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Research Note #6

Assessing the Performance of LED-Based Flashlights Available in the Kenyan Off-Grid Lighting Market

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[1] *The Lumina Project* includes an Off-Grid Lighting Technology Assessment activity to provide manufacturers, re-sellers, program managers, and policymakers with information to help ensure the delivery of products that maximize consumer acceptance and the market success of off-grid lighting solutions for the developing world. Periodic *Research Notes* present new results in a timely fashion between the issuance of more formal and lengthy reports. Our results should not be construed as product endorsements by the authors. For a full archive of *Research Notes* and *Technical Reports* see: http://light.lbl.gov/technology-assessment.html

Abstract

Low cost rechargeable flashlights that use LED technology are increasingly available in African markets. While LED technology holds promise to provide affordable, high quality lighting services, the widespread dissemination of low quality products may make it difficult to realize this potential. This study includes performance results for three models of commonly available LED flashlights that were purchased in Kenya in 2009. Each model is made by a different manufacturer. The performance of the flashlights was evaluated by testing five units for each of the three models. The tests included measurements of battery capacity, time required to charge the battery, maximum illuminance at one meter, operation time and lux-hours from a fully charged battery, light distribution, and color rendering. All flashlights tested performed well below the manufacturers' rated specifications; the measured battery capacity was 30-50% lower than the rated capacity and the time required to fully charge the battery was 6-25% greater than the rated time requirement. Our analysis further shows that within each model there is considerable variability in each performance indicator. The five samples within a single model varied from each other by as much as 22% for battery capacity measurements, 3.6% for the number of hours required for a full charge, 23% for maximum initial lux, 38% for run time, 11% for light distribution and by as much as 200% for color rendering. Results obtained are useful for creating a framework for quality assurance of off-grid LED products and will be valuable for informing consumers, distributers and product manufacturers about product performance.

Introduction

Rechargeable flashlights that use light emitting diode (LED) technology are increasingly common in African markets. In some countries, in fact, LED flashlights have largely displaced incandescent flashlights in retail markets (e.g., see Johnstone, et al., 2009). While LED technology has the potential to provide high quality lighting services, the performance of many low cost LED flashlights appears to be very poor. A survey of flashlight users in Kenya, for example, indicates very high levels of dissatisfaction (Tracy, et al., 2009).

In this study, we present test results for three LED flashlight models purchased from retail markets in Kenya during January, 2009 (see Figures 1-6 for images of the products tested). Each model was made by a different manufacturer. The results from tests conducted in February and March, 2009 confirm that the flashlights perform below advertised levels according to several performance indicators. The results also allow for inter-model comparisons and they provide an estimate of the variability in performance between and within models.

These findings confirm the need for a quality assurance program that allows buyers to distinguish between low and high performance products so that they make informed purchasing decisions. In the absence of such a program, off-grid lighting markets in African countries are likely to remain dominated by low quality goods.

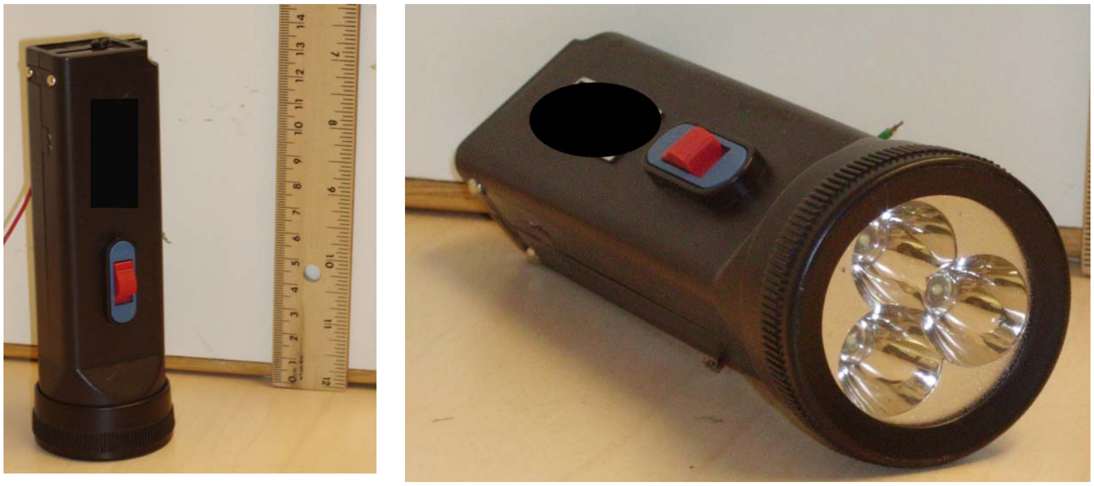

Figure 1-2. Flashlight A. Rechargeable 3 LED flashlight with a 1000 mAh rated battery.

Figure 3-4. Flashlight B. Rechargeable 4 LED flashlight with a 800 mAh rated battery.

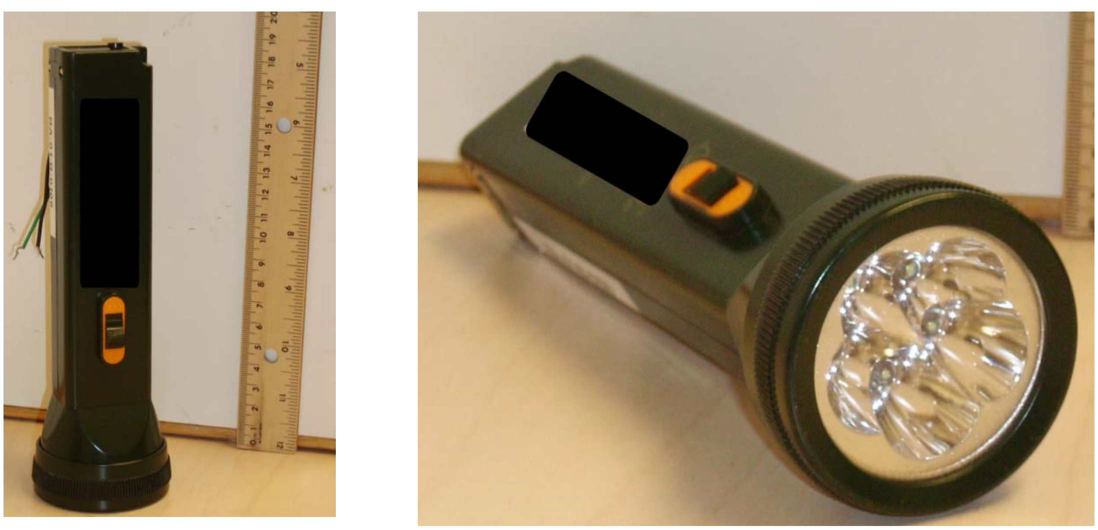

Figure 5-6. Flashlight C. Rechargeable 5 LED flashlight with a 1300 mAh rated battery.

