Dimming Fluorescent Systems Life Experiment

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Abstract: *This paper describes the 11620-hr results of an ongoing life test for dimming fluorescent systems. Representatives from lamp and ballast manufacturers who belong to the National Electrical Manufacturers Association (NEMA) undertook this project. This testing is funded by the manufacturers and the US Department of Energy and is being conducted by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute in Troy, NY. The life test is evaluating one-lamp F32T8 systems at various fixed lamp currents and electrode heating voltages to identify a region of satisfactory performance for lamps and ballasts.*

OVERVIEW

Fluorescent dimming is becoming more important in the marketplace, by some estimates accounting for a few percent and growing of the installed base. Benefits of fluorescent dimming include energy savings and optimizing the light level for the given task. Fluorescent dimming provides additional challenges beyond non-dim operation. With correct installation wiring, good performance is certainly possible. Design of fluorescent dimming ballasts requires particular attention to ensure acceptable system reliability.

DIMMING BASICS

In general the intensity of light emitted by a fluorescent lamp increases with current. Reducing the current below the rated value can dim a fluorescent lamp. Light levels as low as one percent of the rated light level can be obtained. A number of mechanisms limit the lifetime of fluorescent lamps, including consumption of electrode emissive coating, consumption of mercury, and degradation of the phosphor. The emissive mixture is consumed during the normal life of the lamp by evaporation. Mercury is consumed during the normal life of the lamp by chemical combination with barium from the evaporated emissive coating, or from diffusion into the glass.

The fluorescent electrode is a coiled tungsten wire heater holding alkaline-earth oxide powder. The oxide "emitter" enhances thermionic electron emission. In operation, a "cathode fall" potential will develop between the plasma and electrode. This regulates net charge flux (lamp current), accelerates particles and ionizes as necessary. Time and space dependent electrode heating is by the energy of incident charged particles and ohmic processes; cooling is by emitted particles, conduction and radiation. The power balance establishes a temperature profile for the electrode geometry. For any electrode design, there is a "rated current" where the cathode fall is low enough to preclude damage from accelerated ion bombardment and where the electrode temperatures are low enough that emitter material loss by evaporation is in accord with rated life. Barium from evaporated emitter binds with mercury; higher temperatures will increase the rate of mercury consumption, limiting the useful life of lamps with low mercury dose. In dimming, operation below rated current, the power balance requires increased cathode fall or increased ohmic heating. For good lamp life, the solution is supplemental ohmic heating by means of circulating current in the tungsten heater coil. The temperature profile in dimmed operation will be different than at rated current. The temperature and cathode fall limits of normal operation must be maintained in dimming operation.

EXPERIMENT DESIGN

A balance between point location, sample size and costs was needed in the design of this experiment. This experiment is relevant to T8 dimming systems in which the lamps are full-wattage, argon-filled design. To keep the cost and effort reasonable, the scope was limited to F32T8 lamps on ballasts designed to operate single lamps at predetermined electrode heating voltages. Multiple-lamp ballasts and T8 lamps of other lengths and shapes are considered natural extensions of this work.

The experiment is a 4-factor full-factorial design: electrode heating voltage, lamp current, ballast manufacturer, and lamp manufacturer. Factor level selection was based on expert experience with the physics of dimming failure. The physics of electrode electron emission suggests a potentially rapidly changing response could be expected between moderate and low electrode heat levels. A more slowly changing response was anticipated for the region of excessively heated electrodes. To cover both extremes, the upper (6.0 V) and lower (1.5 V) electrode heating levels were set. Lamp current between 20 mA and 110 mA defined the dimming region. This corresponds roughly to a range of dimming light levels from 10% to 60%. Each factor was set at four levels to keep the experimental design sensitive to mapping the location of a rapidly changing system reliability response.

The categorical factors of lamp and ballast manufacturer were chosen to have equal contribution from each participating company. All combinations of lamp and ballast design were included at each experiment design point, ensuring a uniform and unbiased response. A summary of the factors is shown in Figure 1. There are 192 experimental combinations replicated 4 times for a total of 768 systems at the 16 design points. Two control points, also fully replicated, were added at 180 mA lamp current with and without 3.0 V electrode heating voltage.

Factors	**Values**	**Controls**
Electrode Heating Voltage	1.5, 3.0, 4.5, 6.0	0.0, 3.0
Lamp Current (mA)	20, 50, 80, 110	180
Ballast Mfr.	A, B, C, D	A, B, C, D
Lamp Mfr.	X, Y, Z	X, Y, Z

Figure 1: Experimental Design Factor Settings. Control points at 180 mA included.

The primary response variable is system life. A 2-week cycle, including one 4-hour off period, was selected to minimize the potential for biased results due to potential differences in starting effects while retaining the possible failure-to-start mode. The 2-week cycle time will result in extra long lamp life for design points with acceptable electrode heating. Since short-lived design points are of more concern, this was considered an appropriate cycle choice. System failure was defined to be either failure to start or lamp current falling below 5 mA as measured before and after any 2-week cycle interval.

STANDARD ERROR PLOTS

Actual lamp currents and electrode voltages were measured for every system enabling a comparison of standard error plots from three different perspectives. A standard error surface expresses the predicted standard deviation of a measured response normalized to unity standard deviation ($\sigma = 1$). Figure 2 shows symmetric, low-valued, flat contours over the experimental region for a quadratic model. The “one system” or overall perspective combines all the data into one response surface or standard error plot (Figure 2). Any differences due to the categorical lamp or ballast manufacturer factors are ignored. In this perspective, the standard error is ~ 0.068σat the center of the design space.

