Long-Term Performance of Screwbase Compact Fluorescent Lamps

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Abstract

Over the past several years, screwbase compact fluorescent lamps (SCFLs) have been promoted as replacements for incandescent lamps in interior and exterior luminaires. One commonly quoted benefit for SCFLs is longer life. The lamp industry uses the 3-hour-on/20-minute-off switching cycle to determine rated lamp life. However, in residential applications, lamps are switched on and off at different rates and lamp life for SCFLs depends on how frequently they are switched. An experiment was conducted to investigate the effects of different operating cycles on the life of SCFL products.

Data for 11 different SCFL products from six different manufacturers operating in six different cycles are reported. This paper discusses performance characteristics of SCFL and factors affecting fluorescent lamp life. Differences between SCFL products and linear fluorescent lamps are also discussed.

Introduction

Fluorescent lamp systems became commercially available in the late 1930s. Since then, they have been used as an alternative to incandescent-lamp systems in commercial and industrial applications because they have higher output, are more efficient, and have longer life. Fluorescent lamps were first developed in the shape of a linear tube. Over the years these lamps gradually took on other shapes and sizes. Today, fluorescent lamps are available in many different shapes, sizes, wattages, and color characteristics.

The use of rare-earth activated phosphors allowed the development of compact fluorescent lamps (CFLs). CFLs are fluorescent lamps that have a tube diameter of 16 millimeters (mm) or less. They are available in various wattages, shapes and sizes.

SCFL products are used to replace incandescent lamps in luminaires with medium screwbase sockets, such as ceiling- and wall-mounted luminaires, exterior luminaires, recessed downlights, track lighting, and floor and table lamps. Extended lamp life is one of the main justifications for using CFL products, compared to incandescent lamps. However, a recent survey[1] revealed that early burnout of CFLs accounted for 22% of the complaints received about the product. If life is one of the main reasons why a consumer will spend more for a CFL than for an incandescent lamp, factors that lead to early lamp failures should be better understood.

Rated life of both SCFL and linear fluorescent lamps is defined as the time when 50 percent of a large number of lamps have failed. All lamps are operated on standard 3-hour-on/20-minute-off cycle to determine rated life. Previous studies have shown that if linear fluorescent lamps are started more frequently than the standard 3-hour on/ 20-minute off they will have life statistically shorter than their rated life. No previous studies were reported in the literature on the effects of frequent switching of SCFL products.

Background

A fluorescent lamp fails when the emissive coating on their cathodes is exhausted due to evaporation and sputtering. Although the inert gas fill used in SCFLs protects the cathodes to some extent from bombardment by mercury ions, loss of the emissive coating during lamp starting and operation is unavoidable. The rate of coating loss is fairly low and steady during lamp operation. During lamp starting, however, the cathode coating is rapidly lost when it is bombarded by mercury ions, which are accelerated due to a high cathode fall voltage. This occurs because the cathodes are not warm enough to emit electrons thermionically, and starting relies on the physical bombardment of mercury ions. This effect is known as sputtering. Because starting and operating characteristics of SCFLs are similar to linear fluorescent lamps, it had been assumed for the purpose of this study that starting and operating parameters that affect linear fluorescent lamp life are also applicable to SCFL.

Starting method is one of the important factors affecting lamp life.[2,3] Among the SCFLs operated with magnetic ballasts, the preheat-starting circuit probably does the most severe damage to lamp cathodes. It overheats the cathodes and it “blinks” while starting. The rapid-start magnetic ballast, because it heats the electrodes before starting and then limits the current to the lamp is less damaging to the cathodes. Some electronic ballasts are designed with solid-state components to minimize the damage to the lamp. However, instant-start electronic ballasts have greater potential to shorten lamp life compared to rapid-start electronic ballasts because they do not preheat the cathodes.

The American National Standards Institute (ANSI) established requirements for maximum and minimum values for: lamp starting voltage, lamp starting electrode voltage (rapid-start ballasts only), glow current (rapid-start ballasts only), preheat time (rapid-start ballasts only), and starting time.[4,5] Presumably, ANSI established these requirements to improve fluorescent lamp life.

Lamp starting voltage is that voltage applied between the lamp electrodes to initiate the discharge and is generally two or three times greater than the lamp operating voltage. A starting voltage that is less than the minimum recommended by ANSI[4] will cause unreliable starting. A starting voltage that is greater than the recommended maximum will reduce lamp life and cause increased end blackening. End blackening results from the deposition of emissive coating and evaporation of the tungsten on the bulb wall near the electrodes. End blackening also reduces lumen output.