Methodology

The three models of flashlights were tested at the Schatz Energy Research Center at Humboldt State University during an eight-week period in February and March of 2009. The sample size for each of the models tested was five, for a total of 15 flashlights tested. The performance indicators measured in the study included battery capacity, time required to charge the battery, maximum illuminance at one meter, operation time and lux-hours from a fully charged battery, light distribution, and color rendering.

Battery Capacity: The capacity of the batteries was measured using a Cadex 7200 series battery analyzer and the associated computer software program, Battery Shop. The results were reported in milli-ampere hours (mAh). During this test the batteries were isolated electrically from the rest of the system circuit. Measurements were made by discharging the battery at a constant current that corresponded to the 20 hour discharge rate as per the manufacturer's rated specification for battery capacity. The current and voltage pairs for each one minute time step were recorded by the Cadex' data logging system; each measurement had an accuracy of +/-1%. Prior to the battery discharge test, each of the batteries was fully charged using the Cadex C7200 analyzer at a 20-hour charge rate. After reaching a full charge each product also received a two to three hour trickle charge.

Time Required to Charge the Battery: A measurement of the time to fully charge the battery was carried out using the flashlight's internal charging system and 230 VAC, 50 Hz AC power (i.e., the type of power that corresponds to the Kenyan national grid). Because the laboratory where the tests were conducted is in the U.S., where the grid electricity is 120 VAC, 60 Hz, it was necessary to use an AC power supply to deliver the electricity for charging (Figure 7). The power supply consisted of a 230 VAC, 50 Hz true sine wave inverter that was connected to a 12 volt battery. The battery was charged from an external source in order to maintain a constant state of charge throughout the test. The charging tests were conducted after the lamp discharge tests described above. As a result, all were discharged to a state of charge that corresponded to light output corresponding to an illuminance of 5 lux at a distance of one meter in the dark box. The associated battery voltages upon completion of the lamp discharge and prior to the grid charge tests were on the order of 2.6 volts for the nominally four volt sealed lead acid batteries used in the flashlights. During the grid charge test, the current input to the battery was measured using a CR Magnetics DC Current Transducer (model 5210-2; accuracy +/-1.0%; output signal 0.5 VDC). Both the battery voltage and the voltage output from the current transducer were measured and recorded using a Hobo H08-006-04 data logger. The measurements were made at one minute intervals.

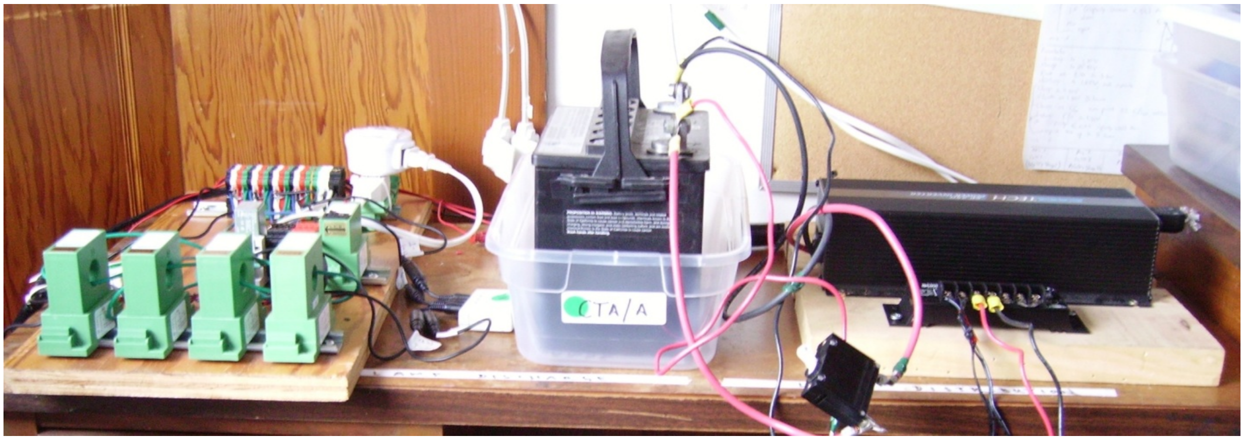

Figure 7. AC Power Supply for Grid Charging. 230V/50Hz pure sine wave inverter (far right), 6 V battery to power the inverter (middle), datalogging equipment (far left).

Lamp Discharge Test: A lamp discharge test was used to measure the initial maximum illuminance at one meter, the number of hours of light delivered from a fully charged battery (i.e., run time), and the number of lux-hours from a fully charged battery. For this test, the flashlight was mounted in a “dark box” at a distance of one meter from the illuminated surface. The dark box consists of a fully enclosed box approximately 122 cm (length) x 76 cm (width) x 76 cm (height) lined with black felt to eliminate reflection from the illuminance produced by the flashlight being tested. The box is designed with an illuminance meter mounted on one end and hardware mounted on the opposite end to hold the flashlight in place with a one-meter separation (Figures 8-9). During the test the current, voltage and illuminance at a distance of one meter were measured and data logged. The flashlight was determined to be “fully discharged” when the illuminance at one meter dropped below 5.0 lux. This number is based on field data collected in Kenya aimed at documenting people’s perceptions of when the light becomes too dim for use (Radecsky, 2009).

Figure 8. Dark Box used to perform the lamp discharge tests. Datalogging equipment on right-hand side of box.

