Title
ENERGY EFFICIENCY AND PERFORMANCE OF SOLID STATE BALLASTS

Author
Verderber, R.

Publication Date
2011-03-24

To be presented at the IESNA Technical Conference, Denver, Colorado, Aug. 27-Sept. 1, 1978

LBL-7828
c.2

Energy and Environment Division

Energy Efficiency And Performance Of Solid State Ballasts

R. Verderber, S. Selkowitz, and S. Berman

June 1978

Lawrence Berkeley Laboratory University of California/Berkeley

Prepared for the U.S. Department of Energy under Contract No. W-7405-ENG-48

ENERGY EFFICIENCY AND PERFORMANCE OF SOLID STATE BALLASTS

R. Verderber, S. Selkowitz,
and S. Berman

Lawrence Berkeley Laboratory

Abstract

The performance of solid state ballasts for operating fluorescent lamps measured in a controlled laboratory environment are described and compared to the performance of typical core-coil type ballasts. Parameters of interest include efficiency, conducted and radiated EMI and results of some accelerated lamp life tests.

The experimental design of the demonstration to retrofit three floors of an office building with solid state ballasts to evaluate their reliability and energy savings in a variety of applications is described. The most recent experimental results are presented.

I. INTRODUCTION

Solid state electronic ballasts for fluorescent lighting systems that promise to be cost effective replacements for the core-coil type ballasts have been developed by several organizations. Although the present initial cost of the solid state ballast is greater, the improved operating efficiencies result in reduced life cycle costs. In addition, the operation of fluorescent lamps with solid state ballasts results in less audible noise, smaller ballast size, lower heat dissipation, and an efficient dimming capability over a wide range of light output levels. These characteristics will permit lighting designers, lamp manufacturers and fixture manufacturers to implement innovative energy conserving lighting system concepts that will produce additional substantial energy savings.

The solid state ballast provides the same primary function as the conventional core-coil ballast; it must start and then safely operate the fluorescent lamps. Published solid state ballast circuit designs (1-5) convert the input 60 Hz to DC, and then invert the DC to drive the lamp at high frequency. The high frequency is generally in the range from 10 KHz to 30 KHz. Fluorescent lamps operated at these frequencies have a higher efficacy (6,7,8,9) than those driven at 60 Hz, and by virtue of the smaller size of the reactive circuit components these ballasts typically have low power losses in the ballast.

In late 1976, based upon prototype performance claims from several manufacturers and a review of the state of development of the solid state ballast the Lawrence Berkeley Laboratory (LBL), with funding provided by the U.S. Department of Energy (DOE), initiated a development and demonstration program to assist in the commercialization of solid state ballasts for fluorescent lighting. Two ballast developers, IOTA Engineering, Tucson, Arizona, and Stevens Luminoptics, Danville, California, were selected by a competitive procurement to participate in the program. In the first phase of the program, the two subcontractors were required to complete engineering development and testing of demonstration models. Prototypes were delivered to LBL and an independent test laboratory to measure various performance characteristics. In the demonstration phase, which is now underway, over one thousand ballasts were retrofit on three floors of an office building to monitor in-site performance and reliability of the units.

This report presents data that has been collected during the development phase of this program by the developers of the ballast, by LBL and by an independent testing laboratory. While measurements will continue, sufficient evidence has been gathered to present a reasonable verification of the performance of these two types of solid state ballasts.

In its present configurations, the IOTA-EXCEL ballast has been engineered for minimum complexity and cost, and is designed for a single light output level, although step dimming can be added. The Stevens ballast as presently designed, has a built-in continuous dimming capability that allows light output to be controlled in several different operating modes but requires more complex circuitry and is thus more expensive. All ballasts in this program are of the rapid start type, designed to operate two 40 watt T-12 fluorescent lamps. The IOTA-EXCEL ballast operates at 120 volts and the Stevens ballast operates at 277 volts.

