# The Influence of Phosphor and Binder Chemistry on the Aging Characteristics of Remote Phosphor Products

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## Abstract

The influence of phosphor and binder layer chemistries on the lumen maintenance and color stability of remote phosphor disks were examined using wet high-temperature operational lifetime testing (WHTOL). As part of the experimental matrix, two different correlated color temperature (CCT) values, 2700 K and 5000 K, were studied and each had a different binder chemistry. The 2700 K samples used a urethane binder whereas the 5000 K samples used an acrylate binder. Experimental conditions were chosen to enable study of the binder and phosphor chemistries and to minimize photo-oxidation of the polycarbonate substrate. Under the more severe WHTOL conditions of 85°C and 85% relative humidity (RH), absorption in the binder layer significantly reduced luminous flux and produced a blue color shift. The milder WHTOL conditions of 75°C and 75% RH, resulted in chemical changes in the binder layer that may alter its index of refraction. As a result, lumen maintenance remained high, but a slight yellow shift was found. The aging of remote phosphor products provides insights into the impact of materials on the performance of phosphors in an LED lighting system.

## 1. Introduction

Solid-state lighting (SSL) technologies are energy efficient illumination sources that are found in lamps and luminaires. In building light engines for SSL devices, manufacturers typical use one of two approaches [1]. In proximate phosphors light emitting diodes (LEDs), white light is generated by placing phosphors in close proximity to the LED. This structure has the advantage of being compact, but can also produce extreme temperatures in the phosphor layer, which can impact performance [2]. In the alternative remote phosphor configuration, the phosphor layer is remotely located from the LED to minimize direct heat transfer from the LED to the light conversion layer. In some cases, this approach has been shown to produce lower temperature rises in the phosphor layer, even at high flux levels [3].

Accelerated life testing (ALT) using high temperature alone or temperature and humidity environments can be used to investigate the aging characteristics of SSL devices. Previous studies have shown that accelerating environments such as 85°C and 85% relative humidity (RH) can produce color shifts in proximate phosphor LEDs that increase the correlated color temperature (CCT) of the devices [4–6]. The extent of these color shifts appears to be related to the color of the LEDs with higher CCT values being more stable and exhibiting less propensity for large color shifts than LEDs with lower CCT values (i.e., warmer colors). This observation may be due to the higher intrinsic stability of cerium-doped yttrium aluminum garnet (Ce:YAG) phosphors used for cool white lighting compared to nitride phosphors used in warm white lighting [7].

Previous studies of accelerated aging of remote phosphors have typically concentrated on cooler CCT materials with higher Ce:YAG content. Dal Lago *et al*. examined the performance of 4000 K remote phosphor plates in accelerated stress testing carried out at temperature levels between 85°C and 145°C [8]. This study, which also included irradiation of the samples with blue light ranging from 40 mW/cm$^2$ to 350 mW/cm$^2$, found a degradation mechanism that significantly reduced luminous flux and produced a color shift. The primary degradation mechanism identified in this study was photo-oxidation of the polycarbonate substrates used for the remote phosphor disks. Mehr, et al. also investigated the optical degradation of remote phosphor plates formed on polycarbonate substrates [9, 10]. This work examined samples with CCT values of 4000 K and 5000 K and observed degradation in luminous flux and color point stability when the polycarbonate samples were exposed to temperatures between 100°C and 140°C for prolonged periods. Higher temperatures produced faster degradation kinetics and consequently faster lumen depreciation and color shift.

We report herein results on accelerated aging of remote phosphor disks (RPD) in temperature and humidity environments. This study was conducted at multiple CCT values to provide insights into the potential effects of different chemistries on lumen maintenance and color stability. In particular, this study examines both warm white (2700 K) and cool white (5000 K) remote phosphor samples to understand the impact of different phosphor and binder materials on lumen maintenance and color point stability. While this investigation focuses on remote phosphor configurations, the findings on phosphor stability in accelerated life tests may have implications for proximate-phosphor LEDs as well.

## 2. Methods

The remote phosphor disk (RPD) samples used in this study were 61.5 mm polycarbonate disks (Intematix) coated on one side with a layer of dispersed phosphors in a binder medium. The samples were purchased from a commercial source around and in 2012. Two different CCT values, 2700 K and 5000 K, were used in this study. Fourier transform infrared spectroscopy (FT-IR) identified the composition of the binder layer in the 2700 K samples to be a polyurethane (61% match) while the binder layer of the 5000 K RPD samples was a poly(methyl methacrylate) (PMMA) (83% match). X-ray diffraction was used to identify the phosphor composition in samples for both CCT values. The 5000 K samples were found to contain a YAG phosphor and the 2700 K formulation used a mixture of YAG and silicon nitride phosphors. Thus, these samples provide the opportunity to investigate the impact of both binder and phosphor chemistry on remote phosphor performance. **Table 1** gives the physical characteristics of the RPD samples as well as the average initial CCT measurement when used in a light engine. In addition to the RPD samples, blank polycarbonate disks were made from stock materials. The disks were cut to 61.5 mm and were used as controls in all experimental runs.

### *2.1. Wet High-Temperature Operational Lifetime (WHTOL) Test*

Wet high-temperature operational lifetime (WHTOL) tests were used to accelerate aging of the RPD samples. One version of this test consisted of a continuous exposure to 85$^{o}$C and 85% RH (hereafter termed 85/85) following procedures outlined in JESD22-A101C, except that no electrical bias was used in the test. In addition, WHTOL tests were also performed on a second population of samples under conditions of 75$^{0}$C and 75% RH (hereafter 75/75).
WHTOL testing was conducted on the RPD samples in two different environmental

chambers (Tenney T20RC-2.0 for 85/85 and Tenney TC10RS for 75/75). The RPD samples were exposed to WHTOL concurrent with luminaire testing. So, the RPD samples were placed on the top shelf in each chamber to avoid direct illumination from the luminaires. Since the rate of polycarbonate photo-oxidation is dependent upon the intensity of blue radiation exposure [11], this configuration minimized photo-oxidation of the polycarbonate substrates and allowed for this study to focus on the effects of temperature and humidity.

