



Pacific Northwest
NATIONAL LABORATORY

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Top Efficacy Performers: Understanding Technology Tradeoffs

A CALiPER project funded by the US
Department of Energy, Solid-State
Lighting Program

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Top Efficacy Performers – An Investigation

Project intent:

- ▶ LED Lighting Facts database has listed over 70,000 luminaires since 2009.
- ▶ Database used to gauge progress of LED lighting in efficacy, color characteristics, power quality, etc.
- ▶ In 2017, many products listed at or near 200 lm/W
- ▶ Really? Do these products really perform at that level, and what are these luminaires? What do they have in common? Let's order some!

Model Number	Light Output	Watts	Efficacy	CRI	CCT
DS242.40K.80.CL.120	23390	102	229.31	83	5308
HBIF3C10AUNVXXXX750NLXXXXXXX	22610	107.8	209.74	76.7	4932
HBIF3D1OAXXXXXXX850LCXXXXXXXXXX	25240	128	197.19	83.2	5024
HBIF3A10AUNVXXXX750NLXXXXXXXXXX	11300	57.88	195.23	76.7	4924
HBIF3B10AUNVXXXX750NLXXXXXXXXXX	14260	73.15	194.94	76.6	4930
HBIF3B20AUNVXXXX750NLXXXXXXXXXX	17120	88.04	194.46	76.6	4930
HBIF3C10AXXXXXXX750NLXXXXXXXXXX	20030	104.6	191.49	77.1	4935
HBIF3B10AXXXXXXX750NLXXXXXXXXXX	13960	73.4	190.19	77	4928
HBIF3D10AUNVXXXX750NLXXXXXXXXXX	24190	127.5	189.73	76.6	4934
HBIF3A10AXXXXXXX750NLXXXXXXXXXX	11210	59.26	189.17	76.9	4934
HBIF3C10AUNVXXXX850NLXXXXXX	20150	106.9	188.49	83.1	4988
HBIF3C10AUNVXXXX850NLXXXXXXXXXX [Update]	20150	106.9	188.49	83.1	4988
HBIF3B20AXXXXXXX750NLXXXXXXXXXX	16690	89	187.53	76.9	4950
HBIF3B10AUNVXXXX850NLXXXXXXXXXX	15280	81.86	186.66	82.7	5018
HBIF3A10AUNVXXXX850NLXXXXXXXXXX	12360	66.35	186.28	82.6	5000
HBIF3C10AXXXXXXX850NLXXXXXXXXXX [Update]	19470	104.7	185.96	82.8	4984
HBIF3A10AXXXXXXX850NLXXXXXXXXXX	12290	66.36	185.2	82.7	5015
HBIF3D10AXXXXXXX750NLXXXXXXXXXX	23660	128.2	184.56	76.9	4952
HBIF3B10AXXXXXXX850NLXXXXXXXXXX	15230	82.67	184.23	82.8	4988
HBIF3D1AAUNVXXXX850LFXXXXXXXXXX	22440	121.9	184.09	82.4	4992
HBIF3B20AXXXXXXX850NLXXXXXXXXXX	18410	100.5	183.18	82.7	4992
HB01-100/H1-5000-60	18828	102.8	183.15	76.4	5098
HBIF3A10AUNVXXXX750LCXXXXXXXXXX	10670	58.84	181.34	77.2	4947
HB01-100/H1-5000-90	18653	102.9	181.27	76.5	5103
HBIF3B20AUNVXXXX850NLXXXXXXXXXX	18310	101.1	181.11	82.6	5023
HBIF3C10AUNVXXXX850NLXXXXXXXXXX	21950	121.4	180.81	82.9	5010
HBIF3C10AXXXXXXX850NLXXXXXXXXXX	22040	122.1	180.51	82.8	4991

Top Efficacy Performers – An investigation

Protocol

- ▶ Identified and ordered 5 top efficacy products from LF database, 140 – 209 lm/W for “low-bay” applications, plus 2 from familiar manufacturers with similar claims
- ▶ 16,000 – 22,000 lm to match 4-lamp T5HO industrial lighting
- ▶ 5000 K, because all the highest efficacy products listed were 5000 K
- ▶ 2 samples LM-79 tested in NVLAP lab, then shipped to Portland, OR mockup lab for mounting in pairs in movable ceiling
- ▶ 23 lighting and energy efficiency experts invited as observers to assess characteristics
- ▶ In situ lighting measurements taken

