SAND2011-3482C

Reactor Pulse Repeatability Studies at the Annular Core Research Reactor[1]

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Abstract

The Annular Core Research Reactor (ACRR) at Sandia National Laboratories is a water-moderated pool-type reactor designed for testing many types of objects in the pulse and steady-state mode of operations. Personnel at Sandia began working to improve the repeatability of pulse operations for experimenters in the facility. The ACRR has a unique UO_2-BeO fuel that makes the task of producing repeatable pulses difficult with the current operating procedure. The ACRR produces a significant quantity of photoneutrons through the $^9Be(\gamma, n)^8Be$ reaction in the fuel elements. The photoneutrons are the result of the gammas produced during fission and in fission product decay, so their production is very much dependent on the reactor power history and changes throughout the day/week of experiments in the facility. Since the photoneutrons interfere with the delayed critical measurements required for accurate pulse reactivity prediction, a new operating procedure was created. The photoneutron effects at delayed critical are minimized when using the modified procedure. In addition, the pulse element removal time is standardized for all pulse operations with the modified procedure and this produces less variation in reactivity removal times.

Keywords

ACRR, Photoneutrons, Reactor kinetics, Experimental repeatability

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[1]Work supported by the United States Department of Energy. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
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Introduction

The Annular Core Research Reactor (ACRR) at Sandia National Laboratories is a water-moderated pool-type reactor designed for testing many types of objects in the pulse and steady-state mode of operations. 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 (i.e., buckets). This feature also requires that the ACRR have more excess reactivity in the control elements than is typical for a research reactor (i.e., the excess reactivity in the control rod bank of 6 elements for an empty cavity is ~$10.00[5]) in order to overcome effects of the negative reactivity experiment packages while performing pulse and steady state operations. This feature also makes an accurate integral reactivity worth curve for the control rods difficult to produce using standard techniques for developing these curves. A previous analytic construction of an integral reactivity worth curve for the control rods highlighted the discrepancies produced by the experimental technique [1]. Experimenters have also focused on updating the integral reactivity curves used for operations in the facility [2] in order to improve the predictability of the energy yield for pulse operations.

Once the integral reactivity curves for the ACRR were updated, personnel at Sandia began working to improve the repeatability of pulse operations for experimenters in the facility. The ACRR has a unique UO_2-BeO fuel that makes the task of producing repeatable pulses difficult with the current operating procedure. Due to the beryllium in the fuel, the ACRR produces a significant quantity of photoneutrons through the $^{9}Be(\gamma, n)^{8}Be$ reaction. The photoneutrons are the result of the gammas produced in fission product decay. Thus, the production of these photoneutrons is very much dependent on the reactor power history and changes throughout the day/week of experiments in the facility. Since the photoneutrons interfere with the delayed critical (DC) measurements required for accurate pulse reactivity prediction, a new operating procedure was created. The photoneutron effects at DC are minimized when using the modified procedure. In addition, the pulse element removal time is standardized for all pulse operations with the modified procedure, and the standardization provides experimenters with less variation in reactivity removal times from one operation to the next.

Experimental Setup and Procedures

The reactor pulse experiments were conducted in environments previously described by Vehar *et al.* [3] (e.g., the ACRR central cavity and the lead-boron (Pb-B_4C) bucket). For all of the reactor pulses, the ACRR pool temperature was 20^o +/- 2^o C. The recommended procedure for the initial pulse of the day was as follows:

- Using the control rod (CR) bank, obtain DC condition at about 0.05% full power with the transient rod (TR) and safety rod (SR) banks fully withdrawn. The CR bank position will be called "Up DC" (i.e., DC position with TR bank fully withdrawn).
- Using the CR bank, obtain DC condition at about 0.05% full power with the TR bank fully inserted and SR bank fully withdrawn. The CR bank position will be called "Down DC" (i.e., DC position with TR bank fully inserted).
- Determine the CR bank position for the desired pulse size using the CR integral worth curve developed by DePriest *et al.* [2].
- Move the CR bank to the corresponding position.
- Lower the SRs and allow the power to decay at least 1 decade.

