Title

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Publication Date

1985-07-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

To be presented at the Annual IEEE-IAS Conference, Toronto, Canada, October 6-11, 1985

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Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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LBL-19778
EEB-L 85-06
L-102

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This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Abstract

Standard 40-watt, F-40, rapid-start, fluorescent lamps were operated with solid-state ballasts following the standard life-testing cycle of 3 hours on and 20 minutes off for more than 20,000 hours at high frequency. Lamp operating characteristics (starting voltage, filament voltage, arc current, and current-crest factor) were studied as factors affecting lamp life. Measurements show that fluorescent lamps can attain rated life at high frequency using solid-state ballasts. When lamps are operated in the dimmed mode, full filament power is required to sustain lamp life. The rate of lamp lumen depreciation is dependent on the lamp loading and not the operating frequency.

Introduction

In 1977 the Department of Energy (DOE) initiated a program to support the development of a solid-state fluorescent ballast. One major concern was determining whether high-frequency operation adversely affected lamp life. This report presents lamp life measurements of 40-watt, F-40, T-12, rapid-start fluorescent lamps operated by two-lamp solid-state ballasts. The standard fluorescent lamp life testing cycle was used. Tests were started in 1978 and used to assist with circuit development; thus the ballasts used are early solid-state prototypes.

We first review the factors that affect the life of fluorescent lamps and then describe our experimental procedures. The results of the measurements and a discussion follow. The final section summarizes the findings.

Factors Affecting Lamp Life

The 40-watt, F-40, T-12, rapid-start fluorescent lamp has a rated life of 20,000 hours when operated with a standard Certified Ballast Manufacturers (CBM) ballast on a cycle of 3-hours on/20 minutes-off, or more than 30,000 hours for continuous operation. The rated life is defined as the period after which 50% of a group of lamps has failed.

Lamps fail soon after they lose all the alkaline rare-earth material (low-work function) that surrounds the tungsten filament. The low-work material is removed primarily during initiation of the discharge, starting the lamp, and by evaporation during the lamp's operation [1].

The type and pressure of gas fill [2] and structure of the filament both affect lamp life. Heavier gases at higher pressures increase lamp life by reducing the evaporation rate.

The electrical input characteristics that influence lamp life are the lamp current, filament voltage, and current crest factor. Lamps are best started at a low voltage after the filaments are properly heated. To obtain the rated life of a particular lamp, the American National Standards Institute (ANSI) has prescribed how a ballast should start and operate a lamp at 60 Hz. For the 40-watt, F-40, T-12, rapid-start lamp, the ANSI C78.1 standard specifies a lamp operating current of 425 mA, and a peak lamp voltage between 360 and 466 volts (V). ANSI C82.1 specifies a filament voltage between 2.5 and 4.0 V and a maximum current crest factor of 1.70. Although these values may differ for high-frequency operation, they have been used as a guideline in the design of solid-state ballasts.

Experimental

Lamp-Life Test Cycle

We followed the IES-recommended procedure for measuring lamp life [3]. We regulated the input voltage to the ballasts, which were operated at their center design voltages of either 120 or 277 V on an operating cycle of 3 hours on and 20 minutes off. The lamps operated with no filament voltage could not be started with heated filaments and were operated continuously.

Ballast Measurement

The key operating factors were measured for each ballast used in the life tests. This included the open-circuit peak voltage, lamp current, filament voltages, and current crest factor. The open-circuit peak voltage is the maximum voltage that can be applied to the lamps and can reflect the maximum starting voltage.

Lamp Life Measurements

For each group of life measurements, we recorded operating time and the time of each lamp's failure. We immediately replaced failed lamps to minimize stress to other parts of the system, i.e., the ballast.

Some of the early life tests were stopped when 50% of the lamps had failed, particularly if it was apparent that a ballast design flaw severely reduced lamp life. Because we could not test a large number of lamps, the lamp life (life at 50% failures) and the average lamp life (total life divided by the number of lamps) were recorded.

In order to test lamp life with no applied filament voltage, we disconnected one lead to the filament. Such lamps cannot be "soft-started" and so were operated continuously. All of the lamps used in these tests were from a single production run. Thus, there should be minimal variation in lamp life due to any variation in manufacturing or materials. As an experimental control in each experiment, a pair of lamps was operated with a standard CBM magnetic core ballast under the same conditions.

