L•PRIZE®

Lumen Maintenance Testing of the Philips 60-Watt Replacement Lamp L Prize Entry

July 2012

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Lumen Maintenance Testing of the Philips 60-Watt Replacement Lamp L Prize Entry

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July 2012

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Executive Summary

The Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy, developed a procedure and facility for testing the lumen maintenance of light-emitting diode (LED) replacement lamps submitted to the L Prize® competition in the 60-watt replacement and PAR38 replacement categories. The lumen maintenance test apparatus (LMTA), in which lamps are operated continuously in a 45°C environment, measures the relative lumen and chromaticity maintenance of up to 200 screw-based lamps. Two hundred samples of a 60-watt LED replacement product submitted by Philips Lighting were measured over a time period of 7,000 hours to determine whether the lamps met the minimum requirements of the L Prize competition. Measurements continue for the purpose of long-term data collection. Spectroradiometric measurements performed by a mobile integrating sphere took place every 100 hours for the first 5,000 hours of operation and weekly (every 168 hours) thereafter.

The light output of the Philips L Prize entry lamps has changed very little during the period of operation to date, which surpassed 18,000 hours in July 2012. Average lumen maintenance for the sample of 200 lamps operating in the LMTA is still greater than 100% of average initial output of the lamp samples. The L Prize competition required at least 70% lumen maintenance at 25,000 hours. Based on the data available after 7,000 hours of operation, lumen maintenance at 25,000 hours was projected to be 97.1%. Further, the L Prize competition requirements allowed for a change in chromaticity of no more than .004 as measured on the International Commission on Illumination 1976 (u′,v′) color space. The average change in chromaticity of the 200 Philips lamps after 7,000 hours of operation was 0.0006. Partly on the basis of this measured performance, the Philips Lighting product was declared the winner of the L Prize in the 60-watt replacement lamp category on August 3, 2011.

The measurements performed in the LMTA are relative measurements that track the change in light output and chromaticity over time for the 200 samples operating continuously in the apparatus, relative to their initial output and chromaticity. The results reported here are for the specific product tested as part of the L Prize competition and should not be generalized to other LED lighting products.

Acronyms and Abbreviations

DOE	U.S. Department of Energy
EISA	Energy Independence and Security Act of 2007
GUI	graphical user interface
IES	Illuminating Engineering Society
L Prize	Bright Tomorrow Lighting Prize
LED	light-emitting diode
LM	lumen maintenance
PLC	programmable logic controller
PNNL	Pacific Northwest National Laboratory
SSL	solid-state lighting
TM	technical memorandum

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1.0   Introduction

The Bright Tomorrow Lighting Prize (L Prize) was established by Congress in the Energy Independence and Security Act of 2007[1] (EISA). The purpose of the L Prize is to encourage the lighting industry to develop energy-efficient, solid-state lighting (SSL) replacements for common light sources, including the 60-watt incandescent light bulb and the PAR38 halogen incandescent lamp (floodlight). The EISA legislation directed the U.S. Department of Energy (DOE) to hold the L Prize competition. DOE publicly announced the competition in May 2008[2] and in September 2009 the first entry was received—a sample of 2,000 60-watt replacement lamps submitted by Philips Lighting North America.

These lamps were subjected to a variety of tests over the next 18 months and the Philips lamp was awarded the first L Prize in August 2011. This paper describes testing conducted to evaluate the product's ability to meet the lifetime/lumen maintenance requirement of the competition, which was: "having 70 percent of the lumen value under subparagraph (A) [producing a luminous flux greater than 900 lumens] exceeding 25,000 hours under typical conditions expected in residential use." A custom test apparatus was designed and constructed for this testing and a statistical approach was developed for use in evaluating the test results.

The L Prize competition is carried out by DOE as part of a comprehensive SSL research, development, and commercialization support program (see Figure 1.1 below). The purpose of the program is to advance the energy efficiency and performance of SSL technology and support successful application of SSL products in the marketplace to realize national energy savings, environmental, and economic goals.

Figure 1.1. DOE SSL Program Approach

1.1   Estimating LED Lifetime

Determining the lifetime of light-emitting diode (LED) lighting products is not straightforward. LEDs can continue to produce light over periods of time much longer than most other light sources. Barring failure of other components (such as the driver, electrolytic capacitor, or other parts), LED light output typically declines slowly over time. Useful life is usually defined in terms of the number of operating hours until the light output has decreased to a given percentage of initial output, often 70% (denoted as L_{70}), but it may differ depending on the needs of the lighting application.

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[1] PUBLIC LAW 110–140—DEC. 19, 2007. ENERGY INDEPENDENCE AND SECURITY ACT OF 2007. Section 655. Bright Tomorrow Lighting Prizes.

[2] See http://www.lightingprize.org/lightfair08.stm for information about the L Prize launch event at LIGHTFAIR® 2008.

The challenge is how to verify LED lumen maintenance (LM) without undertaking full life testing; 25,000 hours of continuous operation takes nearly three years. An industry standard test procedure, Illuminating Engineering Society (IES)-LM-80-08, "Approved Method for Measuring Lumen Maintenance of LED Light Sources," provides a method for LED packages to be tested for at least 6,000 hours, with light output and chromaticity measurements made at least every 1,000 hours. An accompanying document, Technical Memorandum (TM)-21-11, "Projecting Long Term Lumen Maintenance of LED Light Sources," provides a method for estimating lumen maintenance for a period up to six times the LM-80-08 test period.

At the time the L Prize requirements were developed, LM-80-08 was only recently approved and TM-21-11 did not exist. The scope of LM-80-08 is lumen and chromaticity maintenance of LED packages operated under specific temperature conditions and testing is not conducted on end-use products such as integral replacement lamps or complete luminaires. Therefore, methodology for evaluating full lamp lumen and chromaticity maintenance over time was developed by DOE specifically for the L Prize contest.

1.2   L Prize Lifetime Metric

The incandescent light sources targeted for replacement by the L Prize competition have a much shorter lifetime than LED sources. Standard incandescent 60-watt bulbs, for example, are typically rated for 1,000 hours of use. That rating means that, of a statistically significant sample of lamps, 50% will have failed (burned out) by 1,000 hours of operation. There is no significant lumen depreciation over the lifetime of incandescent lamps as they fail catastrophically before degradation of the light output becomes noticeable.

Other conventional light sources have known lumen depreciation behavior over their lifetimes. Lamp manufacturers publish initial lumens and "design lumens" for linear fluorescent, compact fluorescent, and high-intensity discharge lamps. Design lumens typically refer to output at 40% of the lamp's rated average life.

In the L Prize competition, DOE adopted a more rigorous metric. Whereas typical industry standard lifetime ratings as described above for incandescent lamps assume a 50% failure rate (denoted B_{50}), DOE applied a 10% (B_{10}) failure rating, meaning output dropping below 70% of initial output. The sample size for long-term testing was set such that DOE could state with 95% confidence that 90% of the lamps would perform at least as well as the thirteenth worst-performing lamp in the sample. This metric is explained in greater detail in the following section.

2.0   L Prize Requirements

The L Prize Competition Requirements document, dated June 26, 2009, listed the following requirement for Product Lifetime – Lumen Maintenance:

> Products shall have a lifetime exceeding 25,000 hours defined as $L_{70}/C_{95}/B_{10}$, where: L_{70} refers to 70% lumen maintenance, C_{95} refers to 95% statistical confidence, and B_{10} refers to no more than 10% of the products dropping below 70% of their initial (defined as the maximum) lumen value after 25,000 hours.

The document further specified the following evaluation method:

> It is anticipated that lumen and color maintenance testing will be conducted on a sample of 200 lamps, oriented base up in a 45°C environment, randomly drawn from a population of at least 2,000 lamps. Using a non-parametric methodology for establishing confidence intervals, the lower 95%/10% (C_{95}/B_{10}) tolerance limit is the 13th worst performing product, when results are ranked in order of lumen maintenance performance, from lowest to highest. L_{70} is estimated using a best-fit exponential decay function extrapolation, based on data collected from the point in time at which the product reaches its maximum flux (t_{max}) to a point in time 5,000 hours later ($t_{max} + 5000$).

> Compliance with the 25,000-hour color maintenance requirement will be tested in a similar manner. When rank ordered from most color shift to least, the 13th worst performing product must not exhibit color shift of more than .004 (u′,v′) over the time from t_{max} to $t_{max} + 5000$.

A statistical approach yielding a high-confidence interval was adopted for several reasons. First, long-term testing of an integral LED lamp replacement product had not been done before by an independent (non-manufacturer) entity. DOE wanted to provide a high level of rigor and confidence in the results of this testing. Second, the L Prize partners who contributed to development of the L Prize program rules encouraged DOE to conduct long-term testing and do so in a highly rigorous, statistically defensible manner. The extra level of confidence in long-term product performance was seen by energy efficiency program sponsors as critical to the successful uptake of a high-performance product likely to carry a premium price upon market introduction.

To enter the competition, manufacturers were required to submit 2,000 lamps. From these, a sample of 200 was randomly selected for short-term photometric testing according to industry standard test procedure IES-LM-79-08, "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products." Testing was conducted by two independent test laboratories. The same 200 lamps were then evaluated for longer term lumen maintenance using the equipment, procedures, and statistical method described in this paper.

3.0   Lumen Maintenance Testing

3.1   Test Facility

DOE required a facility for testing SSL replacement lamps entered in the L Prize competition. The facility had to maintain specific operating conditions and take accurate, reliable, and repeatable measurements over the intended test period. The requirements identified for the test facility were as follows:

1. Accommodate at least 200 samples operating simultaneously

2. Accommodate two types of lamps: A19 or PAR38, both types with standard Edison medium screw (E26) base

3. Operate lamps in base-up position

4. Maintain 45°C ambient temperature with a temperature tolerance of ± 2°C or less

5. Operate lamps continuously

6. Monitor power conditions to allow detection of failures and anomalies within 24 hours or less

7. Perform relative photometric measurements of each sample at defined intervals, with measurement equipment placed in exactly the same location relative to the sample each time

8. Provide lamp spacing to allow for measurement equipment to be positioned beneath each sample and to capture necessary data without interference from adjacent samples

9. Perform relative measurements of each sample at predetermined time intervals for the following purposes:

    a. To determine when the lamp sample has reached its maximum light output

    b. To measure changes in spectral output (lumen depreciation and chromaticity) during an additional 5000-hour period of operation, beginning at the point of maximum light output

10. Record and store specified data automatically throughout the test period.

3.2   Test Apparatus Development

The Lumen Maintenance Test Apparatus (LMTA) was designed and constructed in Richland, Washington, for the purpose of evaluating long-term lumen maintenance of LED lamps submitted under the L Prize competition. The apparatus has space for testing 202 lamps (in addition to one calibration lamp and one rest-space position) and was designed to maintain a constant ambient temperature of 45°C at a plane coincident with the electronic components of the devices under test.

