Range and Probabilities of LED Junction Temperature Predictions Based Upon Forward Voltage Population Statistics

James Petroski
Mentor Graphics Corporation
8005 SW Boeckman Road
Wilsonville, Oregon, USA
Jim_Petroski@Mentor.com

Abstract

In recent years, the use of the electrical test method (ETM) has become more common to measure the temperature of semiconductor junctions. This method makes use of correlating the relationship of the semiconductor forward voltage to the temperature of the device, which is often linear but is always a unique correlation. This method has been recognized by JEDEC, and in particular for LEDs in 2012 when standards were issued (JESD 51–50 through 53).

The device under test (DUT) must be calibrated, or the Vf-Tj relationship must be determined to use this method. This is a straightforward method, and after completion the DUT may be used in an assembly to fully characterize a system's thermal performance.

However, one issue that may occur is that of an assembly where the DUT may not be easily removed for calibration or, where for various reasons, it is not desired to do so. Without having the DUT calibrated, the unanswered questions are how one may find the junction temperature of the device and to what uncertainty, if at all. This paper attempts to answer these questions for a sample LED population and make some generalizations through the use of population statistics and voltage bins of LEDs.

Two voltage bins of LEDs were obtained from a major LED manufacturer, each populated with 15 LEDs. The LEDs were mounted on small metal core printed circuit boards (MCPCBs) and first calibrated individually. Per the ETM, the calibrations were conducted with low input currents (5 mA); this was significantly lower than the normal current used for Vf bin determination and became significant in the statistical analysis. The results show that when an LED population has a Vf spread of under 0.06 VDC at the 5 mA forward current, the Tj of the LEDs is known to a 12 °C band with 95% confidence and 7 °C with 75% confidence. A tighter bin spread less than 0.035 VDC provides lower bands of 8 °C and 5 °C with 95% and 75% confidence, respectively. The Vf spread at 5 mA drive current is the key factor in determining how close the Tj may be known with reasonable confidence.

Keywords

Light emitting diodes, LED, forward voltage, electrical test method, junction temperature, statistical confidence, hypergeometric distribution

Nomenclature

Vf: forward voltage
Tj: junction temperature
P: probability mass function, or PMF
k_i: LED sub-bins
c: number of different LEDs
m_i: number of LEDs in sub-bin k_i
N: total number of LEDs

1. Background

As light emitting diodes (LEDs) continue to be adopted in many lighting categories, manufacturers of bulbs and luminaires must continue to design for best performance and minimum cost to meet market requirements and gain customer acceptance. While some light sources are sold without any assurance of meeting high standards, many manufacturers have adopted industry and government standards to ensure their customers that the bulb or luminaire is tested to or meets performance or quality goals. Examples of these are the IES standard LM-79, "*Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*", and the US government ENERGY STAR program for light bulbs, "*ENERGY STAR® Program Requirements Product Specification for Lamps (Light Bulbs)*".

Manufacturers tailor the designs to control the LED junction temperature (*Tj*) at appropriate levels to help control light output, light variations, and overall reliability. In doing so, a method must be used to measure *Tj* of the LEDs within the lamp or luminaire. Some standard temperature measurement methods have been used to infer *Tj* (such as measuring the underlying printed circuit board (PCB) temperature or using a thin thermocouple to measure a point on the LED package, but such methods have inherent weaknesses and uncertainties. From these issues, the electrical test method (ETM) came into significant use within the lighting industry, especially with the development of the JEDEC standards for these measurements [1].

The ETM is a method that correlates the forward voltage of the LED, a temperature sensitive parameter (TSP), to the actual junction temperature. This relationship is frequently linear but some devices may exhibit curvature in the function. By heat soaking an LED or LED assembly at appropriate temperatures, the forward voltage may be measured with a small sensing current to find this correlation.

However, the one requirement that may not be easy under some circumstances is characterizing the LEDs in a given assembly. LEDs are mounted to PCBs or, in some rare instances, to a circuit printed on a structural member. It may not be easy or desired to remove the LED PCB assembly from the lamp/luminaire assembly and perform the characterization test. The construction of the Cree LED lamp in Figure 1 is an example. Removing a single board from this assembly would be fairly involved because it is an integrated assembly. Some integrated luminaires have a similar problem where removing an LED PCB assembly requires extensive tear down and perhaps permanent damage to the assembly if the PCB is removed (e.g., it is secured via permanent adhesive to the fixture).

