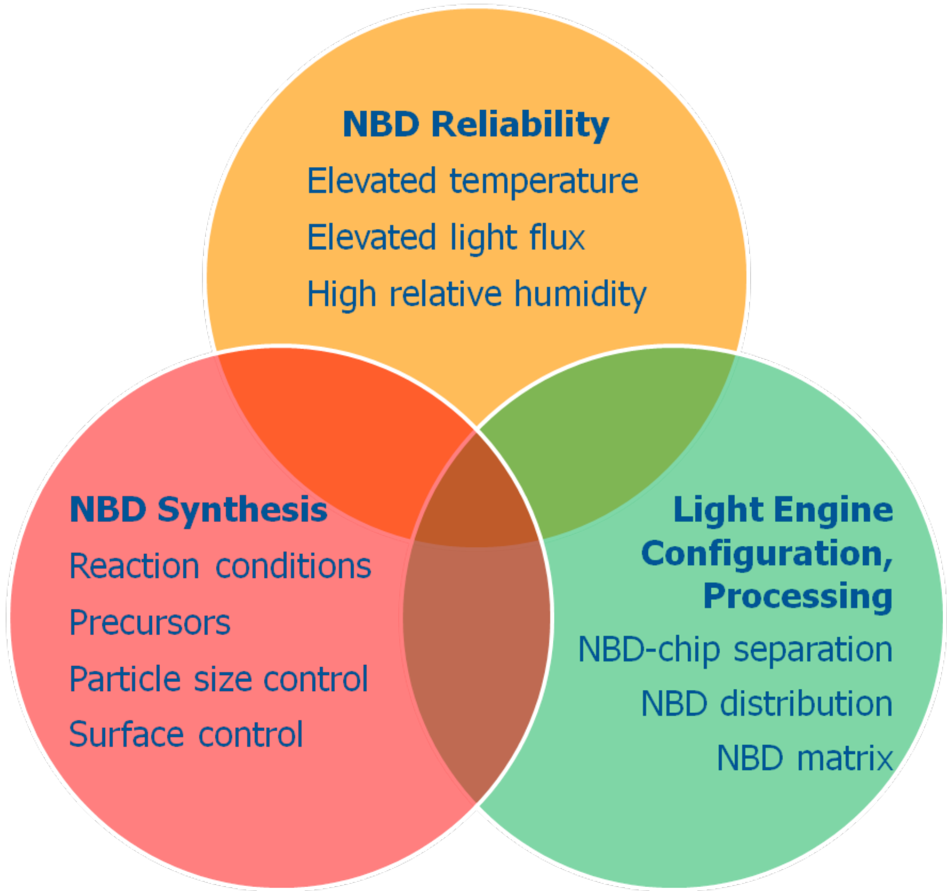
# Materials and Designs for High-Efficacy LED Light Engines

2017 Building Technologies Office Peer Review




*NBD: Narrow-Band Downconverter*

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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**Cree, Inc.**

# Project Summary

**Timeline**:

Start date: 7/1/15

Planned end date: 6/30/17

**Key Milestones:**

1. Month 9: measure red-emitting narrow-band downconverter (NBD) thermal efficiency "droop" of < 10% from room temperature to 85°C.
2. Month 15: confirm <10% LED luminous flux degradation and <0.004 du'v' color shift at >1,000 hrs. of accelerated testing (high-T, high current).

**Budget**:

**Total Project $ to Date**:

- DOE: $1.12M
- Cost Share: $281K

**Total Project $:**

- DOE: $1.5M
- Cost Share: $375K (20% of total)

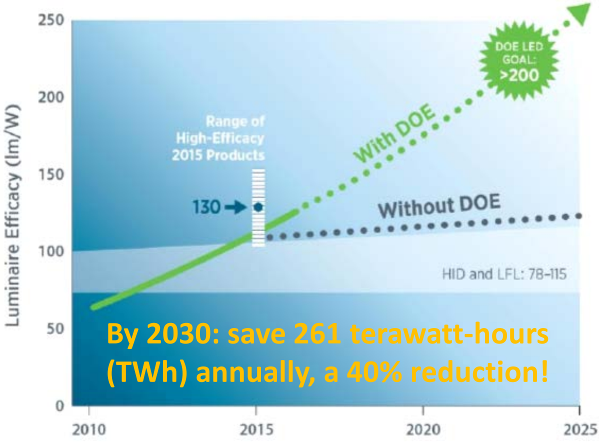
**Project Outcome**:

New red emitting narrow-band down-converter (NBD) materials will enable white solid-state lighting with **10-20% or higher efficacy** compared to conventional phosphors.