Figure 9. Inside Dark Box. The mounting devices for the flashlight is located on the bottom end of the box, the illuminance meter is mounted on the opposite end and the datalogging equipment is mounted on the exterior of the box (right-hand side)

Illuminance, current from the battery to the light, and battery voltage were all measured at one-minute intervals during the discharge. Illuminance was measured with an Extech Datalogging Light Meter (model 401036). Current was measured with a CR Magnetics DC Current Transducer (model 5210-2; accuracy +/-1.0%; output signal 0.5 VDC). The battery voltage and the output signal from the current transducer were measured with a Hobo H08-006-04 Datalogger (8 bit resolution; accuracy +/-3% of reading). Prior to initiating the test, the battery received a full charge on the Cadex Battery Analyzer at a 20-hour charge rate.

Distribution of Light Output: The distribution of light output from the flashlights was measured at 10 cm intervals along horizontal and vertical axes from a center point on a flat plane that was located one meter from the flashlight. Five measurements were made in each of the four directions from the center point, for a total of 21 measurements per flashlight. Data were recorded using the Extech Datalogging

Light Meter (model 401036 [precision 0.01 Lux; accuracy +/-3% of reading]). Prior to testing, the flashlight battery was fully charged using the Cadex battery analyzer.

Color Rendering: The color rendering test involved measurement of the correlated color temperature (CCT) measured in degrees Kelvin. Higher color temperatures (5000 K or more) correspond to "cool" (green–blue) colors and lower color temperatures (2700–3000 K) correspond to "warm" (yellow–red) colors. Moderately cool-colored light is often considered better for visual tasks, while warm-colored light is preferred for indoor lighting. Color is ultimately a matter of end-user preference. Color rendering was measured in a "dark box" at a distance of one meter from the illuminated surface. The flashlight's correlated color temperature (CCT) and CIE 1931 (x, y) chromaticity diagram values were recorded using a Gigahertz-Optik HCT-99 Color Meter (Sampling rate: 1ms, Color uncertainty: <<1%% with CIE standard illuminant A[1]). When the CCT was above approximately 20,000 K, the color meter records only the x,y coordinate. In these instances an equation is used to determine the CCT based upon x and y CIE 1931 coordinates.[2] Prior to testing, the flashlight batteries were fully charged using the Cadex battery analyzer.

Data Analysis

Data were collected from five units each of three flashlight models, for a total of 15 flashlights.[3] The performance of the flashlights allowed for comparisons between rated specifications and measured values, comparisons between models, and estimates of the performance variability within each model. The variability among the five samples for each model was determined by calculating the coefficient of variation (CV) for each performance metric.

The variability in performance between flashlights from the three product lines (i.e., models) was assessed using one-way Analysis of Variance (ANOVA). When assessing the mean difference across models, the equal variance assumption was met in all cases except for color rendering.[4] In the case that violated the equal variance assumption, the Kruskal Wallis Nonparametric Analysis of Variance test was utilized.[5] In addition, because the color rendering data were not normally distributed, CCT values were first $\log_{10}$ transformed prior to performing the Kruskal Wallis test.

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[1] *CIE standard illuminant A* is intended to represent typical, domestic, tungsten-filament lighting. Its relative spectral power distribution is that of a Planckian radiator at a temperature of approximately 2,856 K. CIE standard illuminant A should be used in all applications of colorimetry involving the use of incandescent lighting, unless there are specific reasons for using a different illuminant (International, 1999).

[2] CCT x,y conversion equation, see Appendix A for definition of terms (Hernandez-Andres et al. 1999)

$$\mathbf{CCT = A_0 + A_1 \exp(-n/t_1) + A_2 \exp(-n/t_2) + A_3 \exp(-n/t_3)}$$

[3] However, during testing, one of the Flashlight A samples malfunctioned, and data for color rendering and grid-charge lux hours, run-time and initial maximum lux were not obtained. Also, one of Flashlight C samples malfunctioned prior to collecting color rendering, light distribution, and Cadex-charge lux hours, run-time and initial maximum illuminance at one meter.

[4] The ANOVA test assumes that each of the groups being compared has the same within group variance. An F-test was used to determine if this condition was met for each performance indicator. In cases where the condition was not met, a Kruskal Wallis test was used in place of the ANOVA test, as this alternate test does not require equal variances.

[5] The Kruskal Wallis Nonparametric Analysis of Variance test is a method for testing equality of population medians among groups. It is similar to a one-way ANOVA test; however, unlike the ANOVA test it does not require meeting the assumption of a normally distributed population. The Kruskal Wallis test does assume an identically-shaped and scaled distribution for each group, except for any difference in medians (Corder, 2009).

In all cases where the ANOVA tests were used, Tukey's pair-wise comparison[6] was utilized to further indicate which flashlights differed from one another and Bonferonni confidence intervals[7] were generated to illustrate the directionality of the pair-wise comparison.

To compare the performance of flashlights to advertised levels, a one-sample t-test was used to compare the sample data to a) the rated specification for battery capacity (mAh), and b) the number of charging hours required to receive maximum light output.

Results and Discussion

In this section, we present performance results from tests of the three flashlight models. A summary of the measured results and the associated within model variability is included in Table 1. The within-model variability for the seven key performance metrics included in the study, depicted here by the coefficient of variation (CV), ranged from minimal (<10%) to very high (>70%). The time required to attain a full charge had the least within-model variability, while color rendering had the most. A comparison of the levels of variability within each model reveals that the model C flashlight had the greatest levels of variability for most of the metrics, while model A frequently had the least.

Table 1. Mean, standard deviation, and coefficient of variation (CV) results for the three flashlight models for each of the performance metrics included in the study.