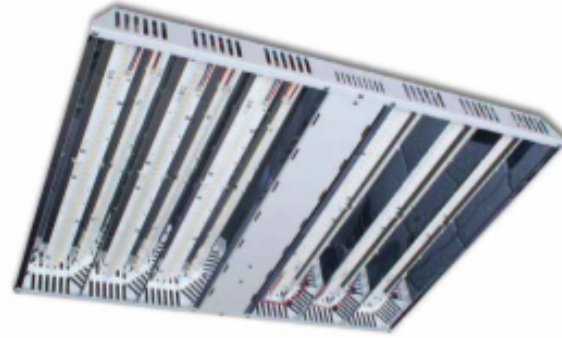


Luminaires spaced 14' o.c., mounted 11'-3" above floor

What did these products look like?



17-S1B and C



17-S2A and B



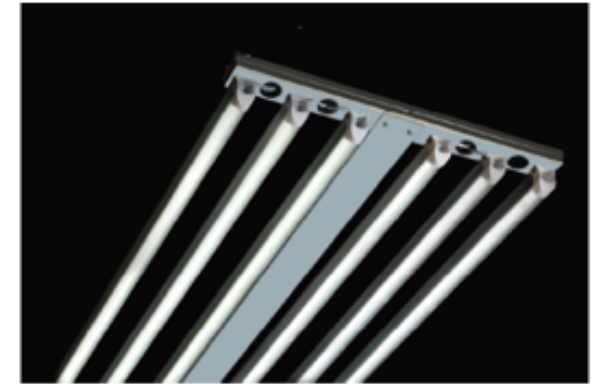
17-S3A and B



17-S4A and B



17-S5A and B



17-S6A and B



17-S7A and B

System ID	Lab Tested CRI	Lab Tested Power (W)	Lab Tested Power Factor	Lab Tested Output (lm)	Lab Tested CCT (K)	Lab Tested Efficacy (lm/W)
17-S1B	85	123.9	1.00	16,925	5143	136.6
17-S1C	84	124.9	1.00	17,018	5115	136.3
17-S2A	83	113.0	1.00	18,883	5022	167.1
17-S2B	83	112.9	1.00	18,617	5032	164.9
17-S3A	79	95.8	0.99	16,091	5218	168.0
17-S3B	79	98.2	0.99	16,234	5220	165.3
17-S4A	77	106.9	0.99	21,336	4895	199.6
17-S4B	77	107.3	0.99	21,178	4894	197.4
17-S5A	83	107.6	0.99	17,412	4986	161.8
17-S5B	83	107.2	0.99	17,431	4995	162.6
17-S6A	82	138.0	0.98	21,975	4951	159.2
17-S6B	82	138.2	0.98	21,502	4970	155.6
17-S7A	74	101.7	1.00	17,729	5062	174.3
17-S7B	74	101.1	1.00	18,127	5058	179.3

Lab testing results



17-S1B and C



17-S2A and B



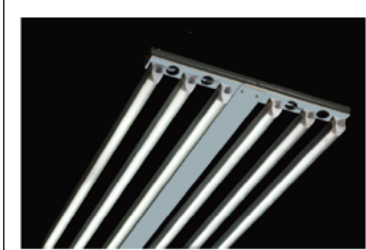
17-S3A and B



17-S4A and B



17-S5A and B



17-S6A and B



17-S7A and B



Top Efficacy Performers – Lab test results

Comparison results of tested vs claimed:

- ▶ Color performance reported with CCT and CRI was consistent with manufacturer claimed values (not those published in LF).
- ▶ Lumen output values were no more than 9.6% above or below the manufacturer reported values.
- ▶ The power draw varied by as much as 6.8% from the manufacturer claimed values... Up to 12% variation in claimed efficacy.
- ▶ Power factors were all above 90%.
- ▶ There really ARE luminaires at 200 lm/W!