Figure 1: Integrated lamp assembly.

The issue leads to whether there is a method that might be suitable for finding *Tj* via the ETM, but without having to characterize the internal board. Given that LEDs are chosen from bins and put onto PCBs, it is worthwhile to investigate if selecting LEDs from those bins could provide a characterization that is close enough for *Tj* determination, and at what limits and confidence level.

2. Method

A suitable plan for using alternate LEDs to characterize a system was developed. First, the bins used to create the LED PCBs in the original assembly are to be used as a source for the alternate LEDs. It is best if these are from the same purchase and lot as before because distributions within a lot may be different for different shipments. Second, the alternate LEDs must be characterized so that each *Vf* corresponds to a temperature. Finally, the LEDs in the lamp or luminaire are then tested, and the *Vf* found from this test is converted to a temperature from the alternate LED characterization.

In this study, two bins of a mid-power LED were supplied by a major LED manufacturer [2]— white LEDs in a 3030 package, operating nominally at 6 V and 120 mA. Fifteen LEDs from each bin were characterized for *Vf* at 25 °C and 120 mA. The two bins were next to each other in the manufacturer's bin measurements (Bin G, at 5.8 to 6.0 V nominal, and Bin H, at 6.0 to 6.2 V nominal). The manufacturer's datasheet also showed a tolerance on the bin voltages of ±0.1 V, so each bin had a maximum range of 0.4 V and overlapped 50% into each bin on either side.

The LEDs were supplied by the manufacturer mounted individually to aluminum metal clad PCBs (MCPCBs). Lead wires were then soldered to each MCPCB (see Figure 2). Each LED was supplied with a unique serial number identifier, and this was used to track each LED individually for use in test matrix creation.

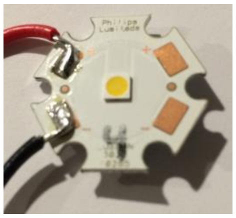


Figure 2: Typical test LED.

A configuration of four LEDs in series was used as the basis of the test to create a realistic test for this sample size. This would simulate a PCB with four LEDs soldered in series on the board and would be the item of interest in a luminaire or lamp. Because each LED produces approximately 80–100 lumens at rated current and 85 °C, four LEDs simulate a light output a bit below a conventional 40 W incandescent lamp. Sixteen LEDs in a luminaire would produce the light output near a 100 W incandescent lamp, so using four LEDs is similar to choosing one PCB with one-quarter of the LEDs in a typical indoor light.

With this test configuration, a series of tests was set up for testing the hypothesis that choosing four alternate LEDs could work for predicting the *Tj* of an unknown PCB in a luminaire. First, the *Vf* characteristics of each LED must be found so the characteristics of the population are known. The LED manufacturer already supplied the *Vf* rating for 120 mA, so a similar test must be performed for low sense currents (for this test, 5 mA was used). The thermal characterization using the ETM was tested from 25 to 75 °C in 10 °C increments. This allows the key parameters of *Vf* at 5mA to be found at various temperatures, along with the sensitivity or "k-factor" of the LED (the slope of the *Vf* curve at 5 mA versus temperature, and measured in mV/K). From these tests, the LEDs were sufficiently characterized for statistical analysis.

Furthermore, tests of strings of four LEDs were conducted. For this case, the LEDs were mounted on a cold plate and connected in series (Figure 3). The cold plate temperature was controlled by a commercially available cryo-chiller using water as the working fluid. In these tests, the LED string *Vf* was measured at 5 mA of current to allow comparisons and predictions.