Figure 3.1 displays the exterior of the LMTA, showing the exhaust fan (top), integrating sphere and track mounting (through open door), and power supply and data collection equipment (at right); while Figure 3.2 shows the interior with lamps mounted base-up, integrating sphere, and track mounting. Lamps had not yet been powered on in this photo.

Figure 3.1. LMTA Exterior *Source: PNNL*

Figure 3.2. LMTA Interior *Source: PNNL*

The apparatus was constructed of Bosch aluminum tubing enveloped by rigid polyisocyanurate insulation (1.5" thick on the top and 1.0" thick on the sides of the apparatus). Original plans called for Plexiglas walls to enable viewing of the testing operation (see Figure 3.3); however, the elevated temperature caused the panels to bow, thus allowing free convection. As a result, the apparatus was unable to reach 45°C passively and the panels were removed and replaced with additional rigid insulation.

Figure 3.3. LMTA with Original Plexiglas Walls *Source: PNNL*

The apparatus was designed to hold the lamps in a rectangular grid configuration, in base-up position, and spaced exactly 8 inches on center. The lamps are mounted within 7-inch aluminum U-channels (see Figure 3.4) measuring approximately 11 feet long, 17 in total, each supporting 12 lamps. The channels are mounted in parallel with a 1-inch space between. The 1-inch space is maintained between all channels and the perimeter containing walls such that, when negative pressure is applied above, the resulting airflow will be approximately uniform.
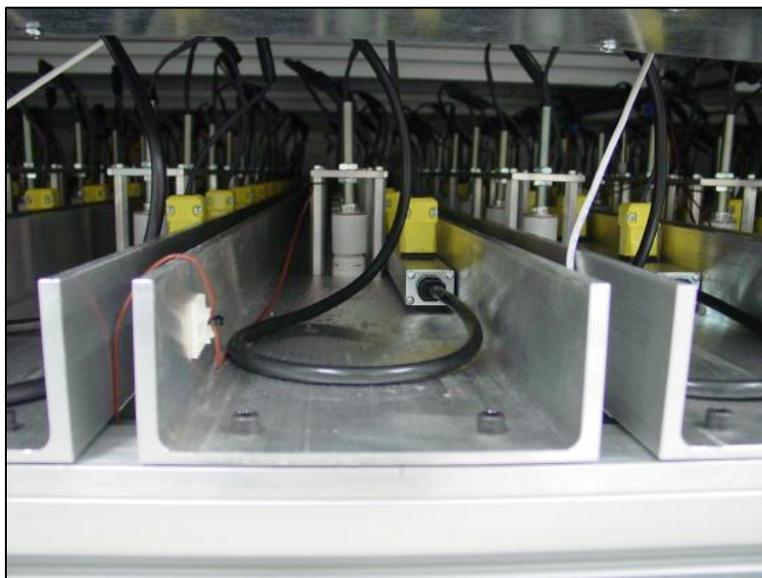
Figure 3.4. Closeup of U-Channels *Source: PNNL*

The lamps are mounted 3 feet above the finished floor. Below the lamps, a custom engineered, 20-inch integrating sphere is mounted to a platform affixed to a computer-numeric-controlled track system, allowing it to move in the x and y directions. The z (vertical) direction is accomplished by a pneumatic

cylinder. A pneumatic system was selected for two reasons: (1) provides compliance in the system for channel deflection and (2) provides the ability to adjust the force applied to the channel for sealing purposes.

Figure 3.5. Integrating Sphere and Computer-Numerical-Control Track System *Source: PNNL*

The integrating sphere, supplied by Orb Optronix, incorporated several custom elements. The most notable difference from a traditional sphere is that the meeting axis for the two lobes is oriented 45° from vertical. This allows for a seamless fixed aperture for lamp insertion. Further, the sphere is outfitted with additional thermocouples for temperature measurement.

The type of emission and lamp type (omnidirectional vs. directional) drives the method of photometry for sphere measurement. Measurement of omnidirectional lamps employs four pi (4π) geometry, in which the lamp is fully inserted into and rests at the center of the sphere during measurement. In contrast, 2π geometry is used for directional lamps. In this geometry the plane of the emitting surface of the lamp is oriented at the sphere aperture such that all emission is captured within the sphere.

The 200 sample lamps sent to independent testing laboratories were measured using 4π geometry in large (2-meter diameter) integrating spheres. Those lamps were then sent to PNNL for the elevated temperature testing. Only the relative change in flux/chromaticity needed to be monitored to meet L Prize and statistical method requirements. While the LMTA system is capable of great accuracy, testing with full 4π geometry measurement would require a considerably larger apparatus as the lamps would need to be spaced much farther apart to allow for clearance when the sphere comes up to meet and envelop the lamp.

The ultimate measurement geometry used in the LMTA was neither 4π nor 2π but rather an "abridged 2π." The desire was to capture all the omnidirectional emission without requiring the lamp to be centered within the integrating sphere. In this abridged 2π geometry, approximately two-thirds of the lamp's maximum overall length is within the sphere during measurement, capturing all the light emission.

3.2.1   Systems Integration

The need for a system that simultaneously maintains a precise thermal environment, samples and records spectral data, and provides a means for repeatability required the integration of three discrete systems into a singular automation and control scheme. To meet the challenge, engineers selected off-the-shelf systems with robust features and flexible configurations and contracted with Orb Optronix, Inc. to customize their SpectralSuite™ software to act as the unifying element and provide the graphical user interface (GUI) for spectral data collection.

SpectralSuite captures and logs spectral data readings, makes requests of the programmable logic controllers (PLCs) to move the integrating sphere, and conducts a series of checks to ensure the system remains within tolerance. The software provides the user with real-time reports of radiometric and photometric measurements as well as the temperatures within the sphere at the time of the reading. The user is also able to view all prior data collection sequences to visually compare changes over the duration of the testing.

The PLCs that control sphere movement receive motion requests from SpectralSuite, providing the electrical signals to operate the xy motors and z pneumatic cylinder, and to monitor the various limit and interlock switches. The PLCs also monitor the status of error modes provided by the Campbell Scientific, Inc. measurement and control system and, in the event of a fault (temperature out of tolerance, power anomalies, etc.), will automatically shut the system down and autodial the operator.

The Campbell Scientific system monitors and logs temperatures inside the apparatus via an array of thermocouples, the current at each of the 17 rows (each row containing 12 lamps, except the first row which has 10), and the output voltage at the main power supply. In addition, the system controls the exhaust fan atop the apparatus, cycling ambient room air through the lamps to maintain $45°C \pm 1°C$.

Figure 3.6 depicts the system integration. The blue arrows indicate directional or bi-directional monitoring or communication between systems, red arrows indicate data collection (logging), and green arrows indicate control.
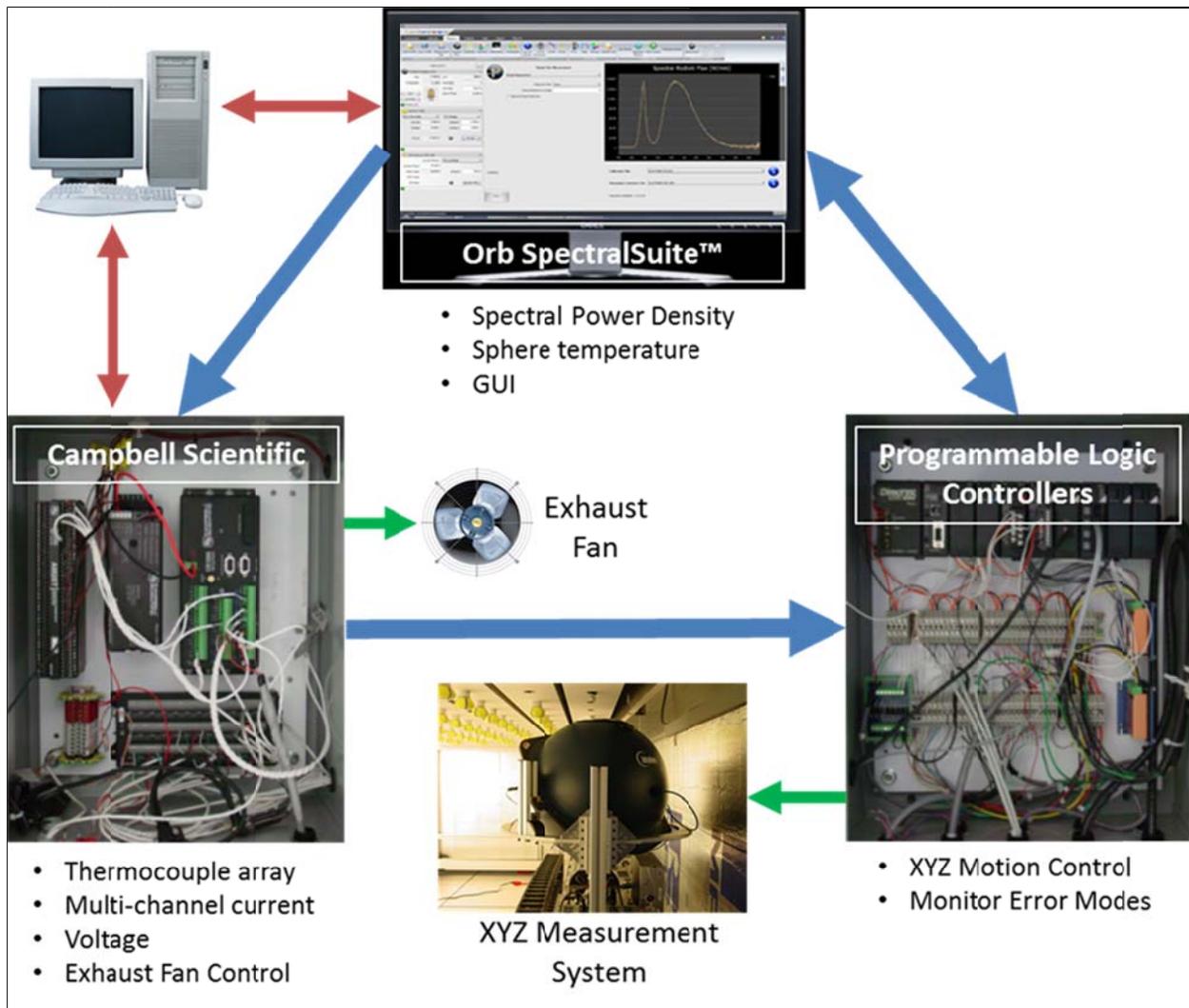
Figure 3.6. Diagram of Systems Integration

3.2.2 Data Collection

The LMTA continuously monitors and logs temperature within the apparatus, the current to each lamp row, and the output voltage of the main power supply. In the event of a catastrophic lamp failure, the system, by virtue of its normal parameter recording, will know when a failure occurred by the change in current to that channel. The exact failed lamp can only be identified by operator visual inspection or the next photometric data collection sequence.

