THE LUMINA PROJECT

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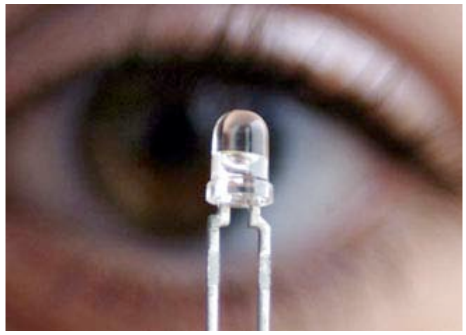
Research Memo #1[*]

Assessing the Performance of 5mm White LED Light Sources for Developing-Country Applications



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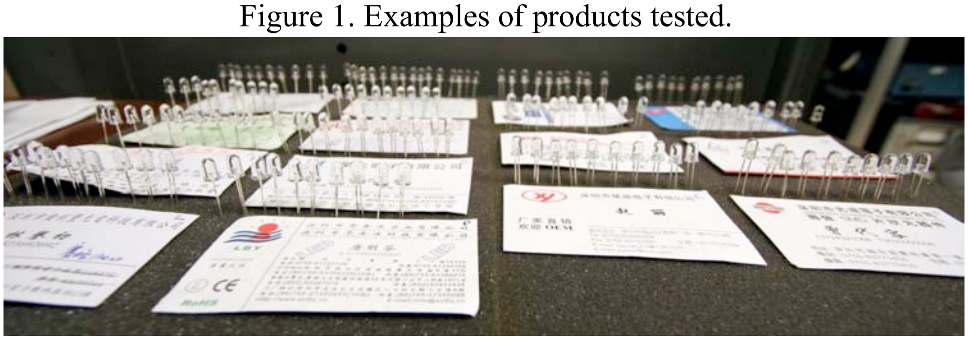
Motivation

Some white light-emitting diode (LED) light sources have recently attained levels of efficiency and cost that allow them to compete with fluorescent lighting for off-grid applications in the developing world. Additional attributes (optics, size, ruggedness, and service life) make them potentially superior products. Enormous reductions in energy use and greenhouse-gas emissions are thus possible, and system costs can be much lower given the ability to downsize the charging and energy storage components compared to a fluorescent strategy.[1] However, there is a high risk of "market-spoiling" if inferior products are introduced and result in user dissatisfaction. Complete systems involve the integration of light sources and optics, energy supply, and energy storage. A natural starting point for evaluating product quality is to focus on the individual light sources.

Sample, Tests, and Experimental Setup

In August 2006, 260 samples of 5mm white LEDs were collected from 26 outlets in Shenzen, China (Fig. 1). Each batch contained about 10 LEDs, which made it possible to quantify the variation in performance within nominally identical batches. We describe these as "nominally" identical, because they are presented to the potential buyer as identical, but may in fact not have been binned according to quality/performance.

Figure 1. Examples of products tested.



[1] Mills, E. 2005. "The Specter of Fuel-Based Lighting," *SCIENCE* 308:1263-1264, 27 May.

[*] *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. For a full archive of *Research Notes* and *Technical Reports* see: http://light.lbl.gov/technology-assessment.html

The LEDs were obtained primarily from the "packagers" and "traders" who assemble the chips, phosphors, and optics into functional devices and distribute them to wholesale buyers. These 5mm units represent the lower-cost "off-brand" LED products encountered in the market by firms designing and assembling complete lighting systems for developing-country markets. Larger-diameter packages, such as the one-watt systems being used by some product developers, are not examined in this study.

We conducted the following three sets of measurements, using the equipment described in Table 1 and shown in Figs. 2-3:

1. Total luminous flux from each light source
2. Voltage drawn by each light source
3. Color quality: color rendering index (CRI), CQS, correlated color temperature (CCT), x/y color coordinates for each light source

Table 1. Test conditions and equipment.

<u>Test conditions</u>
- LEDs powered at 20mA
- LED as load to determine voltage

<u>Photometry</u>
- LEDs in 4" Photodyne integrating sphere
- LED voltage measured with HP 3456A DMM current with Fluke A90 shunts and HP 3455A DMM (+/- 0.25%)
- Light measured with Tektronix J16 photometer and Licor Photometer (210S)
- Sphere / J16 calibrated with a Sylvania 796 quartz halogen lamp calibrated by Labsphere

<u>Spectral measurements</u>
- LEDs in 4" Photodyne integrating sphere
- Ocean Optics SD2000 spectrometer. Software:OOIBase32, ver. 2.0.6.3, and the Excel analysis program is NIST_CQS_Simulation_7.1.xls
- SD2000 calibrated with Ocean Optics LS-1-CAL calibrated lamp to +/- 40K

Figure 3. Voltage measurement.

