U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

CALiPER

Retail Lamps Study 3.2:

Lumen and Chromaticity Maintenance of LED A Lamps Operated in Steady-State Conditions

December 2014

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Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3] Increasingly, CALiPER investigations also rely on new test procedures that are not industry standards; these experiments provide data that is essential for understanding the most current issues facing the SSL industry.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's web page at the time of purchase.

CALiPER purchases products through standard distribution channels, acting in a similar manner to a typical specifier. CALiPER does not accept or purchase samples directly from manufacturers to ensure that all tested products are representative of a typical manufacturing run and not hand-picked for superior performance. CALiPER cannot control for the age of products in the distribution system, nor account for any differences in products that carry the same model number.

Selecting, purchasing, documenting, and testing products can take considerable time. Some products described in CALiPER reports may no longer be sold or may have been updated since the time of purchase. However, each CALiPER dataset represents a snapshot of product performance at a given time, with comparisons only between products that were available at the same time. Further, CALiPER reports seek to investigate market trends and performance relative to benchmarks, rather than as a measure of the suitability of any specific lamp model. Thus, the results should not be taken as a verdict on any product line or manufacturer. Especially given the rapid development cycle for LED products, specifiers and purchasers should always seek current information from manufacturers when evaluating products.

To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights Consortium® (DLC) Qualified Products

[1] IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.iesna.org/.
[2] CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).
[3] CALiPER application reports are available at http://energy.gov/eere/ssl/caliper-application-reports. Detailed test reports for individual products can be obtained from http://www.ssl.energy.gov/search.html.
[4] LED Lighting Facts® is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see http://www.lightingfacts.com.
[5] ENERGY STAR is a federal program promoting energy efficiency. For more information, visit http://www.energystar.gov.

List (QPL),[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, photometric testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully. In the end, the best product is the one that best meets the needs of the specific application.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

[6] The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit http://www.designlights.org/.

1 Report Summary

The lumen depreciation and color shift of 17 different A lamps (15 LED, 1 CFL, 1 halogen) were monitored in a specially developed automated long-term test apparatus (ALTA) for more than 7,500 hours. Ten samples of each lamp model were tested, with measurements recorded on a weekly basis. The lamps were operated continuously at an ambient temperature of 45°C. Importantly, the steady-state test conditions were not optimized for inducing catastrophic failure (to which thermal cycling is a strong contributor) for any of the lamp technologies and are not typical of normal use patterns—which usually include off periods where the lamp cools down. Further, the test conditions differ from those used in standardized long-term test methods (i.e., IES LM-80, IES LM-84), so the results should not be directly compared. On the other hand, the test conditions are similar to those used by ENERGY STAR (when elevated temperature testing is called for). Likewise, the conditions and assumptions used by manufacturers to generate lifetime claims may vary; the CALiPER long-term data is informative but cannot necessarily be used to discredit manufacturer claims. The test method used for this investigation should be interpreted as one more focused on the long-term effects of elevated temperature operation, at an ambient temperature that is not uncommon in luminaires.

On average, the lumen maintenance of the LED lamps monitored in the ALTA was better than that of benchmark lamps, but there was considerable variation from lamp model to lamp model. While three lamp models had average lumen maintenance above 99% at the end of the study period, two products had average lumen maintenance below 65%, constituting a parametric failure. These two products, along with a third, also exhibited substantial color shift, another form of parametric failure.

While none of the LED lamps exhibited catastrophic failure—and all of the benchmarks did—the early degradation of performance is concerning, especially with a new technology trying to build a reputation with consumers. Beyond the observed parametric failures, nearly half of the products failed to meet early-life thresholds for lumen maintenance, which were borrowed from ENERGY STAR specifications. That is, the lumen maintenance was sufficiently low at 6,000 hours that seven of the products are unlikely to have lumen maintenance above 70% at their rated lifetime (which was usually 25,000 hours).

Given the methods used for this investigation, the results should not be interpreted as indicative of a lamp's performance in all environments. Likewise, these results are not directly relatable to manufacturer lifetime claims. This report is best used to understand the variation in LED product performance, compare the robustness of LED lamps and benchmark conventional lamps, and understand the characteristics of lumen and chromaticity change. A key takeaway is that the long-term performance of LED lamps can vary greatly from model to model (i.e., the technology is not homogeneous), although the lamp-to-lamp consistency within a given model is relatively good. Further, operation of LED lamps in an enclosed luminaire (or in other settings involving high ambient temperatures) can induce parametric failure of LEDs well before the end of their rated lifetime; manufacturer warnings about such conditions should be followed if performance degradation is unacceptable.

2 Introduction

Besides efficacy, one of the major competitive advantages of LEDs versus conventional light sources is the promise of longer lifetimes. This attribute may be important to consumers, who must justify the higher cost of LED lamps with a variety of factors—balancing initial cost, lifetime cost, lighting quality, and more. As adoption rates for LED lamps increase, their reputation for long-term performance in real-world installations will solidify, for better or worse, and their rated lifetimes will gain additional context. In the meantime, specialized testing—such as that documented in this report—can help to identify weaknesses and accelerate technological innovation.

Given typical rated lifetimes of 25,000 hours or more and the rapid turnover in products, it is impractical for manufacturers to test all products for the duration of their lifetime. Some modes of failure, such as lumen depreciation, can be projected based on a relatively small number of measurements taken over a relatively short duration, but other failure modes are much more difficult to predict. There is also an important distinction between data for LED packages and data for complete LED lamps and luminaires; oftentimes, LED package data is applied to integral (complete) LED lamps and luminaires by verifying operating conditions similar to the temperatures under which the packages were tested. However, this type of data does not capture other degradation that can occur within the entire integrated lamp system.

The goal of this investigation was to examine the long-term performance of complete LED lamps—in this case, A lamps emitting approximately 800 lumens—operated continuously at a relatively high ambient temperature of 45 °C. This ambient temperature is above what a lamp would experience in a completely open fixture, but is within the range of what an LED lamp might experience if operated in an enclosed fixture, or even in a downlight or track head with only one side open. Importantly, a majority of the tested lamps stated in specification sheets or on product packaging that they were not to be used in enclosed luminaires, and only two (13RT-11 and 13RT-13) stated that use in an enclosed fixture was acceptable (in some cases the language was ambiguous or there was no information at all). Nonetheless, the higher ambient temperatures were used to create a more hostile operating environment, which allows for greater differentiation between the lamp models than if they were opreated in ambient conditions. Further, 45 °C is the ambient temperature required for the ENERGY STAR Elevated Temperature Life Test (for omnidirectional lamps ≥ 10 W).[7] The 45 °C temperature was derived from tests of a 13 W CFL installed in a UL1598 ICAT downlight.

This report documents the long-term performance of 15 of the LED A lamps from CALiPER's third study of lamps available in retail stores (RRL3).[8] Specifically, it focuses on lumen and chromaticity maintenance relative to benchmark halogen and CFL lamps. Importantly, the continuous-operation method used does not lead to the most rapid degradation of LED sources[9] or of the benchmark halogen and compact fluorescent (CFL) lamps. To be exact, the steady-state operating conditions eliminate thermal cycling, which can increase the degradation of many types of components within a lamp. Further, continuous operation eliminates a primary cause of catastrophic failure, especially for the CFL and halogen benchmarks.

There are several key factors to keep in mind when interpreting the results of this study, especially relative to manufacturer lifetime claims:

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[7] Long-term testing at ambient temperatures are permitted for omnidirectional lamps drawing less than 10 W. For more information, see the ENERGY STAR Program Requirements for Lamps (Light Bulbs), available at: https://www.energystar.gov/sites/default/files/ENERGY%20STAR%20Lamps%20V1%201_Specification.pdf

[8] The RRL3 summary report is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_retail-lamps-study3.pdf This report documents the basic performance parameters of each lamp.

[9] For more information, see: Narendran N. 2014. *Accelerated Life-testing Study to Predict LED System Failure.* Strategies in Light. February 27, 2014. Santa Clara, CA.

- The continuous-operation protocol is not similar to most real-world applications. Given the specific protocol, the results for the included products can be compared to one another, but they do not necessarily indicate how long any of the products will perform as intended when installed in a real application, nor the accuracy of the manufacturers' claims.

- The lamps were operated for nearly 8,000 hours—a bit shy of one year—and consequently may not be the same as are currently available for purchase (the lamps were all purchased in 2013). This is further reason to evaluate the results only within the context of this study.

- In 2013, the Illuminating Engineering Society published LM-84-13, *Approved Method for Measuring Lumen and Color Maintenance of LED Lamps, Light Engines, and Luminaires*; as well as TM-28-13, *Projecting long-term lumen maintenance for LED lamps and luminaires*. The investigation covered in this report was initiated before these documents were published, and the procedure is different. Data from this report are not comparable to LM-84 data.

This report is best used to understand the variation in LED product performance, compare the robustness of LED lamps and benchmark conventional lamps, and understand the characteristics of lumen and chromaticity change.

Comparable Long-Term Test Data

Pacific Northwest National Laboratory (PNNL) developed the ALTA[10] in order to test products for the L Prize® competition. Beginning in 2010, 200 samples of Philips Lighting's L Prize entry were evaluated in the ALTA; after approximately 30,000 hours of operation, the sample size was reduced to 32. Through 25,000 hours of testing, the average lumen maintenance of the samples remained 100% of the maximum average output, as noted in the report *Lumen Maintenance Testing of the Philips 60-Watt Replacement Lamp L Prize Entry*.[11] Besides data analysis, the report also includes detailed information about the test apparatus development and measurement procedures.

The L Prize long-term dataset demonstrates, for all practical purposes, the maximum achievable lumen and chromaticity maintenance for LED products. The tested lamps were pre-commercial, but the design eventually turned into a commercial product, and the technological innovation was used in other subsequent products. Still, it is unreasonable to expect all LED lamps to perform to the level of the L Prize lamp, given the considerable tradeoffs between performance and cost, for example. Nonetheless, the L Prize result does provide context for understanding the performance of other lamps that the CALiPER program has subsequently tested.

While the L Prize long-term testing regimen was underway, a second apparatus with near-identical specifications was constructed. This apparatus—deemed the automated long-term test apparatus 2 (ALTA2)—included minor upgrades to improve performance and a mounting configuration to accept PAR38 lamps. This apparatus was used to investigate the long-term performance of the CALiPER Series 20 PAR38 lamps, beginning in early 2013.[12] Notably, that report includes many lamp brands that were also included in the present investigation. Given the different lamp type and likely different components, the results suggest that considering performance at the brand level may be inappropriate, as subsequently discussed.

[10] This device was originally named the lumen maintenance test apparatus (LMTA). That name is used in previous reports that relied on the apparatus.
[11] Available at: http://www.lightingprize.org/pdfs/lprize_60w-lumen-maint-testing.pdf
[12] Available at: http://energy.gov/eere/ssl/downloads/report-204-lumen-and-chromaticity-maintenance-led-par38-lamps

3 Methods

The 15 LED lamps and two benchmark lamps were operated for approximately 7,500 hours in the ALTA. The lamps are identified in Appendix A, and basic performance characterizations are available in the CALiPER Retail Lamps Study 3 summary report. Ten samples of each lamp were evaluated, which allows for some evaluation of the variability in performance for a particular lamp make and model. The procedure did not follow the prescriptions of IES LM-84—which was not complete when testing was initiated—and thus the data should not be extrapolated using the TM-28 projection method.

Apparatus

The following is a brief description of the ALTA. For complete details about the design and construction of the apparatus—previously known as the lumen maintenance test apparatus (LMTA)—see the L Prize long-term testing report.[13]

The ALTA (Figure 1) can accommodate up to 204 lamps, arranged in a 12-by-17 array; one space in the 204-position array is used as a rest location for the mobile integrating sphere, and another is used for a calibration standard lamp, so the effective capacity is 202 lamps. Thirty-four of the available spaces were occupied by a subset of the L Prize lamps undergoing additional evaluation. Unlike with the L Prize lamp testing, it was not

Figure 1. The ALTA apparatus with 170 A lamps from CALiPER Retail Lamps Study 3 (right) and 34 L Prize lamps (left) installed. The lamps protruded approximately 2" into the space below the mounting channels.

[13] Available at: http://www.lightingprize.org/pdfs/lprize_60w-lumen-maint-testing.pdf

possible to machine openings for each of the different lamp models (which often had irregular shapes), which would effectively seal off the emitting area to allow for measurement. Instead, reflector cones typically installed in a 5" downlight were mounted with each socket, sealing off the aperture and creating an interface for the integrating sphere (Figure 2). The lamps protruded approximately 2" below the bottom edge of the reflector (atypical of a real installation), which was the maximum distance possible, given the need to move the integrating sphere around the apparatus. This setup ensured that more of each lamp's output reached the integrating sphere instead of being absorbed by the reflector.

Importantly, the upper opening of the reflector cone did not form a tight seal around the socket; thus, some light may have escaped measurement, or spill light from adjacent lamps may have contributed to the measurements. This light was assumed to be within other measurement tolerances. Regardless of the absolute or relative quantity, the amount of spill light was generally consistent from measurement to measurement and did not significantly affect the results of the investigation.

The lamps were operated continuously, with the ambient temperature maintained at approximately 45°C (always between 44°C and 45°C). The ambient temperature was monitored with an array of thermocouples (Figure 3) and maintained with an exhaust fan that would operate when needed. The thermocouples were located in a plane approximately at the midpoint of the lamp bodies; that is, between the emitting area and the lamp base. A total of nine thermocouples were spaced throughout the apparatus.

Besides some vertical temperature stratification (which was unavoidable), there was some degree of temperature variation within the measurement plane. The coolest area was around the perimeter, and the warmest area was at the center of the apparatus, with an approximate difference of 1–2°C. The temperature control point was based on the location midway between the center and perimeter of the apparatus. Furthermore, it was confirmed that the reflector cone did not alter the air temperature surrounding the lamps, despite differences of at least 15°C in the case temperature of the LED lamps.

The lamp models were distributed as evenly as possible, with all LED lamps spanning from one end of the apparatus to the other along the short axis of the array (see Appendix B), excluding the perimeter sockets. The benchmark lamps were located around the perimeter.

Figure 2. Reflector cones used to isolate individual lamps for measurement. The lamps were not completely sealed off, allowing for a minimal amount of spill light to reach the integrating sphere.

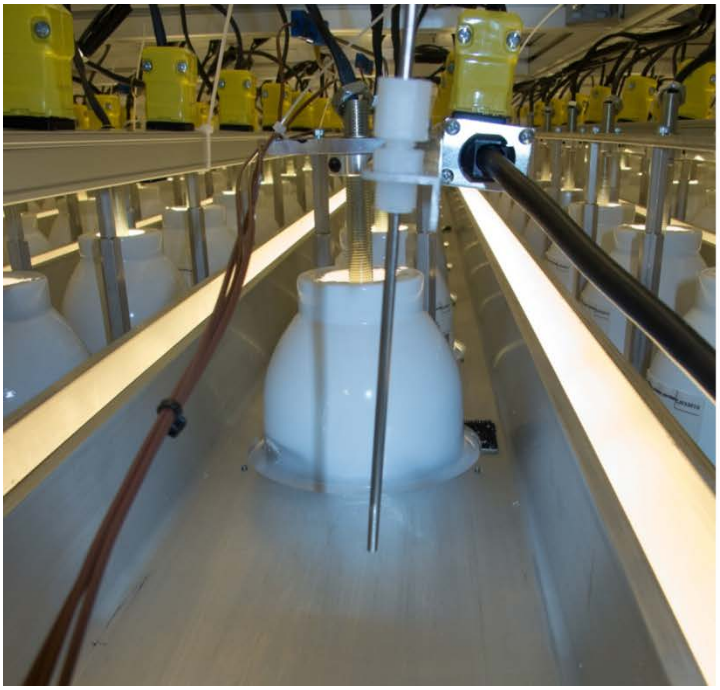


Figure 3. Thermocouples located above the mounting channels. The thermocouples, which provided the data for controlling the ambient temperature, were approximately in the same horizontal plane as the lamp electronics, but were outside of the reflector cone.

Photometric measurements were taken by initiating an automated sequence. Besides the computer and control hardware, the measurement setup included an integrating sphere and accompanying spectroradiometer that were mounted to a track system and could be maneuvered to each lamp—in a highly repeatable manner. The integrating sphere progressed through the lamps in a consistent sequence and, at each lamp, raised until contact with the aperture was achieved. At this point, the lamp was emitting directly into the open port of the integrating sphere, consistent with an approximately 2-pi photometric measurement procedure. The measurements were taken and recorded automatically. The entire procedure took approximately one hour to complete per measurement cycle.

The apparatus included a working standard calibration lamp, which was itself calibrated based on a NIST-certified calibration standard. Prior to each photometric measurement, a calibration measurement was performed, which adjusted for any long-term degradation of the integrating sphere surface or measurement equipment. The calibration lamp was not operated continuously, and was assumed not to degrade over the small amount of time it was operational.

Upon reaching the data analysis stage, it was noticed that all lamps at four measurement times demonstrated an approximately 1% increase in output, which was inconsistent with the measurements before and after. The calibration files for these points were viewed and likewise found to be inconsistent with the adjacent points. To correct the calibration and smooth the data, the measurements were scaled by a factor based on the difference between the luminous flux of the calibration lamp and the average luminous flux of the two time-adjacent measurements. This smoothed the inconsistent data points but had no other effect on the results.

Measurement Sequence

After a brief operational period (approximately three hours) that allowed the ambient temperature to stabilize, the baseline measurement sequence was initiated on January 23, 2014—this is denoted as zero hours. Subsequent measurements were taken approximately 3, 6, 24, and 96 hours thereafter, then approximately every 168 hours (weekly). The last measurement included in this analysis occurred at 7,660 hours.

Over the course of the investigation, all of the halogen and CFL lamps failed. After a detected failure (which usually required one measurement cycle), the failed lamp was replaced with an 11 W incandescent placeholder lamp for the remainder of the experiment. The placeholder lamps were used to prevent an error in the automated measurement sequence (which would have cause a brief delay in the measurement procedure) and to maintain heat balance within the apparatus.

Reported Metrics

Lumen Maintenance

For this report, lumen maintenance for each lamp is reported as the relative value at a given point in time, compared to the baseline measurement for each lamp. An important threshold is the point at which lumen maintenance reaches 70% of its initial value, denoted L_{70}. This threshold is often used as an indicator of parametric failure, or the point at which the lamp would no longer perform its task as desired.

In some instances where the data were averaged over large sets (e.g., the average output of the halogen benchmark), the number of samples included was reduced as the hours increased. That is, once a lamp failed, it was dropped from the average, instead of counting as a zero.

Chromaticity Maintenance

The color appearance of a light source may be described using one of several metrics, all of which relate to the chromaticity of the light. Important characteristics include correlated color temperature (CCT), distance from the black body locus (D_{uv}), and Δu'v', which characterizes the change in chromaticity using the most uniform chromaticity diagram (CIE 1976). For more background on these color metrics, please see the fact sheet *LED Color Characteristics*,[14] or the report *Color Maintenance of LEDs in Laboratory and Field Applications.*[15]

The most relevant color metric for this report is Δu'v'. It is the most accurate and comparable measure of color shift, because it relies on the CIE 1976 chromaticity diagram, which has greater spatial uniformity than its predecessors do. This means that a given value of Δu'v' has approximately the same meaning in terms of color difference, regardless of position within the chromaticity diagram (e.g., starting chromaticity). For context, a circle with a radius of 0.001 in the CIE 1976 chromaticity diagram is roughly equivalent to a 1-step MacAdam Ellipse. Importantly, Δu'v' is only a measure of the magnitude of change and does not indicate the direction of the shift. To better understand the direction of the shift, Δu'v' can be paired with metrics such as ΔCCT and ΔD_{uv}, or plots of chromaticity coordinates can be examined directly.

There are no standards that establish an allowable color shift for LEDs or any other light source. Unlike L_{70} for lumen maintenance, the IES does not suggest that any value of Δu'v' constitutes a parametric failure, for example. In this report, the lamps are evaluated in the context of the ENERGY STAR criterion, which is 0.007. Importantly, this level of difference is readily noticeable in many interior lighting settings,[16] if two lamps with that level of difference are viewed simultaneously. If all the lamps in a room change to that magnitude—and in the same direction—over the course of several years, the occupants may not detect that the lighting has changed—at least not until lamp replacement is necessary.

[14] http://ssl.energy.gov/factsheets.html

[15] Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_color-maintenance.pdf

[16] A just-noticeable difference (JND) is dependent on the viewing condition. There is no universal relationship between a value of Δu'v' and a JND.

4 Results

Lumen Maintenance

On average, the LED lamps outperformed the benchmark halogen and CFL lamps in terms of lumen maintenance, as shown in Figure 4. Note that failed lamps—in this case, all of the benchmarks—were removed from the calculation as the failures occurred; thus, the number of lamps being averaged changes as the hours increase. The plots for the halogen and CFL benchmarks end with data for only one lamp, consequently.

