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Energy Efficiency Lighting on Board Naval Ships: Phase II (The T-8 Lamp System)

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ENERGY EFFICIENCY LIGHTING ON BOARD NAVAL SHIPS

PHASE II

(The T-8 Lamp System)

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PHASE II

(The T-8 Lamp System)

1.0 INTRODUCTION

The first phase of this program has developed a lamp-ballast system that improves the efficacy of the currently used fluorescent lamp-ballasts by 27 percent, from 49 lm/W to 62 lm/W. Equally important has been the development of a ballast that improves the power factor from 60 percent to over 90 percent and the reduction of all the line harmonics to below 3 percent. The specifications for the above system have been prepared and will be evaluated on board a ship in the near future.

In the course of the above Phase I study, further improvements in the system efficacy were measured with the T-8 (1-inch diameter) lamp. This report describes the development and performance of the T-8 fluorescent lamp-ballast system. Similar to the Phase I effort, the cooperation of the lamp and ballast companies (GTE, North American Philips Lighting, and IOTA Engineering) were required for the successful result. The above companies submitted prototype lamps and ballasts to the Lawrence Berkeley Laboratory Lighting Group to evaluate. The lamp designs were modified as required and the optimum system selected. Two-lamp designs and one ballast were chosen and tested to determine if they met the Navy specifications.

The second section describes the lamp-ballast specifications. The measured electrical input-output performance of the lamp-ballast systems are listed in the third section. This section includes the measured thermal performance from an ambient of 10°C to 60°C. The measurements of the electromagnetic conducted and radiated intensities and the line current harmonics are presented in the forth section. In the fifth section the quality assurance, the life and lumen depreciation of the system are presented. The results and status of the T-8 project is discussed. The final section presents the conclusions of this development.

2.0 FLUORESCENT LAMP-BALLAST SPECIFICATIONS

2.1 <u>T-8 Fluorescent Lamp</u>

The lamp shall provide an initial light output of 1200 lumens, have a cool white color and an efficacy greater than 75 lm/W. LBL measured the light output submitted by GTE and Philips and obtained the operating currents of each lamp to achieve the 1200 initial lumen output. Table 2.1 lists the reference ballast settings.

Table 2.1
Reference Ballast Settings for 1200 Lumens

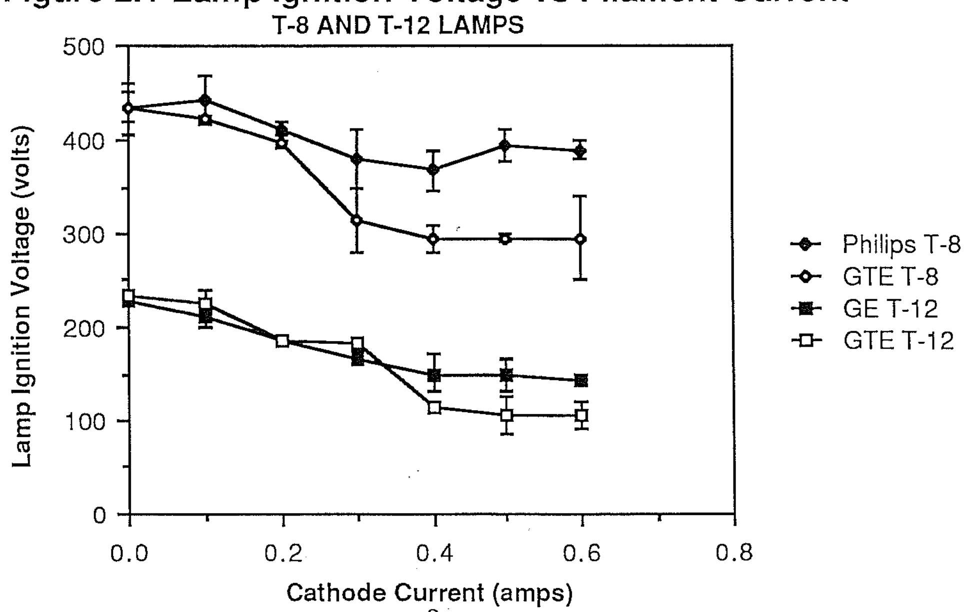
Lamp	$I_{REF(A)}$	$V_{SET(V)}$	$Z_{REF(\Omega)}$
GTE A	.325	93.2	287
GTE B	.342	94.6	277
Philips	.285	86.0	302

All of the lamps submitted were then measured in the integrating sphere with the reference ballast and set to provide 1200 lumens. Table 2.2 lists the average results from five GTE-A lamps, five GTE-B lamps, and ten Philips lamps.