Lamp starting electrode voltage is the voltage supplied by rapid-start ballasts to heat the electrodes before applying the starting voltage. If the electrode heating voltage is high, it can raise the electrode temperature to above 1000 °C (1800 °F), and lamp life will be reduced because of excessive evaporation of the emissive coating. If the electrode heating voltage is low, the electrode may not reach 700 °C (1300 °F) and lamp life can be reduced from loss of the emissive coating due to excessive sputtering.

Preheat time and starting time are also parameters used to characterize rapid-start systems. Preheat time is the length of time that a rapid-start ballast heats the electrode before the lamp arc is initiated. When the length of time that the rapid-start ballast heats the electrode is short, insufficient heating of the electrodes occurs, and the consequences in lamp life are similar to the effects of having low electrode heating voltage as described above. When the length of time that a rapid-start ballast heats the electrode is long, overheating of the electrodes occurs, and the consequences in lamp life are similar to the effects of having high electrode heating voltage. ANSI requires that the preheat time for rapid-start ballasts be greater than 500 ms.

For instant-start ballasts, the length of time that the high voltage is applied to the lamp during starting is an important factor. If the high voltage is applied to the lamp for too long, the potential for reducing lamp life due to sputtering is higher. ANSI[4] requires that the starting time for instant-start ballasts be less than 100 ms.

Another parameter, the glow current, is the current flowing away from the electrodes during the preheat time and includes the current flowing between the lamp electrodes and the current from the electrode to the lamp wall. It reflects the degree to which emissive material is lost during lamp starting before the electrode has reached the operating temperature. High glow current increases lamp end darkening and reduces lamp life, especially if it occurs over an extended period. ANSI[4] specifies a maximum glow current of 25 mA for electronic ballasts.

Lamp current crest factor (CCF) is the ratio of the peak lamp current to the root mean square (rms) lamp current. The CCF for a sine wave is 1.41; a higher CCF indicates a distorted wave shape with the potential for high peak current that can damage to the lamp electrodes due to evaporation and, thus, reduce lamp life.[6]

Lamp operating electrode voltage is the voltage supplied by the ballast to heat the electrodes during lamp operation. For instant-start and modified rapid-start ballasts, there is no lamp operating electrode voltage, but rapid-start ballasts continue to provide approximately 3.5 V to the electrodes during lamp operation. Sputtering of the electrode emissive material can occur during lamp operation for the three ballast types. For rapid-start ballasts, however, although the electrode heating during operation increases the active power of the system, it helps minimizes the sputtering during operation, because the electrode temperature during lamp operation remains above 700 °C (1300 °F).

Lamp operating current may have an indirect effect on lamp life. Lamp operating current is the current flowing between the lamp electrodes during operation. When lamp operating current is reduced, light output of the lamp is also reduced. Lower lamp operating current results in a lower electrode temperature, which may cause electrode sputtering and, thus, reduce lamp life. ANSI[4] sets maximum limits on lamp operating current to minimize the evaporation of the electrode emissive coating and sets minimum limits on ballast factor to minimize sputtering. Low ballast factor is a result of low current flowing is a result of low current flowing between electrodes (low operating current).

Another factor affecting SCFL life is lamp ambient temperature. Although lamp ambient temperature has only secondary effects on lamp life compared to lamp starting, it directly affects ballast life.[2,3] In applications using self-ballasted SCFLs, lamp ambient temperature becomes more critical. Thermal management can become a problem when the lamp and ballast are an integral product, as in an SCFL. When a lamp loses its emissive coating, a great amount of heat is generated in the coil as a result of the continuous power trying to maintain electron supply. The localized heating at the coil can result in melted sockets and cracked lamp glass. In addition, the proximity of the electrodes to the ballast may increase the heat near the ballast components. Also, when the lamp is operated in a base-up position, the heat generated in the lamp will migrate more easily to the ballast. In some cases, the ballast is enclosed in a plastic housing or has no vents. Other SCFLs have globes, which trap even more heat. The thermal problem increases as the wattage of the SCFL increases because the systems have to dissipate more heat.

