Using high-power LEDs in harsh environments

Sébastien Bouchard and Simon Thibault*

Laboratoire de Recherche en Ingénierie Optique
COPL, Univ. Laval, 2375, rue de la Terrasse, Québec, G1V 0A6

ABSTRACT

Light-emitting diodes (LEDs) are becoming common as energy efficient light sources. Their long life, small footprint and low energy consumption show great promise in many applications including those that relate to harsh environments. However, in designing an efficient light source, a mathematical model is required. The development of such a mathematical model was identified as a priority task by the U.S. Department of Energy in 2010 for general lighting. In this paper, we report an experiment involving two high-power white LED models which were stressed with different currents and junction temperatures. It shows the large variation between different models and stress conditions that takes place in the degradation process. This is part of an effort to develop a tool for the simulation of LED degradation for harsh environment lighting conditions.

Keywords: light emitting diodes, LED degradation rate, injection current, lifetest

1. INTRODUCTION

High power light emitting diodes (LEDs) are being used increasingly for lighting in many applications like automobile lights, traffic lights and for exterior and interior lighting. Considerable research has been done to improve their lumen output and efficiency over the last few years. LEDs have now become a very attractive energy efficient light source [1]. Their low energy consumption combined with their extremely long lifetime make them an interesting solution for new light fixtures. They can also easily be modified to meet specific needs. Many parameters like emission spectrum and spatial emission patterns are easy to change. Finally, dimming can be used to change the light output of a LED in real time.

The advantages of LEDs make them a prime candidate to be used in harsh environments where temperature can reach very high levels. However, like all electric light sources, LEDs experience a decrease in light output over time. This light degradation is driven mainly by two mechanisms, heat at the junction and injection current levels [2]. When the current is injected in the LED, significant heat is generated at the junction. LEDs are engineered to extract this heat toward the outside. Usually, the lamp fixture will be designed to evacuate the heat produced by the LEDs so the ambient temperature inside the lamp and the temperature of the fixture remain within a normal range. In harsh environments, there might not be a great difference in temperature between the LED junction and its surroundings. This will make heat exchange very difficult and will produce further degradation of the performance of the lamp.

Predicting the degradation rate of LEDs through a mathematical model is of great interest for lamp designers. There are several studies that have investigated the life of LED light sources [2-6]. The common explanation for this degradation in LED performance is that nonradiative recombination centers are created at the p-n junction. But this is not enough for LED system manufacturers to predict the lumen output values over 10 or even 15 years of operation. We need to develop a mathematical degradation model as listed as a LED Priority Product Development Task from the DOE (US) [7]. At the moment, there are examples of mathematical degradation models that agree with life tests but they are built for low-power white LEDs [6]. For high-power LEDs, a few models have been proposed but they are based on the specific characteristics of the LEDs [8]. To build such mathematical models, a great number of degradation tests must be conducted under different conditions. This allows to identify the importance of each parameter in the light output degradation.

Furthermore, we have shown that LED active aging compensation methods offer additional energy saving while providing a constant or nearly constant lumen output from the luminaire [9]. Aging compensation methods include

Photonic Applications for Aerospace, Commercial, and Harsh Environments IV, edited by Alex A. Kazemi,
Bernard C. Kress, Simon Thibault, Proc. of SPIE Vol. 8720, 87200F · © 2013 SPIE
CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2018238

current compensation where the LED degradation is counterbalanced by gradually increasing the LED current as the LED degrades as well as chain control where the LED degradation is counterbalanced by controlling the number of LEDs turned ON. However, both strategies depend on a reliable mathematical degradation model.

Since one advantage of LEDs over other light sources is their long lifetime, there is a need to accelerate the degradation test. To do so, it is possible to inject a high current in the LED to produce heating at the junction. As given in the Equation 1[4], the increase in the junction temperature comes from the pads temperature (T_p), the input power (P_j) and the thermal resistance (R). For two LEDs from the same model and mounted with the same technique, the only difference will be the junction temperature if two different currents are injected. This makes it possible to link the degradation of the characteristics of the LED with the junction temperature.

$$Tj = Tp + Pj * R \quad (1)$$

To develop a good mathematical model of the light degradation of LEDs, we also need to test samples from different manufacturers. In this paper, we will present results from two companies. LEDs from both companies are stressed with the same conditions. This makes it possible to compare their degradation and so, this is the first step in the process of establishing a global model of light degradation for LEDs.