Table 2.2
Lamp Efficacy of Prototype Lamps

Lamp	Voltage (V)	Current (A)	Power (W)	Light (lm)	Efficacy (lm/W)
GTE-A	55.0	.325	15.2	1200	79.1
GTE-B	52.0	.342	15.2	1200	78.7
Philips	63.7	.285	15.1	1200	79.5

Figure 2.1 Lamp Ignition Voltage vs Filament Current



Philips lamps operate at a higher voltage and lower current than the GTE lamps indicating the lamps from the different suppliers have different fill gases and/or the fill gas is at a different pressure. However, all of the lamps met the target of exceeding an efficacy of 75 lm/W.

2.2 T-8 Ballast

The ballast was required to have a ballast factor of 90 percent or higher resulting in an initial light output of 1080 lumens in a 25°±1°C ambient. The power factor should exceed 90 percent and all line current harmonics should not exceed 3 percent. The lamps should be able to be ignited in a 10°C ambient at a voltage of 10 percent below the center design voltage of 118 volts applied to the ballast.

Since the current-voltage requirements of the GTE and Philips lamps differed a single-ballast design was not possible to meet the ballast factor requirement. The ballast was designed based upon the Philips lamp. Thus, for this study the ballast factor specification will not be met by the GTE lamps.

2.3 Starting Characteristics

2.3.1 Minimum Input Voltage

The lamps were placed in the integrating thermal chamber at an ambient temperature of 10°C. The input voltage to the T-8 ballast was gradually increased until the lamps would ignite. Table 2.3 lists the measured results for the three types of lamps.

Table 2.3
Minimum Input Voltage for Ignition at 10°C

Lamp	Input Voltage (V)
GTE-A	82.5
GTE-B	90.2
Philips	101.8

Each of the lamp types started at an input voltage well below the minimum required voltage (106.2). Note that the Philips lamp started at a higher starting voltage than the GTE lamps.

2.3.2 Lamp Ignition Voltage

The lamp voltage at which the lamps start for a range of filament currents was measured for the T-8 lamps and T-12 lamps. Figure 2.1 shows the results for electrode currents from 0 to 0.8 amperes. The trend is for the ignition voltage to decrease with increasing electrode currents, since the electrodes attain a higher temperature. The larger diameter lamps (T-12) have a much lower ignition voltage than the T-8 lamps.

The GTE lamps have a lower starting voltage than the philips lamps. This is because the Philips lamp is a higher voltage lamp as well as the type of filament in each lamp. The Phillips has a rapid start filament (~2.5Ω) while the GTE has a preheat start filament (high resistance ~6.4Ω). We requested Philips to use filaments with a high resistance and employed a 3.1Ω filament. These lamps were designated Philips (modified) lamps.

Since the dynamic impedance of the ballast is about 200 ohms and the filament impedance small (~10 ohms) only a small portion of the input voltage appears across the filaments. One can increase the filament temperature at starting by increasing the filament resistance. However, the higher the filament resistance the greater will be the I^2R filament loss during operation, particularly toward the end of life.

Since on board ships most lamps are operated continuously, one should use the lowest filament resistance that will start the lamps at an input voltage of 106.2 volts, at 10°C ambient. That is, the lamps are turned *ON* and *OFF* infrequently and it is a viable trade-off to permit a greater loss of oxide per start to reduce energy use during operation.

3.0 FLUORESCENT LAMP-BALLAST SYSTEM PERFORMANCE

3.1 At 25°C Ambient

The measured input-output performance of ten ballasts operating the GTE-B-1 lamp and the Philips modified #2 lamp are listed in Table 3.1. The values are the average from ten (#1 to #10) IOTA, 3 mA118-1-TLD 18W ballasts. The data is obtained at three input voltages, the 118 center voltage and ± about the center voltage.

All of the requirements are met for both lamps, except the ballast factor for the GTE lamps. A previous section indicated that a single ballast cannot be designed to provide the same ballast factor for lamps and a single modification would be required to obtain the proper ballast factor. The higher preheat power to the electrodes (8.2 watts) for the GTE B-#1 lamp is one reason it has a lower lamp ignition voltage than the Philips lamp.

The higher percent flicker for the Philips lamp suggests that the GTE and philips lamp employ a different type of phosphor. The four percent increase in the percent flicker is not significant, i.e., probably would not be noticed.

3.2 From 10°C to 60°C Ambient

The variation in light output and efficacy for the T-8 lamp-ballast systems were measured over an ambient temperature range from 10°C to 60°C. The thermal integrating chamber was used to slowly increase the ambient temperature from 10°C to 60°C; input power to the system, as well as the total light output from the lamp were continuously measured.

Figure 3.1 shows the results for the light output for the two types of lamps; the Philips and the GTE-B. The maximum light output for the Philips lamp occurs at a minimum lamp wall temperature (MLWT) 5°C less than the GTE lamps. More important, the Philips lamp is less sensitive to changes in temperature between the MLWT that lamps generally maintain in a single lamp and three lamp fixture, i.e., 35°C and 55°C, respectively. However, the greatest change in the typical operating range (35°C to 55°C MLWT) is only 3 percent, about the 35°C MLWT, i.e., for the single lamp type fixtures.

