LBL-13206

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

OCT 9 1981

To be presented at the International Energy Management and Facilities Improvement Show, Chicago, IL, November 10-12, 1981

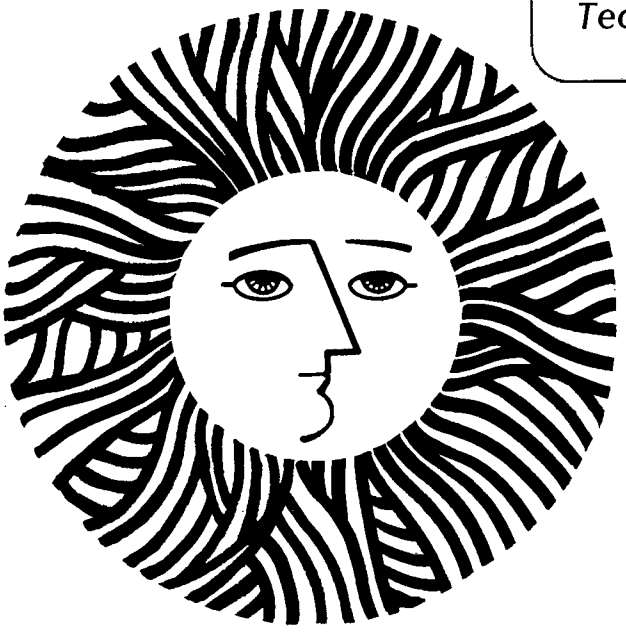
GAS-DISCHARGE LAMPS HAVING SOLID-STATE BALLASTS

R.R. Verderber

August 1981

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782.



LBL-13206 c.2

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-13206
EEB-L-81-09
L-51

Paper to be presented at the International Energy Management and Facilities Improvement Show, Chicago IL, November 10-12, 1981.

GAS-DISCHARGE LAMPS HAVING SOLID-STATE BALLASTS

R. R. Verderber

Lighting Systems Research
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720

AUGUST 1981

The work described in this paper was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research & Development, Building Equipment Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

ABSTRACT

Solid-state ballasts that more efficiently operate gas-discharge lamps (fluorescent, high-intensity discharge) at high frequency have undergone considerable development during the past five years. The progress realized is a result of industrial investments as well as the support of the U.S. Department of Energy's Office of Building and Community Systems.

The above programs included exhaustive testing of solid-state ballasts in a controlled laboratory environment, as well as two large-scale demonstrations of hundreds of solid-state ballasts. The demonstration sites included an office building and a hospital. In the above tasks the primary concerns were always the performance of the systems (reliability and safety) and the cost-effectiveness of the product.

This presentation will review the important characteristics of ballasts and their impact upon energy savings and ballast cost. This information will provide energy managers with a tool for comparing core-coil ballasts with solid-state ballasts.

1.0 INTRODUCTION

Energy managers, who must prescribe energy-reducing measures, often face the unenviable task of considering an investment for equipment they know little about. Comparing a standard product with an energy-efficient product that performs the same function in the same manner requires a relatively simple total cost analysis (initial, operating, etc.). But when considering energy-efficient products that supply features beyond the basic function and that employ a different technology, the analysis becomes difficult.

Selecting a ballast for operating gas-discharge lamps presents the above-mentioned problems for the decision-maker. The ballast industry produces an efficient core-coil ballast, but an even more efficient solid-state ballast has become available. Solid-state ballasts operate fluorescent lamps more efficiently by transforming the 60-Hz input power to a high frequency (20 to 30 kHz). The new circuits required to convert the frequency also allow for new features that enable these lighting systems to save still more energy.

This paper surveys the status of the solid-state ballast. The purpose is to describe the principal characteristics of the ballast and lighting system in order to assist the energy manager in assessing them. In addition, we will discuss the experience that has been gathered to date that relates to their life, reliability, and safety. The following sections describe the present mode of distribution and estimate the energy savings associated with each ballast feature. The final section summarizes this report and presents a prognosis for the energy-efficient ballast.

