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Initial Verification and Validation of RAZORBACK – A Research Reactor Transient Analysis Code

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Abstract

This report describes the work and results of the initial verification and validation (V&V) of the beta release of the Razorback code. Razorback is a computer code designed to simulate the operation of a research reactor (such as the Annular Core Research Reactor (ACRR)) by a coupled numerical solution of the point reactor kinetics equations, the energy conservation equation for fuel element heat transfer, and the mass, momentum, and energy conservation equations for the water cooling of the fuel elements. This initial V&V effort was intended to confirm that the code work to-date shows good agreement between simulation and actual ACRR operations, indicating that the subsequent V&V effort for the official release of the code will be successful.

ACKNOWLEDGMENTS

The author would like to thank the operations staff of the Annular Core Research Reactor for providing the data and log sheets for the pulse operations, installing the spare instrumented element, and executing the power stepdown operation used in this report. In addition, the author would like to thank Gerald Naranjo for his invaluable help in setting up the data acquisition equipment for the power stepdown operation.

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NOMENCLATURE

ACRR	Annular Core Research Reactor
$BeO-UO_2$	Beryllium Oxide-Uranium Dioxide
DOE	Department of Energy
DSA	Documented Safety Analysis
FWHM	Full Width at Half-Maximum
LEHM	Leading Edge (Width) at Half-Maximum
RHU	Rod Holdup
SNL	Sandia National Laboratories
TEHM	Trailing Edge (Width) at Half-Maximum
TR	Transient Rod
TRW	Transient Rod Withdrawal
V&V	Verification and Validation
ρ	Reactivity
$	Dollar (a unit of reactivity)

1. INTRODUCTION

1.1. Background

Razorback is a computer code designed to simulate the operation of a research reactor (such as the Annular Core Research Reactor (ACRR)) by a coupled numerical solution of the point reactor kinetics equations, the energy conservation equation for fuel element heat transfer, and the mass, momentum, and energy conservation equations for the water cooling of the fuel elements. Razorback is intended for eventual use for analyses related to the ACRR Documented Safety Analysis (DSA). As such, it is necessary that the code be verified to be solving these equations correctly, and also have its predictive results validated against data collected from actual ACRR operation.

1.2. Purpose and Scope

The purpose of this report is to document the work done to verify and validate the initial beta release of the Razorback code. This work is not intended to be complete or exhaustive, nor is it intended to be the "final" verification and validation (V&V) for the code which will be released for DSA use. Rather, this V&V of the beta release is intended to provide confidence that the code at this stage of development is moving towards producing acceptable results, and to identify areas for improvement and/or corrective development of its use, application, and solution methodology.

The scope of the verification and validation (V&V) includes addressing analytical solutions as well as data collected under normal operating conditions of the ACRR. The RAZORBACK code can be used to simulate ACRR steady-state, pulse, transient rod withdrawal (TRW), and general operational transient operation. Limitations on its current application include conditions after fuel element materials are considered as failed (i.e., melting, or plastic deformation), or once boiling conditions are attained in the coolant channel.

1.3. Approach

The V&V is accomplished in five areas: (1) comparison to analytical solutions, (2) comparison to ACRR pulse operations, (3) comparison to ACRR TRW operations, (4) comparison to ACRR steady-state operation, and (5) comparison to a general ACRR transient operation. The comparison to analytical solutions will verify that the relevant physical models (i.e., equations) have been properly implemented within Razorback, and are providing a correct solution of those equations. The comparison to pulse operations will determine the validity of the coupled reactor kinetics and thermal-hydraulic solutions implemented within Razorback for simulating large rapid reactivity additions at the ACRR. The comparison to TRW and general ACRR transient operations will determine the validity of the coupled reactor kinetics and thermal-hydraulic solutions implemented within Razorback for simulating general ACRR operation. The comparison to ACRR steady-state operation will determine the validity of the thermal-hydraulic solution implemented within Razorback for determining the temperature conditions within an ACRR fuel element for normal operating conditions.

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2. GENERAL OVERVIEW OF THE RAZORBACK ACRR MODEL

This section provides a high level discussion of the input data pertinent to the validation modeling of the ACRR presented in this report. A sample input file is included in Appendix A.

2.1. Reactor Kinetics

The reactor kinetics model consists of the point reactor kinetics equations (see Ref. 1) using six delayed neutron precursor groups. A neutron generation time of 25.5 μs (Ref. 2) was selected, along with a total delayed neutron fraction of 0.0073 (Ref. 3). The delayed neutron group parameters (group decay constants and production fraction) used are shown in Table 1. These values are from Keepin (Ref. 4), and were used as a carryover of inputs for previous work with PK1D (Ref. 5) analyses of the ACRR. These data are actually for fast fission, where data related to thermal fission would be more suitable for the ACRR. Further, data which also addresses the photoneutron contribution from the BeO would be even more suitable. The selection of more suitable delayed neutron group data should be addressed in the final V&V report.

Table 1. Reactor Kinetics Delayed Neutron Precursor Group Parameters Used.

Delayed Neutron Group	Group Decay Constant λ_i (s^{-1})	Group Fraction β_i
1	1.27×10^{-2}	2.77×10^{-4}
2	3.17×10^{-2}	1.5549×10^{-3}
3	1.15×10^{-1}	1.3724×10^{-3}
4	3.10×10^{-1}	2.9711×10^{-3}
5	1.40	9.344×10^{-4}
6	3.87	1.898×10^{-4}

2.2. Reactivity Control Systems

The differential reactivity worth curve for the TR bank is input to Razorback in the form

$$\frac{d\rho}{dz} = Asin^2\left[B\left(z - z_o\right) + C\right]$$

Where it is noted that the "A" coefficient is normalized to a total TR bank worth, which is a separate input. The values used for A, B, C, and z_o may be determined from TR bank worth calibration operations or a suitable neutronics codes (e.g., MCNP). For pulse simulations, the coefficients were based on 2011 TR bank worth calibration data (since that was the time of the pulse operations which were to be simulated for this report). The coefficients/constants are shown in Table 2. For simulation of TRW operations, a TR bank differential worth curve was determined using MCNP, and the resulting coefficients/constants are also shown in Table 2.

Table 2. Transient Rod Bank Differential Worth Input Parameters.

Pulse Simulation Inputs		TRW Simulation Inputs	
A	0.0278812	A	0.029823
B	0.0438084	B	0.046813
C	-0.225591	C	-0.002728
z_o	--[a]	z_o	13.0
TR Bank Worth	\$4.45		\$4.290

a. Not used for pulse simulations.

The basis for using different worth curves is that the TR bank worth calibration is performed by incrementally inserting the TR bank and using the controls rods to re-establish a delayed critical condition. The reactivity worth difference based on the before and after control rod bank positions is considered to be the TR bank reactivity worth difference for that incremental insertion. This bank tradeoff methodology mirrors the manner in which a pulse operation of a given worth is set up. Thus, the relative positions of the control rod and TR banks will be essentially as they are when a pulse operation is set up. As for a TRW operation, the TR bank total worth varies with control rod bank position, and as such the TR bank worth curve will be different with different control rod bank positions. For the TRW operations simulated herein, the control rod bank position was at ~26.5 cm. Thus, a TR bank worth curve determined using MCNP with the control rod bank at 27.50 cm was used for the TRW operation simulations.

To simulate a pulse operation, there are timing issues which must be addressed. First, an actual pulse operation will initiate TR ejection after an initial delay time programmed by the reactor operator in the pulse countdown timer program. This value has typically been set at 165 ms. Thus, the Razorback input herein was set to account for this initial time delay. Additionally, once the 165 ms is attained, there is a delay associated with how quickly the valve which admits high pressure nitrogen to the TR ejection mechanism can open. This delay time is also an input to the Razorback simulation of a pulse. At this point, Razorback determines the acceleration of the TR rod bank based on the input nitrogen pressure, piston area, and TR mass. The pressure was obtained from ACRR operations (65 psig). The piston area (28.96 cm^2) was determined from the piston drawing.[1] The TR mass (13.75 kg) was set based on past measurements of TR position vs. time data. The valve opening delay time was set at a value for which the simulated pulse peak time approximately matched the measured pulse peak time (for the pulse to be simulated).

Lastly, the ACRR pulse operation system sets a "rod holdup time" (RHU). The RHU time value (0.4 seconds for the pulses being simulated) is the time (from t=0) at which a gravity drop of the transient rods, safety rods, and control rods will be initiated. At this point in the pulse simulation, Razorback will initiate all rods dropping after a simulated electric circuit delay (set using the "Scram Delay Time" input), and the downward acceleration of the rods will be determined assuming that the rods would fall by 55.00 cm over the input "Rod Fall Time." The inputs selected (50 ms scram delay time, and 500 ms rod fall time) were set to attain the impact of the rod drops on the simulated pulse tails.

[1] Automated Concepts Inc. Drawing 2062M205, Rev. A.

2.3. Fuel Element

The fuel element model for the ACRR was defined using the dimensions from ACRR drawings. The model explicitly includes the BeO-UO_2 fuel pellets (inner and outer), the niobium fuel cups, the stainless steel cladding, and the gaps (helium filled) between the fuel pellets, niobium, and cladding. The model dimensions are shown in Table 3. The energy deposition factors were determined using MCNP. Razorback input was set such that radial thermal expansion of the fuel element materials was computed, and radiation heat transfer across the helium filled gaps was computed.

Table 3. Fuel Element Model Dimensions.

Material	Inner Radius (cm)	Outer Radius (cm)	Number of Nodes	Energy Deposition Fraction
BeO-UO_2	0.24130	1.09982	10	0.97846[a]
He	1.09982	1.11760	10	0.0
BeO-UO_2	1.11760	1.68402	10	0.97846[a]
He	1.68402	1.73228	10	0.0
Nb	1.73228	1.77038	10	0.00400
He	1.77038	1.82245	10	0.00
SS-304	1.82245	1.87325	10	0.00456

a. As currently configured in Razorback, the energy deposition factor (EDF) applies to the material, and not to the zone. Thus, 97.846% of the energy deposition is in the BeO-UO_2 material. This is simply an artifact of using a single fuel pellet (vs. two pellets separated by a small gap) in the MCNP model used to compute the EDFs. This approach may be revised in future versions for increased generality.

The radial fission density peaking distribution across the BeO-UO_2 fuel pellet in Razorback is of the form

$$f(r) = Ae^{B \cdot r} + C$$

Values used for A, B, and C are given in Table 4 (Ref. 6).

The axial fission density peaking distribution over the length of the fuel element in Razorback is of the form

$$f(z) = \sum_{i=0}^{6} a_i \left(\frac{z}{H}\right)^i$$

where H is the height of the fuel stack. Values used for the polynomial coefficients are shown in Table 4 (Ref. 6).

Table 4. Pellet Radial and Element Axial Peaking Distribution Parameters.

Fuel Pellet Radial Distribution Coefficients		Fuel Axial Distribution Coefficients	
A	0.0157	a_0	0.7721
B	1.9370 cm^{-1}	a_1	-0.6252
C	0.8211	a_2	24.0903
		a_3	-89.6026
		a_4	141.5383
		a_5	-108.8048
		a_6	33.1631

2.4. Coolant Channel

The coolant channel is the active fuel height (52.25 cm), and the flow wetted perimeter and area based upon the element diameter (3.747 cm), and the hexagonal pitch (4.171 cm) of the element grid.

2.5. Reactivity Feedback

Razorback utilizes five reactivity feedback mechanisms that compensate for control system reactivity inputs which are determined from MCNP calculations:

- Fuel temperature: representing the Doppler broadening of the fuel absorption cross section.
- Fuel expansion: representing the local fuel density change, as well as the outer fuel surface area change.
- Cladding expansion: representing the change in local moderator-to-fuel ratio as the coolant channel area changes with clad expansion/contraction.
- Coolant density: representing the change in moderation and absorption as the density of the coolant changes.
- Coolant temperature: representing the change in the local neutron energy spectrum as the coolant temperature changes.

The reactivity feedback coefficient for fuel temperature is given by

$$\frac{d\rho}{dT}fuel = A_{ft} + \frac{B_{ft}}{\sqrt{T_{fuel}}}$$

where T_{fuel} is the absolute temperature. The coefficients are A_{ft} = -0.00139 \$/K and B_{ft} = -0.0743 \$/$K^{0.5}$.

The reactivity feedback coefficient for fuel expansion is given by the summation of two components, where the first component is

$$\frac{d\rho}{dR}^{fuel} = A_{fr} + B_{fr}R_{fuel}$$

where R_{fuel} is the outer radius of the outer fuel pellet. The coefficients are A_{fr} = -4167.724 \$/cm and B_{fr} = 1243.282 \$/cm^2.

The second component of the reactivity feedback coefficient for fuel expansion is given by

$$\frac{d\rho}{d\Delta R}^{fuel} = C_{fr}$$

where ΔR_{fuel} is the overall thickness of the fuel pellets (the gap between the inner and outer pellets is essentially ignored). The coefficient is C_{fr} = 42.786 \$/cm.

The reactivity feedback coefficient for clad expansion is given by the summation of two components, where the first component is

$$\frac{d\rho}{dR}^{clad} = A_{cr}$$

where R_{clad} is the outer radius of the clad. The coefficient is A_{cr} = -115.06 \$/cm.

The second component of the reactivity feedback coefficient for clad expansion is given by

$$\frac{d\rho}{d\Delta R}^{clad} = B_{cr}$$

where ΔR_{clad} is the thickness of the clad. The coefficient is C_{cr} = -100.85 \$/cm.

The coolant density feedback is given as -0.43 \$/%void.[2] The coolant temperature feedback is given as -0.0014 \$/K.

As noted above, these values have been computed using MCNP. However, the MCNP runs and resulting reactivity coefficients have not been formally documented as calculation at this stage of Razorback development. The determination of these reactivity coefficients should be formally documented for the use in Razorback for DSA analyses.

[2] The unit "%void" is calculated as $(\rho_o-\rho)/\rho_o*100$, where ρ_o is the initial reference density of the coolant, and ρ is the "current" density of the coolant.

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3. COMPARISON TO ANALYTICAL SOLUTIONS

3.1. Reactor Kinetics

The reactor kinetics model of the code has been evaluated previously in Ref 7. In this previous evaluation, the code was used to simulate benchmark cases for step, ramp, and sinusoidal reactivity additions which were documented in Ref. 8. The code results were in excellent agreement with the benchmark results. Tables 5 through 10 below present selected results from Ref. 7.

Table 5. Point Kinetic Benchmark Evaluation for -$1.0 Step Addition.

Time (s)	Code Result	Benchmark	% Difference
0.1	5.2049990E-01	5.205642866E-01	-0.012369
1.0	4.3332231E-01	4.333334453E-01	-0.002570
10.0	2.3610794E-01	2.361106508E-01	-0.001148
100.0	2.8667533E-02	2.866764245E-02	-0.000382

Table 6. Point Kinetic Benchmark Evaluation for -$0.5 Step Addition.

Time (s)	Code Result	Benchmark	% Difference
0.1	6.9885920E-01	6.989252256E-01	-0.009447
1.0	6.0704475E-01	6.070535656E-01	-0.001452
10.0	3.9607494E-01	3.960776907E-01	-0.000694
100.0	7.1582682E-02	7.158285444E-02	-0.000241

Table 7. Point Kinetic Benchmark Evaluation for $0.5 Step Addition.

Time (s)	Code Result	Benchmark	% Difference
0.1	1.5332115E+00	1.533112646E+00	0.006448
1.0	2.5115239E+00	2.511494291E+00	0.001179
10.0	1.4215038E+01	1.421502524E+01	0.000090
100.0	8.0060942E+07	8.006143562E+07	-0.000617

Table 8. Point Kinetic Benchmark Evaluation for $1.0 Step Addition.

Time (s)	Code Result	Benchmark	% Difference
0.1	2.5158849E+00	2.515766141E+00	0.004721
0.5	1.0362726E+01	1.036253381E+01	0.001855
1.0	3.2183405E+01	3.218354095E+01	-0.000422
10.0	3.2469217E+09	3.246978898E+09	-0.001762
100.0	---*	2.596484646E+89	---*

*Run terminated shortly after 10.0 seconds due to prohibitively slow run time.

Table 9. Point Kinetic Benchmark Evaluation for $0.1/s Ramp Addition.

Time (s)	Code Result	Benchmark	% Difference
2.00	1.3382200E+00	1.338200050E+00	0.001491
4.00	2.2284412E+00	2.228441897E+00	-0.000031
6.00	5.5818737E+00	5.582052449E+00	-0.003202
8.00	4.2780238E+01	4.278629573E+01	-0.014158
10.00	4.5061295E+05	4.511636239E+05	-0.122056
11.00	1.7852862E+16	1.792213607E+16	-0.386528

Table 10. Point Kinetic Benchmark Evaluation for $2.0 Step Addition with Feedback.

Time (s)	Code Result	Benchmark	% Difference
10.0	1.0338084E+02	1.033808535E+02	-0.000013
20.0	3.9138865E+01	3.913886903E+01	-0.000010
30.0	2.2003775E+01	2.200377721E+01	-0.000010
40.0	1.4493671E+01	1.449367193E+01	-0.000006
50.0	1.0318610E+01	1.031861108E+01	-0.000010
60.0	7.6633185E+00	7.663319203E+00	-0.000009
70.0	5.8293948E+00	5.829395378E+00	-0.000010
80.0	4.4994266E+00	4.499427073E+00	-0.000011
90.0	3.5074223E+00	3.507422663E+00	-0.000010
100.0	2.7551266E+00	2.755126886E+00	-0.000010

3.2. Fuel Element Heat Transfer

A comparison of the peak measured reactor power from the ACRR's Diagnostic System and those predicted by Razorback are shown in Table 1. The Razorback values are obtained from simulations using the nominal worth as input. Figure 5 displays the results in Table 1 graphically.

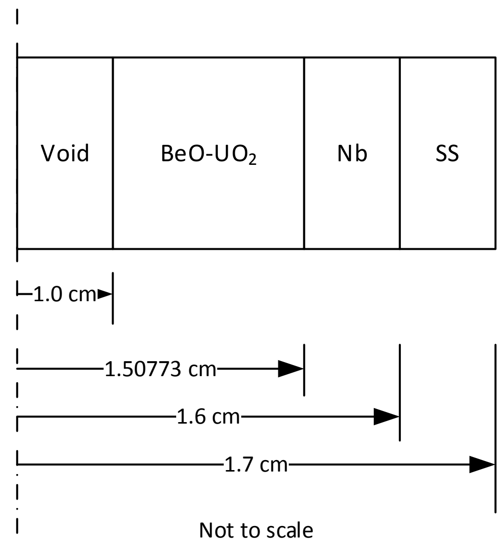

Figure 1. Schematic of Fuel Element for Analytical Verification.

To facilitate an analytical solution, the thermal conductivities of the materials were set at constant (non-temperature dependent) values of 0.16 W/cm-K, 0.5 W/cm-K, and 0.2 W/cm-K for the $BeO\text{-}UO_2$, niobium, and stainless steel, respectively. The inner radius boundary condition is a zero temperature gradient (zero net heat flux/symmetry), and the outer radius boundary condition was a constant 120°C surface temperature.

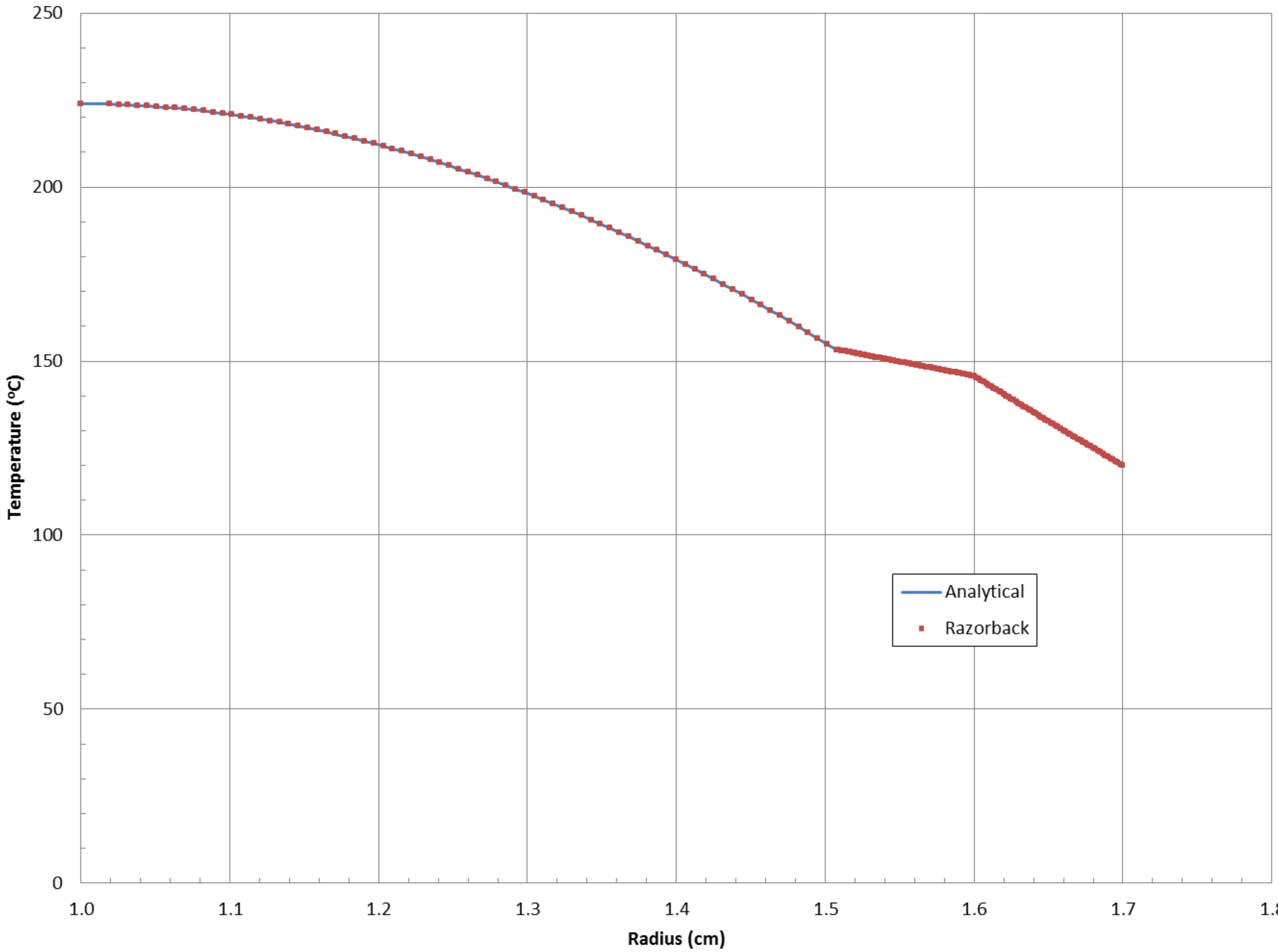

Figure 2. Razorback Fuel Element Temperature vs. an Analytical Result.