Of course, the average for each technology can be strongly misleading. In fact, there was considerable variation in the average lumen maintenance for the 15 LED lamp models, as shown in Figure 5. Most notably, two lamps (13RT-03 and 13RT-09) were found to rapidly decline in lumen output under the test conditions, and both reached an average less than 70% of their initial value. These would be considered parametric failures. For product 13RT-03, the performance of the 10 samples was very consistent, and all of the samples depreciated below the L_{70} threshold. For product 13RT-09, one sample performed differently than the other samples and did not depreciate below the L_{70} threshold. Plots of lumen maintenance for both lamp models are shown in Appendix C, along with plots for all of the other lamps.

The consistency of the lamps is summarized in Figure 6, which shows the range in relative output at the final measurement point (for the halogen and CFL lamps, the last point with all lamps operating was used instead). Some lamps with greater variation (e.g., 13RT-11) exhibited a relatively even spread over the range in performance, which could be interpreted as less predictability. Other lamps with greater variation (e.g., 13RT-09) had one lamp that performed substantially different from the others. This is likely to be a manufacturing defect.

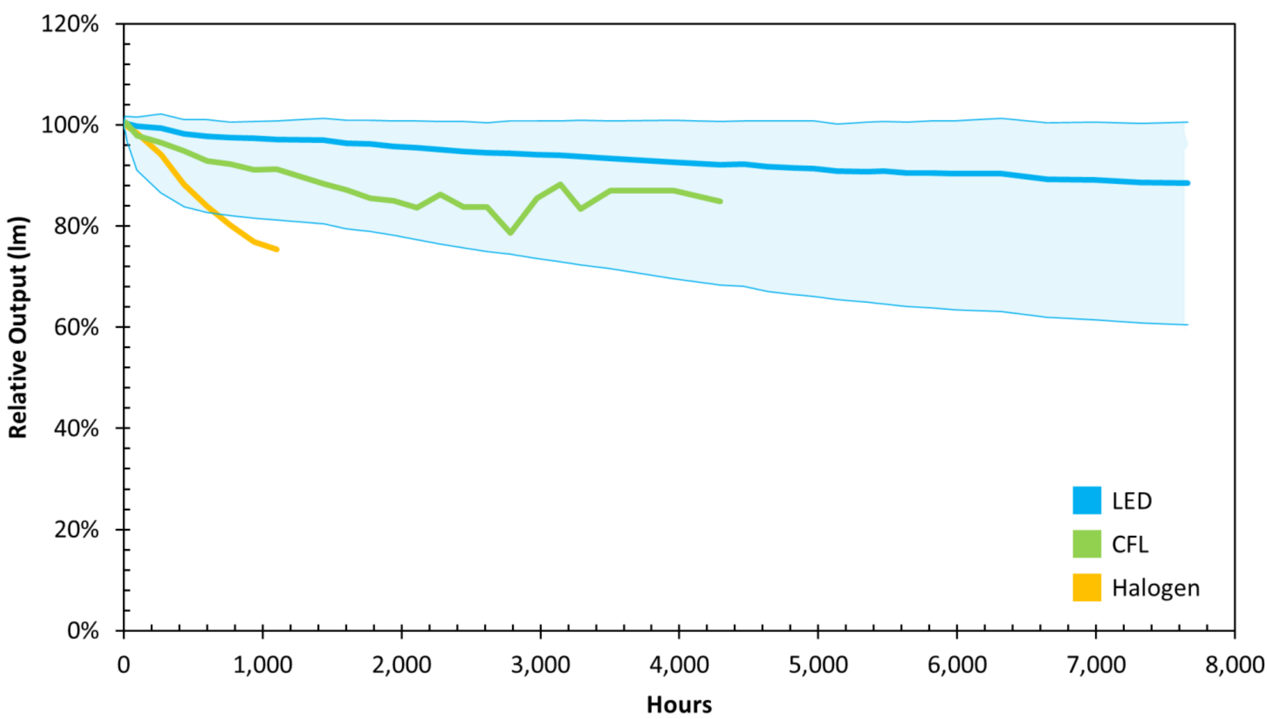


Figure 4. Average lumen maintenance for each source type, with the range in relative output shaded for the LED lamps. Note that the range is for average values for each model at a given time, not for individual samples. Failed lamp samples were dropped from the calculation (rather than included as zeros); this contributes to the inconsistency in relative output for the CFL benchmarks after 2,000 hours.

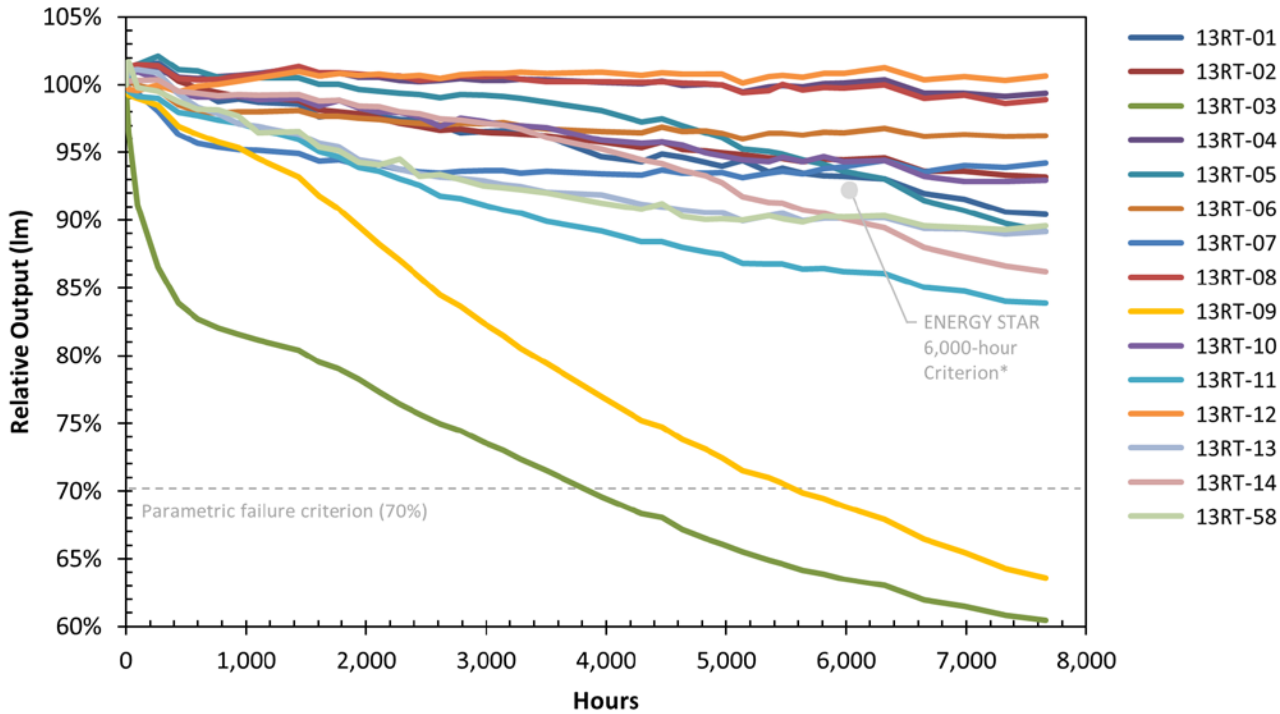


Figure 5. Average lumen maintenance for each of the 15 LED lamp models. Two lamps performed substantially worse than the others, and seven lamps failed to meet the ENERGY STAR criterion for relative output at 6,000 hours. In contrast, three lamps remained above 99% of initial output for the duration of the study period. *The ENERGY STAR criterion shown is for lamps with a 25,000-hour rated lifetime; the criterion is higher for longer rated lifetimes.

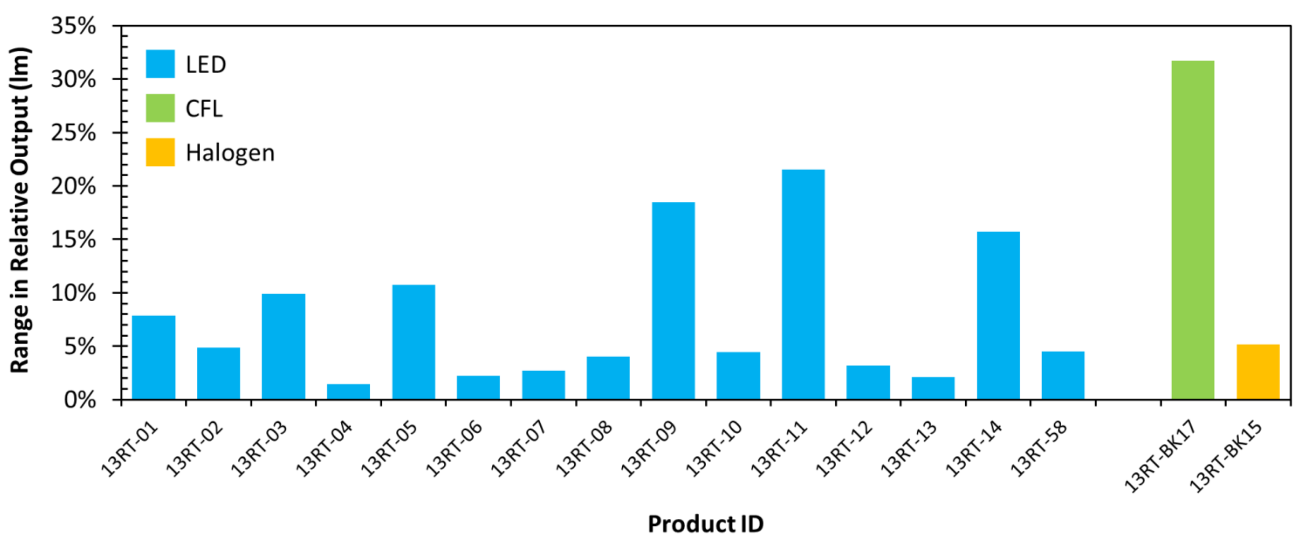


Figure 6. Variation in relative output at the final measurement point. A majority of the LED products were very consistent across the 10 samples, showing less variation than the halogen benchmark. All of the LED lamp models had less variation than the CFL benchmark. This chart does not include differences in absolute lumen output (i.e., product-to-product variation in initial output).

The rapid failure of 13RT-03 and 13RT-09 deserves further consideration. Both had rated lifetimes of 25,000 hours but failed (by reaching L_{70}) in approximately 4,000 and 6,000 hours, respectively. However, it is important to note that at the time the lamps were purchased, there was no standardized procedure for determining the rated lifetime of an LED lamp (although most manufacturers did, and still do, rely on the lumen maintenance of the LED package measured according to IES LM-80 and projected using IES TM-21). Presumably, the rated lifetimes for these lamps were based on different test conditions, such as operation at ambient temperature instead of at elevated temperature. Thus, the takeaway is not that the manufacturers misrepresented the lifetime of those products, but rather that the lifetime of LED products is heavily dependent on the operating conditions. It should be noted, again, that while the relatively high ambient temperatures used in this investigation are not favorable to LEDs, they are not outside the scope of what might occur in a typical residential luminaire in which A lamps might be used. Further, the testing procedure did not involve cycling, which has been shown to accelerate degradation.

Evaluating Lifetime Claims Using ENERGY STAR Threshold

The following analysis is based on current ENERGY STAR specifications. Specifically, it is based on the ENERGY STAR Program Requirements for Lamps (Light Bulbs) Partner Commitments version 1.1, which became effective in September 2014. Critically, *not all of the lamps included in this investigation were ENERGY STAR-qualified.* Those that were ENERGY STAR-qualified at the time of purchase are identified in Appendix A. Importantly, even those lamps listed as ENERGY STAR-qualified in Appendix A were qualified under a different set of specifications (e.g., ENERGY STAR Program Requirements for Integral LED Lamps Partner Commitments version 1.4).

The older ENERGY STAR specifications required that omnidirectional LED lamps emit at least 70% of their initial light output at 25,000 hours, which necessitated an average output for 10 samples of at least 91.8% at 6,000 hours (following the elevated-temperature test protocol for lamps ≥ 10 W). The newer requirements prescribe a variable 6,000-hour threshold based on the manufacturer's lifetime claim, ranging from 86.7% for a claimed lifetime of 15,000 hours to 95.8% for a claimed lifetime of 50,000 hours. The value for a 25,000-hour lifetime (91.8% at 6,000 hours) remained the same.

For comparative purposes only, Figure 7 shows each lamp's average measured lumen maintenance at 5,975 hours (the closest measurement to 6,000 hours) relative to the ENERGY STAR-required value, based on its rated lifetime. Twelve of the fifteen LED lamps had a rated lifetime of 25,000 hours. Beyond the two lamps that reached L_{70} during the study period, five additional lamps failed to meet the ENERGY STAR criterion at 6,000 hours—which is necessary to make the rated lifetime claim if qualification is sought. More broadly, this indicates that the five poor-performing lamps are likely to reach L_{70} before their rated lifetime (e.g., 25,000 hours), although verification would require the testing to continue. The five lamps were 13RT-02, 13RT-10, 13RT-13, 13RT-14, and 13RT-58.

Three out of the seven lamps that did not meet the lumen maintenance thresholds were ENERGY STAR qualified. Of those, one (13RT-02) claimed a 50,000-hour lifetime, which requires greater output at 6,000 hours than the old specification, which it would have met. Another product (13RT-14) was only modestly below the threshold, averaging 90.1% at 6,000 hours (versus the threshold of 91.8%). The third lamp, 13RT-09, was drastically below the ENERGY STAR threshold (91.8%), emitting only 69% of its initial output at 6,000 hours. It remains unclear why the tested samples of this product performed so differently from the ones tested for ENERGY STAR qualification.

Notably, ENERGY STAR allows for lamps drawing less than 10 W to be tested at ambient conditions instead of at elevated temperature. Three LED products in the group of 15 fell into that category (13RT-03, 13RT-08, and 13RT-12). Of those three, only RT13-03 failed to meet the output threshold under the more demanding elevated temperature testing, but it was not ENERGY STAR-qualified at the time of purchase. That product has since

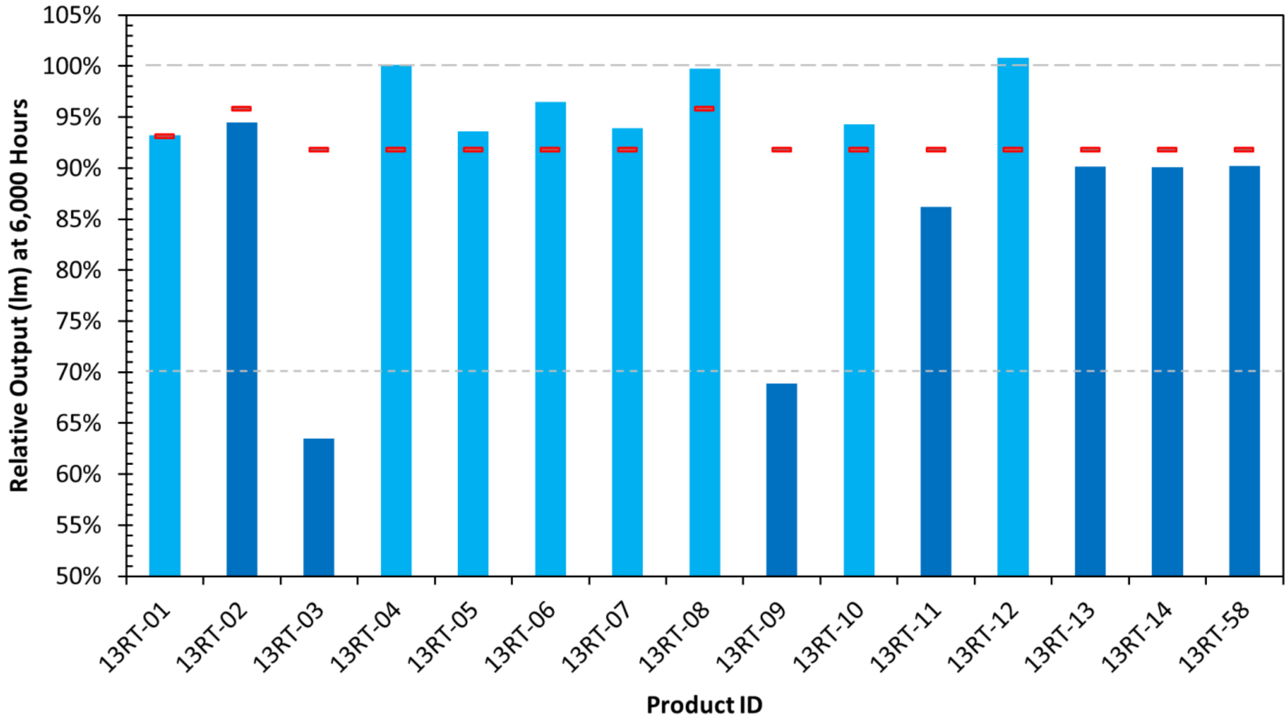


Figure 7. Relative output of each LED lamp at 6,000 hours versus the ENERGY STAR performance criterion (red dash), which is based on the lamp's rated lifetime. Seven of the fifteen lamps (dark blue) failed to meet the ENERGY STAR criterion. Only three of those seven lamps were ENERGY STAR-qualified at the time of purchase, and only two would have failed to meet the test criterion that was in place at the time.

become qualified, although it cannot be verified that the design and performance are exactly the same versus the samples tested, as some small but visible changes have been made since it was first introduced. It is possible that some ENERGY STAR lamps less than 10 W would not qualify if they were greater than 10 W (based on the lumen maintenance criterion). Notably, for this investigation there was no correlation between input power and lumen maintenance. Nonetheless, consumers should be aware of the different testing requirements.

The current ENERGY STAR specification also includes a provision that requires lamps with rated lifetimes greater than 25,000 hours to meet an additional threshold (91.8%) based on a longer test duration that varies from 7,500 hours to 12,500 based on the rated lifetime (30,000 to 50,000 hours). Not enough data are available to investigate whether the products met this condition, but it is possible that more products would have insufficient output at the specified time.

Chromaticity Maintenance

High-level analysis shows that on average, the LED A lamps had fairly similar color stability at a given point in time compared to the halogen and CFL benchmarks (Figure 8). Considering that the color stability of conventional sources is considered acceptable, this is, at first glance, favorable for LEDs. Importantly though, the halogen and CFL benchmarks were measured for the extent of their rated life. By the end of the study period—which corresponds to only about 30% of most of the LED lamps' rated lifetimes (and much less for some)—their average color shift was greater than that of the halogen and CFL lamps.

The average chromaticity maintenance profile for the LED lamps shows rapid change in the first 500 hours, followed by a fairly stable rate of change of 0.004 per 10,000 hours. If this rate of change continued, the average Δu'v' for the LED lamps would exceed the threshold of 0.007 before 25,000 hours of operation. This is a notable

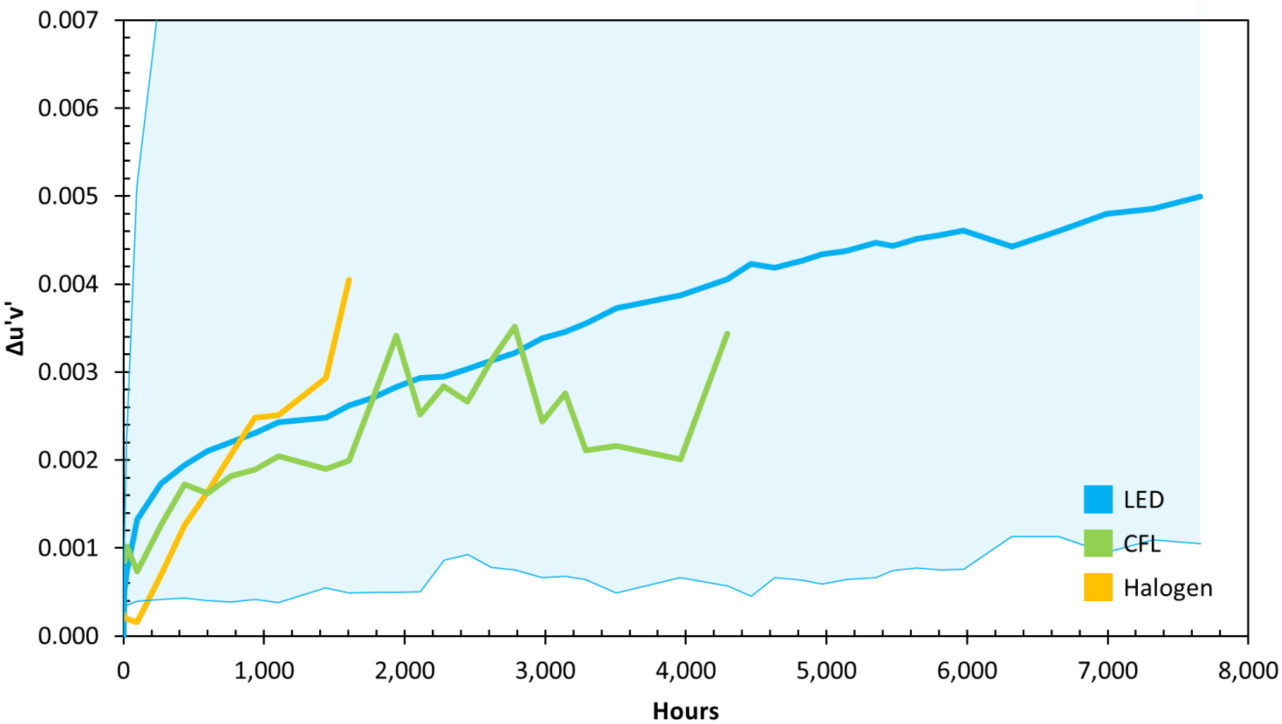


Figure 8. Average change in chromaticity for each source type, with the range of change shaded for the 15 LED lamp models. On average, the LED products demonstrated similar amounts of color shift compared to the other technologies *over the same time period*. There was very large variation, however, with some product types averaging much greater and much more rapid color shift than any of the conventional benchmark lamps.

weakness that should be addressed—and a limitation that may be influenced by the need to lower initial cost. Interestingly, the LED PAR38 lamps that were tested under near-identical conditions exhibited about half the average rate of color shift of the LED A lamps, even though they were approximately a year older. There are several possible contributors to this, but all of them are only speculative. First, the PAR38 form factor offers more volume, which may be used to improve thermal management; this is particularly relevant given that the average lumen output for the two groups was not overwhelmingly different (790 versus 870 lm, respectively). Additionally, there may be more surface area available for LED packages with PAR38 lamps, which may allow for different types of LED packages. Finally, LED A lamps generally require more complex optical systems to provide an omnidirectional distribution; this may limit options for thermal management, or it may simply require more materials in the optical path—which in turn are potential points of degradation.

