Modeling the Impact of Thermal Effects on Luminous Flux Maintenance for SSL Luminaires

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ABSTRACT

Meeting the longevity requirements of solid-state lighting (SSL) devices places extreme demands on the materials and designs that are used in SSL luminaires. Therefore, understanding the aging characteristics of lens, reflectors, and other materials is essential to projecting the long-term performance of LED-based lighting systems. Overlooking these factors at either the design or product specification stage can result in premature failure of the device due to poor luminous flux maintenance and/or excessive chromaticity shifts.

This paper describes a methodology for performing accelerated stress testing (AST) on materials intended for use in SSL luminaires. This test methodology, which consists of elevated temperature and humidity conditions, produces accelerated aging data that can be correlated to expected performance under normal luminaire operating conditions. The correlations can then be leveraged to produce models of the changes in the optical properties of key materials including transmittance versus wavelength of lenses and reflectance versus wavelength for housings and other reflectors. This information has been collected into a lumen maintenance decision support tool (LM-DST) and together with user supplied inputs (e.g., expected operation conditions) can provide guidance on lifetime expectations of SSL luminaires. This approach has been applied to a variety of materials commonly found in SSL luminaires including acrylics, polycarbonates, and silicones used for lenses and paints, coatings, films, and composites used for reflectors.

KEY WORDS: lens, reflector, polycarbonate, polymethyl methacrylate, lumen maintenance

INTRODUCTION

Claims of long lifetimes in Solid State Lighting (SSL) systems are often based solely on the light-emitting diode (LED) luminous flux (i.e., lumen maintenance) information. However, customer experience may be different due to the lifetime of other luminaire system components such as drivers, heat sinks, polymers used for lenses and reflectors, and environmental conditions. Consequential, the true reliability and lifetime of LED lighting systems is often difficult to model. An invalid assumption of long lifetime could create customer dissatisfaction which may slow the acceptance of SSL technologies and produce much lower energy savings than forecasted. Nowhere has this point been more evident than in lessons learned from the introduction of Compact Fluorescent Light (CFL). When CFL products were first introduced into the market, the mismatch between manufacturer promises and the reality that customers experienced resulted in much slower market penetration than expected [1]. Since SSL luminaires compete with established lighting technologies, with known performance and reliability, the absence of comparable information on life performance for SSL luminaires is a potential market impediment.

A better understanding of the expected lifetime for SSL luminaires would help to overcome this market impediment and accelerate the adoption of energy-saving LED light sources. However, in order to understand luminaire system lifetime, methods must be developed to reduce test times to a manageable period using accelerated stress test (AST) methods. In principle, such accelerated reliability testing methods for lighting systems and materials would greatly reduce costs and time-to-market for new lighting products while ensuring that products meet both manufacturers' and consumers' expectations.

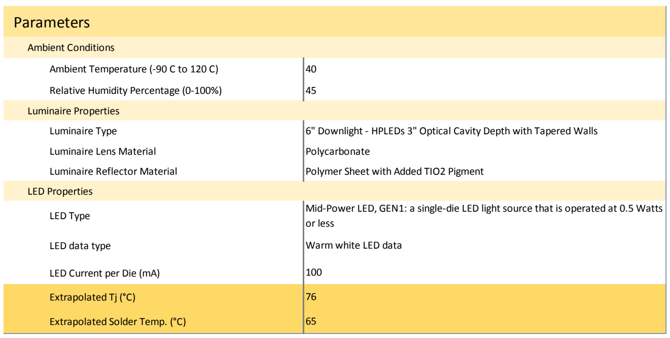
However, the availability of public data on the lifetime of luminaires is extremely limited. Pacific Northwest National Laboratory (PNNL), through funding from the U.S. Department of Energy (DOE), has published findings from lifetime testing on lamps and streetlights [2-4]. There have also been other data published by the lighting industry that provides insights into the aging mechanisms of materials used in SSL luminaires and a listing of some of this art can be found elsewhere [5].