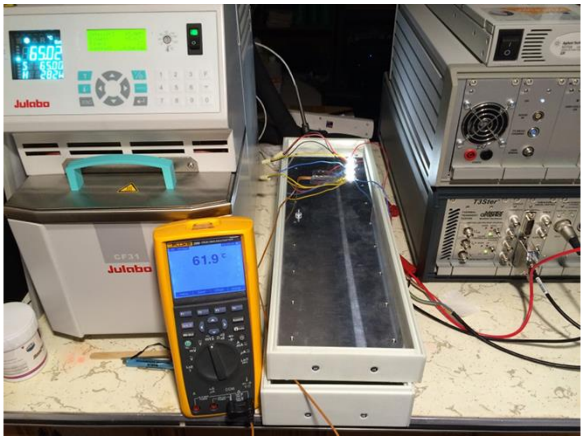
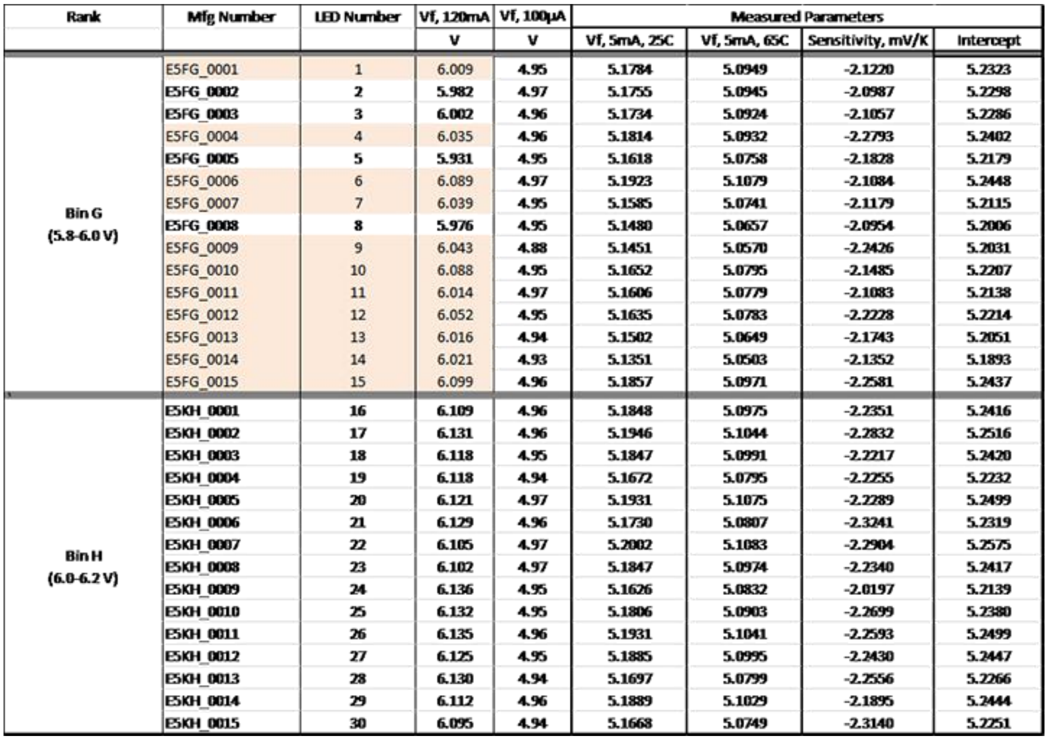


Figure 3: Cold-plate test setup.

The tests were conducted using the Mentor Graphics T3Ster measurement system. This commercially available system allows the ETM tests to be automated and collects the necessary data.



