LED Lifetime and Flicker
A Discussion on Test Methods and Criteria
Steve Coyne
LED Lifetime
Importance of LED Lifetime

• Cost benefit calculation requires:
  − Asset price
  − Energy savings per hour
  − Lifetime - hours of operation
  − Labour charge ($0 ?)

• Need an indication of product lifetime
• Important factor in purchasing choice
Verification for cost benefit

Energy savings per hour

- Measurement of:
  - Electrical power
  - Luminous flux

Product Life (hours of operation)

- Need to determine end of life
  - Time to failure
End of Life: Modes of Failure

• Catastrophic (failure to produce light)
  – Failure to produce light

• Parametric (reduced functionality)
  – Lumen maintenance - Lack of a useful amount of light output
  – Colour maintenance - change in the colour appearance
  – Flicker - Perceptible intermittent light output
Prevalence of LED Failure Modes

- Systematic field data is of very limited availability
- Survey results: Next Generation Lighting Industry Alliance (NGLIA) in the USA
  - Higher incidence of catastrophic failure modes reported by members


Causes of Product Failure

Product End of Life

- Packaging/module related
  - Thermal stress delamination
  - Solder joint failure
  - Bond-wire failure
  - Short circuit
- Chip related
  - Electrostatic discharge
  - Ionizing radiation and UV damage
  - Nucleation & dislocation growth
  - Electromigration
  - Metal diffusion
  - Current crowding
  - Thermal runaway
- System related
  - Remote phosphor degradation
  - Hot environment
- Power supply related
  - Phosphor degradation
  - Epoxy degradation
  - Encapsulation defaults
  - Rectifier branch failure
  - Current control
  - Chemical capacitors & hot spots
  - Direct connection to mains and overvoltage
  - LED hot connection
  - Reverse bias
  - Connectivity & PCB defaults
  - Catastrophic optical damage
- Catastrophic
  - Parametric

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Key Initiators of Catastrophic Failure Modes

- High operating current
- High inrush current
- High ambient temperature
- High operating temperature
- Rapid and large temperature changes
Product Endurance

• Dependent on:
  – Electrical component quality
  – Integrity of electrical interfaces/connections
  – Ability of product to dissipate heat

Source: lightingmatters.com.au
Verification of Product Endurance

- Verifying the lifetime by operating LED products till end of life is not practical

- But the ability of a product to endure certain operating conditions can provide some indication of the model’s likelihood to reach its intended (claimed median) lifetime
Evidence of Failures in the Market

EEPLIANT 2014 Report – LED lamp test results

• After 6,000h of operation
  – 15 lamps (17%) failed lumen maintenance requirements
  – 19 lamps (22%) failed lamp survival requirements

• Note: Models selected were biased to those identified as potentially non-compliant lamps
IEC 62612, IEC 62717 Endurance Tests

1. Accelerated operational life (i.e. Extreme conditions)
   - 10°C above maximum rated operating temperature
   - ON continuously
   - 1000 hours

2. Ambient temperature cycling (i.e. Max rated)
   - -10°C (1h hold) transition for 1h to 40°C (1h hold)
   - ON (34 min): OFF (34 min)
   - 250 thermal cycles (1000 hours)

3. Supply switching (i.e. Typical)
   - 25°C ambient temperature
   - ON (30s): OFF (30s)
   - # cycle equals half the hours of rated life (eg 125 hours for 15k hour product)
Effectiveness of IEC Endurance Tests

Supply Switching Test

EEPLIANT 2014 Report (Dec 2017)

• Findings for LED lamp testing (pages 22, 23)
  – Some screening tests supported the view that the switching of lamps at high frequency does not have a significant impact on lamp life.
  – Indications that switching combined with typical warming and cooling cycles may have a significant impact.

• Policy recommendations (pages 22, 23)
  – Shorten the period for lifetime testing to a maximum of 3000 hours
  – Combine with the use of enforced temperature stress regimes or similar approaches that accelerate the aging of lamps
Options for Improve Endurance Test Conditions

• Modify power supply switching cycle to:
  – Increase temperature range of operation
  – Increase temperature gradient within product

• Research evidence (Lighting Research Center, USA)
  – Suggested increased ON and OFF times achieve stabilised chip temperatures at much higher and lower temperatures.
Effects on Switching Cycle on Temperature

• In-house test results indicate significant difference in LED package/pcb TEMP temperature due to different power supply switching cycles.