To help understand the impact of different design choices on the lifetime of SSL devices, RTI International, under funding from the U.S. Department of Energy, conducted AST experiments on common lighting materials under AST conditions and collected the information in a Lumen Maintenance Decision Support Tool (LM-DST). The purpose of the LM-DST is to provide the users with a centralized platform to investigate the impact of different system component choices on the lumen maintenance of the most common SSL luminaires. The tool allows the creation of simple but informative reports about lumen maintenance for an entire luminaire including LEDs, lenses, and reflectors. While the LM-DST is designed specifically for luminaires, the same principles can be applied to LED lamps. The long-term lumen maintenance projection models for LEDs and luminaires are programmed into the tool to provide the users with a menu of options to examine common luminaires under different conditions using the built-in data. In addition, users can provide their own data to expand the function of the LM-DST. Reports showing lumen maintenance and the impact of different components can be generated to aid the users in decision-making processes related to SSL luminaire design, selection and testing.

MATHEMATICAL MODELS

Basics of the LM-DST

The LM-DST is access through a user interface which is shown in **Figure 1**. The tool contains built-in models for luminaire components, some of which will be described here, and also requires that the user provide information about the SSL luminaire including the operational environment (i.e., ambient temperature and humidity) and the luminaire type (i.e., troffer, downlight, linear fixture). Information on the temperature and humidity of the normal operating environment will be used to calculated acceleration factors, while information on luminaire design will be used to determine the relative impact of lens and reflector aging on lumen maintenance. Both of these topics are discussed further below. The user interface also asks for information about the LED, which is not discussed here.



Parameters	
Ambient Conditions	
Ambient Temperature (-90 C to 120 C)	40
Relative Humidity Percentage (0-100%)	45
Luminaire Properties	
Luminaire Type	6" Downlight - HPLEDs 3" Optical Cavity Depth with Tapered Walls
Luminaire Lens Material	Polycarbonate
Luminaire Reflector Material	Polymer Sheet with Added TIO2 Pigment
LED Properties	
LED Type	Mid-Power LED, GEN1: a single-die LED light source that is operated at 0.5 Watts or less
LED data type	Warm white LED data
LED Current per Die (mA)	100
Extrapolated Tj (°C)	76
Extrapolated Solder Temp. (°C)	65

Figure 1. Picture of the user interface for the LM-DST.

The lumen maintenance of SSL devices has been shown to depend on multiple factors including the lumen maintenance of the LEDs in the light engine, the aging characteristics of the lenses and reflectors used in the luminaire, and the design of the luminaire. At a finer level of granularity, the choice of LED package type [6, 7], materials of construction of the light source, and source design also impact lumen maintenance of any SSL luminaire, light engine, or lamp. Common LED package types include high-power LEDs (HP-LEDs), mid-power LEDs (MP-LEDs), chip-on-board LEDs (COB-LEDs), and chip scale packages. Common lens materials include poly(methyl methacrylate) (PMMA) [8-9], polycarbonate [9-10], and silicones, while common reflector materials include metals, paints, poly(ethylene terephthalate) [11], and polyolefin-TiO_2 composites [9]. The factors impacting lumen maintenance of an SSL device can be broken out into separate terms representing the LEDs and the luminaire as shown in **Equation 1**.

Lumen Maintenance = $\mathcal{F}$(LED, Luminaire Materials, Luminaire Design) (1)

In many SSL devices, the behavior of the LEDs dominates the overall lumen maintenance behavior of the device [12]. This allows separation of the influences of the LED and luminaire factors into separate terms as shown in **Equation 2**.

Lumen Maintenance = $\mathcal{F}1$(LED)$\mathcal{F}2$(Luminaire Materials, Luminaire Design) (2)

The luminaire factors to be considered include the degradation of the lenses and reflector resulting in the loss of transmittance and reflectance for the luminaire, respectively, and a decrease in luminaire efficiency. This paper reports on a method to calculate the change in lens transmittance and reflector reflectance based on models derived from accelerated testing of common materials used in luminaire design. These time-based changes in the characteristics of the optical polymers used in a luminaire are weighted by luminaire design factors (e.g., aperture, mixing cavity size) to build a model for the entire luminaire.

Lens Aging Models

One element of the change in luminaire efficiency during aging is the degradation of optical components such as lenses. In order to accurately model lens aging, the change in the entire transmittance spectrum needs to be determined. In the LM-DST, individual models have been developed for common lens materials such as polymethyl methacrylate (PMMA), polycarbonate, and silicone. These models were built from measurements of the change in the transmittance spectra of the material at different times during accelerated aging of representative samples of these materials in use in actual luminaires.