## *2.2 Testing the RPD Samples*

After each 250 hours of WHTOL exposure, the RPD sample populations, consisting of 10 samples each of 2700 K and 5000 K CCT values, were removed from the environmental chamber and their performance measured in a light engine using a calibrated 65” integrating sphere following procedures in LM-79. The photometric properties of the RPD samples were measured by placing each sample in a light engine (Intematix) that contained six blue LEDs (emission wavelength maximum 450 nm). The light engine was not subjected to aging, but was maintained in pristine condition throughout. All samples were tested using the same light engine.

All integrating sphere measurements of the remote phosphor samples were performed using the 2π configuration with the light engine and RPD samples mounted on the exterior of the sphere with an adapter plate. Corrections to sphere readings were made for zero level and self-absorbance, as outlined in LM-79, and sphere calibrations were performed using a National Institute of Standards and Technology (NIST)-traceable forward flux standard from Labsphere (Model Number FFS-100-1000).

In all experiments, the light from the blue LEDs first traveled through the phosphor layer of the RPD samples, then through the polycarbonate substrate and then into the sphere. The LEDs in the light engine were powered by a BK Precision 1760A lab power supply at a current-limiting setting of 200 milliamps.

In addition to photometric properties, the optical properties of the samples were measured after each 250 hour WHTOL exposure. Total transmittance (%T) measurements were performed using a Cary 5000 UV-Visible-NIR (UV-Vis) spectrometer in conjunction with the Cary Diffuse Reflectance Accessory (DRA). The DRA contains an integrating sphere that is coated with a highly reflective diffuse reflector. All disk transmittance measurements were made with a double beam optical bench and sample blank, and background corrections were applied. In performing %T measurements, the disks were placed on the exterior of the integrating sphere of the

DRA in between the light source and integrating sphere. This configuration closely mimics the intended operation of the RPD samples in a light engine.

Fourier Transform Infrared (FTIR) spectroscopy was used to identify some of the RPD constituent materials and to follow their changes during WHTOL tests. FTIR spectra were acquired using the Attenuated Total Reflection (ATR) technique by placing a sample on an ATR plate. The FTIR spectra were acquired using a Thermo Fisher Nicolet 6700 FTIR spectrometer in conjunction with a Thermo Fisher Nicolet "Smart Orbit" diamond ATR accessory. Identifications of materials were based on the spectral libraries installed in this FTIR system.

## 3. Results

Populations of cool white (5000 K CCT) and warm white (2700 K CCT) RPDs, each with 10 samples, were subjected to both 85/85 and 75/75 WHTOL in increments of 250 hours continuous exposure. Thus, a total sample set of 40 RPDs was studied. The study was terminated after 1,500 hours for the 75/75 populations and after 2,000 hours for the 85/85 populations. As shown in **Figure 1**, the samples subjected to either WHTOL setting were darker than the original (i.e. unexposed) samples. This darkening of the RPD samples can be attributed to changes in the binder layer and is discussed below.

### *3.1 Cool White Remote Phosphor Samples*

Despite the discoloration of the 5000 K, cool white, RPD samples, the lumen maintenance of both the 75/75 and 85/85 populations remained high (**Figure 2**). The lumen maintenance after 1,500 hours of 75/75 was the higher, with only a 1-2% decrease in luminous flux. The 5000 K RPD sample population subjected to the 85/85 test environment exhibited a sharper decline in lumen maintenance, but still maintained luminous flux levels well above 70% (i.e. $L_{70}$) in the test light engine, even after 2,000 hours of 85/85. In general, the lumen maintenance standard deviation observed for the sample population in 75/75 was small (coefficient of variation (COV) was less than 1%), and the standard deviation was somewhat larger for the 85/85 sample population (COV ranged from 0.8% to 2.4%).

In contrast, the color shift behaviors of the 75/75 and 85/85 populations were completely different, see **Figure 3**. The 75/75 populations exhibited a small color shift to yellow and plateaued after 750 hours. A yellow color shift was indicative of either (1) a relative increase in emission from the phosphor or (2) a relative reduction in blue emission from the LEDs. The color shift for the 85/85 populations was significantly larger and generally to blue. As shown in Figure 3, the color of the 85/85 RPD samples shifted steadily over the test period and there was no indication of plateauing like that seen in the 75/75 populations. A blue color shift is indicative of either (1) a reduction in emissions from the phosphor (e.g. lower efficiency or increased absorption after conversion) or (2) an allowed increase in transmittance of blue light from the LEDs through the RPD sample.

This difference in behavior can be understood by examining the changes in the spectral power distribution (SPD) and diffuse transmittance (%T) for representative samples from both test populations, given in **Figure 4**. The yellow shift observed for the RPD samples in 75/75 is small and occurred despite a slight drop in transmittance at the phosphor emission wavelengths (see Figure 4A). Further, the transmittance of the samples was unchanged across the LED emission range (400 to 475 nm). However, there was a slight (< 1%) drop in overall SPD peak maximum for the blue emissions, which suggests that more blue photons were being converted by the phosphor. We, therefore, attribute the small yellow shift observed for the 5000 K RPD samples in 75/75 to a drop in blue photon emission caused by an increase in phosphor conversion.

The blue shift observed for the 85/85 RPD samples can be explained by the more dramatic reduction in phosphor emissions (the spectral region from 500 to 750 nm) compared to the emissions from the blue LED. Judging by the diffuse transmittance spectra given in Figure 4B, it is clear that at least part of the decrease in observed phosphor emissions was due to increased absorption (i.e. reduced transmittance) by the polymer binder over the phosphor emission wavelengths. However, the impact of reduced phosphor efficiency (i.e. lower quantum efficiency) cannot be ruled out as a contributing factor. The Ce:YAG phosphor has been shown to be stable in WHTOL tests, so a reduction in conversion efficiency is deemed to be unlikely [4].