Rank	Mfg Number	LED Number	Vf, 120mA	Vf, 100µA	Measured Parameters			
			V	V	Vf, 5mA, 25C	Vf, 5mA, 65C	Sensitivity, mV/K	Intercept
Bin G (5.8-6.0 V)	E5FG_0001	1	6.009	4.95	5.1784	5.0949	-2.1220	5.2323
	E5FG_0002	2	5.982	4.97	5.1755	5.0945	-2.0987	5.2298
	E5FG_0003	3	6.002	4.96	5.1734	5.0924	-2.1057	5.2286
	E5FG_0004	4	6.035	4.96	5.1814	5.0932	-2.2793	5.2402
	E5FG_0005	5	5.931	4.95	5.1618	5.0758	-2.1828	5.2179
	E5FG_0006	6	6.089	4.97	5.1923	5.1079	-2.1084	5.2448
	E5FG_0007	7	6.039	4.95	5.1585	5.0741	-2.1179	5.2115
	E5FG_0008	8	5.976	4.95	5.1480	5.0657	-2.0954	5.2006
	E5FG_0009	9	6.043	4.88	5.1451	5.0570	-2.2426	5.2031
	E5FG_0010	10	6.088	4.95	5.1652	5.0795	-2.1485	5.2207
	E5FG_0011	11	6.014	4.97	5.1606	5.0779	-2.1083	5.2138
	E5FG_0012	12	6.052	4.95	5.1635	5.0783	-2.2228	5.2214
	E5FG_0013	13	6.016	4.94	5.1502	5.0649	-2.1743	5.2051
	E5FG_0014	14	6.021	4.93	5.1351	5.0503	-2.1352	5.1893
	E5FG_0015	15	6.099	4.96	5.1857	5.0971	-2.2581	5.2437
Bin H (6.0-6.2 V)	E5KH_0001	16	6.109	4.96	5.1848	5.0975	-2.2351	5.2416
	E5KH_0002	17	6.131	4.96	5.1946	5.1044	-2.2832	5.2516
	E5KH_0003	18	6.118	4.95	5.1847	5.0991	-2.2217	5.2420
	E5KH_0004	19	6.118	4.94	5.1672	5.0795	-2.2255	5.2232
	E5KH_0005	20	6.121	4.97	5.1931	5.1075	-2.2289	5.2499
	E5KH_0006	21	6.129	4.96	5.1730	5.0807	-2.3241	5.2319
	E5KH_0007	22	6.105	4.97	5.2002	5.1083	-2.2904	5.2575
	E5KH_0008	23	6.102	4.97	5.1847	5.0974	-2.2340	5.2417
	E5KH_0009	24	6.136	4.95	5.1626	5.0832	-2.0197	5.2139
	E5KH_0010	25	6.132	4.95	5.1806	5.0903	-2.2699	5.2380
	E5KH_0011	26	6.135	4.96	5.1931	5.1041	-2.2593	5.2499
	E5KH_0012	27	6.125	4.95	5.1885	5.0995	-2.2430	5.2447
	E5KH_0013	28	6.130	4.94	5.1697	5.0799	-2.2556	5.2266
	E5KH_0014	29	6.112	4.96	5.1889	5.1029	-2.1895	5.2444
	E5KH_0015	30	6.095	4.94	5.1668	5.0749	-2.3140	5.2251

Figure 4: Base LED data.

The key to understanding if testing an alternate group of LEDs from the same bin(s) is suitable is found using a statistical approach to analyzing the data. There are different scenarios which could be used, but in this study the assumption of a fixed bin population was made. Because several combinations of four LEDs can be drawn from such a bin, resulting in various forward voltages for the LED string, a statistical method to determine probabilities of each possible *Vf* must be used.

The statistical method when members from two categories are drawn from a population is the hypergeometric distribution, and the method is for finding probabilities of a distribution when the elements are picked without replacement (suitable for a fixed population). The more generalized case, called the generalized or multivariate hypergeometric distribution, is used for drawing from several (more than two) selections in a population, again without replacement [3, 4].

The general formula of the probability mass function (PMF) for a multivariate hypergeometric distribution is given as [3]:

$$\left(P(k_1,k_2,\ldots,k_c\right) = \frac{\prod_i^c \binom{m_i}{k_i}}{\binom{N}{n}}$$

Here, *P* is the probability of the LED combination occurring. The number of different LEDs is *c*, and m_i is the number of LEDs in sub-bin *i*, and *n* is number of LEDs chosen. The LED sub-bins are *k*. *N* is the total number of LEDs and defined by

$$N = \sum_{n=1}^{c} m_i$$

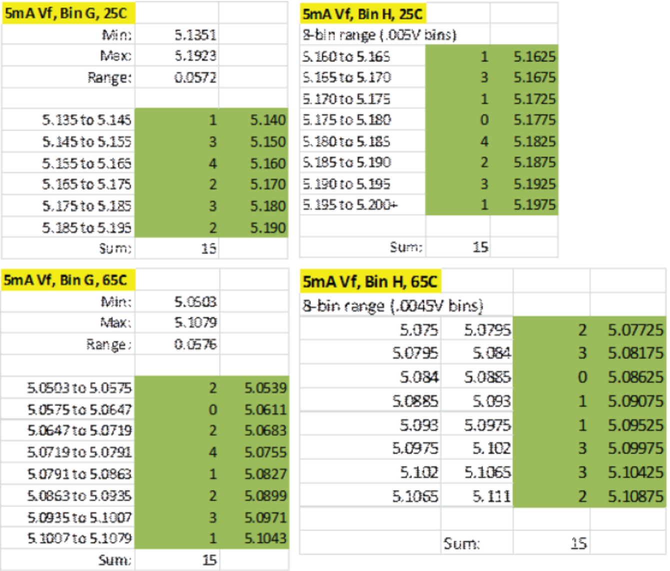
There are various ways to easily solve this, including specialized functions in some available programs such as the statistical program Mini-Tab or general math programs such as Mathematica. For this paper, a simple program was written in the program Mathcad to solve for the matrix of all LED combinations and the corresponding probabilities. This data was then copied into a spreadsheet for final analysis and results plotting.

