INL/EXP-21-63697-Revision-0

Analysis of Lobe Power Calculator and Indication System with Physics and Cycle Based Models

July 2021

Changing the World's Energy Future

Gerardo NMN Herrera

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/EXP-21-63697-Revision-0

Analysis of Lobe Power Calculator and Indication System with Physics and Cycle Based Models

Gerardo NMN Herrera

July 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Analysis of Lobe Power Calculator and Indication System with Physics and Cycle Based Models

Gerardo Herrera

Office of Science, Science Undergraduate Laboratory Internship Program

Boise State University, Boise, ID

Idaho National Laboratory

Idaho Falls, ID

July 28, 2021

Prepared in partial fulfillment of the requirements of the Department of Energy, Office of Science's Science Undergraduate Laboratory Internship Program under the direction of Nathan T. Sparks at Idaho National Laboratory.

Participant: ___________________

Gerardo Herrera

Research Advisor: _________________

Daniel R. Steik

ABSTRACT

The Advanced Test Reactor (ATR) at INL measures reactor power through various methods, two of them being thermal and Nitrogen-16 (N-16) activity. Water power calculator (WPC) is a thermal power system that measures flow and temperature to determine thermal quadrant powers. The N-16 system utilizes a beta detector that outputs Nitrogen activation levels to calculate lobe power through an algorithm called Lobe Power Calculation and Indication system (LPCIS). The LPCIS utilizes the N-16 system and the WPC system to determine reactor core power levels.

The WPC provides accurate calculations of quadrant and total reactor thermal power. With the use of WPC measurements, thermal-to-N-16 (T2N) power ratios are produced to determine if the two indication systems agree on core power. Relative magnitude equations are used to utilize N-16 coefficients and multipliers to improve the indications of the LPCIS. These correct indications are crucial for maintaining safety limits because operators rely on this information for decision making. Currently, the LPCIS system uses linear equations and matrices to calculate lobe power through multipliers and coefficients. Advancements in technology and system upgrades have increased the accuracy of power readings by making the system more dynamic.

The new proposed coefficient and multiplier method implements a cycle specific and physics-based model intended for changing coefficients during operation. This calibration experiment focused on power splitting, outer shim and neck shim, as well as fuel burning into the reactor digital acquisition system (RDAS) weighting factors. Results demonstrated that the physics learning method yields a smaller error margin inside of the desired power range for the data set 166-A. Continuing to improve the physics-based model will help improve the power accuracy of the LPCIS system.

I. INTRODUCTION

Reactor power monitoring and analysis is crucial when operating INL's Advanced Test Reactor's (ATR). It allows operators and engineers to monitor the cores status while maintaining stable conditions. Two methods of measuring reactor power are through thermal and Nitrogen-16 (N-16) activity.[1]

The N-16 system provides measurements to the LPCIS by measuring radioactivity of activated coolant. In ATR's core, the Oxygen-16 (O-16) present in the coolant is activated by fast neurons, producing Nitrogen-16. This N-16 is a radioactive material with a half-life of 7.1 seconds. When N-16 decays back to O-16, it emits beta particles with a distinct energy.[2] This process is measured by beta counters and the signals are sent to the LPCIS algorithm for reactor power calculations. This reaction is measured throughout ten beta chambers that make up the N-16 channels located around the core. LPCIS utilized N-16 activity to provide one form of power indication, and thermal power values were compared with the algorithm for safety purposes.[3] The N-16 system is important because it's the only method in which lobe power distribution is determined.

Power measured through thermal activity utilizes the Water Power Calculator (WPC) to measure both quadrant and thermal power through temperature and flow rates. The WPC provides these power calculations to the reactor digital acquisition system (RDAS). Once in the RDAS, the sum of the quadrant powers are utilized as power constraints for the reactor lobe powers.[1] This is done by the LPCIS, which scales the reactor core lobe and quadrant power indications.

The N-16 and WPC system each measure reactor power, however they are independent of each other. The WPC is based on water flow and is unable provide lobe powers because it is utilized as a safety constrain for the LPCIS that provides lobe power indications. More specific, LPCIS uses the N-16 system with the ten beta detectors to provide the desired measurements.[4] The detectors are placed to maximize count rate, avoid neutron bombardment, and to minimize fluctuation in flow rate (Figure 1).

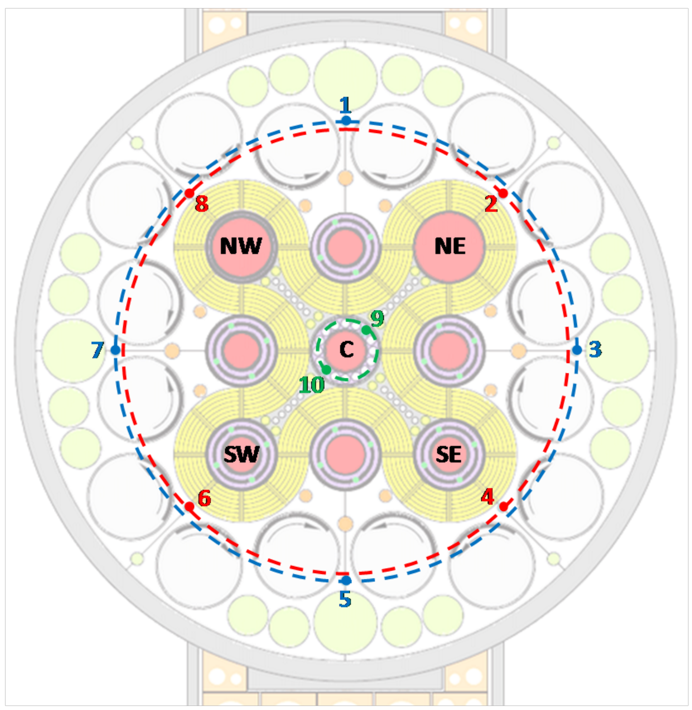

Figure 1. N-16 detector locations.

From the ten detector locations, magnitude equations, as seen in [Eqn. 1] are derived.

M_j represents the multiplier for the j^{th} detector. N_j represents the j^{th} detector signal from the beta detectors. $C_{i,j}$ represents the coefficient for the i^{th} lobe and j^{th} detector. P_i represents the i^{th} power lobe. The calculated lobe power consists of lobe power output (P_i) and lobe power coefficients (c^i_j). The summation of the ten detector equations provides the desired LPCIS indications.[4] Using matrix mathematics, the ten detectors are arranged in a five by ten matrix that require 50 calibrated coefficients. The calculated output is compared with the WPC output to ensure the reactor power levels are being recorded and measured accurately.[5]

This research demonstrates the implementation of high power computing (HPC) to calculate new coefficients through a physics cycle based approach. Power indicated through the traditional solution of least squares method serves as a comparison for power indicated through the HPC coefficients and multipliers.

II. METHODS

A. Data Retrieval

The reactor data gathered for this experiment is retrieved from the RDAS. The data from RDAS is crucial for this experiment considering it allows for the digitizing of power indication. Data used for this research was taken from the 166-A.[1] Other cycles such as the 169-A were utilized for further investigation once the specified coefficients and multipliers produced desired results.

