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TECHNICAL REPORT 3317  
AUGUST 2023

## **An Evaluation of Commercial Graphene Solid State Lighting**

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Naval Information Warfare Center (NIWC) Pacific  
San Diego, CA 92152-5001

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### **Administrative Notes:**

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**NIWC Pacific**  
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**ADMINISTRATIVE INFORMATION**

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## **EXECUTIVE SUMMARY**

### **OBJECTIVE**

The overarching goal of this effort is to provide an independent technical assessment of photometric, electrical, and thermal performance of commercially available Graphene Solid State Lighting (SSL) to provide the Department of Navy (DON) with interior and exterior lighting solutions that reduce energy consumption, reduce maintenance costs, and improve lighting quality, at the lowest life cycle cost in DON Facilities.

### **METHODS**

Our methods are separated into distinctive measurement setups and were performed by both government and academic professionals. For both A19-based lighting architectures and Graphene Tube LED-based architectures, photometric and electrical performance was gathered based upon ANSI LM-79-19 standards, to include the use of an integrating sphere and electrical data collection hardware. The following thermal and electrical performance data was performed upon careful design criteria identified by our teams and included temperature measurements with thermocouples and electrical data collection hardware.

### **CONCLUSIONS AND RECOMMENDATIONS**

This study concludes performance measurements of commercially available graphene solid-state lighting that includes A19 lamps from lighting vendor, Sera Technologies as well as Graphene-enhanced tube LED lamps from lighting vendor, LEDi2 Inc. Electrical, photometric, and thermal data was collected for each lamp type and the results were compared to the Design Lights Consortium (DLC) database, which contains specifications and performance data of over 80 categories of indoor and outdoor commercial LED products.

Our study indicated that the Sera Technologies Graphene A19 lamps showed indications of lowered ambient temperature rise during continuous operation, with a 11% lower operating temperature over conventional lamps. In addition, the Sera Technologies Graphene A19 lamps revealed better photometric and electrical performance data that placed this product within the top 98<sup>th</sup> percentile of high-performance commercial lighting. Therefore, our team recommends adoption of Sera Technologies Graphene A19 lamps within DON Facilities where task lighting adds value. However, it is important to note the Sera Technologies A19 Lamps are a European Variant and require 240 volts to operate. No U.S. variant exists currently. This greatly limits adoption of the Sera Technologies Graphene A19 Lamp to DON operations in the European Union.

Test results for the LEDi2 Graphene Tube LED lamps indicated resultant temperature rises were average within the same class and type, showing no definitive indications of improved performance overall. In addition, LEDi2 Graphene Tube LED lamps photometric and electrical performance data operated within only the top 1/3 of commercial Tube LED lamps, indicating minimal improvement over high performing non-graphene variants. Our team does not recommend adoption of LEDi2 Graphene Tube LED lamps within DON Facilities as the lamps did not perform better in all aspects of photometric, thermal, and electrical performance. Several tube LED lamps are available on the market that perform much better. Future adoption of Graphene Tube LED lamps is dependent on improved industry partnership between reputable LED and graphene suppliers.

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## ACRONYMS

|        |                                                 |
|--------|-------------------------------------------------|
| A19    | A-type Lamp, 19 in diameter                     |
| ANSI   | American National Standards Institute           |
| CCT    | Correlated Color Temperature                    |
| CFL    | Compact Fluorescence Lamp                       |
| CLTC   | California Lighting and Technology Center       |
| CP     | Command Post                                    |
| CRI    | Color Rendering Index                           |
| DAQ    | Data Acquisition                                |
| DoD    | Department of Defense                           |
| DoN    | Department of the Navy                          |
| FLIR   | Forward Looking Infrared                        |
| GA19   | Graphene A-type Lamp, 19 in diameter            |
| GTLED  | Graphene Tube Light Emitting Diode              |
| HVAC   | Heating, Ventilation, and Air Conditioning      |
| LED    | Light Emitting Diode                            |
| NAVFAC | Naval Facilities Engineering Systems Command    |
| NI     | National Instruments                            |
| NIST   | National Institute for Standards and Technology |
| PES    | Photometric and Electrical Setup                |
| SSL    | Solid State Lighting                            |
| TES    | Thermal and Electrical Setup                    |
| TLED   | Tube-type Light Emitting Diode                  |
| UV     | Ultraviolet                                     |

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# **1. INTRODUCTION**

## **1.1 PURPOSE**

Annually, the Department of the Navy (DON) allocated extensive funds on the maintenance and replacement of commercial lighting packages for office, industrial, residential, Forward Operating Bases (FOBs), and Command Posts (CP). There is an urgent need to procure interior and exterior lighting systems that reduce energy consumption, reduce maintenance costs, and improve lighting quality, at the lowest life cycle cost in DON Facilities.

### **1.1.1 Objectives**

The overarching goal of this effort is to provide an independent technical assessment of photometric, electrical, and thermal performance of commercially available graphene solid state lighting (SSL) for potential use in the DON environment. It has been found that coating the Light-Emitting Diode (LED) filaments of commercial style LED lighting products with graphene dissipates heat more efficiently. The results are potentially a longer-lasting (>60,000hrs), brighter, low-power SSL technology that operates at cooler temperatures and is 10% more efficient compared to non-graphene SSL packages. Replacing SSL systems across our warfighting centers with cooler graphene enhanced SSL has the potential to drastically reduce Heating, Ventilation, and Air Conditioning (HVAC) cost by the means of reducing the amount of heat required to be removed by our current AC cooling systems. Furthermore, the longer lifetimes of graphene enhanced SSL technology may cut maintenance and procurement cost of existing lighting contracts because facilities will not have to procure as often.

The experiment was broken up into five main objectives. The objectives were to characterize and quantify the photometric, electrical, and thermal performance of graphene enhanced SSL. The measured data was then used to benchmark against non-graphene variants. A final recommendation was then provided to the reader to provide insight on whether DON adoption is viable at the time of this study. A description of each objective is provided along with a status on whether the objective was met by the completion of this study in the following table:

Table 1. Overall Results of Experiments.

| Experiment Objectives                                                                                                                                | Results                                                                                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Objective 1 - Characterize the photometric and electrical performance metrics of commercially available graphene A19 LED packages.                   | Fully Realized<br>     |
| Objective 2 - Characterize the photometric and electrical performance metrics of commercially available Graphene Tube LED (GTLED) lighting packages. | Fully Realized<br>     |
| Objective 3 - Characterize the thermal performance of commercially available graphene A19 LED packages.                                              | Partially Realized<br> |
| Objective 4 - Characterize the thermal performance of commercially available graphene tube LED lighting packages.                                    | Partially Realized<br> |
| Objective 5 - Provide a recommendation for DoD adoption of graphene enhanced SSL technologies.                                                       |                      |

#### 1.1.1.1 Objective 1

Characterize the photometric and electrical performance metrics of commercially available graphene A19 LED packages.

##### 1.1.1.1.1 Objective 1 Details

To characterize the photometric and electrical performance of graphene enhanced A19 LED packages, an integrating sphere methodology was used and test procedures are described in the Methods section. To summarize, a power supply, power analyzer, and high-resolution spectrometer were interfaced with a 2-meter integrating sphere to calibrate and conduct said measurements in compliance with national standards.

The photometric information acquired using the integrating sphere test methods included total luminous flux (lumens), luminous efficacy (lm/W), correlated color temperature (CCT), and color rendering index (CRI). In addition, chromaticity, spectral power distribution, color quality, and flicker data. Power output and power factor were computed from real-time data logging of the operating current-voltage characteristics. Data collected was compared with vendor data sheets to verify claims and benchmarked with third party lighting databases to weigh overall performance with the LED package class (i.e. compared non-graphene A19 LED package to graphene enhanced LED package).

#### **1.1.1.2 Objective 2**

Characterize the photometric and electrical performance metrics of commercially available Graphene Tube LED (GTLED) lighting packages.

##### **1.1.1.2.1 Objective 2 Details**

To characterize the photometric and electrical performance of graphene enhanced TLED packages, an integrating sphere methodology was used and test procedures are described in the Methods section. To summarize, a power supply, power analyzer, high-resolution spectrometer was interfaced with a 2-meter integrating sphere to calibrate and conduct said measurements in compliance with national standards.

The photometric information acquired using the integrating sphere methodology included total luminous flux (lumens), luminous efficacy (lm/W), correlated color temperature (CCT), and color rendering index (CRI). In addition, chromaticity, spectral power distribution, color quality, and flicker were also measured. Power output and power factor were computed from real-time data logging of the operating current-voltage characteristics. Data collected was compared with vendor data sheets to verify claims and benchmarked with third-party lighting databases to weigh overall performance.

#### **1.1.1.3 Objective 3**

Characterize the thermal performance of commercially available graphene A19 LED packages.

##### **1.1.1.3.1 Objective 3 Details**

To characterize the thermal performance of commercially available graphene A19 LED packages, a temperature test was designed to monitor changes in temperature as the power of the LED package was cycled on. A detailed description of the temperature measurement is described in the Methods Section. To summarize, an LED fixture was mounted in an insulated cooler to act as a light box calorimeter. As the LED package was turned on, changes in temperature were logged with several thermocouples mounted on the LED package and in the calorimeter environment. Thermocouple data was stored with a thermocouple data logger. In addition, the operating power was monitored with a power data logger. Thermal performance measurements were captured for both the graphene enhanced A19 LED package and its non-graphene variants.

#### **1.1.1.4 Objective 4**

Characterize the thermal performance of commercially available GTLED lighting packages.

##### **1.1.1.4.1 Objective 4 Details**

To characterize the thermal performance of commercially available GTLED packages, a temperature test was designed to monitor changes in temperature as the power of the GTLED package was cycled on. A detailed description of the temperature measurement is described in the Methods Section. To summarize, a GTLED fixture was mounted in a large 6-foot insulated cooler to act as a light box calorimeter. As the GTLED package was turned on, changes in temperature were logged with several thermocouples mounted on the GTLED package and in the insulated environment. Thermocouple data was stored with a thermocouple data logger. In addition, the operating power was monitored with a power data logger. Thermal performance measurements were captured for both the GTLED packages and non-graphene variants.

#### **1.1.1.5 Objective 5**

Provide a recommendation for DoD adoption of graphene enhanced SSL technologies.

##### **1.1.1.5.1 Objective 5 Details**

The Naval Facilities Engineering Systems Command (NAVFAC) is the key stakeholder for this effort. Objective 5 aims to educate NAVFAC lighting professionals on graphene enhanced SSL for possible future adoption within the Department of Navy.

## **1.2 BACKGROUND**

### **1.2.1 Lighting as heat sources**

To maintain social work environments, lighting must exist to improve comfort and safety. Unfortunately, lighting has substantial effect on the energy consumption of buildings. For example, in a 1989 study, the National Institute of Standards and Technology (NIST) published a report, “The Interaction of Lighting, Heating, and Cooling systems in buildings.” The aim of this interim report was to model the relationship between commercial lighting, heating, and cooling systems. The results of the report determined that when luminaries were cooled sufficiently by air conditioning, the overall performance of the lighting system would improve. However, the energy required to cool the lighting system forced the air-conditioning systems to work harder to maintain both comfort and sustain lighting efficiency. The significant strain put on commercial air conditioning systems to mitigate the heat production from lighting is costly with respect to both maintenance and energy consumption. [1]

An argument can be made that the heat generated in a building’s interior by lighting systems can be heat gain during winter seasons. However, during the summer months and/or in equatorial regions, the heat from lighting systems increases the demand for cooling; thus, is a negative effect on energy efficiency. In this study, we will focus on the Hawaii Region which maintains a warmer climate annually, therefore, cooler indoor temperatures is a priority to maintain comfort.

#### **1.2.1.1 Lighting Types**

For lighting context, the lighting industry is dominated by four main lamp technologies: incandescent, Compact Fluorescence Lamps (CFL), halogen, and Light-Emitting Diodes (LED). These four technologies are defined as the following:

##### **1.2.1.1.1 Incandescent**

Incandescent lighting creates light through heat. Incandescent is an older inefficient lighting technology that produces light when current passes through a thin tungsten filament. Overtime, the tungsten filament gets hot enough that it begins to glow. However, approximately 90% of the energy from an incandescent lamp is wasted to generate light from heat. Therefore, incandescent lamps have a short lifespan and produce the least light per watt of energy in comparison with other lamp technologies. For this particular reason, incandescent lighting has currently faded out of the market and are typically sold as heat lamps for agricultural and cooler climates.

##### **1.2.1.1.2 Fluorescent**

A fluorescent lamp is a gas-discharge lamp that produces visible light by exciting a fluorescent coating (i.e. Phosphor) on the glass envelope of the lamp. First, UV excitation is achieved from collisions within a hot gas typically comprised of mercury vapor and noble gases. As the gases relax,

UV light is converted to visible light by exciting the phosphor coating. To excite the gas, fluorescent lamps require a ballast which are special inductive circuits that regulate current to maintain constant light emission within the gases. Unfortunately, the maintenance cost of ballast is typically high because ballasts are prone to failure and need to be replaced often.

Fluorescent lamps convert electrical energy into useful light much more efficiently than an incandescent lamp. Only about 30% of the energy from a fluorescent lamp is wasted to generate light. In addition, fluorescent lamps have longer lifespans (i.e. 1-3 years) and have several different form factors to include the most common tube like (i.e. T8, T12) for commercial environments, and compact fluorescent lamps (CFL). CFLs operate similarly to standard fluorescent tube lamps, but have a twisted shape and were first developed to harness the benefits of fluorescent lighting for home use due to its compact shape.

Despite the numerous benefits, fluorescent lamps contain mercury vapor which is a classified hazardous waste by the United States Environmental Protection Agency. The exposure to mercury dust and vapor is dangerous to humans and animals. Therefore, disposal is an issue and proper recycling is required to reduce accidental release of heavy metals into the environment [2].

#### **1.2.1.1.3 Light-emitting Diodes**

A Light-emitting Diode (LED) is the result of bringing an n-type semiconductor and p-type semiconductor together to form a p-n junction. The boundary between the semiconductor materials forms a depletion region. Due to the depletion of free electrons at the junction area, when a power supply is connected across the LED in a forward bias configuration, electrons in the conduction band are then supplied to the LED and recombine with the holes in the valence band of the depletion region. This recombination produces a flux of photons with desirable wavelengths that are associated with the band gap designed into the junction, which is a product of the p and n type material associated with that particular LED. This type of light production has been shown to be very long lasting and efficient.

While LEDs have a high life-cycle, research has shown that this lifetime is significantly reduced when operated at high temperatures, thus reducing the perceived effectiveness of an ideal-scenario (non-heated) LED over conventional lighting [3].

### **1.2.2 Thermal Conductivity and its role in LED lighting**

Analogous to electrical conductivity, which is defined as the measure of current under a potential gradient, thermal conductivity, quantifies the ability of a material to transfer or conduct heat under a temperature gradient. A material with high thermal conductivity is said to be a great conductor of heat as opposed to a material with low thermal conductivity that exhibits a trait of being a poor conductor of heat. In electronics, the ability to design components with materials of high thermal conductivity allows the components to operate more efficiently and typically have longer lifetimes because heat is removed from the component under operation. For example, PC designers spend substantial effort and money on the design considerations of heat sinks and thermal paste in an effort to remove heat more efficiently from computer processing units (CPU).

Although LEDs are considered more efficient than fluorescent lighting, LEDs are affected by heat themselves. The light output of an LED held within a lamp, or alternative within a different housing, all have a rise in temperature of the operating materials. For example, the role of the semiconductor materials in LEDs are designed to create a flux of photons at a desirable wavelength. Often, these semiconductors are not designed to remove heat, therefore, LED designers must consider tradeoffs to maximize lighting efficiency. One way to mitigate heat, is via the lamp housing, while used to trap gas, or maintain a vacuum in alternative lighting, serves as a protection against this high temperature

in LED lights. However, much of the heat in LED lighting systems is contributed to the support electronics, such as the LED drivers. In order to maintain compact lighting systems, LEDs are typically required to be mounted close to the driving electronics to support operation, therefore, making it very difficult to passivate the LEDs from these heat sources. Overall, traditional LEDs undergo some type of heat conduction, and heat rejection, but poses several challenges to maximize performance in LED designs.

### **1.2.3 Graphene for Thermal Management of LED Technologies**

Graphene is best defined as a monolayer of carbon atoms arranged in a honeycomb crystal lattice. Graphene has been shown to exhibit extraordinarily unique optical, electronic, mechanical, and thermal properties, some of which no other material exhibits at room temperature and in a single monolayer [4]. With the first isolation of graphene in 2004 by two Nobel laureates, Andre Giem and Konstantin Novoselov, with the exploitation of a “scotch tape method”, a surge of studies led by the global scientific community has aimed to incorporate graphene into electronic and mechanical devices.

More importantly to our study, Graphene films can provide desirable thermal management properties for electronic devices due to exhibiting one of the highest thermal conductivities within a two-dimensional material. Meaning, for a single monolayer of carbon, graphene exhibits a thermal conductivity of  $\sim 5000 \text{ Wm}^{-1} \text{ K}^{-1}$ . In addition, graphene films enable several unique characteristics that allow for the thermal conductivity to be adjusted when applied to a material. For example, the structure of the graphene can be altered to adjust its intrinsic thermal conductivity. By changing the structure, the number of defects, and or layers, the thermal conductivity can be raised or lowered on a controlled manner by manufacturers. Furthermore, annealing the graphene once deposited on a target surface can also manipulate the end material thermal properties. While this topic is continually debated, the effects of administering graphene in this method has been shown to improve thermal management of materials and devices [5,6].

Additionally, graphene can be used as a heat spreading material through which excessive heat can be efficiently transported away from devices and improve operation. It has been proven that coating the LED filament of a standard A19 lamp with graphene dissipates heat more efficiently [7]. The heat generated within LEDs and power electronics can be directed away from the LED and to areas on the device that can efficiently evacuate the heat from the lighting system. The overall results are longer lasting ( $>60,000$ hrs), brighter, low power lighting technology that operates at cooler temperatures and industry claims said to be 10% more efficient compared to traditional LED lighting. It is important to note the first embodiment of graphene Filament LED was discovered by Nobel Laureates, Andre Giem and Konstantin Novoselov. Their labs at the University of Manchester were to first to share this idea with the world and patent the intellectual property (US9933121B2, US10082256B2). The government of United Kingdom further sponsored additional development and manufacturing efforts as the graphene LED was one of several products that UK Manchester targeted for the commercial market. Their teams later established the company Graphene Lighting PLC in 2013 that aimed to bring next generation lighting technologies to the market. Today, Graphene Lighting PLC owns 50-plus patents and are the main suppliers of graphene enhanced lighting inside of European Union and South East Asia.

From a military perspective, replacing lighting systems across our warfighting centers with cooler graphene LED lighting has the potential to reduce HVAC costs by the means of a reduction in amount of heat removal required to maintain comfortability. Furthermore, the longer lifetimes of graphene LED lighting will cut maintenance and procurement cost because facilities will not have to buy and replace as many lamps.

In the following sections our focus is to provide an independent technical assessment of commercial graphene LED lighting and to provide recommendations on large scale military adoption of the technology for the future warfighter.

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## **2. METHODS AND MATERIALS**

The following section describes our methods to measure the electrical, photometric, and thermal properties of graphene enhanced SSL. To derive these methods, our NIWC Pacific team worked and shared resources with UC Davis California Lighting Technology Center which is a not-for-profit research, development, and demonstration facility dedicated to accelerating the development and commercialization of energy efficient lighting systems.

### **2.1 METHODS**

The two lighting types tested were Graphene-enhanced A19 and the LED Tube lamps. For simplicity, we define the Graphene A19 lamp variant as (GA19) and the Graphene Tube LED lamp variant (GTLED).

The procedures used to determine the electrical, photometric, and thermal properties of the GA-19 variant consist of the following:

1. Procure A19 for comparison and GA19 variant with potential for improvement beyond currently used lamps.
2. Conduct initial photometric and electrical testing of lamps.
3. Conduct thermal and electrical testing of lamps.
4. Aggregate data and perform analysis for comparison to existing specifications to determine the validity of potential improvements.

The procedures used to determine electrical, photometric, and thermal properties of the GTLEDs consist of the following.

1. Procure GTLEDs with potential for improvement beyond currently used Light tubes.
2. Conduct initial photometric and electrical testing of light tubes. Use thermal imaging of product to determine data collection locations and optimum thermal test setups.
3. Conduct thermal and electrical characteristics tests of intact GTLED Light Tubes.
4. Deconstruct GTLED Light Tubes into component parts.
5. Conduct thermal and electrical characteristic tests of deconstructed GTLED Light Tubes.
6. Aggregate data and perform analysis for comparison to existing specifications to determine validity of potential improvements.

#### **2.1.1 A19 Study Design**

The GA19 lamps are claimed to be more energy efficient than the non-graphene version and are claimed to generate 10% less heat during standard operation, thus the photometric and thermal performance data were measured along with the electrical characteristics during tests to verify this claim. Two test setups were built for our study: A19 Photometric and Electrical Setup (A19-PES), and A19 Thermal and Electrical Setup (A19-TES). However, due to the limited budget available to this project, the NIWC Pacific team utilized state-of-the-art expertise and lighting test facility at UC Davis CLTC. Therefore, the photometric and electrical performance measurements were conducted at UC Davis by the CLTC team with their A19-PES. On the other hand, materials were procured to construct the A19-TES which is now at NIWC Pacific's Graphene Microfluidics Laboratory located in Pearl City, Hawaii. In order to cross correlate results, the teams operated the GA19 and GTLEDs under

similar operating conditions. For example, in order to get an electrical baseline for thermal measurements, the UC Davis CLTC conducted the photometric measurements and recorded the operating voltages and current ratings. When conducting the thermal measurements, the NIWC Pacific team ensured they operated the lamps under similar conditions with power logging instruments. Furthermore, the same lamps were used for both photometric and thermal measurements. Table 2 and Table 3 described the equipment used for the lamp test and label the GA19 testing groups, respectively. The following sections describe methods in more detail.



Figure 1. GA19 Light lamp.

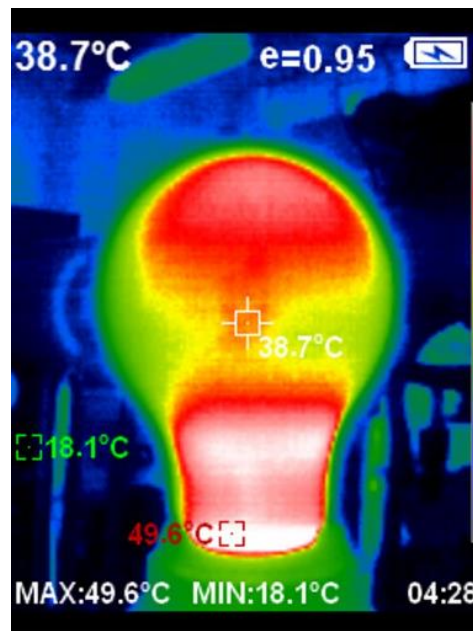


Figure 2. GA19 Lamp FLIR Image.

| Test               | Parameter          | Tool                                                                     |
|--------------------|--------------------|--------------------------------------------------------------------------|
| A19-PES            | Photometric        | SMS-500 Spectrometer                                                     |
| A19-PES            | Power Supply       | California Institute 751iX                                               |
| A19-PES            | Power Measurements | Yokogawa PZ4000                                                          |
| A19-TES            | Temperature        | K-Type Thermocouple<br>National Instruments (NI) cDAQ-9185<br>NI TB-9212 |
| A19-TES            | Power Supply       | BK Precision 9803                                                        |
| A19-TES            | Power Measurements | ONSET HOBO                                                               |
| A19-PES<br>A19-TES | Thermal            | FLIR C5 MSX                                                              |

Table 2. A19 Test Measurement Tools.

| A19 Lamps           |          |
|---------------------|----------|
| Lamp                | Model    |
| Sera Technologies1  | 8W 2700K |
| Sera Technologies2  | 8W 2700K |
| Sera Technologies3  | 8W 2700K |
| Sera Technologies4  | 8W 2700K |
| Sera Technologies5  | 8W 2700K |
| Sera Technologies6  | 8W 2700K |
| Sera Technologies7  | 8W 2700K |
| Sera Technologies8  | 8W 2700K |
| Sera Technologies9  | 8W 2700K |
| Sera Technologies10 | 8W 2700K |

Table 3. A19 Testing Groups, the tests are divided by lamp number for labeling and test data.

### **2.1.1.1 A19 Photometric and Electrical Setup**

A19-PES consists of placing an A19 lamp within an integrating sphere, Figure 3, and measuring its electrical and photometric data during operation. An integrating sphere is defined as hollow spherical cavity in which its interior is covered with a diffuse white reflective coating. An integrating sphere collects electromagnetic radiation from a source completely external to the optical device, usually for flux measurement or optical attenuation. Radiation introduced into an integrating sphere strikes the reflective walls and undergoes multiple diffuse reflections. After numerous reflections, the radiation is dispersed highly uniformly at the sphere walls in that the resulting frequency dependent integrated radiation level is directly proportional to the initial radiation level and may be measured with a spectrometer. Combined with power analysis tools a variety of critical parameters can be measured to fully characterize a light source. In our methods, A19-PES data was taken utilizing the SMS-500 Spectrometer by the CLTC team. Measurements were done in accordance with LM-79-19 ANSI Standard for Optical and Electrical Measurements of Solid-State Lighting Products. Electrical characteristics were sampled during operation with a Yokogawa PZ4000, Figure 3.

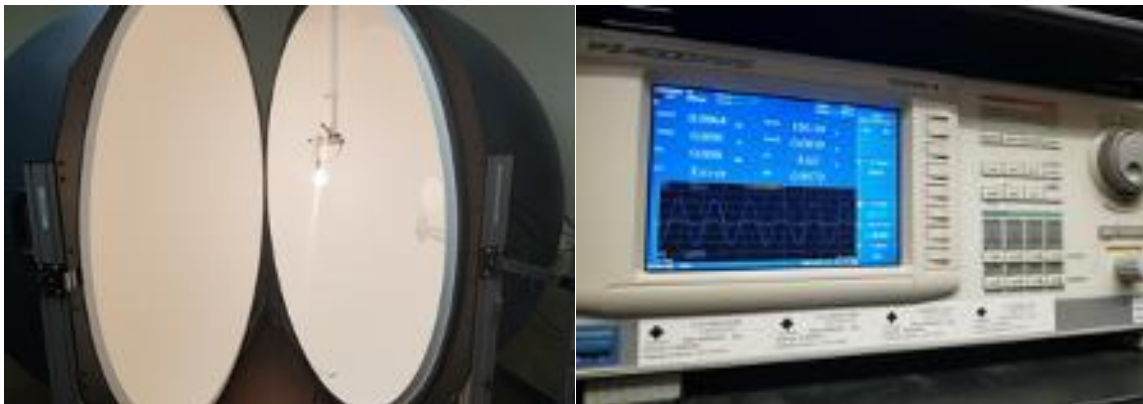


Figure 3. (Left) Integrating Sphere at California Lighting Technology Center used to measure various lighting technologies. (Right) Yokogawa PZ4000 Power Analyzer used in conjunction with integrating sphere.

| Type        | Parameter          | Device               |
|-------------|--------------------|----------------------|
| Photometric | Light Output       | SMS-500 Spectrometer |
| Photometric | CCT                | SMS-500 Spectrometer |
| Photometric | Duy                | SMS-500 Spectrometer |
| Photometric | CRI                | SMS-500 Spectrometer |
| Photometric | Efficacy           | SMS-500 Spectrometer |
| Photometric | Percent Flicker    | SMS-500 Spectrometer |
| Photometric | Flicker Index      | SMS-500 Spectrometer |
| Electrical  | Power Measurements | Yokogawa PZ4000      |

Table 4. A19-PES Testing Parameters.

#### 2.1.1.1.1 A19-PES Measurement Method

Testing for A19-PES is completed by CLTC and consisted of:

- Identify GA19 Lamp to be tested and installing within test chamber.
- Conduct photometric and electrical testing and record data.
- Aggregate and display data for analysis.

#### 2.1.1.2 A19 Thermal and Electrical Setup

To summarize A19-TES, all thermal data was measured in Celsius with K-type thermocouples that are interfaced with a National Instruments (NI) TB-9212 Module attached to a NI cDAQ-9185, which allows for automated data collection in MATLAB. Electrical characteristics were monitored with an ONSET HOBO Plug Load Logger, which collected Voltage, Amperage, and Power data. MATLAB and data manipulation techniques were used to analyze the data from the A19 and GA19 Lamp while in operation to determine the effectiveness of the GA19. Physical locations for thermocouple data collection were determined by the FLIR Thermal imaging of the A19 Lamps. A19 TES consists of placing the A19/GA19 Lamp within an insulated chamber and conducting 120-minute tests to allow for temperature saturation. Temperature data locations were determined using a FLIR C5 MSX thermal camera, and are shown in Figure 2. During testing, temperature data was recorded along predetermined physical locations on the lamp to accurately measure thermal characteristics during operation. Electrical data was recorded utilizing the ONSET HOBO Power Logger and measured alongside temperature data. All data was aggregated for display using the MATLAB suite of software.

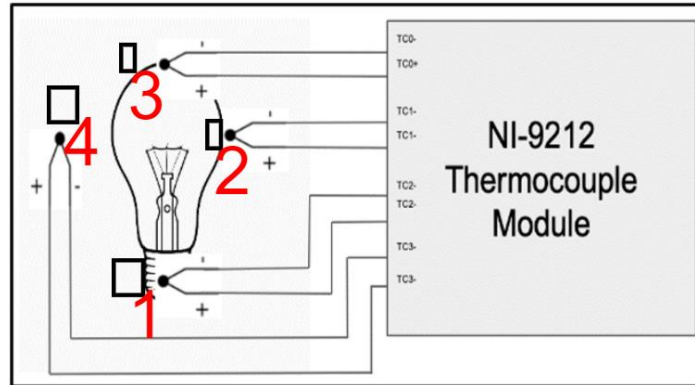


Figure 4. A19-TES Thermal Data Location. Four locations were determined based on potential for heat source to include 1-lamp base, 2-on lamp filament, 3-top of the lamp, and 4-ambient temperature in chamber.



Figure 5. A19-TES Operation during testing with locations of the 3 thermocouples on adhered to the lamp with polyimide. A fourth thermocouple is adhered to the wall of the thermal chamber.

| Type        | Parameter               | Device            |
|-------------|-------------------------|-------------------|
| Temperature | Ambient Air Temperature | NI cDAQ-9185      |
| Temperature | A19 Top                 | NI cDAQ-9185      |
| Temperature | A19 Base                | NI cDAQ-9185      |
| Temperature | A19 Side                | NI cDAQ-9185      |
| Electrical  | Power Supply Power      | BK Precision 9803 |
| Electrical  | Power Supply Voltage    | BK Precision 9803 |
| Electrical  | Power Supply Current    | BK Precision 9803 |
| Electrical  | HOB0 Power              | ONSET HOB0        |
| Electrical  | HOB0 Voltage            | ONSET HOB0        |
| Electrical  | HOB0 Current            | ONSET HOB0        |

Table 5. A19-TES Testing Parameters.

#### 2.1.1.2.1 A19-TES Measurement Method

Testing for A19-TES is completed by conducting a 120-minute run, which consists of:

- Identify A19 or GA19 to be tested and installing within test chamber.
- Set up software and physical test setup, ensuring thermal isolation chamber is isolated from external temperature environment
- Actuate Lamp Power and begin collecting HOB0, and Thermal Data.
- Monitor test while being conducted.
- Complete test and save aggregated data.

#### 2.1.2 GTLED Study Design

Military, academic, and industrial settings mostly utilize tube style LED lighting because LED lighting is more energy efficient and doesn't contain hazardous gases compared to halogen/fluorescent lighting. Graphene enhanced LED tube lamps are claimed to be more energy efficient, thus we measured the photometric and thermal data of GTLEDs to verify industry claims. To facilitate our testing format, three testing setups were identified: GTLED Photometric and Electrical Setup (GTLED-PES), GTLED Thermal and Electrical Setup 1 (GTLED-TES1) and GTLED Thermal and Electrical Setup 2 (GTLED-TES2). Table 6 and Table 7 describe the equipment used for the lamp test

and label the GTLED testing groups, respectively. It is important to note, the GTLEDs acquired for our study contain three separate lighting categories that are a function of the color and color temperature. The following sections describe methods in more detail.

| Test                     | Parameter          | Tool                                                                     |
|--------------------------|--------------------|--------------------------------------------------------------------------|
| GTLED-PES                | Photometric        | SMS-500 Spectrometer                                                     |
| GTLED-PES                | Power Supply       | California Institute 751iX                                               |
| GTLED-PES                | Power Measurements | Yokogawa PZ4000                                                          |
| GTLED-TES1<br>GTLED-TES2 | Temperature        | K-Type Thermocouple<br>National Instruments (NI) cDAQ-9185<br>NI TB-9212 |
| GTLED-TES1<br>GTLED-TES2 | Power Supply       | BK Precision 9803                                                        |
| GTLED-TES1<br>GTLED-TES2 | Power Measurements | ONSET HOBO                                                               |
| GTLED-TES1<br>GTLED-TES2 | Thermal            | FLIR C5 MSX                                                              |

Table 6. GTLED Measurement Tools.



Figure 6. Illustration of Graphene Enhanced Tube LED lamp (GTLED).

| GTLED Categories |                |       |
|------------------|----------------|-------|
| GTLED            | Description    | Group |
| 2                | 9W 4000K       | A     |
| 6                |                |       |
| 7                |                |       |
| 1                | 9W 5000K Green | B     |
| 3                |                |       |
| 10               |                |       |
| 13               |                |       |
| 12               | 18W 3000K      | C     |
| 4                | 18W 5000K      | D     |
| 5                |                |       |
| 8                |                |       |
| 9                |                |       |

Table 7. GTLED Testing Groups. The tests are divided into groups, which separate the GTLED lights into distinctive categories based on their respective wattage, color, and color temperature.

#### **2.1.2.1 GTLED Photometric and Electrical Setup**

GTLED-PES consists of placing the GTLED tube within an integrating sphere and measuring its electrical and photometric data during operation. GTLED-PES data was taken utilizing the SMS-500 Spectrometer by the CLTC team. Measurements were done in accordance with LM-79-19 ANSI Standard for Optical and Electrical Measurements of Solid-State Lighting Products. Electrical characteristics were taken during operation of each lamp, and harmonic power data was logged by the Yokogawa PZ4000 Power Analyzer.

| Type        | Parameter       | Device               |
|-------------|-----------------|----------------------|
| Photometric | Light Output    | SMS-500 Spectrometer |
| Photometric | CCT             | SMS-500 Spectrometer |
| Photometric | Duy             | SMS-500 Spectrometer |
| Photometric | CRI             | SMS-500 Spectrometer |
| Photometric | Efficacy        | SMS-500 Spectrometer |
| Photometric | Percent Flicker | SMS-500 Spectrometer |
| Photometric | Flicker Index   | SMS-500 Spectrometer |
| Electrical  | HOB0 Power      | ONSET HOB0           |
| Electrical  | HOB0 Voltage    | ONSET HOB0           |
| Electrical  | HOB0 Current    | ONSET HOB0           |

Table 8. GTLED-PES Parameters tested.

#### 2.1.2.1.1 GTLED-PES Measurement Method

Testing for GTLED-PES is completed by CLTC and consisted of:

- Identify GTLED tube to be tested and installing within test chamber.
- Conduct photometric and electrical testing and record data.
- Aggregate and display data for analysis.

#### 2.1.2.2 GTLED Thermal and Electrical Setup 1

GTLED-TES1 consists of a GTLED tube held centrally within an insulated chamber, with power and thermocouple leads fed into an insulated container/chamber via an attached gasket. The test consists of three temperature data collection points and electrical measurements. Physical locations for data collection were determined by powering the GTLED and using a FLIR C5 MSX Thermal Imaging Camera, Figure 7, to determine the optimum location to capture thermal characteristics. Figure 8, illustrates the locations above and below the GTLED power inlet, which were determined to be optimal locations for thermal data collection as identified in the thermal imaging. The third thermal data collection point is ambient air temperature at the center of the chamber. The total electrical characteristics are collected by the BK Precision 9803 AC Power Supply interfaced with collection software, whereas the GTLED specific electrical characteristics are collected by the ONSET HOB0 Plug Load Logger interfaced with its collection software.

As illustrated in Figure 8, all temperature data was measured in Celsius with K-type thermocouples which are interfaced with a National Instruments (NI) TB-9212 Module attached to a NI cDAQ-9185, which allows for collection of thermal data via data collection software. All electrical data was measured by a BK Precision 9803 AC Power Supply, and verified with an ONSET HOBO Plug Load Logger, which each collected Voltage, Amperage, and Power. Data collection software and data manipulation techniques were used to analyze the data, and compare power consumed with thermal rise of both the G-LED and its surrounding environment, to determine the effectiveness of the G-LEDs.

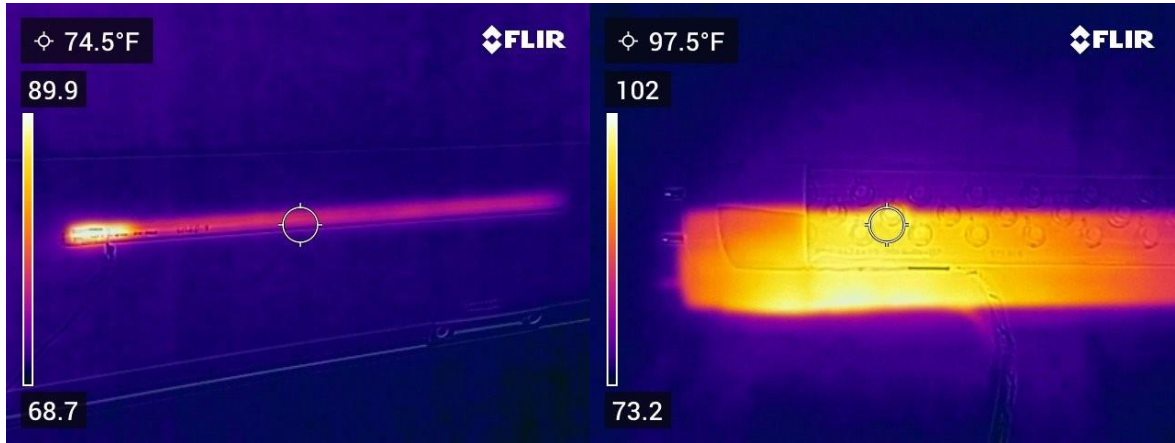


Figure 7. FLIR C5 MSX Thermal Image of Graphene Tube LED (GTLED) tube lamp. It is important to note the non-uniform thermal profile of the lamp. This is due to the heat produced by the LED driver board which is located at the power inlet of the LED tube lamp.

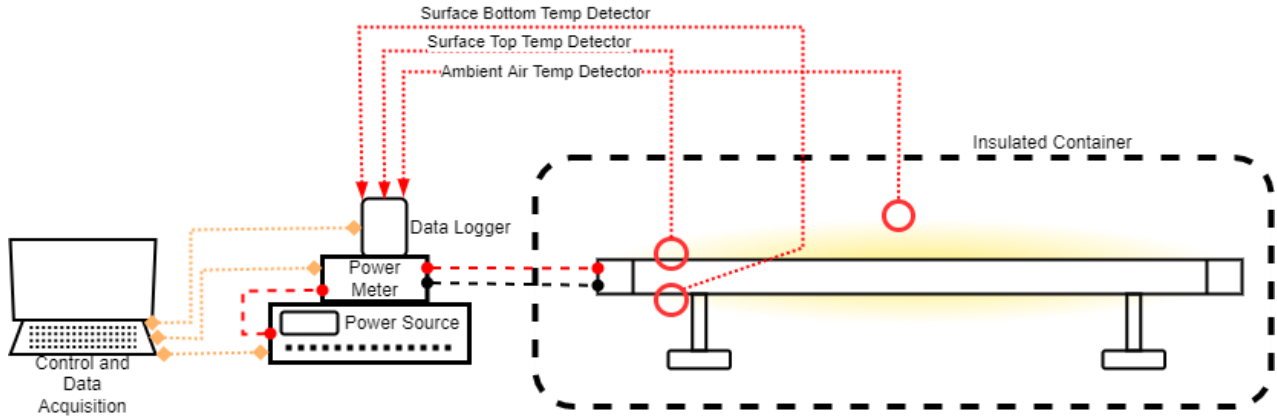


Figure 8. GTLED Setup 1. Locations of the thermocouples are indicated by red circles. The temperature below and above the LED driver were logged with the National Instruments data acquisition device. A third thermocouple was positioned of the centroid on the GTLED to determine the heat dumped into the insulated container environment.

| Type        | Parameter               | Device            |
|-------------|-------------------------|-------------------|
| Temperature | Ambient Air Temperature | NI cDAQ-9185      |
| Temperature | GTLED Top               | NI cDAQ-9185      |
| Temperature | GTLED Bottom            | NI cDAQ-9185      |
| Electrical  | Power Supply Power      | BK Precision 9803 |
| Electrical  | Power Supply Voltage    | BK Precision 9803 |
| Electrical  | Power Supply Current    | BK Precision 9803 |
| Electrical  | HOB0 Power              | ONSET HOB0        |
| Electrical  | HOB0 Voltage            | ONSET HOB0        |
| Electrical  | HOB0 Current            | ONSET HOB0        |

Table 9. GTLED-TES1 Parameters.

#### 2.1.2.2.1 GTLED-TES1 Measurement Method

Testing for GTLED-TES1 is completed by conducting a 60-minute run, which consists of:

- Identify GTLED to be tested and installing within test chamber.
- Set up software and physical test setup, ensuring thermal isolation chamber is isolated.
- Actuate GTLED Power and begin collecting Power Supply, HOB0, and Thermal Data.
- Monitor test while being conducted.
- Complete test and save aggregated data.

#### 2.1.2.3 GTLED Thermal and Electrical Setup 2

The FLIR C5 MSX Thermal Imager identified non-uniform heat production in the GTLED. Therefore, to investigate further, GTLED-TES2 consists of a GTLED tube held centrally within an insulated chamber, with power and thermocouple leads fed into the chamber via an attached gasket. The test consists of three temperature data collection points and electrical measurements contacted to the GTLED Driver Board that has been removed from the tube lamp sheathing, Figure 9. Utilizing thermal imaging again, the locations on the GTLED Driver Board, and GTLED PCB were determined to be optimal locations for thermal data collection. The third thermal data collection point acted as ambient air temperature at the center of the chamber. The total electrical characteristics were collected by the AC Power Supply interfaced with collection software, whereas the GTLED specific electrical

characteristics are collected by the ONSET HOBO Plug Load Logger interfaced with its collection software. Data collection devices were the same as in the GTLED-TES1.

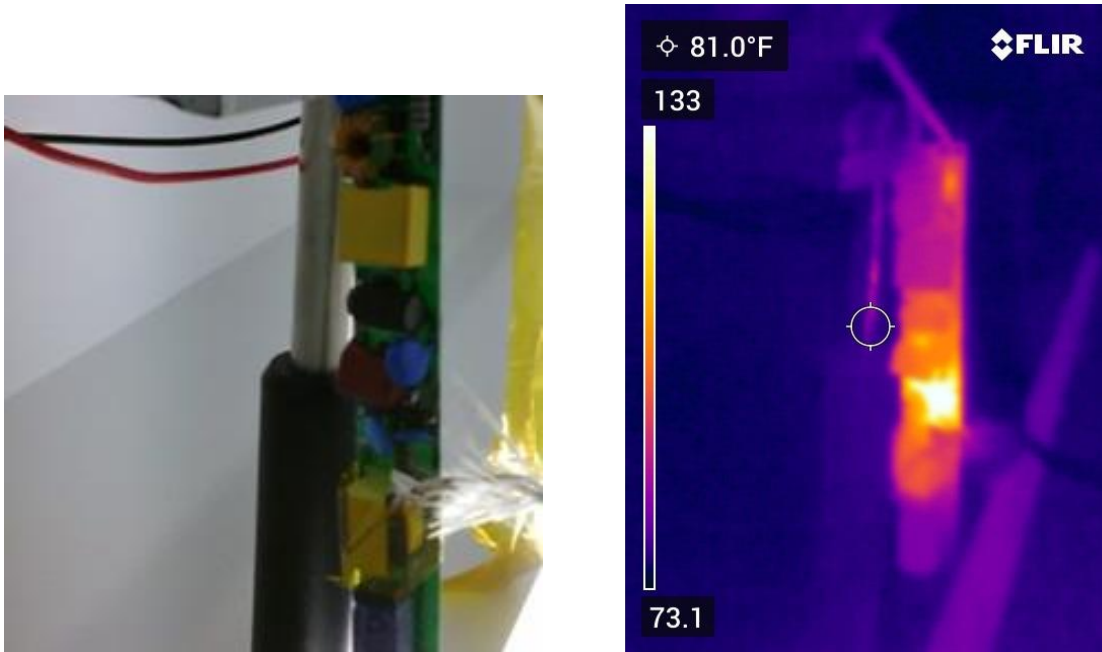


Figure 9. (Left) GTLED Driver removed from tube lamp sheathing and (Right) FLIR Image illustrating non-uniform heat distribution on LED Driver Board.

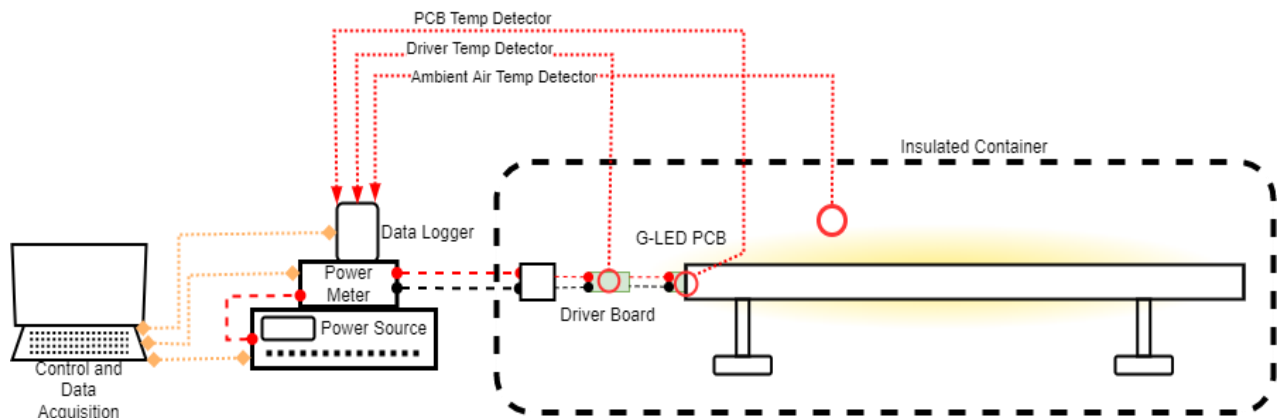


Figure 10. GTLED Setup 2. Locations of the thermocouples are indicated by red circles. The temperature on the Drive Board and on the LED PCB were logged with the National Instruments data acquisition device. A third thermocouple was positioned on the centroid of the GTLED to determine the heat dumped into the insulated container environment.

| Type        | Parameter               | Device            |
|-------------|-------------------------|-------------------|
| Temperature | Ambient Air Temperature | NI cDAQ-9185      |
| Temperature | GTLED Driver Surface    | NI cDAQ-9185      |
| Temperature | GTLED PCB               | NI cDAQ-9185      |
| Electrical  | Power Supply Power      | BK Precision 9803 |
| Electrical  | Power Supply Voltage    | BK Precision 9803 |
| Electrical  | Power Supply Current    | BK Precision 9803 |
| Electrical  | HOB0 Power              | ONSET HOB0        |
| Electrical  | HOB0 Voltage            | ONSET HOB0        |
| Electrical  | HOB0 Current            | ONSET HOB0        |

Table 10. GTLED-TES2 Parameters.

#### 2.1.2.3.1 GTLED-TES2 Measurement Method

Testing for Setup 2 is completed by conducting a 60-minute run, which consists of:

- Identify GTLED to be tested and installing within test chamber.
- Set up software and physical test setup, ensuring thermal isolation chamber is isolated.
- Actuate GTLED Power and begin collecting Power Supply, HOB0, and Thermal Data.
- Monitor test while being conducted.
- Complete test and save aggregated data.

## 2.2 MATERIALS LIST

### 2.2.1 Shared Equipment

#### 2.2.1.1 California Instruments 751iX

The power source used for initial electrical characteristics of the A19 Lamps was the California Instruments 751iX AC Power Supply, which has up to 150/300 Vrms and 6.5/3.25 Arms Lo/Hi outputs respectively.

#### 2.2.1.2 Yokogawa PZ4000

Initial electrical power analysis for the A19 Lamps was conducted with a Yokogawa PZ4000 Power Analyzer, which enabled power detection, as well as total harmonic distortion measurements via its Harmonics mode.

#### **2.2.1.3 SMS-500 Spectrometer**

The photometric properties were taken by an SMS-500 Spectrometer, which enabled chromaticity, directional flux, luminance and radiance contrasts.

#### **2.2.1.4 ONSET HOBO**

The load data logger was the ONSET HOBO Plug Load Data Logger, which boasts a 0.5% RMS Voltage and Current, as well as active power accuracy up to 14 Amps (continuous). Its logging and data collection are completed through included device software and was exported to MATLAB for data processing.

#### **2.2.1.5 National Instruments**

The data acquisition used was the National Instruments cDAQ-9185 system, which is rated to 127 samples per slot with a 32-bit resolution. Its attached module was the NI TB-9212 Module, which offers up to 0.01 C measurement sensitivity.

#### **2.2.1.6 MATLAB**

To allow of remote control and data logging, MATLAB was used for the major portion of the code base with commands and data gathering conducted through a GPIB Interface. Python was used for data cleaning in conjunction with MATLAB.

#### **2.2.1.7 FLIR C5 MSX**

For identification of optimal thermal performance testing location, the FLIR C5 MSX was used, a 5MP thermal imaging camera with 3°C accuracy, and <70mK thermal sensitivity.

### **2.2.2 A19 Test Equipment**

#### **2.2.2.1 A19 Lamp**

The tested non-graphene LED A19 lamp was the PRO-ELEC 8W 2700K LED Filament Light Lamp, which is rated for 950lm luminous flux.

#### **2.2.2.2 GA19 Lamp**

The tested graphene LED A19 lamp was the Sera Technologies 8W 2700K LED Filament Lamp, which is rated to 800lm luminous flux.

### **2.2.3 GTLED Test Equipment**

#### **2.2.3.1 Graphene LED Lighting Tube**

The target for graphene LED tube lighting testing is the LEDi2, I2-ST-T8 brand of lighting, concentrated on the 9W4K, 9W5K, 18W3K, 18W5K variants. They are rated as having a 0.95 or above power factor.

#### **2.2.3.2 BK Precision 9803**

The power source used was the BK Precision 9803 AC Power Source, which is rated to supply up to 300V, with 12A(rms) and notably has the option to interface through GPIB to control output and record active data, including power, voltage, and amperage.

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## 3. RESULTS

### 3.1 RESULTS

The following section describes the results of the GA19 and GTLED tests.

#### 3.1.1 A19 Key Findings

Tests and characterization of the GA19 lamps by CLTC determined that the overall results of the GA19 lamp were significantly better than that of the average A19 lamp in the DLC Database. With this information, comparative experiments were performed subsequently on both the GA19 lamp and a market representative A19 lamp. The analyzed data showcased the relative improvements of graphene enhanced lighting with this type of lamp. Overall, the GA19 lamp operated 11% cooler than the non-graphene A19 variant.

##### 3.1.1.1 A19-PES Results

Table 11 and Table 12 illustrate the photometric data measured by CLTC's Integrating Sphere Test. The GA19 lamp efficacy, which is a measure of how well a source is able to produce visible light as compared to its power usage, averaged 115 lm/W for the 2-degree tests and 122 lm/W for the 10-degree tests. This greatly outmatched most of the A19 lamps on the DLC and Energy Star Databases. The power factor for each of the tested lamps was an average of 0.8, shown in Table 13, which indicated the lamps worked on par with average A19 lamps on the market. This data showed the potential of the graphene enhanced lighting, given the photometric data outperformed traditional A19 lamps. With this data, a test method was devised to compare the thermal performance of the lamps.

| Photometric 1931 2° |         |           |                   |         |         |     |                 |                     |               |
|---------------------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| Lamp                | Power % | Power (W) | Light Output (lm) | CCT (K) | Du      | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| Sera Technologies1  | 100     | 7.60      | 878               | 2749    | -0.0014 | 82  | 115.53          | 27.96               | 0.08          |
| Sera Technologies2  | 100     | 7.59      | 823               | 2758    | -0.0014 | 82  | 108.43          | 27.35               | 0.08          |
| Sera Technologies3  | 100     | 7.61      | 875               | 2771    | -0.0018 | 82  | 114.98          | 29.84               | 0.09          |
| Sera Technologies4  | 100     | 7.58      | 838               | 2743    | -0.0009 | 82  | 110.55          | 28.16               | 0.08          |
| Sera Technologies5  | 100     | 7.8       | 876               | 2780    | -0.0025 | 82  | 115.57          | 28.7                | 0.08          |
| Sera Technologies6  | 100     | 7.39      | 867               | 2746    | -0.0020 | 82  | 117.32          | 29.83               | 0.09          |
| Sera Technologies7  | 100     | 7.36      | 857               | 2754    | -0.0019 | 82  | 116.44          | 30.61               | 0.09          |
| Sera Technologies8  | 100     | 7.43      | 884               | 2750    | -0.0020 | 82  | 118.98          | 29.62               | 0.09          |

|                     |     |      |     |      |         |    |        |       |      |
|---------------------|-----|------|-----|------|---------|----|--------|-------|------|
| Sera Technologies9  | 100 | 7.43 | 869 | 2766 | -0.0027 | 82 | 116.96 | 29.11 | 0.09 |
| Sera Technologies10 | 100 | 7.37 | 855 | 2745 | -0.0012 | 82 | 116.01 | 30.34 | 0.09 |

Table 11. A19 2° Filament Lamp Testing.

| Photometric 2015 10° |         |           |                   |         |         |     |                 |                     |               |
|----------------------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| Lamp                 | Power % | Power (W) | Light Output (lm) | CCT (K) | Du      | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| Sera Technologies1   | 100     | 7.60      | 933               | 2707    | -0.0020 | 82  | 122.76          | 27.96               | 0.08          |
| Sera Technologies2   | 100     | 7.59      | 875               | 2718    | -0.0016 | 82  | 115.28          | 27.35               | 0.08          |
| Sera Technologies3   | 100     | 7.61      | 928               | 2718    | -0.0028 | 82  | 121.94          | 29.84               | 0.09          |
| Sera Technologies4   | 100     | 7.58      | 892               | 2706    | -0.0008 | 82  | 117.68          | 28.16               | 0.08          |
| Sera Technologies5   | 100     | 7.58      | 931               | 2736    | -0.0031 | 82  | 122.82          | 28.70               | 0.08          |
| Sera Technologies6   | 100     | 7.39      | 920               | 2696    | -0.0029 | 82  | 124.49          | 29.83               | 0.09          |
| Sera Technologies7   | 100     | 7.36      | 910               | 2706    | -0.0026 | 82  | 123.64          | 30.61               | 0.09          |
| Sera Technologies8   | 100     | 7.43      | 939               | 2703    | -0.0028 | 82  | 126.38          | 29.62               | 0.09          |
| Sera Technologies9   | 100     | 7.43      | 939               | 2723    | -0.0033 | 82  | 126.38          | 29.11               | 0.09          |
| Sera Technologies10  | 100     | 7.37      | 909               | 2706    | -0.0014 | 82  | 123.34          | 30.34               | 0.09          |

Table 12. A19 10° Filament Lamp Testing.

| Lamp               | Power % | Voltage (V) | Current (A) | Power (W) | Power Factor | UTHD % | ITHD % |
|--------------------|---------|-------------|-------------|-----------|--------------|--------|--------|
| Sera Technologies1 | 100     | 230.2       | 0.0416      | 7.60      | 0.7938       | 0.06   | 55.54  |
| Sera Technologies2 | 100     | 229.64      | 0.0416      | 7.59      | 0.7947       | 0.06   | 55.40  |

|                     |     |        |        |      |        |      |       |
|---------------------|-----|--------|--------|------|--------|------|-------|
| Sera Technologies3  | 100 | 230.28 | 0.0416 | 7.61 | 0.7940 | 0.06 | 55.57 |
| Sera Technologies4  | 100 | 230.28 | 0.0414 | 7.58 | 0.7949 | 0.07 | 55.45 |
| Sera Technologies5  | 100 | 230.30 | 0.0414 | 7.58 | 0.7944 | 0.07 | 55.59 |
| Sera Technologies6  | 100 | 220.26 | 0.0418 | 7.39 | 0.8021 | 0.06 | 54.97 |
| Sera Technologies7  | 100 | 220.28 | 0.0416 | 7.36 | 0.8028 | 0.07 | 54.94 |
| Sera Technologies8  | 100 | 220.30 | 0.0421 | 7.43 | 0.8021 | 0.07 | 55.26 |
| Sera Technologies9  | 100 | 220.27 | 0.0420 | 7.43 | 0.8032 | 0.07 | 54.75 |
| Sera Technologies10 | 100 | 220.29 | 0.0416 | 7.37 | 0.8035 | 0.07 | 54.48 |

Table 13. A19 Electrical Characteristics.

### 3.1.1.2 A19-TES Results

We followed the test methods for A19 lamps as described in section 2.1.1.2 to conduct thermal and electrical data capture over a 120-minute test period. The GA19 (Sera Technologies) lamp and the non-graphene A19 (PROELEC) lamp results are shown in Figure 11 and 12. As a reminder, thermal measurements were taken from the following:

- Base: thermocouple contacted the lighting fixture
- Side: thermocouple sat horizontally in line with the LEDs
- Top: thermocouple at peak of the lamp structure
- Ambient: thermocouple floating inside the test chamber.

The data collected from these four different measurement sites are aggregated and compared between GA19 and A19 lamps, to determine the effect of the graphene on thermal performance. In Figure 11, the data collected from the non-graphene A19 lamp shows the saturation temperature data of the Base at around 76°C, the Side at around 50°C, and the Top around 56°C. The active power and power factor fluctuate due to temperature saturation over time are also presented to monitor the electrical characteristics to compare to that of the electrical and photometric test.

