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Project Title:
"Materials and Designs for High-Efficacy LED Light Engines"

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EXECUTIVE SUMMARY

Cree, Inc. conducted a narrow-band downconverter (NBD) materials development and implementation program which will lead to warm-white LED light engines with enhanced efficacy via improved spectral efficiency with respect to the human eye response. New red (600-630nm) NBD materials could result in as much as a 20% improvement in warm-white efficacy at high color quality relative to conventional phosphor-based light sources. Key program innovations included:

- **High** (>90%) **quantum yield**: on par with or higher than conventional red phosphors;
- **Narrow** (<40nm FWHM) **emission**: enables a warm-white spectral efficiency gain of >15% over red phosphors at the same or higher color quality;
- **Minimized component-level losses** due to “cross-talk” and light scattering among red and yellow-green downconverters, for a >5% system efficacy gain;
- **Improved reliability** to reach parity with conventional phosphors and reach reliability thresholds required for numerous SSL applications.

NBD-enabled downconversion efficiency gains yielded an end-of-project LED light engine efficacy of **>160** lm/W at room temperature and 35 A/cm^2, with a correlated color temperature (CCT) of ~3500K and >90 CRI (Color Rending Index). NBD-LED light engines exhibited equivalent luminous flux and color point maintenance at >1,000 hrs. of highly accelerated reliability testing as conventional phosphor LEDs. A demonstration luminaire utilizing an NBD-based LED light engine had a steady-state system efficacy of >150 lm/W at ~3500K and >90 CRI, which exceeds the 2014 DOE R&D Plan luminaire milestone for FY17 of >150 lm/W at just 80 CRI.[1]

Cree was uniquely positioned to develop a vertically integrated technology which, by combining synthesis evaluation, reliability, and NBD-LED light engine configuration advances with a pathway toward low cost, is clearly differentiated from piecewise or incremental approaches. Because Cree could simultaneously address all of these key focus areas, we not only discerned underlying NBD characteristics that lead to high reliability, but also accelerated NBDs toward application in real LED packages. It is anticipated that this Core Technology development program will enable a new class of cost-effective, high-efficacy LEDs which will accelerate widespread SSL adoption. We anticipate that NBD-LEDs will find use in a broad range of luminaire architectures, thereby proliferating the benefits of this high-efficacy technology.

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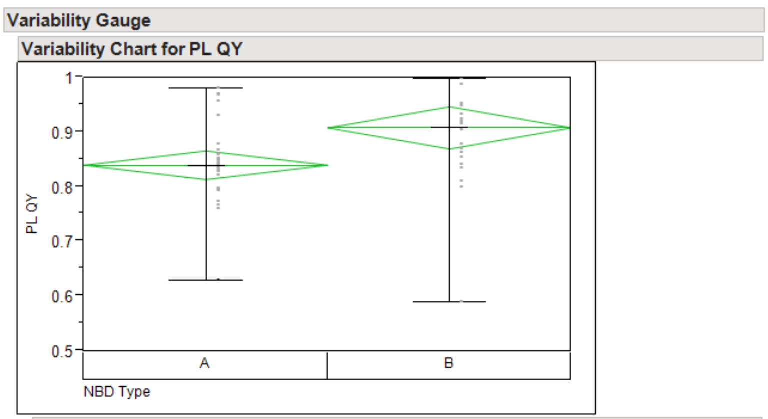
[1] Solid-State Lighting R&D Multi-Year Program Plan, prepared for the U.S. Dept. of Energy; Table 4.4 (April 2014).

GOALS AND ACCOMPLISHMENTS

Task 1: NBD Synthesis

Cree conducted numerous evaluation studies of the synthesis of NBDs which can efficiently down-convert blue (440-460nm) light to red wavelengths (600-630nm). While achieving high "t=0" (as-synthesized) quantum yield (QY) was prioritized since program start, focus also shifted to increasing NBD reliability in accelerated testing conditions (see below). Co-optimizing these two key characteristics was challenging, as the synthesis and processing conditions demonstrated to result in high initial QY may produce inferior long-term reliability, for example. Thus as a part of evaluation, the impact of post-synthesis treatments was quantified. These treatments were designed to modify the chemical and physical characteristics of the NBDs in order to increase their robustness in aggressive high-temperature and high-humidity testing conditions.

Synthesis developmental studies were assess the effects of key synthesis parameters on QY. These parameters were found to be inter-related – for example as composition was altered, the optimal reaction time or temperature might need to be modified. Thus a matrix design-of-experiments approach was utilized, in which key synthesis parameters were systematically varied alone or in combinations. While NBD composition and structure were routinely analyzed, quantum yield and peak emission wavelength reproducibility were of primary concern since they directly affect the color quality and achievable efficacy of LEDs into which they are incorporated.



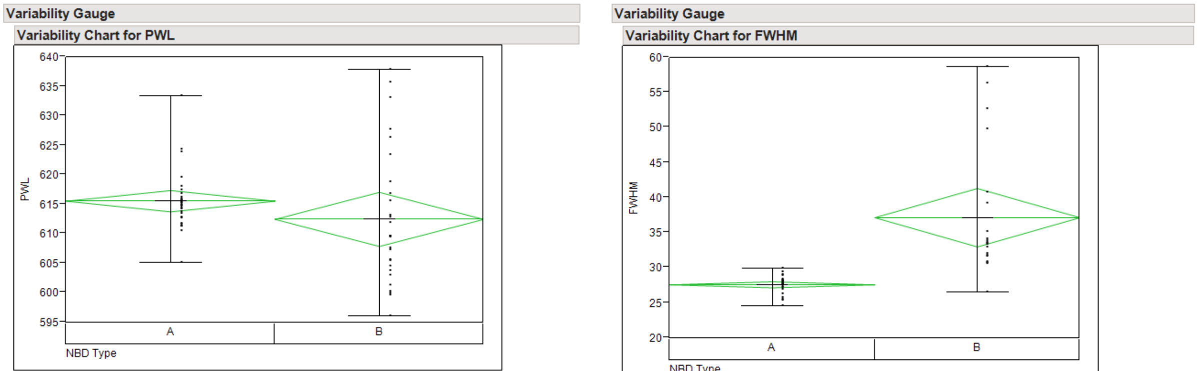
Variability Summary for PL QY

	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Minimum	Maximum	Observations
PL QY	0.873259	0.090493	0.011882	0.849465	0.897053	0.591	1.998	58
NBD Type[A]	0.841452	0.071331	0.012811	0.815287	0.867616	0.631	0.983	31
NBD Type[B]	0.909778	0.097421	0.018749	0.871239	0.948316	0.591	1.998	27

Fig. 1. NBD quantum yield for two compositions, measured as-synthesized in a calibrated comparative fluorimeter. The mean value for composition B was ~91%, exceeding a milestone goal.