The experimental conditions for this study were chosen so as to minimize the extent of photo-oxidation of the polycarbonate substrate in order to concentrate on the impact of the phosphor and binder chemistries. We have previously reported on the changes in polycarbonate lenses under the combined influences of WHTOL testing and irradiation from a warm white light source [5]. These previous results demonstrated that photo-oxidation of polycarbonate in 85/85 changes lens transmittance from greater than 65% over the wavelength range of 350 to 400 nm to between 5% and 35% over the same wavelength range with as little as 1,250 hours of 85/85 exposure. The transmittance change for these WHTOL-aged lens samples was highest at lower wavelengths, indicating that the 350 nm to 380 nm spectral region will show significant changes if photo-oxidation of the polycarbonate substrate is occurring. However, as shown in Figure 4, this spectral region changed little during WHTOL testing under our experimental conditions, indicating that changes in the polycarbonate substrate had a negligible effect on the results observed in these tests.

### *3.2 Warm White Remote Phosphor Samples*

The 2700 K, warm white, RPD samples discolored during WHTOL (see Figure 1) and the final lumen maintenance magnitudes were lower than that observed with the 5000 K, cool white, RPD samples. As shown in **Figure 5**, the lumen maintenance for the 2700 K RPD samples in 75/75 declined to 92% after 1,500 hours of testing, compared to a 98% lumen maintenance level for the 5000 K RPD samples after the same test period. In addition, the 2700 K RPD sample population subjected to the 85/85 test environment exhibited an even sharper decline in lumen maintenance with the average value dropping to below 60% after 2,000 hours of 85/85. There was also a much larger standard deviation in the lumen maintenance measurements for the 85/85 sample population (coefficient of variation was greater than 10% after 1,000 hours of 85/85) than observed for the 75/75 population. This finding suggests that the the phosphor and binder mix used in the 2700 K formulation is not as intrinsically stable as that of the 5000 K formulation, in line with previous findings [4, 7].

The color shifts of the 75/75 and 85/85 populations of 2700 K RPD samples were similar in magnitude (i.e. $\Delta u'v'$), as shown in **Figure 6**. In testing on the standard light engine, the 75/75 RPD population exhibited a small color shift to yellow. The average color shift for the 2700 K RPD samples plateaus after 750 hours at a level slightly higher than observed for the 5000 K samples. Each of the 10 individual samples in the population exhibited the same behavior, although the magnitude of the plateau varied from 0.001 to 0.003.

When tested in the standard light engine, the magnitude of the color shift for the 85/85 population was similar to that of 75/75. However, the direction of the color shift was generally in the blue direction and there was more variation than seen from the other test samples. Forty percent of the warm white, 85/85 samples had a noticeable yellow shift for the first 500 to 750 hours followed by a pronounced blue shift through the remainder of the test period (totaling 2,000 hours). The other 60% of the samples had a consistent blue shift through the test period.

The SPD and %T profiles given in **Figure 7** for representative samples provides insights into the changes occurring in the 2700 K RPD populations. For the representative 75/75 sample, the %T is virtually unchanged at the blue emission wavelengths throughout the exposure period (1,500 hours); however, the SPD shows a drop in overall blue emission intensity. This suggests that more of the blue light is being converted by the phosphor, which will proportionally increase yellow emissions and decrease blue emissions, resulting in a yellow shift. This increase in down conversion could be due to increased scattering in the phosphor layer or a change in the optical properties of the sample [12].

Under 85/85 exposure, a proportionally larger absorption of light from 475 to 650 nm can be observed in the %T spectrum, suggesting that the urethane binder used for the 2700 K samples is absorbing an increasing amount of emissions from the phosphor. The urethane binder also absorbs an increasing amount of blue radiation from the LED. As discussed above, absorption by the polycarbonate substrate can be judged to be no more than a minor contribution, since the spectral region of 350 to 380 nm is unchanged in all 85/85 measurement samples (see Figure 7). If polycarbonate oxidation was occurring to an appreciable extent, this region would show increased absorbance (i.e. decreased transmittance) due to polycarbonate photo-oxidation [5]. Therefore, the general trend of a blue shift in 85/85 appears to be due to urethane binder used for this phosphor formulation.

### *3.3 FTIR Studies of Binder Properties*

FTIR was used to study the change in the binder properties before and after WHTOL and the results are shown in **Figure 8**. For convenience, only the results for an unexposed sample and a representative sample after 2,000 hours of 85/85 are shown. The FTIR results provide clear evidence of changes in the chemical composition of the binder layers for both the 5000 K and 2700 K samples and these changes may account for the discoloration that was observed after WHTOL exposure. These changes may be significant enough to alter the optical properties of the binder layer.

The 2700 K RPD samples used a polyurethane binder. After 85/85, the spectrum of the binder layer underwent several significant changes. First, while the N-H stretching ($\nu$(NH)) mode at ~3318 cm$^{-1}$ was present in both the unexposed and 85/85 samples, the intensity of this peak dropped in the 85/85 samples. In both sample groups, the $\nu$(NH) peak is superimposed on a broad peak that is likely due to the $\nu$(OH) mode of hydrogen bonded water. Second, the frequency of the urea carbonyl stretching mode ($\nu$(CO)) at 1693 cm$^{-1}$ is consistent with significant hydrogen bonding in the film, and there was a change in intensity and a shift in peak location. This suggests additional hydrogen bonding in the film, introduced by the WHTOL environment. These spectral shifts provide an indication of the initial presence of water in the urethane film and the introduction of additional water into the film during 85/85 exposure [13]. There were also changes in peak locations and intensities in the 1000 $cm^{-1}$ to 1630 $cm^{-1}$ region. The spectral changes occurring during WHTOL are characteristic of significant chemical changes in the binder layer, although the exact nature of these changes was not determined.

The 5000 K RPD samples used a PMMA binder. As shown in Figure 8, the most notable differences between the unexposed sample and the sample after 2000 hours of 85/85 was the introduction of OH groups, as evidenced by the appearance of a broad $\nu(OH)$ mode at 3314 $cm^{-1}$. The width of this peak indicates that significant hydrogen bonding is occurring in the film, and this is supported by a noticeable red shift of the $\nu(C=O)$ peak from 1722 $cm^{-1}$ to 1697 $cm^{-1}$. Additional differences between the original and the WHTOL spectra were the emergence of another $\nu(CO)$ mode at 1624 $cm^{-1}$ and a significant change in the ester stretch vibrations ($\nu_s(OCO)$) in the 1140 to 1179 $cm^{-1}$ range [14]. Thus, while it is unclear whether water uptake is occurring within the phosphor particles or the binder, the spectral shifts observed for vibrational modes of the PMMA binder suggest that it *is* involved in the hydrogen bonding. The carbonyl oxygen of PMMA is most likely involved in the moisture uptake process [15]. These observed spectral changes are also indicative of chemical changes occurring in the binder layer, including an increase in hydrogen bonding and the possibility of water sorption into the film.