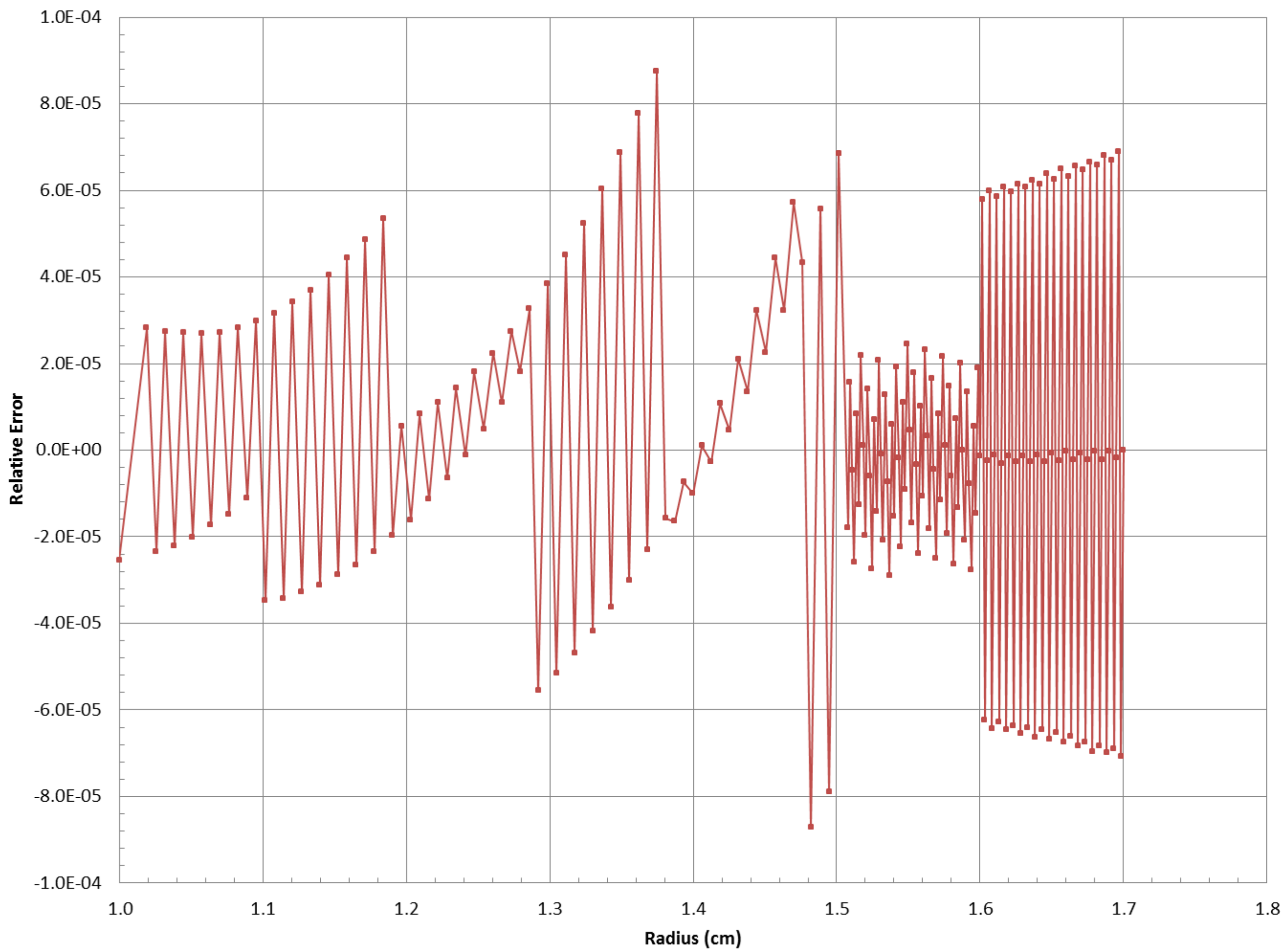

Figure 3. Relative Error of Fuel Temperature Prediction and Analytical Solution.

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4. COMPARISON TO ACRR PULSE OPERATIONS

Razorback was run to simulate the pulse operations 9716, 9718, 9719, and 9720 which were annual calibration pulses performed in January 2011. These were, respectively, nominal \$1.50, \$2.00, \$2.50, and \$3.00 pulse operations. The data from these 2011 operations were selected because the necessary data files (i.e., the pulse diagnostic report and the console log report) were available on the ACRR "Z" drive. Excerpts from the pulse diagnostic reports and the console log reports are included in Appendix B.

It must be noted that the Diagnostic System used to measure and evaluate pulse operations is not a formally calibrated system. The sensitivities (e.g., nA/MW) of the self-powered neutron detectors (SPND) have been calibrated to ACRR power operation in the past (Ref. 9), but that practice no longer continues. Instead, the sensitivities are adjusted regularly so that reactor yield via the SPNDs matches the yield determined by exposure of dosimetry in the ACRR's central cavity. There is a report which documents reasonable agreement of the reactor yield determined by the Diagnostic System with dosimetry measurements (Ref. 12). While the Diagnostic System data is the only available data for comparison of pulse and TRW operations, and is believed to reasonably characterize the performance of the ACRR, work is clearly needed to provide a documented calibration basis for the results.

The Razorback values are obtained from simulations using the nominal worth as input. Specifically, a Transient Rod bank initial position was selected to achieve the desired pulse reactivity worth, and Razorback was run. If the desired total reactivity worth was not achieved, then the initial Transient Rod bank position was changed, and Razorback was run again. Once the desired reactivity worth was achieved, then the Razorback simulation was "officially" run.

Actual ACRR pulse operations do not pneumatically eject the transient rods at t=0. Rather, the ejection of the transient rods is set to occur at a prescribed time delay (typically on the order of 130-170 ms after time zero). After this prescribed delay time, another time delay occurs associated with the time required for the opening of the valves which provide the pressurized nitrogen gas which drives the transient rods upward.

The ACRR pulse were performed in Pulse Reduced Tail mode (i.e., after a preset Rod Hold Up (RHU) time, the control, safety, and transient rod banks are dropped from their current positions). As such, the Pulse Reduced Tail mode was selected in the Razorback simulations. The RHU time functions essentially as a scram signal for the ACRR to initiate dropping of the control, safety, and transient rods to shut down the reactor. In its simulation, Razorback accounts for a scram delay time (a time delay in the electrical circuitry of the scram system between the initial scram signal, and the initiation of dropping rods). A value of 50 ms is used in the pulse simulations. Razorback also accounts for the time required for the rods to fall from a full up position. The simulations here utilize a value of 0.5 seconds, which was selected to reasonably fit the power tail decay.

Figures 4 through 11 show the results of the Razorback simulations superimposed on the ACRR Diagnostic System power measurement channel results. The timing of the transient rod ejection in the simulations (i.e., the initial pulse start time and nitrogen valve delay time) were set in the

Razorback input so that the resulting times of the pulse peaks would match the ACRR data. This allows for a time-matched comparison of the power traces when plotted on the same time scale. More importantly, it also ensures that the RHU time in the simulation functions as it would at the ACRR.

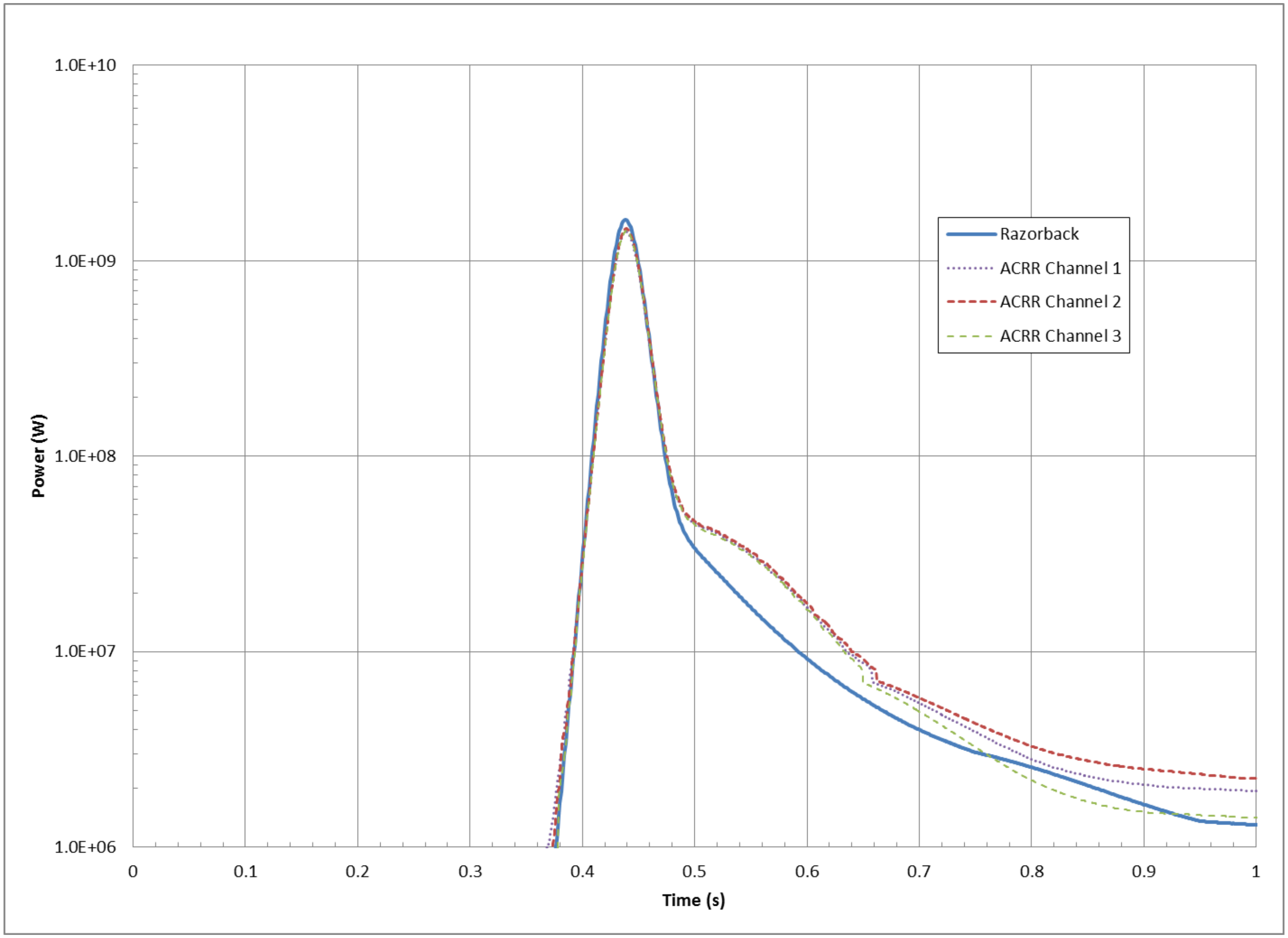

Figure 4. Razorback Simulation of a $1.50 Pulse Operation (#9720).

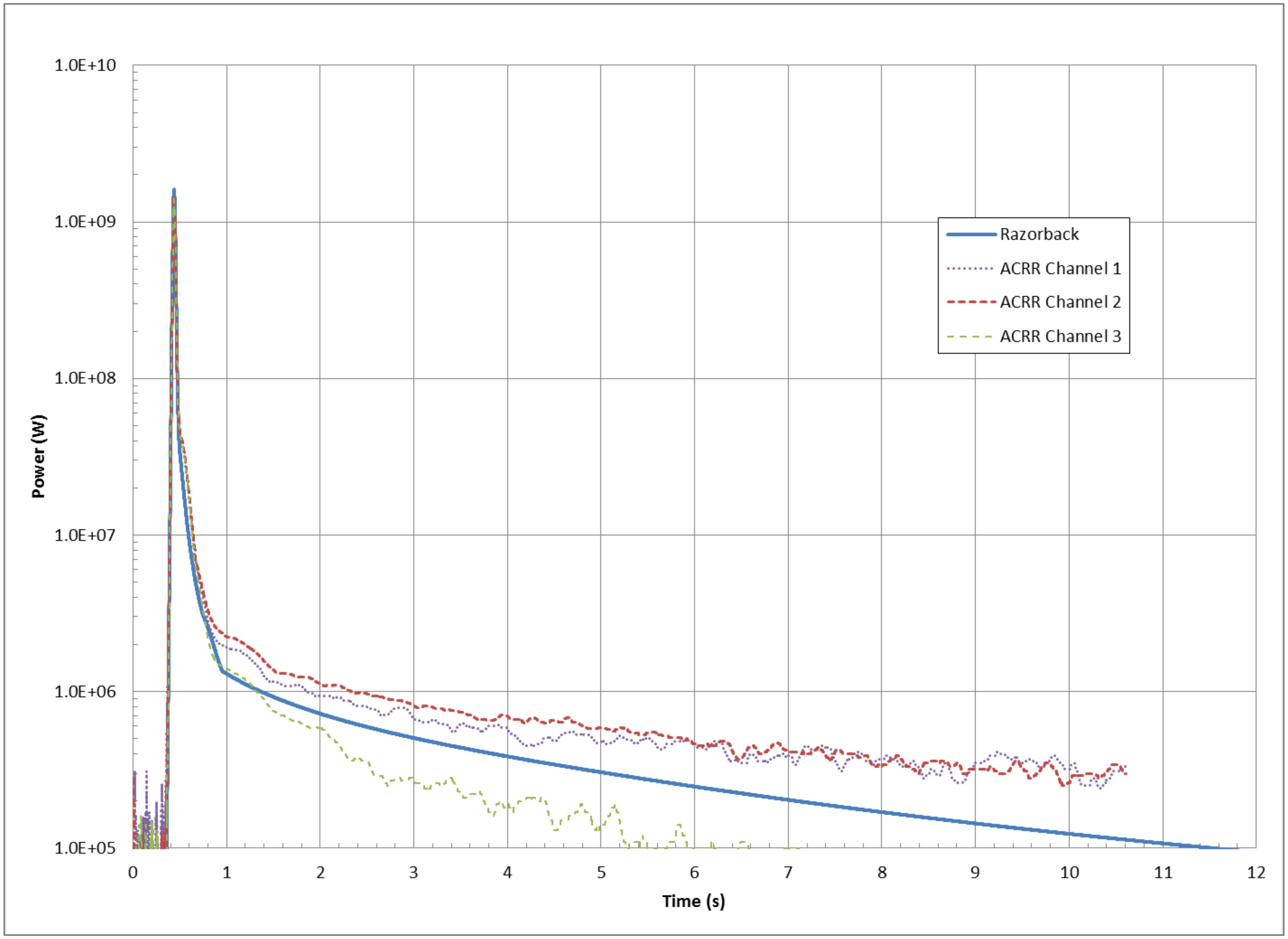

Figure 5. Razorback Simulation of a $1.50 Pulse Operation (#9720) Showing the Pulse Tail.

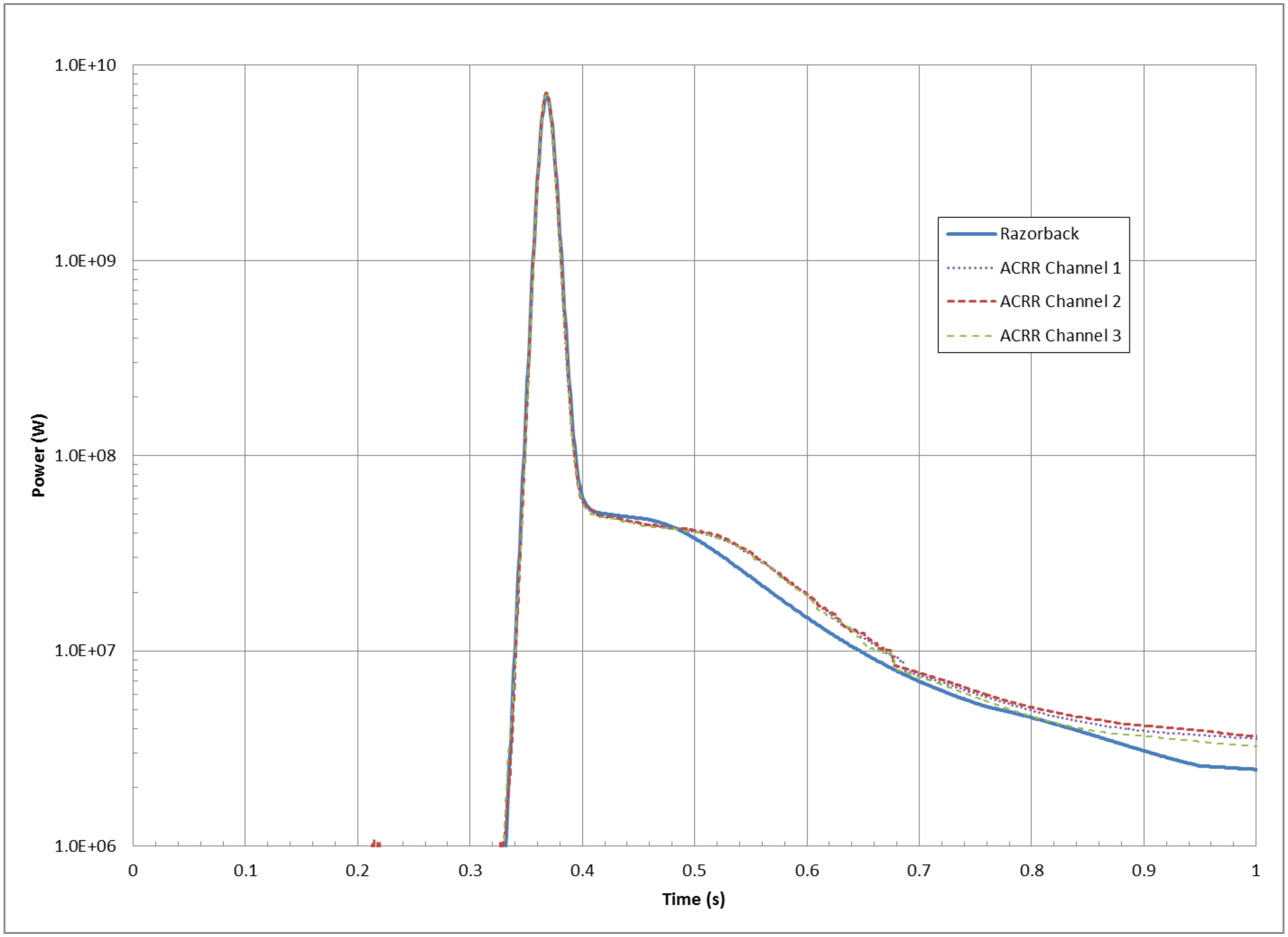

Figure 6. Razorback Simulation of a $2.00 Pulse Operation (#9719).