In accelerated testing, the lens transmittance at each wavelength ($\%T_\lambda$) changes in a linear fashion as described below. This allows the transmittance at any given time to be calculated from the equation:

$$\%T_\lambda(t) = \%T_\lambda(0) + \frac{d(\%T_\lambda)}{dt} * t \qquad (3)$$

where

t: time

$\%T_\lambda(0)$: initial lens transmittance (i.e., t = 0) for wavelength λ

$\%T_\lambda(t)$: lens transmittance at time t for wavelength λ

$d(\%T_\lambda)/dt$: change in lens transmittance with time (experimentally derived from 7575 data

The values for $d(\%T_\lambda)/dt$ of each lens material can be best determined through AST experiments. A typical result for the aging of polycarbonate lenses in an AST of 75°C and 75% relative humidity (75/75) is shown in **Figure 2**. In order to relate experiment data from various AST experiments to aging under actual use conditions, an acceleration factor for the AST must be calculated. This calculation is performed using the conditions provided by the user on the Control Panel of the LM-DST and the built-in models of material aging that are derived from experimental data and literature values.

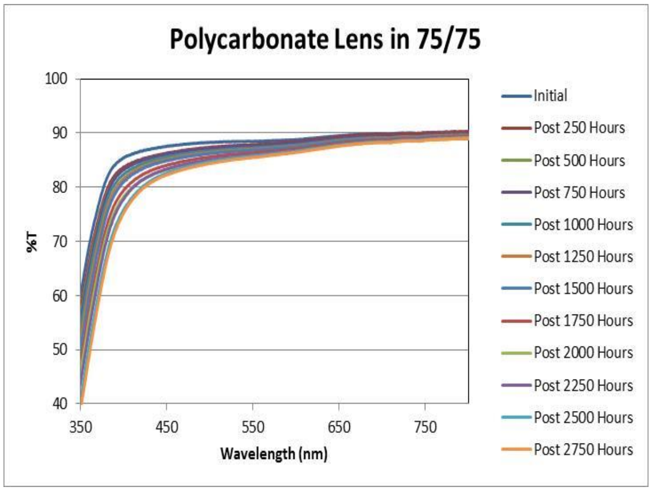


Figure 2: Time dependent change in the transmittance spectra of polycarbonate observed during 75/75.

By studying the aging of optical components under AST conditions, the values for $d\%T_\lambda/dt$ can be shown to change in a predictable, linear fashion**.** By recording the transmittance at periodic intervals during AST, a graph of the lens transmittance at a given wavelength versus time can be created as shown in **Figure 3**. To understand the impacts across the visible spectrum, these graphs must be created at each wavelength of interest. The calculated slope of each graph corresponds to the first derivative of transmittance (i.e. d%T/dt) for that wavelength. A plot of the reciprocal of these first derivative values versus wavelength can also be shown to vary in a predictable, linear fashion (**see Figure 4**). By determining these derivatives, the change in optical properties of the luminaire elements (i.e., lens) can be calculated at any time during the AST measurements and can be correlated to the expected luminaire performance in the use environment provided the acceleration factors have been determined.

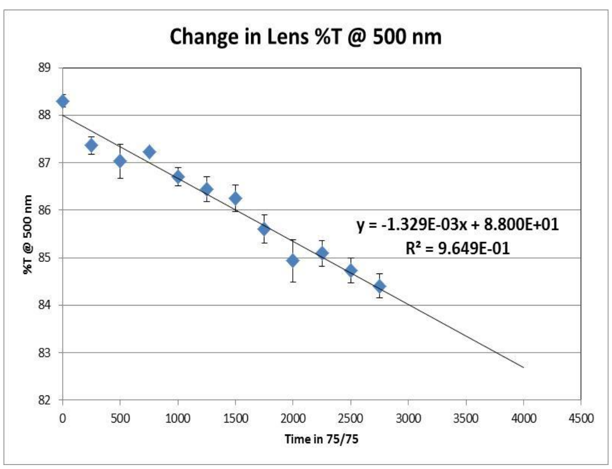


Figure 3: Time dependence of the change in lens transmittance at a wavelength of 500 nm for a polycarbonate lens material for 7575 exposure. Similar measurements at additional wavelengths allow the range of each d%T/dt values to be determined for each accelerated test. The data points represent the average of four different samples and the error bars represent one standard deviation.

