LED – What to Look for Today and in the Future

presented by

Nadarajah Narendran, Ph.D.
Jean Paul Freyssinier, M.S.

Lighting Research Center
Rensselaer Polytechnic Institute
Troy, New York 12180, U.S.A.
Acknowledgments

- Organizers of NALMCO Annual Convention and Tradeshow 2010
- Sponsors of ASSI ST Program
- LRC faculty, staff, and students
SSL Target?

- Solid-state light sources including LED and OLED hold the promise for revolutionizing lighting.

- Energy savings:
  - 15 lm/W
  - 90 lm/W
  - 120 lm/W
  - 150 lm/W

- Lower maintenance cost:
  - 1000 hrs
  - 20,000 hrs
  - 30,000 hrs
  - 100,000 hrs

Picture credits:
GE, OSRAM Sylvania, OSRAM Opto, Philips Lumileds, Nichia, Cree
Commercial white LEDs are approaching 140 lm/W in cool white and 100 lm/W in warm white.
LED Lighting System Performance

- LED system efficiency: 60% at best
  - Optics 85%
  - Driver 85%
  - Thermal 85%
Product Development Challenges

- Secondary optic
- Optic holder
- LED
- PCB

Drawing adapted from Cree

LED Driver
- Driver case temperature (Td)
- LED board temperature (Ts)
- Heat sink
- LEDs and secondary optics

Life
- Power
- Forward voltage
- Forward current
- Efficacy
- Driver efficiency

Tj
- Heat sink size
- Weight

Optics
- Light output

Cost

NALMCO Annual Convention and Tradeshow. October 18, 2010.
© 2010 Rensselaer Polytechnic Institute. All rights reserved.
Heat & Current Affect Life

Rough Rule

10 deg. C increase in pin temperature the life halves

Thermocouple

NALMCO Annual Convention and Tradeshow. October 18, 2010.
© 2010 Rensselaer Polytechnic Institute. All rights reserved.
Failure methods

- **Catastrophic** – Abrupt and complete cessation
  - Device related
  - System related

- **Degradation** – Continuous deterioration over time
  - Time-dependent light loss
  - Time-dependent color shift
LED driver life

- An LED lighting system’s reliability depends on the weakest component of the system.
- Electrolytic capacitors used in drivers have the highest probability of failure
  - Each 10°C increase results in half the life rating

<table>
<thead>
<tr>
<th>Type</th>
<th>Rated Temperature (Tn)</th>
<th>Rated Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolytic</td>
<td>85°C</td>
<td>40,000 h</td>
</tr>
<tr>
<td>Electrolytic</td>
<td>105°C</td>
<td>15,000 h</td>
</tr>
<tr>
<td>Electrolytic</td>
<td>108°C</td>
<td>5000 h</td>
</tr>
</tbody>
</table>

Distribtion of Failre for Each Poer Component

- LED Driver 1: 53%, 1%
- LED Driver 2: 30%, 13%, 9%, 11%, 8%, 5%, 5%
Basing luminaire life using LM80 data for LEDs is incorrect.

- There are many components and several failure modes in a system
  - LED
  - Circuit boards with LED array - interconnections
  - Driver
  - Optics
  - Thermal interface materials
  etc......
Energy Star Qualified LED Downlights

From Energy Star Website, Oct. 2010

Recessed downlights (Commercial)

Recessed downlights (Residential)
ASSIST Program

- Established: 2002
  - Goal: To support the development and widespread application of LEDs for general illumination
    - Identify and reduce the major technical hurdles currently facing solid-state lighting
  - Activities: Industry collaboration, research, demonstration, and education

NALMCO Annual Convention and Tradeshow. October 18, 2010.
© 2010 Rensselaer Polytechnic Institute. All rights reserved.
LED Lighting Institute

- 3-day workshop about LED lighting system and application requirements
  - Twice a year since 2001

- Hands-on workshop
  - Technology
    - Thermal
    - Electrical
    - Optical
  - Fixture design and evaluation