2. EXPERIMENTAL METHODOLOGY

The objective of the setup was to be able to control the junction temperature during experimentation. To obtain an efficient heat exchange between the junction and the outside, LEDs were mounted on a copper plate. This is illustrated in Figure 1. Thermal paste was applied on the heatsink of the LEDs so the heat produced at the junction can flow to the copper plate without resistance.

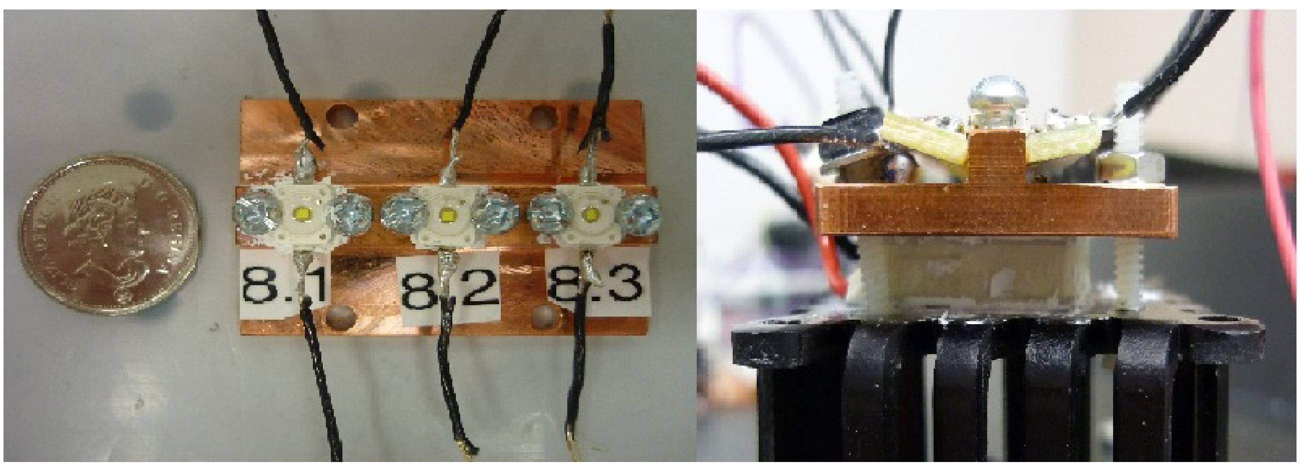

Figure 1: LEDs mounted on the copper plate. On the left side: a copper plate with three LEDs installed on the top surface. On the right side: the setup for temperature control with the copper plate, the heatsink, the thermoelectric controller and a thermistor.

Important characteristics of the LEDs used in the experiment are summarized in Table 1. Both LED models were commercially available. Table 2 gives the stress parameters for each LED during experimentation. With the current (I) injected at the junction, we can calculate the associated junction temperature (T_j) by using Equation 1.

LEDs from both manufacturers were separated in two groups. The first half was mounted like the ones on the left in Figure 1. In this situation, heat will be poorly evacuated from convection around the copper plate. The junction temperature of the LEDs then rises to a high level. For the other half of the LEDs, a thermoelectric controller and an external heatsink is used. Compared with the first half of the LEDs, the temperature of the junction can then be kept cooler for a similar injected current.

Numbers 1-3 were mounted with a thermoelectric controller to be able to manage the junction temperature during the test. The currents that were used are 1000 mA, 800 mA and 500 mA. These values can be compared to the current limit for each LED model presented in Table 1. Numbers 4-6 were stressed with the same current values but no temperature control was used. Finally, number 10 was stressed with 350 mA, which is the recommended current from the manufacturers. No active cooling was used to simulate a LED light fixture where heat is removed only using air convection around the lamp.