FTIR analysis was also performed on a representative polycarbonate substrate from this study. The analysis indicated minimal oxidation of the polycarbonate material, in line with the UV-Vis results discussed above.

## Discussion

Remote phosphor structures have been used in a variety of SSL devices ranging from lamps to light engines for downlights. These products are advantageous because of their flexible designs and their potential ability to provide both high lumen maintenance and excellent color stability. A variety of materials and structures are also possible with remote phosphor devices. For example, the remote phosphor can be coated onto polycarbonate or glass disks or embedded into polymeric lenses during the molding process. However, achieving high luminaire performance requires an understanding of the materials used to construct the remote phosphor plate as well as other substrates used in the SSL device.

Polycarbonate substrates can undergo photo-oxidation in the presence of blue radiation. This degradation process has been shown to have a significant impact on the performance of remote phosphor materials using polycarbonate substrates [8, 9, 11]. Polycarbonate photo-oxidation is characterized by the appearance of a yellow to amber color in the material and a significant reduction in transmittance that is especially pronounced at low wavelengths [5, 9]. The extent of this effect is clearly visible in the sample photos shown by Dal Lago [8] which appear much darker than the samples produced by these experimental protocols. Since this photo-oxidation process has been shown to be thermally activated in the absence of light [8], reducing blue irradiance to a low level and maintaining mild temperatures (< 90ºC) can effectively shut down the polycarbonate oxidation pathway and enable the study of other effects in the phosphor layer.

In this study, we intentionally minimized the light exposure of the RPD samples to enable a focus on the effects of the binder and phosphor chemistries. There were significant differences in the chemical composition of the two sample groups, with the 2700 K RPD samples using a urethane binder and a mix of nitride and YAG phosphors and the 5000 K RPD samples using a PMMA binder and only YAG phosphors.

As shown in the FTIR analysis in Figure 8, both binders undergo significant chemical changes during WHTOL, specifically in their polar groups, e.g., ester and urea linkages. Since the index of refraction of a material is determined in part by the concentration and orientation of polar groups [16], it is not unreasonable to assume that the chemical changes observed in the binder layer with FTIR can also change the refractive index of the polymer. Since the optical path length and light-scattering properties of phosphor particles embedded in a polymer matrix will be a function of the refractive indices of both the polymer and the phosphor [17, 18], the chemical changes observed in the binder layer can be expected to change the light emission properties of the RPG samples. We attribute the yellow shift observed in 75/75 to this effect.

As the chemical reaction proceeds, additional changes in the binder layer occur and the light absorption properties of the material change. This effect is illustrated in Figures 4B and 7B. The increased absorption, especially in the 500 to 800 nm spectral region, will reduce overall emissions from the phosphor and account, at least in part, for the blue shift observed in both CCT groups exposed to 85/85.

The difference in phosphor chemistry also plays a significant role in the performance of the RPD samples in WHTOL. The Ce:YAG phosphor, which is often the only phosphor in cool white LEDs and a component of the phosphor mix for warmer colors, is known to be highly stable. In contrast, the red phosphors typically used in warm white LEDs are known to be less stable and can exhibit both color shifts and a reduction in quantum efficiency [7]. Therefore, the possibility of phosphor degradation should be examined, at least for the 2700 K samples.

We have previously demonstrated that high power LEDs (HPLEDs) using silicone encapsulants and Ce:YAG phosphors (for cool white colors) and doped nitride phosphors (for warm white colors) exhibited significantly different behaviors [4, 19-21]. Cool white LEDs typically exhibit little color shift due to their chemical stability and this study concurred, with the emission peak of Ce:YAG phosphors showing little change from WHTOL. In contrast, the emission peak of doped nitride phosphors underwent a significant green shift in WHTOL. Our work also demonstrated that the matrix material for the phosphor particles has a significant impact on the rate at which these changes will occur. Nitride phosphors combined with silicone binders and encapsulants will exhibit large color shifts in WHTOL, since silicone is permeable to water. In contrast, glass matrix materials, which are impervious to water, will not experience the water effect.

In the current study, the behavior of the Ce:YAG phosphors of the 5000 K RPD samples was in agreement with our previous results for cool white HPLEDs in WHTOL. Therefore, the observed reduction in luminous flux and color shifts for the 5000 K RPD samples is attributed to changes in the binder layer. However, no significant spectra shifts were observed for the warm white RPD samples (see Figure 7) and the observed color shift was minimal. This contrasts greatly with our results with HPLEDs using silicone encapsulants in which $\Delta u'v'$ values as large as 0.02 (10X larger than observed here) were reported after 2,000 hours of 85/85 [19-21]. However, warm white phosphors embedded in a water-impermeable glass were found to exhibit color stability levels comparable to those observed in the study. Since polyurethane has a significantly lower water permeability than silicone [13], the relative color point stability, including the absence of a shift in the phosphor emission maximum, is attributed to the polyurethane binder used in the 2700 K samples. Since the polyurethane layer is preventing the degradation of the warm white phosphor, the observed loss of luminous flux is attributed mainly to light absorption in the binder layer. Secondary effects, such as the loss of quantum efficiency may also be occurring, but likely to a lesser extent.

Although this study has focused on remote phosphor samples, it provides insights into the properties of materials that may be used in LED devices. First, changes in the chemical properties of materials used in remote phosphor binders can not only reduce light emission through absorption effects but can also change the emission color if the chemical changes in the binder are significant enough to change the material’s refractive index. Second, while red phosphors used in warm white LEDs may be subject to color point changes due to oxidation, these changes can be mitigated to some extent through proper material choices, such as the use of less water-permeable materials like polyurethane.