Sponsor: ASSI ST
ASSIST recommends

- A series of publications that provides useful information to end users

- Application guides
  - Recommendations for using LED light fixtures in applications
    - General guide to applications
    - Guide to selecting LED luminaires

- Recommendations for testing and evaluating LED luminaires
  - Proposed test methods
    - Technology-independent
    - Consider application environment
ASSIST recommends
Outdoor Lighting Luminaires

ASSIST recommends
Directional Luminaires

ASSIST recommends
Freezer Case Lighting Luminaires

ASSIST recommends
LED Light Engines

ASSIST recommends
Light Source Color for Retail Lighting

ASSIST recommends
Under-cabinet Lighting Luminaires

NALMCO Annual Convention and Tradeshow. October 18, 2010.
© 2010 Rensselaer Polytechnic Institute. All rights reserved.
ASSIST recommends

Three environmental conditions to test fixtures:

- **Open air:** Light source and driver have plenty of ventilation
- **Semi-ventilated:** Light source and driver have limited ventilation (similar to Non-IC)
- **Enclosed:** Light source and driver have almost no ventilation (similar to IC)
### 2007 Downlights

#### Fixture B
- **(25 W; Aug 2007)**
- Relative Flux: 120%

#### Fixture C
- **(12 W; Oct. 2007)**
- Relative Flux: 120%

#### Fixture D
- **(30 W; Oct. 2007)**
- Relative Flux: 120%

#### T pin (deg. C)

<table>
<thead>
<tr>
<th></th>
<th>Open air</th>
<th>Non IC</th>
<th>IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (24 W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (12 W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D (30 W)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2007 Downlights

Fixtures B, C, and D were tested for their light output over time under different environmental conditions.

- **Fixture B (25 W; Aug 2007)**
  - Relative Light Output
  - Time (hrs)
  - Open air, Semi-ventilated, Enclosed

- **Fixture C (12 W; Oct. 2007)**
  - Relative Light Output
  - Time (hrs)
  - Open air, Semi-ventilated

- **Fixture D (30 W; Oct. 2007)**
  - Relative Light Output
  - Time (hrs)
  - Open air, Semi-ventilated

- **McAdam Ellipses**
  - Time (hrs)
  - Open air, Semi-ventilated, Enclosed
2009 Downlights

### Fixtures

- **Fixture F** (14 W; March 2009)
  - Open air: 57.4°C
  - Non IC: 72.7°C
  - IC: 81.8°C

- **Fixture G** (15 W; June 2009)
  - Open air: 41.3°C
  - Non IC: 52.3°C
  - IC: 70.6°C

- **Fixture H** (12 W; Oct. 2009)
  - Open air: 54.3°C
  - Non IC: 60.1°C
  - IC: 96.9°C

### Lumens and Efficiency

<table>
<thead>
<tr>
<th></th>
<th>F 14 W</th>
<th>G 15 W</th>
<th>H 12 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumens</td>
<td>662.3</td>
<td>605.2</td>
<td>437.0</td>
</tr>
<tr>
<td>%</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>T pin (deg C)</td>
<td>57.4</td>
<td>41.3</td>
<td>54.3</td>
</tr>
<tr>
<td>Im/W</td>
<td>47.8</td>
<td>40.9</td>
<td>441.0</td>
</tr>
<tr>
<td>Lumens</td>
<td>594.2</td>
<td>558.2</td>
<td>441.0</td>
</tr>
<tr>
<td>%</td>
<td>0.90</td>
<td>0.92</td>
<td>1.01</td>
</tr>
<tr>
<td>T pin (deg C)</td>
<td>72.7</td>
<td>52.3</td>
<td>60.1</td>
</tr>
<tr>
<td>Im/W</td>
<td>45.8</td>
<td>38.5</td>
<td>441.0</td>
</tr>
<tr>
<td>Lumens</td>
<td>579.5</td>
<td>495.8</td>
<td>388.0</td>
</tr>
<tr>
<td>%</td>
<td>0.88</td>
<td>0.82</td>
<td>0.89</td>
</tr>
<tr>
<td>T pin (deg C)</td>
<td>81.8</td>
<td>70.6</td>
<td>96.9</td>
</tr>
</tbody>
</table>
2009 Downlights