As shown in Fig. 1, the as-synthesized quantum yield (quantified using a calibrated comparative fluorimeter) was consistently measured over 80%. Composition A, the most commonly synthesized NBD composition, showed an average QY value of 84%. Composition "B", similar to composition A but with a modified structure, exhibited a slightly higher average QY value of ~91%. In conjunction with the average emission peak wavelength and full width at half maximum values shown in Fig. 2 below, this QY exceeded Milestone 1.1 goal of 90%. Peak wavelengh values for composition A and B were similar, at ~616nm and ~613nm, respectiviely.

The average peak widths for these two compostions were 27.7nm and 37.3nm, with composition B showing a broader distribution.



Variability Summary for PWL

	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Minimum	Maximum	Observations
PWL	614.2379	8.747267	1.148572	611.938	616.5379	596.2	638	58
NBD Type[A]	615.6742	4.923885	0.884356	613.8681	617.4803	605.3	633.6	31
NBD Type[B]	612.5889	11.59679	2.231804	608.0013	617.1764	596.2	638	27

Variability Summary for FWHM

	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Minimum	Maximum	Observations
FWHM	31.56346	7.500615	1.040148	29.47528	33.65165	24.7	58.8	52
NBD Type[A]	27.69677	1.159162	0.208192	27.27159	28.12196	24.7	30.1	31
NBD Type[B]	37.27143	9.168486	2.000728	33.09798	41.44487	26.7	58.8	21

Fig. 2. Distributions of NBD composition A and B emission peak characteristics: peak wavelength (left) and full width at half maximum (right).

In addition to synthesis of the NBD emitter material itself, post-synthesis treatments were developed as a means of increasing NBD reliability while also maintaining high QY. Analysis indicated that there was often a direct tradeoff between these two key characteristics, since surface modification of the NBD could have deleterious effects on its radiative efficiency, for example.

Process Control

Process control studies for narrow-band downconverter (NBD) synthesis and post-synthesis treatments were undertaken to assess reproducibility. Numerous process repeats were carried out to establish the degree of control over NBD QY and red centroid wavelength (CWL), since both of these characteristics affect LED color point and efficacy. In Fig. 3 the QY and CWL are plotted for a number of repeated runs consisting of synthesis and post-synthesis treatment. Both characteristics were found to vary less than targeted bands (<10% for QY and <2nm for CWL). This was an encouraging result, since it indicated the potential viability of these synthesis and treatment processes for fabricating NBDs which contribute to a consistent white LED color point. The Milestone 1.3 target was met early, noting that it called for consistency in luminous flux instead of quantum yield. Since the fraction of lumens contributed by a red NBD in a warm-white white LED package is ~30%, total white luminous flux variation caused by a 10% NBD QY change would be limited to 3%.

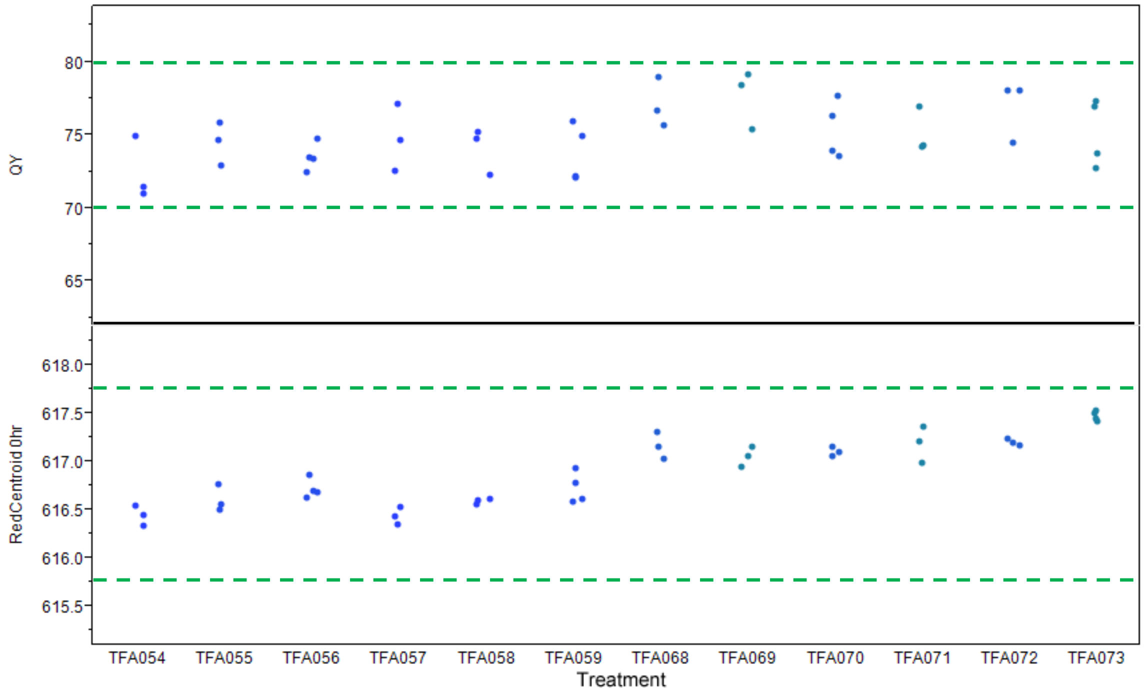


Fig. 3. NBD QY (top) and red CWL (bottom) after post-synthesis treatment for reliability enhancement, for a number of repeated processing runs. Both QY and CWL were within target bands (<10% and <2nm variation, respectively, as indicated by dotted green lines).