Figure 3.2 is a plot of the change in system efficacy for the two types of lamps over the ambient temperature range from 10°C to 60°C. However, the efficacy curves for the two types of systems are about the same. This indicates that as the light output changes, the input power also changes by the same relative amount.

Figure 3.1 LIGHT OUTPUT CHANGE AT VARIOUS LAMP WALL TEMPERATURES

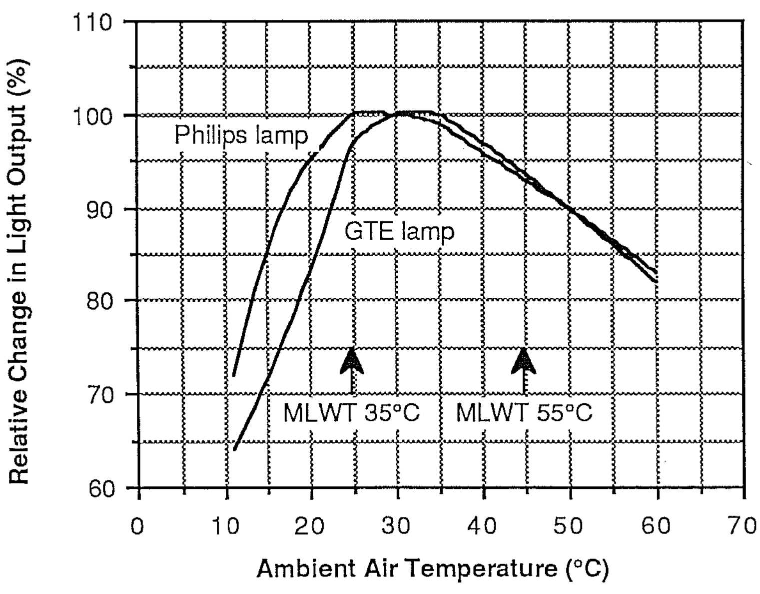
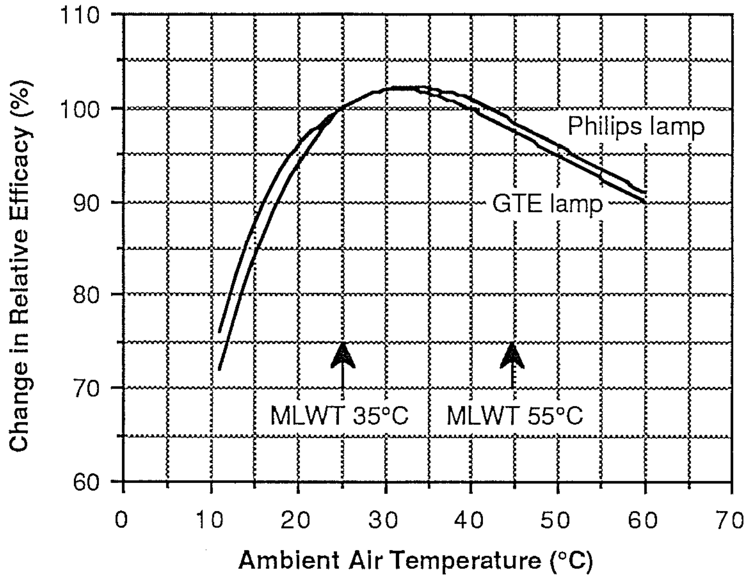


Table 3.1

Performance of Lamp Ballast Systems for IOTA Ballasts

LAMP	GTE, B-1			PHILIPS (Modified) #2		
Ballast Input						
Voltage (V)	106.2	118	129.8	106.2	118	129.8
Current (A)	.133	.150	.172	.137	.152	.172
Power (W)	13.2	15.2	17.5	14.4	17.1	18.9
Power Factor	.94	.86	.78	.99	.95	.89
Lamp						
Voltage (V)	53.0	51.8	50.5	65.9	64.4	62.9
Current (A)	.244	.284	.327	.225	.266	.311
Power (W)	10.8	12.2	13.6	12.3	14.3	16.1
Electrodes						
Voltage (V)	24.0	25.2	27.2	8.1	10.6	14.0
Current (A)	.290	.329	.378	.301	.341	.390
Power (W)	6.9	8.2	10.2	2.4	3.6	5.5
Lamp Current Crest Factor	1.5	1.5	1.5	1.5	1.5	1.6
Output						
Initial (lm)	809	919	1010	960	1120	1250
Ballast Factor		.75			.93	
Regulation (%)	-11		+13	-14		+12
Min. Lamp Wall Temp. (°C)	33	34	35	34	36	37
Flicker (%)	31	30	30	35	34	33
Ballast Eff. (%)	.82	.80	.78	.85	.84	.81
Lamp Eff. (lm/W)	75	75	75	78	78	78
System Eff. (lm/W)	61	61	58	67	65	63