Performance Indicator	Flashlight A			Flashlight B			Flashlight C		
	Mean	Std. Dev	CV	**Mean**	Std. Dev	CV	**Mean**	Std. Dev	CV
Battery Capacity (mAh)	**692**	111	16.0%	**408**	53	13.1%	**664**	144	21.6%
Time to attain Full Charge (hours)[8]	**16.5**	0.4	2.1%	**12.8**	0.4	3.0%	**20.3**	0.7	3.6%
Max Initial Illuminance (lux)[9]	**313**	28	8.9%	**332**	77	23.1%	**516**	54	10.5%
Run-Time on a Fully Charged Battery (hours)[9]	**37**	7	19.6%	**20**	4	21.5%	**36**	14	37.7%
Lighting Service per Charge (lux hours) [9]	**2,242**	536	23.9%	**1,594**	571	35.8%	**3,241**	756	23.3%
Light Distribution (Area containing 90% of Total Lux (cm^2))[9]	**0.222**	0.018	8.1%	**0.161**	0.017	10.6%	**0.186**	0.012	6.5%
Color Rendering Index (degrees Kelvin)[9]	**>20,000**	NA	NA	**10,616**	4,311	40.6%	**14,167**	7,356	51.9%

[6] Tukey's test is a single-step multiple comparison procedure and statistical test generally used in conjunction with ANOVA to find which mean values are significantly different from the others (Linton, 2007).
[7] The Bonferroni method is a simple method that allows many comparison statements to be made (or confidence intervals to be constructed) while still assuring an overall confidence coefficient is maintained. This method applies to an ANOVA situation when the analyst has picked out a particular set of pair-wise comparisons or contrasts or linear combinations in advance (Engineering, 2003).
[8] Test performed after the flashlights received a full charge from the grid charge simulator.
[9] Test performed after the flashlight received a full charge from the Cadex batter Analyzer.

Across models, there was also a significant difference in the mean values for nearly all of the performance metrics ($p << 0.05$). The exception to this trend was in the case of color rendering ($p = 0.20$) (Table 2). Tukey's pair-wise comparison and Bonferonni confidence intervals were used to test whether the differences were statistically significant and also to confirm the directionality of those differences.

Table 2. Results for statistical tests to determine if there were verifiable differences in performance between flashlight models. One-way ANOVA was used to assess all differences except in the case of color rendering. For the color rendering comparison the equal-variance assumption was not met and therefore the Kruskal Wallis test was utilized. When the null hypothesis of equality was rejected for each of the metrics, Tukey's multiple comparison test was used to assess differences among pairs of models. The results of the multiple comparison tests are shown in the last column. Models are ordered from smallest to largest in sample mean, and the underline indicates no significant difference (A=Flashlight A, B=Flashlight B, C=Flashlight C).

Performance Indicator	F-statistic	P-value	Tukey's
Battery Capacity (mAh)	5.68	0.018	B $\underline{A\ C}$
Hours Required for Full Charge[10]	259.24	0.000	B A C
Max Initial Illuminance (lux)[11]	16.8	0.000	$\underline{B\ A}$ C
Run-Time on a Fully Charged Battery[11]	5.74	0.020	B $\underline{A\ C}$
Lighting Service per Charge (lux-Hours)[11]	7.98	0.007	$\underline{A\ B}$ C
Light Distribution: Area containing 90% of Total Lux [11]	34.43	0.000	A B C
Color Rendering[11]	--	0.200	$\underline{A\ B\ C}$

A comparison between the manufacturer's rated specifications and our group's measured values confirms that the flashlights did not perform as advertised with respect to *battery capacity* and the *time required for a full battery charge* ($p << 0.05$) (Table 3). Flashlight A performed 30% below its rated battery capacity (advertised at 1000 mAh) and both Flashlight B and Flashlight C performed 49% below their rated capacities (advertised at 800 mAh and 1300 mAh, respectively) (Figure 10). The *total time required for full a charge* varied minimally within each model. However, a comparison between the models indicates that Flashlight B took about 29% less time to charge than Flashlight A and about 41% less time than Flashlight C. Flashlight A took about 19% less time to fully charge than Flashlight C (Figure 11). In all cases, the measured time to charge was higher than the manufacturer's specifications at the 95% confidence level. It is important to note, though that in the case of Flashlights A and B the difference between advertised levels and measured values, while statistically significant, was modest.

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[10] Test performed after the flashlights received a fully charge from the grid charge simulator.

[11] Test performed after the flashlights received a fully charge from the Cadex battery analyzer.

Manufacturer's specifications were not available for the other performance indicators measured in the study.

Table 3. Results for statistical tests to determine if the measured performance for each model differed significantly from the manufacturer's advertised specifications for battery capacity and the time required for a full charge.

Performance Indicator	Model	T-statistic	P-value
Battery Capacity	Flashlight A	-6.2	0.003
	Flashlight B	-16.5	0.000
	Flashlight C	-9.9	0.001
Hours Required for a Full Charge	Flashlight A	9.6	0.001
	Flashlight B	4.5	0.011
	Flashlight C	15.9	0.000