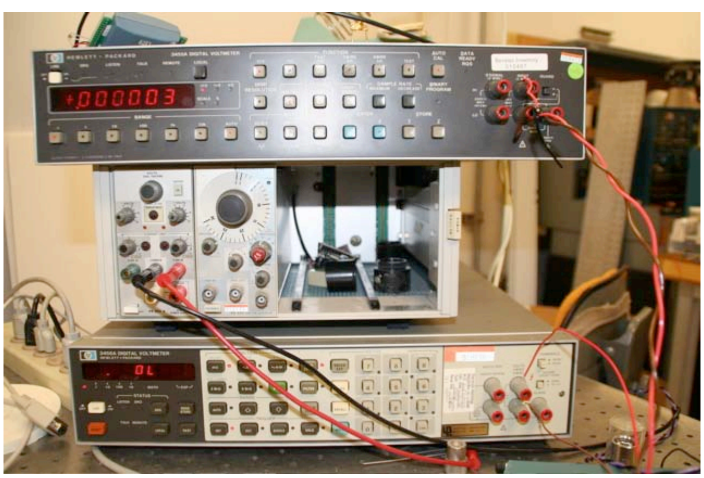
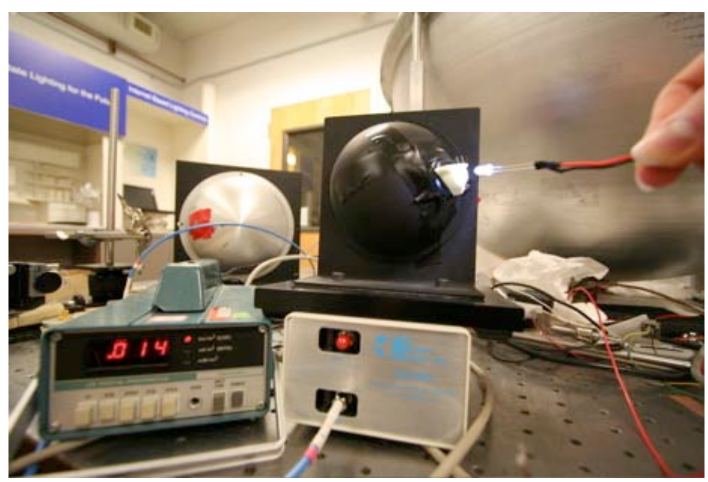


Figure 4. Integrating spheres and spectrometer.



Results

Our measurements indicate remarkable variations in lamp characteristics across the entire sample (Table 2), i.e. 5.0x for light output (lumens), 1.3x for lamp power (Watts) and voltage, and 5.1x for luminous efficacy (lumens/watt), a proxy for energy efficiency. The very wide range of luminous efficacies can be seen in Fig. 4. We also observed a high degree of variation *within* individual batches of products represented as identical (Figs 5-7).

Table 2. Summary results: power and light

	lamp lumens (lm)	Lamp voltage (v)	lamp power (W)	Lamp lumens per watt
Sample size	260	260	260	260
Mean	2.9	3.204	0.064	45
Median	3.0	3.205	0.064	47
Min	0.2	2.926	0.059	2
Max	4.3	4.029	0.081	67
Min-Max Variation (Max/Min)*	5.0	1.3	1.3	5.1

* excluding one otherwise overly influential outlier of 2 lpw.

The high end of the efficiency range for the LEDs we tested is exceptionally good (as good or better than many compact fluorescent lamps), while the low end is no better than the common incandescent lamp. Off-grid lighting products using the poorer LEDs would likely be rejected by end-users. Our analysis thus raises important questions for LED manufacturers and packagers who wish to sell LEDs to quality-conscious customers, for entrepreneurs procuring white LED light sources for inclusion in products, and for policy makers and other entities designing or evaluating initiatives to scale up the delivery of grid-independent lighting systems for the developing world. Surprisingly, despite the large efficiency range, prices quoted did not vary appreciably among these products.