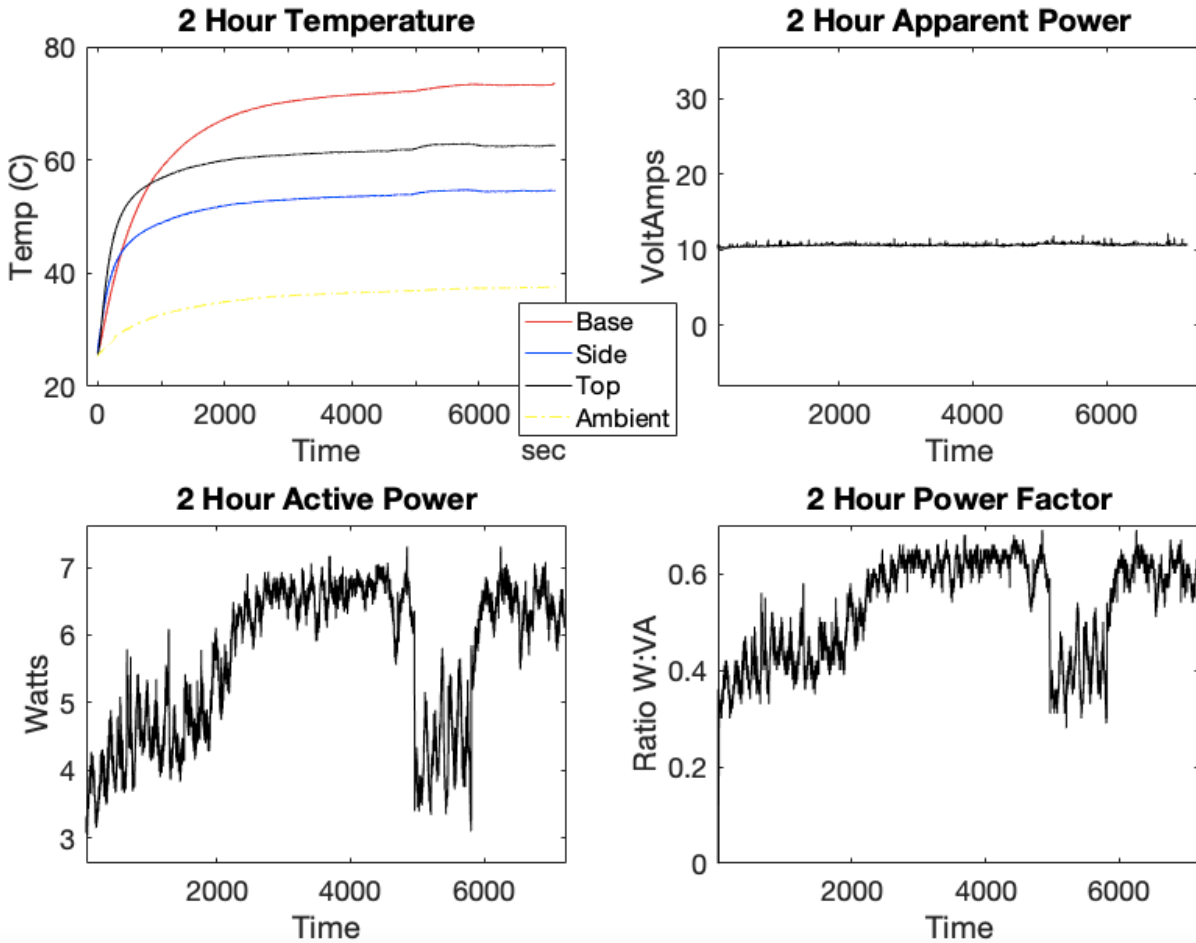


Figure 11. Non-Graphene A19 (PRO-ELEC) Thermal and Electrical Plots.

Additionally, an identical test was then performed on the GA19 lamp for the comparison. Analyzing the saturation temperature data in Figure 12 shows a temperature of the Base at around 56°C at the Side at around 48°C, and the Top around 55°C.

When compared to the non-graphene A19 variant, the GA19 lamp clearly operated with the Base significantly cooler, by around 20°C, signifying an overall cooler operating A19 lamp. The Side and Top also operated at a cooler temperature, with the Base that operated at a larger temperature difference. We have reason to believe, the lower temperature performance at the Side and Top indicated the graphene addition to the LED lamps played an important role in distributing the heat away from the LEDs to the Base. Due to the unique nature of graphene, the thermal conductivity is higher, and potentially allows graphene to effectively conduct heat. We believe this is the reason for the significantly lowered temperatures. With the relation between operating temperature and its potential impact on the lifetime of LED operation, we can conclude that this lowered operating temperature of the GA19 lamp may play a significant role in extending the overall operating life of the product, therefore, somewhat validating the ~65,000 hours lifecycle claimed by the vendor. However, this is our hypothesis and until a lifecycle test can be performed, this is still just a claim. It is also good to note that the LEDs in the Sera Technologies lamp may also be of significantly higher quality in all aspects, therefore, potentially producing less heat than the non-graphene variant.

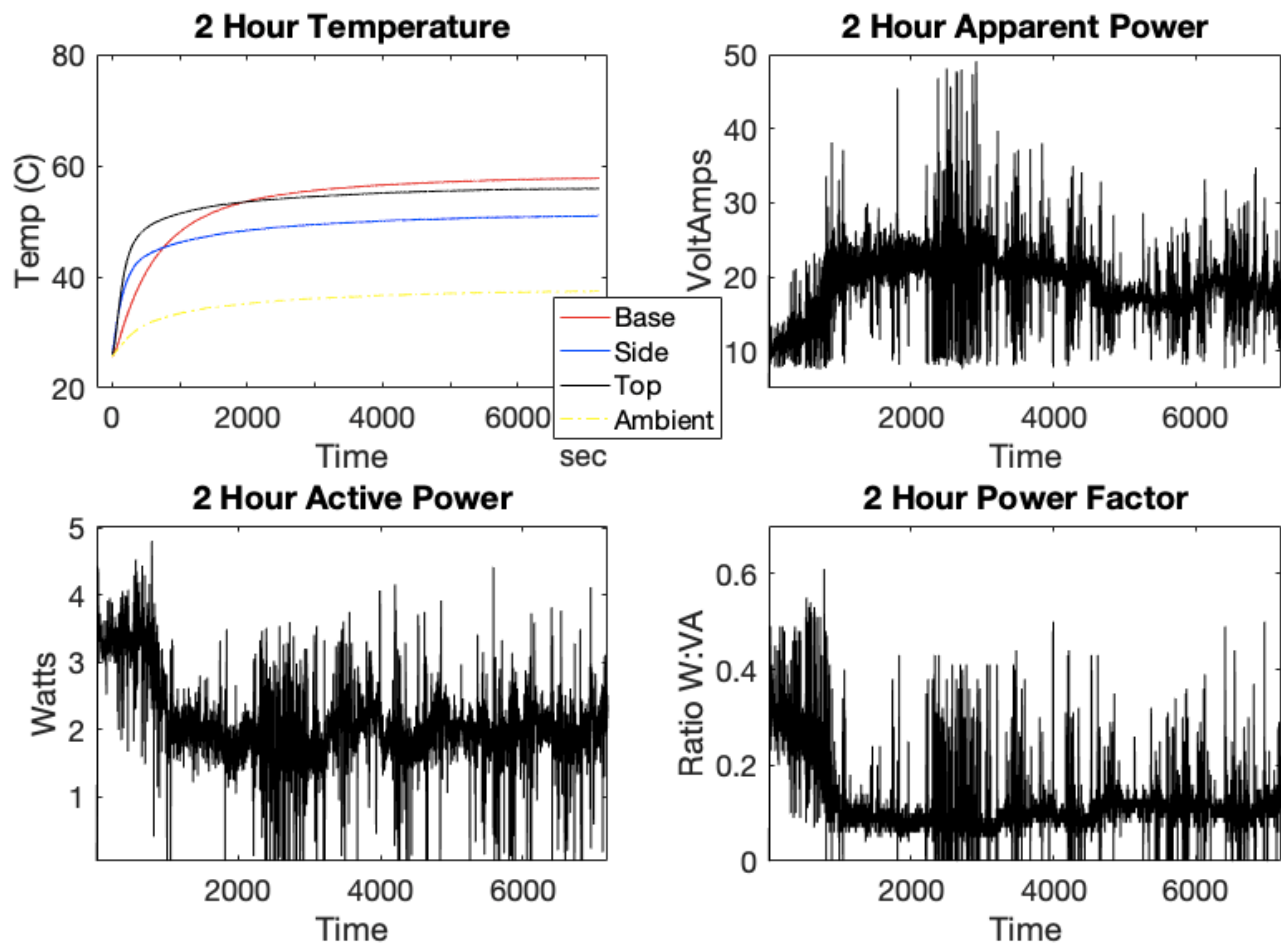


Figure 12. Graphene A19 (Sera Technologies) Thermal and Electrical Plots.

### 3.1.2 GTLED Group A Key Findings

The results of the GA19 testing showcased the potential benefits of graphene enhanced lighting for task lighting applications. To enable the relevance and impact desired for military applications, we needed to test the alternate form factor, the T8 tube style lamps used in various naval applications, to determine whether the benefit of graphene enhancement would also be apparent. This was at the request of NAVFAC.

As a reminder, our performance test for the GTLEDs were broken up into four separate testing groups as described Table 7 that separate the GTLED lights into distinctive categories based on their respective wattage, color, and color temperature. The Group A category represents the relative lower powered range of graphene enhanced T8 lamps that are available on the market. With a power averaging 9.5 Watts, these lamps operated with a very consistent power factor of 0.95 between the lot.

Each GTLED was characterized by CLTC and the data was compared to the DLC Qualified Product List. Photometric data, when compared, was mid to average quality, and showed no apparent benefit from the addition of graphene. Thermal data was compared to GTLEDs of similar properties, and showed relatively consistent operating characteristics within the same Group.

#### 3.1.2.1 GTLED-PES Group A Results

During our test, variations between the test methods was determined based on the electrical data associated with each test. Variations included the average of the PES test power, voltage, and current independently compared to the average of either the TES1 electrical test results, or TES2 electrical test results, with result variations averaged to determine the result. When electrical data was compared for Group A between the PES testing, the variation between the results was 0.36% and 0.55 % for TES1 and TES2 respectively.

| Electrical Characteristics |              |                |                |              |
|----------------------------|--------------|----------------|----------------|--------------|
| GTLED                      | Power<br>(W) | Voltage<br>(V) | Current<br>(A) | Power Factor |
| 2                          | 9.57         | 120.09         | 0.0834         | 0.9559       |
| 6                          | 9.51         | 120.07         | 0.0829         | 0.9554       |
| 7                          | 9.48         | 120.09         | 0.0826         | 0.9549       |

Table 14. Group A Electrical Characteristics.

| Thermal Testing Electrical Characteristics |       |                   |                     |                     |                      |
|--------------------------------------------|-------|-------------------|---------------------|---------------------|----------------------|
| GTLED                                      | Setup | Average Power (W) | Average Voltage (V) | Average Current (A) | Percent Deviation(%) |
| 2                                          | 1     | 9.58              | 120.09              | 0.0826              | 0.2849               |
| 2                                          | 2     | 9.53              | 120.11              | 0.0822              | 0.6134               |
| 6                                          | 1     | 9.51              | 120.11              | 0.0821              | 0.3106               |
| 6                                          | 2     | 9.49              | 120.13              | 0.0818              | 0.4957               |
| 7                                          | 1     | 9.46              | 120.09              | 0.0816              | 0.4739               |
| 7                                          | 2     | 9.45              | 120.12              | 0.0815              | 0.5411               |

Table 15. Group A Thermal Testing Electrical Characteristics.

The photometric results of Group A, are shown in Table 16 and indicated an efficacy that averaged 145 lm/W, which was only slightly above the average of 135 lm/W of all similar products in DLC Qualified List. While efficacy did not display any clear improvements compared to similarly powered products, the thermal characteristics were still necessary to facilitate a full understanding of the GTLED characteristics. Upon inspection of the GTLEDs under infrared imaging, we noted a substantially raised temperature located at the end of the GTLED, where the LED driver boards were located. This information formed the basis for separating our further test into two sections, TES1 and TES2 as described in section 2.1.2.

| Filament Lamp Testing |        |         |           |                   |         |         |     |                 |                     |               |
|-----------------------|--------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| GTLED                 | Degree | Power % | Power (W) | Light Output (lm) | CCT (K) | Duv     | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| 2                     | 2      | 100     | 9.57      | 1349              | 3938    | -0.002  | 69  | 140.96          | 75.55               | 0.24          |
| 2                     | 10     | 100     | 9.57      | 1433              | 3743    | -0.0076 | 69  | 149.74          | 75.55               | 0.24          |
| 6                     | 2      | 100     | 9.51      | 1336              | 3933    | -0.0018 | 69  | 140.48          | 74.95               | 0.24          |
| 6                     | 10     | 100     | 9.51      | 1419              | 3737    | -0.0075 | 69  | 149.21          | 74.95               | 0.24          |
| 7                     | 2      | 100     | 9.48      | 1331              | 3948    | -0.0021 | 69  | 140.40          | 75.34               | 0.24          |
| 7                     | 10     | 100     | 9.48      | 1414              | 3752    | -0.0078 | 69  | 149.16          | 75.34               | 0.24          |

Table 16. Group A Filament Lamp Testing.

### 3.1.2.2 GTLED-TES1 Group A Results

The thermal test setup as described in Section 2.1.2.2, placed thermocouples above and below the substantially warmer producing region of the GTLED tube lamp. The test was conducted for one hour, and thermocouple data was recorded for the bottom, top, and ambient temperature inside of the test chamber. With this thermal analysis, our temperature profiles were compared to GTLEDs with similar wattage and light output vice a direct comparison of GTLEDs and traditional T8 lamps. This decision was due to the relatively average performance of the photometric data as well as limited sourcing of T8 tube style lamps. From our thermal data, we determined that the GTLED Bottom and GTLED Top locations, shown in Figure 13 and Figure 14 respectively, showed very consistent performance with their similar counterparts. We also determined the overall rise in temperature for both are very similar, with the Bottom going from 25C to 40C, and the Top going from 25C to 40C. This indicated that the lamp differences for this particular model was minimal. The relative consistency of the Top and Bottom thermocouples did not identify what precisely was generating the large heat signature on the GTLED. However, we had some indication that the hot area was the location of the LED driver board.

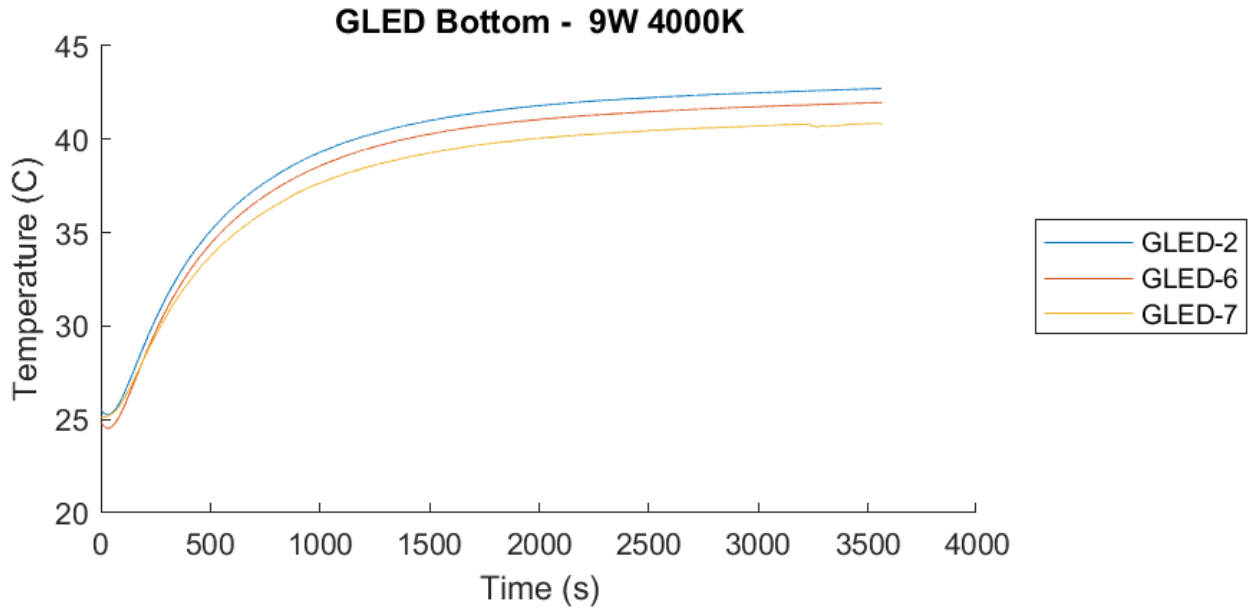


Figure 13. GTLED-TES1 Group A Bottom Temperature.

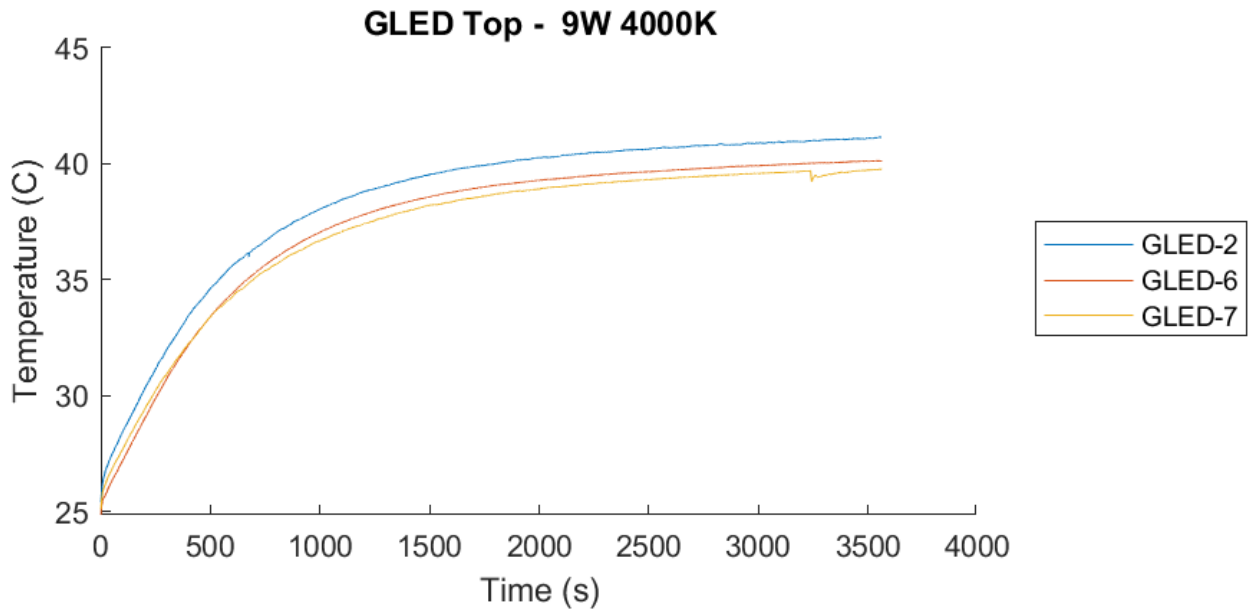


Figure 14. GTLED-TES1 Group A Top Temperature.

### 3.1.2.3 GTLED-TES2 Group A Results

It is important to note the LED Driver produces heat in a LED lamp. Therefore, to determine which component was operating with a higher temperature, the GTLEDs were disassembled, and a thermal testing setup was used as described in Section 2.1.2.3, to quantify the heat generation. This test was conducted for one hour, with the Driver Board and PCB being the focus. Once complete, the data determined that the LED Driver operated at a higher relative temperature than the PCB, shown in Figure 15 and Figure 16. For this test, GTLED-2 had a lower temperature than its counterparts, potentially due to opening the GTLED housing for test performance.

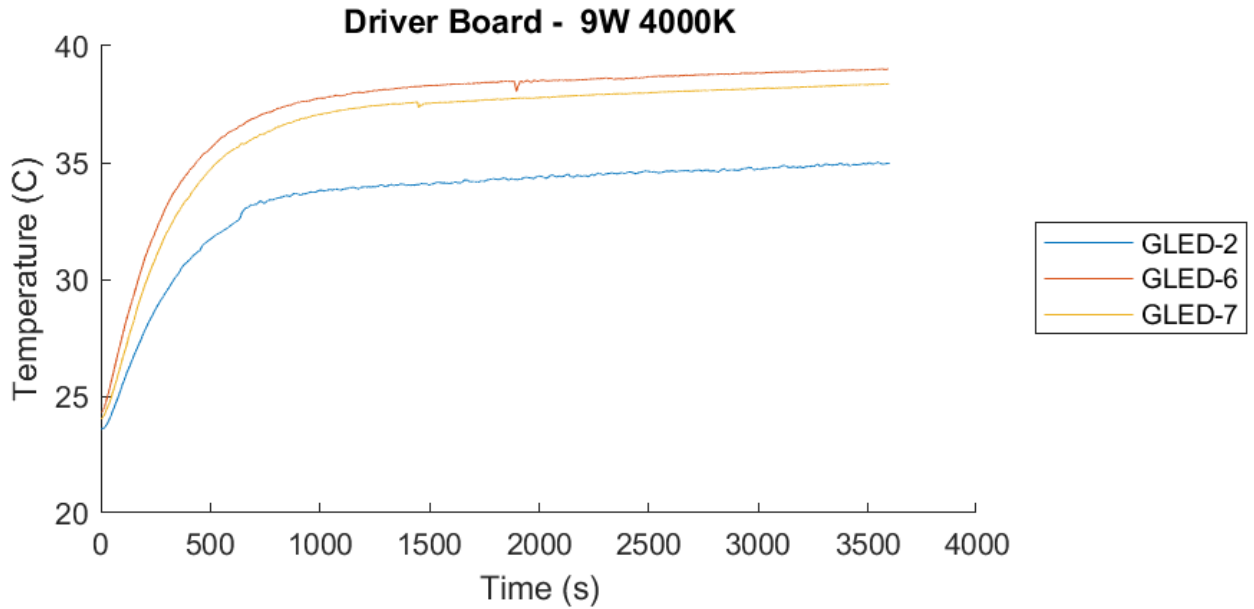


Figure 15. Group A Setup 2 GTLED Driver Board Temperature.

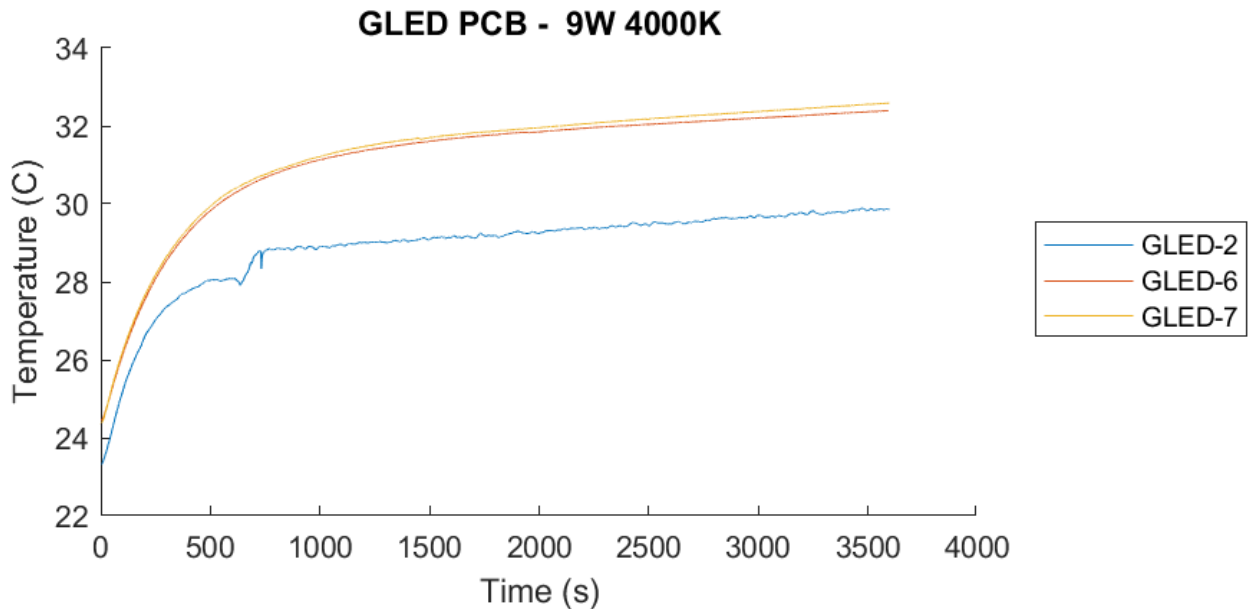


Figure 16. Group A Setup 2 GTLED PCB Temperature.

### 3.1.3 GTLED Group B Key Findings

As a reminder, our performance test for the GTLEDs were broken up into four separate testing groups as described Table 7 that separate the GTLED lights into distinctive categories based on their respective wattage, color, and color temperature. The Group B category represents the relative lower powered range of T8 lamps available on the market, similar to Group A., with a slightly higher Color Temperature of 5000K. With a power averaging 9.5 Watts, these lamps operated with a very consistent power factor of 0.95 between the lot. Each GTLED was characterized by CLTC and the data was compared to the DLC Qualified Product List. Photometric data, when compared, was mid to high

quality, and showed no apparent benefit from the addition of graphene. Thermal data was compared to GTLEDs of similar properties and showed slight deviation of temperature rise between the different GTLEDs. This indicated manufacturing variation between lamps.

### 3.1.3.1 GTLED-PES Group B Results

The electrical data was compared for Group B between the PES testing shown in Table 17, and the TES test methods, shown in Table 18. The variation between the results was 0.45% and 0.72 % for TES1 and TES2 respectively.

| Electrical Characteristics |           |             |             |              |
|----------------------------|-----------|-------------|-------------|--------------|
| GTLED                      | Power (W) | Voltage (V) | Current (A) | Power Factor |
| 1                          | 9.53      | 120.07      | 0.0830      | 0.9559       |
| 3                          | 9.67      | 120.09      | 0.0844      | 0.9547       |
| 10                         | 9.77      | 120.09      | 0.0852      | 0.9547       |
| 13                         | 9.63      | 120.10      | 0.0839      | 0.9556       |

Table 17. Group B Electrical Characteristics.

| Thermal Testing Electrical Characteristics |       |                   |                     |                     |                   |
|--------------------------------------------|-------|-------------------|---------------------|---------------------|-------------------|
| GTLED                                      | Setup | Average Power (W) | Average Voltage (V) | Average Current (A) | Percent Deviation |
| 1                                          | 1     | 9.53              | 120.10              | 0.0822              | 0.3130            |
| 1                                          | 2     | 9.49              | 120.15              | 0.0818              | 0.5996            |
| 3                                          | 1     | 9.66              | 120.10              | 0.0835              | 0.6968            |
| 3                                          | 2     | 9.63              | 120.07              | 0.0831              | 0.9650            |
| 10                                         | 1     | 9.76              | 120.10              | 0.0843              | 0.3835            |
| 10                                         | 2     | 9.73              | 120.13              | 0.0840              | 0.5949            |
| 13                                         | 1     | 9.62              | 120.14              | 0.0829              | 0.4208            |
| 13                                         | 2     | 9.57              | 120.11              | 0.0826              | 0.7214            |

Table 18. Group B Thermal Testing Electrical Characteristics.

The photometric results of Group B, shown in Table 19, indicated an efficacy that averaged 198 lm/W, above the average of 135 lm/W of all similar products in the DLC Qualified List. Efficacy did show improvements compared to similarly powered products, and its improvements were considered for full evaluation of potential sourcing.

| Filament Lamp Testing |        |         |           |                   |         |        |     |                 |                     |               |
|-----------------------|--------|---------|-----------|-------------------|---------|--------|-----|-----------------|---------------------|---------------|
| GTLED                 | Degree | Power % | Power (W) | Light Output (lm) | CCT (K) | Duv    | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| 1                     | 2      | 100     | 9.53      | 2036              | 4600    | 0.0329 | 62  | 213.64          | 82.95               | 0.26          |
| 1                     | 10     | 100     | 9.53      | 2146              | 4318    | 0.0237 | 62  | 225.18          | 82.95               | 0.26          |
| 3                     | 2      | 100     | 9.67      | 1841              | 4703    | 0.0297 | 63  | 190.38          | 76.51               | 0.24          |
| 3                     | 10     | 100     | 9.67      | 1943              | 4427    | 0.0204 | 63  | 200.93          | 76.51               | 0.24          |
| 10                    | 2      | 100     | 9.77      | 1797              | 4748    | 0.0289 | 63  | 183.93          | 78.4                | 0.25          |
| 10                    | 10     | 100     | 9.77      | 1899              | 4474    | 0.0197 | 63  | 194.37          | 78.4                | 0.25          |
| 13                    | 2      | 100     | 9.63      | 1778              | 4709    | 0.0297 | 63  | 184.63          | 76.57               | 0.24          |
| 13                    | 10     | 100     | 9.63      | 1878              | 4432    | 0.0205 | 63  | 195.02          | 76.57               | 0.24          |

Table 19. Group B Filament Lamp Testing.

### 3.1.3.2 GTLED-TES1 Group B Results

The thermal test setup as described in Section 2.1.2.2, placed thermocouples above and below the substantially warmer producing region of the GTLED tube lamp. The test was conducted for one hour, and thermocouple data was recorded for the Bottom, Top, and Ambient temperature inside of the test chamber. Thermal measurements determined that the GTLED Bottom and GTLED Top, shown in Figure 17 and Figure 18 respectively, showed inconsistent performance with their similar counterparts. We can also see the overall rise in temperature for both varies with GTLED, with the Bottom ranging from 23C-27C at the start of the test and ending with a range from 32C-40C. The Top started with a range of 23C-30C and ended with a range of 35C-40C. This indicated that the lamp differences for this model is pronounced. The relative inconsistency of the Top and Bottom temperature profiles indicating large variation in manufacturing quality, despite a higher end efficacy.

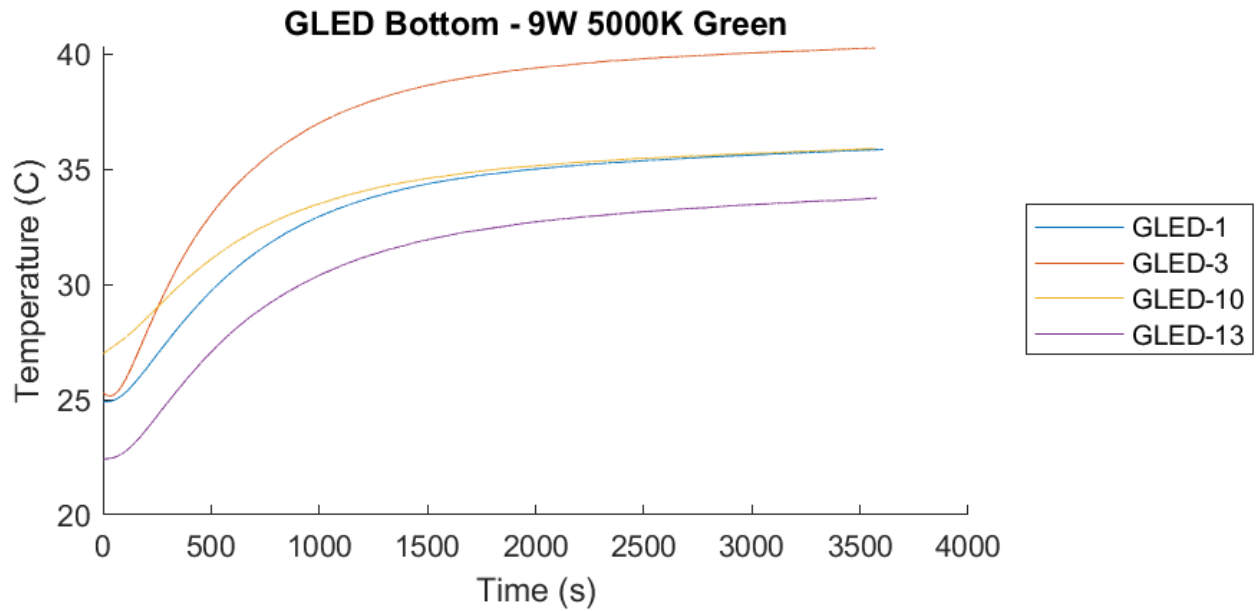


Figure 17. Group B Setup 1 GTLED Bottom Temperature.

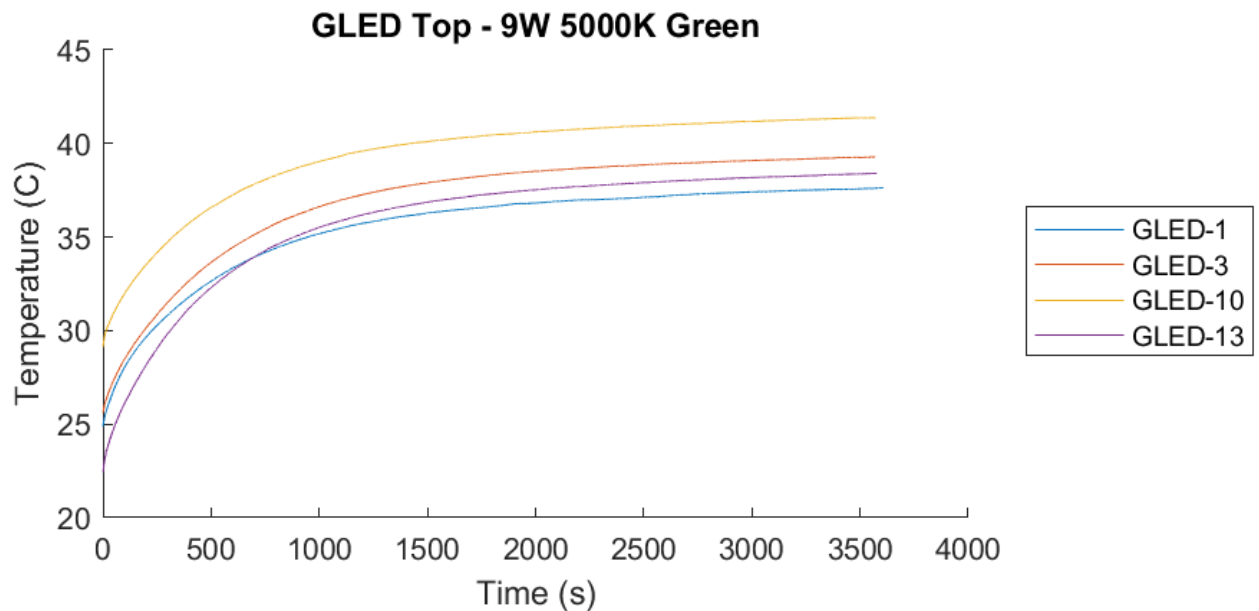


Figure 18. Group B Setup 1 GTLED Top Temperature.

### 3.1.3.3 GTLED-TES2 Group B Results

Similarly, for Setup 2, the GTLED Driver Board and GTLED PCB, shown in Figure 19 and Figure 20 respectively, showed inconsistent performance with their counterparts. We can see the overall rise in temperature for both varies with GTLED, with the Driver Board ranging from 23C-26C at the start of the test and ending with a range from 35C-43C. The PCB started with a range of 22C-25C and ended with a range of 29C-32C. This reinforced the assessment that lamp to lamp variations within manufacturing were pronounced for this Group.

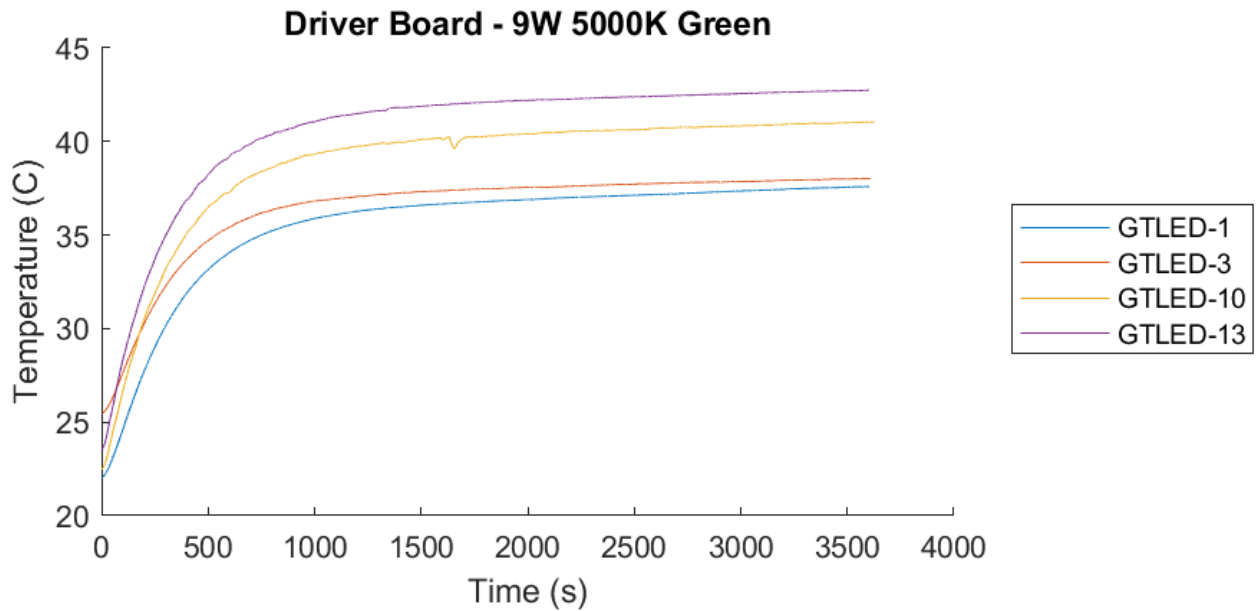


Figure 19. Group B Setup 2 GTLED Driver Board Temperature.

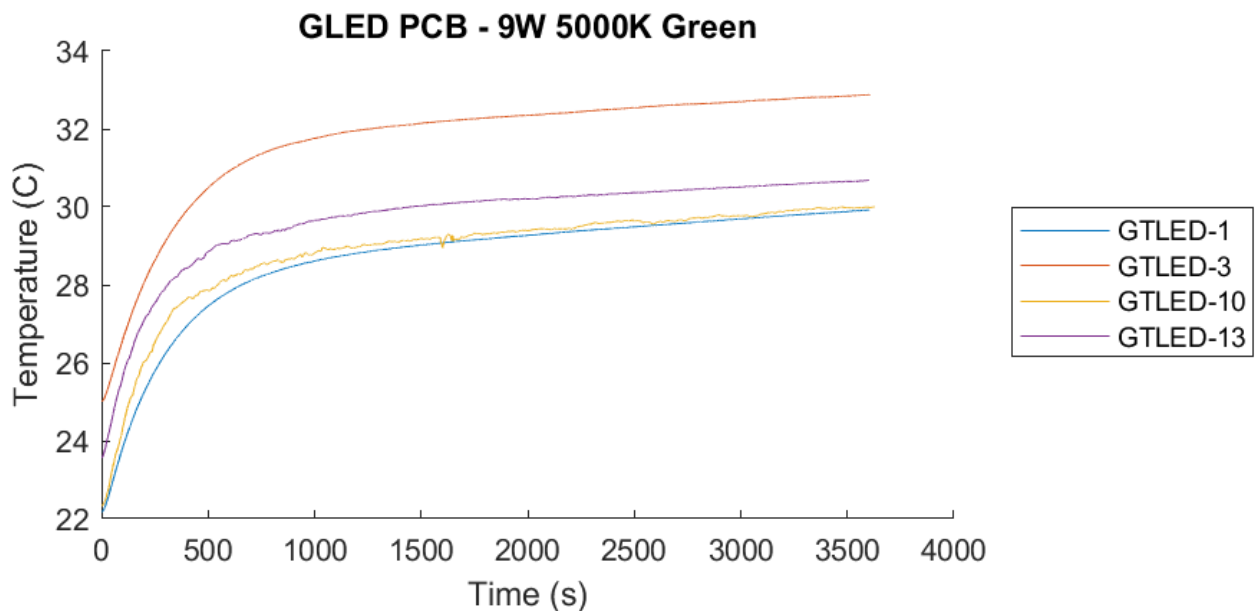


Figure 20. Group B Setup 2 GTLED PCB Temperature.

### 3.1.4 GTLED Group C Key Findings

As a reminder, our performance test for the GTLEDs were broken up into four separate testing groups as described Table 7 that separate the GTLED lights into distinctive categories based on their respective wattage, color, and color temperature. Testing of the GTLED within the Group C category represented the relative higher-powered range of T8 lamps available on the market. With a power averaging 17.6 Watts, this lamp operated with a significantly low power factor of 0.74, which plays a detrimental role in the overall lumen output per watt.

This GTLED was our singular T8 lamp within the category of 18W, 3000K. Photometric data, when compared, was of average quality, and also showed no apparent benefit from the addition of graphene. Thermal data was analyzed and compared to the subsequent group, Group D, and the results displayed a consistent deviation between the operating characteristics in each GTLED lamp, which indicated a high variability for the manufacturing materials used in the production of this model.

### 3.1.4.1 GTLED-PES Group C Results

The electrical data was compared for Group C between the PES testing shown in Table 20, and the TES testing, shown in Table 21, the variation between the results was 9% and 8.48 % for TES1 and TES2 respectively. This deviation between tests indicated that the electrical power consumption varied significantly between tests for higher-powered models. This power deviation can be representative of material and manufacturing margins used within the product itself. For instance, if an included PCB component varied within a 10% value, the subsequent margins for all the other materials would accumulate to have a large range of power consumption.

| Electrical Characteristics |           |             |             |              |
|----------------------------|-----------|-------------|-------------|--------------|
| GTLED                      | Power (W) | Voltage (V) | Current (A) | Power Factor |
| 12                         | 17.78     | 120.74      | 0.1977      | 0.7450       |

Table 20. Group C Electrical Characteristics.

| Thermal Testing Electrical Characteristics |       |                   |                     |                     |                       |
|--------------------------------------------|-------|-------------------|---------------------|---------------------|-----------------------|
| GTLED                                      | Setup | Average Power (W) | Average Voltage (V) | Average Current (A) | Percent Deviation (%) |
| 12                                         | 1     | 17.45             | 120.18              | 0.1489              | 9.0012                |
| 12                                         | 2     | 17.62             | 120.17              | 0.1501              | 8.4830                |

Table 21. Group C Thermal Testing Electrical Characteristics.

The photometric results of Group C, shown in Table 22, indicated an efficacy that averaged 133 lm/W, slightly below the average of 135 lm/W of all similar products in DLC Qualified List. In this case, the efficacy clearly showed poor results when compared to the average product on the market.

| GTLED | Degree | Power % | Power (W) | Light Output (lm) | CCT (K) | Duv     | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
|-------|--------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| 12    | 2      | 100     | 17.78     | 2297              | 3978    | -0.0023 | 69  | 129.19          | 77.44               | 0.25          |
| 12    | 10     | 100     | 17.78     | 2441              | 3780    | -0.008  | 69  | 137.29          | 77.44               | 0.25          |

Table 22. Group C Filament Lamp Testing.

### 3.1.4.2 GTLED-TES1 Group C Results

The thermal test setup as described in Section 2.1.2.2, placed thermocouples above and below the substantially warmer producing region of the GTLED tube lamp. The test was conducted for one hour, and thermocouple data was recorded for the bottom, top, and ambient temperature inside of the test chamber. Thermal measurements determined that the GTLED Bottom and GTLED Top, shown in Figure 21 and Figure 22 respectively, showed a significantly higher rise in temperatures than the lower powered models. When compared to Group D temperature data, this GTLED operated consistent with similarly power models. The rise in temperature for the Bottom was from 25C to 50C and 27C to 54C for the Top.

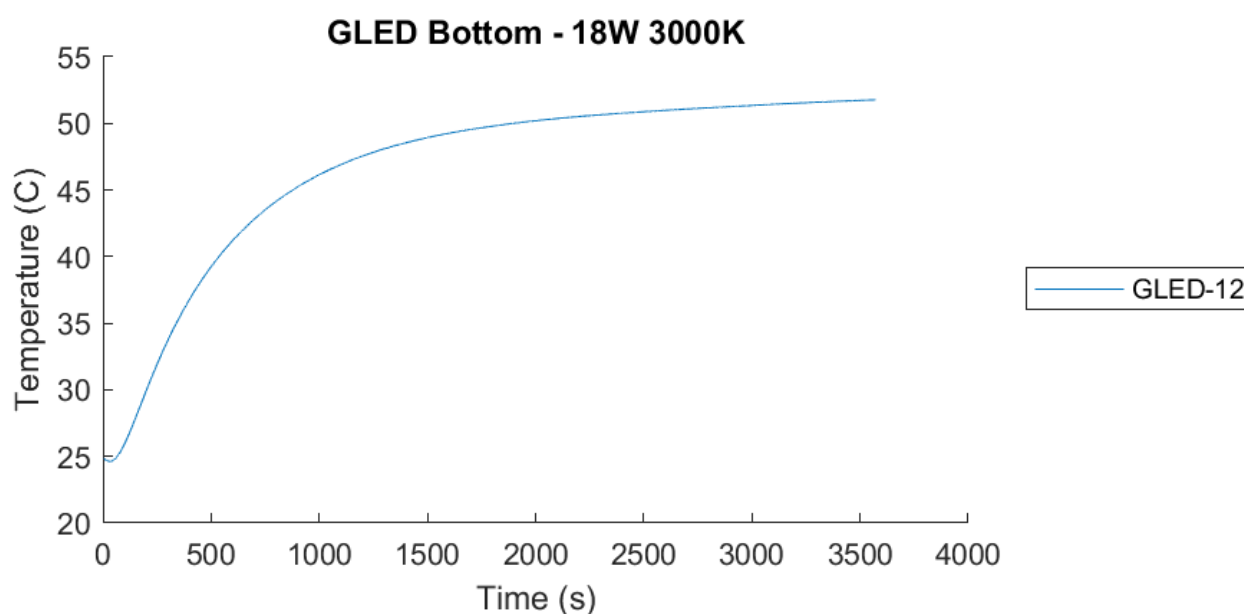


Figure 21. Group C Setup 1 GTLED Bottom Temperature.

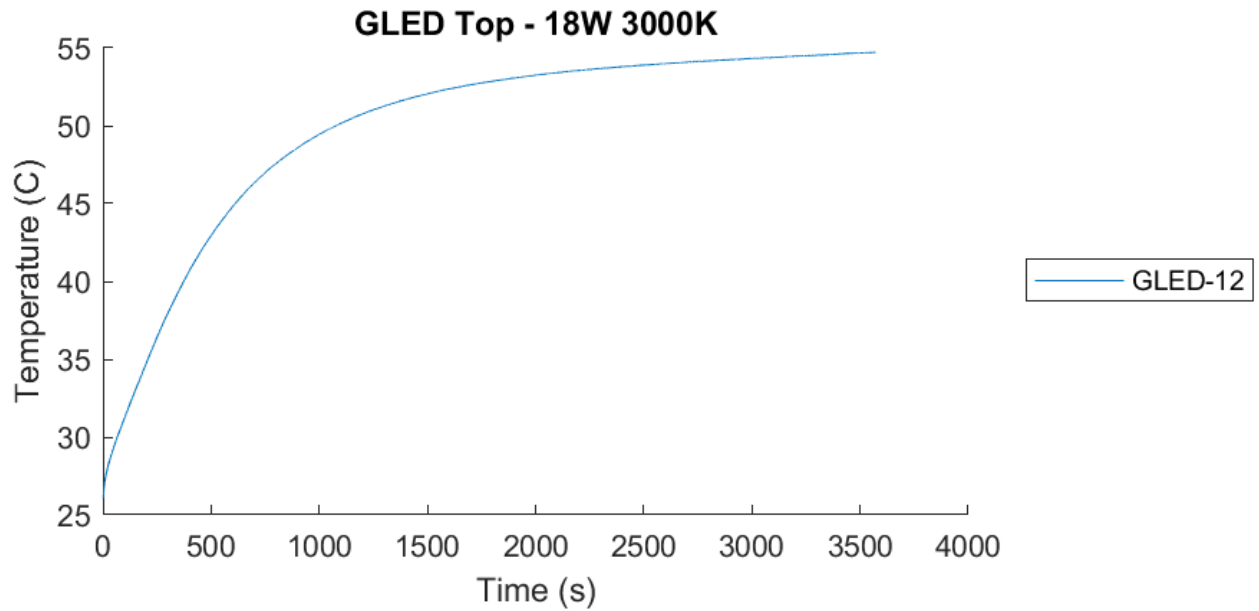


Figure 22. Group C Setup 1 GTLED Top Temperature.

### 3.1.4.3 GTLED-TES2 Group C Results

Similarly, for Setup 2, the GTLED Driver Board and GTLED PCB, shown in Figure 23 and Figure 24 respectively, showed a larger rise in temperature on the Driver board, as opposed to the PCB temperature rise. The rise in temperature for the Driver Board was from 24C to 46C and the PCB was 24C to 35C. The 10C difference at the end of the test between the Driver Board and PCB clearly indicated the major source of heat in this model is the Driver Board.

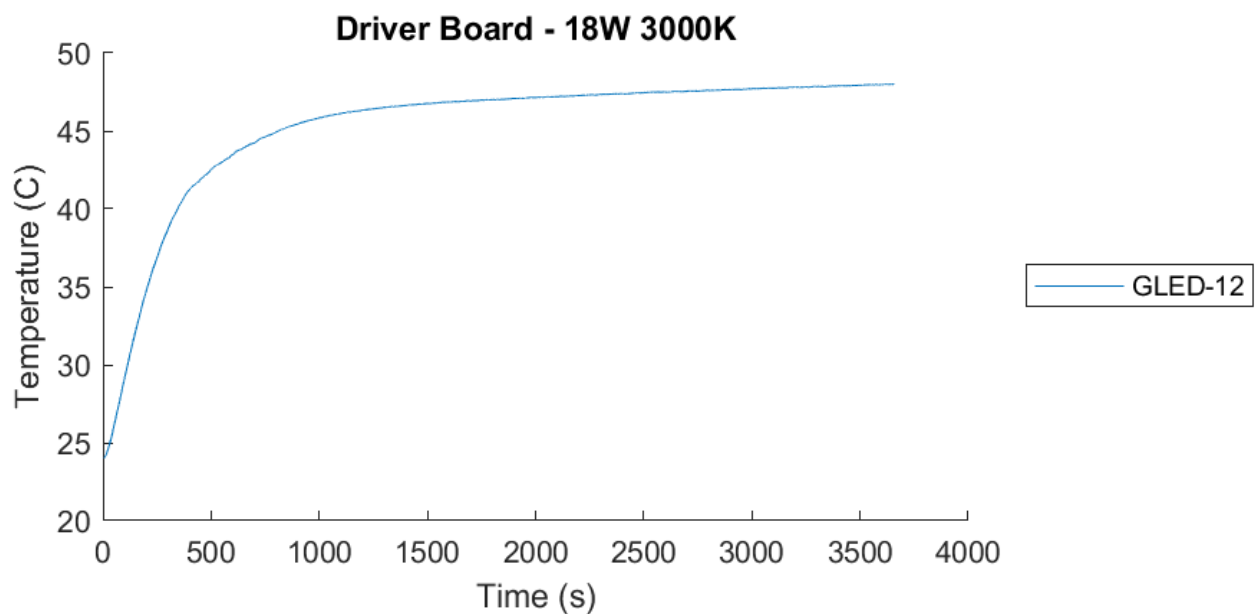


Figure 23. Group C Setup 2 GTLED Driver Board Temperature.

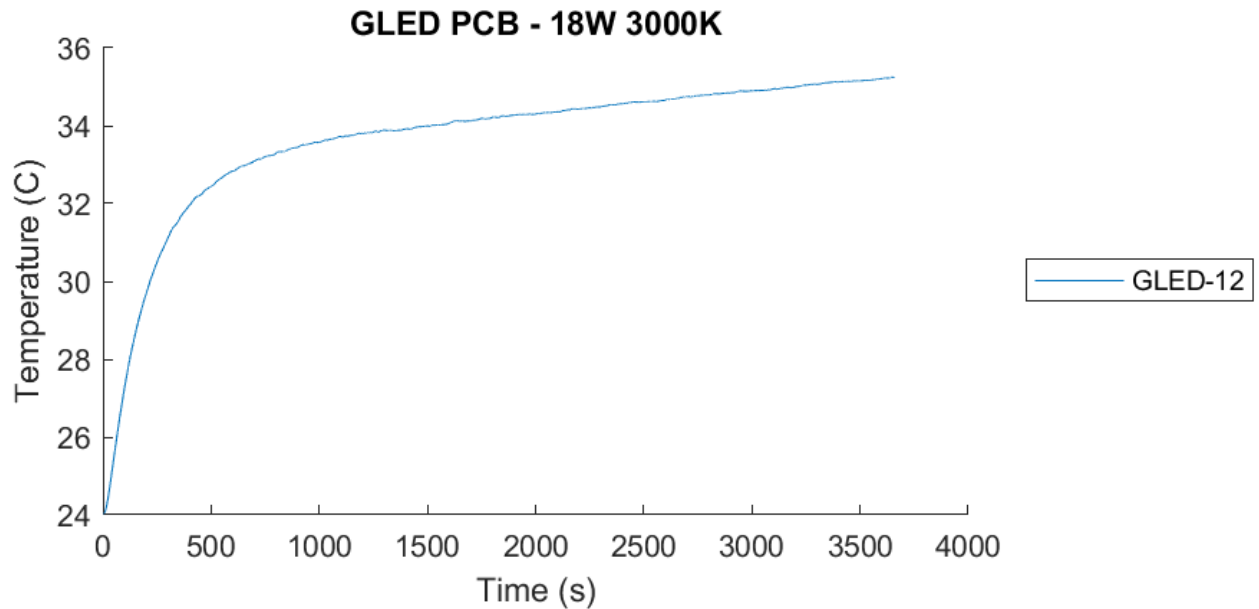


Figure 24. Group C Setup 2 GTLED PCB Temperature.

### 3.1.5 GTLED Group D Key Findings

As a reminder, our performance test for the GTLEDs were broken up into four separate testing groups as described Table 7 that separate the GTLED lights into distinctive categories based on their respective wattage, color, and color temperature. Testing of the GTLED within the Group D category represents the relative higher-powered range of T8 lamps available on the market, similar to the Group C GTLED. With a power averaging 18 Watts, these lamps operated with consistent power factor of 0.74 between the lot. This power factor indicates a lower quality of operation for this model. Photometric data, when compared, was average to low quality, and showed no apparent benefit from the addition of graphene. Thermal data was analyzed and compared to similar products, and the results indicated a consistent deviation between the operating characteristics in each GTLED lamp, which indicated a high variability for the manufacturing materials used in the production of this model.

#### 3.1.5.1 GTLED-PES Group D Results

When electrical data was compared for Group D between the PES testing shown in Table 23, and the TES testing, shown in Table 24, the variation between the results was 8.36% and 7.98% for TES1 and TES2 respectively.

| Electrical Characteristics |           |             |             |              |
|----------------------------|-----------|-------------|-------------|--------------|
| GTLED                      | Power (W) | Voltage (V) | Current (A) | Power Factor |
| 4                          | 18.59     | 120.90      | 0.2074      | 0.7415       |
| 5                          | 17.57     | 120.05      | 0.1979      | 0.7398       |
| 8                          | 17.64     | 120.77      | 0.1979      | 0.7382       |
| 9                          | 18.64     | 120.05      | 0.1977      | 0.7491       |

Table 23. Group D Electrical Characteristics.

| Thermal Testing Electrical Characteristics |       |                   |                     |                     |                       |
|--------------------------------------------|-------|-------------------|---------------------|---------------------|-----------------------|
| GTLED                                      | Setup | Average Power (W) | Average Voltage (V) | Average Current (A) | Percent Deviation (%) |
| 4                                          | 1     | 18.23             | 120.19              | 0.1551              | 9.2469                |
| 4                                          | 2     | 18.35             | 120.13              | 0.1560              | 8.9036                |
| 5                                          | 1     | 17.52             | 120.18              | 0.1493              | 8.2447                |
| 5                                          | 2     | 17.66             | 120.21              | 0.1505              | 7.7687                |
| 8                                          | 1     | 17.33             | 120.20              | 0.1476              | 9.2154                |
| 8                                          | 2     | 17.42             | 120.18              | 0.1485              | 8.8993                |
| 9                                          | 1     | 18.58             | 120.20              | 0.1581              | 6.7424                |
| 9                                          | 2     | 18.70             | 120.23              | 0.1591              | 6.3509                |

Table 24. Group D Thermal Testing Electrical Characteristics.

The photometric results of Group D, shown in Table 25, indicated an efficacy that averaged 142.6 lm/W, slightly above the average of 135 lm/W of all similar products in DLC Qualified List. In this case, the efficacy clearly showed only a slight improvement when compared to the average product on the market.

| Filament Lamp Testing |        |         |           |                   |         |         |     |                 |                     |               |
|-----------------------|--------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| GTLED                 | Degree | Power % | Power (W) | Light Output (lm) | CCT (K) | Duv     | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| 4                     | 2      | 100     | 18.59     | 2743              | 5196    | 0.0078  | 64  | 147.55          | 75.24               | 0.24          |
| 4                     | 10     | 100     | 18.59     | 2920              | 4949    | -0.0019 | 64  | 157.07          | 75.24               | 0.24          |
| 5                     | 2      | 100     | 17.57     | 2303              | 5231    | 0.0047  | 71  | 131.08          | 77.17               | 0.25          |
| 5                     | 10     | 100     | 17.57     | 2475              | 4995    | -0.0019 | 71  | 140.87          | 77.17               | 0.25          |
| 8                     | 2      | 100     | 17.64     | 2312              | 5183    | 0.005   | 71  | 131.07          | 78.04               | 0.25          |
| 8                     | 10     | 100     | 17.64     | 2484              | 4948    | -0.0016 | 71  | 140.82          | 78.04               | 0.25          |
| 9                     | 2      | 100     | 18.64     | 2644              | 5159    | 0.0079  | 64  | 141.85          | 78.18               | 0.25          |
| 9                     | 10     | 100     | 18.64     | 2815              | 4914    | -0.0016 | 64  | 151.02          | 78.18               | 0.25          |

Table 25. Group D Filament Lamp Testing.

### 3.1.5.2 GTLED-TES1 Group D Results

The thermal test setup as described in Section 2.1.2.2, placed thermocouples above and below the substantially warmer producing region of the GTLED tube lamp. The test was conducted for one hour, and thermocouple data was recorded for the bottom, top, and ambient temperature inside of the test chamber. From our thermal data, we can see that the GTLED Bottom and GTLED Top, shown in Figure 25 and Figure 26 respectively, showed somewhat consistent performance with their similar counterparts with the exception of GTLED-9 Bottom temperature. This temperature was anomalous and was likely due to a failing thermocouple that was replaced. The overall rise in temperature for both are similar, with the Bottom going from 23C-25C to 43-45C, and the Top going from 25C-28C to 47C-55C. This indicated that the lamp-to-lamp differences for this model is high.

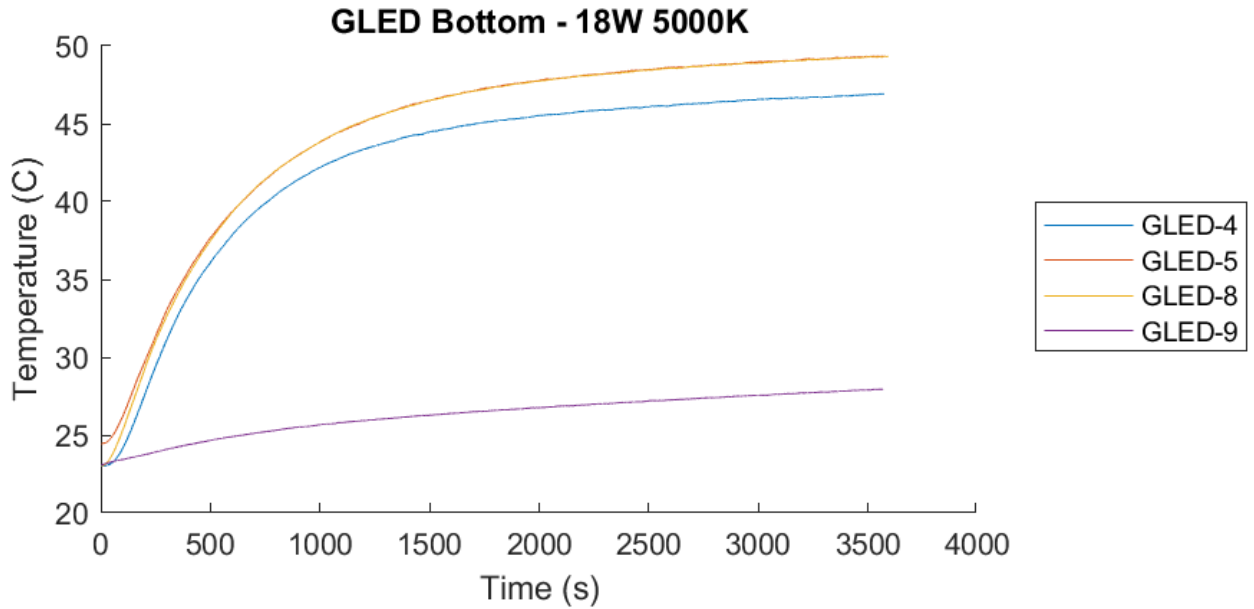


Figure 25. Group D Setup 1 GTLED Bottom Temperature.