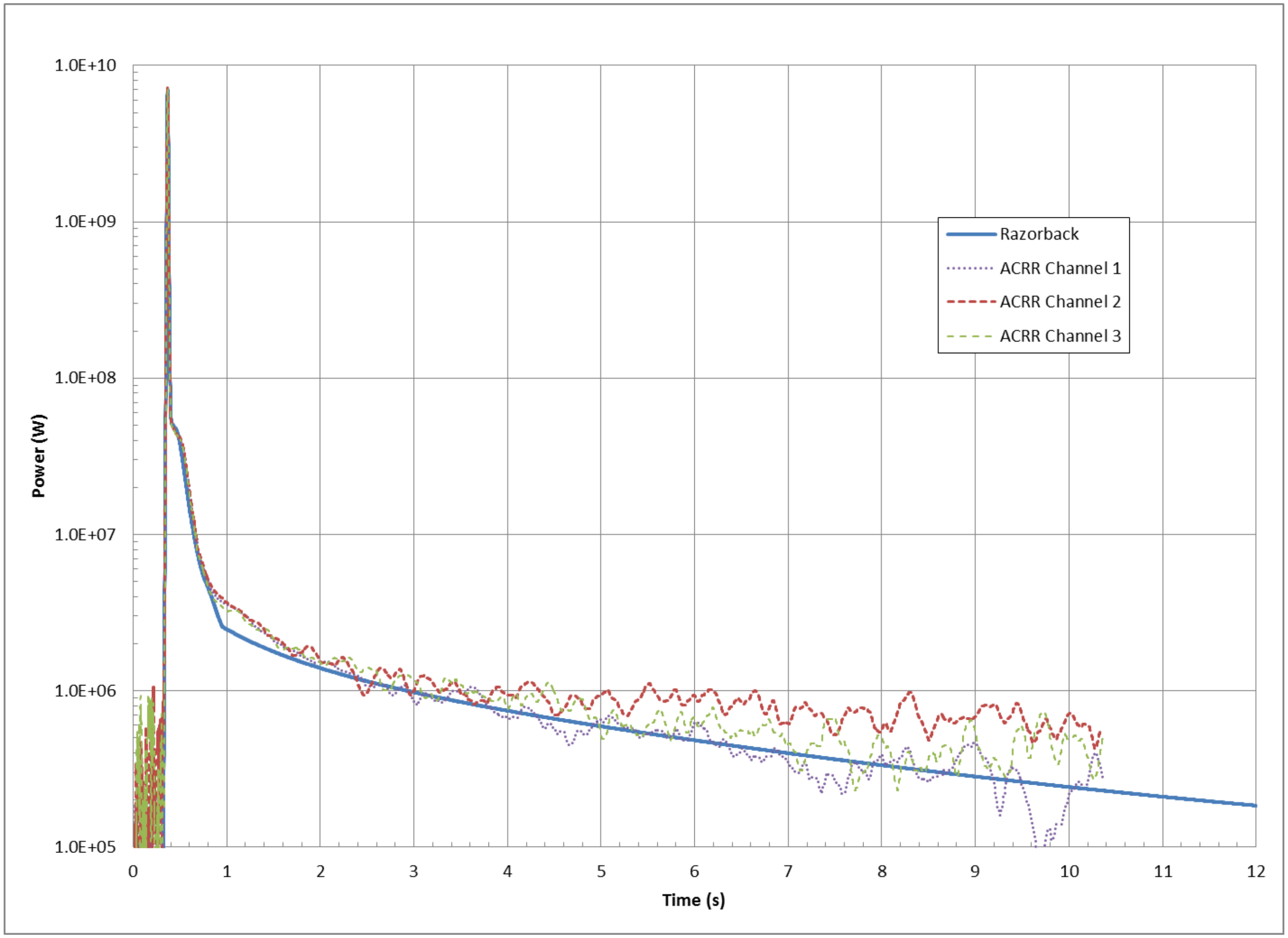

Figure 7. Razorback Simulation of a $2.00 Pulse Operation (#9719) Showing the Pulse Tail.

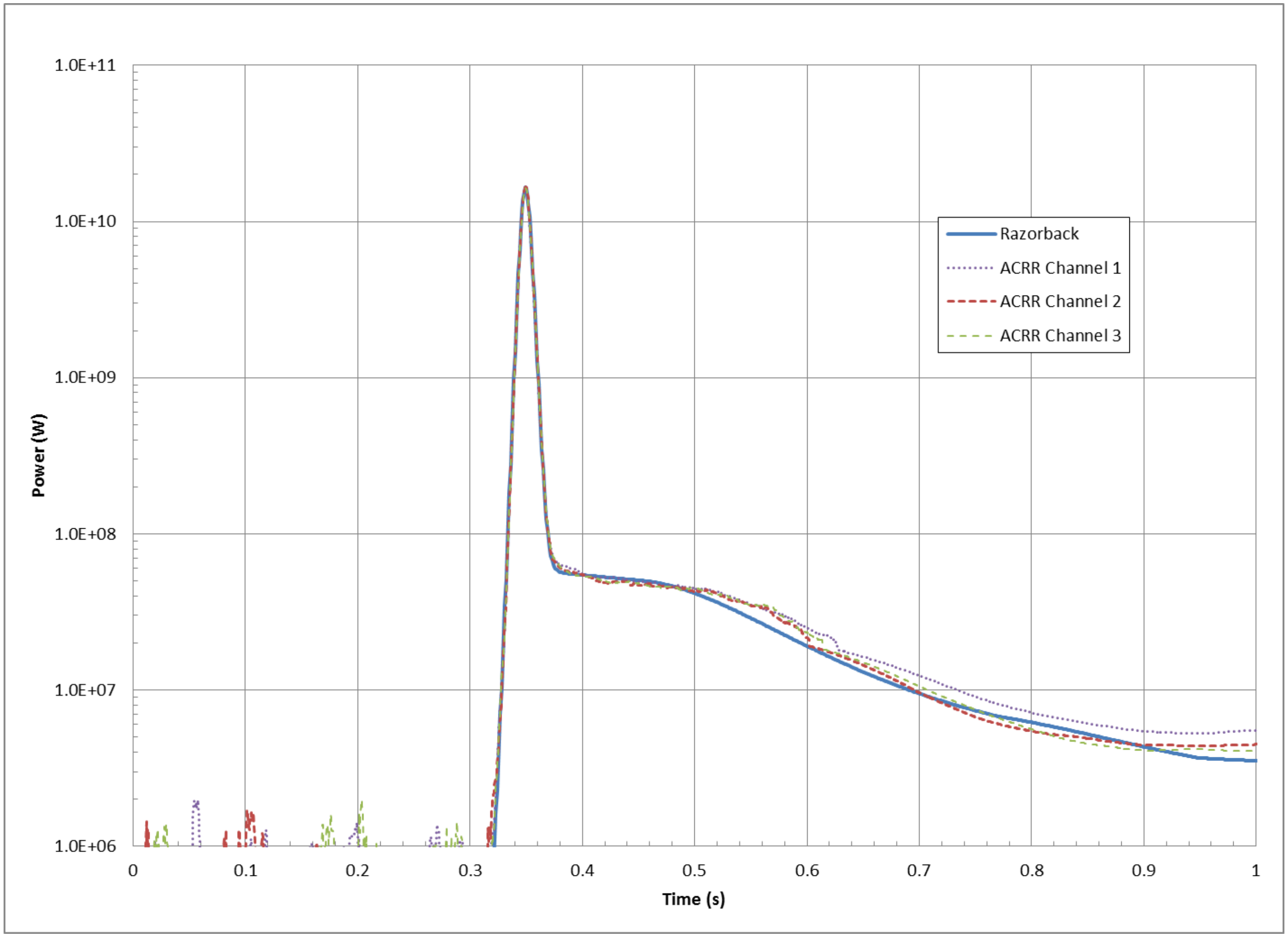

Figure 8. Razorback Simulation of a $2.50 Pulse Operation (#9718).

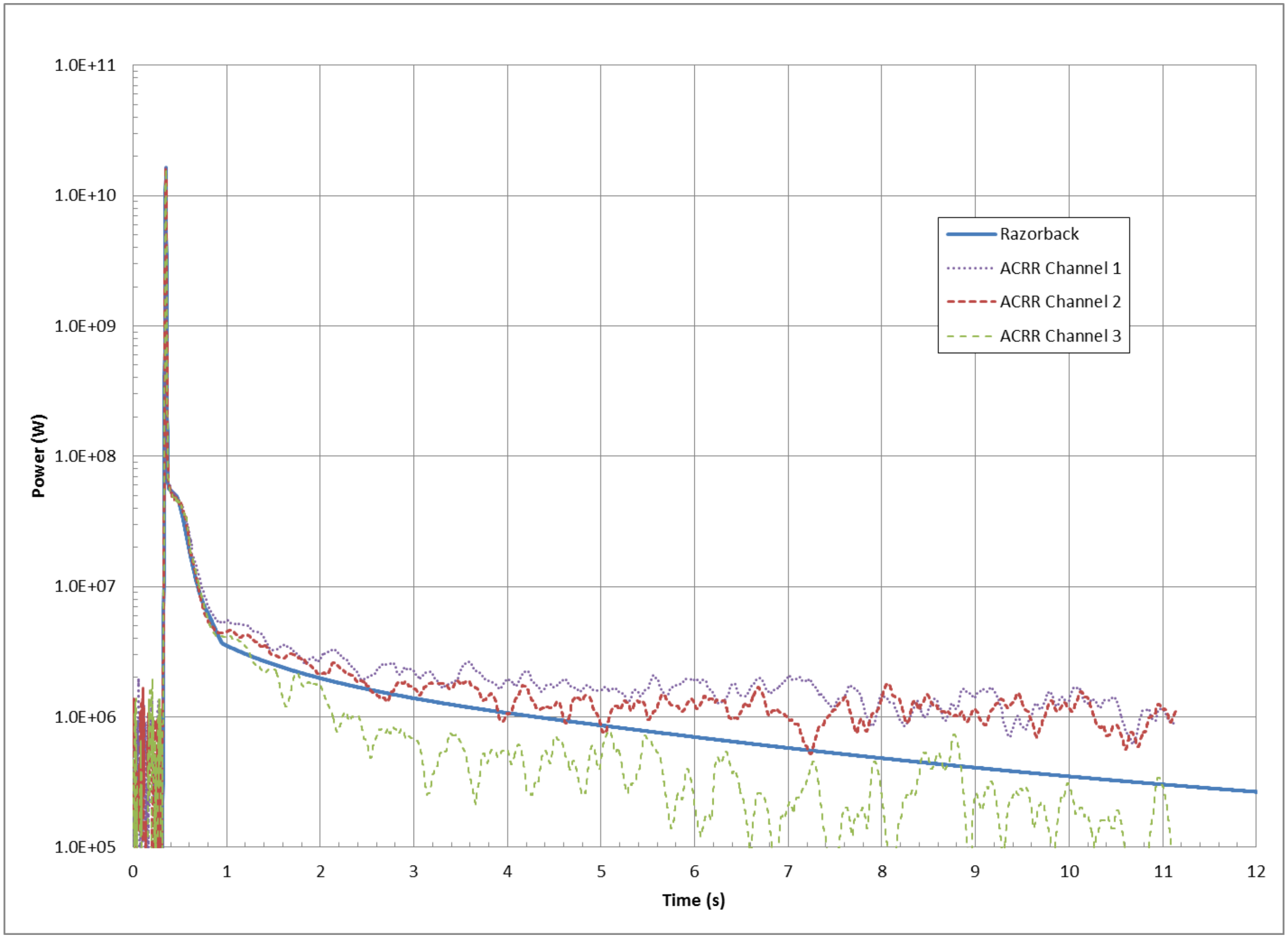

Figure 9. Razorback Simulation of a $2.50 Pulse Operation (#9718) Showing the Pulse Tail.

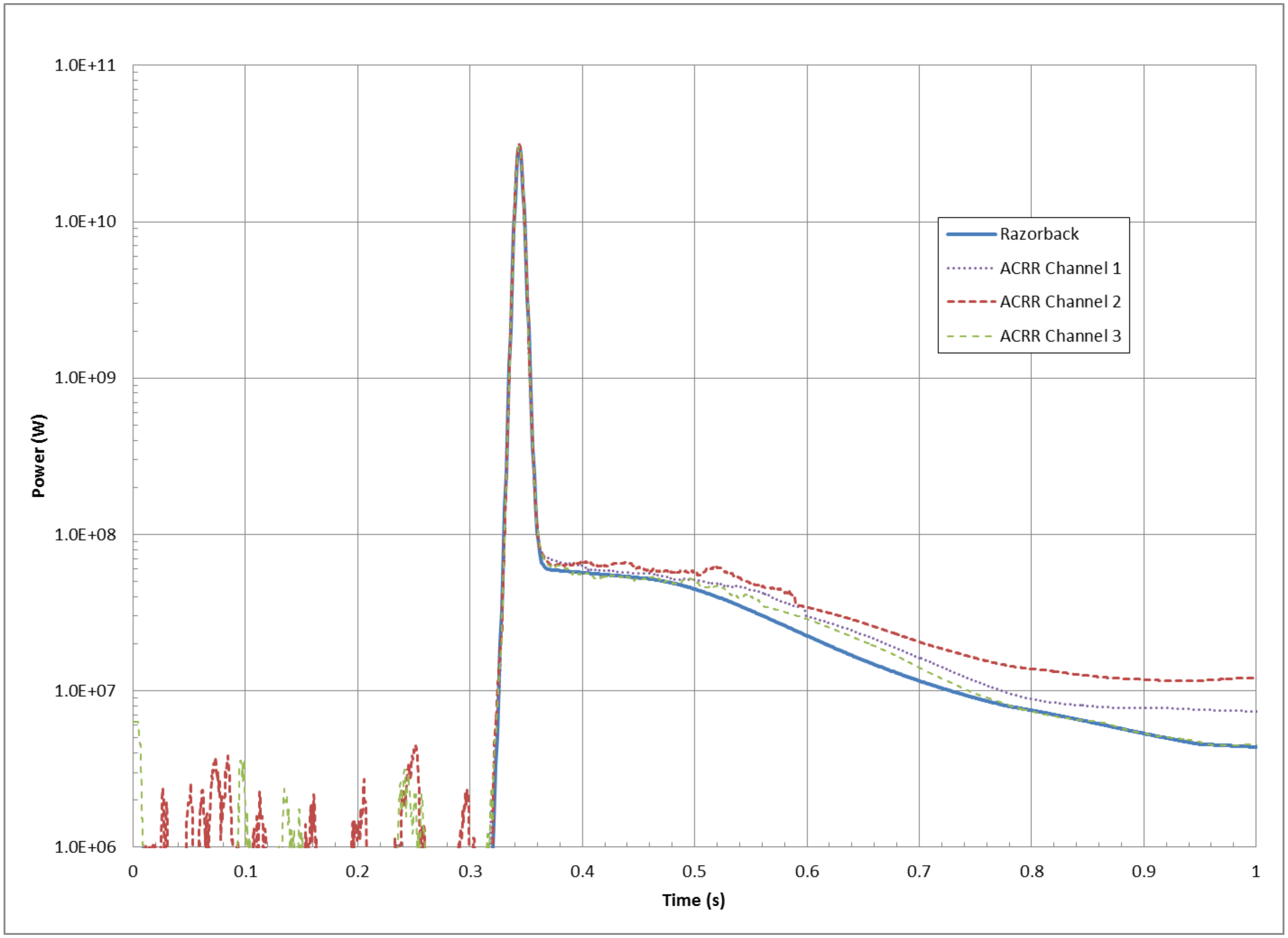

Figure 10. Razorback Simulation of a $3.00 Pulse Operation (#9716).

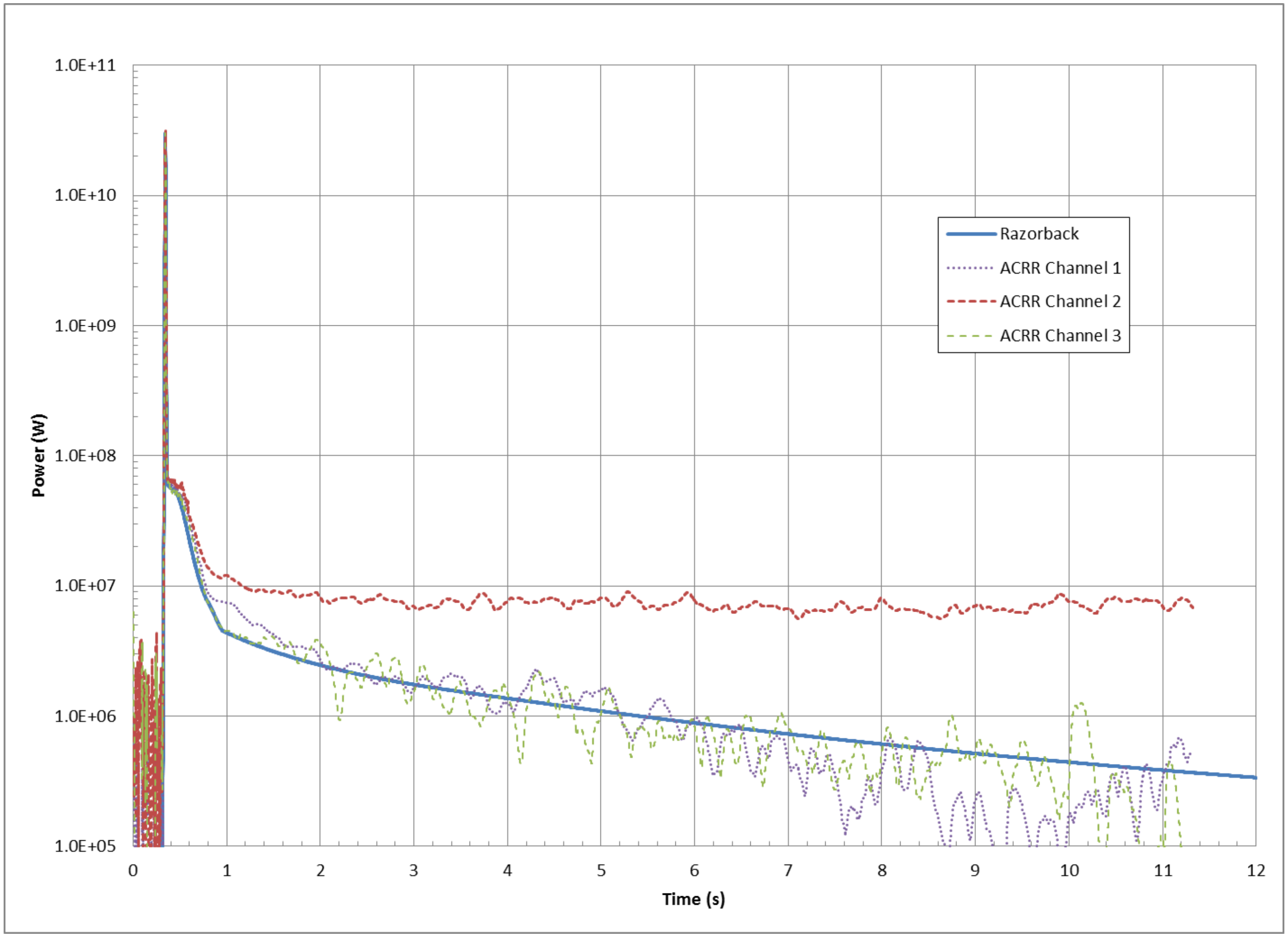

Figure 11. Razorback Simulation of a $3.00 Pulse Operation (#9716) Showing the Pulse Tail.

4.1. Predicted Reactor Peak Power

A comparison of the peak measured reactor power from the ACRR's Diagnostic System and those predicted by Razorback are shown in Table 11. Figure 12 displays the results in Table 1 graphically. Good agreement is seen for the $2.00 and higher pulses. The reason for the larger discrepancy for the $1.50 pulse is not currently known.

Table 11. Reactor Peak Power Comparison for Pulse Operations.

RUN #	9720	9719	9718	9716
Pulse Size ($) (nominal)	1.50	2.00	2.50	3.00
ACRR Diagnostic System Peak Power (GW)[a]	1.4	7.1	16.4	30.8[b]
Razorback Peak Power (GW)	1.62	6.95	16.60	30.19
Deviation (%)	13.3%	-2.1%	1.2%	-2.0%

a. The Diagnostic System records power level from three channels. The peak power reported here is the average of the peaks for Channels 1, 2 and 3.
b. The Channel 1 signal was clipped in this operation, so the value here is the average of the peaks for Channels 2 and 3.

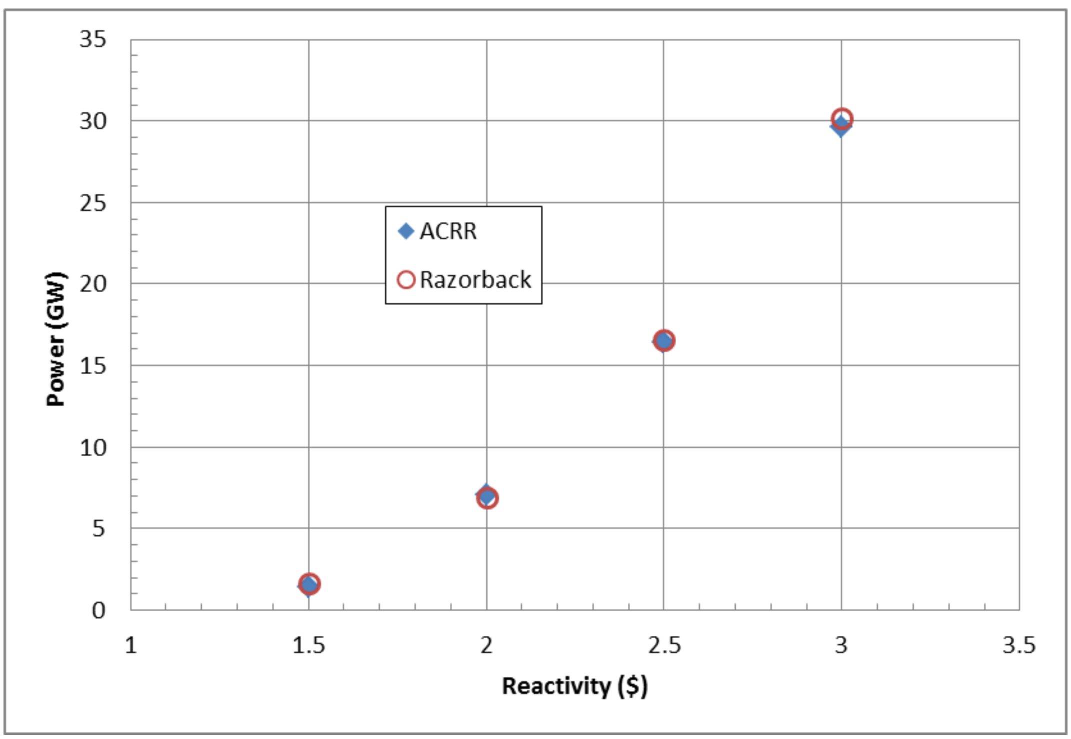

Figure 12. Comparison of Predicted and ACRR Peak Power for Several Pulses.