For electronic ballasts, life is dependent upon the quality of the electronic components, and the degree to which the ballast is protected from line voltage surges and electrical transients. Electronic ballasts use semiconductor devices such as transistors and rectifiers that are more sensitive than magnetic components to line surges. To protect these electronic components from electrical line surges, electronic ballast designs can employ filters and voltage limiters at the ballast input. The rated life of electronic ballasts assumes that the input voltage variation ranges from 10 to 20 percent and an ambient temperature range of 60 to 105 °C (140 to 221 °F).

Although lamp manufacturers perform extensive life cycle tests on their products and their competitors' products, very few data are published. Vorlander and Raddin (1950)[7] conducted a study to determine the effects of various operating cycles on life and performance characteristics of a T-12 preheat, hot-cathode fluorescent lamps. Their study generated a curve (Figure 1) of average life in thousands of hours vs. burning cycles in hour for linear fluorescent lamps. Although the average life of those products was only 4000 to 6000 hours (compared to more than 20,000 hours today), Vorlander and Raddin clearly illustrated that lamp life is shortened when lamps are operated on shorter cycles. Because of the significant improvement in lamp life and performance characteristics of linear fluorescent lamps, this curve cannot be used to predict life for today's lamps. Another study[8] was conducted to determine the effects of design and operating variables on the life of fluorescent lamps. That study provided data for rapid-start and instant-start lamps, which was added to the 1950 curve (Figure 2).

A more recent curve demonstrating the effect of different starting methods on lamp life is found in the Illuminating Engineering Society of North America (IESNA) Lighting Handbook.[2] The curve in Figure 3 have been normalized to 100% for life at 3 hours per start. The preheat-starting circuit has some advantages for lamp life over the rapid-start circuit when operating cycles are greater than 3 hours. However, the graph provides no prediction of lamp life for cycles shorter than 3 hours. A study conducted in 1985[9] documented the effects of two types of rapid-start electronic ballast on the life of 40W T12 lamps.

No published data were available for SCFL life cycle testing. However, a paper published in 1993[10] proposed a model for the cost-effectiveness of SCFLs as influenced by on-times and operating cycles. This model is purely theoretical, but it considers a variety of realistic scenarios and factors critical to SCFL life and thus was a good reference for project scoping.

In order to better understand the effects of frequent switching on the life of fluorescent lamps as well as reduce the life-testing time, some manufacturers have used the following rapid cycles for linear lamps: 10-second on/10-second off, 40-second on/20-second off, 5-minute on/5-minute off, and 15- minute on/5-minute off. These tests may cause *less* damage to the emissive coatings during starting than in typical applications, even though these rapid cycles indeed shorten the life testing time. In essence, there is no clear and convincing relationship between the results from rapid-cycle testing to the results from the standard life testing.

Moreover, because SCFLs are designed mainly as incandescent replacements, the standard cycle does not represent typical applications in residential settings. Therefore, it was interesting to see how the products made by different manufacturers and different lamp shapes affect SCFL life.

Methods

Using industry documentation and company information, eleven 15- to 23-W SCFL products from six different manufacturers were identified. The products were selected so that a variety of ballast designs, starting methods, manufacturers, and lamp shapes would be included. Table 1 shows the starting and operating characteristics for the 11 products.

Six different operating cycles were selected to represent possible applications for SCFL products:

The operating cycles were:	Assumed Application
1: 5-minute on/20-second off	(Pilot Study)
2: 5-minute on/5-minute off	under cabinet
3: 15-minute on/5-minute off	bathrooms
4: 1-hour on/5-minute off	reading, dining
5: 3-hour on/5-minute off	kitchen / living room
6: 3-hour on/20-minute off	(control cycle)

For cycles 1 to 4, eight samples of each product were tested; for cycles 5 and 6, four samples of each product were tested. The number of samples suggested in ANSI Specification C78.5-1997[10] was not used in this study because the goal of this study was to look at factors that might affect life under different operating cycles and not to determine the rated life of the products. All the lamps were operated in a base-up position. Four 6- x 5- x 3-foot (ft) lamp racks were built for this study, each with five "shelves" that held 32 lamps. A 45 kVA voltage regulator (120 V $\pm$ 0.5%) regulated the power to the lamps. A computer monitored and controlled testing. Ambient temperature inside the laboratory was 25 $\pm$ 10 °C (77 $\pm$ 18 °F).