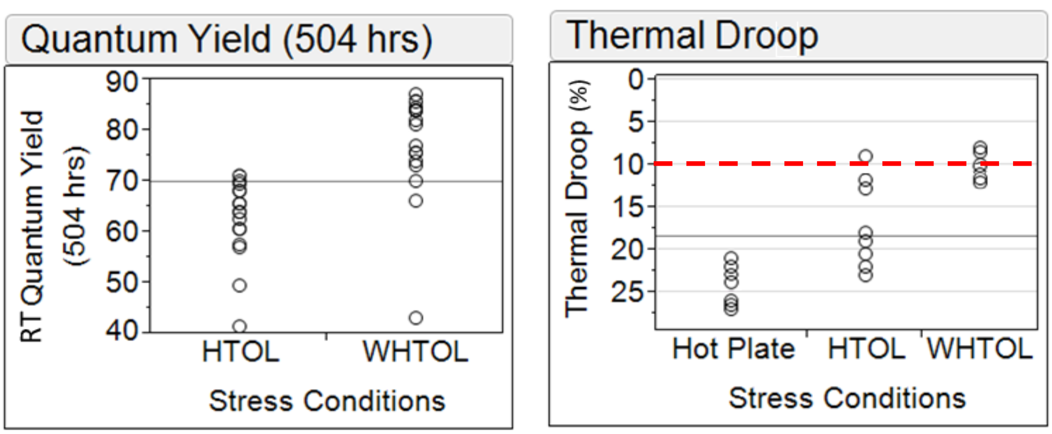


Fig. 4. Left: Room-temperature NBD QY measured in packages stressed for 504 hrs. in HTOL and WHTOL testing conditions. Right: Thermal droop of these NBDs, some of which exhibited <10% drop from RT to 85°C.

While quantifying QY at room temperature provided rapid feedback for synthesis and post-synthesis treatment development, the drop in NBD QY that is observed when measured in package at room temperature vs. 85°C was also measured. In addition, thermal droop for NBDs in LED packages stressed for >504 hrs. in accelerated testing conditions was quantified. This forward-looking approach provided guidance on the prospective behavior of NBDs in demanding application conditions. As shown in Fig. 4, several NBDs showed >10% thermal droop from RT to 85°C, but some were below this threshold. A correlation between post-stress RT QY and the degree of thermal droop was seen, such that as QY increased, droop decreased.

Task 2.0 – NBD Reliability & Test Development

Cree conducted frequent reliability (accelerated lifetime testing) evaluations for various combinations of NBD composition, structure, and post-synthesis treatment. These tests primarily consisted of HTOL (high-temperature operating lifetime: 85°C with stress current) and WHTOL ("wet" high-temperature operating lifetime: 85°C, 85% relative humidity with stress current), which reveal failure mechanisms in a timeframe short enough to provide useful feedback for synthesis development.

As plotted in Fig. 5, we observed improvements in NBD reliability relative to earlier performance. These improvements resulted from both NBD compositional modification and post-synthesis chemical treatment. Here we show combinations of two compositions ("A" and "B") and two treatments ("T1" and "T2"). NBD composition A with no post-synthesis treatment showed rapid QY degradation, as anticipated from earlier testing on a similar composition. Application of treatment T1 significantly improved QY maintenance, but a gradual decay was still observed at ~1,000 hrs. Application of treatment T2 to composition A appears to have resulted in a more stable QY, albeit at fewer testing hours. Meanwhile, composition B showed superior initial QY values than composition A but fell off more quickly for treatment T1.

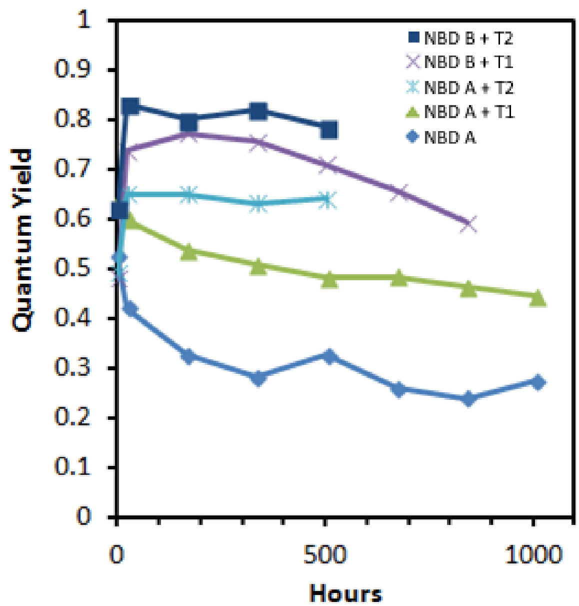


Fig. 5. Estimated QY of NBDs of two compositions and two post-synthesis treatments in LEDs subjected to HTOL testing.

Later NBD reliability testing focused on the fabrication of warm-white (3000-3500K) LED packages via blends of yellow/green phosphors and red NBDs. The luminous flux and color point maintenance of these packages was regularly recorded during long-duration exposure to high temperature, high current (*i.e.* high blue light flux from the chip), and/or elevated relative humidity. By testing at two temperatures (55°C and 85°C) as well as three stress currents (50, 150, 350mA), we built a body of data from which acceleration factors could be derived and used for NBD lifetime prediction (*e.g.* to 90% lumen maintenance). As shown in Fig. 6, both blue light flux and ambient temperature affected color point maintenance, with the combination of 85°C/350mA showing unacceptably large color shift. At >2,000 hrs., there were several current-temperature combinations for which the LF and color point were relatively stable – an encouraging prospect for NBD lifetime in corresponding application conditions.

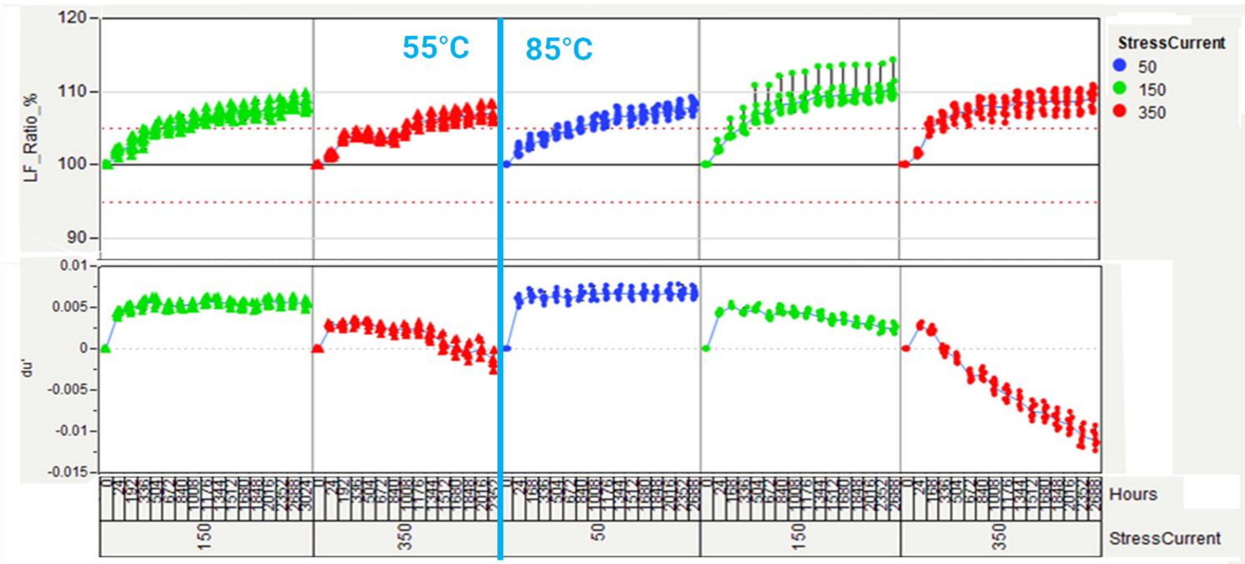


Fig. 6. Shifts in luminous flux (LF, top) and color point (du', bottom) of ~3500K white LEDs under accelerated testing conditions utilizing 55°C (left) and 85°C (right) ambients and three different stress currents.

