Annular Core Research Reactor Improved Pulse Repeatability/ Prediction

September 21, 2010

Tri Q. Trinh*, Dr. K. Russell DePriest+
*Nuclear Facility Operations
+Applied Nuclear Technologies
Sandia National Laboratories, NM
Albuquerque, NM 87185

National Nuclear Security Administration

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

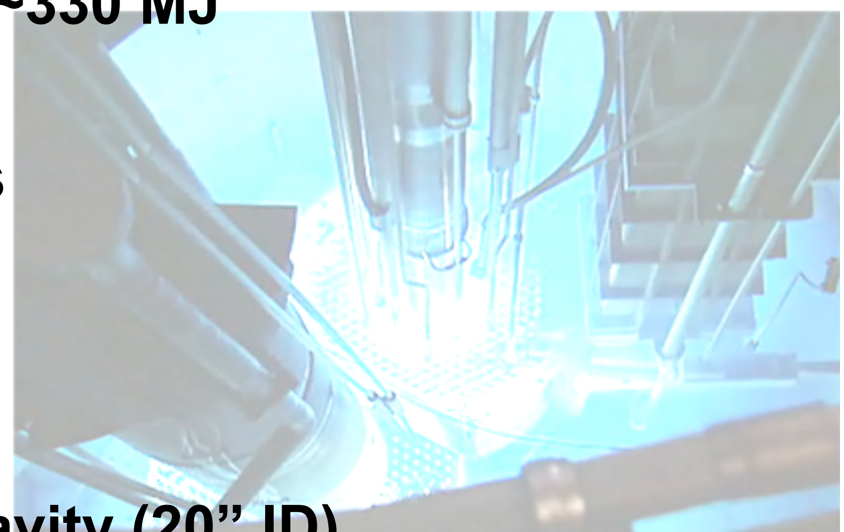
Outline

- Background
  - ❖Annular Core Research Reactor (ACRR)
- Motivation
  - ❖Improved Pulse Repeatability
  - ❖Improved Pulse Prediction
- ACRR Problems/Modifications
  - ❖Photoneutrons
  - ❖Current and Recommended Procedure
  - ❖Pulse Prediction Positive Bias
  - ❖Current and Recommended Worth Curve
- Test Results and Conclusions
- Future Work

Background

Annular Core Research Reactor (ACRR)

- TRIGA-type reactor with special UO_2-BeO fuel
- Pulse Operations
  - ❖ Reactivity Insertion - ~$3
  - ❖ Pulse Max Power ~ 40 GW
  - ❖ Max energy deposition ~330 MJ
  - ❖ Pulse width – 6.5 ms
- Steady State Operations
  - ❖ 2.4 MWt
- Features
  - ❖ Central Cavity (9” ID)
  - ❖ Fuel Ringed External Cavity (20” ID)
  - ❖ Spectrum Modifying Inserts



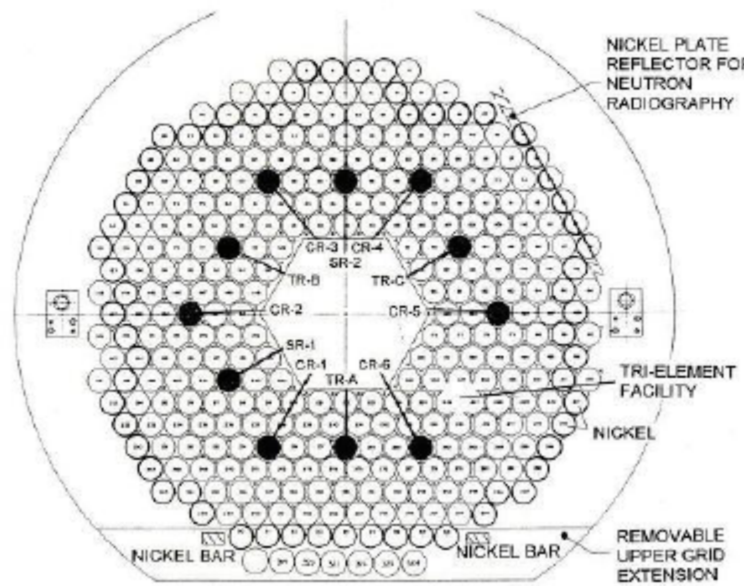
Sandia National Laboratories

Background
Annular Core Research Reactor

Standard Configuration

236 fuel elements (FEs) in hexagonal lattice including 6 control rods, 2 safety rods