B. Methods of Obtaining Coefficients and Multipliers

1. Least Squares Method

Currently coefficients and multipliers being applied to ATR use the least squares method. Magnitude equations are utilized to produce values based on a system of equations. Calculations are preformed using a computer to solve the specified equations.[3] This method has been in implementation for decades and excels at performance however, an update would provide a more accurate power reading while maintaining safety margins.

2. Physics based Method

A physics based approach allows for a more logical and systematic approach to finding equation values. With the help of the HPC, cycle runs were processed to find new coefficients and multipliers that were applied to power calculations. These values vary the longer the HPC operates cycle evaluations. In this experiment, 23 hour, 11 day, and 40 day evaluations were utilized on a certain section of the 166-A data to provide coefficients. The multipliers remain the same for each evaluation.

C. Computer Analysis

In this experiment a MATLAB script was utilized for mathematical representations of power calculation. This further allowed for reproduction of the reactor indications based on coefficients and multipliers. MATLAB was used to input the multipliers and coefficients produced by the HPC. The two methods of power calculations are utilized when running the program. Each method considered the constrained and unconstrained application of values. In constrained the quadrant and total power are restricted to match with the WPC. In unconstrained, LPCIS calculated power without the safety constraints of WPC. When reactor power indication is greater than 3 MW, RDAS will send a signal to run LPCIS as constrained. At this point normalizing/weighting factors will be included to scale the power measurements gathered through N-16 activity.[5]

D. Analyzing Graphs

MATLAB provided power indication results in three-ways quadrant powers, total power, and T2N ratios. The quadrant power is analyzed by splitting the total power into four sections which MATLAB represents as four graphs. In these graphs WPC and LPCIS power levels were compared and measure MW vs days. The sum of these four sections were compared on a total power graph. Finally, the ratio graph compared the four quadrants using a T2N ratio (Thermal power/LPCIS power) which compares the accuracy of LPCIS to WPC. This comparison creates a unitless ratio between the two systems over the course of days. Ideally the results should demonstrate power ratios for the four quadrants at 1. This signifies 100% matching power calculations between WPC and LPCIS.[1]

III. RESULTS

The experiment began with establishing a baseline for testing the current least squares method using data from cycle 166-A. Results for the unconstrained test displayed an error difference of 9% with a T2N ratio ranging from 0.90 to 0.99(Figure 2). The constrained test was applied to three different weighting factors, 10, 100, and 10000. Results demonstrated that more favorable T2N ratios were present as the weighting factor increased.[3] For example, when a weighting factor of 10000 was applied, an error difference resulted in approximately 8% with a T2N ratio ranging from 1.03 to 0.95 (Figure 3). When a weighting factor of 10 was applied, an error difference resulted in 9% with a T2N ratio ranging from 0.99 to 0.90 (Figure 4). Although there wasn't much error difference, the greater weighting factor allowed for a more desirable T2N ratio. This is crucial considering LPCIS and WPS indication levels should be accurate when compared with each other.[3]

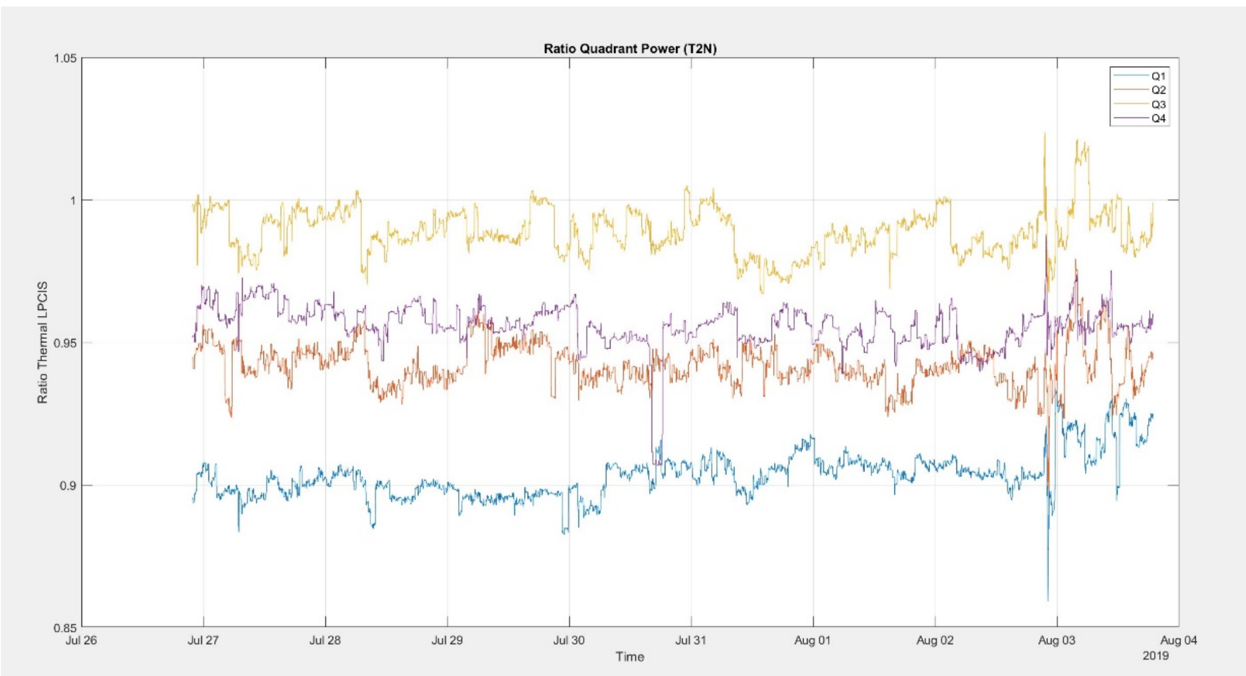

Figure 2. Unconstrained T2N Ratios using least squares method

Figure 3. Constrained T2N Ratios using least squares method (weighting factor 10^4)