Determination of accelerated NBD lifetime factors related to temperature and light flux was made possible by the combinations of each shown above. Note that the blue light flux impinging on the NBDs should scale nearly linearly with stress current, and that current is much easier to monitor and control than flux. Current is also the parameter which is directly translatable into light engine configuration (*e.g.* number of components and strings) for luminaires. Iterative testing revealed that color point stability, more so than relative luminous flux, was the primary criterion by which NBD reliability in white (phosphor + NBD) LED packages should be judged. As shown in Fig. 7, although the highest current multiple (7x baseline) caused color point failure (du'v' > 0.007) at ~2,000 hrs., at a lower multiple of 3x the color shift was acceptable at ~4,000 hrs. Meanwhile, relative luminous flux stayed constant at 99-100%. We thus exceeded our Milestone 2.3 goal of 1,000 hrs. at both 3x and 7x conditions, which were used as input for integration of NBD LEDs into luminaires.

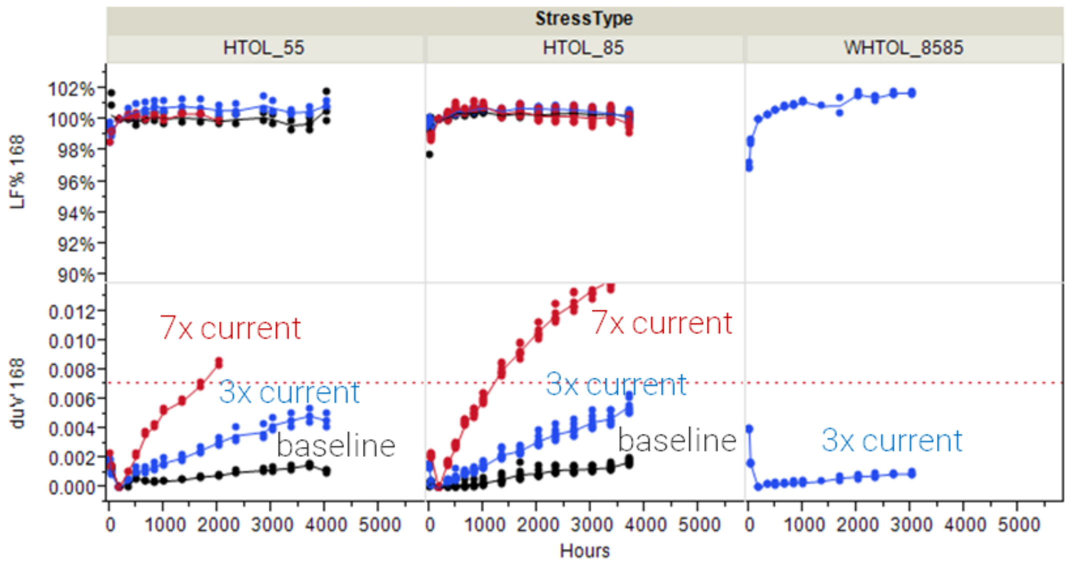


Fig. 7. Shifts in luminous flux (LF, top) and color point (du'v', bottom) of ~3500K white LEDs under accelerated testing conditions at 55°C (left) and 85°C (center), and 85°C/85% relative humidity (right) ambients and three different stress currents (baseline, 3x baseline, and 7x baseline).

Intra-luminaire reliability testing

In conjunction with package-level NBD accelerated testing (high temperature, humidity, and drive current), later in the program we began long-term evaluation of NBD-LEDs integrated into actual luminaires. This was intended to test NBDs in "real world" conditions, and correlate performance with that predicted earlier by accelerated testing analysis. The LED drive current and solder point temperature values were specified to be comparable to those in baseline all-phosphor packages in one of Cree's commercial troffers. These values were also aligned with the drive current and temperature levels predicted to yeidl long lifetime from lifetime prediction modeling.

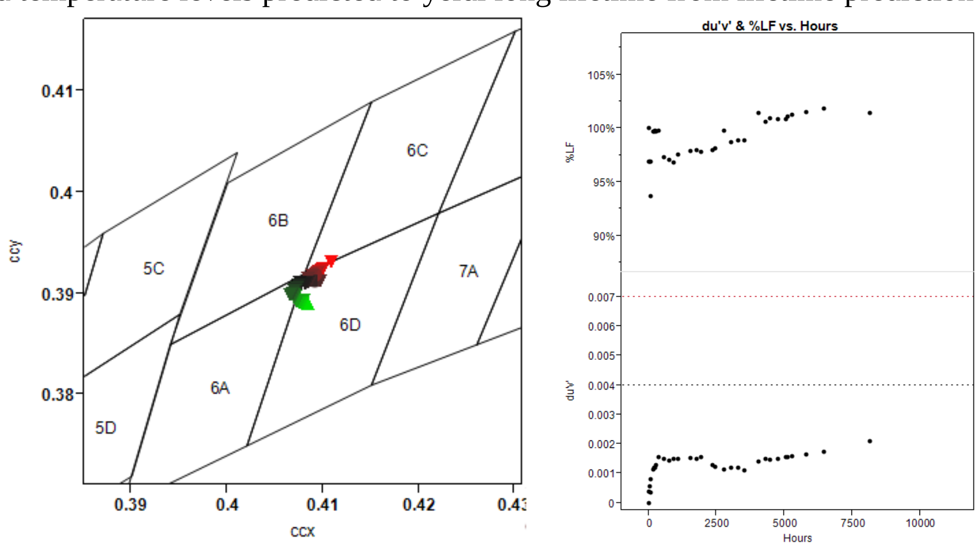


Fig. 8. Left: Troffer CCy/CCy color point over time, with green representing starting values and red as late-stage values. Right: relative luminous flux (top) and color point (bottom) shifts vs. operating time.