- **Control Rods (CRs)**
  - **Motor driven**
  - **B4C poison, fuel followed**
  - **Controlling reactor power**
- **Safety Rods (SRs)**
  - **B4C poison, fuel followed**
  - **Additional shutdown reactivity**
- **Transient Rods (TRs)**
  - **B4C poison, void followed**
  - **Control reactor**
  - **Pulse**



Sandia National Laboratories

Background
ACRR Primary Mission

- Provide appropriate neutron radiation environments for radiation testing and qualification of electronic components and other devices, such as:
  - ❖Passive neutron and/or gamma dosimetry devices (e.g., activation foils, TLDs)
  - ❖Active neutron and/or gamma dosimetry devices (e.g., SNL developed diamond PCDs, calorimeters)
  - ❖Explosive components (including neutron generators)
- Other Applications
  - ❖Reactor fuel materials testing (GNEP, GEN IV)
  - ❖Reactor accident phenomenology testing (Severe core damage in LWRs, LMFBRs)

Motivation

- Facility has already developed and approved operating procedures and documented data
- ACRR pulse procedure modified to:
  - ❖Reduce variability in reactivity insertions
    - Overcome photoneutron effects
    - Fix transient rod (TR) removal time
  - ❖Improve ACRR pulse performance prediction
    - Higher fidelity control rod (CR) bank integral worth curve

ACRR Problems
UO_2-BeO Fuel and Photoneutrons

- **Beryllium produces background neutrons problematic to ACRR operations**

$$^{9}_{4}Be + ^{0}_{0}\gamma \rightarrow ^{8}_{4}Be + ^{1}_{0}n \; \left(1.7\ MeV\ Thr\right)$$
$$^{9}_{4}Be + ^{0}_{0}\gamma \rightarrow ^{4}_{2}He + ^{5}_{2}He$$
$$^{4}_{2}He + ^{5}_{2}He \rightarrow ^{4}_{2}He + ^{4}_{2}He + ^{1}_{0}n$$

- ❖ **Keepin has experimentally separated photoneutron precursors into 9 groups**
- ❖ **Small fraction of delayed neutron fraction (~2%), long-lived decay groups ($\beta_{U235,th}$=0.0065, β_{photo}=0.00015)**
- ❖ **Photoneutron precursors have long half-life compared to delayed neutron precursors**

Problems

- ❖ **Delayed critical established when reaching self-sustaining fission chain reaction**
- ❖ **Photoneutron population acts as source and skews true DC conditions (DC is subcritical)**
- ❖ **Changes control rod (CR) DC positions and intended reactivity insertions**

Group Constants for Delayed Photoneutrons from U235 Fission Products on Beryllium (Keepin 1965)