Two other combined perspectives are the “ballast” and “lamp” perspectives. In these perspectives the analysis is carried out as if only one ballast brand operated all the lamp brands or only one lamp brand operated on all ballast brands. For these perspectives the standard errors at the center of the design space are ~ 0.145σ and ~ 0.120σ respectively. Clearly, the experimental design is significantly more powerful in the overall perspective than the individual perspective. It is anticipated that the overlap, or intersection, of “ballast” and “lamp” perspectives will be useful for standardization discussions.

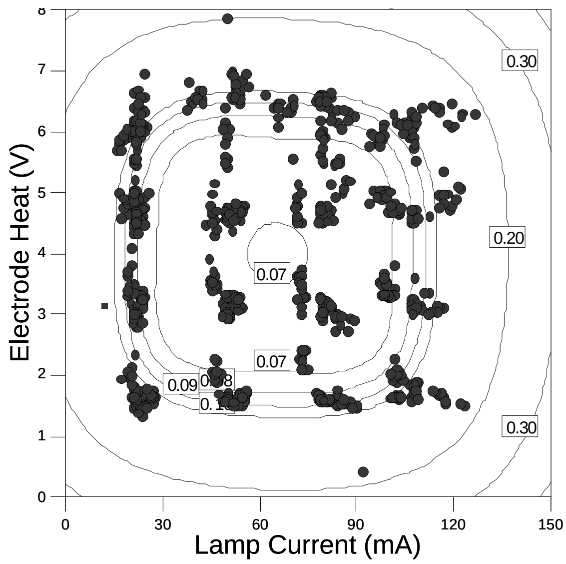

Figure 2: Standard Error of Design for Overall Perspective

SAMPLE PREPARATION

The participating ballast manufacturers modified their single-lamp dimming ballasts to operate at specific design points (lamp current and electrode heating voltage). The ballasts were modified where the lamp was simulated using precision resistors for the lamp electrodes and lamp arc impedance. Resistors were chosen for the purpose of stability. All ballast manufacturers used the same types and values of resistors. Each ballast manufacturer provided 12 samples for all 16 design points and the two control points, for a total of 216 ballasts each. Once produced the ballasts were sent to the LRC for verification. As a spot check, a small sample of ballasts from each manufacturer was measured with resistors to check the design points. Each ballast sample was later verified with lamps as part of the initial characterization of the lamp-ballast system. Each lamp manufacturer supplied four samples of 150 lamps drawn from normal production runs with four different date codes, for a total of 600 lamps per lamp manufacturer, and 1800 lamps total. An important consideration for this experiment was the selection of lamps and ballasts to create lamp-ballast systems, and to determine where each system would be located in the testing facility. A randomized selection process was created to minimize potential response bias due to heat distribution in the facility, since the lamp-ballast systems were going to be operated above, below and next to each other.

SAMPLE CHARACTERIZATION

The lamp current and electrode heating voltage for each lamp-ballast system was measured prior to initiating the life test to determine the actual operating point for each system at each design point. This was important since the ballasts were initially designed using precision resistors. The electrode heating voltage was measured at each end of the lamp and identified as “red” or “blue” based on the color of the ballast wiring that the electrode was connected to. This was another important consideration since either lamp electrode could cause the lamp to fail. These measurements would later be used in place of the design point data (i.e., 20 mA lamp current and 1.5 V electrode heating) to determine the system life response. Figure 3 shows the results for the “red-wire” electrode heating voltage measurements.

During the initial characterization other data was collected that might be related to lamp life. These measurements included lamp current crest factor, lamp voltage, lamp pin currents, and argon emission at 811.5 nm near the electrode. These measurements were stored as waveforms for future analysis. Lamp voltage and the optical emission were two independent techniques used to evaluate electrode damage, specifically if the damage was due to higher than normal cathode fall voltage. A high cathode fall voltage adds to the measured lamp voltage and increases the 811.5 nm emission [1,2]. The lamp pin currents were measured to evaluate the sum-of-squares (SoS) of the current flowing through the lamp pins. This technique has been developed to propose a standard for heating the electrodes during dimming [3,4].