2.0 BALLAST CHARACTERISTICS

2.1 Basic

Table I describes the performance of twelve different two F40 T-12, rapid-start, core-coil and solid-state ballasts for cool white fluorescent lamps. The standard and energy-efficient core-coil ballasts are certified by CBM (Certified Ballast Manufacturers).[1] The table lists ten types of solid-state ballasts to show the possible variations in design and performance. All the measurements were made with a minimum lamp wall temperature of 40°C. This is the temperature at which the lighting system operates at maximum efficiency.[2] Premium fixtures are designed to achieve this temperature.

The 40-watt lamps were selected for comparison because they are the only lamps for which the two F40, rapid-start ballasts are CBM-certified. CBM rating certifies that the ballast conforms to several American National Standards Institute (ANSI) specifications. One requirement is that a CBM ballast provide at least 92.5% of the lamp manufacturer's rated output. Thus, the minimum light output for two F40 lamps is 5830 lumens (.925 x 6300 lumens).

Table I lists the three parameters that are controlled by the circuit design and that directly (system efficiency, input power) and indirectly

(regulation) determine the energy consumed when providing the required illumination. Regulation, along with lumen depreciation, determines the initial illumination that provides the required maintained light level.

Voltage/light regulation is a metric that describes the change in light output from the system for a change in input voltage of ± 10% about the design voltage. Temperature/light regulation describes the change in light output for a change in minimum lamp wall temperature of ± 10°C about 40°C. The change in light output is caused by the change in electric load due to the variation in the pressure of the mercury gas in response to temperature. The table shows that solid-state ballasts can be designed to have excellent regulation with respect to input voltage and load.

2.2 Features

Table II lists several features that derive from the ballast circuit design. Some features reduce energy consumption and/or improve the quality and comfort of the illumination as well as influencing the wave shape of the supply power.

2.2.1 Flicker

Fluorescent lamps operated at 60Hz with core-coil ballasts typically have about twenty-nine percent flicker. This amount of flicker disturbs some people and reduces their productivity. The table shows that most solid-state ballasts substantially reduce flicker and that some designs completely eliminate it.

2.2.2 Power Factor

One requirement of a CBM-certified ballast is that the system have a high power factor (greater than 0.90). High power factors are not required in all applications, and core-coil ballasts having low power factors are available. In Table II we note the power factors for various solid-state ballast designs. Generally, there is a trade-off between power factor and efficiency. However, some designs can achieve both high power factor and high efficiency.

2.2.3 Third-Harmonic Distortion

The magnitude of the third harmonic (180 Hz) indicates how much the input current's wave shape is distorted from sinulsoidal. It determines primarily the magnitude of the current that will flow through the neutral leg of a three-phase wiring system. The United States has established no specifications for the maximum amount of third harmonic. European countries permit a maximum of $(33 \times \frac{\text{power factor}}{0.9})\%$, and the device must be so marked.[3] If a ballast is unmarked, the third-harmonic distortion must be less than $(25 \times \frac{\text{power factor}}{0.9})\%$. The third harmonic for some solid-state ballasts can meet these stringent requirements.

2.2.4 Control of Light Level

Solid-state ballasts can incorporate circuits that permit them to continuously dim fluorescent lamps. The lamps can be dimmed manually by a pot or automatically by the output from a photocell so that they provide a constant light level. In order for fluorescent lamps operated with core-coil ballasts to be dimmed, external phase-control equipment is used which requires switching high electrical power. This method, which controls the duty cycle, generally increases the percent flicker. Manual dimming from a pot on each ballast means that each lamp can be adjusted to the desired light level--i.e., the lighting system can be "tuned." For example, the output of fluorescent lamps in aisles or halls can be reduced by 20%. Generally, about 20% of the floor space has fixtures that illuminate non-critical tasks, thus the ´tuning´ capability can reduce average energy consumption on a floor by 4%.

The capability to maintain a constant illumination level allows these solid-state ballasted systems to utilize daylighting for illuminating a building as well as for recovering some of the losses due to lumen depreciation. In areas where daylighting can be used, energy savings can be at least 25%.[4] The 20% increase in initial light level that is needed because of lumen depreciation can be reduced by 50%, resulting in an energy savings of 10%.