Lumen Depreciation

We measured lamp lumen depreciation for all the lamp/ballast systems. The initial light output was determined by measuring the total light flux of each lamp after 100 hours operation. The total light output was measured with a reference circuit, as specified by ANSI C78.1. The decrease in light output was measured for each lamp after operating periods of 200, 500, 1000, 3000, 5000, and 10,000 hours. Due to lamp failures, the lamp sample became smaller as operating time increased.

Results

Type-A Ballast

Operation Characteristics: Table I lists the operating characteristics of several models of the type-A solid-state ballasts. The values listed are the averages for all the ballasts tested. The filament voltages in the table are the voltages applied during operation. The filament voltages at starting ranged from 3.6 to 4.1 volts and were reduced several seconds after the plasma was ignited. The three filament voltages, V_1, V_2, and V_3, are the voltages applied to the red, blue, and yellow leads from the ballast.

The open-circuit peak voltage is a measure of the highest voltage that can be applied across a lamp. During starting, the voltage across the lamp will usually be less than the measured open-circuit voltage. However, in a suitably cold environment the maximum voltage could appear across the lamp. The measured open-circuit voltage exceeds the ANSI-recommended maximum (466 V).

Lamp-Life: Table II lists the life test results for the lamps operated with several models of the type-A solid-state ballast. The tolerance of the data represents the allowable variations in lamp performance that occur for small test samples. The life test with ballast model 52-P was stopped at 5890 hours before half of the lamps had failed because blackening of the lamp ends indicated excessive sputtering and a reduced lamp life. The results of testing later ballast models showed a progressive improvement in lamp life with improved designs. However, none of these early models approach the lamp manufacturer's life rating.

Table I

Operating Characteristics of Type-A Ballast

No. of Ballasts	Model	Filament Voltage† (V)			Open-Circuit Peak Voltage V		Lamp Current (A)	Current Crest Factor
		V_1	V_2	V_3	Positive	Negative		
8	18-P	1.9	1.8	1.9	705	930	0.295	2.9
28	52-P	3.2	1.9	1.9	727	1326	0.338	1.7
18	62-P	2.1	1.3	1.6	801	1240	0.397	1.9
16	50-E	1.8	2.2	3.2	660	1185	0.309	1.6
24	60-E	1.3	1.5	2.2	698	1110	0.319	1.9
26	60-EE	0	0	0	697	693(P)	0.338	2.0

† - At starting all filament voltages exceeded 3.5 volts.

V_1, V_2, V_3 filament voltage from red, blue, and yellow ballast leads.

P - Applied voltage delayed until filaments were heated.

Table II

Lamp Life with Type-A Ballast

Ballast Model	No. of Lamps	Testing Mode	Time of 50% Failures	Average Lamp Life (hrs)	Tolerance* %
18-P	8	3 hr on /20 min. off	3760	3,860	18
52-P	24	3 hr on /20 min. off	(a)	(a)	12
52-P	4	Continuous	11,830	11,690	>20
62-P	28	3 hr on /20 min. off	4,060	(b)	11
62-P	2	Continuous	7,060	7,060	>20
50-E	16	3 hr on /20 min. off	12,310	(c)	14
60-E	24	3 hr on /20 min. off	7,470	7,080	12
60-EE	20	3 hr on /20 min. off	6,960	7,410	12
60-EE	6	Continuous	10,000	10,740	>20

*IES Guide—Life Performance Testing of Fluorescent Lamps. *Ill. Eng.*, *51*, 595 (Table I) (1956).
(a) Test stopped at 5890 hours, 19 lamps still operating; excessive blackening of ends.
(b) Test stopped at 4360 hours, 14 lamps still operating.
(c) Test stopped at 14,340 hours, 5 lamps still operating.