4.2. Predicted Reactor Yield

The reactor yield parameters used to characterize a pulse at the ACRR are as follows:

- Yield at Peak: This parameter is determined by integrating the pulse power history up to the time of the pulse peak.
- Yield at Peak + 3FWHM: This parameter is determined by integrating the pulse power history up to a time equal to the time of the pulse peak plus three times the FWHM (full width at half-maximum (see Section 4.4)). This time span is intended to result in value which characterizes the energy release of the pulse prior to significant delayed neutron effects.
- Total Yield: This parameter is determined by integrating the pulse power history all the way to the end time of the Diagnostic System data recording. This is typically approximately 12 seconds from time zero for the pulse operation. This time span is intended to result in value which characterizes the total energy release of the pulse including the pulse "tail" which is due to delayed neutron effects.

Figure 13 illustrates the integration timespans for each of these yield parameters.

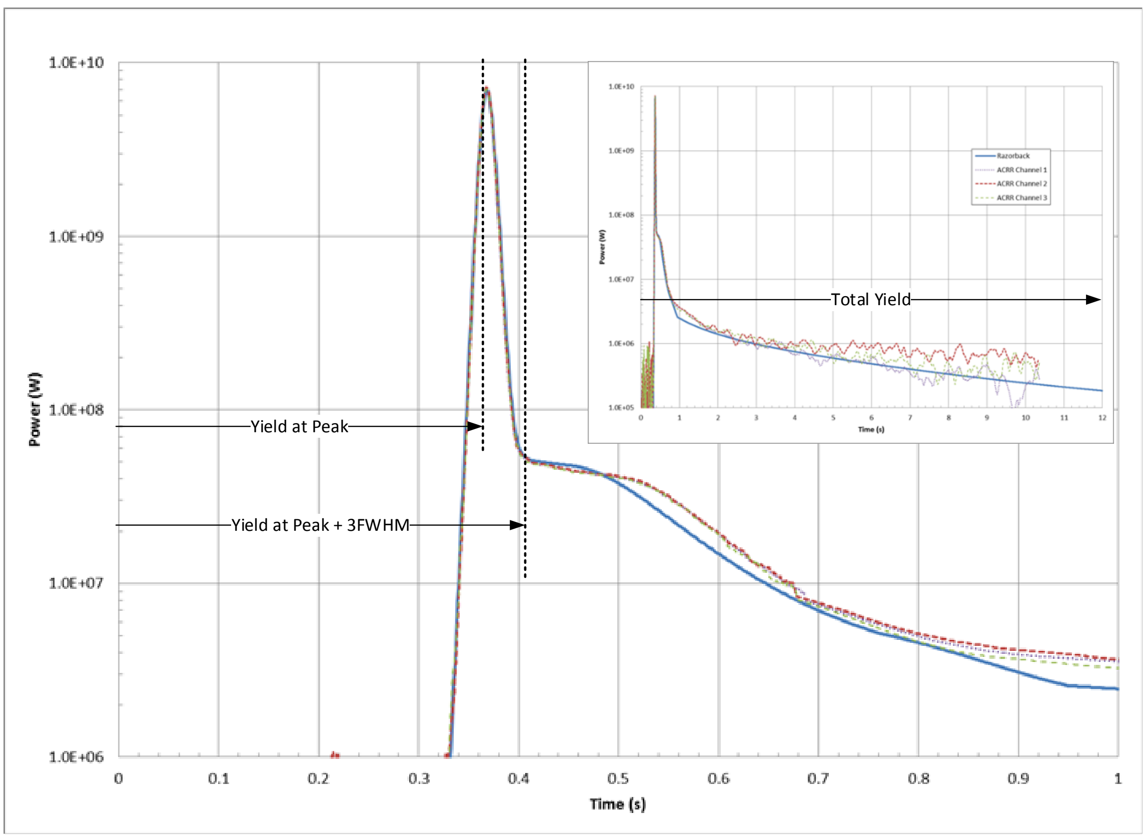

Figure 13. Depiction of the Integration Ranges of the Reactor Yield Parameters.

A comparison of the reactor yield (i.e., the pulse energy release determined by integrating the pulse power history) from the ACRR's Diagnostic System and that predicted by Razorback for the 2011 calibration pulses is shown in Table 12. The Razorback values are obtained from simulations using the nominal worth as input. The results are in reasonable agreement with the ACRR data. It is unclear at this time why the yield at the pulse peak for the $1.50 pulse deviates more than for the other pulse simulations. The deviation for the 3xFWHM yield for the $1.50 pulse may be related to the values used for rod drop delay time, as the peak of the pulse occurs about 40 ms after the RHU time is reached. The discrepancy for the total yield for the $3.00 pulse may be related to the determination of the ACRR tail energy contribution, since Fig. 11 shows that Channel 2 differs significantly from Channels 1 and 3 in the pulse tail timeframe. Figures 14-16 display the results in Table 12 graphically.

Table 12. Reactor Yield Comparison for Pulse Operations.

RUN #	**9720**	**9719**	**9718**	**9716**
Pulse Size ($) (nominal)	1.50	2.00	2.50	3.00
ACRR Diagnostic System				
Yield @ Peak (MJ)	20.9	51.2	81.8	118.5
Yield @ 3xFWHM (MJ)	46.3	107.3	171.7	242.9
Yield @ Total (MJ)	54.9	125.3	201.7	294.1
Razorback				
Yield @ Peak (MJ)	23.7	52.1	83.6	117
Yield @ 3xFWHM (MJ)	50.8	109.3	174.1	240.9
Yield @ Total (MJ)	56.8	125	196	267.4
Deviation				
Deviation @ Peak (%)	13.4%	1.8%	2.2%	-1.3%
Deviation @ 3xFWHM (%)	9.7%	1.9%	1.4%	-0.8%
Deviation @ Total (%)	3.5%	-0.2%	-2.8%	-9.1%

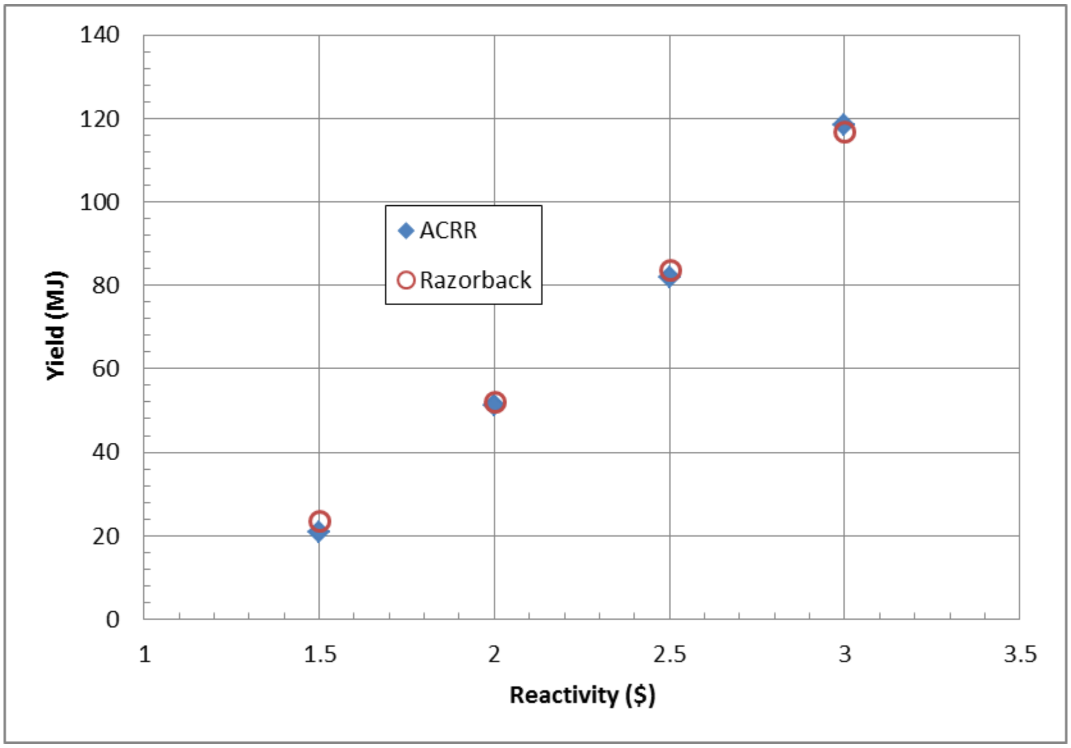

Figure 14. Comparison of Predicted and ACRR Reactor Yield at Pulse Peak for Several Pulses.

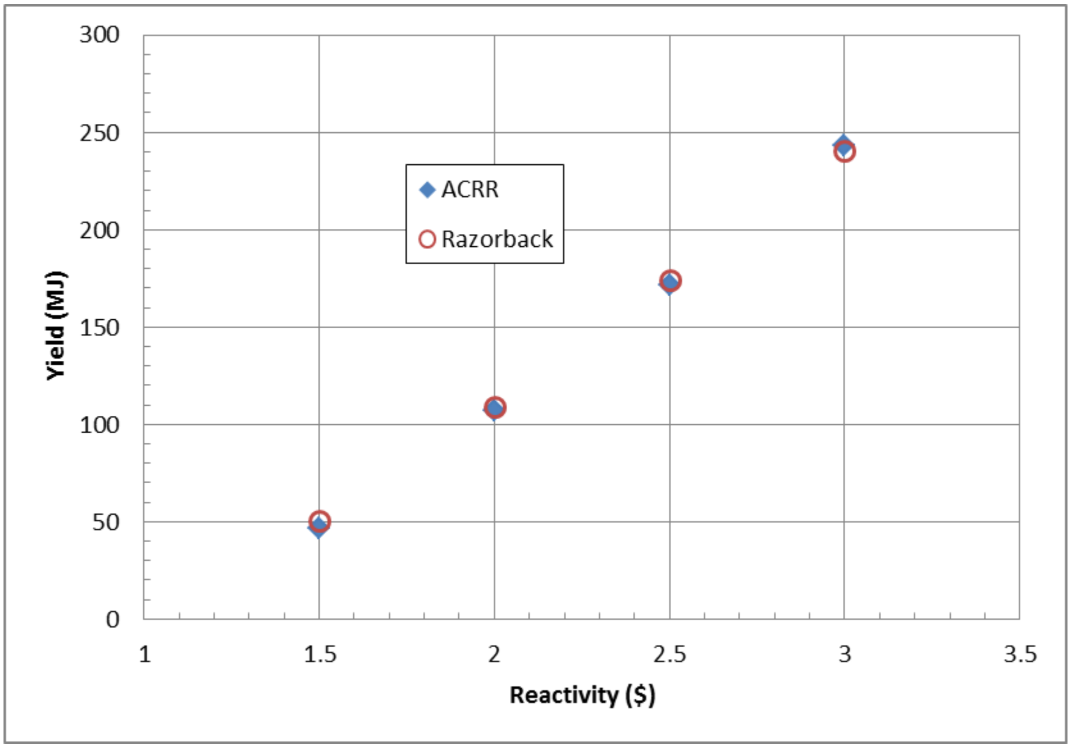

Figure 15. Comparison of Predicted and ACRR Reactor Yield at Peak+3FWHM for Several Pulses.

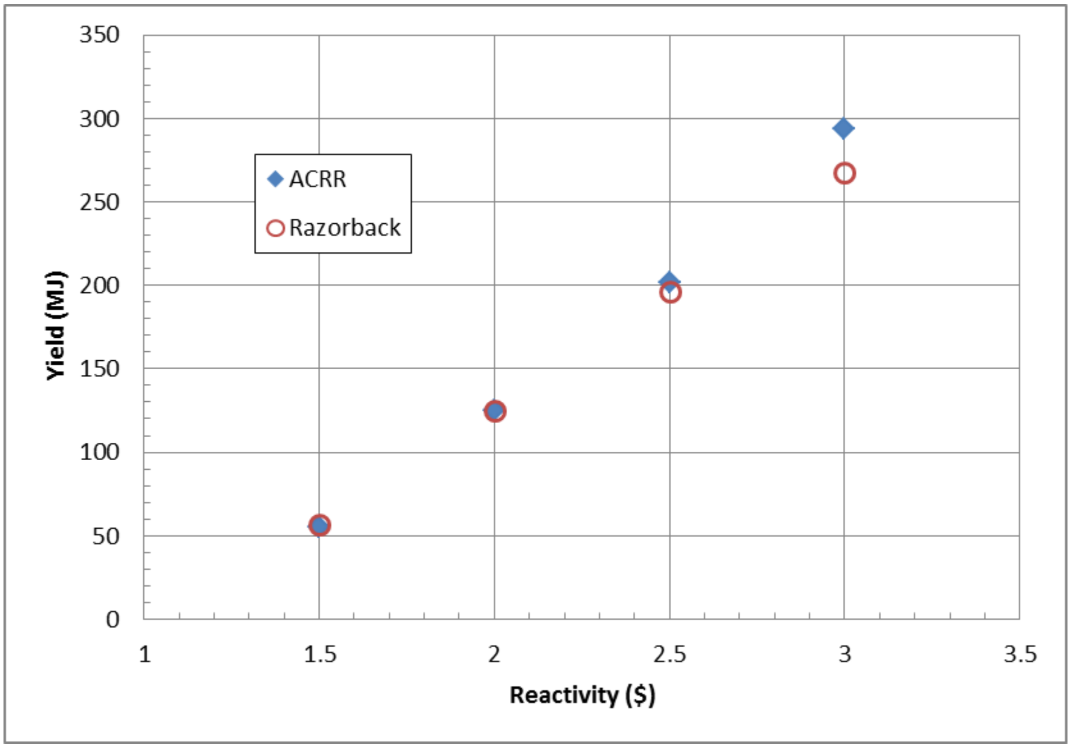

Figure 16. Comparison of Predicted and ACRR Total Reactor Yield for Several Pulses.

4.3. Predicted Fuel Temperatures

A comparison of the peak measured fuel temperatures from the ACRR's Plant Protection System (PPS) and those predicted by Razorback for four pulse operations are shown in Table 13. The temperature input to the PPS is from one of two instrumented fuel elements, each having three thermocouple positioned to measure fuel temperature at the mid-plane of the fuel. The ACRR data below was from the PPS-1 instrumented element in core location 218.

The Razorback temperature values are obtained from simulations using the nominal reactivity worth as input. The "measured" fuel temperature in the Razorback code was set so that the data output was equal to the innermost fuel material node at the mid-plane of the simulated element. The results show Razorback predicting the peak fuel temperatures within 2 to 4% of the PPS instrumented element. Figure 17 displays the results in Table 13 graphically.

Table 13. PPS Peak Fuel Temperature Comparison for Pulse Operations.

RUN #	**9720**	**9719**	**9718**	**9716**
Pulse Size ($) (nominal)	1.50	2.00	2.50	3.00
ACRR Plant Protection System (PPS)				
Peak Fuel Temperature (°C) – PPS1/TC2*	239	454	656	860
Razorback				
Peak Fuel Temperature (°C)	248.6	466.7	672.4	865.6
Deviation (%)	4.0%	2.8%	2.5%	0.7%

*TC2 refers to thermocouple channel #2 for the PPS drawer shown

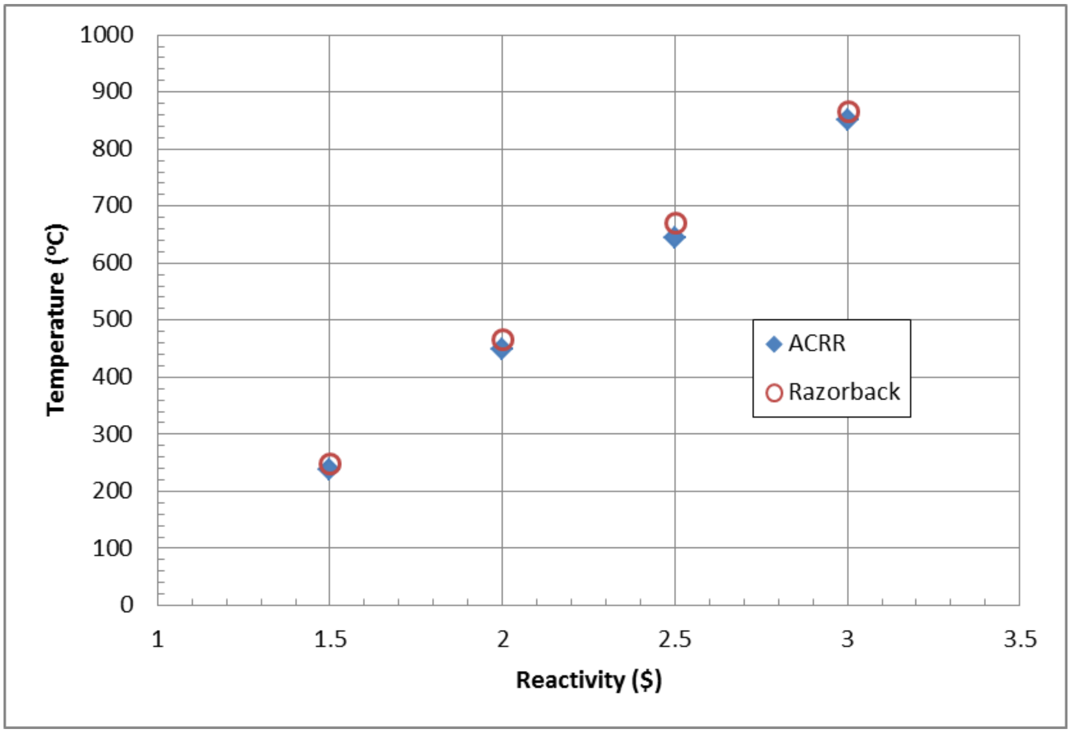

Figure 17. Comparison of Predicted and ACRR Fuel Temperatures for Several Pulses.

4.4. Predicted Reactor Pulse Width Parameters

The pulse width parameters used to characterize a pulse are as follows:

- FWHM: Full Width at Half-Maximum. This parameter is determined by finding the time, before and after the pulse peak, when the power level is equal to one-half of the peak power.
- LEHM: Leading Edge (Width) at Half-Maximum. This parameter is the time difference between the one-half of peak power point before the pulse peak and the pulse peak. For a symmetrical pulse, this timespan would be one-half of the FWHM.
- TEHM: Trailing Edge (Width) at Half-Maximum. This parameter is the time difference between the one-half of peak power point after the pulse peak and the pulse peak. For a symmetrical pulse, this timespan would be one-half of the FWHM.
- LE/TE Ratio: Leading Edge/Trailing Edge Ratio. This parameter is simply the ratio of the LEHM to the TEHM. For a symmetrical pulse, this ratio would be 1. As such, this provides an indication of the asymmetry of the actual pulse. The impact of delayed neutrons on the pulse shape would lead to an LE/TE < 1.

Figure 18 illustrates these pulse width parameters.

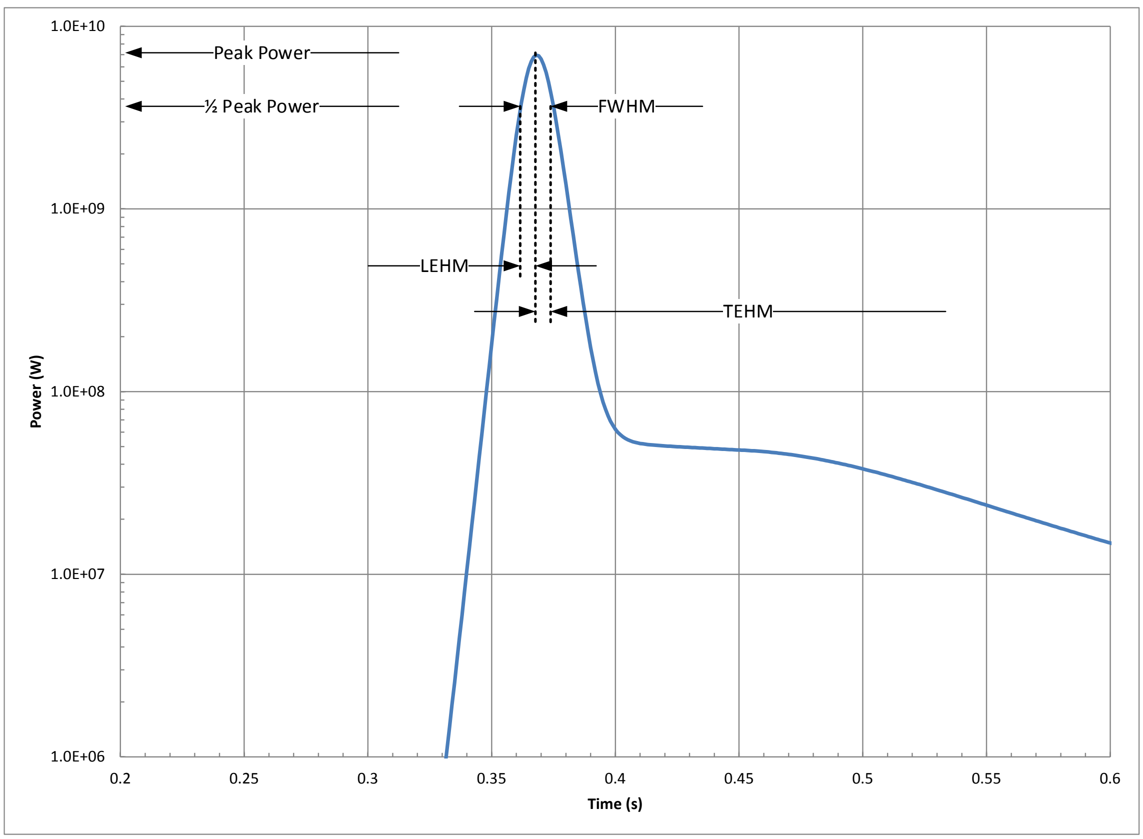

Figure 18. Depiction of Pulse Width Parameters.