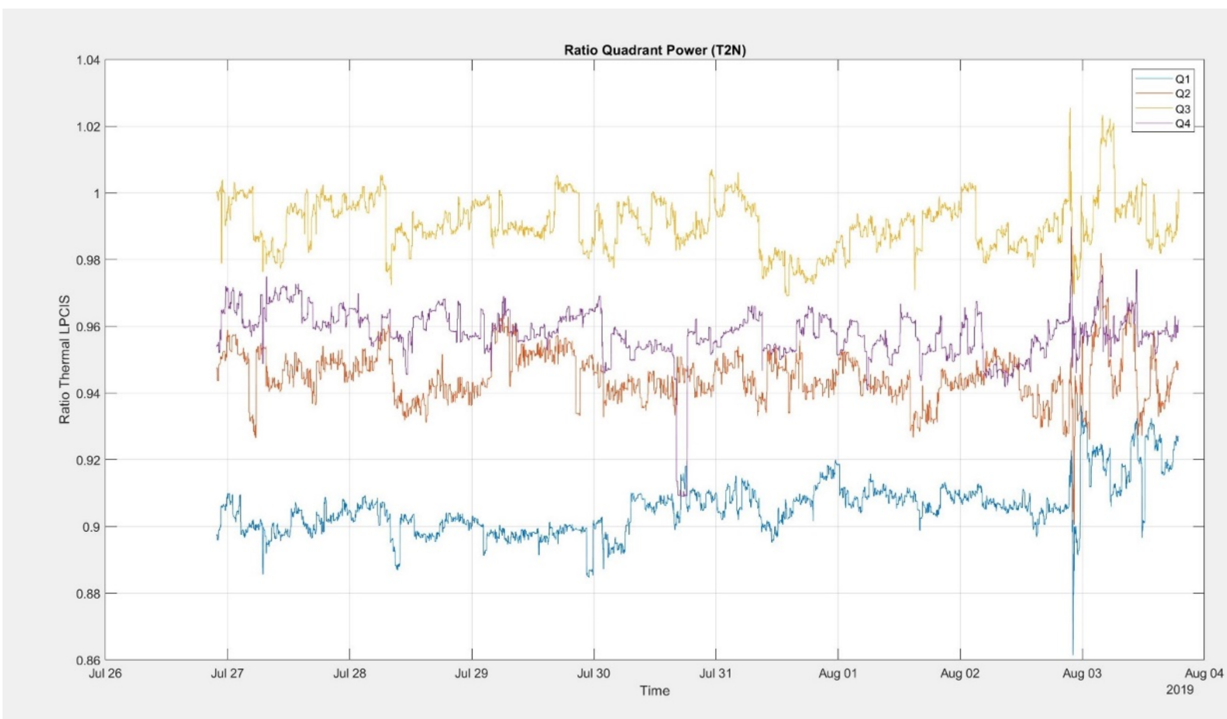

Figure 4. Constrained T2N Ratios using least squares method (weighting factor 10)

The physics based testing consisted of three parts and each part resulted in different coefficients based on HPC calculations. The HPC evaluations consisted of 23 hours, 11 days, and 40 days of processing time. This testing proved to be inefficient because the results provided data that was not desirable. In some constrained cases the error difference resulted in 16% with a T2N ratio ranging from 0.93 to 1.09 (Figure 5). In unconstrained the total power produced WPC readings that were approximately 9 times greater than the LPCIS readings (Figure 6). This resulted in ratios with an error difference of 17% with T2N ratios ranging from 0.24 and 0.08. These power calculations were most likely produced by excluding thermal flow rates and tube core lengths in the HPC simulations.[4] These readings aren't desirable considering they would alert RDAS that power indications aren't correct and reactor safety measures would soon follow.

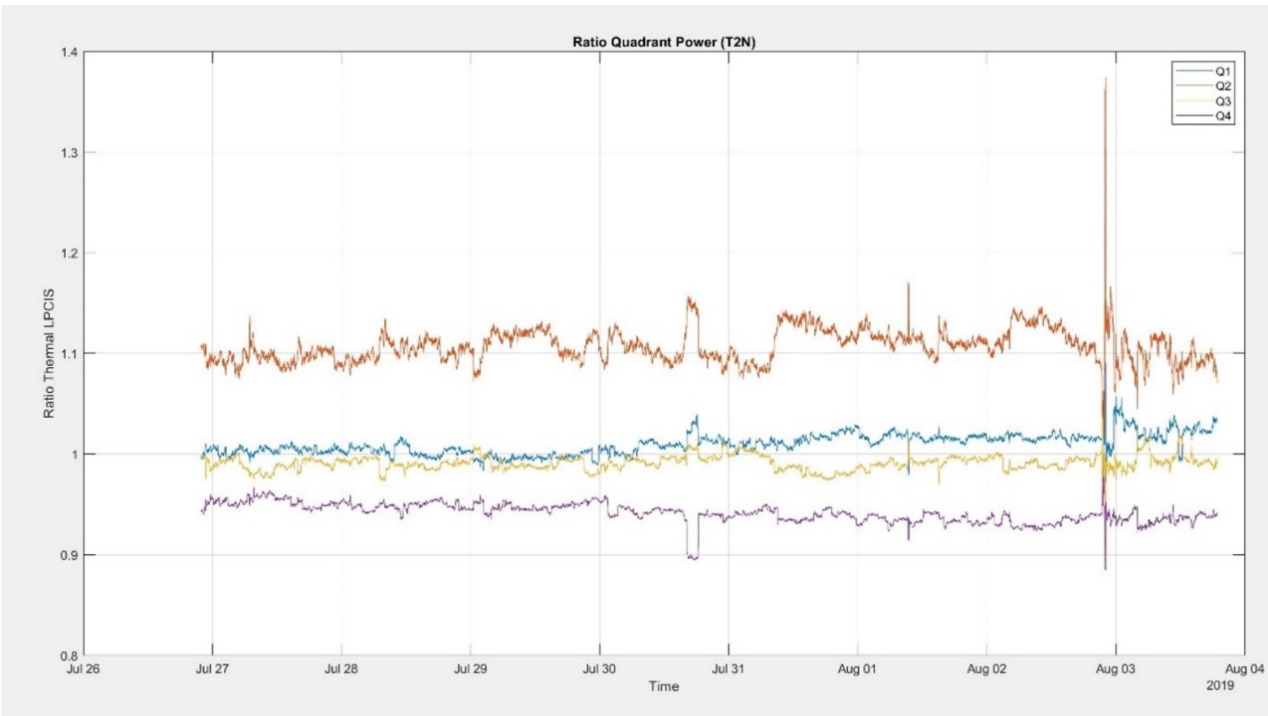

Figure 5. First physics set with errors and implementation of 166-A (weighting factor of 10^4).