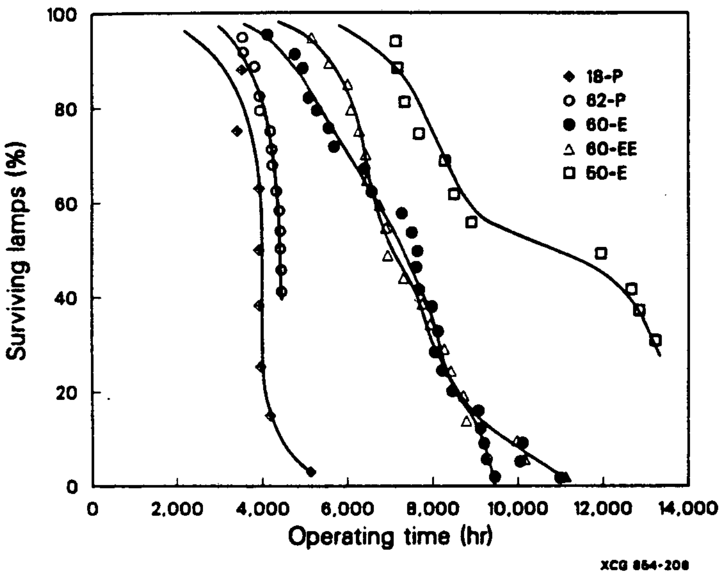

Figure 1. Mortality curves for lamps operated with Type-A ballasts.

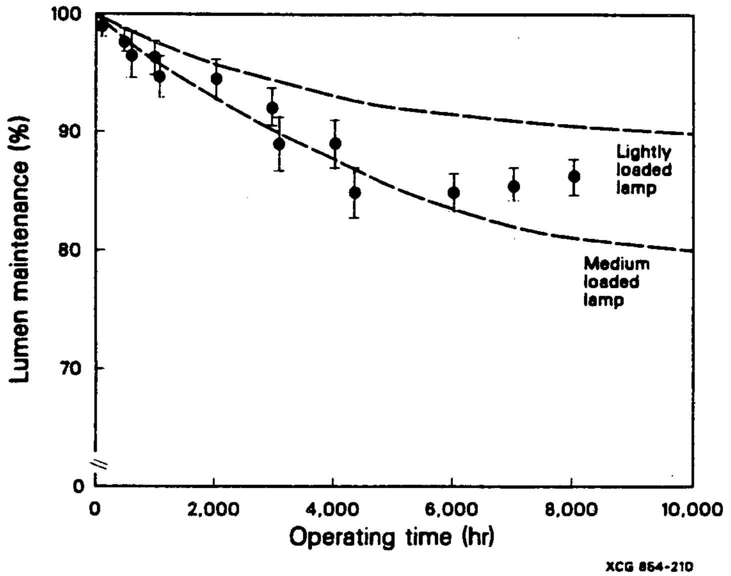

Figure 2. Lumen maintenance curve for lamp operated with Type-A ballasts.

Figure 1 plots the mortality curves typical of fluorescent lamps. Lamps operated with model 50-E show an abnormal break in the curve.

Lamp Lumen Depreciation: Figure 2 plots the lumen depreciation data for lamps operated with various models of the type-A solid-state ballast. The two dashed curves show the rates of lamp lumen depreciation from the IES Lighting Handbook [4] for a lightly loaded and medium-loaded fluorescent lamp. The loading for the tested lamps was about 0.15 arc watts per square inch, which falls between the lightly load lamp (0.12 W/in^2) and the medium-loaded lamp (0.24 W/in^2). The positive slope, or increase in the lumen depreciation curve, at longer operating hours is a result of the reduced blackening of the lamps that had longer life. The lamps with blackened ends tended to fail first and had a larger lumen depreciation.

Type-B Ballast

Operating Characteristics: Table III lists the characteristics of the type-B solid-state ballasts. The S-8 model was designed to remove the filament voltage a few seconds after the lamp was ignited to increase system efficacy. The high open-circuit peak voltage was never applied at starting. The circuit design first applied the filament voltage to heat the filaments for 2 to 3 seconds, then the lamp voltage was applied. Thus, the discharge was generally ignited before the maximum open-circuit voltage was reached. The later L-8 model was designed to maintain a filament voltage of 2.7 to 2.8 V during operation. When this ballast dimmed the lamps, the circuit design allowed the filament voltage to increase. All the type-B solid-state ballasts had current crest factors well below the ANSI-recommended maximum of 1.7.

Table III

Operating Characteristics of Type-B Ballasts

No. of Ballasts	Model	Filament† Voltage (V)			Open Circuit Peak Voltage (V)		Lamp Current (A)	Current Crest Factor
		V_1	V_2	V_3	Positive	Negative		
9	S-8	0	0	0	940	1010(P)	0.296	1.4
15	L-8	2.8	2.7	2.8	350	350	0.292	1.3
3	L-8 (Dimmed)	3.5	3.5	3.7	350	350	0.013	1.6
3	L-8	0	0	0	350	350	0.292	1.3
1	CBM core-coil	3.4	3.4	3.7	440	440	0.430	1.7
1	CBM core-coil	0	0	0	440	440	0.430	1.7

† At starting all filament voltages exceeded 3.5 volts.

