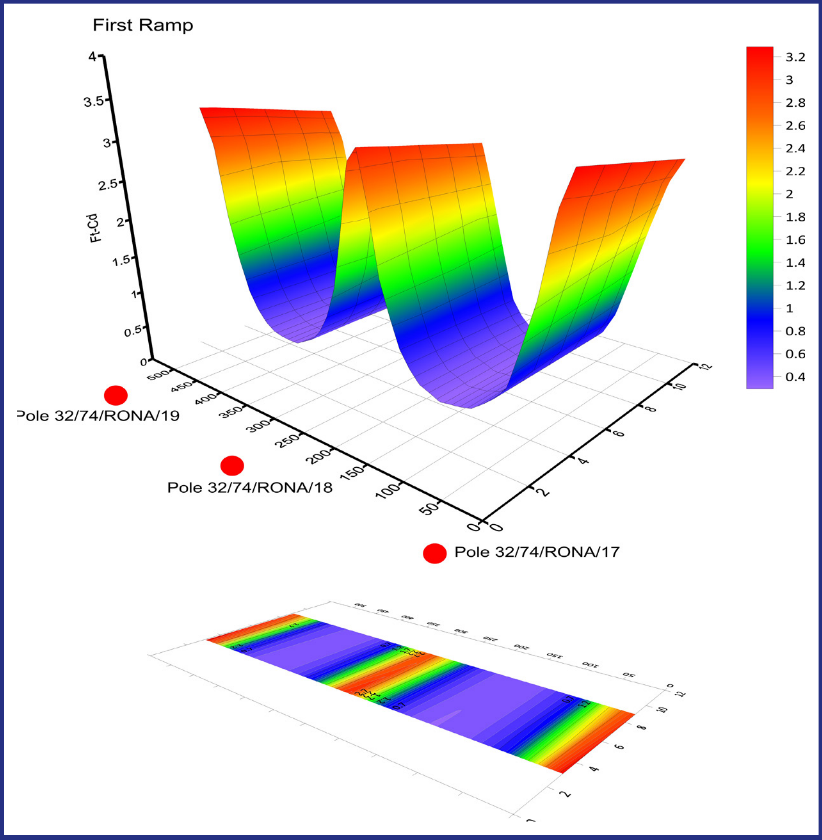
JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

LED Street Lighting Implementation Research, Support, and Testing



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JOINT TRANSPORTATION RESEARCH PROGRAM

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16. Abstract
This report describes the results of technical analysis, field tests, and laboratory tests that were performed for LED highway lighting options by the Energy Efficiency and Reliability Center (EERC) at Purdue University Northwest for the Indiana Department of Transportation (INDOT). This effort was conducted over the past three years to evaluate and test the technology and viability of using modern highway lighting technology to enhance energy efficiency, safety, security and economic development of communities and roadways. During the testing period there was a continuous discussion between INDOT and EERC regarding the laboratory and field testing of INDOT approved luminaires submitted by vendors. There were multiple discussions with INDOT and vendors regarding the individual details and issues for the 29 luminaires that were tested. A comparison study was conducted by EERC of the various alternatives and comparison to currently installed luminaires. Data was collected for field tests of the luminaires by EERC and INDOT personnel for the luminaires. Field data was evaluated and compared to lighting models using vendor supplied ies data files. Multiple presentations were made at three separate Purdue Road Schools regarding the results and procedures of the testing program by EERC in conjunction with INDOT.

A total of 22 final reports, considered confidential by INDOT, for individual vendor luminaires have been prepared as part of this effort. These reports were submitted sequentially to INDOT as testing was completed during the course of this effort. A total of 29 luminaires were tested. Some luminaire testing was terminated during testing due to design issues or vendor requests. All testing was summarized in the INDOT specification sheet attached to each report. Observations regarding the consistency of the supplied test luminaire with the requirements of Section 7.2 of the INDOT test procedure "Procedure for evaluation and approval list requirements for solid state ballasted luminaires ITM 957-17P" is provided in the Appendix to the report for each luminaire. Details regarding how these tests were performed and the respective associated evaluation of performance and reliability are provided in the report. This effort included: consideration of published and vendor information; appraisal of products consistent with national industry standards; review of physical design, thermal performance; laboratory testing of photopic performance, reliability, life cycle data and characteristics, and power characteristics; technical and probabilistic risk studies; and field testing and analysis of LED light sources including comparison to currently installed conventional light sources. Assistance in preparing INDOT standards for highway lighting was provided on multiple occasions.

17. Key Words
roadway lighting, LED, field test, thermal, power quality, electric, photopic, standard, laboratory test, lumen depreciation, modeling, life cycle

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EXECUTIVE SUMMARY

Introduction

This report describes the results of technical analysis, field tests, and laboratory tests that were performed on LED highway lighting options by the Energy Efficiency and Reliability Center (EERC) at Purdue University Northwest for the Indiana Department of Transportation (INDOT). This effort was conducted over the past three years to evaluate and test the technology and viability of using modern highway lighting technology to enhance the energy efficiency, safety, security, and economic development of communities and roadways. During the testing period there was continuous discussion between INDOT and EERC regarding the laboratory and field testing of INDOT-approved luminaires submitted by vendors.

This effort included the following: consideration of published information and vendor information; appraisal of products consistent with national industry standards; review of physical design and thermal performance; laboratory testing of photopic performance, reliability, life cycle data and characteristics, and power characteristics; technical and probabilistic risk studies; and field testing and analysis of LED light sources, including comparison to currently installed conventional light sources. Assistance in preparing INDOT standards for highway lighting was provided on multiple occasions.

As part of this effort, multiple discussions were held with INDOT and vendors regarding the individual details and issues for the 29 luminaires that were tested. A comparison study was conducted by EERC of various alternatives to currently installed luminaires. Data was collected for field tests of the luminaires by EERC and INDOT personnel. Field data was evaluated and compared to lighting models using vendor supplied ies data files. Multiple presentations by EERC and with INDOT were made at three separate Purdue Road Schools regarding the results and procedures of the testing program.

All testing is summarized in the INDOT specification sheet attached to each report. Observations regarding the consistency of the supplied test luminaire with the requirements of Section 7.2 of the INDOT test procedure *Procedure for Evaluation and Approval List Requirements for Solid State Ballasted Luminaires ITM 957-17P* is provided in the Appendix to the report for each luminaire. Details regarding how these tests were performed and the respective associated evaluation of performance and reliability are provided in the report.

Findings

- Modern LED luminaires can provide a cost effective, energy efficient, and reliable alternative to currently installed lighting technology that is approaching the end of its lifespan. When properly evaluated, products can be selected that maximize value and operational characteristics.
- Due to the diversity of available LED luminaire types and designs that are available from a wide variety of sources, it is important to conduct careful, detailed design evaluations and laboratory and field tests of luminaires that have been qualified for potential use by INDOT.
- Testing and evaluation procedures, in both the laboratory and in the field, must consider initial performance as well as performance at subsequent time intervals to ensure both initial and projected long-term performance meets expectations.
- It is important to obtain detailed performance and design data from vendors. It is also crucial that all this data and the LED luminaire design be evaluated and verified through testing.

Implementation

A total of 22 final reports, considered confidential by INDOT, for individual vendor luminaires have been prepared and submitted to INDOT as part of this effort. A total of 29 luminaires were tested. Some luminaire testing was terminated during the testing process due to design issues or vendor requests. All testing was summarized in the INDOT specification sheet attached to each report. These reports were submitted sequentially as testing was completed during the course of this effort. INDOT continues to evaluate the submitted reports and is using this information as part of its efforts for the acquisition of new luminaires for highway lighting consistent with its internal evaluation of options. Observations regarding the consistency of the supplied test luminaire with the requirements of Section 7.2 of the INDOT test procedure *Procedure for Evaluation and Approval List Requirements for Solid State Ballasted Luminaires ITM 957-17P* is provided for each luminaire in the Appendices. Details regarding how these tests were performed and the respective associated evaluation of performance and reliability are also provided in this report.

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1. INTRODUCTION AND GENERAL OBSERVATIONS

This report describes the results of technical analysis, field tests, and laboratory tests that were performed on LED highway lighting options by the Energy Efficiency and Reliability Center (EERC) at Purdue University Northwest for the Indiana Department of Transportation (INDOT). During the testing period there was a continuous discussion between INDOT and EERC regarding the laboratory and field testing of the luminaires. Additionally, there were multiple discussions with INDOT and vendors regarding the individual details and issues for the individual luminaires that were tested. A comparison study of the various alternatives was conducted by EERC. Data was collected for field tests of the luminaires by EERC and INDOT personnel. Multiple presentations were made at three separate Purdue Road Schools regarding the results and procedures of the testing program by EERC in conjunction with INDOT.

A total of 22 final reports, considered confidential by INDOT, for individual vendor luminaires have been prepared as a part of this effort. These reports were provided to INDOT. A total of 29 luminaires were tested. Some luminaire testing was terminated during the testing process due to design issues or vendor requests. Due to confidentiality requirements, the material presented here is an assemblage of data for different sections of the final reports from randomly selected test luminaires and is only intended to illustrate the basic test methodology. All testing was summarized in the INDOT specification sheet attached to each report. Observations regarding the consistency of the supplied test luminaire with the requirements of Section 7.2 of the INDOT test procedure *Procedure for Evaluation and Approval List Requirements for Solid State Ballasted Luminaires ITM 957-17P* is provided in the Appendix to the report for each luminaire. Details regarding how these tests were performed and the respective associated evaluation of performance and reliability are provided in the following sections of this report.

Over the past three years the Energy Efficiency and Reliability Center (EERC) at PNW has been performing research regarding the technology and viability of using modern street lighting technology to enhance energy efficiency, safety, security and economic development of communities and roadways. This work has been conducted as part of a grant from the Indiana Department of Transportation. Efforts have involved the evaluation of over 29 different vendor LED products. This effort included the following: consideration of published and vendor information; appraisal of products consistent with national industry standards; laboratory testing of light and power characteristics of various light sources; technical and probabilistic risk studies; and field testing and analysis of new light sources as compared to currently installed conventional light sources. Assistance in preparing standards for highway lighting was provided on multiple occasions. Several students participated in both the appraisal effort as well as the actual collection of data in the field for various locations in the municipalities.

Initially INDOT received evaluation requests and information from various lighting vendors. Those vendors that passed initial appraisal by INDOT were asked to submit luminaire samples to EERC for testing. For those vendors that supplied test luminaires an evaluation of the design, projected reliability, power profile, light output, and value was conducted. Simultaneously EERC developed, designed, programmed, and implemented an evaluation system to fully vet the performance of the tested luminaires. Both laboratory and field tests, conducted by EERC and INDOT, were done to determine the basic physical structure of the luminaires as well as their projected performance over time. The target life for the units was specified as 100,000 hours which is approximately 20 years. Issues regarding maintenance and installation costs were also considered as well as operating costs and efficiency in general. For the template of the summary provided in each report of observations on the consistency of the test unit with INDOT's Standards (Section 7.2 of ITM 957) see Appendix D.

Various presentations have been made to Indiana government offices as well as the Purdue Road School regarding the EERC effort.

Identified benefits of LED street lighting include:

- Reduced cost (electric and maintenance).
- Increased reliability (10 year warranty, 100,000+ hour life).
- Whiter light than high pressure sodium.
- Energy savings → reduced emissions.
- Improved safety.
- Improved perception of area.
- Light levels can be controlled by use and time of day or activity level.

Highways benefit from LED lighting in various ways including:

- Lighting assists in efforts to improve the appearance of various areas.
- In highway light performance tests conducted by the EERC and INDOT in the field it has been noted on numerous occasions that the white light of LED luminaires makes it easier to detect vehicles, detail and motion in the areas illuminated by LED lights as compared to the same area illuminated by HPS light.
- Contractors and maintenance crews report that LED lighting facilitates night time work—reducing the need for temporary work area lighting.
- It is clear that the presence of LED lights reduce safety concerns related to traffic during the data collection process.
- Transitioning to LED street lights substantially improves nighttime vision and in turn improve safety and security there helping improve the areas as a whole.
- The benefits provided by LED technology contribute to revitalization of areas by improving both the quality of lighting and the penetration of lighting.
- Good road lighting contributes to a feeling of security by persons in the area.

2. LABORATORY TESTING

Due to confidentiality requirements, the data shown in this section are examples taken randomly from the results for all the vendors considered. The displayed results are not identified for any individual vendor. As such they do not represent the complete results for any individual vendor.

All tested luminaires were evaluated for a variety of aspects. One basic issue was the design of the case. Figure 2.1 shows an example of a typical luminaire. Aspects for the case design included mechanical design, connections, seals, and overall ability to withstand the requirements for lighting applications. Another important aspect is the initial as well as the projected performance of the driver which supplies electric power to the LEDs. Special consideration was given to the physical and thermal design of the driver since failure of this component is responsible for a large portion of luminaire failures with time. The driver is contained in the case. The case of the tested units was either sealed or provided with drain holes. The first option is to completely seal the case and does not allow water to escape. The second option allows water to escape through drainage holes and thereby allows any trapped water to exit the case. Since water may enter the case from various sources including wicking through the power cables, the drainage option offers advantages over the sealed case approach. Figure 2.1 shows an example of the basic case structure.

The INDOT specification requires that all luminaires include a driver unit that contains surge suppression which is important to mitigate electrical disturbances resulting from indirect lighting strikes or other electrical disturbances.

A typical infrared thermal image of the outside side of the case above the LEDs is shown in Figure 2.2. This figure shows the fins used to enhance heat removal. Component failures are directly related to operating temperature and hence special care is needed to assure proper heat management.

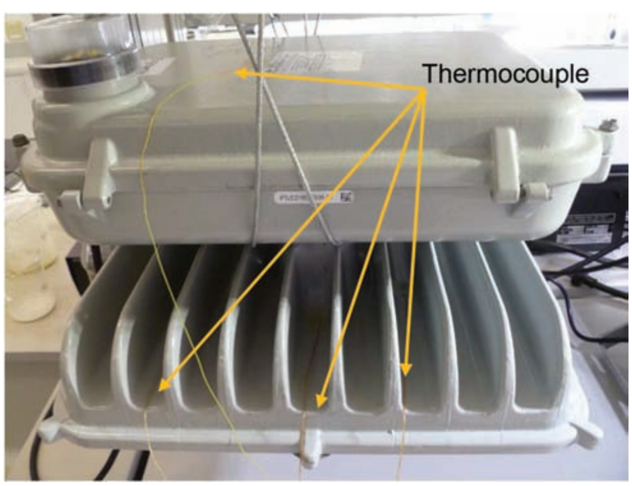


Figure 2.1 Basic structure.

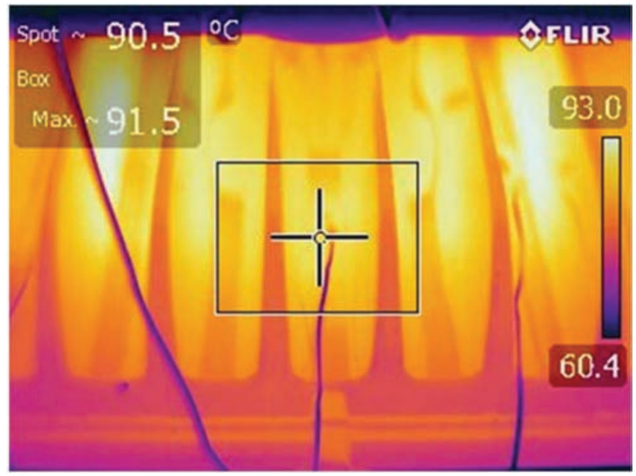


Figure 2.2 Case showing heat emission pattern.

The results of the infrared thermal analyses were verified by direct thermocouple readings. Typical locations of thermocouples (blue wires) can be seen in Figures 2.1 and 2.2. These measurements were repeated at least once per day over a three-day period to assure consistency in the measured equilibrium values. These readings were acquired with the case closed during normal operation after thermal equilibrium had been reached.

3. ILLUMINANCE MEASUREMENTS OVER TIME

Tests of the performance of the luminaire light output and configuration were conducted. Results of these tests were correlated with results from the vendor supplied ies files. The luminaire was mounted in a test room that is dedicated to lumen level testing. This room has a matrix of 18 test points located on the wall opposite the mounting location of the luminaire. The luminaire is mounted with the light projecting horizontally onto the opposite wall that contains the test matrix. Values of illuminance are recorded at each of the 18 test points. Each reading is repeated two more time to assure consistency of data collection. This process is repeated once per day for five days over a period of one week. The intent of this procedure is to determine if there is any loss of illuminance over time. The entire procedure for lumen depreciation is repeated periodically to verify performance over a longer time interval. Results from a typical lumen depreciation test for a typical luminaire operating at the rated operating voltage are depicted in Figure 3.1. The layout of the test area and the matrix point arrangement is shown in Appendix B.

Figure 3.2 depicts similar test results when the unit was operated at the operating voltage minus 10 volts. Figure 3.3 depicts similar test results when the unit was operated at the operating voltage plus 10 volts. It is anticipated in normal operation some voltage variation will occur but that this variation should normally be in the tested range, excluding transients that are

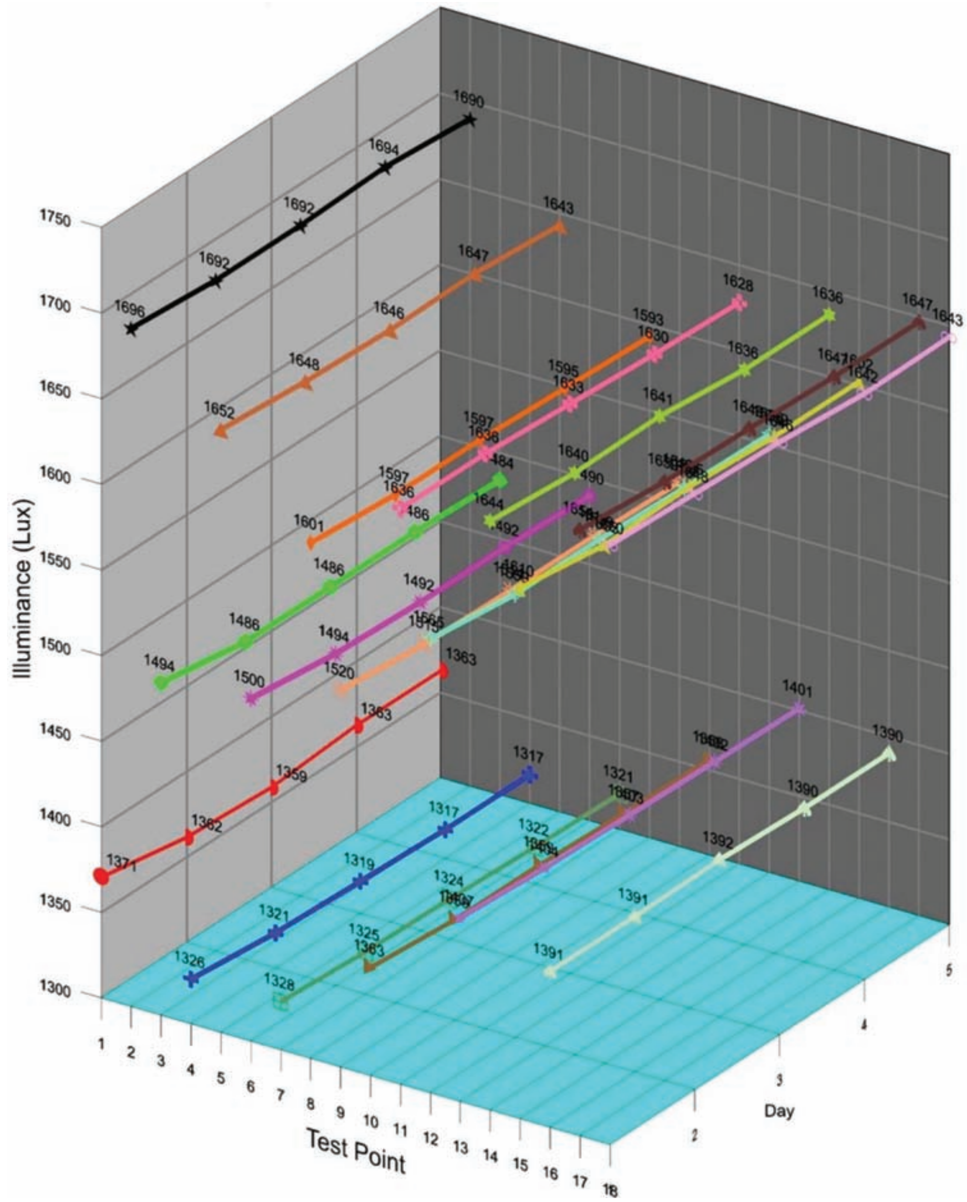


Figure 3.1 Illuminance test matrix data.

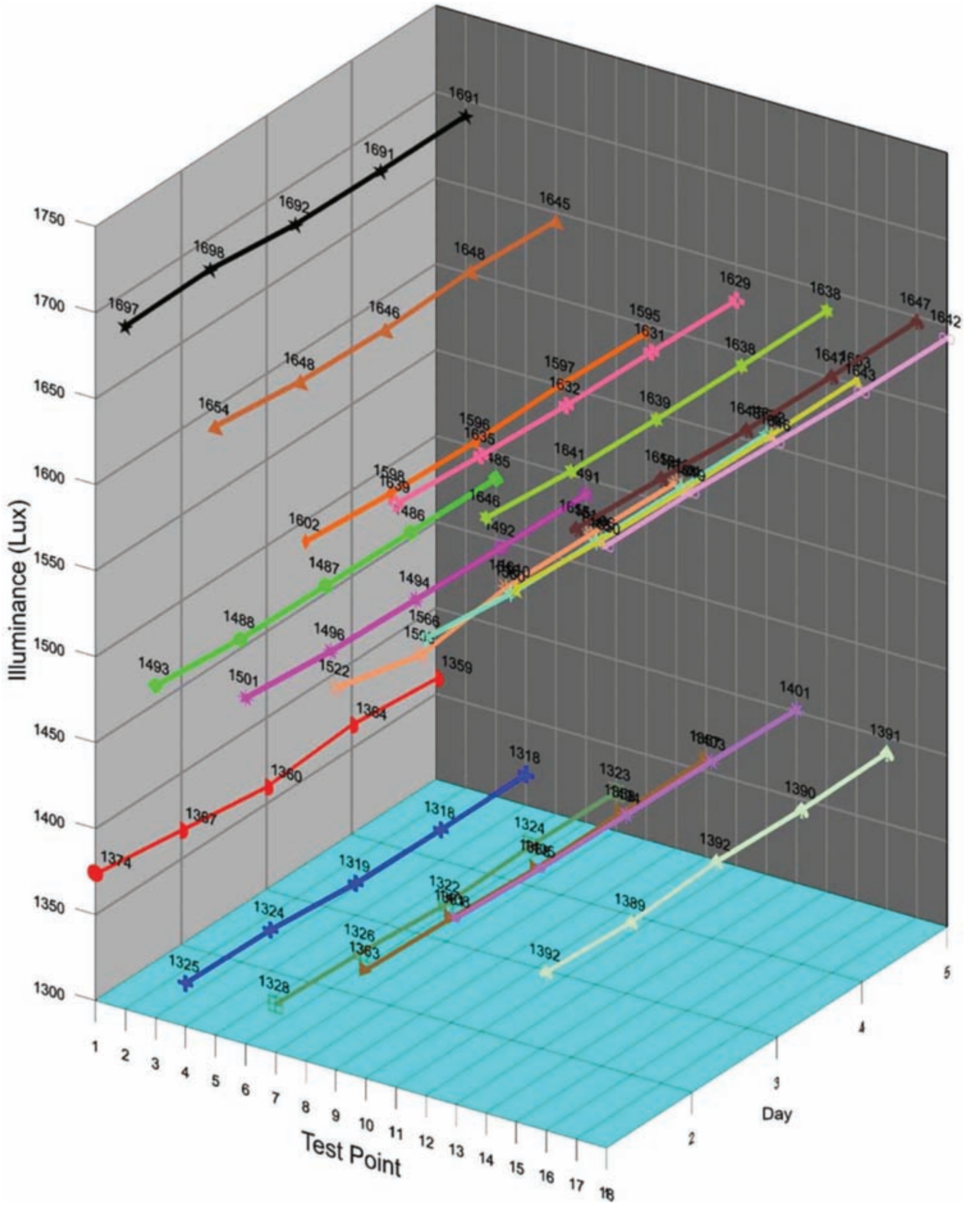


Figure 3.2 Illuminance test matrix data at -10V operation.