Cree is overcoming challenges in NBD **efficiency** and **reliability** (robustness) in typical LED operating conditions to accelerate these materials toward real applications.

# Purpose and Objectives

**Problem Statement**: simultaneous achievement of red-emitting NBDs with high **down-conversion efficiency**, high **spectral efficiency**, and high **robustness** in application conditions




**Target Market and Audience**: LEDs integrated into nearly all solid-state lamps and luminaires, particularly warm white (2700-3500K CCT).

**Impact of Project**:

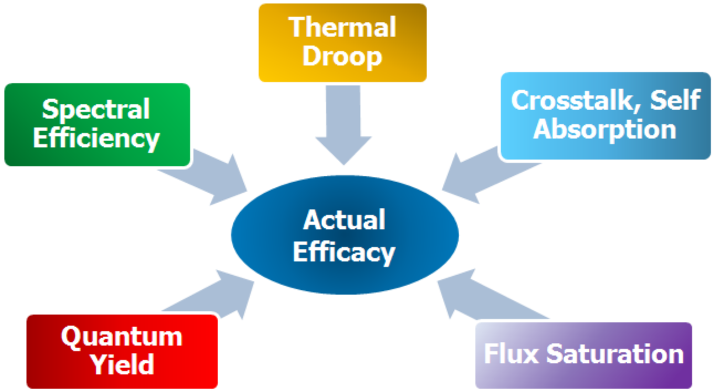
1. *Output*: stable and efficient red-emitting NBD materials as drop-in replacements for conventional red phosphors in white LEDs.
2. *Primary contribution*: increase warm-white LED efficacy in a timeframe that meets or exceeds DOE SSL roadmap goals
   a. Near term: >160 lm/W* in low- to medium-power LED packages
   b. Intermediate term: >170 lm/W* in low- to medium power LED packages
   c. Long term: proliferation into high-power LED packages

*At DOE SSL baseline LED drive current of 35 A/cm$^2$ (~1 W/mm$^2$). LED efficacy at lower currents will be significantly higher (>180 lm/W).

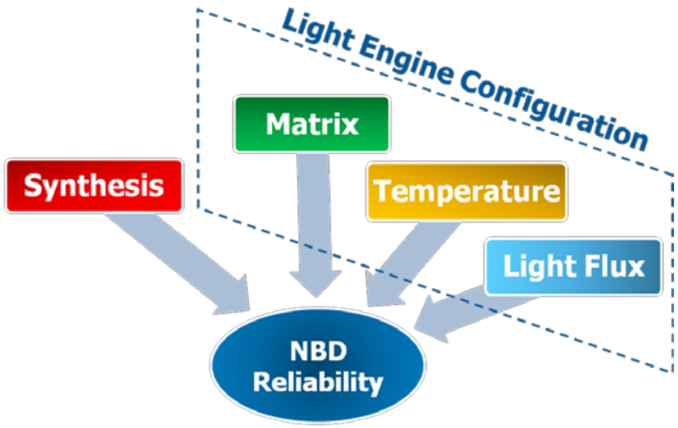
# Approach

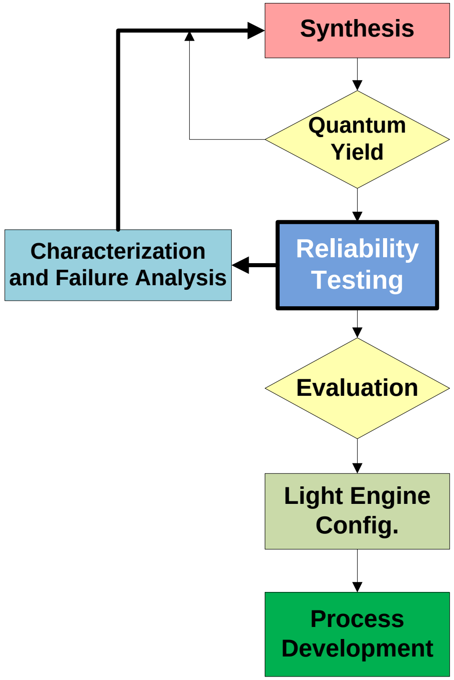
**Approach**: Synergistically combine advances in materials synthesis, light engine configuration & processing, and reliability (robustness).