We also evaluated the color characteristics of the LED samples (Table 3). Color Rendering Indices (CRI) were largely quite good (on a par with those for compact fluorescent lamps), with an overall range was from 69 to 91. The range was a bit broader (72 to 90) for CQS,[2] which is an alternate metric that some prefer to CRI for evaluating LED light sources. Correlated Color Temperature (CCT) measurements were extraordinarily variable, with most of the products presenting a strongly blue profile. The "warmest" value was over 7000, which is far higher than that found among conventional fluorescent light sources. Lowering the CCT into a "warmer" zone would likely reduce the efficacy of the LED light sources. Variation within batches was significant in many cases (Fig. 8). There was no observed correlation between luminous efficacy and CRI, CQS, or CCT.

[2] Davis, W. and Y. Ohono. 2005. "Toward an Improved Color Rendering Metric," *Proceedings of the Fifth International Conference on Solid State Lighting,* edited by Ian T. Ferguson, John C. Carrano, Tsunemasa Taguchi, Ian E. Ashdown, *Proc. of SPIE* Vol. 5941 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.615388.

Table 3. Summary results: color properties

	Correlated Color Temperature (K)	Color Rendering Index	CQS	x	y
Sample size*	246	259	160	259	259
Mean	19,053	80	77	0.271	0.280
Median	10,885	81	77	0.272	0.287
Min	7,058	69	72	0.232	0.216
Max	471,843	91	90	0.301	0.387
Min-Max Variation (Max/Min)	66.9	1.3	1.3	1.3	1.8

* values were out of range of the test equipment in some cases, resulting in counts less than 260.

It is important to note that other types of light sources are subject to wide performance variations. Incandescent and fluorescent light sources have also exhibited these problems, especially off-brand products.[3] The problems have been addressed in the past through standards and/or voluntary rating and labeling programs. Those specifying or purchasing such systems can ensure product quality by setting performance criteria.

Further Research Needs

White LED technology is undergoing rapid improvement and thus such testing needs to be replicated on a continuous basis. A wider variety of LED samples should be independently tested; there are likely some that perform outside the bounds of the (already wide) range we have observed here. Additional testing of the light sources should focus on life testing. In tandem with the effort described here, *The Lumina Project* is conducting a broader range of testing activities in collaboration with Humboldt State University, focusing on the application of white LEDs such as those characterized here in integrated systems that include charging, energy storage, and illumination.[4]