Top Efficacy Performers - Observations

Observers:

- ▶ 23 unpaid* observers recruited from local IES section in Portland (specifiers), plus utility program energy efficiency experts, and facility managers from APEM
- ▶ All were lighting knowledgeable
- ▶ 1-hour sessions scheduled over 3 days

* Except for homemade lemon bars and chocolate chip cookies



Pillsbury.com

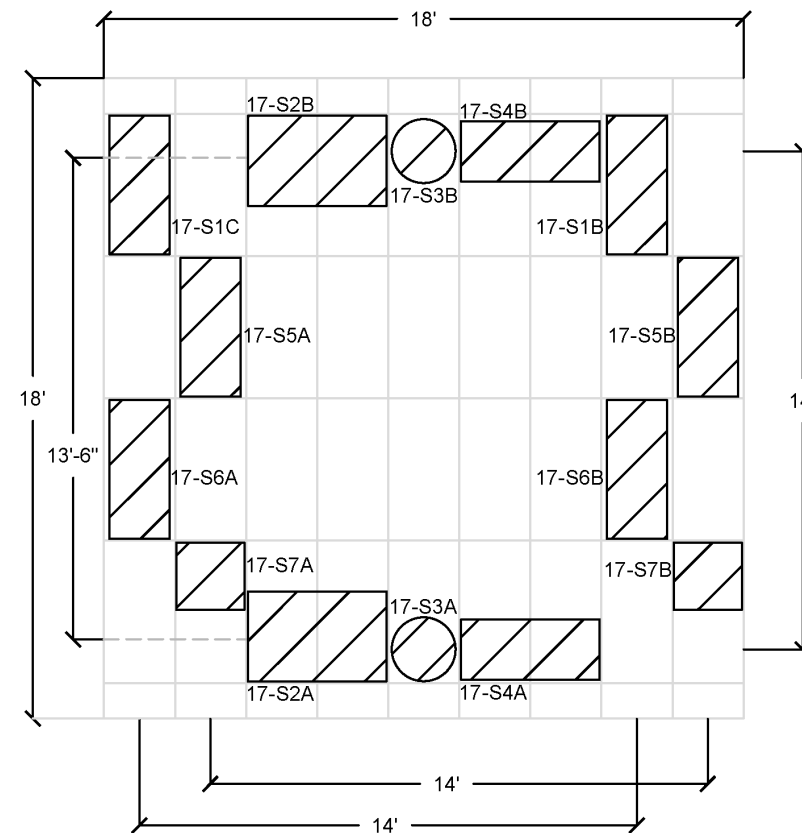




Top Efficacy Performers - Observations

Observer questionnaire rules:

- ▶ Groups given 3 minutes to move around the space in the shoes of the industrial employee and the building owner
- ▶ Advised not to stare at the luminaires, but were free to glance at them briefly if need be
- ▶ No talking among subjects to reduce bias. Randomized presentation order of luminaire pairs for each group
- ▶ Asked to comment on visual comfort, distribution on the workplane, shadows, color, appearance, and overall \$\$ value



Reflected ceiling plan

Top Efficacy Performers Questionnaire

Group No.

Profession:	Engineer	Lighting Designer	Rep or Agent	Architect	Facility Mgr	Contractor	Other
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Years of experience in lighting and/or construction:

Instructions: Pairs of industrial luminaires are mounted at 11'-3" above the floor. A table is located between the two, with a variety of objects you can use to simulate an assembly task. Take 3 minutes to walk around the tables and provide comments/observations on each type. Please do not share your thoughts with others, yet.