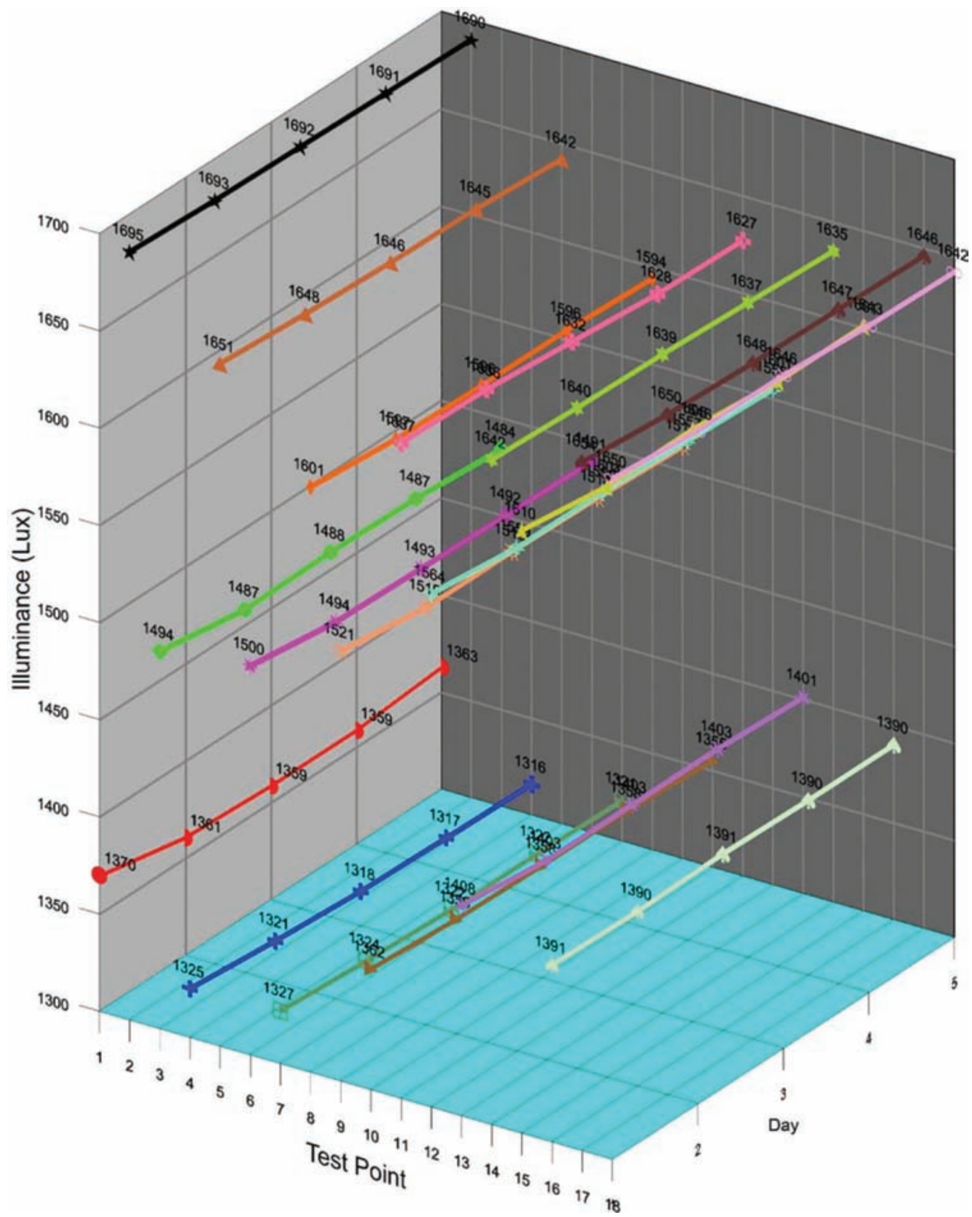


Figure 3.3 Illuminance test matrix data at +10V operation.

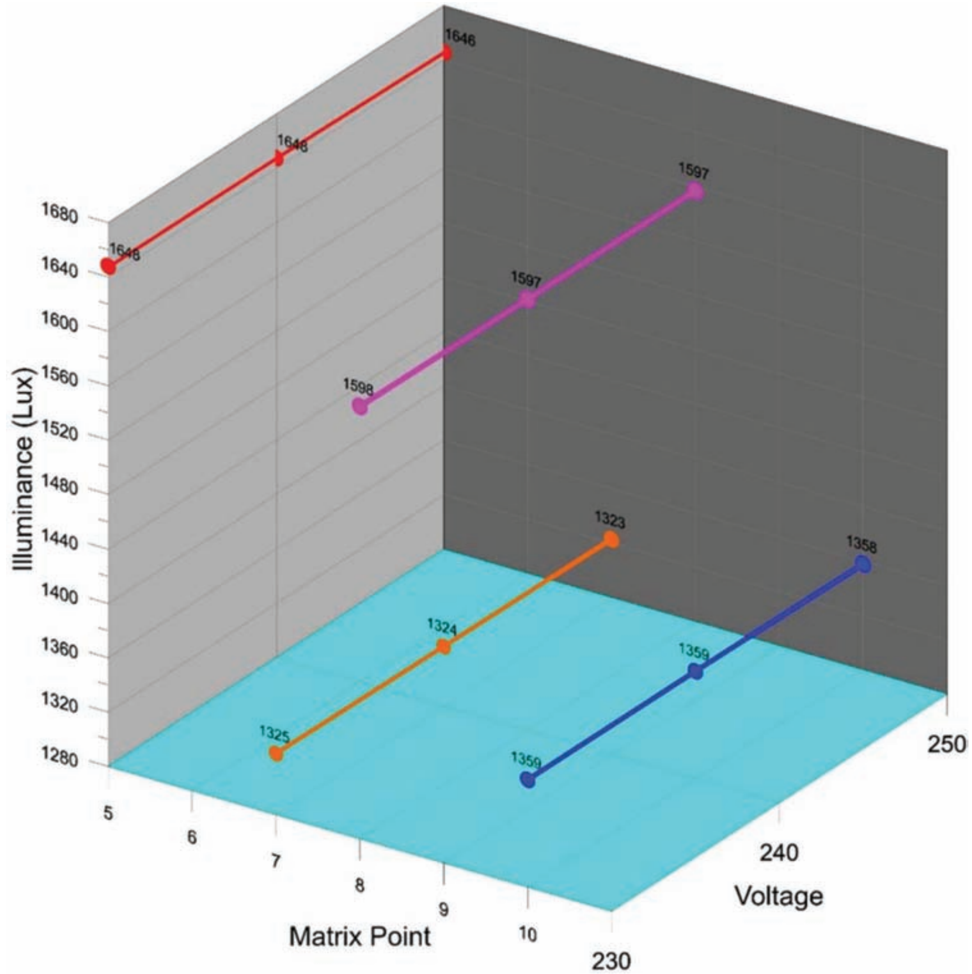


Figure 3.4 Illuminance test matrix data for voltage variations.

considered in the surge suppression testing considered as part of the power quality analysis.

Figure 3.4 depicts the illuminance levels as a function of supply voltage for the second test day at test matrix points 5, 7, 8, and 9. Other matrix points and days show similar results.

These values were compared to those expected from the ies files analysis. A computer model (AGI32, Lighting Analysists, Inc.) was used to simulate light patterns based on vendor submitted ies file data. Vendor supplied data was verified to have been conducted by a certified testing laboratory for each vendor.

4. SPECTRAL POWER DENSITY

The spectral power density was measured with an illuminance spectrophotometer and these results were compared to manufacturer's data from the LM79 test results as well as additional data obtained from the manufacturer. LM 79 is a test and reporting procedure developed by the Illuminating Engineering Society on electrical and photometric performance of LED luminaires that facilitates identification of models appropriate for the location or type of lighting system. Results of these tests for a typical luminaire are depicted in Figure 4.1.

In Figure 4.1 the top left two tables give results for the color rendition index (CRI). The illuminance spectrophotometer measures the color composition in terms of R values ranging from R1 to R15. Ra is the average of the indicated color values from R1 to R8 used in the classic calculation (CIE 1931). The highest possible Ra value for each individual CRI is 100, dropping to negative values for certain light sources (e.g., low pressure sodium lighting). This rating describes how a light source makes the color of an object appear to human eyes and how well subtle variations in color shades are revealed. The higher the CRI rating is, the better its color rendering ability. CRI is not the only factor in light quality, because it only contains measurements for R1-R8 values, which are pastel colors, and does not measure red, for example, which is present in skin tones and wood finishes. A light also needs to have solid "R" values from R9-R15 that measure how well the light brings out saturated colors. The R9 value produces strong, vibrant reds. Food retailers care about

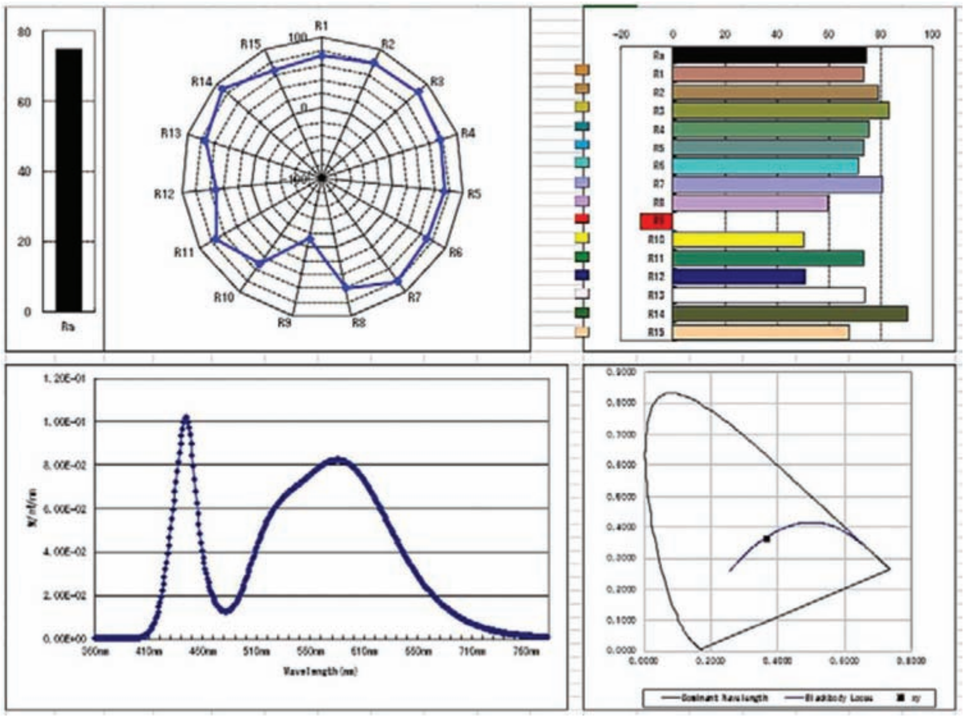


Figure 4.1 Spectral data.

positive R9 because strong reds are prevalent in grocery store produce and meats. Hospitals should care because strong reds are the most critical color for surgical procedures. The two graphs to the right are a graphic representation of this data. The graph on the lower left is the spectral power density for the third set of data from Table 4.1. This graph shows the normalized intensity of light as a function of wavelength between values of 360 and 775 nm. The graph to the right on the bottom depicts the classic color composition in terms of x and y components as well as the Planckian locus (Black body). The Planckian locus (or black body locus) is the path (here indicated by the central curved line) that the color of an incandescent black body would take in a particular chromaticity space as the blackbody temperature changes. This graph shows the color of the LED in comparison to a black body radiator. In this case the phosphors used to convert the internal LED blue light into white light have yielded a color close to the indicated black body value.

Table 4.1 shows the amount of light present based upon its wavelength measured in nm. Multiple trials were run for each case for varying distances and positions. Data from column three was used as the basis for Figure 4.1. Calculations using the other columns produced similar results.

TABLE 4.1
Spectral Power Density

No.	1	2	3	4	5
Date & Time	—	—	—	—	—
Serial No.	10001261	10001261	10001261	10001261	10001261
Ev	10941.6	9852.1	11432.5	13054.3	6147.7
x	0.3705	0.3658	0.3673	0.3700	0.3701
y	0.3671	0.3598	0.3620	0.3661	0.3665
Tcp [K] (JIS)	4216	4314	4280	4224	4225
Duv (JIS)	-0.0016	-0.0036	-0.0030	-0.0019	-0.0017
u′	0.2224	0.2222	0.2223	0.2225	0.2223
v′	0.4958	0.4917	0.4930	0.4953	0.4954
X	11043.5	10015.7	11599.7	13193.0	6207.8
Y	10941.6	9852.1	11432.5	13054.3	6147.7
Z	7819.6	7512.8	8545.5	9407.0	4417.4
Dominant Wavelength	579.3	580.6	580.2	579.5	579.3
Purity	21.4	17.7	18.9	20.9	21.1
Scotopic Lux	17338.3	15909.5	18352.8	20734.6	9760.2
S/P Ratio	1.58	1.61	1.61	1.59	1.59
Peak Wavelength	444	444	444	444	444
Ra	74	75	75	74	74
R1	73	74	74	73	73
R2	79	79	79	79	79
R3	83	83	83	83	83
R4	75	76	76	75	75
R5	73	74	74	73	73
R6	71	71	71	71	71
R7	81	81	81	81	81
R8	59	60	60	59	59
R9	-15	-12	-13	-15	-15
R10	50	50	50	50	50
R11	73	74	74	73	73
R12	50	51	51	50	50
R13	73	74	74	73	73
R14	90	90	90	90	90
R15	67	68	68	67	67
360nm	3.132E-04	1.302E-04	2.667E-04	3.228E-04	6.456E-04
361nm	4.949E-04	4.524E-04	4.887E-04	6.622E-04	7.041E-04
362nm	7.523E-04	7.533E-04	7.330E-04	1.096E-03	7.624E-04
363nm	1.067E-03	1.023E-03	1.000E-03	1.570E-03	8.125E-04
364nm	1.456E-03	1.224E-03	1.352E-03	1.954E-03	8.198E-04
365nm	1.865E-03	1.373E-03	1.729E-03	2.265E-03	8.026E-04
366nm	2.246E-03	1.483E-03	2.076E-03	2.514E-03	7.776E-04
367nm	2.561E-03	1.558E-03	2.361E-03	2.683E-03	7.508E-04
368nm	2.673E-03	1.619E-03	2.476E-03	2.691E-03	7.447E-04
369nm	2.640E-03	1.653E-03	2.461E-03	2.580E-03	7.501E-04
370nm	2.523E-03	1.645E-03	2.362E-03	2.397E-03	7.570E-04
371nm	2.342E-03	1.587E-03	2.192E-03	2.160E-03	7.624E-04
372nm	2.098E-03	1.399E-03	1.914E-03	1.856E-03	7.526E-04
373nm	1.823E-03	1.139E-03	1.580E-03	1.531E-03	7.342E-04
374nm	1.552E-03	8.787E-04	1.253E-03	1.234E-03	7.161E-04
375nm	1.312E-03	6.544E-04	9.700E-04	1.003E-03	7.016E-04
376nm	1.212E-03	6.180E-04	8.949E-04	1.015E-03	7.118E-04
377nm	1.217E-03	7.139E-04	9.677E-04	1.195E-03	7.363E-04
378nm	1.253E-03	8.374E-04	1.076E-03	1.406E-03	7.573E-04
379nm	1.299E-03	9.534E-04	1.181E-03	1.599E-03	7.677E-04
380nm	1.282E-03	9.374E-04	1.151E-03	1.582E-03	7.329E-04
381nm	1.215E-03	8.167E-04	1.013E-03	1.403E-03	6.646E-04
382nm	1.141E-03	6.749E-04	8.581E-04	1.197E-03	5.917E-04
383nm	1.069E-03	5.341E-04	7.092E-04	1.003E-03	5.243E-04
384nm	1.030E-03	4.601E-04	6.376E-04	9.586E-04	4.965E-04
385nm	1.020E-03	4.491E-04	6.387E-04	1.044E-03	5.044E-04
386nm	1.019E-03	4.598E-04	6.666E-04	1.155E-03	5.228E-04
387nm	1.023E-03	4.850E-04	7.127E-04	1.264E-03	5.459E-04

TABLE 4.1
(Continued)

No.	1	2	3	4	5
388nm	1.013E-03	5.043E-04	7.589E-04	1.275E-03	5.565E-04
389nm	9.919E-04	5.168E-04	8.013E-04	1.193E-03	5.539E-04
390nm	9.810E-04	5.368E-04	8.472E-04	1.103E-03	5.498E-04
391nm	9.879E-04	5.666E-04	8.953E-04	1.026E-03	5.460E-04
392nm	1.048E-03	6.188E-04	9.415E-04	1.034E-03	5.458E-04
393nm	1.158E-03	6.920E-04	9.854E-04	1.132E-03	5.503E-04
394nm	1.277E-03	7.704E-04	1.029E-03	1.252E-03	5.590E-04
395nm	1.390E-03	8.485E-04	1.074E-03	1.379E-03	5.725E-04
396nm	1.435E-03	8.910E-04	1.098E-03	1.442E-03	5.852E-04
397nm	1.409E-03	8.989E-04	1.105E-03	1.438E-03	5.993E-04
398nm	1.394E-03	9.256E-04	1.140E-03	1.453E-03	6.279E-04
399nm	1.416E-03	9.900E-04	1.221E-03	1.513E-03	6.771E-04
400nm	1.531E-03	1.135E-03	1.385E-03	1.677E-03	7.535E-04
401nm	1.766E-03	1.378E-03	1.650E-03	1.968E-03	8.632E-04
402nm	2.073E-03	1.685E-03	1.989E-03	2.342E-03	1.010E-03
403nm	2.450E-03	2.055E-03	2.402E-03	2.796E-03	1.198E-03
404nm	2.866E-03	2.459E-03	2.865E-03	3.289E-03	1.429E-03
405nm	3.314E-03	2.891E-03	3.375E-03	3.812E-03	1.706E-03
406nm	3.861E-03	3.414E-03	3.992E-03	4.459E-03	2.047E-03
407nm	4.532E-03	4.053E-03	4.740E-03	5.265E-03	2.461E-03
408nm	5.338E-03	4.823E-03	5.628E-03	6.268E-03	2.950E-03
409nm	6.300E-03	5.743E-03	6.674E-03	7.507E-03	3.520E-03
410nm	7.475E-03	6.861E-03	7.942E-03	8.999E-03	4.204E-03
411nm	8.902E-03	8.207E-03	9.470E-03	1.077E-02	5.021E-03
412nm	1.063E-02	9.814E-03	1.130E-02	1.283E-02	5.990E-03
413nm	1.270E-02	1.171E-02	1.347E-02	1.520E-02	7.130E-03
414nm	1.512E-02	1.394E-02	1.602E-02	1.797E-02	8.457E-03
415nm	1.790E-02	1.652E-02	1.896E-02	2.117E-02	9.988E-03
416nm	2.109E-02	1.951E-02	2.235E-02	2.489E-02	1.175E-02
417nm	2.470E-02	2.298E-02	2.623E-02	2.921E-02	1.375E-02
418nm	2.874E-02	2.687E-02	3.060E-02	3.406E-02	1.601E-02
419nm	3.322E-02	3.119E-02	3.545E-02	3.947E-02	1.852E-02
420nm	3.819E-02	3.595E-02	4.083E-02	4.543E-02	2.133E-02
421nm	4.367E-02	4.118E-02	4.677E-02	5.199E-02	2.445E-02
422nm	4.963E-02	4.684E-02	5.323E-02	5.910E-02	2.784E-02
423nm	5.605E-02	5.295E-02	6.019E-02	6.676E-02	3.149E-02
424nm	6.295E-02	5.953E-02	6.769E-02	7.499E-02	3.541E-02
425nm	7.039E-02	6.665E-02	7.576E-02	8.387E-02	3.960E-02
426nm	7.822E-02	7.416E-02	8.427E-02	9.322E-02	4.400E-02
427nm	8.639E-02	8.200E-02	9.317E-02	1.030E-01	4.858E-02
428nm	9.484E-02	9.012E-02	1.024E-01	1.130E-01	5.332E-02
429nm	1.035E-01	9.843E-02	1.118E-01	1.233E-01	5.817E-02
430nm	1.123E-01	1.070E-01	1.215E-01	1.339E-01	6.313E-02
431nm	1.214E-01	1.157E-01	1.314E-01	1.447E-01	6.820E-02
432nm	1.305E-01	1.246E-01	1.415E-01	1.556E-01	7.336E-02
433nm	1.398E-01	1.337E-01	1.518E-01	1.669E-01	7.862E-02
434nm	1.492E-01	1.428E-01	1.621E-01	1.782E-01	8.392E-02
435nm	1.585E-01	1.521E-01	1.725E-01	1.895E-01	8.924E-02
436nm	1.679E-01	1.613E-01	1.829E-01	2.008E-01	9.456E-02
437nm	1.776E-01	1.709E-01	1.937E-01	2.126E-01	1.001E-01
438nm	1.869E-01	1.801E-01	2.042E-01	2.239E-01	1.054E-01
439nm	1.957E-01	1.887E-01	2.139E-01	2.345E-01	1.103E-01
440nm	2.035E-01	1.965E-01	2.228E-01	2.441E-01	1.148E-01
441nm	2.103E-01	2.033E-01	2.304E-01	2.524E-01	1.187E-01
442nm	2.157E-01	2.087E-01	2.366E-01	2.591E-01	1.218E-01
443nm	2.194E-01	2.125E-01	2.409E-01	2.638E-01	1.239E-01
444nm	2.212E-01	2.144E-01	2.430E-01	2.661E-01	1.249E-01
445nm	2.197E-01	2.131E-01	2.416E-01	2.646E-01	1.241E-01
446nm	2.162E-01	2.098E-01	2.380E-01	2.605E-01	1.222E-01
447nm	2.107E-01	2.046E-01	2.321E-01	2.542E-01	1.192E-01
448nm	2.034E-01	1.976E-01	2.243E-01	2.456E-01	1.151E-01
449nm	1.937E-01	1.883E-01	2.137E-01	2.341E-01	1.097E-01

TABLE 4.1
(Continued)

No.	1	2	3	4	5
450nm	1.827E-01	1.777E-01	2.017E-01	2.210E-01	1.035E-01
451nm	1.708E-01	1.662E-01	1.888E-01	2.068E-01	9.684E-02
452nm	1.585E-01	1.543E-01	1.753E-01	1.920E-01	8.991E-02
453nm	1.466E-01	1.427E-01	1.622E-01	1.778E-01	8.322E-02
454nm	1.349E-01	1.314E-01	1.493E-01	1.637E-01	7.663E-02
455nm	1.237E-01	1.204E-01	1.368E-01	1.501E-01	7.026E-02
456nm	1.130E-01	1.100E-01	1.250E-01	1.372E-01	6.423E-02
457nm	1.038E-01	1.010E-01	1.148E-01	1.260E-01	5.899E-02
458nm	9.548E-02	9.285E-02	1.056E-01	1.159E-01	5.425E-02
459nm	8.793E-02	8.546E-02	9.722E-02	1.067E-01	4.994E-02
460nm	8.111E-02	7.878E-02	8.965E-02	9.844E-02	4.605E-02
461nm	7.507E-02	7.285E-02	8.293E-02	9.109E-02	4.261E-02
462nm	6.967E-02	6.753E-02	7.690E-02	8.451E-02	3.954E-02
463nm	6.481E-02	6.274E-02	7.148E-02	7.858E-02	3.678E-02
464nm	6.040E-02	5.841E-02	6.657E-02	7.323E-02	3.428E-02
465nm	5.625E-02	5.433E-02	6.198E-02	6.820E-02	3.193E-02
466nm	5.242E-02	5.057E-02	5.775E-02	6.356E-02	2.976E-02
467nm	4.893E-02	4.714E-02	5.389E-02	5.934E-02	2.777E-02
468nm	4.576E-02	4.402E-02	5.038E-02	5.550E-02	2.597E-02
469nm	4.287E-02	4.116E-02	4.712E-02	5.198E-02	2.432E-02
470nm	4.027E-02	3.857E-02	4.416E-02	4.879E-02	2.282E-02
471nm	3.796E-02	3.625E-02	4.150E-02	4.594E-02	2.149E-02
472nm	3.592E-02	3.420E-02	3.915E-02	4.343E-02	2.032E-02
473nm	3.415E-02	3.243E-02	3.714E-02	4.127E-02	1.932E-02
474nm	3.264E-02	3.091E-02	3.544E-02	3.943E-02	1.847E-02
475nm	3.138E-02	2.963E-02	3.401E-02	3.790E-02	1.777E-02
476nm	3.036E-02	2.858E-02	3.285E-02	3.666E-02	1.721E-02
477nm	2.956E-02	2.776E-02	3.193E-02	3.568E-02	1.676E-02
478nm	2.897E-02	2.714E-02	3.125E-02	3.497E-02	1.643E-02
479nm	2.860E-02	2.672E-02	3.079E-02	3.450E-02	1.621E-02
480nm	2.843E-02	2.649E-02	3.054E-02	3.427E-02	1.611E-02
481nm	2.845E-02	2.641E-02	3.048E-02	3.425E-02	1.609E-02
482nm	2.866E-02	2.651E-02	3.062E-02	3.445E-02	1.617E-02
483nm	2.905E-02	2.677E-02	3.094E-02	3.486E-02	1.635E-02
484nm	2.961E-02	2.720E-02	3.145E-02	3.549E-02	1.663E-02
485nm	3.031E-02	2.777E-02	3.212E-02	3.630E-02	1.702E-02
486nm	3.116E-02	2.850E-02	3.296E-02	3.731E-02	1.751E-02
487nm	3.220E-02	2.941E-02	3.400E-02	3.856E-02	1.811E-02
488nm	3.345E-02	3.051E-02	3.527E-02	4.004E-02	1.883E-02
489nm	3.495E-02	3.183E-02	3.682E-02	4.183E-02	1.969E-02
490nm	3.670E-02	3.337E-02	3.864E-02	4.390E-02	2.068E-02
491nm	3.866E-02	3.510E-02	4.068E-02	4.622E-02	2.177E-02
492nm	4.082E-02	3.701E-02	4.292E-02	4.877E-02	2.298E-02
493nm	4.315E-02	3.908E-02	4.534E-02	5.153E-02	2.429E-02
494nm	4.564E-02	4.131E-02	4.791E-02	5.450E-02	2.570E-02
495nm	4.829E-02	4.368E-02	5.065E-02	5.766E-02	2.720E-02
496nm	5.110E-02	4.620E-02	5.355E-02	6.100E-02	2.878E-02
497nm	5.407E-02	4.886E-02	5.662E-02	6.451E-02	3.044E-02
498nm	5.719E-02	5.166E-02	5.984E-02	6.817E-02	3.217E-02
499nm	6.041E-02	5.454E-02	6.318E-02	7.196E-02	3.396E-02
500nm	6.370E-02	5.751E-02	6.660E-02	7.586E-02	3.579E-02
501nm	6.704E-02	6.051E-02	7.007E-02	7.982E-02	3.767E-02
502nm	7.038E-02	6.353E-02	7.357E-02	8.383E-02	3.958E-02
503nm	7.377E-02	6.657E-02	7.711E-02	8.789E-02	4.151E-02
504nm	7.718E-02	6.965E-02	8.069E-02	9.199E-02	4.346E-02
505nm	8.064E-02	7.275E-02	8.432E-02	9.614E-02	4.540E-02
506nm	8.413E-02	7.587E-02	8.799E-02	1.003E-01	4.733E-02
507nm	8.761E-02	7.898E-02	9.164E-02	1.045E-01	4.925E-02
508nm	9.106E-02	8.206E-02	9.526E-02	1.086E-01	5.115E-02
509nm	9.443E-02	8.508E-02	9.879E-02	1.126E-01	5.304E-02
510nm	9.769E-02	8.802E-02	1.022E-01	1.165E-01	5.489E-02
511nm	1.009E-01	9.089E-02	1.055E-01	1.203E-01	5.671E-02