P Applied voltage delayed 2 to 3 seconds after filaments were heated.

Table IV

Lamp Life with Type-B Ballast

Ballast Model	No. of Lamps	Testing Mode	Time of 50% Failures	Average Lamp Life (hrs)	Tolerance* %
S-8	18	3 hr on/20 min. off	11,630	11,680	13
L-8	30	3 hr on/20 min. off	18,790	19,700	10
L-8 (Dimmed)	6	3 hr on/20 min. off	14,940	20,800	>20
L-8 (no filament)	6	Continuous	13,950	17,980	>20
Core-Coil (CBM)	2	3 hr on/20 min. off	14,510	14,510	>20
Core-Coil (CBM) (no filament)	2	Continuous	24,220	24,220	>20

*IES Guide—Life Performance Testing of Fluorescent Lamps, *Ill. Eng.*, *51*: 595 (Table I) (1956).

Lamp Life: Table IV presents the life test results for lamps operated with type-B solid-state ballasts. Within the tolerance level for testing 30 lamps, the results provide evidence that high-frequency operation of fluorescent lamps meet the manufacturer's rated life of 20,000 hours. Fifty percent of the lamps failed at 18,790 hours. The average life of all 30 lamps was 19,700 hours. The results are also evidence that fluorescent lamps properly operated in the dimmed mode can offer normal lamp life. Note that the average lamp life in the dimmed mode is 20,000 hours. The dimmed lamps were also operated on the cycle of 3 hours-on/20 minutes-off; thus the results include the reduction of lamp life due to starting. The circuit was designed so that lamps always started at full light output (full power) and after 10 to 20 seconds automatically dimmed to the preset level. Not included in the table was life data for lamps operated in the dimmed mode (~20% of full light output) but having only 2.5 V applied to the filaments. These lamps exhibited end blackening after 200 to 300 hours, with lamp failures occurring after less than 1000 hours of operation.

The results for the two monitoring systems (core-coil, CBM ballasts) are included in the table to show that the tested lamps can be considered typical. That is, these lamps exhibited no serious manufacturing flaw when used with standard 60-Hz ballasts. However, no attempt should be made to consider this data for these few ballasts as an accurate measure of the life of lamps operated at 60 Hz with CBM ballasts.

Figure 3 plots the life data for each lamp for the S-8 and L-8 models. They are close to the typical shapes of mortality curves for fluorescent lamps. The solid line is the mortality curve for a 20,000-hour lamp life. Within the the 20% tolerance for a batch of 30 lamps, the lamps operated with the L-8 ballasts also show the same magnitude of lamp life as the 20,000-lamp mortality curve.

Lamp-Lumen depreciation: Figure 4 plots the lumen depreciation for the lamps operated with the S-8 and L-8 ballasts. The lamps operated with S-8 ballasts show a more rapid lumen depreciation, had a shortened life, and exhibited darkening at the ends. This darkening covers the phosphor, thereby increasing lamp lumen depreciation and resulting in a poor

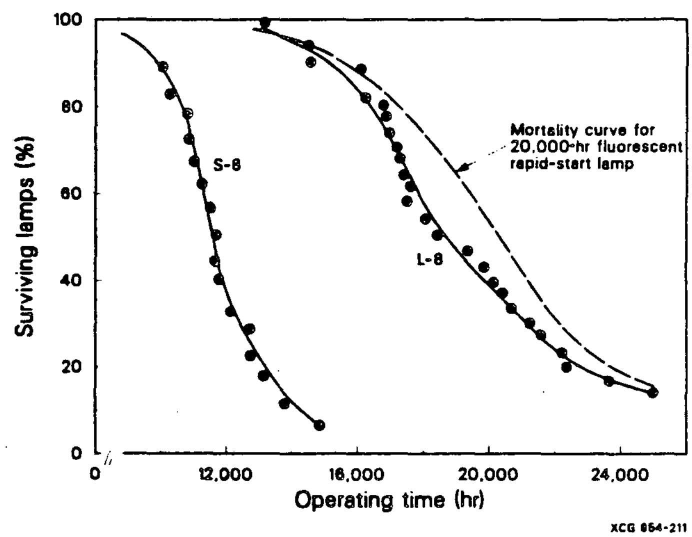

Figure 3. Mortality curves for lamps operated with Type-B ballasts.

