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Bootstrap Techniques Versus Full Core Model for Control Rod Calibration

Research Reactor Modeling Session

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Outline

- Background
  - Annular Core Research Reactor (ACRR)
  - Radiation Effects Sciences (RES) Modeling
  - Motivation for Present Investigation
- Procedures
  - Experimental bootstrap technique
  - Calculation techniques
    - Bootstrap simulation
    - Full reactor simulation
- Comparison of Simulation and Experiment
  - Discussion of discrepancies
- Conclusions
- Questions/Comments

ACRR Facility at Sandia National Laboratories

- TRIGA-type reactor with special $BeO\text{-}UO_2$ fuel
- Features
  - Central Cavity for Experiments
  - Fuel-Ringed External Cavities using U-ZrH fuel from ACPR
  - Spectrum modifying inserts
- Pulse Operations
  - ~$3.00 Max Insertion
  - 6.5 ms Pulse Width
  - 1.7 ms Reactor Period
  - ~30,000 MW Peak Power
  - ~300 MJ Energy Release
- Steady State Operation
  - 2.4 MW

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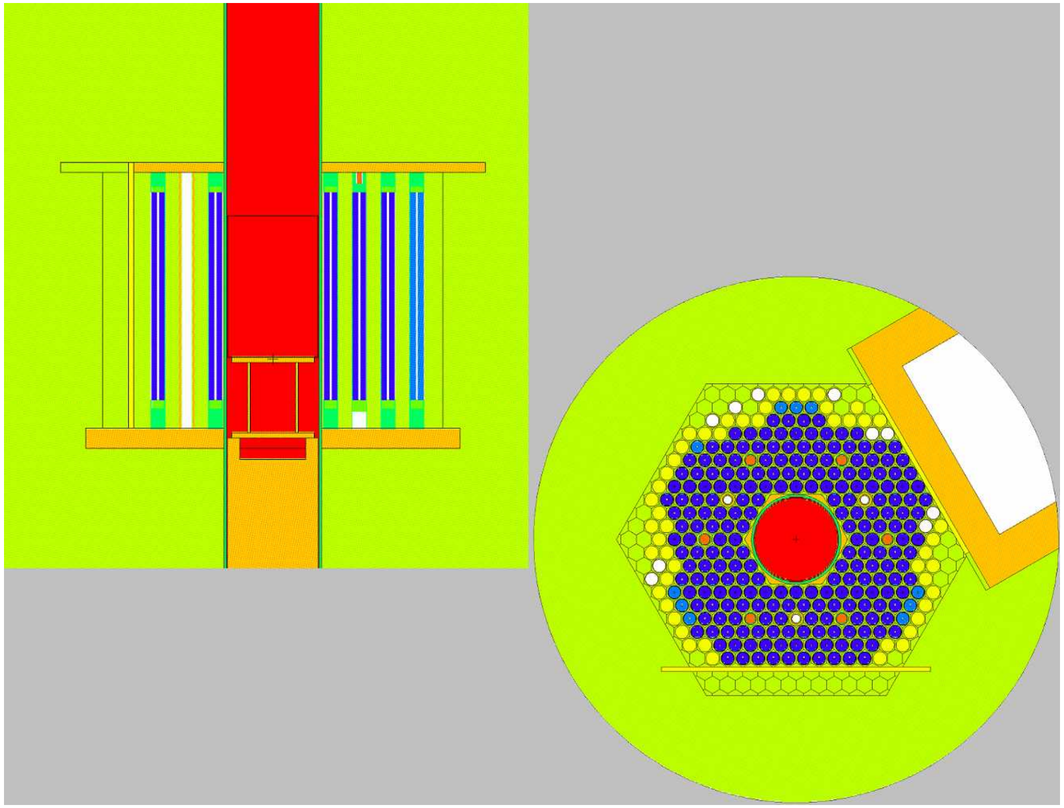
ACRR Facility Mission