TABLE 4.1
(Continued)

No.	1	2	3	4	5
512nm	1.040E-01	9.370E-02	1.087E-01	1.240E-01	5.849E-02
513nm	1.070E-01	9.645E-02	1.119E-01	1.276E-01	6.021E-02
514nm	1.100E-01	9.913E-02	1.149E-01	1.311E-01	6.186E-02
515nm	1.128E-01	1.017E-01	1.179E-01	1.345E-01	6.346E-02
516nm	1.156E-01	1.042E-01	1.208E-01	1.378E-01	6.499E-02
517nm	1.183E-01	1.066E-01	1.235E-01	1.409E-01	6.647E-02
518nm	1.208E-01	1.088E-01	1.261E-01	1.439E-01	6.787E-02
519nm	1.232E-01	1.110E-01	1.286E-01	1.468E-01	6.921E-02
520nm	1.255E-01	1.130E-01	1.310E-01	1.495E-01	7.050E-02
521nm	1.277E-01	1.150E-01	1.333E-01	1.521E-01	7.174E-02
522nm	1.298E-01	1.169E-01	1.355E-01	1.546E-01	7.292E-02
523nm	1.318E-01	1.187E-01	1.376E-01	1.570E-01	7.406E-02
524nm	1.337E-01	1.204E-01	1.396E-01	1.593E-01	7.515E-02
525nm	1.355E-01	1.221E-01	1.416E-01	1.615E-01	7.619E-02
526nm	1.373E-01	1.236E-01	1.434E-01	1.636E-01	7.717E-02
527nm	1.390E-01	1.251E-01	1.451E-01	1.656E-01	7.810E-02
528nm	1.406E-01	1.265E-01	1.468E-01	1.675E-01	7.900E-02
529nm	1.422E-01	1.279E-01	1.484E-01	1.694E-01	7.985E-02
530nm	1.437E-01	1.293E-01	1.500E-01	1.712E-01	8.067E-02
531nm	1.451E-01	1.306E-01	1.515E-01	1.729E-01	8.146E-02
532nm	1.465E-01	1.319E-01	1.530E-01	1.746E-01	8.223E-02
533nm	1.478E-01	1.331E-01	1.543E-01	1.761E-01	8.296E-02
534nm	1.490E-01	1.342E-01	1.556E-01	1.776E-01	8.367E-02
535nm	1.502E-01	1.352E-01	1.568E-01	1.790E-01	8.436E-02
536nm	1.514E-01	1.362E-01	1.580E-01	1.804E-01	8.502E-02
537nm	1.525E-01	1.372E-01	1.592E-01	1.818E-01	8.566E-02
538nm	1.536E-01	1.383E-01	1.603E-01	1.831E-01	8.628E-02
539nm	1.547E-01	1.393E-01	1.615E-01	1.844E-01	8.687E-02
540nm	1.558E-01	1.403E-01	1.625E-01	1.857E-01	8.744E-02
541nm	1.568E-01	1.412E-01	1.636E-01	1.869E-01	8.798E-02
542nm	1.577E-01	1.420E-01	1.646E-01	1.879E-01	8.849E-02
543nm	1.586E-01	1.428E-01	1.655E-01	1.890E-01	8.897E-02
544nm	1.594E-01	1.436E-01	1.664E-01	1.900E-01	8.945E-02
545nm	1.603E-01	1.443E-01	1.673E-01	1.909E-01	8.992E-02
546nm	1.611E-01	1.451E-01	1.682E-01	1.920E-01	9.041E-02
547nm	1.619E-01	1.458E-01	1.691E-01	1.930E-01	9.090E-02
548nm	1.627E-01	1.466E-01	1.699E-01	1.941E-01	9.140E-02
549nm	1.636E-01	1.473E-01	1.708E-01	1.951E-01	9.189E-02
550nm	1.644E-01	1.481E-01	1.717E-01	1.961E-01	9.239E-02
551nm	1.653E-01	1.488E-01	1.726E-01	1.971E-01	9.290E-02
552nm	1.661E-01	1.496E-01	1.735E-01	1.982E-01	9.340E-02
553nm	1.670E-01	1.503E-01	1.744E-01	1.992E-01	9.391E-02
554nm	1.679E-01	1.512E-01	1.754E-01	2.003E-01	9.442E-02
555nm	1.689E-01	1.520E-01	1.764E-01	2.015E-01	9.494E-02
556nm	1.699E-01	1.529E-01	1.774E-01	2.026E-01	9.546E-02
557nm	1.708E-01	1.537E-01	1.784E-01	2.037E-01	9.599E-02
558nm	1.719E-01	1.546E-01	1.794E-01	2.049E-01	9.655E-02
559nm	1.729E-01	1.555E-01	1.805E-01	2.061E-01	9.711E-02
560nm	1.739E-01	1.564E-01	1.815E-01	2.073E-01	9.768E-02
561nm	1.749E-01	1.572E-01	1.825E-01	2.085E-01	9.824E-02
562nm	1.758E-01	1.581E-01	1.835E-01	2.097E-01	9.878E-02
563nm	1.768E-01	1.589E-01	1.845E-01	2.108E-01	9.930E-02
564nm	1.777E-01	1.598E-01	1.855E-01	2.119E-01	9.982E-02
565nm	1.786E-01	1.606E-01	1.865E-01	2.130E-01	1.003E-01
566nm	1.795E-01	1.614E-01	1.874E-01	2.141E-01	1.008E-01
567nm	1.803E-01	1.621E-01	1.882E-01	2.151E-01	1.013E-01
568nm	1.811E-01	1.628E-01	1.890E-01	2.160E-01	1.018E-01
569nm	1.819E-01	1.635E-01	1.898E-01	2.170E-01	1.022E-01
570nm	1.827E-01	1.642E-01	1.907E-01	2.180E-01	1.027E-01
571nm	1.834E-01	1.649E-01	1.915E-01	2.189E-01	1.031E-01
572nm	1.842E-01	1.655E-01	1.923E-01	2.198E-01	1.035E-01
573nm	1.848E-01	1.661E-01	1.931E-01	2.207E-01	1.039E-01

TABLE 4.1
(Continued)

No.	1	2	3	4	5
574nm	1.855E-01	1.667E-01	1.937E-01	2.214E-01	1.043E-01
575nm	1.860E-01	1.673E-01	1.943E-01	2.221E-01	1.046E-01
576nm	1.865E-01	1.677E-01	1.948E-01	2.227E-01	1.049E-01
577nm	1.870E-01	1.682E-01	1.953E-01	2.232E-01	1.052E-01
578nm	1.875E-01	1.686E-01	1.957E-01	2.238E-01	1.054E-01
579nm	1.879E-01	1.690E-01	1.961E-01	2.243E-01	1.056E-01
580nm	1.882E-01	1.693E-01	1.965E-01	2.247E-01	1.058E-01
581nm	1.885E-01	1.695E-01	1.968E-01	2.251E-01	1.059E-01
582nm	1.887E-01	1.696E-01	1.969E-01	2.252E-01	1.060E-01
583nm	1.888E-01	1.696E-01	1.970E-01	2.253E-01	1.061E-01
584nm	1.888E-01	1.696E-01	1.970E-01	2.254E-01	1.061E-01
585nm	1.888E-01	1.695E-01	1.970E-01	2.253E-01	1.061E-01
586nm	1.888E-01	1.695E-01	1.970E-01	2.253E-01	1.061E-01
587nm	1.888E-01	1.695E-01	1.970E-01	2.252E-01	1.061E-01
588nm	1.886E-01	1.694E-01	1.969E-01	2.250E-01	1.060E-01
589nm	1.884E-01	1.693E-01	1.967E-01	2.247E-01	1.058E-01
590nm	1.880E-01	1.690E-01	1.963E-01	2.243E-01	1.057E-01
591nm	1.875E-01	1.686E-01	1.959E-01	2.238E-01	1.054E-01
592nm	1.870E-01	1.681E-01	1.953E-01	2.232E-01	1.052E-01
593nm	1.864E-01	1.676E-01	1.946E-01	2.226E-01	1.048E-01
594nm	1.858E-01	1.671E-01	1.940E-01	2.219E-01	1.045E-01
595nm	1.852E-01	1.665E-01	1.933E-01	2.212E-01	1.041E-01
596nm	1.846E-01	1.659E-01	1.925E-01	2.203E-01	1.037E-01
597nm	1.838E-01	1.652E-01	1.917E-01	2.194E-01	1.032E-01
598nm	1.829E-01	1.644E-01	1.907E-01	2.183E-01	1.027E-01
599nm	1.819E-01	1.635E-01	1.897E-01	2.172E-01	1.022E-01
600nm	1.809E-01	1.624E-01	1.886E-01	2.159E-01	1.016E-01
601nm	1.798E-01	1.614E-01	1.875E-01	2.145E-01	1.010E-01
602nm	1.786E-01	1.603E-01	1.863E-01	2.131E-01	1.003E-01
603nm	1.773E-01	1.593E-01	1.850E-01	2.116E-01	9.957E-02
604nm	1.760E-01	1.581E-01	1.837E-01	2.100E-01	9.878E-02
605nm	1.746E-01	1.569E-01	1.823E-01	2.084E-01	9.797E-02
606nm	1.732E-01	1.556E-01	1.808E-01	2.067E-01	9.715E-02
607nm	1.716E-01	1.542E-01	1.792E-01	2.049E-01	9.632E-02
608nm	1.701E-01	1.528E-01	1.775E-01	2.031E-01	9.546E-02
609nm	1.684E-01	1.513E-01	1.758E-01	2.011E-01	9.457E-02
610nm	1.667E-01	1.497E-01	1.740E-01	1.991E-01	9.361E-02
611nm	1.650E-01	1.481E-01	1.721E-01	1.970E-01	9.263E-02
612nm	1.632E-01	1.464E-01	1.702E-01	1.948E-01	9.161E-02
613nm	1.614E-01	1.447E-01	1.682E-01	1.926E-01	9.058E-02
614nm	1.595E-01	1.430E-01	1.663E-01	1.903E-01	8.957E-02
615nm	1.576E-01	1.413E-01	1.643E-01	1.881E-01	8.854E-02
616nm	1.556E-01	1.395E-01	1.623E-01	1.857E-01	8.750E-02
617nm	1.536E-01	1.378E-01	1.603E-01	1.834E-01	8.642E-02
618nm	1.516E-01	1.360E-01	1.582E-01	1.810E-01	8.529E-02
619nm	1.495E-01	1.342E-01	1.561E-01	1.786E-01	8.411E-02
620nm	1.475E-01	1.324E-01	1.540E-01	1.761E-01	8.291E-02
621nm	1.453E-01	1.306E-01	1.519E-01	1.736E-01	8.170E-02
622nm	1.433E-01	1.287E-01	1.497E-01	1.711E-01	8.048E-02
623nm	1.411E-01	1.268E-01	1.475E-01	1.685E-01	7.926E-02
624nm	1.390E-01	1.248E-01	1.453E-01	1.660E-01	7.803E-02
625nm	1.369E-01	1.229E-01	1.431E-01	1.634E-01	7.680E-02
626nm	1.348E-01	1.209E-01	1.408E-01	1.608E-01	7.557E-02
627nm	1.326E-01	1.190E-01	1.384E-01	1.582E-01	7.435E-02
628nm	1.304E-01	1.170E-01	1.361E-01	1.556E-01	7.312E-02
629nm	1.282E-01	1.151E-01	1.337E-01	1.530E-01	7.187E-02
630nm	1.258E-01	1.130E-01	1.312E-01	1.502E-01	7.059E-02
631nm	1.235E-01	1.109E-01	1.287E-01	1.474E-01	6.930E-02
632nm	1.211E-01	1.088E-01	1.263E-01	1.446E-01	6.800E-02
633nm	1.187E-01	1.067E-01	1.238E-01	1.418E-01	6.671E-02
634nm	1.165E-01	1.048E-01	1.216E-01	1.392E-01	6.547E-02
635nm	1.144E-01	1.029E-01	1.194E-01	1.367E-01	6.425E-02

TABLE 4.1
(Continued)

No.	1	2	3	4	5
636nm	1.123E-01	1.010E-01	1.173E-01	1.343E-01	6.304E-02
637nm	1.102E-01	9.909E-02	1.151E-01	1.318E-01	6.183E-02
638nm	1.081E-01	9.715E-02	1.129E-01	1.292E-01	6.060E-02
639nm	1.059E-01	9.518E-02	1.106E-01	1.266E-01	5.937E-02
640nm	1.038E-01	9.321E-02	1.083E-01	1.240E-01	5.815E-02
641nm	1.016E-01	9.124E-02	1.061E-01	1.214E-01	5.694E-02
642nm	9.944E-02	8.928E-02	1.038E-01	1.188E-01	5.575E-02
643nm	9.729E-02	8.732E-02	1.016E-01	1.163E-01	5.458E-02
644nm	9.517E-02	8.538E-02	9.944E-02	1.137E-01	5.342E-02
645nm	9.306E-02	8.346E-02	9.727E-02	1.112E-01	5.227E-02
646nm	9.097E-02	8.154E-02	9.509E-02	1.086E-01	5.109E-02
647nm	8.891E-02	7.965E-02	9.294E-02	1.061E-01	4.993E-02
648nm	8.689E-02	7.782E-02	9.082E-02	1.037E-01	4.877E-02
649nm	8.493E-02	7.606E-02	8.876E-02	1.013E-01	4.765E-02
650nm	8.309E-02	7.451E-02	8.682E-02	9.914E-02	4.658E-02
651nm	8.131E-02	7.305E-02	8.495E-02	9.709E-02	4.554E-02
652nm	7.958E-02	7.162E-02	8.312E-02	9.509E-02	4.453E-02
653nm	7.786E-02	7.018E-02	8.131E-02	9.309E-02	4.353E-02
654nm	7.611E-02	6.859E-02	7.951E-02	9.095E-02	4.251E-02
655nm	7.436E-02	6.693E-02	7.771E-02	8.876E-02	4.150E-02
656nm	7.260E-02	6.525E-02	7.590E-02	8.655E-02	4.049E-02
657nm	7.083E-02	6.355E-02	7.408E-02	8.435E-02	3.950E-02
658nm	6.899E-02	6.187E-02	7.216E-02	8.217E-02	3.853E-02
659nm	6.716E-02	6.020E-02	7.022E-02	8.002E-02	3.758E-02
660nm	6.534E-02	5.856E-02	6.829E-02	7.792E-02	3.665E-02
661nm	6.358E-02	5.695E-02	6.641E-02	7.587E-02	3.574E-02
662nm	6.193E-02	5.539E-02	6.465E-02	7.393E-02	3.483E-02
663nm	6.036E-02	5.388E-02	6.296E-02	7.208E-02	3.395E-02
664nm	5.886E-02	5.244E-02	6.133E-02	7.028E-02	3.308E-02
665nm	5.741E-02	5.106E-02	5.977E-02	6.854E-02	3.224E-02
666nm	5.606E-02	4.983E-02	5.829E-02	6.687E-02	3.144E-02
667nm	5.475E-02	4.867E-02	5.687E-02	6.524E-02	3.066E-02
668nm	5.346E-02	4.755E-02	5.547E-02	6.363E-02	2.990E-02
669nm	5.217E-02	4.645E-02	5.410E-02	6.204E-02	2.915E-02
670nm	5.080E-02	4.531E-02	5.267E-02	6.040E-02	2.840E-02
671nm	4.940E-02	4.415E-02	5.125E-02	5.876E-02	2.765E-02
672nm	4.800E-02	4.298E-02	4.985E-02	5.714E-02	2.690E-02
673nm	4.662E-02	4.181E-02	4.849E-02	5.553E-02	2.617E-02
674nm	4.527E-02	4.060E-02	4.721E-02	5.396E-02	2.545E-02
675nm	4.396E-02	3.939E-02	4.597E-02	5.243E-02	2.474E-02
676nm	4.269E-02	3.820E-02	4.476E-02	5.094E-02	2.405E-02
677nm	4.147E-02	3.706E-02	4.357E-02	4.949E-02	2.338E-02
678nm	4.031E-02	3.599E-02	4.231E-02	4.808E-02	2.274E-02
679nm	3.921E-02	3.499E-02	4.107E-02	4.673E-02	2.213E-02
680nm	3.816E-02	3.404E-02	3.988E-02	4.544E-02	2.154E-02
681nm	3.716E-02	3.315E-02	3.877E-02	4.423E-02	2.097E-02
682nm	3.625E-02	3.236E-02	3.790E-02	4.319E-02	2.042E-02
683nm	3.538E-02	3.162E-02	3.711E-02	4.222E-02	1.988E-02
684nm	3.453E-02	3.089E-02	3.634E-02	4.127E-02	1.936E-02
685nm	3.368E-02	3.017E-02	3.554E-02	4.032E-02	1.885E-02
686nm	3.274E-02	2.938E-02	3.450E-02	3.920E-02	1.834E-02
687nm	3.180E-02	2.858E-02	3.341E-02	3.806E-02	1.784E-02
688nm	3.088E-02	2.777E-02	3.232E-02	3.693E-02	1.735E-02
689nm	2.998E-02	2.696E-02	3.125E-02	3.581E-02	1.687E-02
690nm	2.918E-02	2.615E-02	3.037E-02	3.483E-02	1.639E-02
691nm	2.841E-02	2.535E-02	2.953E-02	3.389E-02	1.592E-02
692nm	2.767E-02	2.456E-02	2.873E-02	3.298E-02	1.546E-02
693nm	2.694E-02	2.381E-02	2.793E-02	3.208E-02	1.502E-02
694nm	2.619E-02	2.312E-02	2.707E-02	3.115E-02	1.461E-02
695nm	2.546E-02	2.246E-02	2.621E-02	3.023E-02	1.421E-02
696nm	2.473E-02	2.183E-02	2.537E-02	2.932E-02	1.382E-02
697nm	2.403E-02	2.121E-02	2.457E-02	2.844E-02	1.344E-02

TABLE 4.1
(Continued)

No.	1	2	3	4	5
698nm	2.338E-02	2.059E-02	2.384E-02	2.762E-02	1.306E-02
699nm	2.273E-02	1.999E-02	2.316E-02	2.683E-02	1.268E-02
700nm	2.210E-02	1.939E-02	2.249E-02	2.606E-02	1.231E-02
701nm	2.146E-02	1.879E-02	2.183E-02	2.531E-02	1.194E-02
702nm	2.075E-02	1.815E-02	2.112E-02	2.455E-02	1.159E-02
703nm	2.006E-02	1.753E-02	2.044E-02	2.381E-02	1.125E-02
704nm	1.938E-02	1.694E-02	1.978E-02	2.309E-02	1.092E-02
705nm	1.875E-02	1.642E-02	1.917E-02	2.241E-02	1.060E-02
706nm	1.822E-02	1.609E-02	1.867E-02	2.182E-02	1.028E-02
707nm	1.772E-02	1.579E-02	1.820E-02	2.124E-02	9.970E-03
708nm	1.724E-02	1.549E-02	1.776E-02	2.067E-02	9.672E-03
709nm	1.675E-02	1.512E-02	1.730E-02	2.007E-02	9.386E-03
710nm	1.617E-02	1.455E-02	1.675E-02	1.936E-02	9.118E-03
711nm	1.561E-02	1.394E-02	1.622E-02	1.865E-02	8.861E-03
712nm	1.509E-02	1.335E-02	1.570E-02	1.799E-02	8.614E-03
713nm	1.466E-02	1.283E-02	1.525E-02	1.744E-02	8.377E-03
714nm	1.442E-02	1.250E-02	1.494E-02	1.714E-02	8.149E-03
715nm	1.422E-02	1.222E-02	1.466E-02	1.689E-02	7.927E-03
716nm	1.402E-02	1.195E-02	1.438E-02	1.664E-02	7.708E-03
717nm	1.374E-02	1.163E-02	1.404E-02	1.630E-02	7.488E-03
718nm	1.326E-02	1.117E-02	1.355E-02	1.570E-02	7.260E-03
719nm	1.275E-02	1.071E-02	1.304E-02	1.506E-02	7.035E-03
720nm	1.223E-02	1.027E-02	1.254E-02	1.441E-02	6.816E-03
721nm	1.178E-02	9.942E-03	1.210E-02	1.383E-02	6.608E-03
722nm	1.147E-02	9.824E-03	1.180E-02	1.341E-02	6.419E-03
723nm	1.118E-02	9.725E-03	1.150E-02	1.303E-02	6.237E-03
724nm	1.089E-02	9.598E-03	1.121E-02	1.266E-02	6.058E-03
725nm	1.051E-02	9.311E-03	1.083E-02	1.226E-02	5.873E-03
726nm	9.975E-03	8.727E-03	1.029E-02	1.176E-02	5.675E-03
727nm	9.445E-03	8.118E-03	9.759E-03	1.128E-02	5.480E-03
728nm	8.962E-03	7.552E-03	9.263E-03	1.085E-02	5.291E-03
729nm	8.651E-03	7.215E-03	8.927E-03	1.056E-02	5.120E-03
730nm	8.606E-03	7.248E-03	8.842E-03	1.047E-02	4.975E-03
731nm	8.605E-03	7.334E-03	8.782E-03	1.041E-02	4.839E-03
732nm	8.591E-03	7.396E-03	8.689E-03	1.032E-02	4.709E-03
733nm	8.413E-03	7.218E-03	8.379E-03	1.004E-02	4.579E-03
734nm	7.988E-03	6.685E-03	7.761E-03	9.502E-03	4.445E-03
735nm	7.523E-03	6.103E-03	7.111E-03	8.918E-03	4.310E-03
736nm	7.061E-03	5.544E-03	6.499E-03	8.343E-03	4.172E-03
737nm	6.728E-03	5.217E-03	6.129E-03	7.916E-03	4.022E-03
738nm	6.564E-03	5.186E-03	6.065E-03	7.686E-03	3.860E-03
739nm	6.436E-03	5.213E-03	6.078E-03	7.509E-03	3.700E-03
740nm	6.315E-03	5.244E-03	6.117E-03	7.356E-03	3.546E-03
741nm	6.115E-03	5.107E-03	6.036E-03	7.147E-03	3.409E-03
742nm	5.824E-03	4.780E-03	5.812E-03	6.869E-03	3.293E-03
743nm	5.527E-03	4.436E-03	5.573E-03	6.601E-03	3.191E-03
744nm	5.246E-03	4.117E-03	5.345E-03	6.359E-03	3.102E-03
745nm	5.028E-03	3.949E-03	5.199E-03	6.204E-03	3.037E-03
746nm	4.879E-03	3.932E-03	5.139E-03	6.131E-03	2.989E-03
747nm	4.775E-03	3.972E-03	5.116E-03	6.092E-03	2.946E-03
748nm	4.716E-03	4.050E-03	5.122E-03	6.072E-03	2.900E-03
749nm	4.740E-03	4.157E-03	5.164E-03	6.043E-03	2.829E-03
750nm	4.820E-03	4.266E-03	5.223E-03	6.002E-03	2.738E-03
751nm	4.903E-03	4.338E-03	5.269E-03	5.958E-03	2.642E-03
752nm	4.963E-03	4.347E-03	5.282E-03	5.909E-03	2.543E-03
753nm	4.906E-03	4.153E-03	5.210E-03	5.874E-03	2.453E-03
754nm	4.762E-03	3.821E-03	5.063E-03	5.832E-03	2.369E-03
755nm	4.584E-03	3.450E-03	4.859E-03	5.753E-03	2.289E-03
756nm	4.384E-03	3.078E-03	4.602E-03	5.620E-03	2.213E-03
757nm	4.178E-03	2.813E-03	4.211E-03	5.299E-03	2.135E-03
758nm	3.979E-03	2.624E-03	3.768E-03	4.887E-03	2.061E-03
759nm	3.803E-03	2.483E-03	3.353E-03	4.487E-03	1.996E-03

TABLE 4.1
(Continued)

No.	1	2	3	4	5
760nm	3.661E-03	2.387E-03	3.011E-03	4.149E-03	1.943E-03
761nm	3.667E-03	2.400E-03	2.994E-03	4.148E-03	1.921E-03
762nm	3.725E-03	2.451E-03	3.123E-03	4.286E-03	1.915E-03
763nm	3.771E-03	2.486E-03	3.276E-03	4.427E-03	1.914E-03
764nm	3.766E-03	2.472E-03	3.394E-03	4.507E-03	1.914E-03
765nm	3.500E-03	2.199E-03	3.214E-03	4.188E-03	1.898E-03
766nm	3.147E-03	1.847E-03	2.922E-03	3.730E-03	1.873E-03
767nm	2.788E-03	1.500E-03	2.595E-03	3.248E-03	1.841E-03
768nm	2.470E-03	1.209E-03	2.270E-03	2.805E-03	1.799E-03
769nm	2.455E-03	1.277E-03	2.119E-03	2.697E-03	1.745E-03
770nm	2.508E-03	1.425E-03	2.004E-03	2.682E-03	1.680E-03
771nm	2.558E-03	1.565E-03	1.888E-03	2.690E-03	1.608E-03
772nm	2.555E-03	1.634E-03	1.746E-03	2.678E-03	1.528E-03
773nm	2.196E-03	1.266E-03	1.393E-03	2.410E-03	1.427E-03
774nm	1.785E-03	8.222E-04	1.033E-03	2.112E-03	1.326E-03
775nm	1.383E-03	3.736E-04	7.138E-04	1.827E-03	1.232E-03
776nm	1.059E-03	1.759E-07	4.950E-04	1.603E-03	1.155E-03
777nm	1.037E-03	0.000E+00	6.114E-04	1.612E-03	1.126E-03
778nm	1.107E-03	6.502E-06	8.051E-04	1.679E-03	1.112E-03
779nm	1.243E-03	1.199E-04	1.028E-03	1.777E-03	1.110E-03
780nm	1.424E-03	2.708E-04	1.213E-03	1.870E-03	1.116E-03

5. THERMAL MEASUREMENTS

One major aspect of the reliability of the luminaire is its expected thermal characteristics. The temperature distribution for the unit operating in an ambient temperature of 70°F with good air circulation were recorded using Infrared imaging. A sample of the results for typical luminaires are depicted in Figures 5.1 and 5.2 for randomly selected vendor luminaires.