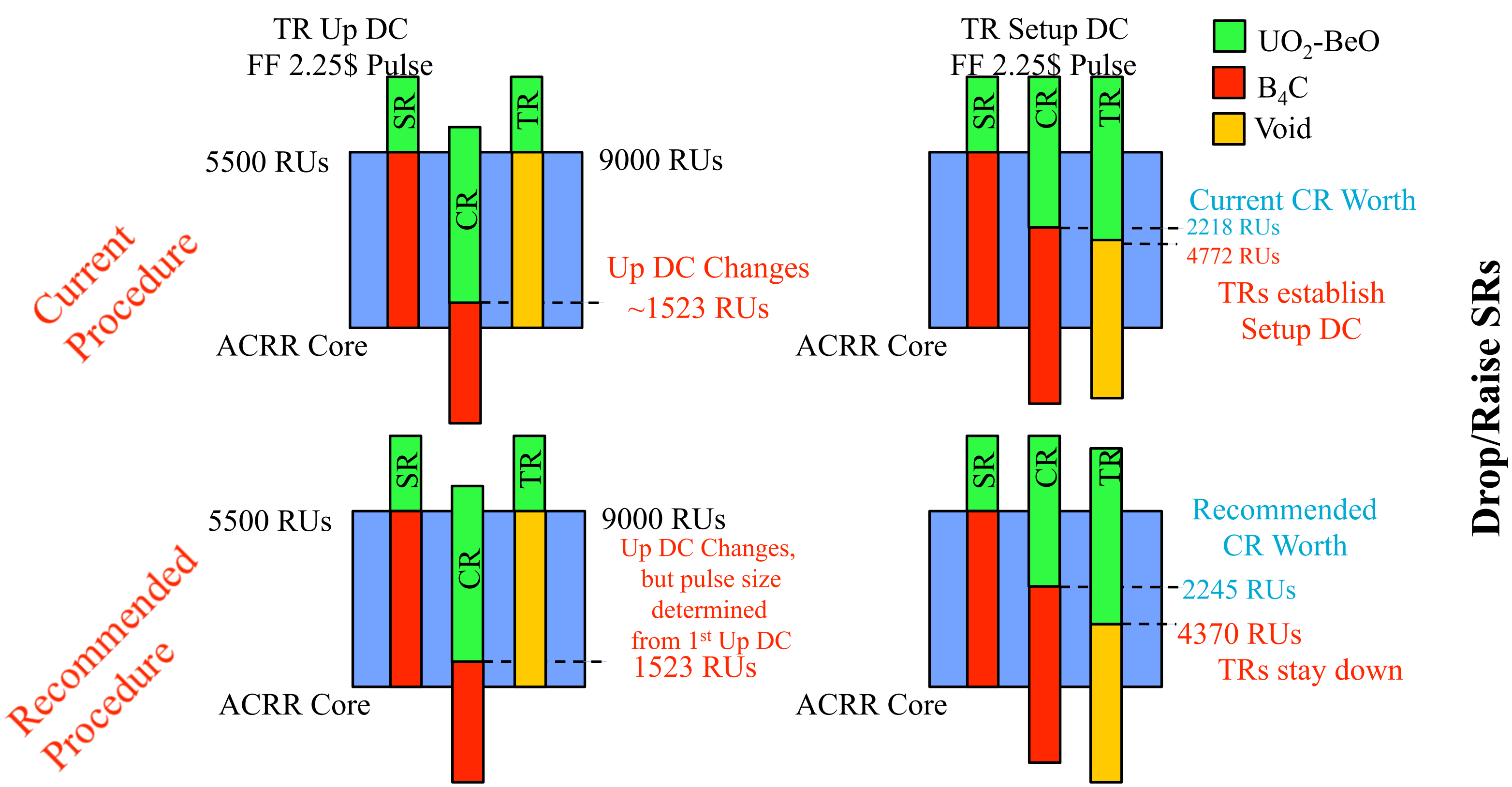
Group Index, j	Group half-life	Group Fraction β_i (10^{-5})
1	12.8 d	0.057
2	77.7 h	0.038
3	12.1 h	0.260
4	3.11 h	3.20
5	43.2 m	0.36
6	15.5 m	3.68
7	3.2 m	1.85
8	1.3 m	3.66
9	0.51 m	2.07
Total	-	15.175

Group Constants for Delayed Neutrons from U235 Thermal Fission

Group Index, i	Group half-life	Group Fraction β_I (10^{-5})
1	55.0 s	21
2	23.0 s	142
3	6.2 s	127
4	2.3 s	257
5	0.61 s	75
6	0.23 s	27
Total	-	650

Modifications
Pulse Repeatability

- **Current ACRR pulse procedure:**
  - ❖ **Uses current CR DC position to determine pulse size**
  - ❖ **Establishes DC at CR setup position**
- **Modified ACRR pulse procedure modified for testing:**
  - ❖ **Fixed TR Up DC CR position for reactivity insertion determination (photoneutrons)**
  - ❖ **Setup DC Modification, Pulse from Pedestals (reduce variability)**