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[5] For clarity, we refer to $\rho = \beta_{eff}$ as \$1.00 of reactivity. For example, reactivity (ρ) of \$1.50 in the ACRR would

- Raise SRs and perform reactor pulse operation.

For subsequent pulses within the same day, the procedure is similar except that the Down DC determination is not required.

In the current ACRR procedure, a “Setup DC” position (the TRs are placed somewhere between fully inserted and full withdrawn) obtained prior to the pulse is used to determine the CR bank position for the desired pulse size. Thus, this method is subject to additional photoneutron effects (during the Setup DC) and more dependent on the previous reactor operating history. In addition, pulses of different sizes will have different reactivity removal times (an undesired effect) based on the distance that the TRs have to travel to leave the reactor core due to their different Setup DC positions.

The ACRR pulse diagnostic system includes several cadmium-based self-powered neutron detectors (SPND) on the core periphery to analyze the pulse size. The active dosimetry fielded in the reactor cavity included an SPND, a diamond photoconducting detector (PCD), and an ionization chamber (IC). The ability of these detector systems to characterize the reactor environment has been previously described [4]. The reactivity insertion for the reactor pulses was determined by analyzing the time-dependent response from each of these detectors using the Fuchs-Hansen model of reactor pulse kinetics.

Results

The results of the six days of reactor operations (40 reactor pulses) are found in

correspond to $\rho = 1.5\ \beta_{eff} = 0.01095\ \Delta k/k = 1095$ pcm. In the text, tables, and figures below, 1 cent of reactivity is equal to \$0.01.

Table 1. Preliminary tests (days 1-3) examined the photoneutron effects in the core over the course of the day. In these tests, the recommended control rod worth curve and procedure were used [2]. Pulses were conducted in the central cavity, and the desired reactivity insertion was \$2.25. Utilizing the ACRR pulse diagnostic system SPNDs, the average pulse size (based on the minimum period value for the pulse waveform) on day 1 and day 2 was \$2.235 ± 0.025 and \$2.210 ± 0.007, respectively. Since the reactor cavity configuration and the desired size for the pulse was the same on day 1 and day 2, the results from those two days are combined for an average reactivity insertion of \$2.221 ± 0.021.

For day 3, the current control rod worth curve and procedure were used with central cavity configuration and \$2.25 desired pulse size maintained. The average pulse size was \$2.120 ± 0.017. The standard deviation in the average pulse size for day 3 is similar to the value computed for days 1 and 2, but the trend in the pulses sizes and the photoneutron effects will be detailed in the following section. The reader will observe that there is no uncertainty value computed for individual pulses on days 1, 2, and 3 since the ACRR pulse diagnostic system was used to estimate the reactivity. Thus, only one measurement was available for the estimate of reactivity.

For the remaining 3 days of experiments, data was taken utilizing active dosimetry within the central cavity. During days 4 and 5, the pulses were performed in the central cavity, and the desired pulse size was a \$1.50 reactivity insertion. The average pulse size (based on the full width at half maximum [FWHM] value for the pulse waveform) on day 4 and day 5 was \$1.450 ± 0.017 and \$1.454 ± 0.012, respectively. Since the reactor cavity configuration and the desired size for the pulse was the same on day 4 and day 5, the results from those two days are combined for an average reactivity insertion of \$1.452 ± 0.015.

The operations on day 6 were slightly different with the experimental setup occupying the Pb-B_4C bucket rather than the central cavity. In addition to the different cavity configuration, day 6 experiments alternated between small pulses ($1.23 desired size) and large pulses ($2.43 desired size). The alternating pulse size was intended to limit the daily integrated energy deposition on the Pb-B_4C bucket (safety constraint) in addition to allowing the experimenters to determine if the additional energy deposited during the large pulses would change the energy yield (as measured by reactivity insertion) of the small pulses. The average small pulse was $1.232 ± 0.013 while the average large pulse was $2.360 ± 0.037. There is some evidence that the ionization chamber may have had a saturated response during the large pulses on day 6. If the ionization chamber results are removed from the analysis, the average for a large pulse on day 6 becomes $2.382 ± 0.022.