A comparison of the measured pulse width parameters from the ACRR's Diagnostic System and those predicted by Razorback are shown in Table 14. The Razorback values are obtained from simulations using the nominal worth as input. The deviations are nominally in the +/-5% range. Figure 19 displays the full-width at half-maximum (FWHM) results in Table 14 graphically.

Table 14. Pulse Shape Comparisons for Pulse Operations.

RUN #	**9720**	**9719**	**9718**	**9716**
Pulse Size ($) (nominal)	1.50	2.00	2.50	3.00
ACRR FWHM (ms)	27.12	13.24	9.20	7.24
Razorback FWHM (ms)	26.79	13.75	9.25	7.07
Deviation (%)	-1.2%	3.9%	0.5%	-2.3%
ACRR LEHM (ms)	12.88	6.44	4.48	3.60
Razorback LEHM (ms)	12.99	6.69	4.50	3.46
Deviation (%)	0.9%	3.9%	0.4%	-3.9%
ACRR TEHM (ms)	14.24	6.88	4.72	3.64
Razorback TEHM (ms)	13.80	7.06	4.74	3.61
Deviation (%)	-3.1%	2.6%	0.4%	-0.8%
ACRR Ratio LE/TE	0.904	0.936	0.949	0.989
Razorback Ratio LE/TE	0.941	0.948	0.949	0.958
Deviation (%)	4.1%	1.2%	0.0%	-3.1%

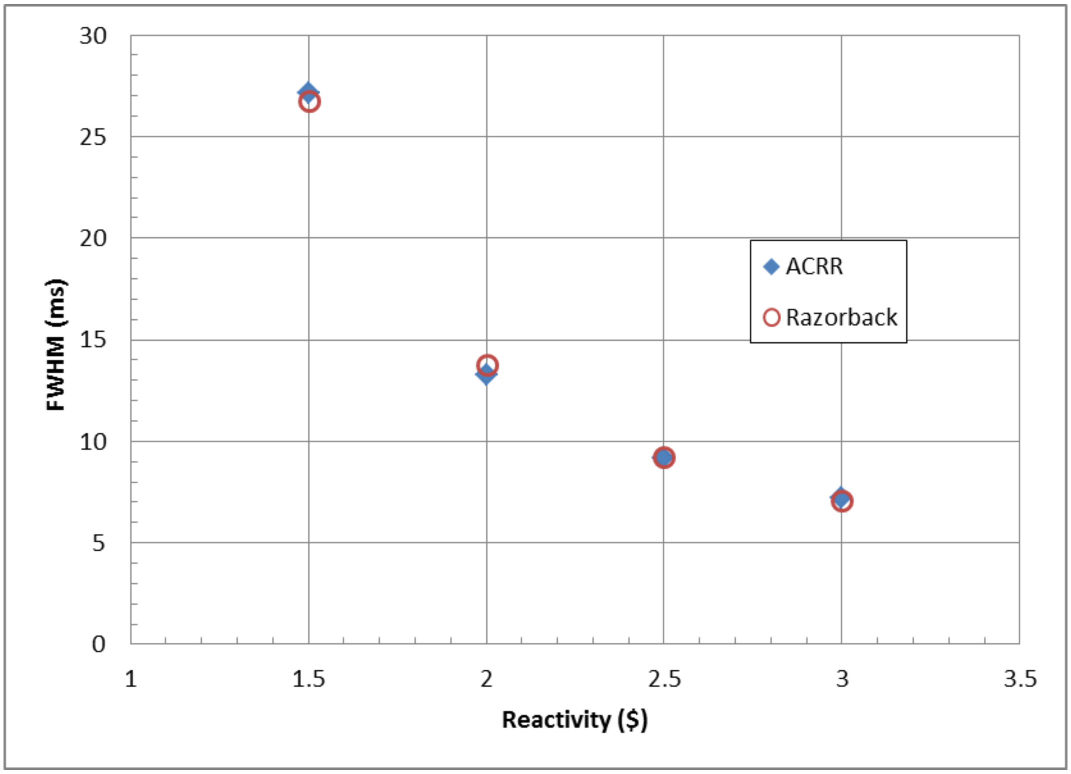

Figure 19. Comparison of Predicted and ACRR Pulse Widths for Several Pulses.

4.5. Predicted Reactor Minimum Period

A comparison of the minimum reactor period determined from the ACRR's Diagnostic System and those predicted by Razorback are shown in Table 15. The minimum period value selected from the Diagnostic System data report was the "average" minimum period, as opposed to selecting the minimum period from Channels 1, 2, or 3. The "averaging" algorithm within the Diagnostic System coding should be reviewed for the final V&V effort.

Table 15. Minimum Period Comparison for Pulse Operations.

RUN #	**9720**	**9719**	**9718**	**9716**
Pulse Size ($) (nominal)	1.50	2.00	2.50	3.00
Minimum Period				
ACRR (ms)	7.76	3.42	2.34	1.74
Razorback (ms)	6.93	3.49	2.37	1.88
Deviation (%)	-10.7	2.0	1.3	8.0

The interest in this parameter is that the minimum reactor period provides a means, assuming no appreciable delayed neutron effects or reactivity feedback effects, to determine the reactivity addition of the pneumatically-ejected transient rods, given a value for Λ/β.[3] As shown in Table 15, except for the $1.50 case, Razorback predictions for minimum period are quite good (within 3%). However, if one computes a reactivity addition based on the minimum period (see Table 16), the values obtained using the ACRR Diagnostic System minimum period are low with regard to the presumed reactivity addition. If one uses Λ=25.5 μs for the ACRR values, the results are much closer to the presumed reactivity.

Table 16. Estimation of Reactivity Addition Using the Minimum Period.

RUN #	**9720**	**9719**	**9718**	**9716**
Pulse Size ($) (nominal)	1.50	2.00	2.50	3.00
Minimum Period-Based Reactivity Addition				
ACRR ($)[a]	1.42	1.96	2.40	2.89
Razorback ($)[b]	1.50	2.00	2.47	2.86

a. Using Λ=24 ms and β_{eff}=0.0073
b. Using Λ=25.5 ms and β_{eff}=0.0073

[3] The Diagnostic System appears to utilize a value of 0.003288 (Λ=24 μs, β=0.0073). Recall that Razorback uses a slightly different generation time (Λ=25.5 μs).

There is another issue, however, with the minimum periods determined by the ACRR Diagnostic System. Figure 20 shows the reactor period derived as $\tau = \Delta t/\ln(P_n/P_{n-1})$ from the data recorded in the ACRR Diagnostic System data report (the $1.50 Shot #9720 is used here). As seen in Fig. 20, the signal is quite noisy in the region where one would expect to extract the minimum period. Although the algorithm is not readily available, it is possible that the Diagnostic System software adequately filters the data to obtain a true value for the minimum period. However, it would seem prudent to seek a means to reduce the noise for the power channels, or use another detector to more confidently determine the minimum period.

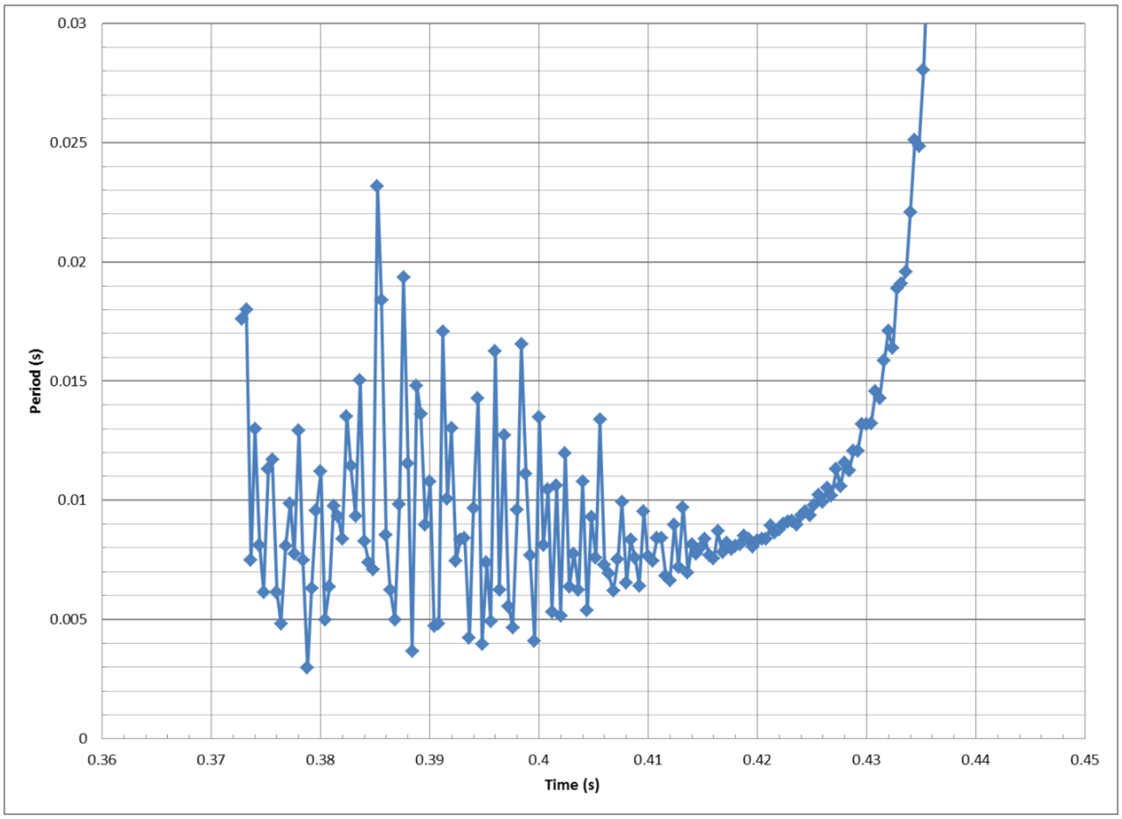

Figure 20. ACRR Reactor Period Produced From Tabular Power/Time Data in the Diagnostic System Report for Pulse 9720 ($1.50).

Since there is no "noise" in the Razorback simulation, the reactivity addition as computed using the minimum period should be identical to the input reactivity. This is the case for the $1.50 and $2.00 pulse simulation results shown in Table 16. However, the results for the $2.50 and $3.00 pulse in Table 16 are less than the input reactivity. This is due to the impact of reactivity feedback attaining appreciable levels prior to the addition of the full reactivity input. At the ACRR, this phenomenon is often referred to colloquially as "walking on the rods," but is referred to in the ACRR Technical Safety Requirements as "dynamic reactivity worth" (Ref. 10). The time required to fully eject the Transient Rod bank, using the normal pneumatic system settings, is insufficient to attain full reactivity worth addition prior to fuel temperature reactivity feedback. Thus, in terms of resulting pulse parameters, the effective reactivity worth of the

Transient Rod bank is less than what would be attained if the addition were near instantaneous (or at least occurred faster than appreciable feedback is developed). This appears to be happening in the Razorback results for $2.50 and greater pulse reactivity additions. Thus, Razorback may be able to predict the "dynamic reactivity worth" of the Transient Rod bank, but the timing of the Transient Rod bank ejection should be measured/verified at the ACRR to ensure that the Razorback model adequately predicts the ejection timing.

5. COMPARISON TO ACRR TRANSIENT ROD WITHDRAWAL OPERATIONS

Simulations using Razorback were performed for ACRR Runs 9022 and 9023. These were both TRW operations, with relatively similar TRW programs beginning from a position of 3500 units. The Console Logs are included as Appendix B. An initial power level of 1.2 kW (0.05% of full power) was utilized for both simulations, and the pool water was assumed to be at 20°C. The results are shown in Figs. 22 and 23, which show ACRR power levels as measured by Channels 1, 2, and 3 of the Diagnostic System, along with the power level as determined by the Razorback simulation.

Razorback achieves a good match with the initial pulse resulting of TRW operation 9022, but both the peak power and timing of the pulse peak are off for TRW operation 9023. A possible reason for the discrepancy is that the demanded (or programmed) TR bank position vs. time, which is an input to the TRW controller, is not necessarily achieved. The actual TR bank position vs. time is not available, but may have been such that the reactivity addition resulting in the initial pulse was not as high as that demanded by the controller.

In general, the Razorback results demonstrate reasonable agreement with the TRW operations. This is considered to be noteworthy given the interplay of the various reactivity feedback mechanisms (i.e., fuel temperature, fuel and cladding expansion, coolant density and temperature). Note that the second peak power level in both TRWs is not attained in the Razorback simulations. This may be indicative of the simulated reactivity feedback being stronger than it should be (due to over-estimated coolant channel conditions, or over-estimated reactivity coefficients), or perhaps due to inadequate representation of the transient rod reactivity worth for the position range at the time near the second peak ($5.5 \text{ sec} < t < 6.5 \text{ sec}$).

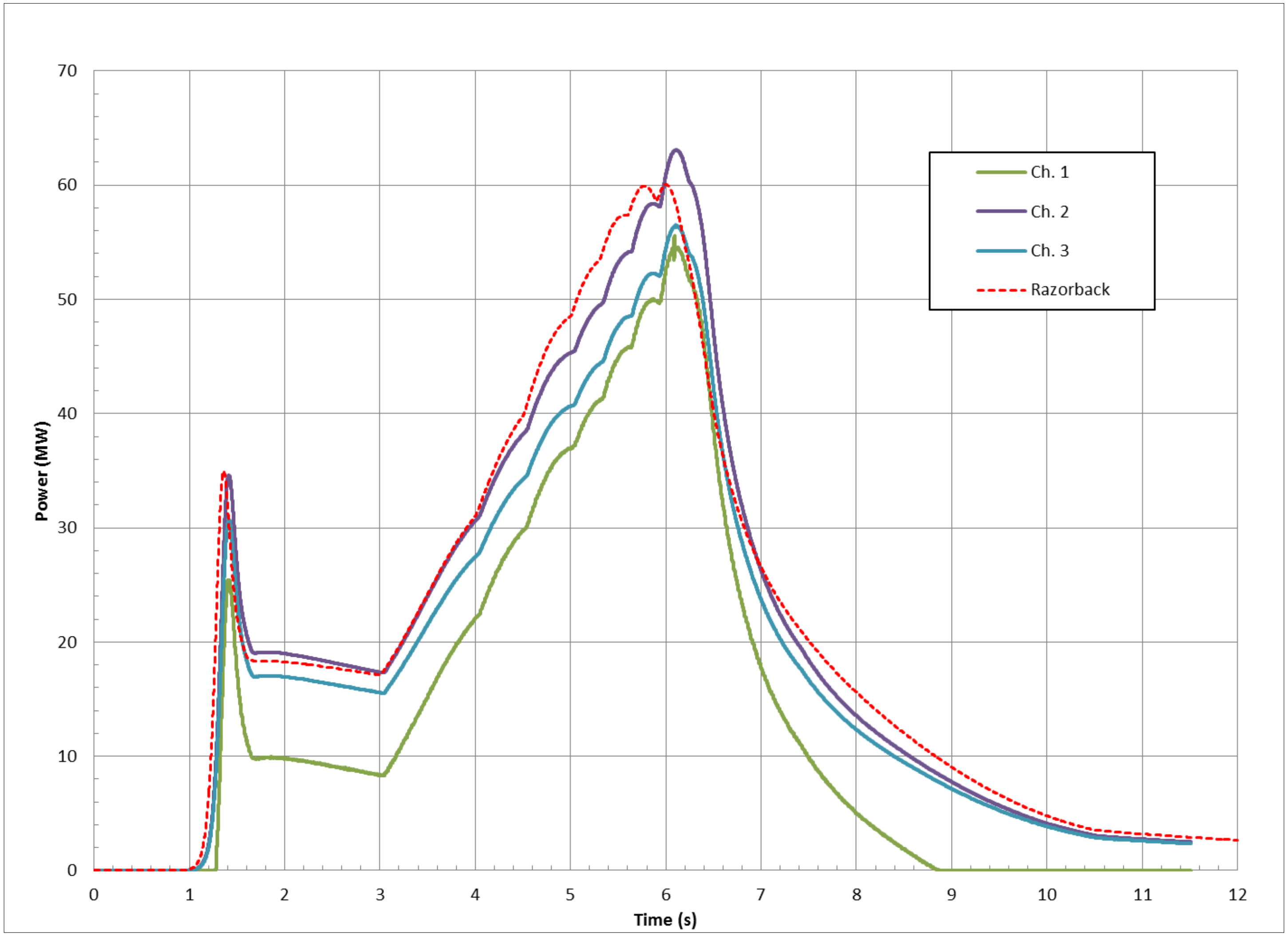

Figure 21. Razorback Simulation of TRW Operation 9022.

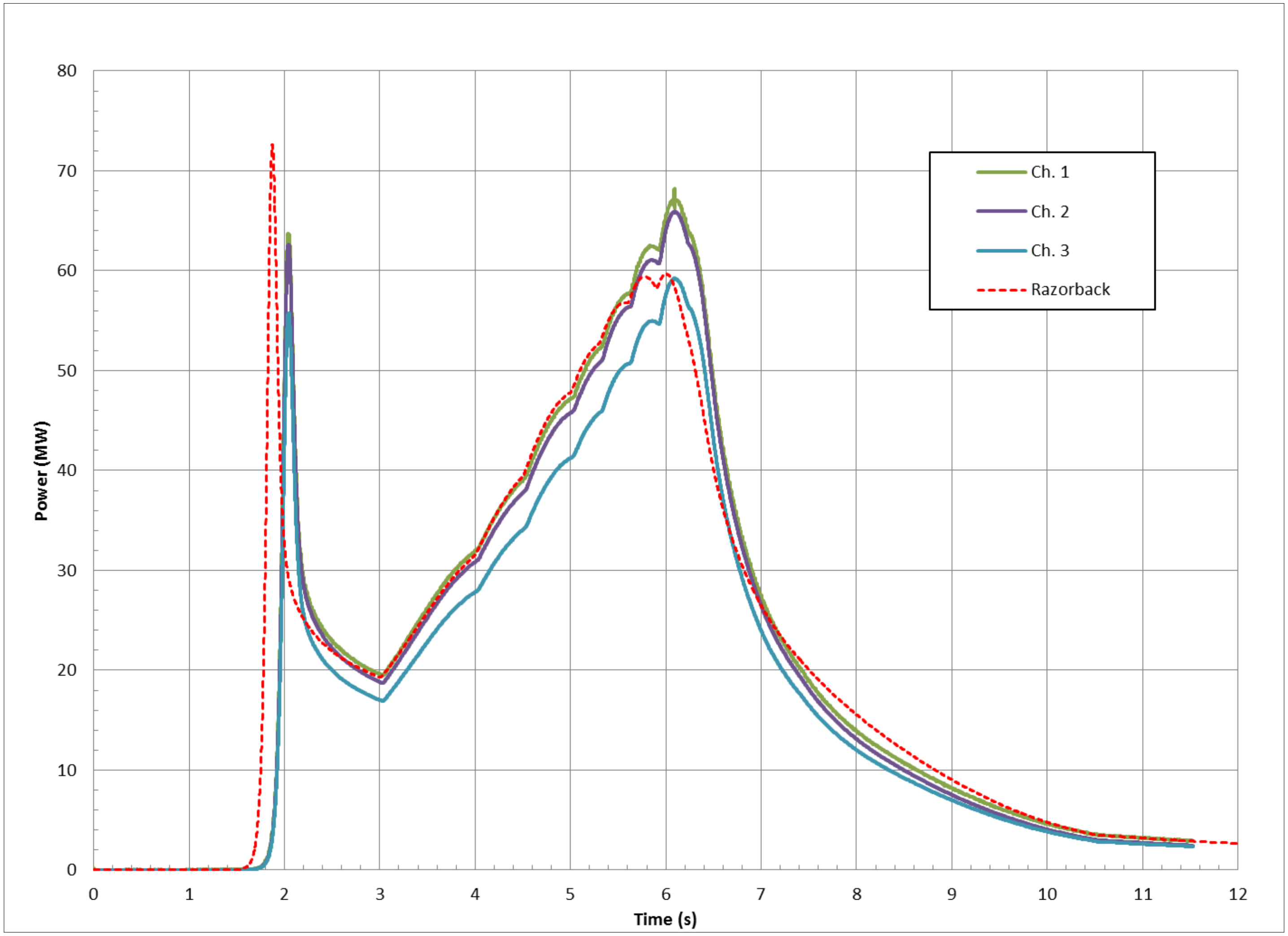

Figure 22. Razorback Simulation of TRW Operation 9023.