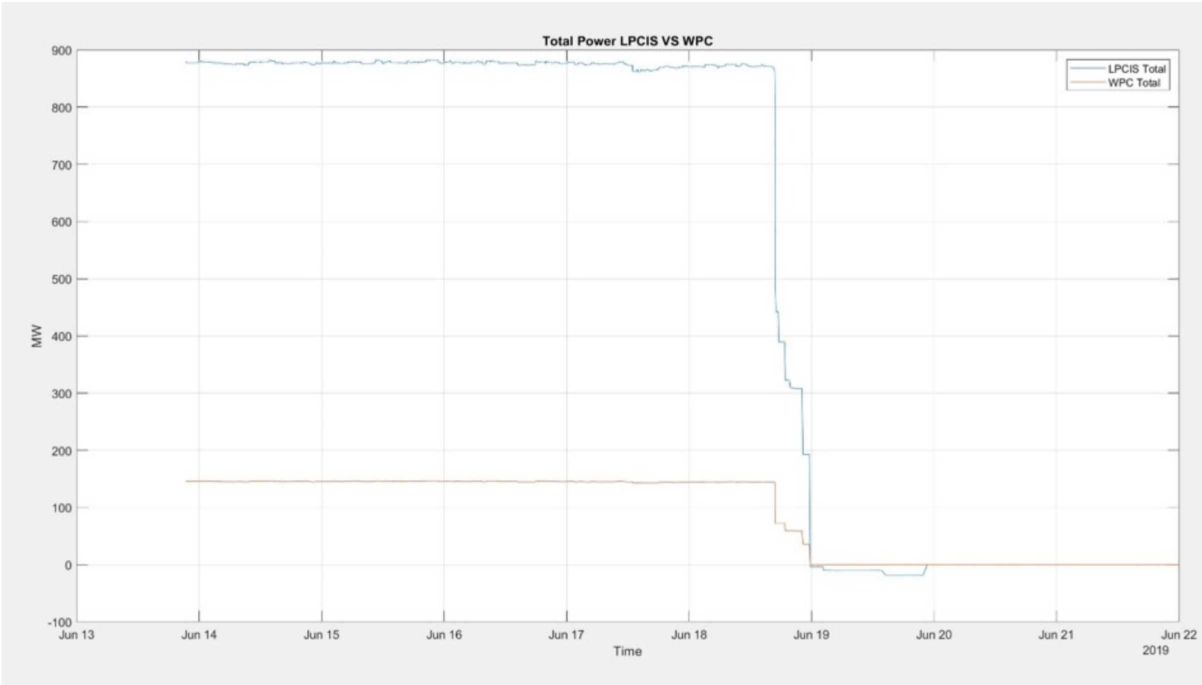

Figure 6. Unconstrained total power comparison of LPCIS and WPC.

Power calculations improvements were notable when applying new updated coefficients to include thermal flow rates and core tube lengths in the HPC simulation. In this experiment the same 23 hour, 11 day, and 40 day HPC evaluations were utilized for power calculations. The longer the HPC calculated coefficients the better the results. When applying constrained testing the least desirable case appeared at 23 hour calculations while the most desirable case appeared at 40 day calculations. This is likely due to the HPC utilizing more time to process the data patterns. The weighting factors also determined the results of power calculations. In many cases as the weighting factor increased, error decreased, and a positive shift was seen on the overall quadrant powers. Comparison of the unconstrained results further supports the improvement of the physics based method. The most desirable unconstraint case produced was evaluated with 40 day calculations. The least desirable case was produced by 23 hour calculations and produced results similar to those of the unconstrained traditional least squared method.

Based on the 166-A cycle, coefficients and multipliers were applied to the least squares and physics based methods to compare the differences in the updated approach (Figures 7,8). It is evident that the new physics approach produces slightly less ratio error, which is desirable when comparing power calculation. The physics approach additionally has a more favorable T2N ratio because it stays within the desired range. The physics method is also supported by the results of total power calculations. It’s notable that the physics approach follows the WPC trendline with less deviation (Figure 9). The two power calculating methods are similar; however, the least squares method has a slight shift to the LPCIS calculations causing more error (Figure 10). The WPC is used as reference considering its thermal power calculation is more direct and accurate.[3]

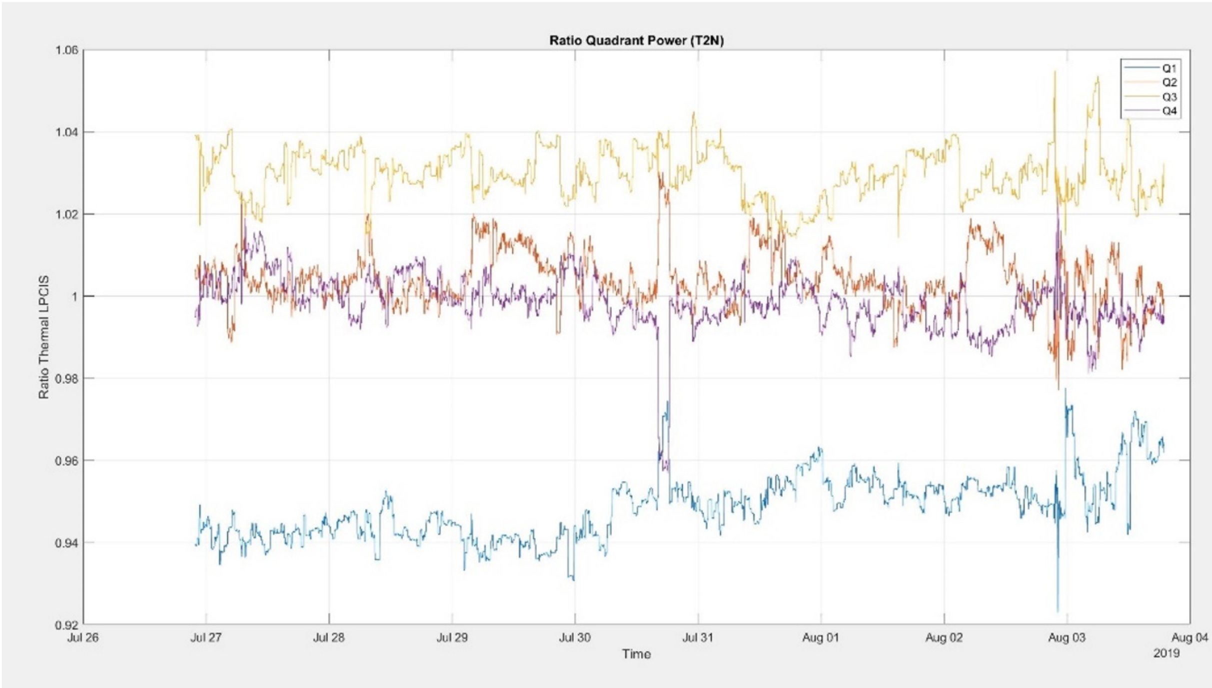

Figure 7. Traditional least squares method implemented on 166-A (weighting factor of 10^4).

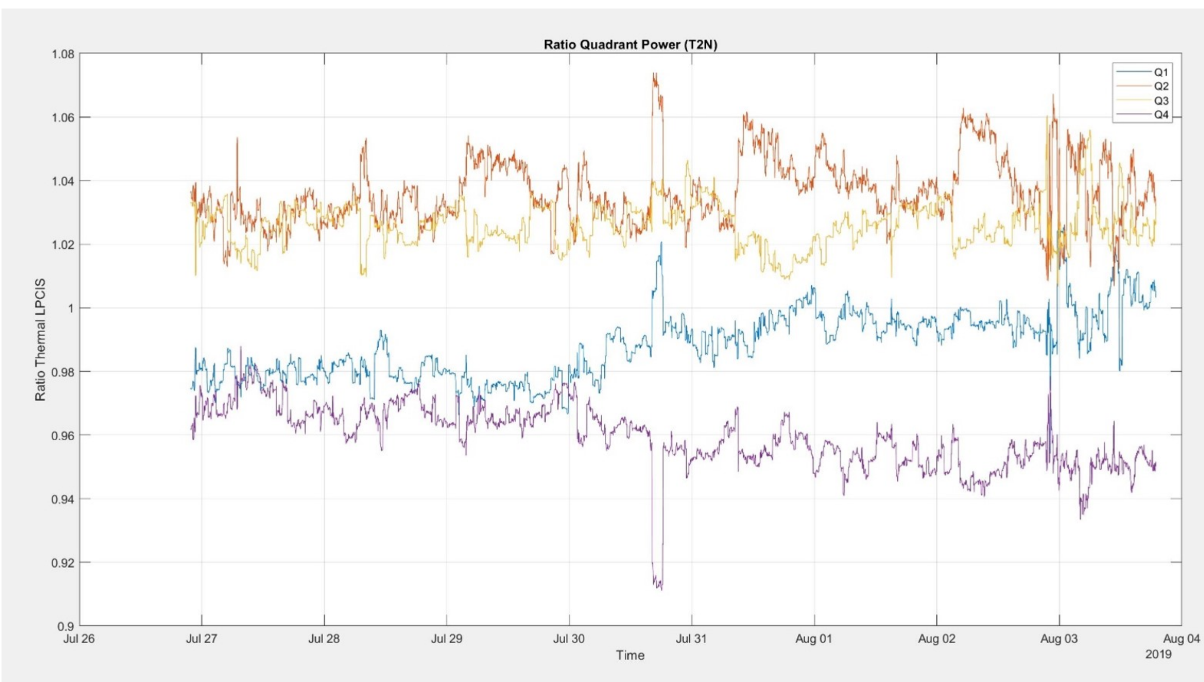

Figure 8. Physics method with 40 day evaluation implemented on 166-A (Weighting factor 10^4).