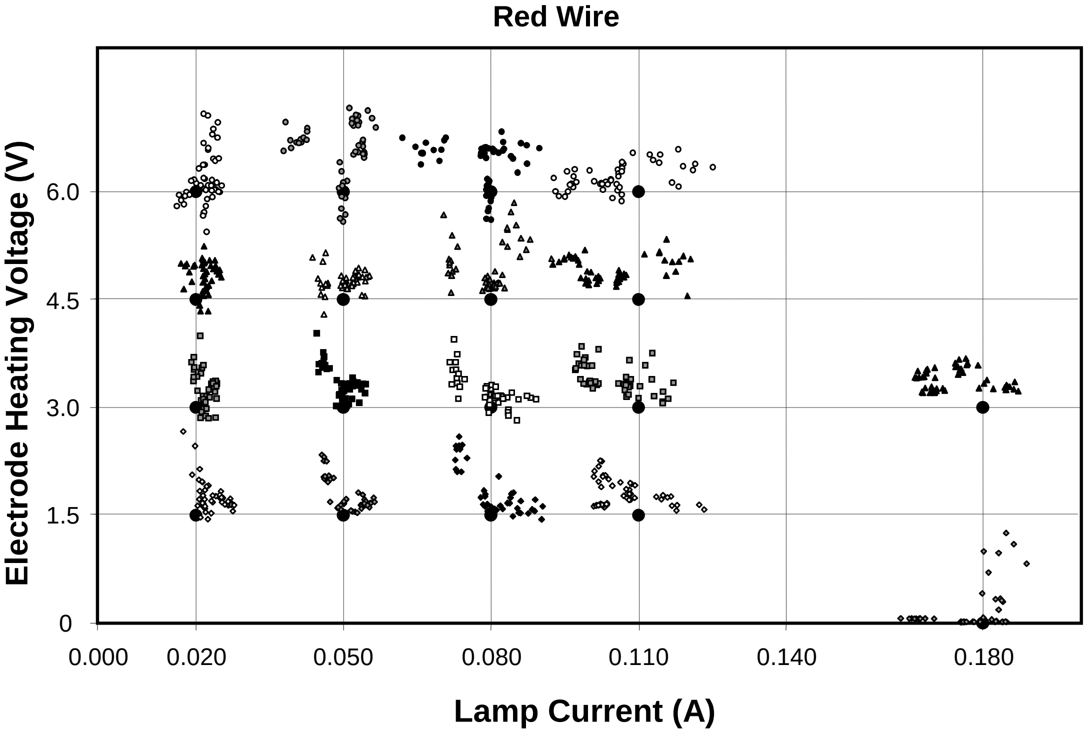

Figure 3: Initial testing of lamp current and electrode heating voltage measured on the "red wire".

EXPERIMENTAL FACILITY

A total of 16 test racks were used for the life test. Each test rack consisted of nine layers with six lamps on each layer for a total of 54 lamps per rack. The lamps were operated in the horizontal position and the lamp centers were spaced 3 inches apart. The lamp, socket and ballast were mounted to a single piece of extruded aluminum, which also acted as a grounded starting plane. The lamps and ballasts were not separated between the lamp-ballast system initial characterization and the start of the life test. This ensured that the initial testing conditions would be as close as possible to the life test condition.

A controller halts the test after two weeks of operation operates the racks. They are off for inspection, for approximately four hours, and then manually turned back on. The controller starts one rack at a time, rather than simultaneously, to minimize any input voltage impact on the starting of the each system. The controller also stores the accumulated operating time, in hours, and the number of starts for each rack. A regulated voltage supply powers the racks. In the event of a power outage, the controller records the outage and restarts the test racks automatically. The central room temperature is monitored and the test is shutdown if this temperature exceeds 45°C. A data logger records room temperature, relative humidity and light output during the life test. This data is used to monitor the operation of the life test.

FAILURE DATA

Although the experiment is ongoing, this paper presents test results after 11,620 hours of operation. A total of 161 failures are recorded in Figure 4. Each experiment design point is given a group number. Entries are the number of failed systems overall (large center numbers and percentages) and subtotals arranged by each lamp (X, Y, Z), ballast (A, B, C, D) and system (XA, …, ZD) type. Shading of the chart indicates when 50-99% (light gray) and complete (dark) failure in a system or group is observed.

The raw data show two areas of significant failure counts. The lower two rows are systems that fail due to under-heated (cold) electrodes. The upper row failures are from over-heated (hot) electrodes. Figure 5 shows fitted survival curves for groups 1, 2 and 5 with cold electrode failures. Only systems with 2 or more failures out of 4 replications are considered "at risk" and included in the reliability fits. Reliability for these fits refers to the surviving fraction of "at risk" systems for each failure mode only. It does not imply that all dimming systems are failing at these rates. All systems in group 1 fail rapidly with characteristic life, η =

940 hours. Groups 2 and 5 have “at risk” systems with η ~ 6500 - 6700 hours; these cold failures have slightly more electrode heat available from the ballast or arc.

Group	Lamp		System		Group	Lamp		System		Group	Lamp		System		Group	Lamp		System	
	X	0	XA	0		X	1	XA	0		X	1	XA	0		X	0	XA	0
	Y	1	XB	0		Y	1	XB	1		Y	1	XB	1		Y	0	XB	0
	Z	10	XC	0		Z	12	XC	0		Z	7	XC	0		Z	4	XC	0
	11		XD	0		14		XD	0		9		XD	0		4		XD	0
4			YA	0	8			YA	0	12			YA	0	16			YA	0
	23%		YB	1		29%		YB	1		19%		YB	1		8%		YB	0
6.0 V			YC	0	6.0 V			YC	0	6.0 V			YC	0	6.0 V			YC	0
20 mA	Ballast		YD	0	50 mA	Ballast		YD	0	80 mA	Ballast		YD	0	110 mA	Ballast		YD	0
	A	2	ZA	2		A	4	ZA	4		A	4	ZA	4		A	4	ZA	4
	B	1	ZB	0		B	2	ZB	0		B	2	ZB	0		B	0	ZB	0
	C	4	ZC	4		C	4	ZC	4		C	0	ZC	0		C	0	ZC	0
	D	4	ZD	4		D	4	ZD	4		D	3	ZD	3		D	0	ZD	0