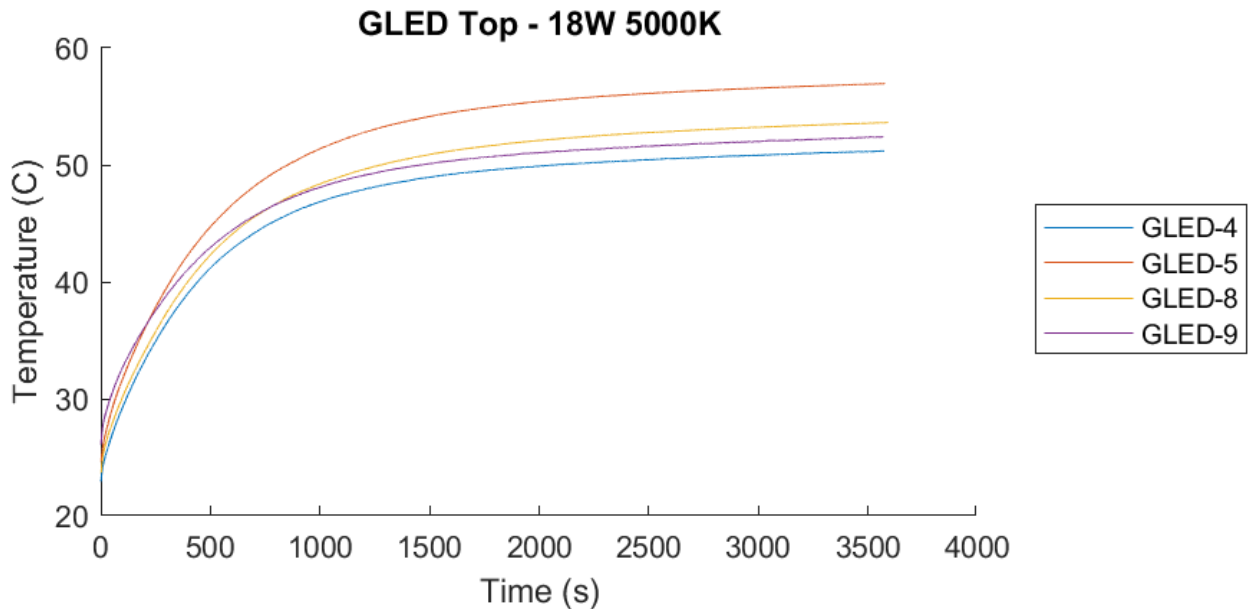


Figure 26. Group D Setup 1 GTLED Top Temperature.

### 3.1.5.3 GTLED-TES2 Group D Results

Additionally, in Setup 2, the GTLED Driver Board and GTLED PCB, shown in Figure 27 and Figure 28 respectively, showed inconsistent performance with their counterparts. We can see the overall rise in temperature for both varies with GTLED, with the Driver Board ranging from 21C-24C at the start of the test and ending with a range from 45C-52C at the end. The PCB started with a range of 22C-25C and ended with a range of 27C-40C. There was a temporary temperature excursion during the GTLED-4 trial, but the overall trend remained unaffected. The temperature results reinforced the indication that the lamp-to-lamp differences for this model is pronounced.

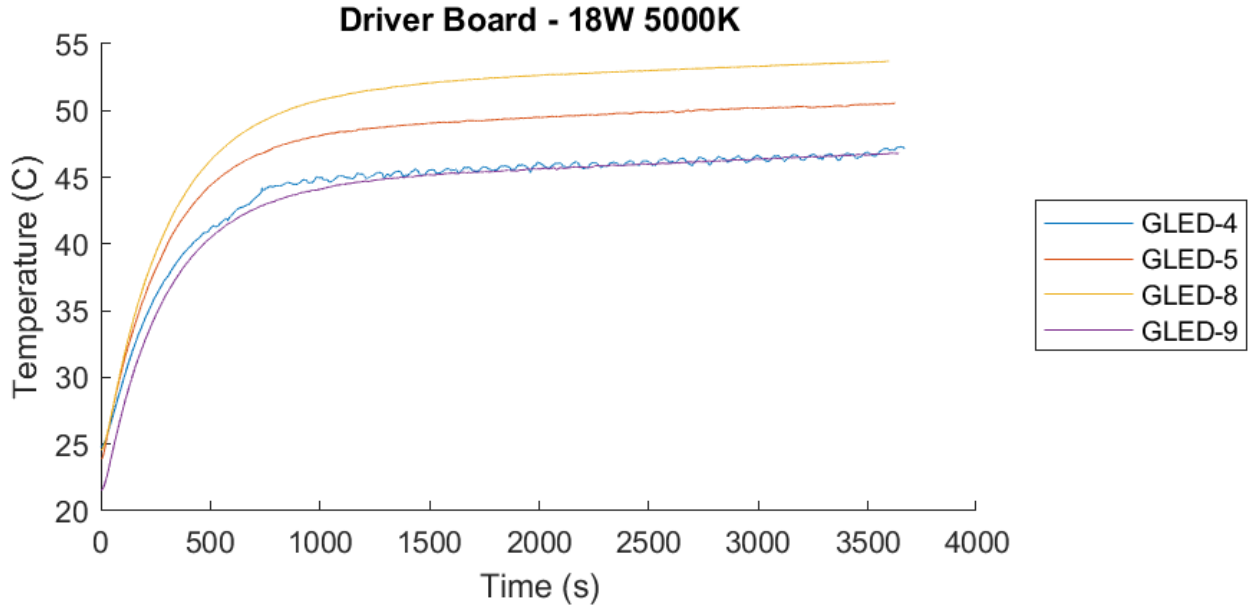


Figure 27. Group D Setup 2 GTLED Driver Board Temperature.

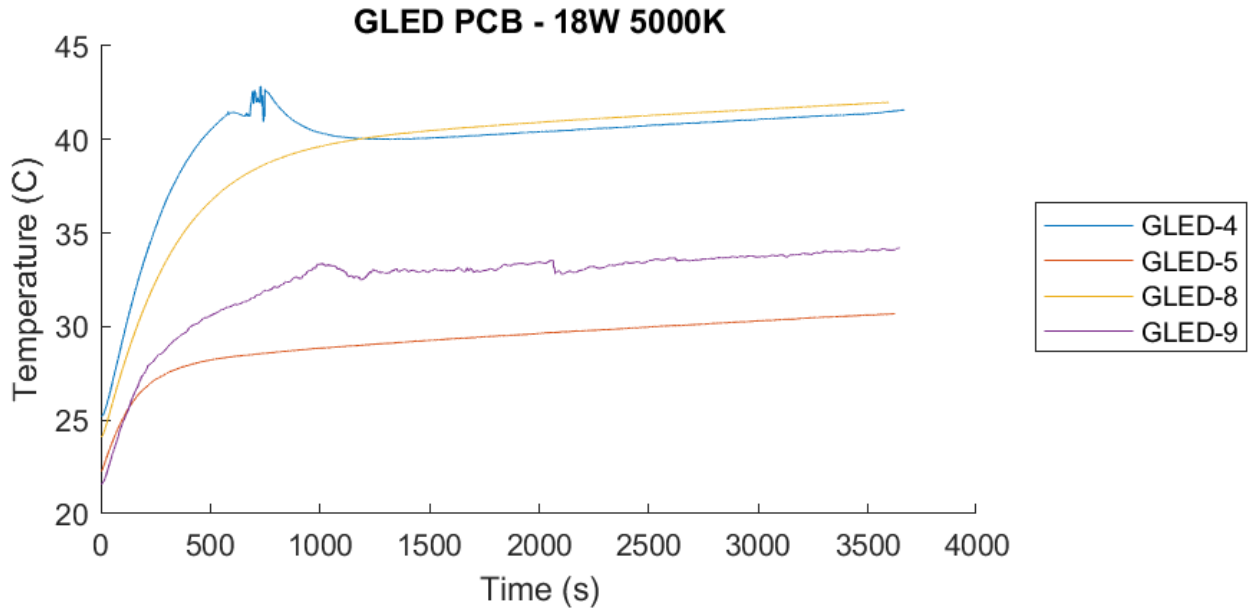


Figure 28. Group D Setup 2 GTLED PCB Temperature.

### 3.2 STATISTICAL ANALYSIS

The analysis of electrical data for both the PES and TES1 and TES2 were compared throughout the testing and shown in Table 26. The variations associated with each were used to compare both the tests and the materials used for each of the GTLEDs. For the 9W range of GTLED lamps, the deviation in electrical data was 0.46% and 0.58% for Group A and Group B respectively. This <1% difference indicated that our testing setup did not deviate enough to cause a significant impact from the testing performed by CLTC. When performing the Group C and Group D tests, our testing deviation jumped up from <1% to <10%. Due to the low previous testing deviation, we concluded

that this change was not due to a testing error, but due to manufacturing material deviations causing a large range at higher power(18W).

| <b>GTLED</b>   | <b>TES1<br/>Deviation<br/>(%)</b> | <b>TES2<br/>Deviation<br/>(%)</b> | <b>Total<br/>Deviation<br/>(%)</b> |
|----------------|-----------------------------------|-----------------------------------|------------------------------------|
| <b>Group A</b> | 0.36                              | 0.55                              | 0.46                               |
| <b>Group B</b> | 0.45                              | 0.72                              | 0.58                               |
| <b>Group C</b> | 9                                 | 8.48                              | 8.74                               |
| <b>Group D</b> | 8.39                              | 7.98                              | 8.17                               |

Table 26. Electrical data TES deviation from PES.

## **4. DISCUSSION**

### **4.1 MAJOR FINDINGS**

Our major findings and recommendations are provided in the following sections. The overall findings were separated into their distinctive lighting types: Graphene A19 (GA19) lamps and Graphene Tube LED (GTLED). It is important to note our findings and recommendations are based on the availability of the graphene lighting products that were made available at the time of our study and do not represent the entirety of the graphene lighting industry.

#### **4.1.1 Finding Details**

The findings and recommendations for this effort are based upon real measurements and empirical data. There are several takeaways that were determined for both the GA19 and GTLED lighting types. For comparison of photometric and electrical data associated with these products, several databases were used. This includes the DLC Qualified Products Lists, which lists high performing and energy saving LED lighting solutions and their information, as well as the Energy Star product list, which lists products tested for Energy Star certification. These databases were chosen to give a reasonable representation of energy efficient lighting products that can be used for comparison of operating characteristics, and to determine the comparative efficacy of the graphene lighting products measured during our effort.

##### **4.1.1.1 A19 Finding Details**

Overall, the GA19 lamps from Sera Technologies Technology operated well above the industry standards and showcased outstanding results when compared with non-graphene A19 variants. Out of the 3375 A19 lighting products listed within the Energy Star Database, the GA19 lamps performed better than 3317 of them, placing the GA19 lamps in the 98th percentile. Out of the 301 that were of similar wattage, these GA19 lamps had a higher efficacy and light output than 300 products, placing the GA19 lamps within the 99th percentile. For the photometric characteristics, the GA19 lamps were compared to 1260 products with similar CCT. The GA19 lamps outperformed 1260 products, placing it at the 100th percentile. For the thermal operating characteristics, the GA19 lamps operated 11% cooler at the base when compared to a non-graphene A19 variants.

We conclude the photometric, electrical, and thermal performance results of the GA19 lamps illustrated strong promise as a replacement for non-variant graphene A19 lamps. Furthermore, may have displayed the ability for graphene to take a portion of the heat away from the LEDs, thus improving the overall performance characteristics. Additionally, but not part of this effort, a life cycle test can be performed to verify the lifetime of the GA19 lamps.

##### **4.1.1.2 GTLED Finding Details**

Overall, the GTLED from LEDi2 performed sub-optimally when compared to industry standards, operating only within the top third of all products in the DLC Qualified Products List and showcased minor benefits when compared to non-graphene tube type LEDs. For comparison, there are a total of 2112 Type B TLED lamps on the DLC database that had a power equal or under 20.1W. There were 853 products listed with a photometric efficacy over 137, 390 products with photometric efficacy greater than 148, and 119 products that have over 159 lm/W. 159 TLED products have an R9 value greater than -40 and with efficacy greater than 137. Therefore, there are 159 products that have a comparable and or greater efficacy and R9 values compared to the GTLED out of the 2112 products, placing the GTLEDs within the 92<sup>nd</sup> percentile for those respective criteria. For the thermal operating characteristics, the GTLEDs operated with relatively similar characteristics with their counterpart

GTLEDs of the same color temperature and wattage, showcasing a relative consistency for operating characteristics.

The authors conclude the photometric, electrical, and thermal performance for the GTLEDs are sub-optimal and do not illustrate significant benefits when compared to non-graphene TLED lamps. Although, the graphene in the GTLEDs may have a role in removing heat from the overall LED lighting components, the relatively subpar electrical and photometric performance are not ideal and do not provide enough reasoning to widely adopt these lamps as a revolutionary lighting product. It is important to spectral output of the GTLED lamps were different. For example, LEDi2 provided our team a GTLED with a green color in which they market as a grow light. Although, interesting our study did not focus on the performance of grow lights, but rather a comparison of the electrical, photometric, and thermal performance of the GTLED. For the GTLED variants with standard white light spectral output, we did not see an overall benefit over the non-graphene TLEDs as compared within the DLC database.

#### **4.1.1.3 Implications**

The overarching goal of this effort was to provide an independent technical assessment of photometric, electrical, and thermal performance of commercially available graphene solid state lighting (SSL) for potential use in the Department of Navy (DON) environment. Used most often in DON installations is the Tube LED (TLED). However, due to a shortage of U.S.-based vendors of graphene enhanced TLEDs, our assessment for graphene enhanced TLEDs was limited to a single vendor, LEDi2, which provided lighting products with origins from South East Asia. Although, LEDi2 provided multiple Graphene TLED variants for our team to evaluate, the team believes the limiting factor in our performance measurement results may be due to the poor-quality of the LED components used within the lighting packages provided as opposed to an underperformance of graphene used to mitigate heat production. The combination of the substandard LEDs measured, and the potential dubious graphene implementation may have served to undercut the theoretical performance gain of the tube lamps tested. When compared to the GA19 type lamps that were recommended by the University of Manchester experts (the original patent holders and originators of the graphene enhanced lighting technology), it became clear that utilizing high performing LEDs from a European origin in conjunction with properly applied graphene can and did showcase improved performance over non-graphene variants. Given the empirical improvements shown with the Sera Technologies graphene A19 lamp, our team expects that an improved graphene LED tube type lamp can be achieved with proper application of graphene and high quality LEDs.

#### **4.1.1.4 Recommendations**

- For A19 type lighting solutions, our team recommends the adoption of Sera Technologies graphene LED lamps for installations where A19 type task lighting would provide and operational benefit to naval commands in EUCOM. Since the A19 graphene lighting products tested from Sera Technologies operate off 220V(50Hz) supply voltages, the lamps are limited to operations in the EUCOM or regions in which 220V(50Hz) power is a common place.
- For the GTLED type lighting solutions, our team does not recommend the adoption of LEDi2 graphene LED tube type lamps for any LED tube type applications at naval commands due to minimal benefits as were determined by our independent technical assessment.

- To further benefit from graphene enhanced solid state lighting, our team recommends the DON needs to invest in U.S. partnerships of high-quality graphene and LED providers. In addition, promote collaboration amongst these industries to bring increase the amount of graphene enhanced lighting products to include several different form factors.

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## 5. CONCLUSIONS

This effort concludes performance measurements of commercially available graphene solid-state lighting that includes A19 lamps from lighting vendor, Sera Technologies, as well as Graphene-enhanced tube LED lamps from lighting vendor, LEDi2 Inc. Electrical, photometric, and thermal data was collected for each lamp type and the results were compared to the Design Lights Consortium (DLC) database, which contains specifications and performance data of over 80 categories of indoor and outdoor commercial LED products.

The authors indicated that the Sera Technologies Graphene A19 lamps showed indications of lowered ambient temperature rise during continuous operation, with an 11% lower operating temperature over their non-graphene variants. In addition, the Sera Technologies Graphene A19 lamps revealed better photometric and electrical performance data that placed this product within the top 98th percentile of high-performance commercial lighting. Therefore, our team recommends adoption of Sera Technologies Graphene A19 lamps within DON Facilities where task lighting adds value. However, it is important to note the Sera Technologies A19 Lamps are a European Variant and require 240V(50Hz) supply voltages to operate. No U.S. variant exists at this time. This greatly limits adoption of the Sera Technologies Graphene A19 Lamp to DON operations in the European Union or regions in which 240V(50Hz) is standard.

Test results for the LEDi2 Graphene Tube LED lamps indicated resultant temperature rises were average within the same class and type, showing no definitive indications of improved performance overall. In addition, LEDi2 Graphene Tube LED lamps photometric and electrical performance data operated within only the top 1/3 of commercial Tube LED lamps, indicating minimal improvement over high performing non-graphene variants. Our team does not recommend adoption of LEDi2 Graphene Tube LED lamps within DON Facilities as the lamps did not perform better in all aspects of photometric, thermal, and electrical performance. Several tube LED lamps exist on the market that perform much better.

Partnering with UC Davis California Lighting Technology Center and by completion of this effort, our team has successfully characterized both graphene enhanced A19 and TLED lamp that were currently available in the marketplace at the time of this study. We have at a minimum partially realized our goals to test the thermal performance of graphene lighting products and the ability of graphene to remove heat from the LED components; therefore, improving overall performance over non-graphene variants. In conclusion, our team sees value in graphene enhanced lighting products, however, to realize this capability in the U.S. fully, future adoption of graphene enhanced lighting is dependent on improved industry partnership between reputable LED and graphene suppliers.

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| Photometric 1931 2° |         |           |                   |         |         |     |                 |                     |               |
|---------------------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| Lamp                | Power % | Power (W) | Light Output (lm) | CCT (K) | Duv     | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| Sera Technologies1  | 100     | 7.60      | 878               | 2749    | -0.0014 | 82  | 115.53          | 27.96               | 0.08          |
| Sera Technologies2  | 100     | 7.59      | 823               | 2758    | -0.0014 | 82  | 108.43          | 27.35               | 0.08          |
| Sera Technologies3  | 100     | 7.61      | 875               | 2771    | -0.0018 | 82  | 114.98          | 29.84               | 0.09          |
| Sera Technologies4  | 100     | 7.58      | 838               | 2743    | -0.0009 | 82  | 110.55          | 28.16               | 0.08          |
| Sera Technologies5  | 100     | 7.8       | 876               | 2780    | -0.0025 | 82  | 115.57          | 28.7                | 0.08          |
| Sera Technologies6  | 100     | 7.39      | 867               | 2746    | -0.0020 | 82  | 117.32          | 29.83               | 0.09          |
| Sera Technologies7  | 100     | 7.36      | 857               | 2754    | -0.0019 | 82  | 116.44          | 30.61               | 0.09          |
| Sera Technologies8  | 100     | 7.43      | 884               | 2750    | -0.0020 | 82  | 118.98          | 29.62               | 0.09          |
| Sera Technologies9  | 100     | 7.43      | 869               | 2766    | -0.0027 | 82  | 116.96          | 29.11               | 0.09          |
| Sera Technologies10 | 100     | 7.37      | 855               | 2745    | -0.0012 | 82  | 116.01          | 30.34               | 0.09          |

Appendix Table 1. A19 2° Filament Lamp Testing.

| Photometric 2015 10° |         |           |                   |         |         |     |                 |                     |               |
|----------------------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| Lamp                 | Power % | Power (W) | Light Output (lm) | CCT (K) | Duv     | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| Sera Technologies1   | 100     | 7.60      | 933               | 2707    | -0.0020 | 82  | 122.76          | 27.96               | 0.08          |
| Sera Technologies2   | 100     | 7.59      | 875               | 2718    | -0.0016 | 82  | 115.28          | 27.35               | 0.08          |
| Sera Technologies3   | 100     | 7.61      | 928               | 2718    | -0.0028 | 82  | 121.94          | 29.84               | 0.09          |
| Sera Technologies4   | 100     | 7.58      | 892               | 2706    | -0.0008 | 82  | 117.68          | 28.16               | 0.08          |
| Sera Technologies5   | 100     | 7.58      | 931               | 2736    | -0.0031 | 82  | 122.82          | 28.70               | 0.08          |
| Sera Technologies6   | 100     | 7.39      | 920               | 2696    | -0.0029 | 82  | 124.49          | 29.83               | 0.09          |
| Sera Technologies7   | 100     | 7.36      | 910               | 2706    | -0.0026 | 82  | 123.64          | 30.61               | 0.09          |
| Sera Technologies8   | 100     | 7.43      | 939               | 2703    | -0.0028 | 82  | 126.38          | 29.62               | 0.09          |
| Sera Technologies9   | 100     | 7.43      | 939               | 2723    | -0.0033 | 82  | 126.38          | 29.11               | 0.09          |
| Sera Technologies10  | 100     | 7.37      | 909               | 2706    | -0.0014 | 82  | 123.34          | 30.34               | 0.09          |

Appendix Table 2. A19 10° Filament Lamp Testing.

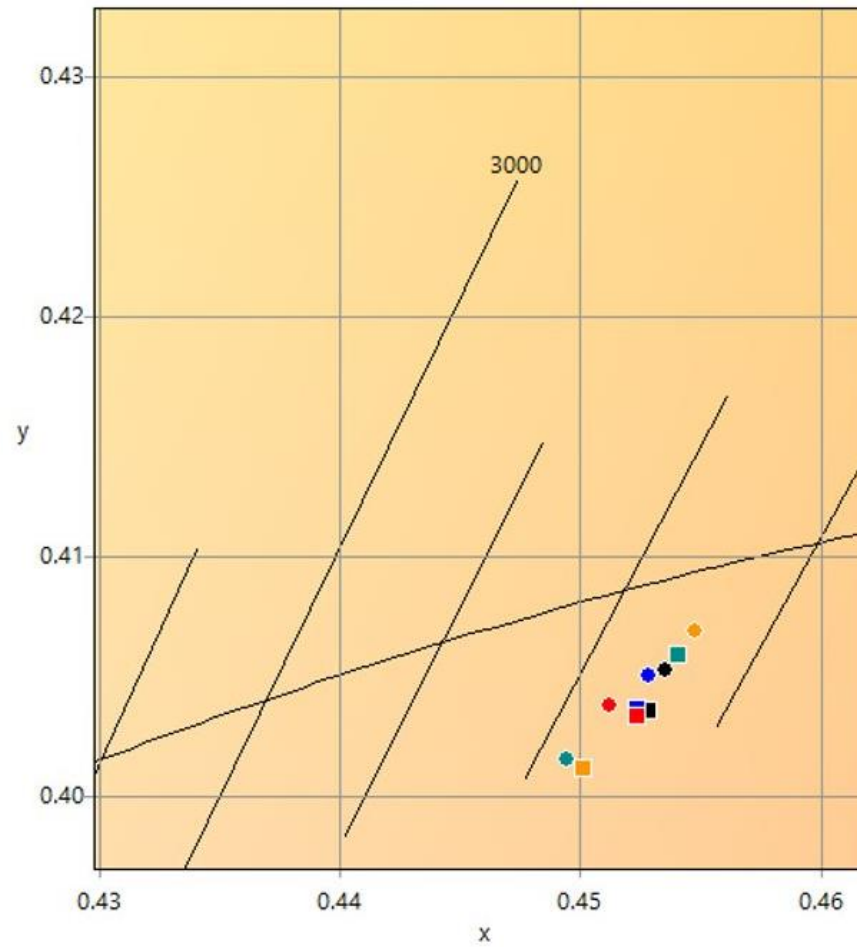
| Lamp                | Power % | R1    | R2    | R3    | R4    | R5    | R6    | R7    |
|---------------------|---------|-------|-------|-------|-------|-------|-------|-------|
| Sera Technologies1  | 100     | 91.94 | 94.96 | 90.21 | 78.27 | 82.83 | 94.77 | 78.31 |
| Sera Technologies2  | 100     | 82.71 | 96.21 | 88.53 | 78.16 | 83.79 | 95.66 | 77.68 |
| Sera Technologies3  | 100     | 81.19 | 93.61 | 92.04 | 78.5  | 81.96 | 93.21 | 70.09 |
| Sera Technologies4  | 100     | 83.19 | 96.93 | 87.59 | 77.97 | 84.23 | 95.88 | 77.26 |
| Sera Technologies5  | 100     | 82.41 | 95.23 | 90.23 | 78.63 | 83.34 | 94.63 | 78.36 |
| Sera Technologies6  | 100     | 81.56 | 94.06 | 91.51 | 78.65 | 82.39 | 93.77 | 78.84 |
| Sera Technologies7  | 100     | 81.92 | 94.61 | 90.91 | 78.58 | 82.77 | 94.29 | 78.62 |
| Sera Technologies8  | 100     | 81.87 | 94.65 | 90.75 | 78.39 | 82.70 | 94.27 | 78.46 |
| Sera Technologies9  | 100     | 82.40 | 95.11 | 90.43 | 78.77 | 83.34 | 94.54 | 78.42 |
| Sera Technologies10 | 100     | 82.93 | 96.28 | 88.64 | 78.37 | 83.94 | 95.70 | 77.79 |
|                     | R8      | R9    | R10   | R11   | R12   | R13   | R14   | RA    |
| Sera Technologies1  | 54.88   | 5.92  | 89    | 78.05 | 80.11 | 85.5  | 95.26 | 82.02 |
| Sera Technologies2  | 55.09   | 7.53  | 91.89 | 78.02 | 81.99 | 86.51 | 94.28 | 82.23 |
| Sera Technologies3  | 55.01   | 4.65  | 85.87 | 78.06 | 79.32 | 84.45 | 96.33 | 81.82 |
| Sera Technologies4  | 55.17   | 8.51  | 93.53 | 78.03 | 81.4  | 87.12 | 93.73 | 82.28 |
| Sera Technologies5  | 55.52   | 7.34  | 89.46 | 78.39 | 80.35 | 85.98 | 95.33 | 82.29 |
| Sera Technologies6  | 55.08   | 5.56  | 86.96 | 78.41 | 79.87 | 84.89 | 96.04 | 81.98 |
| Sera Technologies7  | 55.19   | 6.2   | 88.12 | 78.34 | 79.83 | 85.37 | 95.70 | 82.11 |
| Sera Technologies8  | 55.02   | 6.02  | 88.22 | 78.11 | 79.48 | 85.35 | 95.62 | 82.01 |
| Sera Technologies9  | 55.55   | 7.47  | 89.21 | 78.57 | 80.68 | 85.92 | 95.46 | 82.32 |
| Sera Technologies10 | 55.37   | 8.22  | 92.03 | 78.38 | 81.17 | 86.70 | 94.36 | 82.38 |

Appendix Table 3. A19 Color Rendering Index.

## Photometric - Chromaticity

| Lamp                | Model    | Symbol                                                                              | CIE x  | CIE y  |
|---------------------|----------|-------------------------------------------------------------------------------------|--------|--------|
| Sera Technologies1  | 8W 2700K |    | 0.4535 | 0.4053 |
| Sera Technologies2  | 8W 2700K |    | 0.4528 | 0.4051 |
| Sera Technologies3  | 8W 2700K |    | 0.4512 | 0.4038 |
| Sera Technologies4  | 8W 2700K |    | 0.4548 | 0.4069 |
| Sera Technologies5  | 8W 2700K |    | 0.4494 | 0.4016 |
| Sera Technologies6  | 8W 2700K |    | 0.4528 | 0.4036 |
| Sera Technologies7  | 8W 2700K |    | 0.4524 | 0.4037 |
| Sera Technologies8  | 8W 2700K |   | 0.4524 | 0.4034 |
| Sera Technologies9  | 8W 2700K |  | 0.4501 | 0.4012 |
| Sera Technologies10 | 8W 2700K |  | 0.4541 | 0.4059 |

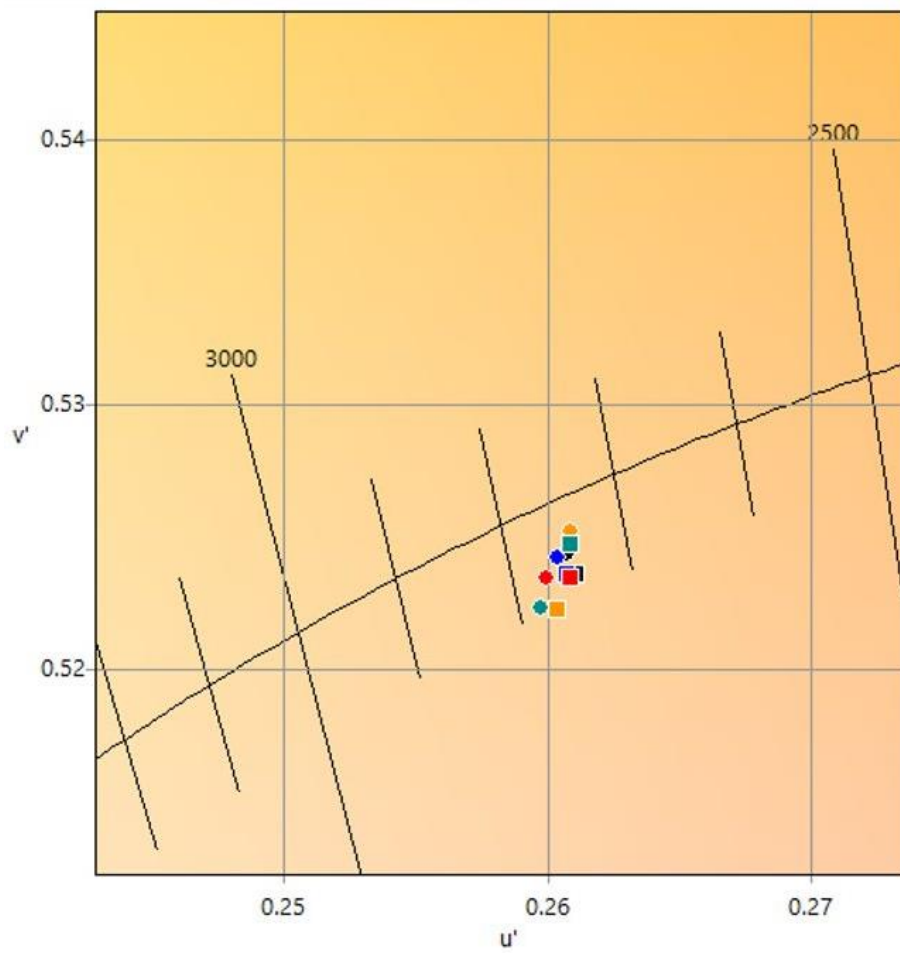
Appendix Table 4. A19 1931 2° x & y Chromaticity Table.



Appendix Figure 1. A19 1931 2° x & y Chromaticity Diagram.

| Lamp                | Model    | Symbol                                                                             | CIE x  | CIE y  |
|---------------------|----------|------------------------------------------------------------------------------------|--------|--------|
| Sera Technologies1  | 8W 2700K |   | 0.2608 | 0.5244 |
| Sera Technologies2  | 8W 2700K |   | 0.2604 | 0.5242 |
| Sera Technologies3  | 8W 2700K |   | 0.26   | 0.5234 |
| Sera Technologies4  | 8W 2700K |   | 0.2609 | 0.5252 |
| Sera Technologies5  | 8W 2700K |   | 0.2598 | 0.5223 |
| Sera Technologies6  | 8W 2700K |   | 0.2611 | 0.5236 |
| Sera Technologies7  | 8W 2700K |   | 0.2607 | 0.5236 |
| Sera Technologies8  | 8W 2700K |   | 0.2609 | 0.5235 |
| Sera Technologies9  | 8W 2700K |   | 0.2604 | 0.5222 |
| Sera Technologies10 | 8W 2700K |  | 0.2609 | 0.5247 |

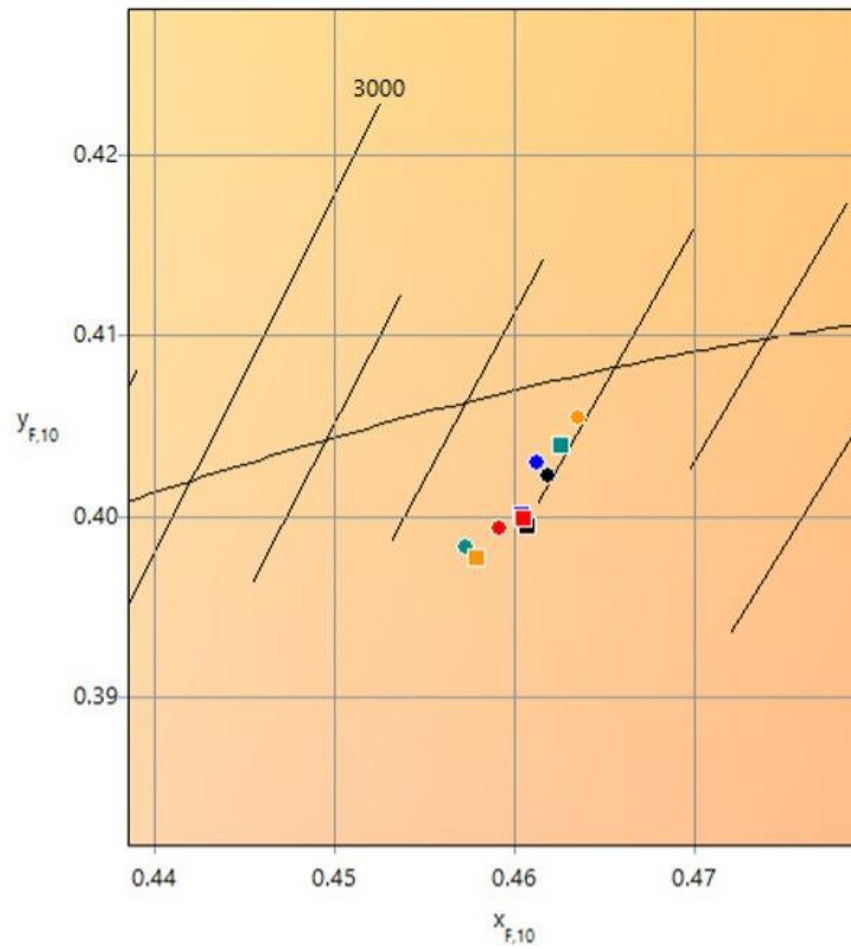
Appendix Table 5. A19 1976 2° u' & v' Chromaticity Table



Appendix Figure 2. A19 1976 2°  $u'$  &  $v'$  Chromaticity Diagram.

| Lamp                | Model    | Symbol                                                                             | CIE x  | CIE y  |
|---------------------|----------|------------------------------------------------------------------------------------|--------|--------|
| Sera Technologies1  | 8W 2700K |   | 0.4619 | 0.4022 |
| Sera Technologies2  | 8W 2700K |   | 0.4612 | 0.4030 |
| Sera Technologies3  | 8W 2700K |   | 0.4592 | 0.3993 |
| Sera Technologies4  | 8W 2700K |   | 0.4635 | 0.4055 |
| Sera Technologies5  | 8W 2700K |   | 0.4573 | 0.3983 |
| Sera Technologies6  | 8W 2700K |   | 0.4607 | 0.3994 |
| Sera Technologies7  | 8W 2700K |   | 0.4604 | 0.4001 |
| Sera Technologies8  | 8W 2700K |   | 0.4605 | 0.3998 |
| Sera Technologies9  | 8W 2700K |   | 0.4579 | 0.3977 |
| Sera Technologies10 | 8W 2700K |  | 0.4626 | 0.4039 |

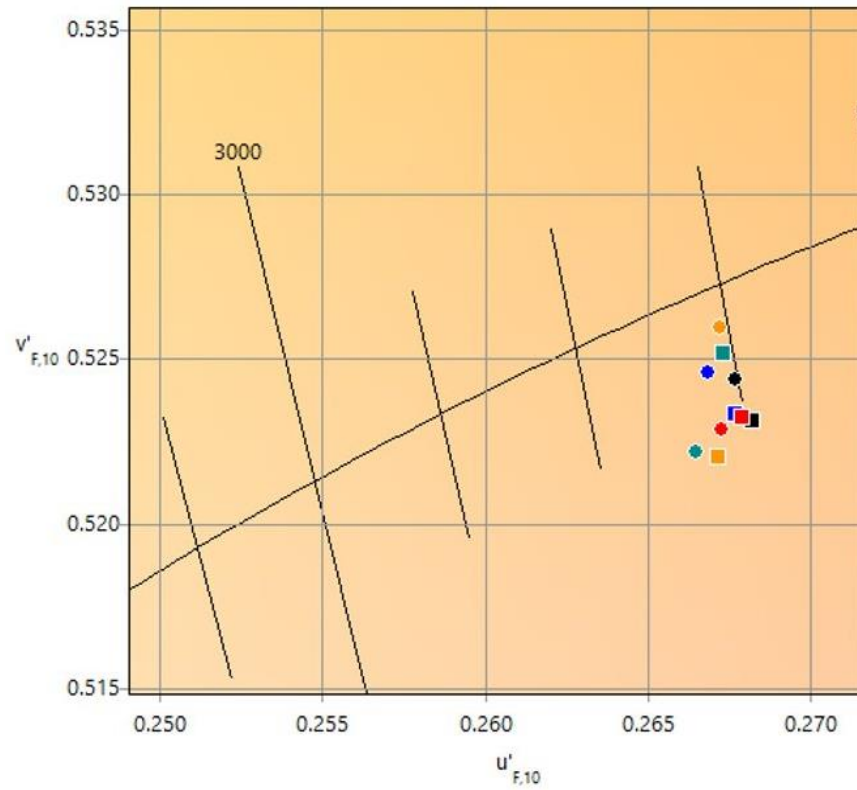
Appendix Table 6. A19 2015 10° x & y Chromaticity Table.



Appendix Figure 3. A19 2015 10° x & y Chromaticity Diagram.

| Lamp                | Model    | Symbol                                                                             | CIE x  | CIE y  |
|---------------------|----------|------------------------------------------------------------------------------------|--------|--------|
| Sera Technologies1  | 8W 2700K |   | 0.2677 | 0.5244 |
| Sera Technologies2  | 8W 2700K |   | 0.2668 | 0.5246 |
| Sera Technologies3  | 8W 2700K |   | 0.2672 | 0.5229 |
| Sera Technologies4  | 8W 2700K |   | 0.2972 | 0.5260 |
| Sera Technologies5  | 8W 2700K |   | 0.2664 | 0.5222 |
| Sera Technologies6  | 8W 2700K |   | 0.2682 | 0.5231 |
| Sera Technologies7  | 8W 2700K |   | 0.2677 | 0.5234 |
| Sera Technologies8  | 8W 2700K |   | 0.2678 | 0.5233 |
| Sera Technologies9  | 8W 2700K |   | 0.2671 | 0.5220 |
| Sera Technologies10 | 8W 2700K |  | 0.2673 | 0.5252 |

Appendix Table 7. A19 2015 10° u' & v' Chromaticity Table.



Appendix Figure 4. A19 2015 10°  $u'$  &  $v'$  Chromaticity Diagram

| Lamp                | Model    | Rf | Rg |
|---------------------|----------|----|----|
| Sera Technologies1  | 8W 2700K | 84 | 93 |
| Sera Technologies2  | 8W 2700K | 84 | 91 |
| Sera Technologies3  | 8W 2700K | 85 | 94 |
| Sera Technologies4  | 8W 2700K | 83 | 90 |
| Sera Technologies5  | 8W 2700K | 84 | 93 |
| Sera Technologies6  | 8W 2700K | 85 | 94 |
| Sera Technologies7  | 8W 2700K | 85 | 94 |
| Sera Technologies8  | 8W 2700K | 84 | 94 |
| Sera Technologies9  | 8W 2700K | 85 | 94 |
| Sera Technologies10 | 8W 2700K | 84 | 91 |

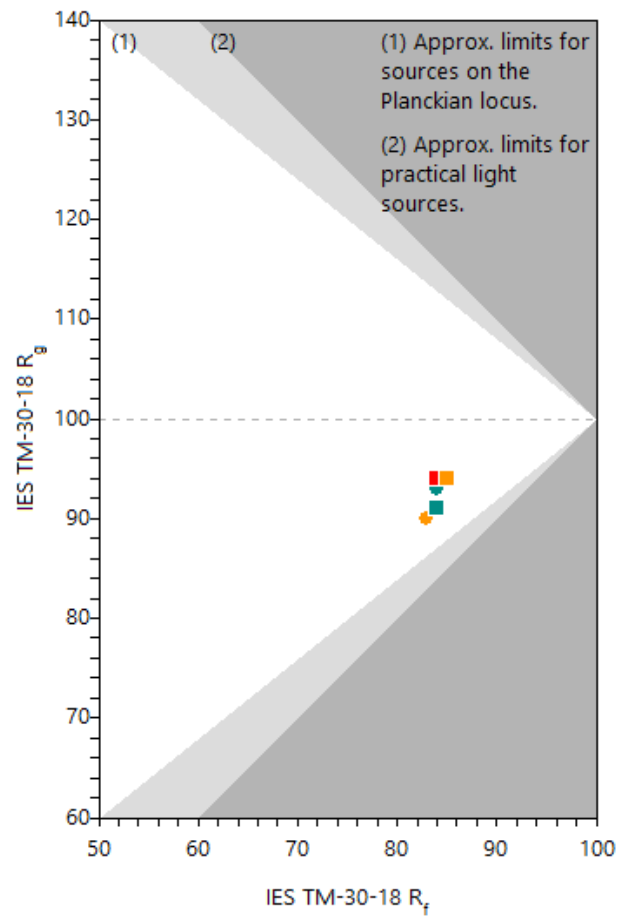
Appendix Table 8. A19 Color Fidelity & Gamut

| Lamp                | Model    | Symbol                                                                             | Rf | Rg |
|---------------------|----------|------------------------------------------------------------------------------------|----|----|
| Sera Technologies1  | 8W 2700K |   | 84 | 93 |
| Sera Technologies2  | 8W 2700K |   | 84 | 91 |
| Sera Technologies3  | 8W 2700K |   | 85 | 94 |
| Sera Technologies4  | 8W 2700K |   | 83 | 90 |
| Sera Technologies5  | 8W 2700K |   | 84 | 93 |
| Sera Technologies6  | 8W 2700K |   | 85 | 94 |
| Sera Technologies7  | 8W 2700K |   | 85 | 94 |
| Sera Technologies8  | 8W 2700K |   | 84 | 94 |
| Sera Technologies9  | 8W 2700K |   | 85 | 94 |
| Sera Technologies10 | 8W 2700K |  | 84 | 91 |

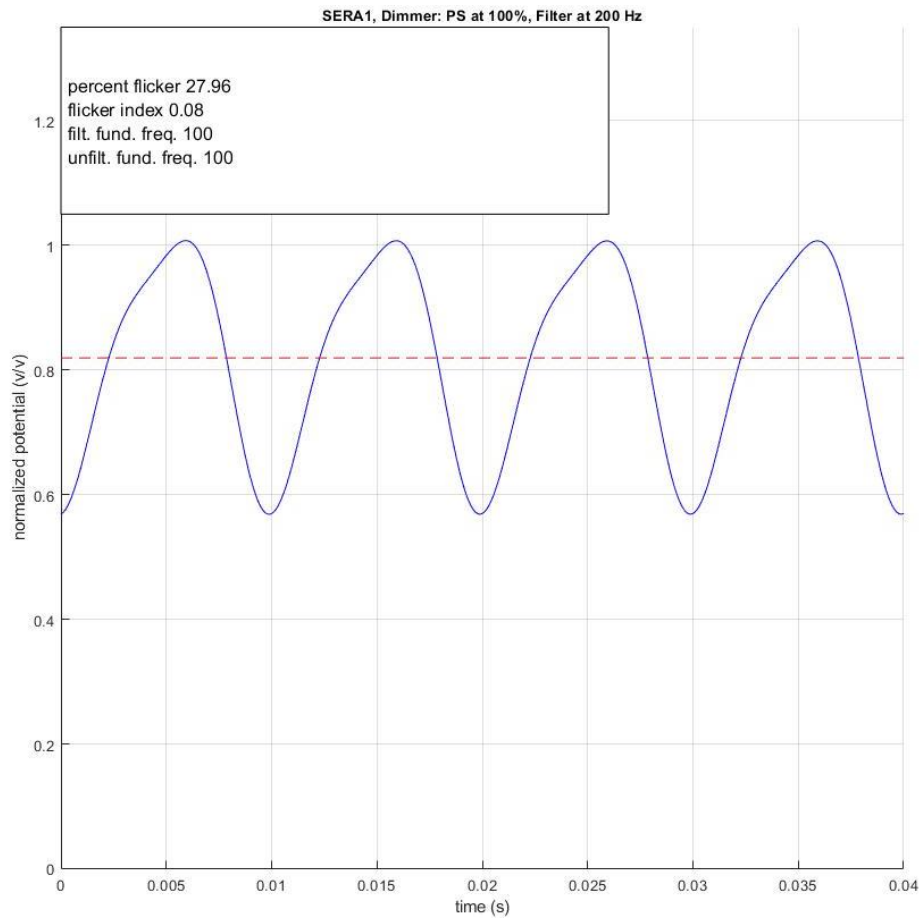
Appendix Table 9. A19 Color Quality.

| A19 Color Distortion Plot |                     |                    |                    |
|---------------------------|---------------------|--------------------|--------------------|
| Sera Technologies1        | Sera Technologies2  | Sera Technologies3 | Sera Technologies4 |
|                           |                     |                    |                    |
| Sera Technologies5        | Sera Technologies6  | Sera Technologies7 | Sera Technologies8 |
|                           |                     |                    |                    |
| Sera Technologies9        | Sera Technologies10 |                    |                    |
|                           |                     |                    |                    |

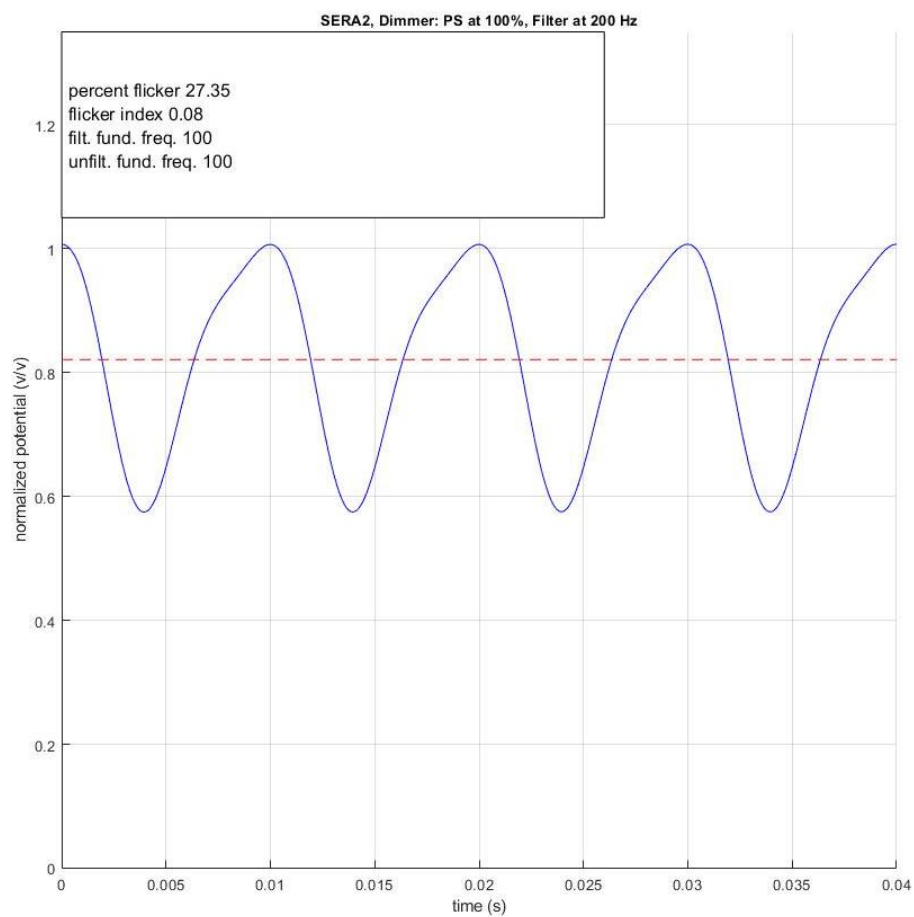
Appendix Table 10. A19 Color Distortion Plot.



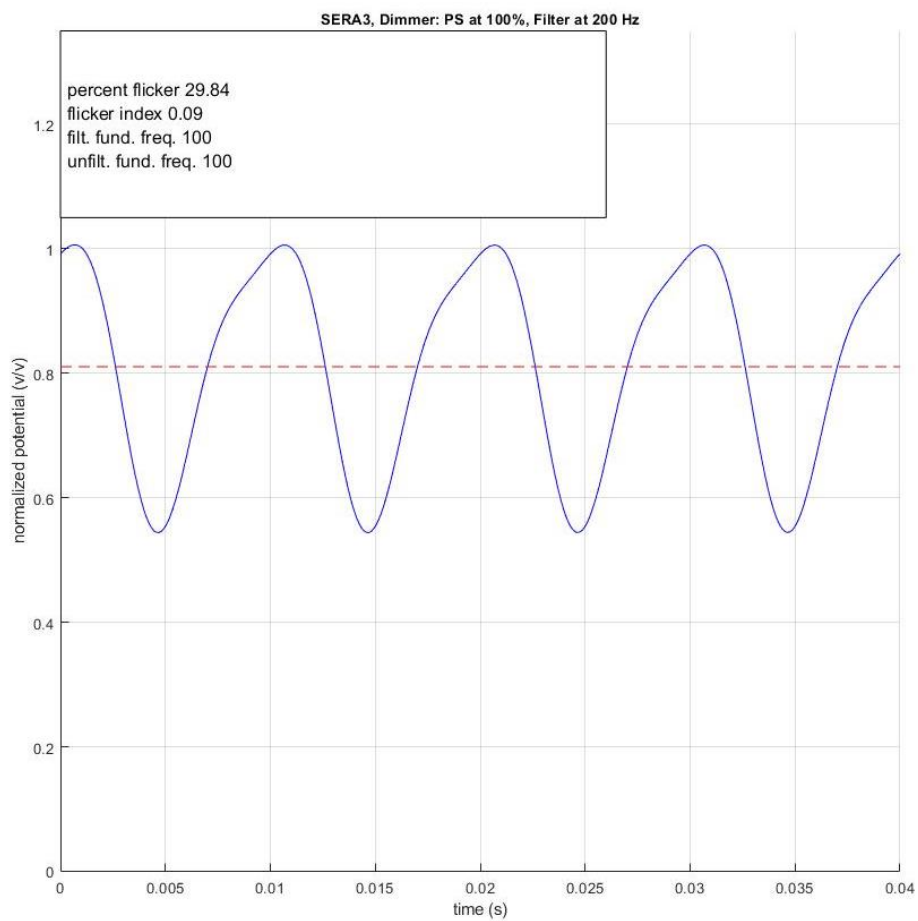
Appendix Figure 5. A19  $R_f$  vs  $R_g$  Plot.



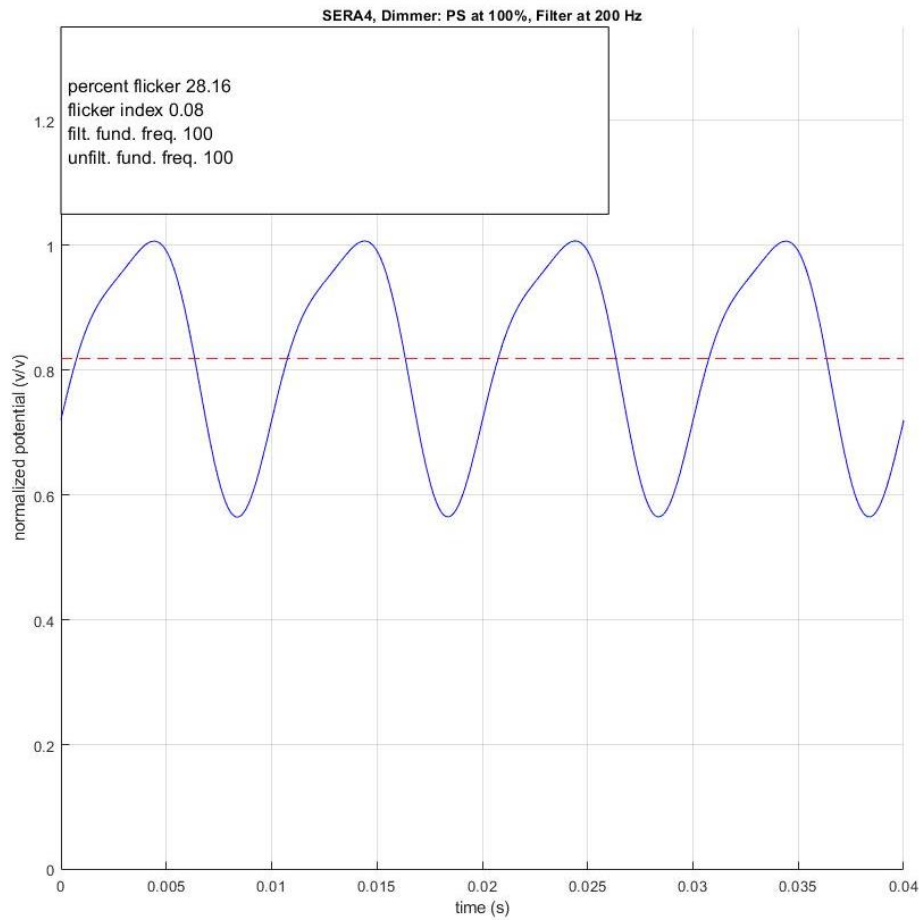
Appendix Figure 6. Sera Technologies1 Flicker Data.



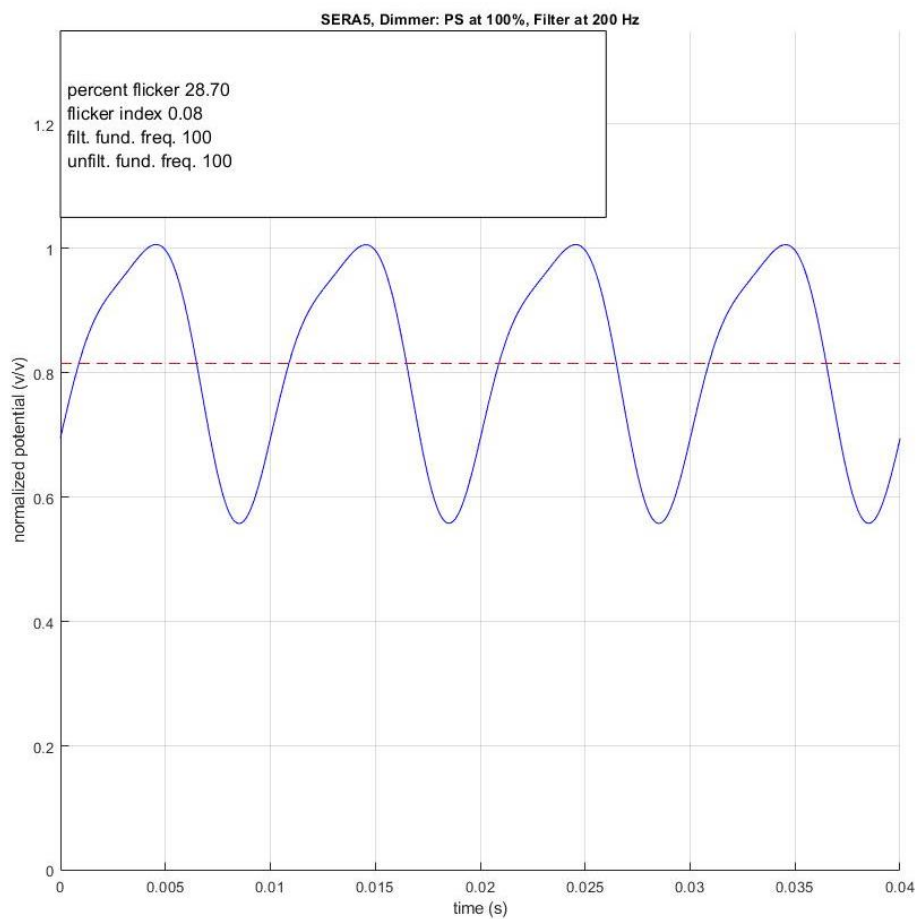
Appendix Figure 7. Sera Technologies2 Flicker Data.



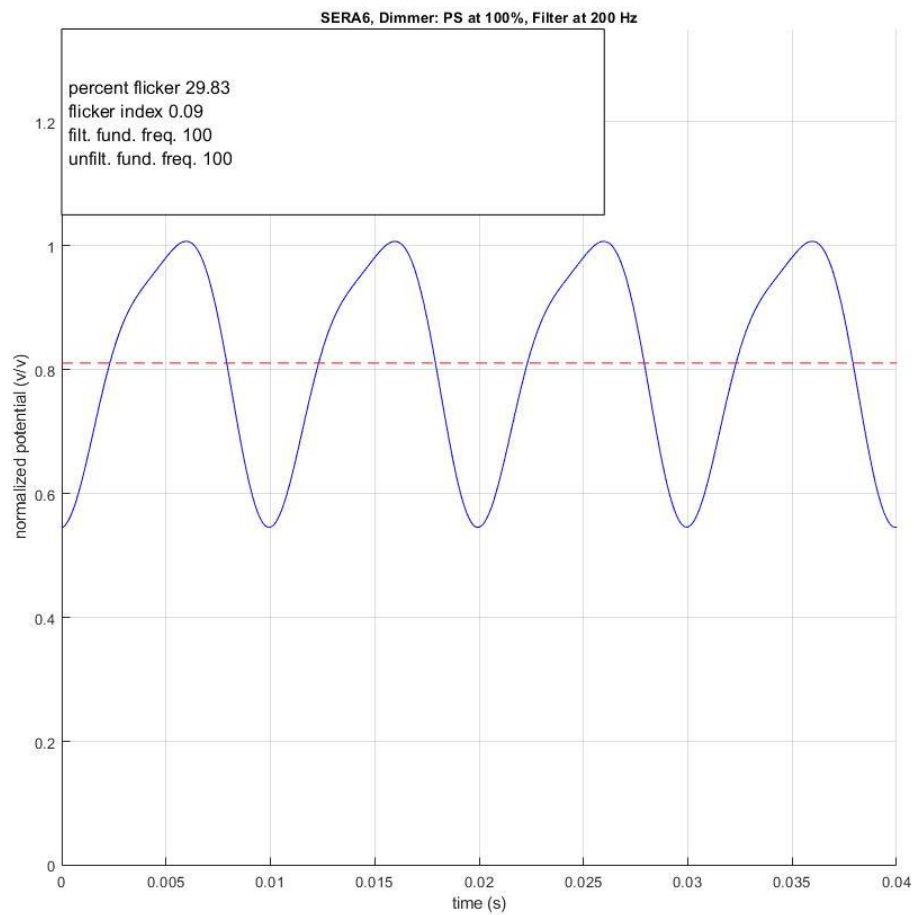
Appendix Figure 8. Sera Technologies3 Flicker Data.