As with average lumen maintenance for all LED lamps, the average chromaticity maintenance can be a misleading statistic. Figure 9 shows the average chromaticity maintenance for each lamp model, and the chromaticity maintenance of each sample (grouped by model) is available in Appendix C. Figure 9 shows that three of the LED lamps (13RT-03, 13RT-09, 13RT-11) exceeded the ENERGY STAR chromaticity maintenance criterion (0.007) in less than 6,000 hours. Only one of those products (13RT-09) was ENERGY STAR-qualified. Two of the three products (13RT-03, 13RT-09) also exhibited rapid lumen depreciation to less than L_{70} within the study period, while the third product failed to meet the ENERGY STAR 6,000-hour lumen maintenance threshold. In short, these three products were poor performers in terms of both lumen maintenance and chromaticity maintenance—although the two do not always degrade simultaneously.

The average performance characteristics shown in Figure 9 can be divided into three groups. One set of products exhibited minimal change in chromaticity over the duration of the study period, whereas another set

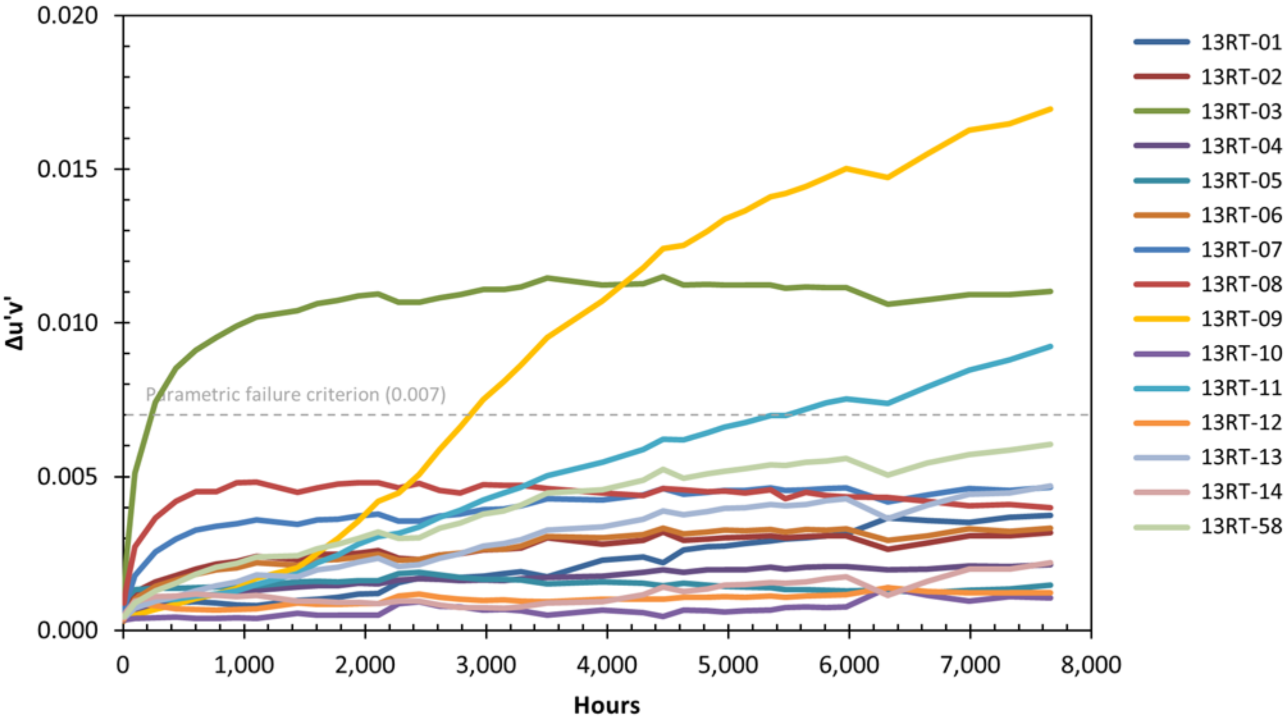


Figure 9. Average chromaticity maintenance for each LED model. Some of the LED products exhibited rapid color shift, while others maintained exceptionally consistent chromaticity.

exhibited relatively consistent change in chromaticity. The third group demonstrated rapid change over the first 1,000 hours, with little to no change thereafter. The lamps exceeding the parametric failure criterion fell into both of the latter two categories. The individual causes of these performance characteristics are indeterminable at this time, although they may be related to changes in optical systems or changes in LED package emissions.

Comparing Figures 5 and 9 provides some insight into the relationship between lumen maintenance and chromaticity maintenance. For example, product 13RT-03 shows two phases of lumen depreciation: the first phase corresponds to the rapid change in color, with the second phase corresponding to a period of steady color (and an approximately constant rate of lumen depreciation). A similar trend can be seen for product 13RT-07, but with only the initial color change being associated with reduced output, followed by steady output. These two products exemplify two potential mechanisms for lumen depreciation. The first mechanism is a change in color, which may be related to the LED package or other materials in the optical path; and the second mechanism is change in the electrical components (i.e., the driver). Changes to the driver are less likely to lead to color shift. Overall, there was a fairly strong correlation between lumen depreciation and color shift, as shown in Figure 10 (R^2 = 0.76). However, the correlation is heavily influenced by the two outlier points, and the sample size is relatively small.

Figure 11 shows the range in chromaticity maintenance for the 10 samples of each model. Many of the products had modest performance differences similar to those observed in the benchmark lamps, but two products (13RT-09, 13RT-11) had very high variation. For 13RT-09, the range was due to one product that was inconsistent with the remaining nine products; whereas for 13RT-11, the samples were evenly spread throughout the range. Either of these situations could be problematic in a real installation. Consistent shift, even if it is substantial, may be less noticeable. The difference between these two situations may be apparent in

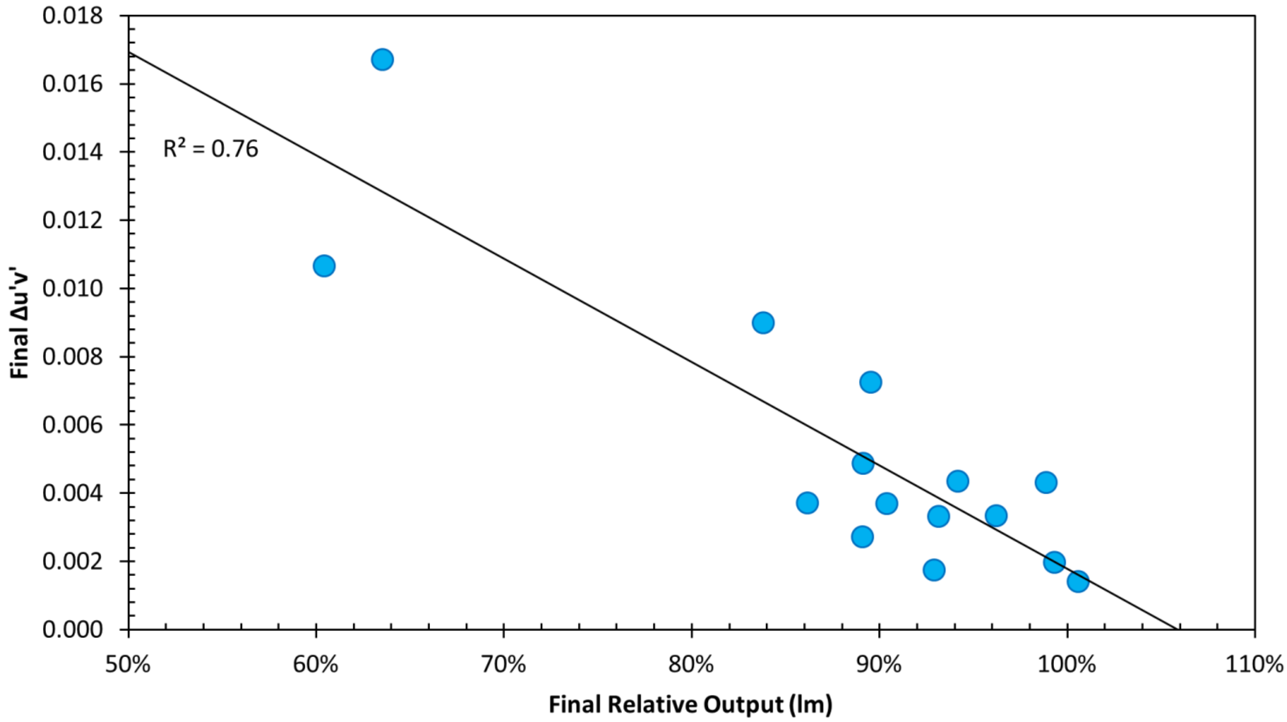


Figure 10. Final average color shift versus final average lumen maintenance. The correlation indicates that the two types of degradation tend to occur simultaneously (but not always). The R^2 without the outliers is 0.26.

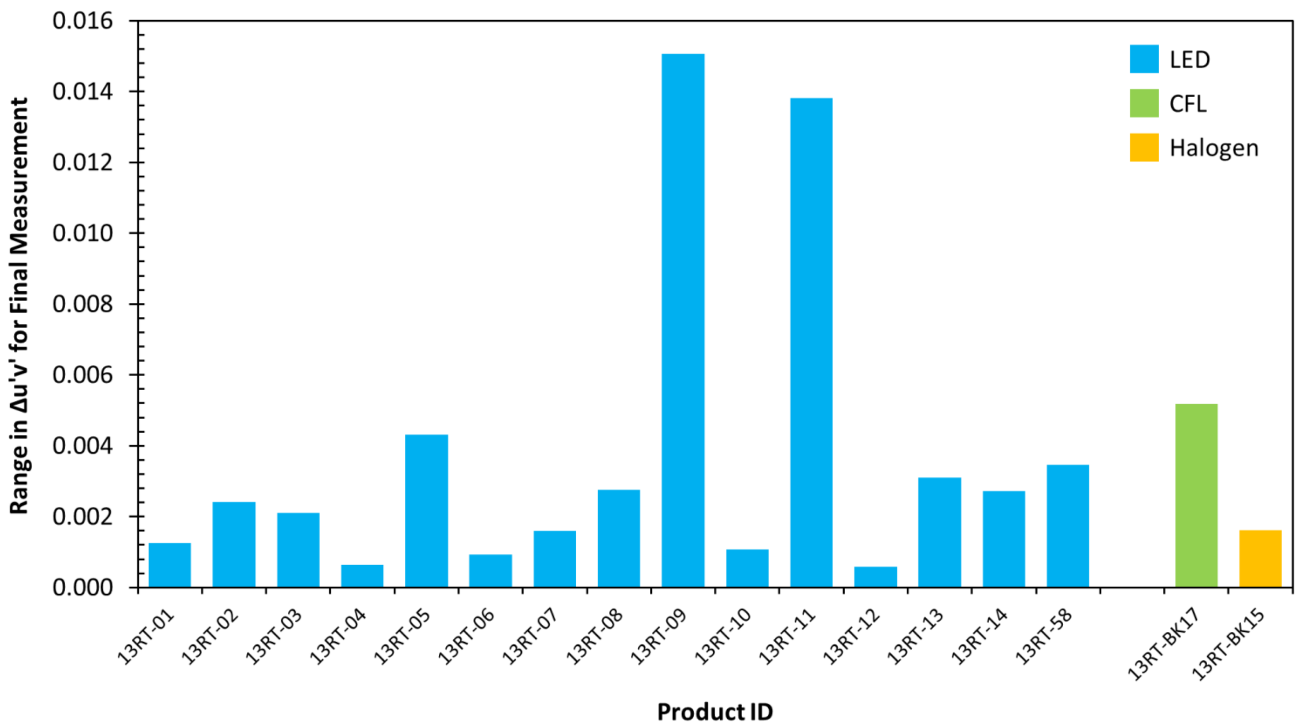


Figure 11. Range in the final measured Δu'v' for the 10 samples of each product. For the benchmark products, the variation is shown for the last measurement point where all samples were operational. The products with the largest variation tended to also have large variation in lumen maintenance, but not always.

manufacturer warranties, some of which only state that the lamps will remain consistent over time, rather than stating that the whole group will not shift.

The most appropriate measure for characterizing the magnitude of color shift is Δu'v', but it does not indicate the direction of the shift. Figure 12 shows plots for the average CCT and D_{uv} of each LED lamp model over the course of the investigation. Unlike the PAR38 lamps previously tested by CALiPER, there did not appear to be a tendency for the A lamps to shift in a particular direction. The two lamps that shifted the most (13RT-03 and 13RT-09) increased CCT by about 300 K and 500 K, respectively, with little change in D_{uv}.

Comparison Between PAR38 and A Lamp Long-Term Testing Results

Long-term testing for the A lamps (described in this report) and the CALiPER Series 20 PAR38 lamps was conducted simultaneously in the two ALTA apparatuses—although the PAR38 lamps had a nine-month head start. Of the 15 LED models tested for this investigation (representing 14 manufacturers), 11 were also represented in the PAR38 study. A comparison of the results, shown in Tables 1 and 2, reveals a strong lack of correlation in performance between lamps from the same manufacturer. Of the seven A lamps that emitted less than 91.8% of their output at 6,000 hours, only one the PAR38 lamps having the same manufacturer also failed (CALiPER lamps 13RT-11[A lamp] and 12-64 [PAR38]). Likewise, there were two manufacturers with lamps in both studies, of which only the PAR38 lamp failed to meet the ENERGY STAR threshold at 6,000 hours, based on its rated lifetime; and there was no overlap in manufacturers for the lamps that exhibited a Δu'v' greater than 0.0007.

This trend may be a bit disconcerting, because it indicates that brand loyalty may be misplaced. At the same time, it is not necessarily unexpected. Many of the mechanisms leading to lumen depreciation and color shift occur at the component level. A manufacturer of integral LED lamps is likely to use components from different suppliers in different lamps. For example, the manufacturer's PAR38 design might include a chip-on-board LED package from manufacturer Y, whereas the A lamp might include high-power LEDs from manufacturer Z.

Even different models of the same lamp type (i.e., A lamp) from the same manufacturer may exhibit substantially different performance over time. This is exemplified by products 13RT-03 and 13RT-58, both of which were made by the same manufacturer. Without intensive investigation and breakdown of the lamps, it is not possible to further understand the differences in performance.

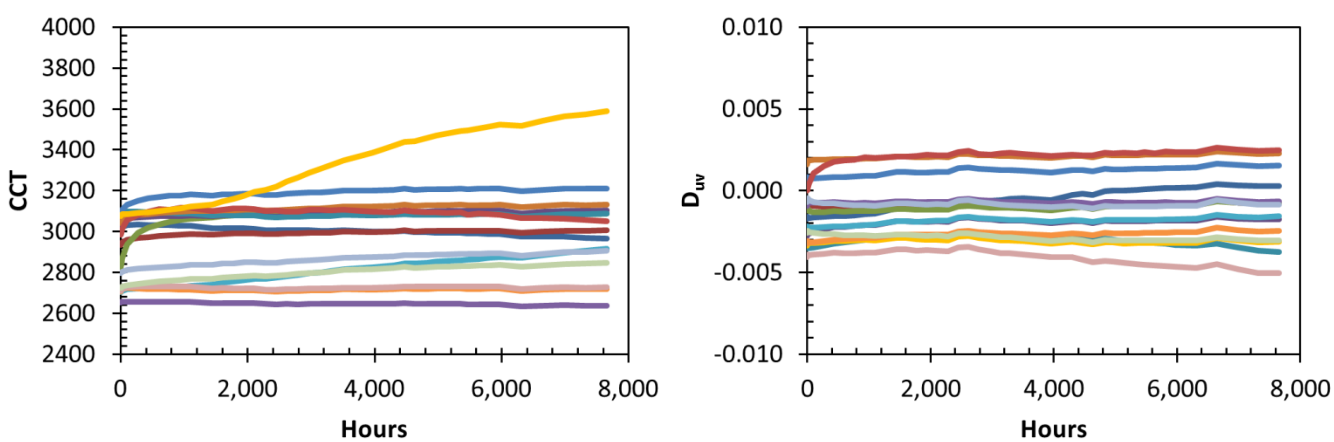


Figure 12. Average CCT and average D_{uv} for each of the LED product types over the course of the investigation. There was no consistent trend in the type of color shift experienced, although the products experiencing the most shift typically changed in D_{uv} rather than in CCT.

Table 1. Comparison of long-term lumen maintenance results for the A lamps and PAR38 lamps. There was little correlation in performance for lamps from the same manufacturers.

	Retail Lamps 3				CALiPER Series 20 PAR38			
Manufacturer	**Product ID**	**ENERGY STAR Threshold**	**Measured Value**	**Result**	**Product ID**	**ENERGY STAR Threshold**	**Measured Value**	**Result**
A	13RT-01	93.1%	93.2%		NA			
B	13RT-02	95.8%	94.5%	FAIL	NA			
C	13RT-03	91.8%	63.5%	FAIL	12-67	95.8%	101.2%	
D	13RT-04	91.8%	100.1%		12-65	95.8%	98.1%	
E	13RT-05	91.8%	93.6%		12-73	93.1%	97.6%	
F	13RT-06	91.8%	96.5%		12-75	95.8%	98.1%	
G	13RT-07	91.8%	93.9%		NA			
H	13RT-08	95.8%	99.8%		12-85	95.8%	92.0%	FAIL
I	13RT-09	91.8%	68.9%	FAIL	12-80	91.8%	100.0%	
J	13RT-10	91.8%	94.3%		12-140	91.8%	99.0%	
K	13RT-11	91.8%	86.2%	FAIL	12-64	95.8%	93.2%	FAIL
L	13RT-12	91.8%	100.8%		12-74	93.1%	89.2%	FAIL
M	13RT-13	91.8%	90.1%	FAIL	NA			
N	13RT-14	91.8%	90.1%	FAIL	12-72	91.8%	97.8%	
C	13RT-58	91.8%	90.2%	FAIL	12-67	95.8%	101.2%	

Table 2. Comparison of long-term chromaticity maintenance results for the A lamps and PAR38 lamps. There was little correlation in performance for lamps from the same manufacturers.

	Retail Lamps 3			CALiPER Series 20 PAR38		
Manufacturer	**Product ID**	**Measured Value**	**Result**	**Product ID**	**Measured Value**	**Result**
A	13RT-01	0.0038		NA		
B	13RT-02	0.0032		NA		
C	13RT-03	0.0110	FAIL	12-67	0.0012	
D	13RT-04	0.0021		12-65	0.0019	
E	13RT-05	0.0015		12-73	0.0050	
F	13RT-06	0.0033		12-75	0.0011	
G	13RT-07	0.0047		NA		
H	13RT-08	0.0040		12-85	0.0152	FAIL
I	13RT-09	0.0170	FAIL	12-80	0.0006	
J	13RT-10	0.0011		12-140	0.0028	
K	13RT-11	0.0092	FAIL	12-64	0.0019	
L	13RT-12	0.0012		12-74	0.0097	FAIL
M	13RT-13	0.0047		NA		
N	13RT-14	0.0022		12-72	0.0020	
C	13RT-58	0.0061		12-67	0.0012	

5 Conclusions

The lumen depreciation and color shift of 17 different A lamps (15 LED, 1 CFL, 1 halogen) were monitored in the ALTA for more than 7,500 hours. Ten samples of each lamp model were tested, with measurements recorded on a weekly basis. The lamps were operated continuously at an ambient temperature of 45°C.