Table 1: LED characteristics for the two models used in the degradation test.

Characteristics	Model A	Model B
Maximum forward current (T_A = 25°C)	1000 mA	400 mA
Storage temperature range	-40…+110 °C	-40…+100°C
Maximum junction temperature	125 °C	135 °C
Typical color temperature (CCT)	6500 K	5600 to 9000 K

Table 2: Degradation conditions used in the experiment for each plate and LED model.

	#1	#2	#3	#4	#5	#6	#10
Injection current (A)	**A:**1,0(1) **B:**0,95(5)	**A:**0,80(5) **B:**0,80(5)	**A:**0,50(5) **B:**0,50(5)	**A:**1,0(1) **B:**1,0(1)	**A:**0,8(1) **B:**0,80(5)	**A:**0,50(5) **B:**0,50(5)	**A:**0,3(1) **B:**0,35(5)
Average junction temperature (°C)	**A:**82 **B:**100	**A:**72 **B:**88	**A:**59 **B:**67	**A:**106 **B:**134	**A:**90 **B:**109	**A:**67 **B:**72	**A:**47 **B:**56

Each LED was completely characterized before the beginning of the degradation experiment. Measurements like current-voltage curve (I-V), emission spectrum, lumen flux, correlated color temperature (CCT) and emission profile were taken so as to have a reference for each LED. Periodically, the degradation test was stopped and LEDs were measured again. It is worth noting that we looked only at the relative degradation during the test. We were not equipped to measure absolute value of the parameters of the LEDs. The uncertainty of the measurement was evaluated. For example, the uncertainty of the lumen flux was obtained from the maximum variation between two or three measurements. Before being tested, the LEDs were cooled until the junction temperature reached the room temperature of (21±1) °C. This was done so that all measurements were taken under the same conditions. It is possible that heating and cooling the junction many times during the test may cause some kind of degradation of the LED by itself. However, we chose this approach to be able to compare the measurements of the LEDs stressed with different conditions.

3. RESULTS

The first result, which is quite important for a LED lamp manufacturer, is the lumen output degradation of the LEDs. Presented in Figure 2, the lumen output over time shows a dramatic drop during the first two hundred hours of the test. Each curve represents the mean value of the three LEDs on a plate. This serves to reduce uncertainty of the measurement. The drop is more significant for LED model A for which it reached 12-20% depending on the conditions. For LED model B, the drop is somewhere between 2-15%, which is still significant. For both LED models, after this initial drop, there is only a very small decrease until the end of the test. For clarity reasons, the error bars have not been added on the graphs. However, it is about 3% for each point.

It is worth noting that the relation between stress conditions (junction temperature) and lumen output degradation is not the same for each LED model. For model A, the degradation rate was found to increase with increasing junction temperature levels which is in accordance with other research group results [5, 6]. In all cases, current value and junction temperature were clearly under the limit fixed by the manufacturer.

For LED type B (fig 3b), the initial degradation period was also about 200 hours. We can notice that two plates #10 and #6 have a stable luminosity after 400h and degradation less than 10%. These plates have a corresponding junction temperature of 56°C and 72°C respectively. Other plates (#1, 4 and 5) have a junction temperature higher than 75°C and the degradation was found to increase and the light drops slowly. Plate #3 which has a junction temperature of 67°C has a very important initial decrease and the luminosity after 400h remains stable as with plates #10 and #6. One possible explanation for this deviation could be the variation between similar LEDs due to manufacturing issues. After review, we found that one of the three LEDs on plate #3 has a very high degradation (-0.15), which considerably reduces the mean value shown on the graphs. If we remove the data from this LED, the relative lumen output becomes about 0.87 after 1400h. We also have a large variation with LEDs on plate #2. The relative lumen output if we remove the LED is about 0.84 after 1400h. For the type B LED, the variation between similar LEDs was larger than for the type A. A larger number of LEDs on each plate would be required to avoid such a large variation. However, a large deviation between similar LEDs is not desirable when modeling the LED performances. For LED model B, current was over the limit fixed by the manufacturer for plates 1-6. Plate 4 reached a junction temperature at the limit fixed by the manufacturer. This can also explain the soft relation between degradation rate and junction temperature of the LEDs.