Visual inspection for lamp life is described in the IESNA LM-65-1991[12] life-testing standard. This method does not require any materials, set-up time or set-up labor, but it has the disadvantage of lower precision compared to other methods, because an experimenter would not be able to check the lamps at night or during weekends and holidays. However, a simple analysis was conducted to determine if this method would provide acceptable accuracy for this project. It showed that a maximum error in lamp life determination would be 1.5%. Since the cost was minimal with this approach, the visual inspection method was selected for measuring lamp failure in this project.

In addition to lamp life, lamp starting characteristics (starting time, electrode preheat current, and lamp starting voltage) and lamp electrical characteristics (lamp operating current and CCF) were measured for one sample of each of the 11 products. A post-mortem analysis of the failed SCFLs was conducted to determine whether the ballast or the lamp had caused the product failure.

Results

The IESNA LM-65-1991[12] describes the procedures for obtaining data on individual and average lamp life of a single-ended compact fluorescent lamp. The use of median life instead of mean life by the manufacturers can be justified by the fact that a long period of time would be necessary until all the samples have failed and the average life could be calculated. Though the manufacturers refer to lamp life as "average rated life", this number refers to the median, not to the mean life of a large group of lamps, and to be consistent with the manufacturers' data, this report will also address the median, not the mean, life of the products tested. Statistical analyses were, however, conducted using the mean number of on-time hours for each product operating on different cycles. One-tail t-tests were used when the direction of the results was predicted. Two-tail t-tests were used to see if there were significant differences between cycles 5 and 6 and when the predicted direction was wrong. The small sample size used in this experiment resulted in a large standard deviation, which reduced the chances of achieving statistical significant differences (reduced power).

In general, lamp operating current was within the range of 160 to 553 mA. Only B1 had a very high lamp operating current (553 mA). Current crest factor ranged from 1.46 to 2.14. Only D1 and D2 products had current crest factors higher than the maximum recommended by ANSI, which is 1.7. The starting time varied from 0.5 to 1.10 s for the electronic preheat ballasts. For the magnetic preheat ballast, the starting time was 1.7 s, while for the electronic instant-start ballasts, the starting time was 0.08 s. The electrode preheat current ranged from 217 to 725 mA, although one product (B2) had an electrode preheat current of 725 mA. The lamp starting voltage ranged from 106 to 235 V.

Table 2 shows the median (and mean) lamp life in hours for the 11 products operating on six different cycles. Manufacturer's rated life (7500 to 12,000 hrs) should be considered only for the standard cycle (3-hour on and 20-minute off cycle). All products but B1, B2, and C1 met the manufacturer's rated life, while A1, A2, and C2 more than doubled their rated life. Although products are expected to reach rated life only when operating on the standard cycle, many products reached and exceeded rated life when operating on cycles other than the standard.

Figure 4 shows the on-time vs. the median life for cycles 2, 3, 4, and 5. For the same off-time, a longer on-time typically results in a greater life. This effect is more noticeable when the on-time is less than 1 hour. In other words, the difference in life between 1-hour and 3-hour on-time is smaller than the difference between 5-minute and 1-hour on-time. For each of the 11 products, t-tests were conducted comparing cycles 1 and 2. Mean life for cycle 2 (5-minute on-time), except for A2, was significantly shorter ($p < 0.05$) than for cycle 3 (15-minute on-time). Mean life for cycle 2 was significantly shorter ($p < 0.05$) than for cycle 4 (1-hour on-time) for all products. Except for D2 and F1, mean life for cycle 2 was significantly shorter ($p < 0.05$) than for cycle 5 (1-hour on-time). Mean life for cycle 3 (15-minute on-time), except for D1, F1, and F2 was significantly shorter ($p < 0.05$) than for cycle 4 (1-hour on-time). Mean life for cycle 3, except for D1 and A1, was significantly shorter ($p < 0.05$) than for cycle 5 (3-hour on-time). Contrary to what was expected, however, D2 had significantly greater ($p < 0.05$) mean life for cycle 4 than for cycle 5. Mean life for cycle 4 (1-hour on-time), except for D1, D2, F1, B1, B2, A1, C1, C2 was significantly shorter ($p < 0.05$) than for cycle 5 (3-hour on-time). Contrary to what was expected, D2 and F2 had significantly greater ($p < 0.05$) life for cycle 4 than for cycle 5.