The LED sub-bins are created by obtaining the 5 mA *Vf* for each LED and then looking at this population and creating a new group of sub-bins for each overall bin G and H. In general, the *Vf* distribution at full rated current (120 mA) will not be the same compared to the smaller 5 mA sense *Vf* distribution. Not only are the voltages quite different (approximately 6 V versus 5.2 V), but the higher *Vf* at full rated current may not be a higher *Vf* at the lower 5 mA current.

Two *Tj* values were evaluated in this work. The PMF for various LED groups was found for *Tj* of 25 °C and 65 °C. From these PMF graphs, the confidence factor and temperature range expected from testing alternate LEDs are found.

3. Results

The LEDs of bins G and H were each individually characterized using the T3Ster system and the automated calibration unit, which is a thermoelectric cooler (TEC) based system for characterization of small and low power LEDs (under 5 W). Of interest is that the LEDs supplied by the manufacturer had two different population characteristics; bin G was more scattered, and the rated current *Vf* was above the nominal band for 11 of the 15 LEDs (but within the 0.1 V tolerance). Bin H was much tighter and fit within half the bin range allotted to it. Figure 4 shows the base data collected.



5mA Vf, Bin G, 25C		
Min:	5.1351	
Max:	5.1923	
Range:	0.0572	
5.135 to 5.145	1	5.140
5.145 to 5.155	3	5.150
5.155 to 5.165	4	5.160
5.165 to 5.175	2	5.170
5.175 to 5.185	3	5.180
5.185 to 5.195	2	5.190
Sum:	15	

5mA Vf, Bin H, 25C		
8-bin range (.005V bins)		
5.160 to 5.165	1	5.1625
5.165 to 5.170	3	5.1675
5.170 to 5.175	1	5.1725
5.175 to 5.180	0	5.1775
5.180 to 5.185	4	5.1825
5.185 to 5.190	2	5.1875
5.190 to 5.195	3	5.1925
5.195 to 5.200+	1	5.1975
Sum:	15	

5mA Vf, Bin G, 65C		
Min:	5.0503	
Max:	5.1079	
Range:	0.0576	
5.0503 to 5.0575	2	5.0539
5.0575 to 5.0647	0	5.0611
5.0647 to 5.0719	2	5.0683
5.0719 to 5.0791	4	5.0755
5.0791 to 5.0863	1	5.0827
5.0863 to 5.0935	2	5.0899
5.0935 to 5.1007	3	5.0971
5.1007 to 5.1079	1	5.1043
Sum:	15	

5mA Vf, Bin H, 65C			
8-bin range (.0045V bins)			
5.075	5.0795	2	5.07725
5.0795	5.084	3	5.08175
5.084	5.0885	0	5.08625
5.0885	5.093	1	5.09075
5.093	5.0975	1	5.09525
5.0975	5.102	3	5.09975
5.102	5.1065	3	5.10425
5.1065	5.111	2	5.10875
	Sum:	15	

Figure 5: 5mA *Vf* sub-bins.

The following sub-bins were created after sorting the 5 mA Vf for each G and H bin.