Group	Lamp		System		Group	Lamp		System		Group	Lamp		System		Group	Lamp		System	
	X	0	XA	0		X	0	XA	0		X	2	XA	1		X	0	XA	0
	Y	1	XB	0		Y	0	XB	0		Y	0	XB	0		Y	0	XB	0
	Z	0	XC	0		Z	0	XC	0		Z	0	XC	1		Z	0	XC	0
	1		XD	0		0		XD	0		2		XD	0		0		XD	0
3			YA	1	7			YA	0	11			YA	0	15			YA	0
	2%		YB	0		0%		YB	0		4%		YB	0		0%		YB	0
4.5 V			YC	0	4.5 V			YC	0	4.5 V			YC	0	4.5 V			YC	0
20 mA	Ballast		YD	0	50 mA	Ballast		YD	0	80 mA	Ballast		YD	0	110 mA	Ballast		YD	0
	A	1	ZA	0		A	0	ZA	0		A	1	ZA	0		A	0	ZA	0
	B	0	ZB	0		B	0	ZB	0		B	0	ZB	0		B	0	ZB	0
	C	0	ZC	0		C	0	ZC	0		C	1	ZC	0		C	0	ZC	0
	D	0	ZD	0		D	0	ZD	0		D	0	ZD	0		D	0	ZD	0

Group	Lamp		System		Group	Lamp		System		Group	Lamp		System		Group	Lamp		System	
	X	15	XA	4		X	4	XA	4		X	0	XA	0		X	0	XA	0
	Y	12	XB	4		Y	4	XB	0		Y	0	XB	0		Y	0	XB	0
	Z	0	XC	4		Z	0	XC	0		Z	0	XC	0		Z	0	XC	0
	27		XD	3		8		XD	0		0		XD	0		0		XD	0
2			YA	4	6			YA	3	10			YA	0	14			YA	0
	56%		YB	2		17%		YB	0		0%		YB	0		0%		YB	0
3.0 V			YC	4	3.0 V			YC	1	3.0 V			YC	0	3.0 V			YC	0
20 mA	Ballast		YD	2	50 mA	Ballast		YD	0	80 mA	Ballast		YD	0	110 mA	Ballast		YD	0
	A	8	ZA	0		A	7	ZA	0		A	0	ZA	0		A	0	ZA	0
	B	6	ZB	0		B	0	ZB	0		B	0	ZB	0		B	0	ZB	0
	C	8	ZC	0		C	1	ZC	0		C	0	ZC	0		C	0	ZC	0
	D	5	ZD	0		D	0	ZD	0		D	0	ZD	0		D	0	ZD	0

Group	Lamp		System		Group	Lamp		System		Group	Lamp		System		Group	Lamp		System	
	X	16	XA	4		X	7	XA	4		X	3	XA	1		X	0	XA	0
	Y	16	XB	4		Y	11	XB	1		Y	5	XB	2		Y	1	XB	0
	Z	16	XC	4		Z	9	XC	2		Z	1	XC	0		Z	0	XC	0
	48		XD	4		27		XD	0		9		XD	0		1		XD	0
1			YA	4	5			YA	4	9			YA	0	13			YA	0
	100%		YB	4		56%		YB	3		19%		YB	2		2%		YB	0
1.5 V			YC	4	1.5 V			YC	2	1.5 V			YC	1	1.5 V			YC	0
20 mA	Ballast		YD	4	50 mA	Ballast		YD	2	80 mA	Ballast		YD	2	110 mA	Ballast		YD	1
	A	12	ZA	4		A	12	ZA	4		A	2	ZA	1		A	0	ZA	0
	B	12	ZB	4		B	5	ZB	1		B	4	ZB	0		B	0	ZB	0
	C	12	ZC	4		C	7	ZC	3		C	1	ZC	0		C	0	ZC	0
	D	12	ZD	4		D	3	ZD	1		D	2	ZD	0		D	1	ZD	0

Figure 4: System Failures at 11620 hours. Control cells at 180 mA show no failures.

Hot electrode failures from “at risk” systems in groups 4 and 8 are fitted to reliability curves also in Figure 5. The characteristic life ranges from η = 1062 to 2162 hours at lower lamp currents. Curiously, the systems at high electrode heating and higher lamp current (groups 12 and 16) are more robust, possibly due to arc cooling effects at the electrode.

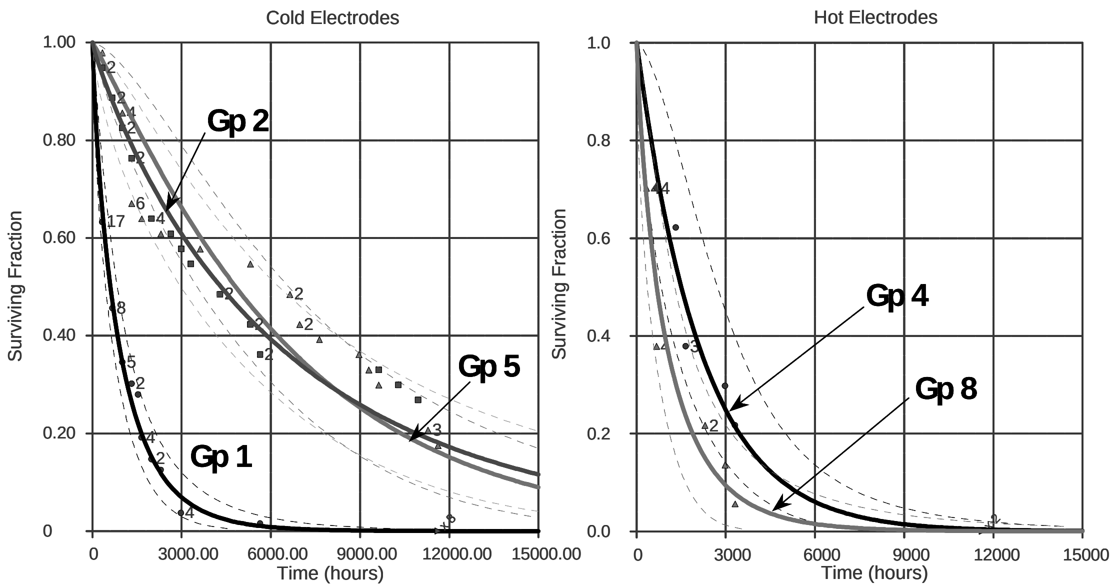

Figure 5: Weibull reliability fits to systems "at risk" of cold and hot electrode failure.