On average, the lumen maintenance of the LED lamps monitored in the ALTA was better than for either of the benchmark lamps, but there was considerable variation from lamp model to lamp model. While three lamp models had average lumen maintenance above 99% at the end of the study period, two products had average lumen maintenance below 65%, constituting a parametric failure. These two products, along with a third, also exhibited substantial color shift, another form of parametric failure. Such early failures are a notable concern for the reputation of LED technology, and there is little way for consumers to know or predict that such degradation will occur. In fact, some manufacturers had lamps perform poorly in this study but perform well in a separate study of PAR38 lamps that was also recently published.

Beyond the three observed parametric failures (in less than 7,500 hours), almost half of the products failed to meet early-life thresholds for lumen maintenance, which were borrowed from ENERGY STAR specifications. That is, the lumen maintenance was sufficiently low at 6,000 hours that seven of the products were unlikely to have lumen maintenance above 70% at their rated lifetime (which was usually 25,000 hours).

Given the methods used for this investigation, the results should not be interpreted as indicative of a lamp's performance in all environments. Likewise, these results are not directly relatable to manufacturer lifetime claims. This report is best used to understand the variation in LED product performance, compare the robustness of LED lamps and benchmark conventional lamps, and understand the characteristics of lumen and chromaticity change. A key takeaway is that the long-term performance of LED lamps can vary greatly from model to model (i.e., the technology is not homogeneous), although the lamp-to-lamp consistency within a given model is relatively good. Further, operation of LED lamps in an enclosed luminaire (or in other settings involving high ambient temperatures) can induce parametric failure of LEDs well before the end of their rated lifetime; manufacturer warnings about such conditions should be followed if performance degradation is unacceptable.

Appendix A: Lamp Identification and Rated Lifetime

Table A1. Identifying information for the lamps included in the CALiPER RRL3 long-term testing investigation. For additional product performance information, see CALiPER Retail Replacement Lamps Study 3. ENERGY STAR qualification is based on the status at the time of purchase.

ID	Brand	Model	Rated Lifetime (hours)	ENERGY STAR Qualified
13RT-01	3M	RRA19B3	27,500	
13RT-02	Bulbrite	LED12A19/0/30K/D	50,000	Yes
13RT-03	Cree	BA19-08027OMF-12DE26-1U100	25,000	
13RT-04	EcoSmart	ECS A19 WW 60WE 120	25,000	
13RT-05	Feit Electric	A19/OM800/LED	25,000	Yes
13RT-06	GE Lighting	LED13DA19/830, 65386	25,000	Yes
13RT-07	Insignia	NS-LED60FB	25,000	Yes
13RT-08	LEDnovation	LEDH-A19-60-1-27D-IO-E	50,000	Yes
13RT-09	MaxLite	SKBO10DLED30	25,000	Yes
13RT-10	Philips Lighting	BC11A19/AMB/2700 DIM120V	25,000	Yes
13RT-11	Great Value	GVRLAS11W27KND	25,000	
13RT-12	Satco	LED/9.8W/2700K/120V	25,000	
13RT-13	Switch	Switch 60/ A22141FA1-R	25,000	
13RT-14	OSRAM Sylvania	LED12A19/DIM/O/827/HVP/	25,000	Yes
13RT-58	Cree	BA19-08027OMN-12DE26-1U100	25,000	
BK13RT-15	Philips Lighting	EL/mdT2 13W 6/4 (819798)	12,045	Yes
BK13RT-17	Philips Lighting	43A19/EV 120V 6/4	1,000	

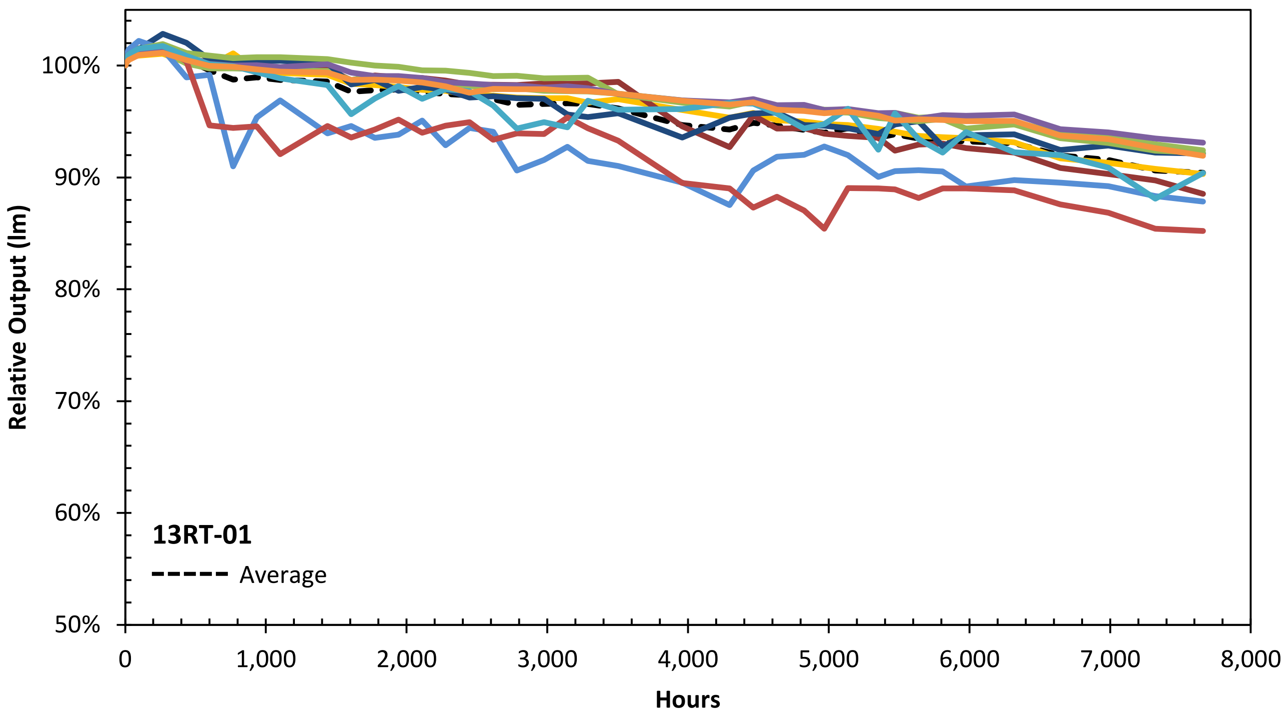
Appendix B: ALTA Installation Matrix

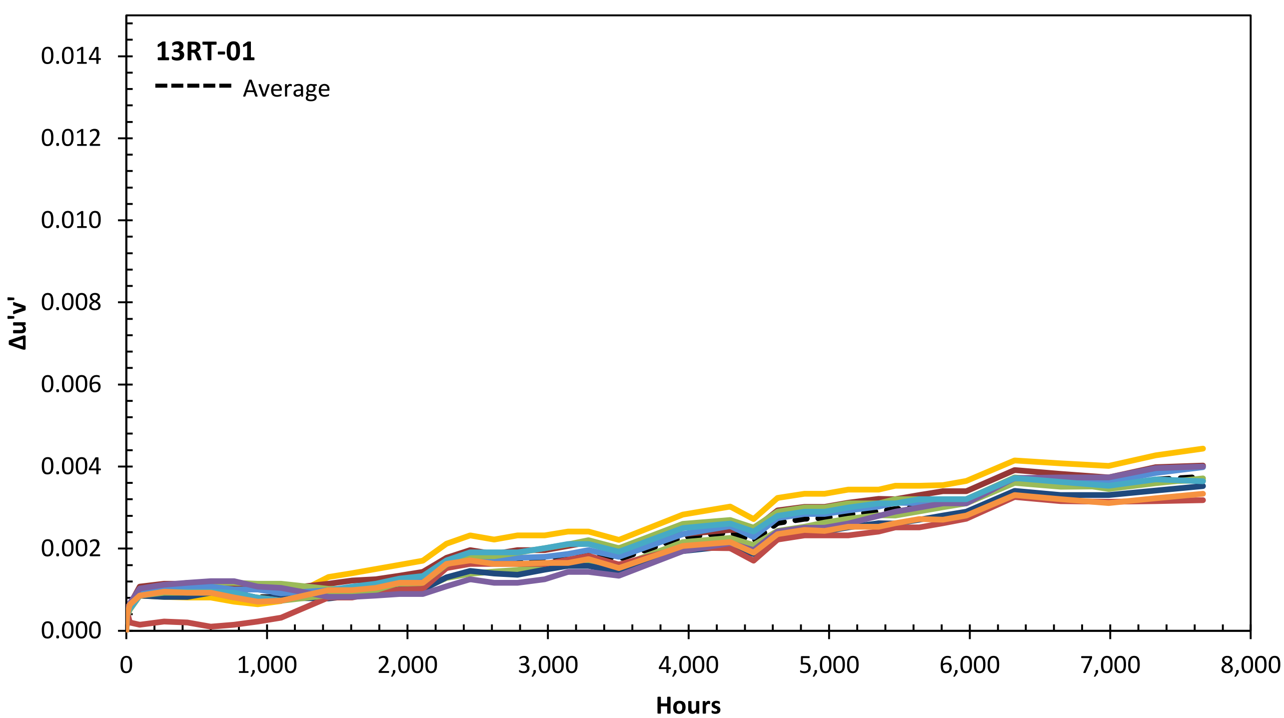
Table B1. Installation matrix for long-term testing of the A lamps from CALiPER Retail Lamps Study 3. The apparatus was simultaneously used to test a subsample of the L Prize lamps.

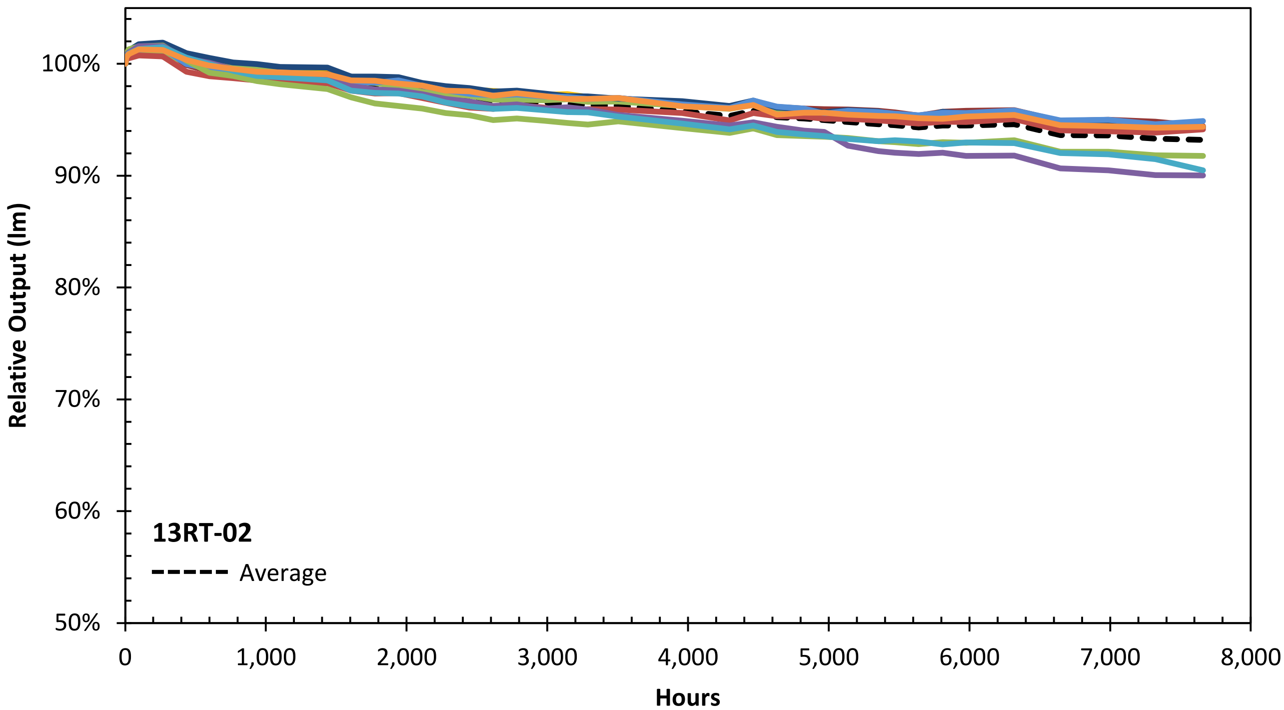
Rest	LP-487	LP-976	RT58	RT58	RT5	RT5	BKRT-17	BKRT-17	BKRT-17	BKRT-17	BKRT-17	BKRT-17	BKRT-17	BKRT-17	BKRT-17	BKRT-17
Cal	LP-1917	LP-1448	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-967	LP-657	LP-1106	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-456	LP-1997	LP-1667	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-192	LP-1419	LP-1893	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-1403	LP-885	LP-890	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-369	LP-1757	LP-863	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-1330	LP-641	LP-982	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-1696	LP-1360	LP-1897	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-1993	LP-587	LP-1632	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-492	LP-1645	RT58	RT1	RT2	RT3	RT4	RT5	RT6	RT7	RT8	RT9	RT10	RT11	RT12	RT13	RT14
LP-1790	LP-877	RT58	RT58	RT58	RT58	RT58	BKRT-15	BKRT-15	BKRT-15	BKRT-15	BKRT-15	BKRT-15	BKRT-15	BKRT-15	BKRT-15	BKRT-15

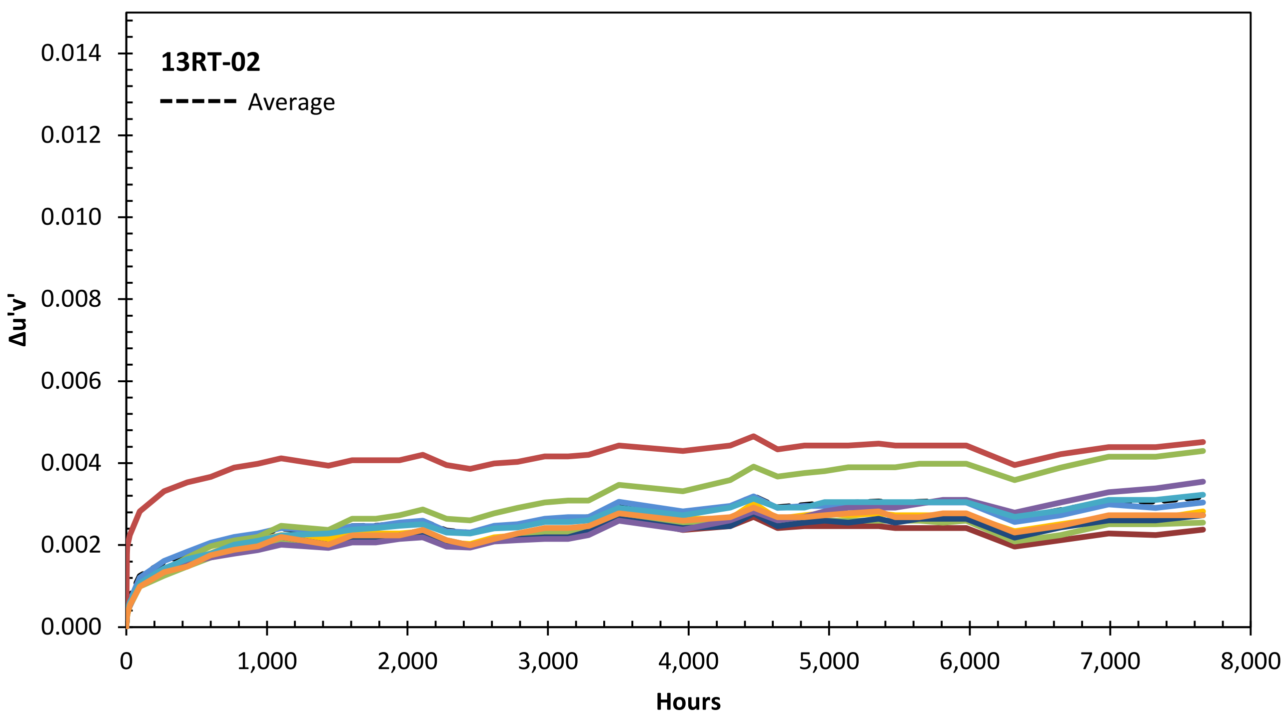
Appendix C: Lamp Model Lumen and Chromaticity Plots

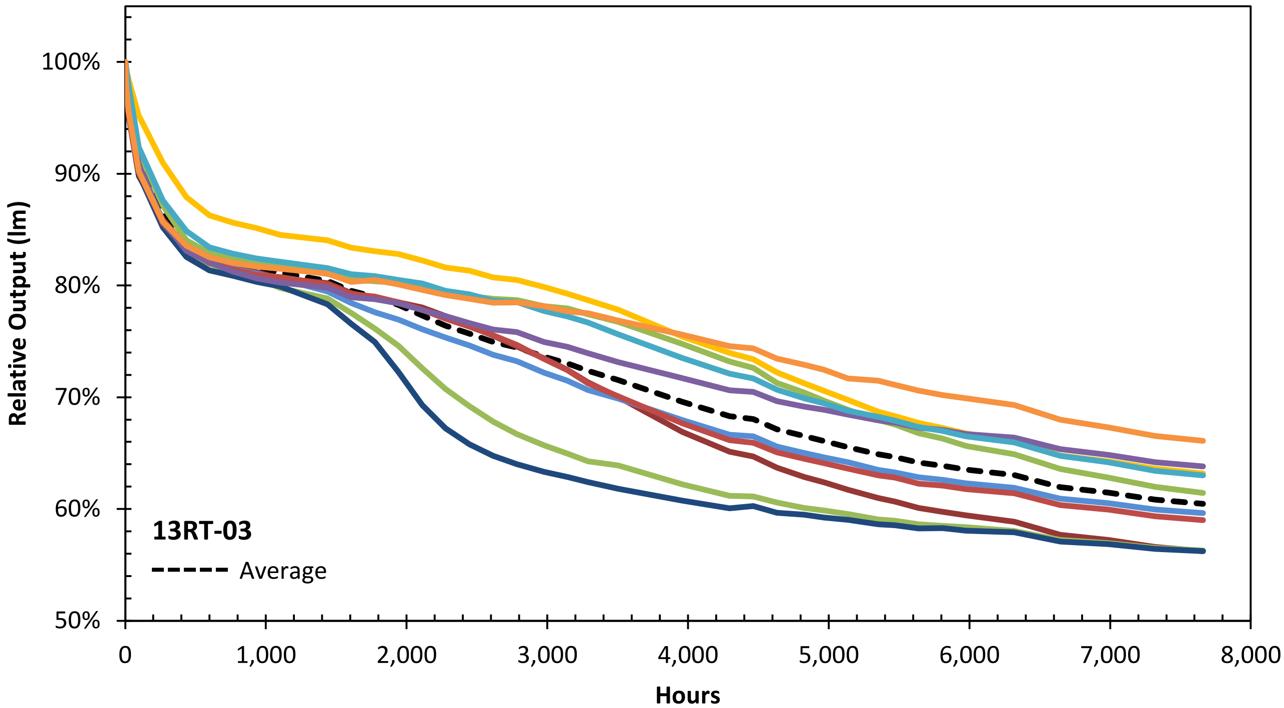
The plots in this appendix show the lumen maintenance and chromaticity maintenance for each lamp sample. Each page shows the results for one lamp model.

