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Measurement of Optical Efficiency of Fluorescent Luminaires

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Abstract

By controlling the lamp wall temperature of fluorescent lamps with a Peltier device, the optical efficiency of luminaires can be measured directly. Measurements of the fixture efficiency for a luminaire can vary by over 8% depending upon the lamp-ballast system used in the measurement. The authors suggest that optical efficiency may be an improved metric for evaluating fixture designs.

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Introduction

This paper describes a technique for measuring the optical efficiency of fluorescent luminaires. Peltier devices are connected to the lamps to maintain them at the same minimum lamp wall temperature (MLWT) that was obtained when the bare lamps were photometered in open air. The fixture and optical efficiency of the luminaires are measured with three different types of lamp-ballast systems, (40-watt F40 T-12, 34-watt F40 T-12, and 32-watt F40 T-8 lamps). Because the laboratory does not have a gonio-photometer to directly determine the lumen output from the fixture, a procedure was developed to estimate the total light flux by measuring the illumination beneath the fixture. The relative measurement allowed us to compare efficiencies of the different lamp-ballast combinations for each luminaire and demonstrate the technique of employing the Peltier device in a laboratory measurement.

Background

The IES approved method for photometric testing of indoor luminaires has been carefully developed to ". . . promote adequate and uniform test methods in determining and reporting the photometric characteristics of indoor fluorescent luminaires. . ."[1] The characteristics permit designers to compare the features of different types of luminaires. Fixture efficiency, one of the parameters used to characterize luminaires, can fail the above goal, since it not only depends upon geometric design and material properties, but upon the type of lamp-ballast system used in the measurement. The problems in obtaining uniform results and lighting designs have been discussed and solutions suggested.[2,3,4] In the past, the problem of uniform results was not significant since only one type of lamp-ballast system (certified ballast manufacture (CBM) ballast and 40-watt F40 T-12 lamps) was in common use. Today, with the large variety of lamps and ballasts that can be used interchangeably, different values for the fixture efficiency for the same luminaire can be obtained.

Experimental

To demonstrate the technique the fixture efficiency and the optical fixture efficiency of typical two- and four-lamp luminaire were measured using 40-watt F40 T-12, 34-watt F40 T12 and 32-watt F40 T-8 lamps operated with core-coil ballasts. Optical efficiency is the ratio of the total light flux from the luminaire divided into the total light flux from the bare lamps with the lamps at the same MLWT. This metric is simply a function of the fixture geometric design and material characteristics, i.e., reflectivity and transmittance. In order to obtain the desired MLWT in the fixture, a Peltier device was used to lower the temperature of a small portion of each lamp surface to the temperature measured when the lamps were measured in open air.

Luminaires

The luminaires are good quality, standard two by four-foot enclosed two- and four-lamp luminaires. The internal finish is baked white enamel of minimum 88 percent reflectivity and an acrylic prismatic lens. The fixture efficiency of the two- and four-lamp fixture are given as 71 and 63 percent, respectively.

Light Output Measurements

Open Air - Measurements of the light output were made for four lamps, each of the three types (40-watt, 34-watt and 32-watt) in an integrating sphere at a 25±1°C room ambient. The sphere and photometer had been calibrated with calibrated fluorescent lamps to convert the lux readings of the photometer to lumens (513.0 lm/lux). Each pair of lamps was operated by a specific CBM magnetic ballast for the 40-watt and 34-watt lamps and ballasts designed specifically to operate the 32-watt T-8 lamps. In the open air measurement the light output of each lamp was measured, while the second lamp of the two-lamp system was positioned outside the integrating sphere. The MLWT of both lamps were recorded, as well as the input power to the two-lamp ballast. In all these measurements, as well as in the fixture, the Peltier device system was attached to each lamp.