SYSTEM LIFE RELIABILTY

Groups 3, 7, 10, 11, 14 and 15 have only a few random failures and show the best region at 11620 hrs for avoiding the cold and hot electrode failures. Systems in these groups are expected to survive until normal lamp wear-out failure occurs. Defining this region is the focus of the next two sections. After the life test was started, five systems were found with one open electrode based on characterization data. There were three from group 1, and one apiece in groups 8 and 11. These systems were removed from this analysis.

Electrode heating voltage – lamp current design space

The system life reliability response is summarized in Figure 6. Entries are the fraction of the total systems surviving, S, in each group by perspective. Columns 2 and 3 contain the average lamp current and electrode voltage (EV) for each group. Column 4 has the average measured sum-of-squares pin currents to allow regression with these SoS values also. The specific lamp and ballast perspectives are shown in the subsequent columns. Examining the data, a wide variation in the responses can be seen depending on lamp or ballast type. Regression models of the S-response with lamp current and electrode heating voltage factors were made for each perspective. Since S is bounded between 0 and 1, a logit transformation was used for regression,

$$\text{logit}(S) = \ln(S) - \ln(1 - S). \tag{1}$$

Reduced cubic models with backward regressions (α = 0.05) fit the data well. The models are statistically significant with r^2 values from 0.80 to 0.97. Figure 7 summarizes these fits in the transformed response. Figure 8 shows the variety of different shapes to the response surfaces. In each case there is a clear cold failure zone at low lamp current and electrode voltage. Most response surfaces show a zone of hot failures at high electrode voltage. In addition, each surface has a flattop area of reliable operation that narrows as the lamp current is lowered.

Figure 9a helps visualize the overlap of the reliable flattop areas for each perspective at 11,620 hrs. Contours of S>90% reliability are drawn for each lamp and ballast perspective, then the overlap region in lamp current and electrode voltage space is shaded white. Repeating the analysis for the system reliability response at earlier intervals shows the relative stability of this region through time (Figure 9b). The boundaries generally shift inward as more failures are added, however, a fairly large region of S>90% remains. Two system failures were observed within the S>90% overlap region. Estimating ~288 systems in the overlap region, the binomial 95% lower confidence limit puts the reliability at S>97.8%. A two-sample hypothesis test (α = 0.05) for proportions comparing with control systems (0 fail of 96 systems) shows the failure rates to be consistent with random statistical events found in full wattage operation.

Surviving fractions at 11620 hrs

Group	Ave Lp Current	Ave EV	Ave SoS	Perspective Lamp X	Lamp Y	Lamp Z	Ballast A	Ballast B	Ballast C	Ballast D
1	23.5	1.7	0.096	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	22.1	3.2	0.179	0.063	0.250	1.000	0.333	0.500	0.333	0.583
3	21.8	4.8	0.265	1.000	0.938	1.000	0.917	1.000	1.000	1.000
4	21.9	6.1	0.359	1.000	0.938	0.375	0.833	0.917	0.667	0.667
5	51.2	1.8	0.096	0.563	0.313	0.438	0.000	0.583	0.417	0.750
6	50.0	3.3	0.183	0.750	0.750	1.000	0.417	1.000	0.917	1.000
7	50.6	4.7	0.269	1.000	1.000	1.000	1.000	1.000	1.000	1.000
8	49.4	6.5	0.393	0.933	0.938	0.250	0.636	0.833	0.667	0.667
9	80.5	1.8	0.094	0.813	0.688	0.938	0.833	0.667	0.917	0.833
10	79.5	3.2	0.186	1.000	1.000	1.000	1.000	1.000	1.000	1.000
11	79.4	4.9	0.284	0.933	1.000	1.000	0.917	1.000	1.000	1.000
12	77.6	6.3	0.396	0.938	0.938	0.563	0.667	0.833	1.000	0.750
13	107.2	1.8	0.094	1.000	0.938	1.000	1.000	1.000	1.000	0.917
14	105.0	3.3	0.199	1.000	1.000	1.000	1.000	1.000	1.000	1.000
15	106.4	4.9	0.292	1.000	1.000	1.000	1.000	1.000	1.000	1.000
16	107.0	6.2	0.396	1.000	1.000	0.750	0.667	1.000	1.000	1.000

Figure 6: System Life Reliability – Surviving fraction, S, by design point group and manufacturer perspective. Shading indicates systems with S=25-75% surviving (light gray) and S<25% (dark gray). Systems with open electrodes are removed.