We fabricated NBD-LEDs to match the color point of their all-phosphor counterparts, and were assembled into luminaire light engines as a 1-to-1 replacement for the conventional packages. The luminaires were then operated continuously at full output, with periodic measurements of luminous flux (LF) and color point made (more frequently early in testing than later on). In Fig. 8 we plot the LF, color point, and color point shift (du'v') values exhibited by an NBD-LED based troffer over time. Although early (<100 hr.) LF and color point shifts were observed, LF recovered to the starting value (and even rose slightly higher), while color point stabilized at <0.002 du'v'. After >7,500 hrs. of continuous run-time testing the takeaway was that state-of-the-art NBD-LEDs in actual troffer application conditions display high stability. This stability will be confirmed with further testing as input for refining lifetime prediction using our previously developed models.

Task 3 - NBD-LED Light Engine Configuration and Process Development

Silicone Curing

In addition to assessing NBD reliability in accelerated testing conditions, we also identified silicone curing conditions in which NBDs exhibit minimal QY drop. As shown in Fig. 9, we explored numerous silicone formulation & curing modifications relative to a baseline condition ("A" in Fig. 9). Although silicone formulation changes had a measurable impact on QY drop after curing, the curing conditions themselves had a larger effect, with formulations H and O showing ~3% QY drop after curing in the condition shown at right in Fig. 9. This satisfied our Milestone 3.1 goal of <5% drop, and also indicated the potential for further process refinement to yield NBDs with no discernible QY drop during this critical LED processing step.

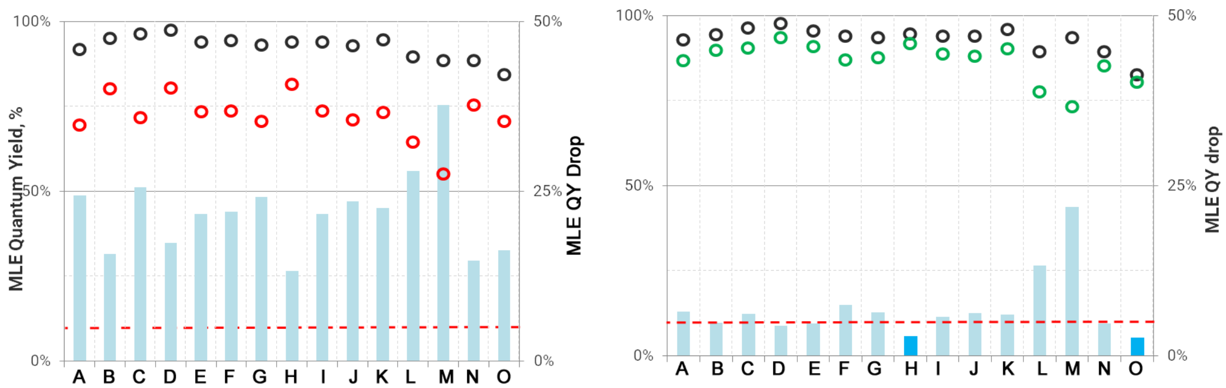
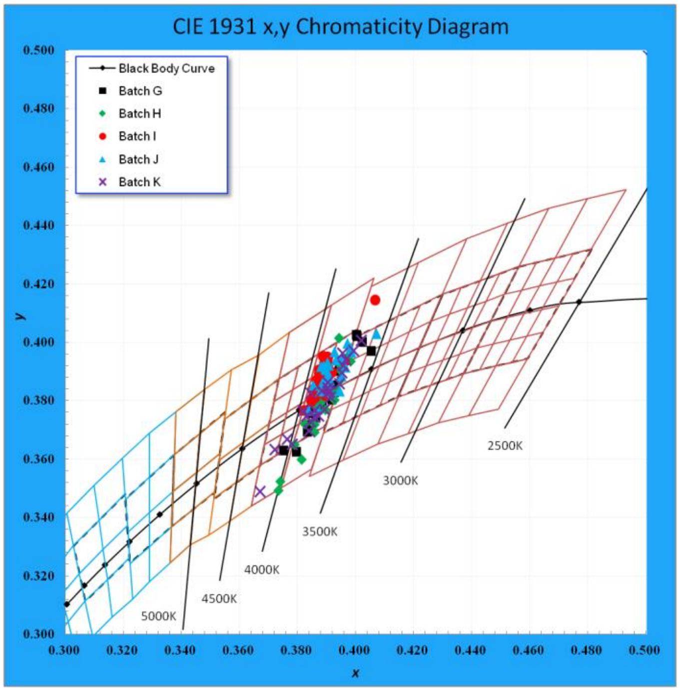


Fig. 9. NBD quantum yield before (black circles) and after (red & green circles) curing in silicones. Blue bars are the resulting percentage drop, plotted in units indicated on the right-hand y-axis. Left plot: curing condition 1, with various silicone formulations. Right plot: curing condition 2, with the same silicone formulations.

NBD-LED fabrication consistency

Once consistency in key NBD synthesis and post-synthesis treatment parameters was demonstrated, Cree then investigated the corresponding consistency with which white NBD-LEDs could be fabricated using color-tuned blends of red-emitting NBDs and green/yellow conventional phosphors. This work centered on packages with color points around ~4000K on the black-body locus, and is representative of the wide CCT range (2700-5000K) in which red NBDs are expected to find application (particularly for CRI >90). After initial targeting and optimization runs we were able to achieve color point yields (consistency) exceeding our Milestone 3.2 goals. As shown in Fig. 10, each of the five batches had >80% yield to the four-step ANSI E5 bin, and taken together these batches had an ~88% yield to bin. This is a good indicator that NBD-LEDs will have a comparable color point yield to conventional all-phosphor formulations.



Batch ID	Total Parts	Parts In Bin	Bin Yield (%)
G	28	24	85.7
H	27	22	81.5
I	26	23	88.5
J	27	25	92.6
K	28	26	92.9
Cumulative	136	120	**88.2%**

Fig. 10. Left: Color points of prototype NBD-containing white LEDs color targeted at 4000K CCT on the black-body locus. Right: tabulated color point yield of each fabrication batch (and all batches combined) to the 4-step ANSI E5 bin. This color point consistency, achieved after a handful of optimization runs, is encouraging for eventual LED mass production.