The range of temperature values from the Infrared measurements were verified by comparison to direct thermocouple readings as described previously in Section 1. The relatively small differences in the directly measured thermocouple values and the Infrared values are attributable to differences in emissivity and absorptivity constants of the surface of the measured areas from the calibration conditions and the irregular geometry of the surfaces. As indicated in Figures 5.1 and 5.2 there are no unusual hot spots for these particular examples of case design indicating that the heat sink design is efficiently removing the heat. This is important since temperature directly influences driver life and specifically degradation of capacitors in the driver.

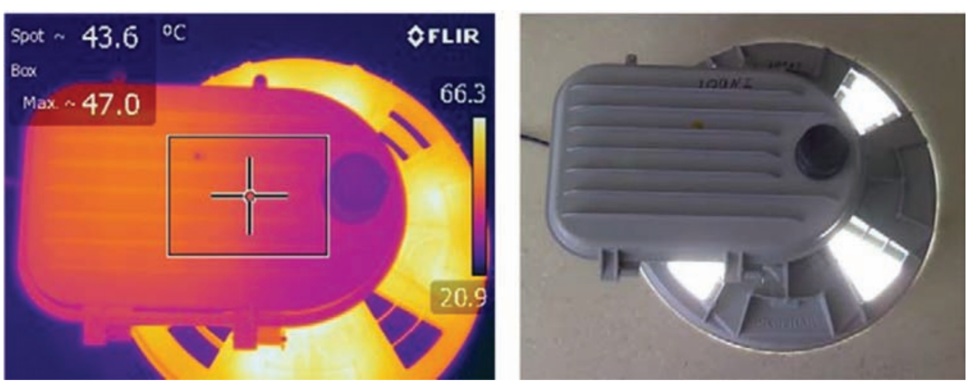


Figure 5.1 Top view thermal profile.

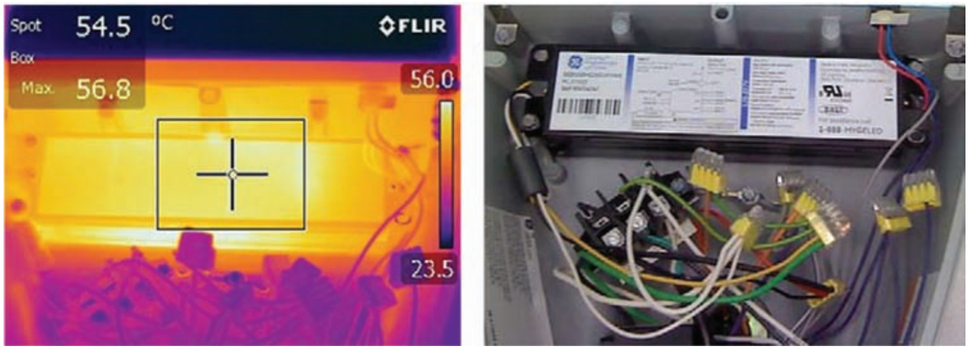


Figure 5.2 Driver thermal profile.

6. ELECTRICAL MEASUREMENTS AND POWER QUALITY

Electrical properties of a typical test unit were determined by using a Dranetz Power Quality meter. Test data was compared to manufacturer's specifications and all data was found to be consistent. Figure 6.1 is an example of a basic wave shape of the supply power with the luminaire connected and operating. Figure 6.2 depicts the harmonic content. This information is relevant since it is indicative of the quality of the driver design as well as indicating any potential problems that may arise from operating multiple luminaires on an electric power supply circuit.

In Figure 6.1 the top graph is the voltage waveform read at the connection point between the luminaire and the power lead. It shows a sine wave that is not distorted indicating a well-designed power supply filtering circuit. The second graph is the current waveform read at the connection point between the luminaire and the power lead. It shows a sine wave that is not distorted indicating a well-designed power supply filtering circuit. The third graph is the RMS (root mean square) value of the current. It shows small variations in the RMS current as a function of time indicating stable operation and sufficient capacitors in the power supply circuitry. The fourth graph is the DC component of the current. It shows no DC current component which is expected for a well-designed driver. The fifth graph is the RMS value of the voltage. It shows small variations in the RMS current as a function of time indicating stable operation and sufficient capacitors in the power supply circuitry. The sixth graph is the DC component of the voltage. It shows no DC voltage offset which is expected for a well-designed driver.

Figure 6.2 is an example of the current and voltage harmonic content measured at the point of coupling between the luminaire and the power line. Values of harmonic distortion are given on the vertical axes for current and for voltage for each of the measured frequencies shown on the horizontal axis. These values are important since large values of harmonic distortion can lead to issues of interaction between luminaires and potential equipment damage both for the luminaire and potentially other electrical equipment attached to the circuit that supplies the power. At the bottom of Figure 6.2 there is a summary table of the measured values of current and voltage harmonic distortion. RMS indicated the root mean square values and FND indicates the values for the fundamental (60 cycle). THD indicates total harmonic distortion.

A test of the stability of the unit was performed for turn on and off cycles as part of the power cycling tests. The luminaire was placed on a timer circuit that cycled

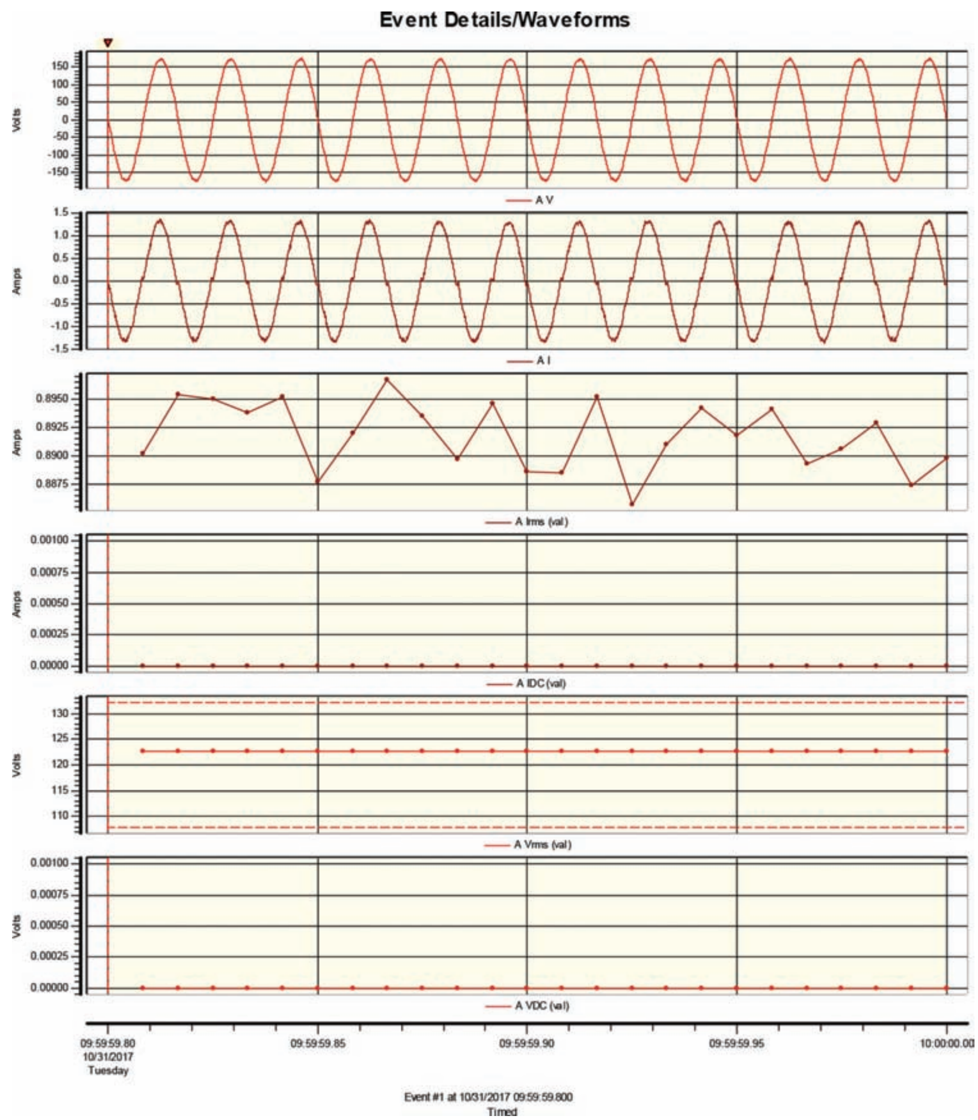
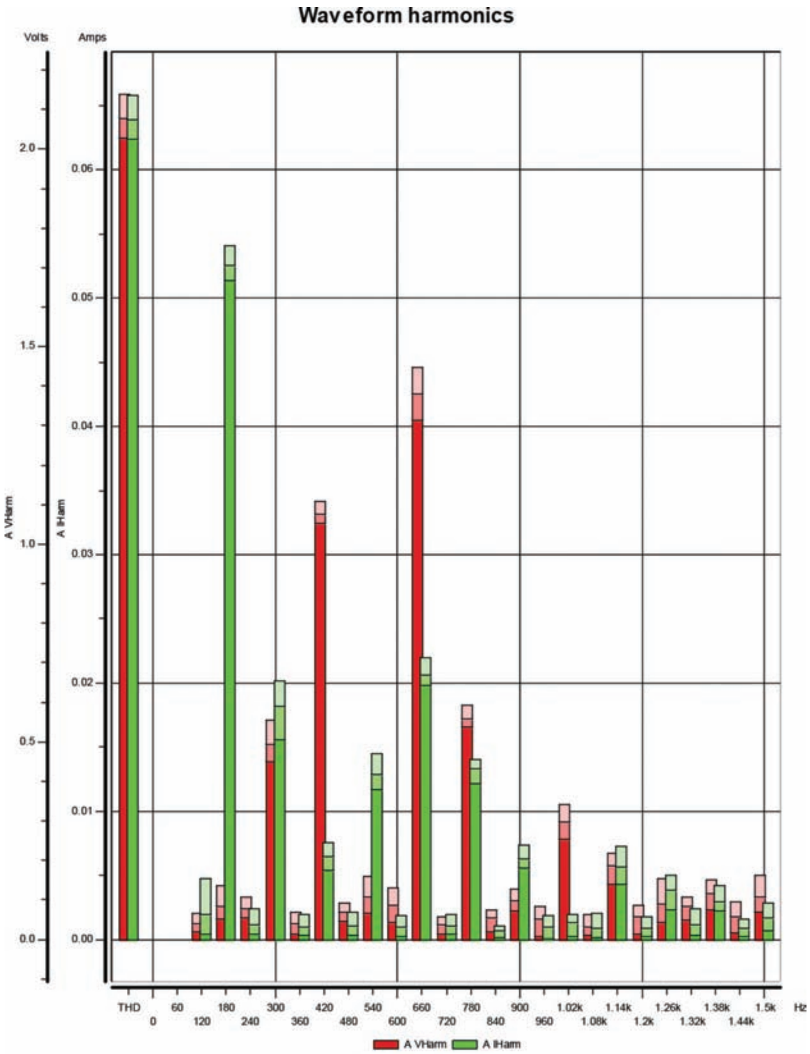


Figure 6.1 Wave shape.



	AV	DV	AI	DI
RMS	122.62	0.10	0.89	0.00
FND	122.61	0.00	0.89	0.00
DC	0.01	0.03	0.00	0.00
THD	2.08	0.11	0.06	0.00

Figure 6.2 Harmonic content.

the unit on and off every 15 minutes for a 24 hour period. Appendix A contains more detail regarding the power quality measurements.

7. ADDITIONAL TESTING

Additional tests were performed at various time intervals. This was done to assure the luminaire meets the specification for performance from an electrical, thermal, and illumination perspective. To verify the operation of the unit in actual operating conditions, horizontal illuminance and spectral data were gathered at field test locations. These tests assure consistency with the ies data submitted by the manufacturer and performance in actual field operating conditions.

8. FIELD TEST RESULTS

Field test data was collected by EERC and INDOT personnel for the tested luminaires. In this testing horizontal illuminance values were collected for points on a rectangular matrix as shown in an example in Figure 8.1 and 8.2 for a high mast and roadway luminaire respectively. Based on the field data these luminaires provide a uniform light pattern for a field installation as per the manufacturer's specification.

As can be observed in Figures 8.1 and 8.2 there is generally good distribution of light for the test areas. Color Correlation Temperature (CCT) data was gathered by EERC for various locations. It should be noted that some of the CCT/spectral readings have +10% error bands due to very low light levels at some measurement locations. The field tests were repeated as needed to verify results.

Field data was gathered for the LED luminaires for a variety of situations and compared to light distributions from computer simulations based on vendor supplied ies files. A comparison was also made to the existing (HPS) lighting. Test results for each luminaire were compared to light distribution determined with a lighting model (AGI32, Lighting Analysts, Inc). A sample of the comparison are shown in Figure 8.3. Such results allowed the design of the lighting installation and the choice of a particular luminaire to be custom tailored to the local requirements for light level and uniformity as well as comparing vendor luminaire performance.

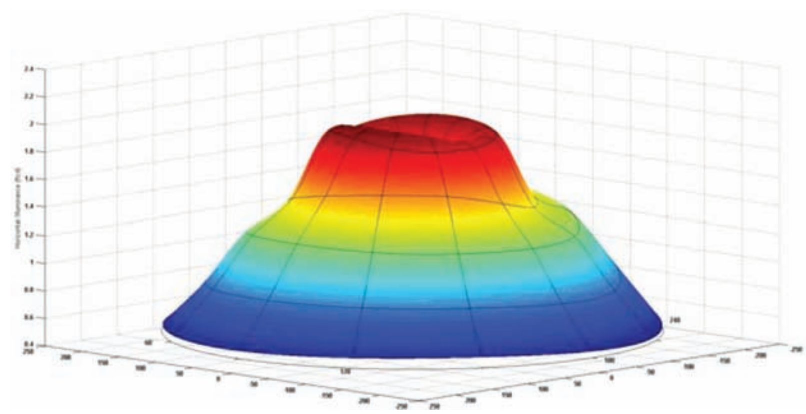


Figure 8.1 Horizontal illuminance value example for high mast luminaire, pole is located at (0, 0, 0).

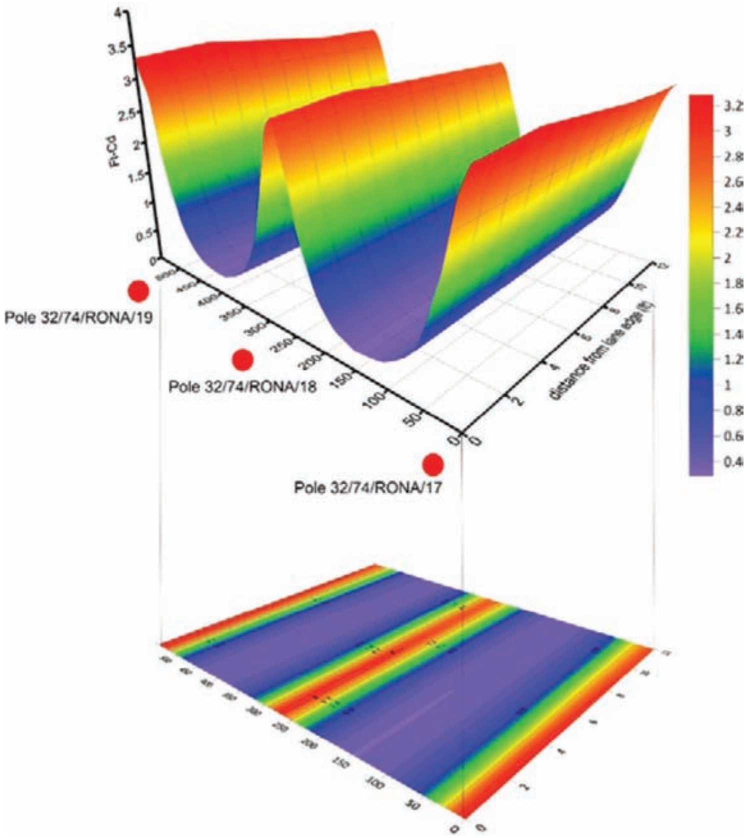


Figure 8.2 Horizontal illuminance value example for roadway luminaire.

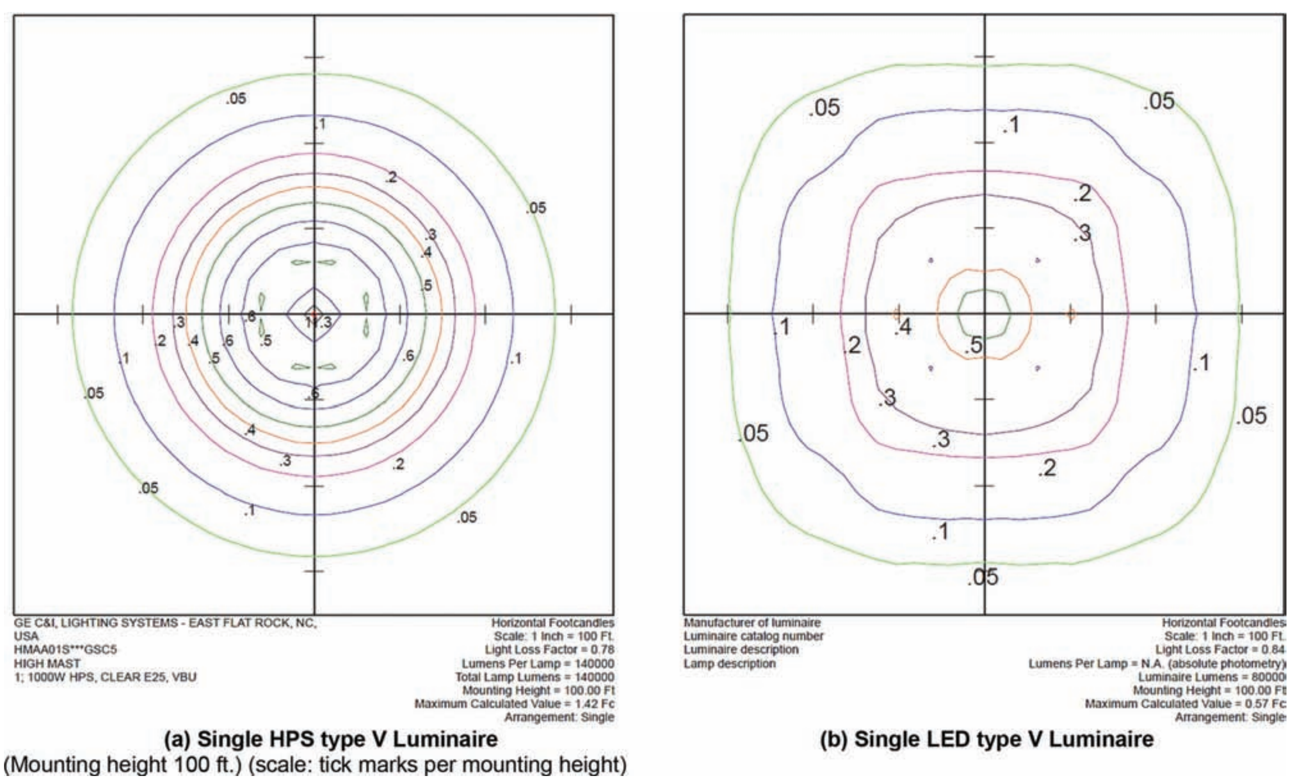


Figure 8.3 Comparison example.