Analysis

In Figure 1, the variability on Day 1 is largely due to the operations staff adjusting to the modified procedure while Day 2 essentially shows the results one would expect from random variations about a mean value. The reactivity results from Day 3 are typical of operations at the ACRR using the standard pulse procedure (i.e., the same nominal reactivity insertion yields a decreasing pulse result as the day/week of experiments progresses). The photoneutron effects are apparent here, as the neutron source increases over the course of the day, the operators adjust to the increased photoneutron level by lowering the Up DC position. This results in a decrease in the reactivity insertion as the day/week progresses.

Table 1. ACRR Pulse Data for Pulse Repeatability Experiments

ACRR Operation Number	Old Predicted Reactivity Insertion ($*)	New Predicted Reactivity Insertion ($*)	Reactivity Insertion with 1σ Uncertainty ($*)
Day 1			
9408	2.350	2.250	2.238
9409	2.350	2.250	2.240
9410	2.350	2.250	2.200
9411	2.350	2.250	2.270
9412	2.350	2.250	2.228
Day 2			
9414	2.350	2.250	2.206
9415	2.350	2.250	2.219
9416	2.350	2.250	2.205
9417	2.350	2.250	2.215
9418	2.350	2.250	2.200
9419	2.350	2.250	2.213
9420	2.350	2.250	2.212
Day 3			
9421	2.252	2.158	2.148
9422	2.251	2.157	2.128
9423	2.251	2.158	2.130
9424	2.251	2.157	2.120
9425	2.248	2.155	2.101
9426	2.250	2.156	2.108
9427	2.251	2.157	2.102
Day 4			
9770	1.559	1.500	1.477 +/- 0.013
9771	1.559	1.500	1.452 +/- 0.010
9773	1.559	1.500	1.447 +/- 0.010
9774	1.559	1.500	1.432 +/- 0.008
9775	1.559	1.500	1.443 +/- 0.010
Day 5			
9789	1.559	1.500	1.471 +/- 0.018
9790	1.559	1.500	1.451 +/- 0.015
9791	1.559	1.500	1.455 +/- 0.018
9792	1.559	1.500	1.450 +/- 0.012
9793	1.559	1.500	1.452 +/- 0.012
9794	1.559	1.500	1.459 +/- 0.013
9795	1.559	1.500	1.453 +/- 0.012
9796	1.559	1.500	1.447 +/- 0.012
Day 6			
9812	1.364	1.227	1.243 +/- 0.005
9813	2.758	2.429	2.369 +/- 0.042
9814	1.364	1.227	1.231 +/- 0.004
9815	2.758	2.429	2.372 +/- 0.044
9816	1.364	1.227	1.242 +/- 0.003
9817	2.758	2.429	2.354 +/- 0.040
9818	1.364	1.227	1.213 +/- 0.005
9819	2.758	2.429	2.345 +/- 0.037
NOTE: ACRR Operation Number 9772 was part of the experiment series. However, the data acquisition system did not receive a trigger signal, and the data were not obtained by the active dosimetry during the operation.			

From the results in

Table 1, it is clear that the recommended integral worth curve more accurately predicts the reactivity insertion than the current integral worth curve. For days 4 and 5, the calculated bias and uncertainty for the old and new predicted reactivity insertions are -$0.106 ± 0.01 and -$0.047 ± 0.01, respectively. The old reactivity insertion prediction bias increases with increased reactivity insertion, becoming -$0.398 ± 0.013 for the day 6 large pulses. This phenomenon stems from the method used to determine the CR bank integral worth curve, which is further discussed elsewhere [1]. Differences in integral worth in the current and recommended curves in Figure 2, Figure 3, and Figure 4 show the largest differential worth differences in the upper CR bank region (between 2200 - 5500 RUs). Thus, for larger pulse sizes, as in Figure 4 where we are in the upper CR bank region, there is a significant difference in predicted reactivity insertion ($0.329). For large pulse sizes, the recommended curve bias is similar to smaller pulse sizes (-$0.032 ± 0.010), and it provides more predictable results.