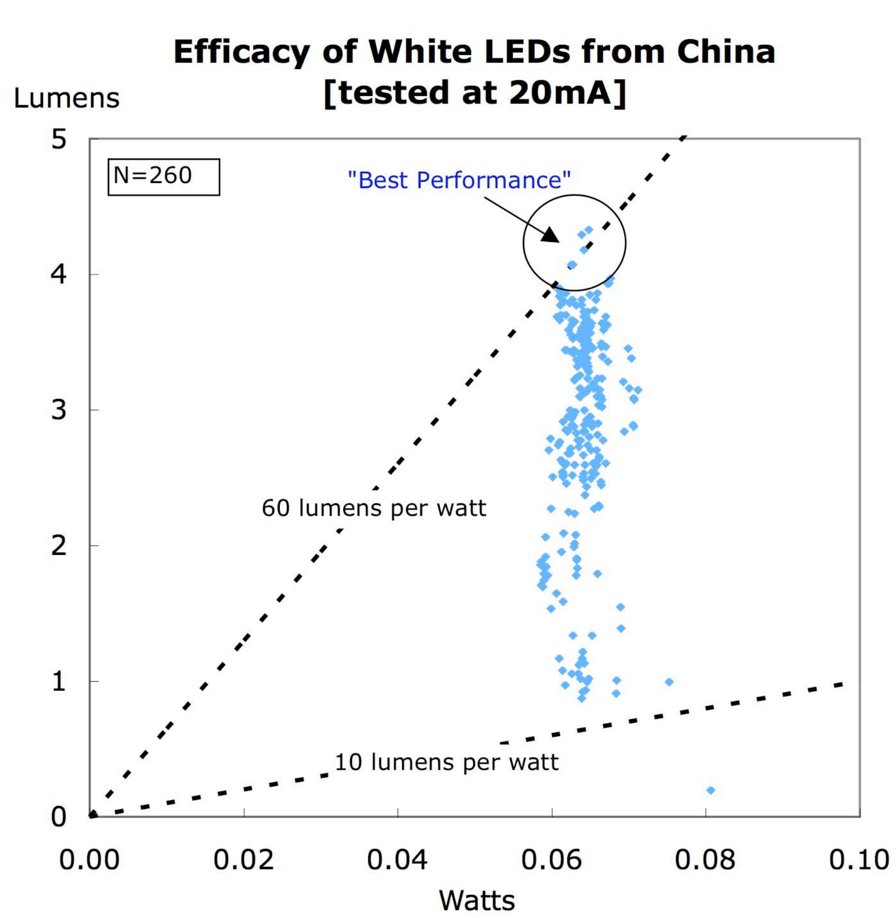
Acknowledgments

This work was funded by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 through The Rosenfeld Fund of the Blum Center for Developing Economies at UC Berkeley and by the Global Roundtable on Climate Change through the Earth Institute at Columbia University. Stewart Craine collected the LED samples in Shenzen, China and generously made them available for this project. Steve Johnson and Francis Rubinstein provided access to Lawrence Berkeley National Laboratory's lighting laboratory, staff, and equipment. Jim Galvin established the experimental setup and calibrated the equipment. Dmitriy Bolotov performed the spectral measurements. Arne Jacobson and Kathryn Conway provided helpful discussions and Francis Rubinstein furnished review comments on a draft of this report.

[3] See Fu Min, G., E. Mills, and Q. Zhang. 1997. "Energy-Efficient Lighting in China: Problems and Prospects." *Energy Policy* 25 (1): 77-83. http://eetd.lbl.gov/emills/PUBS/china.html and duPont, P. 2006. "International CFL Market Review: A Study of Seven Asia-Pacific Economies." Australian Greenhouse Office. (August)

[4] See http://light.lbl.gov

Figure 4. Variation in efficacy of LEDs tested.



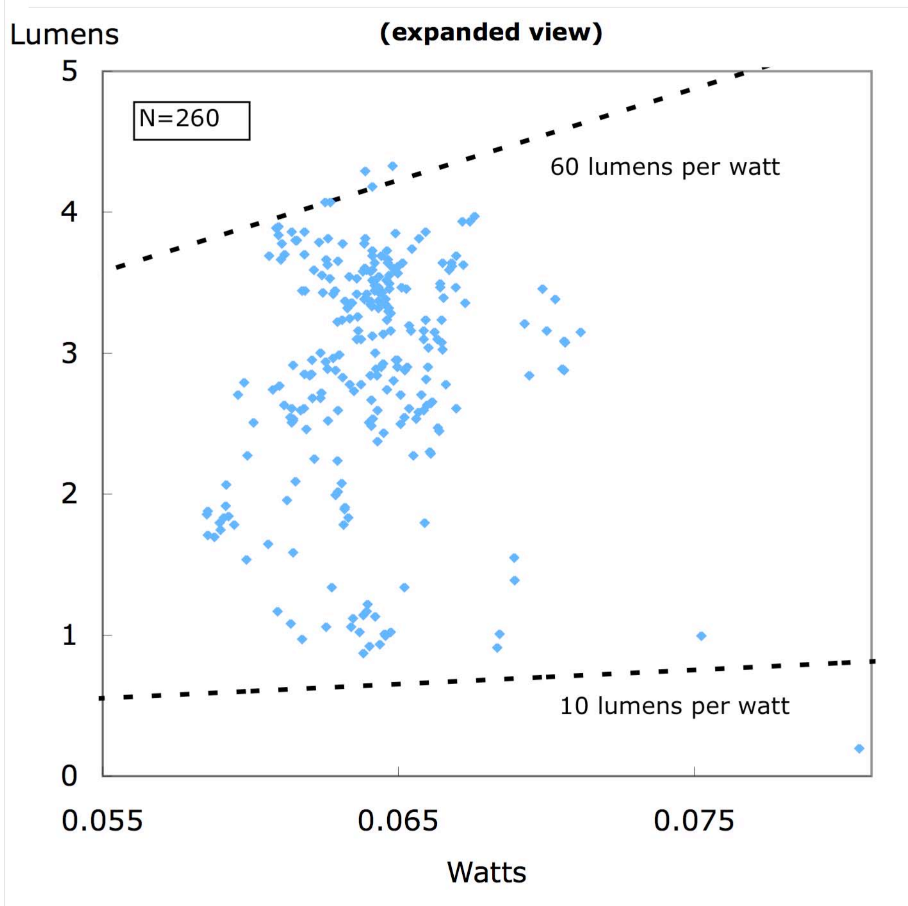


Figure 5.

