivity insertion. One way to assess whether the recommended reactivity curve is a better approximation of the actual reactivity insertion is to compare the predictions of both curves with the reactivity determined for the calibration pulses using the minimum period from the pulse diagnostics system (this assumes that the pulse system inserts all the reactivity into the reactor before feedback effects become significant).

Table 2 contains the comparison of the reactivity predictions with the calibration pulses from January 2007. Table 2 shows that the current reactivity curve overestimates the reactivity of the 4 calibration pulses by an average of +8.5 cents (σ = 5.9 cents). Every predicted reactivity insertion by the current control rod curve is greater than the measured reactivity (this phenomenon matches the operator's experience). This suggests that there is a systematic bias in the current control rod curve. The recommended reactivity curve differs from the measurements by an average of -0.9 cents (σ = 3.9 cents). The predictions from this curve are both above and below the measurements. The predictions from the recommended reactivity curve cannot be statistically distinguished from the experimental results.

Table 2. The predicted reactivity insertions for the current and recommended curves are compared with the pulse diagnostics system determination of the reactivity insertion.

ACRR Shot Number	**Pulse Diagnostic System Reactivity ($)**	**Current Control Rod Reactivity Curve ($)**	**Recommended Control Rod Reactivity Curve ($)**
8646	2.966	3.138	3.002
8647	2.450	2.501	2.399
8648	1.952	2.001	1.922
8649	1.434	1.501	1.443
Average Difference from Measurement		**0.085**	**-0.009**
Standard Deviation from Measurement		**0.059**	**0.039**

While the data in Table 2 suggest excellent agreement between the recommended integral reactivity curve and the response of the reactor, it is a very small sample. Therefore, the operations log was mined for additional comparison points. Approximately 50 pulse operations were performed between January and September 2007. A comparison of the deviations between the current and recommended control rod reactivity curves and the actual reactivity is found in Figure 3.

The "perfect" agreement line for the comparison is found in the figure along with the linear regressions from both the recommended and current reactivity curves. The R^2 values for both the recommended and current linear regressions are greater than 0.98. The linear regression for the recommended curve contains the perfect agreement line within its 95% prediction interval while portions of the current curve fall outside the 95% prediction interval. These results indicate that the reactivity curve recommended in this paper is a better model of the reactor response than reactivity curve currently being used by the ACRR operations staff.

5 Conclusions

A series of experiments were performed to determine the integral reactivity worth curve for the ACRR. The experiments were compared to both a previous bootstrap construction of the curve and an MCNP5 calculation of the curve. Using the experiment series and MCNP5 calculations, the recommended control rod reactivity worth curve was constructed. The predicted values of the reactivity insertion from the recommended curve and the current curve were compared to the actual reactor response for over 50 reactor pulses. The comparison found that the curve recommended in this paper produced better agreement with the reactor response than the curve that is currently being used by the ACRR operations staff.

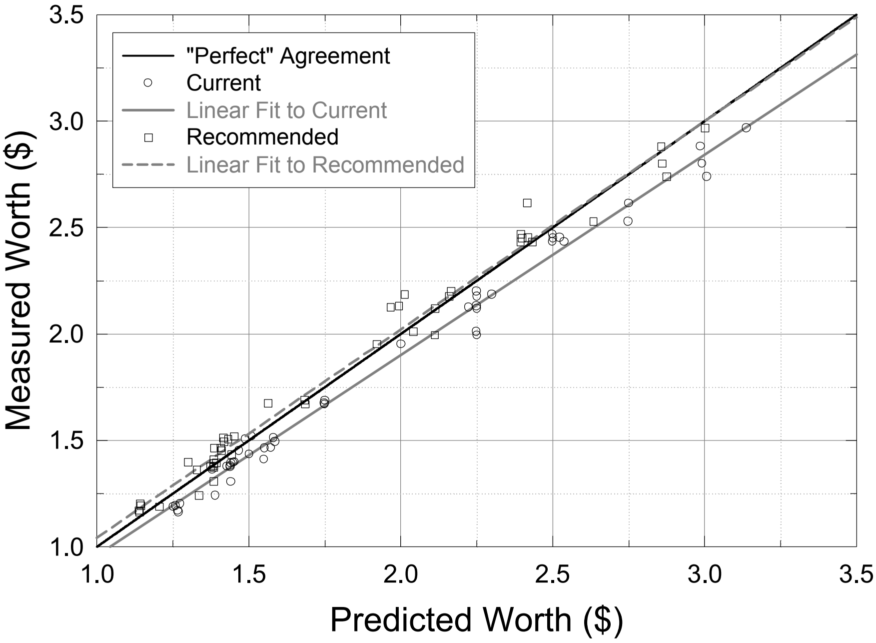

Figure 3. A comparison of the deviations between the predicted prompt reactivity insertion for both the current and recommended control rod reactivity worth curves.

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References

1. K. R. DePriest. “Bootstrap Techniques Versus Full Core Model for Control Rod Calibration.” American Nuclear Society *Transactions*, Vol. 95, pp. 409-410, November 2006.
2. J. J. Duderstadt and L. J. Hamilton. *Nuclear Reactor Analysis*. John Wiley & Sons, New York, 1976.
3. F. B. Brown (Team Leader) and X-5 Monte Carlo Team, “MCNP – A General Monte Carlo N-Particle Transport Code, Version 5,” LA-UR-03-1987, Los Alamos National Laboratory, Los Alamos, NM, April 2003.
4. K. R. DePriest, P. J. Cooper, E. J. Parma, “MCNP/MCNPX Model of the Annular Core Research Reactor,” SAND Report, SAND2006-3067, Sandia National Laboratories, Albuquerque, NM, May 2006.