The following section presents the measured performance characteristics addressing system efficiency, reliability, EMI emission,and dimming. The third section briefly describes the demonstration plan,and the final section summarizes the report.

II. Ballast Performance Characteristics

A. System Efficiency

1. Measurement

The data presented in this section has been collected at IOTA Engineering, the Lighting Research Laboratory (LRL), Orange, California, Stevens Luminoptics,and at LBL. At each location the measuring method was basically the same. The ballasts and lamps were in free air, the input power, voltage and current were measured,and a portion of the total light output from the lamps was measured with a photometer.

LBL employed a Weston wattmeter, a HP3400A rms. voltmeter and a Tektronix J16 photometer. At Stevens and LBL no attempt was made to obtain an absolute measure of the total lumen output of the lamps. IOTA and LRL employed lamps calibrated against a standard to obtain an absolute measure of the total lumen output. All laboratories used well seasoned fluorescent lamps, with greater than 100 hours of operation, for the ballast tests. Measurements were also made using standard, high power factor, core ballasts. Normalizing all measurements with respect to the measurements made with the standard core ballast systems permitted the data to be compared between laboratories.

2. Results

Tables I through IV list the data measured at LBL, IOTA, LRL, and Stevens, respectively. The designations forthe ballasts are: Core-standare core ballasts, Eff-high efficiency core-coil ballasts. The data listed in each column is the average value measured for several ballasts. The number of ballasts of each model tested is indicated in parenthesis.

In the last column of each of the tables, the relative efficacy is normalized with respect to the efficacy of the standard core-coil ballasts.

Comparison of the performance measurements for the core ballasts and the same model IOTA ballasts listed in Tables I, II, and III shows good agreement. The 18 PCT and 22 PCT units should be compared in Tables II and III, and the 62P and 52P models compared in Tables I and II. Note the improvement in the efficacy of the IOTA-EXCEL advanced prototype model 62P and 52P compared to the first models submitted to LBL (18 PCT and 22 PCT). The advanced units show an efficacy improvement of approximately 20%.

Measurements of the relative efficacy for the 277 volt core and Stevens ballasts, S-8441, shown in Tables I and IV are also in good agreement. These units show an increase in efficacy of 24%.

3. Ballast Performance Considerations

To best assess the data presented in Tables I through IV one must have some concept of the total system performance. Table V is an attempt to elucidate the effect of the minimum lamp wall temperature upon the lighting system performance. The core and electronic ballasts-lamp systems were evaluated with the minimum lamp wall between 30°C to 50°C. Lamps are designed for optimum at a lamp wall temperature of 40°C. In these measurements the ballasts were in a free air ambient of 22°C.

The power input for the core ballasts decreases as the lamp temperature rises, as does the light output. Peak efficacy is obtained at the 42°C temperature. The next to last column in Table V shows a 3% increase in efficacy.

The IOTA-EXCEL ballast performs somewhat similarly, but light output is maximum at the 43°C temperature and the efficacy is maintained well above the optimum temperature. The last column in Table V compares the efficacy of the IOTA with the core ballast at the same lamp temperature. Note for I-52P-3, efficiencies are nearly 30% greater for the IOTA ballast. This is significant since the higher lamp temperature best simulates the actual operating temperature of lamps installed in buildings.

These Stevens ballasts do not show the profound improvement as the IOTA ballasts. In fact, the Stevens power input to the Stevens ballast increase with lamp operating temperature, but also note the increase in light output.

The most significant feature of these solid state ballasts is their ability to maintain the light output over a wide range of temperatures. This means that the usual over design requirement, to account in the fall in intensity of core ballast lamp systems at their rated output at the required measuring temperature 25°C, may not be required for the solid state ballast-lamp systems. Thus, less fixtures may be required for an installation and/or solid state ballasts can be designed to obtain lower level light output to be compatible with presently installed systems.