## Conclusions

Understanding the chemical properties of materials used in LED devices is critical to developing products that meet or exceed lifetime expectations. Accelerated testing of remote phosphor disks (RPD) was performed using wet high-temperature operational lifetime (WHTOL) testing. The results demonstrated that the chemical properties of phosphors and binders used in RPDs have a significant impact on lumen maintenance, color stability, and the directions of color shifts. Chemical changes in the RPD polymer binder from WHTOL include increased absorption at certain wavelengths and altered index of refraction of the RPD. Both of these changes caused a color shift in the RPDs, although in different directions. The phosphor chemistry also had a big effect, with YAG phosphors exhibiting higher stability and better lumen maintenance than YAG:silicon nitride phosphor blends. In addition to providing insights into the performance of remote phosphor devices, these findings emphasize that understanding the properties of materials used in LED devices is critical to achieving high lumen maintenance and color point stability over the life of the product.

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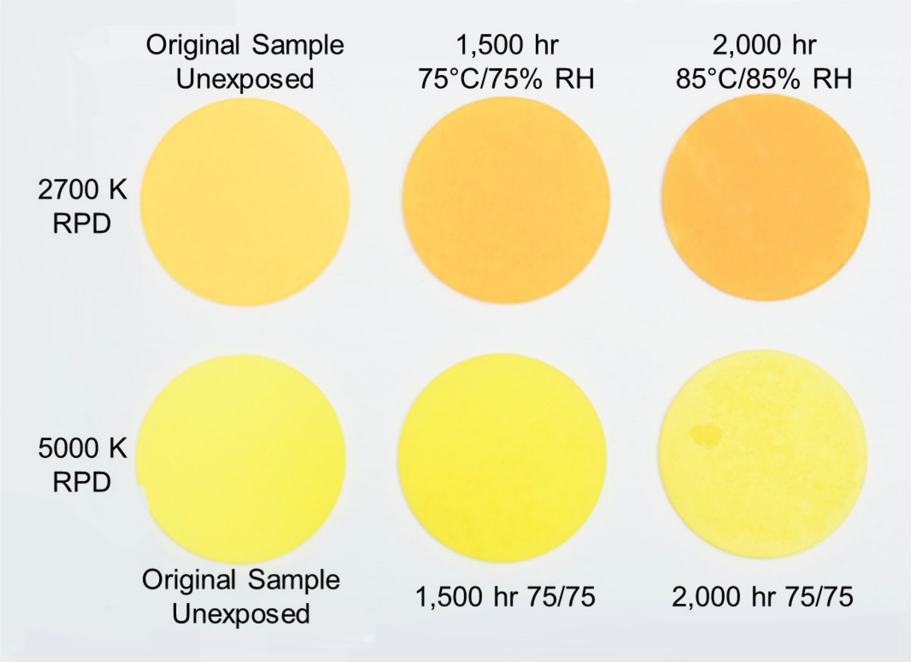

**Figure 1:** Picture of representative RPD samples from this study. The 2700 K RPD samples are shown in the top row with an unexposed sample on the left, a sample exposed to 1,500 hours of 75/75 in the center, and a sample exposed to 2,000 hours of 85/85 on the right. The 5000 K RPD samples are shown in the bottom row with an unexposed sample on the left, a sample exposed to 1,500 hours of 75/75 in the center, and a sample exposed to 2,000 hours of 85/85 on the right.

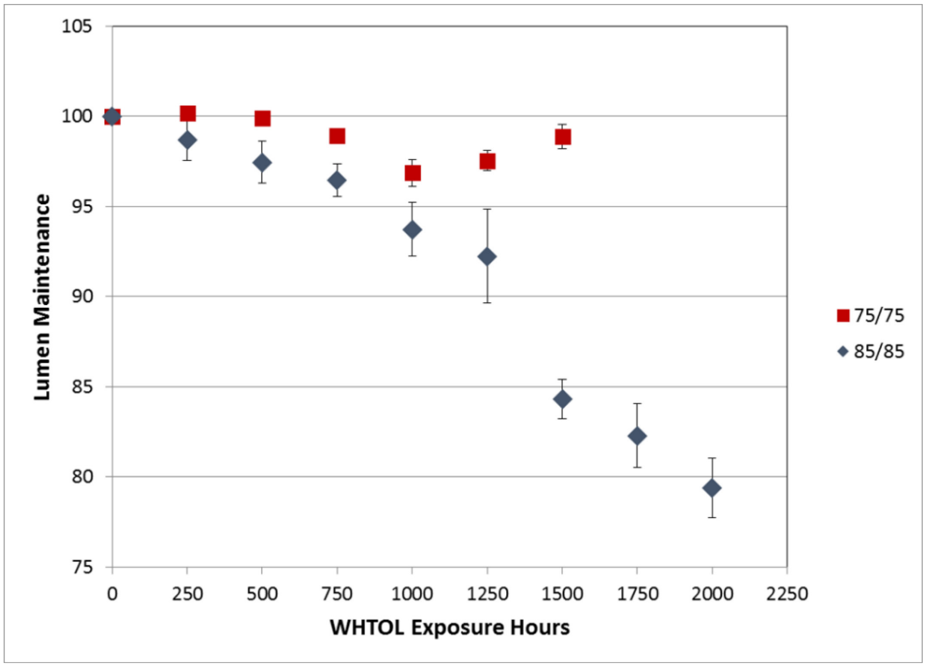

**Figure 2:** Average lumen maintenance of two separate populations of 5000 K RPD samples subjected to 75/75 (red squares) and 85/85 (blue diamonds). The error bars represent one standard deviation for measured values of the sample population at each measurement point.