Measurements of each lamp are made weekly (every 168 hours) using the integrating sphere. (NOTE: For the first approximately 2,000 hours of LMTA operation, measurements were made more frequently—every 100 hours—to provide greater detail for identification of the maximum average output point for the lamps under test.) The data collection sequence takes just over one hour for all 202 lamps. Each time the integrating sphere runs a measurement sequence, the following data are recorded:

1. Full spectral power distributions from which all radiometric, photometric, and colorimetric properties are calculated

3.6

2. The temperature within the sphere at the time of measurement.

Figure 3.7 shows a screen capture of data collection in progress. The system has completed measurements on all lamps represented by green cells in the grid and is currently taking measurements on the lamp in cell K7. The display is set to show luminous flux but can be changed, under Property to Display in the lower middle of the screen, to show temperature, radiant flux, or saturation (related to chromaticity).
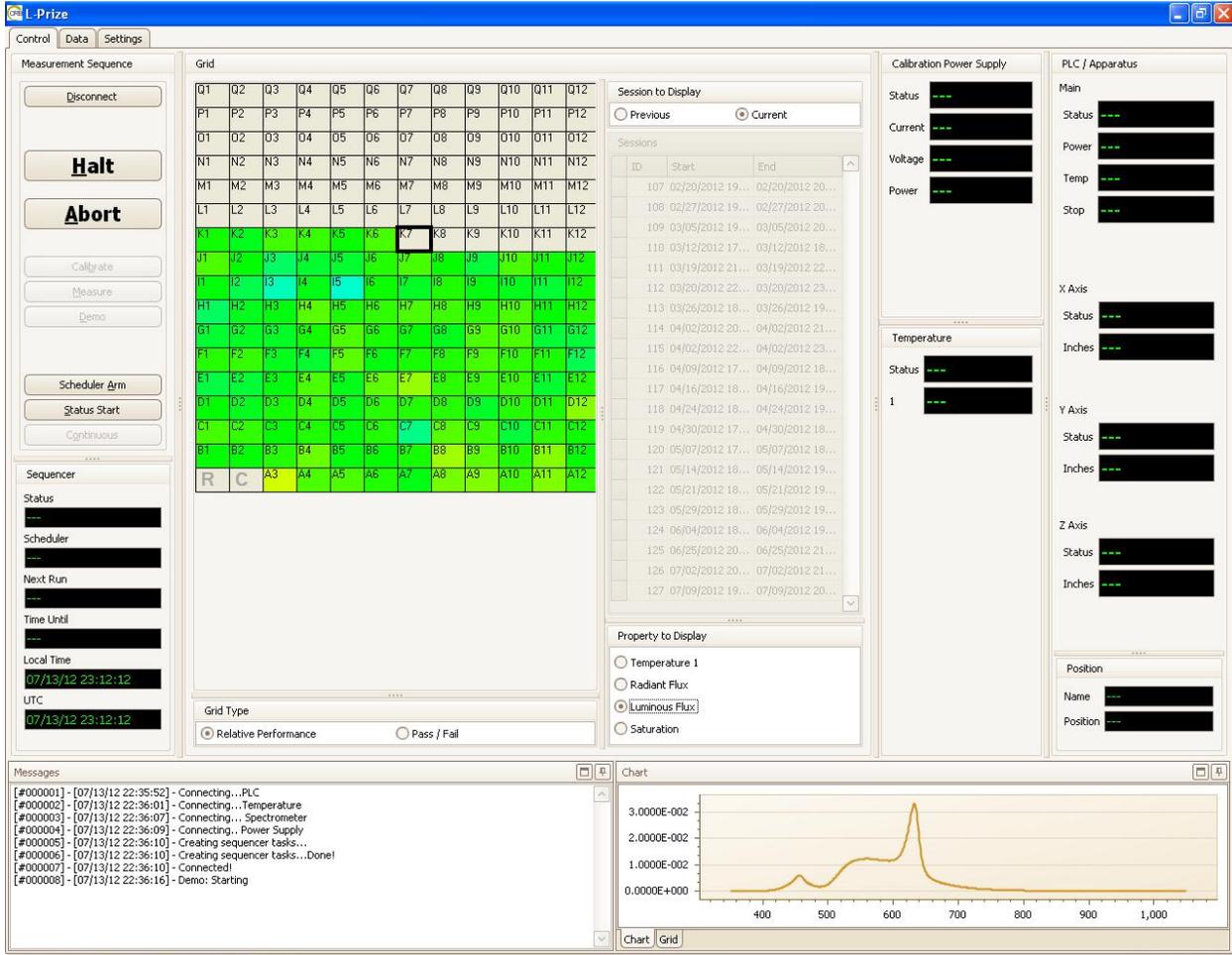

Figure 3.7. Data Collection Showing Luminous Flux

4.0   Interpreting Results: Statistical Method

The software and test equipment capture and store significant and highly accurate data regarding the performance of the lamps under test. Each weekly measurement yields 143,000 separate data points (the number is high because the measurements include full spectral power distributions each time, for each lamp). Several analytical techniques were used to evaluate these data and verify the level of performance of the lamps relative to the L Prize requirements.

4.1   Non-Parametric Statistical Approach

Non-parametric confidence interval estimation was used to drive the sample size and analyze the resulting data because, when the L Prize competition rules were written, DOE did not know which companies would enter the competition, and therefore did not know in advance what kind of lumen maintenance behavior (performance distribution) to expect from an entry. This statistical approach makes no assumptions about the shape of the products' lumen maintenance distribution. The reason this is necessary is illustrated in the figure below.

a. Skewed Left Distribution	b. Standard Normal Distribution	c. Skewed Right Distribution
Graphs a, b, and c show various types of skewness. With the area under the curve representing the amount of products that have the lifetime represented, it is clear that the shown distributions have comparatively different amounts of products that meet or exceed the 25,000-hour lifetime requirement. Unlike other techniques, a non-parametric approach can be used to build a conservative sample size for evaluating these or any other distribution.		

Figure 4.1. Illustration of Non-Parametric Statistical Approach

The statistical approach for evaluating L Prize entries' ability to meet the long-term performance requirements of the competition was based on the following parameters:

1. Lumen maintenance at least 70%: Entrant maintains a forecasted lamp output of at least 70% of its maximum (initial) lumen rating.

    a. The EISA legislation defined lifetime for the L Prize product as follows: the product must maintain at least 70% of the defined light output (greater than 900 lumens for the 60-watt replacement category) for at least 25,000 hours of operation.

2. Failure rate 10%: No more than 10% of products are expected to fail (fall below L_{70}) within 25,000 hours of operation.

    a. In accordance with goals for large-scale manufacturing, requiring a failure rate of no greater than B_{10} puts measurable bounds on quality assurance. When production goals are in the millions of

fixtures, having a failure rate of greater than 1 in 10 is expensive and inefficient; entrant's products must be both capable and reliable.

3. Confidence level 95%: 95% statistical confidence in the L Prize tolerance limit.

   a. 95/90 tolerance limit: Lumen value, based on a sample of tested fixtures, assures with 95% confidence level that 90% of the underlying fixture lumen values will exceed.

   b. Because of uncertainty in the production process, testing samples only give an estimation of how the entire population of devices will perform. As the confidence level, commonly 90%, 95%, or 99%, $(C_{90}, C_{95}, $ or $C_{99})$, increases, the tolerance limit will decrease thereby increasing the possibility of rejecting a product even though it performs satisfactorily. Conversely, lowering the confidence level increases the tolerance limit, generally making it easier for a product to qualify. The specific confidence level used will influence the likelihood of making such incorrect decisions.

   c. C_{95} was selected for this application. Increasing the confidence level protects consumers from receiving a faulty product when the manufacturer meets the statistical criteria, while a lower confidence level makes it easier and less expensive for manufacturers to qualify but may increase the risk of consumers receiving faulty lamps.

4. Testing will be performed on a random sample of 200 from the 2,000 quality control lamps provided.

5. A non-parametric approach will used to determine confidence intervals.

6. According to this non-parametric approach, when test results are ranked from worst (x_1) to best (x_{200}), the thirteenth worst-performing unit (x_{13}) is the lower tolerance limit, which asserts that, subject to C_{95}/B_{10} criteria, we have 95% statistical confidence that 90% of the lamps produced will perform at least as well as the thirteenth worst unit.

For the C_{95} & B_{10} standards, 10% or 200 of the 2,000 samples submitted is a sufficiently large portion to provide accurate results while not being encumberingly large. A larger sample size would increase the confidence limit, but would also increase testing costs.

According to this non-parametric approach, when test results are ranked from worst (x_1) to best (x_{200}), the thirteenth worst-performing unit (x_{13}) provides a 95/90 tolerance limit. This approach does not depend on the underlying shape of the lumen distribution, but rather only on the n = 200 tested units and the 10% (B_{10}) target. When appropriate distributional knowledge is available for the lamps being evaluated, satisfying the B_{10} criteria for a sample of 200 would result in a tighter lower bound or a smaller sample could be used to attain a comparable lower bound.