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6. COMPARISON TO A SLOW REACTOR TRANSIENT OPERATION

On February 2, 2015, a planned slow reactor transient was conducted with the intent of stepping down in reactor power in controlled increments, attaining a steady power level for a few minutes after each step down. Specifically, the following operation plan was followed:

- Achieve steady-state at ~90% of full power.
- Drive the control rod bank in 50 units, and allow the reactor to attain a new steady power level.
- Drive the control rod bank in 100 units, and allow the reactor to attain a new steady power level.
- Drive the control rod bank in 150 units, and allow the reactor to attain a new steady power level.
- Drive the control rod bank in 200 units, and allow the reactor to attain a new steady power level.
- Drive the control rod bank in 200 units, and allow the reactor to attain a new steady power level.
- Drive the control rod bank to full down, and allow the reactor to attain a new steady power level.

This operation was simulated in Razorback by constructing a set of control rod operation commands to match the actual control rod motion of the ACRR as recorded by the Logmaster computer. The control rod commands input to Razorback were as follows:

```
*------------------------------------|---------------------------------|
*     Control Rod Bank Control       |   Number of CR Bank Commands    |
*  (1=on w/curve, 0=off, 2=ramp)     |          (up to 20)             |
*------------------------------------|---------------------------------|
               1                                   12
*
*----------------------|----------------------|------------------------|
*      CR Start        |        CR End        |     CR Speed (cm/s)    |
*      Time (s)        |       Time (s)       |     or Ramp ($/s)      |
*----------------------|----------------------|------------------------|
         0.0                     5.3                    -0.10
         5.3                   204.0                     0.00
       204.0                   213.9                    -0.10
       213.9                   453.0                     0.00
       453.0                   467.9                    -0.10
       467.9                   738.0                     0.00
       738.0                   758.2                    -0.10
       758.2                  1108.0                     0.00
      1108.0                  1128.2                    -0.10
      1128.2                  1558.0                     0.00
      1558.0                  1754.4                    -0.10
      1754.4                  3600.0                     0.00
*----------------------------------------------------------------------|
```

The comparison of the Razorback rod motion due to this input with the ACRR control rod motion is shown in Figure 23.

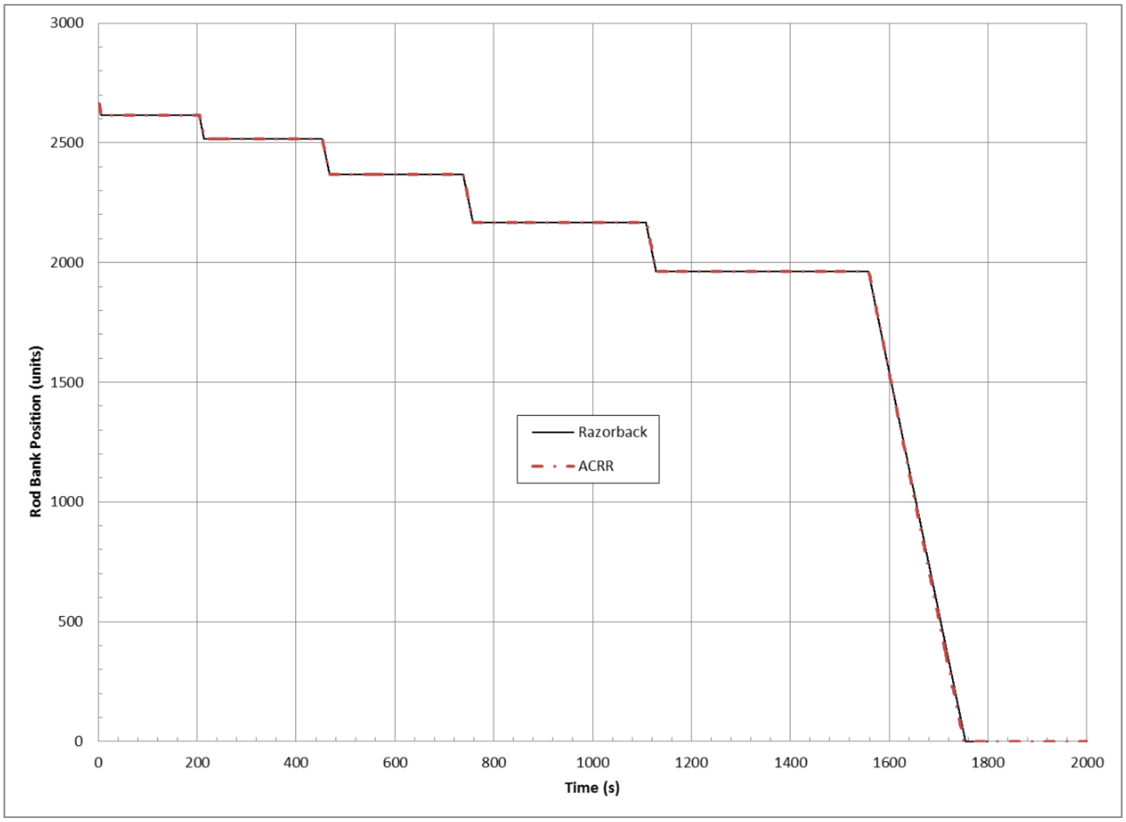

Figure 23. Comparison of ACRR and Razorback Control Rod Bank Motion During Operation 11278.

Figures 24 and 25 show the results for the power and "measured" fuel temperature history of the Razorback simulation compared to the ACRR power (Wide Range Log Power, Channel 1) and temperature (PPS1-TC2) history. The power history results match reasonably well, with better agreement at power levels above about 20-30 %Full Power (%FP). A significant discrepancy arises around 10-20%FP. The temperature history matches well in general shape, but there is clearly an offset in the magnitude of the predicted temperature which is on the order of 150-200°C. This offset is similar in magnitude to that seen in the comparison of steady-state fuel temperatures (see Section 7), and is expected to be due to the same factors discussed in Section 7.

Regarding the significant discrepancy for the power history shortly after the 1200 second mark, Figure 26 presents the reactivity feedback components computed in the Razorback simulation. The fuel temperature reactivity feedback is clearly the dominant factor, contributing bulk of the positive feedback as the fuel temperature decreases in the power stepdown. However, as the fuel cools down, the fuel, niobium, and cladding expanded dimensions begin to contract back to their original room temperature dimensional state. The feedback from the cladding contraction is seen to become relatively significant from 1100 s to 1300 s. The power history discrepancy may be due to either the cladding contraction or the cladding feedback coefficients being over estimated.

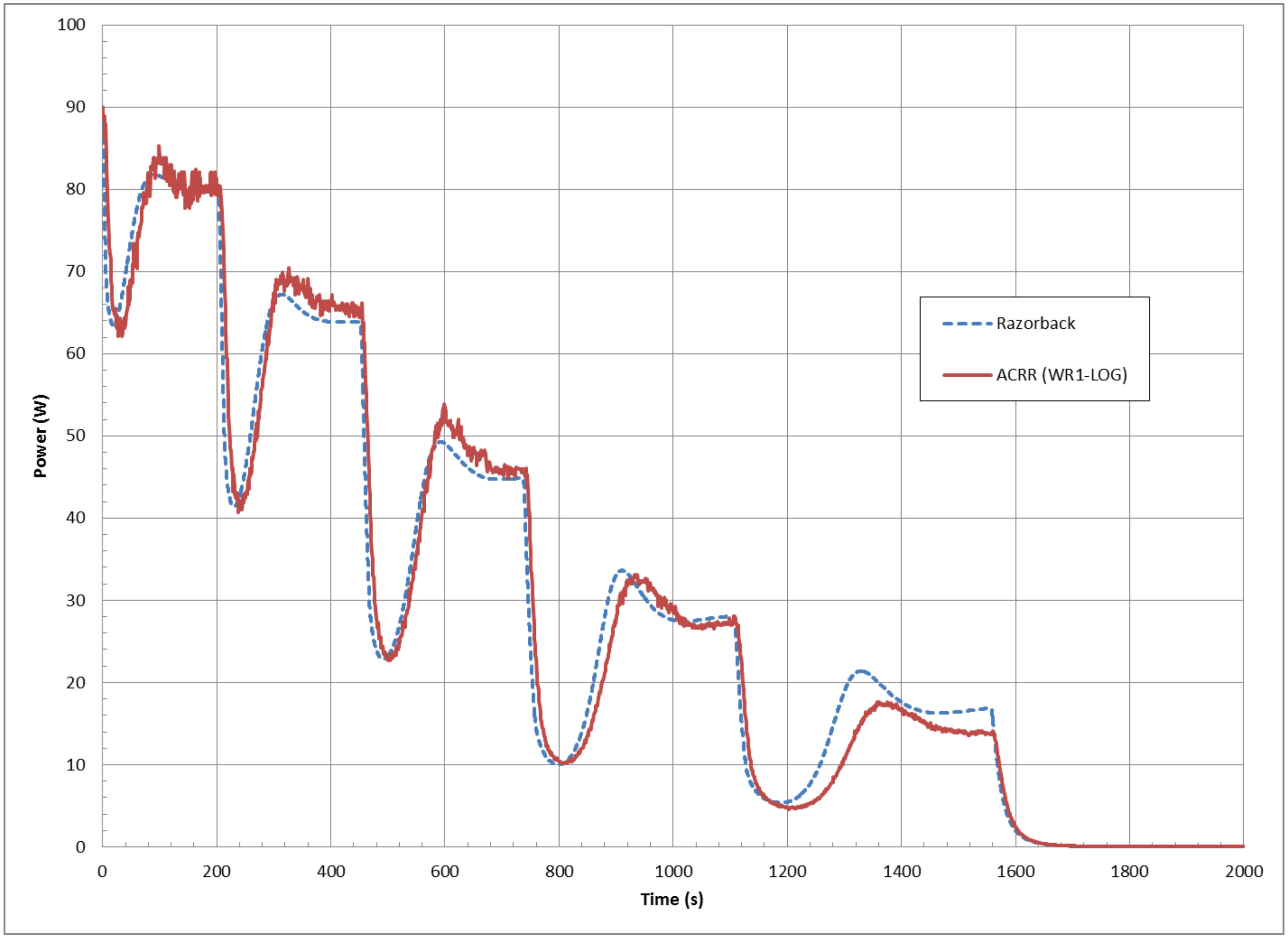

Figure 24. Comparison of Razorback Predicted Power History to Operation 11278.

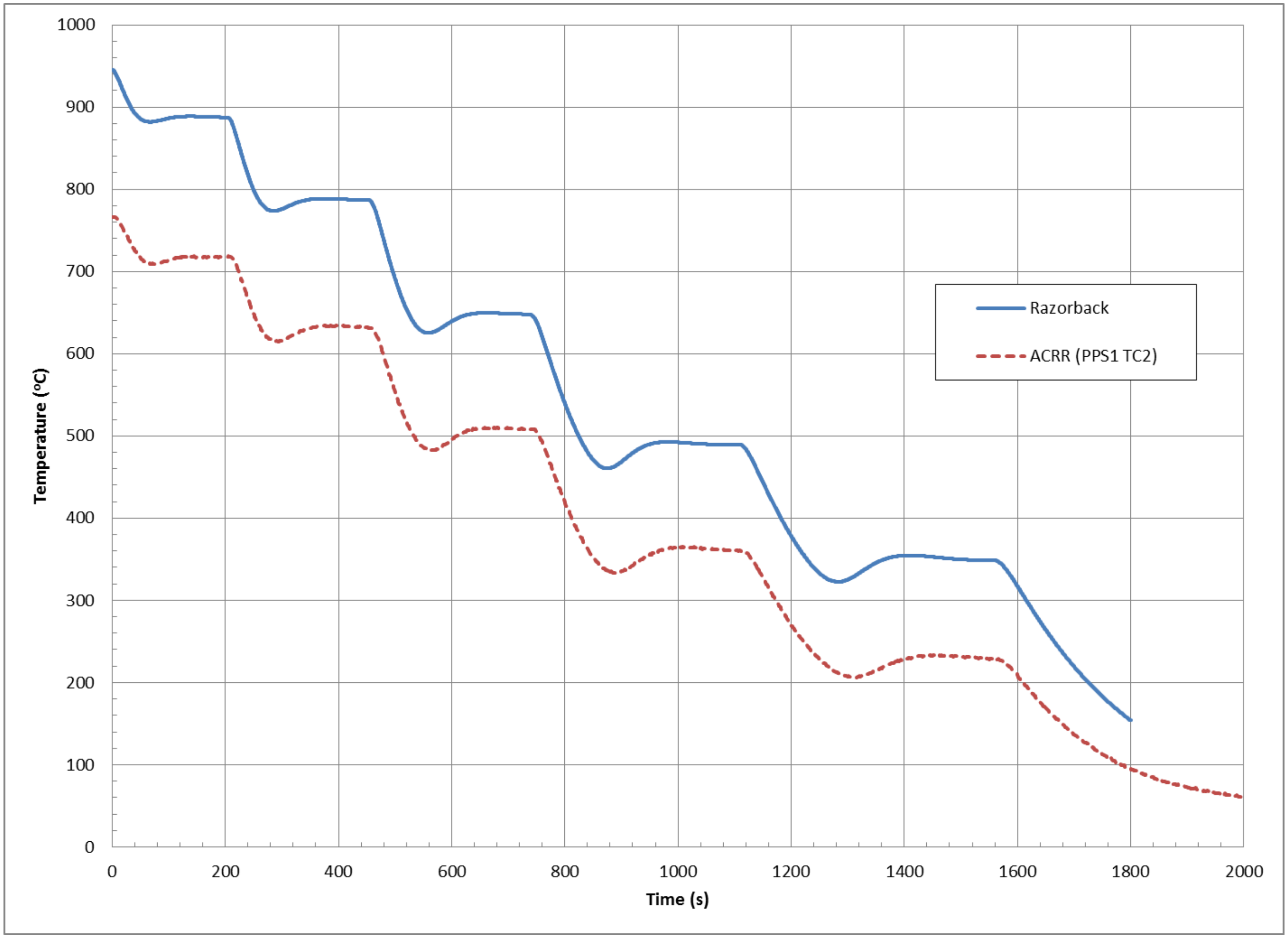

Figure 25. Comparison of Razorback Predicted Fuel Temperature for Operation 11278.

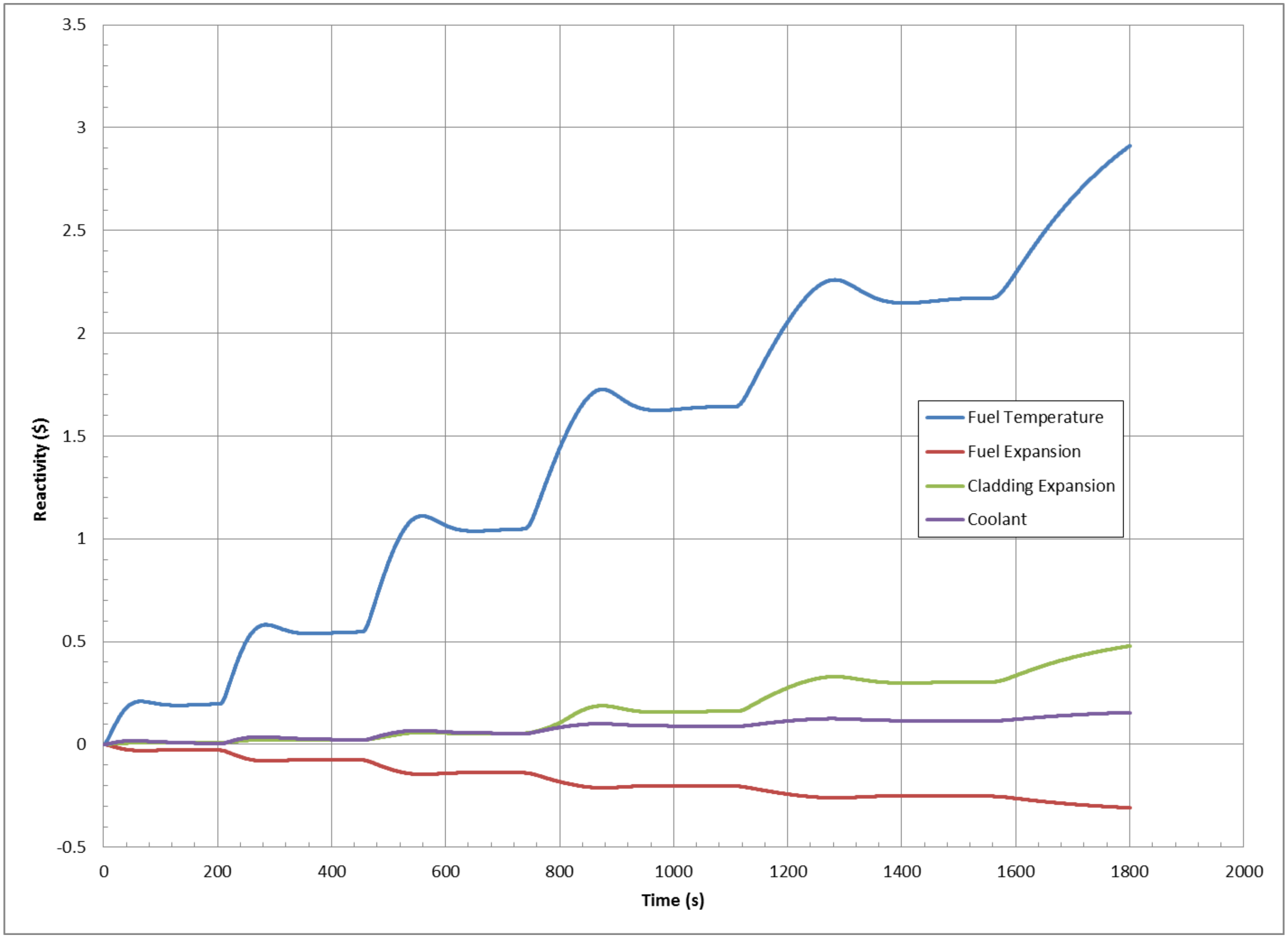

Figure 26. Components of Reactivity Feedback in Razorback Simulation of Operation 11278.

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7. COMPARISON TO ACRR STEADY STATE OPERATION

The Razorback code was run in steady-state mode to compute estimates of the measured fuel temperature in the ACRR for various power levels. The results are shown in Fig. 27. The data presented in Fig. 27 for the actual ACRR measured fuel temperatures was based on a power-law correlation of fuel temperatures measured in December 1999 testing, when the ACRR was returned to pulse operation mode.[4] Also included on Fig. 27 are temperatures corresponding to the power plateaus for Operation 11278 (see Section 6). Thus, the ACRR temperature correlation appears to overestimate fuel temperature. Razorback clearly predicts higher fuel temperatures for all appreciable power levels.

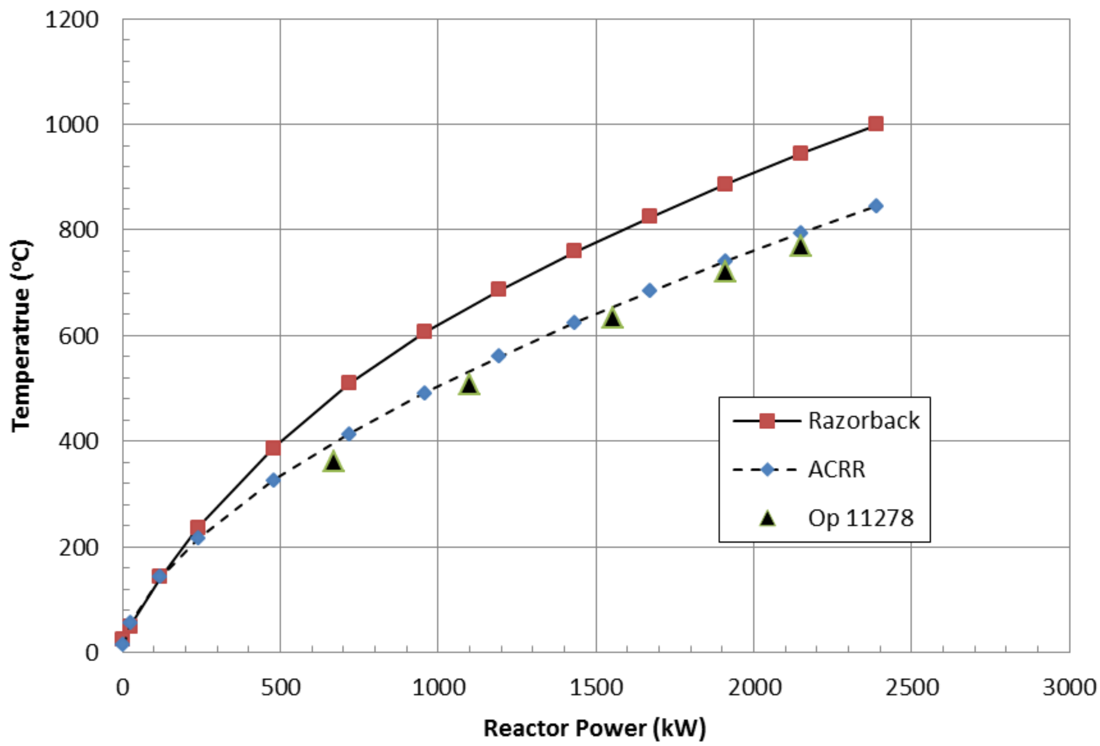

Figure 27. Comparison of Steady-State Fuel Temperatures.

Figures 28 and 29 show the error in the predicted temperatures (absolute and relative, respectively) as a function of reactor power level. Potential causes for the errors, which should be investigated in future work include:

- The actual fuel pellet dimensions may be such that the gaps between the fuel pellets and the niobium fuel cup are smaller than indicated on drawings, which would lead to lower predicted fuel temperatures.
- The assumption of plane strain for the fuel element material thermal expansion is underestimating the magnitude of the thermal expansion.