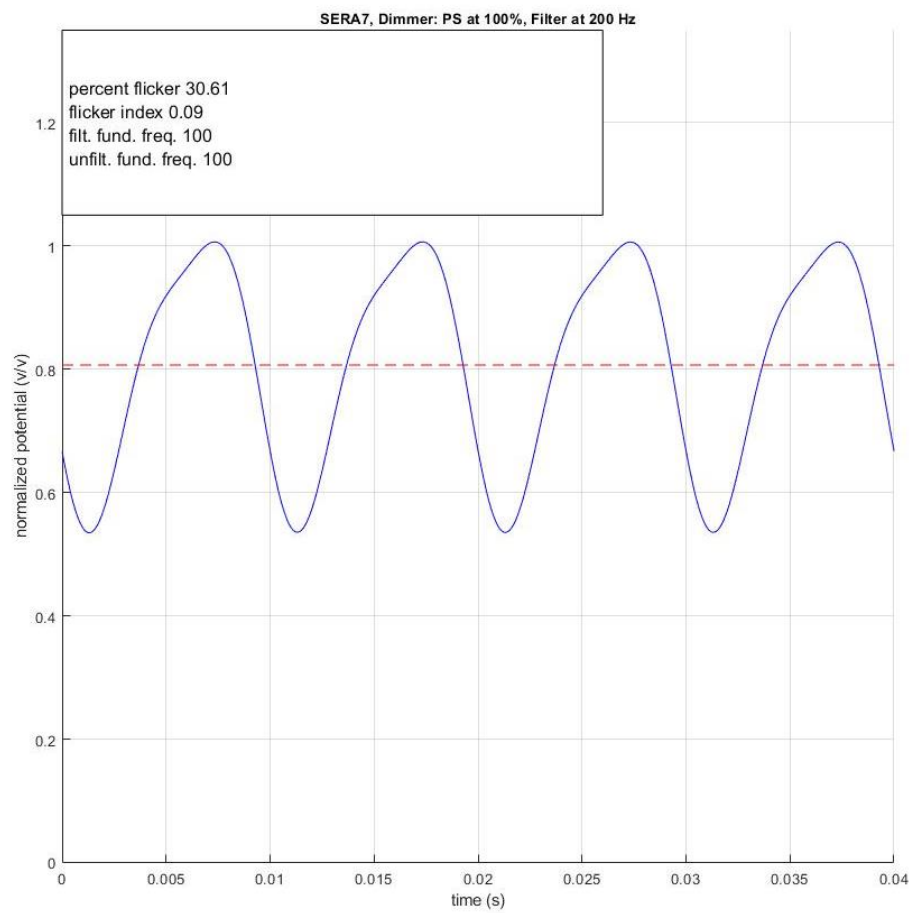
Appendix Figure 9. Sera Technologies4 Flicker Data.



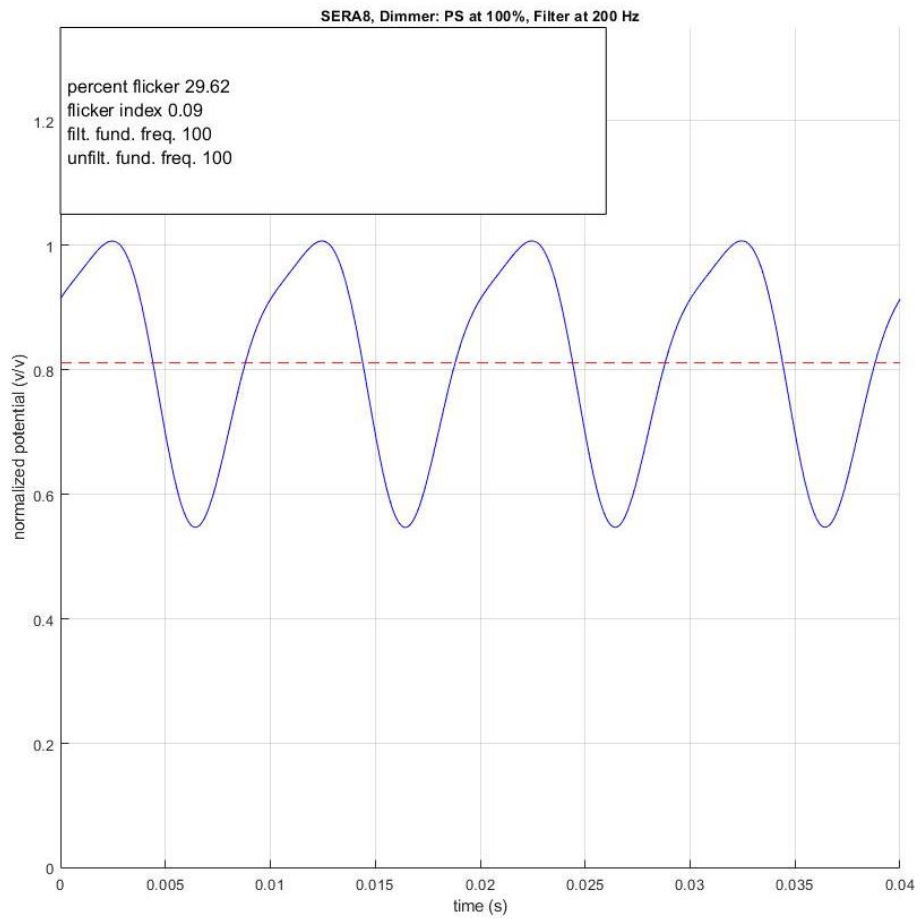
Appendix Figure 10. Sera Technologies5 Flicker Data.



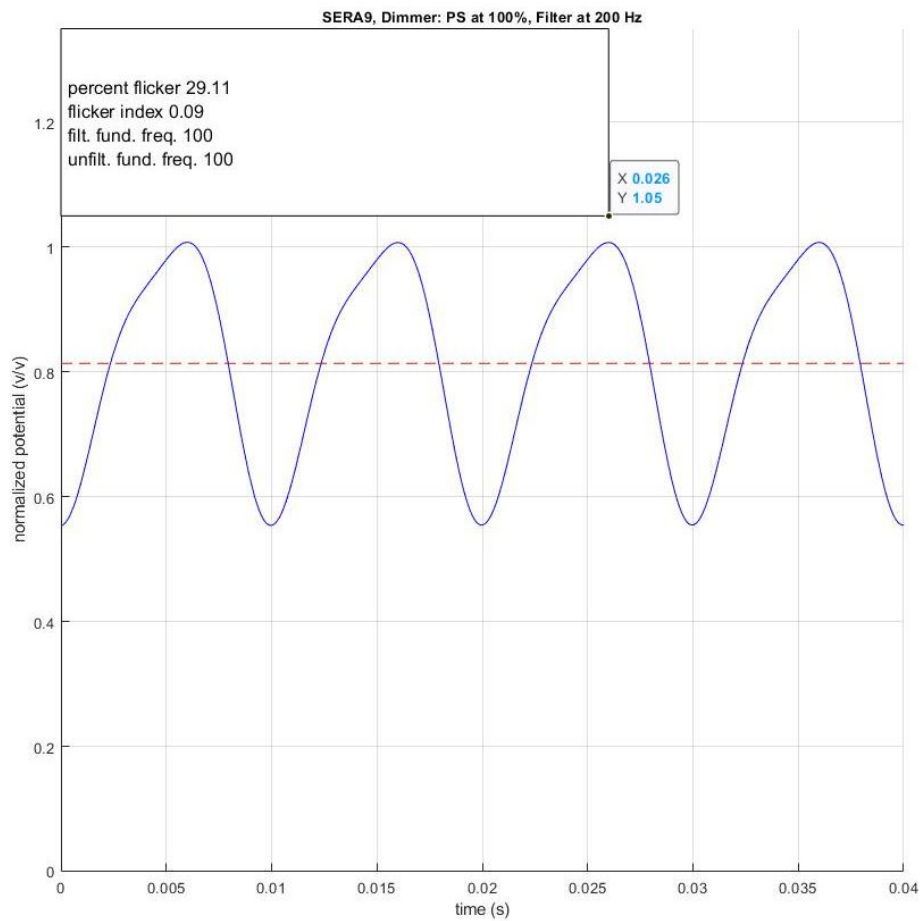
Appendix Figure 11. Sera Technologies6 Flicker Data.



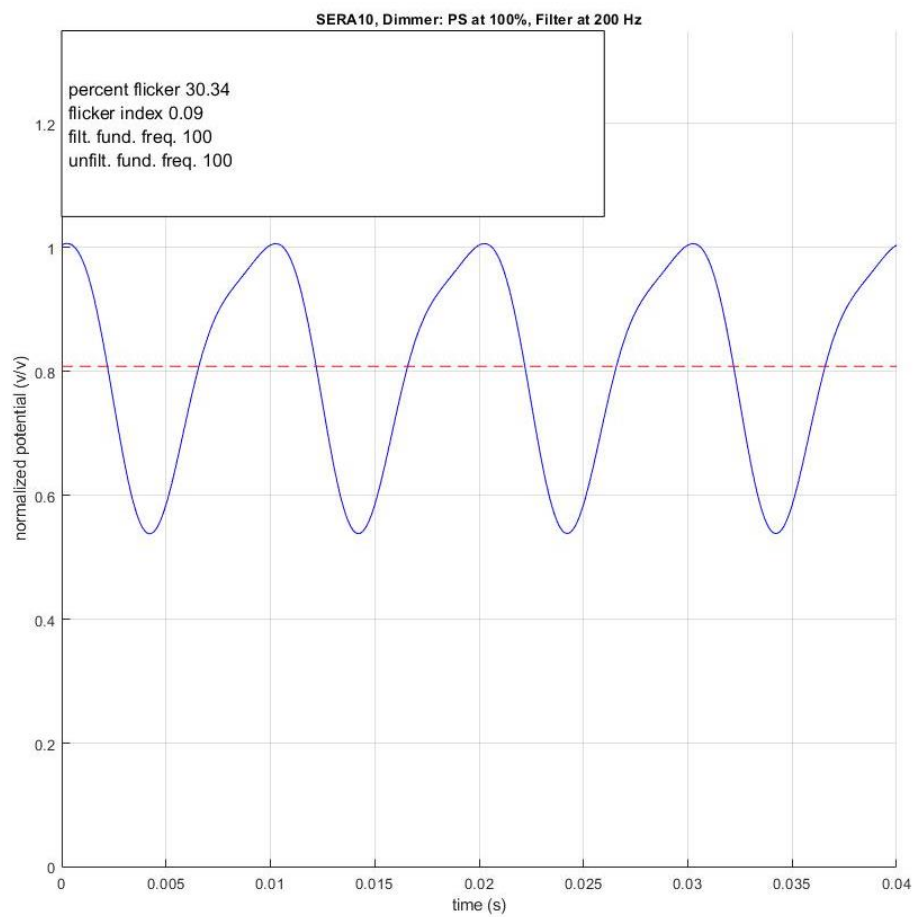
Appendix Figure 12. Sera Technologies7 Flicker Data.



Appendix Figure 13. Sera Technologies8 Flicker Data.



Appendix Figure 14. Sera Technologies9 Flicker Data.



Appendix Figure 15. Sera Technologies10 Flicker Data.

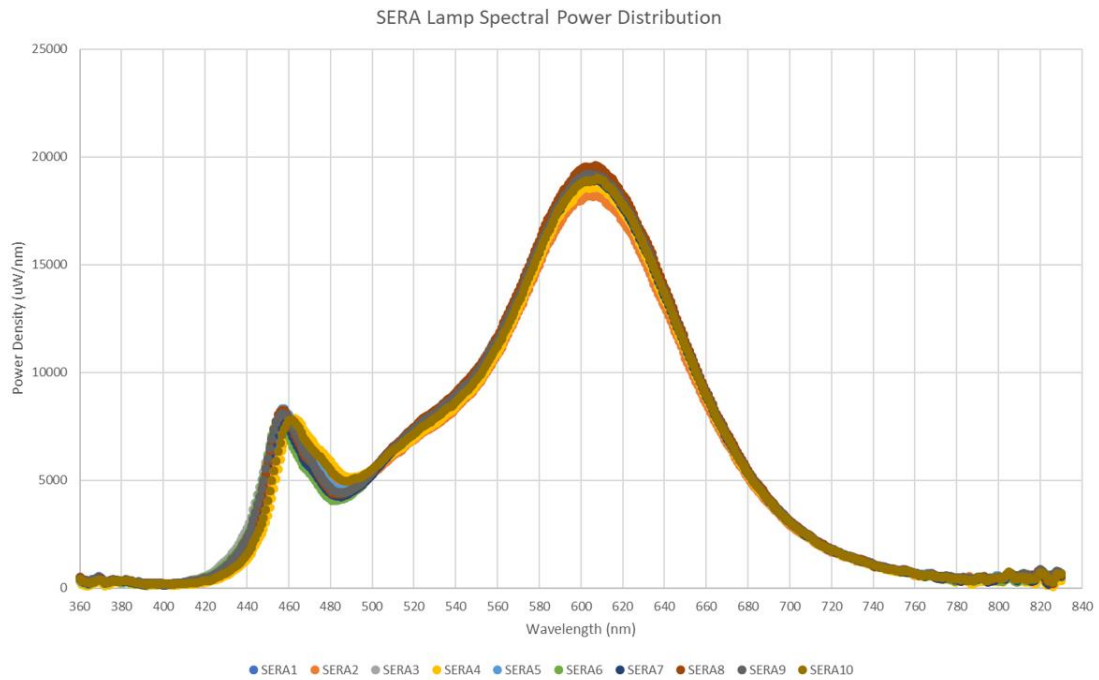
| A19 Flicker Data    |                     |               |
|---------------------|---------------------|---------------|
| Lamp                | Percent Flicker (%) | Flicker Index |
| Sera Technologies1  | 27.96               | 0.08          |
| Sera Technologies2  | 27.35               | 0.08          |
| Sera Technologies3  | 29.84               | 0.09          |
| Sera Technologies4  | 28.16               | 0.08          |
| Sera Technologies5  | 28.70               | 0.08          |
| Sera Technologies6  | 29.83               | 0.09          |
| Sera Technologies7  | 30.61               | 0.09          |
| Sera Technologies8  | 29.62               | 0.09          |
| Sera Technologies9  | 29.11               | 0.09          |
| Sera Technologies10 | 30.34               | 0.09          |

Appendix Table 11. A19 Flicker Data.

#### A-1.2 A19-PES Electrical

| Lamp                | Power % | Voltage (V) | Current (A) | Power (W) | Power Factor | UTHD % | ITHD % |
|---------------------|---------|-------------|-------------|-----------|--------------|--------|--------|
| Sera Technologies1  | 100     | 230.2       | 0.0416      | 7.60      | 0.7938       | 0.06   | 55.54  |
| Sera Technologies2  | 100     | 229.64      | 0.0416      | 7.59      | 0.7947       | 0.06   | 55.40  |
| Sera Technologies3  | 100     | 230.28      | 0.0416      | 7.61      | 0.7940       | 0.06   | 55.57  |
| Sera Technologies4  | 100     | 230.28      | 0.0414      | 7.58      | 0.7949       | 0.07   | 55.45  |
| Sera Technologies5  | 100     | 230.30      | 0.0414      | 7.58      | 0.7944       | 0.07   | 55.59  |
| Sera Technologies6  | 100     | 220.26      | 0.0418      | 7.39      | 0.8021       | 0.06   | 54.97  |
| Sera Technologies7  | 100     | 220.28      | 0.0416      | 7.36      | 0.8028       | 0.07   | 54.94  |
| Sera Technologies8  | 100     | 220.30      | 0.0421      | 7.43      | 0.8021       | 0.07   | 55.26  |
| Sera Technologies9  | 100     | 220.27      | 0.0420      | 7.43      | 0.8032       | 0.07   | 54.75  |
| Sera Technologies10 | 100     | 220.29      | 0.0416      | 7.37      | 0.8035       | 0.07   | 54.48  |

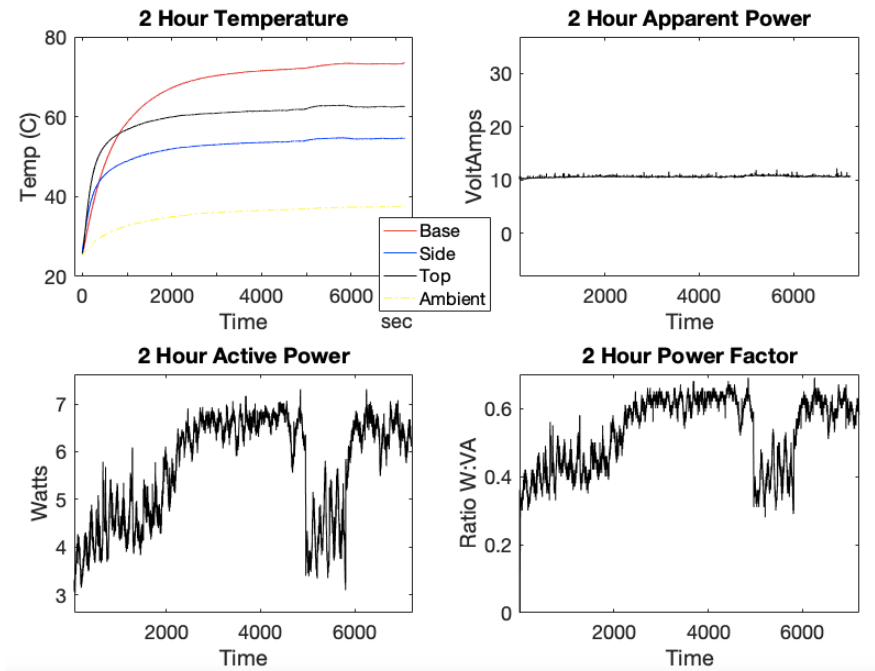
Appendix Table 12. A19 Electrical Characteristics.



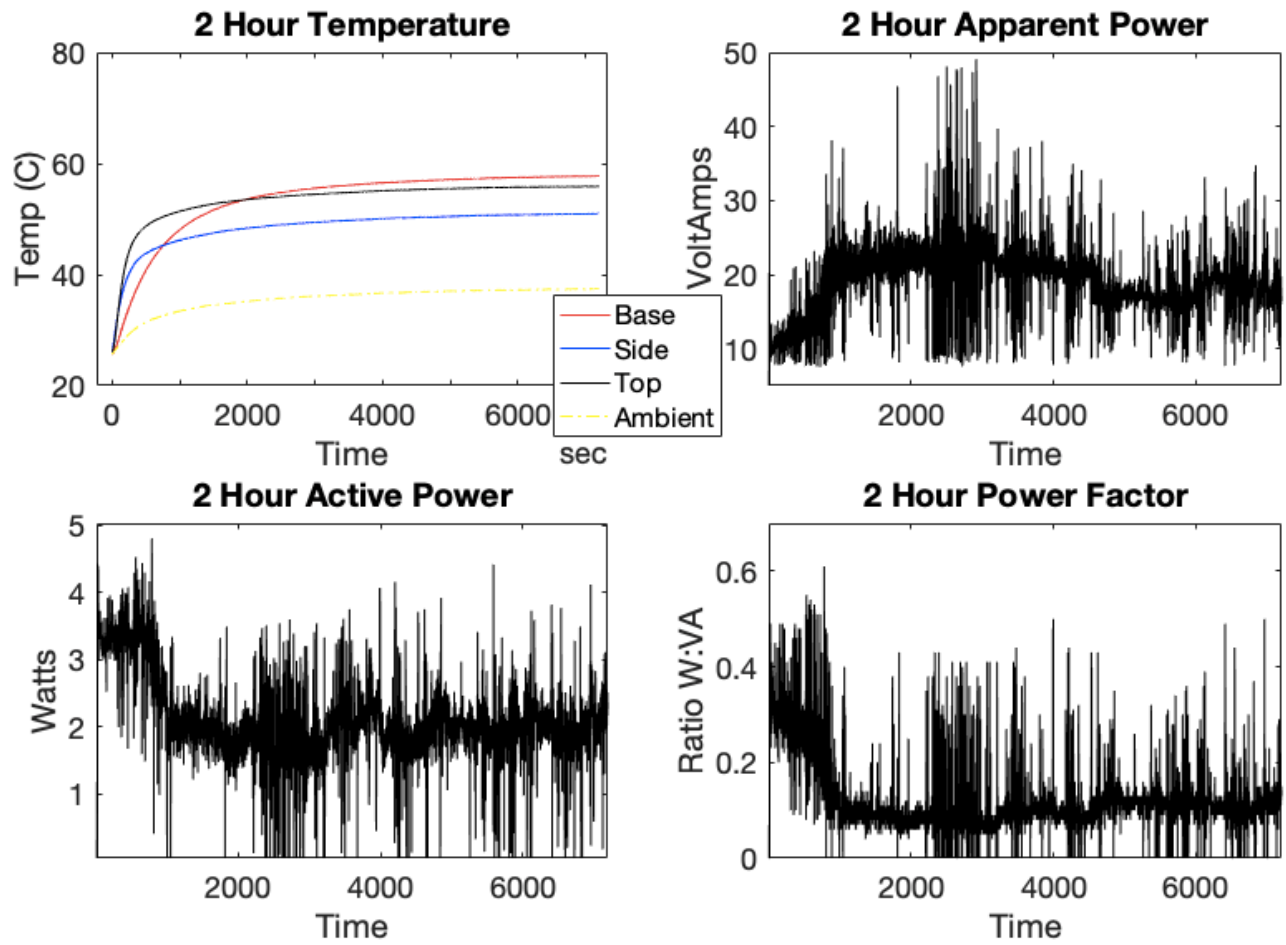
Appendix Figure 16. Sera Technologies GA19 Spectral Power Distribution.

**A-2 A19-TES**

### A-2.1 A19-TES Thermal and Electrical



Appendix Figure 17. Non-Graphene A19 (PRO-ELEC) Thermal and Electrical Plots.



Appendix Figure 18. Graphene A19 (Sera Technologies) Thermal and Electrical Plots.

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# APPENDIX B

## GTLED ADDITIONAL FIGURES AND TABLES

### B-1 GTLED-PES/B-1.1 GTLED-PES Photometric.

| Photometric 1931 2° |         |           |                   |         |         |     |                 |                     |               |
|---------------------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| Lamp                | Power % | Power (W) | Light Output (lm) | CCT (K) | Duy     | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| GTLED1              | 100     | 9.53      | 2036              | 4600    | 0.0329  | 62  | 213.64          | 82.59               | 0.26          |
| GTLED2              | 100     | 9.57      | 1349              | 3938    | -0.0020 | 69  | 140.96          | 75.55               | 0.24          |
| GTLED3              | 100     | 9.67      | 1841              | 4703    | 0.0297  | 63  | 190.38          | 76.51               | 0.24          |
| GTLED4              | 100     | 18.59     | 2743              | 5196    | 0.0078  | 64  | 147.55          | 75.24               | 0.24          |
| GTLED5              | 100     | 17.57     | 2303              | 5231    | 0.0047  | 71  | 131.08          | 77.17               | 0.25          |
| GTLED6              | 100     | 9.51      | 1336              | 3933    | -0.0018 | 69  | 140.48          | 74.95               | 0.24          |
| GTLED7              | 100     | 9.48      | 1331              | 3948    | -0.0021 | 69  | 140.40          | 75.34               | 0.24          |
| GTLED8              | 100     | 17.64     | 2312              | 5183    | 0.0050  | 71  | 131.07          | 78.04               | 0.25          |
| GTLED9              | 100     | 18.64     | 2644              | 5159    | 0.0079  | 64  | 183.92          | 78.18               | 0.25          |
| GTLED10             | 100     | 9.77      | 1797              | 4748    | 0.0289  | 63  | 130.31          | 78.4                | 0.25          |
| GTLED11             | 100     | 17.88     | 2330              | 5199    | 0.0048  | 71  | 129.19          | 78.18               | 0.24          |
| GTLED12             | 100     | 17.78     | 2297              | 3978    | -0.0023 | 69  | 129.19          | 78.4                | 0.25          |
| GTLED13             | 100     | 9.63      | 1778              | 4709    | 0.0297  | 63  | 184.63          | 76.51               | 0.24          |
| GTLED14             | 100     | 9.55      | 1800              | 4652    | 0.0309  | 62  | 188.48          | 76.93               | 0.24          |
| GTLED15             | 100     | 17.96     | 2390              | 5191    | 0.0048  | 71  | 133.07          | 77.08               | 0.25          |
| GTLED16             | 100     | 9.48      | 1308              | 3949    | -0.0016 | 69  | 137.97          | 74.94               | 0.24          |

Appendix Table 13. GTLED 2° Filament Lamp Testing.

| Photometric 1931 10° |         |           |                   |         |         |     |                 |                     |               |
|----------------------|---------|-----------|-------------------|---------|---------|-----|-----------------|---------------------|---------------|
| Lamp                 | Power % | Power (W) | Light Output (lm) | CCT (K) | Duy     | CRI | Efficacy (lm/W) | Percent Flicker (%) | Flicker Index |
| GTLED1               | 100     | 9.53      | 2146              | 4318    | 0.0237  | 62  | 225.18          | 82.95               | 0.26          |
| GTLED2               | 100     | 9.57      | 1433              | 3743    | -0.0076 | 69  | 149.74          | 75.55               | 0.24          |
| GTLED3               | 100     | 9.67      | 1943              | 4427    | 0.0204  | 63  | 200.93          | 76.51               | 0.24          |
| GTLED4               | 100     | 18.59     | 2920              | 4949    | -0.0019 | 64  | 157.07          | 75.24               | 0.24          |
| GTLED5               | 100     | 17.57     | 2475              | 4995    | -0.0019 | 71  | 140.87          | 77.17               | 0.25          |
| GTLED6               | 100     | 9.51      | 1419              | 3737    | .0.0075 | 69  | 149.21          | 74.95               | 0.24          |
| GTLED7               | 100     | 9.48      | 1414              | 3752    | -0.0078 | 69  | 149.16          | 75.34               | 0.24          |
| GTLED8               | 100     | 17.64     | 2484              | 4948    | -0.0016 | 71  | 140.82          | 78.04               | 0.25          |
| GTLED9               | 100     | 18.64     | 2815              | 4914    | -0.0016 | 64  | 151.02          | 78.18               | 0.25          |
| GTLED10              | 100     | 9.77      | 1899              | 4474    | 0.0197  | 63  | 194.37          | 78.40               | 0.25          |
| GTLED11              | 100     | 17.88     | 2504              | 4964    | -0.0017 | 71  | 140.04          | 76.88               | 0.24          |
| GTLED12              | 100     | 17.78     | 2441              | 3780    | -0.0080 | 69  | 137.29          | 77.4                | 0.25          |
| GTLED13              | 100     | 9.63      | 1878              | 4432    | 0.0205  | 63  | 195.02          | 76.57               | 0.24          |
| GTLED14              | 100     | 9.55      | 1899              | 4373    | 0.0217  | 62  | 198.85          | 76.93               | 0.24          |
| GTLED15              | 100     | 17.96     | 2568              | 4955    | -0.0018 | 71  | 142.98          | 77.08               | 0.25          |
| GTLED16              | 100     | 9.48      | 1389              | 3752    | -0.0073 | 69  | 146.52          | 74.94               | 0.24          |

Appendix Table 14. GTLED 10° Filament Lamp Testing.

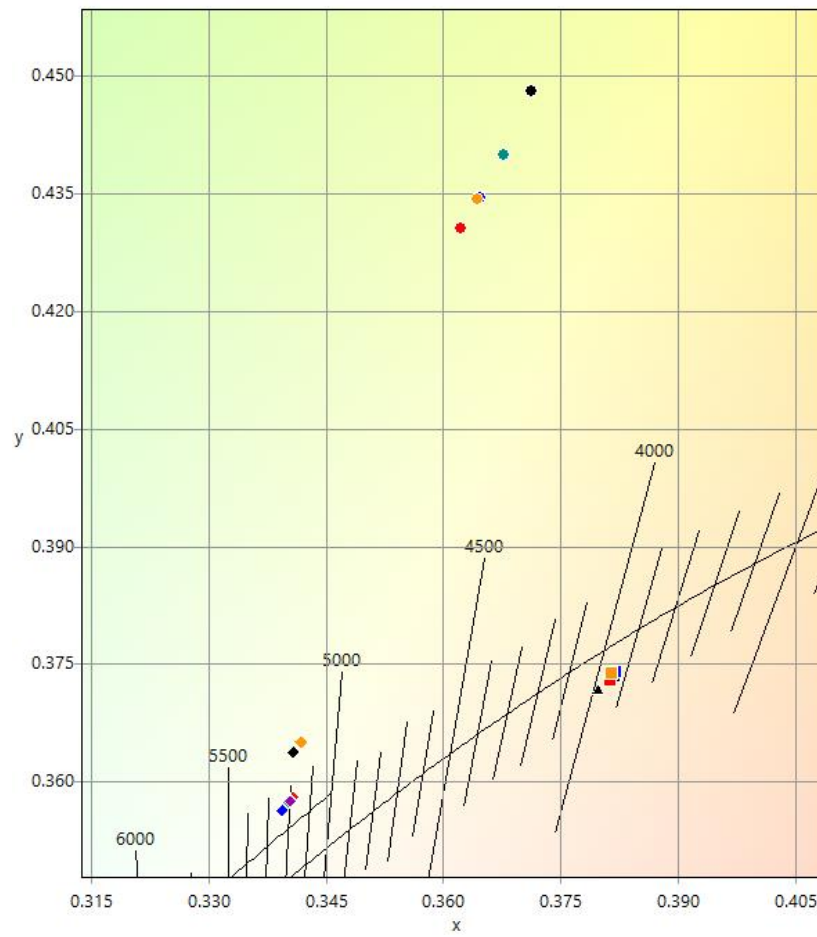
| Lamp    | Power % | R1     | R2    | R3    | R4    | R5    | R6    | R7    |
|---------|---------|--------|-------|-------|-------|-------|-------|-------|
| GTLED1  | 100     | 52.37  | 65.54 | 83.16 | 61.88 | 54.06 | 55.64 | 82.65 |
| GTLED2  | 100     | 65.61  | 78.52 | 86.93 | 65.2  | 64.85 | 67.61 | 79.07 |
| GTLED3  | 100     | 53.49  | 65.9  | 81.86 | 62.54 | 55.25 | 56.04 | 81.29 |
| GTLED4  | 100     | 61.59  | 67.62 | 73.43 | 66.24 | 63.33 | 57.96 | 73.16 |
| GTLED5  | 100     | 67.95  | 76.98 | 82.48 | 70.84 | 68.57 | 67.43 | 81.79 |
| GTLED6  | 100     | 65.40  | 78.44 | 86.98 | 65    | 64.64 | 67.5  | 79.01 |
| GTLED7  | 100     | 65.58  | 78.47 | 86.89 | 65.2  | 64.85 | 67.56 | 79.02 |
| GTLED8  | 100     | 67.62  | 76.73 | 82.42 | 70.6  | 68.24 | 67.14 | 81.65 |
| GTLED9  | 100     | 61.75  | 67.86 | 73.82 | 66.44 | 63.47 | 58.27 | 73.38 |
| GTLED10 | 100     | 53.75  | 66.15 | 81.81 | 62.57 | 55.52 | 56.31 | 81.3  |
| GTLED11 | 100     | 67.71  | 76.88 | 82.56 | 70.62 | 68.34 | 67.31 | 81.71 |
| GTLED12 | 100     | 65.32  | 78.34 | 86.72 | 64.89 | 64.65 | 67.32 | 78.95 |
| GTLED13 | 100     | 53.37  | 65.97 | 82.06 | 62.36 | 55.14 | 56.09 | 81.45 |
| GTLED14 | 100     | 53.01  | 65.92 | 82.63 | 62.15 | 54.71 | 56    | 82.05 |
| GTLED15 | 100     | 67.75  | 76.88 | 82.52 | 70.65 | 68.36 | 67.3  | 81.71 |
| GTLED16 | 100     | 65.35  | 78.39 | 86.94 | 65.02 | 64.63 | 67.45 | 79.05 |
| Lamp    | R8      | R9     | R10   | R11   | R12   | R13   | R14   | RA    |
| GTLED1  | 42.5    | -82.29 | 24.35 | 55.1  | 21.11 | 53.72 | 90.72 | 62.23 |
| GTLED2  | 47.58   | -39.06 | 47.88 | 57.55 | 36.16 | 67.97 | 92.53 | 69.42 |
| GTLED3  | 43.67   | -78.82 | 24.65 | 56.29 | 22.92 | 54.71 | 89.98 | 62.51 |
| GTLED4  | 50.26   | -54.84 | 24.9  | 64.88 | 35.18 | 61.02 | 84.92 | 64.2  |
| GTLED5  | 55.37   | -35.26 | 44.27 | 66.18 | 38.68 | 69.51 | 90.1  | 71.42 |
| GTLED6  | 47.27   | -39.89 | 47.71 | 57.29 | 35.86 | 67.79 | 92.56 | 69.28 |
| GTLED7  | 47.53   | -39.33 | 47.79 | 57.59 | 36.15 | 67.93 | 92.51 | 69.39 |
| GTLED8  | 54.95   | -36.28 | 43.79 | 65.9  | 38.25 | 69.16 | 90.07 | 71.17 |
| GTLED9  | 50.32   | -54.26 | 25.54 | 65.06 | 35.53 | 61.21 | 85.15 | 64.41 |
| GTLED10 | 43.93   | -78.21 | 25.07 | 56.35 | 23    | 55.01 | 89.95 | 62.67 |
| GTLED11 | 55.01   | -36.06 | 44.11 | 65.9  | 38.49 | 69.29 | 90.15 | 71.27 |

|         |       |        |       |       |       |       |       |       |
|---------|-------|--------|-------|-------|-------|-------|-------|-------|
| GTLED12 | 47.51 | -39.77 | 47.38 | 57.03 | 36.62 | 67.68 | 92.4  | 69.21 |
| GTLED13 | 43.44 | -79.51 | 24.8  | 56.02 | 22.64 | 54.66 | 90.08 | 62.48 |
| GTLED14 | 43.01 | -80.53 | 24.85 | 55.59 | 21.91 | 54.36 | 90.41 | 62.44 |
| GTLED15 | 55.05 | -35.87 | 44.1  | 65.93 | 38.48 | 69.32 | 90.13 | 71.28 |
| GTLED16 | 47.3  | -40.1  | 47.62 | 57.35 | 35.79 | 67.75 | 92.54 | 69.27 |

Appendix Table 15. GTLED Color Rendering Index

| Lamp    | Model     | Symbol | CIE x  | CIE y  |
|---------|-----------|--------|--------|--------|
| GTLED1  | 9W 5000K  | ●      | 0.3712 | 0.4481 |
| GTLED2  | 9W 4000K  | ■      | 0.3818 | 0.3734 |
| GTLED3  | 9W 5000K  | ●      | 0.3647 | 0.4345 |
| GTLED4  | 18W 5000K | ◆      | 0.3408 | 0.3638 |
| GTLED5  | 18W 5000K | ◆      | 0.3394 | 0.3564 |
| GTLED6  | 9W 4000K  | ■      | 0.3821 | 0.374  |
| GTLED7  | 9W 4000K  | ■      | 0.3813 | 0.3729 |
| GTLED8  | 18W 5000K | ◆      | 0.3408 | 0.3581 |
| GTLED9  | 18W 5000K | ◆      | 0.3418 | 0.3651 |
| GTLED10 | 9W 5000K  | ●      | 0.3623 | 0.4306 |
| GTLED11 | 18W 5000K | ◆      | 0.3403 | 0.3574 |
| GTLED12 | 18W 3000K | ▲      | 0.3798 | 0.3716 |
| GTLED13 | 9W 5000K  | ●      | 0.3644 | 0.4343 |
| GTLED14 | 9W 5000K  | ●      | 0.3677 | 0.44   |
| GTLED15 | 18W 5000K | ◆      | 0.3405 | 0.3576 |
| GTLED16 | 9W 4000K  | ■      | 0.3815 | 0.3739 |

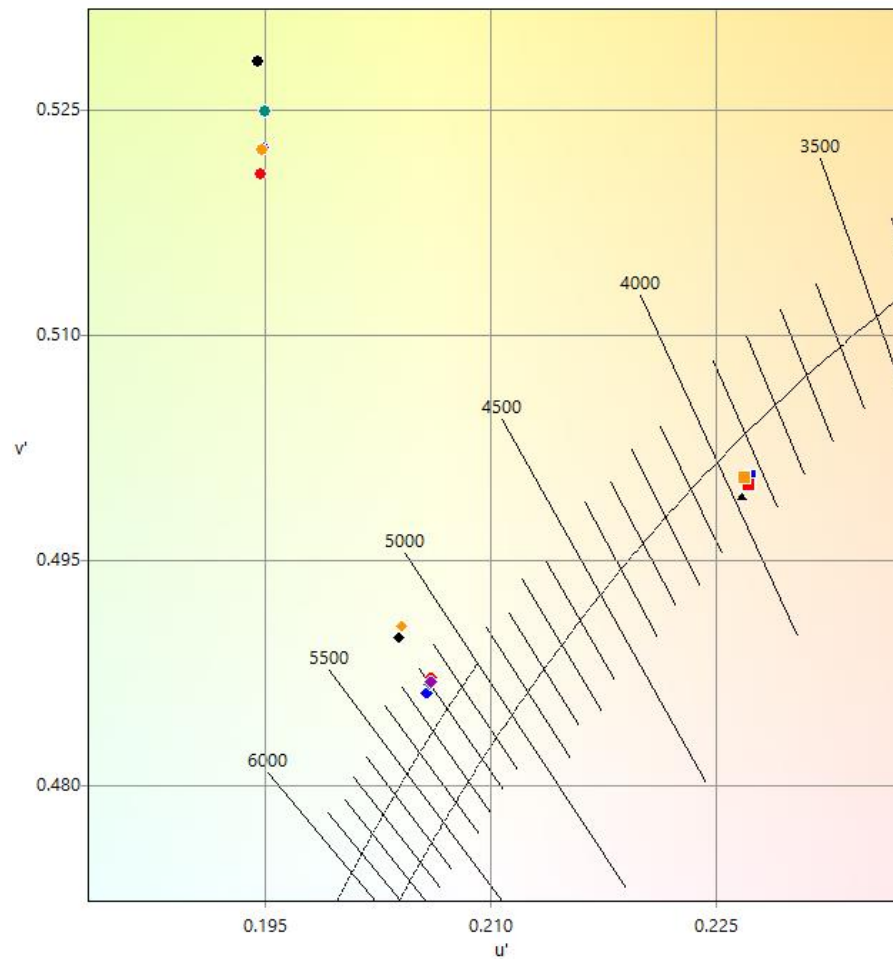
Appendix Table 16. GTLED 1931 2° x & y Chromaticity Table



Appendix Figure 19. GTLED 1931 2° x & y Chromaticity Diagram.

| Lamp    | Model     | Symbol | CIE x  | CIE y  |
|---------|-----------|--------|--------|--------|
| GTLED1  | 9W 5000K  | ●      | 0.1945 | 0.5282 |
| GTLED2  | 9W 4000K  | ■      | 0.2273 | 0.5003 |
| GTLED3  | 9W 5000K  | ●      | 0.1949 | 0.5225 |
| GTLED4  | 18W 5000K | ◆      | 0.2039 | 0.4899 |
| GTLED5  | 18W 5000K | ◆      | 0.2058 | 0.4861 |
| GTLED6  | 9W 4000K  | ■      | 0.2273 | 0.5006 |
| GTLED7  | 9W 4000K  | ■      | 0.2272 | 0.5    |
| GTLED8  | 18W 5000K | ◆      | 0.206  | 0.4872 |
| GTLED9  | 18W 5000K | ◆      | 0.2042 | 0.4906 |
| GTLED10 | 9W 5000K  | ●      | 0.1947 | 0.5207 |
| GTLED11 | 18W 5000K | ◆      | 0.206  | 0.4868 |
| GTLED12 | 18W 3000K | ▲      | 0.2268 | 0.4992 |
| GTLED13 | 9W 5000K  | ●      | 0.1948 | 0.5224 |
| GTLED14 | 9W 5000K  | ●      | 0.1949 | 0.5249 |
| GTLED15 | 18W 5000K | ◆      | 0.2061 | 0.4869 |
| GTLED16 | 9W 4000K  | ■      | 0.227  | 0.5005 |

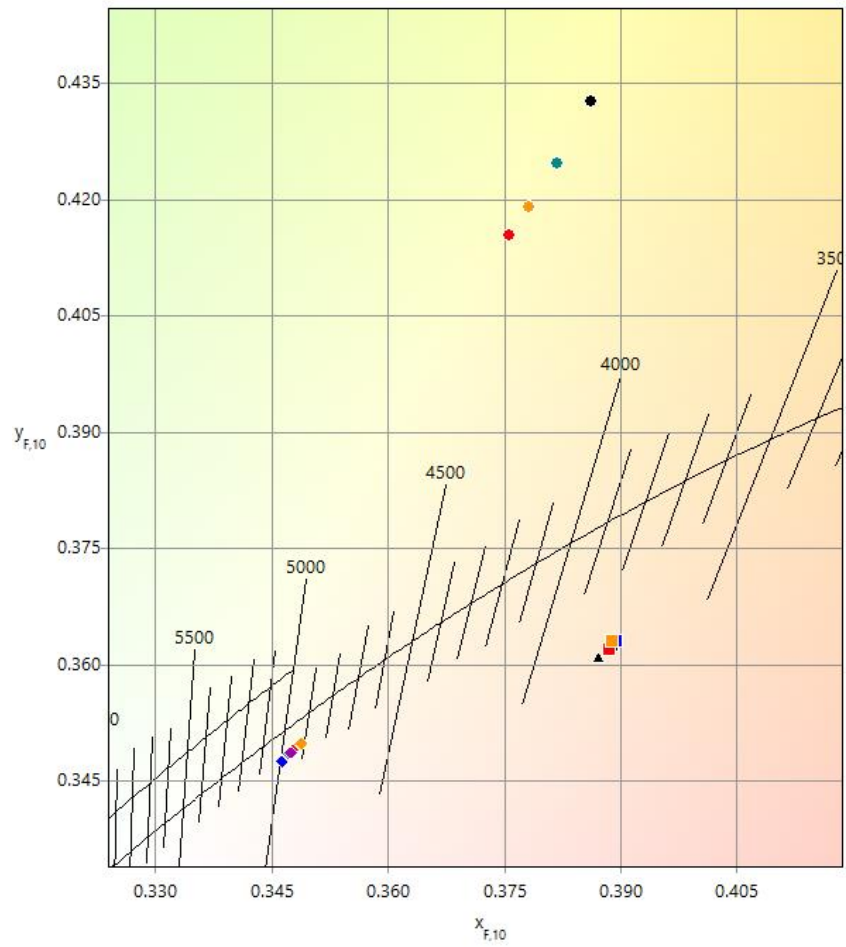
Appendix Table 17. GTLED 1976 2° u' & v' Chromaticity Table.



Appendix Figure 20. GTLED 1976 2°  $u'$  &  $v'$  Chromaticity Diagram.

| Lamp    | Model     | Symbol | CIE x  | CIE y  |
|---------|-----------|--------|--------|--------|
| GTLED1  | 9W 5000K  | ●      | 0.3862 | 0.4328 |
| GTLED2  | 9W 4000K  | ■      | 0.389  | 0.3625 |
| GTLED3  | 9W 5000K  | ●      | 0.3783 | 0.4191 |
| GTLED4  | 18W 5000K | ◆      | 0.3476 | 0.3485 |
| GTLED5  | 18W 5000K | ◆      | 0.3463 | 0.3475 |
| GTLED6  | 9W 4000K  | ■      | 0.3895 | 0.3631 |
| GTLED7  | 9W 4000K  | ■      | 0.3885 | 0.362  |
| GTLED8  | 18W 5000K | ◆      | 0.3477 | 0.349  |
| GTLED9  | 18W 5000K | ◆      | 0.3488 | 0.3498 |
| GTLED10 | 9W 5000K  | ●      | 0.3756 | 0.4155 |
| GTLED11 | 18W 5000K | ◆      | 0.3472 | 0.3485 |
| GTLED12 | 18W 3000K | ▲      | 0.387  | 0.3607 |
| GTLED13 | 9W 5000K  | ●      | 0.3781 | 0.4191 |
| GTLED14 | 9W 5000K  | ●      | 0.3819 | 0.4248 |
| GTLED15 | 18W 5000K | ◆      | 0.3475 | 0.3486 |
| GTLED16 | 9W 4000K  | ■      | 0.3889 | 0.3631 |

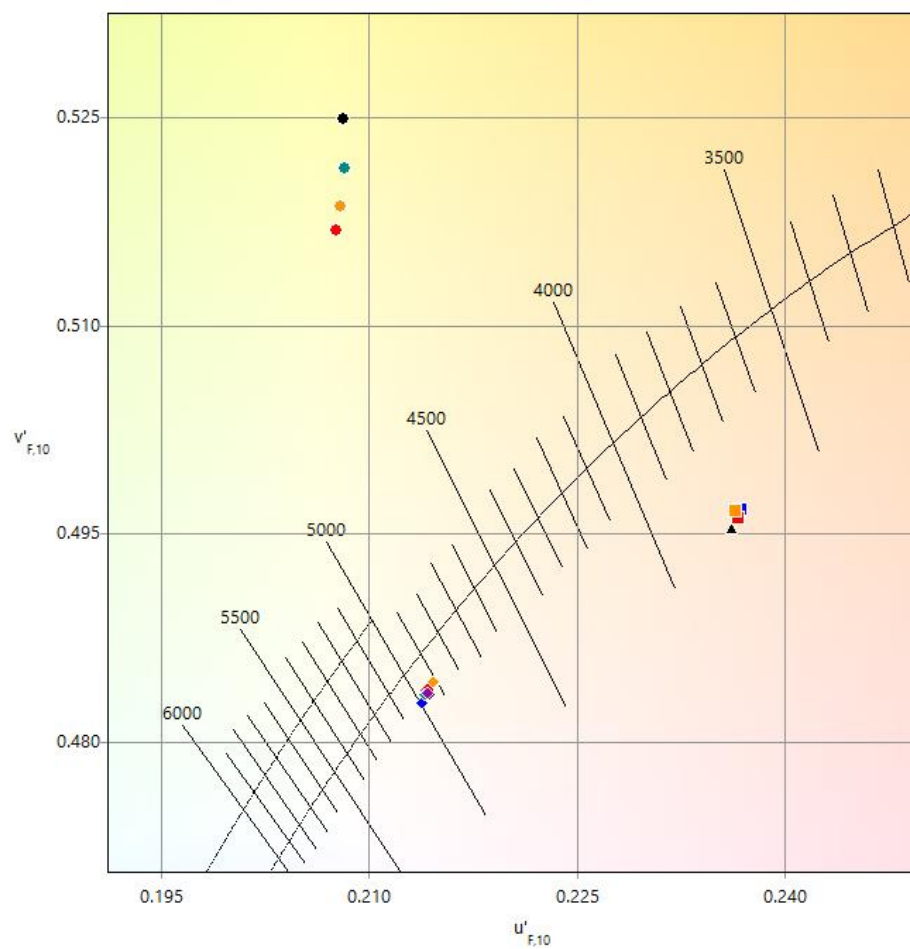
Appendix Table 18. GTLED 2015 10° x & y Chromaticity Table.



Appendix Figure 21. GTLED 2015 10° x & y Chromaticity Diagram.

| Lamp    | Model     | Symbol | CIE x  | CIE y  |
|---------|-----------|--------|--------|--------|
| GTLED1  | 9W 5000K  | ●      | 0.2082 | 0.5249 |
| GTLED2  | 9W 4000K  | ■      | 0.2368 | 0.4964 |
| GTLED3  | 9W 5000K  | ●      | 0.2081 | 0.5187 |
| GTLED4  | 18W 5000K | ◆      | 0.2144 | 0.4835 |
| GTLED5  | 18W 5000K | ◆      | 0.2138 | 0.4828 |
| GTLED6  | 9W 4000K  | ■      | 0.2368 | 0.4968 |
| GTLED7  | 9W 4000K  | ■      | 0.2366 | 0.4961 |
| GTLED8  | 18W 5000K | ◆      | 0.2142 | 0.4838 |
| GTLED9  | 18W 5000K | ◆      | 0.2146 | 0.4843 |
| GTLED10 | 9W 5000K  | ●      | 0.2076 | 0.5169 |
| GTLED11 | 18W 5000K | ◆      | 0.2141 | 0.4835 |
| GTLED12 | 18W 3000K | ▲      | 0.2362 | 0.4953 |
| GTLED13 | 9W 5000K  | ●      | 0.2079 | 0.5186 |
| GTLED14 | 9W 5000K  | ●      | 0.2083 | 0.5213 |
| GTLED15 | 18W 5000K | ◆      | 0.2142 | 0.4835 |
| GTLED16 | 9W 4000K  | ■      | 0.2364 | 0.4967 |

Appendix Table 19. GTLED 2015 10° u' & v' Chromaticity Table.



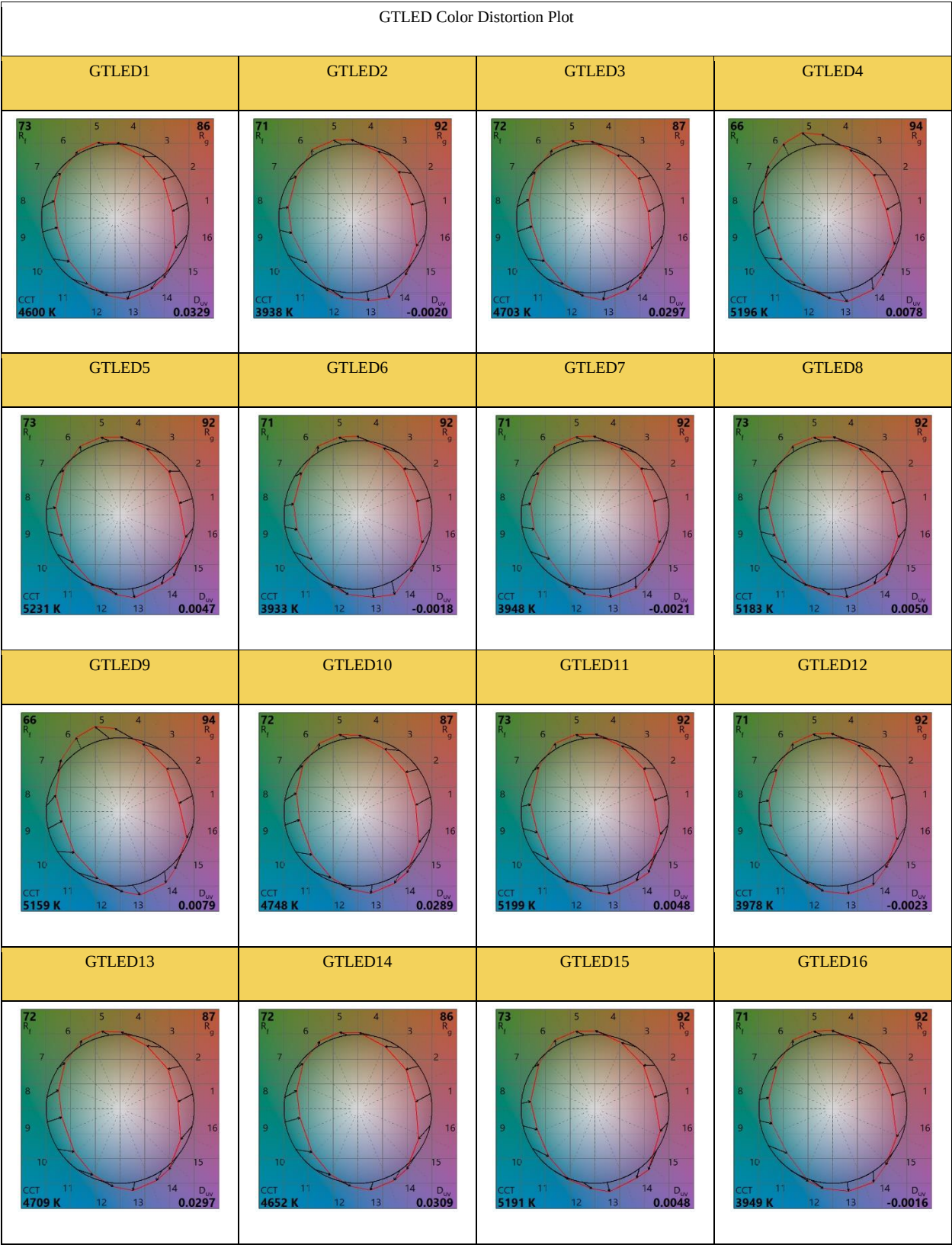
Appendix Figure 22. GTLED 2015 10°  $u'$  &  $v'$  Chromaticity Diagram

| Color Fidelity & Gamut |           |    |    |
|------------------------|-----------|----|----|
| Lamp                   | Model     | Rf | Rg |
| GTLED1                 | 9W 5000K  | 73 | 86 |
| GTLED2                 | 9W 4000K  | 71 | 92 |
| GTLED3                 | 9W 5000K  | 72 | 87 |
| GTLED4                 | 18W 5000K | 66 | 94 |
| GTLED5                 | 18W 5000K | 73 | 92 |
| GTLED6                 | 9W 4000K  | 71 | 92 |
| GTLED7                 | 9W 4000K  | 71 | 92 |
| GTLED8                 | 18W 5000K | 73 | 92 |
| GTLED9                 | 18W 5000K | 66 | 94 |
| GTLED10                | 9W 5000K  | 72 | 87 |
| GTLED11                | 18W 5000K | 73 | 92 |
| GTLED12                | 18W 3000K | 71 | 92 |
| GTLED13                | 9W 5000K  | 72 | 87 |
| GTLED14                | 9W 5000K  | 72 | 86 |
| GTLED15                | 18W 5000K | 73 | 92 |
| GTLED16                | 9W 4000K  | 71 | 92 |

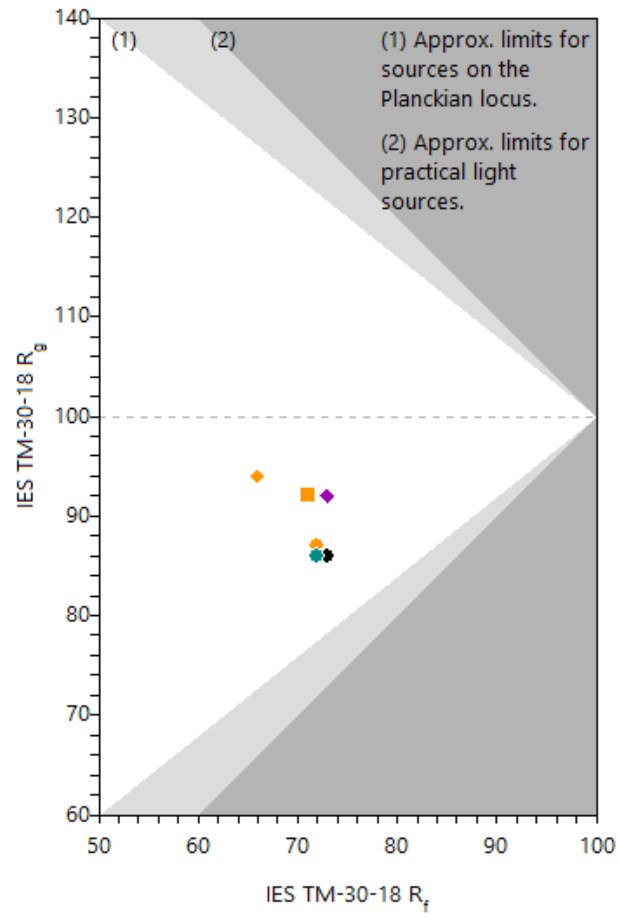
Appendix Table 20. GTLED Color Fidelity & Gamut.

| GTLED Color Quality |           |        |    |    |
|---------------------|-----------|--------|----|----|
| Lamp                | Model     | Symbol | Rf | Rg |
| GTLED1              | 9W 5000K  | ●      | 73 | 86 |
| GTLED2              | 9W 4000K  | ■      | 71 | 92 |
| GTLED3              | 9W 5000K  | ●      | 72 | 87 |
| GTLED4              | 18W 5000K | ◆      | 66 | 94 |
| GTLED5              | 18W 5000K | ◆      | 73 | 92 |
| GTLED6              | 9W 4000K  | ■      | 71 | 92 |
| GTLED7              | 9W 4000K  | ■      | 71 | 92 |
| GTLED8              | 18W 5000K | ◆      | 73 | 92 |
| GTLED9              | 18W 5000K | ◆      | 66 | 94 |
| GTLED10             | 9W 5000K  | ●      | 72 | 87 |
| GTLED11             | 18W 5000K | ◆      | 73 | 92 |
| GTLED12             | 18W 3000K | ▲      | 71 | 92 |
| GTLED13             | 9W 5000K  | ●      | 72 | 87 |
| GTLED14             | 9W 5000K  | ●      | 72 | 86 |
| GTLED15             | 18W 5000K | ◆      | 73 | 92 |
| GTLED16             | 9W 4000K  | ■      | 71 | 92 |

Appendix Table 21. GTLED Color Quality.