- Provide a means to subject various components or systems to pulsed or steady-state neutron irradiation environments
- Typical Irradiation Experiments
  - Electronic circuit boards and components (e.g., transistors, diodes)
  - 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)

RES Modeling of the ACRR Facility

- **Experimenters need a prediction of radiation environments prior to performing expensive tests**
- **Reactor operators need a prediction of the reactivity worth ($\Delta\rho$) of experiment packages**
- **Post-experiment analysis often identifies a need for calculated radiation environments**



Motivation

- This work is an attempt to quantify and provide a theoretical basis for the “tribal knowledge” of the reactor supervisors and reactor operators
  - At the ACRR facility, it is well-known (from hundreds of pulses) that the actual reactivity insertion (and energy yield) from a pulse operation will be less than the reactivity determined from the rod worth tables
  - Intuition and experience guides the RS/RO to adjust the transient rod positions to get the energy yield desired from pulse operations

How did the ACRR build its control rod reactivity worth curve?

- Fuel elements were removed from the core until the assembly was sub-critical with the fuel-followed control elements fully withdrawn (all the poison out of the reactor)
  - For the ACRR, this is achieved with 183 fuel elements (with external Ni-reflectors)
- A fuel element is added to the core
  - This sends the reactor on a positive period
    - The period is measured
  - The control rods are inserted into the core until the reactor returns to delayed critical (DC)
  - The reactivity of the element is calculated
    - This gives the differential worth of the control rod poison section
- Repeat the process to build the reactor core has a total of 236 fuel elements
- This method is referred to as a “bootstrap” technique

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Sample Data From Actual Core Loading Using the Bootstrap Technique

Core Location of Element	# of Elements	Doubling Time (seconds)	Reactor Period (seconds)	Element Worth (cents)	DC Bank Position (Rod Units)	Integral Worth (cents)
633	184	110	158.7	6.6	5314	6.6
606	185	17.2	24.8	24.8	4979	31.4
614	186	16.8	24.2	25.1	4750	56.5
642	187	18.9	27.3	23.4	4588	79.9
623	188	37.6	54.2	15.2	4483	95.1
651	189	21.1	30.4	22.0	4370	117.1
604	190	15.5	22.3	26.3	4240	143.4
631	191	15.0	21.6	26.8	4121	170.2
734	229	10.0	14.4	33.0	1959	875.5
704	230	---	---	---	---	---
707	231	7.74	11.38	37.1	1843	912.6
745	232	---	---	---	---	---
748	233	12.5	18.0	29.5	1756	942.1
714	234	---	---	---	---	---
717	235	14.1	20.2	27.8	1665	969.9
718	236	98	142.5	7.3	1638	977.2