[4] The correlation was presented at an ACRR Committee meeting on December 6, 1999 (Ref. 11).

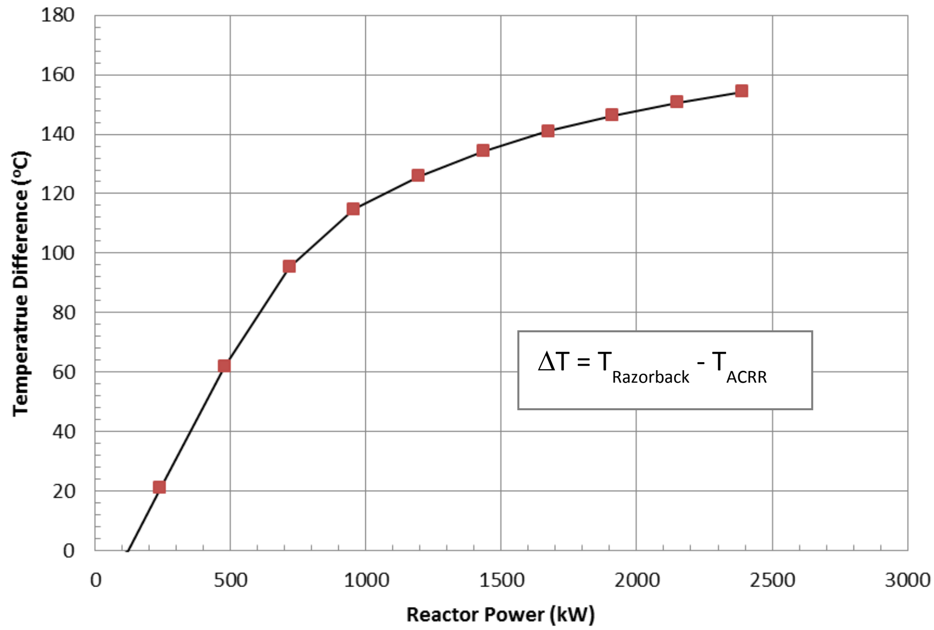

Figure 28. Difference in Predicted vs. ACRR Fuel Temperature.

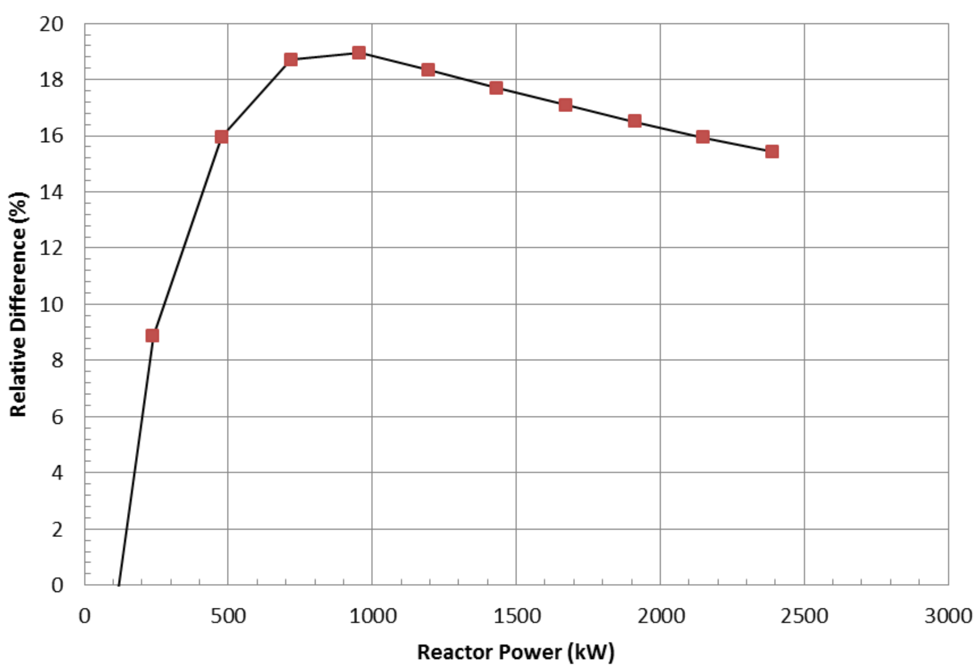

Figure 29. Relative Difference in Predicted vs. ACRR Fuel Temperature.

8. CONCLUSIONS

The results of this initial V&V effort are quite promising. In Section 3, it is seen that the agreement of the code results with analytical solution data is excellent for both the reactor kinetics model (covering a wide variety of reactivity inputs) and the heat transfer within a fuel element. An analytical solution for the coolant channel model is not presented due to the complicated nature of the coupled nonlinear partial differential equations governing its behavior. In addition, an analytical check on the thermal expansion of the fuel element materials is not presented. Such an analytical solution should be pursued to verify the thermal expansion model implementation.

The pulse operation simulations agree very well with the Diagnostic System data. While further work is needed to document the determination of reactivity feedback coefficients, the values utilized appear to be adequate. Based on the results herein, the beta release is capable of simulating normal ACRR pulse operations.

The TRW operation simulations agree reasonably well with the Diagnostic System data. The discrepancies in initial pulse peak power and timing may be attributable to actual vs. demanded Transient Rod bank position for the TRW operation. TRW mode is not currently available, but new TRW operations should be run when it becomes available in order to obtain additional and more complete data for V&V comparison. Based on the results herein, the beta release is capable of simulating normal ACRR TRW operations. However, further work is needed to determine if better Transient Rod bank worth curves or feedback coefficients improve the accuracy of the simulations in the later time portion of the TRW operations.

The general transient operation simulation agrees well with the ACRR reactor power history data. However, there is a clear offset in the prediction of the ACRR measured fuel temperatures for that power history. The offset also arises in the prediction of ACRR fuel temperature with Razorback in steady-state mode. Further work is needed to determine the reason for this offset in predicted fuel temperatures. Likewise, fuel coolant channel outlet temperature measurements are needed to address the validation of the coolant channel flow model. Based on the results herein, the beta release is capable of simulating normal ACRR transient and steady-state operations, but predicted fuel temperatures are conservatively overestimated.

The beta release of the Razorback code is considered adequately verified and validated, but further work is needed prior to the full release of the code.

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9. RECOMMENDATIONS FOR FURTHER WORK

The following areas for additional work have been identified over the course of developing and evaluating the results presented herein:

- An analytical solution for verification of the thermal expansion model is needed.
- The final V&V report should address the selection of the most suitable delayed neutron precursor group data.
- The values used for reactivity feedback coefficients should be documented in formal calculations of record.
- A means of providing a documented calibration basis for the Diagnostic System is needed.
- A means of reducing the Diagnostic System power trace noise in order to better estimate the minimum reactor period should be pursued.
- The source of the discrepancy between the predicted fuel temperatures and the ACRR fuel temperatures, while conservative in regards to safety analysis, should be determined.
- Obtain channel outlet temperature measurements for use in V&V of steady-state and transient simulations.

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10. REFERENCES

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APPENDIX A: SAMPLE RAZORBACK INPUT FILE

```
***********************************************************************
*                       RAZORBACK Input File
*  Note: an "*" in the first column denotes a comment statement
***********************************************************************
*                   CALCULATION AND PRINTING CONTROLS
***********************************************************************
*-------------------------------|-------------------------------------|
*                               |                      |  Number of    |
*      Calculation Type         |   Total Transient    | Title Cards   |
* (1=steady-state,0=transient)  | Calculation Time (s) |  (up to 20)   |
*-------------------------------|----------------------|---------------|
            0                             12.0                7
*---------------------------------------------------------------------|
*                            Title Cards                               |
*---------------------------------------------------------------------|
  Simulation of Pulse 9716: Nominal $3.00 Calibration Pulse Jan. 2011
   - Initial power 0.05% (1.2 kW)
   - 0.4 second Rod Hold Up time
   - TR set to position yielding ~$3.00
   - CR at 24.00 cm; SR at 55.00 cm
   - N2 valve delay set to approximate time-to-peak
   - 0.05 second scram delay time; 0.5 second rod fall time
*
*------------------------------|--------------------------------------|
*  Number of Time Step Ranges  |   Initial Condition Stabilization    |
*       (up to 20)             |     Duration (s) | Time Step (s)     |
*------------------------------|------------------|-------------------|
            1                            0.0               0.01
*-----------------|-----------------|---------------------------------|
*                 |                 |      Time Step Control (TSC)    |
*                 |                 |       (If TSC is off, then      |
*                 |                 |    dt = max time step of range) |
*   Time Range    |    Time Step    |  T/H         TSC      |    TSC   |
* Begin(s)/End(s) | max(s) / min(s) |  dt(s)    | "Error"   | (1=y/0=n) |
*-----------------|-----------------|----------|-----------|-----------|
   0.0 10000.00      1.0d-3  1.0d-9     1.0d-3      1.0d-3       1
*
*
*-------------------------------------|-------------------------------|
*  Number of Print Increment Ranges   |                               |
*          (up to 20)                 |                               |
*-------------------------------------|-------------------------------|
              2
*-------------------------------|------------|------------|------------|
*                               |   screen   |   plot     |   file     |
*     Print Time Range          |   print    |   print    |   print    |
*      Begin(s)/End(s)          |   incr.(s) |  incr.(s)  |  incr.(s)  |
*-------------------------------|------------|------------|------------|
       0.0    1.0                  1.0e-3      1.0e-3       5.0e-2
       1.0  10000.0                1.0e-2      1.0e-3       5.0e-1
*-------------------------------|-------------------------------------|
* pulse parameter file print    |      fuel rod screen/file print      |
*     (1=yes, 0=no)             |            (1=yes, 0=no)             |
*-------------------------------|-------------------------------------|
             1                                 1
*
***********************************************************************
*                 REACTOR POWER AND INITIAL CONDITIONS
***********************************************************************
*--------------------|----------------------------|--------------------|
```

```
*  Initial Reactor   |    100% Reactor Power      |      Element        |
*    Power (%)       |           (W)              |  Peak-to-Average   |
*--------------------|----------------------------|--------------------|
      5.0e-02                2.39e+06                     1.45
*----------------------------------------------------------------------|
*
***********************************************************************
*                 REACTIVITY ADDITION SYSTEM CONTROLS
***********************************************************************
*
*-----------------------------------|---------------------------------|
*     Control Rod Bank Control      |   Number of CR Bank Commands    |
*  (1=on w/curve, 0=off, 2=ramp)    |          (up to 20)             |
*-----------------------------------|---------------------------------|
              0                                  2
*
*----------------------|----------------------|------------------------|
*      CR Start        |        CR End        |     CR Speed (cm/s)    |
*      Time (s)        |       Time (s)       |     or Ramp ($/s)      |
*----------------------|----------------------|------------------------|
          0.0                     1.0                     0.00
          1.0                 10000.0                     0.00
*----------------------------------------------------------------------|
*
*  Note: 0.1 cm/s CR Speed = slow speed; 2.0 cm/s CR Speed = fast speed
*
*----------------------|----------------------|------------------------|
*      CR Start        |       CR down        |         CR Up          |
*    Position (cm)     |    Position (cm)     |     Position (cm)      |
*----------------------|----------------------|------------------------|
         24.00                    0.0                   55.00
*----------------------------------------------------------------------|
*
*------------------|---------------------------------------------------|
*    CR Bank       |      CR Bank Differential Reactivity Curve        |
*     Total        |           drho/dz = A sin2[ B(z) + C]             |
*   Worth ($)      |        A        |        B        |       C       |
*------------------|-----------------|-----------------|---------------|
       12.00          0.02822125          0.0432           0.31852
*----------------------------------------------------------------------|
*
*-----------------------------------|---------------------------------|
*       Safety Rod Bank Control     |   Number of SR Bank Commands    |
*  (1=on w/curve, 0=off, 2=ramp)    |          (up to 20)             |
*-----------------------------------|---------------------------------|
               0                                     2
*
*----------------------|----------------------|------------------------|
*      SR Start        |        SR End        |     SR Speed (cm/s)    |
*      Time (s)        |       Time (s)       |     or Ramp ($/s)      |
*----------------------|----------------------|------------------------|
         0.0                    1.0                    0.0
         1.0                10000.0                    0.0
*----------------------------------------------------------------------|
*
*  Note: 0.24 cm/s CR Speed = slow speed, 7.26 cm/s = fast speed
*
*----------------------|----------------------|------------------------|
*      SR Start        |       SR down        |         SR Up          |
*    Position (cm)     |    Position (cm)     |     Position (cm)      |
*----------------------|----------------------|------------------------|
        55.00                     0.0                   55.00
*----------------------------------------------------------------------|
```

```
*
*-------------------|-------------------------------------------------|
*    SR Bank        |      SR Bank Differential Reactivity Curve       |
*     Total         |           drho/dz = A sin2[ B(z) + C]            |
*   Worth ($)       |       A        |       B        |       C        |
*-------------------|----------------|----------------|----------------|
       2.15            0.02822125        0.0432          0.31852
*
*-----------------------------------|--------------------------------|
*    Transient Rod Bank Control      |   Number of TR Bank Commands    |
*      (0=off, 1=on w/curve)         |          (up to 20)             |
*        (2=pulse, 3=ramp)           |                                 |
*-----------------------------------|--------------------------------|
              2                                  1
*
*----------------------|----------------------|------------------------|
*      TR Start        |       TR End         |     TR Speed (cm/s)    |
*      Time (s)        |      Time (s)        |     or Ramp ($/s)      |
*----------------------|----------------------|------------------------|
*
*   Pulse Operation (1 TR Bank Command; only TR Start Time is needed)
        0.165               1.000                   0.000
*--------------------------------------------------------------------|
*
*----------------------|----------------------|------------------------|
*      TR Start        |       TR down        |         TR Up          |
*    Position (cm)     |    Position (cm)     |     Position (cm)      |
*----------------------|----------------------|------------------------|
*        55.09                43.70                  90.00    ($1.50 2011 cal data)
*        50.90                43.70                  90.00    ($2.00 2011 cal data)
*        46.85                43.70                  90.00    ($2.50 2011 cal data)
        42.70                42.69                  90.00    ($3.00 2011 cal data)
*--------------------------------------------------------------------|
*   Note:  TR full down = 22.00 cm    TR pedestal down = 43.00 cm
*
*------------|-------------------------------------------------------|
*  TR Bank   |          TR Bank Differential Reactivity Curve         |
*  Total     |            drho/dz = A sin2[ B(z - z0) + C]            |
*  Worth($)  |      A      |      B      |      C      |      z0      |
*------------|-------------|-------------|-------------|--------------|
  4.45         0.0279912     0.0438084     -0.225591        0.0
** 2011 cal data for pulse (z0 not used for pulse)
*
*--------------------------------------------------------------------|
*  cubic spline approach for TR reactivity worth data                 |
*  (if number of entries below is non-zero,                           |
* this will override the TR worth specified above)                    |
*--------------------------------------------------------------------|
*
** (0 skips this) (ten entries per line max)
0
*--------------------------------------------------------------------|
*     Range of Validity for TR Bank Differential Reactivity Curve     |
*             lower end (cm)       |      upper end (cm)              |
*---------------------------------|----------------------------------|
                 12.0                          85.0
*--------------------------------------------------------------------|
*              Transient Rod Pulse Pneumatic System                   |
*   N2 Valve        |      N2         |     Piston           |    TR     |
* opening time (s) | Pressure (psig) |Effective Area (cm2) | Mass (kg) |
*------------------|-----------------|---------------------|-----------|
    88.0e-3              65.0              28.96               13.75  (for Pulse 9716)
*--------------------------------------------------------------------|
```

```
*
*  Pulse Rod Holdup (= time after pulse when rods drop back into core)
*  Time begins from t=0
*  PRT submode all rods drop
*  Pulse submode TRs and SRs drop (CRs do not)
*-------------------------------------|--------------------------------|
*         Transient Rod Pulse         |        Pulse Submode           |
*         Rod Holdup Time (s)         |      (Pulse=0 or PRT=1)        |
*-------------------------------------|--------------------------------|
              0.4e0                               1
*
*----------------------------------|-------------|----------------------|
*  Functional Reactivity Addition | Number of    |  Time to Turn        |
*  (0=off, 1=polynomial,  2=sine) | Terms(</=5)  |  Addition Off (s)    |
*----------------------------------|-------------|----------------------|
              0                          1                1e10
***********************************************************************
*                    REACTOR KINETICS PARAMETERS
***********************************************************************
*
*----------------------|----------------------|------------------------|
*  Neutron Generation   |  Effective Delayed   |     No. of Delayed     |
*      Time (s)         |  Neutron Fraction    |     Neutron Groups     |
*----------------------|----------------------|------------------------|
       25.5e-06              0.0073                        6
*
*---------------------------------------------------------------------|
*                         Delayed Neutron                              |
*            Group Decay Constants (1/s) - lambda i's                  |
*      (up to 18 groups allowed -- up to 6 lambdas per line)          |
*----------|-----------|-----------|-----------|-----------|-----------|
  1.27e-02    3.17e-02    1.15e-01    3.10e-01     1.40        3.87
* (Typical ACRR values for 6 groups)
*---------------------------------------------------------------------|
*
*---------------------------------------------------------------------|
*                         Delayed Neutron                              |
*                    Group Fractions - beta i's                        |
*        (up to 18 groups allowed -- up to 6 betas per line)          |
*----------|-----------|-----------|-----------|-----------|-----------|
  2.774e-04  1.5549e-03  1.3724e-03  2.9711e-03  9.344e-04  1.898e-04
*(Typical ACRR values 6 groups)
*---------------------------------------------------------------------|
*
*--------------------------------------|-------------------------------|
*     Fuel Temperature Feedback        |       Coolant Reactivity      |
*     drho/dT = c1 + c2/(T**0.5)       |       Feedback Coefficients   |
*        c1     |         c2           |    Density      |   Spectral  |
*      ($/K)    |     ($/K^1/2)        |   ($/%void)     |    ($/K)    |
*---------------|----------------------|-----------------|-------------|
    -0.00139          -0.0743                -0.43           -0.0014
*
*
*--------------------------------------|-------------------------------|
*     Fuel Expansion Feedback          |   Clad Expansion Reactivity   |
*      Feedback Coefficients           |     Feedback Coefficients     |
*     c11    |   c12      |    c2      |        c1      |       c2     |
*    ($/cm)  | ($/cm^2)   |  ($/cm)    |      ($/cm)    |     ($/cm)   |
*------------|------------|------------|----------------|--------------|
  -4167.724    1243.282     42.786       -115.06         -100.85
*
*---------------------------------------------------------------------|
*          Reactivity Feedback Scaling and Adjustment Factors          |
```

```
* -------------- Scaling ------------------|---------------------------|
*  Fuel T | Fuel Exp |  Clad  |  Coolant    |  PLA (not used by code)    |
*---------|----------|--------|------------|---------------------------|
    1.0       1.0       1.0       1.0             1.45
*
*-----------------------------------------|
*    Point Kinetics Solver Selection       |
* (1=R-K Gill, 2=1st Order Taylor Series)  |
*-----------------------------------------|
                   1
*
************************************************************************
*                  REACTOR PROTECTION SYSTEM SETTINGS
************************************************************************
*
*----------------------|----------------------|------------------------|
*       Percent         |       Reactor        |        Element         |
*      Power (%)        |      Power (W)       |       Power (W)        |
*----------------------|----------------------|------------------------|
      115.0e+40              2.50e+46               25.00e+43
*
*----------------------|----------------------|------------------------|
*       Reactor         |      Rod Block       |       Rod Block        |
*     Period (s)        |    (1=on,0=off)      |      Rate  (dpm)       |
*----------------------|----------------------|------------------------|
       8.50e-20                 0                     4.0e10
*
*-------------------------------|--------------------------------------|
*       Reactor Yield (J)        |         Fuel Temperature (C)         |
*-------------------------------|--------------------------------------|
           1.0e40                              1250.0e20
*
*-------------------------------|--------------------------------------|
*      Pool Level Scram          |          Inlet Temperature           |
*    (cm below tank top)         |              Scram (C)               |
*-------------------------------|--------------------------------------|
         100.0e20                            40.0e20
*
*-------------------------------|--------------------------------------|
*     Scram Delay Time (s)       |          Rod Fall Time (s)           |
*-------------------------------|--------------------------------------|
            0.050                            0.5
*
*-------------------------------|--------------------------------------|
*        Scram Failure           |            Manual Scram              |
*      (1 = yes, 0 = no)         |           Delay Time (s)             |
*-------------------------------|--------------------------------------|
              0                               10.0
*
************************************************************************
*              POOL WATER AND POOL WATER COOLING SYSTEM
*                INITIAL CONDITIONS AND TRANSIENT(S)
************************************************************************
*
*---------------------------------------------------------------------|
*                     |                                | Cooling System  |
* Initial Pool Water | Initial Pool Water Level (cm) |  Heat Removal   |
*  Temperature (C)   | (Distance Below Tank Lip)     | (% of Rx Power) |
*--------------------|-------------------------------|-----------------|
       20.0                   100.0                         0.0
*
*---------------------------------------------------------------------|
*                            Pool Heatup                               |
```

```
*   Flag = 0 -> no pool heatup (constant Tpool = Tinlet)                 |
*   Flag = 1 -> pool heatup by reactor/cooling system (Tpool = Tinlet) |
*   Flag = 2 -> pool temperature ramp (Tpool = Tinlet)                   |
*   Flag = 3 -> inlet temperature ramp (constant Tpool <> Tinlet)        |
*                                                                        |
*      Flag        |  Ramp (degC/s)  | Start Time (s)  |  End Time (s) |
*------------------|-----------------|-----------------|---------------|
       0                 0.0           0.0               0.0
*
*----------------------------------------------------------------------|
*                   Loss of Coolant Accident                            |
*      Flag     |    Start     |      Break     |  Effective Reactor   |
* (1=on, 0=off) |   Time (s)   |   Size (cm2)   |      Power (W)       |
*---------------|--------------|----------------|----------------------|
        0           0.1             40.64             2.0e6
*
*----------------------------------------------------------------------|
*                     Loss of Heat Sink Accident                        |
*        Flag          |      Start Time      |   Flowrate Coastdown   |
*   (1=on, 0=off)      |          (s)         |       Time  (s)        |
*----------------------|----------------------|------------------------|
         0                      5.0                     1.00
*
*-----------------------------------------|
*    Decay Heat Option (1=on,0=off)        |
*-----------------------------------------|
                  0
*
************************************************************************
*                      NUMERICAL SOLUTION SETTINGS
************************************************************************
*--------------------------------------|
*     Implicit Formulation Factors      |
*--------------------------------------|
*    Theta    |     Phi     |    Psi    |
*--------------------------------------|
     1.00          1.00         1.00
*-------------|-------------|-----------|
*
*----------------------------------------------------------------------|
*                      Iteration Error Limits                           |
*               Steady-State                  |       Transient        |
*----------------------|----------------------|------------------------|
*     Temperature      |        Flow          |     Temperature        |
*----------------------|----------------------|------------------------|
        1.0e-4              1.0e-3                   1.0e-3
*
************************************************************************
*                        FUEL ELEMENT MODEL
************************************************************************
*
*               Standard ACRR Thermal-Hydraulics Model
*----------|----------|----------|-------------------------------------|
*  Number  |  Number  |   Fuel   |   Fuel Coordinate System Geometry   |
*  of Fuel |  of Fuel |  R_inner |       0 = plate geometry            |
* Elements |  Zones   |   (cm)   |       1 = cylindrical geometry      |
*          | (10 max) |          |                                     |
*----------|----------|----------|-------------------------------------|
     236        7       0.24130                  1
*
*------------|----------|----------|---------|-------------------------|
* Zone Outer |  Number  | Material |   Gap?  |    Fission Energy       |
* Radius (cm)| of nodes |   Type   |(0=n/1=y)|  Deposition Fraction    |
```

```
*------------|----------|----------|---------|------------------------|
  1.09982        10         1        0          0.97846        BeO-UO2 Fuel
  1.11760        10         3        1          0.0            He Gap
  1.68402        10         1        0          0.97846        BeO-UO2 Fuel
  1.73228        10         3        1          0.0            He Gap
  1.77038        10         2        0          0.00400        Nb Cup
  1.82245        10         3        1          0.0            He Gap
  1.87325        10         4        0          0.00456        SS-304 Cladding
*------------|----------|----------|---------|------------------------|
*
*---------------------------|--------------------|----------------|
*   Material # in which      |       Allow        |     Allow      |
*   fission occurs           | Thermal Expansion  |  Gap Rad HX    |
*   (only one per element)   |   (0=no,1=yes)     | (0=off,1=on)   |
*---------------------------|--------------------|----------------|
           1                          1                  1
*
*---------------------------|-----------------------------------|
*  # of fuel "Thermocouples" |     Radial node(s) of "TC(s)"     |
*                            |      (at half fuel height)        |
*---------------------------|-----------------------------------|
           2                      1   5
*
*----------------------------------------------------------------------|
*        Fuel Pellet Radial Fission Density Peaking Distribution       |
*                         f(r) = A*exp(B*r) + C                        |
*-----------------------|-----------------------|----------------------|
*          A            |           B           |          C           |
*-----------------------|-----------------------|----------------------|
       0.0157                   1.9370                  0.8211
*----------------------------------------------------------------------|
*        Fuel Element Axial Fission Density Peaking Distribution       |
*               f(z) = SUM{a(i)*(z/H)^(i)} for i = 0 to 6              |
*----------|---------|---------|---------|---------|---------|---------|
   0.7721   -0.6252    24.0903  -89.6026  141.5383  -108.8048  33.1631  CR @ 27.50 cm
*
*
***********************************************************************
*                      COOLANT CHANNEL MODEL
***********************************************************************
*
*----------------------------------------------------------------------|
*                     Coolant Channel Option                           |
*             (0 = fuel coupled to coolant, 1 = channel only)          |
*----------------------------------------------------------------------|
                                 0
*
*----------------------------------|---------------------------------|
*                 |                  |      (if Forced Convection)     |
*  Coolant Type   |   Flow Type      |    Inlet       |    Outlet      |
*  (1 = water)    |(1=Natural Conv.) |  Pressure      |   Pressure     |
*                 |(0=Forced Conv.)  |   (psia)       |    (psia)      |
*----------------|---------------------------------|-------------------|
      1                   1               25.0            24.1
*
*------------------------------|--------------------------------------|
*   Coolant n & gamma Heating   |        Atmospheric Pressure          |
*     (J/g/J of Rx Power)       |      Above Pool Water (psia)         |
*------------------------------|--------------------------------------|
          0.261e-6                               12.5
*
*----------------------------------------------------------------------|
*                     Inlet (Unheated Length)                          |
```

```
*-----------------------------------------------------------------------|
*     Total Length (cm)         |           Number of Nodes             |
*-------------------------------|---------------------------------------|
             0.0                                0
*-----------------------------------------------------------------------|
*                     Inlet Unheated Length Description                 |
*-----------------------------------------------------------------------|
* Node Height |  Flow Area | Wetted Perimeter |       Inlet             |
*    (cm)     |    (cm2)   |       (cm)       |  Loss Coefficient       |
*-------------|------------|------------------|-------------------------|
*     1.0          4.042398        11.76998              0.0
*-----------------------------------------------------------------------|
*                        Fuel (Heated Length)                           |
*-----------------------------------------------------------------------|
*              |          |   Pitch or   |      Pitch/Flow Geometry     |
*     Fuel     |  Number  | Channel O.D. | (1=square pitch,2=hex pitch |
*  Length (cm) | of Nodes |     (cm)     |     3=annulus, 4=tube)      |
*--------------|----------|--------------|-----------------------------|
     52.25          52       4.171                  2
*
*-----------------------------------------------------------------------|
*                      Outlet (Unheated Length)                         |
*-----------------------------------------------------------------------|
*          Length (cm)          |           Number of Nodes             |
*-------------------------------|---------------------------------------|
             0.0                                 0
*-----------------------------------------------------------------------|
*                    Outlet Unheated Length Description                 |
*-----------------------------------------------------------------------|
* Node Height |  Flow Area | Wetted Perimeter |       Inlet             |
*    (cm)     |    (cm2)   |       (cm)       |  Loss Coefficient       |
*-------------|------------|------------------|-------------------------|
*     1.0          4.042398        11.76998              0.0
*
*---------------|--(not used)---|------------------|-------------------|
*    Chimney    |    Suppress    |  Channel Inlet   |    Channel Exit   |
*  Length (cm)  | Boiling (1=y)  | Loss Coefficient | Loss Coefficient  |
*---------------|----------------|------------------|-------------------|
      0.0                 0               0.5                 1.0
*
************************************************************************
*  Test Options (only the "Reactor Only" option is currently available)
************************************************************************
*
*-----------------------------------------------------------------------|
*                              Test Mode                                |
*-----------------------------------------------------------------------|
*   0 = Normal (no test; next 3 cards not required, so comment out)     |
*   1 = Specify BCs and/or Conductivities (next 2 cards required)       |
*-----------------------------------------------------------------------|
                                0
*
*  Fuel Element Surface BC  1=convection / 2=constant T --> BC Temp
*           2                                                  120.0
*
*
*  Fuel Element Material Constant Thermal Conductivity 1=yes / 0=no
*           1
*
*  Conductivity (W/cm/K) -- 6 entries required for materials 1-6
*      0.160  0.500  0.160   0.150  0.160  0.160
*
*
```

```
*  Module Selection
*
*----------------------------------------------------------------------|
*                    Reactor Only Test Option                           |
*----------------------------------------------------------------------|
*   Reactor Only (1=y/0=no)      |   Energy Yield Feedback ($/J-Rx)     |
*-------------------------------|--------------------------------------|
               0                        -3.87597e-4
*
***********************************************************************
*  Defined Power History Option     (Uses constant Time Step)
*     (1=y/0=no)   (1 Turns Reactor Module Off)
***********************************************************************
         0
*
* if selected, create a power history file (pwrhis.dat)
* to be read in by code
*
***********************************************************************
```