Figure 3.2 EFFICACY CHANGE AT VARIOUS LAMP WALL TEMPERATURES



4.0 CONDUCTED, RADIATED ENERGY

4.1 Line Current Harmonics

The initial measurements of the line harmonics indicated that the third harmonics was greater than 3 percent with the T-8 lamp ballast system. Measurement of the third harmonic from the power supply showed that there was a slight distortion in which the third harmonic was slightly greater than 1 percent. A Wavetech signal generator and a Crown power supply was then used that had no detectable distortion. In order to verify our set-up a lamp and ballast was sent to each of the three laboratories that measured the harmonics (LBL, GTE, and IOTA Engineering) and results compared. Good agreement of the data was found. Table 4.1 lists the results taken at LBL with the new power source. The data was obtained with an input voltage of 118 volts, at 60 Hz at a 25±1°C ambient temperature, and is the average obtained with measurements made for five IOTA T-8 prototype ballasts.

Table 4.1
Line Current Harmonics

Lamp Ballast	GTE - B-1			Philips (modified) #2		
Harmonic	Starfield	IOTA T-8	(Max)	Starfield	IOTA T-8	(Max)
2	0.2	0.6	0.8	0.4	0.9	1.0
3	9.2	1.5	1.8	10.2	2.8	3.0
5	0.9	2.0	2.1	2.0	2.2	2.3
7	1.6	1.0	1.1	1.7	1.3	1.4
9	0.6	0.4	0.5	1.0	0.7	0.7

The table includes measurements with the Navy's standard for field ballasts in which the third harmonic exceeds 3 percent. The table also lists the maximum value measured for one of the five ballasts tested. Note that none of the systems exceeded the 3 percent limit.

The higher harmonics, up to the thirty second, were measured for each system. The third and fifth harmonics were measured for ten Philips T-8 lamps with the IOTA C280 ballast and a Philips T-8 #2 lamp measured with five different IOTA ballasts. Table 4.3 lists the results. The results show that there is very little variation in the harmonics for the different lamps. However, there is a 29 percent variation for the five different ballasts. This variation is obtained because these are prototypes and have slight design variations. The production models should provide much less variation when the ballast design is set. Table 4.1 shows that for the same ballast, lamps with different gas fills will also affect the line harmonic content.

Table 4.2 lists the measured values for the IOTA ballast #297 and Philips lamp #2 and GTE lamp B-1.

4.2 Electromagnetic Interference (EMI)

The same circuit layout and procedure were used to measure the conducted and radiated EMI for the F17 T-12 system[1].

Table 4.2
Line Current Harmonics

Lamp-Ballast Harmonic	Philips #2 (%)	GTE B-1 (%)
2	0.9	0.7
3	2.8	2.4
4	0.2	0.1
5	2.2	2.4
6	0.1	0.1
7	0.8	0.3
8	<0.1	0.5
9	0.4	0.5
10	<0.1	<0.1
11	0.5	0.3
12	<0.1	<0.1
13	0.2	0.2
14	<0.1	<0.1
15	<0.1	0.1
16	<0.1	<0.1
17	0.2	0.2
18	<0.1	<0.1
19	0.1	0.1
20	<0.1	<0.1
21	0.1	0.1
22	<0.1	<0.1
23	0.1	0.1
24	<0.1	<0.1
25	<0.1	0.1
26	<0.1	<0.1
27	0.1	0.1
28	<0.1	<0.1
29	0.1	0.1
30	<0.1	<0.1
31	<0.1	<0.1
32	<0.1	<0.1

4.2.1 Conducted

Figure 4.1 plots the narrow band data for the Philips modified T-8 lamp and the IOTA T-8 ballast from 60 Hz to 6.5 KHz. It is virtually the same as the T-12 system[1] and well below the CEO narrow band limit.

Figure 4.2 is the data obtained for the broad band measurements from 300 Hz to 10 KHz. These EMI levels are the same as the T-12 system[1] and well below the C EOI broad band limit. Only between 1 KHz and 8 KHz does the EMI levels exceed the instrument noise levels.

4.2.2 Radiated

Figure 4.3 plots the results of the radiated EMI from the Philips T-8 lamp over the range of frequencies 14 KHz to 500 KHz. The EM radiation from the lamp-ballast system is less than 10 db above the background noise level, and well within the RE 02 broad band limit. The radiate level is about 10 db below the levels measured for the T-12 system.