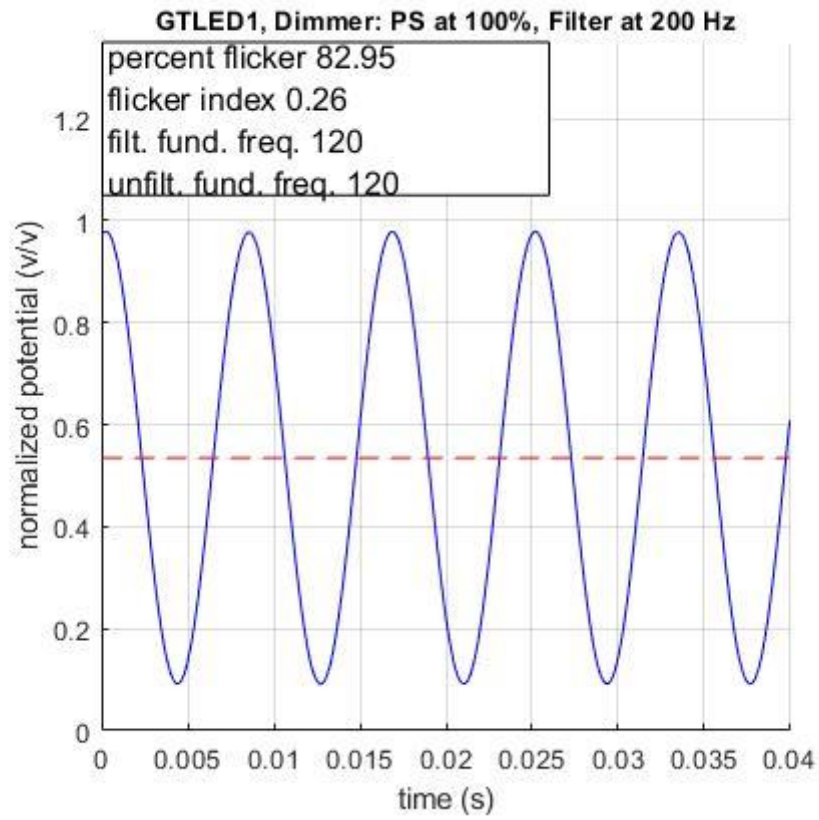
Appendix Table 22. Color Distortion Plot



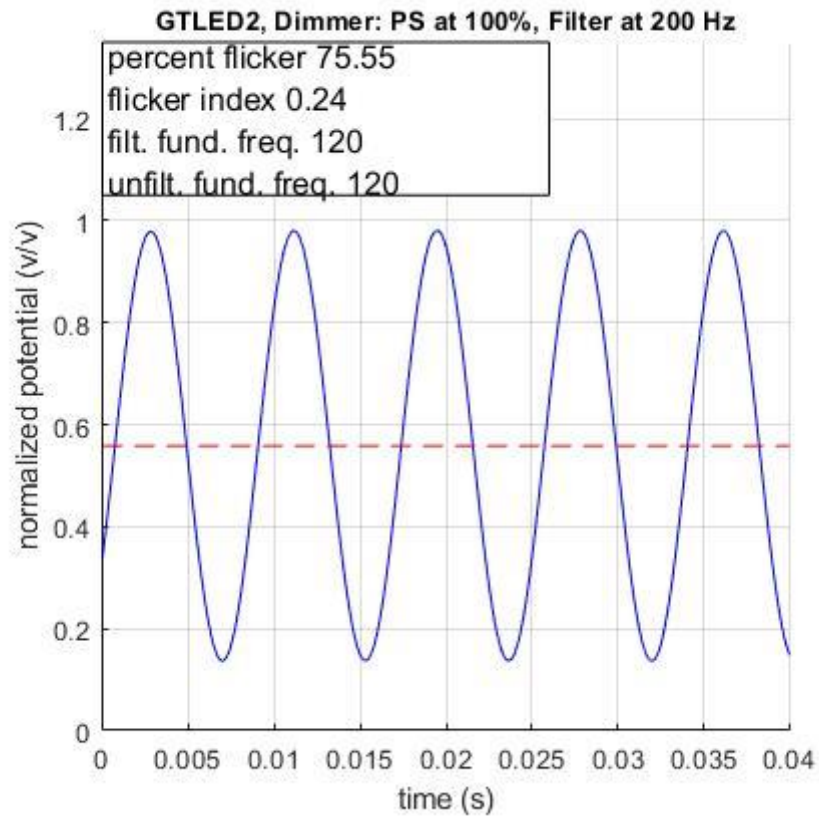
Appendix Figure 23.  $R_g$  vs  $R_f$  Plot.

| GTLED Flicker Data |                     |               |
|--------------------|---------------------|---------------|
| Lamp               | Percent Flicker (%) | Flicker Index |
| GTLED1             | 82.95               | 0.26          |
| GTLED2             | 75.55               | 0.24          |
| GTLED3             | 76.51               | 0.24          |
| GTLED4             | 75.24               | 0.24          |
| GTLED5             | 77.17               | 0.25          |
| GTLED6             | 74.95               | 0.24          |
| GTLED7             | 75.34               | 0.24          |
| GTLED8             | 78.04               | 0.25          |
| GTLED9             | 78.18               | 0.25          |
| GTLED10            | 78.4                | 0.25          |
| GTLED11            | 76.88               | 0.24          |
| GTLED12            | 77.44               | 0.25          |
| GTLED13            | 76.57               | 0.24          |
| GTLED14            | 76.93               | 0.24          |
| GTLED15            | 77.08               | 0.25          |
| GTLED16            | 74.94               | 0.24          |

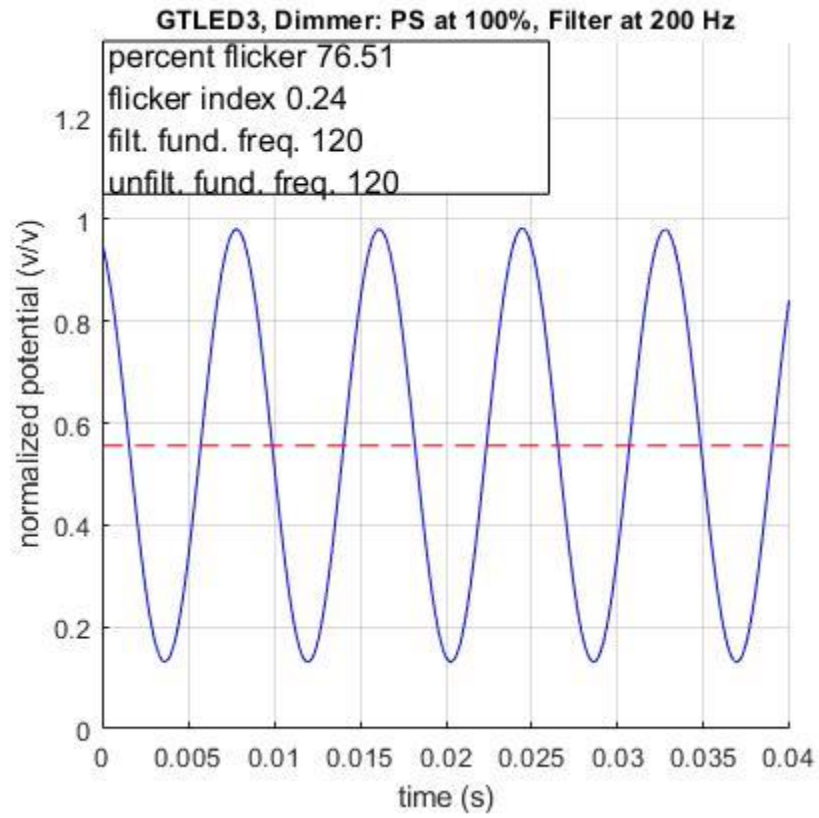
Appendix Table 23. GTLED Flicker Data.



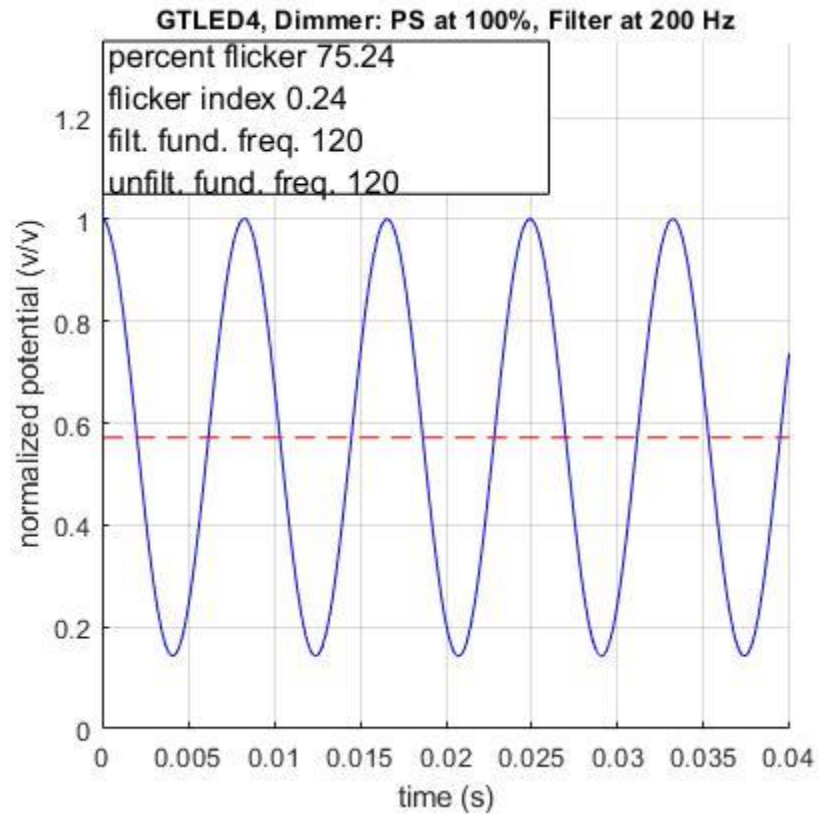
Appendix Figure 24. GTLED1 Flicker Test.



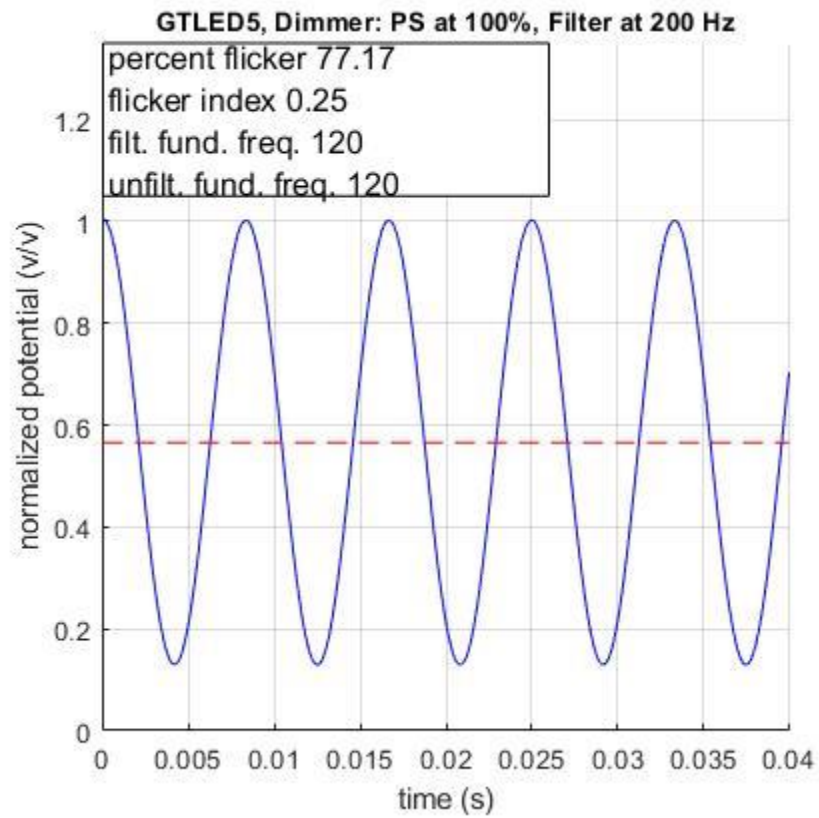
Appendix Figure 25. GTLED2 Flicker Test.



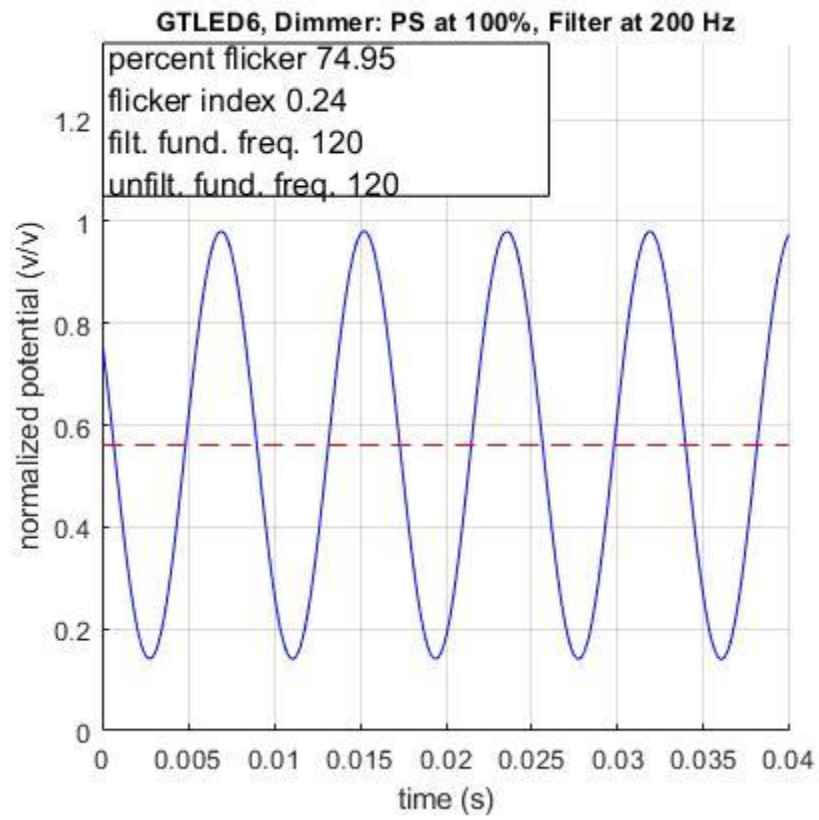
Appendix Figure 26. GTLED3 Flicker Test.



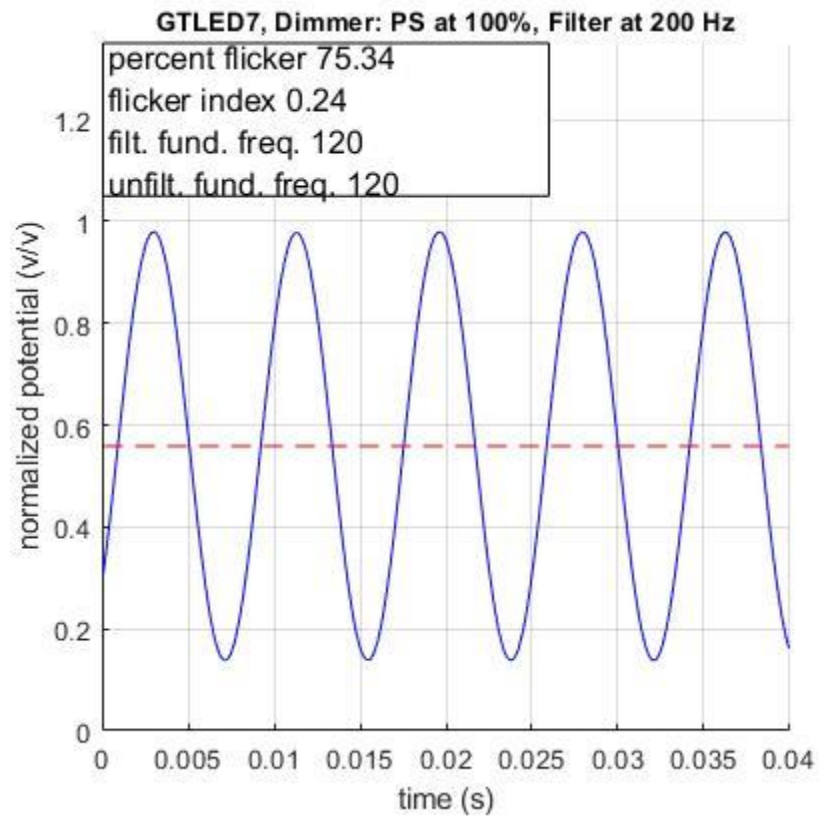
Appendix Figure 27. GTLED4 Flicker Test.



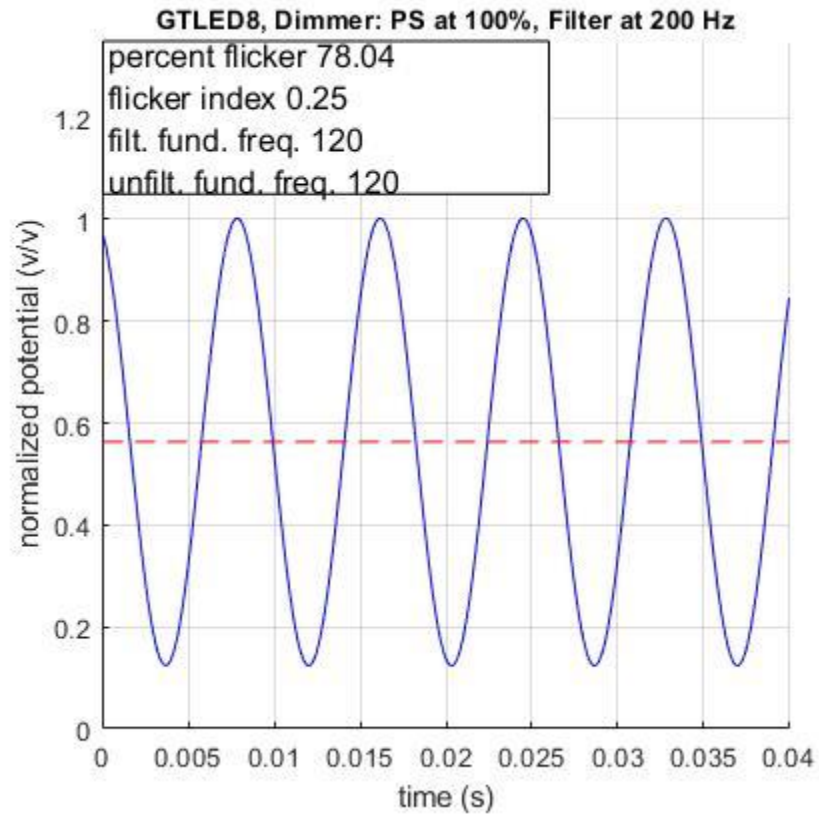
Appendix Figure 28. GTLED5 Flicker Test.



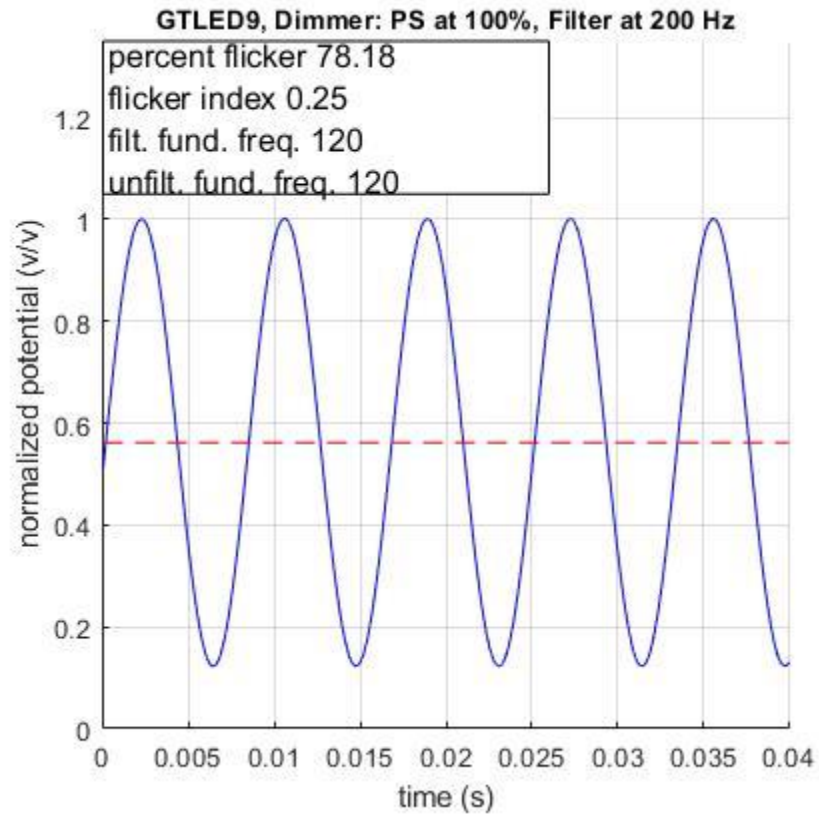
Appendix Figure 29. GTLED6 Flicker Test.



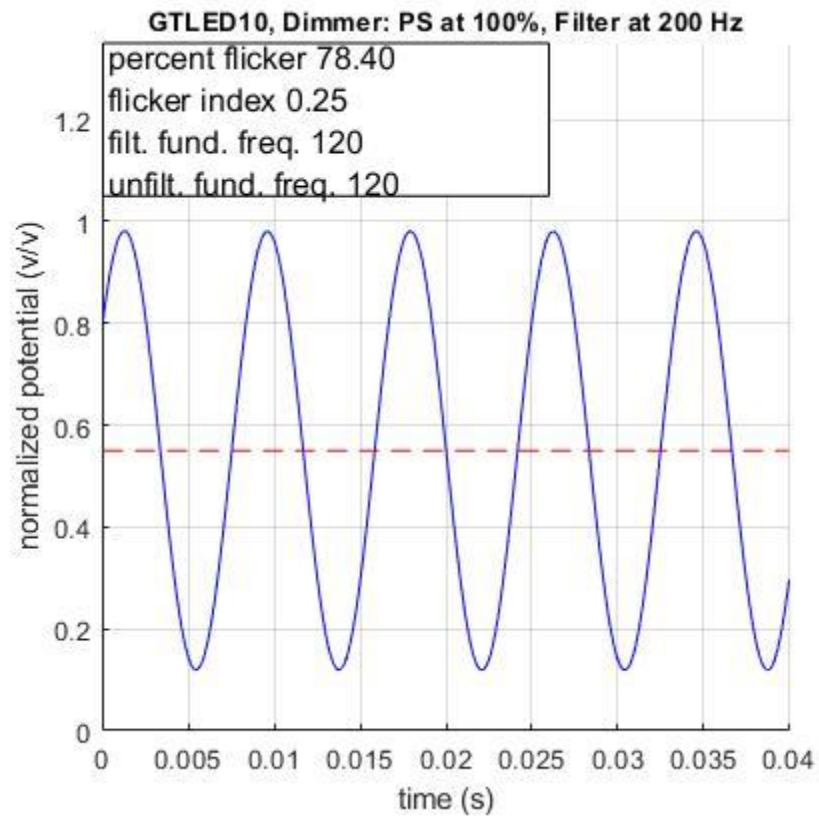
Appendix Figure 30. GTLED7 Flicker Test.



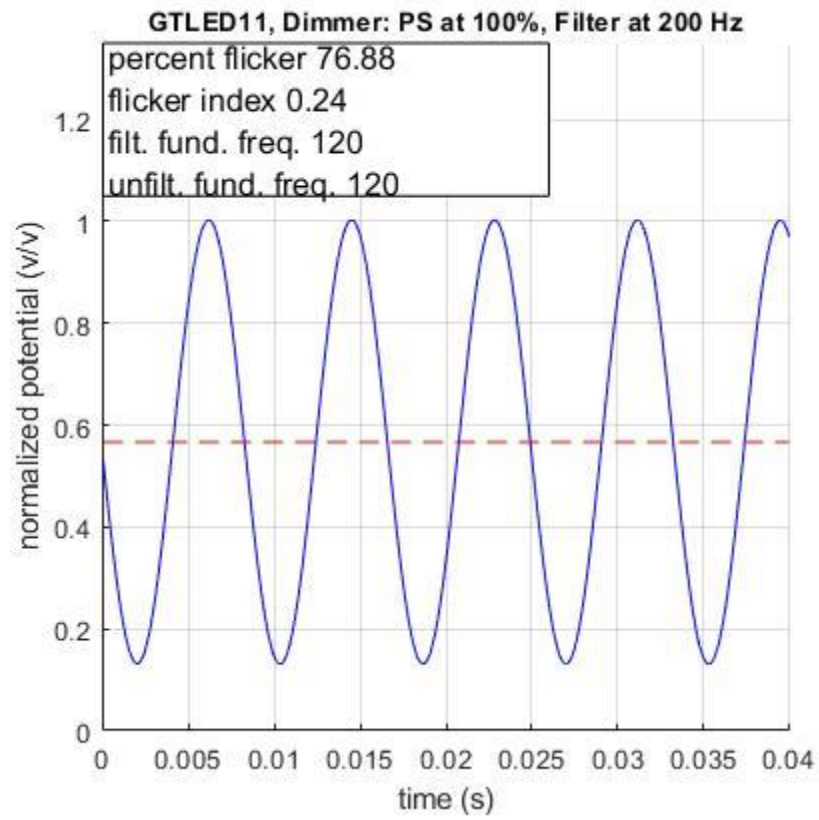
Appendix Figure 31. GTLED8 Flicker Test.



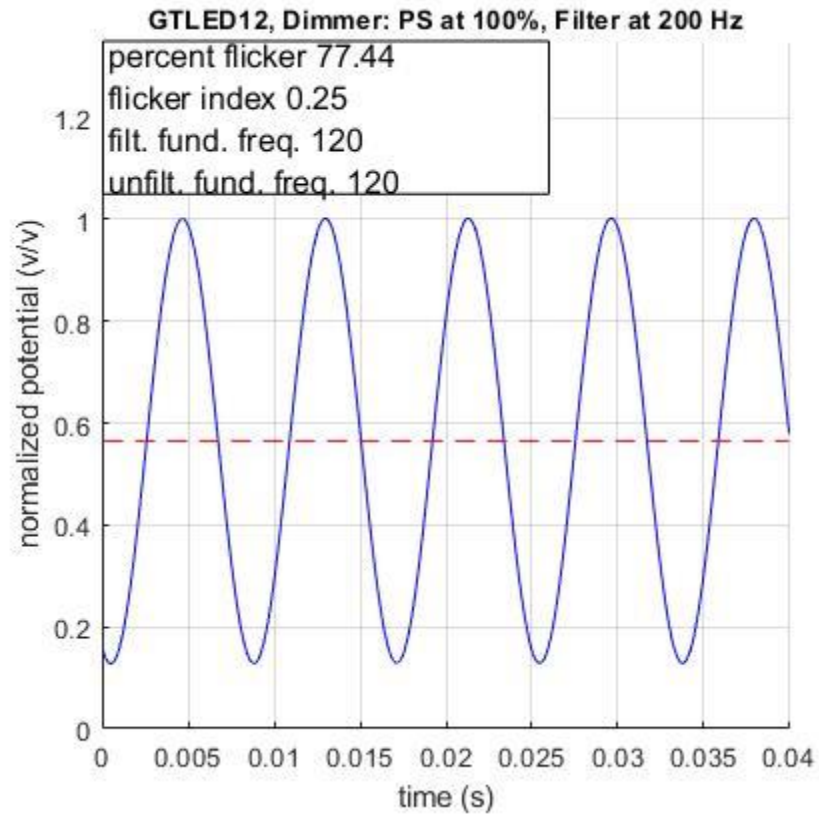
Appendix Figure 32. GTLED9 Flicker Test.



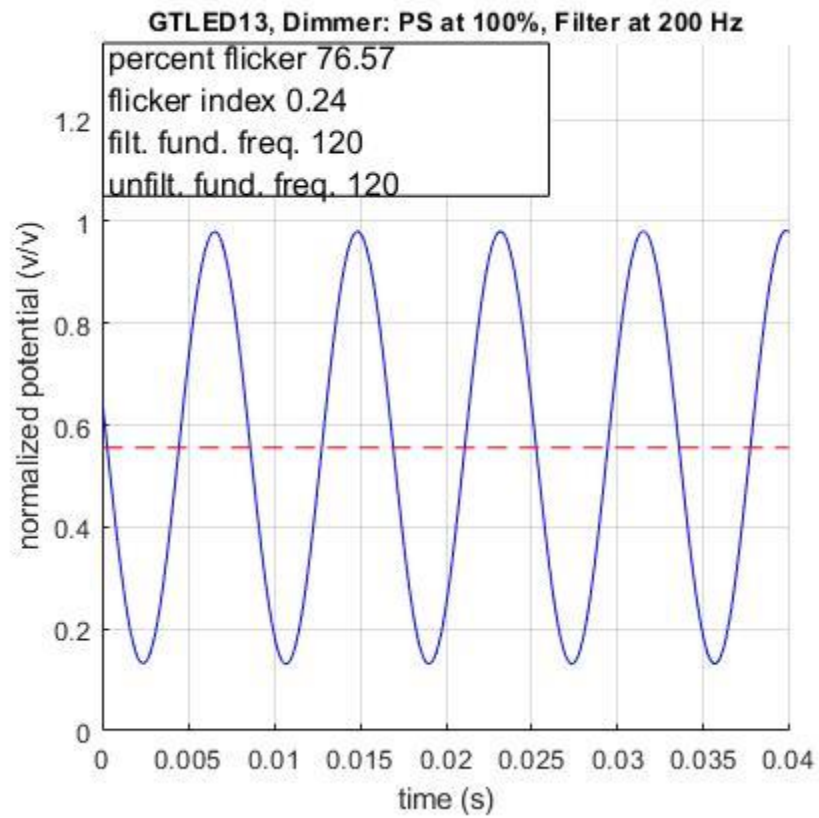
Appendix Figure 33. GTLED10 Flicker Test.



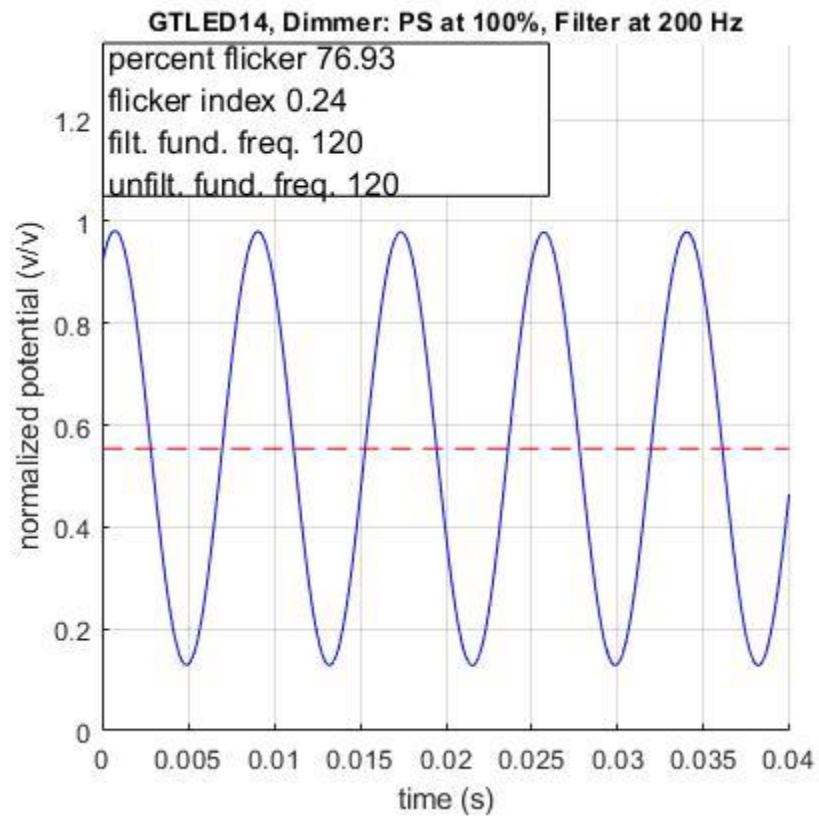
Appendix Figure 34. GTLED11 Flicker Test.



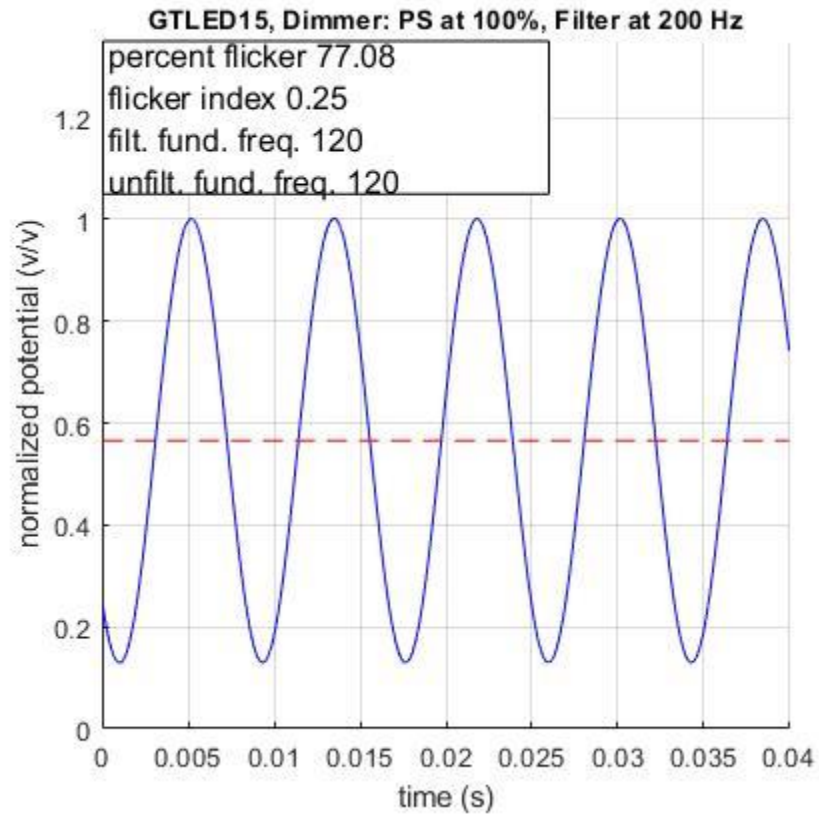
Appendix Figure 35. GTLED12 Flicker Test.



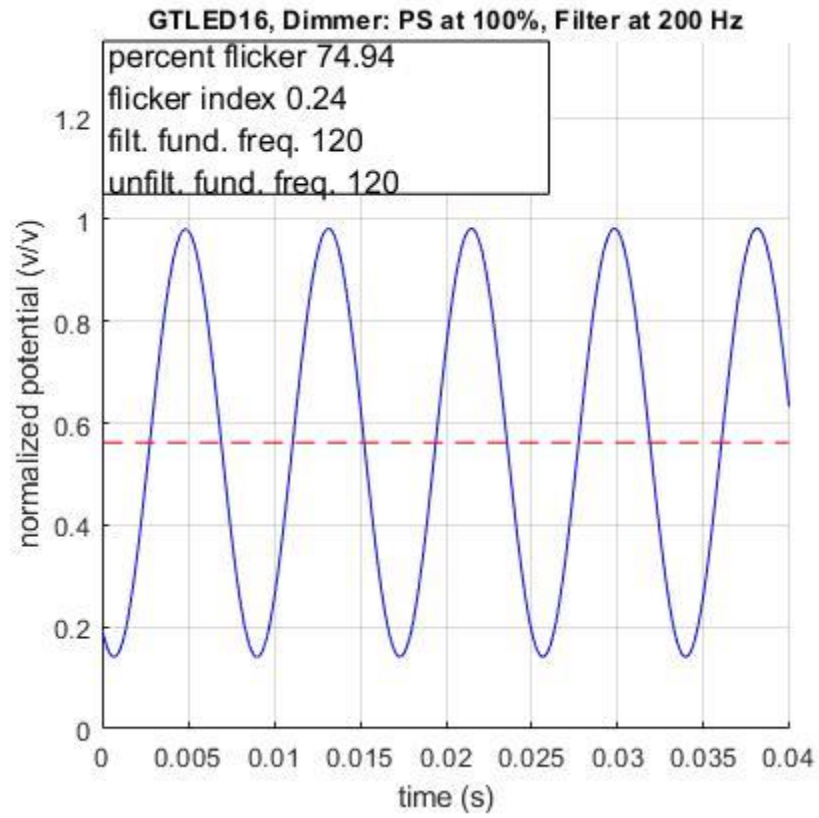
Appendix Figure 36. GTLED13 Flicker Test.



Appendix Figure 37. GTLED14 Flicker Test.



Appendix Figure 38. GTLED15 Flicker Test.

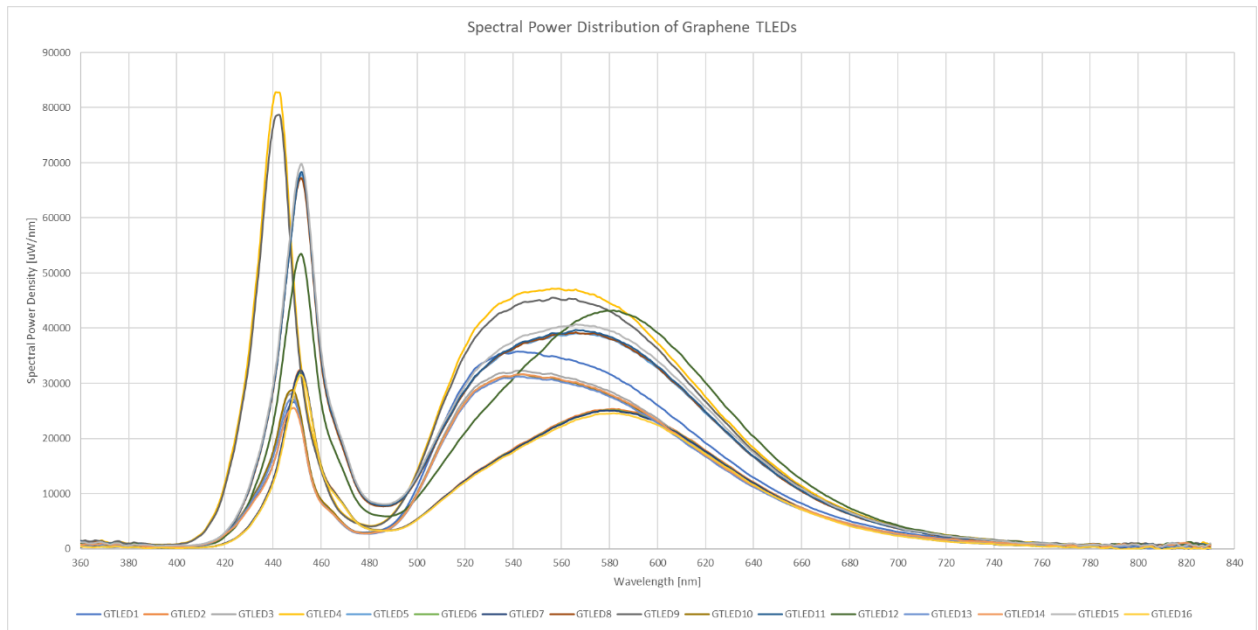


Appendix Figure 39. GTLED16 Flicker Test

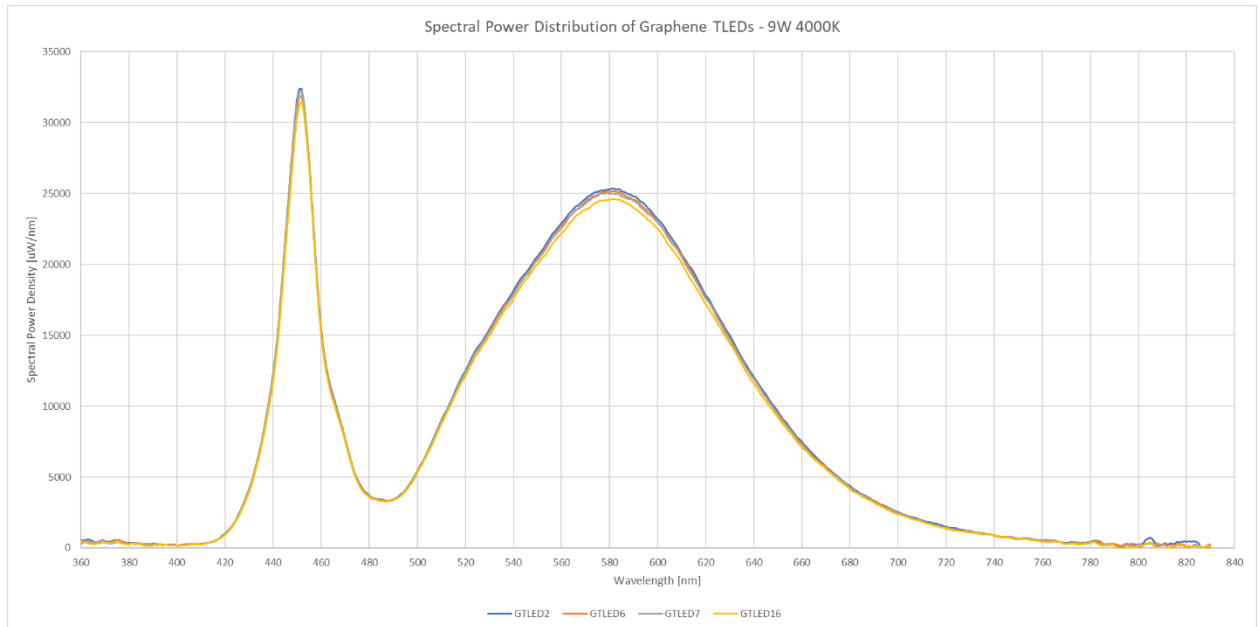
### B-1.2 GTLED-PES Electrical

| Lamp    | Power % | Voltage (V) | Current (A) | Power (W) | Power Factor | UTHD % | ITHD % |
|---------|---------|-------------|-------------|-----------|--------------|--------|--------|
| GTLED1  | 100     | 120.07      | 0.0830      | 9.53      | 0.9559       | 0.03   | 22.66  |
| GTLED2  | 100     | 120.09      | 0.0834      | 9.57      | 0.9559       | 0.03   | 23.97  |
| GTLED3  | 100     | 120.09      | 0.0844      | 9.67      | 0.9547       | 0.03   | 24.25  |
| GTLED4  | 100     | 120.90      | 0.2074      | 18.59     | 0.7415       | 0.08   | 21.56  |
| GTLED5  | 100     | 120.05      | 0.1979      | 17.57     | 0.7398       | 0.05   | 20.99  |
| GTLED6  | 100     | 120.07      | 0.0829      | 9.51      | 0.9554       | 0.03   | 22.94  |
| GTLED7  | 100     | 120.09      | 0.0826      | 9.48      | 0.9549       | 0.03   | 24.23  |
| GTLED8  | 100     | 120.77      | 0.1979      | 17.64     | 0.7389       | 0.05   | 21.20  |
| GTLED9  | 100     | 120.05      | 0.2072      | 18.64     | 0.7491       | 0.05   | 21.46  |
| GTLED10 | 100     | 120.09      | 0.0852      | 9.77      | 0.9547       | 0.03   | 24.22  |
| GTLED11 | 100     | 120.74      | 0.1973      | 17.88     | 0.7503       | 0.05   | 20.95  |
| GTLED12 | 100     | 120.74      | 0.1977      | 17.78     | 0.7450       | 0.05   | 20.90  |
| GTLED13 | 100     | 120.10      | 0.0839      | 9.63      | 0.9556       | 0.03   | 24.15  |
| GTLED14 | 100     | 120.12      | 0.0832      | 9.55      | 0.9555       | 0.03   | 24.09  |
| GTLED15 | 100     | 120.02      | 0.1985      | 17.96     | 0.7538       | 0.04   | 20.18  |
| GTLED16 | 100     | 120.10      | 0.0826      | 9.48      | 0.9555       | 0.03   | 24.06  |

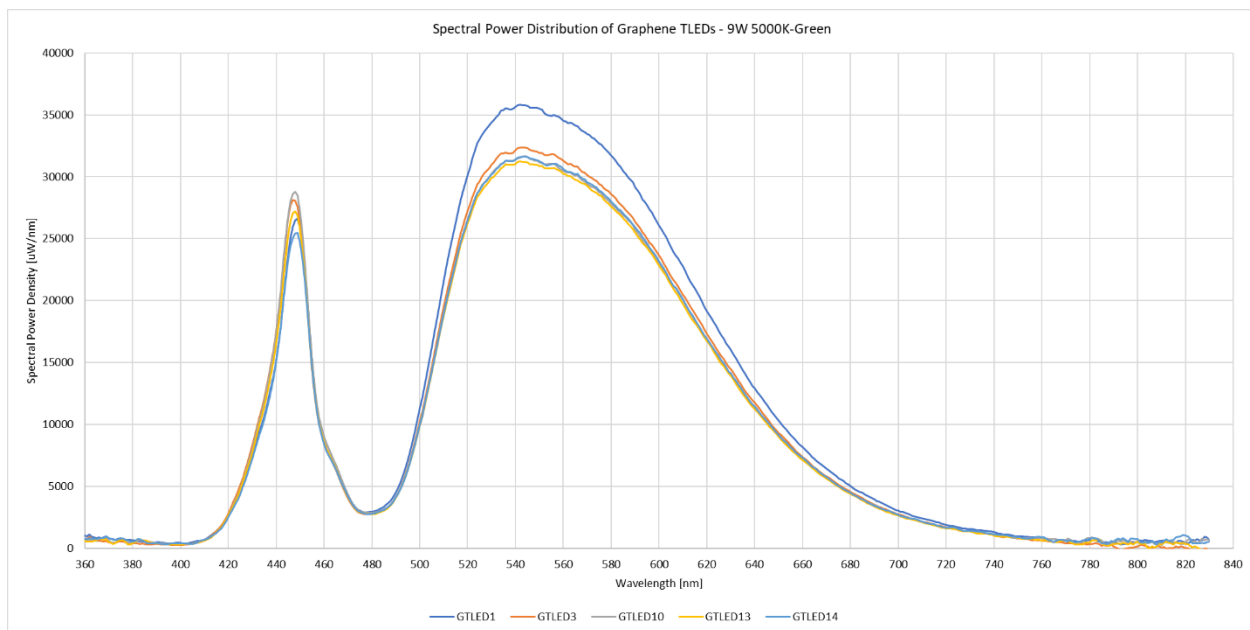
Appendix Table 24. GTLED Electrical Characteristics.



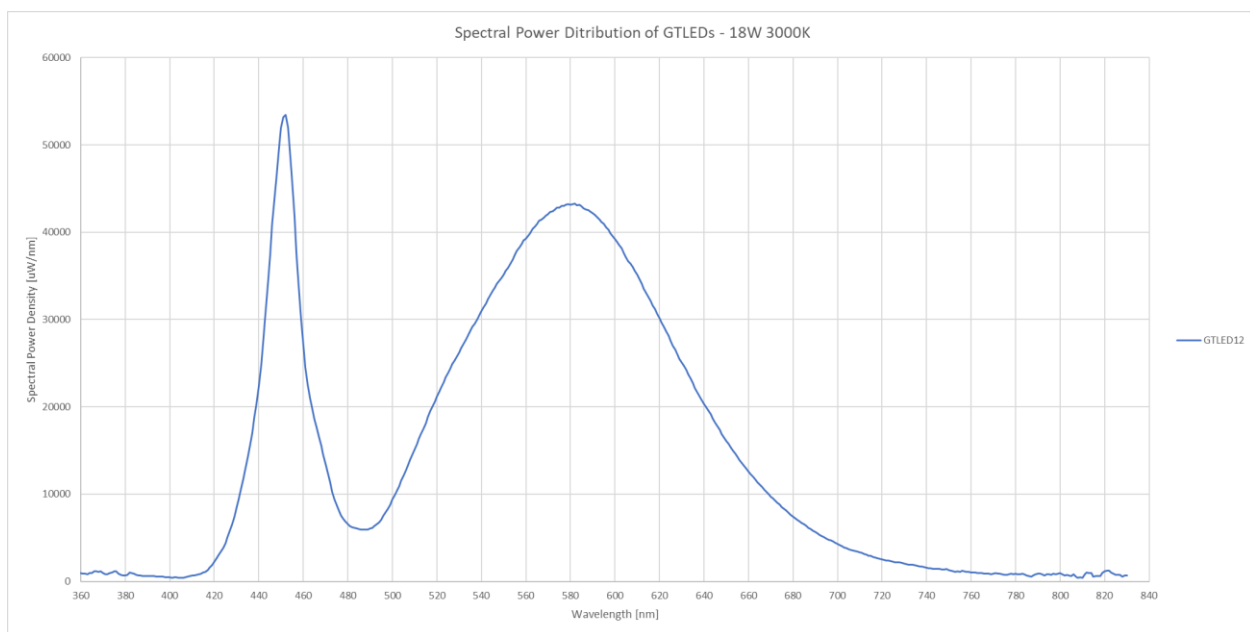
Appendix Figure 40. GTLED Spectral Power Distribution.



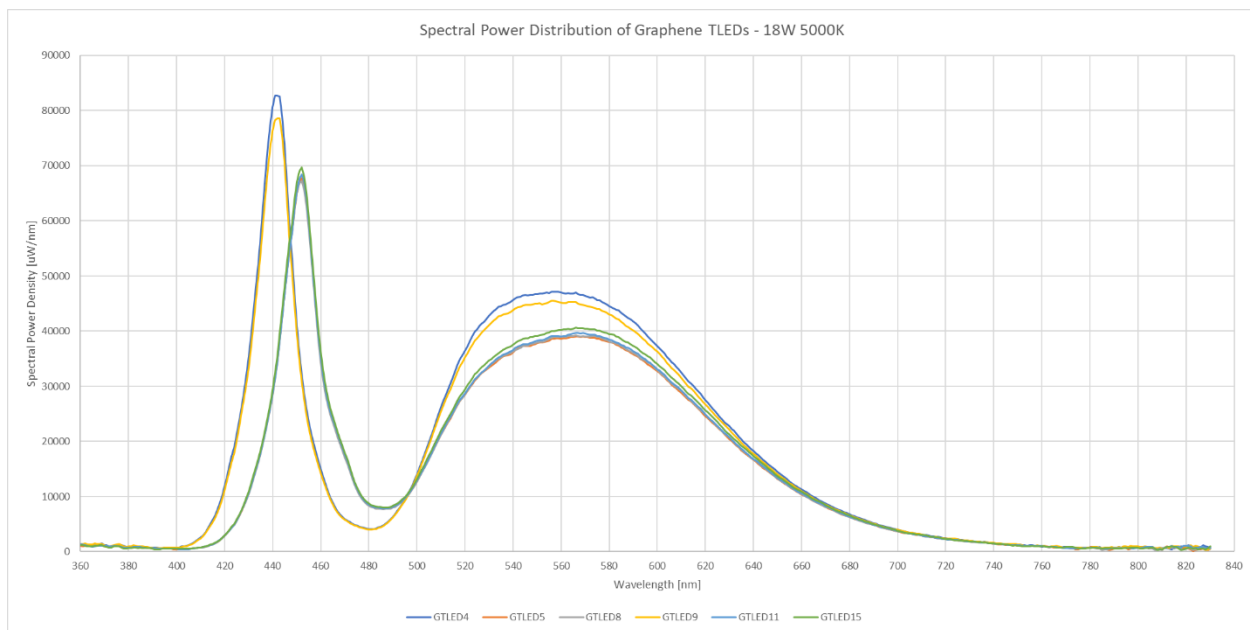
Appendix Figure 41. GTLED Group A Spectral Power Distribution.



Appendix Figure 42. GTLED Group B Spectral Power Distribution.



Appendix Figure 43. GTLED Group C Spectral Power Distribution.

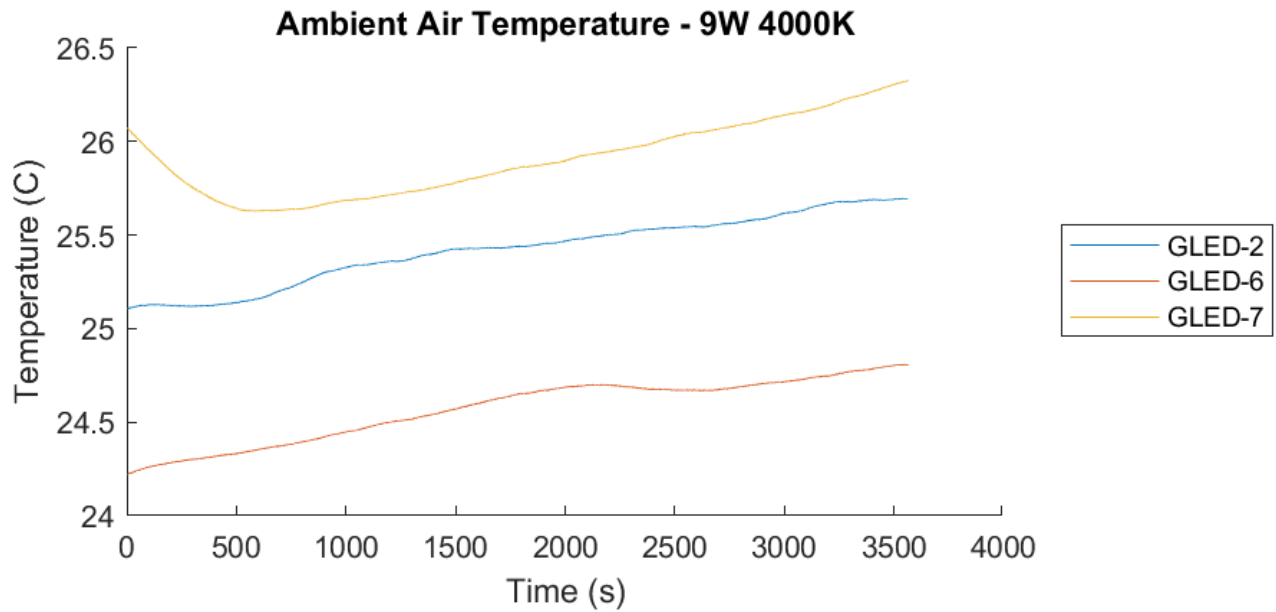


Appendix Figure 44. GTLED Group D Spectral Power Distribution.

## B-2 GTLED-TES Group A

### GTLED-TES1 GROUP A

#### B-2.1 GTLED-TES1 Group A Thermal



Appendix Figure 45. TES1 Group A Ambient Air Temperature.

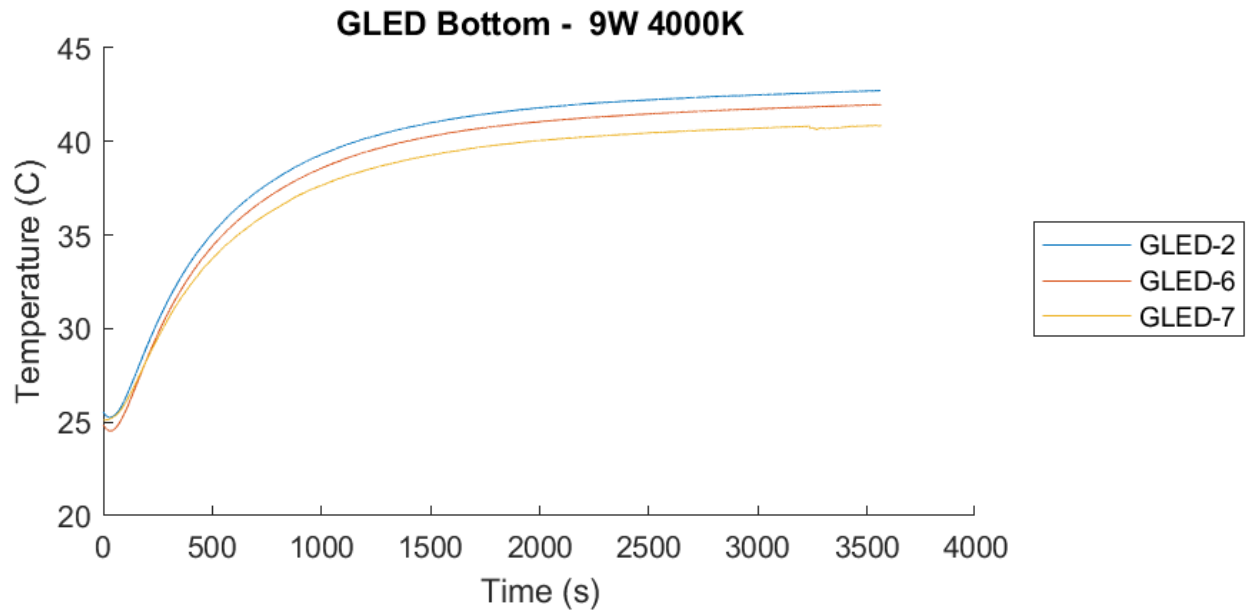
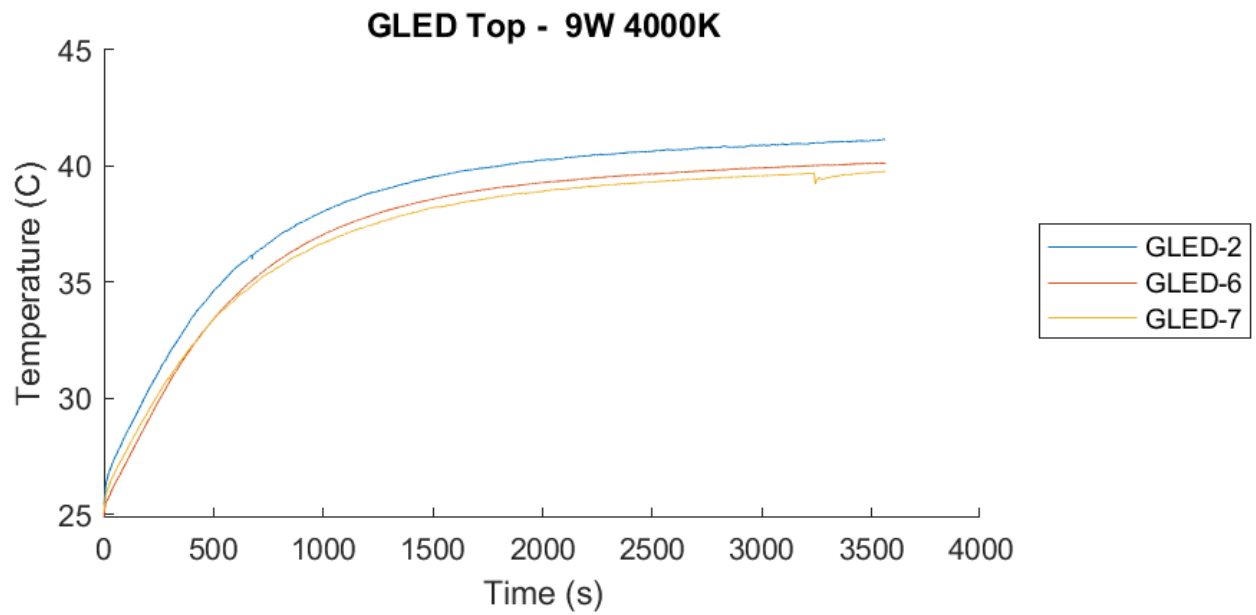
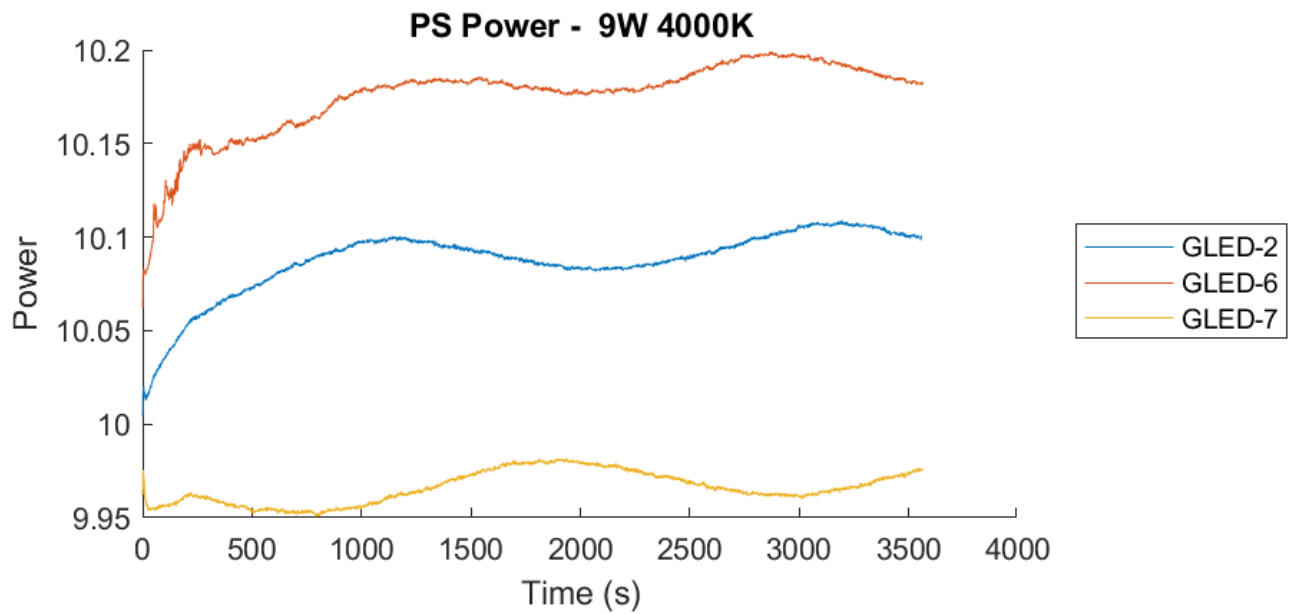


Figure 46. TES1 Group A GTLED Bottom Temperature.