These results are a bit different than many similar studies on LED degradation. In most cases, there is an annealing period of a few hundred hours at the beginning of the test. Here, the LEDs were tested immediately after being taken out of their package. The degradation test was then started without annealing time. LED manufacturers usually sell their products with a promise of a 50000 hour lifetime. This pledge is based on an extrapolation of the lumen output degradation of the first few hundred hours (after annealing). In Figure 2, we could obtain such lifetime by removing the first 200 hundred hours and extrapolating the degradation curve. However, if one is designing a LED lamp fixture that requires a certain lumen output, one will calculate the number of LEDs needed according to the recommendations of the manufacturer. But, the lumen output will drop fast during the first few hundred hours, which means that the lamp that has been designed will rapidly fall to about 80% of its planned lumen output even under normal operating conditions. In many applications, this is not something that is desirable. So, lamp manufacturers should take this initial lumen drop into account when designing their systems, particularly when the lamp will be used in harsh environments.

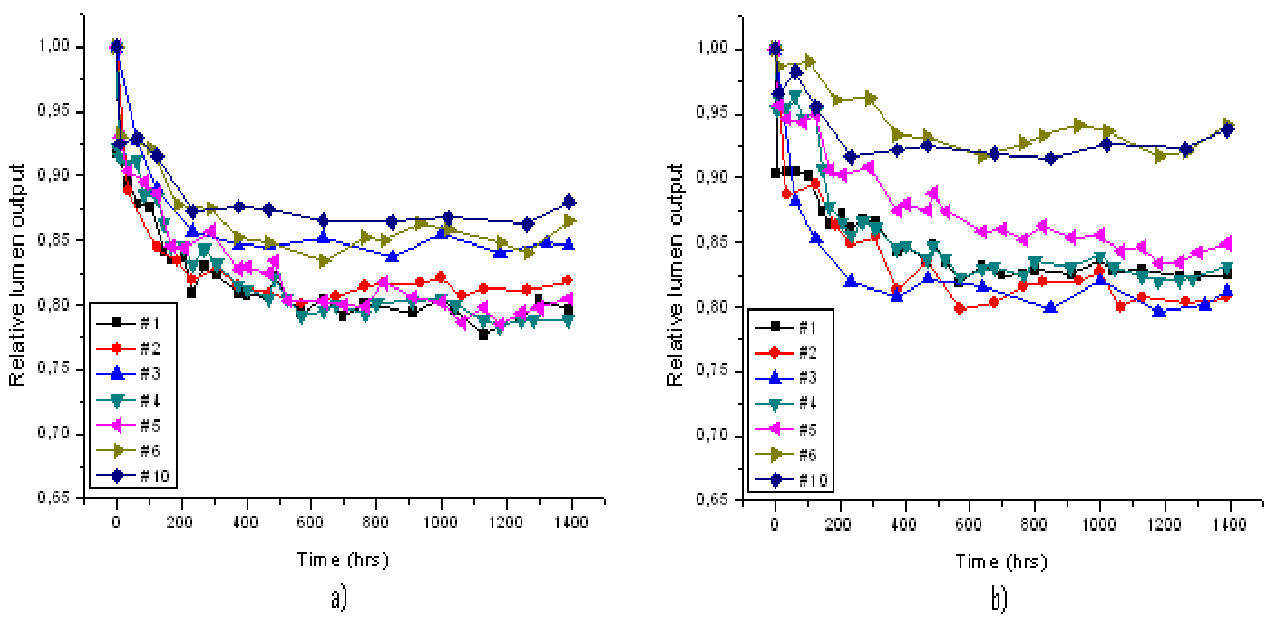

Figure 2: Relative lumen output degradation for a) model A and b) model B under seven different stress conditions.