Factors contributing to **Efficacy**:




Factors contributing to **Reliability**:



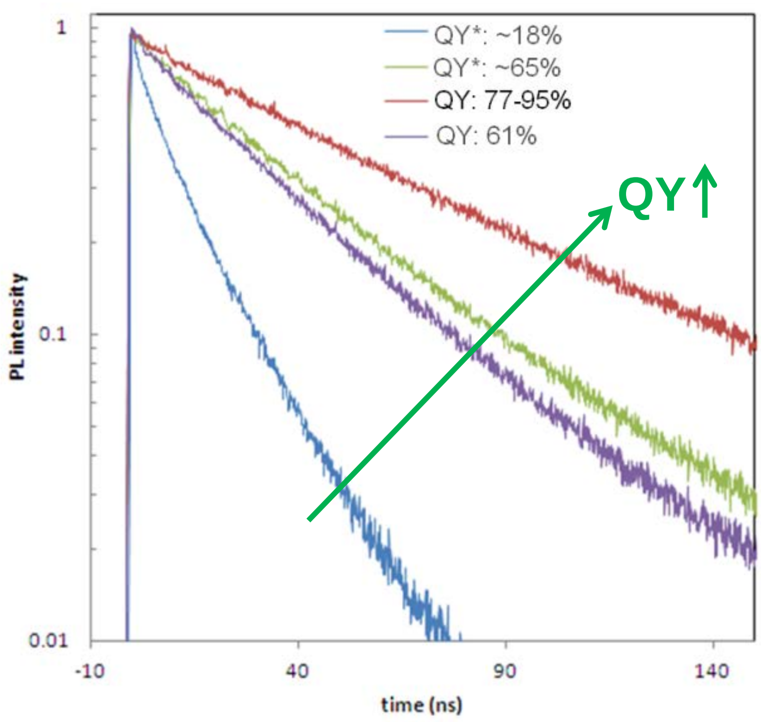

**Key Issues**: primary challenge is achieving high red NBD **reliability** in accelerated testing conditions (high light flux, T, & RH) while maintaining high **down-conversion efficiency** (*i.e.* turning blue photons into red photons).

**Distinctive Characteristics**: a multi-thrust approach with continuous application-centric reliability testing is quickly transitioning NBDs toward commercialization.

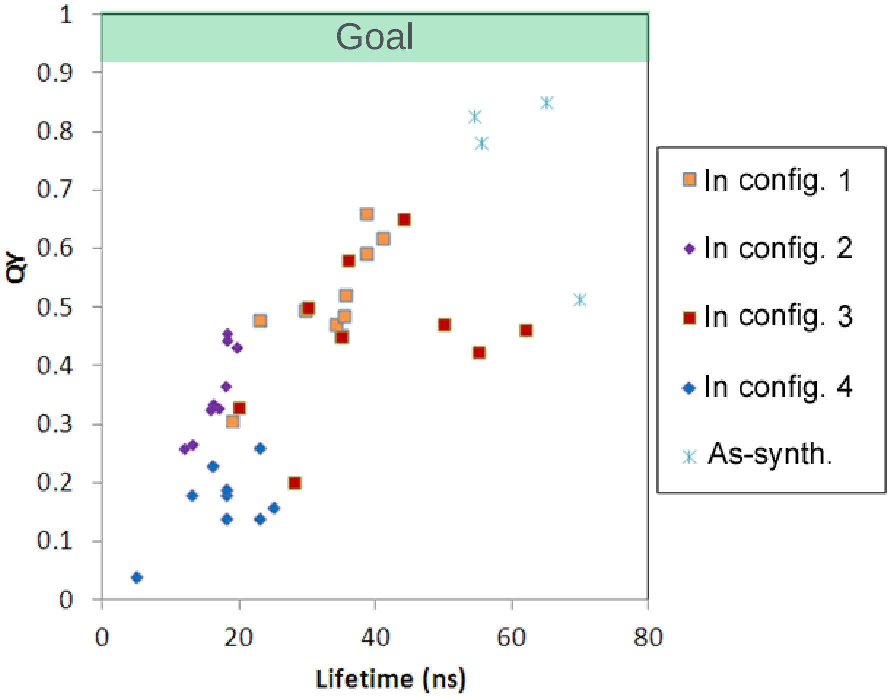
# Progress and Accomplishments – NBD Synthesis

- NBD synthesis and post-synthesis treatment are being systematically varied and evaluated based on characterization and reliability testing

Time-resolved photoluminescence




NBD Quantum Yield




- Lessons learned: NBD composition, purity, morphology, and post-synthesis treatment are all factors in optimizing QY. Optimization of some of these parameters may not result in high NBD reliability!