To protect against faulty assumptions about the underlying distribution, this non-parametric approach was adopted and will widen the lower bound as compared to a parametric approach due to the increase in the assumed uncertainty or, in this case, increase sample size requirements to attain the same lower bound.

While this approach may potentially discount lighting products that would otherwise have met the L Prize criteria, it ensures that the samples that pass are highly qualified.

4.2   Determining Point of Maximum Flux

The lumen maintenance testing and evaluation approach defined by DOE required identification of the point of maximum output of the lamps under test, i.e., the time in run hours at which the normalized lumen maintenance trend reached its maximum. To identify this point required an accurate estimate of the average behavior of these lamps over time.

The data showed that the behavior of normalized lumen maintenance was variable from one lamp to another. Characterization of the mean normalized lumen maintenance across run hours was developed based on the raw measurements for all 202 lamps at each run hour.

The goal was to obtain a correct estimate of the mean across run hours. Figure 4.2 is a scatterplot of the data with a local quadratic loess fit with span = 0.5 superimposed. The "X" on the plot corresponds to the maximum value of the mean function (2694 hours). The solid black dots correspond to the means at each measurement hour.
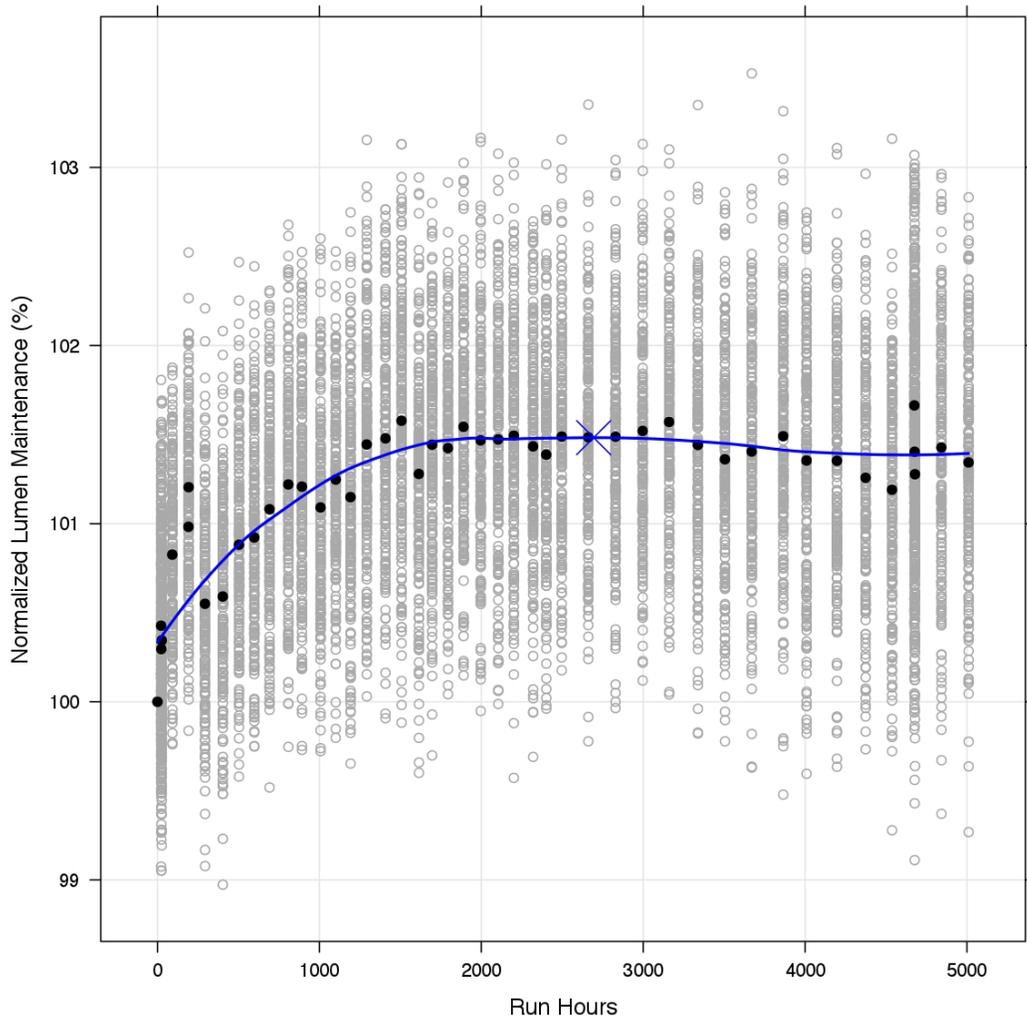
Figure 4.2. Measurement Data for All Lamps at 100-Hour Intervals

While there might be a parametric model that could reasonably fit these data, we were mainly interested in obtaining the best fit to the mean trend, for which non-parametric local methods such as loess (local regression) are suited. For this loess modeling, local quadratic fitting with a span parameter of 0.5 was used to handle the curvature in the lumen maintenance trend. The span parameter controls how smooth or wiggly the fit to the data is. Figure 4.3 displays the residuals from the loess fit to demonstrate the reasonability of the fitting decisions and to check for deviations from zero.

In this plot, the solid line is a loess fit to the residuals; this time it is simply to highlight deviations from zero. In the first 500 hours, the loess model is not fitting the data well due to the sudden peak in the data during that time. However, it is not important to have reliable mean estimates within this region of time. After the first 500 hours, it appears that the mean of the residuals is appropriately varying around 0 (representing an unbiased estimating procedure).
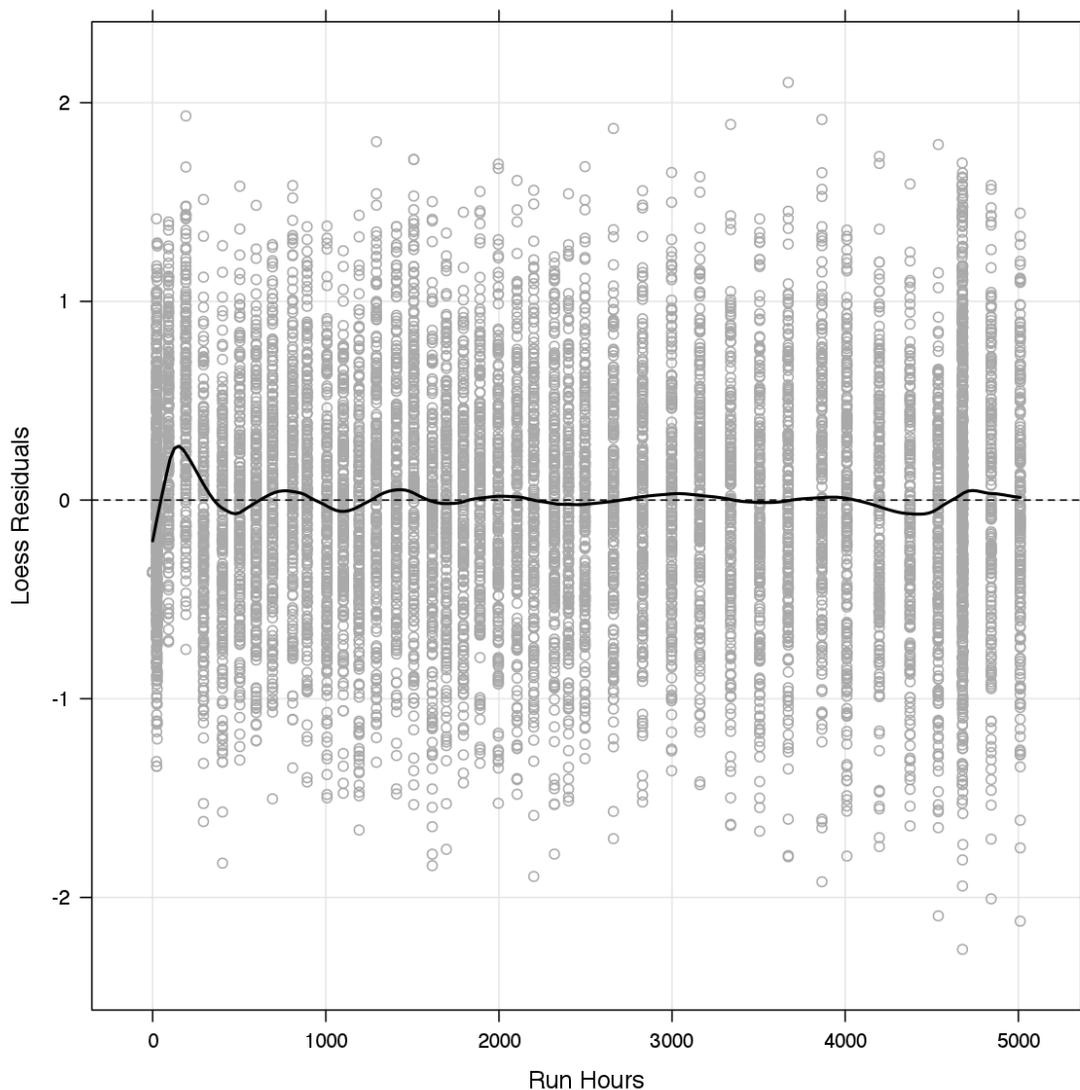
Figure 4.3. Residuals from the Loess Fit

4.4

The mean estimate described above is just that, an estimate. As with all estimates, there is a measure of uncertainty associated with it; thus there is also uncertainty about the maximum value obtained from the mean estimate. We can calculate the uncertainty about the mean estimate provided that the residuals are normally distributed (which they are) and use this to construct confidence intervals about the mean.