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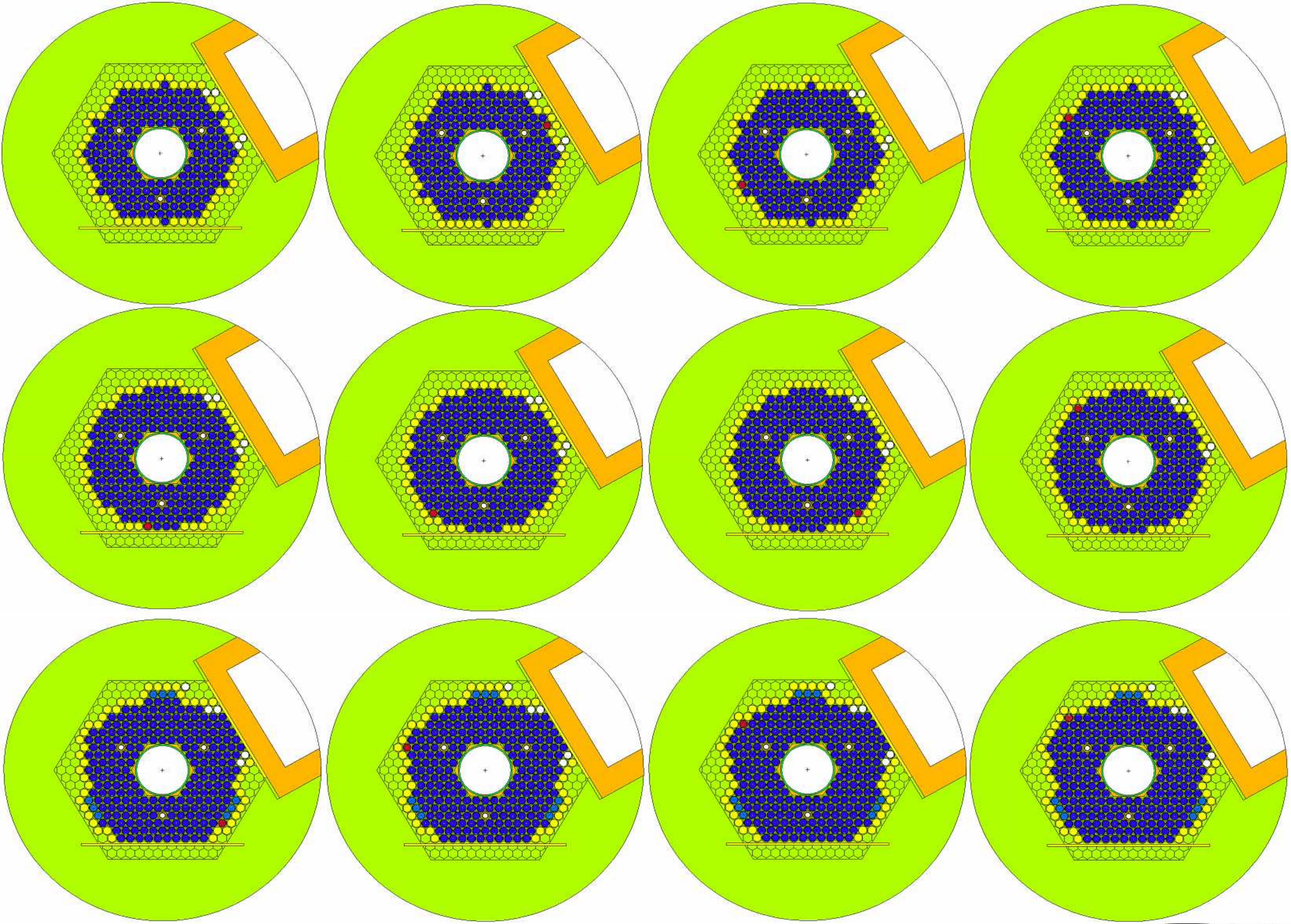