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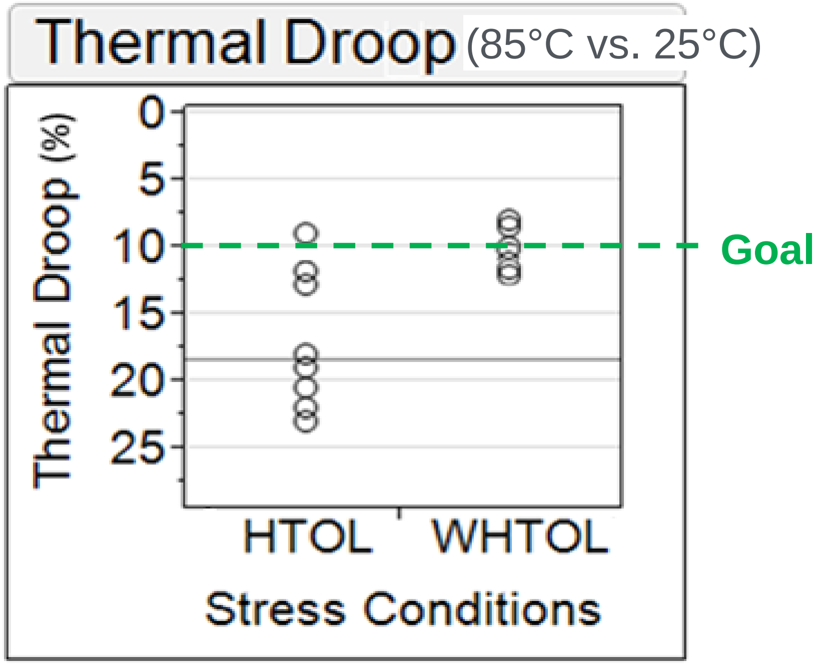
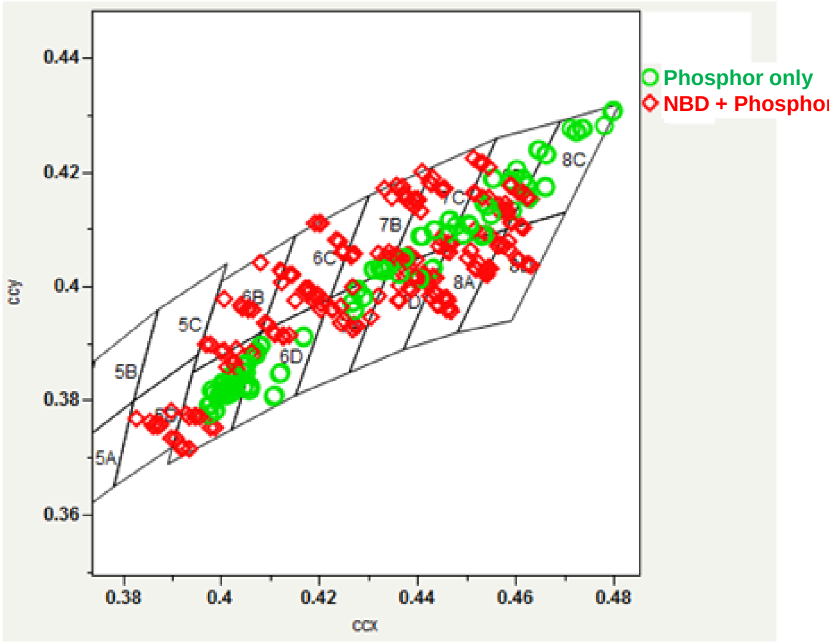
# Progress and Accomplishments – Light Engine

- White NBD-containing LEDs fabricated and tested under steady-state conditions at various temperatures.

| XHG2 - 3500K – 55°C - 65mA | | | | |
|---|---|---|---|---|
| | LF | LF gain | CRI $R_a$ | CRI $R_9$ |
| All Phosphor | 23.8 | - | 92.5 | 60 |
| NBD | 26.2 | +10% | 93.0 | 70 |