Figure 4.4 shows the scatterplot of the data with the loess fit superposed as before, but also adds a 99% upper bound for the mean trend function. This bound means that we are 99% confident that the mean value lies below this line. Note that this plot is focused within a smaller y-axis ranged for a better view of the curve. Following the assumption that the data follow the pattern of increasing and then reaching a plateau before descending again, it is possible that this plateau is reached before the observed maximum—highlighted by the orange box superimposed in the plot. The lower bound of the orange box is at 1636 hours. Choosing this as the point at which the data reach the plateau does not seem reasonable, but there is a local maximum inside the region of the box that is almost as high as the true maximum.
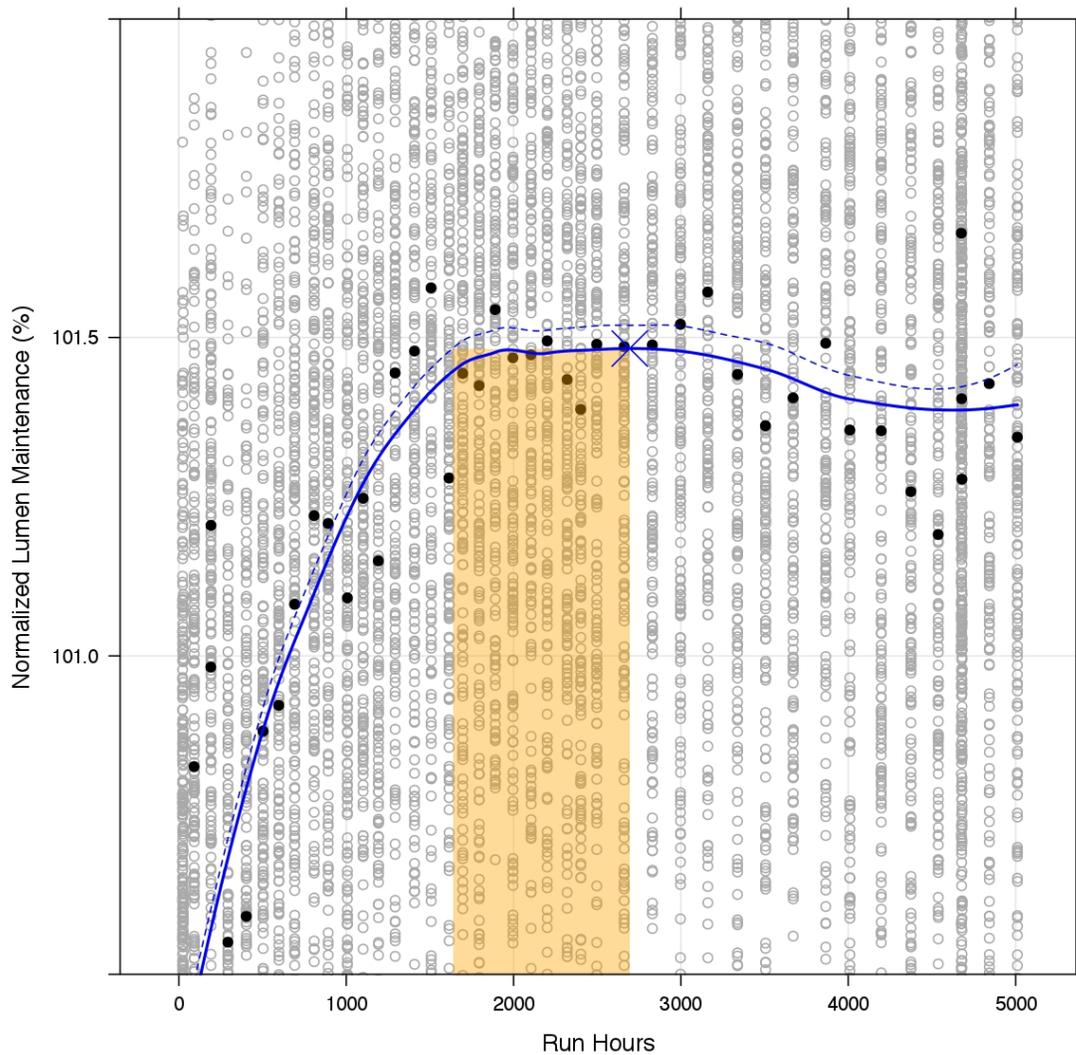
Figure 4.4. Loess Fit with 99% Upper Bound for Mean Trend Function

4.5

To better determine where the mean trend is expected to reach its plateau, a statistical technique called the bootstrap was used. The bootstrap process requires the data to be resampled, with replacement, many times and for each sample. The loess mean fit is calculated and the maximum value for that fit is recorded. The bootstrap process was done 1,000 times to get the results shown in Figure 4.5.
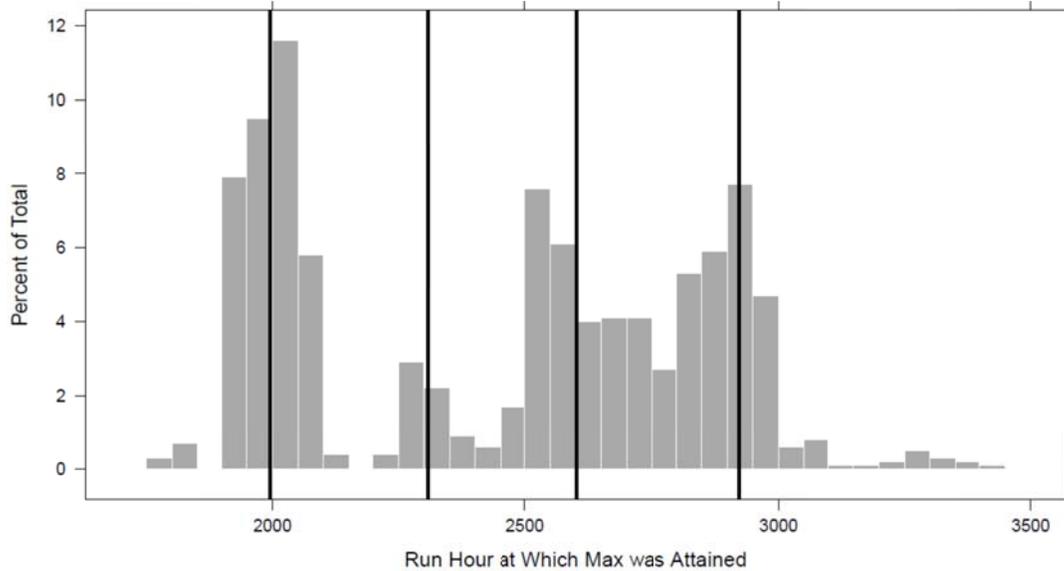

Figure 4.5. Frequency Distribution by Run Hours

Figure 4.5 shows the frequency of different run hour values at which the maximum occurred. It appears that there are four clusters, meaning there are four different places competing to be the maximum. Figure 4.6 shows that, regardless of which one is chosen, the distribution of the resulting maximum is essentially the same. This is good evidence that the plateau is reached at the first run hour cluster (having a mean of just under 2,000 run hours).
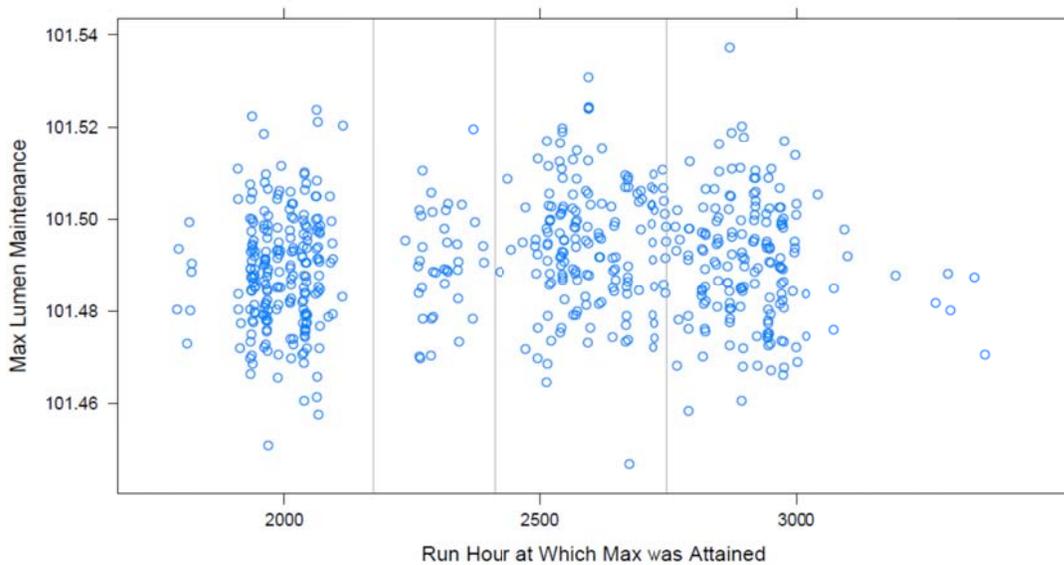
Figure 4.6. Distribution of Four Possible Maximum Output Periods

5.0   Test Results for First L Prize Winner

5.1   Lumen Maintenance

The maximum average light output for the 200-lamp samples under test (L_{max}) was statistically estimated to have occurred at 1,996 hours. L Prize rules required lumen maintenance to be based on L_{max} + 5000 hours, = 6,996 hours. This point was reached on April 10, 2011.