As red-emitting NBDs are ultimately intended as direct replacements for conventional red phosphors in LED packages, we have evaluated the impact of NBDs on not just efficacy but color point and intensity over angle. These characteristics are important for system optical design, since they influence diffuser, lens, and/or reflector configurations. We fabricated representative warm-white (~3000K) LED packages of two types: green/yellow phosphor blended with red NBDs, vs. all-phosphor (standard recipe). The two types were not precisely color matched, and had an offset in integrated v' (the vertical axis on the CIE 1976 diagram) but were well matched in integrated u' (horizontal axis). We therefore compared their far-field u' values and relative intensity as a function of angle, using a goniophotometer. The results are shown in Figs. 11 and 12. In the former, it is apparent that the maximum difference between u' color coordinate was far less than 0.004, satisfying a milestone goal. The u' coordinate, which roughly corresponds to red-green variation in the vicinity of the blackbody locus, was lower for phosphor/NBD than all-phosphor on axis, but then became greater at very high angles. This difference is also evident in Fig. 12, which compares the intensity vs. angle for the two package types. The phosphor/NBD packages had higher intensity than all-phosphor over all angles, and the difference increased at high angles. The asymmetry in this difference was due to the prototypical (hand-built) nature of the packages, and would be expected to decrease in production packages. We believe the u' and intensity differences between phosphor/NBD and all-phosphor packages are acceptable.

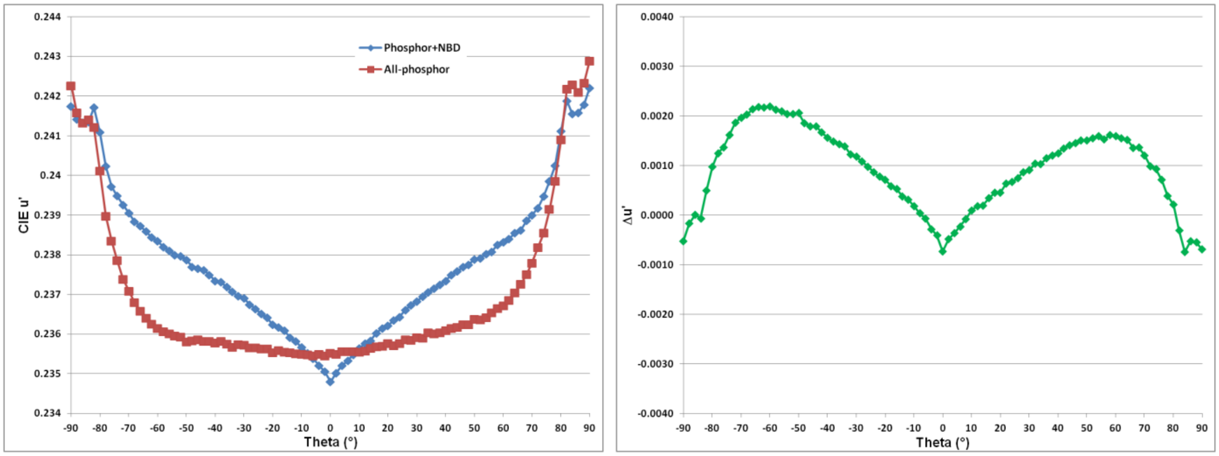


Fig. 11. Left: CIE u' color coordinate vs. angle for LED packages containing green/yellow phosphors blended with red NBDs, vs. those with conventional red phosphors. Right: the difference in u' coordinate between the two package configurations. The u' values differed by up to ~0.002.

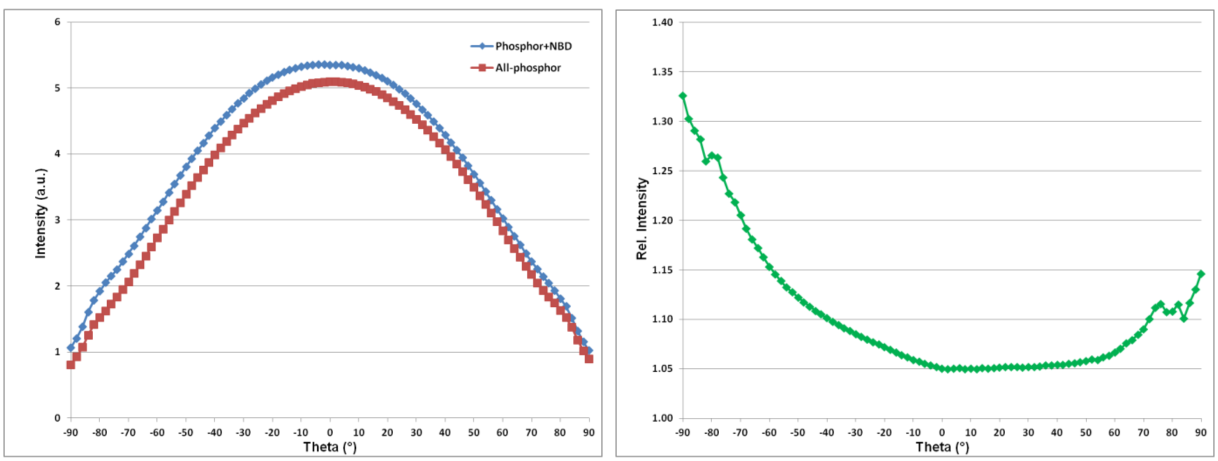


Fig. 12. Left: Intensity vs. angle for LED packages containing green/yellow phosphors blended with red NBDs, vs. those with conventional red phosphors. Right: the relative intensity of the phosphor/NBD packages compared to all-phosphor. The intensity of the former was always higher than the latter, and varied by up to ~30% at high angles.

<u>Task 4.0 – NBD-LED Light Engine Spectral Engineering</u>

Spectral efficiency

One of the primary motivations for utilizing red-emitting NBDs over conventional red phosphors is their comparatively narrow spectral width (<40nm, vs. 90-100nm). This reduces the amount of light emitted beyond the generally accepted range of human eye sensitivity, which decreases to near-zero at ~700nm. Thus the luminous efficacy of radiation (LER), which is a convolution of the radiant spectrum with the eye response, is markedly improved for NBDs. Coupled with high (>80%) quantum yield, the net efficacy ("useful" light per input electrical watt) of white NBD-LEDs will be correspondingly superior to that offered by conventional red phosphors.