APPENDICES

Appendix A. Example of Power Quality Detail Monitored at Feed to Luminaire

Appendix B. Lumen Measurement Room Design

Appendix C. Testing Check Lists

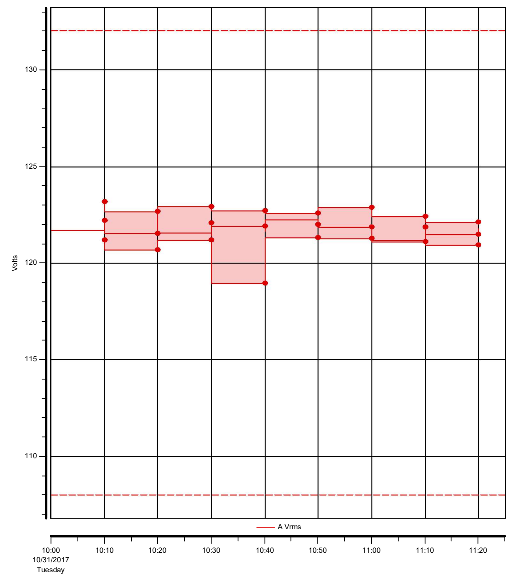
Appendix D. Observations for Section 7.2 of Procedure for Evaluation and Approval List Requirements for Solid State Ballasted Luminaires ITM 957-17p

APPENDIX A: EXAMPLE OF POWER QUALITY DETAIL MONITORED AT FEED TO LUMINAIRE

VOLTAGE TIMEPLOTS

Site:

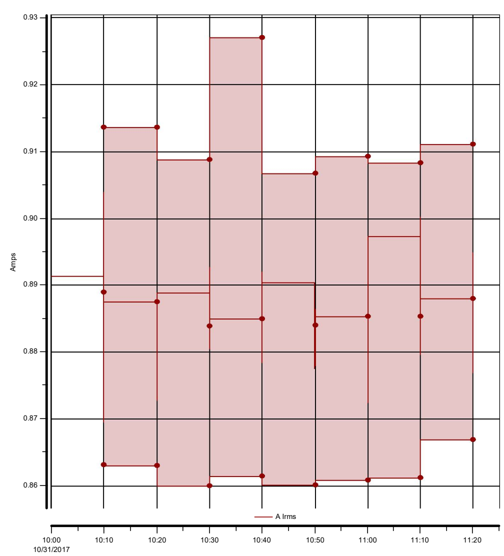
Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0



CURRENT TIMEPLOTS

Site:

Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0



MIN/MAX/AVG POWER REPORT
Site:
Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0

POWER

ACTIVE POWER, P (W)

	A	B	C	TOTAL
Min kW	0.107	0.000	0.000	0.107 on 10/31/2017 10:30:00
Max kW	0.109	0.000	0.000	0.109 on 10/31/2017 10:10:00
Median kW	0.107	0.000	0.000	0.107
Average kW	0.107	0.000	0.000	0.107

APPARENT POWER,S (VA)

	A	B	C	TOTAL
Min kVA	0.108	0.000	0.000	0.108 on 10/31/2017 11:00:00
Max kVA	0.110	0.000	0.000	0.110 on 10/31/2017 10:10:00
Median kVA	0.108	0.000	0.000	0.108
Average kVA	0.108	0.000	0.000	0.108

REACTIVE POWER Q, AT FUND. FREQ. (VAR)

	A	B	C	TOTAL
Min kVAR	-0.011	0.000	-0.000	-0.011 on 10/31/2017 10:10:00
Max kVAR	-0.011	0.000	0.000	-0.011 on 10/31/2017 10:40:00
Median kVAR	-0.011	0.000	-0.000	-0.011
Average kVAR	-0.011	0.000	-0.000	-0.011

POWER FACTOR, PF

	A	B	C	TOTAL
Min	-0.992	0.373	-0.328	-0.992 on 10/31/2017 10:40:00
Max	-0.990	0.407	0.327	-0.990 on 10/31/2017 10:30:00
Median	-0.992	0.390	-0.899	-0.992
Average	-0.992	0.390	-0.895	-0.992

DEMAND

REAL POWER DEMAND

	A	B	C	TOTAL
Min kWh/h				0.107 on 10/31/2017 10:30:00
Max kWh/h				0.108 on 10/31/2017 10:10:00
Median kWh/h				0.107
Average kWh/h				0.107

ENERGY

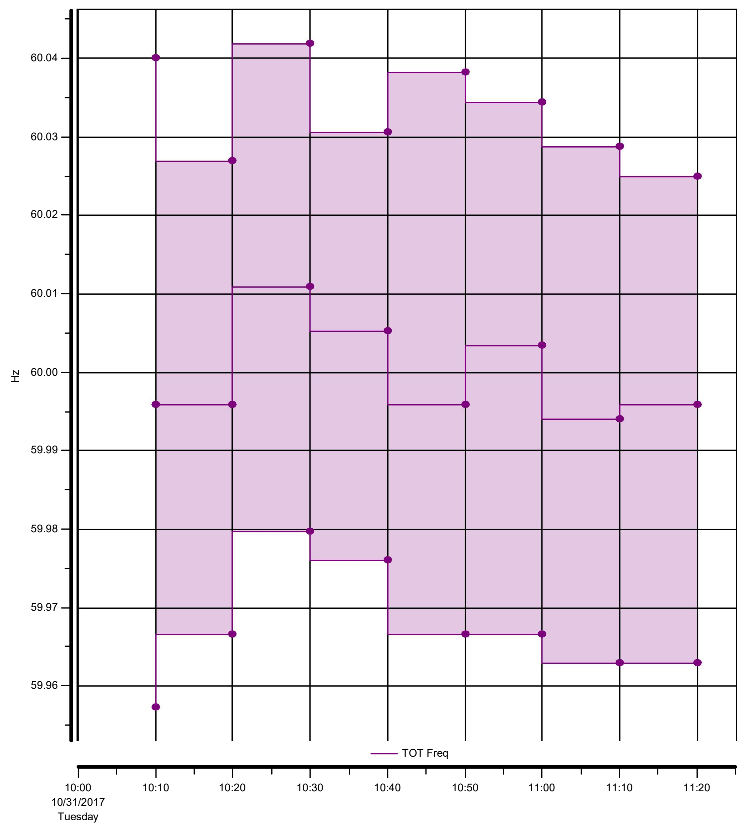
ENERGY - INTEGRATED ACTIVE POWER (W-HRS)

	A	B	C	TOTAL
kWh	0.152	0.000	0.000	0.152 on 10/31/2017 11:25:00

VOLTAGE FREQUENCY TIMEPLOTS

Site:

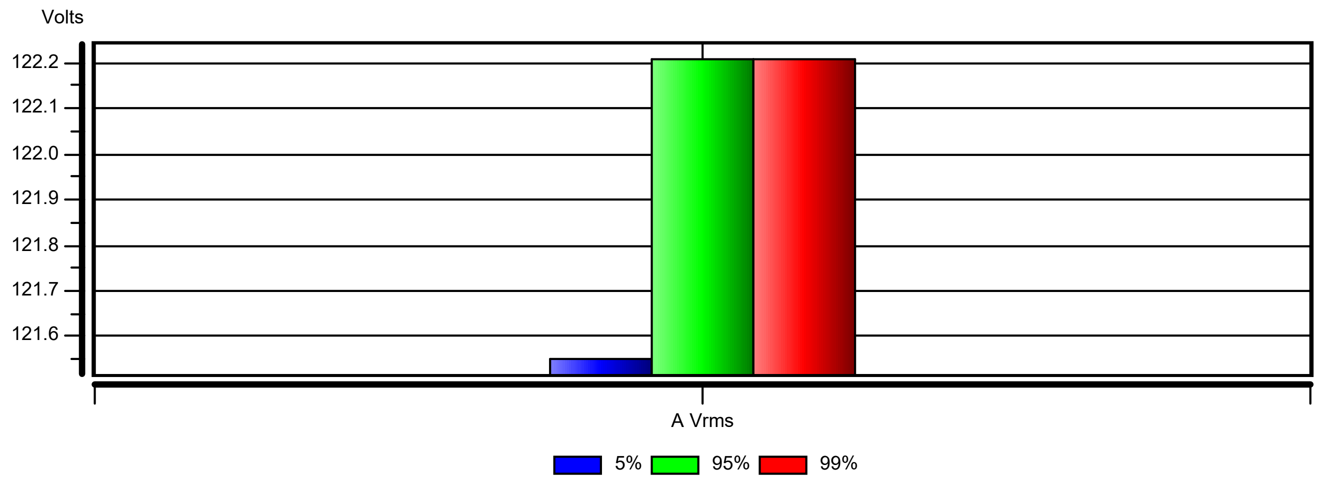
Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0

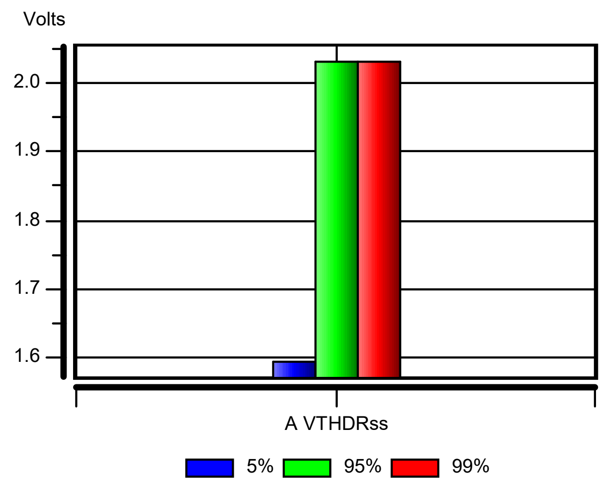


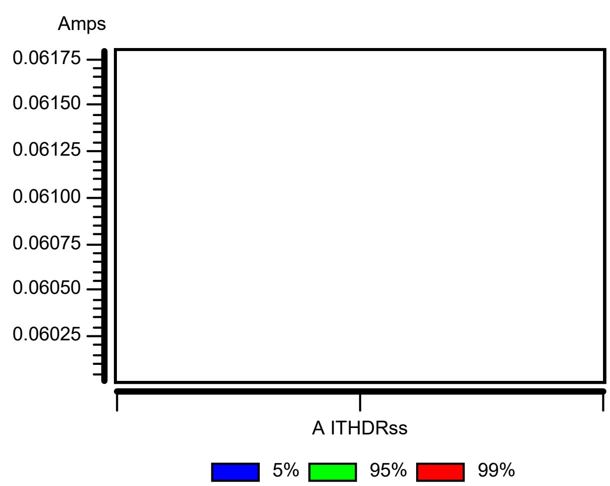
QUALITY OF SUPPLY

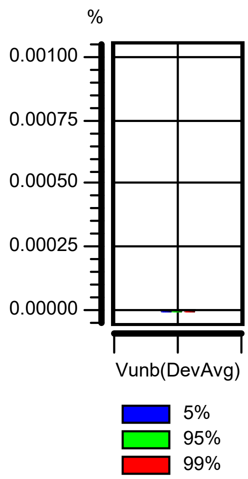
Site:

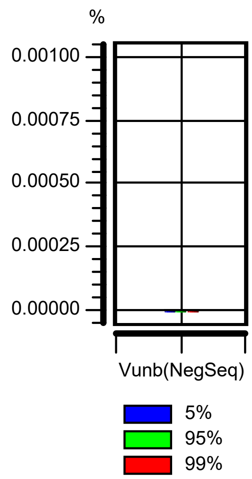
Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0

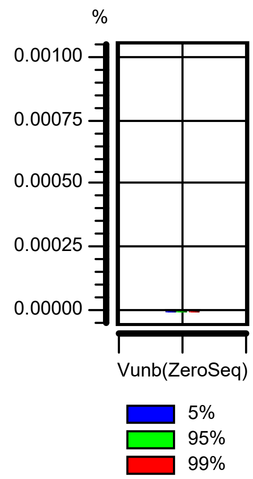


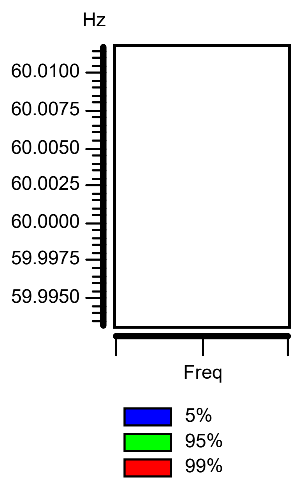





%
0.00100
0.00075
0.00050
0.00025
0.00000
Vunb(DevAvg)
5%
95%
99%


%
0.00100
0.00075
0.00050
0.00025
0.00000
Vunb(NegSeq)
5%
95%
99%


%
0.00100
0.00075
0.00050
0.00025
0.00000
Vunb(ZeroSeq)
5%
95%
99%


Hz
60.0100
60.0075
60.0050
60.0025
60.0000
59.9975
59.9950
Freq
5%
95%
99%

MIN/MAX/AVG SUMMARY REPORT

Site:

Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0

VOLTAGE

	Channel A	Channel A-B
Min Volts	118.95 on 10/31/2017 10:40:00	118.93 on 10/31/2017 10:40:00
Max Volts	123.18 on 10/31/2017 10:10:00	123.16 on 10/31/2017 10:10:00
Median Volts	121.91	121.89
Average Volts	121.93	121.91

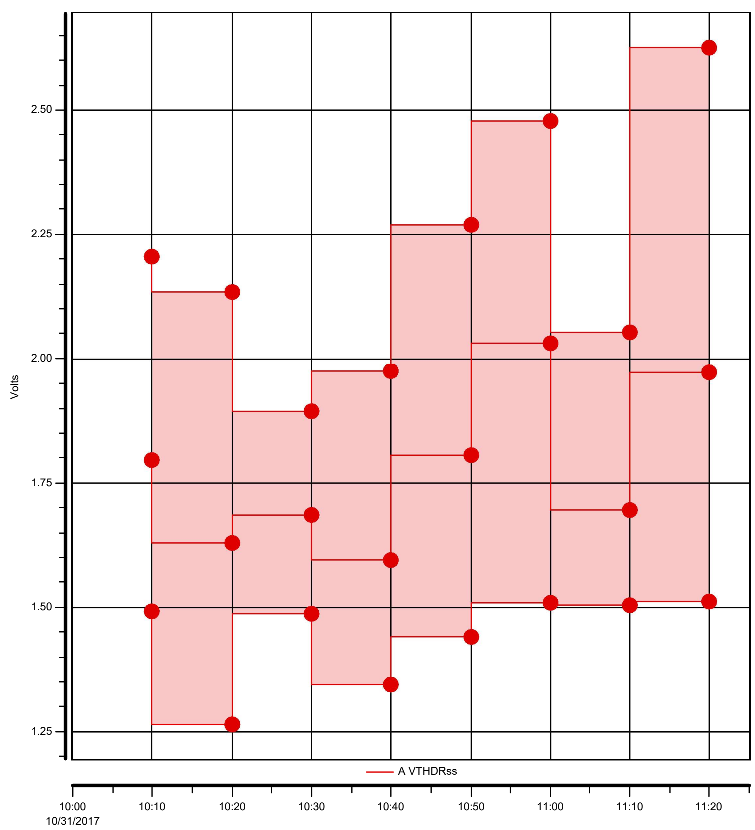
CURRENT

	Channel A
Min Amps	0.860 on 10/31/2017 10:30:00
Max Amps	0.927 on 10/31/2017 10:40:00
Median Amps	0.885
Average Amps	0.886

VTHD TIMEPLOTS

Site: GE ERLH 110W

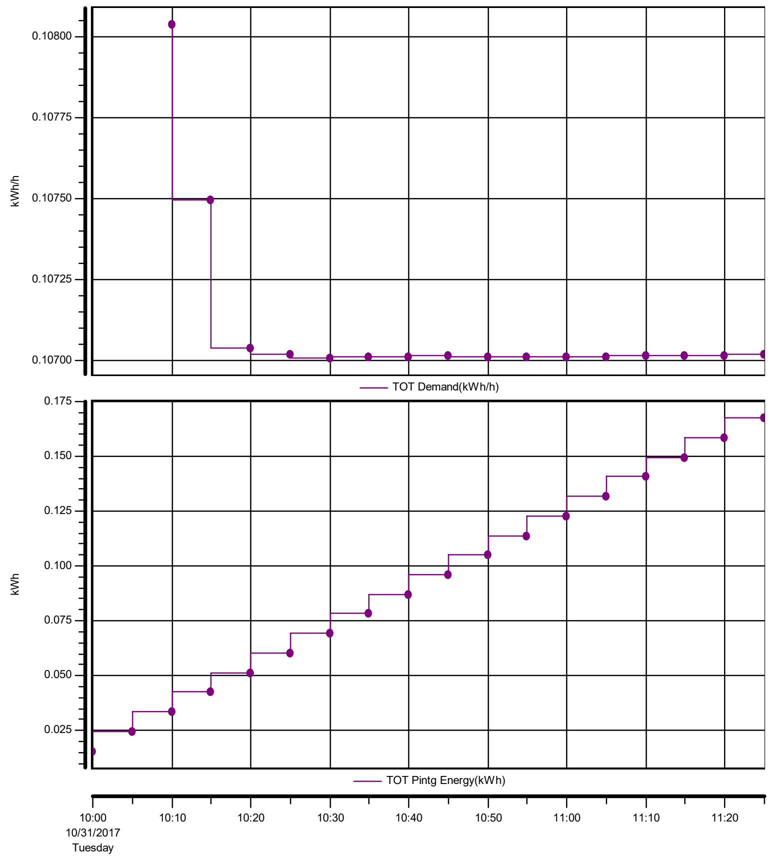
Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0

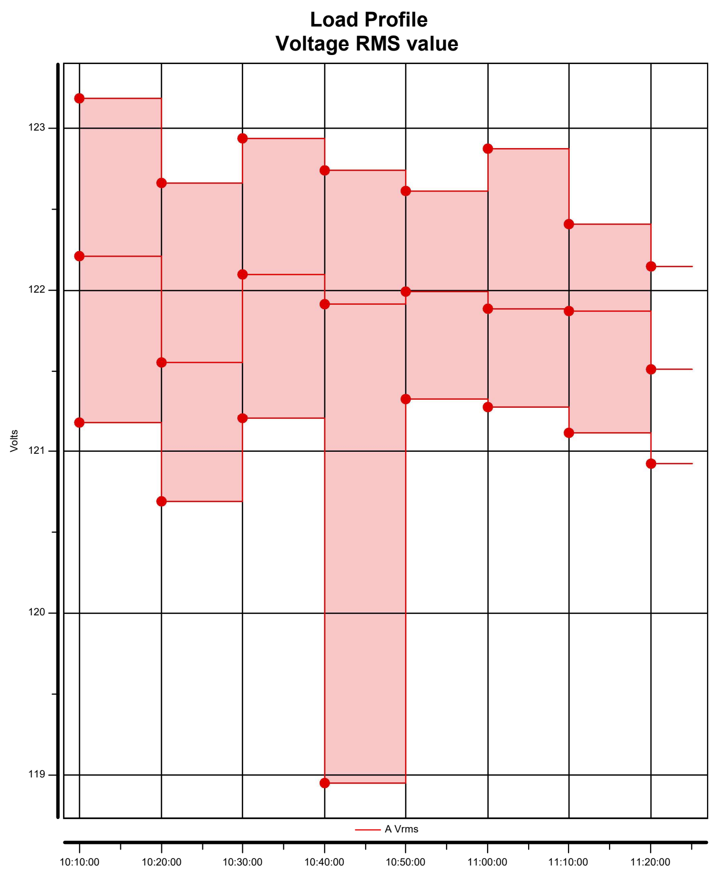


DEMAND AND ENERGY TIMEPLOTS

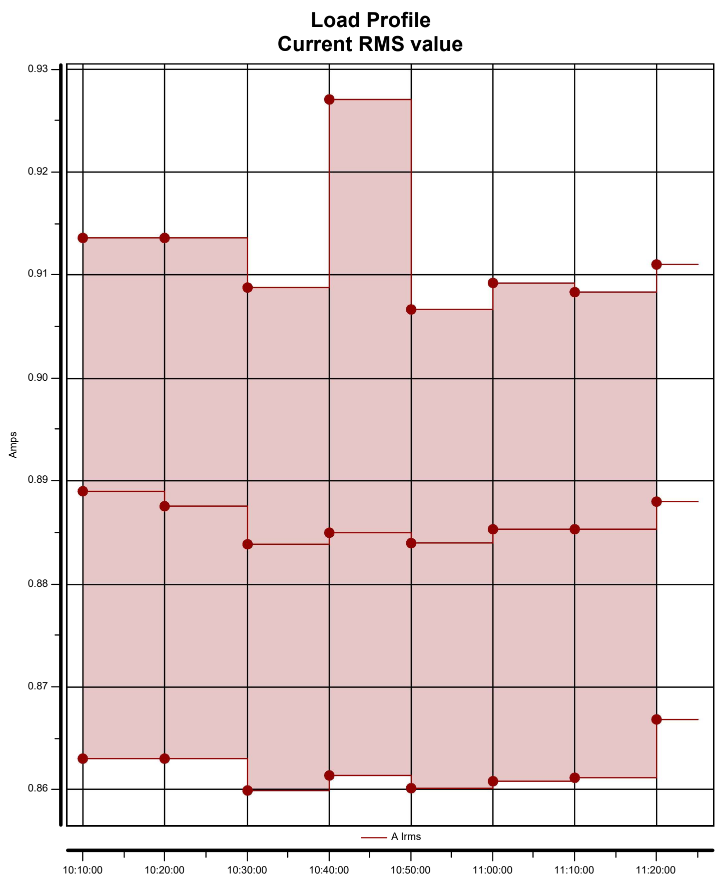
Site:

Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0

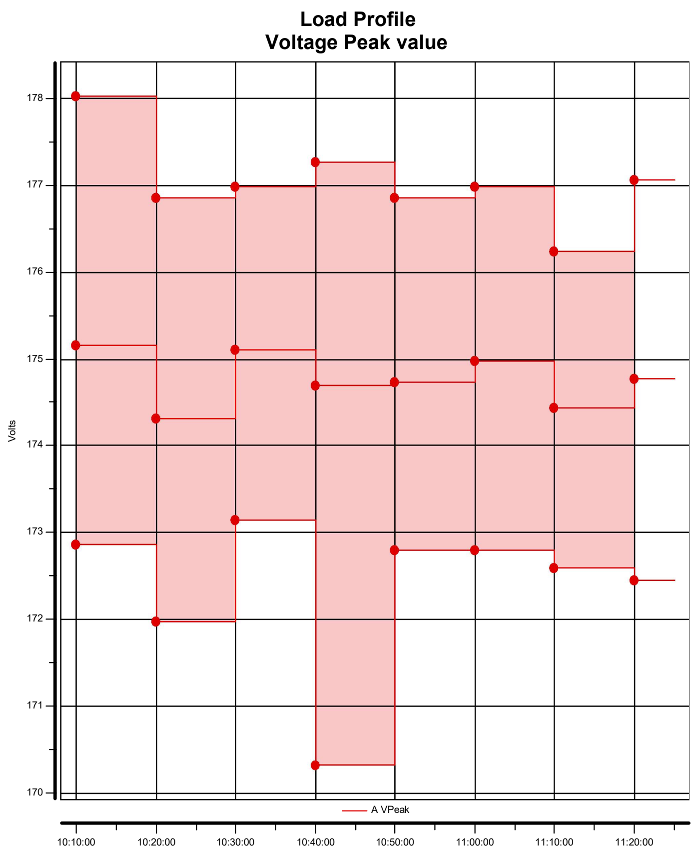




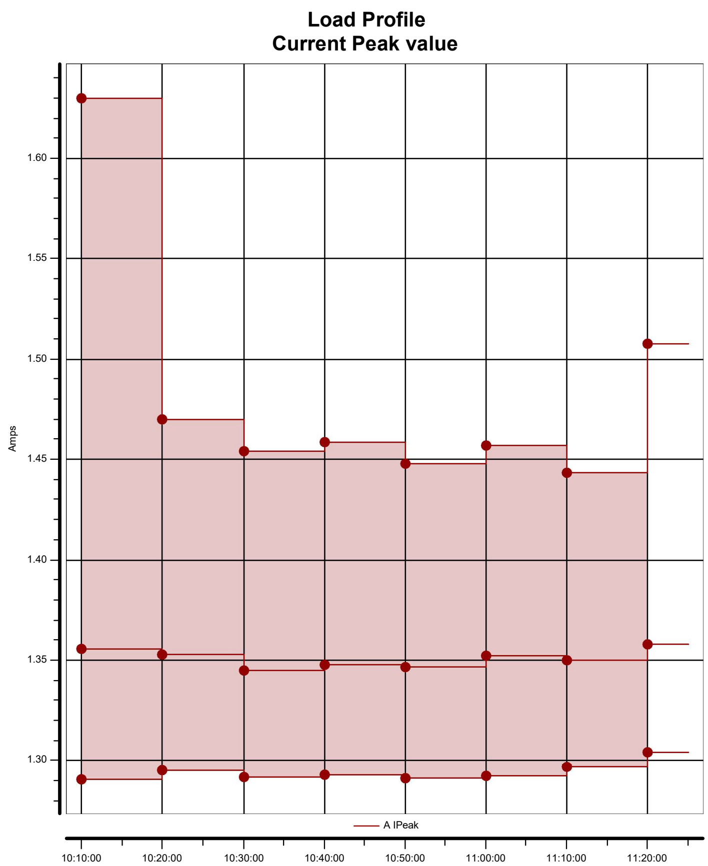
Load Profile
Voltage RMS value
Volts
123
122
121
120
119
A Vrms
10:10:00
10:20:00
10:30:00
10:40:00
10:50:00
11:00:00
11:10:00
11:20:00



Load Profile
Current RMS value
Amps
0.93
0.92
0.91
0.90
0.89
0.88
0.87
0.86
A Irms
10:10:00
10:20:00
10:30:00
10:40:00
10:50:00
11:00:00
11:10:00
11:20:00

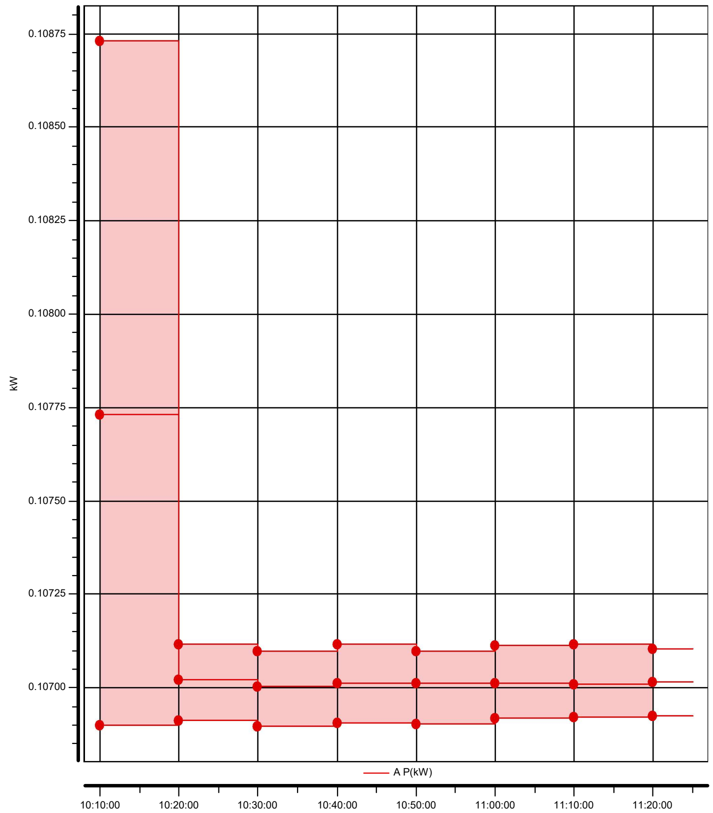


Load Profile
Voltage Peak value
178
177
176
175
174
173
172
171
170
Volts
A VPeak
10:10:00
10:20:00
10:30:00
10:40:00
10:50:00
11:00:00
11:10:00
11:20:00

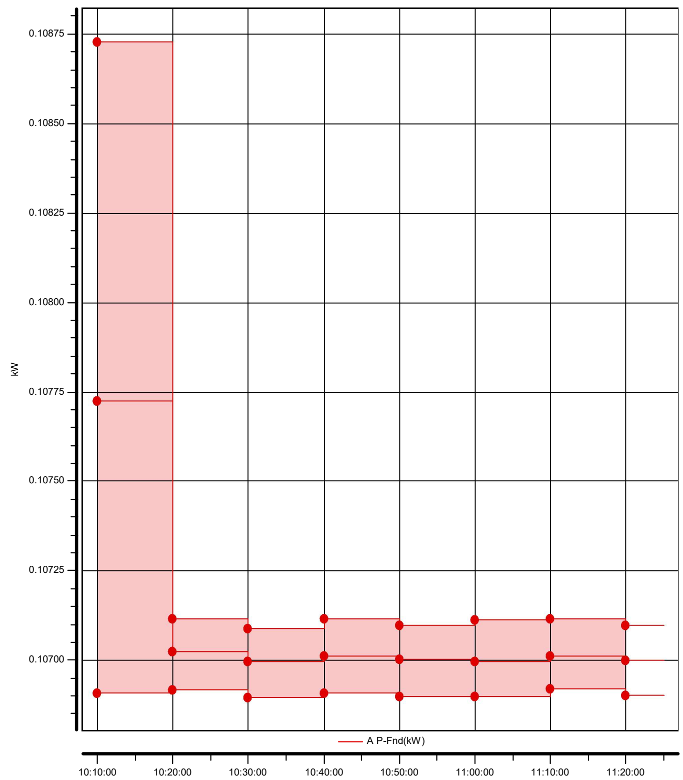


Load Profile
Current Peak value
Amps
1.60
1.55
1.50
1.45
1.40
1.35
1.30
A IPeak
10:10:00
10:20:00
10:30:00
10:40:00
10:50:00
11:00:00
11:10:00
11:20:00