2.3 Energy-Efficient Lamps

There are two types of energy-saving F40 (35-watt) lamps, one with cool white phosphor, and the other (type II lamps) with a different spectral distribution that contains more yellow-green light. The latter lamp is rated to produce 3050 initial lumens (100 lumens less than the standard F40 cool white) with 35 watts input. Taking into account the ballast loss for each lamp, the increase in system efficiency is 7% for lamps having the special phosphor. Because of the ANSI test procedures for lamps and ballasts, the CBM ballast that must meet the specification for minimum light output with the F40 do not meet this requirement with the F40 (35-watt) lamps. Hence, there are no ballasts for the F40 (35-watt) lamps that have CBM certification. Table III gives the system efficiency for ballasts operating the type II F40 (35-watt) lamps at 5830 lumens output. Figures are 7% greater than the data presented in Table I.

2.4 Ballast Designations

We have described several characteristics of ballasts that will enable a person to compare the cost-effectiveness of various designs. Ballast manufacturers provide the information necessary for an electrical contractor to install a ballast so that the circuit wiring and associated electrical equipment can safely carry the necessary current. The information presented in the catalogs is necessary for the electrical circuit designer; however, it is not useful for comparing the performances of different types of ballasts. The information in Table III is a helpful guide for comparing ballast information from catalogs. The input power listed for each type of ballast is for lamps operating at 40°C,

supplying 5830 lumens, with F40 cool white lamps and F40 (35-watt) type II lamps. If the power of any system is much less than that listed the Table III, the light output would probably be less than the 5830 lumens. This could be due to the design of the system, or the measurements could have been made with the minimum lamp wall temperature above 40°C.

2.5 Ballast Life, Safety, and Reliability

Standard core-coil ballast designs have evolved during the past forty years. It is well documented that the expected life of a well-made core-coil ballast is 10 to 12 years.

The solid-state ballast has become available only during the past year, and no documentation for a ten-year life is at hand. The LBL program has demonstrated some early prototype models[4] and those recently designed.[5,6] While failures occurred in the early demonstration at the Pacific Gas and Electric building, after the infant mortalities the failures virtually ceased; the rest of the ballasts are still performing after four years. In recent demonstrations, the infant mortality has been very low, and we expect it to approach 1/2% within the year. Even the failures provide valuable evidence of the ballasts' safety since none presented a hazzard (fire or electric shock). Further credible evidence of the solid-state ballasts' safety is that the Underwriters Laboratory (U/L) has certified several solid-state systems.

In a more recent demonstration at a VA Medical Center in Long Beach, California,[4] about 250 ballasts were installed. In the first few months 13 units failed (about 5%). The cause was identified as defective components. The solid-state ballast manufacturers expect to achieve a 0.5% failure rate, the same as for core-coil ballasts. The 5% rate mentioned above is attributable to the transfer of new technology to a manufacturing line. This failure rate occured in 1980 and has been reduced this year. In fact, for a current demonstration 2000 solid-state ballast have been installed in 19 locations.[6] After a few months, only twelve failures have been reported. These latter studies provide evidence that the solid-state ballast is a commercially viable product.

3.0 AVAILABILITY

Standard core-coil ballasts are available at all levels of distribution —retail, wholesale, and OEM. It is well known that for each level of distribution which serves a market segment that purchases a low volume, the product price is increased.

Because solid-state ballast technology is still being transferred into a hard-tooled line, the unit volume of production is low and manufacturing costs per unit are high. Thus, the present distribution of solid-state ballasts is factory-direct (through sales representatives and corporate sales offices). If designers or architects desire solid-state ballasts they must specify them. The unit may cost more, but installation cost should be the same. In fact, the lower weight of the solid-state ballasts should make them less costly to ship and install.

As the market grows and cost-reduction developments are transferred to the product line, distribution of the solid-state ballasts will soon occur at all levels.