Perspective	**Std. Dev.**	**Mean**	**C.V.**	**PRESS**	**R^2**	**Adj R^2**	**Pred R^2**	**Adeq Precision**
Lamp X	2.42	3.53	68.56	149.82	0.7995	0.6658	0.4288	9.332
Lamp Y	1.45	3.00	48.23	45.72	0.8998	0.8634	0.8012	17.659
Lamp Z	0.93	3.59	25.97	33.77	0.9690	0.9536	0.8799	23.990
Ballast A	1.95	1.85	105.19	83.85	0.8598	0.8089	0.7183	15.438
Ballast B	1.96	3.87	50.67	128.25	0.8613	0.7688	0.4856	11.559
Ballast C	1.66	3.78	43.96	66.41	0.8950	0.8425	0.7467	14.485
Ballast D	1.53	3.52	43.48	109.91	0.9232	0.8560	0.5486	14.107

Figure 7: Summary of voltage regression model quality-of-fit measures in the transformed S-response. C.V. = Coefficient of Variation; PRESS = Predicted Residual Sum of Squares

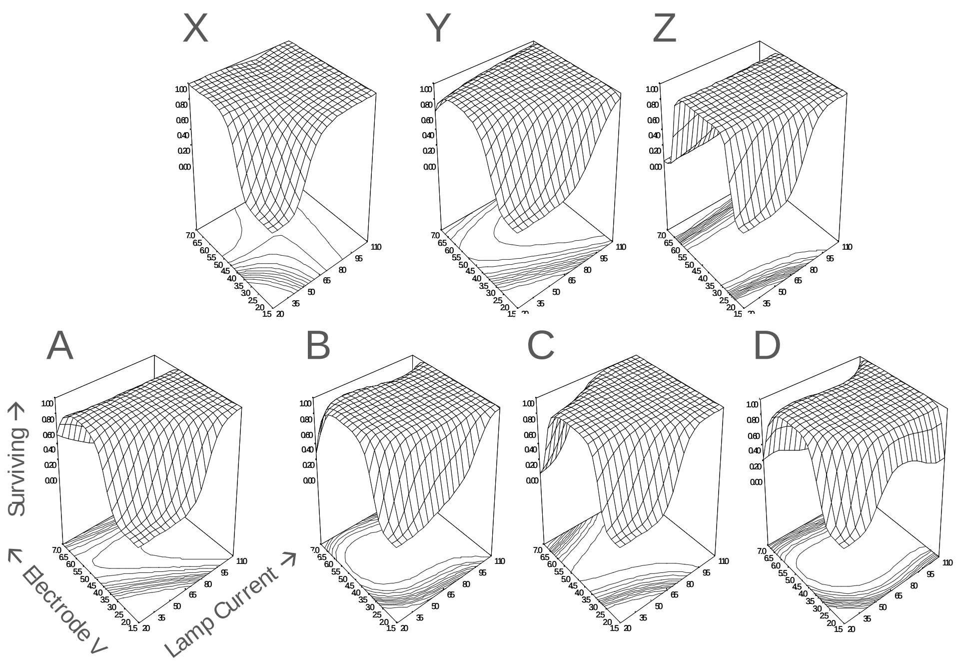

Figure 8: Regression model S-response surface plots for each manufacturer perspective

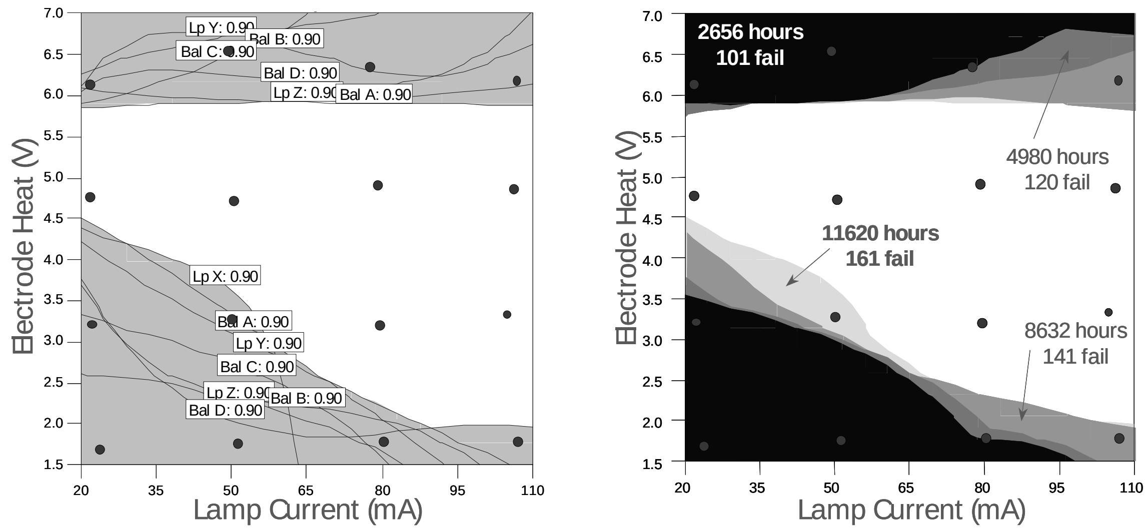

Figure 9: (a) Overlap region of reliability >90% for dimming systems at 11620 hours.
(b) Temporal development of overlap region of reliability >90% for T8 dimming systems

Sum-of-squares – lamp current design space

The analysis presented in the previous section was repeated using the average sum of squared pin currents (SoS) instead of the electrode voltage for evaluating electrode heat. Figure 10 shows a good correlation of SoS to electrode voltage measurements for each lamp design. Differences observed in the regression lines are due to electrode design. Repeating the regression analysis for each lamp manufacturer and making an overlay plot yields a very similar result for the S>90% region expressed in terms of SoS vs lamp current (see Figure 11). This demonstrates that SoS coordinates are functionally equivalent to the electrode voltage coordinates for identifying the high reliability region for dimming systems.