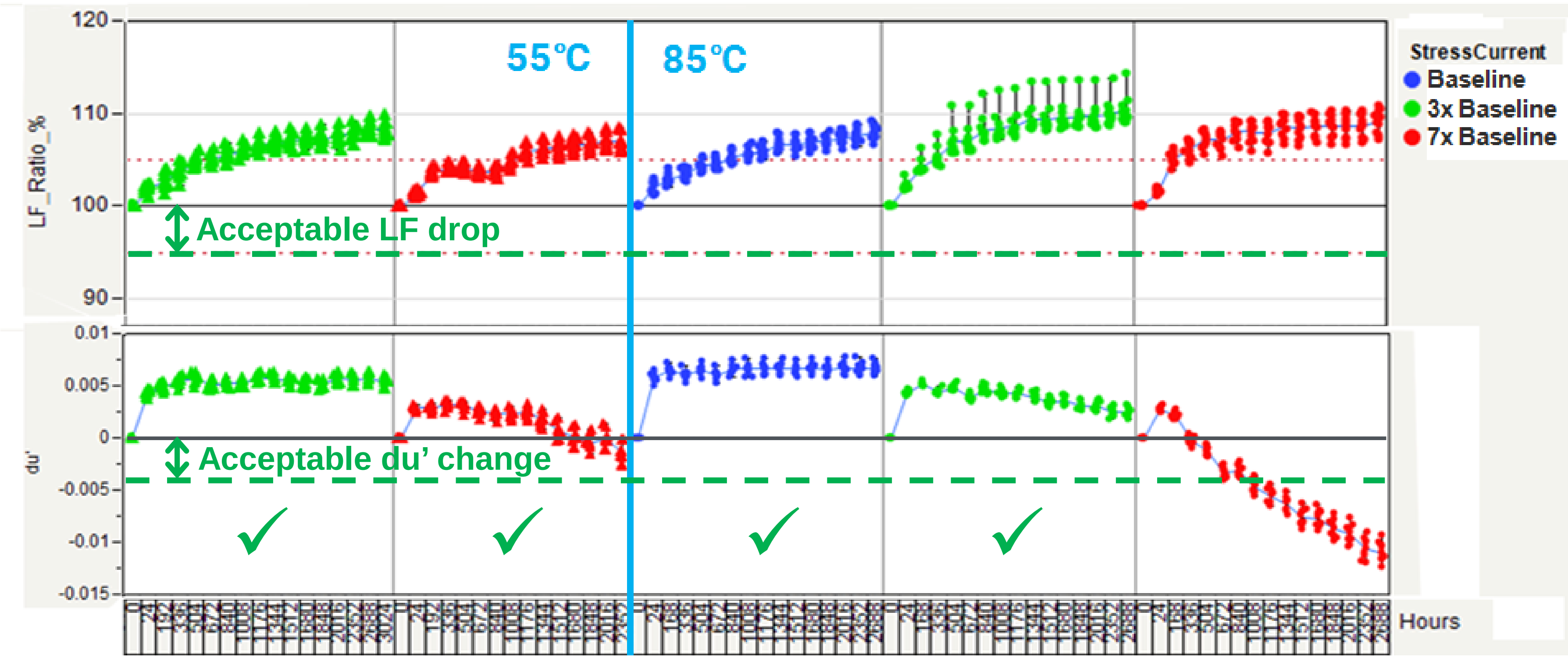



- Lessons learned: NBD thermal droop must be factored into “real world” white LED performance. Further white LED luminous flux (LF) gains expected as red NBD QY and thermal droop improve

# Progress and Accomplishments - Reliability

- LED accelerated testing in high-current, high-T, high-RH ambients acts as synthesis feedback and helps define the application space.
- Progressively higher stress currents (and therefore blue flux) are being applied.




- Lesson learned: NBD-containing LEDs often exhibit luminous flux **rise** early in testing; color point change (namely du') is a better indicator of NBD stability and lifetime prediction.



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# Project Integration and Collaboration

**Project Integration**: project R&D staff continually communicate with **Cree LED product development groups** to ensure timeliness and relevance of project goals and achievements.

*Synthesis*: how reproducible is NBD synthesis? How scalable? $/lumen?

*Light Engine*: are NBDs compatible with existing LED fabrication processes and package configurations?

*Reliability*: how does evolving NBD reliability map onto projected lifetime (>50,000 hrs.) in various luminaire application conditions?