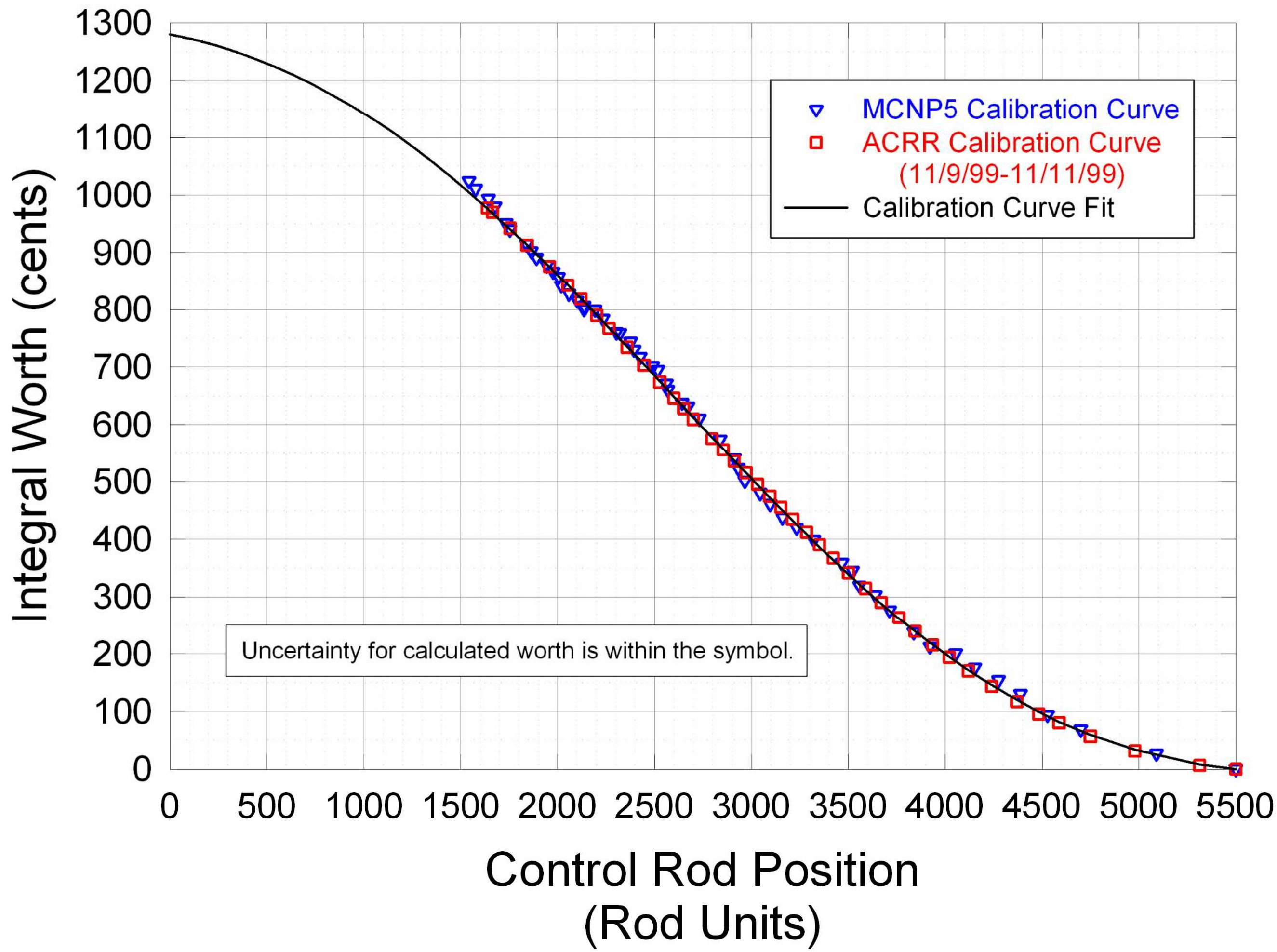
MCNP5 Bootstrap Simulation