• Supply Switching cycles
  – 2.5h ON : 0.5h OFF
  – 1m ON : 1m OFF (equipment not capable of 30s intervals)

• Ambient temperature
  – Uncontrolled. Approximately 16°C - 23°C
### Effects on Switching Cycle on Temperature

<table>
<thead>
<tr>
<th>Non-directional GSL lamp 12W (65g)</th>
<th>Directional PAR38 lamp 18W (465g)</th>
<th>Downlight with remote driver 18W (module = 285g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image of GSL lamp]</td>
<td>[Image of PAR38 lamp]</td>
<td>[Image of Downlight with remote driver]</td>
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<tr>
<td>TMP</td>
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</table>

**TMP = Temperature Measurement Point**
Example 1: Non-directional lamp

Power: 12W
Weight: 65g

Switch Cycle:
1 min ON - 1 min OFF

ΔT = 3°C
Example 1: Non-directional lamp

- Power: 12W
- Weight: 65g
Example 1: Non-directional lamp

- Power: 12W
- Weight: 65g

Switch Cycles Summary

- $\Delta T_{\text{max}} \approx 16^\circ \text{C}$
- $\Delta T_{\text{min}} \approx 24^\circ \text{C}$
Example 2 & 3: PAR38 Lamp and Downlight

- **Power:** 18W
- **Weight:** 285g

- **Power:** 18W
- **Weight:** 465g
Impact on Product of Slower Switch Cycle

- Higher max TMP temperature
- Lower min TMP temperature
- Larger temperature difference (max-min)
- Temperature gradients between adjacent materials within a product will also be greater, due to differences in thermal resistance and mass.
- Sheer forces between materials will increase (different coefficients of thermal expansion) and their bonding integrity.

  ▪ Example: Electrical components will have increased thermal stress

![Thermal expansion coefficients of GaN/Si and GaN/sapphire. (Source: [S.Leng 17])]
Comparison with IEC Endurance Switching Test

**Australian LED Lamp Laboratory Test (2018) Findings**

- **30s ON : 30s OFF (life/2 cycles)**
  - 20 LED lamp models, 5 samples of each created zero failures

- **2.5h ON : 0.5h OFF (1200 cycles)**
  - Subset of 11 models
  - 5 samples of each

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<tr>
<th>Model</th>
<th>Failures Total</th>
<th>Average Lumen Maintenance</th>
<th>Required Minimum</th>
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<td>B</td>
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<td>103.0%</td>
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<td>C</td>
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<td>89.1%</td>
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<td>E</td>
<td>0/5</td>
<td>114.7%</td>
<td>93.1%</td>
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<td>F</td>
<td>0/5</td>
<td>98.7%</td>
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<td>G</td>
<td>3/4</td>
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<td>95.8%</td>
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<td>H</td>
<td>0/4</td>
<td>65.8%</td>
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<td>I</td>
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<td>96.5%</td>
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<td>J (linear)</td>
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<td>K (linear)</td>
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<td>no claim</td>
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Summary: Improved Endurance Test & Criteria

Compromise between extensive testing and sufficient testing to identify product endurance issues.

Test Conditions
• Power supply switching cycle:
  − ON 2.5 h and OFF 0.5 h
  − 1200 cycles (3000 h of operation)
  − Uncontrolled ambient temperature

Criteria
• Catastrophic Failure
  − Maximum of 1 of 10 samples fail to operate at end of test
• Parametric
  − Minimum lumen maintenance level (based on claimed life)
Temporal Light Artefacts
Light Variation with Time

• Temporal variation in light output from a light source known as Temporal Light Modulation (TLM)

• TLM can have visual and non-visual effects on a person.

• The term for these effects, as defined by CIE, is Temporal Light Artefacts (TLA).

• There are three main situations where TLAs are visually perceivable.
Flicker

• Light source: stationary but varies in intensity or colour
• Observer’s eyes: not moving (i.e., without saccades)
• Illuminated object: stationary
• Variation in light: above threshold of visual perception
• Visual effect: light is flashing

http://bestanimations.com/HomeOffice/Lights/Bulbs/Bulbs.html
Stroboscopic Effect

- Light source: stationary but varies in intensity or colour
- Observer’s eyes: not moving (ie without saccades)
- Illuminated object: moving (translation or rotation)
- Variation in light: above the threshold of visual perception
- Visual effect: impression that the object is moving at a different rate to its actual translation or rotation speed
Phantom Array Effect (Ghosting)

- Light source: stationary but varies in intensity or colour
- Observer’s eyes: moving (e.g., large eye movement known as saccades)
- Illuminated object: stationary
- Variation in light: above the threshold of visual perception
- Visual effect: gives the impression of a ghosting trail of the object in a person’s vision.
Biological Effects

Non-visual effects have been reported as physiological and psychological manifestations including:

- Migraine
- Anxiety
- Eyestrain
- Autistic behaviour
- Seizures
- Reduction in task performance
- Vertigo
- Vertigo

• Research activities on visual and non-visual effects of TLAs have endeavoured to establish the:
  - light modulation frequencies (some progress) and
  - associated thresholds (limited knowledge of some TLAs) of activation
Mapping the Effects with Frequency Regions

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<th>Modulation frequency (Hz)</th>
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<td>0</td>
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<tr>
<td>Biological effects</td>
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<tr>
<td>visible flicker</td>
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<td>Photosensitivity seizures</td>
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<td>Stroboscopic effect (moving object)</td>
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<td>Phantom array (saccade eye movement)</td>
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<td>Task performance and eyestrain</td>
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<td>Migraine</td>
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<td>Autistic behaviour</td>
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<td>Flicker vertigo</td>
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<td>Panic attack/anxiety</td>
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</table>