For the recommended control rod bank integral worth curve, it is unclear whether the reactor operators are dealing with a bias or an uncertainty when using the curve for predictions of reactivity insertion. There are reasonable explanations to allow an experimenter to justify the differences observed between the measured and predicted reactivity as either uncertainty or bias. The operators know that the uncertainty in the recommended curve is on the order of $0.20 over its entire span due to the methodology used in generating the curve [2]. Thus, for any given region of the worth curve, there would be an uncertainty on the order of a few cents of reactivity. It also known from reactor kinetics that, for a critical system, the neutron population increases linearly for a constant (time-independent) source [5]. The photoneutron source in the ACRR is a time-dependent source and the effect on the measured DC positions in the ACRR is on the order of a few cents [6]. The effect of the photoneutron source on the DC positions also changes throughout a day/week of operations because the reactor power history changes with each operation.

The evidence for an experimental bias (rather than an uncertainty effect) is stronger because the measured worth in this experiment series is always smaller than the pre-pulse prediction. While the measured worth is always smaller than the pre-pulse predicted, the variation in the measurement between nominally identical pulses is what one would expect for random variation in the measurement of an independent variable. The variation is also within the accuracy and precision limitations of the active dosimetry instrumentation. Finally, the photoneutron source adds to the neutron population in such a way that would drive the estimated DC positions to values that would lead to systematic overestimation of the pre-pulse prediction.

Future Work

It has been hypothesized that the current operating procedures at the ACRR are more subject to a fuel-temperature feedback effects than a full TR ejection procedure would be [7]. This “reactivity cheating” phenomenon is a situation in which the negative feedback effects due to fuel temperature increase begins to dominate before all of the intended reactivity insertion from the TR withdrawal is completed. The current procedure is designed to perform the pulse operation from the Setup DC (or “at power”). The result of the pulse operation from this DC power level is that the fuel-temperature feedback effect begins to occur as (and while) the TR are being ejected. In the newly recommended procedure, the TR bank is always withdrawn from its lowest position (i.e., full stroke). Since most pulse operations at the ACRR are less than the maximum reactivity, the subcritical start for a pulse operation under this procedure will give the TR time to leave the reactor before the fuel-temperature feedback effects dominant the reactor power trace. The authors are planning a series of tests that will examine the difference between pulse operations that use the current procedure and the recommended procedure for the same CR position for the pulse setup.

Conclusions

Experiments were conducted in different environments within the ACRR facility to examine the effect of photoneutrons and a modified pulse procedure on the resulting pulse energy yields. The predicted reactivity insertion was compared to the measured reactivity for two different integral worth curves (the current operating curve and the recommended operating curve generated in previous work [2]). Overall, the recommended curve performs better for pre-pulse predictions of the reactivity insertion. Large reactivity insertions in the upper portion of the CR worth curve showed the greatest discrepancy between the current curve and the recommended curve. A systematic bias in the performance of the reactor pulse procedure (particularly the determination of the Up DC control rod position) leads to an over-prediction of the reactivity insertion that will occur during a reactor operation. The bias is created by the photoneutron source that exists in the ACRR as a result of the unique UO_2-BeO fuel. Experimenters are planning tests to look at the effect of the variable TR withdrawal time created by the current procedure. The planned test series will examine whether or not the current procedure is more sensitive to fuel-temperature feedback effects than a full TR ejection procedure would be.

Acknowledgments

The authors would like to thank the ACRR Operations Staff (particularly Lonnie Martin, Lance Lippert, and Dave Clovis) for access to the facility on days not normally scheduled for operations.