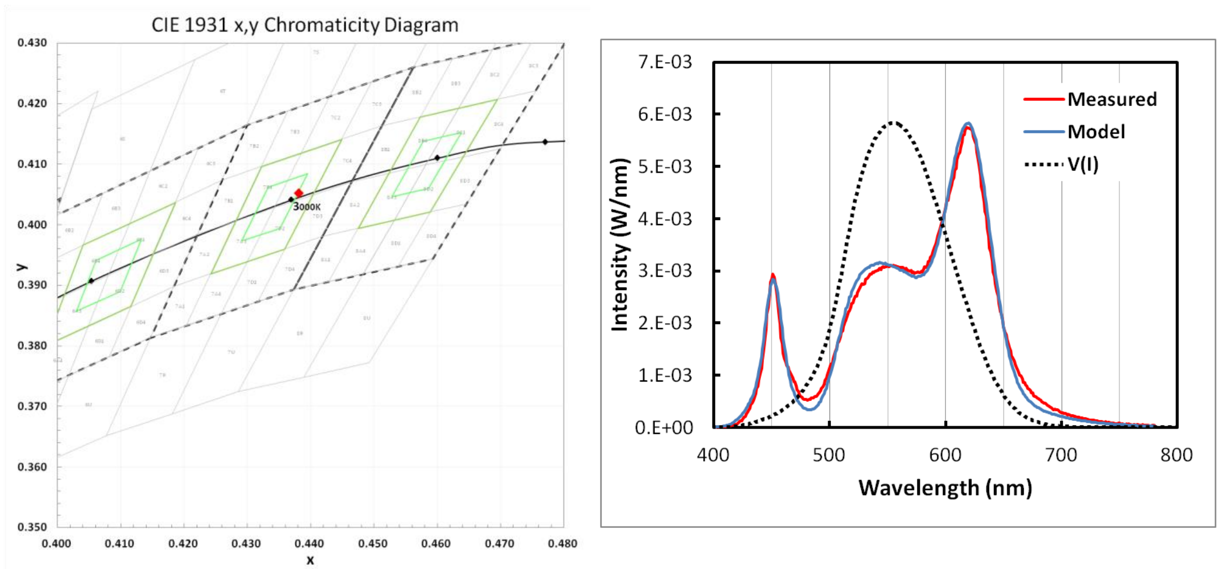


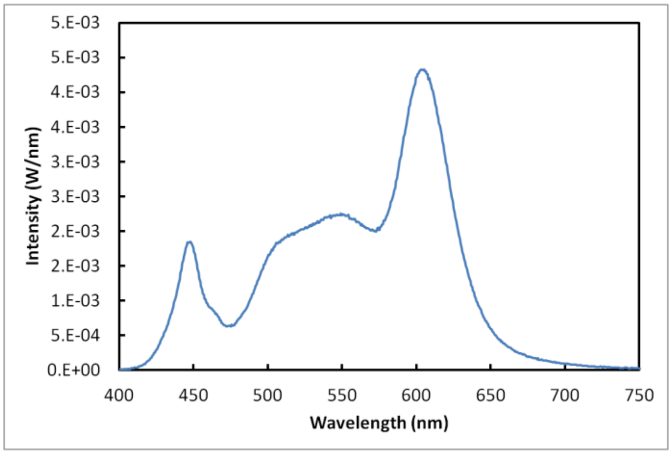
Fig. 13. Left: CIE x,y chromaticity diagram indicating the ~3000K color point of the NBD-based white LED formulation. Right: Spectra of the measured vs. modeled formulation, overlaid with the photopic eye response (dashed line).

Early in the program we experimentally confirmed the LER gains which had been previously predicted by spectral modeling. The models were built using inputs from blue chip spectra combined with those from green/yellow phosphor blends and a predicted red NBD emission peak and full width at half maximum. Corresponding LED formulations were made to assess the accuracy of the model, namely any non-idealities occurring in an actual LED. As shown in Fig. 13 above, the measured color point of a representative formulation was on the black-body locus at ~3000K, and the modeled and measured spectra overlapped closely. An LER value of ~350 lm/W_{opt} (vs. 354 lm/ W_{opt} modeled) was achieved at 2,990K and 90 CRI, satisfying the criterion for Milestone 4.1. Based on this validated model, further gains in LER (and correspondingly, efficacy) are expected as NBR peak width decreases.

NBD-LED Efficacy

We projected that the largest efficacy gains enabled by red-emitting NBDs over conventional red phosphors will be realized at >90 CRI, but numerous indoor and outdoor lighting applications require only ~80 CRI. To explore achievable white LED efficacy at 80 CRI and benchmark against the conventional all-phosphor LED development tracked in DOE's SSL R&D roadmap, we fabricated NBDs with a peak wavelength of ~604 nm, which is shorter than that required for >90 CRI. This required only a minor modification to our NBD synthesis procedure, and showed high reproducibility in line with the results we reported above. We ensured that NBD quantum yield remained high (>80%) through post-synthesis treatment and incorporation into the silicone LED encapsulant. By combining the NBDs with state-of-the-art blue-emitting (~450nm) chips and green/yellow phosphors, we were able to achieve an "instant-on", room-temperature component efficacy of 161.5 lm/W at DOE's benchmark current density of 35 A/cm^2, thus exceeding our

Milestone 4.3 target. The emission spectrum and key characteristics of this warm-white package as measured in a calibrated integrating sphere are shown in Fig. 14.



Characteristic	Value
Drive Current Density	35 A/cm^2
Temperature	21 °C
Luminous Efficacy	**161.5 lm/W**
Color Rendering Index R_a	83.5
Correlated Color Temperature	3457 K
Color Point CCx, Ccy	0.4009, 0.3890
Luminous Efficacy of Radiation	364 lm/W_{opt}

Fig. 14. Spectrum (left) and key characteristics (right) of a white LED fabricated with a red-emitting NBD and conventional green/yellow phosphors. The instant-on efficacy of 161.5 lm/W at 35 A/cm^2 is significantly higher than achievable with all-phosphor formulations at the same color point and color quality, owing to the superior spectral efficiency of the NBD.

In parallel with instant-on, room-temperature efficacy benchmarking, we also assessed NBD thermal droop (roll-off in quantum yield at elevated temperature), since real-world luminaires do not enable a steady-state LED junction temperature (T_j) of ~20°C. Depending on application requirements and luminaire design and cost constraints, components may experience a T_j of 85°C or higher. We note that thermal droop in LED efficacy is also a concern due to chip and green/yellow phosphor efficiency roll-off, but these are already well characterized. NBD thermal droop is a subject of ongoing study and optimization, since we have seen indications that it depends at least in part on NBD post-synthesis treatment. In line with our later Task 5 activities (see below), we fabricated a prototype white NBD-LED light engine and integrated it into a troffer luminaire to evaluate thermal droop. At an approximate LED solder-point temperature of 50°C (reached after ~30 min. of equilibration), the decrease in light engine luminous flux was ~5%, which was largely attributed to NBD thermal droop (since chip and green/yellow phosphor droop are relatively low at this temperature). This result was in line with earlier NBD materials testing we had performed, and met our Milestone 3.4 criterion.