The measurement of the relative lumen output is the most important parameter to consider if you want to model it over time. However, by simply measuring the lumen output, no significant information on the physics of the degradation process can be achieved. Particularly, the degradation of the phosphors and the package can play a role in the degradation process. The package and the phosphors are mostly correlated with the thermal effects. Usually, they degrade when the LEDs are exposed to temperatures in the range of 100 and 200 °C [10]. Spectral data is obtained during the experiment for each plate of LEDs. Our stress conditions were found to induce no significant changes both on blue and yellow compositions of the power spectra distribution. The change in the color coordinates and temperature was within the manufacturer's tolerances. The ratio between the lumen over the optical power (watt) remains mostly constant for all plates (less than 1%). For the highest junction temperature, plate #4, the ratio drops by 3% after 1000h. Consequently, no severe browning of the material and darkening of the package were observed during the experiment. We also observed that the spatial distribution of the lumen output was constant over the tests for each plate as an indicator of the integrity of the LED package, as illustrated in Figure 3 and Figure 4.

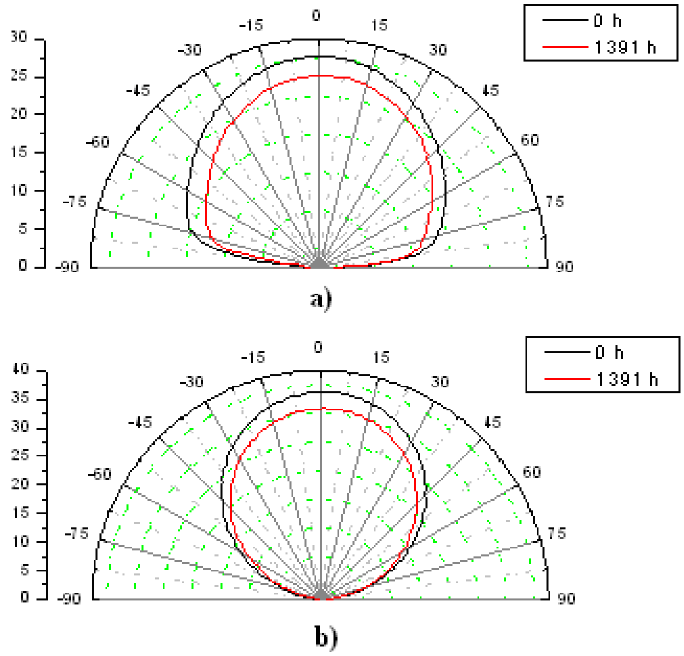

Figure 3: Evolution of the spatial emission pattern of plate #1 during the degradation test for a) LED model A and b) LED model B.

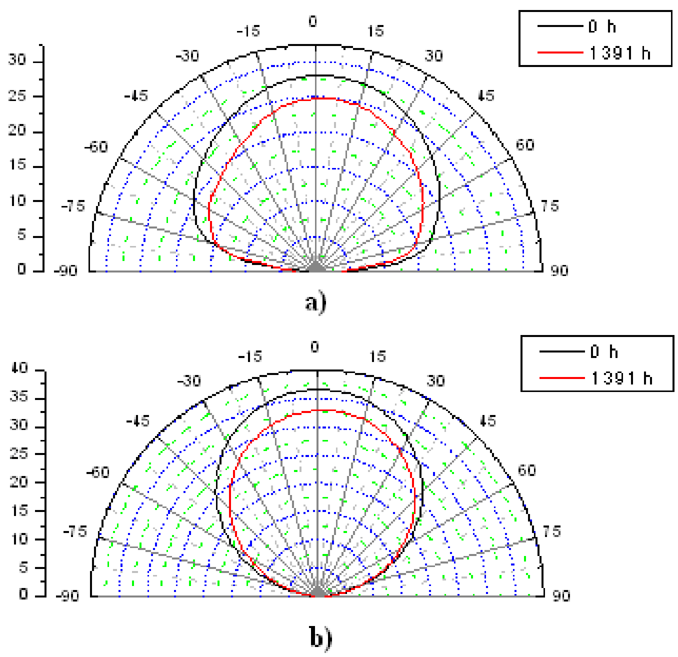

Figure 4: Evolution of the spatial emission pattern of plate #4 during the degradation test for a) LED model A and b) LED model B.