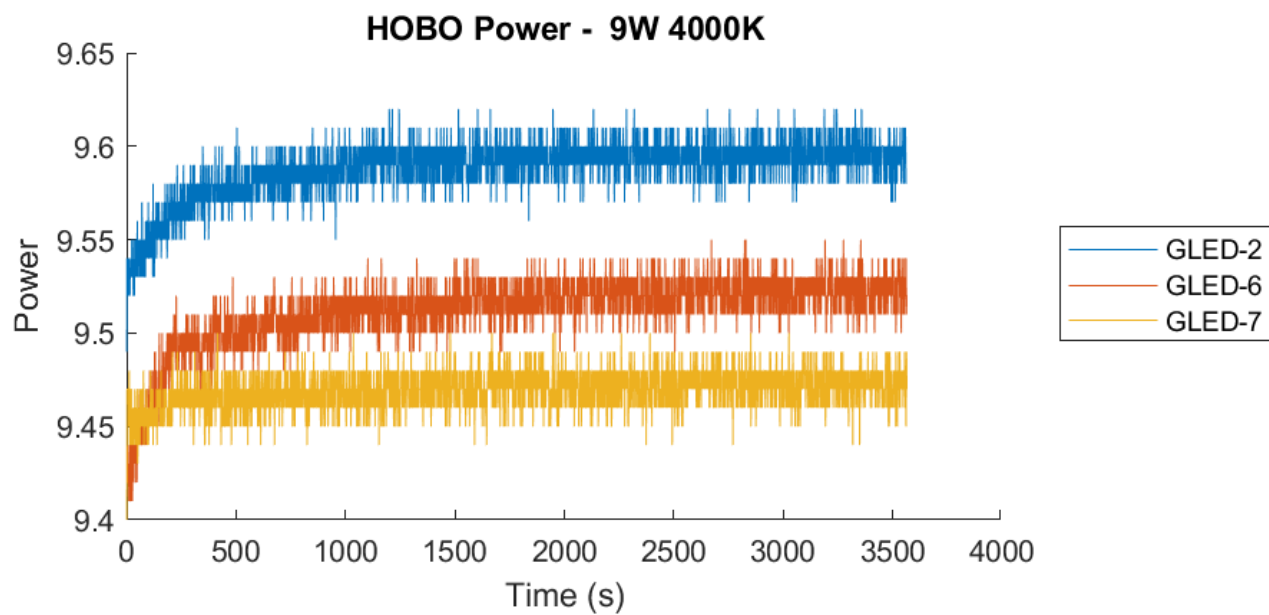


Appendix Figure 47. TES1 Group A GTLED Top Temperature.

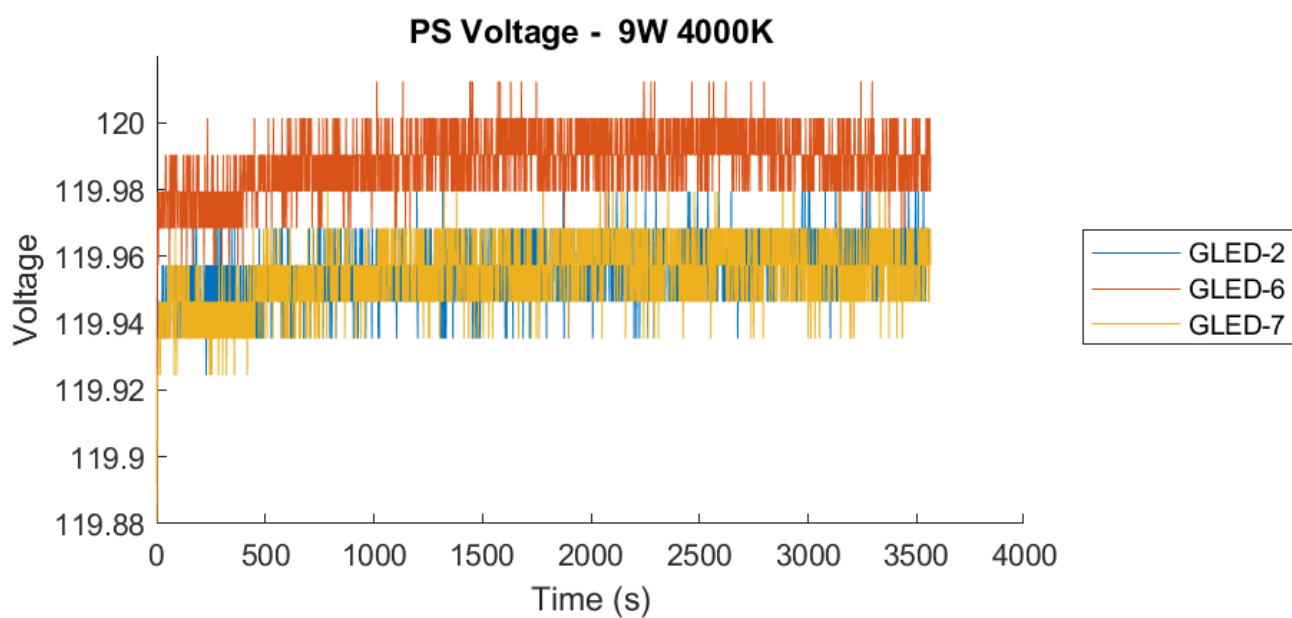
#### B-2.2 GTLED-TES1 Group A Electrical



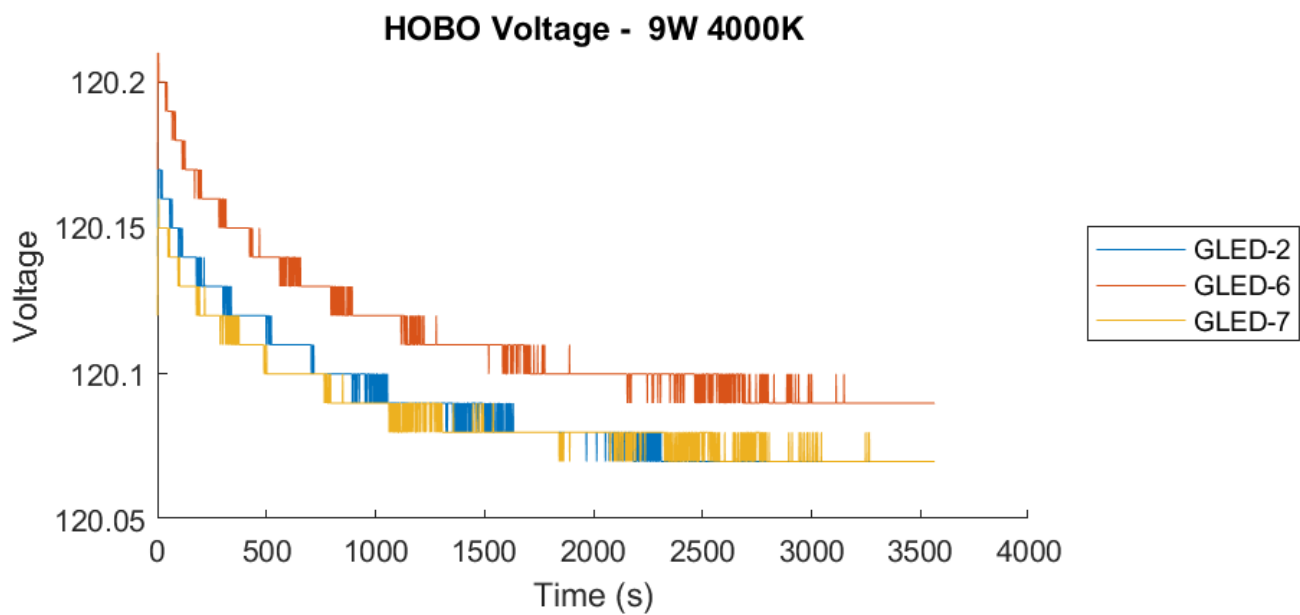
Appendix Figure 48. TES1 Group A PS Power.



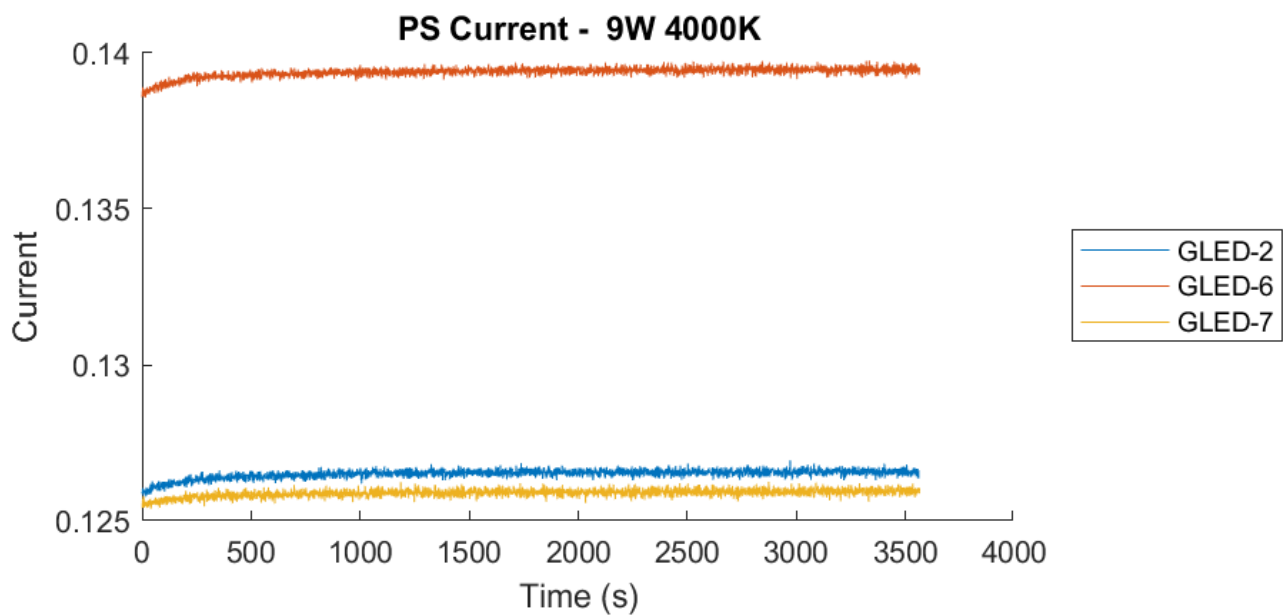
Appendix Figure 49. TES1 Group A HOBOT Power.



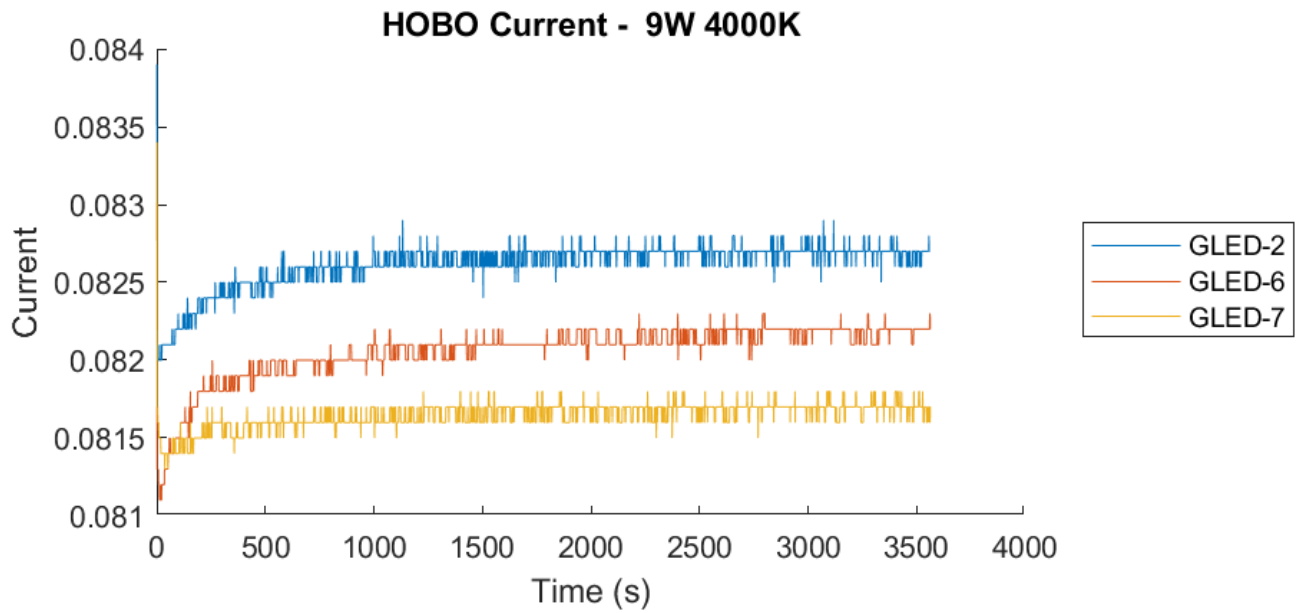
Appendix Figure 50. TES1 Group A PS Voltage.



Appendix Figure 51. TES1 Group A HOB0 Voltage.



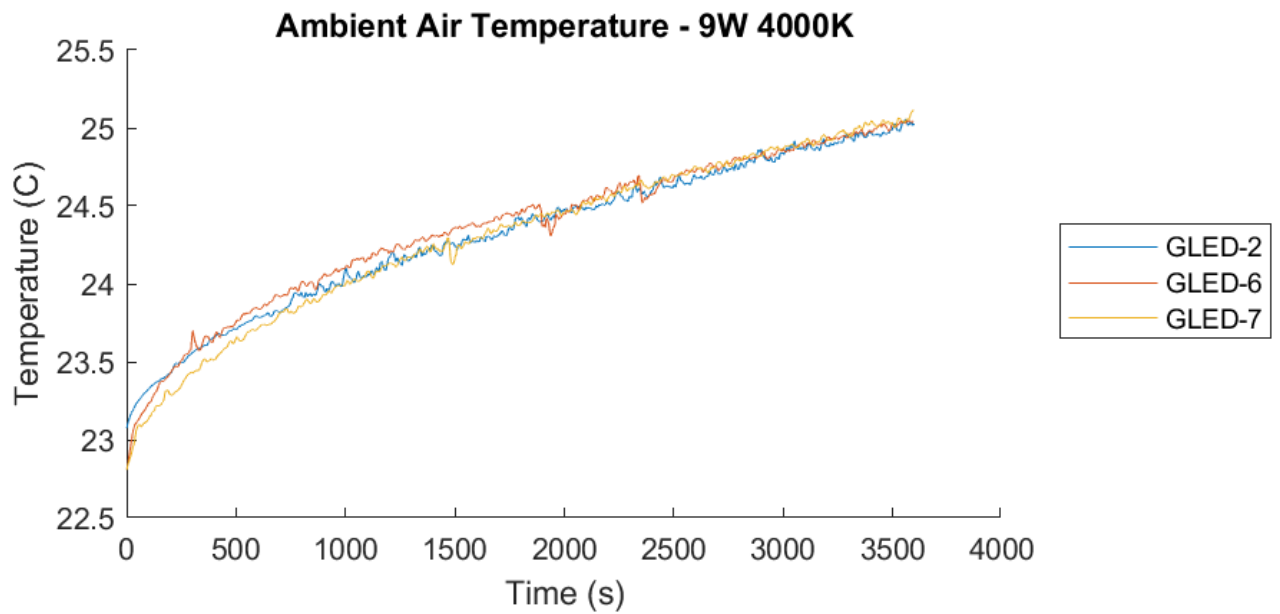
Appendix Figure 52. TES1 Group A PS Current.



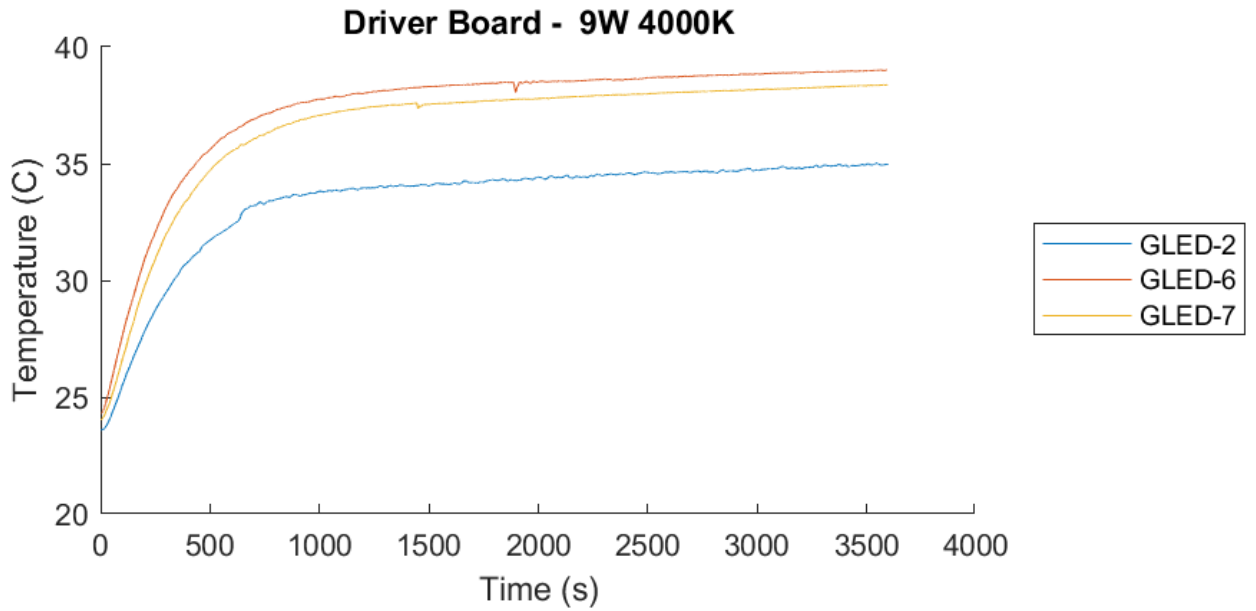
Appendix Figure 53. TES1 Group A HOBO Current.

## GTLED-TES2 GROUP A

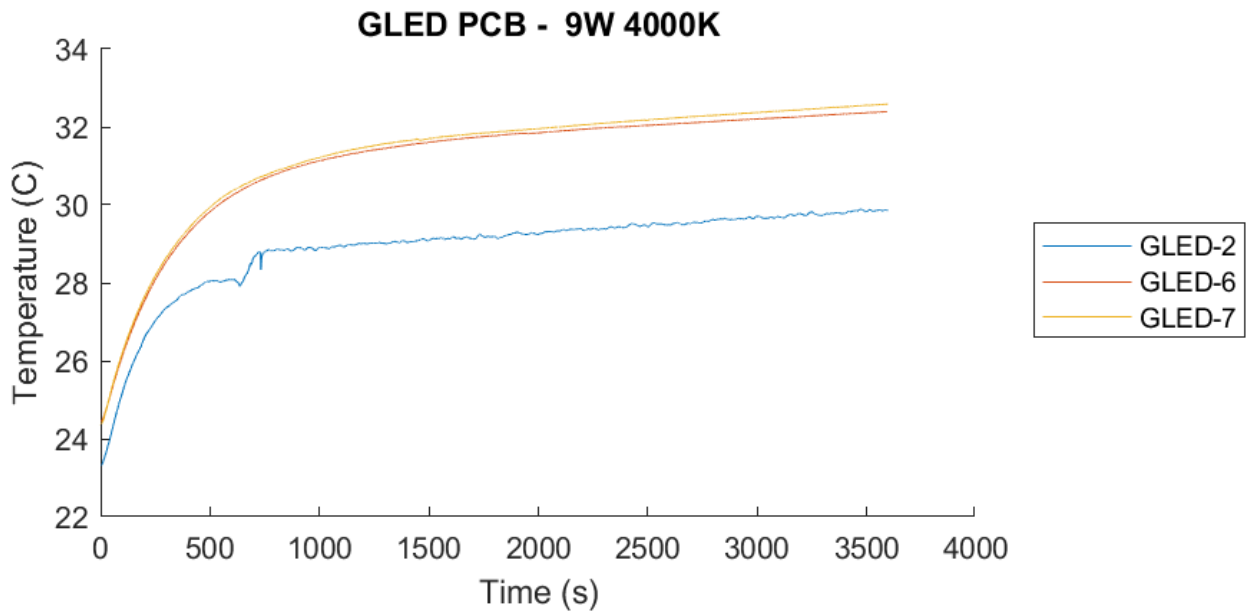
### B-2.3 GTLED-TES2 Group A Thermal



Appendix Figure 54. TES2 Group A Ambient Air Temperature.

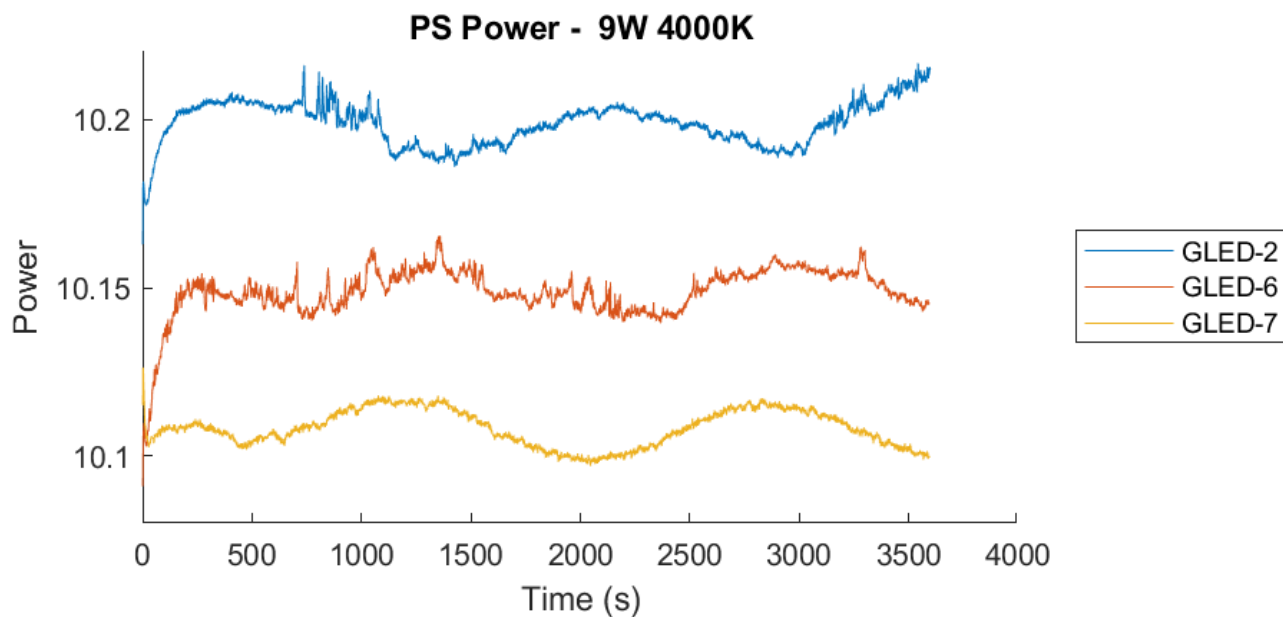


Appendix Figure 55. TES2 Group A GTLED Driver Board Temperature.

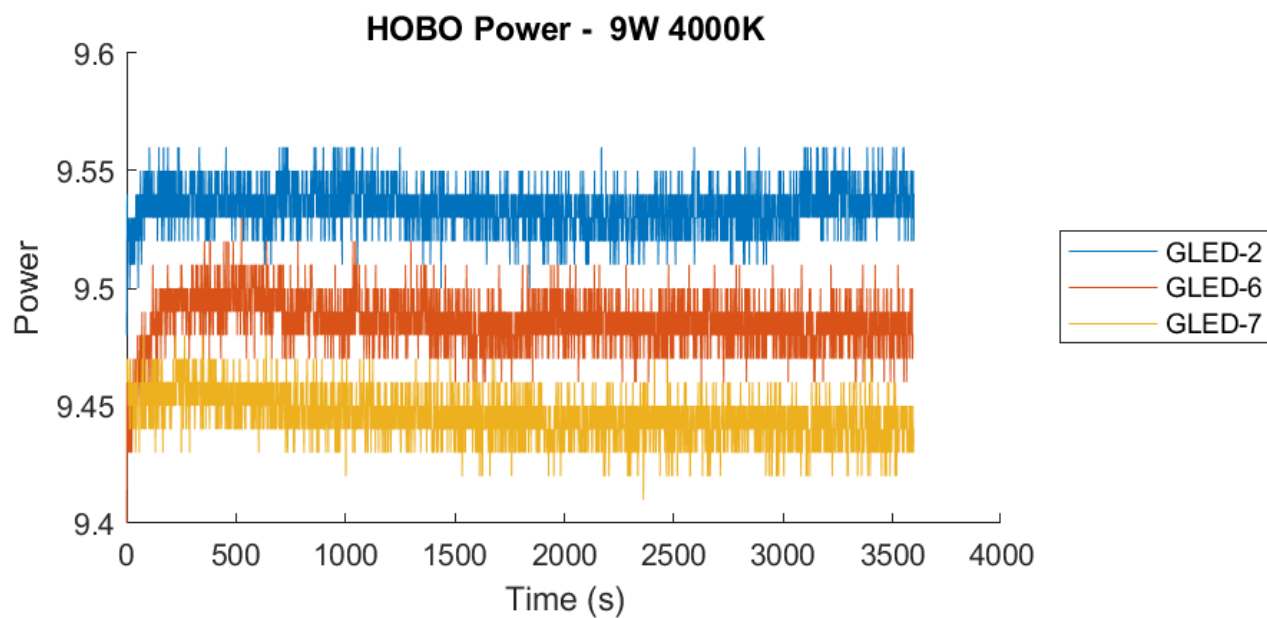


Appendix Figure 56. TES2 Group A GTLED PCB Temperature.

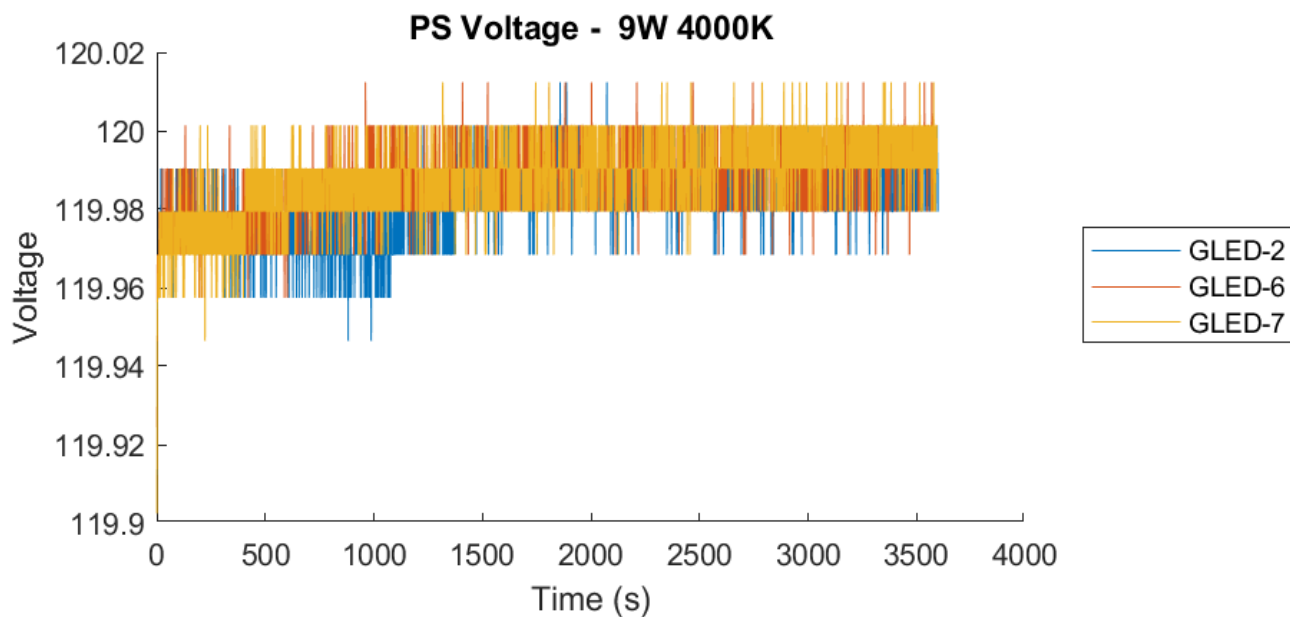
#### B-2.4 GTLED-TES2 Group A Electrical



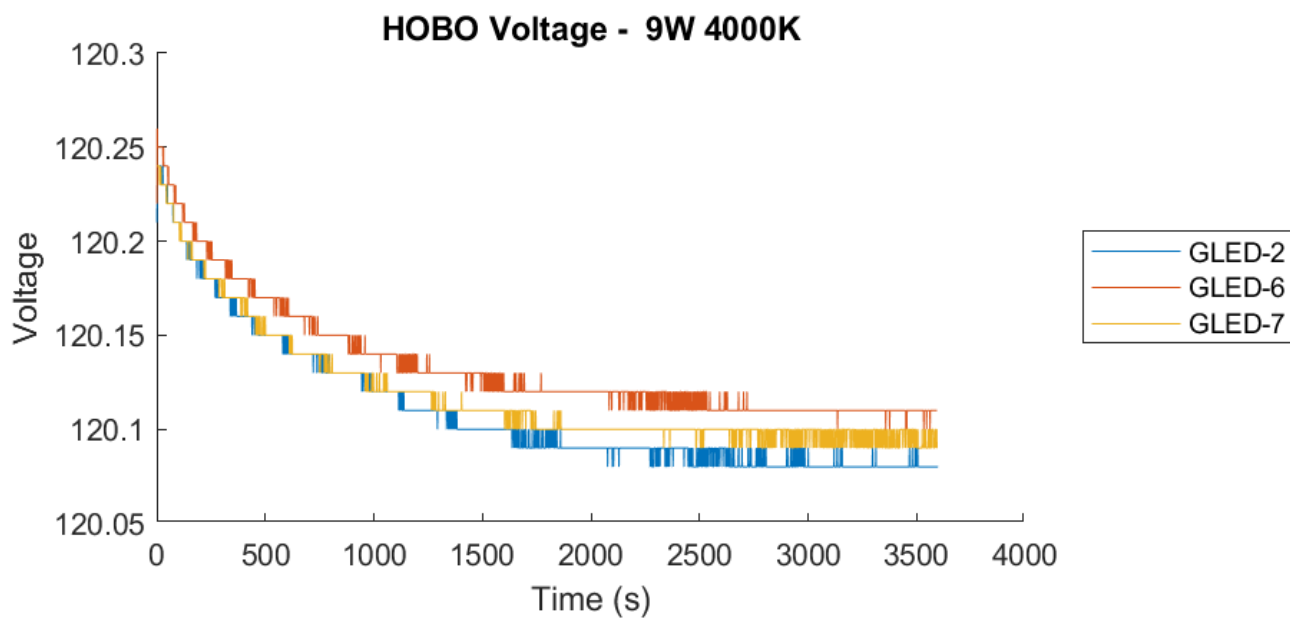
Appendix Figure 57. TES2 Group A PS Power.



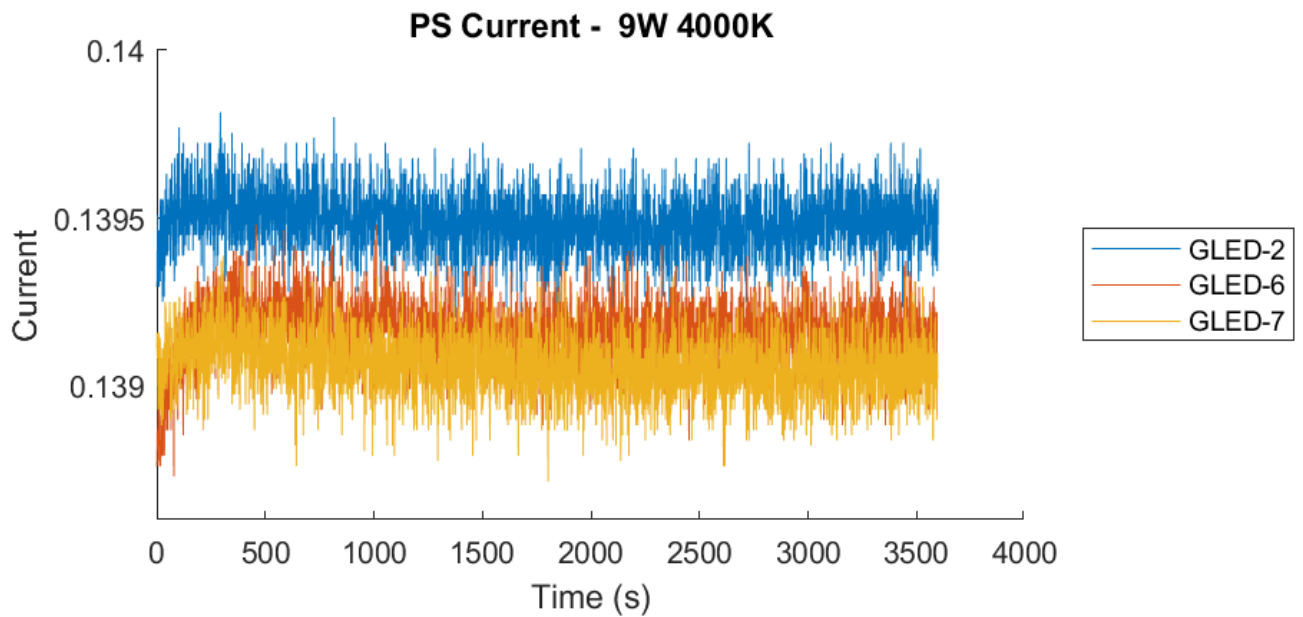
Appendix Figure 58. TES2 Group A HOBO Power.



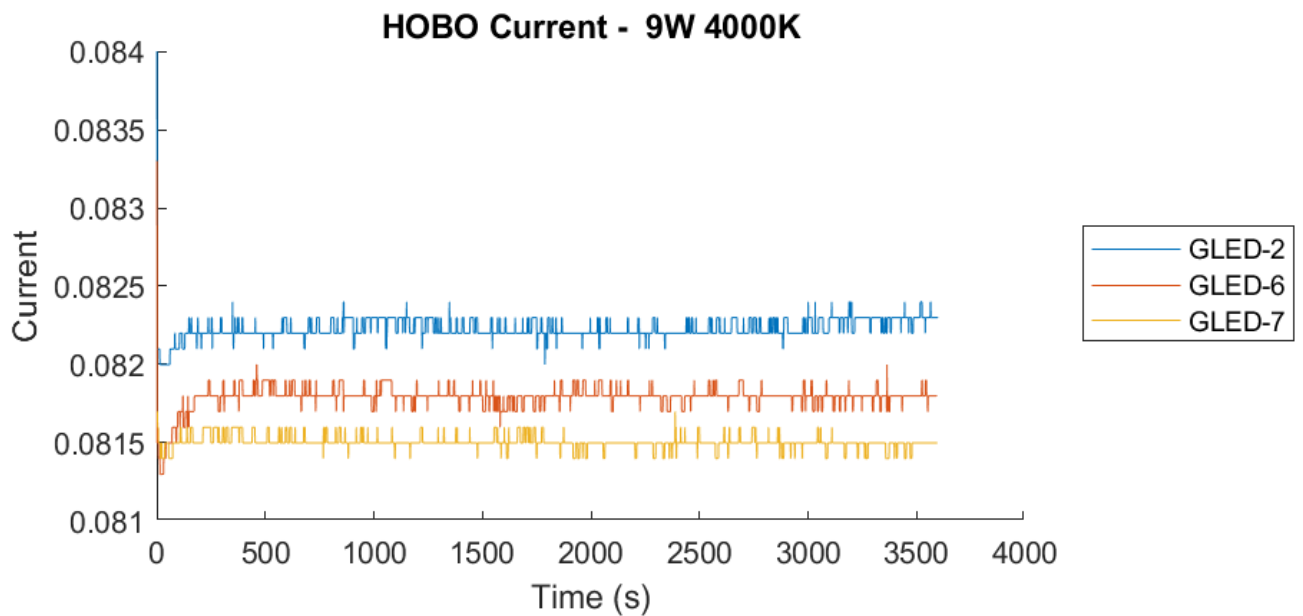
Appendix Figure 59. TES2 Group A PS Voltage.



Appendix Figure 60. TES2 Group A HOB0 Voltage.



Appendix Figure 61. TES2 Group A PS Current.

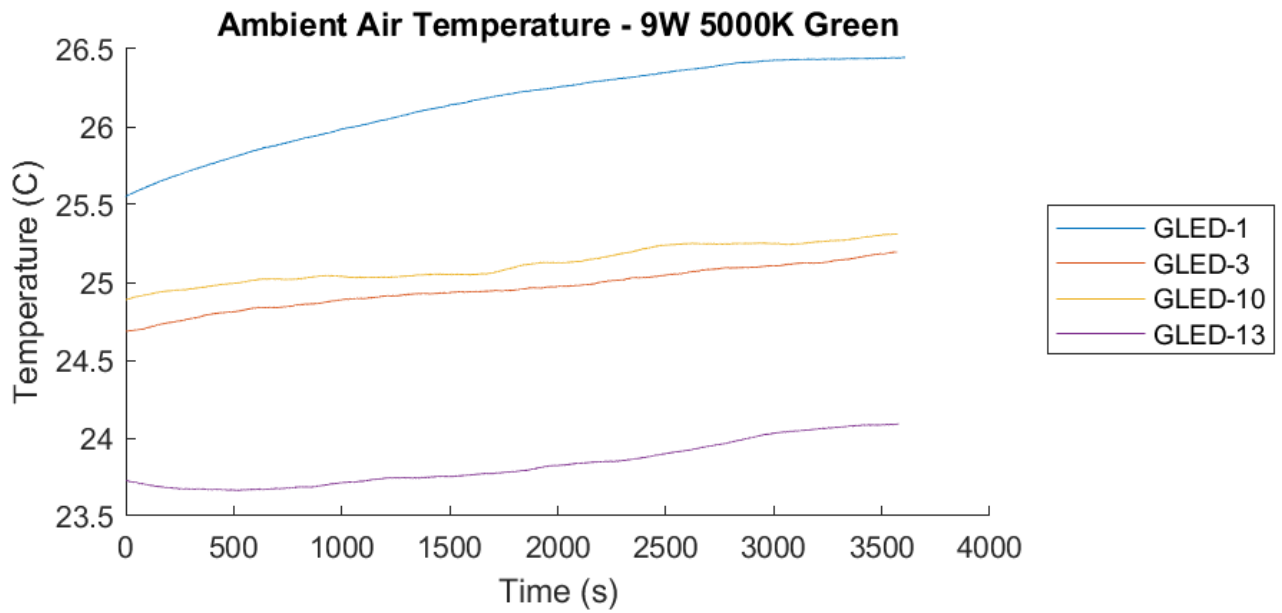


Appendix Figure 62. TES2 Group A HOB0 Current.

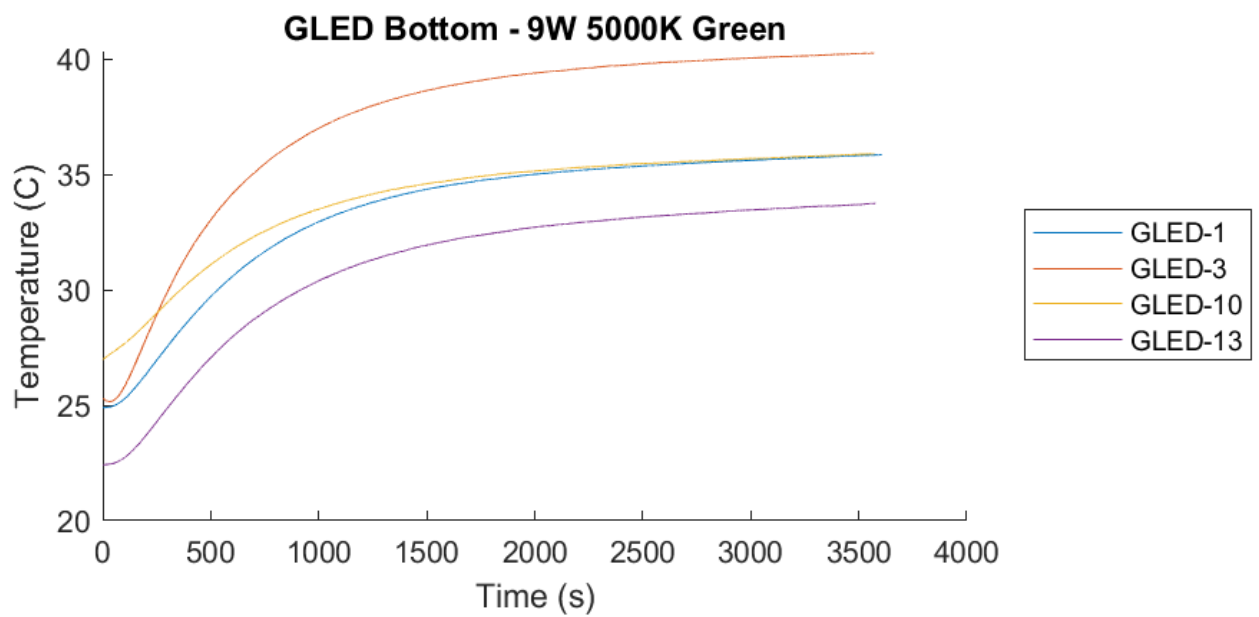
### B-3 GTLED-TES GROUP B

#### GTLED-TES1 GROUP B

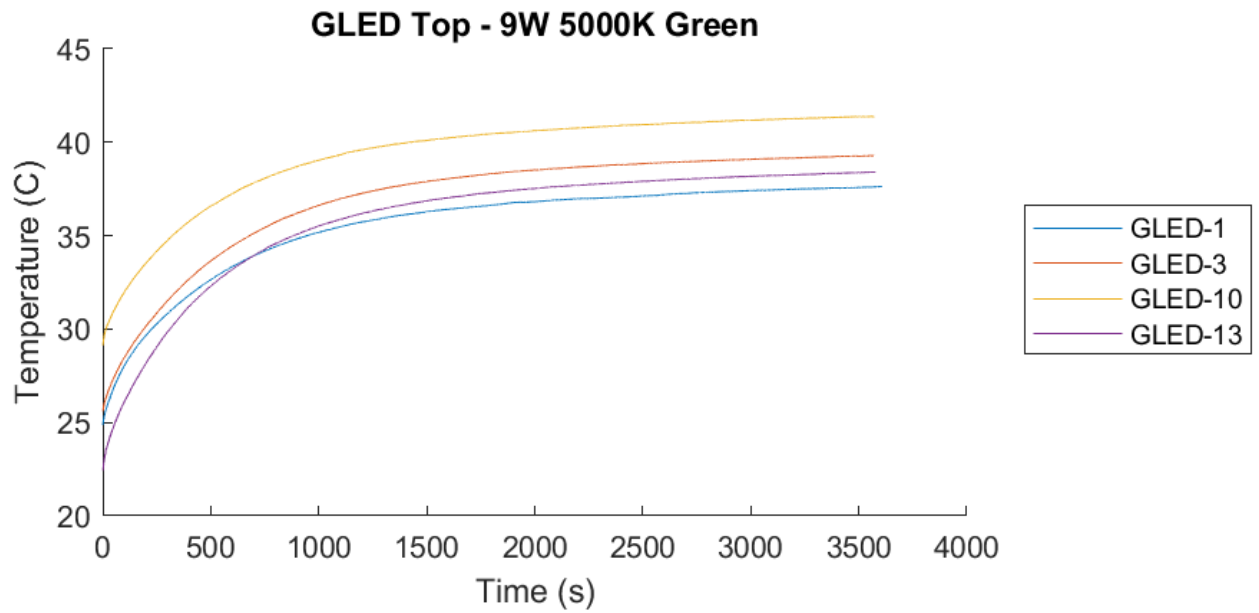
##### B-3.1 GTLED-TES1 Group B Thermal



Appendix Figure 63. TES1 Group B Ambient Air Temperature.

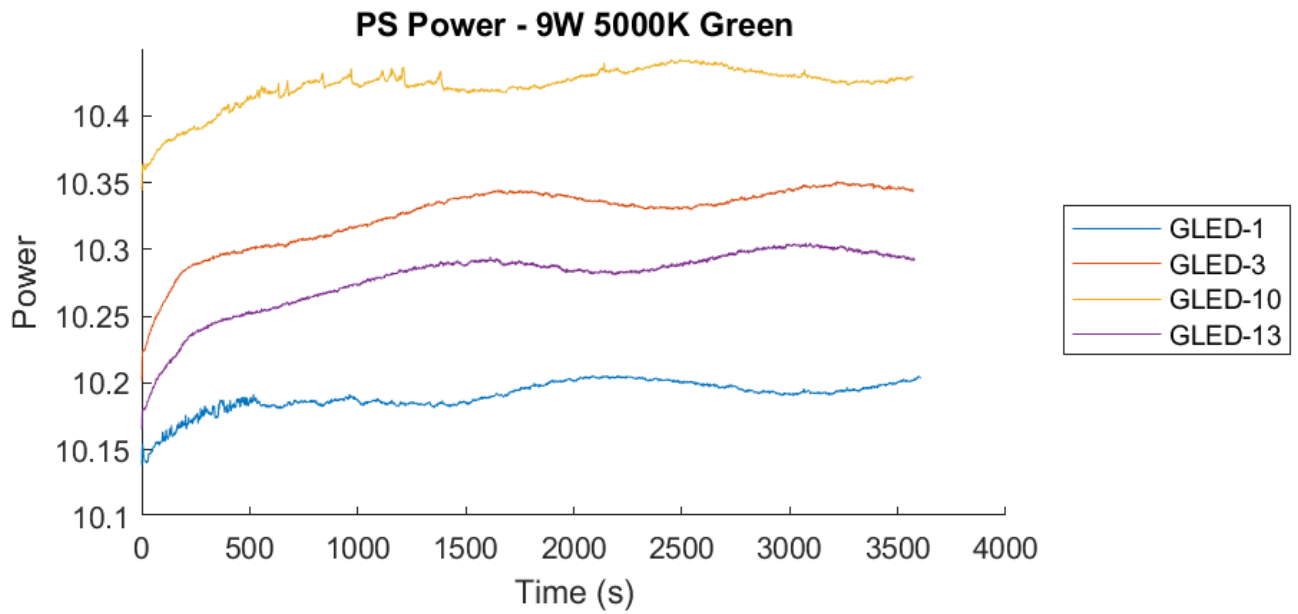


Appendix Figure 64. TES1 Group B GTLED Bottom Temperature.

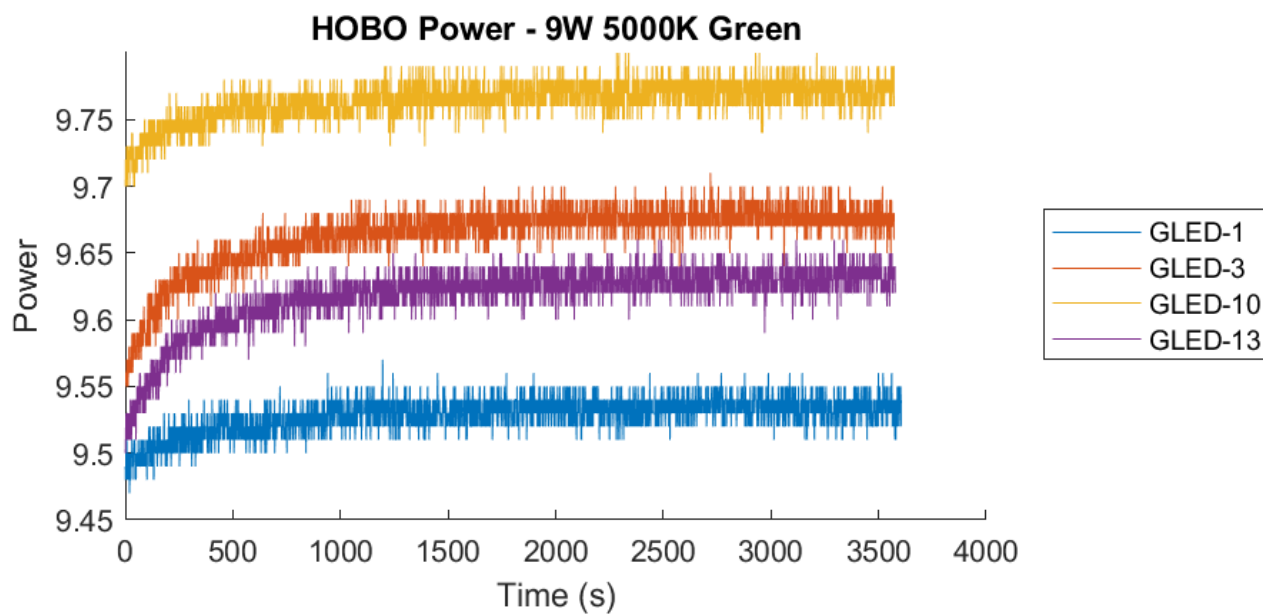


Appendix Figure 65. TES1 Group B GTLED Top Temperature

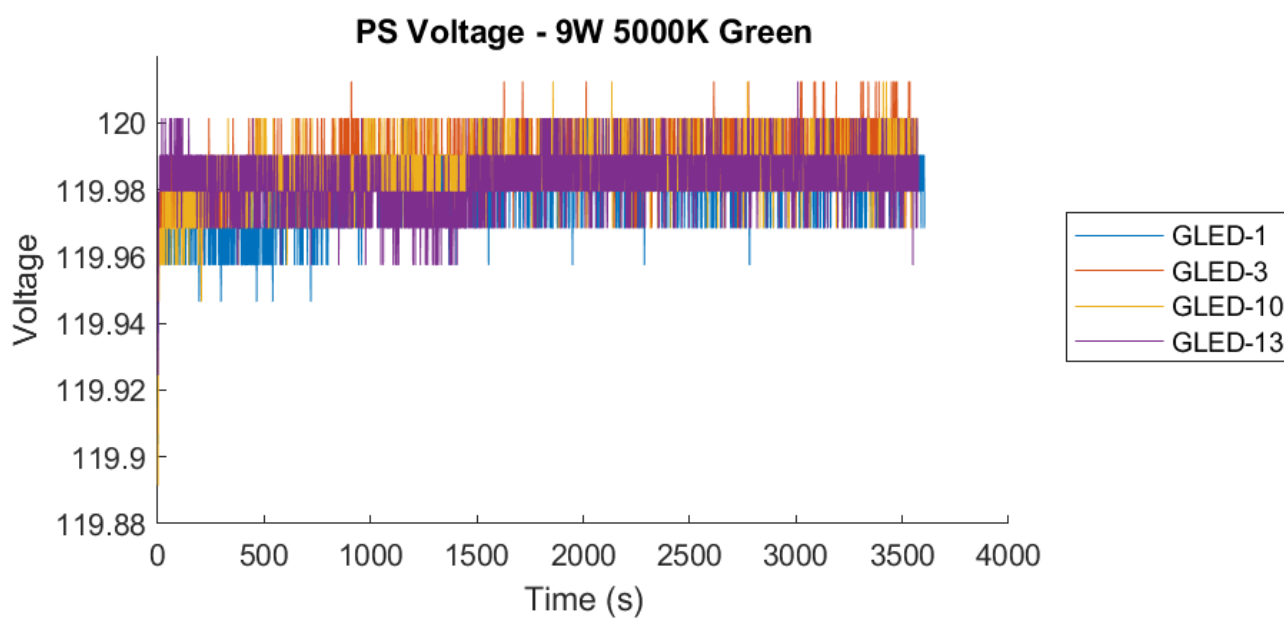
### B-3.2 GTLED-TES1 Group B Electrical



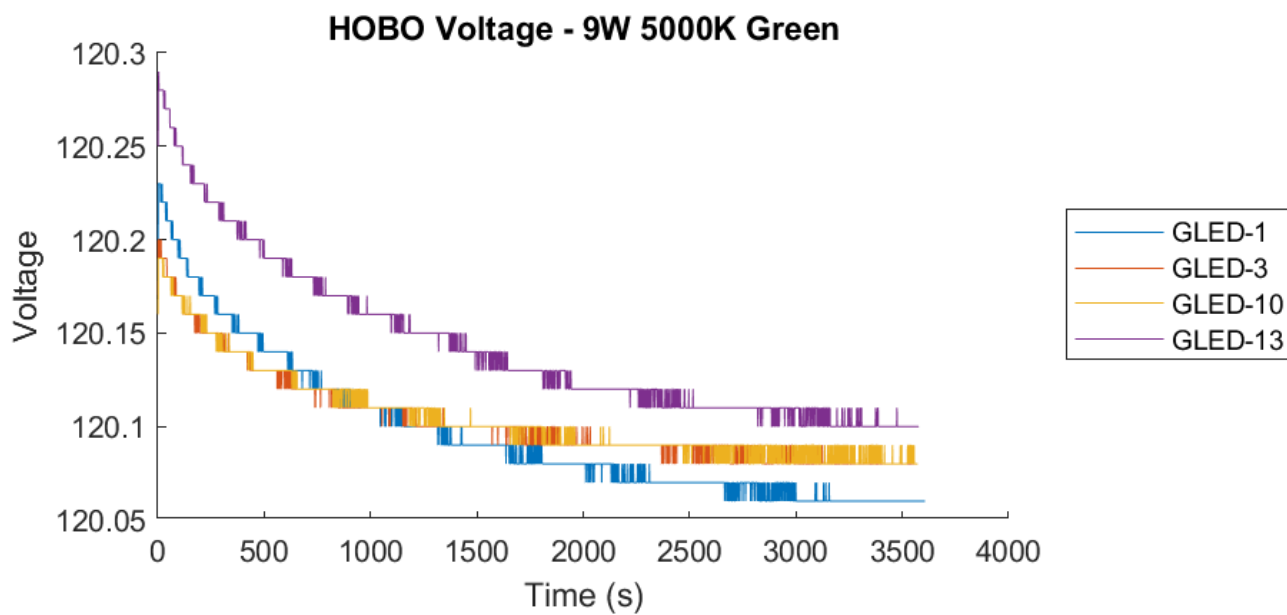
Appendix Figure 66. TES1 Group B PS Power.



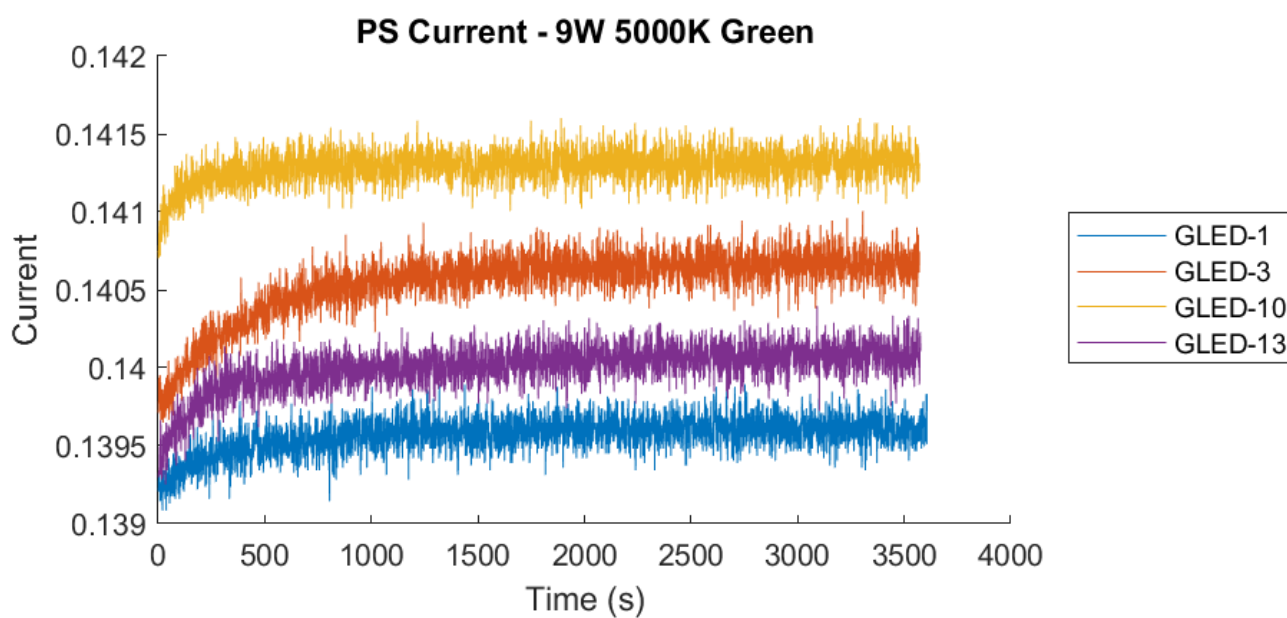
Appendix Figure 67. TES1 Group B HOBO Power.



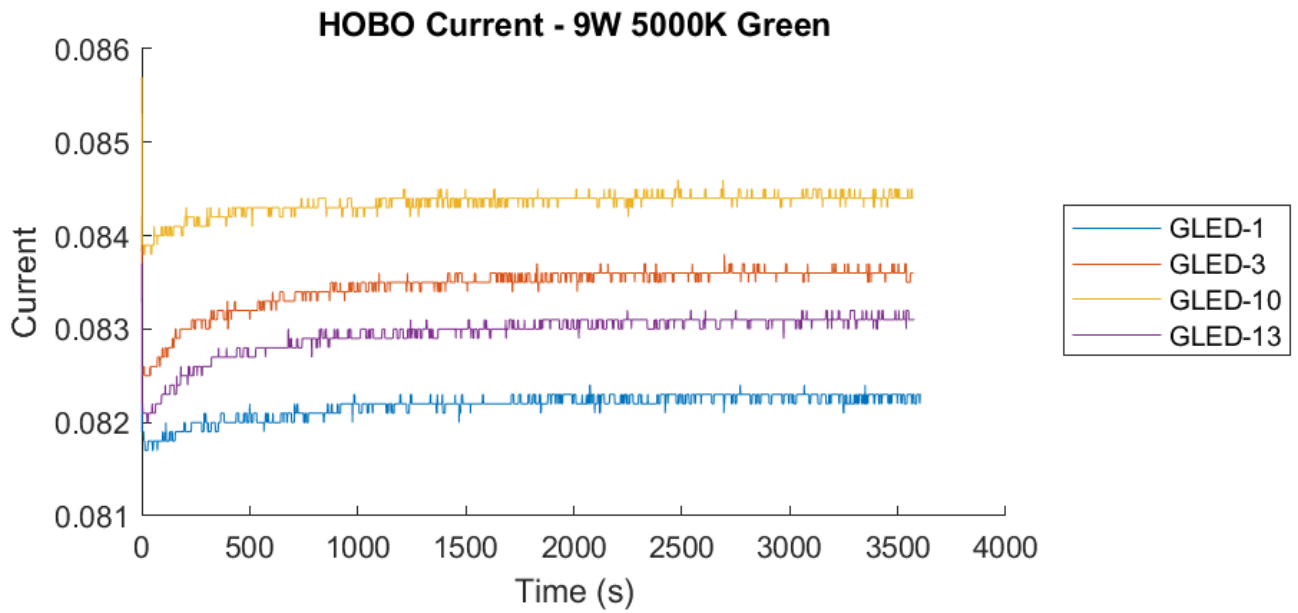
Appendix Figure 68. TES1 Group B PS Voltage.