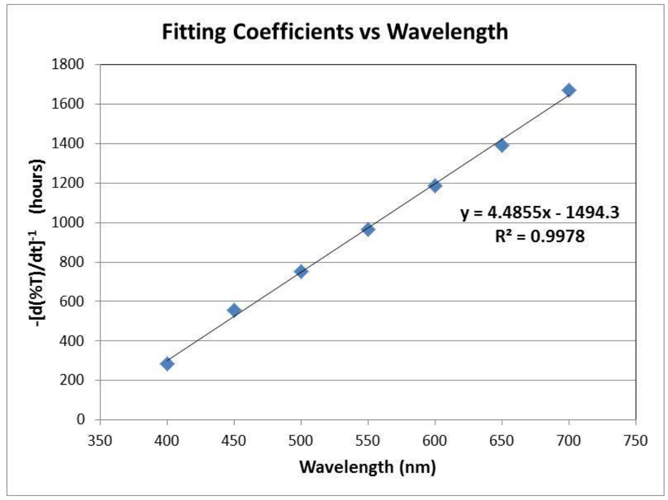


Figure 4: Fitting Coefficients for polycarbonate lenses as a function of wavelength for exposure to 7575.

The time of a given change in lens transmittance in 7575 is given by t_{ast} and the equivalent operation time of a luminaire under normal conditions is given by t_{op}. The experimental data for the models in the LM-DST were acquired at 75°C and 75% RH, and if the temperature and humidity under normal operating conditions are provided, Peck's Law can be used to calculate the relationship between t_{alt} and t_{op}. Since $t_{op} = t_{AST}$ * Acceleration Factor, the AST test results built into the LM-DST can be used to predict the spectral response of lenses at any future time under any stress conditions, provided the stresses are given.

Model Validation

The model for polycarbonate was validated by comparing the predicted result with the actual measured lens transmittance from a luminaire that had been operated in an environment of 65˚C and 90% relative humidity for 2,250 hours. The agreement between the predicted value and the measurements on the physical sample was excellent as shown in **Figure 5**.

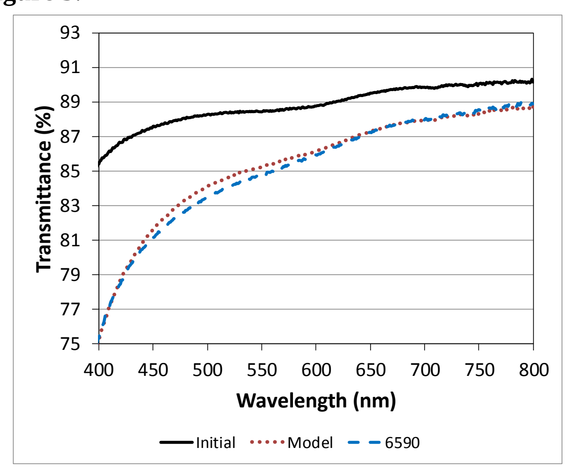


Figure 5: Comparison of the initial measurement of a polycarbonate lens (black solid line) with a measurement of a polycarbonate lens after exposure to 65˚C and 90% RH. The value of %T predicted using these models is given by the dotted red line.

Reflector Aging Models

A second element of the change in luminaire efficiency during aging is the degradation of the reflectors in the device. In order to accurately represent the impact of reflector aging, the change in the entire spectrum needs to be modeled. In the LM-DST, individual models have been developed for common reflector materials such as coil coatings, high performance paints, and various polymer reflectors including those based on polyethylene terephthalate (PET) foams [11], PET films [9, 11], and TiO_2-containing polymers [9]. These models were built from measurements of the change in the reflectance spectra at different times during accelerated aging in 7575 of representative samples of these materials in actual luminaires.

In accelerated life testing, the reflectance of a reflector at each wavelength ($\%R_\lambda$) changes in a linear fashion as described below. This allows the reflectance at any given time to be calculated from the equation:

$$\%R_\lambda(t) = \%R_\lambda(0) + \frac{d(\%R_\lambda)}{dt} * t \quad (4)$$

where

t: time

$\%R_\lambda(0)$: initial reflectance (i.e., t = 0) for wavelength λ

$\%R_\lambda(t)$: reflectance at time t for wavelength λ

$d(\%R_\lambda)/dt$: change in lens transmittance with time (experimentally derived from 7575 data)

The values for $d(\%R_\lambda)/dt$ of each reflector material can be best determined through accelerated tests. A typical result for the aging of polyolefin-TiO_2 composite reflector in 75/75 is shown in **Figure 6**. In order to relate experiment data from AST experiments to aging under actual use conditions, an acceleration factor calculated through user supplied inputs and Peck's law, must be determine. This calculation is performed using the environmental conditions provided by the user on the Control Panel of the LM-DST and the built-in models of reflector material aging derived from experimental data and literature values.