Figure 5.1 shows the relative lumen maintenance data from 2,000 to 7,000 hours for the thirteenth worst-performing sample, which represents the 95% confidence limit.
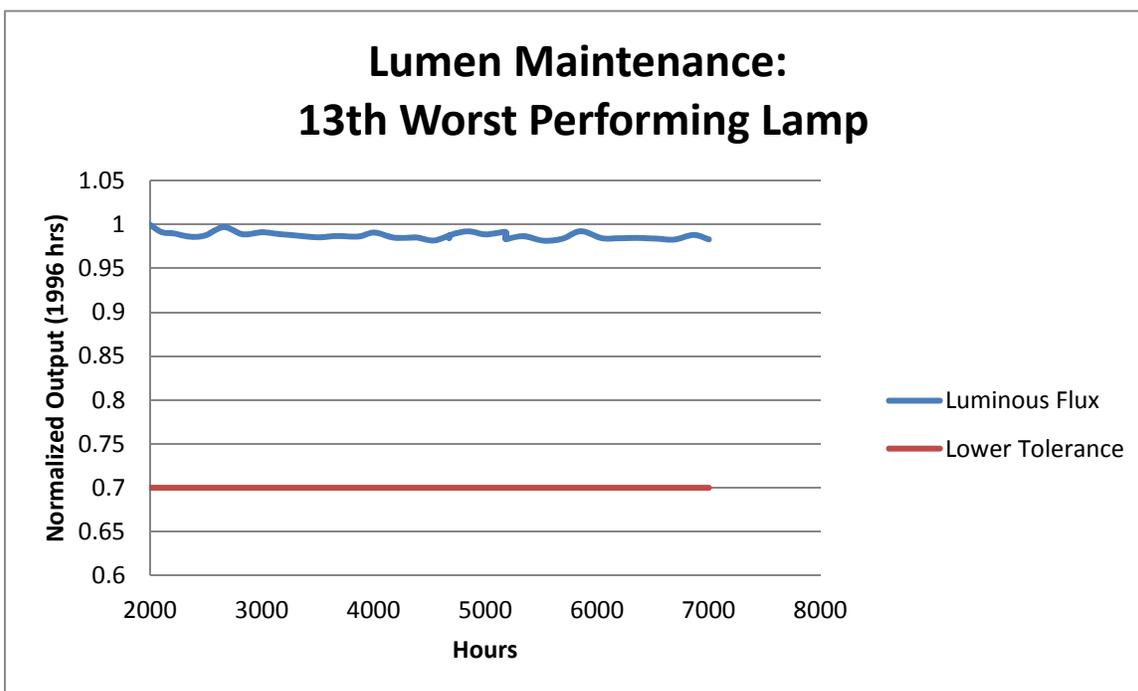
Figure 5.1. Measured Lumen Maintenance

The normalized lumen data were used to forecast the lumen output at 25,000 hours for each individual lamp (see Figure 5.2). The box plot at 25,000 hours shows the range of predictions from each of the 200 lamps. The red dot identifies the thirteenth worst-performing item. The non-parametric statistical methodology says the $L_{70}/B_{10}/C_{95}$ estimate is based on performance of this thirteenth worst-performing lamp in the 200-lamp sample. When an exponential decay function is fit to the data for thirteenth worst-performing lamp, lumen maintenance must be ≥70% at 25,000 hours. As of April 10, 2011, at test hour 7001.03, the thirteenth worst-performing lamp of the 200 samples under test had projected lumen maintenance of 97.08% at 25,000 hours.[3]

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[3] Projected lumen maintenance was originally reported as 99.3%. An error in the projection calculations was subsequently discovered and corrected. The corrected value is reported here.
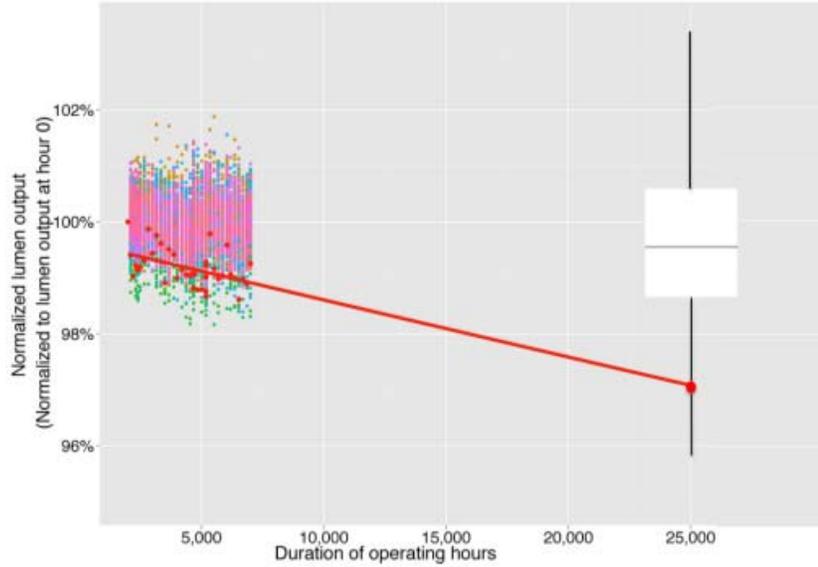
Figure 5.2. Forecast for Thirteenth Worst-Performing Lamp

5.2   Chromaticity Maintenance

Chromaticity data were collected at the same time as lumen maintenance data in the same apparatus. Since there is no consensus methodology for extrapolating chromaticity maintenance data, L Prize rules required lamps to show no more than 0.004 $\Delta u',v'$ at L_{max} + 5000 hours. Using the same non-parametric methodology, we selected the thirteenth worst-performing lamp to determine compliance with this requirement. At test hour 7001.03, the thirteenth worst-performing lamp had a measured chromaticity maintenance value of 0.0006 $\Delta u',v'$. Figure 5.3 shows the chromaticity performance of the 200 lamps over the first 7,000 hours. The black dots and line show the trend at each measurement time. The horizontal blue line marks the L Prize established criterion below which each contestant's measurements must be measured at 7,000 hours. All 200 products were well within the requirement.
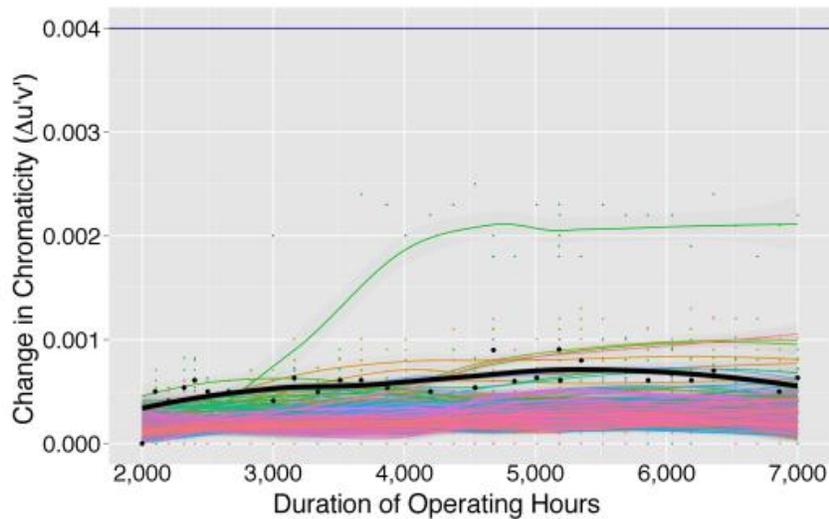

Figure 5.3. Change in Chromaticity over Test Period

5.3 Updated Results Since L Prize Award

Although the minimum test period defined for the competition (t_{max} + 5000 hours) was reached in April 2011, DOE continues to operate the Philips lamps in the LMTA on a continuous basis. Automatic measurements continue weekly. The reasons for continuing longer term operation of the lamps, even after the L Prize evaluation was completed and the award made, are the following:

1. To collect independent, high-quality, long-term, statistically valid lumen and chromaticity maintenance data for the L Prize winning LED replacement lamp product and make the data publicly available

2. To compare long-term data with lumen maintenance predictions based on shorter term (6,000-hour) lamp aging data and LM-80-08 data for the LED packages used in the integral lamp.

In January 2012, the accumulated operating hours for these lamp samples had passed 14,000 run hours; some additional statistical analysis was done at that time. Figure 5.4 depicts the average lumen maintenance (blue line) for the 200 lamps installed in the apparatus, normalized to 100% at hour 0. Note the scale of the vertical axis is "zoomed in" to show just the region between 99.5% and 103.0% normalized lumen maintenance and 38° to 44°C average sphere temperature. The red line represents the average temperature inside the integrating sphere. The temperature drop that occurred between 10,000 and 11,000 hours and the corresponding uptick in average light output was anomalous and due to a door being left open temporarily on the test apparatus.
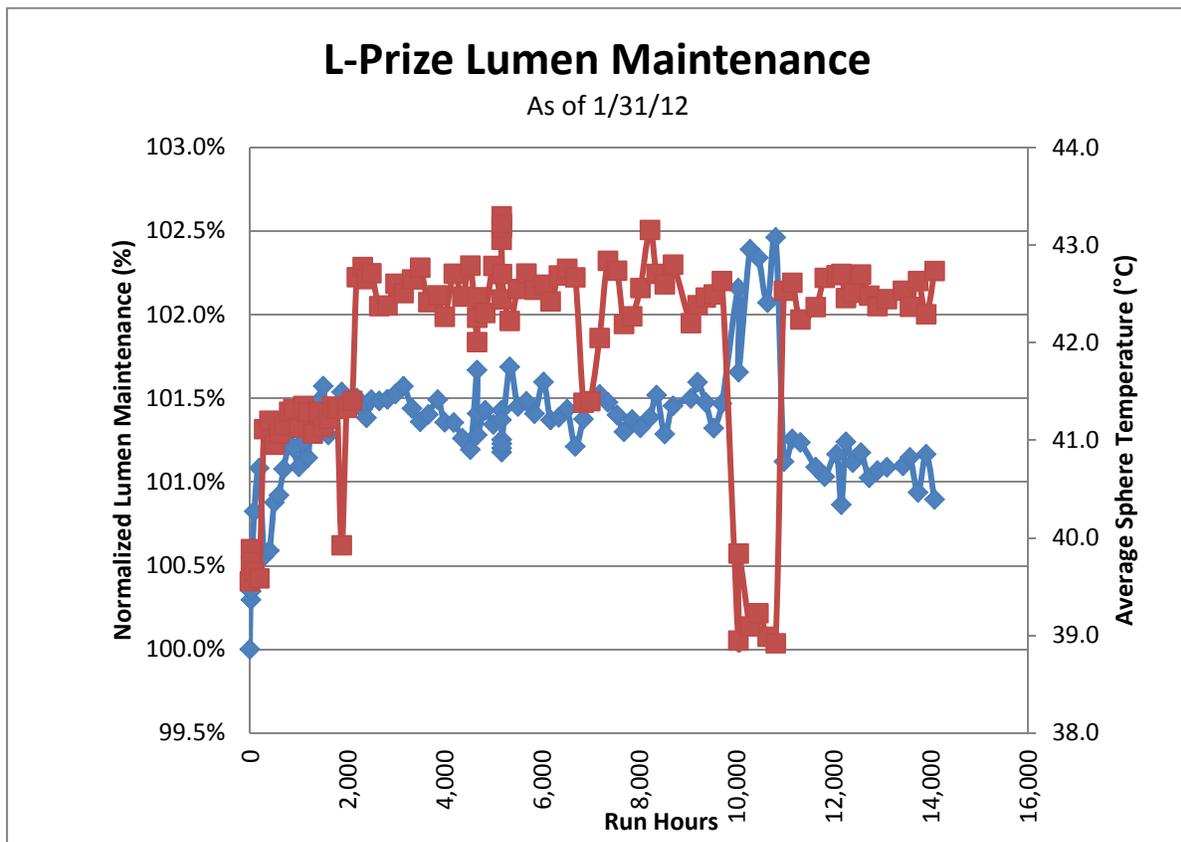

Figure 5.4. Average Lumen Maintenance and Sphere Temperature to 14,000 Hours

The following graphs summarize the results for each of the 200 lamps. Each box plot represents the range of 25,000-hour predictions of the individual lamps, based on the data collected to date by that time. The first observation was made after 2,000 hours.