? <--- Migraine --> ?
Flicker vertigo

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CIE Recommendations


Scope:
• Visibility of temporal light artefacts

Out of scope:
• Application specific acceptability thresholds
• Non-visual effects
• Chromatic flicker

• Recommends Short Term Flicker metric, $P_{st}^{LM}$ (from IEC)
• Defines and recommends Stroboscopic Visibility Measure (SVM)
• Defines Phantom Array effects

NOTE: $P_{st}^{LM}$ and SVM are normalised parameters such that a value of 1.0 is when a person with normal vision will perceive the effect 50% of the time.
% Modulation metric

\[
\% \text{ Modulation} = \frac{\text{Amplitude}}{\text{DC component}} = \frac{(E_{\text{Max}} - E_{\text{Min}})}{(E_{\text{Max}} + E_{\text{Min}})}
\]
Determining Frequency Elements
Possible causes for temporal light modulation

- Light source technology and its driver topology (poor product design)
- Dimming technology of externally applied dimmers or internal light level regulators (poor compatibility)
- Mains voltage fluctuations intentionally applied for mains-signalling purposes (poor immunity)
- Mains voltage fluctuations caused by electrical apparatus connected to the mains (conducted electromagnetic disturbances) (poor immunity)
IEC TR 61547-1: Short-term Flicker: $P_{st}^{LM}$

IEC TR 61347-1: 2017. Equipment for general lighting purposes – EMC immunity requirements –

Part 1: An objective light flickermeter and voltage fluctuation immunity test method

Describes an objective light flickermeter, including test conditions:

- Sampling > 10 kS/s
- Duration >180 s
- Frequency low pass filter 3dB @ 1 kHz
- Signal resolution: >10 bit (I in 1024)

$P_{st}^{LM}$ calculation is a weighted percentile formula based on voltage variations creating perceptible flicker from a 60W incandescent lamp

Figure 1 – Full EMC approach for mains voltage fluctuations

Source: IEC TR 61347-1: 2017
IEC TR 63158 2018: SVM

IEC TR 63158: 2018. Equipment for general lighting purposes – Objective test method for stroboscopic effects of lighting equipment

Describes an objective stroboscopic effect meter, including test conditions:
- Sampling > 20 kS/s
- Duration > 1 s
- Frequency low pass filter 3dB @ 3 kHz
- Signal resolution: >12 bit (I in 4096)

Source: IEC TR 63158: 2018
IEC TR 63158 2018: SVM Calculation

- Based on Minkowski summation of each relative modulation of each frequency component in the light waveform.
- Sensitivity Threshold

\[ SVM = 3.7 \sqrt{\sum_{i=1}^{N(\leq 2 \text{kHz})} \left( \frac{C_i}{T_i} \right)^{3.7}} \]

Minkowski summation

With the high the power (here: 3.7) there is less influence from the frequency terms beyond the largest. (This is very important to note!)
Test results on lamps

Light Waveform

Spectral content - flicker region

Spectral content - stroboscopic region
Test results on lamps

Light Waveform

Spectral content - flicker region

Spectral content - stroboscopic region

DF = 100 Hz
MD = 11.21%
FI = 2.79%
Pst = 0.0367
SVM raw = 0.3292
SVM clean = 0.3467
Test results on lamps

Light Waveform

Spectral content - flicker region

Spectral content - stroboscopic region
Test results on lamps
Test results on lamps

Light Waveform

- DF = 1 Hz
- MD = 23.65%
- FI = 2.08%
- Pst = 4.9658
- SVM raw = 0.0377
- SVM clean = 0.1182

Spectral content - flicker region

- Spectral components
- Pst Sensitivity Curve

Spectral content - stroboscopic region

- Spectral components
- SVM Sensitivity Curve
Another important point is the probability levels assigned to thresholds differ in terms of the proportion of the population affected. The threshold limit levels are defined as:

- 50\textsuperscript{th} percentile of the population, or
- Low risk level (possibly 90\textsuperscript{th} – 95\textsuperscript{th} percentile of the population)
- No observable effect level (possibly 99\textsuperscript{th} – 100\textsuperscript{th} percentile of the population)
# Mapping All Elements with Frequency Regions

<table>
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<th>Modulation frequency (Hz)</th>
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<td>Parallel ½ wave LED string ccts</td>
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<td>Standards and other bodies (Proposed metrics)</td>
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<td>IEC: Flicker Meter - $P_{st}$ limit</td>
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<td>IEEE: Freq based % modulation limits</td>
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<td>CIE: Freq based modulation limits - Stroboscopic Visibility Measure (SVM) &amp; Phantom Array Measure</td>
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<td>CEC: time based % modulation limits with low pass filters</td>
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<td>LRC Assist: freq based modul$^n$ limit</td>
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Summary: Temporal Light Modulation

Establishing the TLA requirements for residential and commercial lighting requires careful consideration of:

• Adverse effects which the population should be protected against

• Proportion of the population that is intended to be protected

• TLA status of all light source technologies (inc historical)

• Harmonised metrics and test methods

• Levels which should be set as the limit
Thank you

Questions?

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