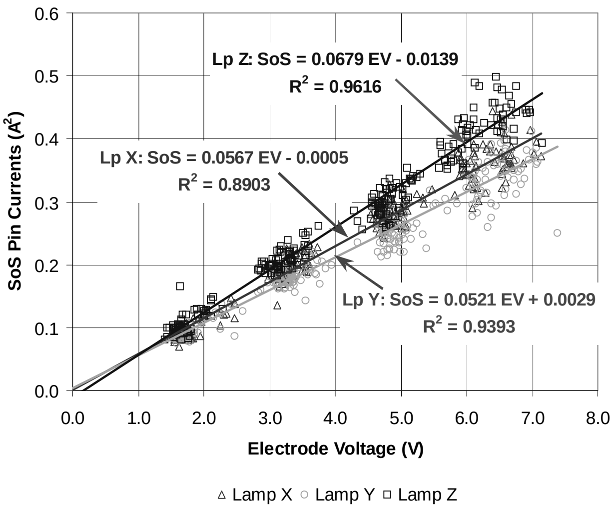

Figure 10: Correlation of SoS Pin Currents and Electrode Voltage for each lamp manufacturer

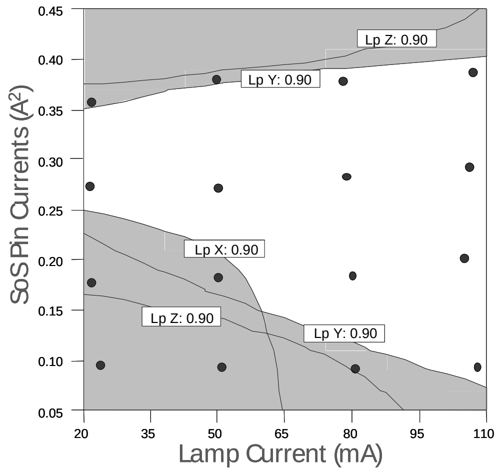

Figure 11: Overlap region of reliability > 90% for T8 dimming systems at 11620 hours expressed in SoS coordinates

RADIATION DATA

Radiation emission at 811.5 nm coming from the electrode region was measured for each lamp-ballast system at the beginning of the experiment. Figure 12 shows example measurements at fixed current and increasing electrode voltage for a single ballast manufacturer and a single lamp manufacturer. As an absolutely calibrated monochromator was not available, each radiation signal has been normalized by the mean of the lowest quartile. In Figure 12 several features are evident which are quite general across the whole dataset: (1) Ballast designs are such that current waveforms do not change significantly with electrode voltage. (2) Increase of the radiation occurs ~1.5 microseconds after the beginning of the cathode half-cycle (positive lamp current). (3) Compared to the anode half-cycle, radiation during the cathode half-cycle is strong for 1.5 V and 3.0 V but is much lower for higher values of supplemental electrode voltage. The interpretation of the radiation signal at lower lamp current is that an electrode heating voltage threshold is observed that suppresses the 811.5 nm radiation [1]. Above this threshold, thermionic electron emission contributes significantly to the lamp current and the cathode fall remains low. Below the threshold, the cathode fall voltage increases and initiates ion sputtering to compensate for a lack of thermionic emission, thus damaging the electrode. When the cathode fall voltage exceeds 13.1 V, direct excitation of argon atoms from the ground state to the 4p state and subsequent 4p $\rightarrow$ 4s radiation at 811.5 nm occurs [1]. The electrode voltage threshold that results in a "break" in radiation is near to the lower heating limit that risks high cathode fall and subsequent limited lamp life.

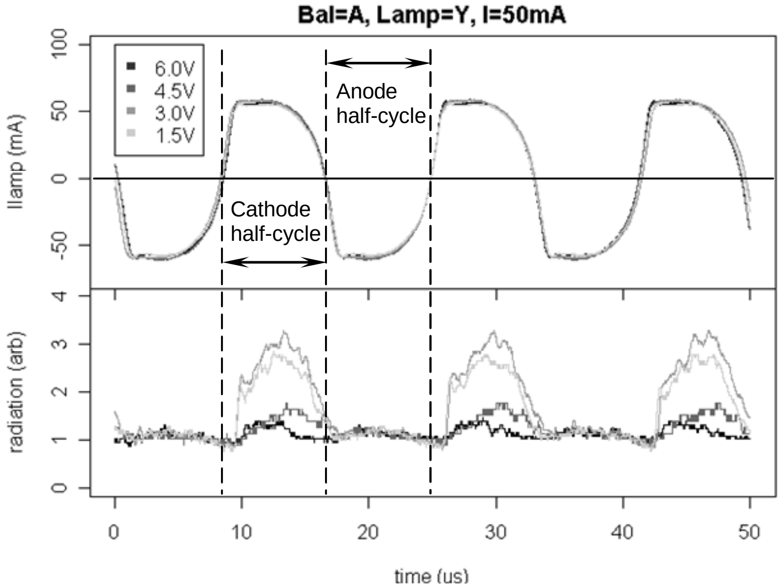

Figure 12: Example of 811.5 nm radiation from electrode region for different values of electrode heating voltage. Radiation during cathode half cycle drops when heating voltage between 3.0 V and 4.5 V.