Figure 5.5 shows how the ability to project 25000-hour lumen maintenance improves with longer data collection.
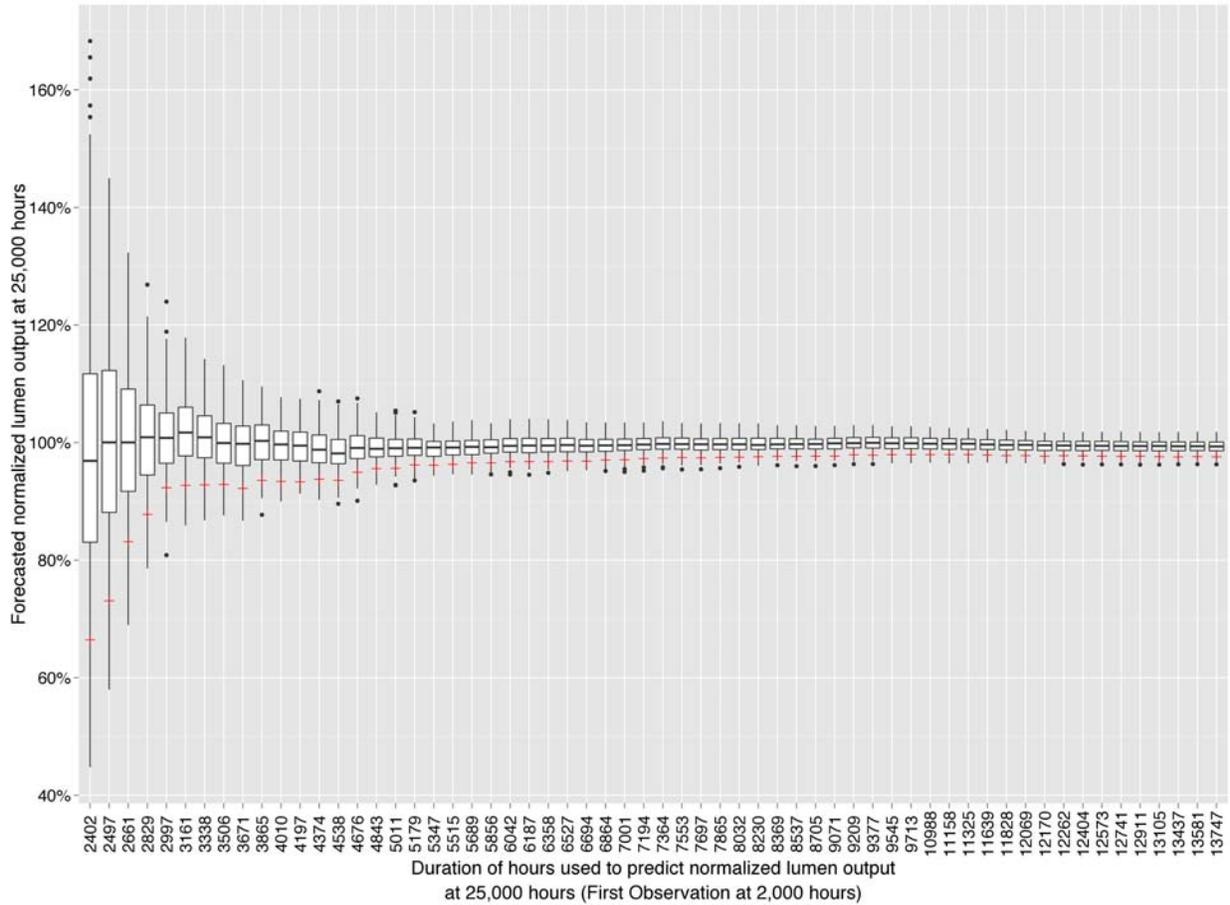

Figure 5.5. Range of 25,000-Hour Lumen Maintenance Forecasts

Figure 5.6 zooms in on the predictions between 4,500 and 14,000 hours, showing that the range of predictions starts to moderate between 6,000 to 7,000 hours.

5.4
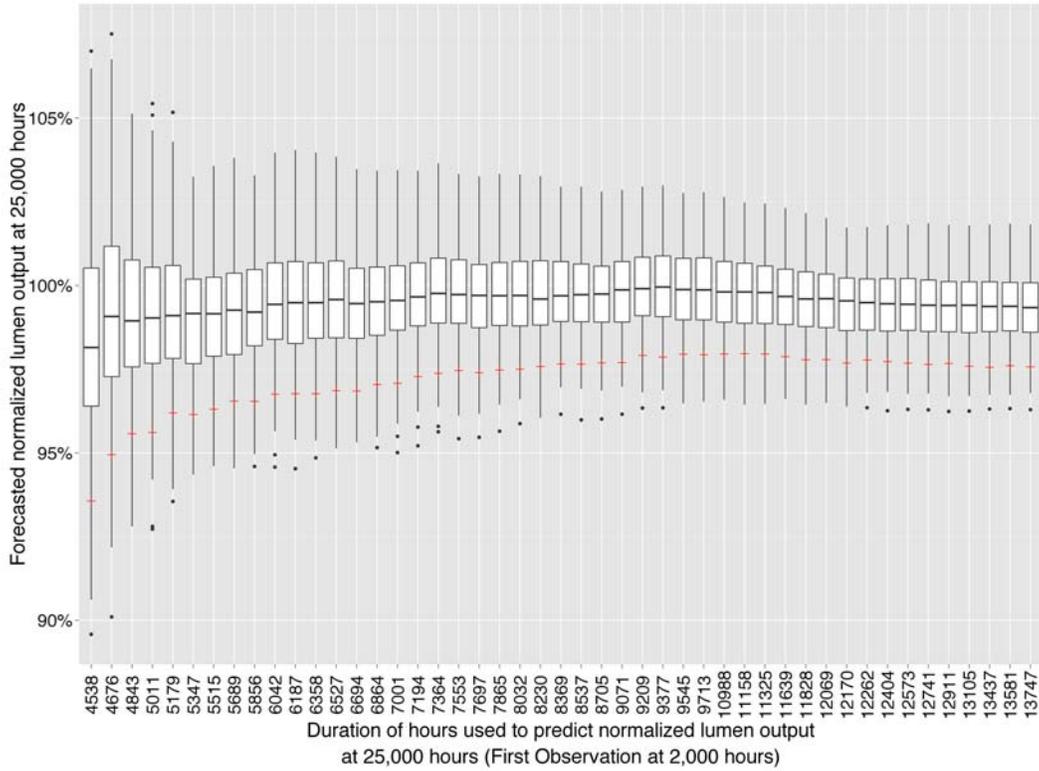
Figure 5.6. Predictions between 4,500 and 14,000 Hours

In fact, the forecasts using 14,000 hours of data are very similar to the forecasts using 7,000 hours as shown in Figure 5.7.
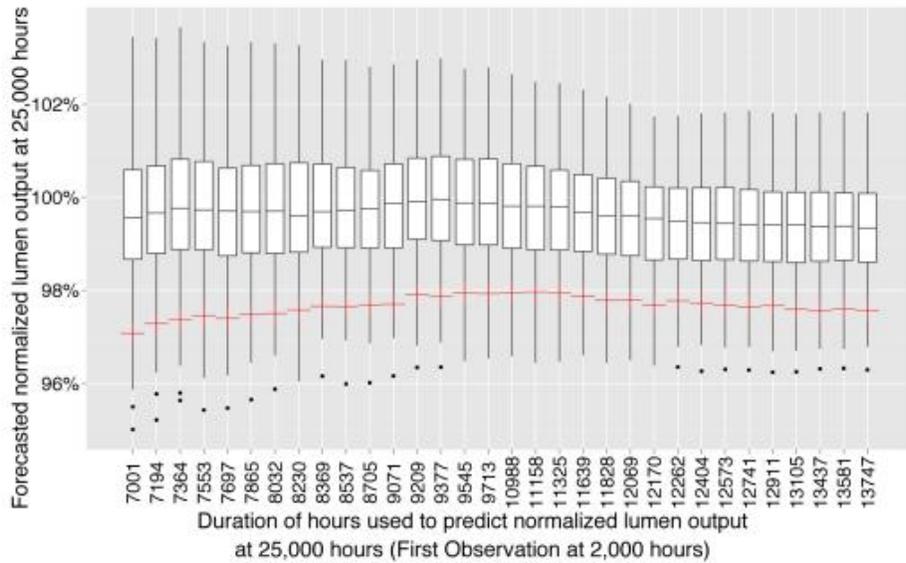

Figure 5.7. Forecasts of 7,000-Hour Data Similar to 14,000-Hour Data

The chromaticity maintenance of the L Prize winning lamps after 14,000 hours of operation remained well within the parameters required by the competition for the L_{max}+5000 hours minimum test period, as shown in Figure 5.8.
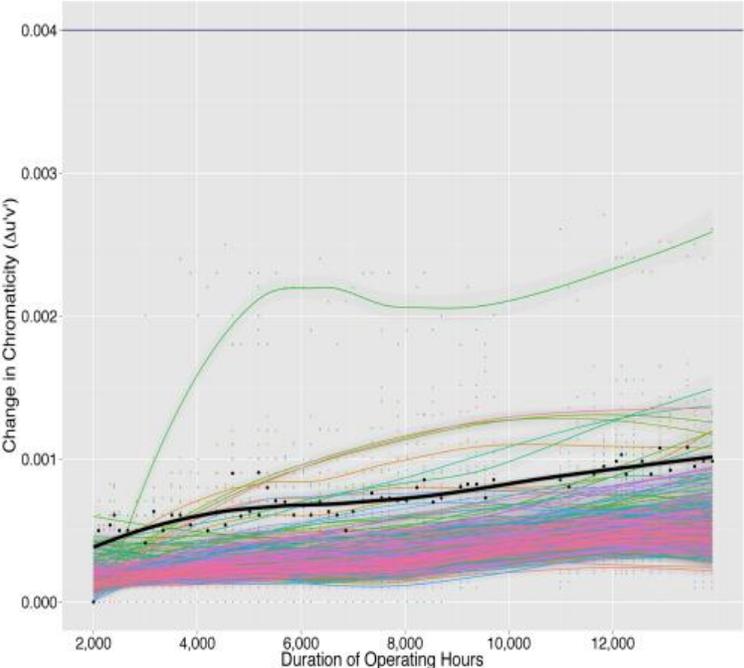