B. Reliability

1. Ballasts

A formalized measure of the reliability of the solid state ballasts will be obtained from the scheduled demonstration tasks, as well as from our standard lamp life testing task now in progress. It should also be noted that circuit changes made as the ballasts evolve toward final commercial design may invalidate specific data generated in this phase of the testing program.

In order to obtain an initial confidence level in ballast reliability, all ballasts were installed in fixtures, in a maintenance shop at LBL. After operating continuously for two weeks (336 hours) the ballasts are accepted by LBL. To date the experience has been that most ballast failures have occured within one week of operation. The causes for all of the failures have been identified and corrected and have typically been poor quality control of parts and prototype packaging flaws.

No attempt was made to conduct a large scale life test at this time, however, two IOTA-EXCEL ballasts and one Stevens ballast have been left operating since they have been received. To date, they have accumulated a total of 2160 and 960 hours of operation, respectively. Operating times for ballasts in excess of these have been reported by the ballast developers.

2. Lamps

A standard lamp life testing facility is being set up at LBL. We will measure the lumen maintenance of the fluorescent lamps operated with the solid state ballasts on the standard testing cycle of 3 hours on and 20 minutes off.

IOTA Engineering has devised an accelerated life test, in order to more quickly evaluate any possible adverse affects their ballasts may have upon the lamp life. The life test consisted of an on-off cycle of either 6 minutes or 3 minutes conducted with both standard and electronic ballasts. These cycle times are particularly harsh on the filaments. If the IOTA-EXCEL ballast design had a significant adverse effect on the filaments during starting, it would become evident. Typically, lamps operated with the IOTA-EXCEL ballast withstood greater than 15,000 starts. These results compare favorably with lamps operated in the same manner with standard core ballasts.

C. EMI Emission

Fluorescent lamps operated at 60 Hz generate EMI in the radio frequency band. The major pulse of noise occurs at the beginning of each cycle (120 times per second) and is designated as reignition noise (10). For lamp installations where this EMI is not acceptable there are methods to suppress its magnitude (11).

Solid state ballasts drive the lamps at 10KH$_z$ to 30 KH$_z$ For some circuit designs the high frequency is modulated in a 120 Hz envelope. This is usually a performance trade-off that must be implemented to obtain a suitably high power factor, (greater than 90%). Voltage wave shape also affects the lamp efficacy and may reduce the total system efficacy by as much as 10 to 15%. For large scale industrial and commercial installations a suitably high "shape" power factor is required. The IOTA-EXCEL ballast utilizes a modulated wave and we have anticipated EMI levels equivalent to lamps driven at 60 Hz, since reignition of the lamp will occur 120 times per second for both systems.

Figures Ia and Ib display measurements of the conducted and radiatied EMI from lamps driven by the first IOTA-EXCEL ballast (model PCT-18) and a standard core ballast. These radiated EMI measurements were obtained at LBL with a vertical whip antenna located one foot from the center of the lamp fixture. In Figure Ia the curves, 1,2, and 3, show the radiated EMI emission from the lamps using the IOTA-EXCEL ballast, a standard core ballast, and the same

IOTA-EXCEL ballast in which a model P691-6 line filter (Electro Magnetic Company) has been installed in the fixture, respectively. With the filter installed the noise level is well below that of the lamp driven by the standard core ballast.

The conducted EMI emission was examined by IOTA Engineering. They found the greatest difference of EMI emission was in the radio band. Figure Ib shows results of measurements of the noise level for the IOTA-EXCEL ballast relative to the conducted EMI for a standard core ballast. Curve 1 is the EMI for a lamp driven by an early model IOTA-EXCEL ballast. The curves, 2, 3, and 4, show the reduction of the EMI noise after RF grounding of the common plus a line filter, filtering of the transistor input, and adding a RF suppressor in the B+ line. These quick fixes do not represent the ultimate that can be achieved in suppressing the EMI noise, however, they demonstrate that suitable noise reductions can be achieved.