The electrical characteristics of white LEDs can also be altered as a consequence of high temperature or high current [11]. In particular, it is shown that stress can induce a variation on the operating voltage of the LEDs. Such variation can impact the design of efficient driving electronics for LEDs with long operating times. For all plates, the I-V characteristics were measured all along the aging experience. Our results show a decrease of the forward voltage most of the time with a decrease of the series resistance of the LED. For example, Figure 5 shows the variation ($V_{t=0h} - V_{t=1000h}$) of the forward voltage versus the injection current after 1000h for both type of LEDs. The LED model A shows a large decrease of the forward voltage of 1.5% (50mV) for plate #10 and about 2.5% for plates #2, 3 and 6 over the first 1000h. For junction temperatures higher than 75°C, the decrease is as large as 5% over 1000h (plates #1, #4 and #5). The forward voltage variation appears mostly during the first hundreds of hours followed by a steady decrease with a rate of 5-15 mV/1000h after 1000h, similar numbers have been reported in the literature [11]. Such rates will produce a large variation of the forward voltage over long operation times, which is quite significant for the driving electronics of the luminaire.

The LED model B has a smaller forward voltage variation of less than 1% over 1000h for most of the stress conditions. However, the decrease behavior is different than in the LED model A. Notice that the current scale is from 0 to 0.4 mA. We can see that increasing the current reduces also the forward voltage variation. We have not been able to identify for this type of LED any regular variation rate of the forward voltage over time as we have for the LED model A. Moreover, the plate #4 of LED model B has a different behavior than the other plates. This result is however in accordance with the observed increase operating voltage of the LEDs when submitted to high temperature storage [10]. We recall that the junction temperature was 134°C for the LEDs on plate #4 (highest temperature in the experiment). Consequently for this plate #4, we have an increase of the series resistance of the LEDs, with subsequent decrease in the power efficiency conversion as reported in the literature. Also, the junction temperature of plate #4 was at the limit recommended by the manufacturer. All plates except for #10 were stressed with currents over the limit recommended by the manufacturer. It might explain why there is no clear relation between the variation in forward voltage and the stress parameters for LED model B.