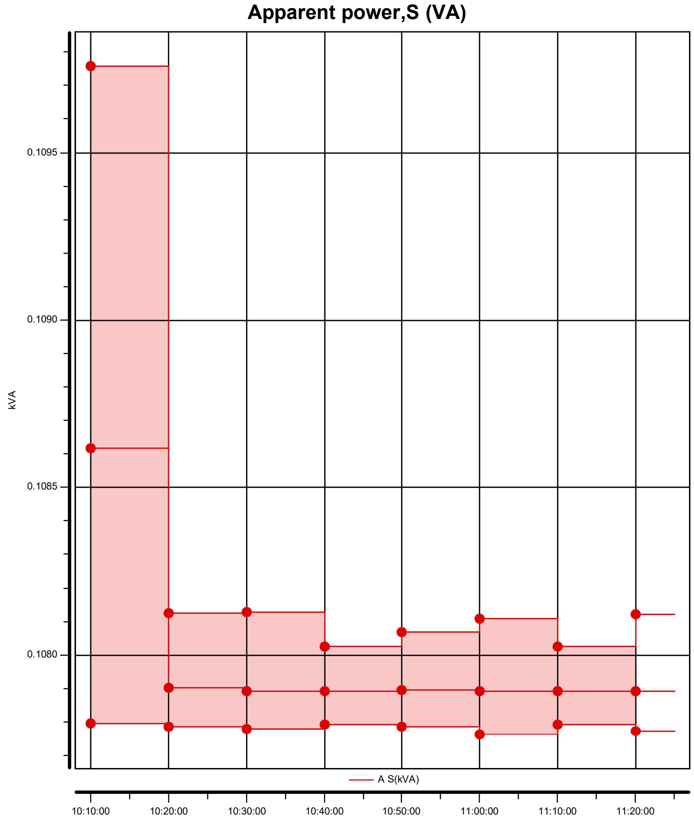
Load Profile
Active power, P (W)



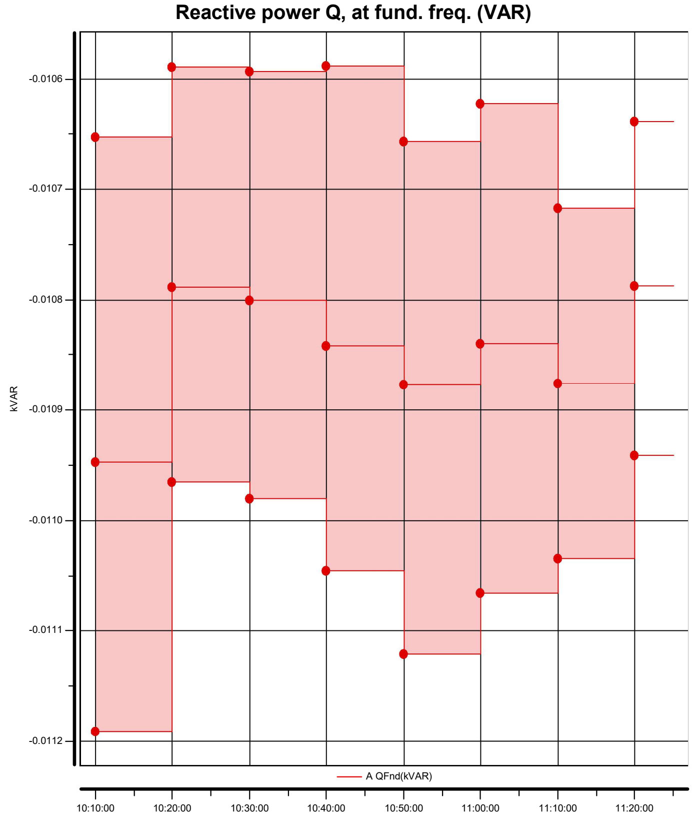
Load Profile
Real Power P,at fund. freq. (W)



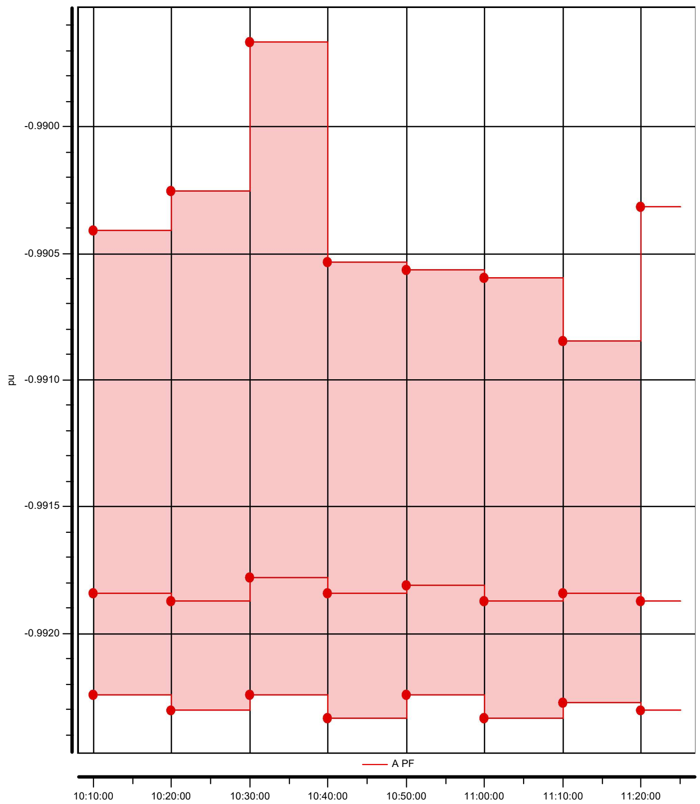
Load Profile
Apparent power,S (VA)

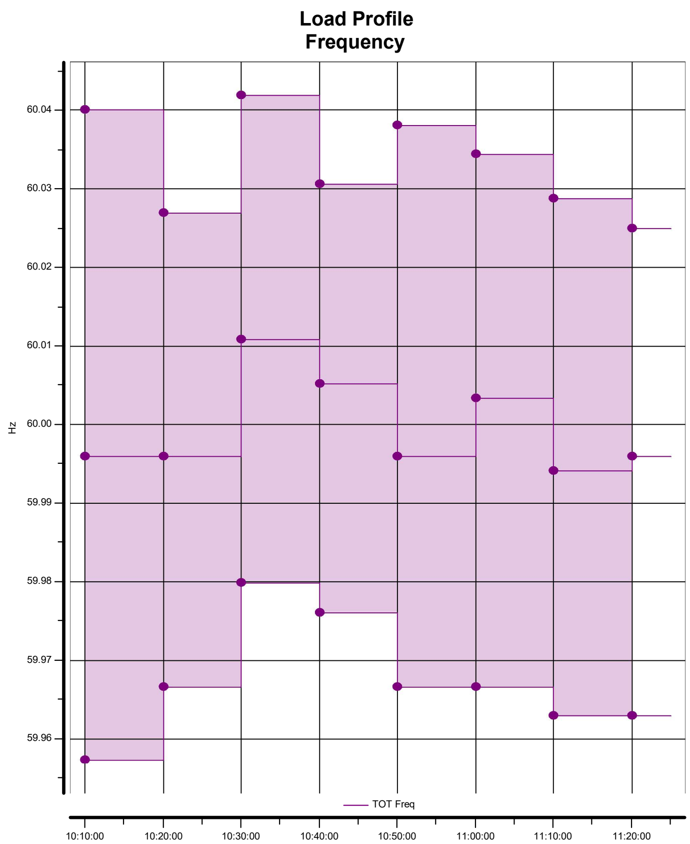


Load Profile
Reactive power Q, at fund. freq. (VAR)

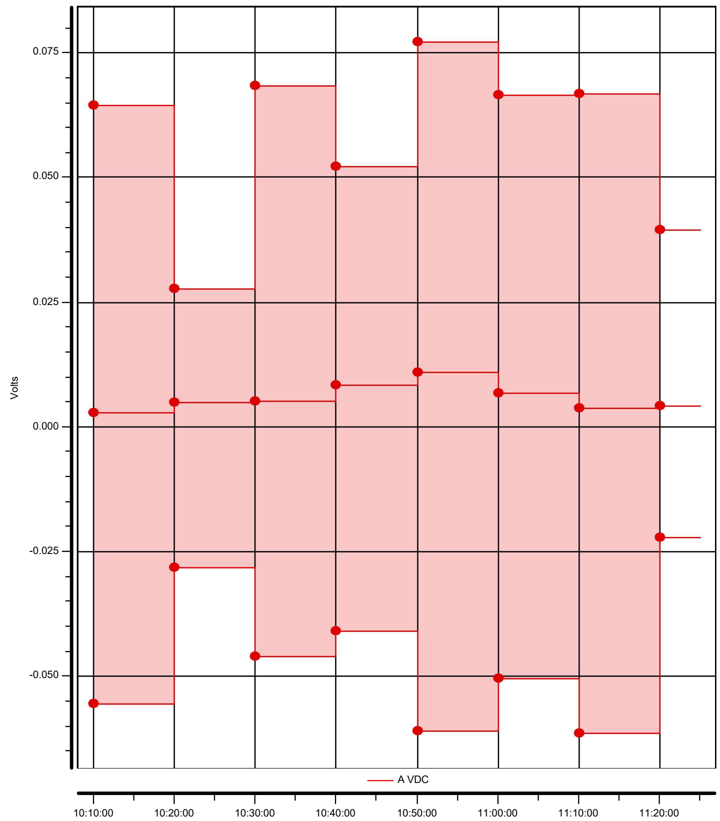


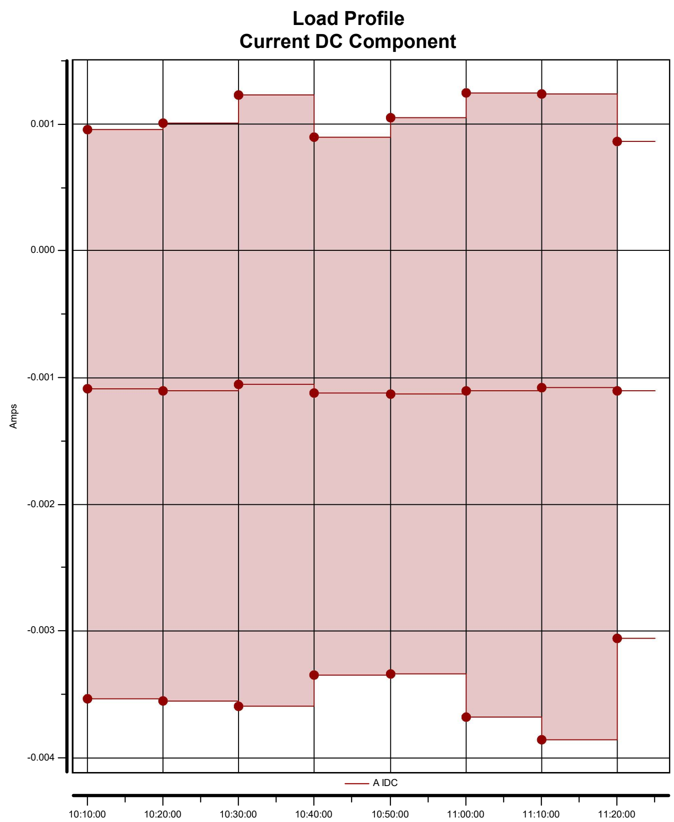
Load Profile
Power Factor, PF



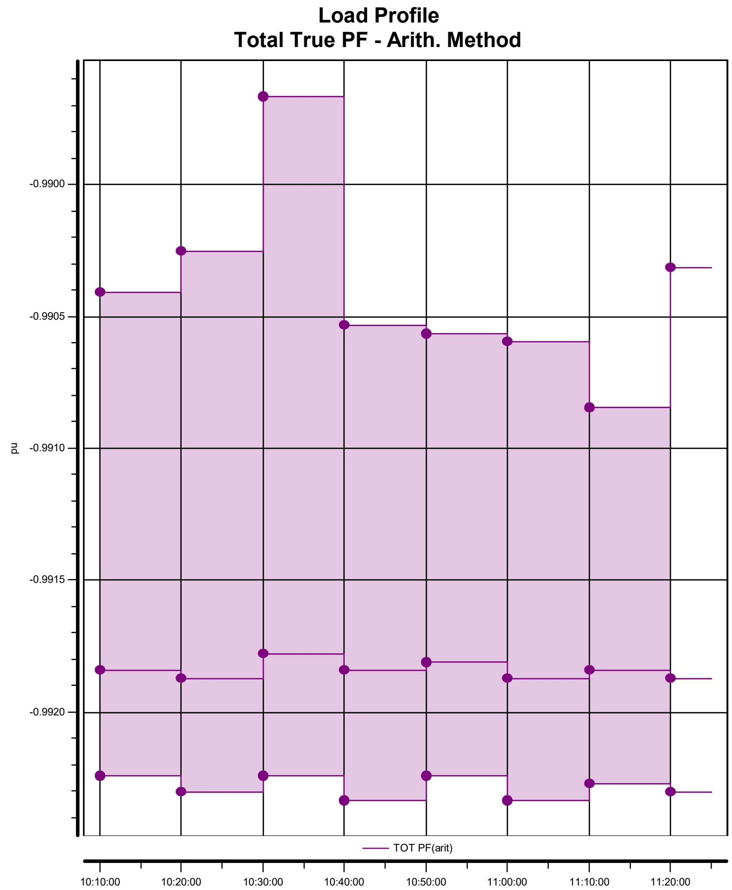

Load Profile
Frequency
Hz
60.04
60.03
60.02
60.01
60.00
59.99
59.98
59.97
59.96
TOT Freq
10:10:00
10:20:00
10:30:00
10:40:00
10:50:00
11:00:00
11:10:00
11:20:00

Load Profile
Voltage DC Component

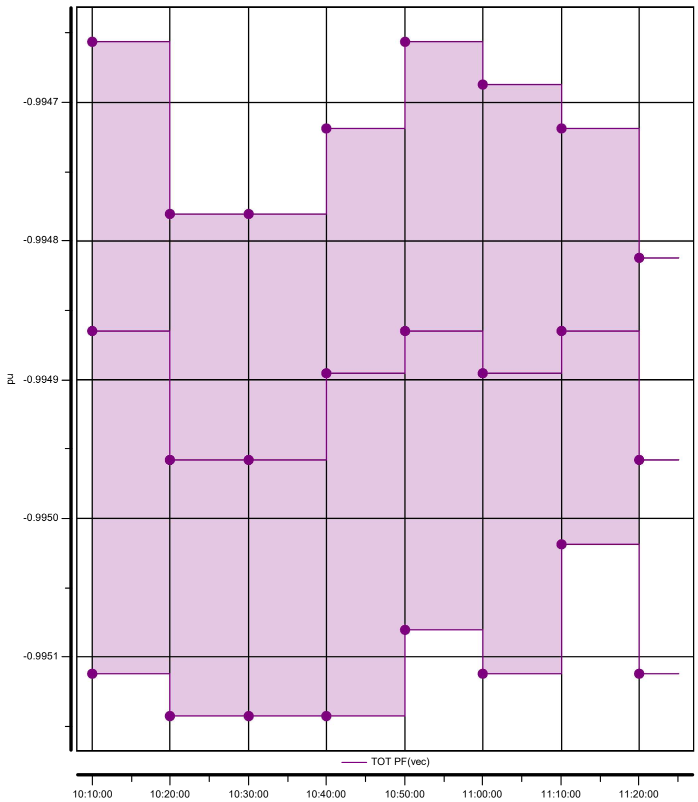




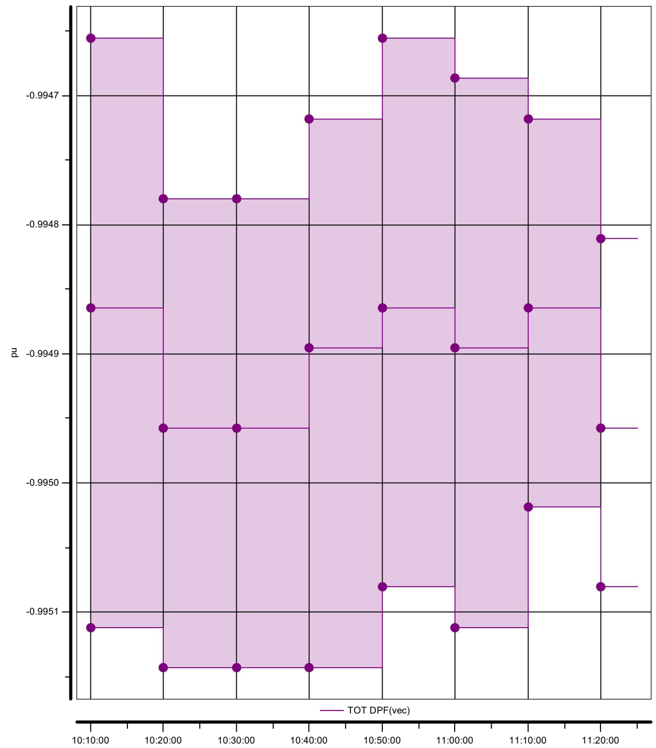
Load Profile
Current DC Component
0.001
0.000
-0.001
-0.002
-0.003
-0.004
Amps
A IDC
10:10:00
10:20:00
10:30:00
10:40:00
10:50:00
11:00:00
11:10:00
11:20:00


Load Profile
Total True PF - Arith. Method
-0.9900
-0.9905
-0.9910
-0.9915
-0.9920
pu
TOT PF(arit)
10:10:00
10:20:00
10:30:00
10:40:00
10:50:00
11:00:00
11:10:00
11:20:00

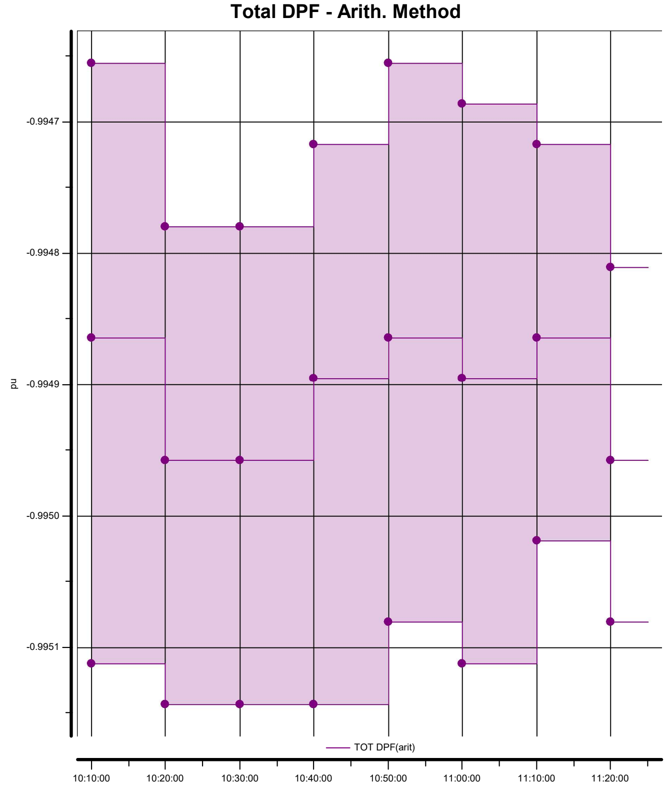
Load Profile
Total True Power Factor - Vector Method.

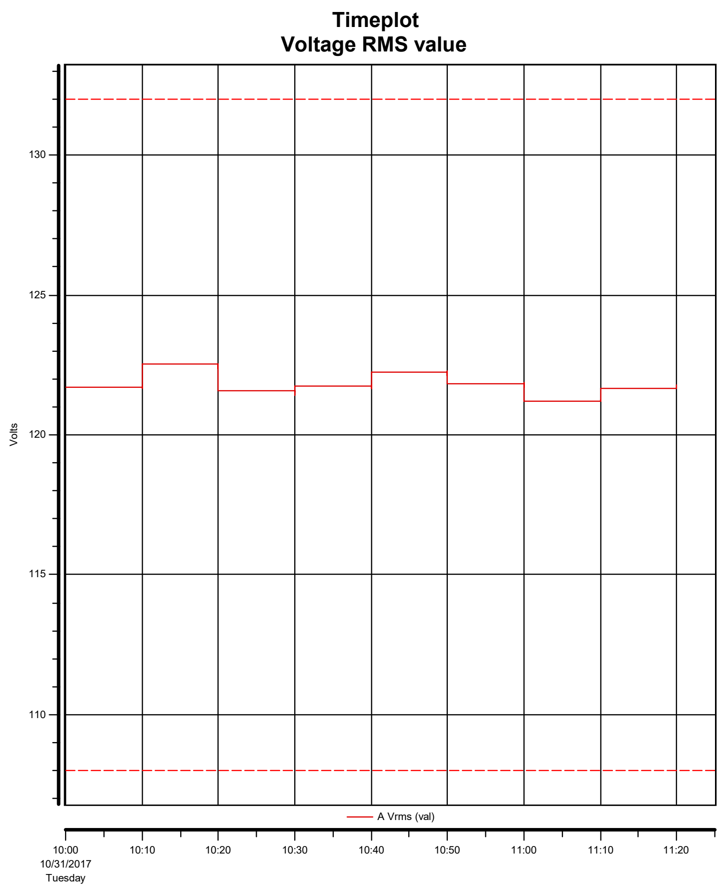


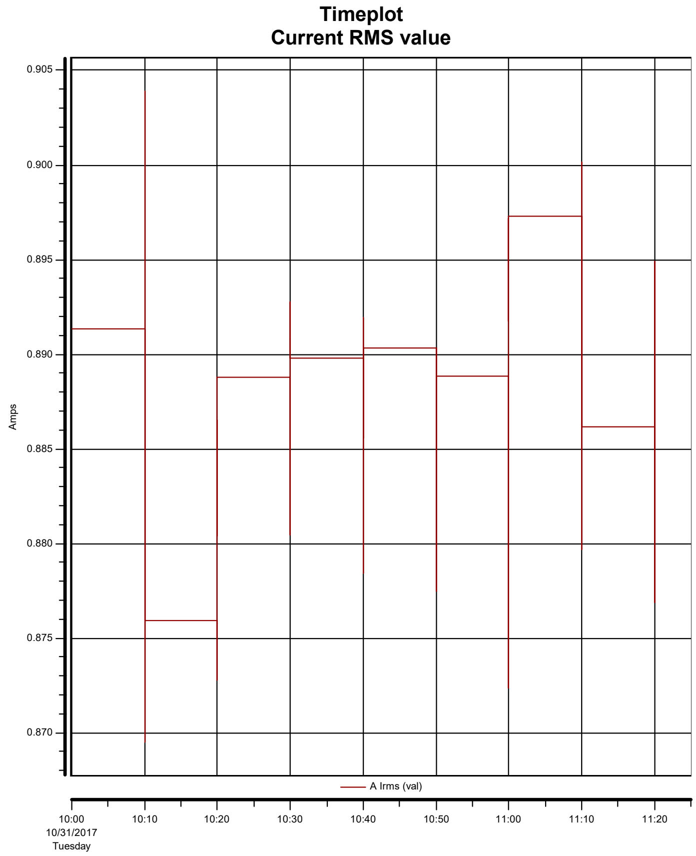
Load Profile
Total Displacement Power Factor - Vector Method.