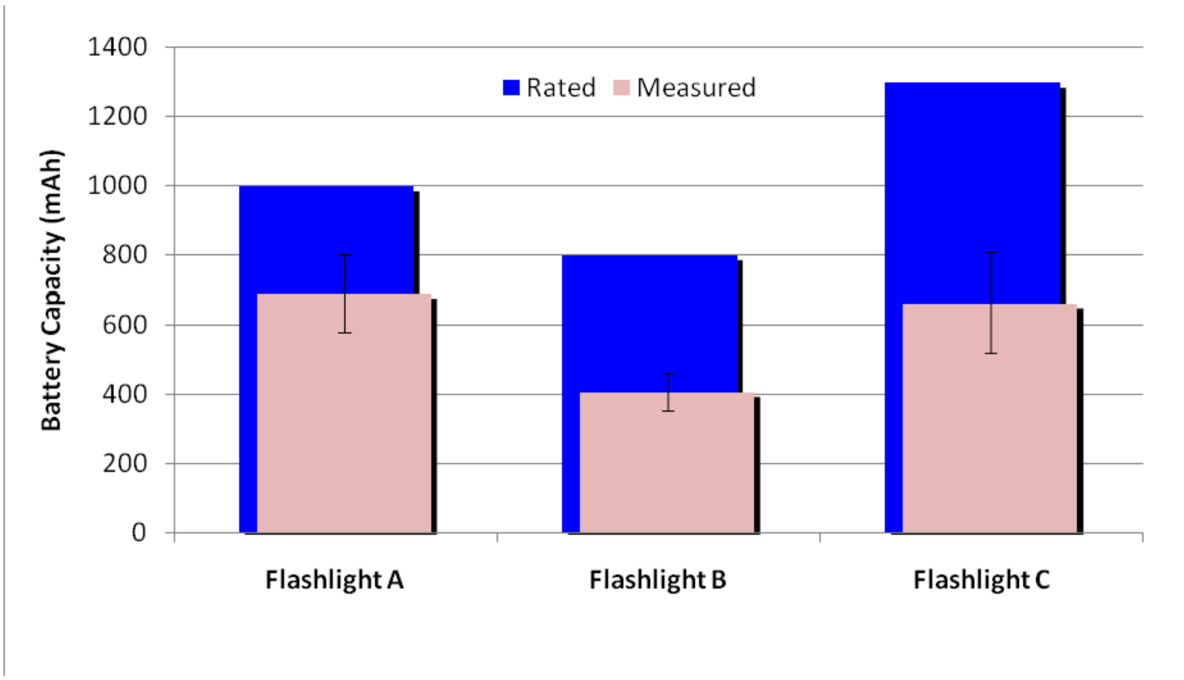


Figure 10. Manufacturers rated battery capacity (blue) in comparison to measured battery capacity (light pink). The black error bar lines indicate the 95% confidence interval around the mean measured value.

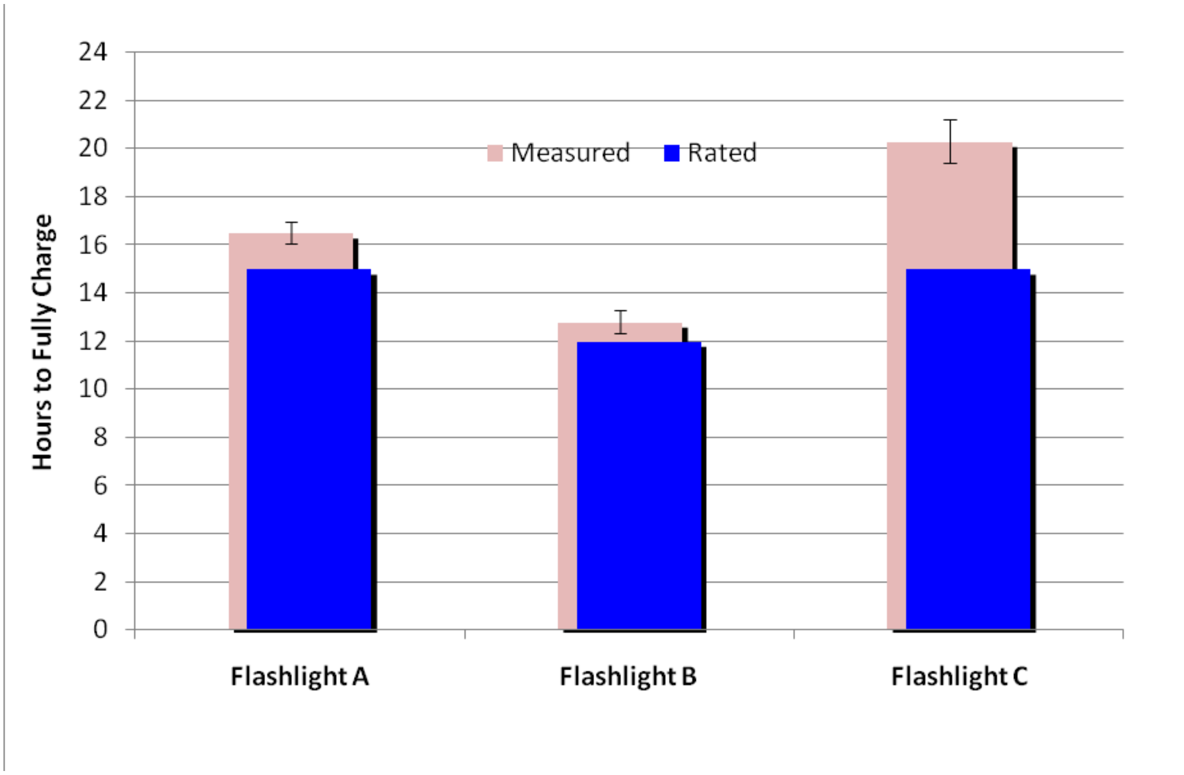


Figure 11. Time required for a full charge. The rated values for each flashlight are shown in blue, while the measured values are shown in pink. The black error bar lines indicate the 95% confidence interval around the mean measured value.

The *maximum initial illuminance (lux)* varied moderately within all three models, though the variation was about 13% greater for Flashlight B. A comparison between the models indicates that Flashlight C outperformed the others in terms of initial maximum illuminance, providing light that was 35-40% brighter than the other two models (Figure 12). The *run-time* on a fully charged battery also had moderate within-model variation for Flashlight A and Flashlight B. The within model variation for Flashlight C was somewhat greater. A cross model comparison indicates little difference between models A and C, but the run time for Flashlight B was significantly lower. The lighting service from a fully charged flashlight, measured in *total lux hours*, varied moderately within each model (Figure 13). The differences between the three models were more substantial. The lighting service from flashlight C was higher than that for the other three models by approximately 46%. Flashlight models A and C provided approximately 36.5 hours of "useable" light on average, where "useable" means that the illuminance at one meter exceeded 5.0 lux. Using the same definitions, Flashlight B delivered only 20 hours of usable light from a fully charged battery.