		Written comments Please provide comments on the luminaires, using your knowledge and experience. Consider respond to the following issues: SPREAD OF LIGHT ON THE TABLE TOP, SHADOWS, VISUAL COMFORT, COLOR QUALITY, APPEARANCE, FUNCTIONALITY, ETC.	If this type of luminaire costs \$200 on average, what would you pay for this one?	Additional comments? Where would you recommend this product?
Luminaire Label	A		<input type="checkbox"/> \$100 <input type="checkbox"/> \$250 <input type="checkbox"/> \$150 <input type="checkbox"/> \$300 <input type="checkbox"/> \$200	
	B		<input type="checkbox"/> \$100 <input type="checkbox"/> \$250 <input type="checkbox"/> \$150 <input type="checkbox"/> \$300 <input type="checkbox"/> \$200	
	C		<input type="checkbox"/> \$100 <input type="checkbox"/> \$250 <input type="checkbox"/> \$150 <input type="checkbox"/> \$300 <input type="checkbox"/> \$200	
	D		<input type="checkbox"/> \$100 <input type="checkbox"/> \$250 <input type="checkbox"/> \$150 <input type="checkbox"/> \$300 <input type="checkbox"/> \$200	
	E		<input type="checkbox"/> \$100 <input type="checkbox"/> \$250 <input type="checkbox"/> \$150 <input type="checkbox"/> \$300 <input type="checkbox"/> \$200	
	F		<input type="checkbox"/> \$100 <input type="checkbox"/> \$250 <input type="checkbox"/> \$150 <input type="checkbox"/> \$300 <input type="checkbox"/> \$200	
	G		<input type="checkbox"/> \$100 <input type="checkbox"/> \$250 <input type="checkbox"/> \$150 <input type="checkbox"/> \$300 <input type="checkbox"/> \$200	



Top Efficacy Performers - Observations

Observer results:

- ▶ Few responses on appearance, but round luminaire (17-S3, left) and 2'x 2' luminaire (17-S7, right) received the top ratings for preferred appearance