No EMI noise measurements have been completed using the Stevens ballast. The results should be of interest since the high frequency their ballast applies to the lamp is unmodulated. Thus, we expect a lower level of EMI noise.

D. Dimming of Fluorescent Lamps

One of the more important attributes of the solid state ballast is its capability to control the light output of fluorescent lamps over a broad range.

The Stevens ballast has incorporated a dimming circuit within each ballast in which the light level of the lamps can be controlled by an external screw adjustment or by applying an appropriate voltage signal to a control lead.

We have measured the input power to the system as the light output was reduced and have plotted the results for two Stevens ballasts, (see Figure 2b). The curves show that the power and the light output are nearly proportional. For example, reduction of the light level by 60% results in a power reduction of 50%.

The IOTA-EXCEL ballast can be easily adapted to dim fluorescent lamps over a wide range of light levels. A dimming demonstrator designed to dim one to ten fixtures was delivered to LBL. There was no major change in the basic circuit and a control was added to alter the internal reactance by an external low voltage source. Figure 2a plots the relationship between the input power and the light level for one fixture and three fixtures. Good linearity between the light level and power input is obtained between 70% and 100% light output.

Dimmable solid state ballasts can be used in buildings to reset light levels,periodically based on changes in task requirements,or lumen maintenance,or to alter light output in response to variable stimuli (ambient natural light level or space occupancy) to further reduce general illumination costs, while providing good quality lighting. It appears likely that solid state ballasts with dimming capabilities can be sold at little extra cost compared to non-dimmable units.

III. Ballast Demonstration

The ballast demonstration will be conducted on three floors of a Pacific Gas and Electric Company (PG&E) office building in San Francisco. The general plan is to retrofit three floors of this building with energy efficient ballasts. One floor is alloted to the Stevens ballast, one floor is alloted to the IOTA-EXCEL ballast,and one floor will be retrofited with energy efficient core-coil ballasts (Advance Mark III).

PG&E has metered the two main lighting input power lines on each of the three floors with watt hour meters. They will also measure the voltage, KWH, and KQH at the main,as well as the current on the neutral line of their three phase system. Computer printouts by 15 minute intervals during each month will show KVA, KW, RKVA, and power factor. IOTA-EXCEL ballast is a 120 volt system and PG&E has transformed the input voltage to 120 volt from 277 volts for the IOTA-EXCEL floor. This floor was first refitted with standard 120 volt core ballasts to obtain base line data.

Both of the solid state ballasts are designed as direct retrofits with ANSI standard color coded leads, and screw locations. The ballasts will be installed by the lighting maintenance organization that is employed by PG&E, without special instructions. There are no changes in the electrical wiring on any of the floors to accomodate either of the solid state ballasts.

LBL has installed a 60 channel data acquisition system to collect 1) detailed data for selected circuits on each floor, 2) data for other essential parameters (e.g. temperatures), and 3) other experiments that have been planned as part of the overall demonstration.

Base line data are presently being collected by PG&E and LBL with the current lighting system (i.e. core type ballasts). Prior to recording data, the floors were relamped and the ballasts of the delamped fixtures were removed. All major lamp manufacturers (Sylvania, Westinghouse, General Electric, North American Philips, and Duro-Test) have contributed fluorescent lamps for the demonstration. These lamps will be installed after the solid state ballasts are in place.

After the appropriate number of operating hours, sample quantities will be returned to each manufacturer for inspection and analysis to assist in studying any observable effects of ballast operation on lamp life.

LBL has placed thermocouples in several fixtures on each floor to measure input and output air temperature, ballast temperature, and bulb wall temperature. An attempt will be made to correlate the energy consumption of the lighting system with summer and winter HVAC loads. Ambient sound levels with core ballasts on the three floors have also been measured and Smith Hinchman and Grylls Associates was retained by PG&E to make photometric measurements. These measurements will be repeated after the energy efficient ballasts are installed.