Figure 4.1 NAVY NARROW BAND AND CONDUCTED

T8 LAMP AND BALLAST

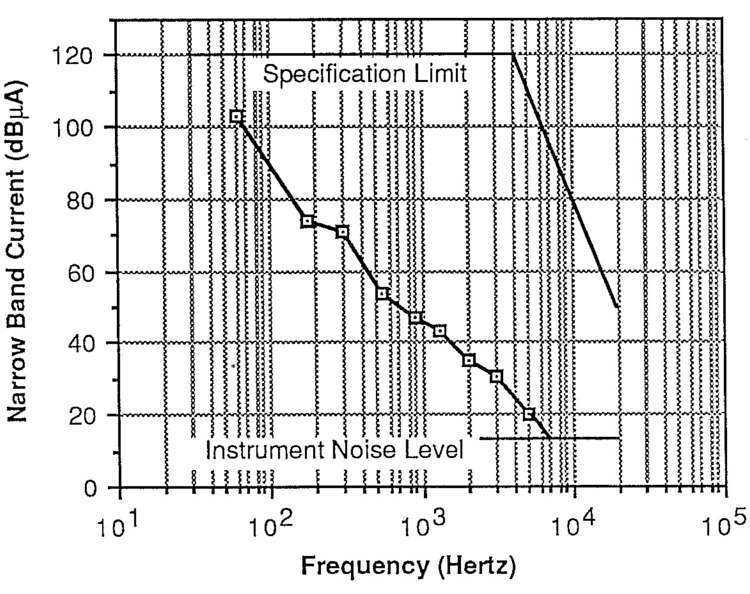


Table 4.3
Variation in Harmonics for Ballasts and Lamps

Philips T-8 (IOTA Ballast C280)

#	3rd	5th
1	2.64	2.21
2	2.61	2.21
3	2.56	2.17
4	2.61	2.21
5	2.56	2.21
6	2.64	2.21
7	2.64	2.22
8	2.61	2.21
9	2.68	2.22
10	2.54	2.18
	2.61 ± .04	2.21 ± .02

IOTA Ballast (Philips T-8 #2

	3rd	5th
C274	3.00	2.11
C279	2.41	2.22
C280	2.44	2.21
C281	2.69	2.20
	2.37 ± .7	2.17 ± .06

5.0 PRODUCT UNIFORMITY AND LIFE

5.1 Ballasts

Twenty-five IOTA ballasts 3MA118-1-TLD 18W #1 through #25 were received. To determine the uniformity of this shipment we tested ten ballasts #1 through #10 with the GTE-B-1 lamp and three ballasts #1 through #3 with the Philips modified #2 lamp. The results of the measurements are listed in Table 5.1. The variation in the performance of the system for input power, light output shows that the ballasts can be made within a variation of 2%. The larger variation in the measurement of the third harmonic reflects the limits of the measurement technique of ±0.1. The uniformity of this IOTA production model is better than the original five prototypes, i.e., the variation of the third harmonic for the production ballast is ±.1 compared to the ±.7 for the prototype ballasts (see Table 4.2).

5.2 Lamps

Table 5.2 lists the measurement of the lamps characteristics after 100 hours burn in. The measurements are made under ANSI conditions in an integrating sphere operated with the reference ballast setting to provide an initial light output of 1200 lumens.