Appendix Figure 69. TES1 Group B HOBO Voltage.



Appendix Figure 70. TES1 Group B PS Current.

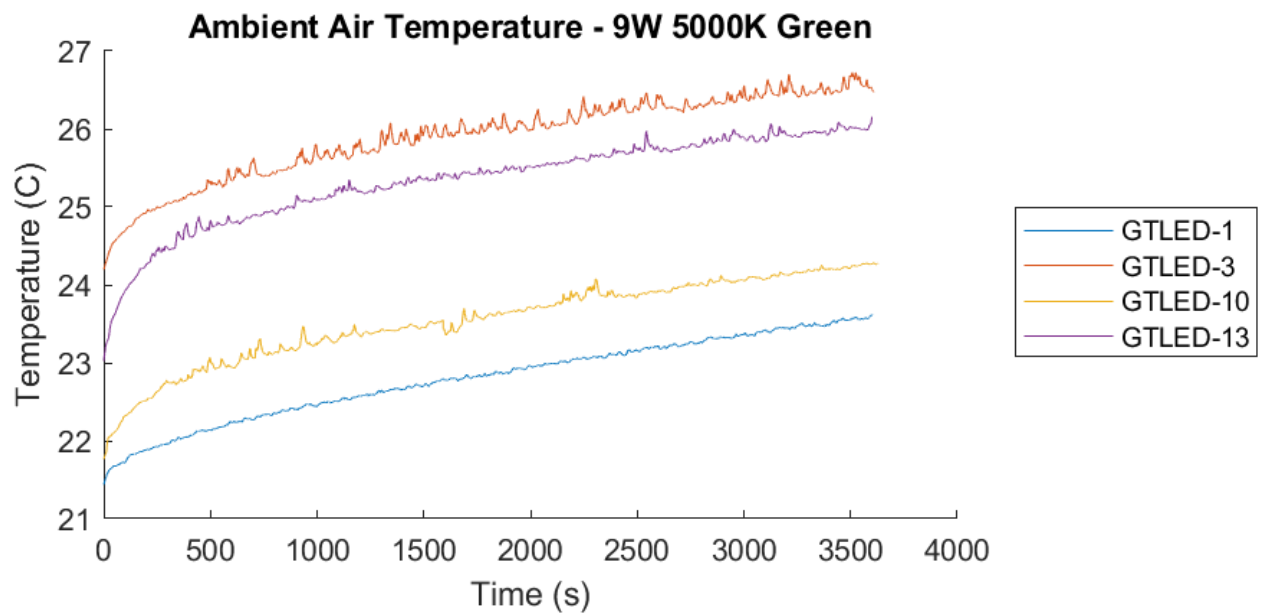


Appendix Figure 71. TES1 Group B HOBO Current.

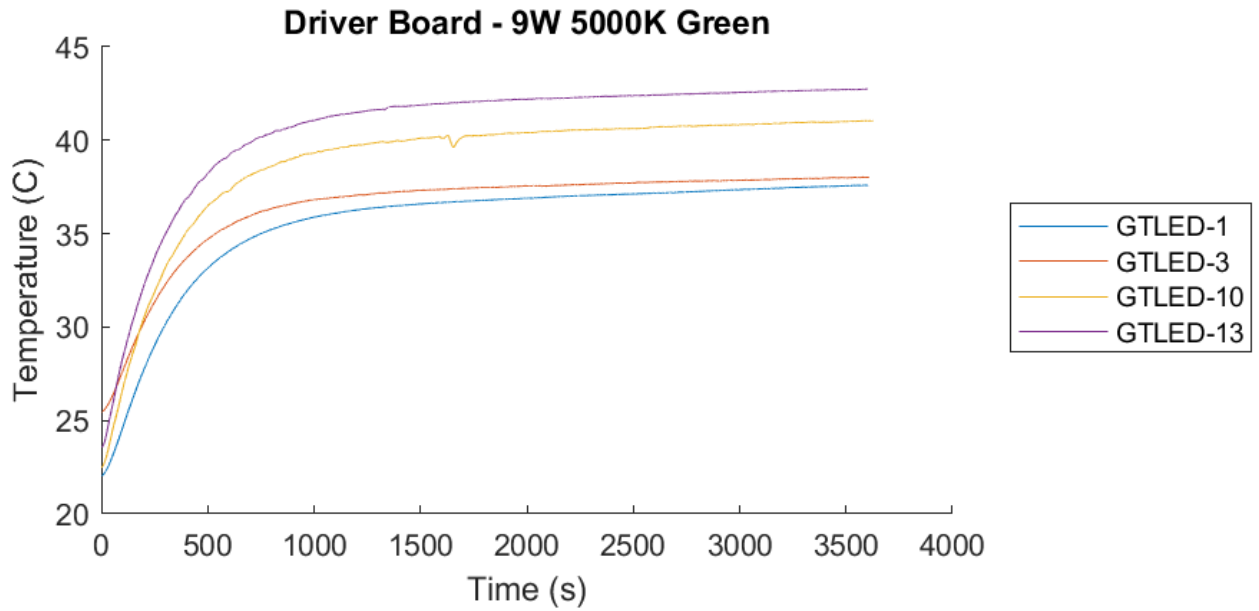
## GTLED-TES2 GROUP B

### B-3.3 GTLED-TES2 Group B Thermal

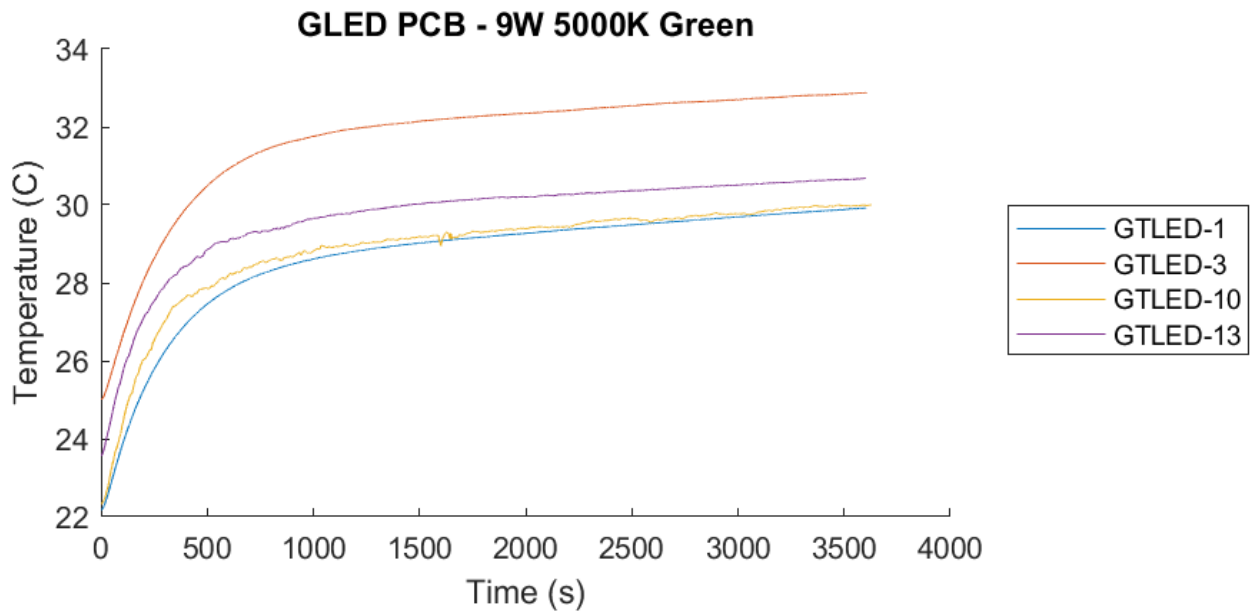
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Appendix Figure 72. TES2 Group B Ambient Air Temperature.

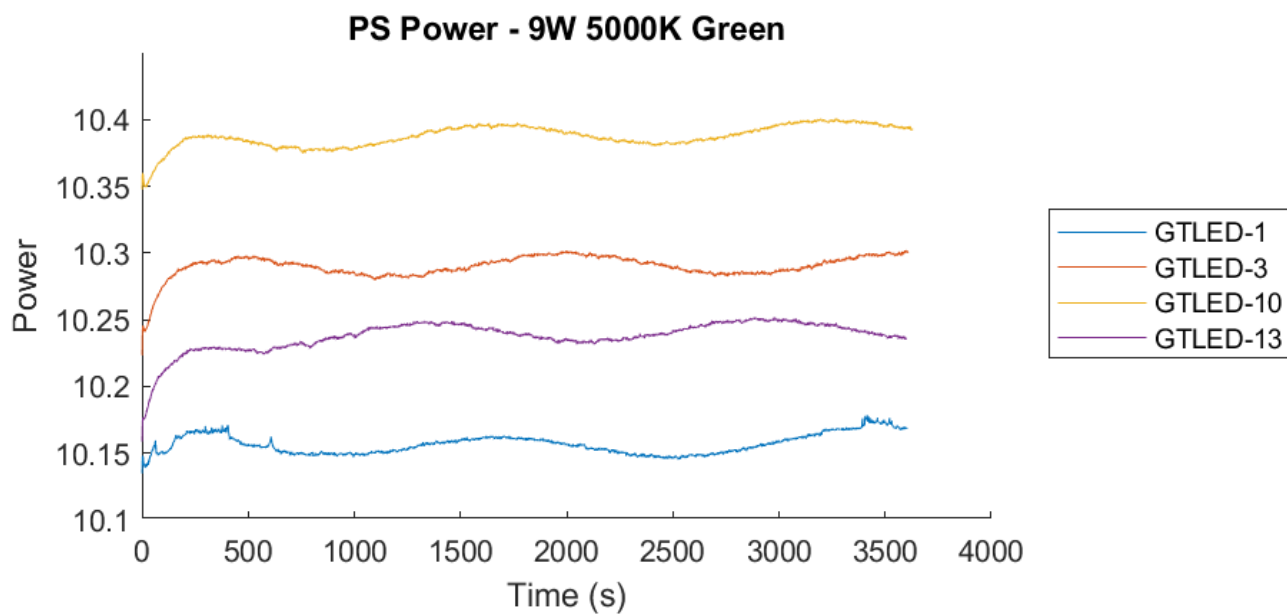


Appendix Figure 73. TES2 Group B GTLED Driver Board Temperature.

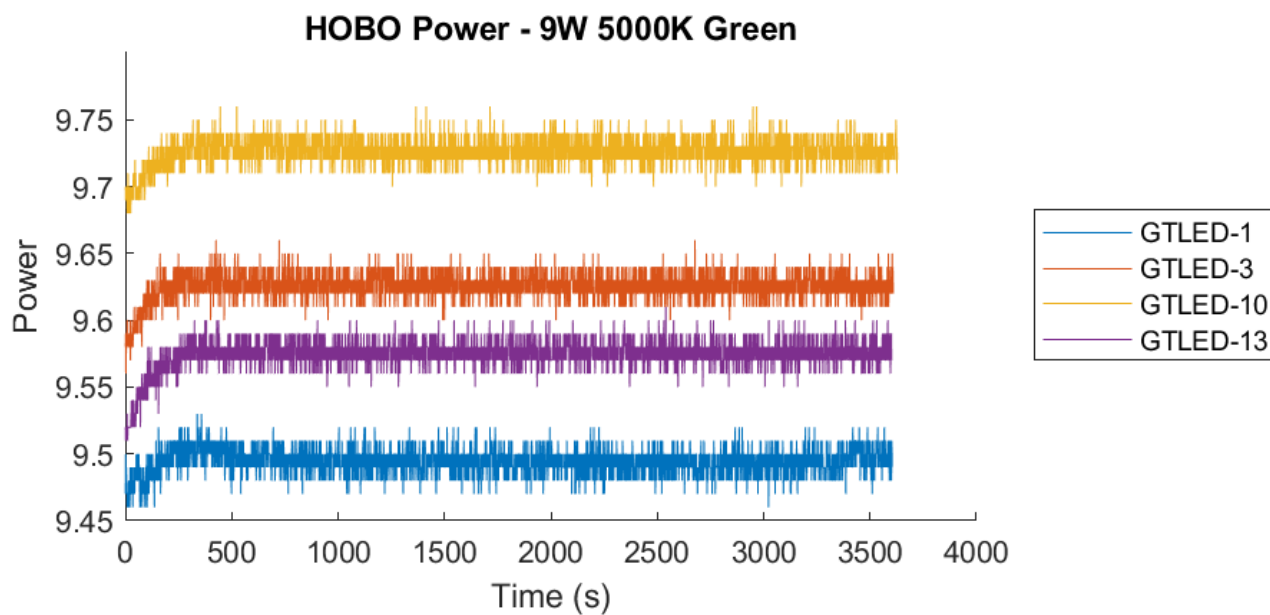


Appendix Figure 74. TES2 Group B GTLED PCB Temperature.

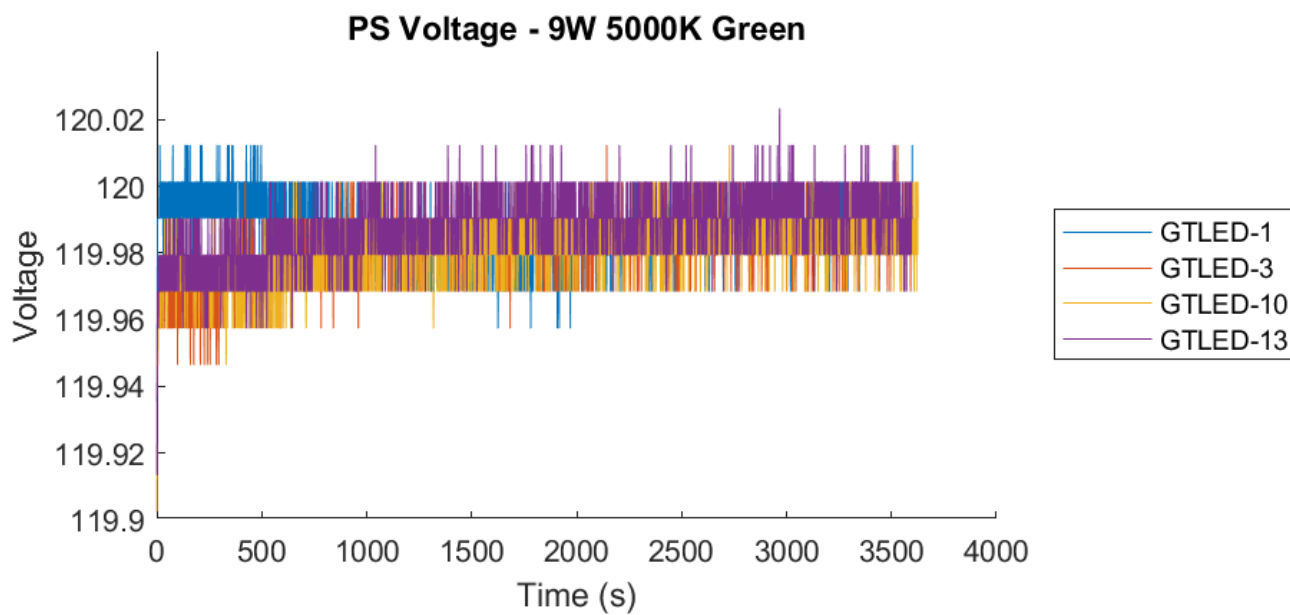
### B-3.4 GTLED-TES2 Group B Electrical



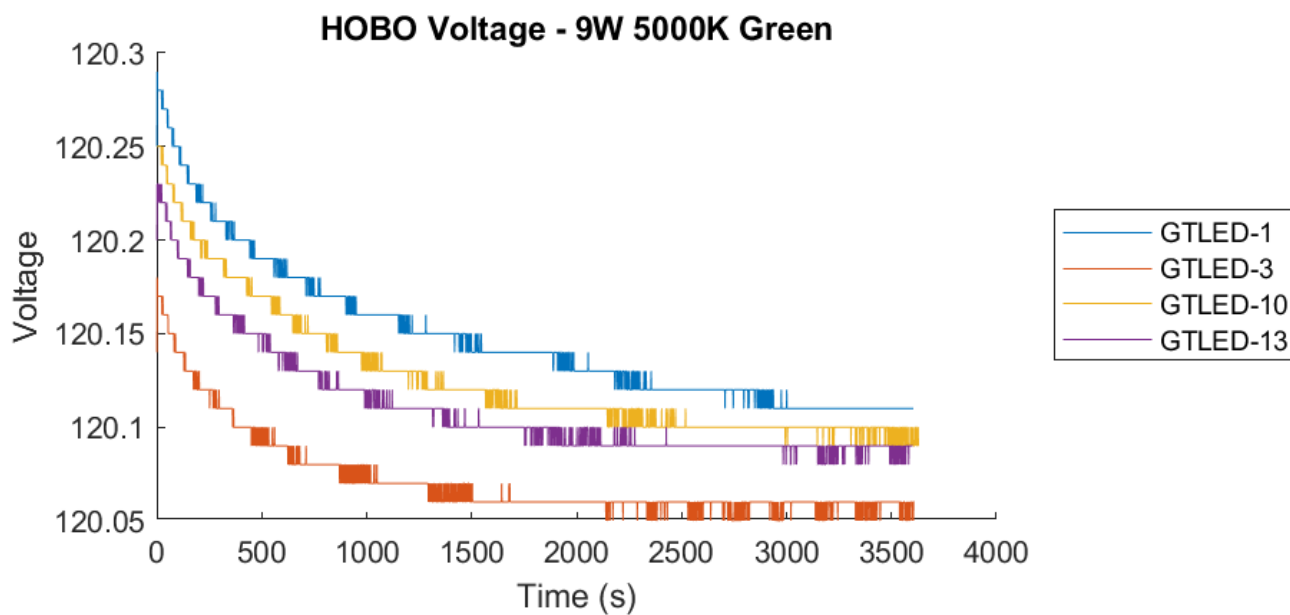
Appendix Figure 75. TES2 Group B PS Power.



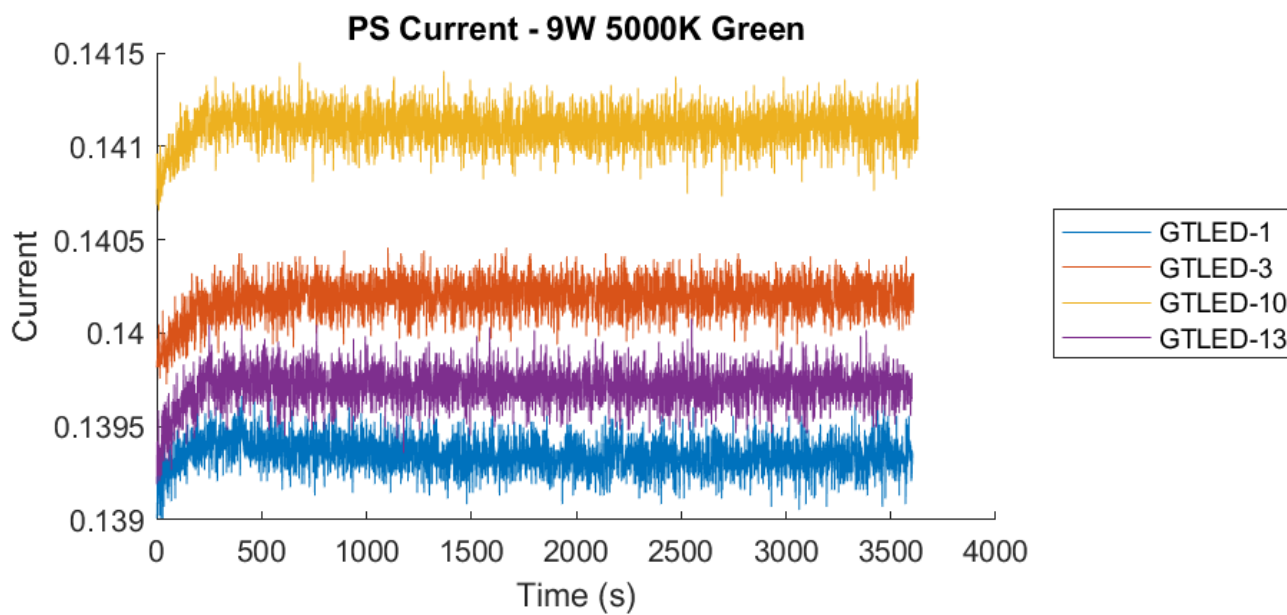
Appendix Figure 76. TES2 Group B HOBO Power.



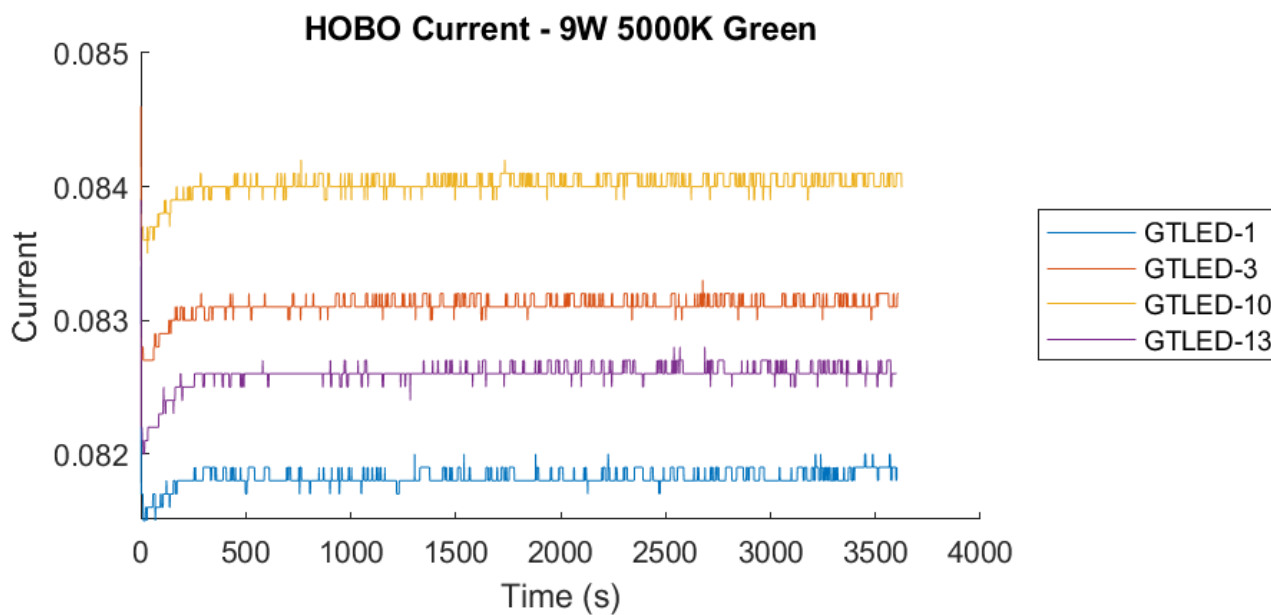
Appendix Figure 77. TES2 Group B PS Voltage.



Appendix Figure 78. TES2 Group B HOB0 Voltage.



Appendix Figure 79. TES2 Group B PS Current.

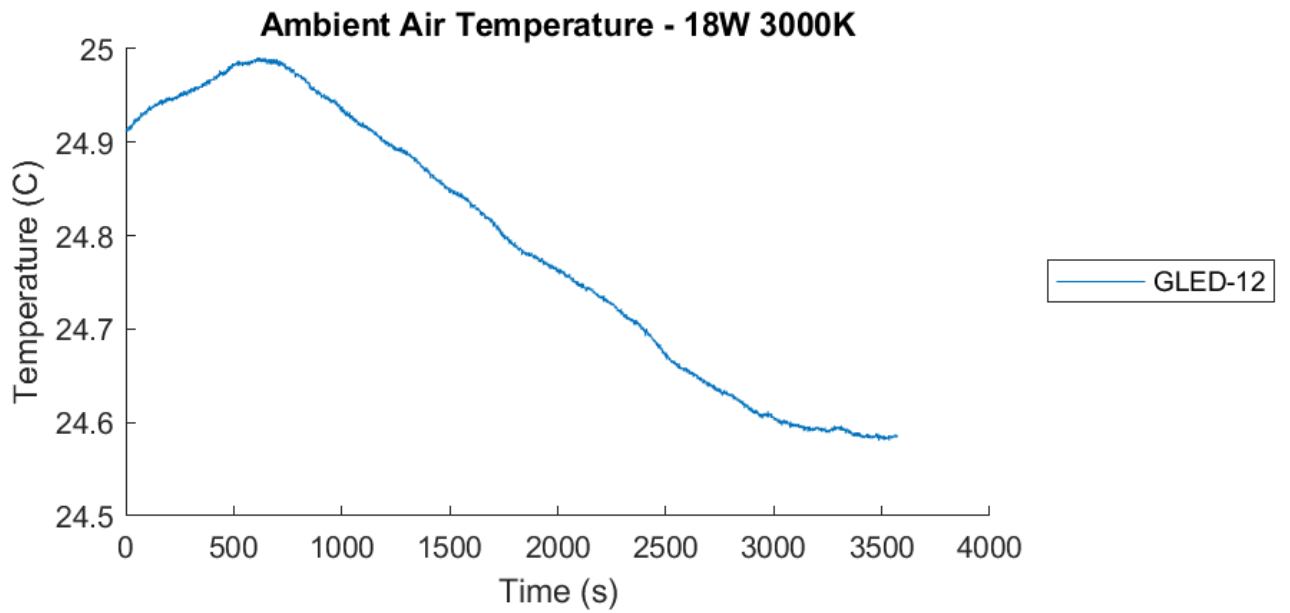


Appendix Figure 80. TES2 Group B HOB0 Current.

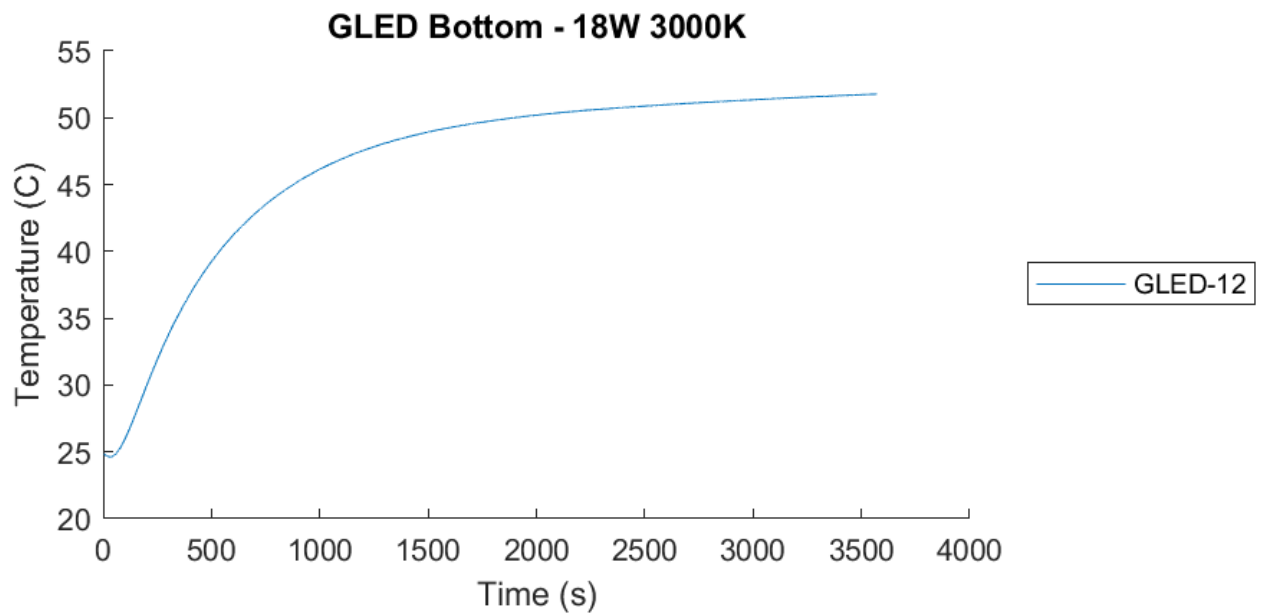
#### B-4 GTLED-TES GROUP C

##### GTLED-TES1 GROUP C

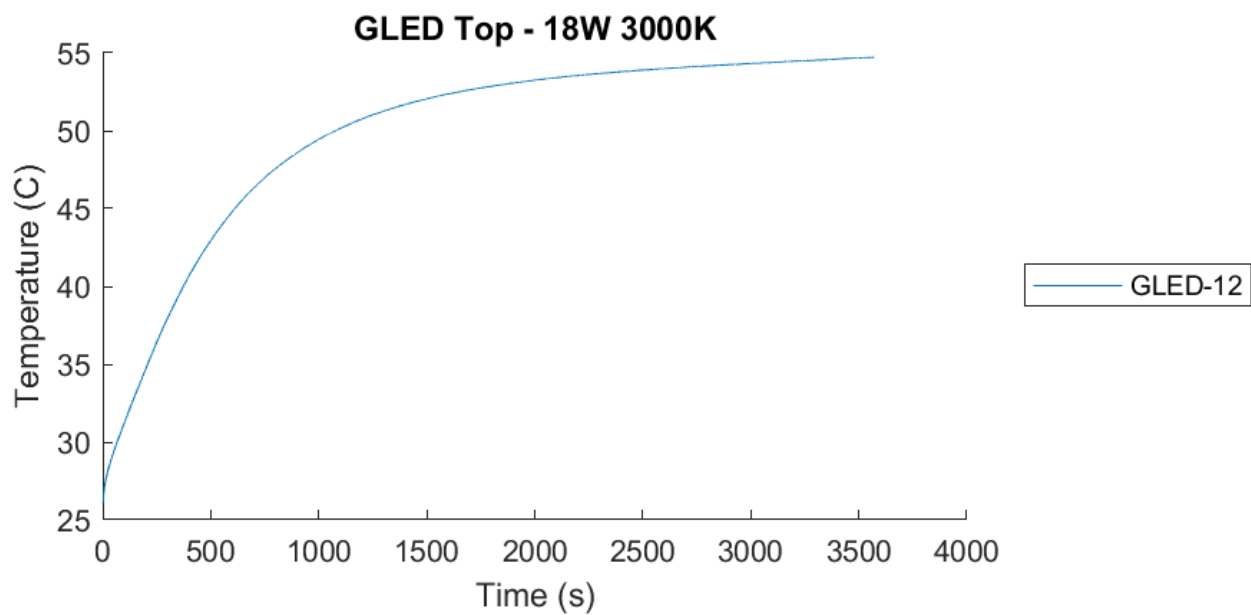
##### B-4.1 GTLED-TES1 Group C Thermal



Appendix Figure 81. TES1 Group C Ambient Air Temperature.

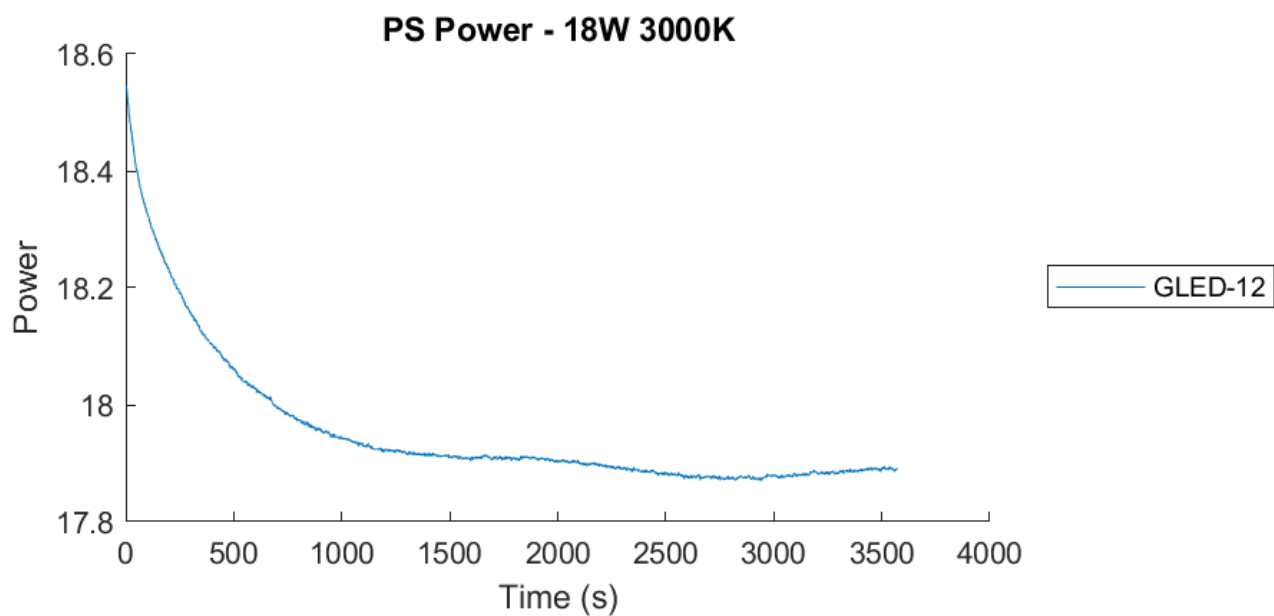


Appendix Figure 82. TES1 Group C GTLED Bottom Temperature.

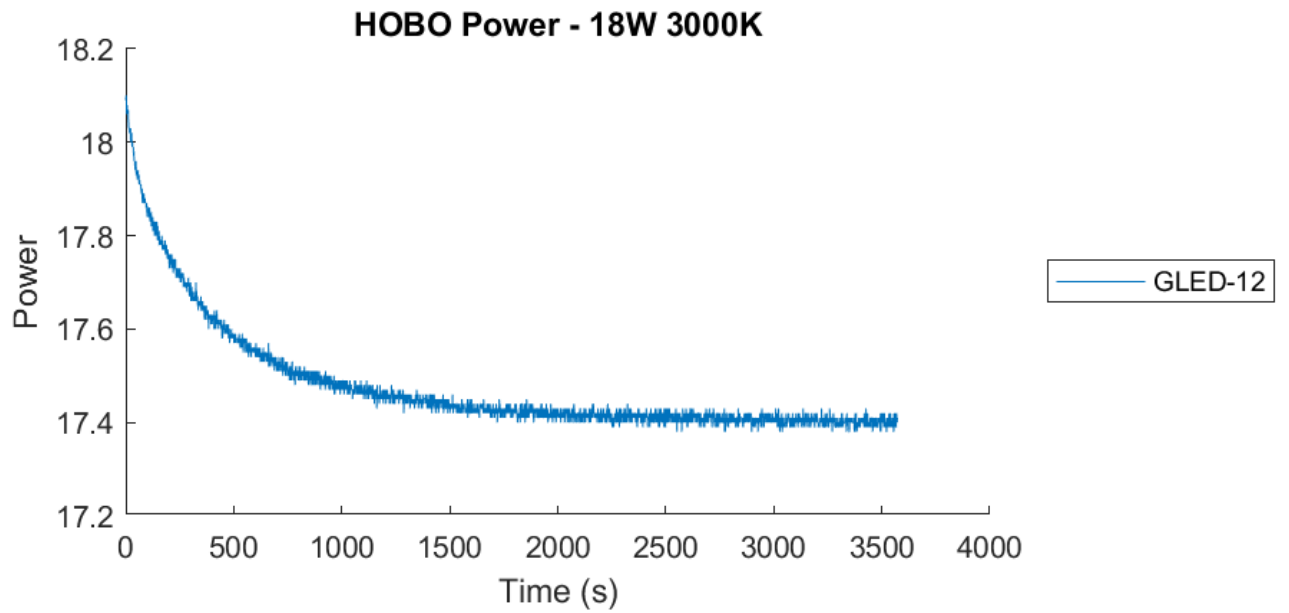


Appendix Figure 83. TES1 Group C GTLED Top Temperature.

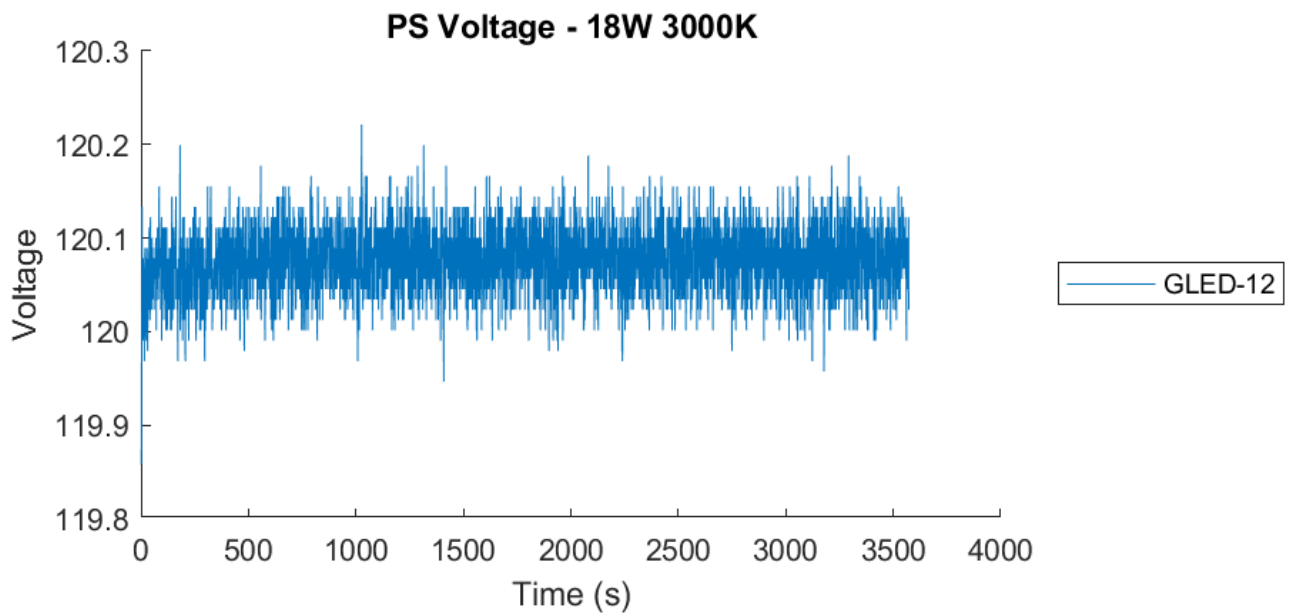
#### B-4.2 GTLED-TES1 Group C Electrical



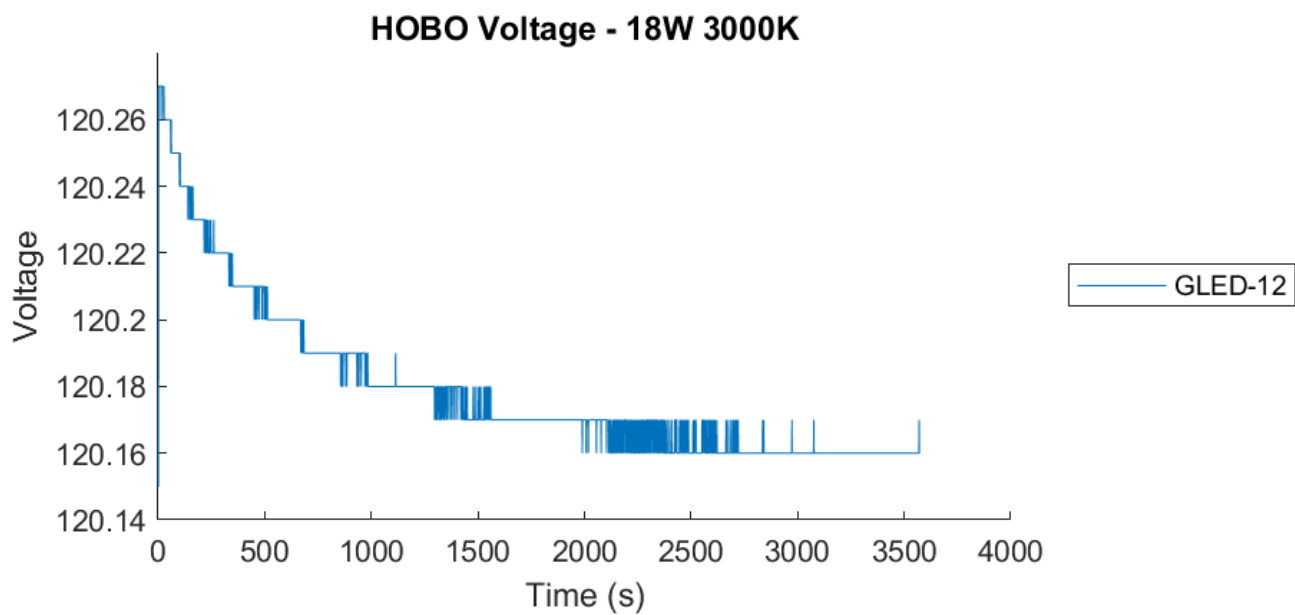
Appendix Figure 84. TES1 Group C PS Power.



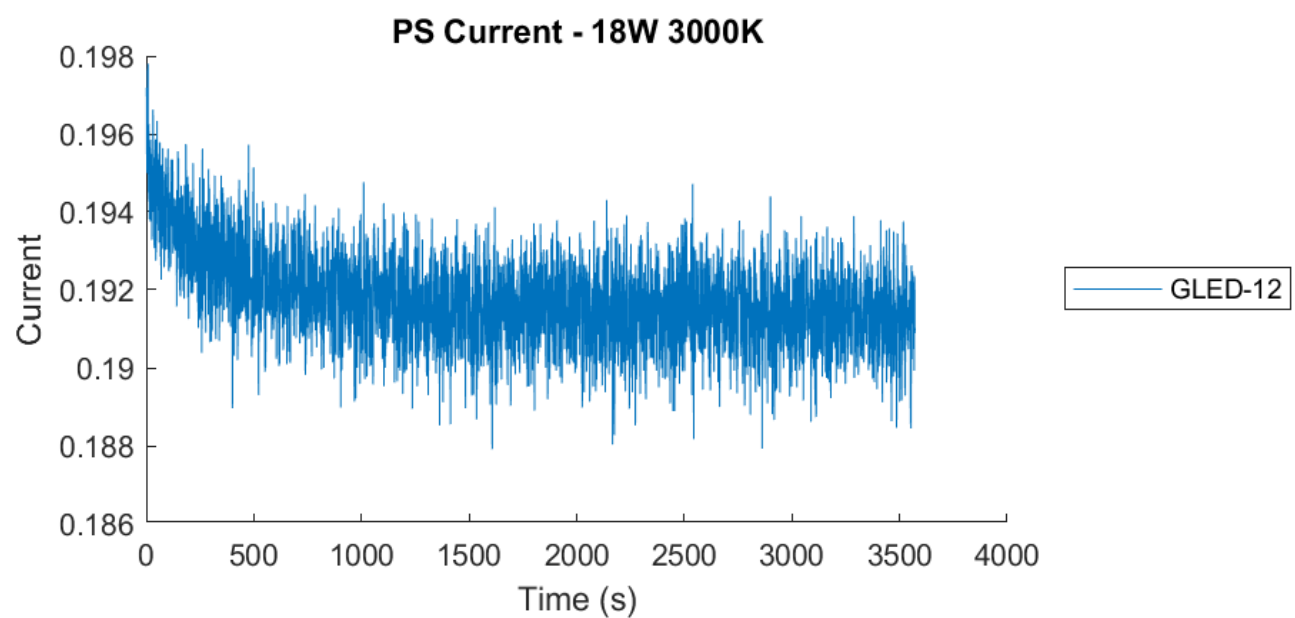
Appendix Figure 85. TES1 Group C HOB0 Power



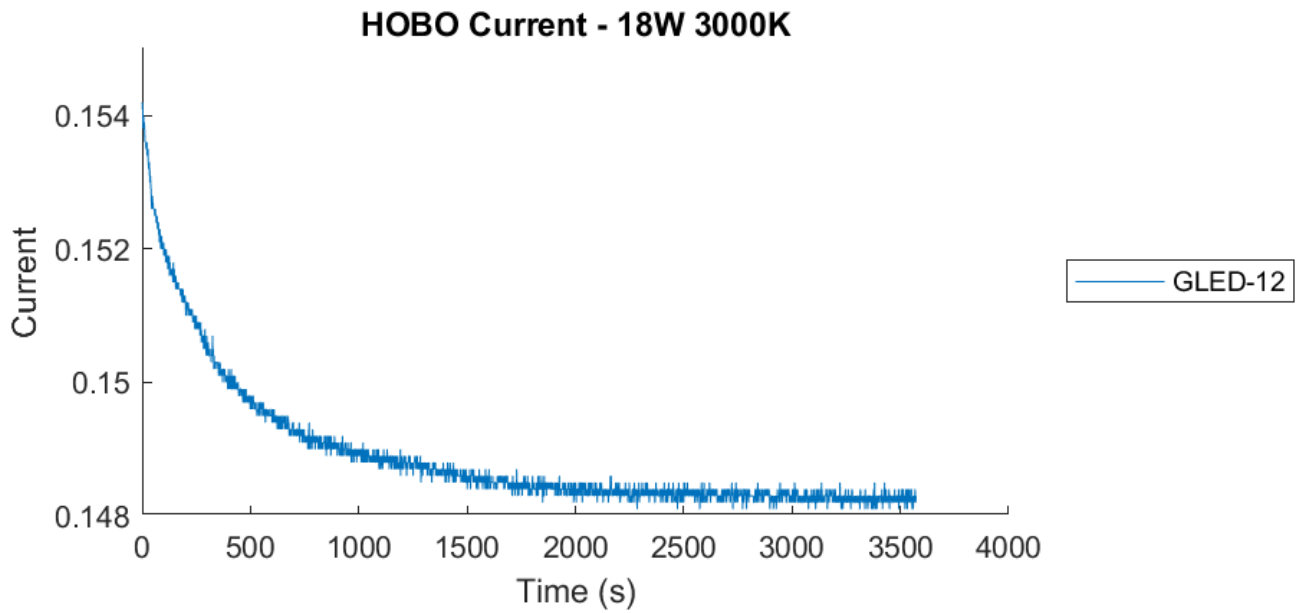
Appendix Figure 86. TES1 Group C PS Voltage.



Appendix Figure 87. TES1 Group C HOB0 Voltage



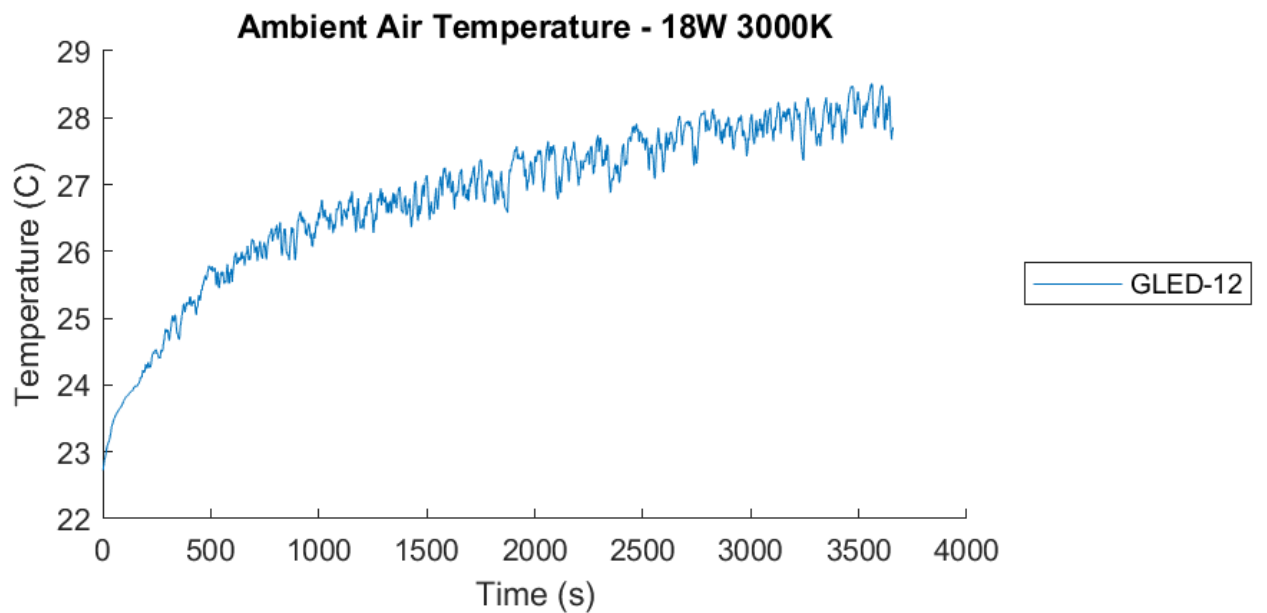
Appendix Figure 88. TES1 Group C PS Current.



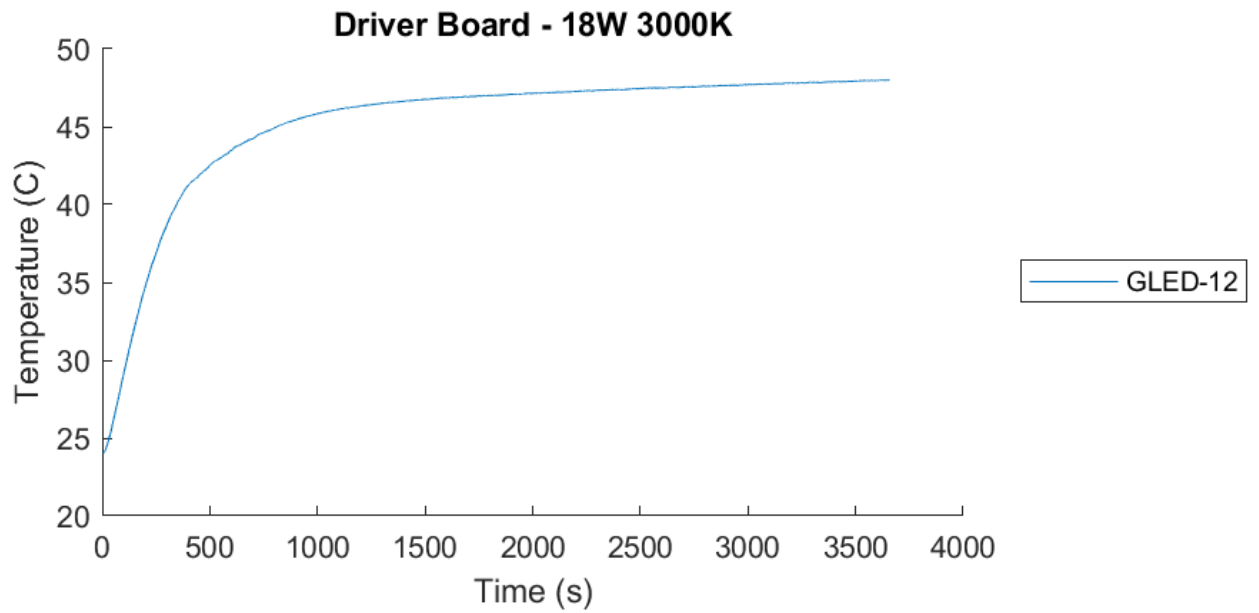
Appendix Figure 89. TES1 Group C HOBO Current.

## GTLED-TES2 GROUP C

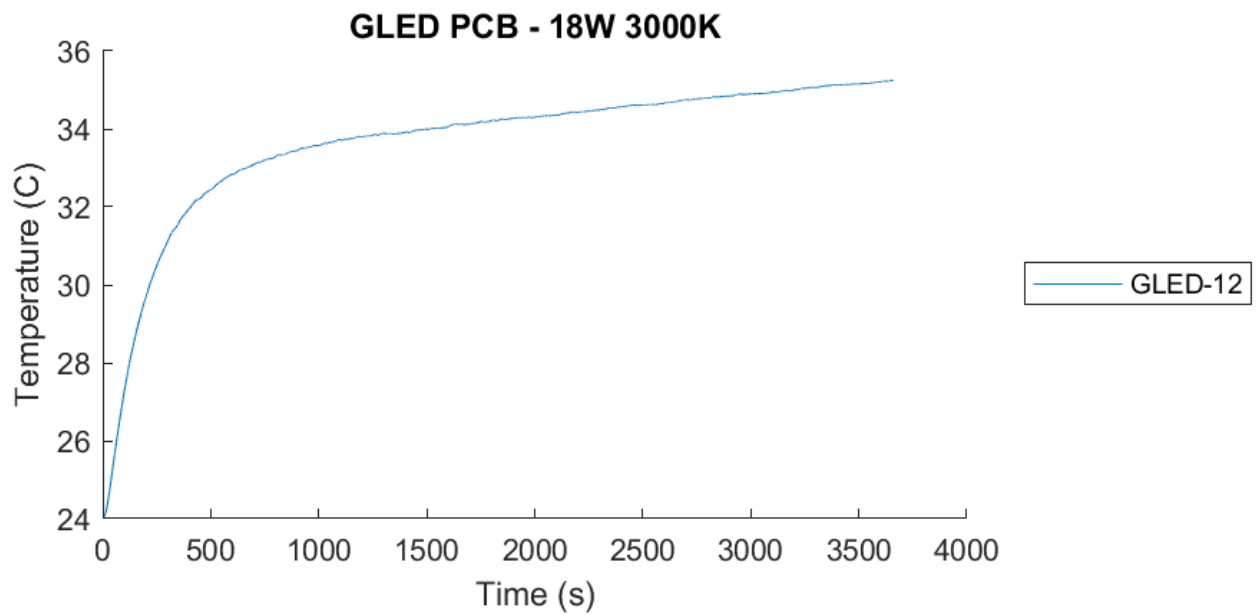
### B-4.3 GTLED-TES2 Group C Thermal



Appendix Figure 90. TES2 Group C Ambient Air Temperature.

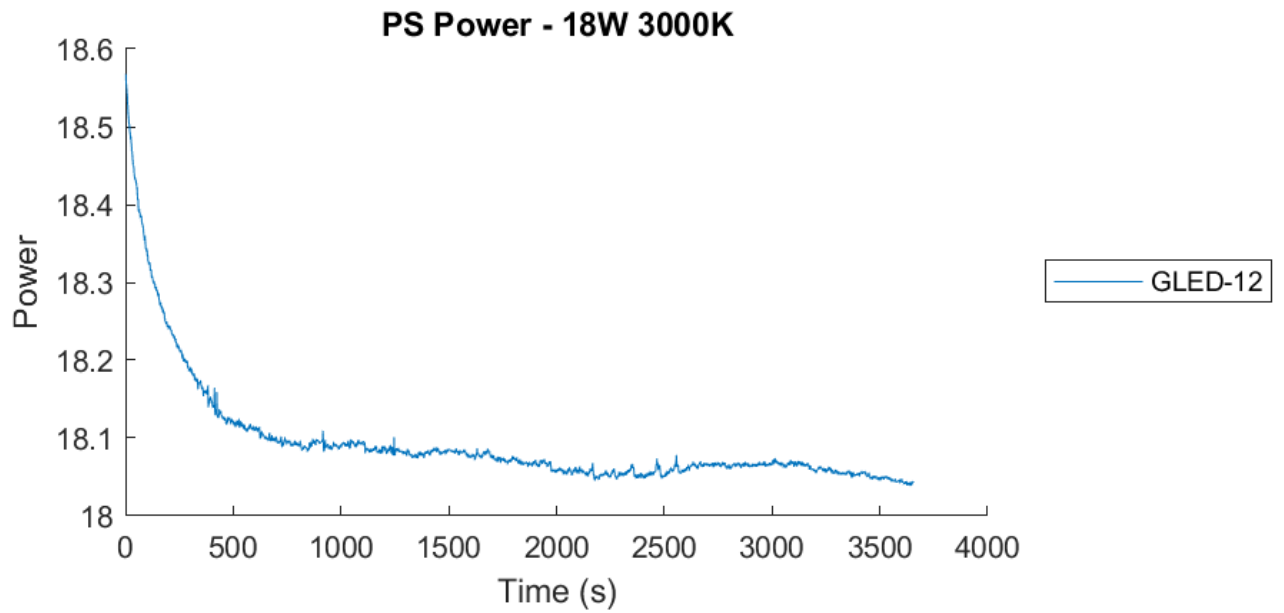


Appendix Figure 91. TES2 Group C GTLED Driver Board Temperature.

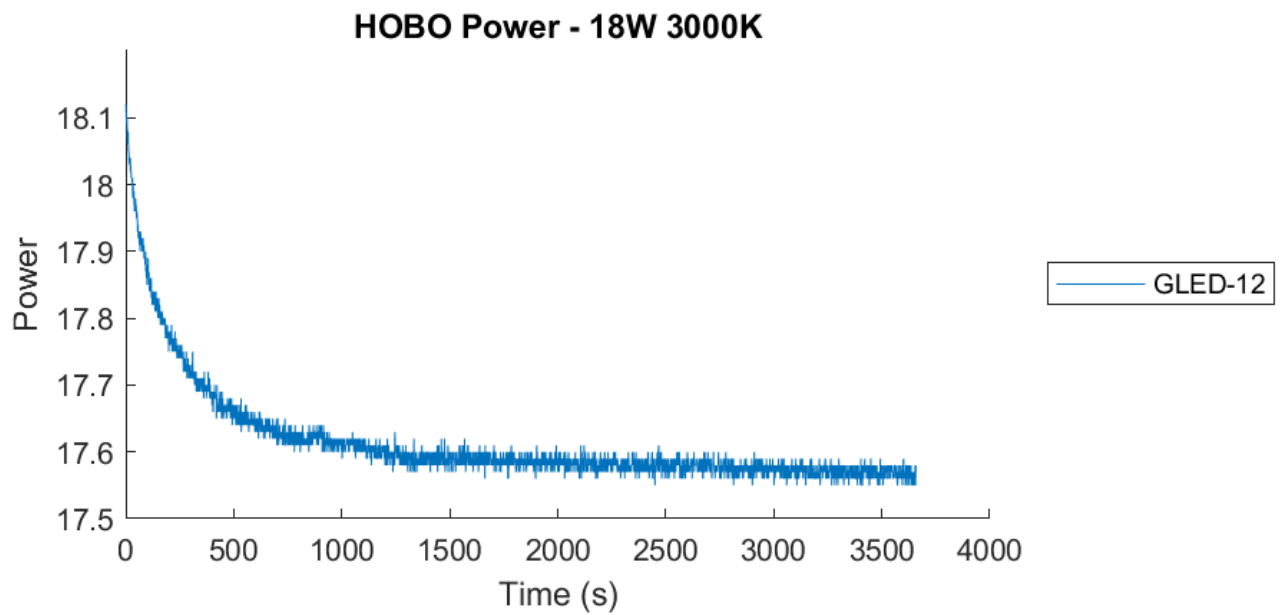


Appendix Figure 92. TES2 Group C GTLED PCB Temperature.