Sandia National Laboratories

ACRR Problems
Pulse Predictability

- Due to photoneutron effects, reactor operators (ROs) experience a decrease in the control rod DC positions and measured reactivity insertion (~3 ¢) over the course of the day
- For "clean" core conditions (no photoneutrons), reactivity insertion is typically overpredicted (5 – 20 ¢)
- Overprediction stems from "Bootstrap" method used to develop the CR Integral Worth curve

"Bootstrap" Method for CR Integral Worth Determination

Core Condition

❖ 183 fuel elements (FEs)

❖ CR bank fully withdrawn

❖ DC condition

Procedure

❖ Add fuel element and measure positive period

❖ Insert CR bank to re-establish DC and determine differential worth

❖ Repeat until reaching ACRR full core configuration (236 FEs)

Sandia National Laboratories

ACRR Modifications
Pulse Predictability

- **With difference in starting (183) and final core sizes (236), measured CR bank integral worth may be overestimated (CR bank is larger fraction of total core fuel for small cores, dρ/dz ↑)**
- **CR bank integral worth determination with full ACRR core configuration (236 FEs) performed to increase fidelity of CR bank integral worth curve**

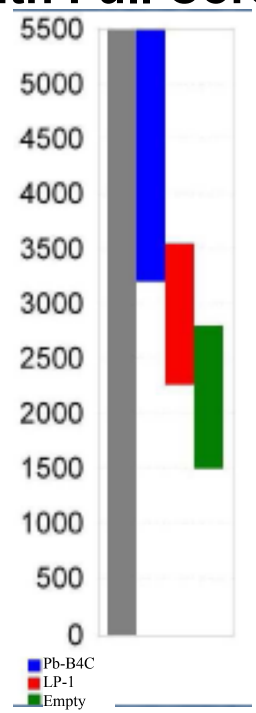
Procedure to determine CR Bank Integral Worth with Full Core

Core Condition

- ❖ 236 FEs
- ❖ CR bank raised
- ❖ TR bank raised to DC condition

Procedure

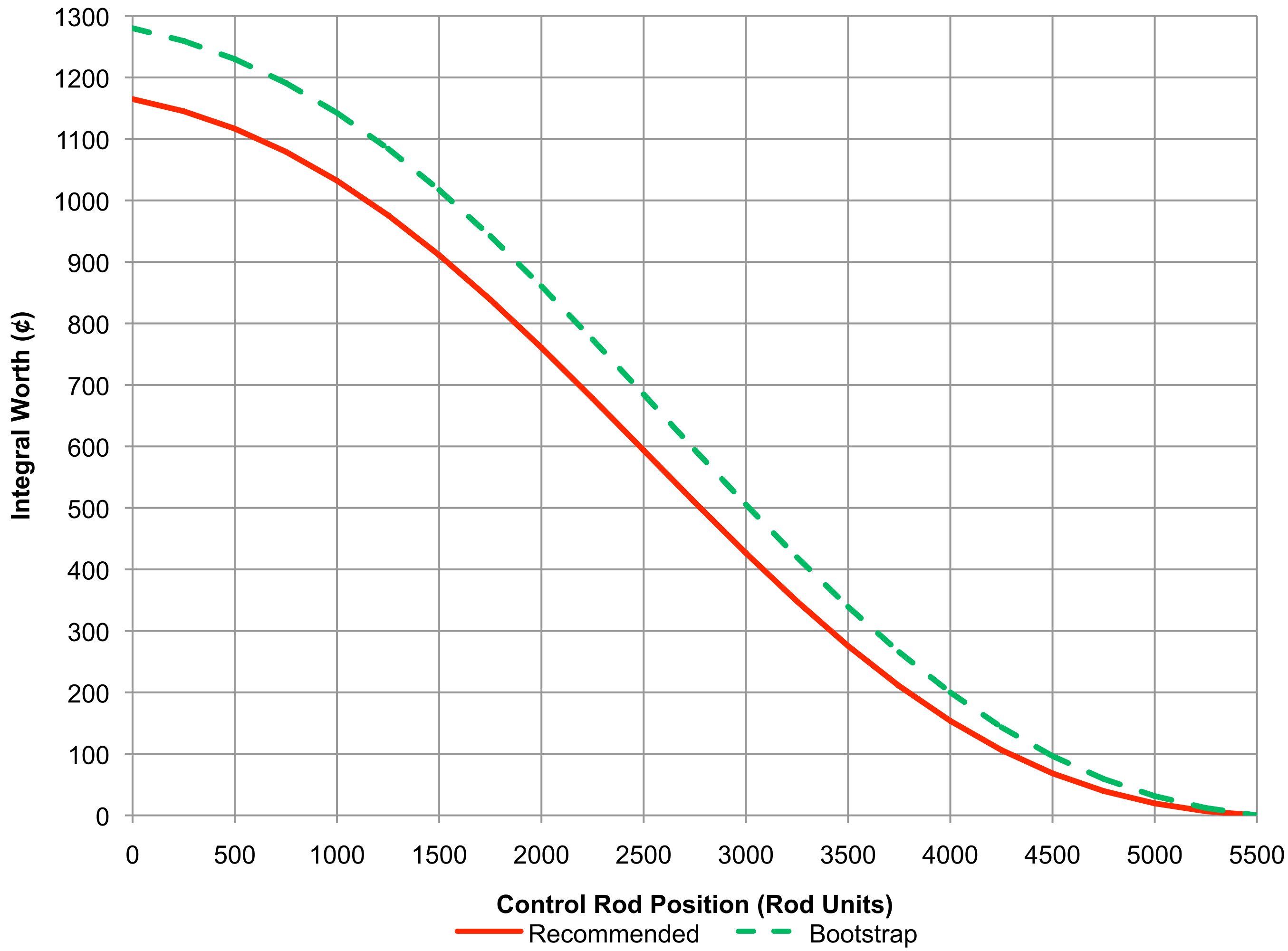
- ❖ Raise TRs and measure positive period
- ❖ Lower CRs, re-establish DC, and determine differential worth
- ❖ Use spectrum inserts of different worths to generate CR bank integral worth