Figure 4.2 BROADBAND CONDUCTED

T8 LAMP AND BALLAST

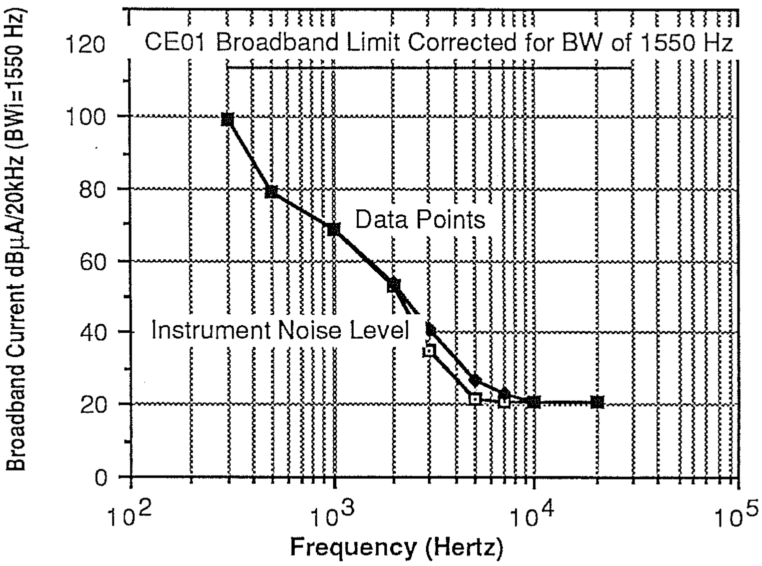


Figure 4.3 NAVY RADIATED BROADBAND

T8 LAMP AND BALLAST

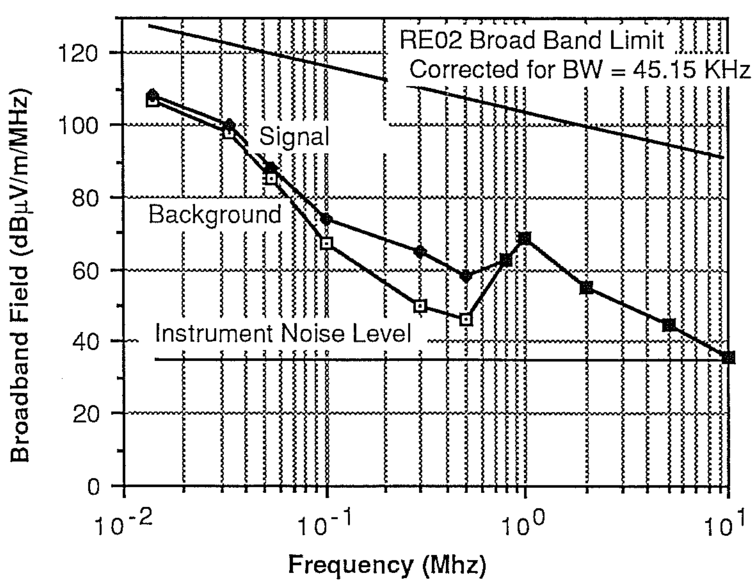


Table 5.1
Ballast Uniformity

	GTE B-1 Lamp			Philips #2 Lamp		
Ballast #	Power Input (W)	Light Output (lm)	Third Harmonic (%)	Power Input (W)	Light Output (lm)	Third Harmonic (%)
1	15.4	933	1.6	17.1	1123	2.7
2	15.1	938	1.8	17.0	1118	3.0
3	15.3	933	1.6	17.1	1109	2.8
4	15.3	933	1.4			
5	15.1	928	1.4			
6	15.2	913	1.3			
7	15.1	918	1.6			
8	15.1	913	1.6			
9	15.2	888	1.4			
10	15.1	893	1.7			
	15.2±.09 (±1%)	919±14 (±2%)	1.5±.1 (±7%)	17.1±.03 (±.1%)	1117±5 (±.4%)	2.8±.1 (±4%)

The variation in the light output and efficacy of both types of lamps is ±1.2%. This indicates that good product uniformity can be achieved with these lamps.

5.3 Lumen Depreciation and Life

Fifteen lamps of each type were operated at the standard test cycle of 3 hours *ON* and 20 minutes *OFF*. Five of each type were operated in a continuous mode to simulate the usual operation on board ship. At 100, 516, 1000 and 3000 hours the light output of each lamp was measured with the reference ballast at the appropriate ballast setting. The results are listed in Table 5.3.

Table 5.2
Lamp Uniformity at 100 Hours

	GTE -.B			PHILIPS		
Lamp #	Power (W)	Light (lm)	Efficacy (lm/W)	Power (W)	Light (lm)	Efficacy (lm/W)
1	15.3	1230	80	15.5	1200	78
2	15.4	1230	80	15.5	1210	78
3	15.5	1210	78	15.4	1210	79
4	15.5	1230	80	15.5	1210	78
5	15.4	1220	79	15.5	1210	78
6	15.4	1240	80	15.3	1220	80
7	15.4	1240	80	15.5	1210	78
8	15.3	1210	79	15.5	1210	78
9	15.3	1230	81	15.4	1210	79
10	15.2	1180	78	15.3	1230	80
11	15.3	1230	80	15.4	1210	78
12	15.5	1190	77	15.4	1210	79
13	15.3	1220	79	15.4	1210	79
14	15.3	1210	79	15.4	1200	78
15	15.2	1190	79	15.4	1210	79
16	15.4	1220	79	15.5	1210	78
17	15.5	1200	78	15.6	1210	77
18	15.5	1220	79	15.5	1210	78
19	15.5	1230	79	15.4	1210	79
20	15.4	1230	80	15.4	1210	79
	$15.4 \pm .8$	1220 ± 15	79 ± 1.0	$15.4 \pm .6$	1210 ± 5	78 ± 1

Table 5.3
Lumen Depreciation

Operating Hours	GTE -B Light Output (lm) 3 Hr. Cycle (lm)	relative	Continuous (lm)	relative	Philips Light Output (lm) 3 Hr. Cycle (lm)	relative	Continuous (lm)	relative
100	1217±14	1.00	1220±6	1.00	1210±1	1.00	1211±1	1.00
516	1175±14	0.97	1183±9	0.97	1192±6	0.99	1188±7	0.98
1000	1103±16	0.91	1164±7	0.95	1192±6	0.99	1205±5	1.00
3000	1100±20	0.90	1123±7	0.92	1148±10	0.95	1161±6	0.96

Figures 5.1 and 5.2 plot the data for the lumen depreciation of the GTE and Philips lamps, respectively. The GTE-B lamps fall on the expected curve for a lamp loading of 0.1 amps/in^2. The Philips lamps actually show an increase in light output at 1000 hours. This appears to be an experimental error.