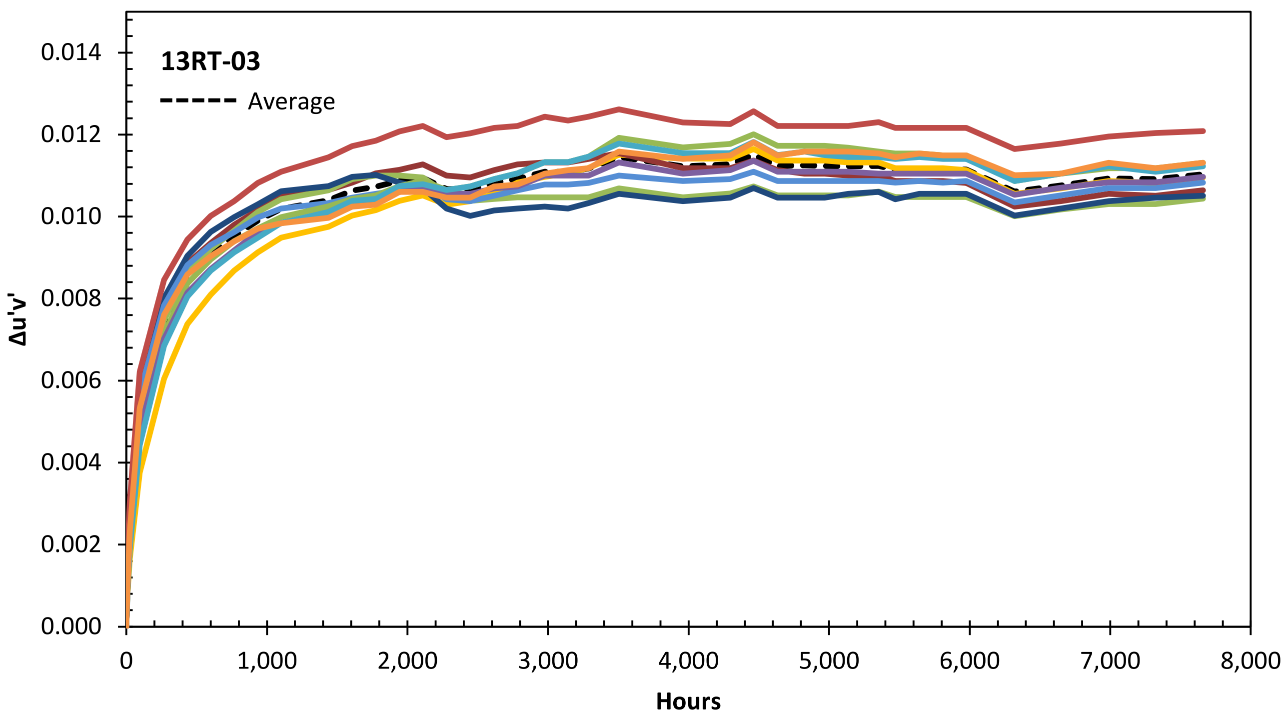





13RT-02
Average
Relative Output (lm)
100%
90%
80%
70%
60%
50%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours


13RT-02
Average
Δu'v'
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours


100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-03
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours


0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
13RT-03
Average
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1,000
2,000
3,000
4,000
5,000
6,000
7,000
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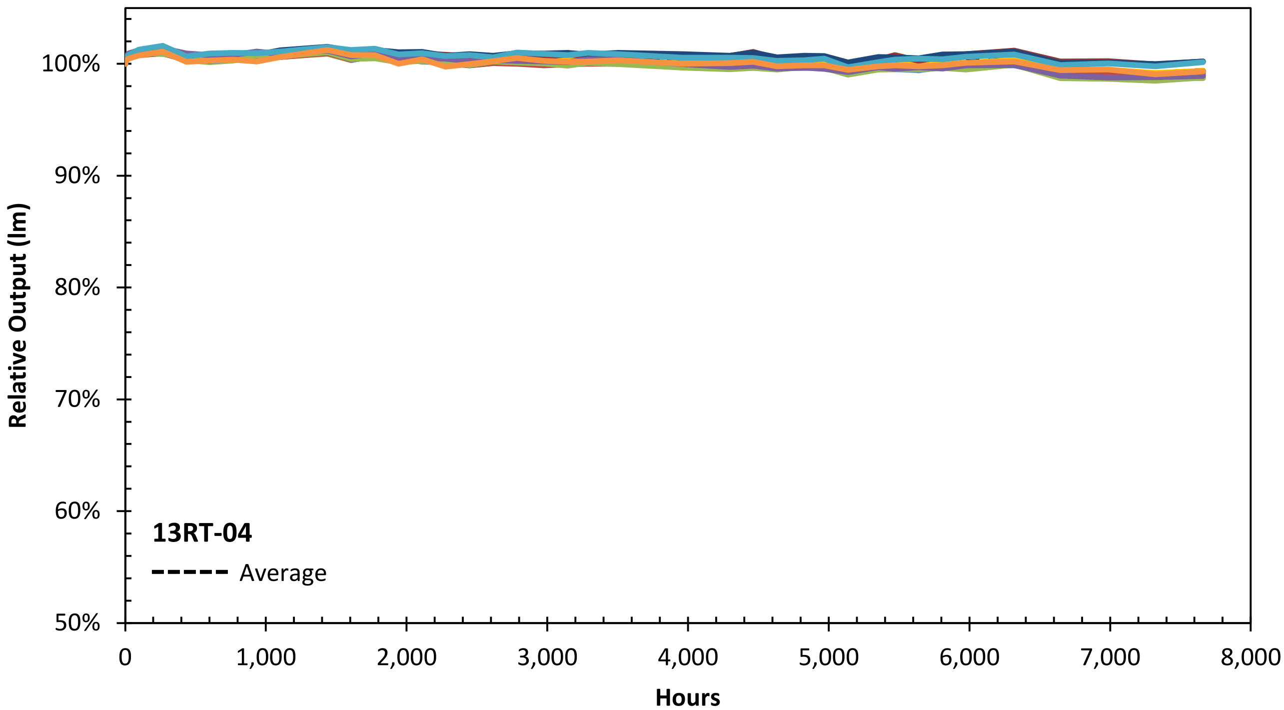
Hours



100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-04
Average
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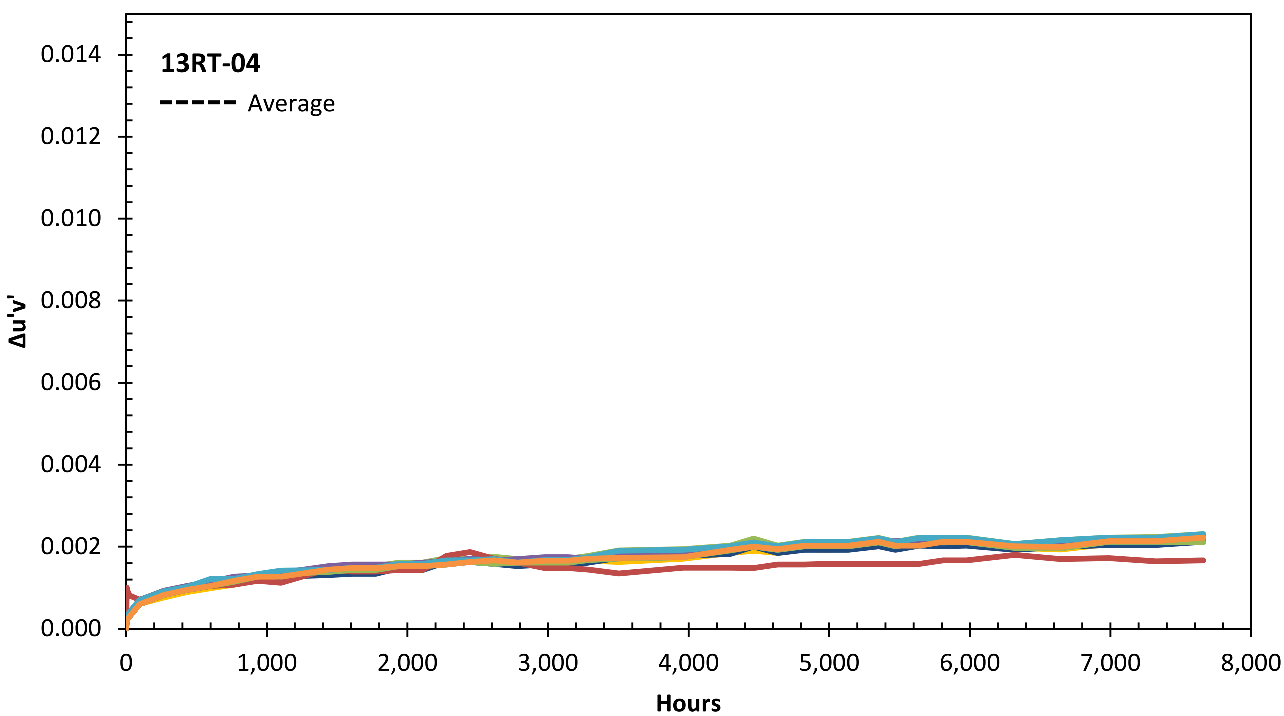
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
13RT-04
Average
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3,000
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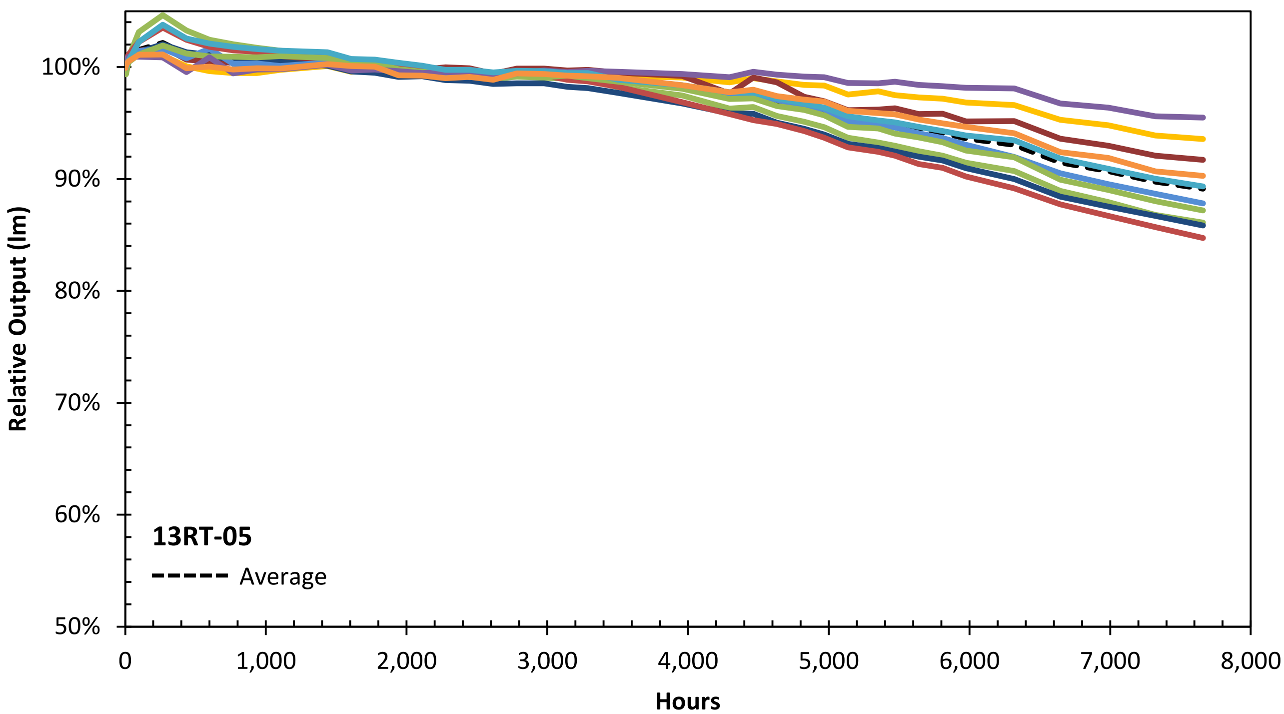
6,000
7,000
8,000
Hours



100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-05
Average
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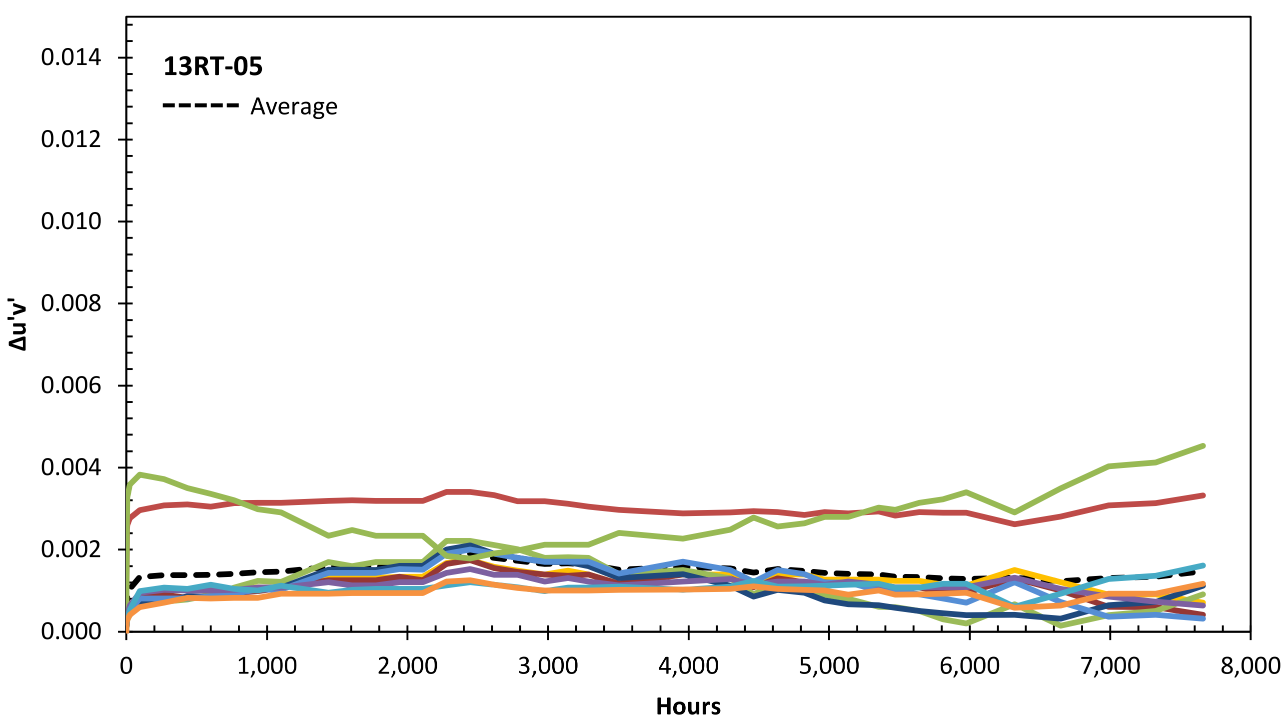
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



0.014
0.012
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0.008
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0.002
0.000
Δu'v'
13RT-05
Average
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7,000
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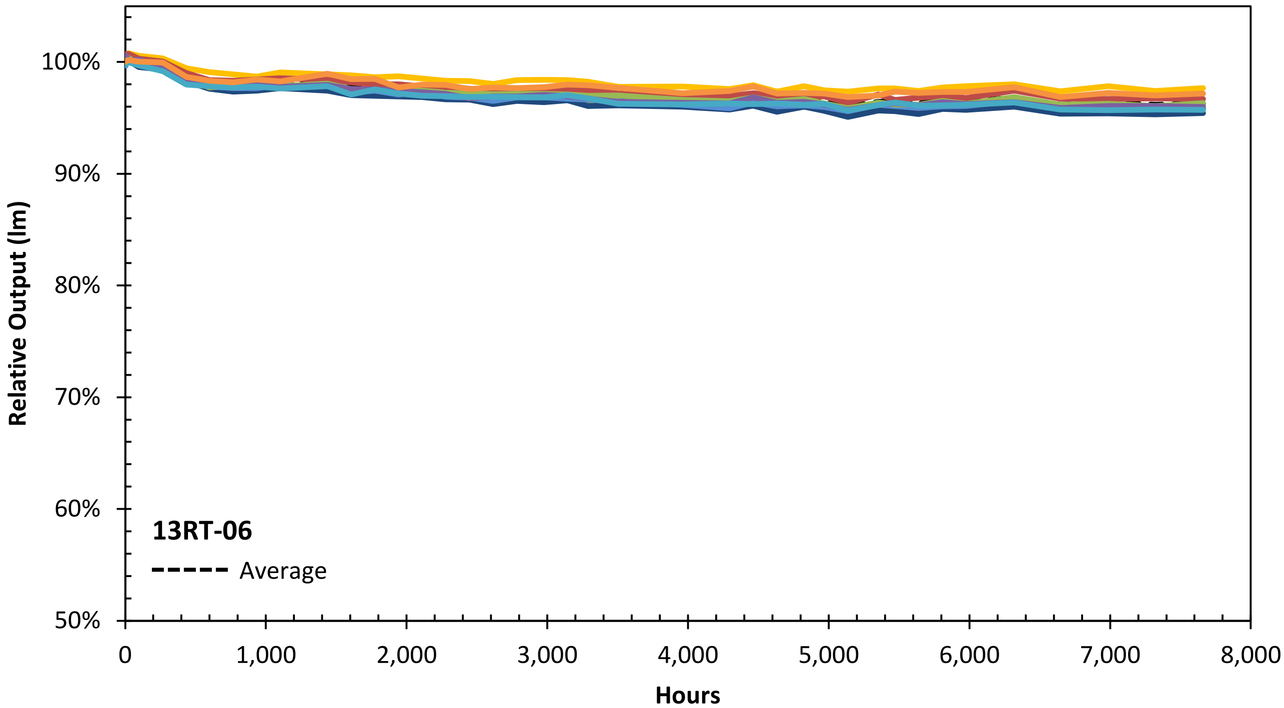
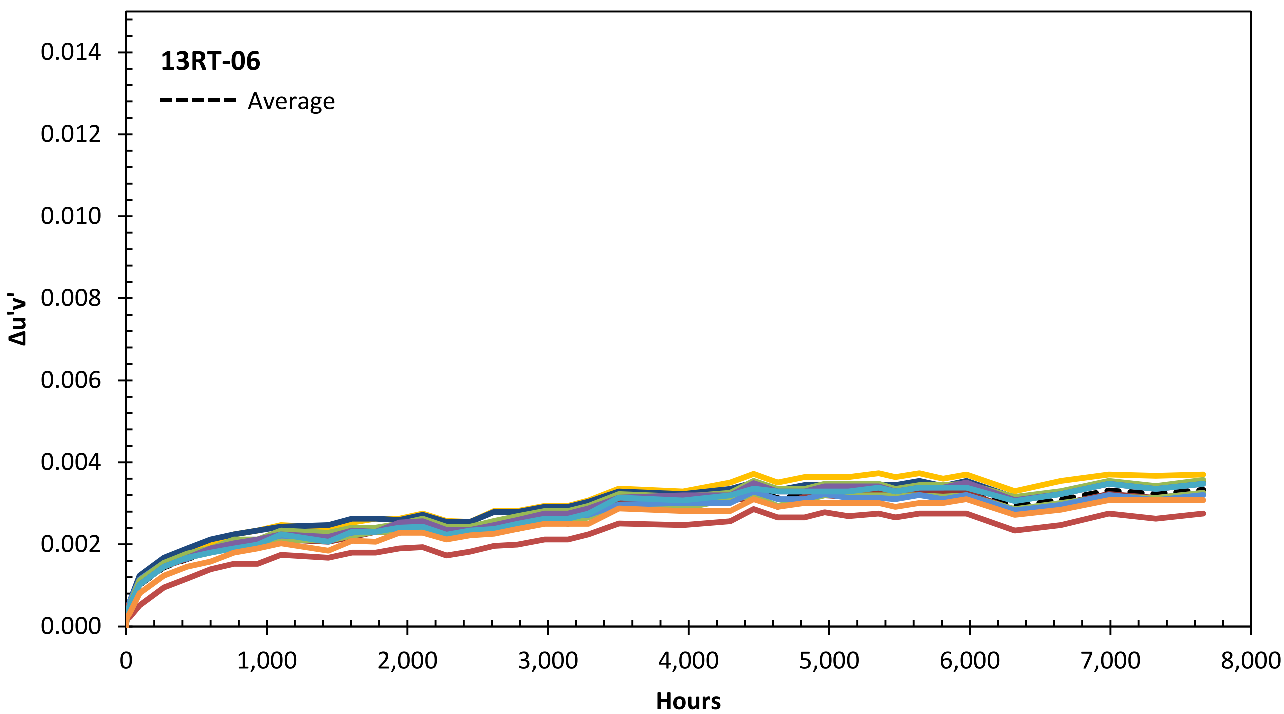
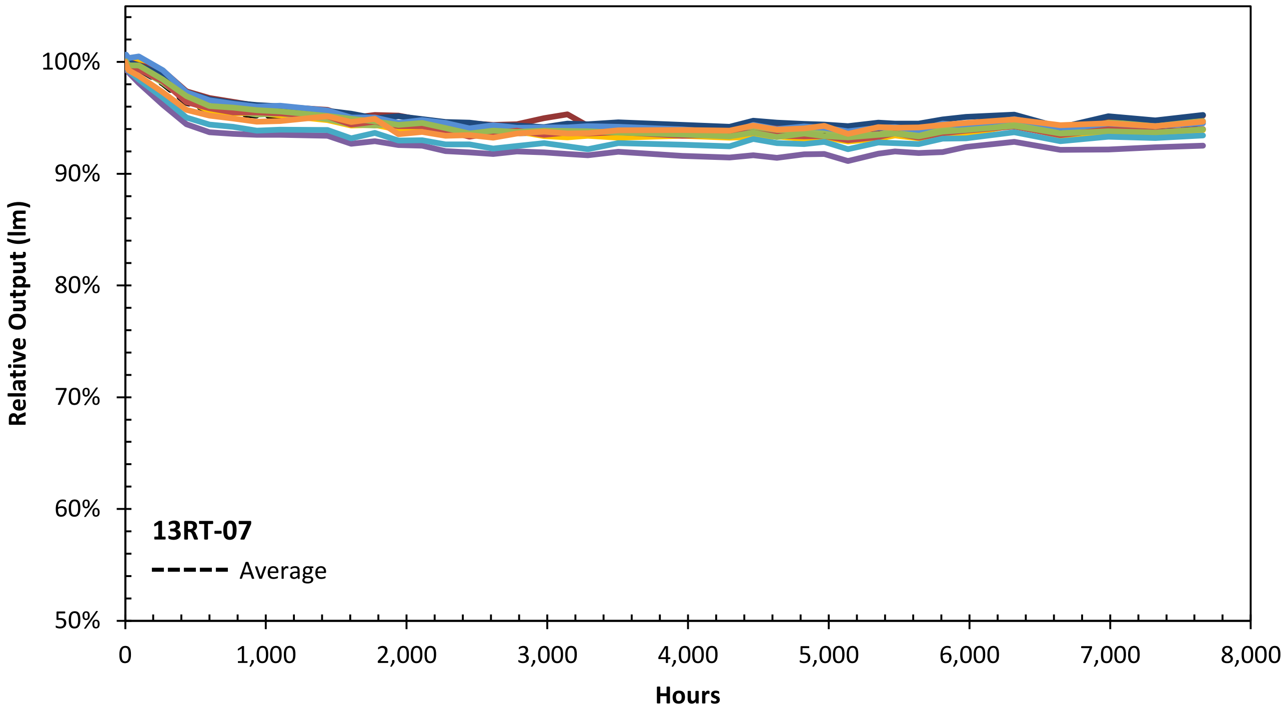
Hours