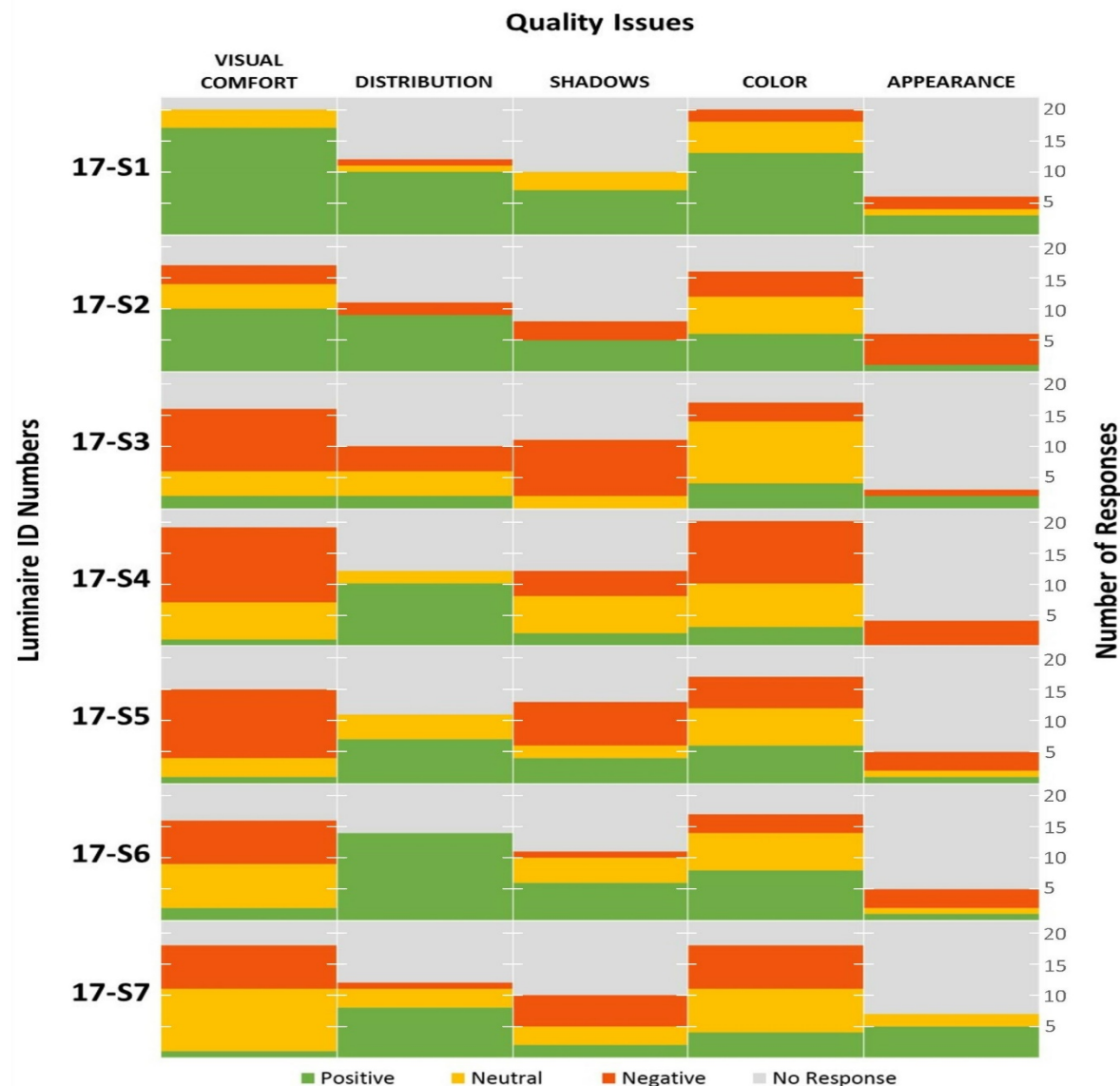




Top Efficacy Performers - Observations

Observer questionnaire responses:

- ▶ Visual comfort dominated the responses and corresponded to positive ratings and higher overall \$\$ value. Luminaires with poorest glare ratings also got lowest overall values



Top Efficacy Performers – In situ

Results from in situ measurements – Horizontal illuminances:

Table 7. Horizontal illuminances from each pair of luminaire types, with maximum-to-minimum uniformity values.

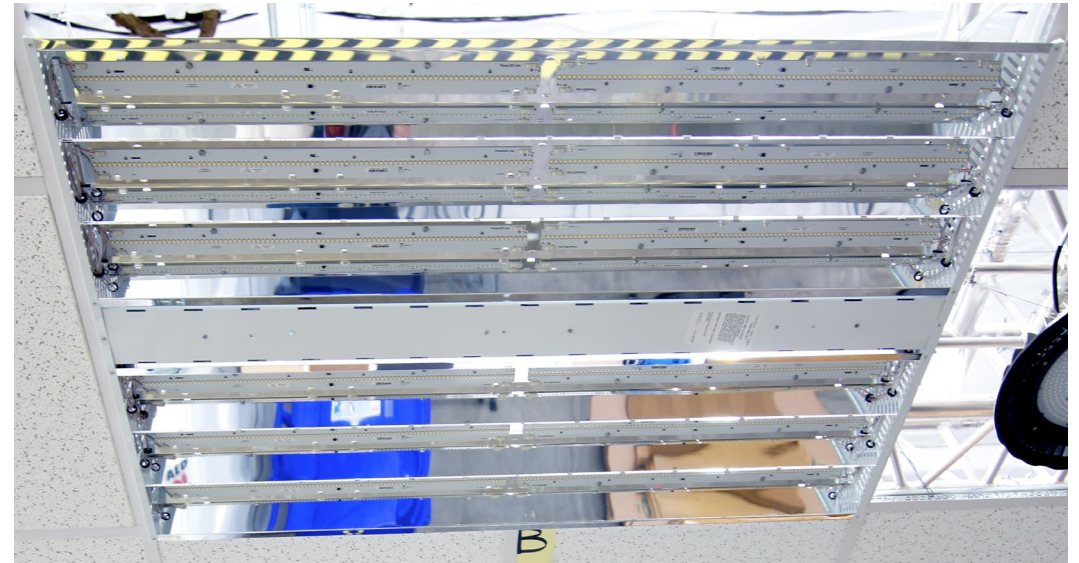
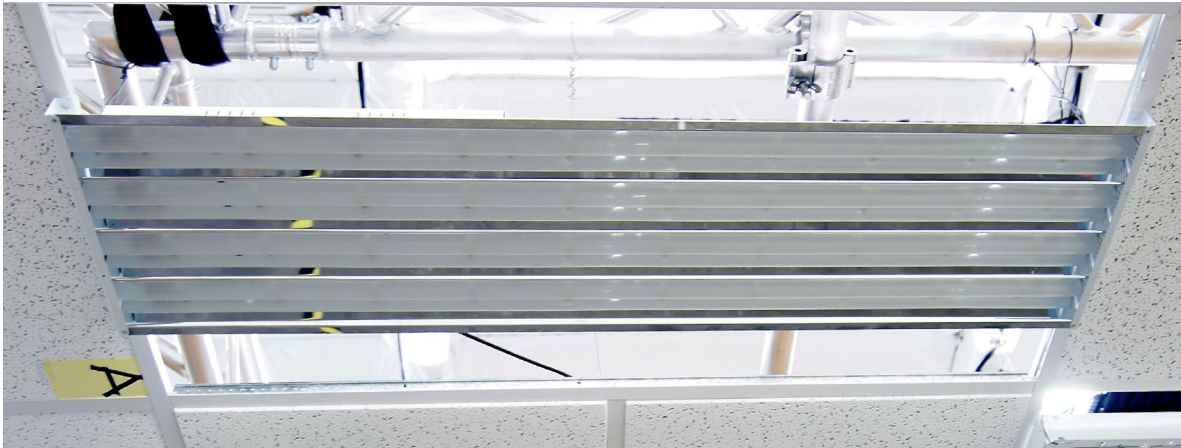