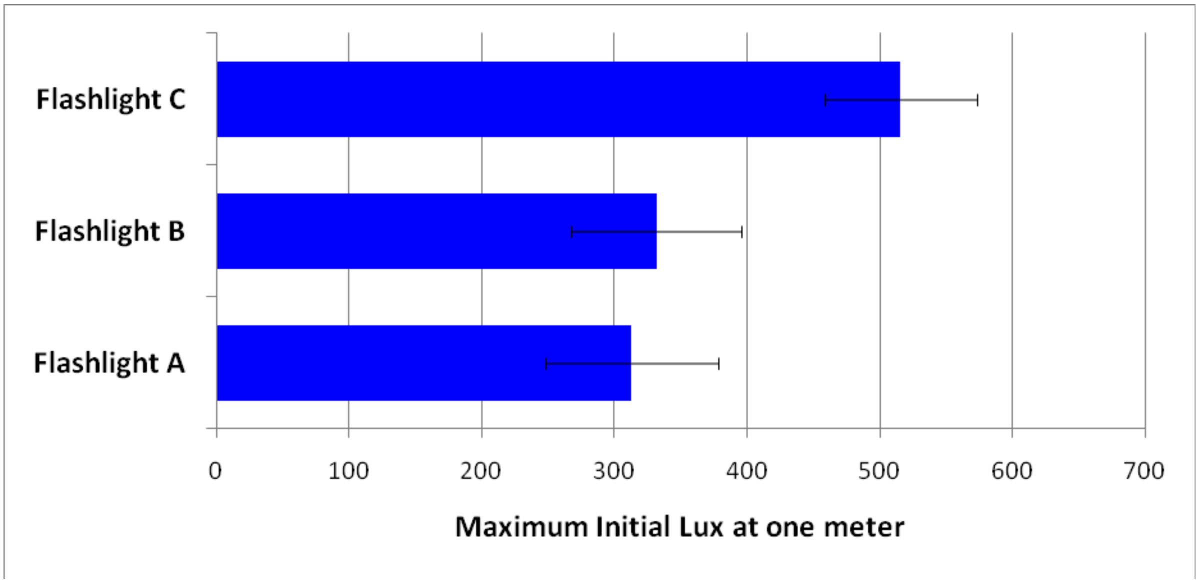
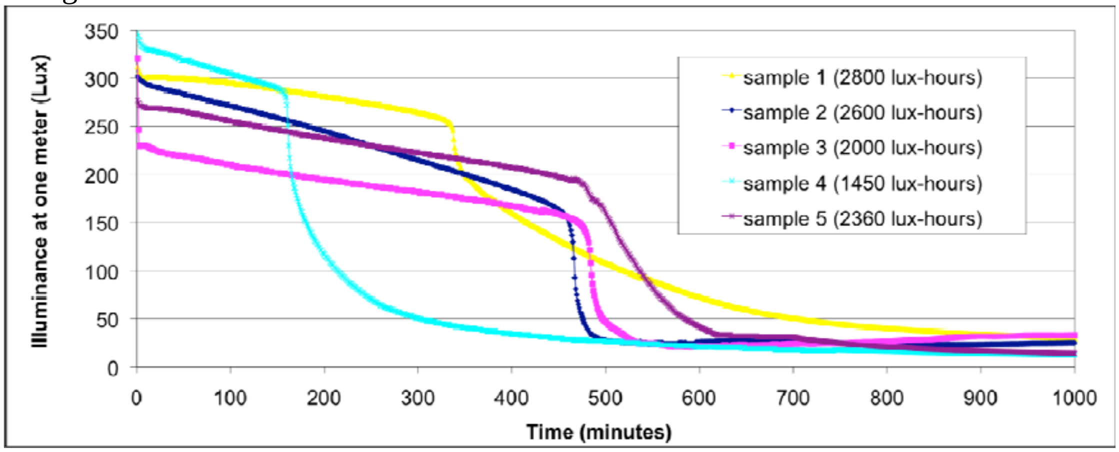
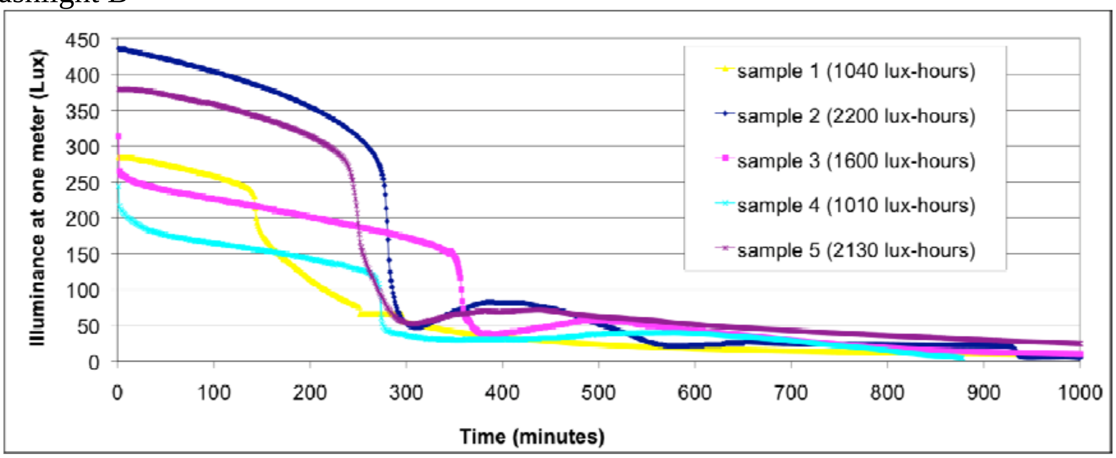


Figure 12. The maximum initial illuminance at a distance of one meter for all three flashlight models. Of the three models, Flashlight C is the brightest and Flashlight A and B are essentially the same. The black error bar lines indicate the 95% confidence interval around the mean value.