- The fuel load log from the control rod calibration was examined
  - A previous “full core” model of the ACRR was modified to simulate the fuel load found in the logs
- Process is an exact simulation analog to the control rod calibration experiment
  - Add a fuel element to the proper location in the model
  - Calculate k_{eff} and $\Delta\rho$ for the new reactor configuration
  - Move the control rods (in the model) to obtain a DC position.
  - Sum the $\Delta\rho$ (for the integral worth) and keep track of the control positions
- Some of the reactor core configurations are shown on the next slide



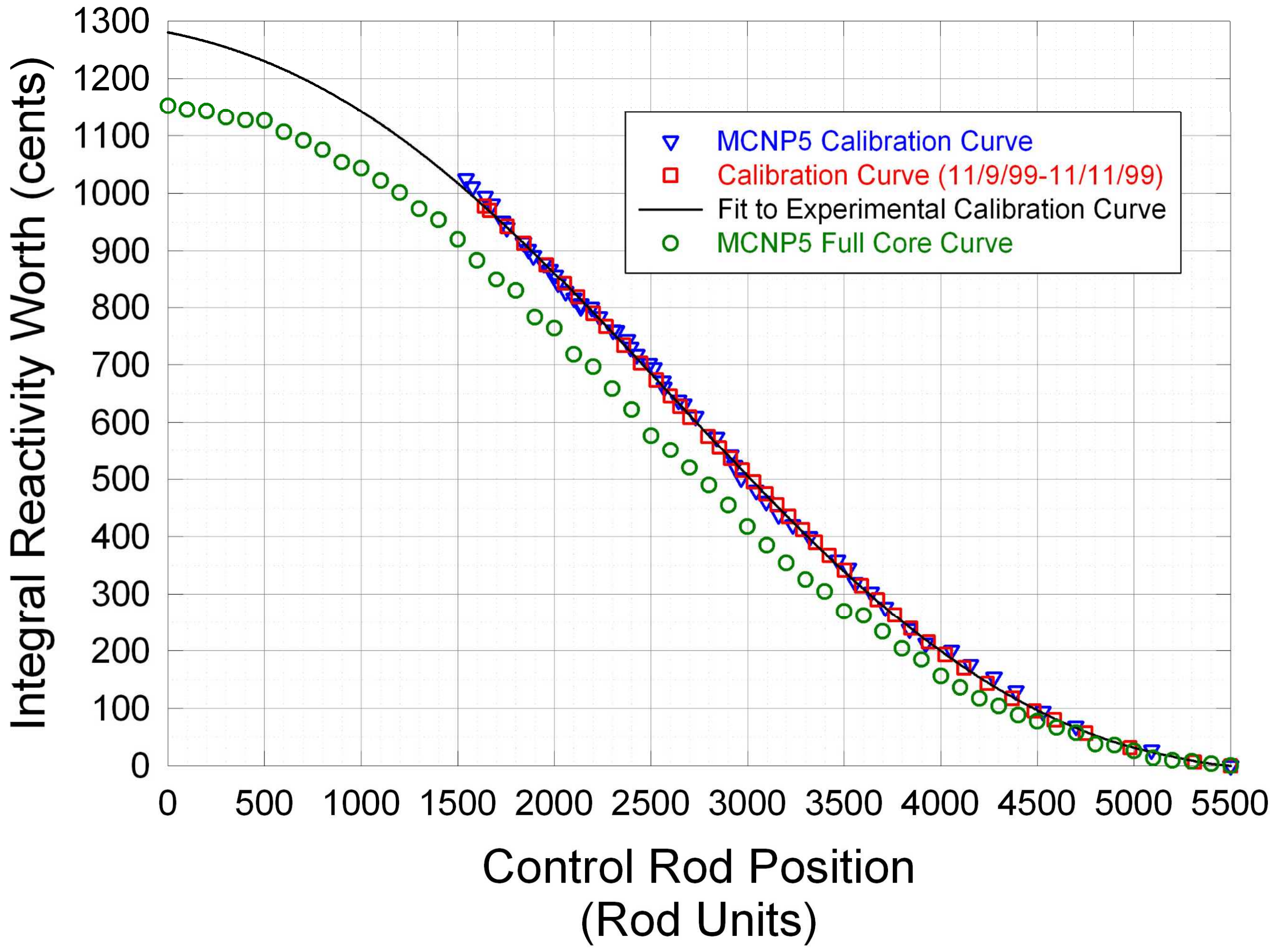
How well does the model follow the control rod calibration curve?



Full Core Model

- It is clear from the previous figure that the model of the ACRR predicts k_{eff} and $\Delta\rho$ quite well
- Now, let's look at what the control rod curve looks like when the full core model is used.
- Here is the process:
  - Calculate k_{eff} and ρ for the control rods fully withdrawn
  - Move the control rods into the reactor by 100 rod units (1 cm) and calculate a new k_{eff} and ρ
  - Use the data to construct an integral worth curve as a function of the control rod position.