Illuminance Measurements at Floor, in lux							
CALiPER #	Under Luminaire	Quarter Point	Between Luminaires	Quarter Point	Under Luminaire	Average (weighted)	Uniformity (max/min)
17-S1B, C	748	711	648	719	746	706	1.2
17-S2A, B	725	847	732	818	668	773	1.3
17-S3A, B	595	574	535	572	594	569	1.1
17-S4A, B	677	659	622	672	704	661	1.1
17-S5A, B	472	528	502	514	552	514	1.2
17-S6A, B	834	790	709	784	792	774	1.2
17-S7A, B	701	661	616	650	657	651	1.1
Illuminance Measurements at 37" <u>Workplane Height</u> , in lux							
17-S1B, C	1242	962	724	940	1245	967	1.7
17-S2A, B	1401	988	811	996	1362	1044	1.7
17-S3A, B	970	787	632	830	1020	811	1.3
17-S4A, B	1131	882	719	927	1121	914	1.6
17-S5A, B	1023	849	683	889	1071	867	1.6
17-S6A, B	1362	1096	878	1035	1270	1081	1.6
17-S7A, B	1135	900	719	880	1036	896	1.6



Top Efficacy Performers – In situ

Results from in situ measurements – Horizontal illuminance max:min ratios:
17-S1 (left) and 17-S2 (right) produced the highest max:min ratios for workplane illuminance because they both had linear baffles to limit glare and control distribution



(Frankly, the other luminaires didn't perform much differently: 1.7 versus 1.6 max:min)

Top Efficacy Performers – In situ



Results from in situ measurements - Flicker:

- ▶ Several observers commented on flicker
- ▶ Luminaire 17-S6 produced 45% flicker, 120 Hz, which exceeds IEEE Standard P1789-2015 low-risk level. Flicker Index of 0.139, SVM of 1.684
- ▶ Compare to magnetically ballasted fluorescent at Flicker Index at 0.09
- ▶ All other luminaires were much higher frequency, lower Flicker Index

Table 5. Flicker metrics of the seven installed luminaire types.

Flicker Measurements					
CALiPER System ID	Modulation Frequency	Percent Flicker	Flicker Index	SVM	Meets IEEE Standard P1789-2015 Low Risk Criteria
17-S1B	1490 Hz	33.1	0.063	0.127	Yes
17-S2A	1950 Hz	5.7	0.009	0.035	Yes
17-S3A	120 Hz	0.6	0.001	0.022	Yes
17-S4A	1100 Hz	3.9	0.006	0.022	Yes
17-S5A	1460 Hz	9.3	0.019	0.033	Yes
17-S6A	120 Hz	45.4	0.139	1.684	No
17-S7A	>2000 Hz	10.6	0.017	0	Yes

Top Efficacy Performers – In situ



Results from in situ measurements - Glare:

- ▶ Luminance of top-rated luminaire with diffuser over LEDs for visual comfort was 40,000 cd/m² (compare to T5HO at 25,000 cd/m²)
- ▶ Luminances of visible LED packages VERY high and corresponded to rankings of low visual comfort, at least at mounting height of 11'-3" aff

Table 4. Measured luminances of the seven luminaires installed at the mockup site.