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Figures

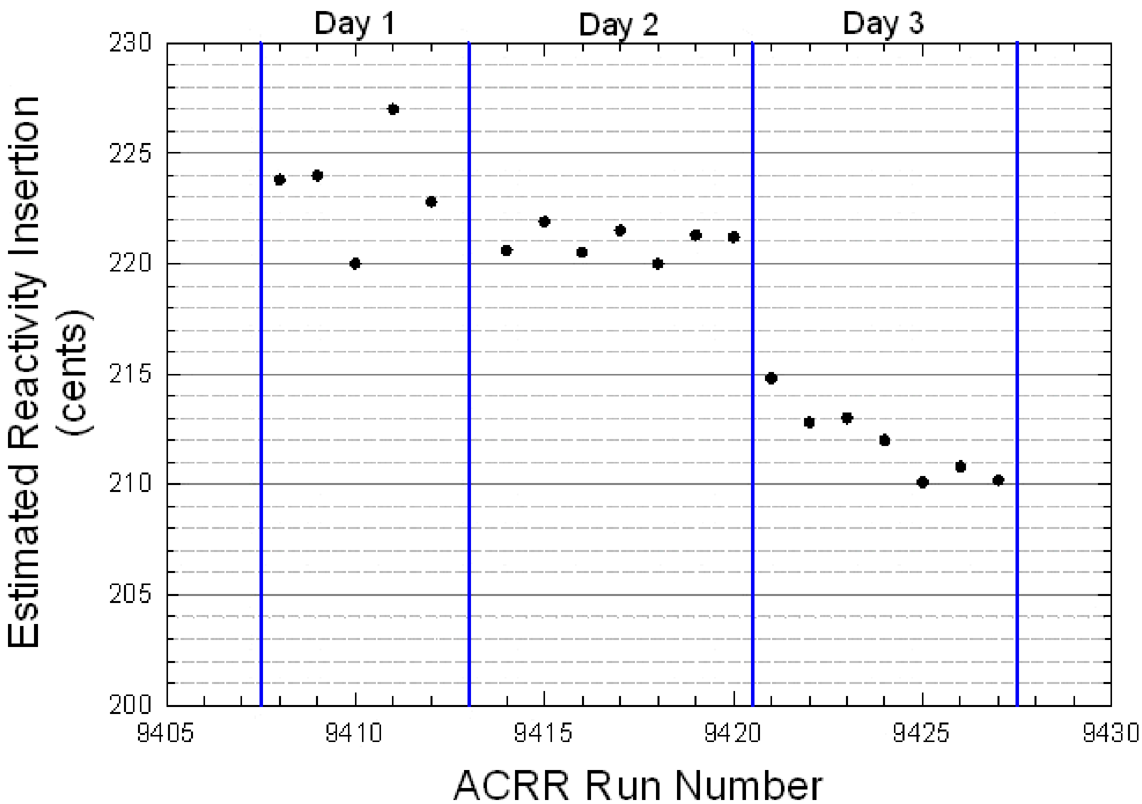

Figure 1. Pulse Repeatability Shots Using ACRR Pulse Diagnostic System for Data Acquisition