A. Flashlight A



B. Flashlight B



C. Flashlight C

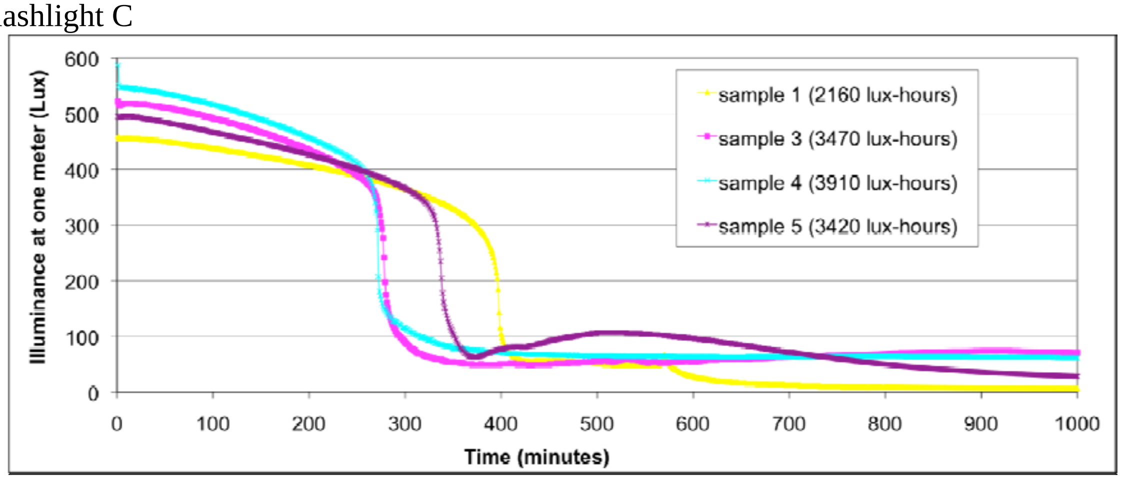


Figure 13. Graphs generated from the lamp discharge test showing the illuminance at a distance of one meter over for flashlights that start with a fully charged battery. Total measured lighting service in lux-hours for each flashlight is in parentheses. Note that one sample from the Flashlight C model malfunctioned and was not included in the test. The variability within each model for maximum initial illuminance at one meter (lux) can be seen on the left axis where the discharge line begins. Variability can also be seen for the total lighting service, measured in lux hours, by the difference in the area under the discharge line.

The *light distribution* within each model varied minimally. Flashlight A had the least focused beam among the three models. In this case, 90% of its total illuminance at one meter fell within 0.22 m^2 of the center beam. Flashlight B had the most focused beam, with 90% of its total illuminance at one meter falling within 0.16 m^2 of the center beam, while Flashlight C fell in between (0.19 m^2) (Figure 14). The *correlated color temperature* (CCT) varied substantially within each model. Because of this high variability, the CCT measurements did not indicate a significant difference across the 3 models. All models delivered a light color that falls in the blue range (Figure 15).

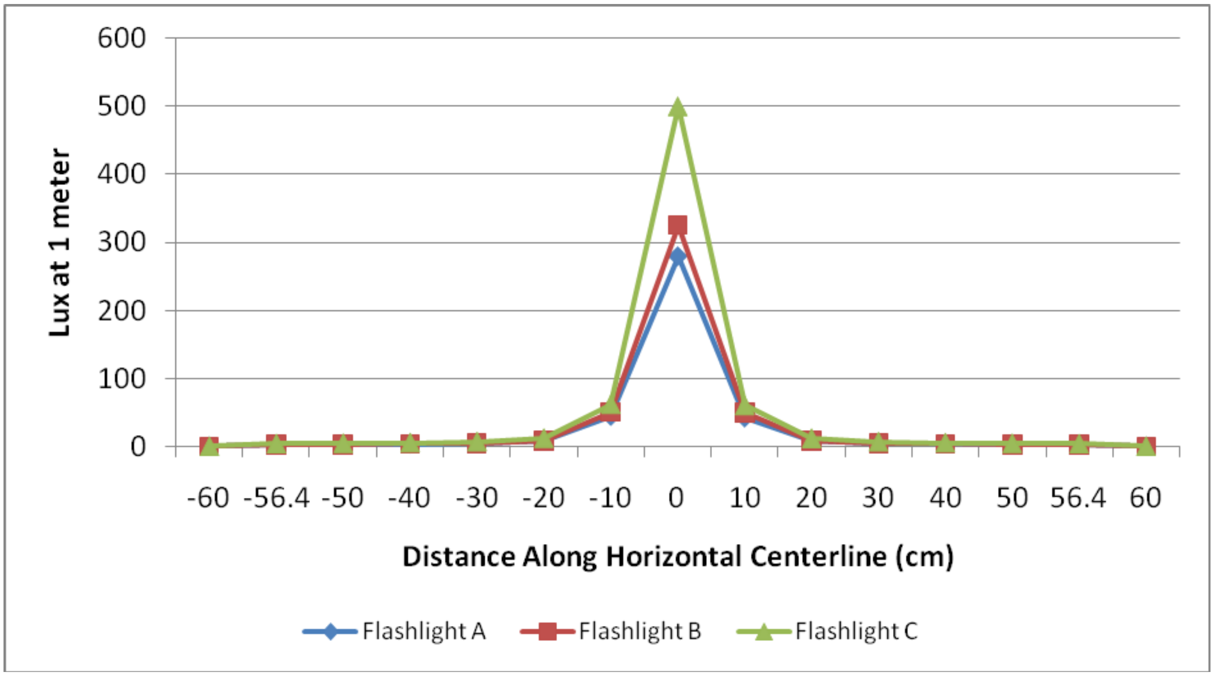


Figure 14. The light distribution measured at a distance of one meter for all three flashlight models. The size of area (cm^2) containing 90% of the total illuminance (lux) measured over one square meter is smallest for Flashlight B, and largest for Flashlight A. In other words, Flashlight B has the most focused beam while Flashlight A has the least focused beam.