Figure 5.3 plots the mortality curve for fluorescent lamps. At the rated life of these lamps 400 hours, 50% of the lamps will have failed. We have operated these lamps for 3000 hours (33.3% of life) and recorded no failures. One lamp did fail after a few hundred hours and an air leak was noted at the seal. This obvious defect was not counted as a failure, and was considered an initial manufacturing defect.

Figure 5.1
LUMEN DEPRECIATION FOR GTE - B LAMP

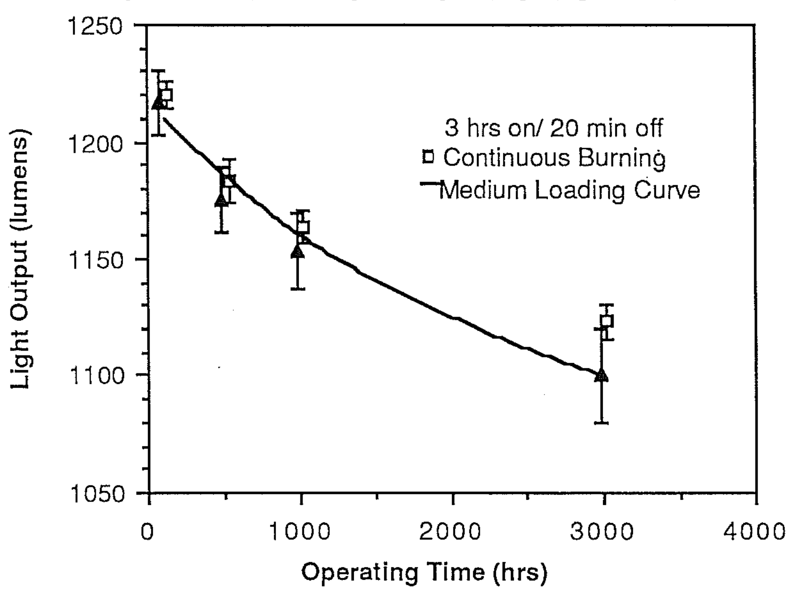


Figure 5.2
LUMEN DEPRECIATION FOR PHILIPS LAMP

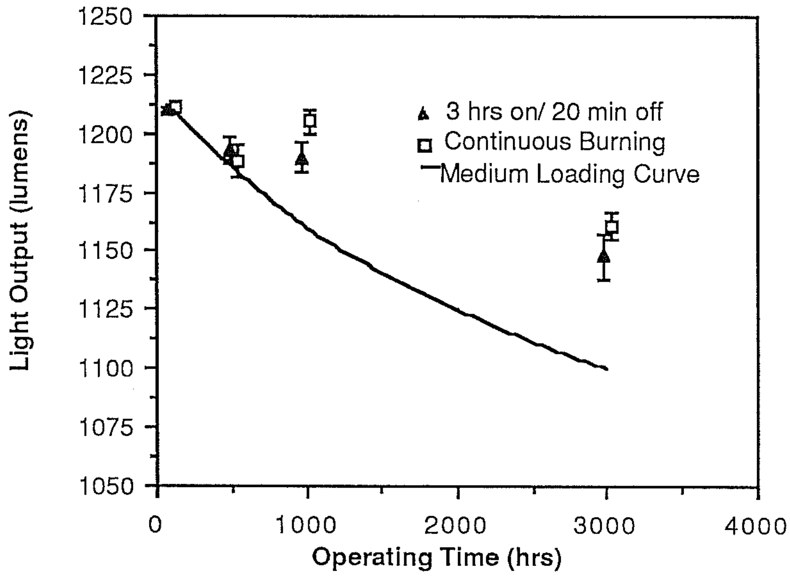
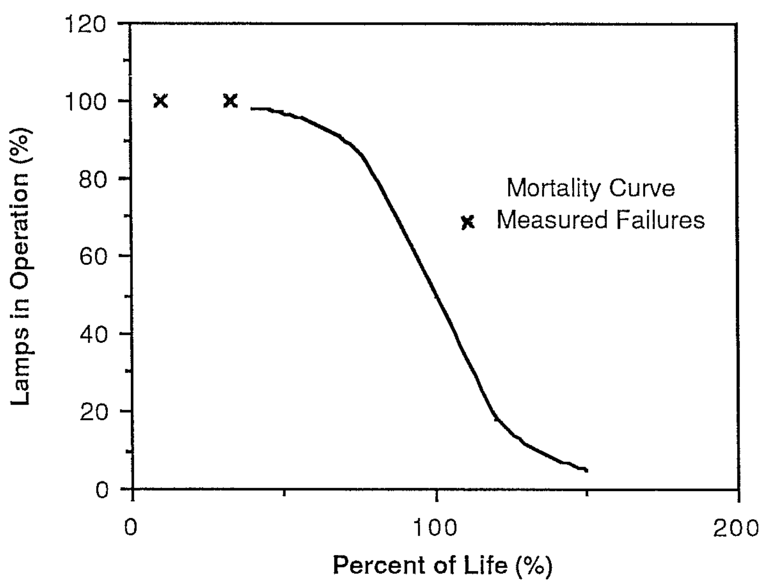