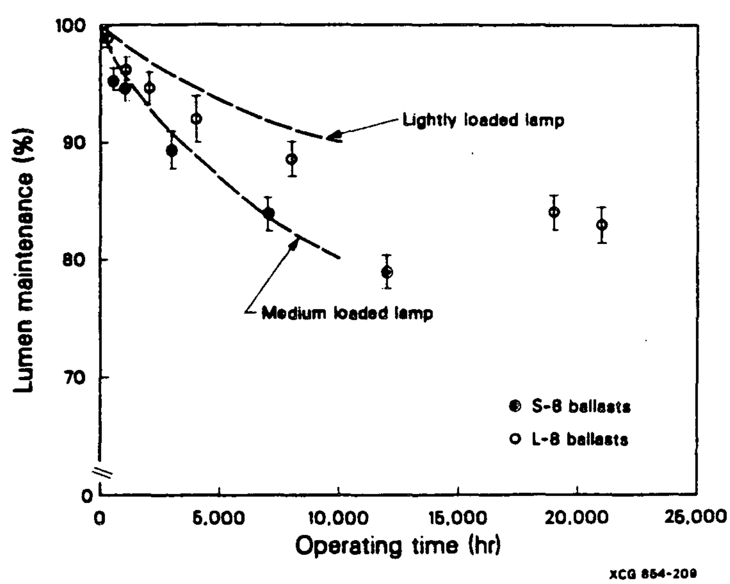

Figure 4. Lumen maintenance curve of lamps operated with Type-B ballasts.

maintenance curve. The lamps operated with L-8 ballasts showed a lumen depreciation one would expect at 60 Hz with lamp loading of 0.18 W/in^2.

Discussion

High-Frequency Lamp Life

The primary result shows that standard 40-watt, F-40, rapid-start lamps can achieve manufacturer's rated life when operated at high frequency at full light output or dimmed to 20% of full light output. Full rated life occurs only if the solid-state ballast is designed to operate the lamp properly. These ballasts were operated in accordance with accepted practices: start the lamps when filaments are heated, provide filament power during operation, limit the current crest factor [5], and maintain a suitable arc current. Because these factors interact, there is a range of allowable values that will provide normal lamp life.

One must also recognize that the factors may be somewhat different for high-frequency operation of lamps compared to 60-Hz operation. The only difference in lamp characteristics for the two modes of operation is the reduction in anode fall from 17 V to 6 V at high frequency [6]. Waymouth [1] has described how the anode fall accelerates the lamp current at the anode to contribute to heating the filaments. Measurements of filament temperatures [7] with and without filament power provide further evidence of the effect of anode fall and arc current in heating the filaments. Thus, the present ANSI-specified ranges may have to be amended with respect to filament power and arc current to maintain the lamps' rated life or for any special lamps designed to operate optimally at high frequency.

This study also implies that many new products on the market that operate fluorescent lamps at reduced light levels may adversely affect lamp life. That is, when the devices reduce the lamp filament power, they also lower arc current or increase current crest factor.

The results also suggest that removal of filament power from a rapid-start lamp will reduce its life. Our experiments showed lamps operated with no filament power equaled or exceeded the lamp life operated with the 3-hour cycle only because the tests were run continuously. The effect becomes more pronounced for the high-frequency system because the lamp is operated at a lower current and has a reduced anode fall. However, it may be a cost-effective trade-off since the input power is reduced by about 6%.

Lamp Lumen Depreciation

High-frequency operation of lamps does not influence the rate of lumen depreciation. The rate of lumen depreciation for a lamp is determined primarily by the power in the positive column (i.e., proportional to the light output). Koedam and Verweij [6] showed that high-frequency operation only reduces the loss at the anode. Thus, for a lamp to have the same light output at low and high frequency the power supplied to the positive column (generating the ultra-violet radiation), or the loading must also be the same.

Summary

The factors that affect the life of fluorescent lamps operated at 60 Hz also affect high-frequency operation. However, due to the decreased anode fall at high frequency, the range of values for these factors may differ from those for lamps operated at 60 Hz. Fluorescent lamps can be suitably operated in a dimmed mode, but full filament power must be supplied to maintain the rated lamp life.

Most importantly, this study shows how the solid-state ballast technology developed since 1976 has addressed the design factors that affect lamp life. By the late 1970s solid-state ballasts were available that could operate standard, F-40, rapid-start fluorescent lamps in a manner to obtain normal lamp life.

Acknowledgement

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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