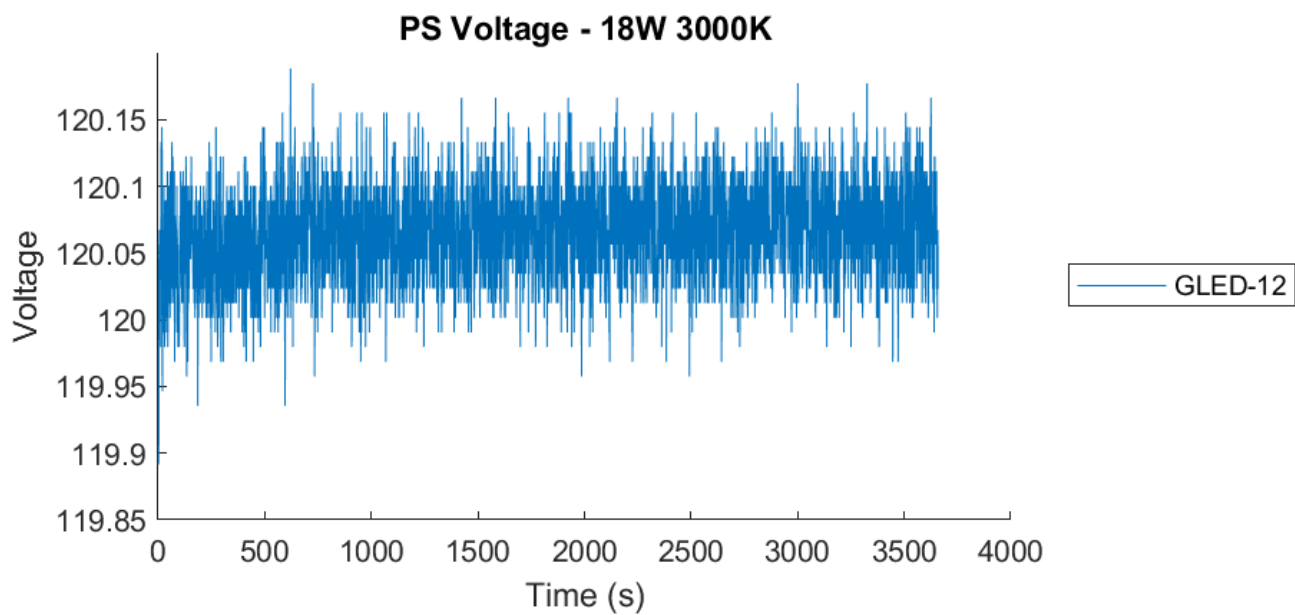
#### B-4.4 GTLED-TES2 Group C Electrical



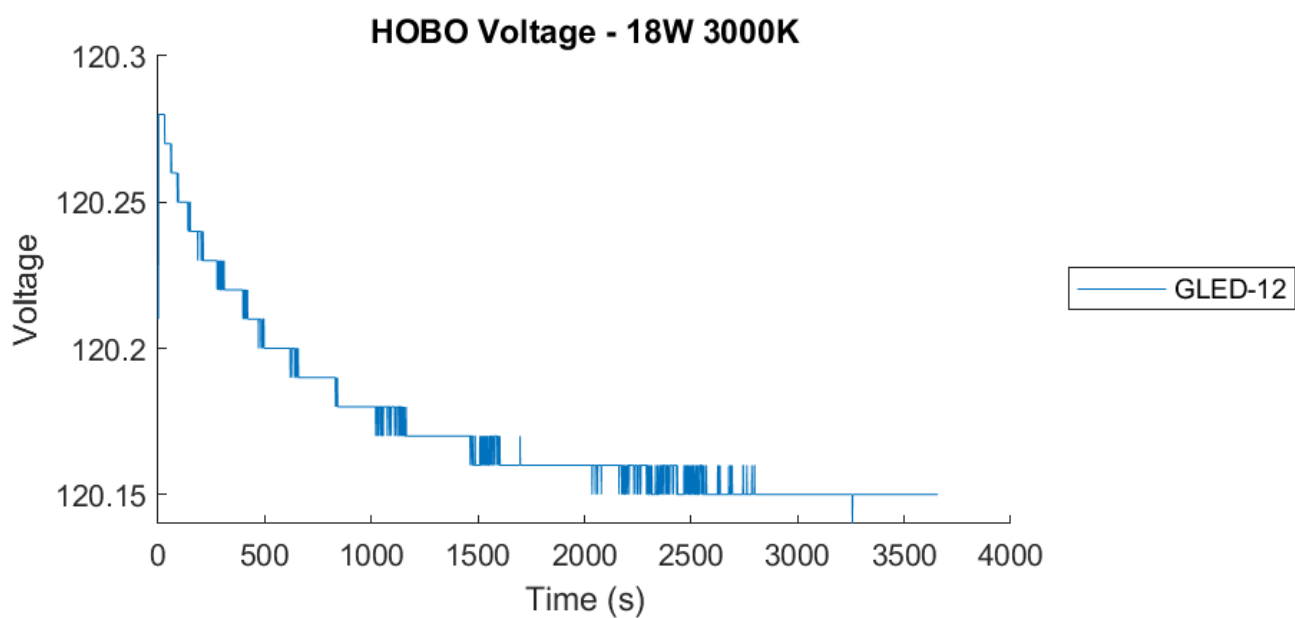
Appendix Figure 93. TES2 Group C PS Power



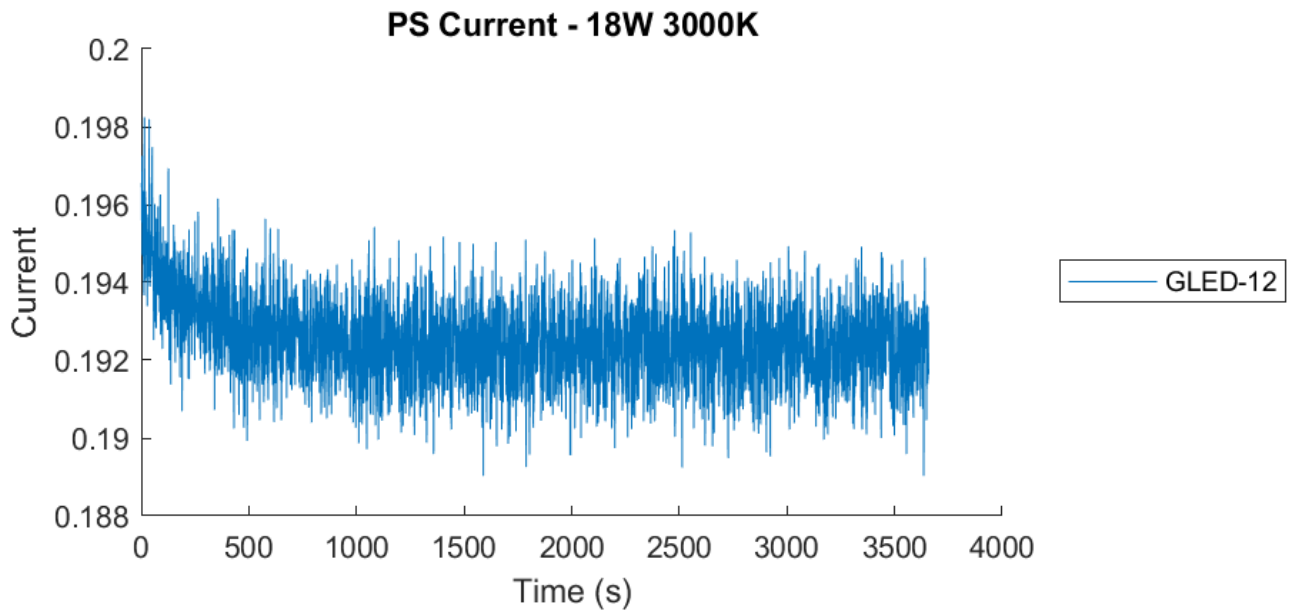
Appendix Figure 94. TES2 Group C HOB0 Power.



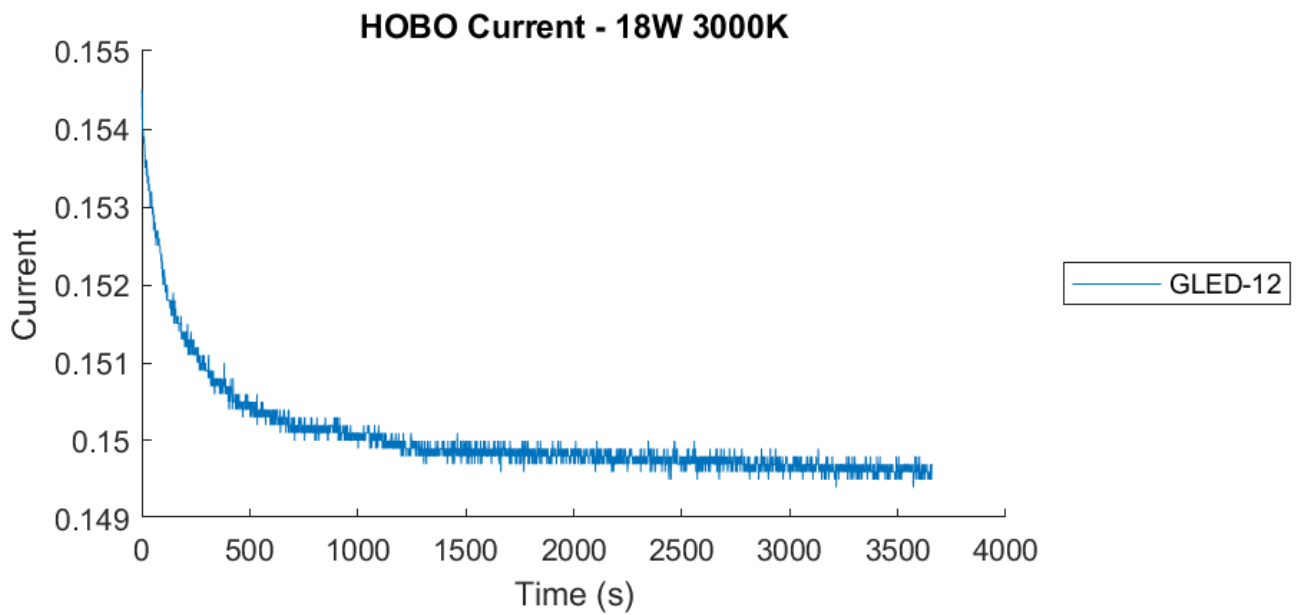
Appendix Figure 95. TES2 Group C PS Voltage



Appendix Figure 96. TES2 Group C HOBO Voltage.



Appendix Figure 97. TES2 Group C PS Current.



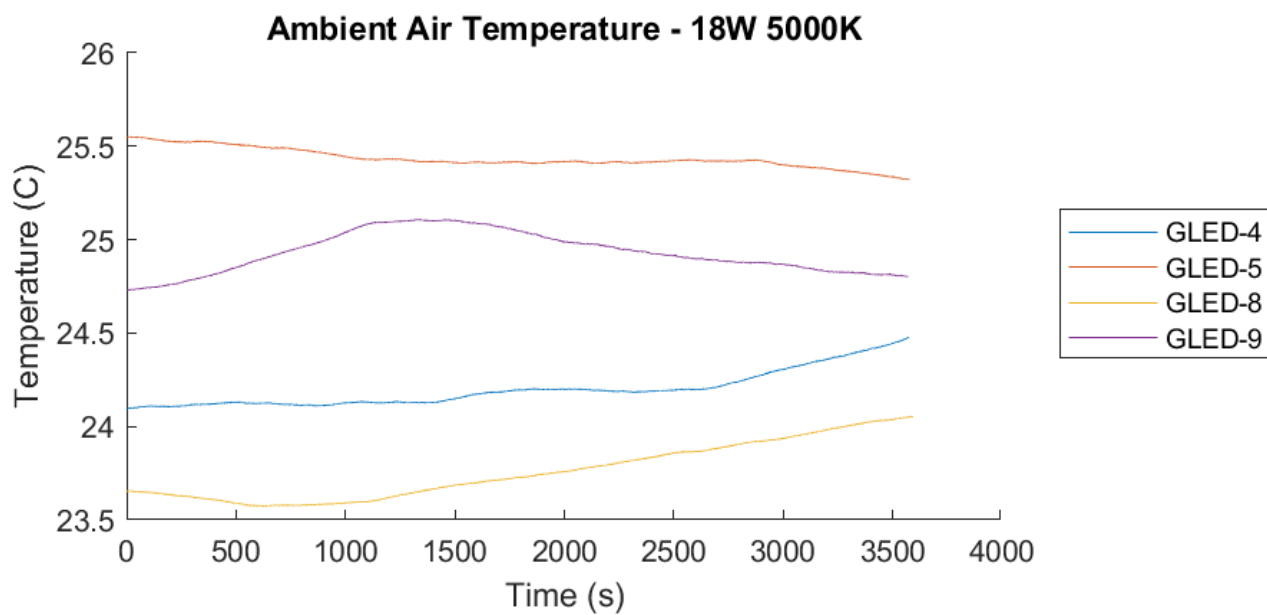
Appendix Figure 98. TES2 Group C HOBO Current.

## B-5 GTLED-TES GROUP D

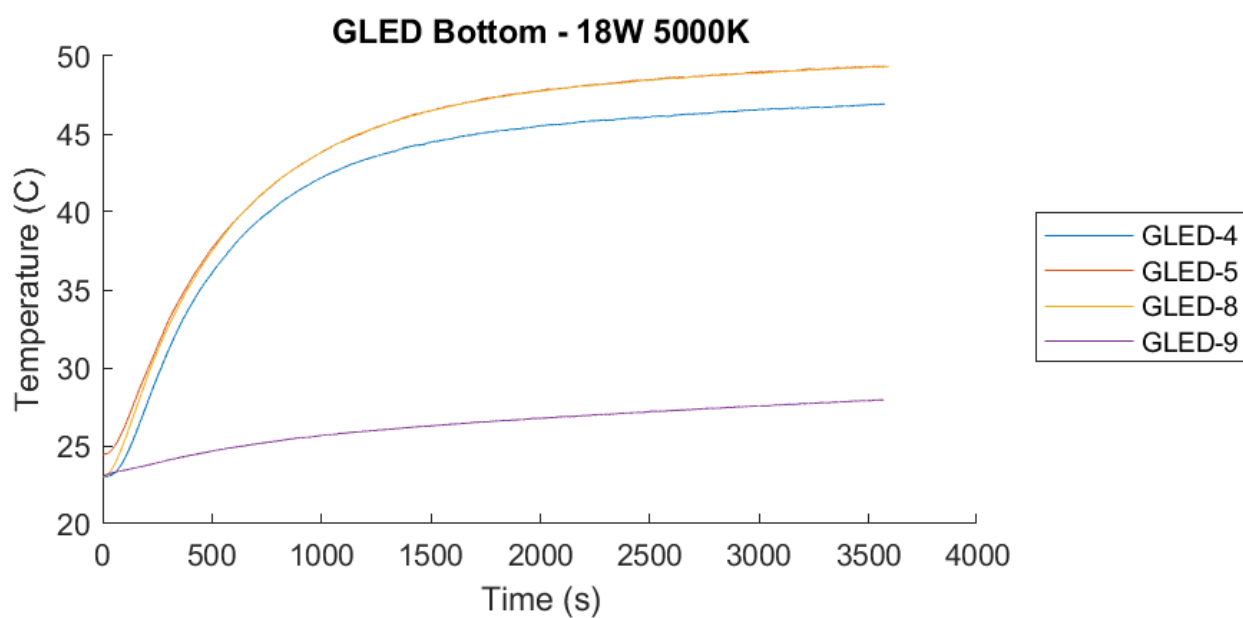
### GTLED-TES1 GROUP D

#### B-5.1 GTLED-TES1 Group D Thermal

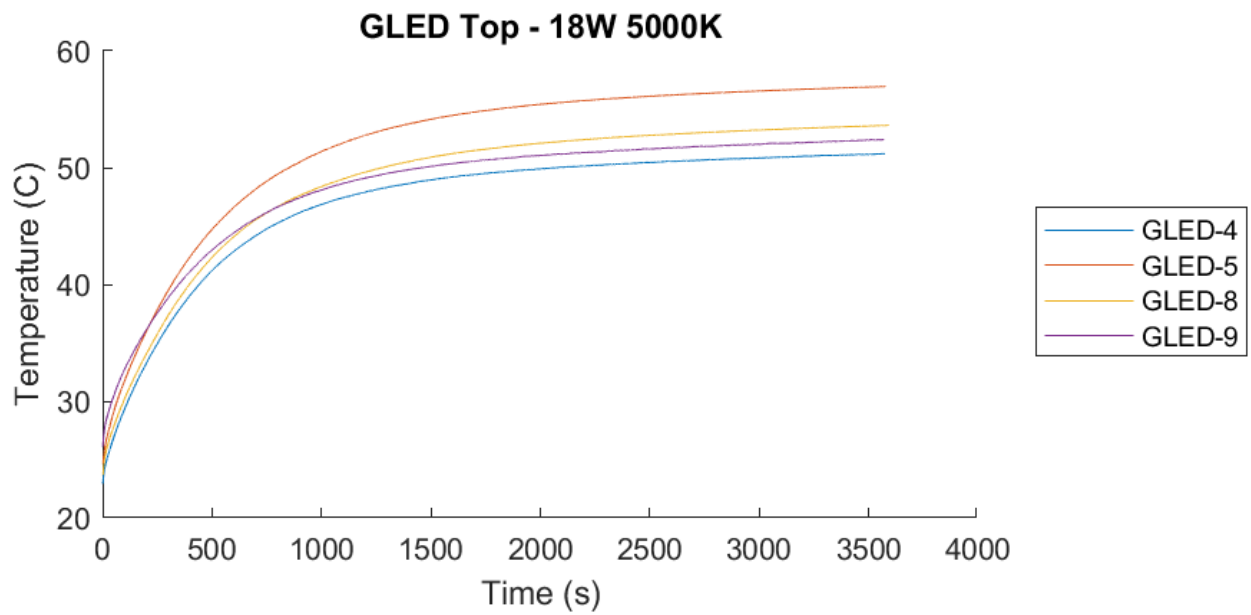
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Appendix Figure 99. TES1 Group D Ambient Air Temperature.

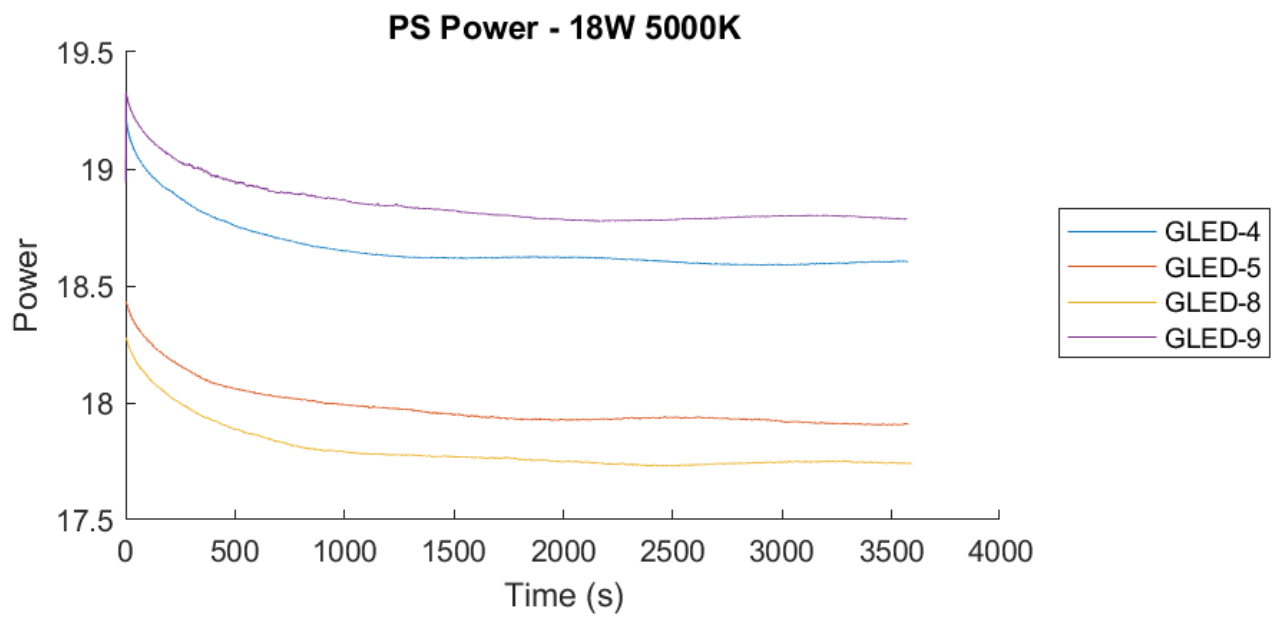


Appendix Figure 100. TES1 Group D GTLED Bottom Temperature.

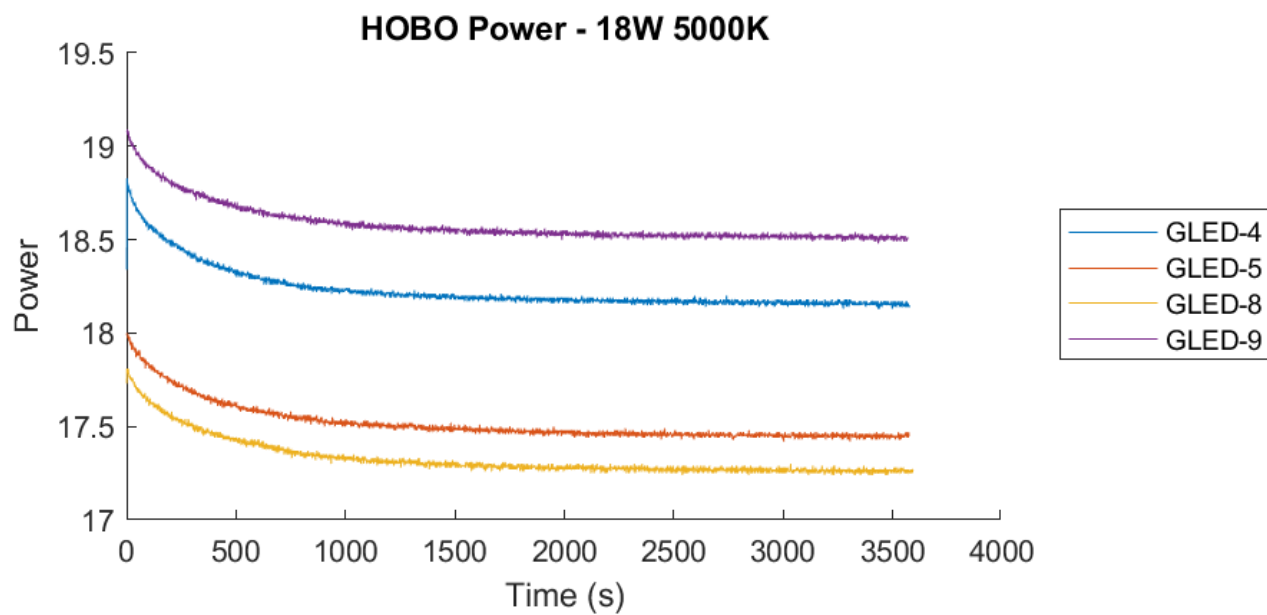


Appendix Figure 101. TES1 Group D GTLED Top Temperature.

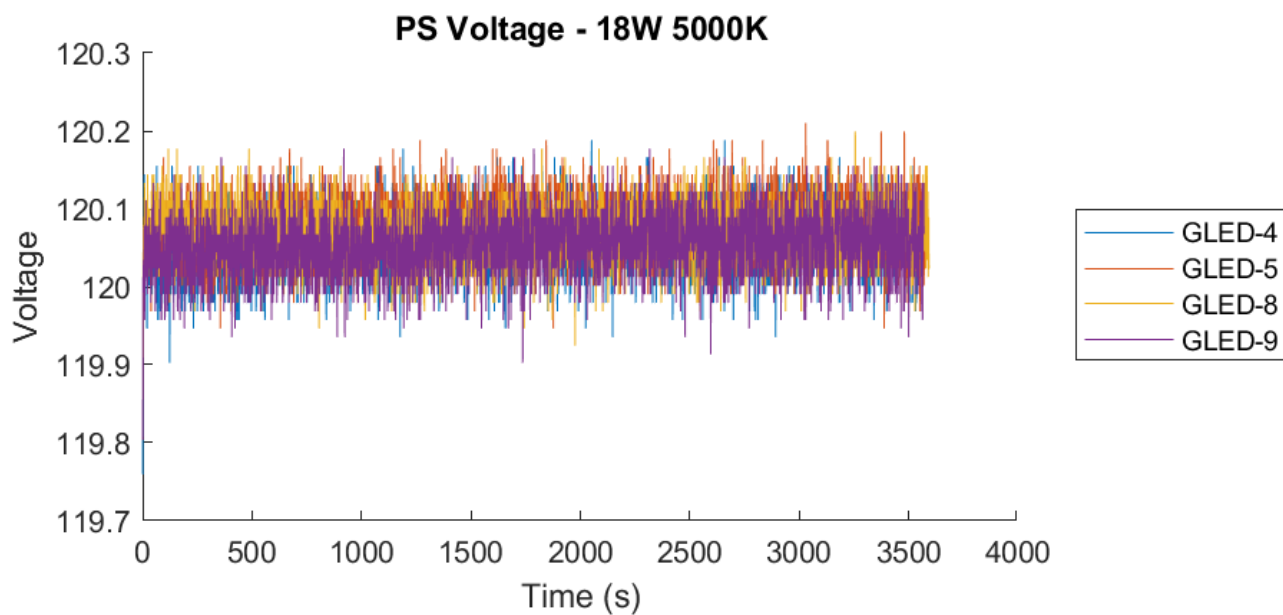
#### B-5.2 GTLED-TES1 Group D Electrical



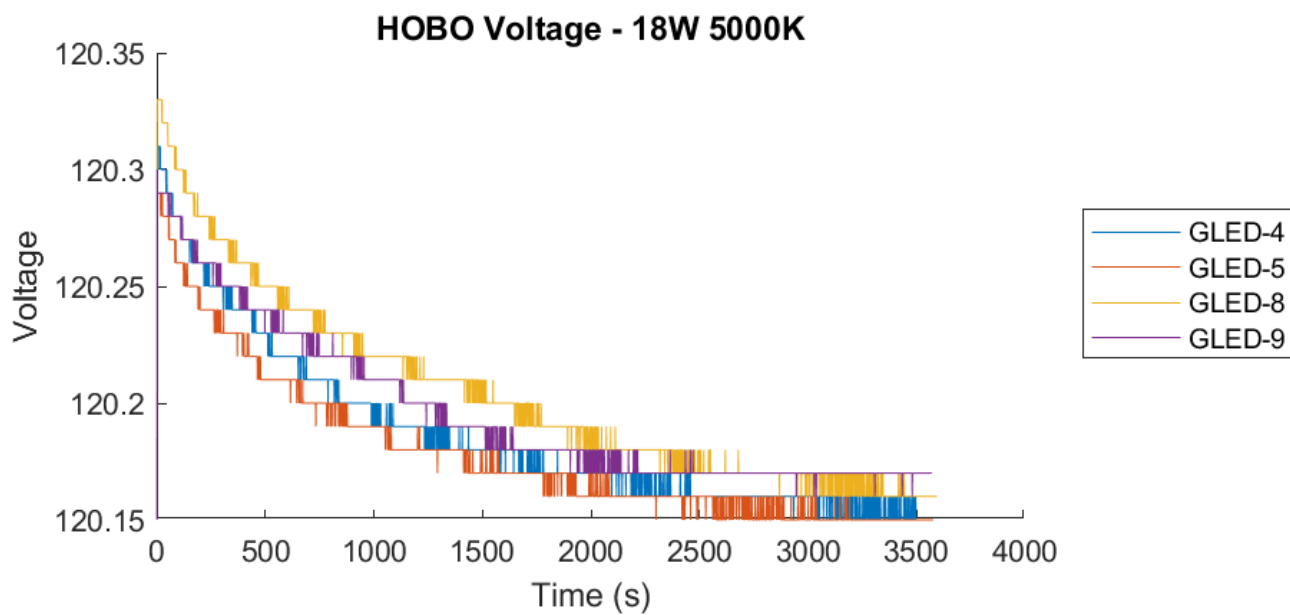
Appendix Figure 102. TES1 Group D PS Power.



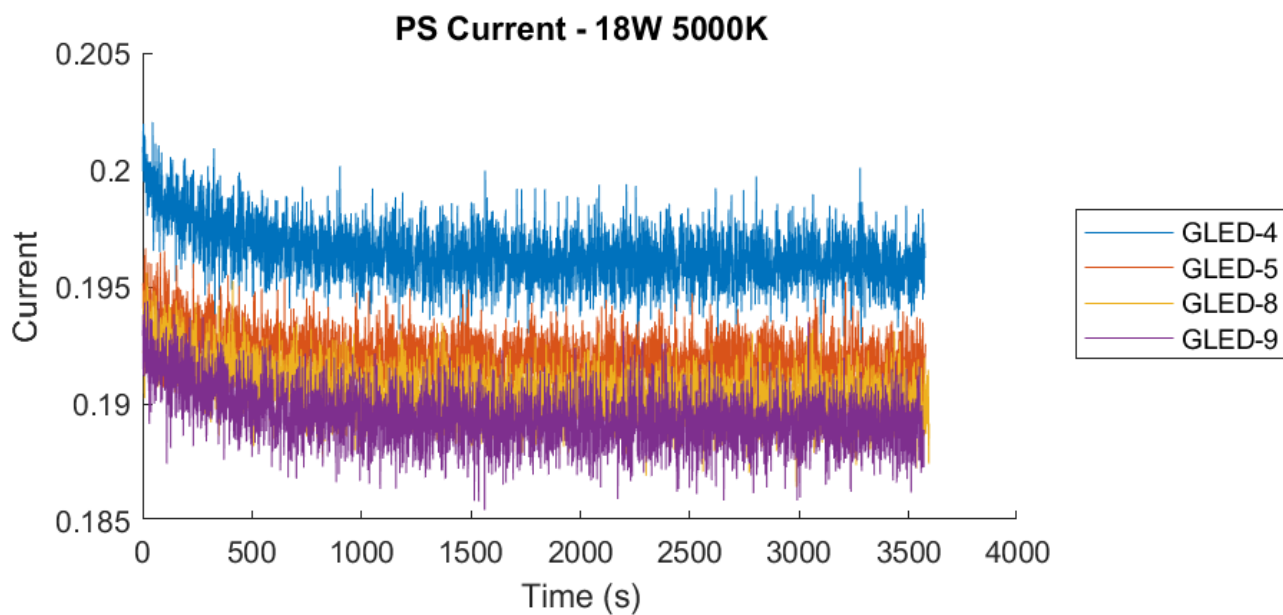
Appendix Figure 103. TES1 Group D HOB0 Power.



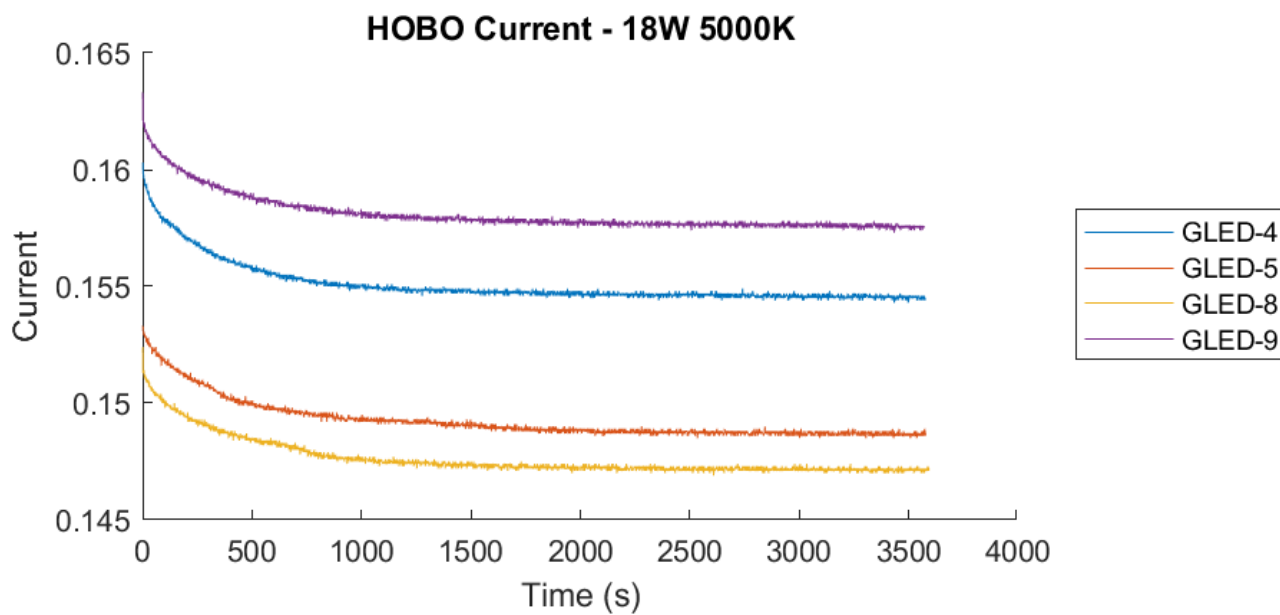
Appendix Figure 104. TES1 Group D PS Voltage.



Appendix Figure 105. TES1 Group D HOB0 Voltage.



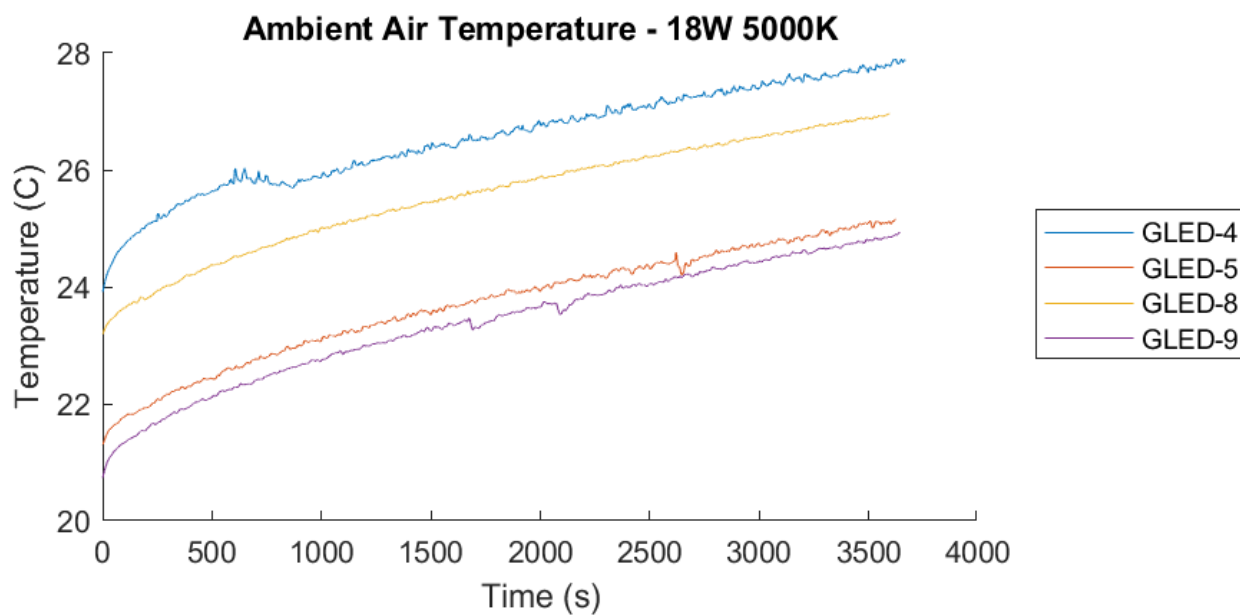
Appendix Figure 106. TES1 Group D PS Current.



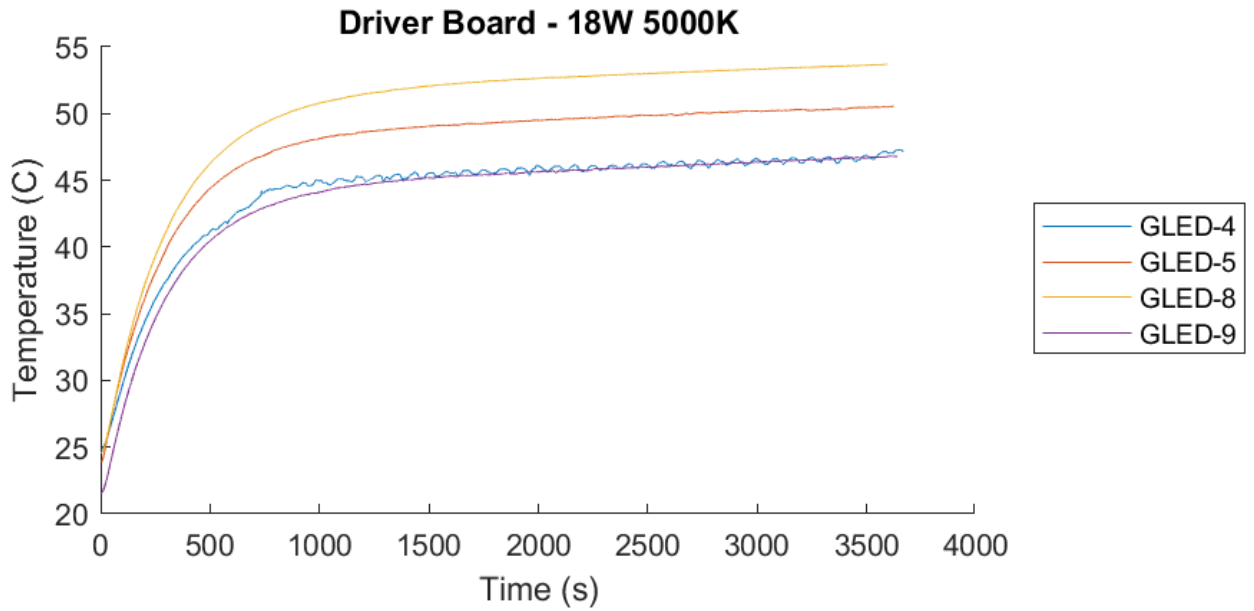
Appendix Figure 107. TES1 Group D HOBO Current.

## GTLED-TES2 GROUP D

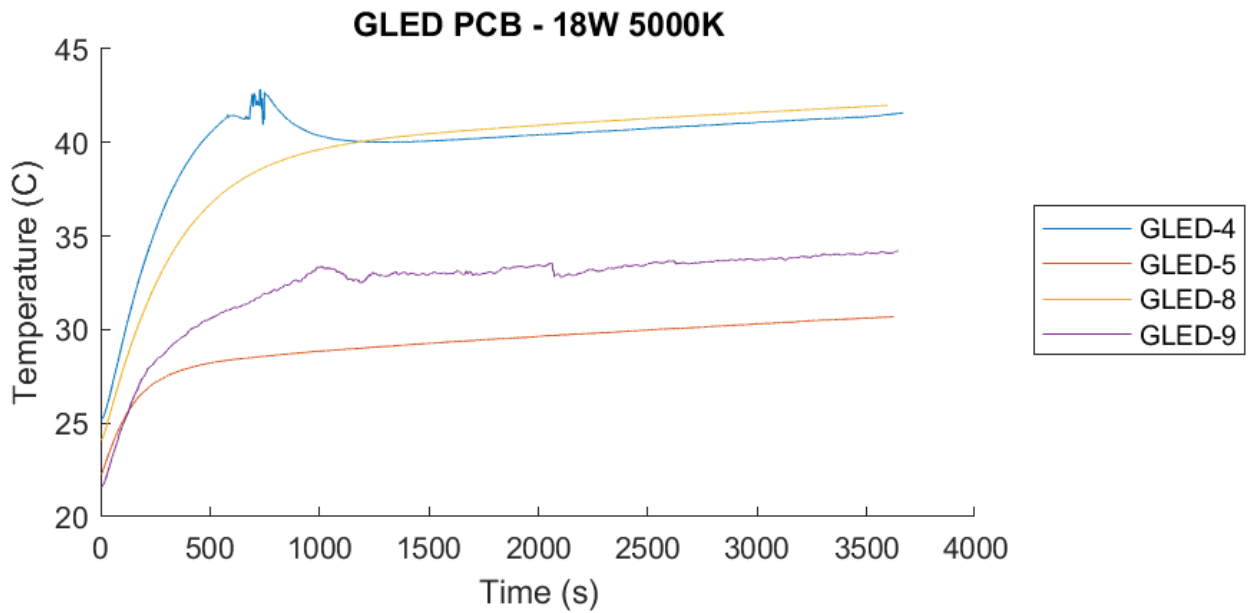
### B-5.3 GTLED-TES2 Group D Thermal



Appendix Figure 108. TES2 Group D Ambient Air Temperature.

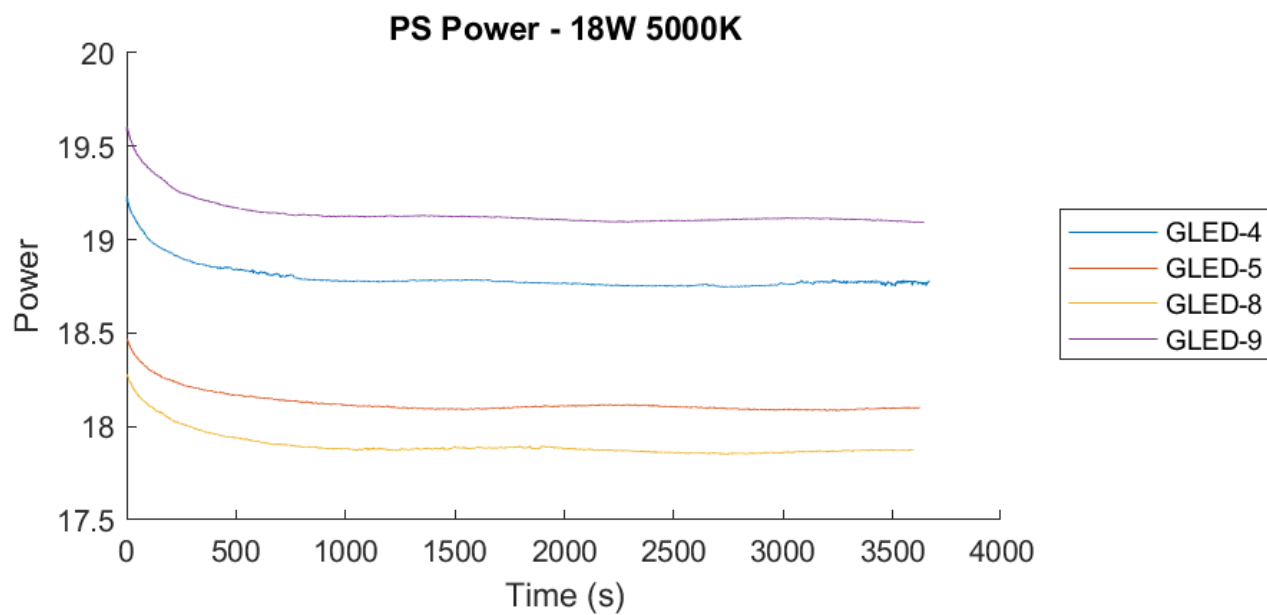


Appendix Figure 109. TES2 Group D GTLED Driver Board Temperature.

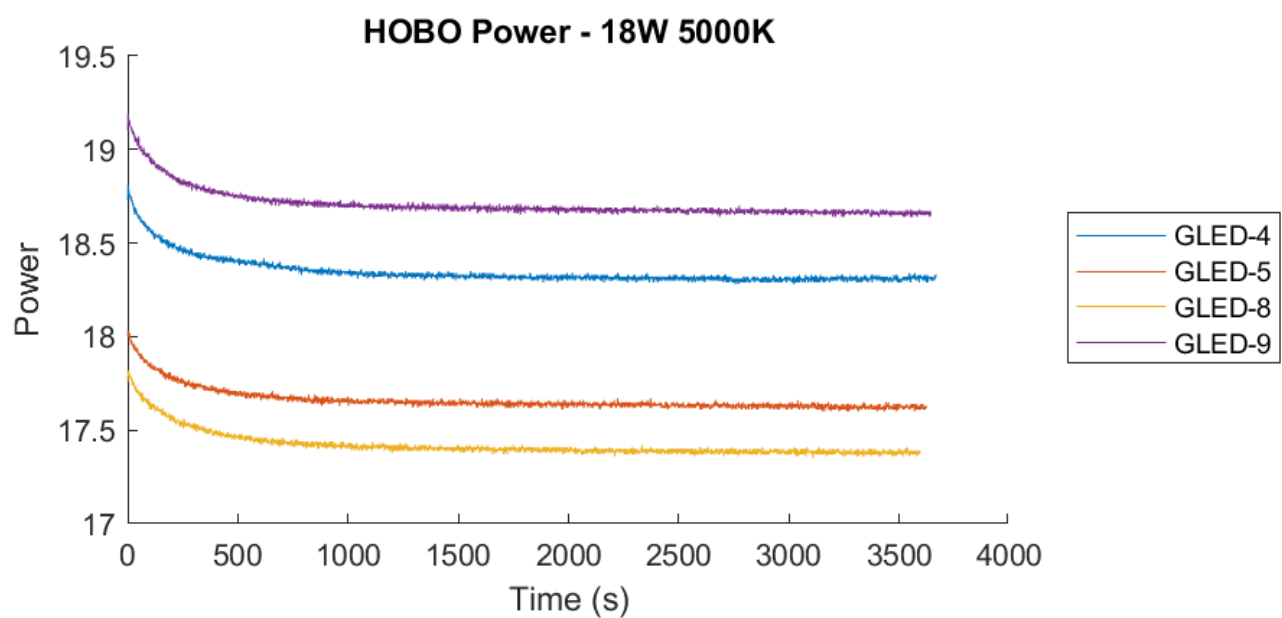


Appendix Figure 110. TES2 Group D GTLED PCB Temperature.

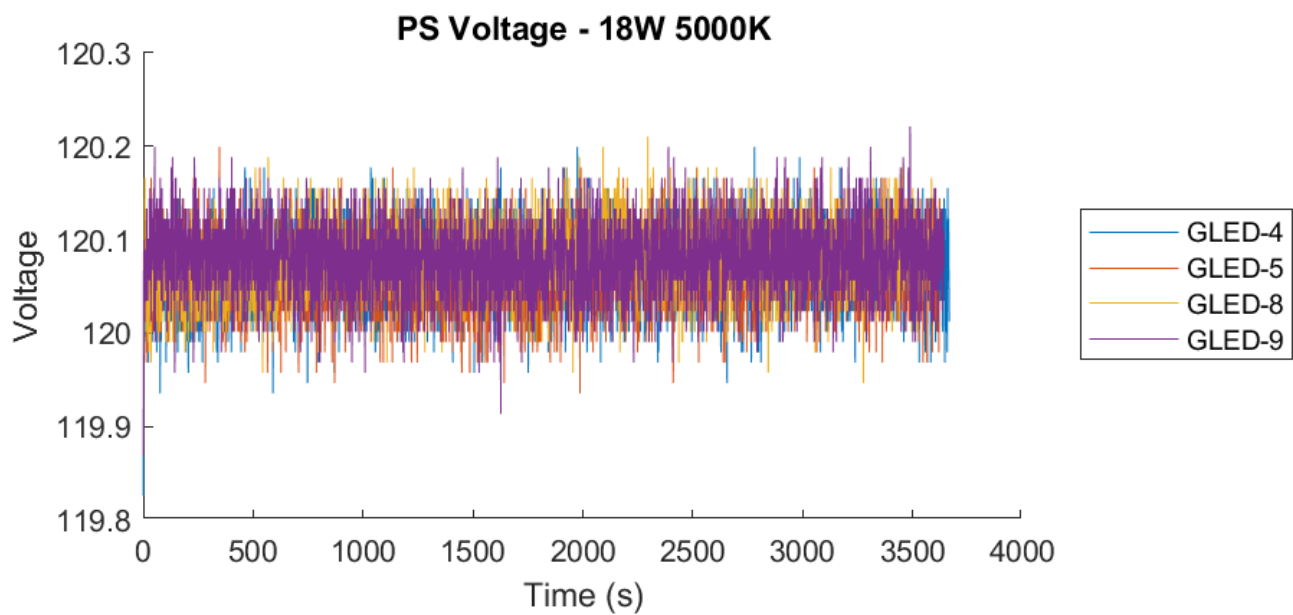
#### B-5.4 GTLED-TES2 Group D Electrical



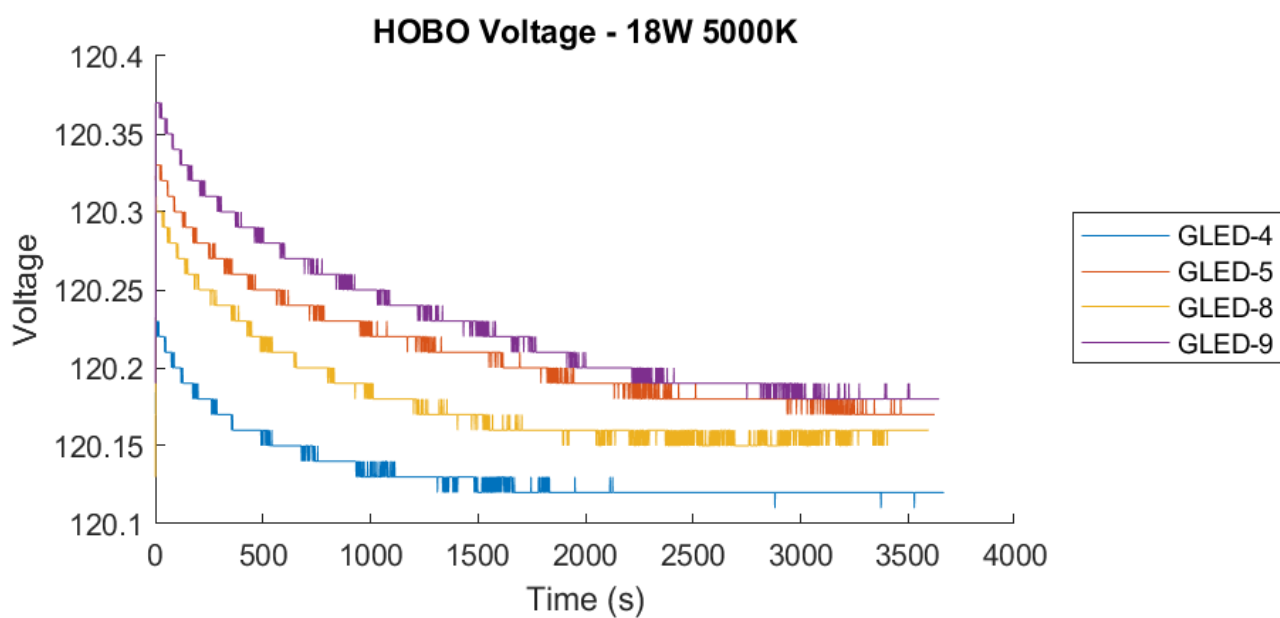
Appendix Figure 111. TES2 Group D PS Power.



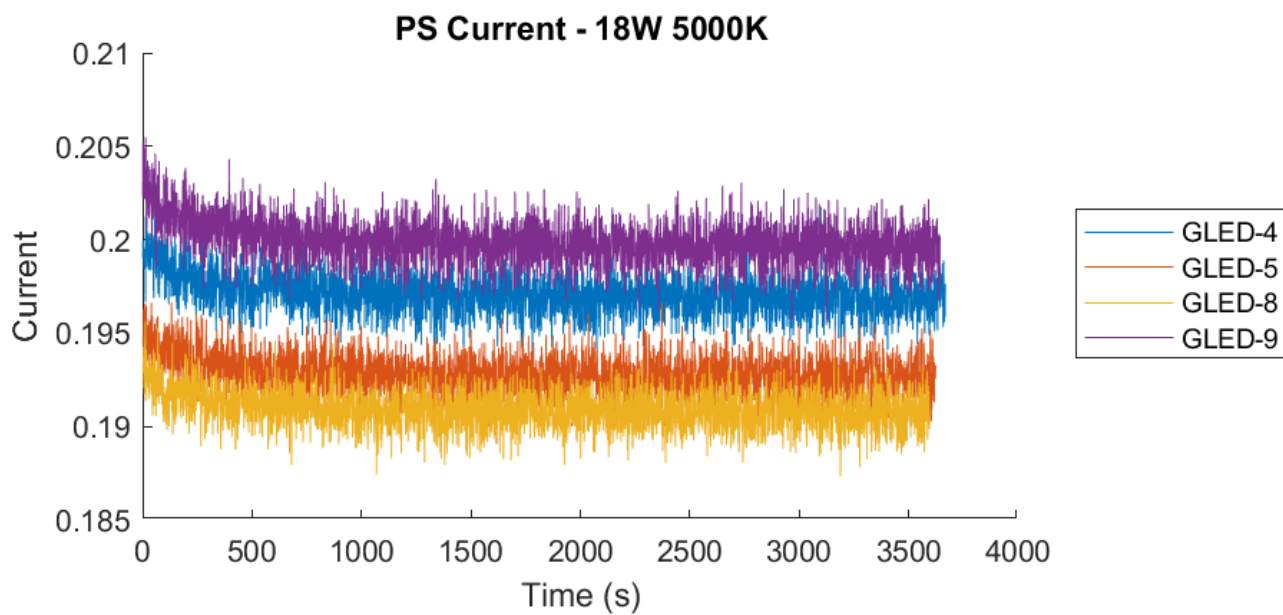
Appendix Figure 112. TES2 Group D HOBO Power.



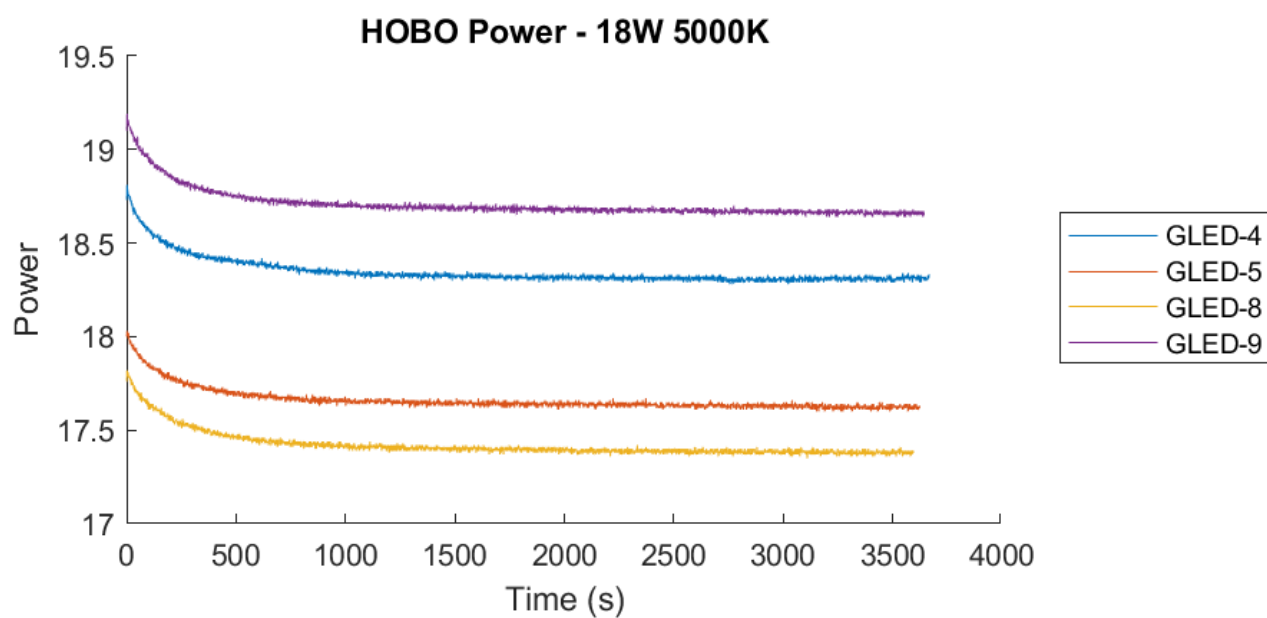
Appendix Figure 113. TES2 Group D PS Voltage.



Appendix Figure 114. TES2 Group D HOBO Voltage.



Appendix Figure 115. TES2 Group D PS Current.



Appendix Figure 116. TES2 Group D HOBO Currents.

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| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |                       |                                   | Form Approved<br>OMB No. 0704-01-0188           |                                           |
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| <b>1. REPORT DATE (DD-MM-YYYY)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    | <b>2. REPORT TYPE</b> |                                   | <b>3. DATES COVERED (From - To)</b>             |                                           |
| August 2023                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                    | Final                 |                                   |                                                 |                                           |
| <b>4. TITLE AND SUBTITLE</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |                       |                                   | <b>5a. CONTRACT NUMBER</b>                      |                                           |
| An Evaluation of Commercial Graphene Solid State Lighting                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |                       |                                   | <b>5b. GRANT NUMBER</b>                         |                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |                       |                                   | <b>5c. PROGRAM ELEMENT NUMBER</b>               |                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |                       |                                   | <b>5d. PROJECT NUMBER</b>                       |                                           |
| <b>6. AUTHORS</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                    |                       |                                   | <b>5e. TASK NUMBER</b>                          |                                           |
| <div style="display: flex; justify-content: space-between;"> <div> Richard C. Ordonez, PhD<br/> Cody K. Hayashi<br/> Lewis Hsu, PhD<br/> Christopher I. Aguilar<br/> <b>NIWC Pacific</b> </div> <div> Keith Graeber<br/> Tristan Bond<br/> Manuel Lopez<br/> <b>California Lighting Technology Center</b> </div> </div>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |                       |                                   | <b>5f. WORK UNIT NUMBER</b>                     |                                           |
| <b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |                       |                                   | <b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> |                                           |
| NIWC Pacific<br>53560 Hull Street<br>San Diego, CA 92152-5001                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                    |                       |                                   | TR-3317                                         |                                           |
| <b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |                       |                                   | <b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>         |                                           |
| ONR Next Strategic Evaluation Program<br>53560 Hull Street<br>San Diego, CA 92152-5001                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                    |                       |                                   | ONR NextSTEP                                    |                                           |
| <b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |                       |                                   | <b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>   |                                           |
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| <b>13. SUPPLEMENTARY NOTES</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |                       |                                   |                                                 |                                           |
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| <b>14. ABSTRACT</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                    |                       |                                   |                                                 |                                           |
| <p>We provide an independent technical assessment of photometric, electrical, and thermal performance of commercially available graphene solid state lighting (SSL) for potential use in the DON environment. It has been found that coating the Light-Emitting Diode (LED) filaments of commercial style LED lighting products with graphene dissipates heat more efficiently. The results are potentially a longer-lasting (&gt;60,000hrs), brighter, low power SSL technology that operates at cooler temperatures and is ~10% more efficient compared to non-graphene SSL packages. Replacing SSL systems across our warfighting centers with cooler graphene enhanced SSL has the potential to drastically reduce HVAC cost by the means of reducing the amount of heat required to be removed by our current AC cooling systems. Furthermore, the longer lifetimes of graphene enhanced SSL technology may cut maintenance and procurement cost of existing lighting contracts because facilities will not have to procure as much. Results are provided for graphene enhanced A19 and tube LED lamps that were commercially available on the market at the time of this study and we conclude with our recommendations for potential DON adoption.</p> |                    |                       |                                   |                                                 |                                           |
| <b>15. SUBJECT TERMS</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                    |                       |                                   |                                                 |                                           |
| Graphene, Graphene Lighting, Solid State Lighting                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                    |                       |                                   |                                                 |                                           |
| <b>16. SECURITY CLASSIFICATION OF:</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                    |                       | <b>17. LIMITATION OF ABSTRACT</b> |                                                 | <b>18. NUMBER OF PAGES</b>                |
| <b>a. REPORT</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <b>b. ABSTRACT</b> | <b>c. THIS PAGE</b>   |                                   |                                                 | 19a. NAME OF RESPONSIBLE PERSON           |
| U                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | U                  | U                     | SAR                               |                                                 | Richard C. Ordonez                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |                       |                                   |                                                 | 19b. TELEPHONE NUMBER (Include area code) |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |                       |                                   |                                                 | (808)-349-1459                            |

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