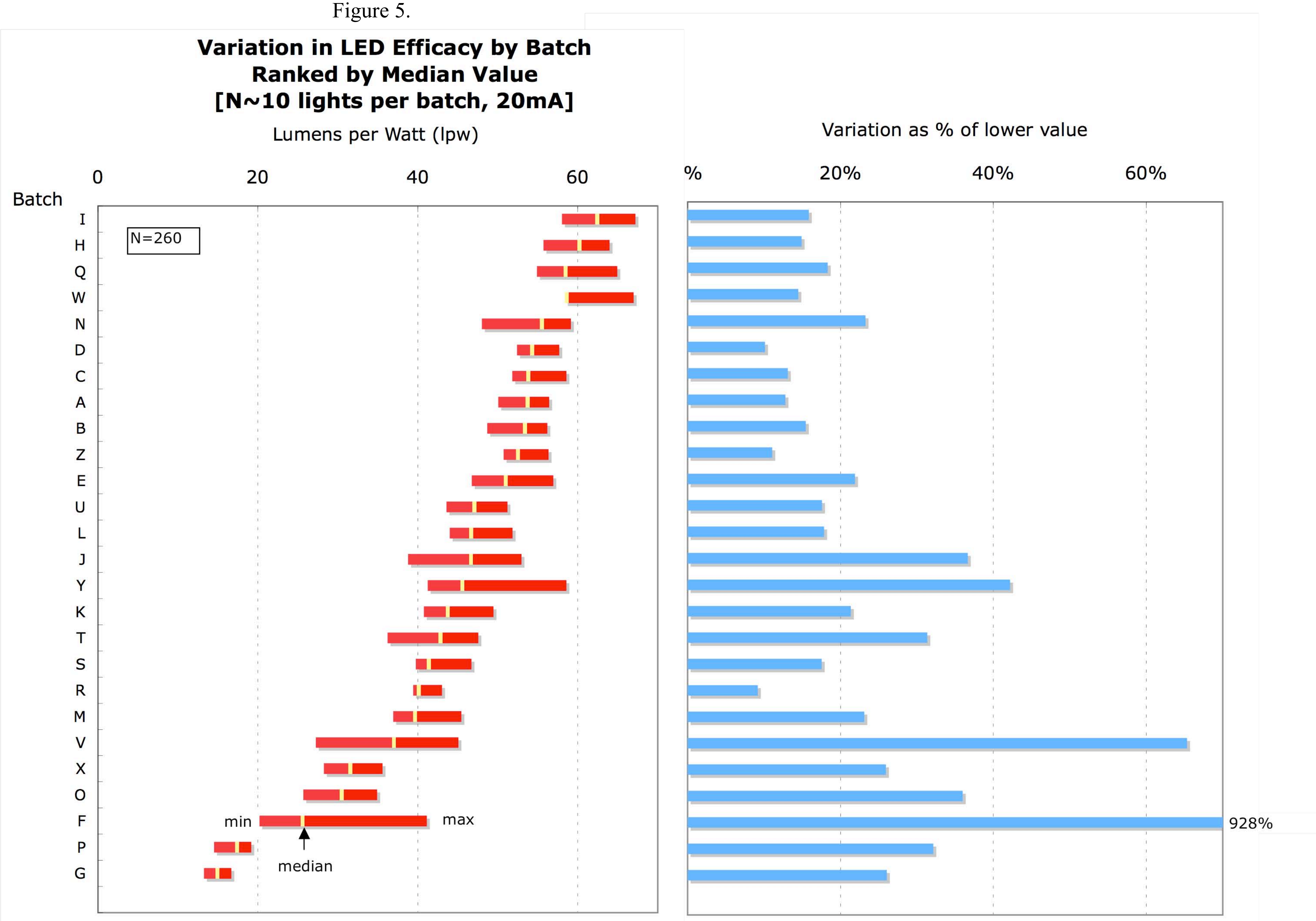