Figure 5 shows the median life and Figure 6 shows the mean life of each product for cycles 1 (5-minute on/20-second off) and 2 (5-minute on/5-minute off). For the same on-time, B1, B2, E1, and C1 had significantly greater mean life ($p < 0.05$) when the off-time was shorter (cycle 1). D2 and F2, though not statistically significant, had greater mean life when the off-time was shorter (cycle 1). D1, A2, F1, and C2 had significantly greater mean life ($p < 0.05$) when the off-time was longer (cycle 2). A1, though not statistically significant, had greater mean life when the off-time was longer (cycle 2).

Figure 7 shows the median life and Figure 8 shows the mean life of each product for cycles 5 (3-hour on/5-minute off) and 6 (3-hour on/20-minute off). For the same on time, C2 had statistically significant greater mean life ($p< 0.05$) when the off-time was longer (cycle 6). D2, A1, A2, B2, E1, F1, and C1 had greater mean life with a longer off-time (cycle 6), but, as expected, the difference in lamp life was not statistically significant. D1, F2, and B1 had greater mean life with shorter off-time (cycle 5), but, as expected, the difference in lamp life was not statistically significant.

Post-mortem analyses were conducted to determine whether the lamp or the ballast had caused the system failure. After the system had failed, the test lamp was connected to a new ballast and the test ballast was connected with a new lamp. This procedure allowed determination of the failed component. In general, early system failures were caused by ballast failures. The majority of the system failures, however, were due to lamp failure.

Discussion

As expected, shorter operating cycles significantly reduce the median lamp life of most of the products. In addition, some products tested did not meet their rated lamp life at the standard 3-hour on and 20-minute off cycle. These results indicate that using rated lamp life for economic analyses regardless of operating cycle and without independent confirmatory data, is unjustified.

Figure 4 shows that lamp life (in hours) was directly related to on-time duration. In general, the longer the on-time, the longer the lamp life. It is interesting to note, however, that the number of starts has a greater impact on lamp life when the on-time is short. For the same off-time and different on-times (cycles 2, 3, 4, and 5), the effect of the number of starts seems to be greater below 1-hour on-time. This is probably because after 1 hour, lamp life is determined not only by the number of starts, but also by operating time, which contributes to reducing lamp life through coating evaporation.

It was expected that all products would have greater life on cycle 1 (5-minute on/20-second off) than on cycle 2 (5-minute on/5-minute off) because 20 seconds off-time would not be enough to cool down the electrodes and less damage due to sputtering would occur the next starting sequence. Only 4 out of the 11 products had significantly greater mean life when the off-time was shorter (cycle 1). Two out of the 11 products, though not statistically significant, had greater mean life when the off-time was shorter (cycle 1). Five out of the 11 products had greater mean life when the off-time was longer (cycle 2). The testing results do not support the hypothesis that a 20-second off-time will have longer life than a 5-minute off-time. This may be due to the fact that the proximity of the electrode to the ballast in integral products does not allow the electrode to cool down even after 5 minutes off. Another possibility is that the hot electrode may affect ballast life.

Based on a previous pilot study, it was expected that there would be no significant difference between cycles 5 (3-hour on/5-minute off) and 6 (3-hour on/20-minute off). Results showed that although 8 out of 11 products had greater mean life when the off time was longer (cycle 6), only 1 product had significantly greater mean life ($p < 0.05$) when the off time was longer (cycle 6). When measurements were taken in the pilot study, the lamps were physically separated from ballasts, and this may have facilitated the cooling process. During the final testing, the lamps were placed in the rack and the cooling of the electrodes may not have occurred quickly for some of the products, especially the ones with higher wattages. The data presented here does not fully support the hypothesis that a 5-minute off time is enough to cool down the electrodes. However, because one product had significantly greater life when the off time was longer, and because no data were gathered for off-times between 5 and 20 minutes, it is recommended that a more detailed study be conducted, where data for off-times between 5 and 20 minutes are collected. This will allow a more accurate relationship between short off-times and standard test methods to be determined.

Table 2 also shows that most of the products met or exceeded their rated lives on the standard 3-hour-on and 20-minute-off cycle, although two products did not even achieve 50% of their rated lives. It is also interesting to note that some products achieved their rated life in almost all operating cycles, even though the products are expected to achieve this many hours only on the standard 3-hour on and 20-minute off cycle. This suggests that the quality of the components (e.g., electrodes, electronics), and lamp design, which affect thermal management, may play major roles in lamp life.