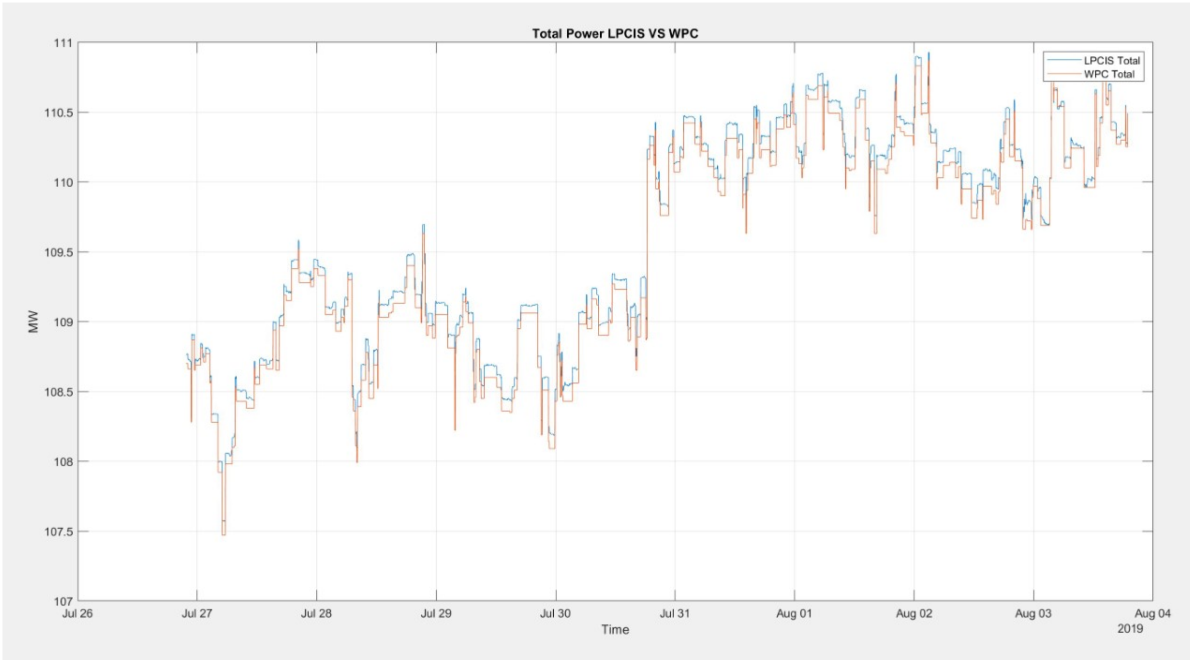

Figure 9. Total power of physics method with constrained comparison of LPCIS and WPC (weighting factor 10^4).

Figure 10. Total power of least squares method with constrained comparison of LPCIS and WPC (weighting factor 10^4).

Once the testing of physics based coefficients and multipliers was completed, the same values were applied to a different reactor cycle (169-A). This allowed for a better understanding of the calculated coefficient and multiplier applications. Results showed that applying 166-A physics based coefficients on different cycles produced calculations with more error. The results consisted of power calculations ranging from 0.90 to 1.05 (Figure 11). Alternatively, the current traditional least square multipliers and coefficients produced desirable power calculations ranging from 0.97 to 1.02 with a T2N ratio error of 5% (Figure 12). Results from testing the 169-A cycle were most likely due to the physics coefficients calculated from 166-A data.

Figure 11. Physics method with 40 day evaluation implemented on 169-A (weighting factor 10^4).

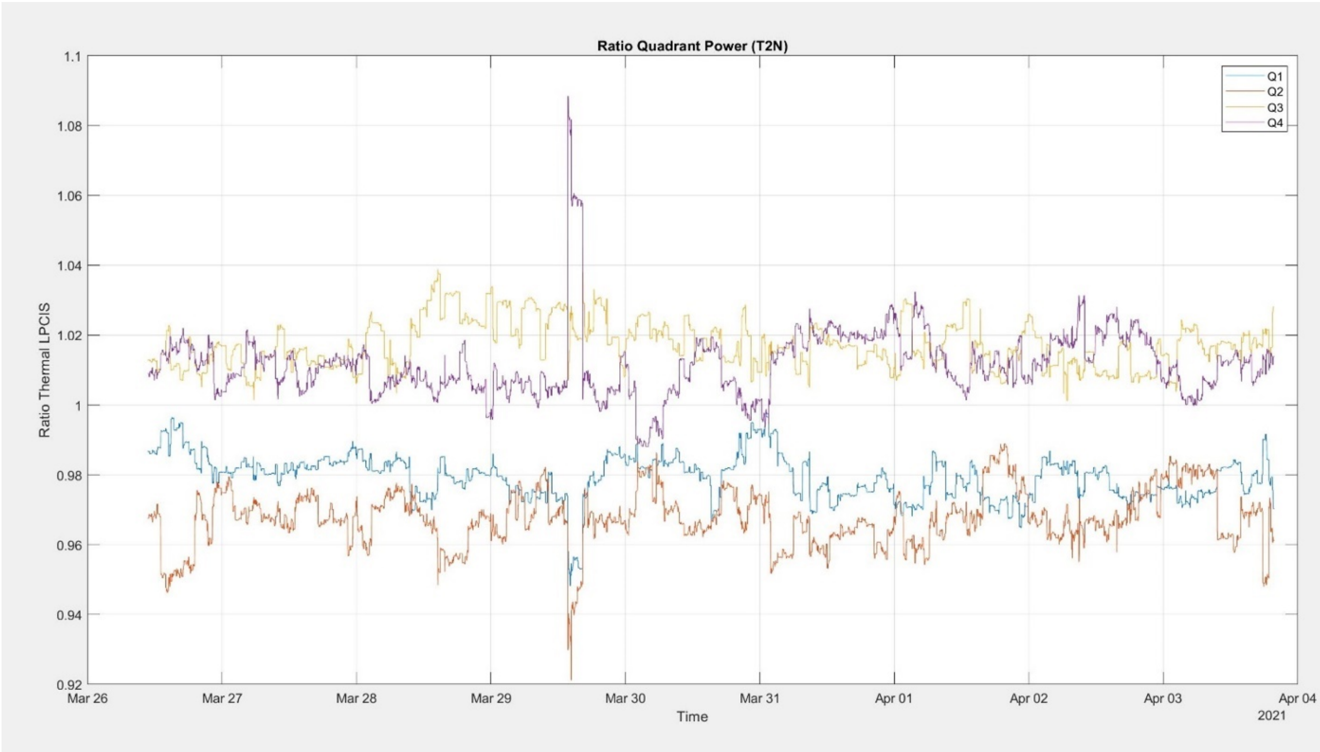

Figure 12. Least squares method with 40 day evaluation implemented on 169-A (weighting factor 10^4).