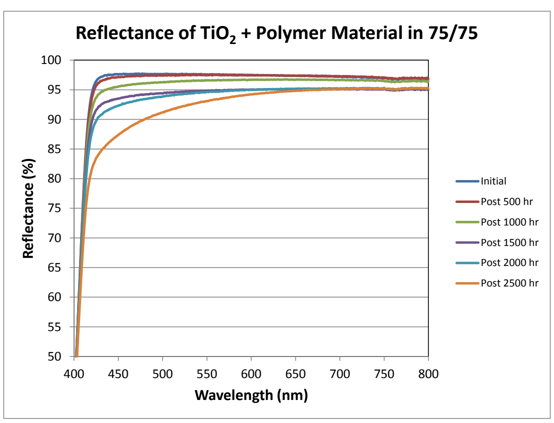


Figure 6: Time dependent change in the reflectance spectra of a composite reflector material made from a composite of TiO_2 and polymer observed during 75/75 AST.

By studying the aging of optical components under AST conditions, the values for $d\%R_\lambda/dt$ can be shown to change in a predictable, linear fashion**.** By recording the reflectance at periodic intervals during AST, a graph of the reflectance versus time in the accelerating environment can be created as shown in **Figure 7**. Since this reflector material contains rutile-phase TiO_2 pigment, a strong absorbance occurs below 420 nm. Therefore, the uncertainty of the model increases significantly below 420 nm due to the rapid change in reflectance.

Graphs of reflectance versus time must be created at each wavelength of interest, and the calculated slope corresponds to the first derivative of reflectance (i.e. d%R/dt) for that material. In many cases, a plot of the first derivative values versus wavelength can also be shown to vary in a predictable, linear fashion. However, in instances where high absorption occurs in some region of the spectral interval, the reciprocal of $d\%R_\lambda/dt$ versus wavelength is often linear, as shown in **Figure 7**. In either case, the value of $d\%R_\lambda/dt$ can be determined at any wavelength for which the model is valid using a linear relationship such as shown in **Figure 8**. By determining these derivatives, the change in optical properties of the luminaire elements (i.e. reflectors) can be calculated at any time for the AST measurements, and can be correlated to changes in the usage environment provided the acceleration factors have been determined.

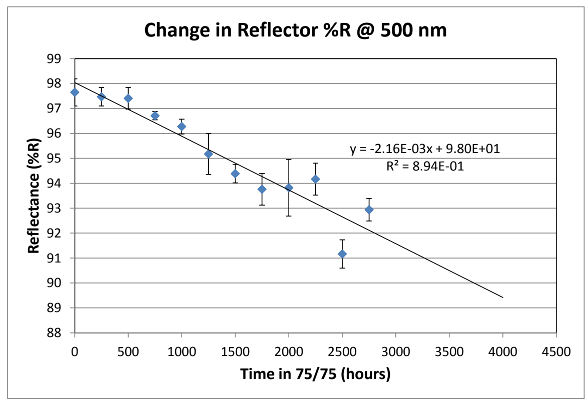


Figure 7: Change in reflectance at a wavelength of 500 nm for a TiO_2-doped polymeric reflector material as a function of time in the accelerating 7575 environment. Similar measurements at additional wavelengths allow the range of each d%R/dt values to be determined. The data points give the average value from four different samples and the error bars represent one standard deviation.

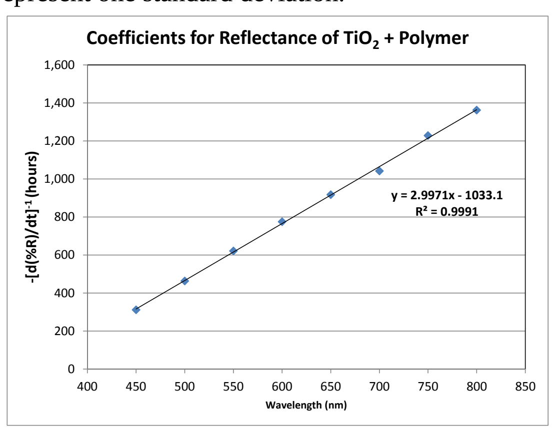


Figure 8: Fitting Coefficients for TiO_2-doped polymeric reflector material as a function of wavelength.