Figure 5.3 LAMP MORTALITY CURVE



6.0 DISCUSSION

6.1 Comparison of Lamps

While both types of lamps meet the Naval requirements it is apparent from the results in section 3.0 that there is a difference in the designs. The Philips is a higher voltage lamp compared to the GTE-B lamp. This results in a higher system efficacy by about 6%. The difference in the performance is speculated to be due to the gas fill. The GTE-B may have Krypton gas and/or a gas at a higher pressure. It should not be difficult for the GTE-B to be made compatible with the Philips lamp.

6.2 Efficacy

Table 6.1 lists the improvements that have been realized by the Phase I and Phase II program.

The power decreased was by a factor of 1.5 and due to the increased power factor the line current decreased by about 2.4 times, compared to the presently used system on board ships. Compared to the F17, T-12 system that is being refitted on a ship there will be a savings of 2 more watts, or a savings of over 10%.

Table 6.1
Lamp Ballast Improvements

	Standard F20 T-12	Eff. Ballast F17 T-12	Adv. ballast F17 T-12	Adv. Ballast F17 T-8
Voltage (V)	118	118	118	118
Current (I)	0.362	0.329	0.176	0.152
Power (W)	25.4	20.8	19.0	17.1
Power Factor	.60	.54	.92	.95
Harmonics (3rd)%	7.7	6.1	2	2.8
Ballast Eff. (%)	.764	.875	.84	.84
Lamp Eff. (lm/W)	63	70	71	78
System Eff. (lm/W)	48.1	61	59	66
Light Output (lm)	1220	1270	1121	1120

The lamp efficacy of the T-8 lamp is 78 lumens per watt, the added features in the advanced ballast design, high power factor and low third harmonic results in a slight decrease in the ballast efficiency 0.875 to 0.84

6.3 Fuel Savings

Referencing the calculation in the Navy Report, *Upgrade Power Circuits and Equipment High Efficiency Ballasts and Fluorescent Lamps,* C51 - 1.011 contract N0024-82-C-2011, April 2, 1986, page 4. The present connected load for 5245 20W lamps on board is:

25.4W x 5245 = 133 kW.

The F17 system reduces this to:

19.0 x 5245 = 100 kW.

the T-8 system will reduce this load to:

17.0 x 5245 = 89 kW.

With a demand of 0.5 the savings:

11 x 0.5 = 5.5 kW.

This is equivalent to:

5.5 kW x 3412 Btu/kWh = 18,800 Btu/h.

Estimates that 75% of the upgrade will be located in air conditioned compartments:

18,800 Btu/h x 0.75 = 14100 Btu/h.

Lower refrigeration will be required of:

$$\frac{14{,}100 \text{ Btu - T/h}}{12{,}000 \text{ Btu/h}} = 1.2 \text{ ton refrigeration.}$$

The 1.2 ton is equivalent to:

1.2 ton 1 kW/2 ton = 0./6 kW.

The total savings is then:

11.0 kW + 0.6 kW = 11.6 kW.

The fuel savings conversion:

$$1 \text{ kw-h} = 1 \text{ lb.}$$

Over a period of 30 years at one half use of share power the fuel savings is:

$$1 \text{ lb/kWh} \times 11.6 \text{ kWh} \times 24 \text{ h/da} \times 365 \text{ da/yr} \times 15 \text{ yr} = 1{,}520{,}000 \text{ lb},$$

as well as saving 1,520,000 kWh on-shore.

Thus, this new T-8 system at virtually the same cost of the ballast and a slight increase in lamp cost would significantly reduce the fuel consumption on board ship.

7.0 CONCLUSION

The T-8 fluorescent lamp advanced ballast system has been shown to meet all of the performance requirements for use on board Naval ships. It can reduce the power consumption for lighting on board ship by over 10% with respect to the new F17 T-12 system and by over 32% with respect to the system currently in use.

The system presents no additional reliability risk and requires a simple fitting at each connection to secure the lamp in the socket.

References

1 R. Verderber, Quality Assurance Assessment of New Efficient Lighting Systems for Naval Ships, LBL Report 18425, pg. 13, (August 1984).