IV. CONCLUSION

The efficiency of power calculation was analyzed by implementing the current least squares method and the new physics and cycle based method. It was hypothesized that the new physics method would increase power reading accuracy and calculations while at the same time maintaining safety limits. For this theory the application of physics based coefficients and multipliers, derived from a specific cycle, demonstrated promising results to reaching our goal. However, the cycle based coefficients and multipliers aren't adaptable to different reactor cycles.

Furthermore, the physics method approach is not an ideal way to derive coefficients and multipliers for power calculations. Invalidation is confirmed by comparison of power calculations produced by different reactor cycles. A different approach that considers the behavior of each independent cycle must be researched in order to derive a reliable physics based method.

V. FURTHER RESEARCH

While the current least squares method will continue to operate, power calculation alternatives will be explored to maximize reactor reading accuracy. As technology continues to improve, the implementation of a machine learning method is additionally considered for testing. For the time being, efforts will be focused on the implementation of 100% physics based coefficients that operate in real time. These values will be better equipped to handle the variation of reactor cycles.

VI. ACKNOWLEDGEMENTS

I would like to acknowledge and give a special thanks to my advisor Nathan T. Sparks. His in-depth knowledge and instruction about the LPCIS algorithm and WPC made this work possible. I would also like to thank Daniel R. Steik for his advice and support. Finally, I would like to thank Daren Norman and Matthew P. Johnson, their support was instrumental to completing this work. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI) program.

VII. APPENDIX

Appendix A. Physics-Based C and M Values

Table A1. M values and their locations on the reactor.

N	24.2
NE	62.48
E	19.63
SE	59.93
S	15.42
SW	55.37
W	17.73
NW	57.44
CMID	102.02
C	46.76

Table A2. 23 hour C evaluations and their locations on the reactor.

	NW	NE	C	SW	SE
N	5.922291	5.895544	1.250698	0.100168	0.099876
NE	0.187549	31.62087	0.558427	0.027361	0.193545
E	0.073361	4.723666	1.050964	0.083962	4.55535
SE	0.028104	0.232367	0.768894	0.237585	40.26463
S	0.070065	0.076948	1.203432	4.40701	4.453857
SW	0.206876	0.030651	0.764615	39.21042	0.234199
W	5.126521	0.086782	1.110782	4.786819	0.08538
NW	41.68385	0.213918	0.58445	0.197267	0.026559
CMID	4.698427	12.27856	46.57121	2.042815	4.883438
C	4.32359	1.958745	48.02531	9.688293	4.35992

Table A3. 11 day C evaluations and their locations on the reactor.

	NW	NE	C	SW	SE
N	5.904347	6.00914	1.307769	0.101229	0.100697
NE	0.198691	32.60673	0.566753	0.027184	0.194548
E	0.078947	4.776996	1.043951	0.083455	4.598316
SE	0.029651	0.233103	0.756003	0.237704	40.75511
S	0.076042	0.07885	1.187426	4.471758	4.517761
SW	0.218434	0.03064	0.76582	40.36201	0.236499
W	5.090149	0.086735	1.149617	4.863436	0.087124
NW	39.34264	0.21543	0.619943	0.1981	0.026952
CMID	5.08431	12.19481	46.58146	2.007886	4.859126
C	4.727851	1.968617	48.28377	9.646424	4.402973

Table A4. 40 day C evaluations and their locations on the reactor.

	NW	NE	C	SW	SE
N	5.970765	6.088963	1.283259	0.103027	0.101325
NE	0.197491	35.5327	0.555146	0.027723	0.19583
E	0.078255	4.907505	1.049838	0.08542	4.635967
SE	0.029329	0.227092	0.777504	0.240998	41.2657
S	0.075634	0.078005	1.2349	4.483398	4.528935
SW	0.217522	0.029979	0.786779	40.1951	0.238043
W	5.169009	0.085032	1.155682	4.877041	0.088422
NW	40.78501	0.209416	0.611225	0.200613	0.027257
CMID	5.006407	11.62694	45.66256	2.04206	4.902892
C	4.687383	1.899493	49.44472	9.966935	4.482594

Appendix B. Complete Testing procedure (40 Day calculation)

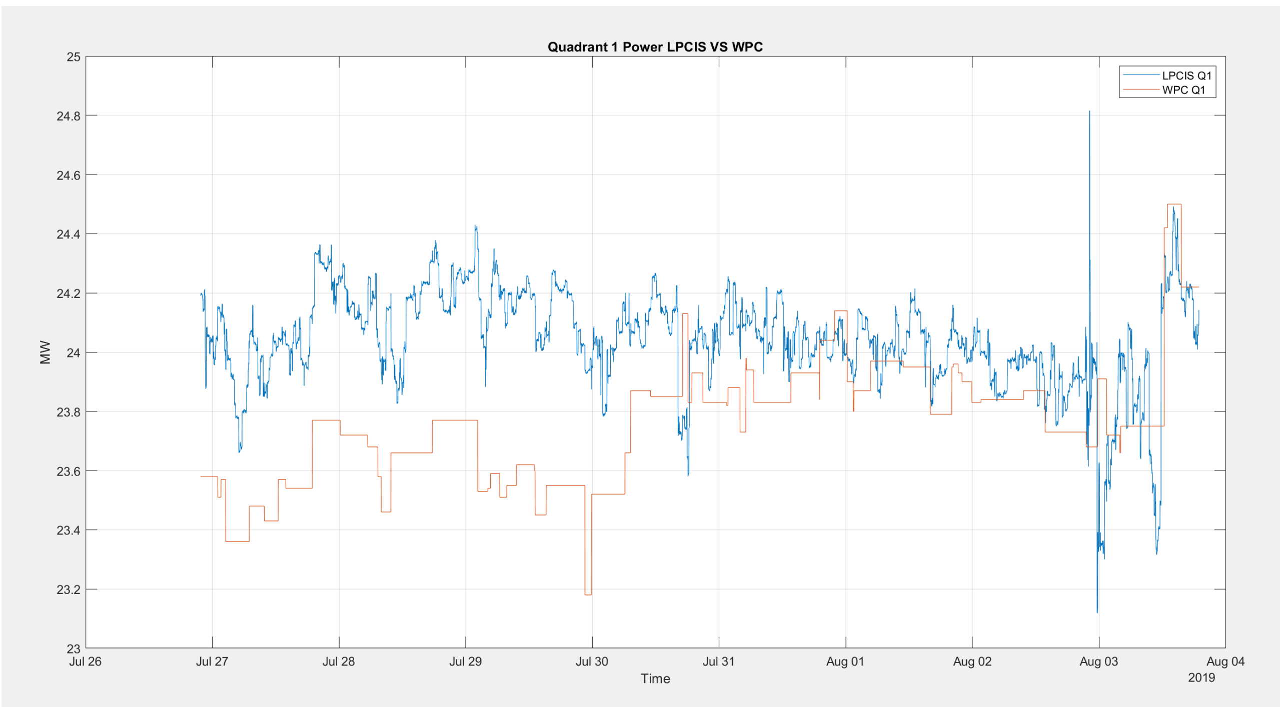

Figure B1. Quadrant 1 power calculated by 40 day physics evaluation of 166-A (10^4 weighting factor).