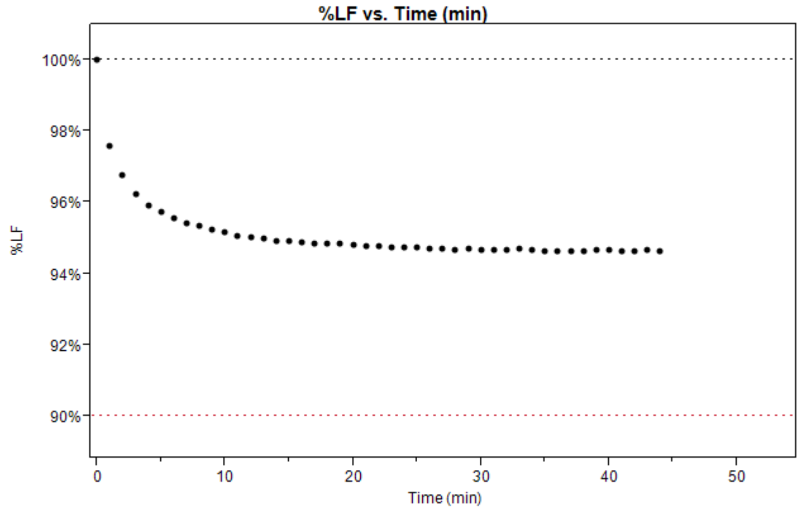
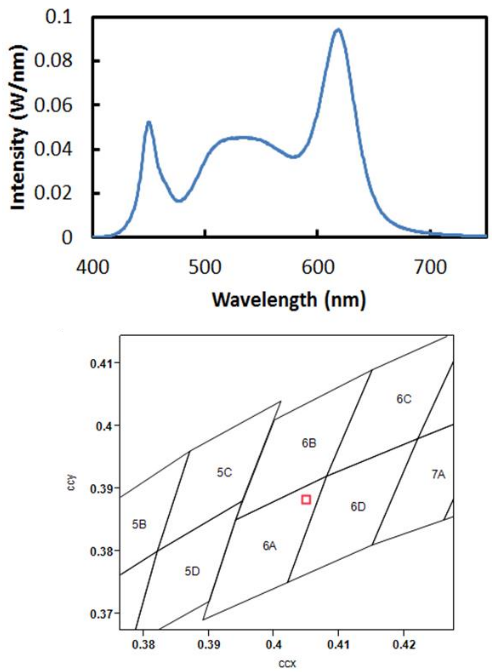


Fig. 15. Luminous flux vs. time for an NBD-based light engine in a prototype luminaire, with an approximate component solder-point temperature of ~50°C.

Task 5: Demonstration Luminaire

Using numerous reliability (Task 2), package efficacy (Task 3) and thermal droop (Task 3) data as guidance, we identified an LED package geometry as well as a drive current and operating temperature range within which NBD-LEDs would efficiently and reliably operate, as per our Milestone 5.1 goal. These characteristics led us to choose a troffer geometry as our final demonstration luminaire form factor. This is based on a new Cree troffer design which will be released soon, and which is specified for a nominal baseline warm-white efficacy of ~130 lm/W. We fabricated a new light engine using NBD-LEDs tuned to a ~3500K color point, but otherwise we kept the other luminaire sub-systems (housing, diffuser, driver) the same.

Via board-level testing in a calibrated integrating sphere we first verified that the light engine efficacy was in line with earlier component-level measurements. The peak room-temperature, instant-on efficacy was ~190 lm/W, which was adequate to meet our 150 lm/W net system efficacy goal, given expected sub-systems losses (optical, electrical, & thermal). The light engine was integrated into the luminaire, and system-level measurements were made in the same integrating sphere. From these data we were able to quantify sub-system losses, as well as confirm that a steady-state luminaire efficacy of 151 lm/W at >90 CRI was achieved. In Fig. 16 we plot the luminaire spectrum and color point, and also tabulate key characteristics of the NBD-based demo luminaire to the baseline version. The demo luminaire showed a >13% efficacy increase over the all-phosphor baseline at comparable luminous flux. In addition, while the demo luminaire CRI R_a (average) value of 92 was comparable to that of the baseline, its R_9 value of 72 was much higher, indicating superior rendering of saturated red and deep-red colors. We note that further increases in NBD-based luminaire efficacy would be expected with a purpose-built, higher-efficiency driver, but this was outside the scope of this project.



	Baseline	NBD-based
Fixture Efficacy (lm/W)	130AC (3,000K) 136AC (4,000K)	**151** AC (3,489K)
LED Efficacy (RT/IO) (25°C, op. current)	164 (3,000K) 174 (4,000K)	190 (3,489K)
CRI R_a	>90 (R_9~40)	92 (R_9~72)
Optical Eff.	95%	94%
Electrical Eff.	84-86% AC Mains	84% AC Mains
Thermal Eff. (LPW)	98%	98%
CCT	Variable (3000K-5000K)	Variable (3000K-5000K)
Lumens (SS)	3200	3300

Fig. 16. Left: Spectrum (above) and color CCx/CCy color point (below) of the demonstration luminaire. Right: table comparing baseline Cree troffer performance characteristics vs. those of the NBD-based demo luminaire. The demo luminaire exhibited a >13% efficacy increase at comparable CRI R_a and higher R_9.

PROJECT OUTPUT

A. Publications
No project-related articles, papers, or presentations were made during this reporting period.

B. Technologies/Techniques
New technologies or techniques were developed under the Award, and are being considered for further independent development by Cree.

C. Status Reports
None.

D. Media Reports
No media articles during this reporting period.

E. Invention Disclosures
No subject inventions during this reporting period.

F. Patent Applications

No domestic or foreign patent applications arising out of subject inventions during this reporting period.

G. Licensed Technologies
No subject inventions licensed to third parties during this reporting period.

H. Networks/Collaborations Fostered
No partnerships or other arrangements were concluded with respect to the project or technology area during this reporting period.

I. Websites Featuring Project Work or Results
No web site or other internet sites that reflect the work or results of this project were established during this reporting period.

J. Other Products
No additional project output, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment was produced during this reporting period.

K. Awards, Prizes, and Recognition
No awards, prizes, or other recognition for project work or results, subjection inventions, patents or patent applications were received during this reporting period.