Luminaire Efficiency Change Models

When a luminaire is new, its luminaire efficiency, which is defined as the ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps used therein [13], is at its maximum value. As the optical components of the luminaire age, the luminaire efficiency will degrade in a systematic manner and fewer lumens will be produced even if the LED light source does not change. We have investigated this phenomenon using “virtual luminaires” that were created in Photopia. Photopia is an optical design software, sold by LTI Optics, that provides highly accurate virtual designs of luminaires for evaluation. The “virtual” luminaires that were modeled for the LM-DST covered a wide variety of designs including troffers, parking garage luminaires, downlights, and linear luminaires. In addition, several design options were also included in the virtual models including the choice of using either HP-LEDs, MP-LEDs, and COB-LEDs; optical cavity depth; and the use of straight sidewalls versus tapered sidewalls in the luminaire.

In this analysis, each luminaire type was modeled at various physical parameters including size and optical cavity depth. Aging of materials used in luminaire could be easily accommodated in the Photopia software by attenuation the optical properties of materials used in the luminaire. For example, the impact of a 10% drop in lens transmittance can be simulated by reducing lens transmittance by 10%. From a lumen maintenance standpoint, the transmittance and reflectance values used in these virtual luminaires can be thought of as the spectral transmittance or reflectance weighted by the photopic sensitivity curve. By systematically changing the design parameters and simulating aging of the optical surfaces, a power law model was created to account for the change in luminaire efficiency with aging and can be simply stated as:

$$\Phi_{tot} = \Phi_{init} F_{leds} [L(t)]^m [R(t)]^n \qquad (5)$$

where,

Φ_{tot}: total luminous flux from the luminaire at time t

Φ_{init}: initial luminous flux from the luminaire at time 0. This value is also the product of the initial luminous flux from the light engine and the luminaire efficiency.

F_{led}: lumen maintenance factor of the LED at time t (not discussed in this report)

L(t): change in the normalized lens transmittance [%T(t)/%T(t=0)] at time t, weighted by the photopic sensitivity curve

m: design dependent factor for the lens determined from an optimization routine

R(t): change in the normalized reflector reflectance [%R(t)/%R(t=0)] at time t, weighted by the photopic sensitivity curve

n: design dependent factor for reflector determined from an optimization routine.

An example of the inputs, Photopia outputs, and power law model for a 2x2 troffer containing 121 MP-LEDs in a 3” deep optical mixing cavity in shown in **Table 2**. The yellow boxes are the user inputs and the lens transmittance and housing reflectance can be seen to decrease in a pre-determined systematic fashion in 5% increments. The Photopia outputs are provided in the green boxes and include overall luminaire efficiency, output luminous flux from the luminaire, and other properties. For example, with the lens transmittance and housing reflectance at 100% of their pristine values, the efficiency of this luminaire is calculated by Photopia to be 94.2% and the device produces 2,279 lumens. However, if the lens transmittance drops to 90% of its initial value and the housing reflectance is unchanged, the luminaire efficiency drops to 75.9% and the device produces only 1,838 lumens. By comparison, if the housing reflectance drops by 10% and the lens transmittance is unchanged from its pristine value, the luminaire efficiency declines to 89.3% and the luminous flux drops to 2,161 lumens. Clearly, there is a bigger impact from a change in lens transmittance than housing reflectance in this design, so m > n for this example.

The outputs from the power law model are shown in the blue boxes along with a comparison of the power law model’s prediction for luminaire efficiency with that of Photopia. The exponents in the power law model were optimized in an iterative fashion using the limitations that m > n and both m and n are positive. In general, the fit between the Photopia model and the power law estimation of luminaire efficiency was excellent, and since luminaire efficiency is proportional to lumens produced this approach provides a direct way to calculate the impact of optical component degradation on the luminous flux output from a luminaire.