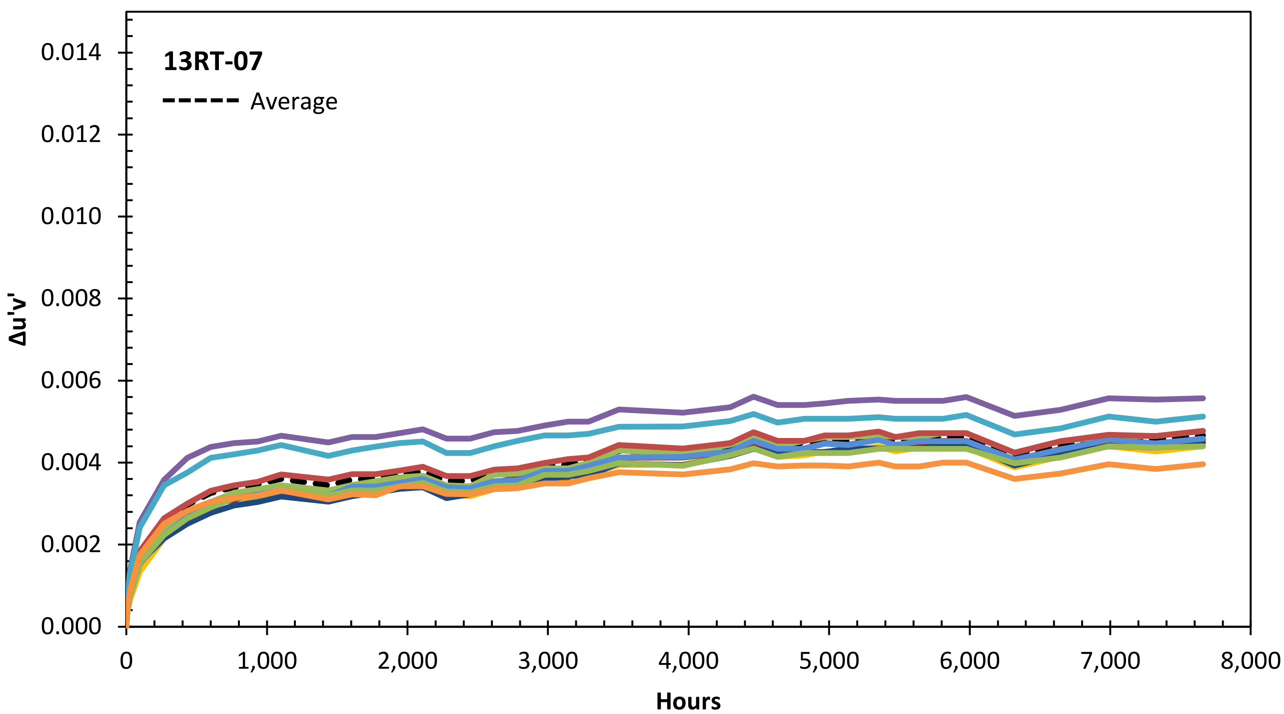
100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-06
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



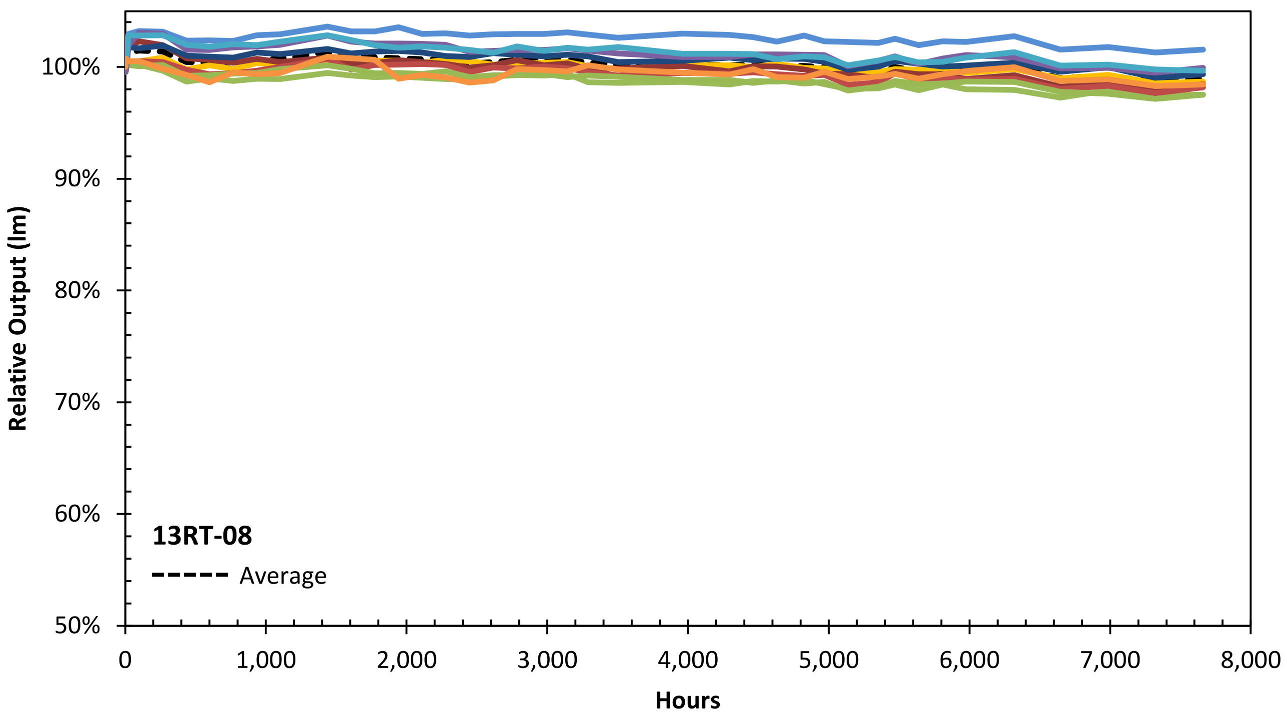
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
13RT-06
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

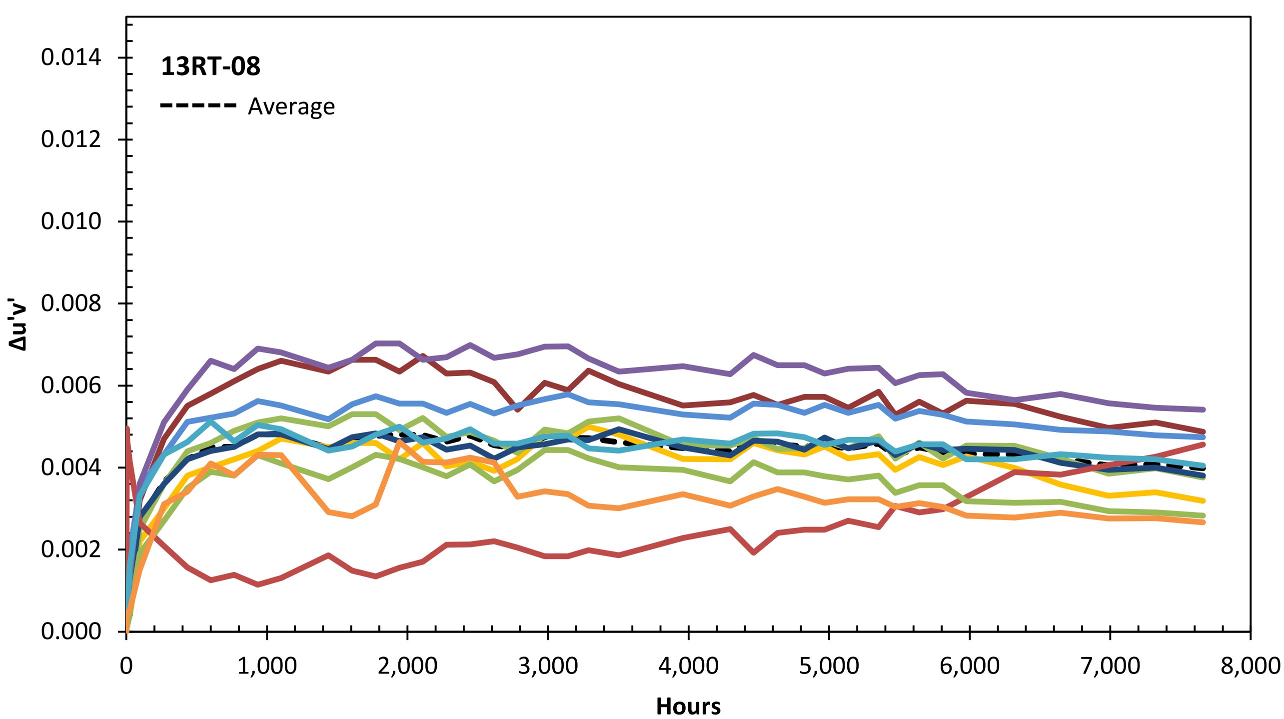


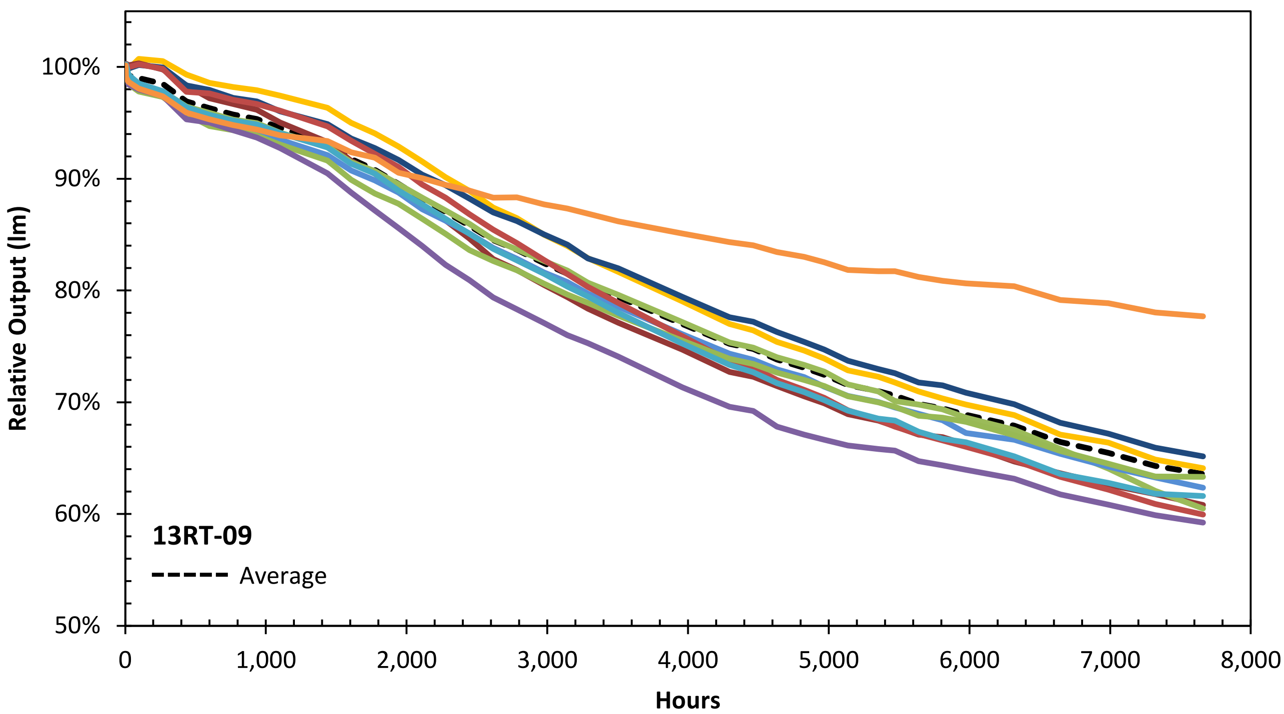
100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-07
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

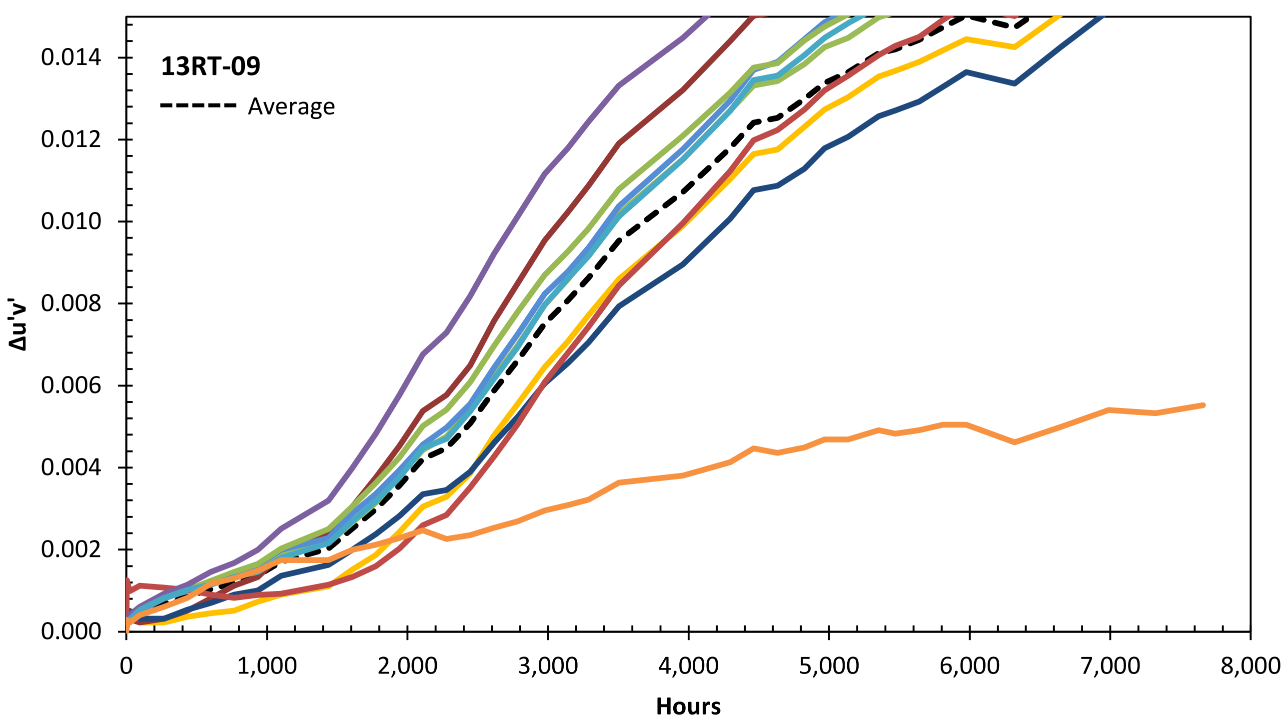


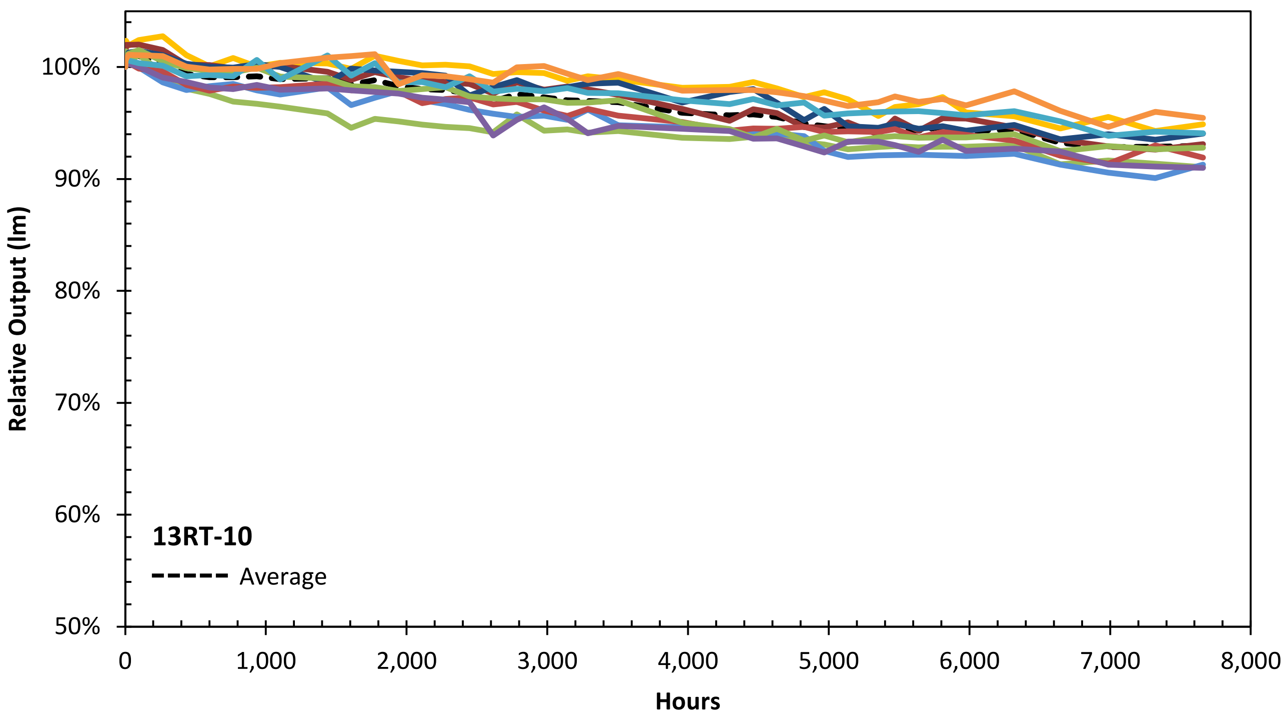
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
13RT-07
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours


13RT-08
Average
Relative Output (lm)
100%
90%
80%
70%
60%
50%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

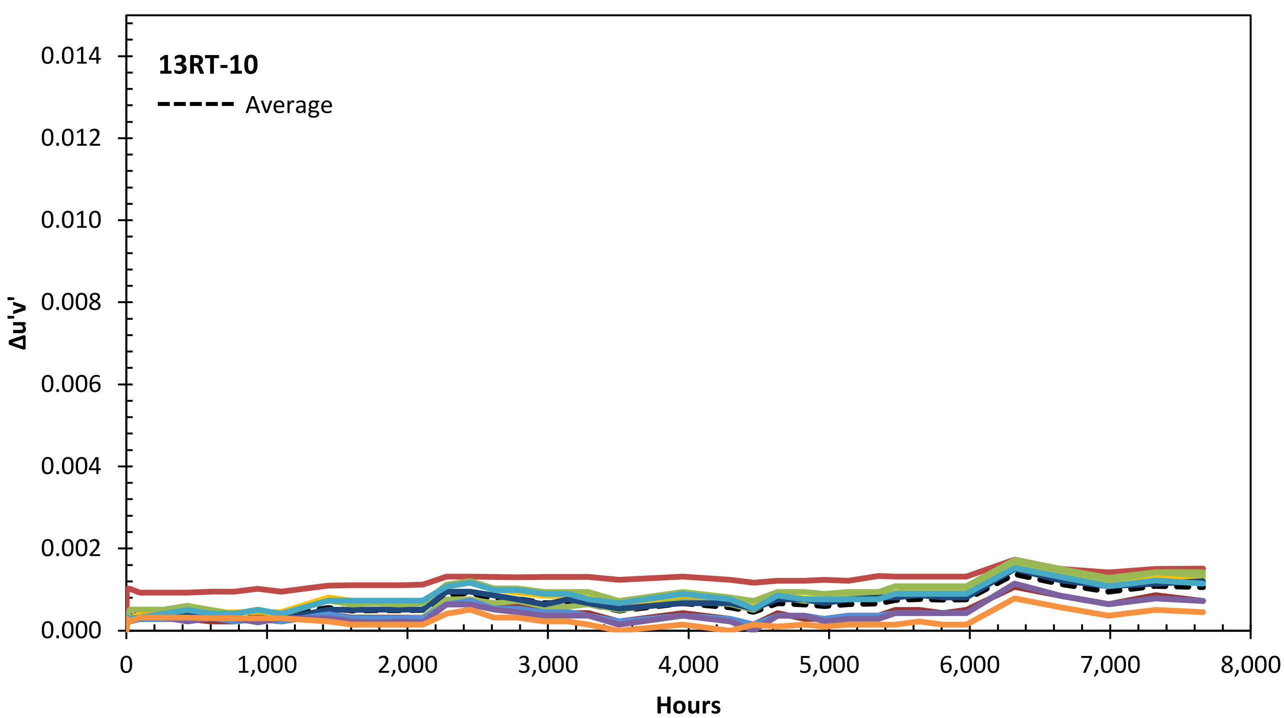

13RT-08
Average
Δu'v'
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours


100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-09
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