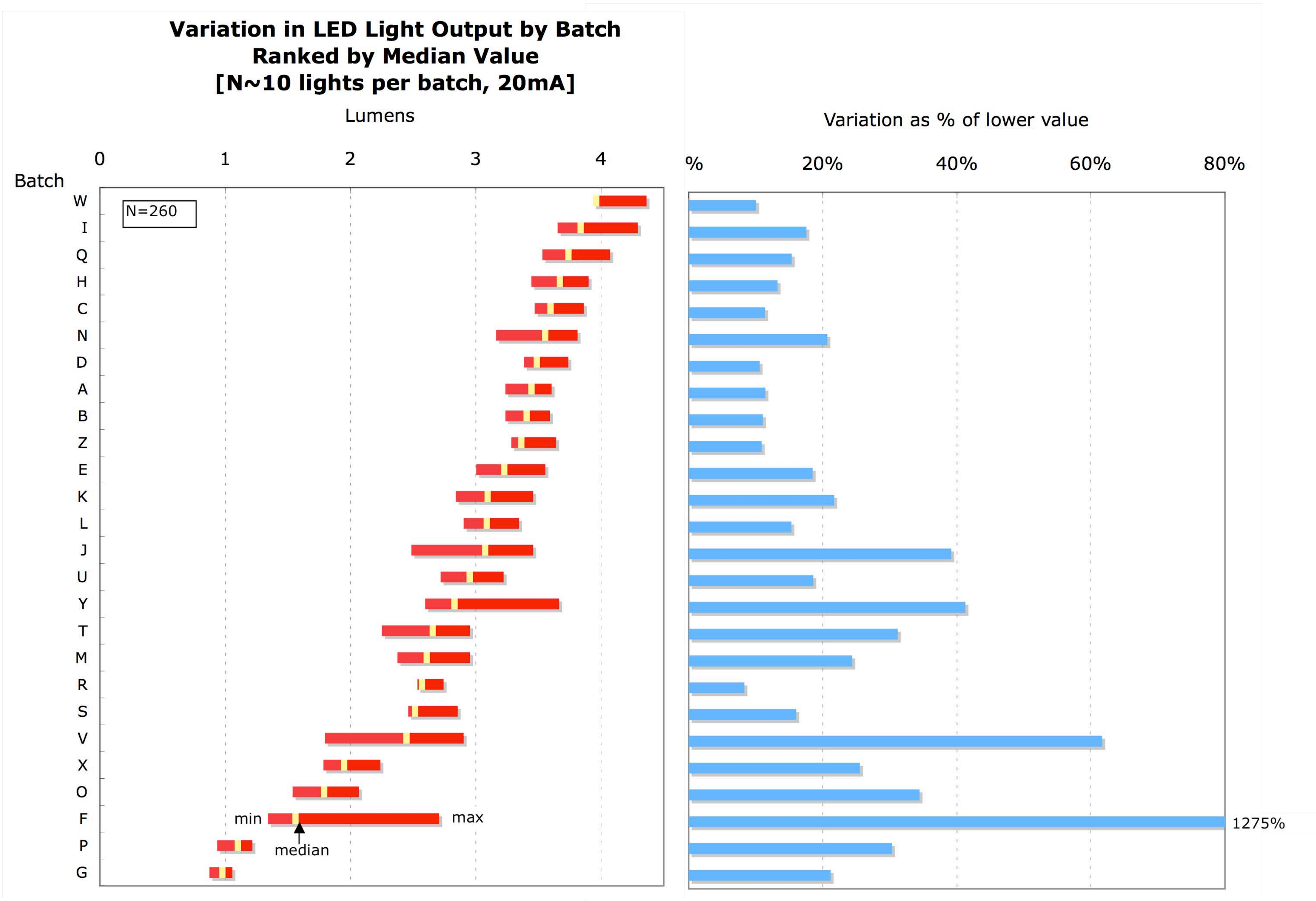