Fixtures:
- Fixture F (14 W; March 2009)
- Fixture G (15 W; June 2009)
- Fixture H (12 W; Oct. 2009)

Graphs show:
- Relative Light Output
- McAdam Ellipses

Time (hrs):
- 0
- 5000
- 10000
- 15000

Conditions:
- Open air
- Semi-ventilated
- Enclosed

NALMCO Annual Convention and Tradeshow. October 18, 2010.
© 2010 Rensselaer Polytechnic Institute. All rights reserved.
Energy Star Qualified LED Downlights

Recessed downlights (Commercial)

Recessed downlights (Residential)

Luminaire efficacy (lumens/Watt)

Lumens

Lumens
Luminaire life estimation:

- Greater than 91.8% lumen maintenance at 6000 hrs, 25,000 hrs life (Residential)
- Greater than 94.1% lumen maintenance at 6000 hrs, 35,000 hrs life (Commercial)

Fixture G (15 W; June 2009)

- Open air
- Semi-ventilated
- Enclosed
A-Lamp Replacements

- 60 W Incandescent
- 20 W CFL
- 10 W LED
Late 2009 Commercial LED A-lamps

- Power: 5 to 11 W
- Flux: 180 to 570 lumens
- Efficacy: 22 to 65 lm/W
- Price $20 to $60
Late 2009 Commercial LED A-lamps

- In the first 4000 hours, 7 out of 22 lamps have completely failed
- High lumen depreciation during warm up time for many products
- A few products have shown reasonable lumen maintenance after an initial 10% drop during warm up period
Light source efficacy and energy savings

- Energy use depends on the connected load and time of use
  - Watt-hours

- **MYTH:** High efficacy light sources always save more energy than low efficacy light sources.
  - Spatial – light not reaching the application area is wasted light (energy)
  - Temporal – light beyond the required time is wasted light (energy)
Forms of Luminous Efficacy

- **Light source efficacy:** Total lumens out of the light source divided by the total input power
  - Measured at 25°C ambient temperature

- **Luminaire efficacy:** Total lumens exiting the luminaire divided by the total input power
  - Measured at 25°C ambient temperature

- **Application efficacy:** Total lumens reaching a task area and meeting the application’s lighting requirements divided by the total input power
  - Measured in the application environment
  - More appropriate to evaluate energy savings
Application Efficacy – Spatial and Temporal

Spatial

- Illuminating the picture on the wall
  - Wasted lumens: Lumens beyond the area of the picture

Time of use

- Not switching off the light at times not needed wastes energy
Outdoor area lighting luminaires

- LED is becoming a potential light source for street and parking lot lighting applications.

- Many commercial products
  - Claims of
    - One-to-one replacement of traditional light sources
    - Short payback time
      - High efficacy
      - Long life

- How to screen for good-quality products?
ASSIST metric

Application Efficacy:
- Considers how effectively light is delivered to the task
  - How much light on task area
  - How much of the light meets the application’s needs
    - Minimum light levels and uniformity ratios
  - How large is the coverage of the beam in terms of luminaire classification types
    - Larger coverage means smaller number of luminaires
- Good correlation with application’s power density

Visual Efficacy:
- Accounts for how effectively the light source caters to nighttime vision
  - Peripheral vision is more important under low light levels
  - Field demos have shown up to 30% energy savings

NALMCO Annual Convention and Tradeshow. October 18, 2010.
© 2010 Rensselaer Polytechnic Institute. All rights reserved.
ASSIST – Outdoor Lighting

Outdoor Lighting

Outdoor Lighting: A Short Guide to Applications, Objectives and Considerations
Vol. 6 Issue 1
Visual Efficacy – Mesopic vision
Vol. 6 Issue 2