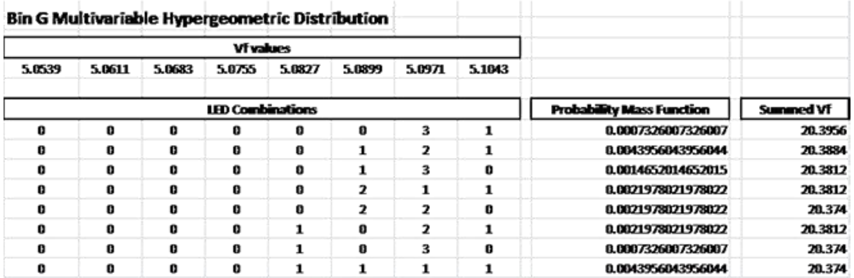
six to eight sub-bins and that the bins change between the 25 °C and 65 °C condition (since Vf changes as temperature changes).

From this data, all the combinations of four LEDs is found using the multivariate hypergeometric distribution and the subsequent forward voltage at 5 mA for the four LED string. Figure 6 shows a portion of the distribution table for bin G at 65 °C.

From this, each summed Vf is then totaled across the distribution; Figure 7 shows this again for bin G at 65 °C, and Figure 8 shows the plot of this distribution.

This type of analysis was done for each bin (G and H) at the 25 °C and 65 °C temperatures.

Finally, using the PMF distribution plots and the overall sensitivity of the LED sets of four LEDs, one can find the temperature ranges and the confidence levels for those predictions.

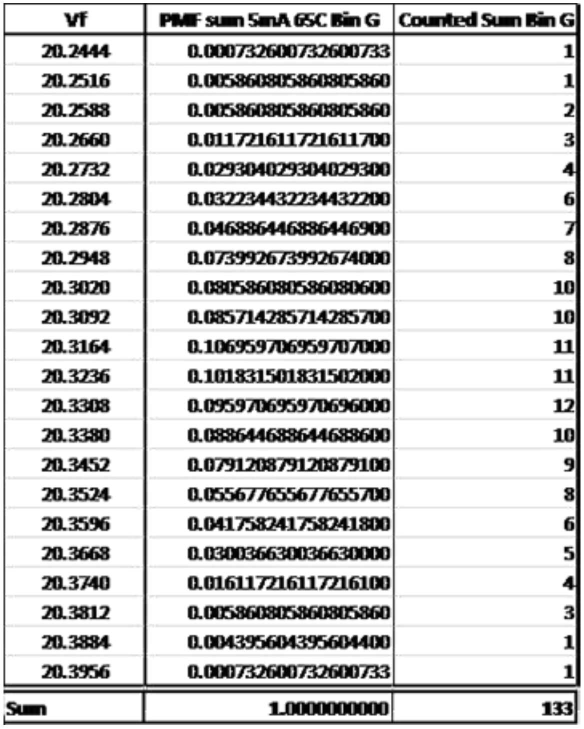


Bin G Multivariable Hypergeometric Distribution

Vf values									
5.0539	5.0611	5.0683	5.0755	5.0827	5.0899	5.0971	5.1043		
LED Combinations								Probability Mass Function	Summed Vf
0	0	0	0	0	0	3	1	0.0007326007326007	20.3956
0	0	0	0	0	1	2	1	0.0043956043956044	20.3884
0	0	0	0	0	1	3	0	0.0014652014652015	20.3812
0	0	0	0	0	2	1	1	0.0021978021978022	20.3812
0	0	0	0	0	2	2	0	0.0021978021978022	20.374
0	0	0	0	1	0	2	1	0.0021978021978022	20.3812
0	0	0	0	1	0	3	0	0.0007326007326007	20.374
0	0	0	0	1	1	1	1	0.0043956043956044	20.374

Figure 6: Portion of Bin G distribution table.

Figure 7: PMF distribution Bin G 65 °C.



Vf	PMF sum 5mA 65C Bin G	Counted Sum Bin G
20.2444	0.000732600732600733	1
20.2516	0.005860805860805860	1
20.2588	0.005860805860805860	2
20.2660	0.011721611721611700	3
20.2732	0.029304029304029300	4
20.2804	0.032234432234432200	6
20.2876	0.046886446886446900	7
20.2948	0.073992673992674000	8
20.3020	0.080586080586080600	10
20.3092	0.085714285714285700	10
20.3164	0.106959706959707000	11
20.3236	0.101831501831502000	11
20.3308	0.095970695970696000	12
20.3380	0.088644688644688600	10
20.3452	0.079120879120879100	9
20.3524	0.055677655677655700	8
20.3596	0.041758241758241800	6
20.3668	0.030036630036630000	5
20.3740	0.016117216117216100	4
20.3812	0.005860805860805860	3
20.3884	0.004395604395604400	1
20.3956	0.000732600732600733	1
Sum	1.0000000000	133

Across the bar plot in Figure 8, one can find a voltage range, and summing the probabilities of those bars gives the total probability of that range occurring. Dividing that voltage range by the sensitivity of the LED set corresponds to a temperature range with that confidence level. Thus, one can find the predictability or temperature uncertainty from using an alternate set of LEDs. Figures 9 through 12 show the results for both bins at both temperatures, with the 95% and 75% confidence levels plotted.