Representation of CR positions that can be used to produce delayed critical configurations in the ACRR with various spectrum modifying inserts (Depriest, 2006)

Sandia National Laboratories

Modifications
Pulse Predictability

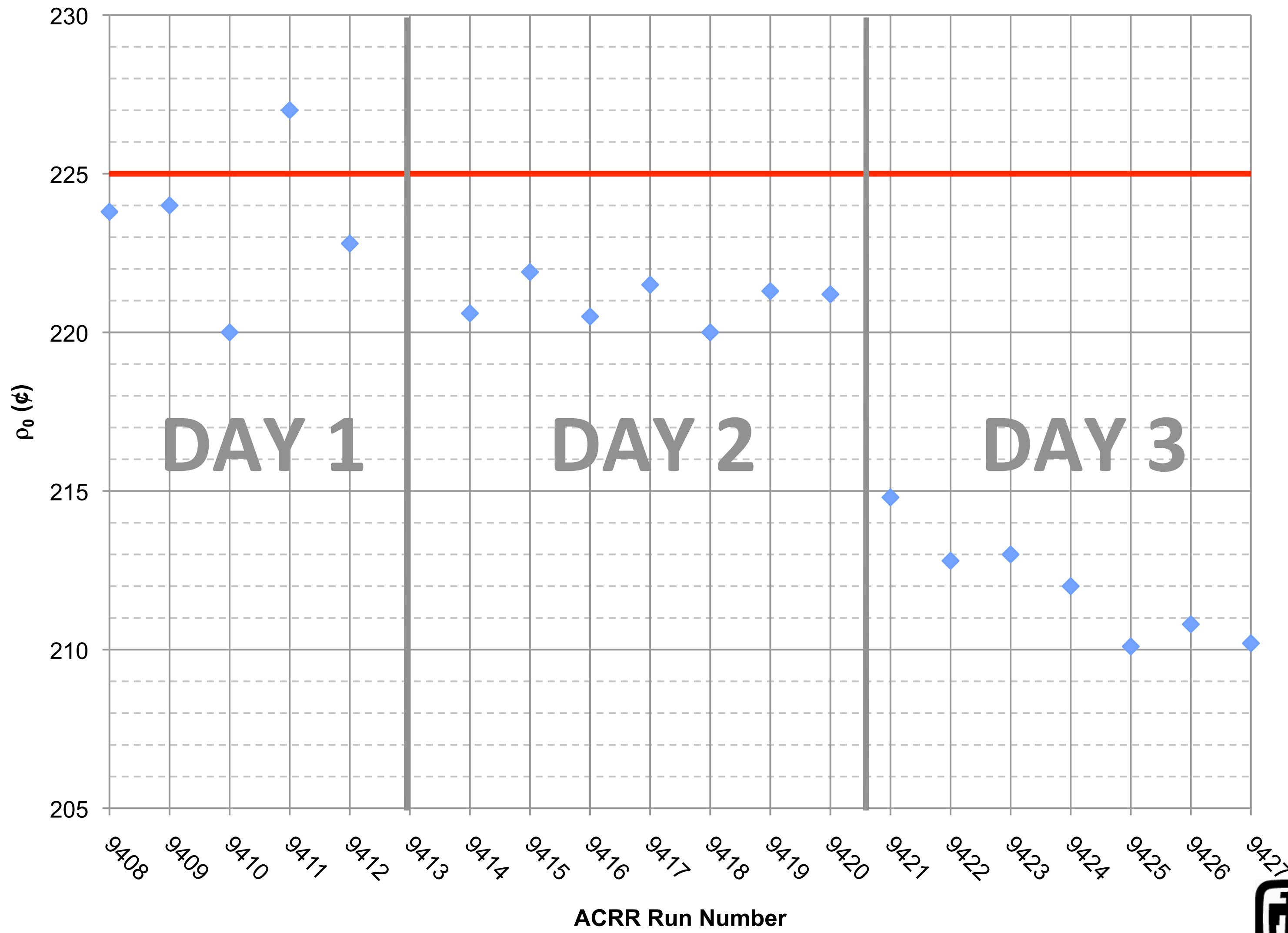


Integral Reactivity Curves Obtained from High-order Polynomial/Perturbation Theory Fits to Positive Period Measurements of "Bootstrap" and ACRR Full Core Experiments (DePriest 2006)

Sandia National Laboratories

Results and Conclusions

Recommended Pulse Procedure + Curve



Sandia National Laboratories

Results and Conclusions

CR Integral Worth Curve and Procedure Used for Experiments

Day	Curve	Procedure
1	Recommended	Recommended
2	Recommended	Recommended
3	Current	Current

- **Results obtained from ACRR pulse diagnostics (SPND/LabVIEW)**
- **Large deviation in measured reactivity insertion on Day 1 from operator adjustment to new procedure**
- **Day 2 shows expected results from modified procedure/curve**
- **Day 3 results are typical ACRR operations (photoneutron)**

Bias in Predicted Reactivity Insertion for Modified and Current CR Worth Curves