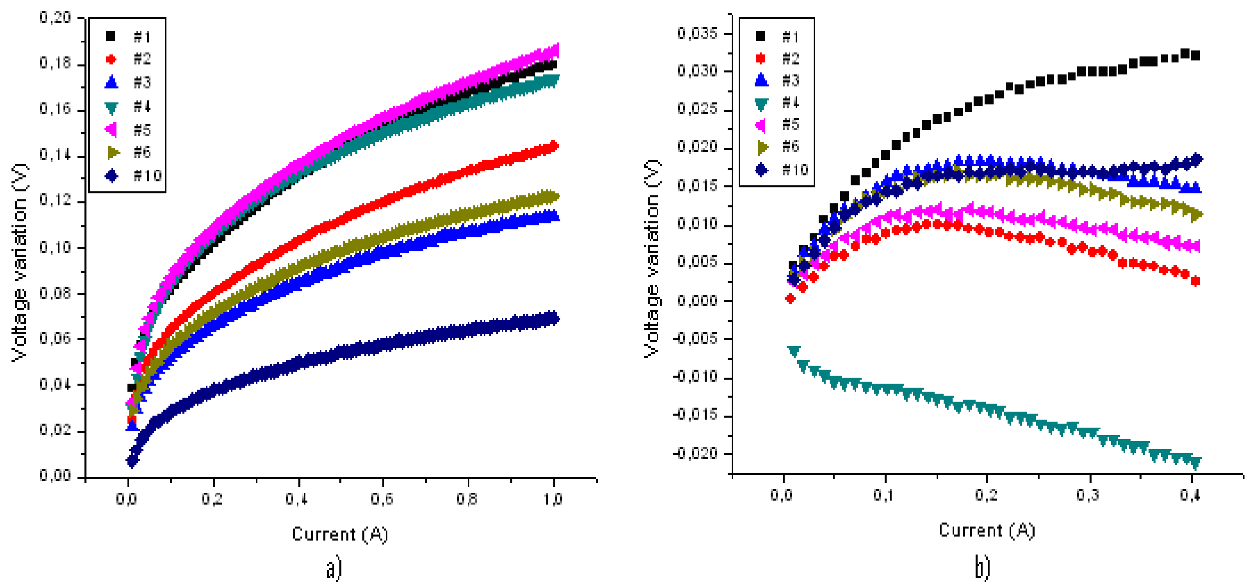

Figure 5: Forward voltage variation for a) model A and b) model B under seven different stress conditions.

White light is produced by LEDs from blue light scattered through a phosphor layer. The mix of blue light from the chip and yellow light from the phosphor will produce white light. Spectral properties of LEDs are modified by the stress. For example, the ratio yellow peak / blue peak is presented on Figure 6. Here, we chose to show the result only for LED model A over a longer period of time. In fact, for the first 1000 hours of the test, there was a decrease in the ratio. This means that there was a yellowing of the phosphor layer for all degradation conditions in the test. This finding has been reported extensively in the literature [12-14]. Since the junction temperatures used in the test are close, it was not possible to link the decrease of the ratio with the stress conditions as other groups have done.

If we look over a longer time, it appears that the ratio increases after the initial drop. To our knowledge, we were the first to report such an increase [2] since most degradation tests are stopped after a few hundred hours. This increase in the ratio points toward a second degradation mechanism taking place in the LED. The initial drop comes from the yellowing of the epoxy, which is more severe for harsh stress conditions. Then, there might be a second degradation mechanism that takes over.

The confirmation of the second degradation mechanism comes from the total light power emitted by the LED. These results are not presented here. We assume that the power emitted by the LED can only decrease or stay constant when submitted to stress under harsh conditions. It appears that there is a continuous decrease in the power emitted by the LEDs. The fact that the total emitted power decreases while the yellow peak ⁄ blue peak ratio increases is an indication that the chip producing blue light is degrading. The phosphor layer yellowing is the dominant factor of the initial period in the degradation of the spectrum of LEDs. After about 1000-1200 hours, the main contribution to the spectrum degradation becomes the junction. Again, this effect has been observed under all stress conditions. Even for LEDs stressed with the current recommended by the manufacturer, there is still a modification of the spectrum during the test. This needs to be taken into account when designing a LED lamp, even if it will be used in normal conditions.