APPENDIX B: PULSE LOG SHEET EXCERPTS

Operation 9716 Console Log

```
DATE  01-05-11
TIME  16:56
RUN NO      09716

PPS1

NV    33310
NVT   312
TEMPERATURE 1 PEAK      37
TEMPERATURE 2 PEAK      860
TEMPERATURE 3 PEAK      860


PPS2

NV    34240
NVT   330
TEMPERATURE 1 PEAK      819
TEMPERATURE 2 PEAK      842
TEMPERATURE 3 PEAK      815


FREC

TEMPERATURE 1 PEAK      28
TEMPERATURE 2 PEAK      207


      CR Bank Position (RU)   CR Bank Worth (cents)
TR UP DC           1488        1020.5
Free Field DC      1501        1016.8
Experiment Worth        3.7

TR Down DC         2410        717.0
TR Bank Worth           303.5

Setup DC           2400        720.6
Pulse Size         299.9

      TR Bank Position (RU)   TR Bank Worth (cents)
Setup Pulse Size  4185        309.8
```

Operation 9716 Diagnostic System Report (Excerpt)

Shot Information			Predicted Values		
Run Number	9716		Expected MW		35500
Operator	Dave Clovis		Expected TTP		0.3125
Date \ Time	1/5/2011 16:52		Expected MJ		286.26
Experimenter Name	ACRR		Expected Fuel Temp		837.2
Experiment Plan #	MP 11		Dialed In MW		32285.51
Package Worth $	0.037				
Shot Worth $	3.035				
Rod Hold Up (sec)	0.4				
FREC Mode	Decoupled				
FREC RODS	DOWN				

Comments

	Average	CH-1	CH-2	CH-3	CH-4
Detector		DE2-3	DE4-9	DE5-1	
Detector Calibration		42.6	40.2	40.6	
Channel Type		PXI Amp	SR570 Amp	SR570 Amp	
Average Used		Both	Both	Both	
Period Used		Yes	Yes	Yes	
PEAK DATA:					
Peak (MW)	**29605.9**	27216.3	31278.5	30395.7	
TTP (sec)	0.34356	0.34208	0.34352	0.34356	
FWHM (sec)	0.00724	0.00768	0.00708	0.00708	
LEHM (sec)	0.0036	0.00252	0.0034	0.0034	
TEHM (sec)	0.00364	0.00516	0.00368	0.00368	
Ratio (LE/TE)	0.989	0.488	0.924	0.924	
Shot Worth	2.851	3.179	3.068	3.029	
YIELD DATA:					
Total Yield (MJ)	**294.132**	266.532	350.252	270.045	
TTP+3fwhm (MJ)	242.895	236.182	249.605	242.814	
Yield @ Peak (MJ)	118.517	80.292	118.256	115.563	
Min Period (sec)	0.001738	0.001474	0.001554	0.001584	

Operation 9718 Console Log

```
DATE  01-06-11
TIME  13:39
RUN NO      09718

PPS1

NV    17867
NVT   229
TEMPERATURE 1 PEAK      36
TEMPERATURE 2 PEAK      656
TEMPERATURE 3 PEAK      654


PPS2

NV    18347
NVT   242
TEMPERATURE 1 PEAK      618
TEMPERATURE 2 PEAK      635
TEMPERATURE 3 PEAK      612


FREC

TEMPERATURE 1 PEAK      27
TEMPERATURE 2 PEAK      160


      CR Bank Position (RU)   CR Bank Worth (cents)
TR UP DC           1484        1021.6
Free Field DC      1481        1022.5
Experiment Worth        -0.9

TR Down DC         2408        717.8
TR Bank Worth           303.8

Setup DC           2257        771.5
Pulse Size         250.1

      TR Bank Position (RU)   TR Bank Worth (cents)
Setup Pulse Size  4561        260.5
```

Operation 9718 Diagnostic System Report (Excerpt)

Shot Information			Predicted Values		
Run Number	9718		Expected MW		18000
Operator	Kraig Deike		Expected TTP		0.3208
Date \ Time	1/6/2011 13:35		Expected MJ		209.34
Experimenter Name	ACRR Staff		Expected Fuel Temp		618.5
Experiment Plan #	OP-2/OP AID 29		Dialed In MW		16398.82
Package Worth $	-0.009				
Shot Worth $	2.501				
Rod Hold Up (sec)	0.4				
FREC Mode	Decoupled				
FREC RODS	DOWN				

Comments ACRR Cal pulse per MP-11

	Average	CH-1	CH-2	CH-3	CH-4
Detector		DE2-3	DE4-9	DE5-1	
Detector Calibration		42.6	40.2	40.6	
Channel Type		PXI Amp	SR570 Amp	SR570 Amp	
Average Used		Both	Both	Peak	
Period Used		Yes	Yes	Yes	
PEAK DATA:					
Peak (MW)	**16393**	16256	16659.8	16292.5	
TTP (sec)	0.34928	0.34904	0.34932	0.34936	
FWHM (sec)	0.0092	0.00916	0.00924	0.0092	
LEHM (sec)	0.00448	0.0044	0.00444	0.00444	
TEHM (sec)	0.00472	0.00476	0.0048	0.00476	
Ratio (LE/TE)	0.949	0.924	0.925	0.933	
Shot Worth	2.378	2.665	2.875	2.839	
YIELD DATA:					
Total Yield (MJ)	**201.706**	203.771	202.722	189.433	
TTP+3fwhm (MJ)	171.709	170.027	174.429	170.663	
Yield @ Peak (MJ)	81.805	80.265	82.363	80.856	
Min Period (sec)	0.002343	0.001935	0.001716	0.00175	

Operation 9719 Console Log

```
DATE  01-10-11
TIME  15:56
RUN NO      09719

PPS1

NV    7755
NVT   144
TEMPERATURE 1 PEAK      39
TEMPERATURE 2 PEAK      454
TEMPERATURE 3 PEAK      458


PPS2

NV    7962
NVT   155
TEMPERATURE 1 PEAK      432
TEMPERATURE 2 PEAK      444
TEMPERATURE 3 PEAK      424


FREC

TEMPERATURE 1 PEAK      30
TEMPERATURE 2 PEAK      113


      CR Bank Position (RU)   CR Bank Worth (cents)
TR UP DC          1485        1021.4
Free Field DC     1481        1022.5
Experiment Worth        -1.1

TR Down DC        2405        718.8
TR Bank Worth           302.6

Setup DC          2115        821.2
Pulse Size        200.2

      TR Bank Position (RU)   TR Bank Worth (cents)
Setup Pulse Size  4946        210.9
```

Operation 9719 Diagnostic System Report (Excerpt)

Shot Information			Predicted Values		
Run Number	9719		Expected MW		7000
Operator	Lance Lippert		Expected TTP		0.3395
Date \ Time	1/10/2011 15:54		Expected MJ		136.15
Experimenter Name	ACRR STAFF		Expected Fuel Temp		413.8
Experiment Plan #	MP-11		Dialed In MW		6528.42
Package Worth $	-0.011				
Shot Worth $	2.002				
Rod Hold Up (sec)	0.4				
FREC Mode	Decoupled				
FREC RODS	DOWN				

Comments

	Average	CH-1	CH-2	CH-3	CH-4
Detector		DE2-3	DE4-9	DE5-1	
Detector Calibration		42.6	40.2	40.6	
Channel Type		PXI Amp	SR570 Amp	SR570 Amp	
Average Used		Both	Both	Both	
Period Used		Yes	Yes	Yes	
PEAK DATA:					
Peak (MW)	**7092.1**	6991.4	7227.2	7061.9	
TTP (sec)	0.36816	0.36788	0.36816	0.3682	
FWHM (sec)	0.01324	0.01324	0.01324	0.0132	
LEHM (sec)	0.00644	0.00636	0.00636	0.00636	
TEHM (sec)	0.0068	0.00688	0.00688	0.00684	
Ratio (LE/TE)	0.947	0.924	0.924	0.93	
Shot Worth	1.947	2.082	2.215	2.398	
YIELD DATA:					
Total Yield (MJ)	**125.349**	122.929	129.803	125.204	
TTP+3fwhm (MJ)	107.281	105.702	109.316	106.807	
Yield @ Peak (MJ)	51.18	49.785	51.56	50.518	
Min Period (sec)	0.003415	0.002989	0.00266	0.002309	

Operation 9720 Console Log

DATE 01-13-11
TIME 11:04
RUN NO 09720

PPS1

NV 1560
NVT 68
TEMPERATURE 1 PEAK 35
TEMPERATURE 2 PEAK 239
TEMPERATURE 3 PEAK 236

PPS2

NV 1616
NVT 71
TEMPERATURE 1 PEAK 227
TEMPERATURE 2 PEAK 233
TEMPERATURE 3 PEAK 223

FREC

TEMPERATURE 1 PEAK 27
TEMPERATURE 2 PEAK 68

	CR Bank Position (RU)	CR Bank Worth (cents)
TR UP DC	1491	1019.6
Free Field DC	1481	1022.5
Experiment Worth	-2.9	
TR Down DC	2419	713.8
TR Bank Worth	305.8	
Setup DC	1973	869.5
Pulse Size	150.1	

	TR Bank Position (RU)	TR Bank Worth (cents)
Setup Pulse Size	5404	156.5

Operation 9720 Diagnostic System Report (Excerpt)

Shot Information			Predicted Values		
Run Number	9720		Expected MW		1500
Operator	Lonnie Martin		Expected TTP		0.4085
Date \ Time	1/13/2011 11:03		Expected MJ		62.57
Experimenter Name	ACRR staff		Expected Fuel Temp		207.1
Experiment Plan #	MP-11		Dialed In MW		1300.77
Package Worth $	-0.029				
Shot Worth $	1.5				
Rod Hold Up (sec)	0.4				
FREC Mode	Decoupled				
FREC RODS	DOWN				

Comments TRW Worth Determination

	Average	CH-1	CH-2	CH-3	CH-4
Detector		DE2-3	DE4-9	DE5-1	
Detector Calibration		42.6	40.2	40.6	
Channel Type		PXI Amp	SR570 Amp	SR570 Amp	
Average Used		Both	Both	Both	
Period Used		Yes	Yes	Yes	
PEAK DATA:					
Peak (MW)	**1429.8**	1412.8	1457.8	1419.1	
TTP (sec)	0.43896	0.43888	0.43944	0.43904	
FWHM (sec)	0.02712	0.02716	0.02712	0.02708	
LEHM (sec)	0.01288	0.013	0.01328	0.01284	
TEHM (sec)	0.01424	0.01416	0.01384	0.01424	
Ratio (LE/TE)	0.904	0.918	0.96	0.902	
Shot Worth	1.416	1.732	1.702	2.077	
YIELD DATA:					
Total Yield (MJ)	**54.787**	55.594	57.937	51.656	
TTP+3fwhm (MJ)	46.28	45.804	47.2	45.856	
Yield @ Peak (MJ)	20.892	20.829	21.879	20.667	
Min Period (sec)	0.007756	0.004422	0.004615	0.003002	

Operation 9022 Console Log

```
DATE  05-30-08
TIME  11:27
RUN NO      09022

PPS1

NV    65
NVT   311
TEMPERATURE 1 PEAK      37
TEMPERATURE 2 PEAK      718
TEMPERATURE 3 PEAK      723


PPS2

NV    98
NVT   306
TEMPERATURE 1 PEAK      732
TEMPERATURE 2 PEAK      769
TEMPERATURE 3 PEAK      752


FREC

TEMPERATURE 1 PEAK      213
TEMPERATURE 2 PEAK      195


      CR Bank Position (RU)   CR Bank Worth (cents)
TR UP DC          1514        1013.1
Free Field DC     1505        1015.6
Experiment Worth        -2.5

TR Down DC        2818        570.1
TR Bank Worth           443.0

Setup DC          2668        624.0
Pulse Size        389.1

      TR Bank Position (RU)   TR Bank Worth (cents)
Setup Pulse Size  3500        388.6
```

Operation 9023 Console Log

```
DATE  05-30-08
TIME  12:48
RUN NO      09023

PPS1

NV    44
NVT   308
TEMPERATURE 1 PEAK      35
TEMPERATURE 2 PEAK      722
TEMPERATURE 3 PEAK      726


PPS2

NV    98
NVT   307
TEMPERATURE 1 PEAK      730
TEMPERATURE 2 PEAK      767
TEMPERATURE 3 PEAK      749


FREC

TEMPERATURE 1 PEAK      214
TEMPERATURE 2 PEAK      195


      CR Bank Position (RU)   CR Bank Worth (cents)
TR UP DC          1504        1015.9
Free Field DC     1505        1015.6
Experiment Worth        0.3

TR Down DC        2818        570.1
TR Bank Worth           443.0

Setup DC          2654        629.1
Pulse Size        386.8

      TR Bank Position (RU)   TR Bank Worth (cents)
Setup Pulse Size  3500        388.6
```

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