Figure B2. Quadrant 2 power calculated by 40 day physics evaluation of 166-A (10^4 weighting factor).

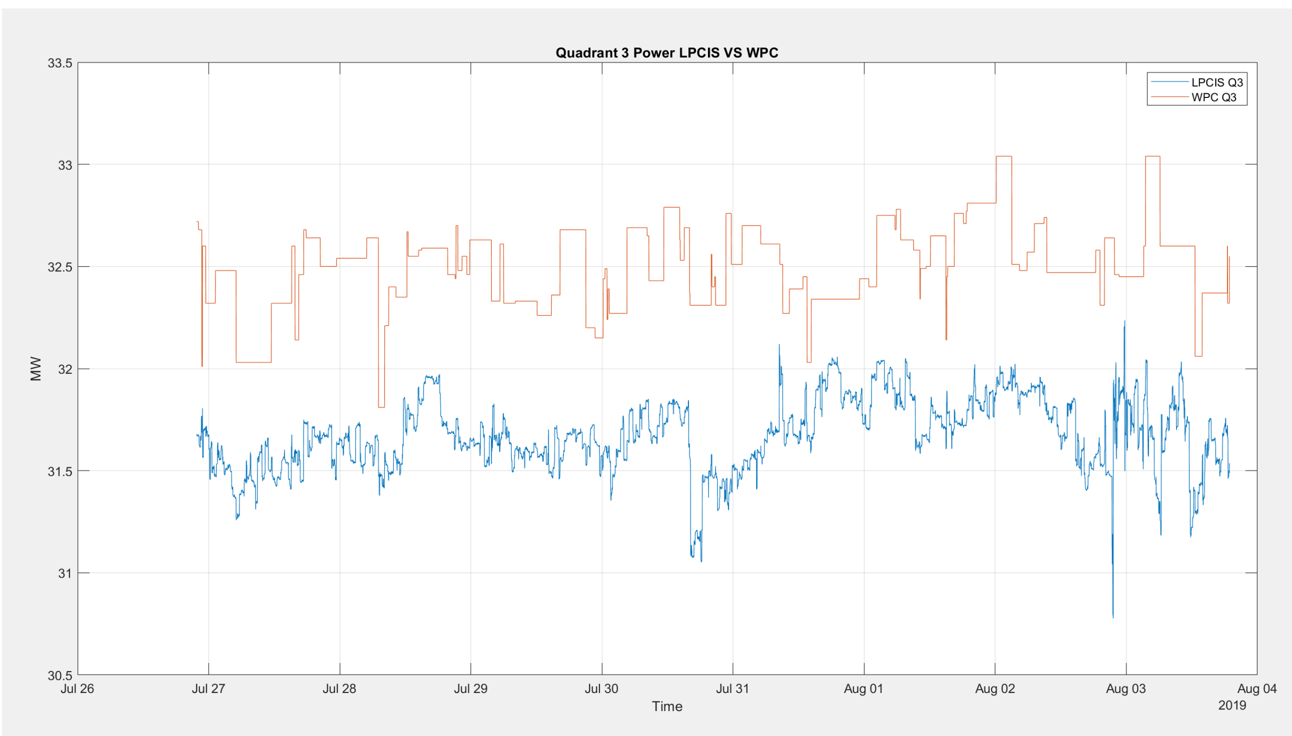

Figure B3. Quadrant 3 power calculated by 40 day physics evaluation of 166-A (10^4 weighting factor).

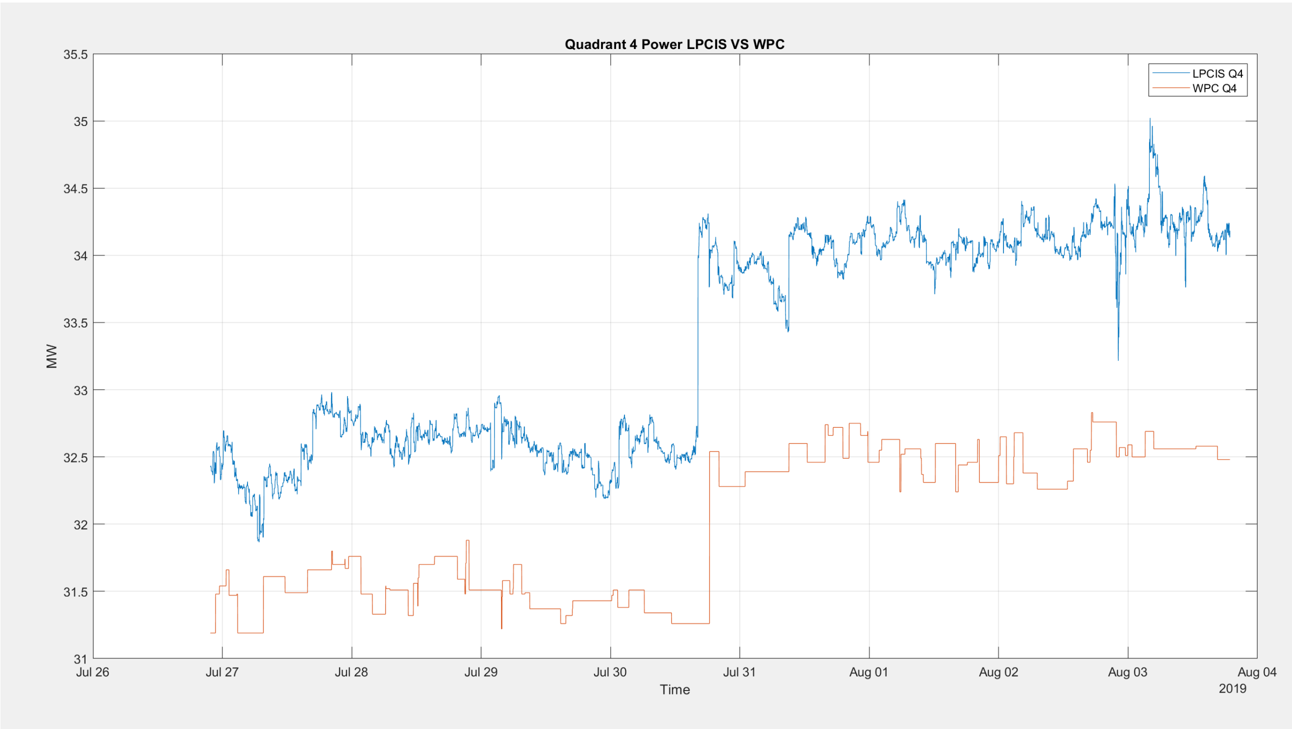

Figure B4. Quadrant 4 power calculated by 40 day physics evaluation of 166-A (10^4 weighting factor).