Variation in LED Efficacy by Batch
Ranked by Median Value
[N~10 lights per batch, 20mA]
Lumens per Watt (lpw)
0
20
40
60
Batch
I
H
Q
W
N
D
C
A
B
Z
E
U
L
J
Y
K
T
S
R
M
V
X
O
F
P
G
N=260
min
max
median
Variation as % of lower value
%
20%
40%
60%
928%

Figure 6.



Variation in LED Light Output by Batch
Ranked by Median Value
[N~10 lights per batch, 20mA]
Lumens
0
1
2
3
4
Batch
N=260
W
I
Q
H
C
N
D
A
B
Z
E
K
L
J
U
Y
T
M
R
S
V
X
O
F
P
G
min
max
median
Variation as % of lower value
%
20%
40%
60%
80%
1275%

Figure 7.

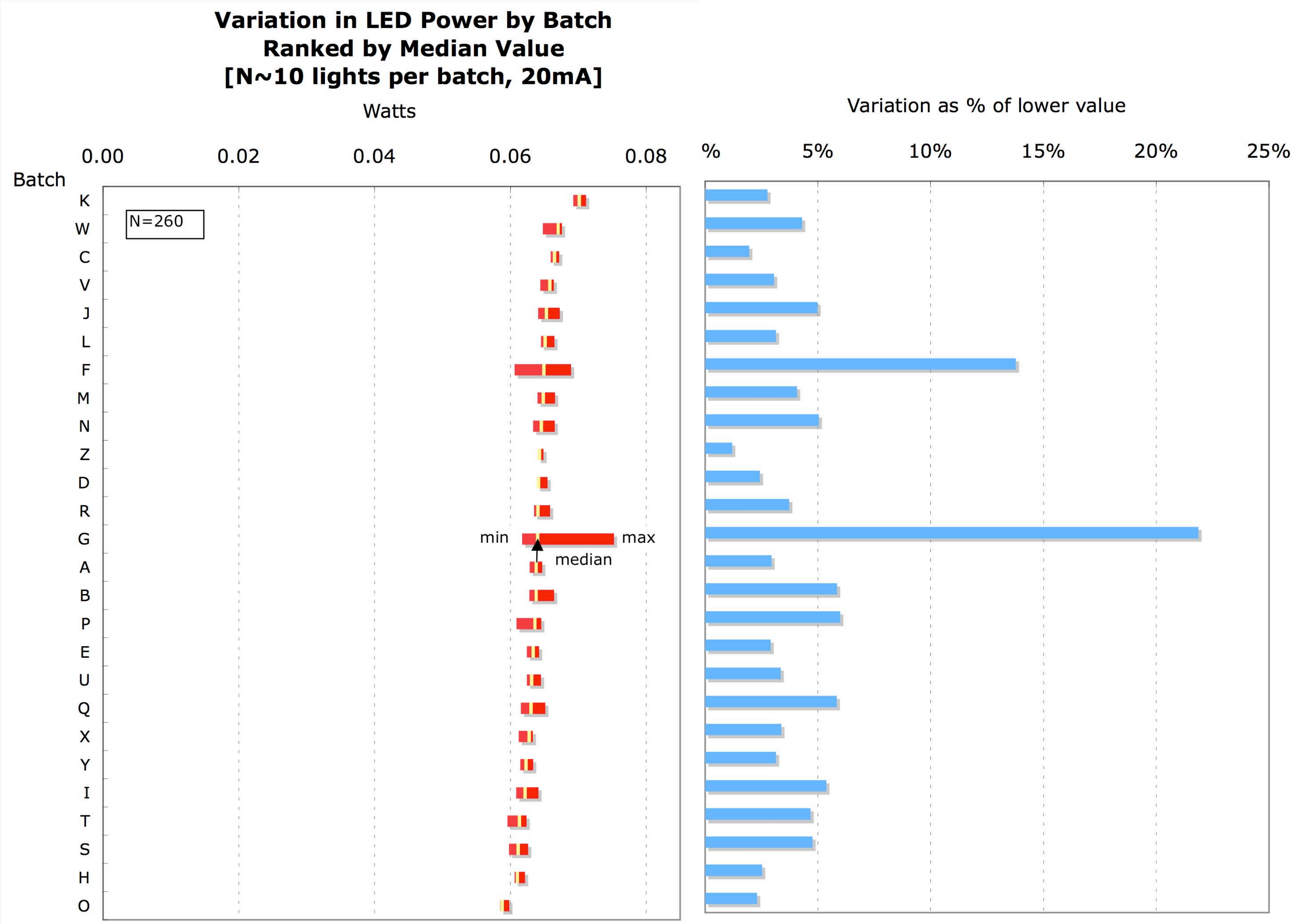
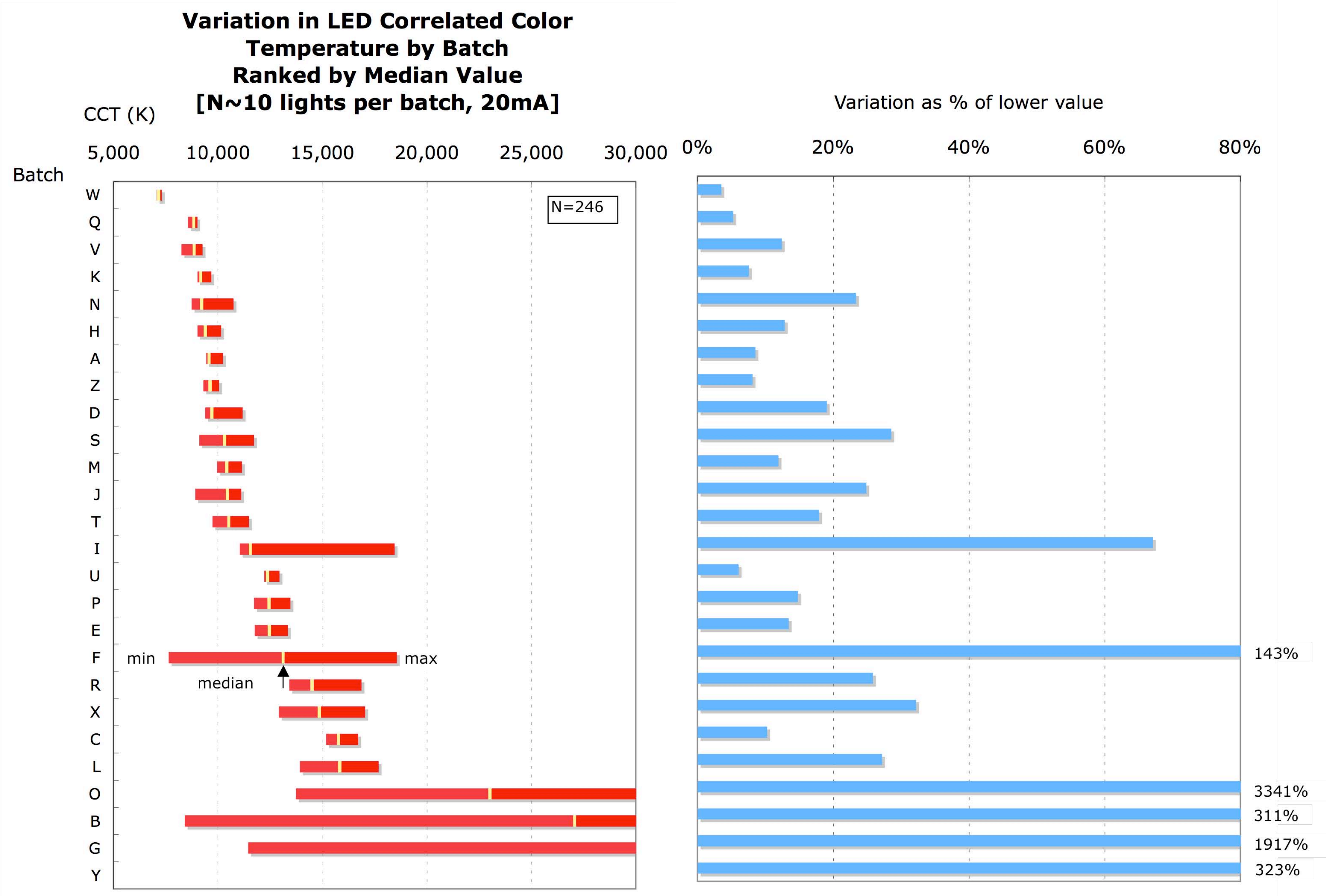

Variation in LED Power by Batch
Ranked by Median Value
[N~10 lights per batch, 20mA]
Watts
0.00
0.02
0.04
0.06
0.08
Batch
K
W
C
V
J
L
F
M
N
Z
D
R
G
A
B
P
E
U
Q
X
Y
I
T
S
H
O
N=260
min
max
median
Variation as % of lower value
%
5%
10%
15%
20%
25%

Figure 8.


Variation in LED Correlated Color Temperature by Batch Ranked by Median Value [N~10 lights per batch, 20mA]
CCT (K)
5,000
10,000
15,000
20,000
25,000
30,000
Batch
W
Q
V
K
N
H
A
Z
D
S
M
J
T
I
U
P
E
F
R
X
C
L
O
B
G
Y
N=246
min
max
median
Variation as % of lower value
0%
20%
40%
60%
80%
143%
3341%
311%
1917%
323%