Figure 13 shows scatter plots of the lamp-ballast system life versus the radiation signal intensity (ratio of averages of upper and lower quartiles) for nominal value of lamp current and electrode voltage. Different symbols and colors are used to represent ballast and lamp companies, respectively. The radiation intensity of surviving systems is denoted with tick marks joined to a horizontal line. Several features can be noted: (1) For all ballast companies and for especially for lamp companies X and Y, there is a clear break in radiation intensity between electrode voltages of 3.0 V and 4.5 V. (2) At the lower lamp currents, the boundary between premature system failures and acceptable life also occurs between electrode voltages of 3.0 V and 4.5 V. (3) For the higher lamp currents there seems to be no relationship between radiation intensity and premature lamp failure, as electrode thermionic emission supports the arc current at all heating levels.

CONCLUSIONS

One of the major findings of this ongoing experiment is that electrode heating voltage and lamp current look promising for defining a region of operation for many lamp and ballast designs. A relatively large region in the experimental design space has been identified that has satisfactory performance at this point in the experiment. Sum-of-squares also shows a similar large region of satisfactory performance. In addition, argon radiation data supports the lower boundary observed in the life data when the electrode is operating too cold. Another finding at this point in the experiment is that life can be very short in the "hot" and "cold" regions.

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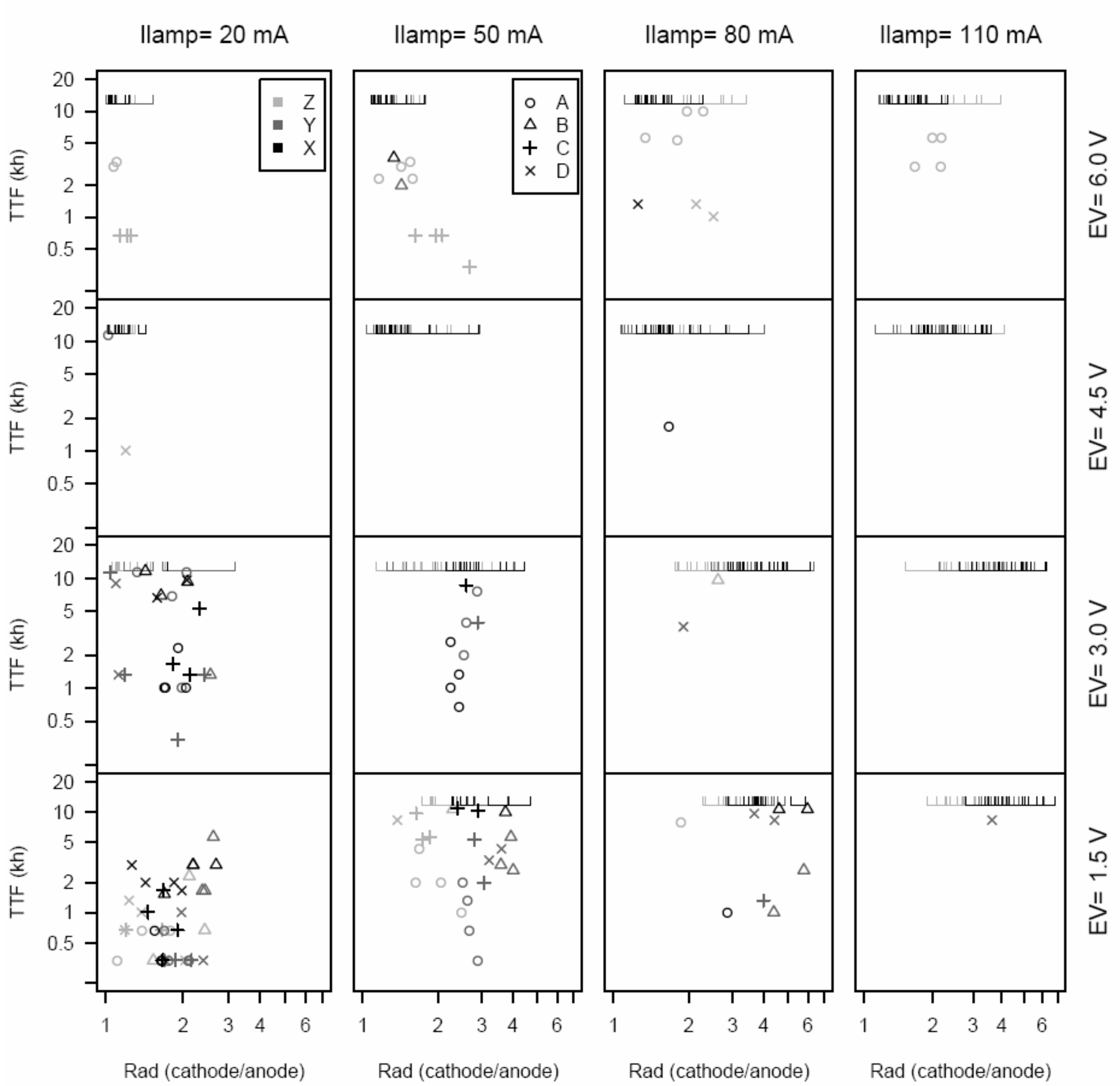

Figure 13: Time to failure (thousands of hours) vs. ratio of radiation amplitude during cathode and anode half cycles. Tick marks at 11620 hours joined by horizontal line indicated radiation measurements of unfailed systems.

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