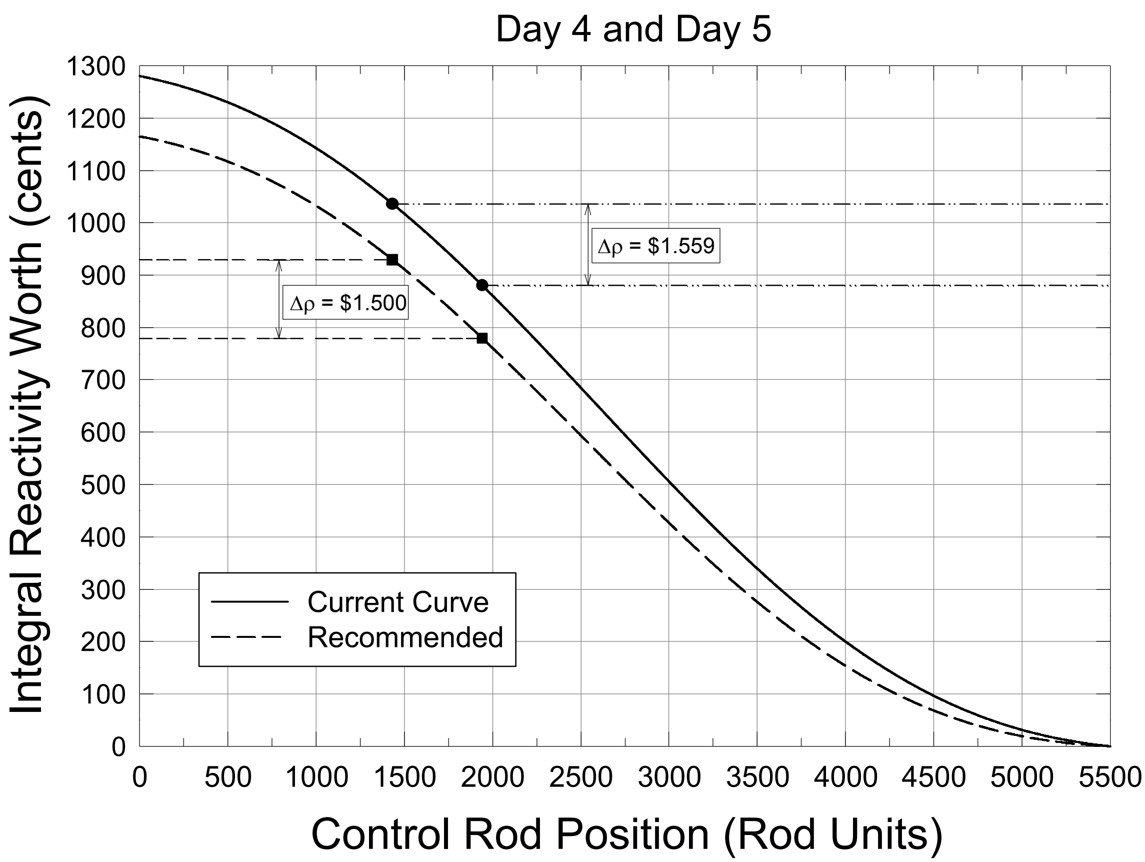

Figure 2. Day 4 and Day 5 Reactivity Insertions

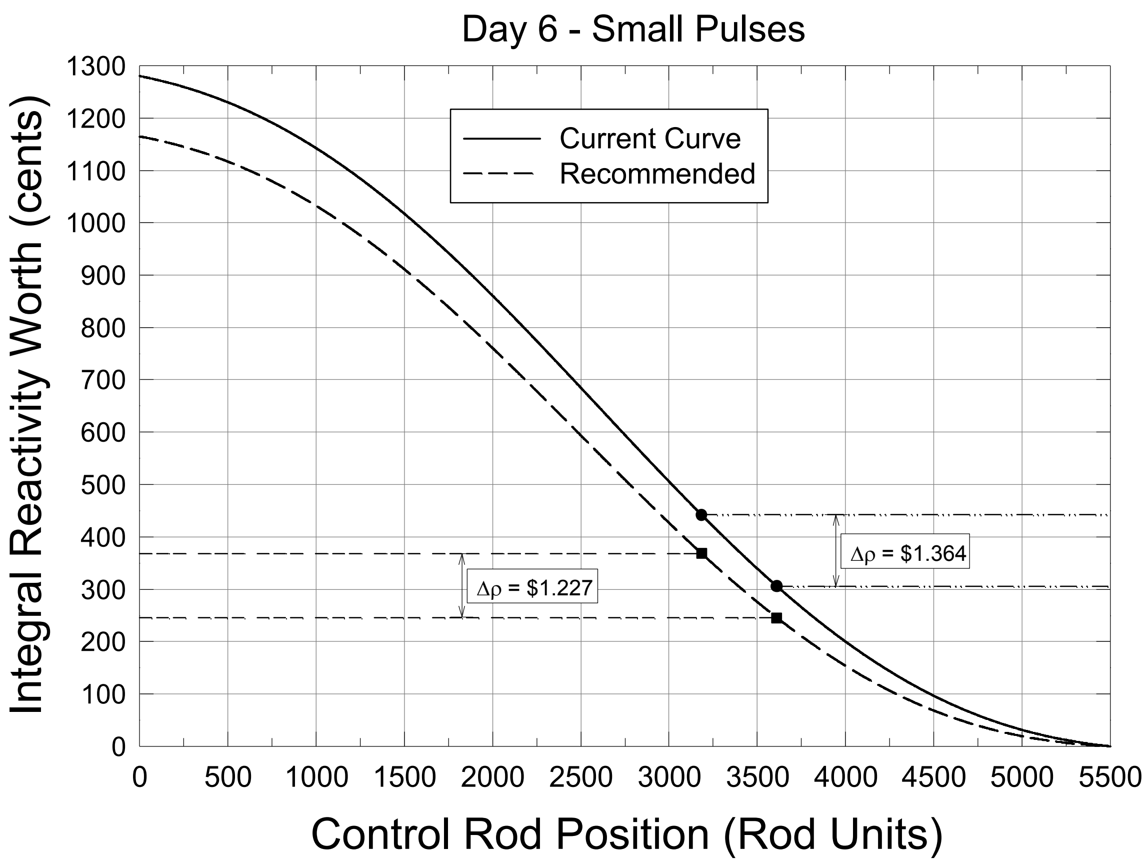