There are three other tasks that are planned for the demonstration:

1. On the Stevens floor, the lamps in the perimeter offices with windows will be controlled to maintain a constant illumination in the offices. A variety of control systems will be studied to determine those best suited for maximizing energy savings by utilizing available daylight.

2. As part of its daylighting program, LBL is studying analytical methods which might be used to convert solar radiometric measurements to illumination availability data. Pyranometers and photometric sensors have been installed on the roof of the PG&E building to measure horizontal and vertical radiometric and photometric data throughout the demonstration period. Other daylighting experiments are being planned as part of the demonstration.

3. Several fixtures incorporating Stevens and IOTA-EXCEL ballasts will be modified to act as emergency lighting systems. Periodic performance tests will be conducted.

IV. SUMMARY

The information presented in this report should provide a basis for an evaluation of the different types of solid state ballasts that are being developed. It should be recalled that the measurements on the ballast/lamp systems have been obtained on a relatively small number of early prototype models. However, the good agreement between the measurements from the different laboratories gives credibility to these results. This information has provided a comparative reference for improvements that have been incorporated in subsequent ballast models and for identifying additional problem areas that must be addressed.

Comparative measurements between the IOTA-EXCEL, Stevens, and standard core ballasts show:

1. In free air measurements lighting systems with solid state ballasts can operate with 18 to 23% greater efficiency than systems using standard core-coil ballasts.

2. In higher temperature environments relative efficiency improvement can reach 30%. (See Table V)

3. When ballast failures occur, they appear to occur within the first 200 hours of operation.

4. There has been no evidence that fluorescent lamps are adversly affected when operated with the IOTA-EXCEL ballast.

5. The IOTA-EXCEL ballast prototypes show EMI emission greater than standard core ballasts, but suitable suppression of this EMI can be achieved.

6. Solid state ballasts can dim fluorescent lamps smoothly and efficiently over large ranges of light output levels.

   The near linear power-light level relation indicates that total operational savings from dimmable solid state ballasts may well exceed the 20 to 30% reported in 1. and 2. above, for lighting systems that are designed to effectively utilize the dimming capability.

Acknowledgment

The authors are indebted to the many people and organizations in the lighting industry that have contributed to this program. The program is supported by the U.S. Department of Energy.

References

1. Shultz, H.E., Transistor Inverter Ballasting Circuit, U.S. Patent 3, 247, 422. (April 1966).

2. Herzog, R.R., Electronic Ballast for Gaseous Discharge Lamps, U.S. Patent 3, 969, 652. (July 1966).

3. Perper, L.J. Power Sources for Fluorescent Lamps and the Like, U.S. Patent 4, 017, 782. (April 1977).

4. Zaderej, A., et al., Fluorescent Lamps with High Frequency Power Supply With Inductive Coupling and SCR Starter, U.S. Patent, 4, 042, 852. (August 1977).

5. Harver, R.J., The Verdict Is In: Solid State Fluorescent Ballasts Are Here, EDN, Vol. 21, Pg. 54, (November 1976).

6. Campbell, J.H., High Frequency Operation of Fluorescent Lamps, Illuminating Engineering, Vol. XLIII, Pg. 125, (February 1948).

7. Waymouth, J.F., Electric Discharge Lamps, MIT Press, Pg. 39-46, (1971).

8. Polman, J., et al., Low Pressure Gas Discharge, Philips Tech Rev., Vol. 35, Pg. 321, (1975).

9. Campbell, J.H., The History and Technical Evolution of High Frequency Fluorescent Lighting (to be published as an LBL report), (1978).

10. Culp, W.J., Noise in Gaseous Discharge Lamps., Illuminating Engineering, Vol. XLVII, Pg. 37, (January 1952).

11. Walter, G., Suppression of Radio Frequency in Fluorescent Lighting Installations, Illuminating Engineering, Vol. XLIX, Pg. 295. (June 1954).