Figure 5.8. Change in Chromaticity up to 14,000 Hours

As of July 2012, accumulated hours of operation have passed 18,000 hours. Figure 5.9 shows the average lumen maintenance for the entire sample of lamps under test to date.
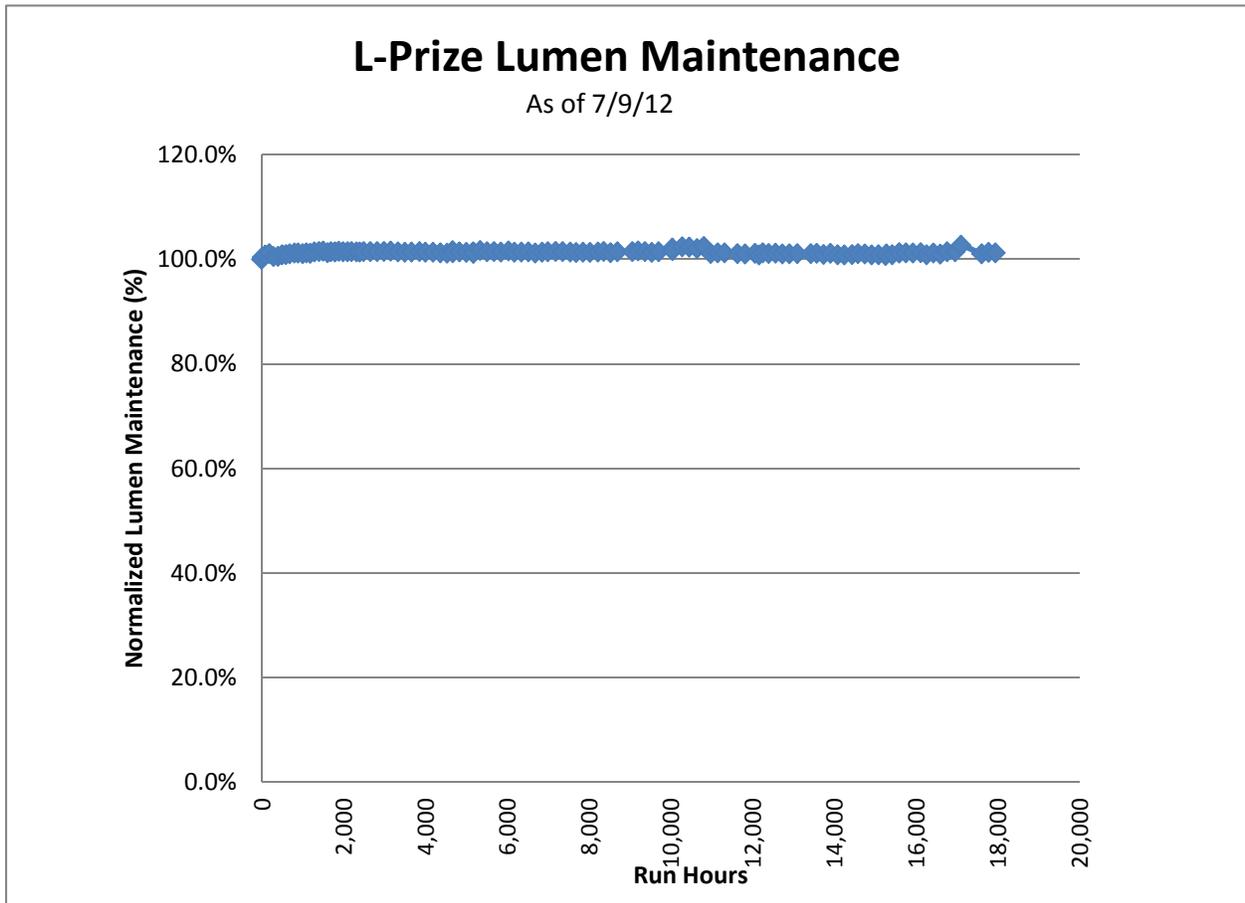

Figure 5.9. Average Lumen Maintenance after 18,000 Hours of Operation

Figure 5.10 and Figure 5.11 show updated lumen maintenance and chromaticity data, respectively, for the thirteenth worst-performing lamp, representing the 95% confidence limit. Based on these most recent data, projected lumen maintenance at 25,000 hours for the thirteenth worst-performing lamp is 97.8%.
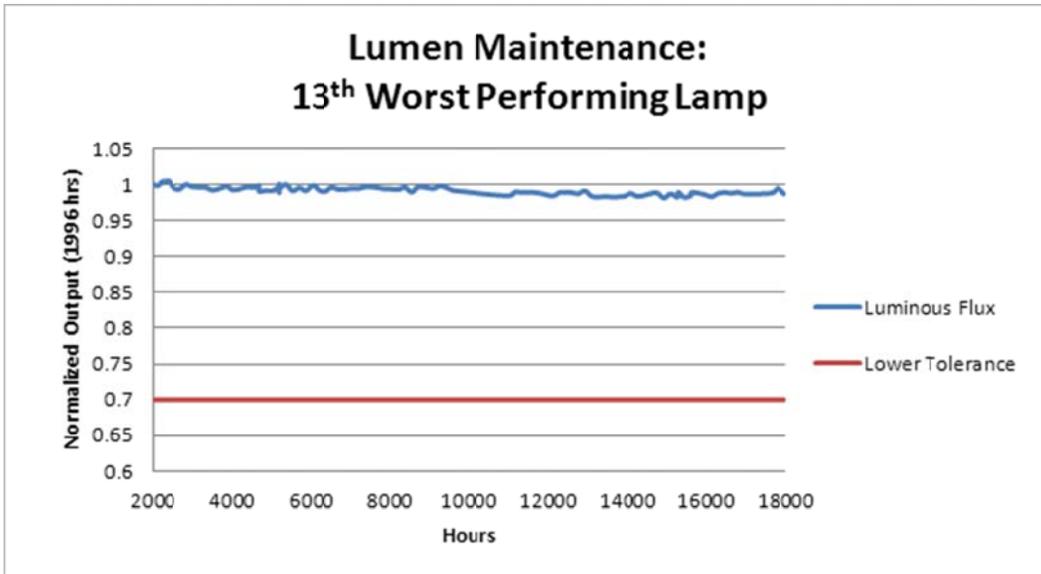
Figure 5.10. Lumen Maintenance after 18,000 Hours of Operation
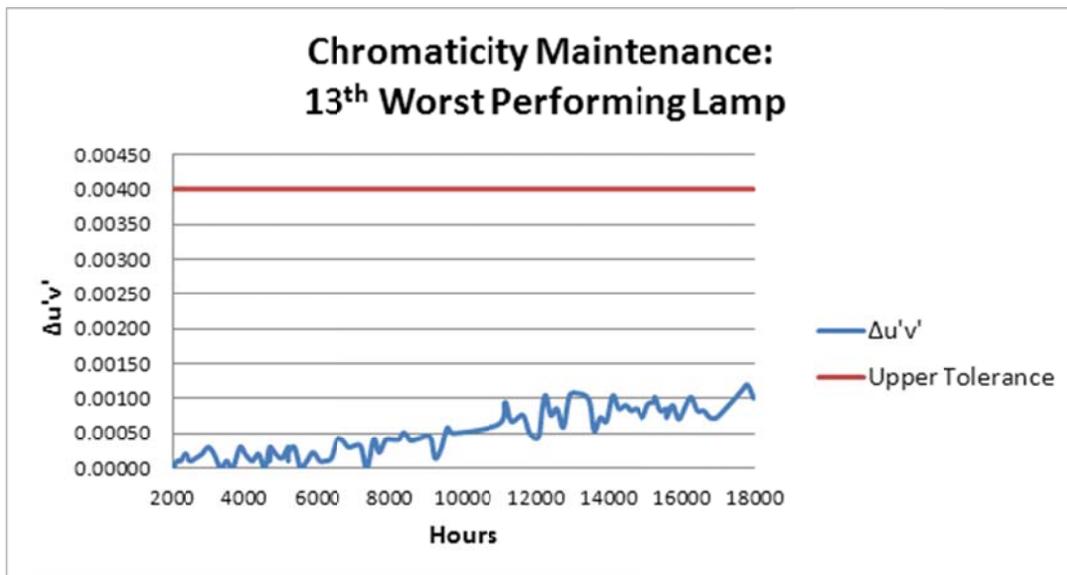

Figure 5.11. Chromaticity Maintenance after 18,000 Hours of Operation

6.0   Future Testing and Analysis

DOE plans to continue to operate the L Prize winning lamps in the LMTA to 25,000 hours and beyond. This will be the only publicly available, third-party data set of long-term LED product operation.

Future testing in the LMTA could include assessment of the market-available version of the Philips L Prize winning lamp, for comparison with the preproduction version tested as part of the L Prize evaluation process.

7.0 References

1. Energy Independence and Security Act of 2007, Pub. L. no. 110–140 (2007). Print.

2. DOE – U.S. Department of Energy. Revision 1, June 26, 2009. *Bright Tomorrow Lighting Competition (L Prize).*08NT006643.

3. IES – Illuminating Engineering Society. 2008. "Approved Method for Measuring Lumen Maintenance of LED Light Sources." IES-LM-80-08.

4. IES – Illuminating Engineering Society. 2011. "Projecting Long Term Lumen Maintenance of LED Light Sources." TM-21-11.

5. IES – Illuminating Engineering Society. 2008. "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products." IES-LM-79-08.