Figure 3. Day 6 Small Reactivity Insertions

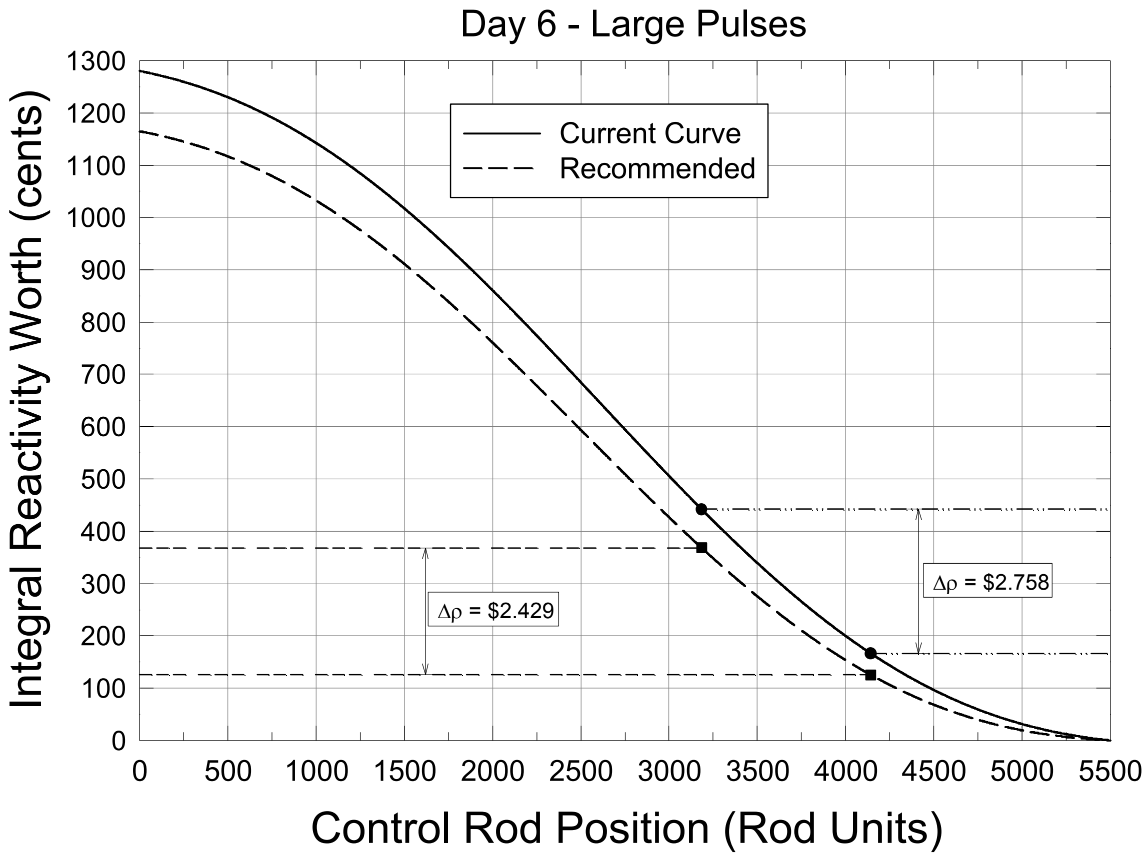

Figure 4. Day 6 Large Reactivity Insertions