4. Conclusions

Based on the results of Figures 9 through 12, one can see that for a 95% confidence factor, the temperature bands are quite high, especially for bin G. This is explained by the *Vf* range for the LEDs being tested.

In Figure 4, the *Vf* range for bin G in the 5 mA current is 0.0572 V and 0.0576 V at 25 °C and 65 °C, respectively. This is a large variation and leads to a wide voltage variation across the PMF.

For bin G, the 95% confidence level voltage spread is approximately 0.10 V. When this is compared to the LED set sensitivity, which varies from -8.5 to -8.75 mV/K, this results in nearly a 12 °C band.

Similarly, bin H is tighter and the 95% voltage range is from 0.070 to 0.075 V. This causes a smaller temperature range for the 95% and 75% confidence levels of approximately 8 °C and 5 °C, respectively.

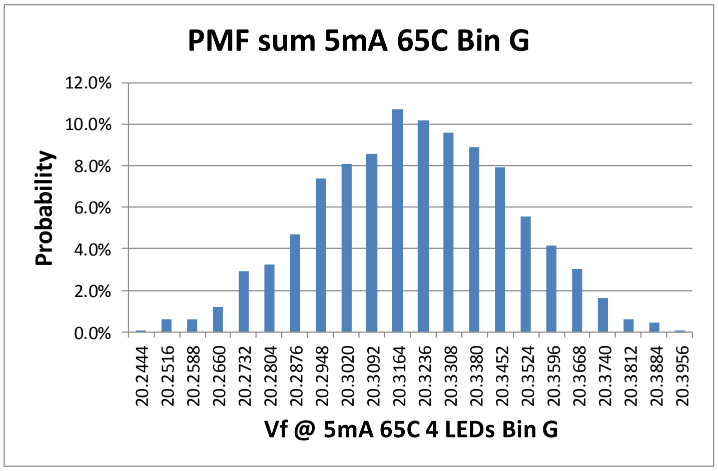


Figure 8: PMF distribution plot.

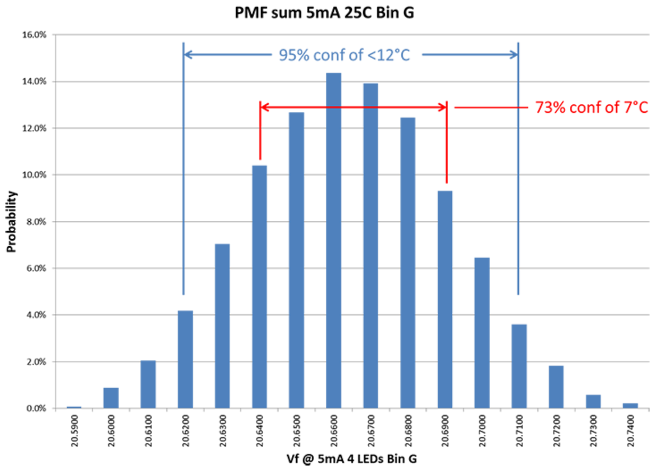


Figure 9:

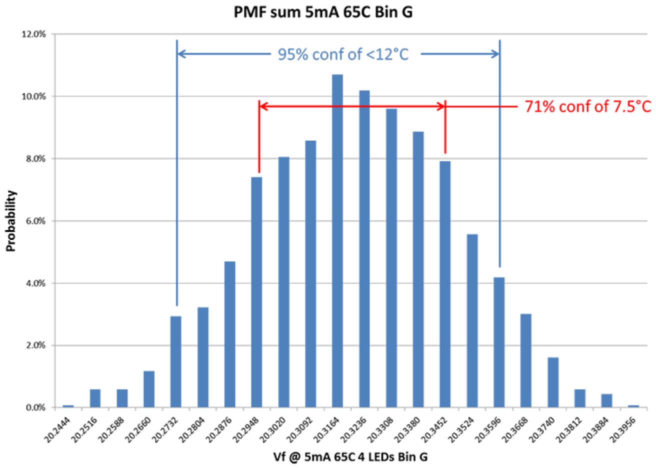


Figure 10:

The question that results from this is what type of LED *Vf* distribution would one need to see to have a reasonable assurance of close temperature predictions using alternate LEDs. From this study, and a previous unpublished study made by the author, the key is *Vf* band at 5 mA versus the LED sensitivity. For typical LEDs with a sensitivity of -2 to -2.5 mV/K, a *Vf* range of 0.025 V at 5mA will produce acceptable results of 3–4 °C temperature bands for 95% confidence levels. If the LED sensitivities are larger, the *Vf* range can be proportionately larger. However, a *Vf* range of 0.035 V (bin H) is probably the limit of acceptability, as the 95% confidence level is now quite high (8–9 °C) though the 75% band is better around 5 °C. And at the 0.05–0.06 V *Vf* range, the results are rather poor with temperature bands approaching 12 °C for the 95% confidence level.

Acknowledgments

The author wishes to thank Philips Lumileds Lighting for supplying the LEDs mounted on MCPCBs used in this study.

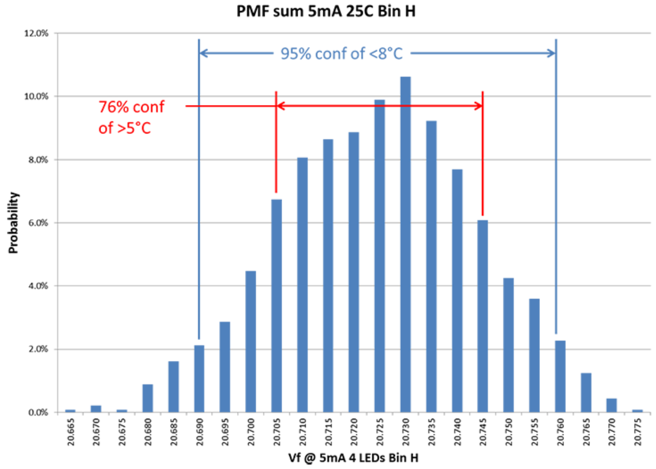


Figure 11:

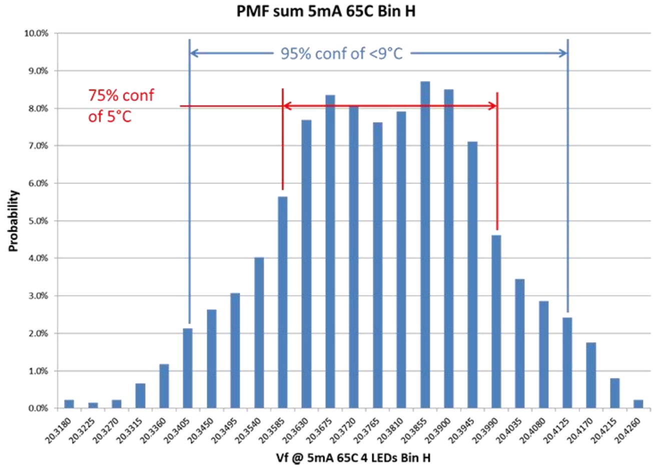


Figure 12:

References

1. JESD 51-50 through 53, Joint Electron Device Engineering Council (JEDEC), http://www.jedec.org/
2. Luxeon 3030 2D LEDs supplied by Philips Lumileds. Datasheet DS207, version 20140706.

3. Walck, Christian, Handbook on Statistical Distributions for Experimentalists, Internal Report SUF–PFY/96–01, University of Stockholm, revised 10 Sept 2007, http://www.fysik.su.se/~walck/suf9601.pdf, retrieved 16 Dec 2014, pp 79–80.
4. Weisstein, Eric W. “Hypergeometric Distribution,” From MathWorld—A Wolfram Web Resource. http://mathworld.wolfram.com/HypergeometricDistribution.html, retrieved 17 Dec 2014.