TABLE I

LBL Ballast Measurements

Ballast Type	(No.)	Lamp Temp. °C end	Lamp Temp. °C center	Power (watts)	Volt. (volt)	Current (amps)	Light[1] (Fc)	Power Factor	Efficacy[2] Fc/watt	Relative Efficacy
Core	(4)	45	33	94.1	115	.85	51.2	.96	.540	1.00
Eff-Core	(2)	45	32	84.0	115	.76	49.7	.96	.592	1.10
I 62P	(4)	36	32	71.2	115	.71	45.9	.87	.644	1.19
I 52P	(4)	37	31	59.0	115	.59	38.0	.87	.644	1.19
Core	(1)	45	35	97	276	.37	50.2	.95	.518	1.00
S 8441	(4)	35	34	77.8	277	.31	49.6	.91	.638	1.23

Notes: 1. Relative lamp output, in uncalibrated units.

2. A Relative veasure: "light" ÷ "power"

TABLE II

IOTA Ballast Measurements

Ballast Type	(No.)	Power (watts)	Light (lumens)	Efficacy (1/w)	Relative Efficacy
Core	(1)	94.0	6023	64.1	1.00
I 62P	(15)	76.0	6019	79.2	1.24
I 52P	(15)	64.9	4959	76.4	1.19
I 18PC	(2)	64.8	4699	72.5	1.13
I 22PC	(1)	80.8	5937	73.4	1.15

TABLE III

LRL Ballast Measurements

Ballast Type	(No.)	Lamp Temp (^{o}C)	Power (watts)	Volt (volt)	Current (amps)	Light (lumens)	Power Factor	Efficacy (1/w)	Relative Efficacy
Core	(4)	38^{o}	94.5	120	.80	6068	.98	64.2	1.00
Eff-Core	(4)	38^{o}	88.9	277	.33	5985	.97	67.3	1.05
I 18PCT	(3)	35^{o}	64.0	120	.56	4602	.95	71.7	1.12
I 22PCT	(1)	38^{o}	80.3	120	.73	6031	.92	75.1	1.17

TABLE IV

Stevens Ballast Measurements

Ballast Type	(No.)	Power (Watts)	Voltage (Volt)	Current (amps)	Relative Light	Power Factor	Relative Efficacy
Core	(1)	98.2	277	.36	1.00	.98	1.00
S-8441	(13)	78.9	277	.30	1.00	.95	1.24

TABLE V

Ballast Performance at Different Lamp Temperature

Ballast type	Minimum Lamp Temperature	Power (Watts)	Voltage (volt)	Current (amps)	Light[1]	Power Factor	Efficacy [2]	Relative Efficacy Ballast	Relative Efficacy Temp
Core	33	95	115	.86	51.1	.94	.537	1.00	1.00
	42	86	115	.82	48.4	.91	.555	1.03	1.00
	49	86	115	.79	46.2	.95	.537	1.00	1.00
I-62P-1	32	76	116	.76	48.1	.86	.633	1.00	1.18
	43	75	116	.75	50.9	.86	.679	1.07	1.22
	47	73	116	.72	49.2	.88	.673	1.06	1.25
I-52P-3	31	60	116	.60	39.3	.86	.655	1.00	1.22
	42	58	116	.59	40.8	.85	.703	1.07	1.27
	47	57	116	.56	39.8	.88	.698	1.06	1.30
S-8441-019	32	77	277	.30	49.3	.93	.636	1.00	1.18
	45	74	277	.29	48.7	.92	.658	1.03	1.19
	48	85	277	.34	54.0	.90	.635	1.00	1.18
S-8441-023	32	82	277	.33	52.0	.90	.634	1.00	1.18
	45	83	277	.33	53.5	.91	.648	1.02	1.17
	48	88	275	.35	55.7	.91	.632	1.00	1.18