4.0 ENERGY SAVINGS

All energy-efficient ballasts have a higher initial cost than do standard core-coil ballasts. In past years initial cost was such a decisive factor in the purchasing decision that ballast manufacturers used aluminum wire in place of copper wire as well as using less costly magnetic materials to reduce product costs. This made the ballast less efficient as well as reducing ballast life because it operated at higher temperatures.

Now that the cost of energy is so high, the greater initial cost of the efficient ballasts must be justified on a lower total cost (initial plus operating). In this section we estimate the savings in operating costs for ballasts having a certain efficiency as well as for those having new features. Table IV lists the efficiencies of several ballasts and the higher initial illumination level that must be supplied because of the nonrecoverable light-loss factors (voltage and temperature regulation) and a recoverable light-loss factor (lumen depreciation). We have estimated the energy reductions possible with a ballast having the manual and automatic dimming features that allow for control strategies such as daylighting and tuning, as well as making it possible to recover losses due to lumen depreciation. We have used ballast 3 in the table to compute the savings with and without a daylighting strategy.

Other features we consider important are power factor, third-harmonic distortion, and flicker. These do not affect energy costs, but high power factor and low third-harmonic distortion permit the use of smaller wires, transformers, and other auxillary electrical equipment, thereby reducing initial costs for these products. Lowering the percent flicker provides a better quality of illumination, eliminating one major cause of discomfort for many workers. The savings are difficult to assess but will be reflected in productivity.

The results show that for dedicated solid-state ballasts the annual savings can reach $6 to $7. Dimming solid-state ballasts can save nearly $12 annually; in those areas where daylighting can be exploited, more than $16 can be saved annually.

5.0 SUMMARY AND PROGNOSIS

This paper has reviewed the present status of the solid-state ballast and has provided a basis on which to compare the standard ballast with the solid-state ballast as well as comparing different solid-state ballast designs.

The solid-state ballast provides the highest system efficiency and has features that improve the quality of illumination. Successive on-site demonstrations have provided evidence that solid-state ballasts can be made safe and reliable and should have a life expectancy equal to that of good quality core-coil ballasts.

Although solid-state ballasts are available, their present distribution is limited to direct sales from the manufacturer. These manufacturers have passed through the difficulties of transferring the technology to the product line. In a short time, we can expect the proper quality assurance (failure rate less than 0.5%) from most manufacturers.

A varied product mix of solid-state ballasts is available for operating other types of gas-discharge lamps (low-power fluorescent lamps, three and four F40 lamps, high-output F40 Lamps, instant-start 96-watt fluorescent lamps, and high-pressure sodium lamps). The solid-state ballast manufacturers are now developing integrated circuits and power-hybrid technology to improve performance, increase reliability, and reduce product costs. We can expect a broad distribution of these systems in the near future.

Finally, a simple cost-saving exercise has shown that a range of annual paybacks from more than $6 to $16 is possible depending upon ballast features. These savings reflect only the few characteristics discussed. For the total energy savings realized by the building operator, one must also consider the reduction in a building's air-conditioning load due to less heat dissipation by these efficient systems as well as increased productivity due to improved comfort and quality of illumination.

ACKNOWLEDGEMENT

The work described in this paper was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Building Energy Research & Development, Energy Conversion Equipment Branch of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

REFERENCES

1. Certified Ballast Manufacturers Association, Basic Facts About Ballast You Should Know! Certified Ballast Manufacturers Association, Cleveland OH, 1976.

2. E. Kaufman, ed., IES Lighting Handbook, 5th ed., pp. 8-26. Waverly Press, Inc., Baltimore MD, 1972.

3. International Electrotechnical Commission, Draft of Proposed Third-Harmonic Specification. International Electrotechnical Commission Committee 34-C, December, 1979.

4. J. Jewell, S. Selkowitz, and R. R. Verderber, Solid-State Ballasts Prove to Be Energy Savers, Lighting Design & Application 10 (10):36 (January, 1980).

5. R. R. Verderber et al., Energy Savings with Solid-State Ballasts in a VA Medical Center. LBL Report No. 12461, May 1981.