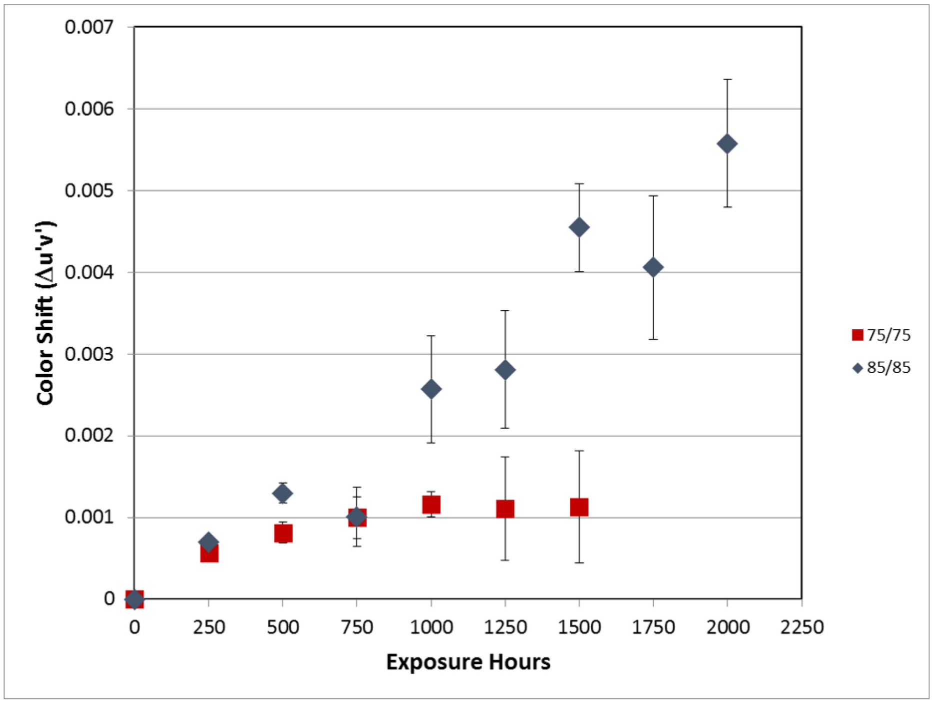

**Figure 3:** Average color shift of two separate populations (10 samples in each set) of 5000 K RPD samples subjected to 75/75 (red squares) and 85/85 (blue diamonds). The error bars represent one standard deviation for measured values of the sample population at each measurement point.

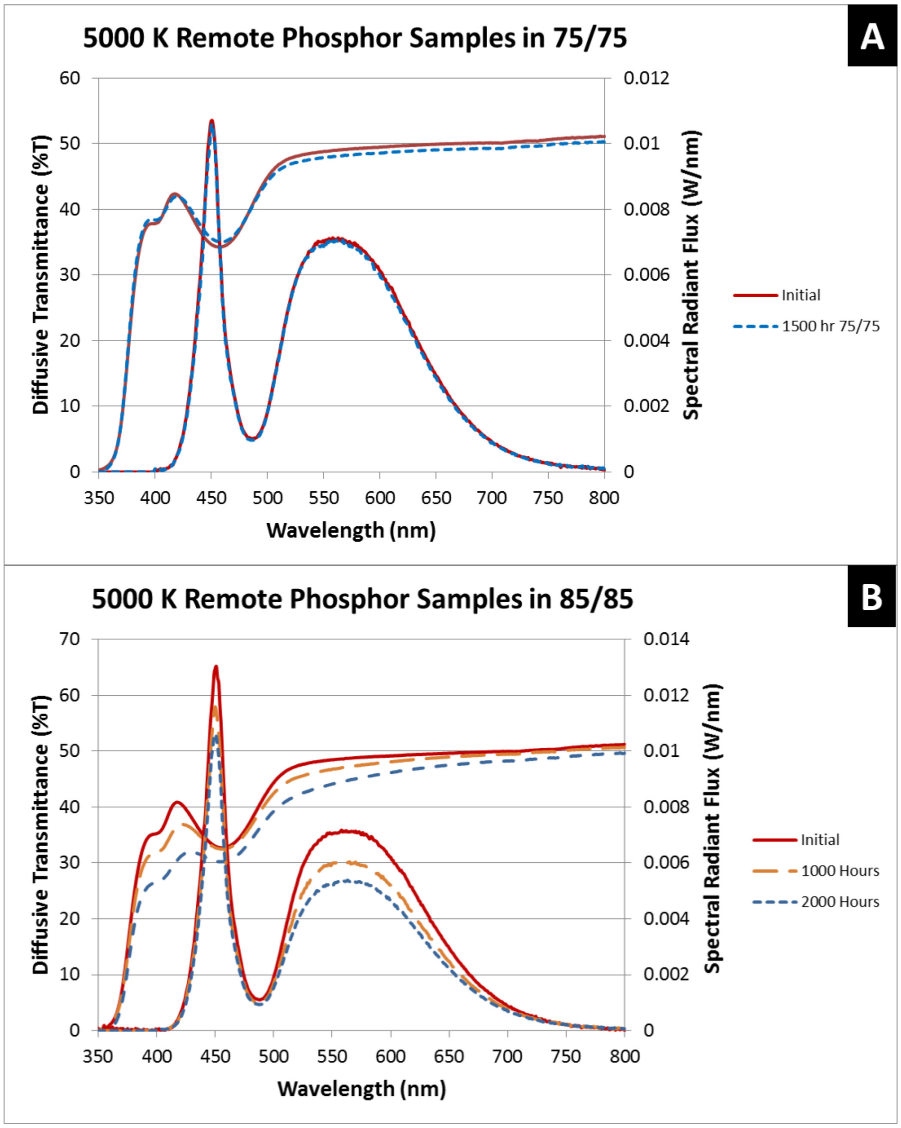

**Figure 4:** Diffuse transmittance (%T) and spectral power distribution (SPD) of representative 5000 K RPD samples. All samples in the test matrix were evaluated and exhibited similar behavior. Changes in %T and SPD for the representative sample as received and after 1,500 hours of 75/75 exposure are shown in A. Changes in %T and SPD for another representative sample as received, after 1,000 hours of 85/85, and after 2000 hours of 85/85 are shown in B.