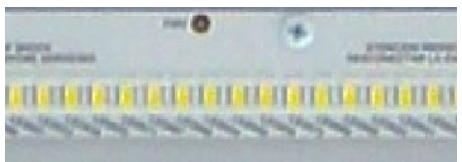
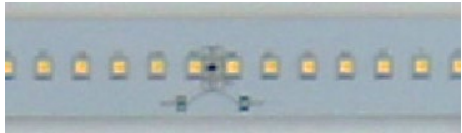
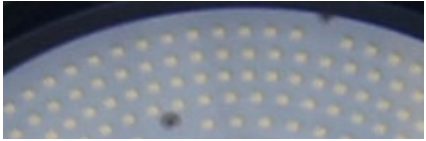
System ID	Measured luminance (cd/m ²) ^a	Area measured	Number of packages	Notes
17-S1B	40045	LEDs behind diffuse tubular cover	Not visible	Diffuse tube. Measured luminance value realistic.
17-S2A	>283700 ^a	Bare LED	1080	LEDs filled less than the meter's capture angle
17-S3A	>424800 ^a	Bare LED behind clear glass shield	536	LEDs filled less than the meter's capture angle
17-S4A	>400000 ^a	Bare LED	756	LEDs filled less than the meter's capture angle
17-S5A	>289000 ^a	Bare LED	672	LEDs filled less than the meter's capture angle
17-S6A	>154000 ^a	Bare LED, behind clear acrylic cover	2862	LEDs filled less than half the meter's capture angle
17-S7A	>478000 ^a	Bare LED, behind clear acrylic cover	576	LEDs filled less than the meter's capture angle

(a) Luminance meter capture angle was 1/3°. The individual LED package did not fill the full capture angle, and therefore the measured value may underrepresent the actual luminance.

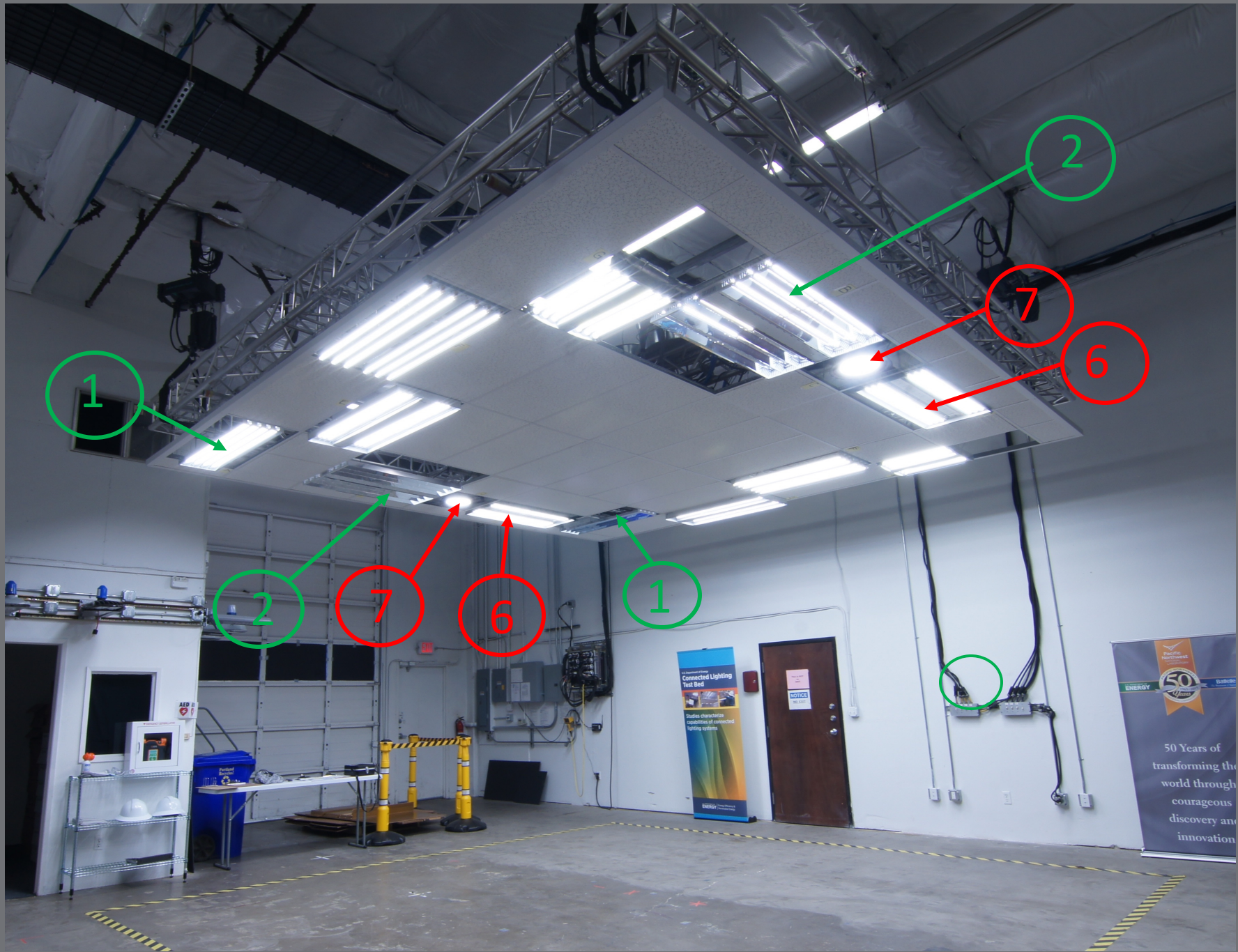
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(a) Luminance meter capture angle was 1/3°. The individual LED package did not fill the full capture angle, and therefore the measured value may underrepresent the actual luminance.