Table 2. Photopia simulation inputs, outputs, and comparison to RTI’s models for a virtual 2x2 troffer with a 3” deep optical mixing cavity.*

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Reflector % (of original reflectance)	100%	100%	100%	95%	95%	95%	90%	90%	90%
Lens % (of original trasmittance)	100%	95%	90%	100%	95%	90%	100%	95%	90%
Cavity Height	3"	3"	3"	3"	3"	3"	3"	3"	3"
Photopia Calcuated Values									
Efficiency	94.2%	84.8%	75.9%	91.6%	82.5%	73.9%	89.3%	80.5%	72.1%
Output Lumens	2279	2052	1838	2217	1997	1789	2161	1947	1745
Intensity at Nadir (candela)	839.2	746.3	675.2	816.1	736.3	663.0	801.0	714.1	644.3
Full Beam Angle (90-270° plane)	107.3	108.0	107.7	107.4	107.5	107.0	107.0	107.2	107.1
Spacing Criterion (90-270° plane)	1.26	1.27	1.27	1.27	1.26	1.26	1.26	1.27	1.26
RTI Power Law Model									
RTI Model Prediction	94.2%	84.8%	76.0%	91.7%	82.6%	74.0%	89.2%	80.3%	71.9%
Difference Between RTI and Photopia	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	-0.1%	-0.2%	-0.2%
Percent	0.0%	0.0%	0.1%	0.2%	0.1%	0.1%	-0.1%	-0.2%	-0.2%
Absolute Value	0.0%	0.0%	0.1%	0.2%	0.1%	0.1%	0.1%	0.2%	0.2%

* Inputs to the Photopia simulation tool are given in the yellow boxes, outputs from the simulation are given in the green boxes, and the outputs from the power law model are given in the blue boxes.

Therefore, a model for luminaire efficiency can be created using the formula:

$$LE(t) = LE(t=0)[L(t)]^m [R(t)]^n \qquad (6)$$

where,

LE(t): luminaire efficiency at time t

LE(t=0)Φ_{init}: initial luminaire efficiency.

L(t): change in the normalized lens transmittance [%T(t)/%T(t=0)] at time t, weighted by the photopic sensitivity curve

m: design dependent factor for lens determined from an optimization procedure

R(t): change in the normalized reflector reflectance [%R(t)/%R(t=0)] at time t, weighted by the photopic sensitivity curve

n: design dependent factor for reflector determined from an optimization procedure.

The parameters m and n take into account the impact of the luminaire design on the relative contributions of lens and reflector aging on degradation in luminaire efficiency. For example, in the 2x2 troffer design shown in **Table 2**, m is approximately 2 and n is approximately 0.5 confirming that the degradation of the lens has a much greater impact on changes in luminaire efficiency than degradation of the reflectors. However, for luminaires with smaller apertures and proportionally deeper optical mixing cavities, the value of n can equal or surpass the value of m, indicating that reflector degradation can have a significant impact on overall luminaire efficiency changes in some designs.

Conceptually, the value of n can be thought of as being proportional to the likelihood that light emitted by from LED at the base of an optical cavity will strike the reflector in that optical cavity and be impacted by reflector degradation. For example, with a 6" downlight with a 3" optical mixing cavity with tapered walls (i.e. aperture is ~6" and optical mixing cavity depth is 3" for a ~6:3 ratio), there is an increased likelihood that aging of the reflector will impact luminaire efficiency, so the value of n is high. In contrast, for a 6" downlight with a 1" optical mixing cavity (i.e. aperture is ~6" and optical mixing cavity depth is 1" for a ~6:1 ratio), the impact of reflector aging on luminaire efficiency is reduced so n is less. In either case, the light must pass through the lens so the impact of its degradation on luminaire efficiency is significant for both. Consequently, the impact of reflector degradation can be reduced by shrinking the optical mixing cavity, but this may also change the distribution and homogeneity of the light emitted by the luminaire (which was not examined in this work).

Summary & Conclusions

The understanding of the long-term performance of SSL luminaires is still growing and better models are needed to project the long-term behavior of common luminaires such as troffers and downlights. By assembling our own experimental data under AST conditions such as 7575 and literature studies under a variety of conditions, we have created a lumen maintenance decision support tool that allows an examination of the impact of luminaire design, materials choice, and use environments on lumen maintenance. This work demonstrated that changes in lens transmittance and housing reflectance occur in a predictable and linear manner for all wavelengths of interest in general lighting. In addition, the relative impact of changes in lens transmittance and housing reflectance is highly dependent upon the luminaire design with deep optical mixing cavities placing more emphasis on stable reflectance values throughout the cavity. This information is important in matching SSL products to the application and the expectations of the end user.

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