	Day 2 (Recommended)	Day 2 (Current)	Day 3 (Recommended)	Day 3 (Current)
Avg Bias (¢)	4.0	14.0	3.7	13.1
Std. Dev. (¢)	0.7	0.7	1.6	1.6

Future Work

- Preliminary results suggest improvement in pulse prediction/repeatability
- Test pulse repeatability for small reactivity insertions (<1.5$)
- Field active dosimetry inside central cavity for further testing and analysis of reactor time varying behavior
  - ❖Boron Calorimeter
  - ❖Fission Chamber

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, Nuclear Reactor Analysis, John-Wiley and Sons, Canada 1976.

3) G. R. Keepin, Physics of Nuclear Kinetics, Addison-Wesley, Reading, MA 1965.

4) J. R. Lamarsh and A. J. Baratta. Introduction to Nuclear Engineering, 3rd Edition, Prentice Hall, Upper Saddle River, NJ 2001.

5) P. S. Pickard, J. P. Odom, "Reactor Physics Design Calculations for the ACPR Upgrade," SAND80-0764, Sandia National Laboratories, NM, February 1982.

6) D. G. Talley, L. E. Martin, R. Danny Beets, "Sandia National Laboratories' Radiation Effects Testing Reactor Facilities." Proceedings of the Space Nuclear Conference 2005, June 2005.

Comments/Questions?