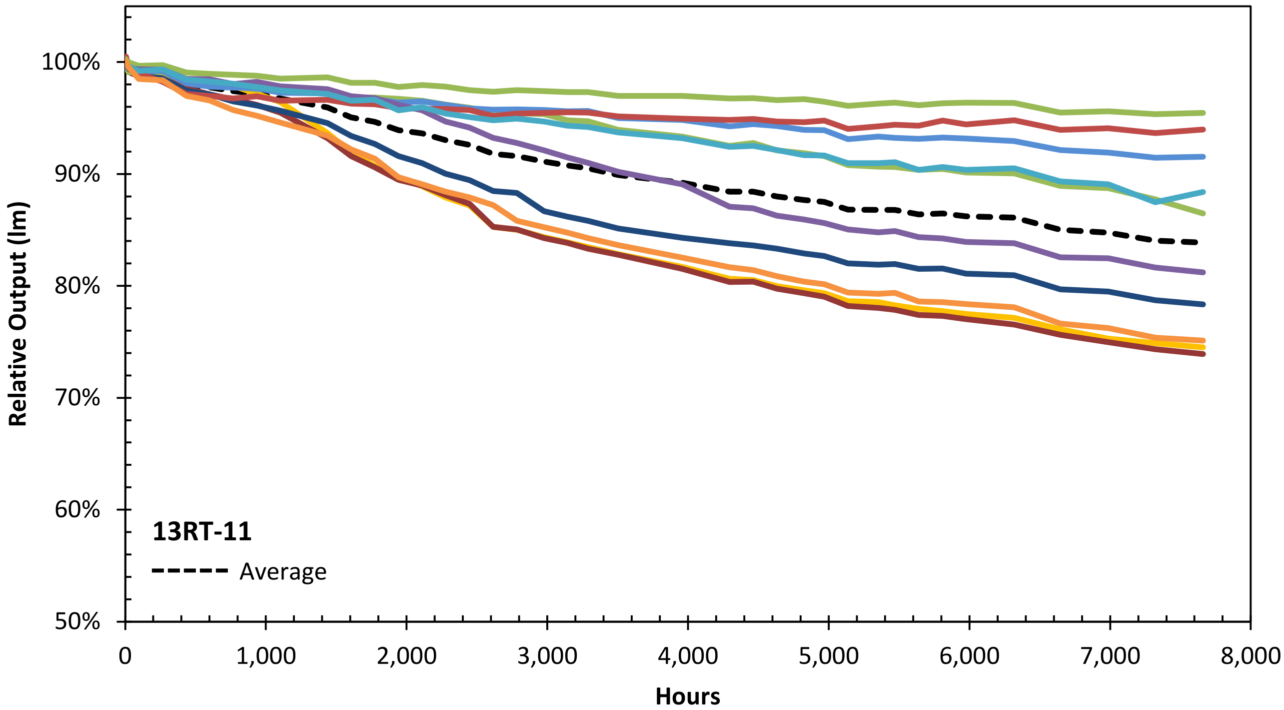

0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
13RT-09
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



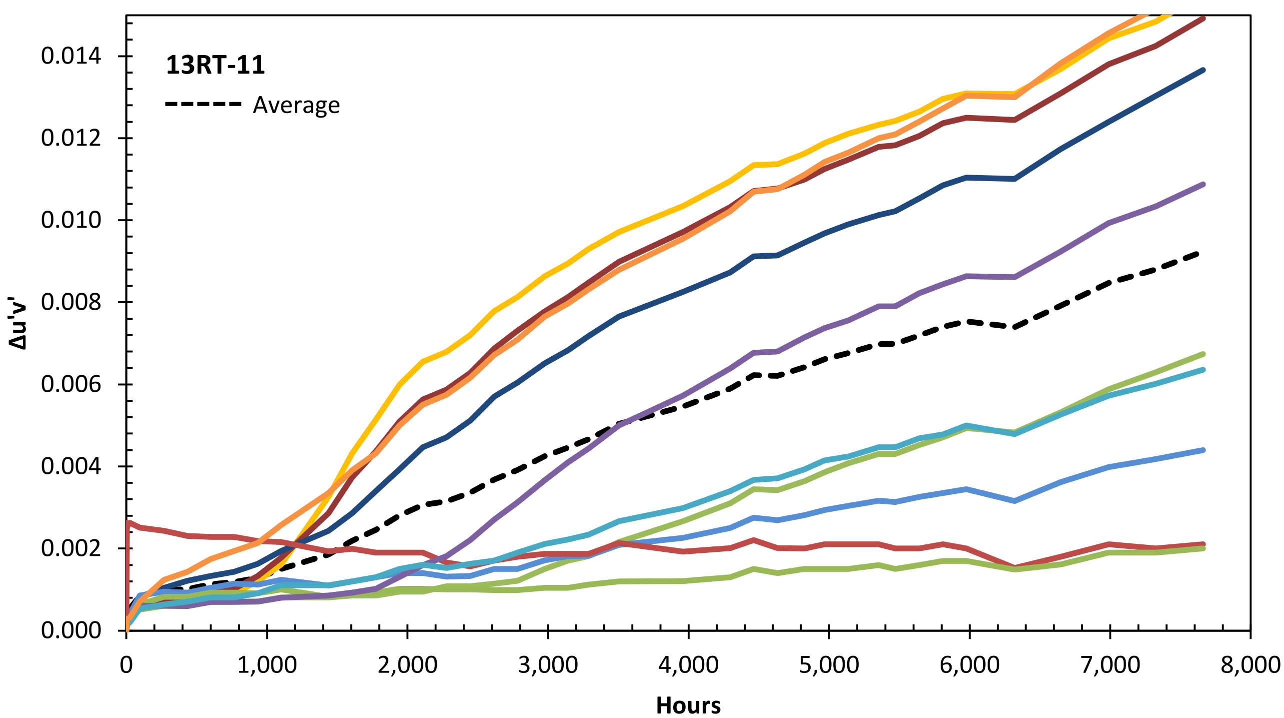
13RT-10
Average
Relative Output (lm)
100%
90%
80%
70%
60%
50%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



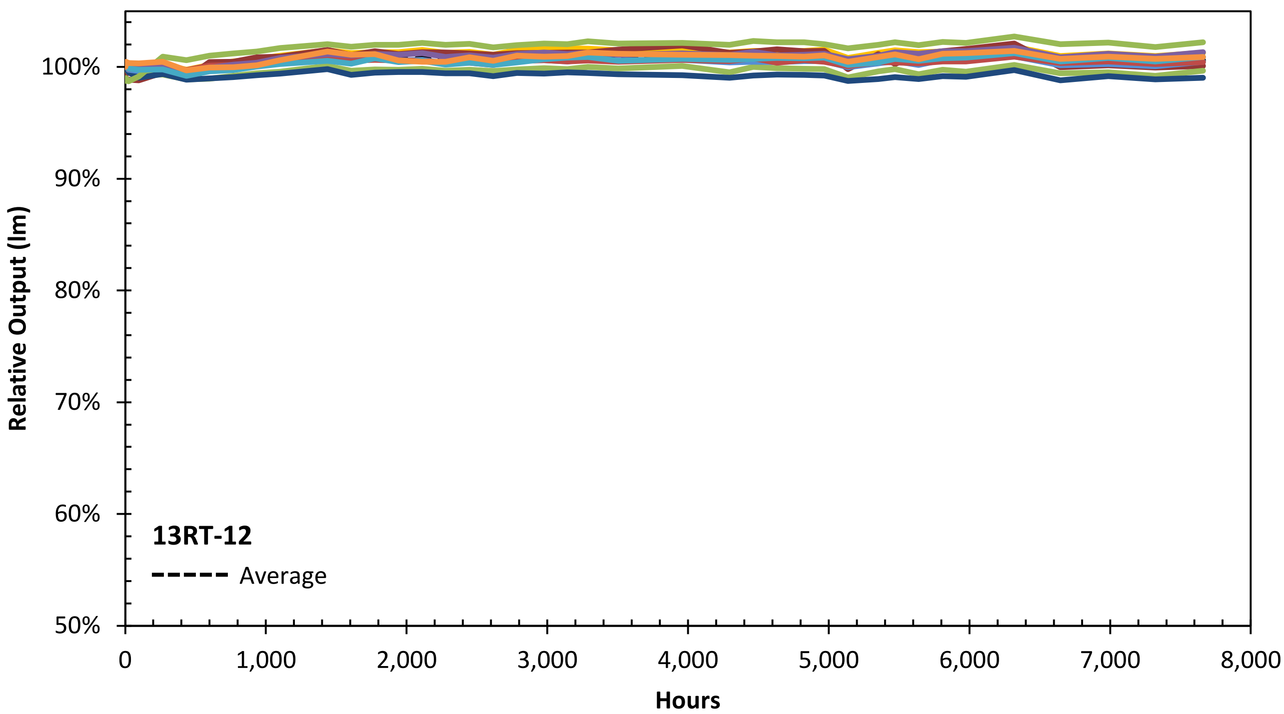
13RT-10
Average
Δu'v'
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

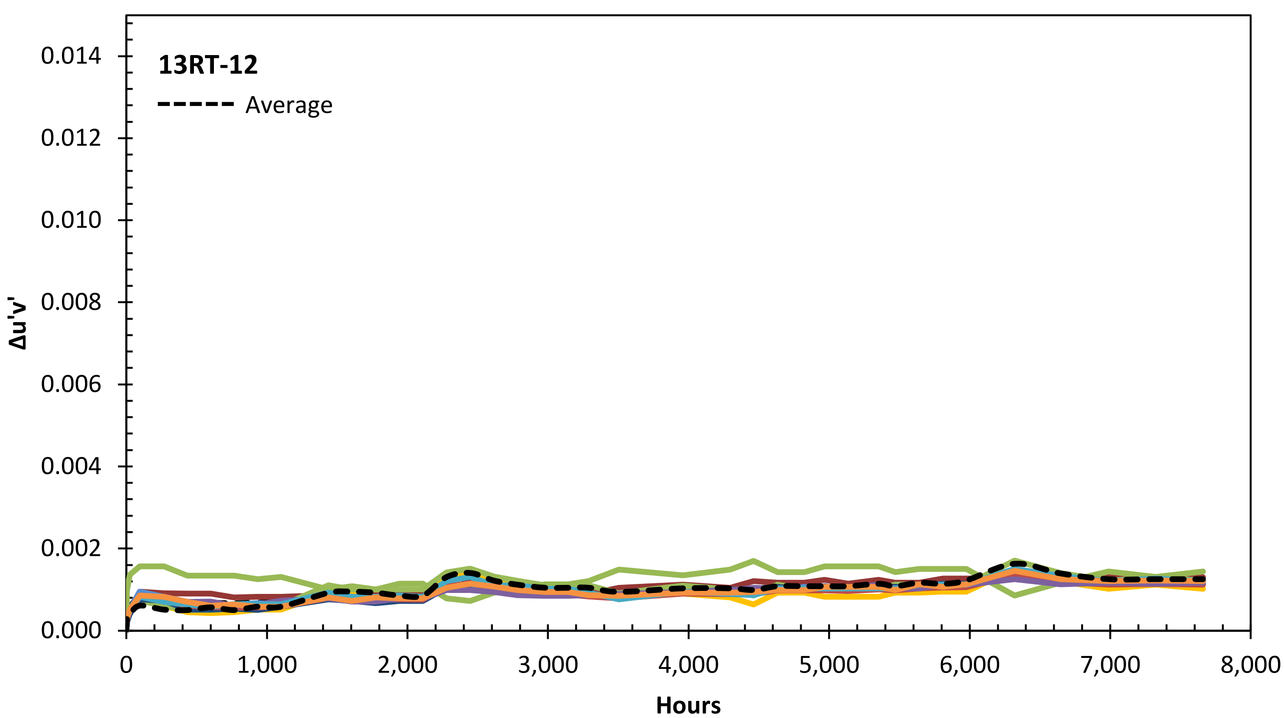


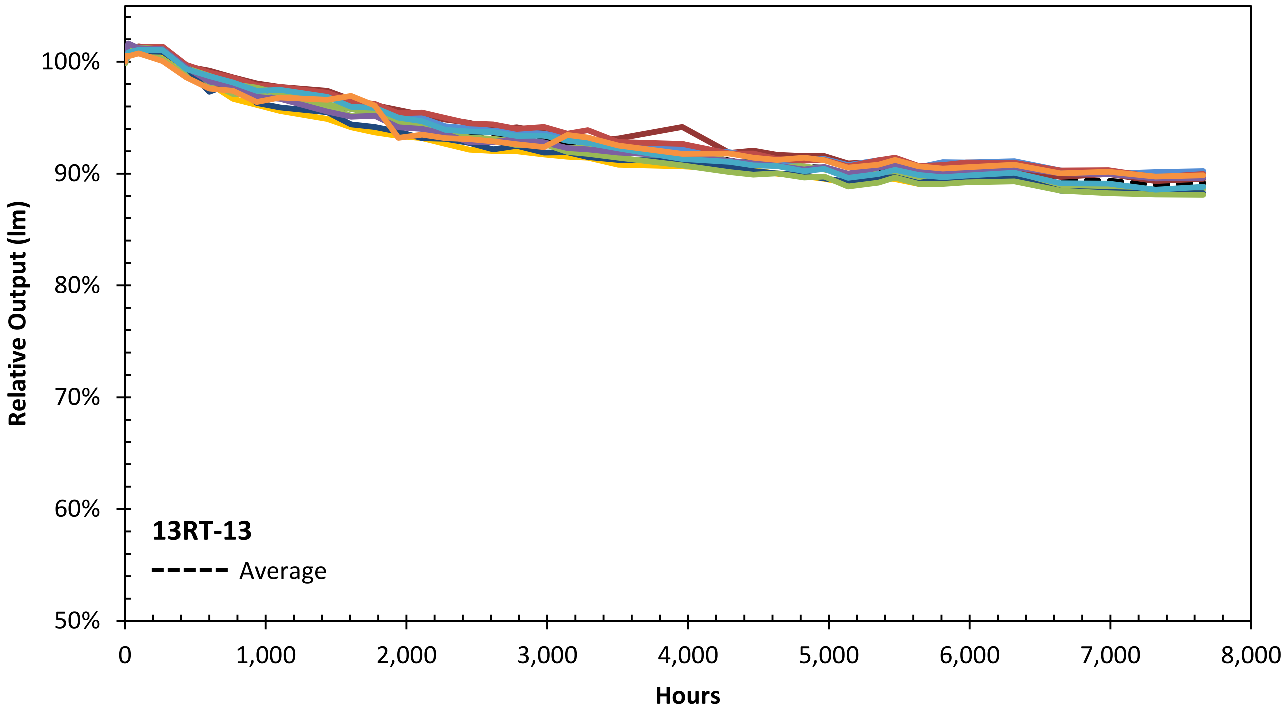
13RT-11
Average
Relative Output (lm)
100%
90%
80%
70%
60%
50%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

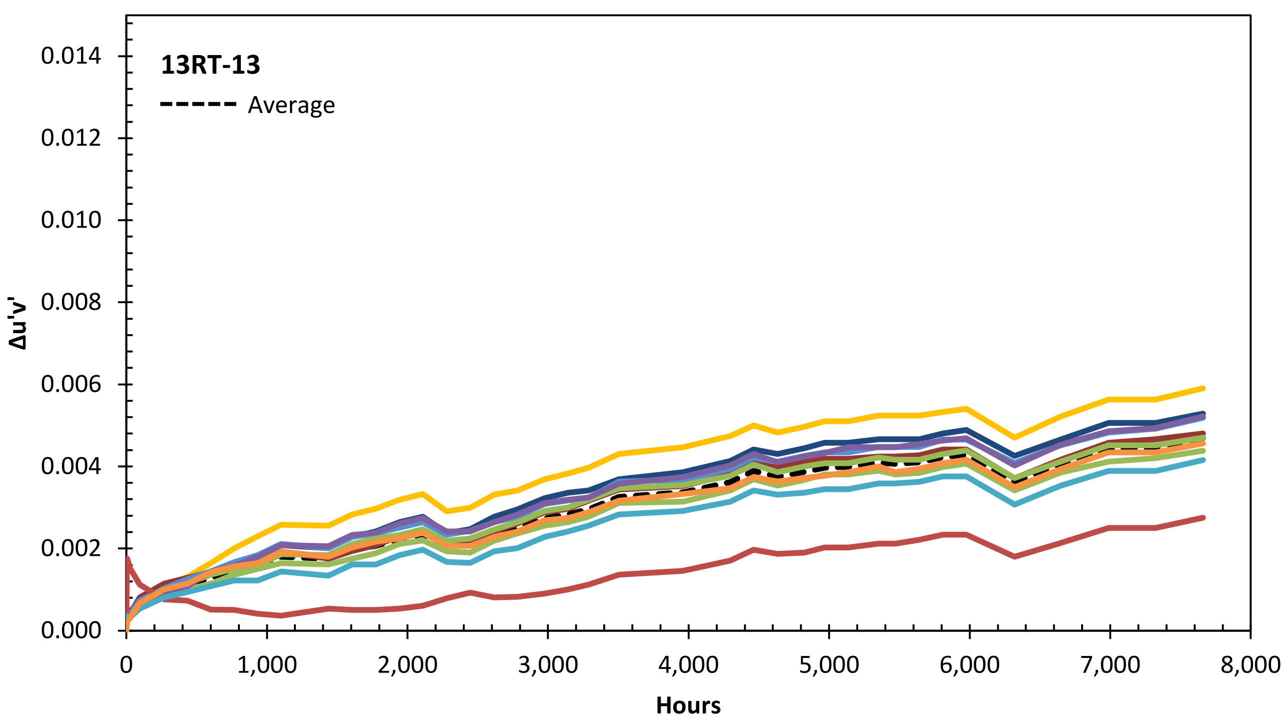


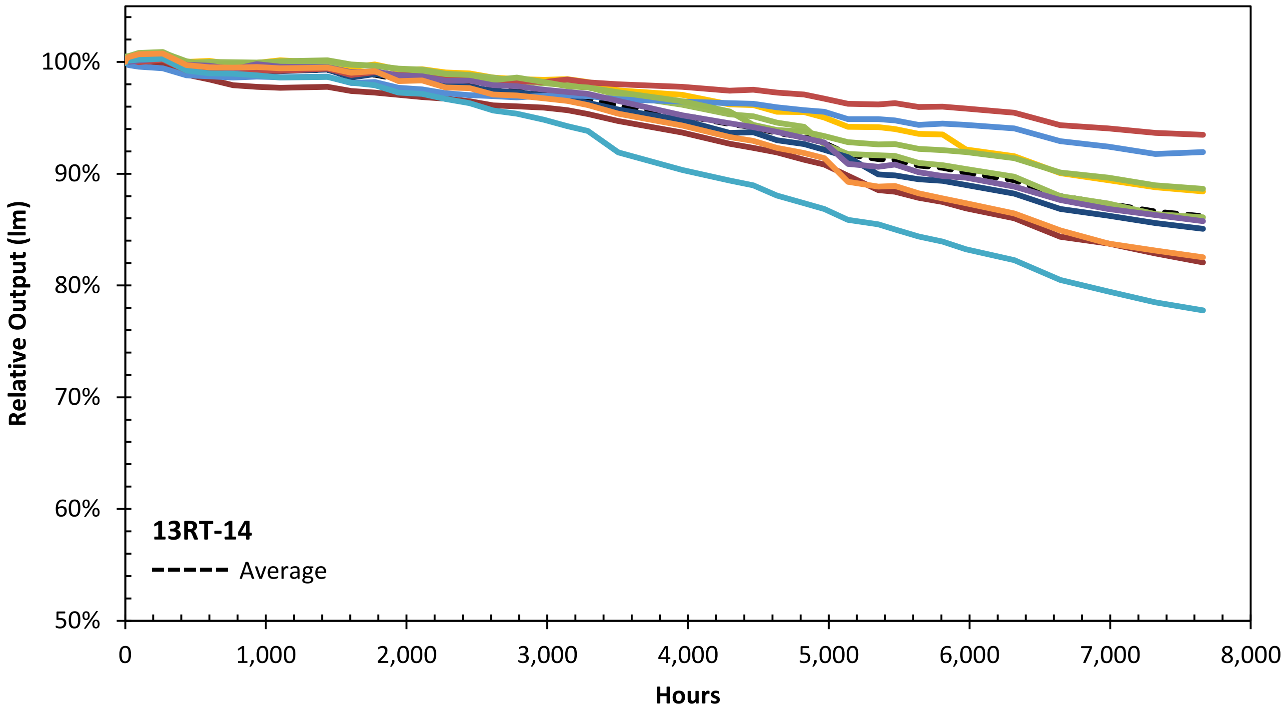
13RT-11
Average
Δu'v'
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours


Relative Output (lm)
100%
90%
80%
70%
60%
50%
13RT-12
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