System ID	Measured luminance (cd/m ²) ^a	Area measured	Number of packages	Observer ranking	Estimated value
17-S1B	40045	LEDs behind diffuse tubular cover	Not visible	1	\$230
17-S2A	>283700 ^a	Bare LED	1080	2	\$196
17-S3A	>424800 ^a	Bare LED behind clear glass shield	536	7	\$168
17-S4A	>400000 ^a	Bare LED	756	6	\$173
17-S5A	>289000 ^a	Bare LED	672	5	\$174
17-S6A	>154000 ^a	Bare LED, behind clear acrylic cover	2862	3	\$192
17-S7A	>478000 ^a	Bare LED, behind clear acrylic cover	576	4	\$191



Top Efficacy Performers - Caveats

Limitations of this CALiPER study:

- ▶ Some applications for this luminaire type have mounting heights of 20' or higher, while some are lower
- ▶ The luminaires were mounted for observation in a ceiling that was intended to reach 15', but only 11'-3" above the floor was achieved. Average horizontal illuminances under and between pairs of luminaires ranged from 811 to 1081 lx
- ▶ Lower mounting height may have exaggerated the glare from the luminaire for the observers, although this height is not unusual for fine detail industrial tasks
- ▶ The volunteer observers were lighting-knowledgeable, with experience in industrial lighting. Although care was taken to reduce bias and order effects through the evaluation protocol, this was not a rigorously-designed human factors study. **However, it is often informative to get feedback from industry experts.**

Top Efficacy Performers - Conclusions

Results from study:

- ▶ Luminances of exposed LED packages were VERY high and corresponded to rankings of low visual comfort
- ▶ Highest efficacy product (~200 lm/W) had luminance $>400,000$ cd/m² and received rating of 6th out of 7
- ▶ Lowest efficacy product (136 lm/W) had diffuser with luminance of 40,000 cd/m² and received top observer rating (1st out of 7)
- ▶ Results on glare support the development and adoption of a glare metric that incorporates luminaire *luminance distribution*



Top Efficacy Performers - Conclusions

More results from study:

- ▶ Warmer CCT options would result in 13% to 17% drop in lm/W for some of these luminaires
- ▶ Optics to help control distribution and glare likely to reduce efficacy further
- ▶ The LED Lighting Facts and similar databases can be an excellent source of information, but it is incumbent on the specifier to investigate the performance of the *specific* product needed. Listings can often be based on the top-performing product in a family
- ▶ Consider other lighting quality issues: visual comfort, flicker, light distribution, color quality, but be prepared for the inevitable minor tradeoffs in efficacy



Top Efficacy Performers – Thanks!

Final report can be accessed [here](#):

Many thanks to our 23 IES and APEM observer volunteers!

And thanks to my PNNL co-authors:

- ▶ Tracy Beeson
- ▶ Joshua McIntosh
- ▶ Sarah Safranek



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