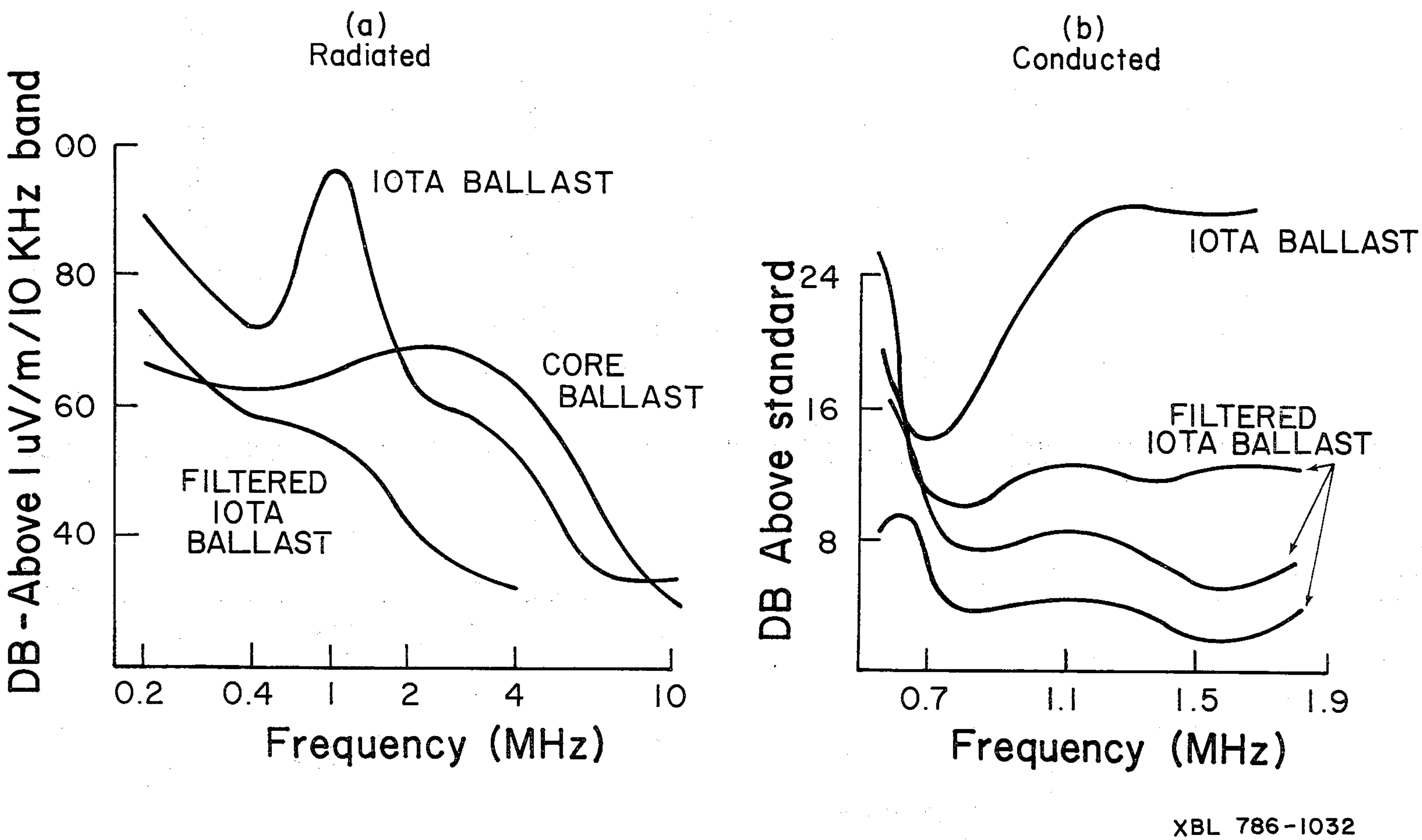
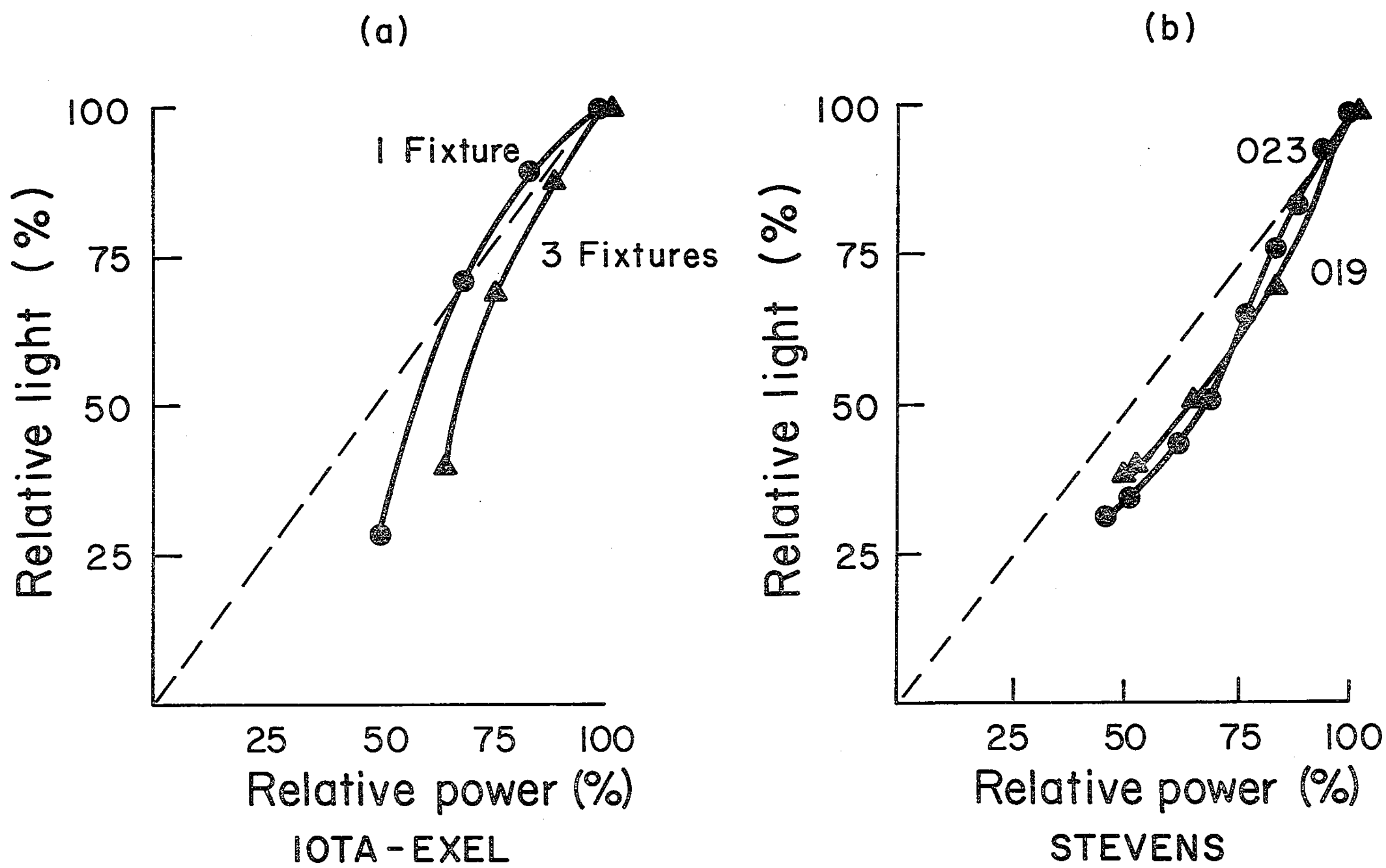


Fig. 1 EMI noise from fluorescent lamp



XBL 786-1031

Fig. 2 Dimming performance of solid state ballasts

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720