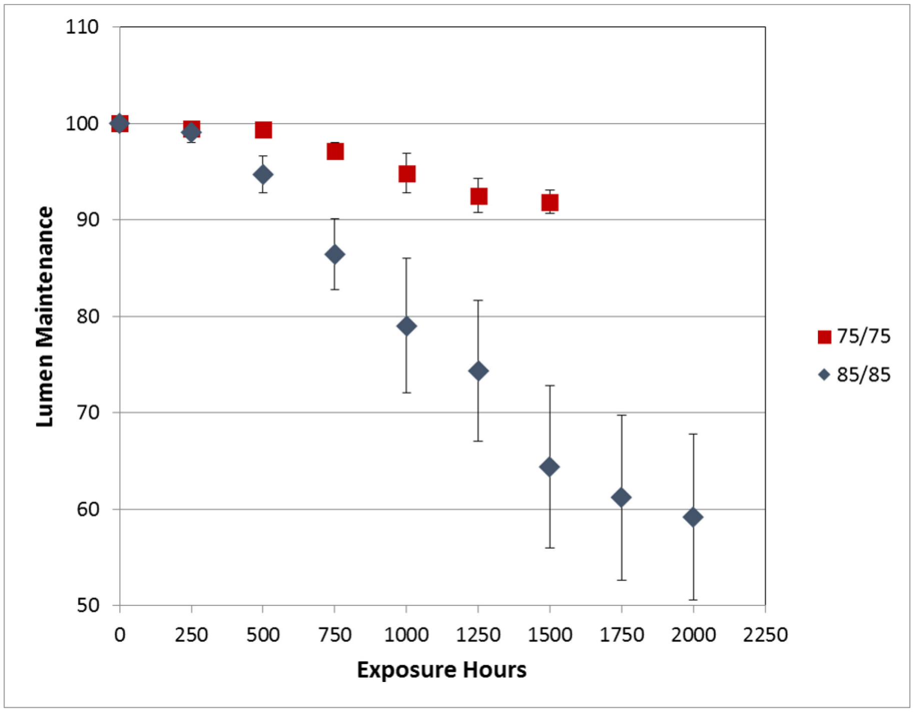

**Figure 5:** Average lumen maintenance of two separate populations of 2700 K remote phosphor samples subjected to 75/75 (red squares) and 85/85 (blue diamonds). The error bars represent one standard deviation for measured values of the sample population at each measurement point.

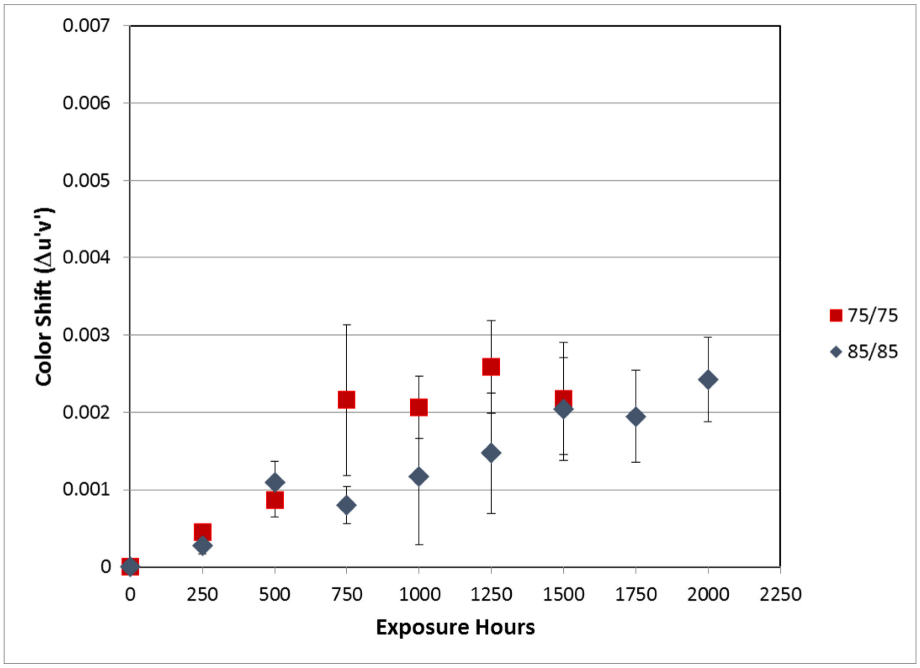

**Figure 6:** Average color shift of two separate populations (10 samples in each set) of 2700 K RPD samples subjected to 75/75 (red squares) and 85/85 (blue diamonds). The error bars represent one standard deviation for measured values of the sample population at each measurement point.