**Partners, Subcontractors, and Collaborators**: no external partners.

**Communications**: project results presented at annual DOE SSL R&D Workshops.

# Next Steps and Future Plans

**Next Steps and Future Plans**:

- *By end of project*: package-level evaluation and multiple-condition REL studies to help elucidate NBD failure mechanisms and ways to overcome them.  Luminaire-level demonstration for comparison w/ all-phosphor.

- *After project*: continue intensive synthesis/package/REL cycle in the drive to create robust red-emitting NBDs

- *Future*: establish "technical" vs. "fundamental" NBD limitations, and compare to other nascent red down-converter materials systems.  Apply "lessons learned" in synthesis and robustness improvements from current project to new materials systems, if applicable.

# REFERENCE SLIDES

# Project Budget

**Project Budget**: $1.5M Federal Share / $375K Cree Cost Share

**Variances**: currently at +$98K (6.7% of combined of Federal + Cost Share budget) No modifications to project plan.

**Cost to Date (as of 2/18/17)**: $1.25M Federal / $251K Cost Share (83.6% of total)

**Additional Funding**: none.

| Budget History | | | | | |
|---|---|---|---|---|---|
| 7/1/15 – 9/30/16 (project start to end of FY16) | | 10/1/16 – 6/30/17 (FY17) | | FY 2018 – N/A N/A | |
| DOE | Cost-share | DOE | Cost-share | DOE | Cost-share |
| $929,459 | $185,892 | $323,748 | $64,750 | *N/A* | *N/A* |

# Project Plan and Schedule – Past Work

- All Milestones except 3.2 met early or on time.
- Milestone 3.2 deferred (with DOE PM approval) to later in program due to task re-prioritization.

| **Project Schedule** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project Start: 7/1/15 | | Completed Work | | | | | | | | | | |
| Projected End: 6/30/17 | | Active Task (in progress work) | | | | | | | | | | |
| | | Milestone/Deliverable (Originally Planned) | | | | | | | | | | |
| | | Milestone/Deliverable (Actual) | | | | | | | | | | |
| | FY2015 | | | | FY2016 | | | | FY2017 | | | |
| Task | Q1 (Oct-Dec) | Q2 (Jan-Mar) | Q3 (Apr-Jun) | Q4 (Jul-Sep) | Q1 (Oct-Dec) | Q2 (Jan-Mar) | Q3 (Apr-Jun) | Q4 (Jul-Sep) | Q1 (Oct-Dec) | Q2 (Jan-Mar) | Q3 (Apr-Jun) | Q4 (Jul-Sep) |
| **Past Work (Year 1)** | | | | | | | | | | | | |
| 1.1 RT QY of > 90% @600-630nm and <40nm FWHM | | | | | | | | | | | | |
| 2.1 < 10% QY, < 5nm change @ >1,000 hrs of REL testing | | | | | | | | | | | | |
| 3.1 <5% QY change in cured polymer matrix | | | | | | | | | | | | |
| 3.2 NBD LED color point: 75%/65% single/5-run yield | | | | | | | | | | | | |
| 4.1 Spectra w/ LER >350 lm/W @ CRI > 90 & 3000-3500K | | | | | | | | | | | | |
| 4.2 NBD LED w/ 145 lm/W @ > 80 CRI (RT, 35 A/cm$^2$) | | | | | | | | | | | | |
| | | | | | | | | | | | | |

*See next slide for Current/Future work*

# Project Plan and Schedule – Current/Future Work

| Project Schedule | | | | | | | | | | | | | |
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| Current/Future Work (Year 2) | | | | | | | | | | | | | |
| 1.2 QY thermal droop of < 10% from RT to 85°C | | | | | | | | | | | | | |
| 1.3 <10% LF & <2nm peak WL variation for 5 LED runs | | | | | | | | | | | | | |
| 2.2 REL testing acceleration factors determined | | | | | | | | | | | | | |
| 3.3 NBD-LED FF CAU within 0.004 du'v' of all-phosphor | | | | | | | | | | | | | |
| 3.4 < 10% NBD-LED LF drop, instant on to steady state | | | | | | | | | | | | | |
| 4.3 NBD-LED w/ >160 lm/W at >80 CRI, RT, 35 A/cm$^2$ | | | | | | | | | | | | | |
| 4.4 NBD-LED w/ >180 lm/W peak at >80 CRI, RT | | | | | | | | | | | | | |
| 5.1 Down-select demonstration luminaire form factor | | | | | | | | | | | | | |
| 5.2 Demonstration Luminaire w/ >150 lm/W, 90 CRI | | | | | | | | | | | | | |