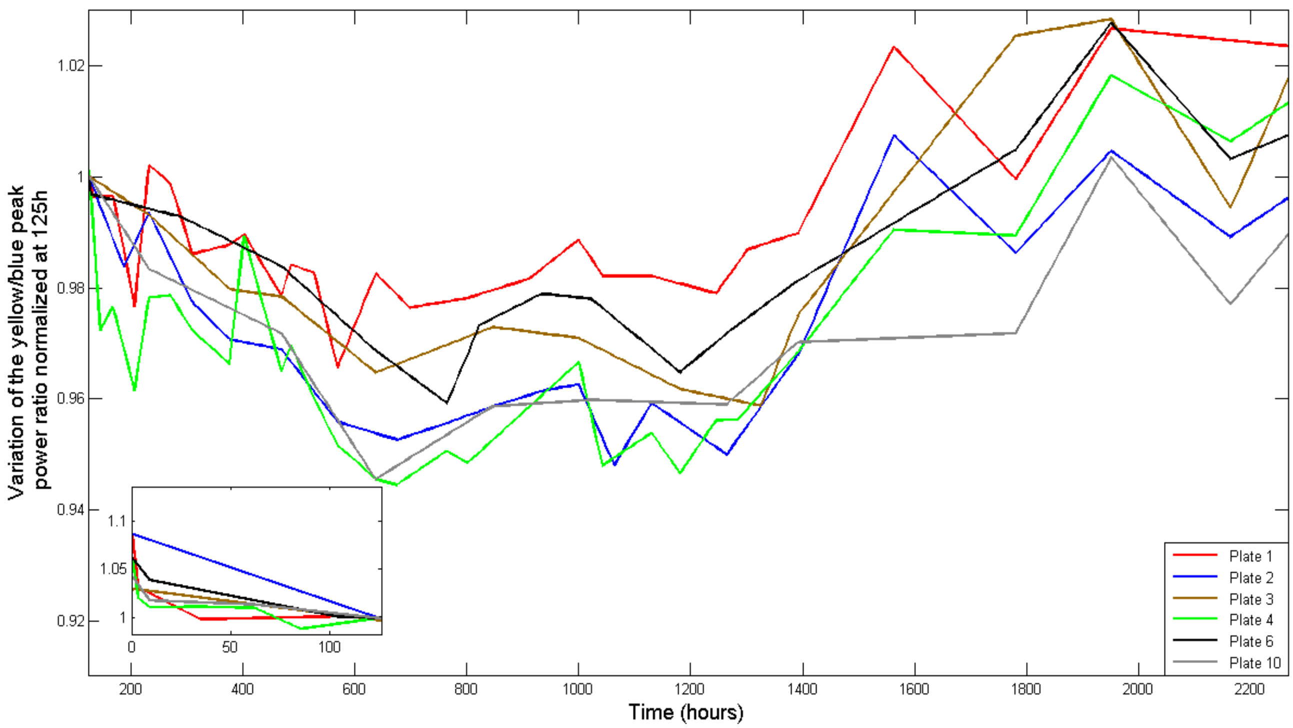

Figure 6: Evolution of the yellow peak ⁄ blue peak ratio for six different operating conditions for LED model A.

4. CONCLUSION

The results presented in this paper indicate that the properties of a LED are significantly modified when current is injected at the junction. The heat produces degradation of the lumen output, the forward voltage and the emitted spectrum. However, the spatial emission pattern is kept constant. Operation of the LED under harsh conditions will only accelerate such phenomenon.

The relative lumen output results indicated that the degradation rates change with the operating conditions as well as from different manufacturers. The lumen output drops as a function of time but also as a function of operating stress conditions. Consequently, it would mean that the lifetime prediction model needs to be changed when the operating current and temperature change during the life of the luminaire. The results also show two operation regimes under 70-75^{o}C and over 75^{o}C. For a lower junction temperature (under 70^{o}C), after the initial drop (annealing), the light output is mainly stable but for a higher junction temperature, the initial drop is worse and the light output drops slowly. We are not aware of any published data about this effect even under the recommend operating conditions. The relative lumen results show the variation between similar LEDs due to manufacturing issues. Our results show a decrease of the forward voltage most of the time which corresponds to a decrease in the series resistance of the LED over the lifetime of the luminaire. Over a long term, the variation of the voltage can exceed 10% which can be quite significant for the design of driving electronics. We also observed that the forward voltage variation is lower for junction temperatures under 70-75^{o}C. Finally, under stress conditions, no severe browning of the material and darkening of the package were observed during the experiment as an indicator of the integrity of the LED package.

In conclusion, our results show that the LEDs available on the market can be used in a luminaire with a junction temperature under 75^{o}C to limit the relative lumen output degradation. LEDs used in harsh conditions will suffer rapid degradation during the initial period of operation. We recommend using the lumen output after a 200 hour annealing period to design the luminaire which seems to be at least 10-15% under the number quoted by the manufacturer. Due to LED degradation variations from LED manufacturers, it is still difficult to develop a universal LED degradation model. Consequently, compensation strategies should be based on an active lumen measurement and not on a mathematical model. Furthermore, the decrease of the variation voltage can be important and should be part of the optimization strategy of the efficient LED luminaire design.

ACKNOWLEDGEMENT

We would like to thank the two LED manufacturers who supplied us with LEDs for testing and answered our questions regarding the specific characteristics. This work was supported by the NSERC Industrial Research Chair in Optical Design.

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