How does the full model curve compare to the simulated/experimental bootstrap curve?



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Discussion

- There is obviously a large discrepancy between the full core and the bootstrap technique.
- Over the full length of the calibration curve, the difference in integral ρ between the techniques is ~$1.10
- The bootstrap technique yields a larger reactivity than the full core. WHY?
  – Bootstrap technique starts with a smaller core.
    - Control elements are larger percentage of the core
      – Thus, the control rods have a bigger influence in the smaller core
  – Intuition points to full core simulation as closer to the reality that reactor operators experience

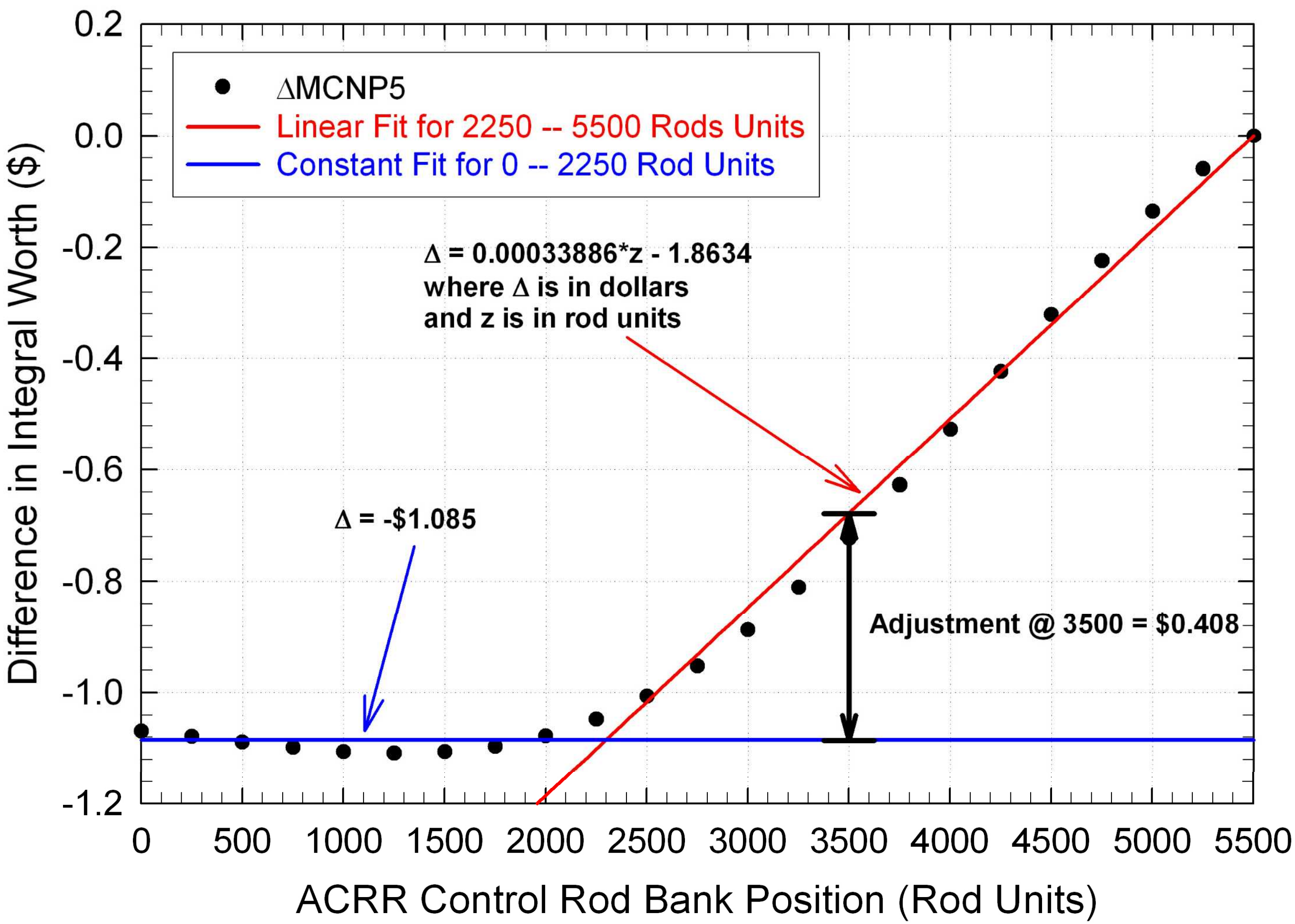
Using Full Core Results

- The ACRR Facility continues to use the curve from the rod calibration experiments
  - Challenge is now to relate the full core model to the calibration curve
- For small reactivity worth experiments, this is no problem
  - The difference between model and reality is basically a constant offset
- For larger reactivity worth experiments (i.e., control rod withdrawals greater than 2250 rod units), a linear empirical relationship has been developed:

$$\Delta\rho(\$) = 0 \qquad \left[0 \le z \le 2250\right]$$

$$\Delta\rho(\$) = (0.00033886z - 1.8634) + 1.085 \qquad \left[2250 < z \le 5500\right]$$

Adjustment for Large Rod Withdrawals



How well do we do with these models?

Static Experiment Worth Predictions

Experiment	Model ρ	Adjusted Model ρ	Experimental ρ	Δ between Model and Experiment
$Pb\text{-}B_4C$ Spectrum Modifying Bucket	-$6.29 +/- 0.14	-$5.95 (z = 3290 units => $0.34 adjustment)	-$5.82	-$0.13
LP-1 Spectrum Modifying Bucket	-$2.67 +/- 0.13	---- (z = 2160 units)	-$2.59	-$0.08
4" Diameter HDPE Sphere	-$0.59 +/- 0.15	---- (z = 1510 units)	-$0.67 +/- 0.05	$0.08
4" Diameter Al6061 Sphere	-$0.24 +/- 0.14	---- (z = 1345 units)	-$0.11 +/- 0.05	-$0.13