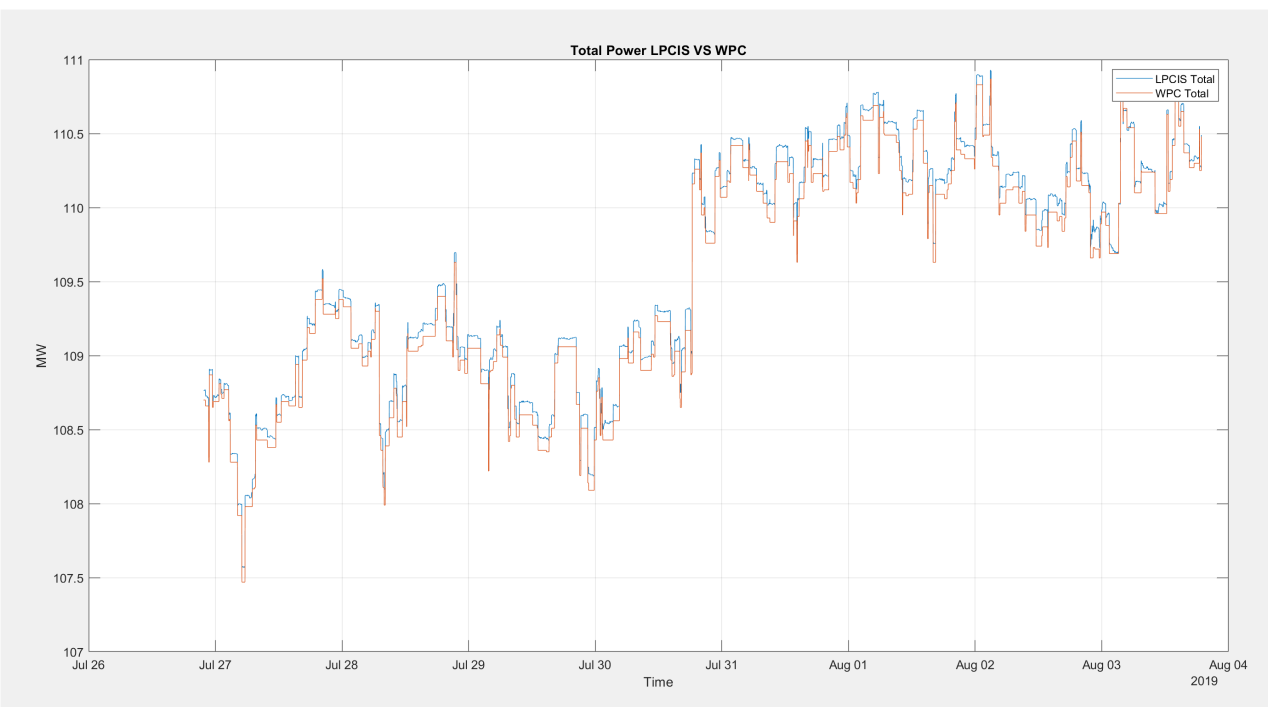

Figure B5. Total quadrant power calculated by 40 day physics evaluation of 166-A (10^4 weighting factor).

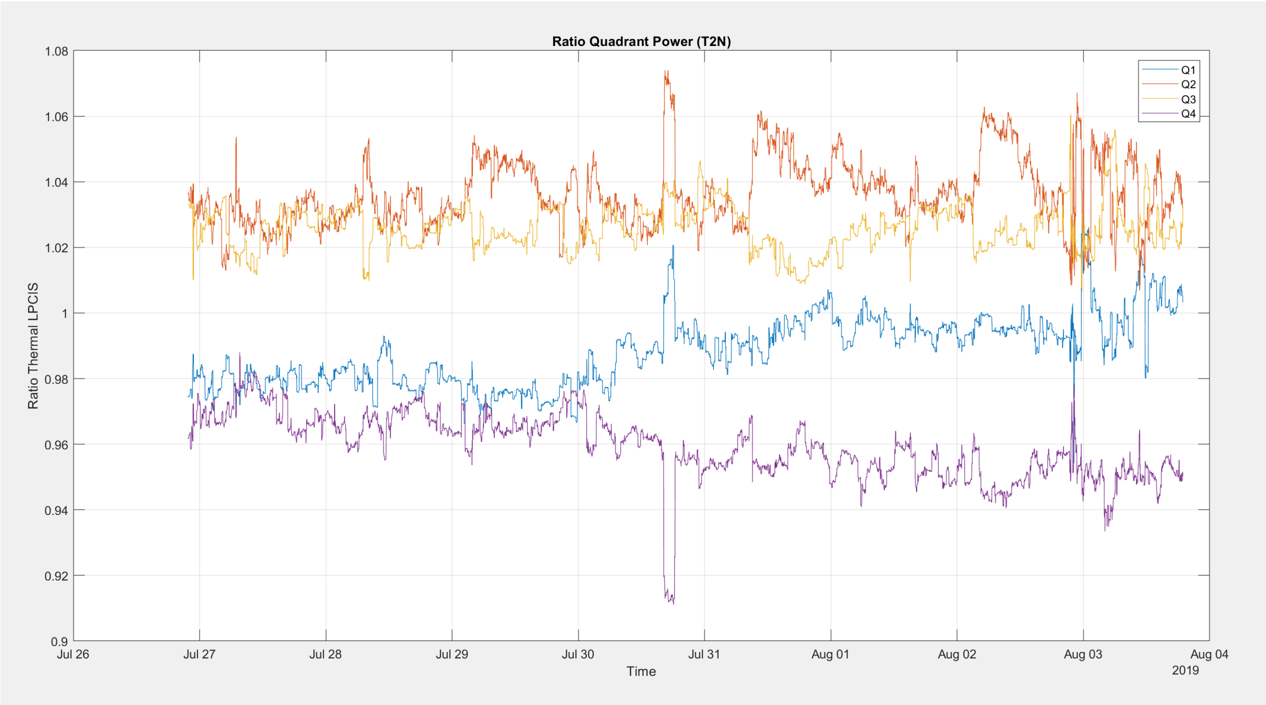

Figure B6. Quadrant T2N ratio by 40 day physics evaluation of 166-A (10^4 weighting factor).

VIII. REFERENCES

[1] SAR-153-7, 2018, "Instrumentation and Controls," Rev. 30, September 19, 2018.

[2] RE-P-78-063,1978, "The ATR ^{16}N System," Rev. 0, July 24, 1978.

[3] CI-1041, 1967, "Calibration of the ATR Lobe Power Monitoring System," Rev. 0, August 1, 1967.

[4] ECAR-3045, 2012, "Engineering Calculations and Analysis," Rev. 6, March 1, 2012.

[5] TEV-1733, 2013, "Calculation of New Multipliers for the Lobe Power and Indication System (LPCIS)," Rev. 0, February 5, 2013.