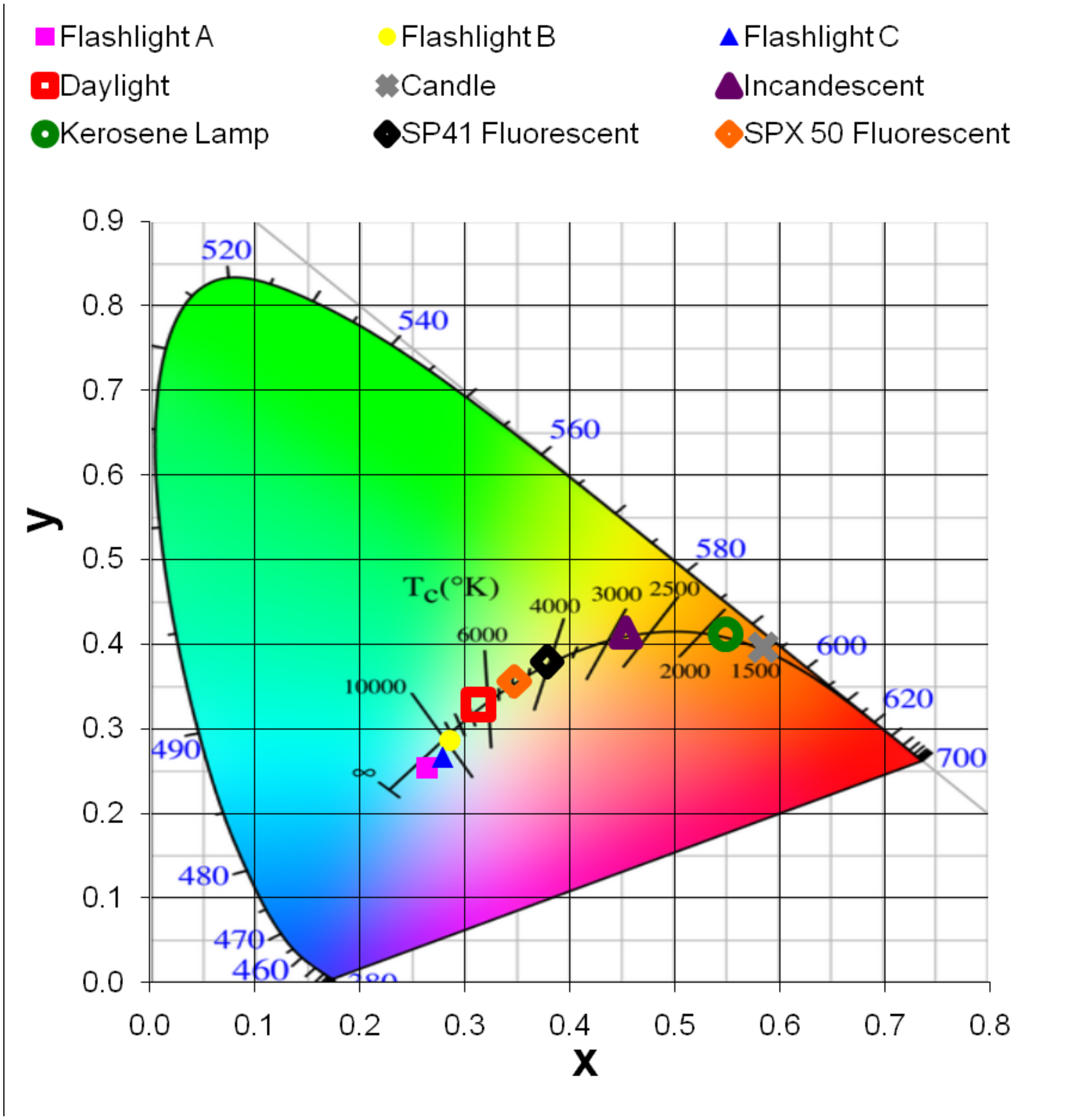


Figure 15. Correlated color temperature (CCT) and color rendering index (CRI) values for the three LED flashlight models as well as several other reference light sources. Flashlight A is indicated by the pink square, Flashlight B by the yellow circle, and Flashlight C by the blue triangle. Other light sources shown include daylight (red hollow square), two types of fluorescent lamps (black and orange diamonds), incandescent lamp (purple hollow triangle), kerosene lamp (green hollow circle), and candle light (grey X). Note that all three LED flashlights fall within the area that is considered to be bluish colored light.

Summary and Conclusions

In this study, we measured the performance of three models of inexpensive rechargeable LED flashlights that are commonly available in Kenya. The tests included five samples for each of the three models, for a total of 15 flashlights tested. The results indicated considerable variation within and between models, and they also confirmed that the performance of the flashlights fell below the manufacturer's specifications for the two metrics for which we had advertised values.

These results raise concerns about the performance of these flashlights, and they indicate that the respective manufacturers should re-evaluate their product ratings to match actual performance.

Concerns about quality and performance notwithstanding, the type of information presented here can be used to compare the performance of rechargeable flashlights as well as other similar lighting products. Different buyers may have different preferences with respect to the various performance metrics, and these will govern their choices. For example, a buyer who wished to purchase the brightest flashlight (in terms of initial illuminance at a distance of one meter) might choose Flashlight C, while someone who wanted a flashlight with a relatively long run-time could choose either Flashlight A or C. Buyers wishing to select among these three models based on other parameters might consider the following:

1) Flashlight A had the battery with the largest capacity in mAh; this flashlight also had batteries that performed closest to their advertised values.
2) Flashlight C delivered the most lighting service per charge as measured in lux-hours at a distance of one meter.
3) Flashlight B had the most focused light while flashlight A had the least focused light.
4) All three flashlights had light that was fairly blue in color.
5) Flashlight B took the least time to charge, although all three flashlights took considerably more than eight hours to receive a full charge.

It is important to note that these test results, while valuable, do not provide information about key measures of product quality and durability, such as lumen depreciation over time, battery life, vulnerability to breakage, and quality of the wiring, switches, and solder joints. Such measurements would provide additional important information about the performance of these flashlights. Moreover, the test results presented here represent the performance of only three of the many models of flashlights that are available. A more comprehensive study covering a wider range of products would be very valuable.

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Appendix A. CCT x,y conversion equation: Definition of terms

$$CCT = A_0 + A_1 \exp(-n/t_1) + A_2 \exp(-n/t_2) + A_3 \exp(-n/t_3)$$

$$n = (x - x_e) / (y - y_e)$$

	Valid CCT Range (K)	
Constant	3000-50,000	50,000-8 x 10^5
x_e	0.3366	0.3356
y_e	0.1735	0.1691
A_0	-949.86315	36284.48953
A_1	6253.80338	0.00228
t_1	0.92159	0.07861
A_2	28.70599	5.4535 x 10^{-36}
t_2	0.20039	0.01543
A_3	0.00004	
t_3	0.07125	

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