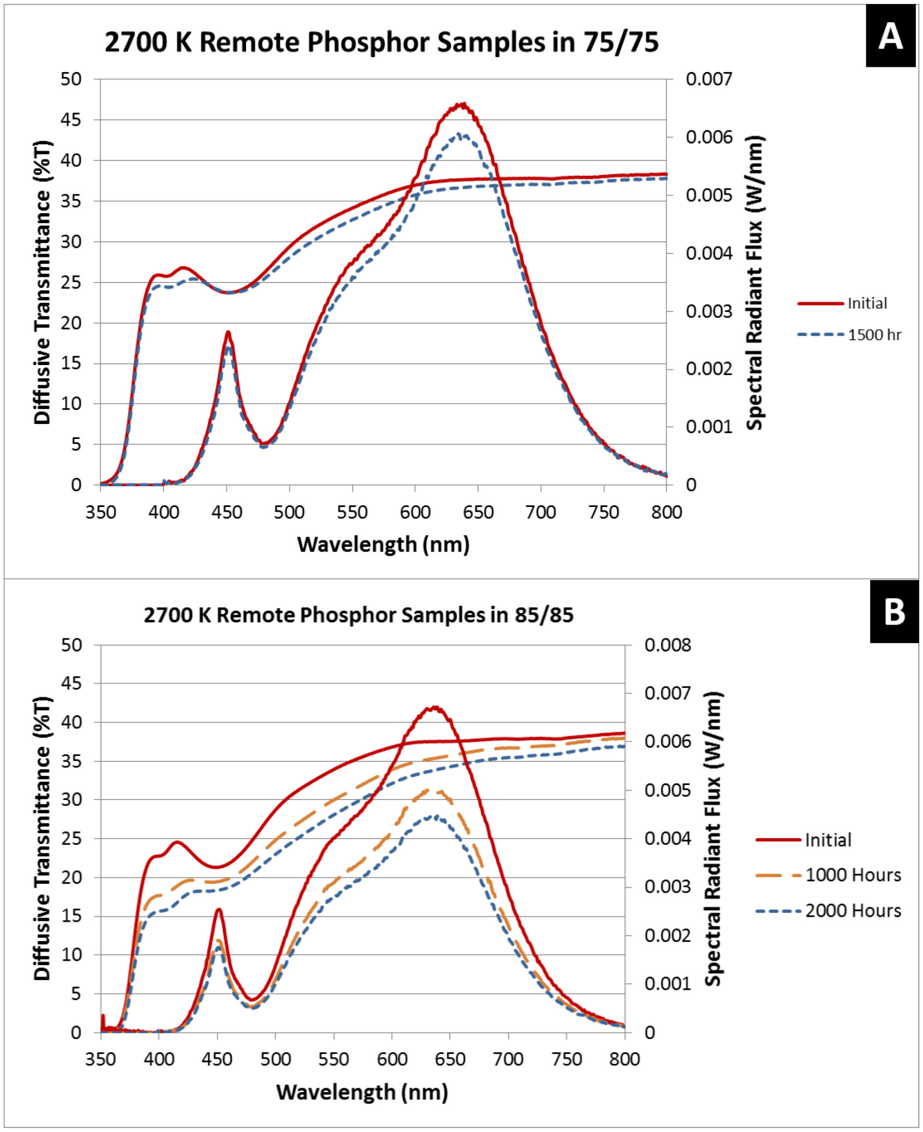

**Figure 7:** Diffuse transmittance (%T) and spectral power distribution (SPD) of representative 2700 K RPD samples. All samples in the test matrix were evaluated and exhibited similar behavior. Changes in %T and SPD for the representative sample as received and after 1,500 hours of 75/75 exposure are shown in A. Changes in %T and SPD for another representative sample as received, after 1,000 hours of 85/85, and after 2000 hours of 85/85 are shown in B.

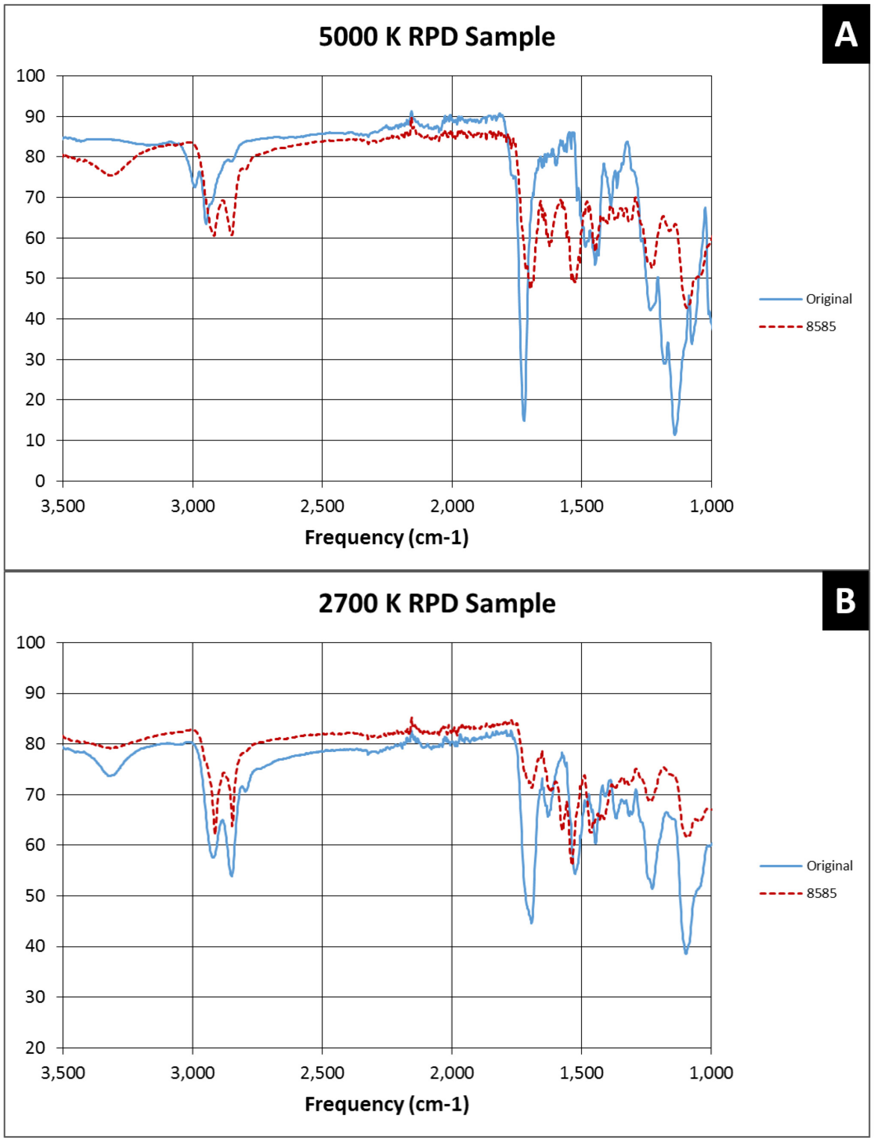

**Figure 8:** FTIR spectra of the binder-phosphor layers for the 2700 K and 5000 K RPD samples. The top panel shows the spectra for representative 2700 K RPD samples both as received and after 2,000 hours of 85/85. The bottom panel shows the spectra for representative 5000 K RPD samples both as received and after 2,000 hours of 85/85.

**Table 1:** Physical characteristics of the remote phosphor samples used in this study.

| Intematix Disks in WHTOL | | | | | |
|---|---|---|---|---|---|
| Intematix Color Series | Part Number | CRI | Average Initial CCT Measured at RTI | Diameter (mm) | Thickness (mm) |
| 2700K | CL-927-LR-PC | 90 | 2687 | 61.5 | 2.12 |
| 5000K | CL-750-LR-PC | 70 | 4935 | 61.5 | 2.12 |