Application-specific ASSIST recommends

Parking Lot Lighting
Test and Evaluation Methods
Vol. 7 Issue 3

Online Calculator

www.lrc.rpi.edu/parkinglot/
### Sample Calculation – 30’ mounting height

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Luminous Flux (lm)</th>
<th>Application Luminous Flux (lm)</th>
<th>Luminaire Input Power (W)</th>
<th>Luminaire Application Efficacy (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 W HPS, Type III S</td>
<td>7064 lm</td>
<td>5213 lm (0.66 fc)</td>
<td>188 W</td>
<td>27.7 lm/W</td>
</tr>
<tr>
<td>150 W LED, Type III S</td>
<td>4745 lm</td>
<td>3184 lm (0.46 fc)</td>
<td>146 W</td>
<td>21.8 lm/W</td>
</tr>
<tr>
<td>150 W MH, Type III S</td>
<td>4918 lm</td>
<td>3039 lm (0.48 fc)</td>
<td>185 W</td>
<td>16.4 lm/W</td>
</tr>
</tbody>
</table>

1. Luminous flux in grid cells meeting criteria (white cells inside red rectangle)
2. Percentage of cells meeting criteria (0.2 fc < E < 0.4 fc) (% of white cells inside rectangle)
3. Application luminous flux (1 × 2) and average illuminance (fc) on task area
4. Luminaire input power
5. Luminaire application efficacy (3 ÷ 4)
Retrofit Lamps for Outdoor

- Challenges in retrofitting lamps
  - Lamp size – may not fit all fixtures
  - Lamp weight
  - Thermal management
  - Moisture sealing
  - Beam distribution may not match
Freezer Case Lighting Luminaires

Project Sponsor: ASSIST
Background

- **2001** – LRC laboratory study
  - Demonstrated the benefits of using LEDs in refrigerated display cases

- **2003** – LRC conducted a field study
  - With NYSERDA funding

- **2006** – LRC published the results
  - Field Test DELTA Snapshot

- **2008 and beyond** – Market transformation
  - Many retailers are using LED lighting fixtures
  - Number of commercial products are increasing
In 2009, ASSIST published a technology-independent method for testing and evaluating the performance of white light luminaires used in refrigerated display cases.

Proposed method:

\[ \text{Application efficacy} = \frac{\text{Total lumens on the task}}{\text{Total power}} \]

- Total lumens on the task
  - Flux on the task area at application temperature
- Total power
  - Fixture power + extra power demanded by the freezer at application temperature
The results show significant performance differences between room and application temperature.

- For example, fixture B has better room temperature fixture efficacy (42 lm/W) than fixture C (28 lm/W).

- However, when both fixtures are compared under application conditions, fixture B’s application efficacy is lower and requires 30% more power.
Retail lighting has several important goals:

- Attract attention, generate interest, create a comfortable atmosphere, integrate with store identity, be flexible, etc.
- Good color rendering is necessary to achieve these goals.

Good color rendering is necessary to achieve these goals.

Addresses:
- the color rendering needs of retail lighting
- the strengths and limitations of color rendering metrics, including color rendering index (CRI) and gamut area index (GAI)

Describes:
- a simple to use, practical method to evaluate color rendering properties of light sources
  - two metric approach using CRI and GAI based on several LRC experiments
  - helpful to predict higher ratings of acceptability than with single metrics

*Rea et al. 2004; Figueiro et al. 2006; Rea and Freyssinier 2007; Rea and Freyssinier 2009.
Summary

- LED technology has been steadily advancing and is in the process of transforming certain markets.
- Cost is expected to reduce over time
- All LED products are not created equal
- LM 80 is not a good indicator of system reliability
- Replacement consideration
  - Availability of the same product in the future if replacement is needed.
- Industry experts are predicting up to 25% of the sales from LED products by 2015
More Information…

- www.lrc.rpi.edu/programs/solidstate