Table 1 shows the electrical and starting parameters and observations about product design can be made. D1 and D2 had CCF greater than 1.7, but they still had very long lamp life. ANSI standards[4] currently limit CCF for fluorescent lamps to a maximum of 1.7, since higher CCFs are expected to reduce lamp life. D1 and D2 low lamp operating current relative to other products limits the peak lamp current (even with a higher CCF); the reduced peak current reduces damage to the electrodes, which may explain why the lamp life was maintained. B2 had very short life. This product had a high cathode preheat current and a very short starting time relative to other electronic preheat products, which may indicate that lower preheat currents for a longer starting time are better for the lamp. Similar results were found for lamp starting parameters for four-foot linear T8 fluorescent lamps.[13] B1 had a very high lamp operating current, which might have increased the evaporation of the electrode emissive coating, resulting in shorter lamp life.

Conclusions

This study has shown that different operating cycles, different lamp and ballast designs, as well as thermal management affect the life of an SCFL product. However, these factors are not always easy for the end user to determine when selecting an SCFL product. Further studies need to be done to identify what are the key factors that affect the life of SCFL products.

In only a few cases the results suggest that the products tested did not meet their rated lives on the standard 3-hour on and 20-minute off cycle. Even on the shortest cycle (cycle 1), a few products exceeded their rated life. A large percentage of the products reached more than 20,000 hours. In summary, for the same operating cycle, products differ from each other with regard to life.

The data presented here do not support the hypothesis that 5-minute off-time is enough to cool down the electrodes because in one case, there was a significant difference in life between cycles 5 and 6 ($p < 0.05$), and in two cases, there was an almost significant difference in lamp life ($p = 0.08$). The industry's goal is to establish rapid-cycling testing for SCFL products and a new set of data with a greater number of samples should be gathered for off-times between 5 and 20 minutes. This would eliminate questions that are still unanswered as to whether 5-minute off-time can be used instead of the 20-minute off-time.

It was clear from the results of this study that SCFL products are different from other fluorescent lamp systems. Some of ANSI standards specifications established for fluorescent lamp systems may not be applicable for SCFL. A more detailed research program should be conducted to establish a set of electrical and performance standards for SCFL, which would include the effects of lamp ambient temperature, ballast design, lamp shapes, sizes and wattages. The establishment of this new set of standards would be more likely to improve SCFL life.

Future research to better understand the optimum off-time for rapid cycling should also be conducted. This would allow manufacturers to reduce the time of the life testing without overestimating the rated lamp life.

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Prepared Discussion

Lamp life is always a topic that produces considerable interest in the lighting industry and among consumers alike. This paper shows the wide range of lifetimes produced with varying product designs and under different application conditions. The analysis and explanation offered by the authors for the results obtained are very insightful and intriguing. Other explanations, however, are possible and perhaps as probable.

For example, the off-time in the cycle test described in the paper also effects the Hg vapor pressure in the lamp. This would be expected to have much greater influence on cathode fall potential (and hence lamp life) during lamp starting than the small residual temperature effect on the lamp filament. A life test including a mercury-amalgam lamp would be very informative in this regard. Also, the ratio of hot-to-cold filament resistance (R_H/R_C) is a key indicator of lamp performance. This lamp design parameter will significantly influence lamp performance for a particular cycle time and ballast type. It would be interesting to include the effect of filament temperatures based on R_H/R_C values in the interpretation of the test data. My final comment relates to the sample size and to the degree it affects the conclusions drawn by the authors. Lamp-to-lamp and day-to-day lamp manufacturing variations (fill pressure, cathode coating mass) are inherent in any high-speed manufacturing process. These variables can significantly alter the comparative results for any single life test.

An expanded follow-up test including the points raised would be very helpful towards a fuller understanding and appreciation of the test data.

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Authors' Response

Mr. Roche's brought up a very good point regarding the influence of Hg vapor pressure in the lamp on the cathode fall potential during lamp starting. The authors agree that further investigation using amalgam lamps would be useful. Regarding Rh/Rc, it is important to point out that Rh/Rc is a good predictor of life for rapid start systems, but it is more difficult to make these measurements for integral systems. The lead length between the lamp and ballast is very short and the lamp and ballast operate in close proximity to each other. Further, the measurement probes can affect the results.

The authors are sympathetic with the point that a larger sample size would provide more confidence in the results, but we believe that the data gathered here can be helpful for further studies. It should be noted, however, that statistical power values for these tests were all close to 1.00, indicating that the tests were highly reliable and that additional samples would not affect the statistical inferences.