Load Profile
Total DPF - Arith. Method

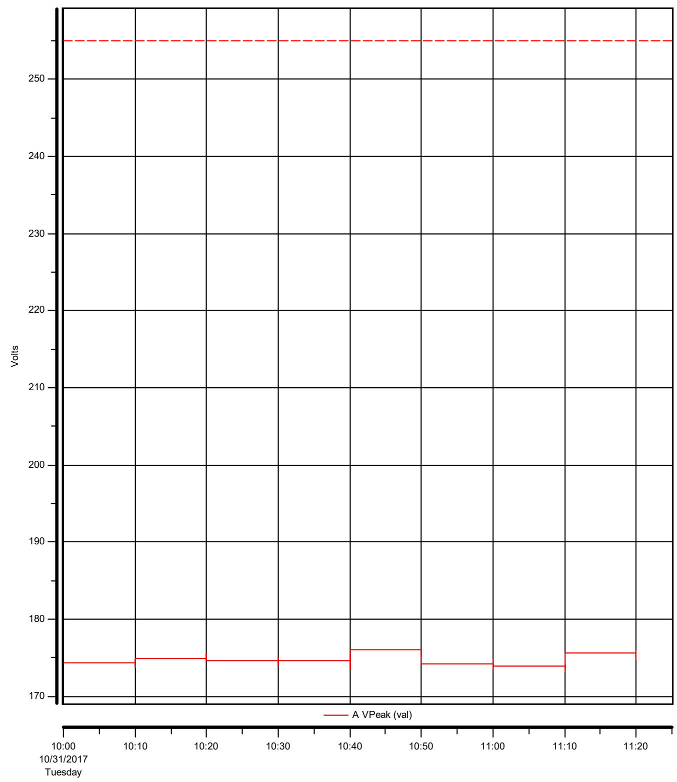



Timeplot
Voltage RMS value
Volts
130
125
120
115
110
A Vrms (val)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

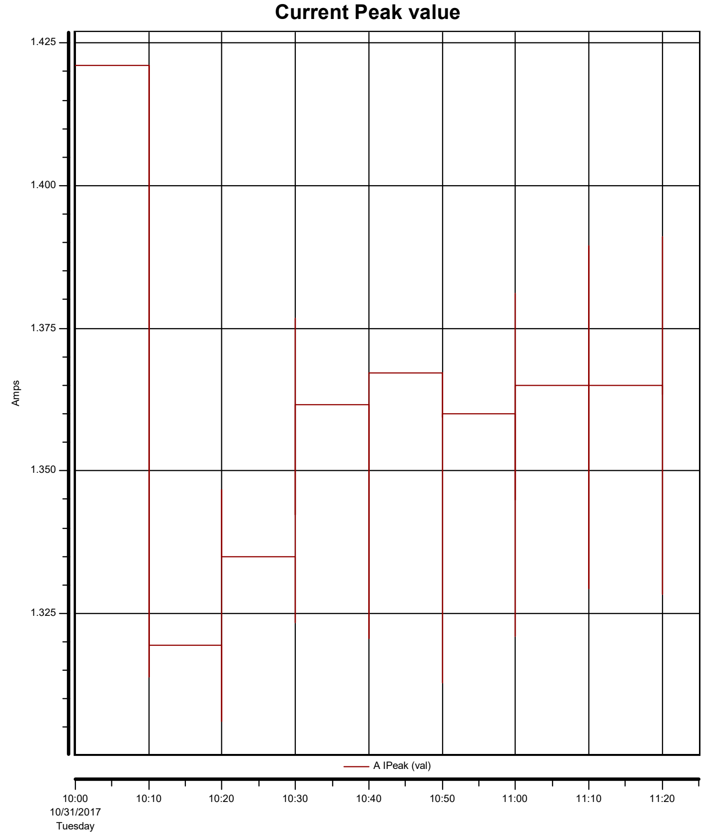


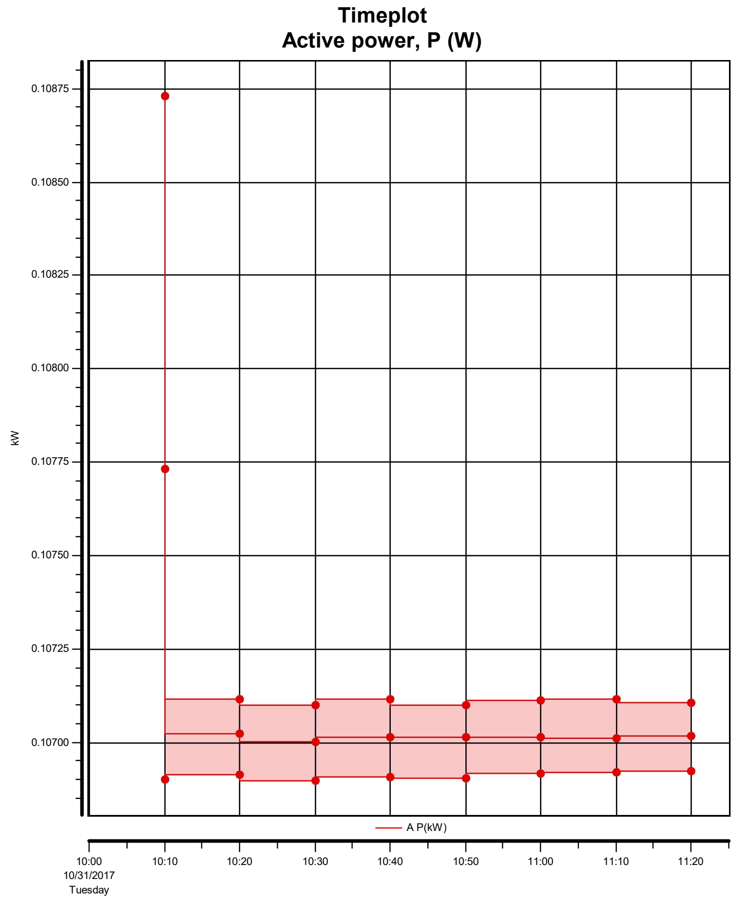
Timeplot
Current RMS value
Amps
0.905
0.900
0.895
0.890
0.885
0.880
0.875
0.870
A Irms (val)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

Timeplot
Voltage Peak value

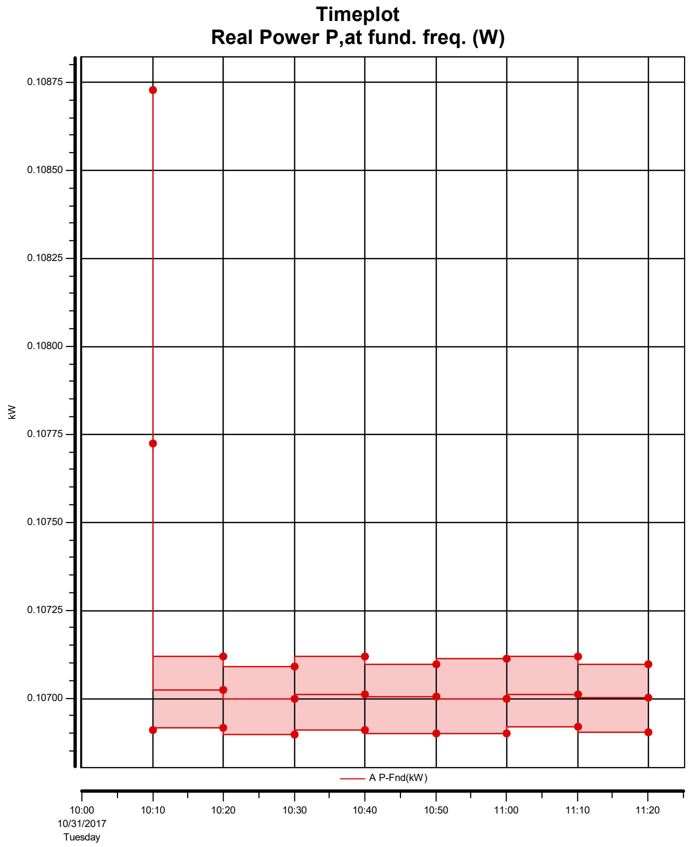


Timeplot
Current Peak value

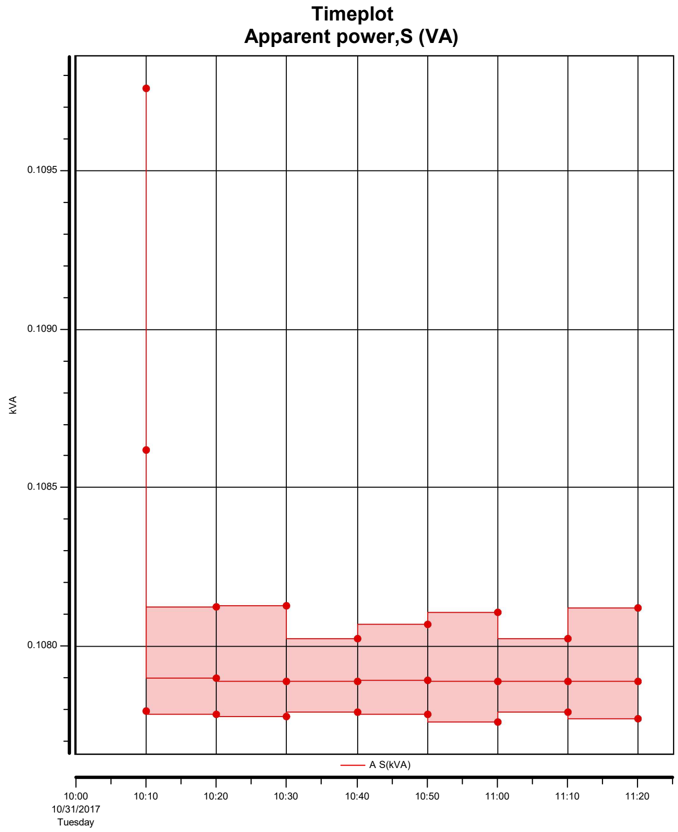


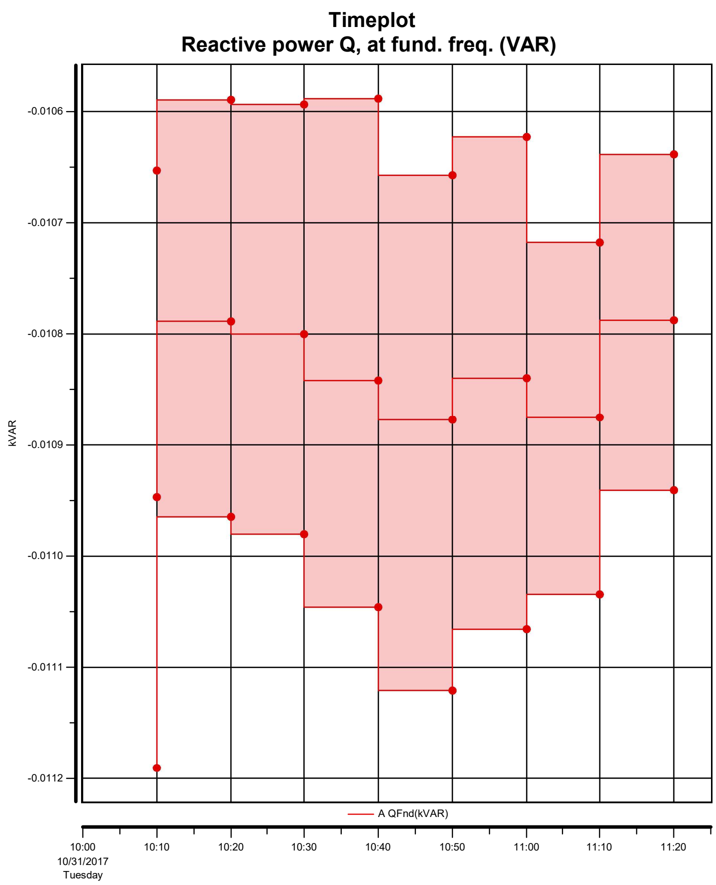


Timeplot
Active power, P (W)
kW
0.10875
0.10850
0.10825
0.10800
0.10775
0.10750
0.10725
0.10700
A P(kW)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

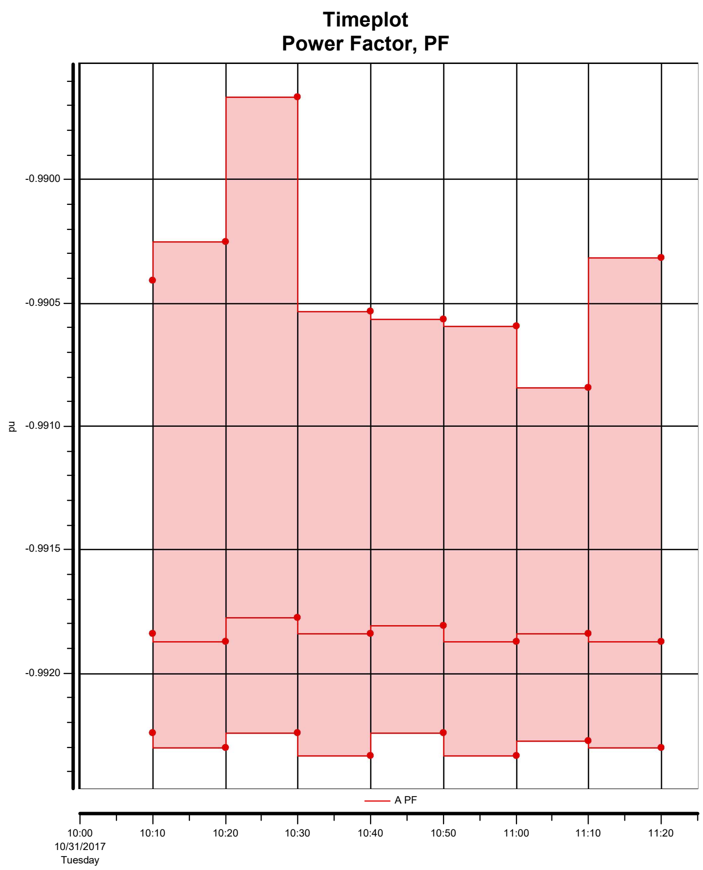


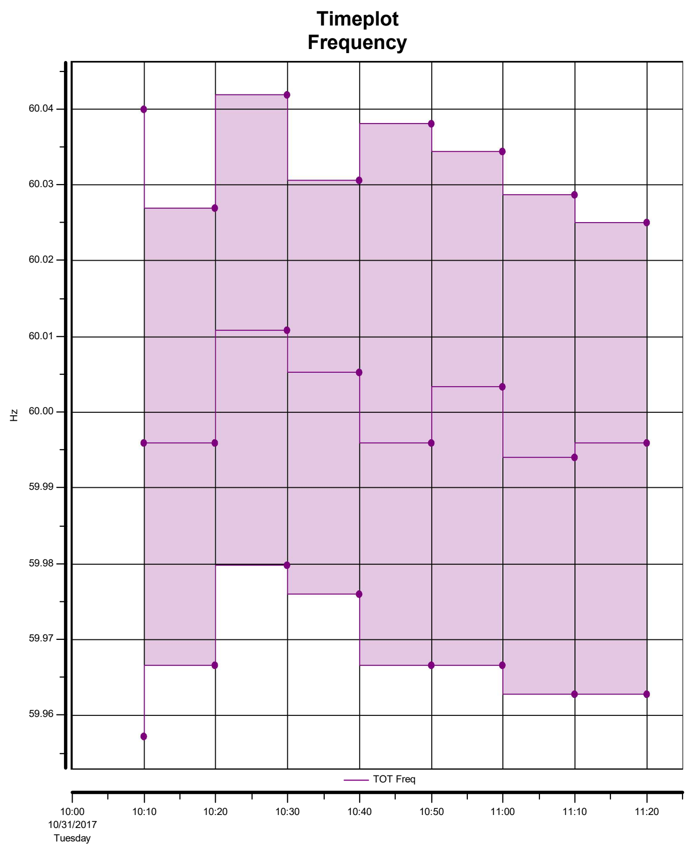
Timeplot
Real Power P,at fund. freq. (W)
kW
0.10875
0.10850
0.10825
0.10800
0.10775
0.10750
0.10725
0.10700
A P-Fnd(kW)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

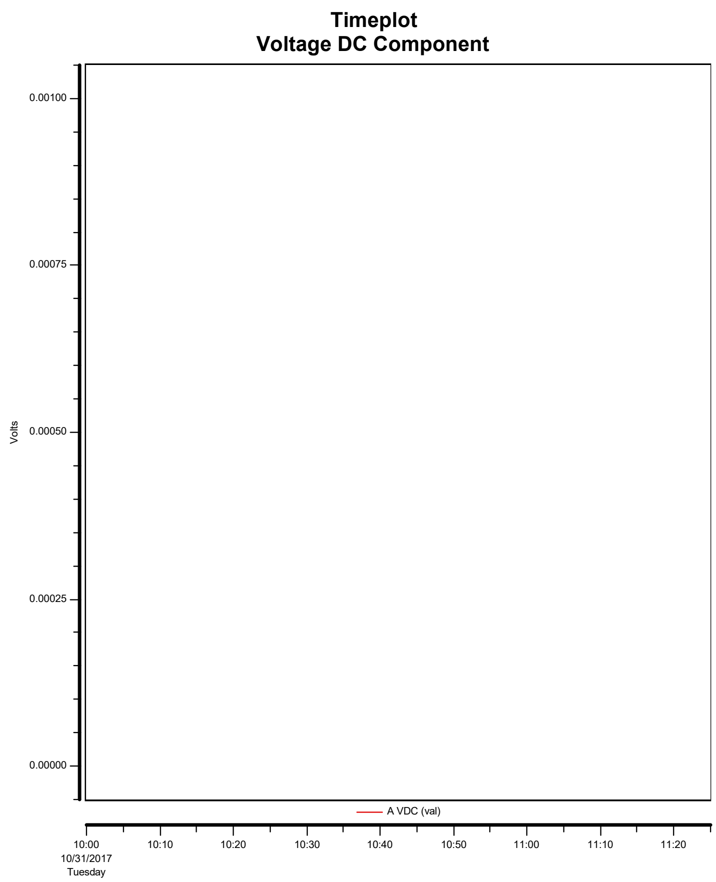

Timeplot
Apparent power,S (VA)
0.1095
0.1090
0.1085
0.1080
kVA
A S(kVA)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20



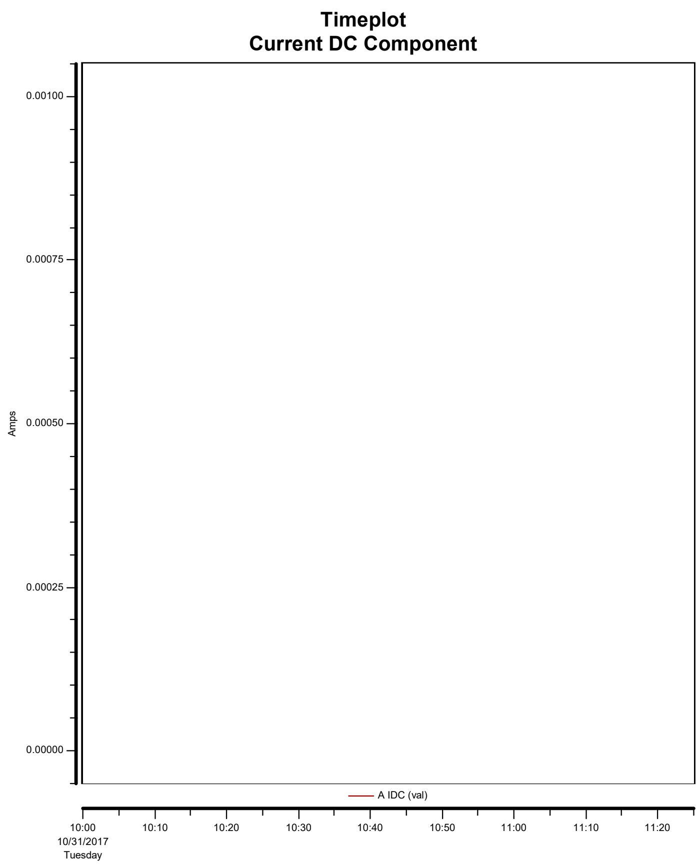
Timeplot
Reactive power Q, at fund. freq. (VAR)
kVAR
-0.0106
-0.0107
-0.0108
-0.0109
-0.0110
-0.0111
-0.0112
A QFnd(kVAR)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20


Timeplot
Power Factor, PF
-0.9900
-0.9905
-0.9910
-0.9915
-0.9920
pu
A PF
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

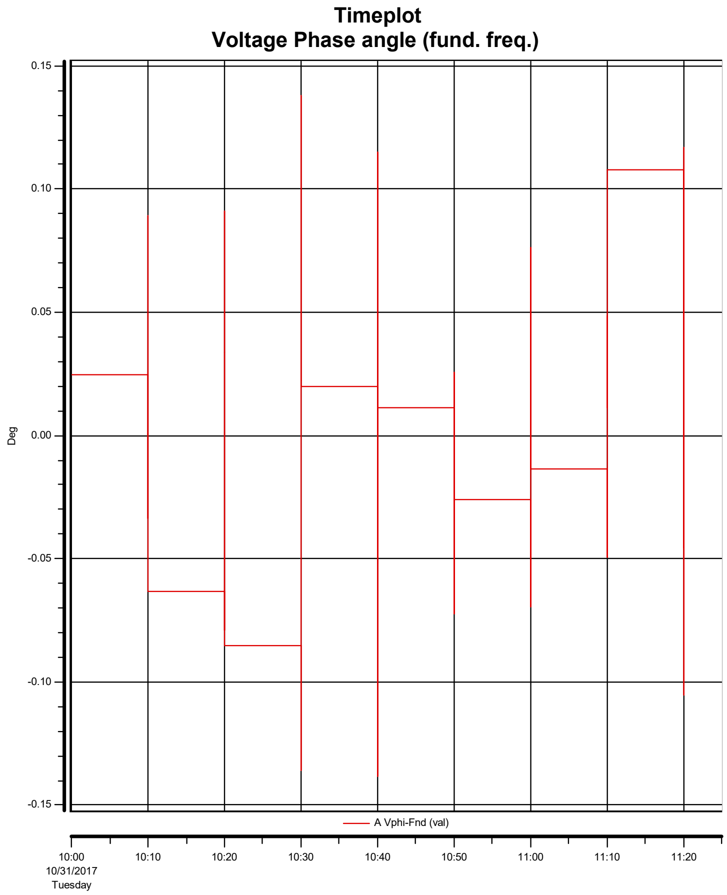

Timeplot
Frequency
60.04
60.03
60.02
60.01
60.00
59.99
59.98
59.97
59.96
Hz
TOT Freq
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20



Timeplot
Voltage DC Component
0.00100
0.00075
0.00050
0.00025
0.00000
Volts
A VDC (val)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

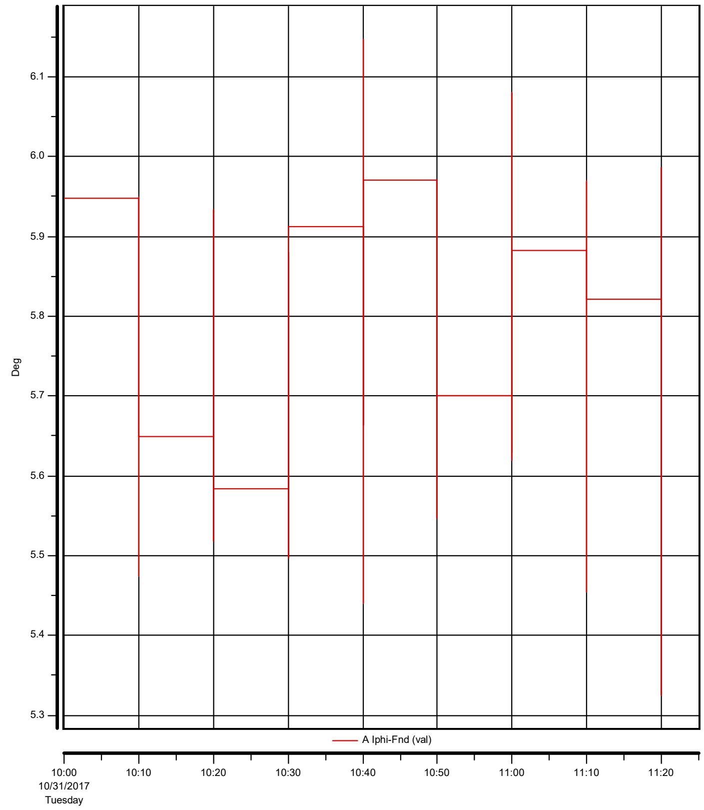


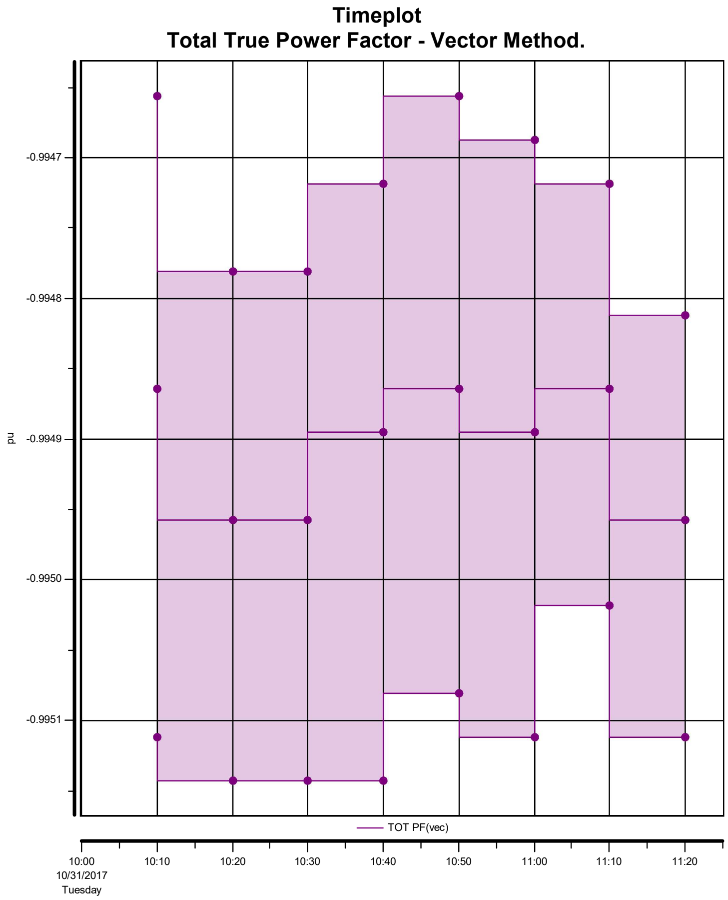
Timeplot
Current DC Component
Amps
0.00100
0.00075
0.00050
0.00025
0.00000
A IDC (val)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20



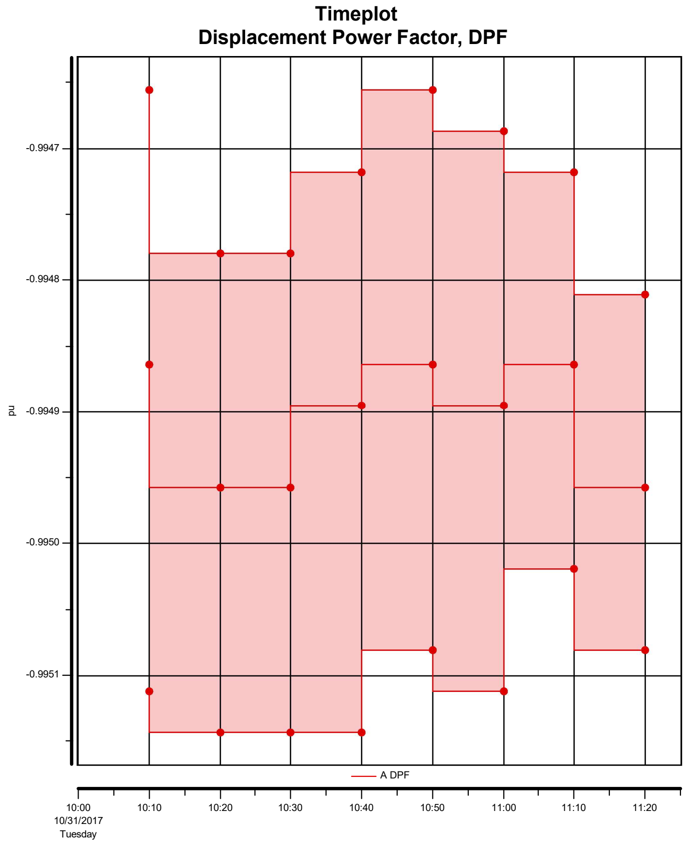
Timeplot
Voltage Phase angle (fund. freq.)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
Deg
A Vphi-Fnd (val)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

Timeplot
Current Phase angle (fund. freq.)