6. Lighting Systems Research Program, A ballast demonstration in progress, supported by the U.S. Department of Energy (Contract No. 4450 8210). LBL Report to be published 1981.

TABLE I
CHARACTERISTICS OF DEDICATED BALLAST DESIGNS

PARAMETER	CBM CORE-COIL BALLAST		SOLID-STATE BALLAST									
	STANDARD	EFFICIENT	1	2	3	4	5	6	7	8	9	10
SYSTEM EFFICIENCY (ℓ/w)	63	68	79	78	80	78	70	77	79	79	78	78
POWER[1] (watt)	93	86	74	75	73	75	83	76	74	74	75	75
REGULATION												
VOLTAGE/LIGHT[2]	±5%	±5%	±5%	—	±0.5%	—	—	—	±11%	±11%	±10%	±10%
TEMP./LIGHT[3]	∓6%	∓6%	∓1%	—	∓1.0%	—	—	—	∓1%	∓1%	∓1%	∓1%

[1]For two-F40 T-12 rapid-start, cool white fluorescent lamps at lamp wall temperature of 40°C, providing 5830 intial lumens.
[2]For input voltage ±10% about the center design voltage.
[3]For lamp wall temperature ∓10°C about 40°C.

TABLE II
FEATURED CHARACTERISTICS OF BALLAST DESIGNS

PARAMETER	CBM CORE-COIL BALLAST		SOLID-STATE BALLAST									
	STANDARD	EFFICIENT	1	2	3	4	5	6	7	8	9	10
FLICKER (%)	29	29	3	0	0	2	11	0	11	11	2	2
POWER FACTOR	.98	.98	.92	.66	.90	.59	.95	.94	.81	.90	.95	.94
THIRD-HARMONIC DISTORTION (%)	6 to 14	6 to 14	—	—	14	—	11	25	25	22	25	25
DIMMING	no	no	no	no		no		no	no	no	no	no
Manual					yes		yes					
Automatic					yes		yes					
Range (%)					70		70					

TABLE III
PERFORMANCE OF BALLASTS HAVING STANDARD F40 LAMPS AND ENERGY-EFFICIENT F40 (35-watt) LAMPS

PARAMETER	CBM[1] CORE-COIL BALLAST		SOLID-STATE BALLAST
	STANDARD	EFFICIENT	
F40 LAMPS			
SYSTEM EFFICIENCY (ℓ/w)	63	68	80
POWER (watt)	93	86	73
F40 (35-watt) LAMPS[2]			
SYSTEM EFFICIENCY (ℓ/w)	67	73	86
POWER (watt)	87	80	68

[1]Core-coil ballast CBM-certified for F40 lamps only.
[2]Type II energy-efficient lamps.

TABLE IV
RELATIVE ENERGY SAVINGS FOR BALLASTS HAVING VARIOUS FEATURES

PARAMETER	CBM CORE-COIL BALLAST		SOLID-STATE BALLAST						
	STANDARD	EFFICIENT	1	3	3	7	8	9	10
SYSTEM EFFICIENCY (ℓ/w)	63.0	68.0	79.0	80.0	80.0	79.0	79.0	78.0	78.0
INITIAL ILLUMINATION (%)									
Voltage Regulation	5.0	5.0	5.0	0.5	0.5	11.0	11.0	10.0	10.0
Temperature Regulation	6.0	6.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Lumen Depreciation	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
ENERGY RECOVERY (%)									
Lumen Depreciation				10.0	10.0				
Daylighting					25.0				
Tuning				4.0	4.0				
TOTAL INITIAL ILLUMINATION (%)	133.6	133.6	127.3	105.2	78.9	134.5	134.5	133.3	133.3
WATTS PER BALLAST	123.6	114.5	93.9	76.7	57.5	99.3	99.3	99.6	99.6
ANNUAL COST[1] ($)	30.3	28.1	23.0	18.8	14.1	24.3	24.3	24.4	24.4
RELATIVE ANNUAL SAVINGS ($)	0	2.2	7.3	11.5	16.2	6.0	6.0	5.9	5.9

[1]For annual use of 3500 hours and $0.07 per kWh

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

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

1-71