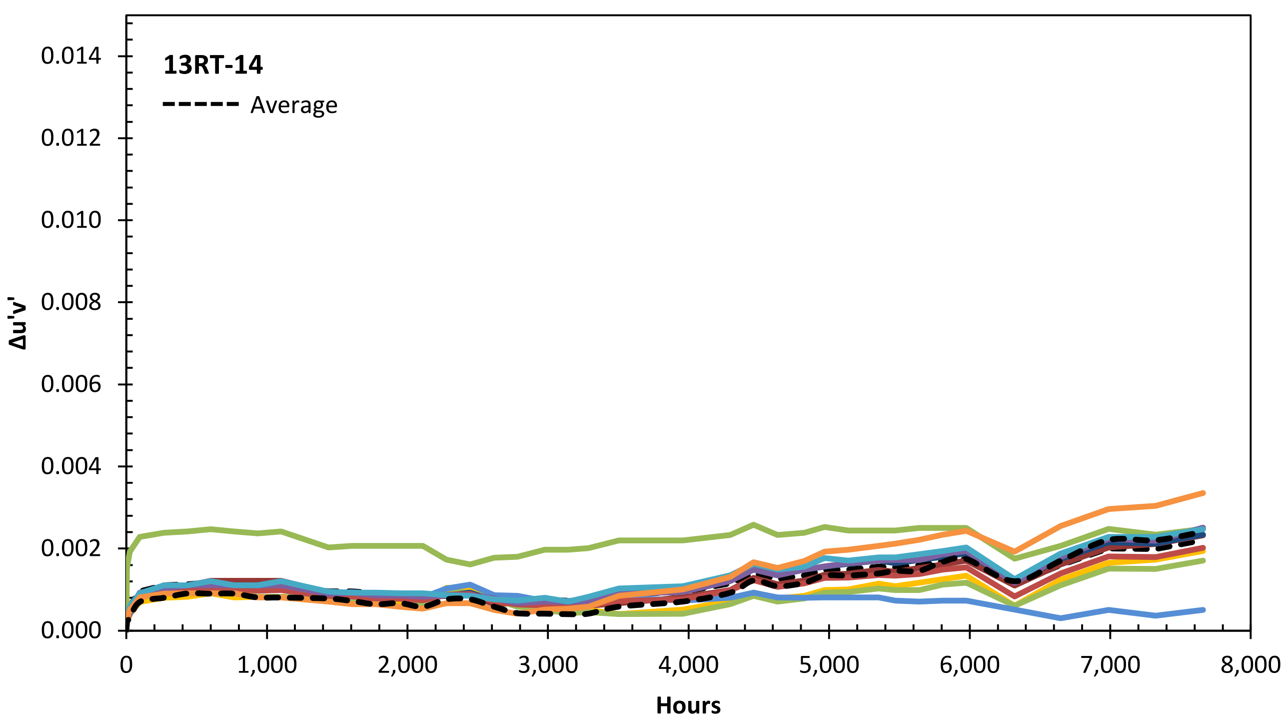

Δu'v'
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
13RT-12
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours


100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-13
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

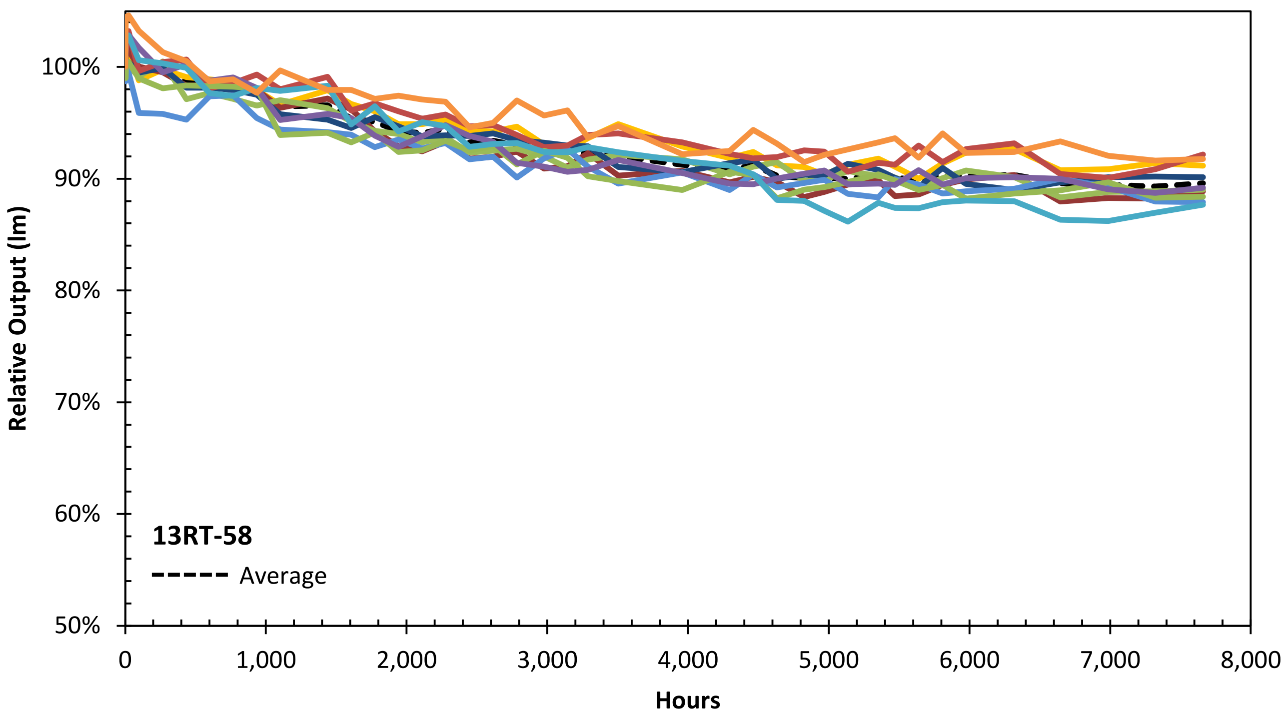

0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
13RT-13
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



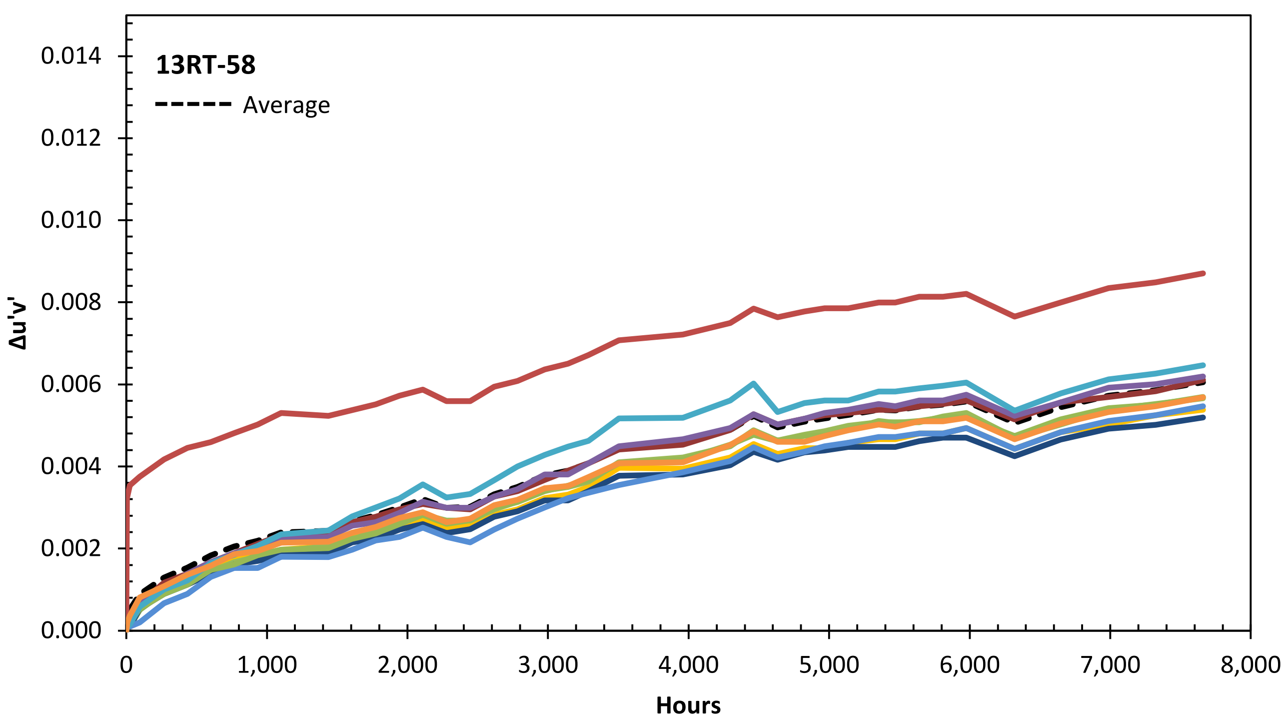
100%
90%
80%
70%
60%
50%
Relative Output (lm)
13RT-14
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



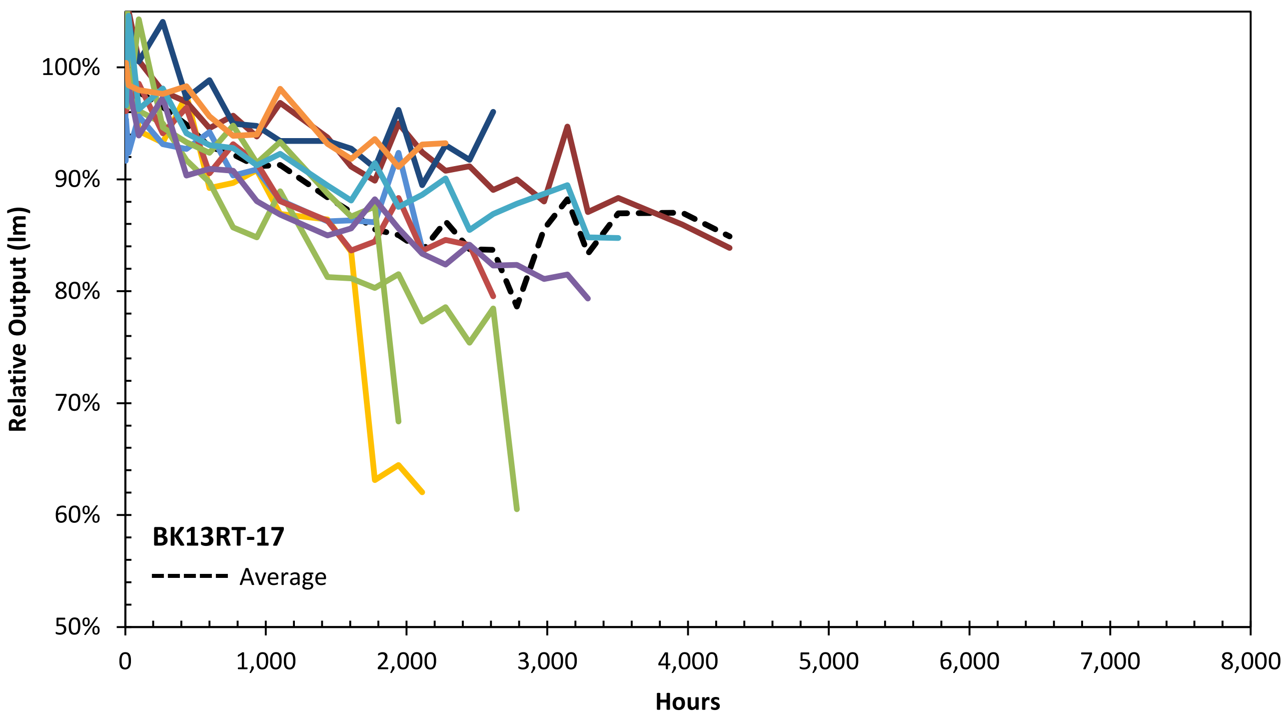
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
13RT-14
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



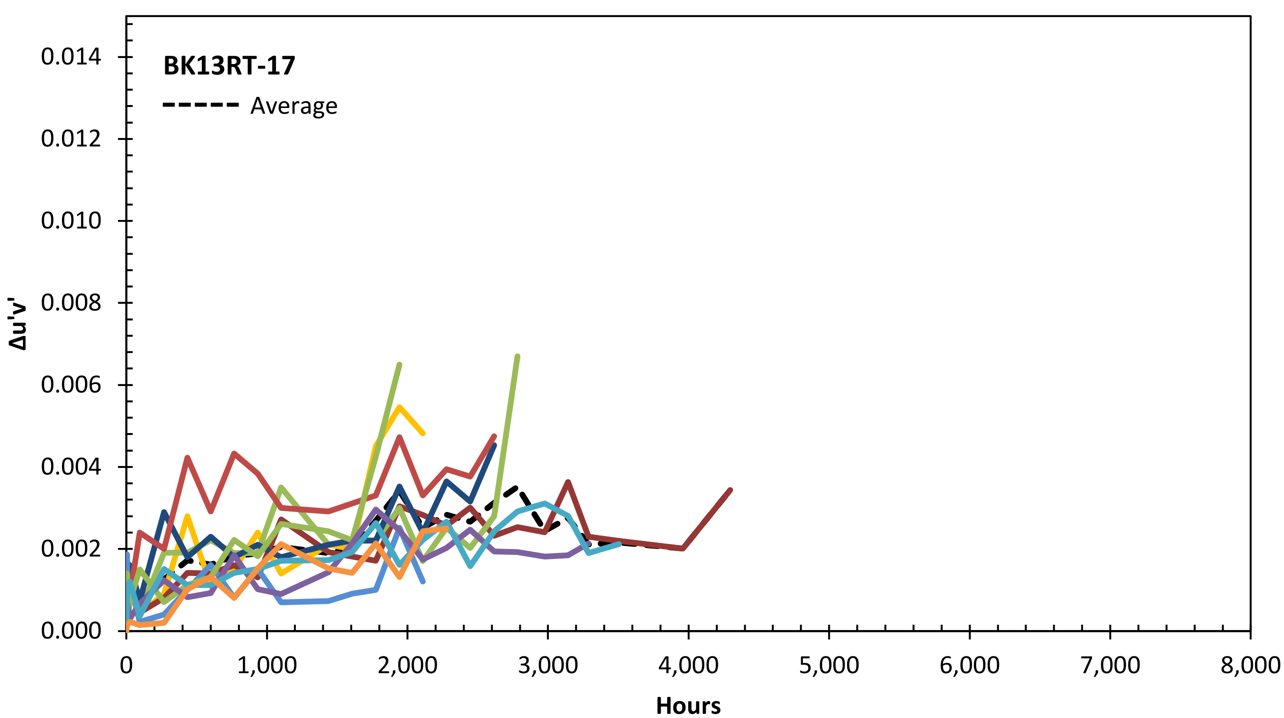
13RT-58
Average
Relative Output (lm)
100%
90%
80%
70%
60%
50%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



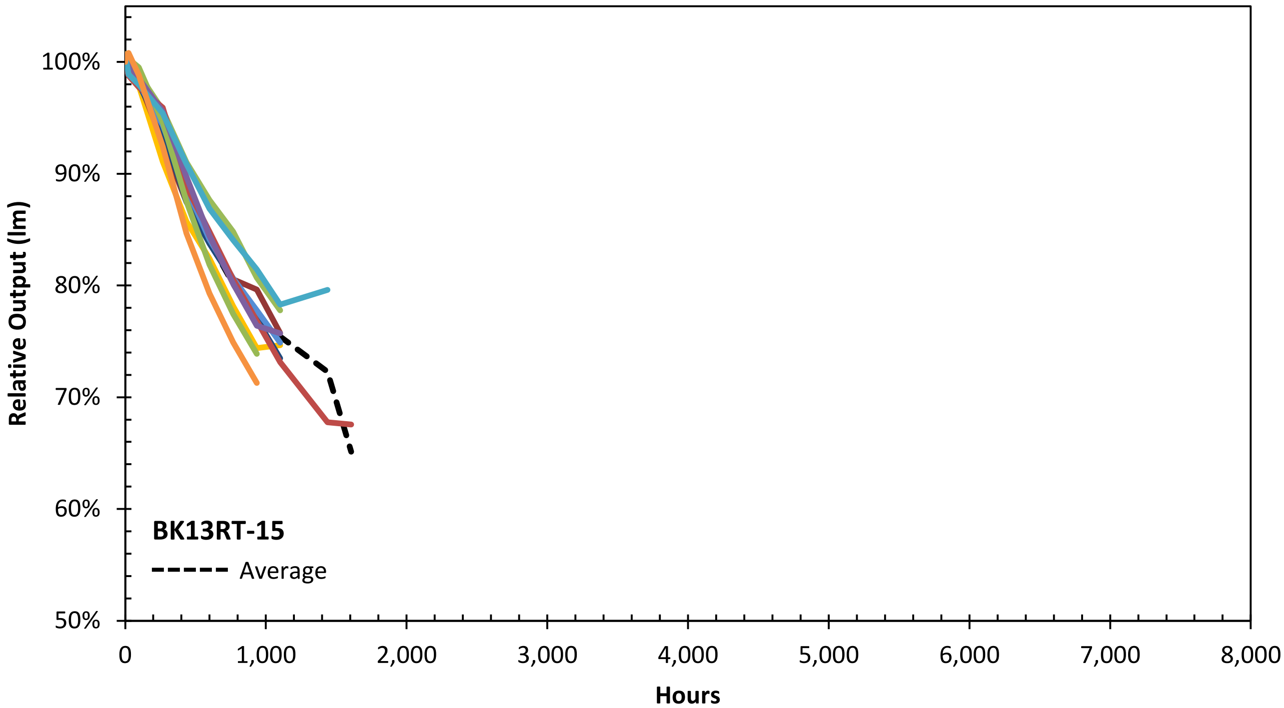
13RT-58
Average
Δu'v'
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



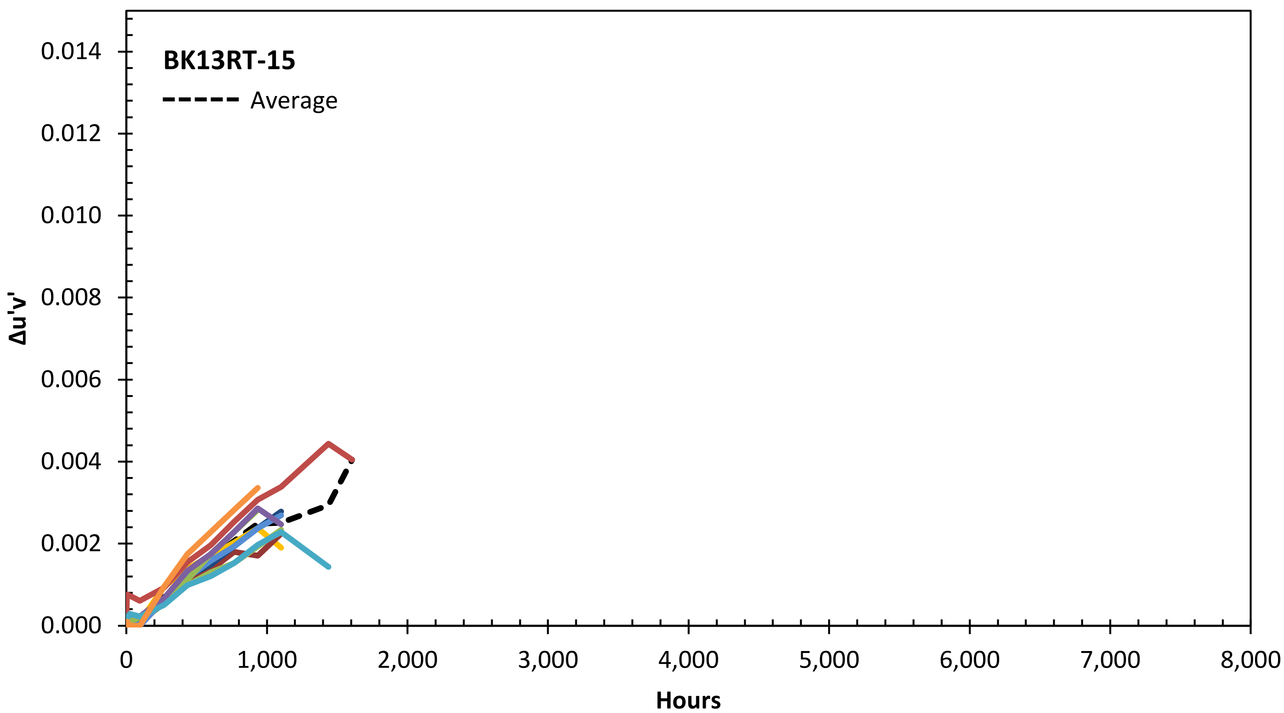
BK13RT-17
Average
Relative Output (lm)
100%
90%
80%
70%
60%
50%
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



BK13RT-17
Average
Δu'v'
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



100%
90%
80%
70%
60%
50%
Relative Output (lm)
BK13RT-15
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours



0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Δu'v'
BK13RT-15
Average
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Hours

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