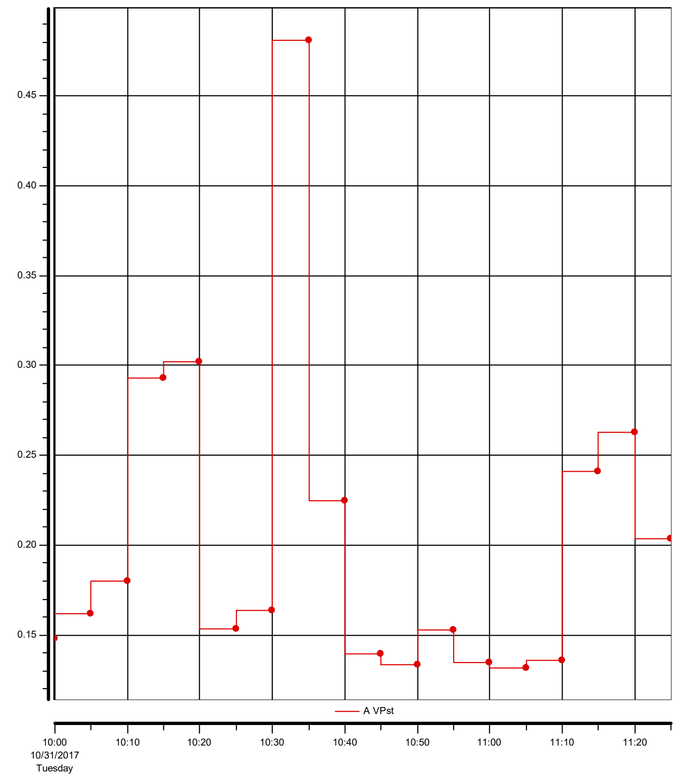


Timeplot
Total True Power Factor - Vector Method.
pu
-0.9947
-0.9948
-0.9949
-0.9950
-0.9951
TOT PF(vec)
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

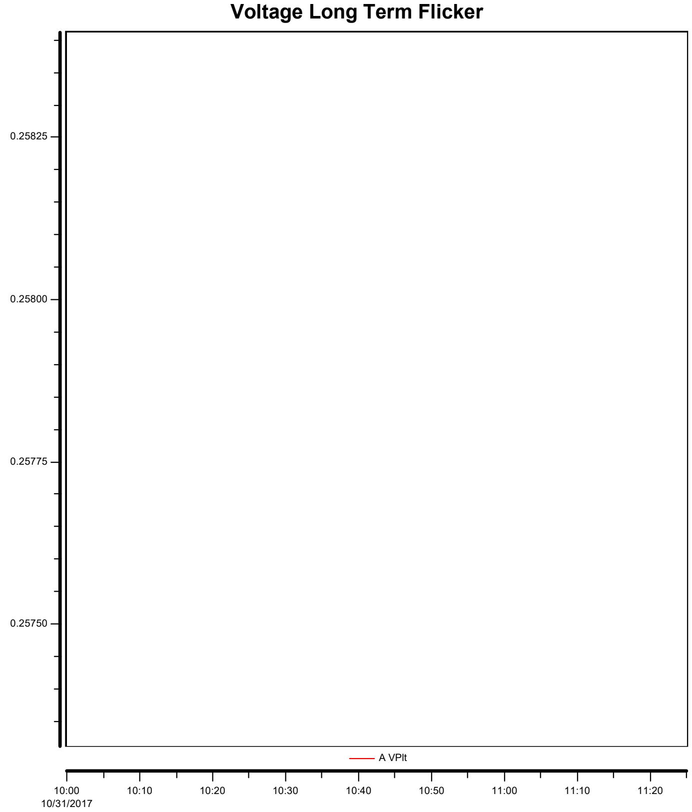


Timeplot
Displacement Power Factor, DPF
pu
-0.9947
-0.9948
-0.9949
-0.9950
-0.9951
A DPF
10:00
10/31/2017
Tuesday
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20

Timeplot
Voltage Short Term Flicker



Timeplot
Voltage Long Term Flicker



Instrument Configuration

Dranetz Power Xplorer Configuration

Firmware	Power Xplorer (c) 2009 Dranetz-BMI Oct 09 2015 @ 16:29:01 Ver.: V 4.3, Build: 3, DB ver.: 0
Serial Number	PX50HA219
Site/Filename	
Measured from	10/31/2017 09:51:23
Measured to	10/31/2017 11:26:03
File ending	OK
Synchronization	Standard A
Configuration	SINGLE PHASE
Monitoring type	STANDARD PQ
Nominal voltage	120.0 V
Nominal current	0.9 A
Nominal frequency	60.0 Hz
Use inverse sequence	No
Using currents	Yes
Characterizer mode	IEEE 1159

Current probes

Chan A	Unknown (Scale=2.00)
Chan B	Other (Scale=1.00)
Chan C	Other (Scale=1.00)
Chan D	Other (Scale=1.00)

Voltage scale factors

Chan A	1.000
Chan B	1.000
Chan C	1.000
Chan D	1.000

Current scale factors

Chan A	1.000
Chan B	1.000
Chan C	1.000
Chan D	1.000

Trigger Response Setups

Summary Pre-trigger cycles	6 cycles
Summary Post-trigger cycles IN-TO-OUT	6 cycles
Summary Post-trigger cycles OUT-TO-IN	6 cycles
Waveform Pre-trigger cycles	2 cycles
Waveform Post-trigger cycles	2 cycles

Trigger-	Saved waveforms										
channel	**Va**	**Vb**	**Vc**	**Vd**	**Ia**	**Ib**	**Ic**	**Id**	**AB**	**BC**	**CA**
Volts A	Va	-	-	-	Ia	-	-	-	-	-	-
Volts B	-	-	-	-	-	-	-	-	-	-	-
Volts C	-	-	-	-	-	-	-	-	-	-	-
Volts D	-	-	-	Vd	-	-	-	-	-	-	-
Amps A	Va	-	-	-	Ia	-	-	-	-	-	-
Amps B	-	-	-	-	-	-	-	-	-	-	-
Amps C	-	-	-	-	-	-	-	-	-	-	-
Amps D	-	-	-	Vd	-	-	-	Id	-	-	-
Volts A-B	-	-	-	-	-	-	-	-	-	-	-
Volts B-C	-	-	-	-	-	-	-	-	-	-	-
Volts C-A	-	-	-	-	-	-	-	-	-	-	-

Timed Waveform savings every: 600 seconds
After recording: REARM

Limit Setups

Voltages	A	B	C	D	A-B	B-C	C-A
RMS High:	132.0	0.0	0.0	0.0	0.0	0.0	0.0
RMS Low:	108.0	0.0	0.0	0.0	0.0	0.0	0.0
RMS Very Low:	12.0	0.0	0.0	0.0	0.0	0.0	0.0
Crest:	255.0	0.0	0.0	0.0	0.0	0.0	0.0
Wave:	24.0	0.0	0.0	0.0	0.0	0.0	0.0
DC:	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DEG:	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WAVE Window Mag:	24.0	0.0	0.0	0.0	0.0	0.0	0.0
WAVE Window Dur:	15.0	0.0	0.0	0.0	0.0	0.0	0.0
HF:	200.0	0.0	0.0	0.0	0.0	0.0	0.0

Currents	A	B	C	D
RMS High:	0.0	0.0	0.0	0.0
RMS Low:	0.0	0.0	0.0	0.0
RMS Very Low:	0.0	0.0	0.0	0.0
Crest:	0.0	0.0	0.0	0.0
Wave:	0.0	0.0	0.0	0.0
DC:	0.0	0.0	0.0	0.0
DEG:	0.0	0.0	0.0	0.0
WAVE Window Mag:	0.0	0.0	0.0	0.0
WAVE Window Dur:	0.0	0.0	0.0	0.0
HF:	0.0	0.0	0.0	0.0

Periodic Journal Intervals

Voltage	10.0 minutes	
Current	10.0 minutes	
Power	10.0 minutes	
Harmonics	10.0 minutes	
Demand	5.0 minutes, Subintervals/Intervals:	3
Energy	10.0 minutes	
Inst. flicker	10.0 minutes	
Short term flicker	5.0 minutes	
Long term flicker	60.0 minutes	
EN50160 compliance	10.0 minutes	

Journal Limits

Voltage	VeryHi	High	Low	VeryLo	Sens.	Hyst.	Nom.
RMS_PhAN	144.0	132.0	108.0	96.0	-	-	-
CycRMS_PhAN	144.0	132.0	108.0	96.0	-	-	-
FreqHz	-	60.6	59.4	-	-	-	-

Current	VeryHi	High	Low	VeryLo	Sens.	Hyst.	Nom.
RMS_PhA	1.417	1.151	-	-	-	-	-
CycRMS_PhA	1.417	1.151	-	-	-	-	-

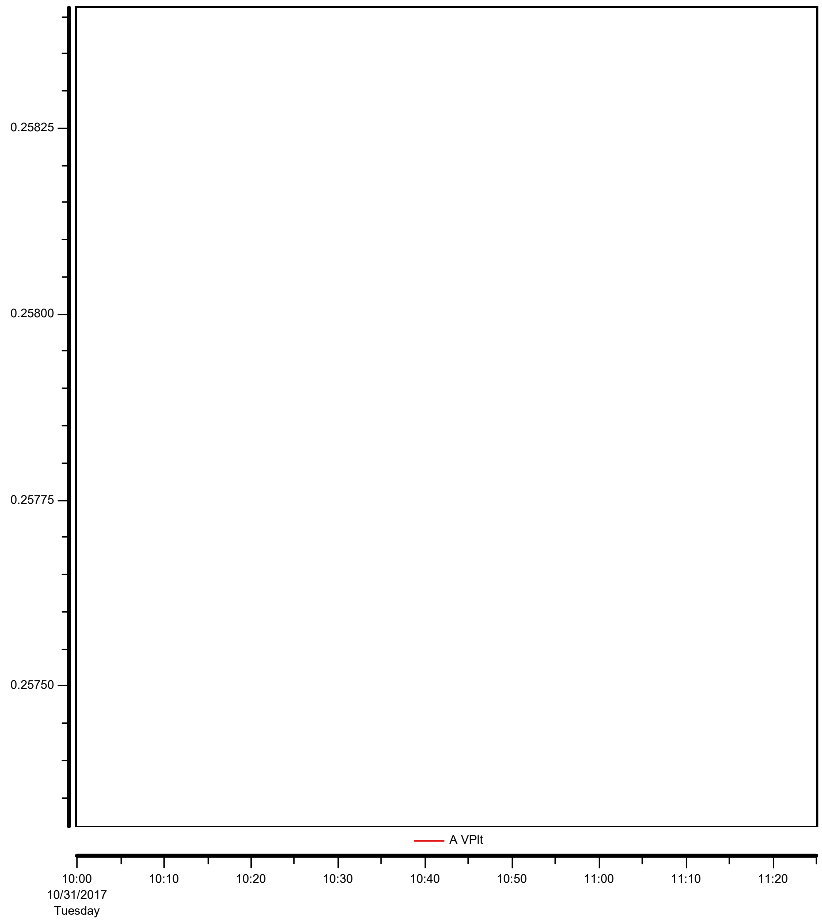
Harmonics	VeryHi	High	Low	VeryLo	Sens.	Hyst.	Nom.
VoltageFundNormTHD_PhA	8.0	5.0	-	-	-	-	-

Short term flicker	VeryHi	High	Low	VeryLo	Sens.	Hyst.	Nom.
Pst_PhA	-	1.0	-	-	-	-	-

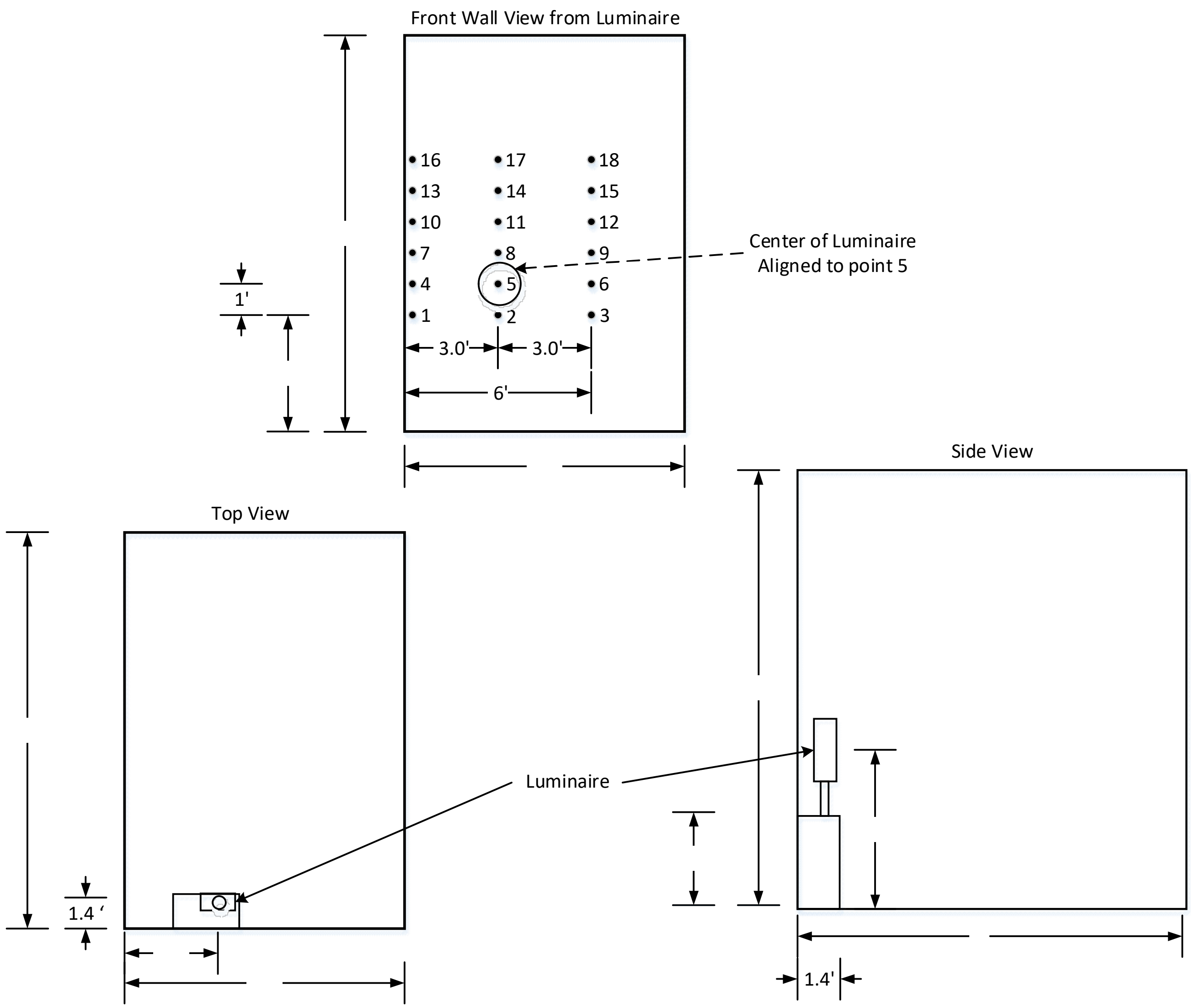
FLICKER (PLT) TIMEPLOTS

Site:

Measured from 10/31/2017 09:59:59.0 to 10/31/2017 11:25:00.0



APPENDIX B. LUMEN MEASUREMENT ROOM DESIGN



APPENDIX C. TESTING CHECK LISTS

Confidential
5/15/17

PURDUE UNIVERSITY NORTHWEST
Energy Efficiency and Reliability Center

Laboratory Lumen Depreciation, Spectral, and Voltage Tolerance Testing Procedure Check List

Luminaire ____ **Start Date** ______________

Test Equipment:

1. Illuminance meter : Konica Minolta, T-10A
2. BOSCH GLL 1P Line and Point Laser Level
3. Bubble level
4. True RMS voltmeter.
5. 0-140V Variac
6. Spectrophotometer: Konica Minolta CL 500A
7. FLIR IR camera
8. Thermocouples and Thermocouple Meter

Test Procedure

- ☐ **A.** Initially the luminaire is placed on a mounting post located at one end of the room and is leveled and aligned with the assistance of a laser level such that the center of the luminaire light emitting area is aligned with point 5 of the measurement matrix. The distance between the luminaire and the center of the data collection matrix is 10'8".
- ☐ **B.** Verify that the plane of the light emitting area of the luminaire is normal to the vector connecting the center of the light emitting area and point 5 of the matrix.
- ☐ **C.** Do a final check to assure that the illuminance meter has been aligned correctly.
- ☐ **D.** Turn off room lights and verify that the only light entering the test area is from the test luminaire.
- ☐ **E.** Measure the nominal supply voltage from the wall socket and record this value.
- ☐ **F.** Plug the Variac into the wall socket and then connect the luminaire to the output of the Variac.
- ☐ **G.** Plug the True RMS Voltage Meter into the power connector for the luminaire.
- ☐ **H.** Connect the luminaire and the voltmeter to the output of the Variac. Set the voltage level to 120V.
- ☐ **I.** The illuminance (oriented so readings are taken in a plane parallel to the plane of the wall) for the luminaire being considered is measured at 18 data collecting points distributed in a matrix located on the opposite wall. Verify consistency of data values for repeated readings.
- ☐ **J.** The illuminance readings shall be recorded in the log book for each matrix element.
- ☐ **K.** These readings shall be repeated two more times to assure statistical consistency of the data. If any inconsistencies are noted then the alignment shall be checked again, the status of the batteries in the Illuminance Meter shall be verified, and the lack of spurious light sources in the room shall be verified. The measurements shall then be repeated 3 more times to assure consistency. Should this second set of readings not be consistent a separate appraisal of the situation must be conducted after consultation with the PI.
- ☐ **L.** Measure the spectral content of the light from the test luminaire at locations 4, 5, and 6 using the CL 500A meter. This data should be downloaded from the meter and logged in the electronic data base after processing with the Konica software.
- ☐ **M.** Take illuminance readings for all 18 matrix data points using the T-10A meter for luminaire input voltage levels of 110V and 130V. Record these data values in the log book.
- ☐ **N.** Horizontal illuminance readings for each of the 18 matrix points should be repeated for five days of the initial test week for each luminaire tested.
- ☐ **O.** Proceed to Power Quality Testing as per the relevant procedure.
- ☐ **P.** After the temperature has stabilized, collect IR data for the outside and inside of the luminaire (pay special attention to driver temperature). Using a directly attached thermocouple collect temperature data from the outside of the luminaire and directly on the driver. Verify and assure consistency of data between IR and thermocouple readings.
- ☐ **Q.** Perform power cycling test. For 24 hours cycle the unit on and off at 15 minutes intervals.
- ☐ **R.** The luminaire should be remounted in the test area and steps A-J shall be repeated once per month after the initial tests for the designated test period.

Laboratory Power Quality Testing Procedure Check List

Luminaire ____ **Start Date** ________________

Test Equipment:
1. Dranetz Power Explorer meter
2. Associated voltage probes and CTs
3. Power monitoring cable

Test Procedure

- ☐ **A.** Plug the luminaire into the power test cable and verify that the luminaire is working properly.
- ☐ **B.** Assure that the battery is charged and/or is connected to the battery charger. If the battery charger is used assure that it is plugged into a surge suppressor protected outlet.
- ☐ **C.** Turn on the CT range box and assure that it is set to the 3A range. Verify the current usage of the luminaire and increase this value if necessary for large luminaires.
- ☐ **D.** Assure proper direction of the CT (arrow in the direction of the current) and align the plane of the CT loop normal to the power carrying conductor.
- ☐ **E.** Turn on the Power Explorer and assure proper startup and self test.
- ☐ **F.** Perform an initial check of the wave form using the Scope Mode and assure consistency with normally expected values. Resolve any inconsistencies before proceeding.
- ☐ **G.** Press Start/Setup
- ☐ **H.** Use the Setup Wizard to initiate the testing.
- ☐ **I.** Verify that the CT type and range is set correctly (at 3 A or as appropriate for the particular luminaire) and that "enable currents" is checked.
- ☐ **J.** Press next and then verify electric configuration type setup (single phase)
- ☐ **K.** Accept subsequent default values in the Setup Wizard and sequence through the screens.
- ☐ **L.** Stop at the Journal Entries screen and enter the following values: flicker short, 5min; flick long, 1hr, Harmonics,1 minute interval; Demand and Energy, 5 minutes and 3 minutes; Power Values, 1 minute interval; and turn on waveform snapshot.
- ☐ **M.** Press "Finish"
- ☐ **N.** At the next screen: change the name to that for the current luminaire; include EERC file ID, the manufacturer, and the wattage of the unit.
- ☐ **O.** Reformat the flash memory.
- ☐ **P.** Initiate testing and collect data for 1 hour.
- ☐ **Q.** After 1 hour and 5 minutes of operation press the Stop button and verify the action when requested.
- ☐ **R.** Turn off the Dranetz Power Explorer and the current loop attachment.
- ☐ **S.** Remove the flash memory card and process data.
- ☐ **T.** Enter data into the data base for the specific luminaire

APPENDIX D. OBSERVATIONS FOR SECTION 7.2 OF PROCEDURE FOR EVALUATION AND APPROVAL LIST REQUIREMENTS FOR SOLID STATE BALLASTED LUMINAIRES ITM 957-17P

7.2 Physical Inspection/Laboratory Testing. Once all the required documentation is reviewed and found to be acceptable the following will be verified by INDOT or the Purdue Energy Efficiency and Reliability Center:

7.2.1 The unit requires no assembly; it is single and self-contained.

7.2.2 A four bolt slip-fitter is provided that is capable of mounting to a 2 inch mounting bracket with adjustments ±5° from level.

7.2.3 Housing is aluminum and is powder coat finished in light gray.

7.2.4 The weight of luminaire is no more than 53 lb.

7.2.5 The effective projected area is no more than 2.4 sq. ft.

7.2.6 External and internal labels in accordance with ANSI C136.15 and ANSI C136.22 respectively are provided. The external sticker also provides the following information: light source type, manufacturer, model, wattage, date of manufacture, and warranty period.

7.2.7 Fans or other mechanical cooling systems are not used for thermal management.

7.2.8 Access (door) to optical and electrical components is provided. Hinges and latches are made of stainless steel and remain closed during the operation. Latches are positive and on the street side.

7.2.9 Connectors are crimp type.

7.2.10 A three position terminal block shall be provided for power wiring. The contacts shall accommodate #14 - #6 AWG stranded or solid, copper or aluminum conductors.

7.2.11 The luminaires has a seven wire photocontrol receptacle in accordance with ANSI C136.41 for future installation of adaptive lighting control. A shorting cap shall be provided for the receptacle.

7.2.12 Power driver, LED arrays, surge protection and other primary components are as shown in documentation.

7.2.13 Power driver operation is consistent and temperature is adequately controlled while performing within the luminaire.

7.2.14 The construction of the luminaire and arrangement of components do not hinder heat dissipation from the light source. Internal electronics shall be pre-wired and positioned for optimal heat dissipation through the housing heat sink. Temperatures at various points/components of the luminaire will be measured to check for even heat flow/points of heat build-up.

7.2.15 Loss of an LED does not result in loss of the entire luminaire or in flickering as perceived by the unaided eye. Loss of an LED does not increase operating temperature or reduce service life.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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