7" Diameter HDPE Sphere	-$2.84 +/- 0.14	---- (z = 2000 units)	-$2.83 +/- 0.05	-$0.01
7" Diameter Al6061 Sphere	-$0.33 +/- 0.14	---- (z = 1450 units)	-$0.37 +/- 0.05	$0.04
4" Diameter HDPE Sphere in $Pb\text{-}B_4C$ Bucket	-$7.05 +/- 0.14	-$6.62 (z = 3575 units => $0.43 adjustment)	-$6.55	-$0.07
4" Diameter Al6061 Sphere in $Pb\text{-}B_4C$ Bucket	-$6.23 +/- 0.14	-$5.88 (z = 3320 units => $0.35 adjustment)	-$5.83	-$0.05

Further Work

- The next task is to relate the full core model to the reactivity insertion curve used for pulse setups
- This will require a large number of pulse operations with the reactor in multiple configurations (i.e., different experiment package reactivity)
- Working with ACRR operators to determine accuracy of model predictions

Conclusions

- Experimenters notice a deviation between predicted and measured reactivity of experiment packages for large movements of the control rod bank.
  - The deviation is consistent and has been characterized for control rod bank withdrawals greater than 2250 rod units.
- Pulse operation setups are based on the experimentally determined control rod reactivity curve.
  - Since the total integral reactivity of the control rods is actually significantly less than that predicted by the bootstrap methods, the measured reactivity insertion will yield less reactivity than the control rod calibration curve indicates.
    - This has been experimentally verified (again and again).
  - The results presented here show that the observation of a difference between "static" versus "dynamic" worth are not valid.
    - Prompt excursions show the actual worth (dynamic worth) of the transient rods.
    - Static worth determinations suffer the limitation of being measured against a bootstrap determination of the control rod calibration curve.

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QUESTIONS/COMMENTS