Luminaire - Each pair of lamps was placed in the two-lamp luminaires and the illuminance beneath the luminaire was measured at nine positions about one foot apart, Figure 1. The luminaire was positioned in our luminaire test chamber (Figure 1) which was completely surrounded with a black cloth on the sides and on the floor. One measurement was made with the Peltier devices maintaining the same MLWT that was recorded for the lamps in the open air measurements. The power to the Peltier devices was then reversed, the normal MLWT of lamps in the luminaire at the 25±1°C ambient temperature was obtained, and the illumination measured at the nine positions. If power to the Peltier was only turned off, it would define the cold spot since it could disapate more heat. By reversing the DC current, the Peltier device behaved as a heat source, permitting the MLWT to be established at its normal site on the lamp wall. In all of these measurements, both the MLWT's and the input power to the ballast were recorded. The room ambient was held at 25 ± 1°C throughout. The entire series of measurements were repeated with the four-lamp luminaire for the three types of lamp-ballast systems.

Peltier Device Systems

A Peltier device is a semiconductor junction that can be cooled or heated, depending upon the direction of the current across the junction.

The use of a Peltier device to control the MLWT of fluorescent lamps to maintain constant light output has been described.[5,6] The portable device system used in these experiments is shown in Figure 2. The copper block (3/4 or 1/2-inch radius) makes contact with the lamp wall and is soldered (indium solder) to the Peltier device. A 1-

inch by 1-1/2-inch copper plate is soldered to the other side of the device and bolted to a finned aluminum heat sink to dissipate the heat. The copper-glass and copper-aluminum interfaces are coated with a silicone grease to reduce thermal impedance. The entire Peltier system is strapped to the lamp and controlled with a 4-amp DC power supply. The copper block has a slot to insert a thermistor, used to measure the temperature.

Fixture Proportionality Factor (C_f)

The laboratory did not have an instrument to measure the total light flux from the fixture. It was possible to relate the average of the nine illumination measurements to the total light flux for each luminaire by using the manufacturers cited fixture efficiency. That is:

$$E_f\,(40) = \frac{I_t(40) \times C_f}{\varphi_b(40)} \times 100\,(\%) \qquad (1)$$

where E_f (40) is the fixture efficiency for the 40-watt lamps, I_t (40)(fc) is the average illuminance for the luminaire at the normal temperature (t), $\varphi_b(40)$ (lm) is the total flux measured for the 40-watt lamps in open air at temperature b and C_f (lm/fc) the fixture proportionality factor. A different C_f was determined for each luminaire. The C_f converts all the average illumination measurement to total flux (lm). That is, we took the average of the nine illuminance measurements and multiplied it by the fixture proportionality constant. These values are listed in Tables 1 through 4. The use of C_f can be applied if the distribution of the flux is unchanged. To determine the light distribution, the ratios between the nine illuminance measurements were calculated. We found that within one percent the ratios were the same. The distributions measured for the two luminaires were slightly different, as well as their fixture proportionality constant.

In order to use the manufacturers fixture efficiency, we assumed that the 40-watt F40 T-12 lamps were used in their measurements and were at the same MLWT. This would be fortuitous and is of no concern in this study since we are interested in determining the relative change in the fixture and optical efficiencies for each luminaire. Thus, we cannot compare the absolute values of the efficiencies between the two- and four-lamp luminaires. The data could have been presented without converting the illuminance measurements to lumens, however, we felt the use of the normal units would facilitate understanding the calculations and approach the absolute values.

Results

Open Air

Table 1 lists the measured light output (φ_b) and the MLWT of each lamp. In the parenthesis is the MLWT of the lamp that was outside the integrating chamber. Lamps 1 and 2, and 3 and 4, were paired with a ballast. The input power to the two-lamp ballast was also recorded. Both the MLWT and the power are measures of the lamp-ballast operating conditions. It was our aim to control the MLWT to ±1°C and the input power to ±1-watt in the luminaires with the Peltier device, for the determination of the optical efficiency. The light output for the two- and four-lamps are listed in the final two columns. They are the sums of the light output of the individual lamps.

Two-Lamp Luminaires

Table 2 lists the light output from the luminaire with the lamps at the normal MLWT determined by the environment and controlled by the Peltier device system to achieve the same MLWT as measured in open air. The measured MLWT and the input power to the lamps when temperature controlled with the Peltier device in the luminaire met our lamp operations criteria as discussed above. The light output listed in lumens is the product of the measured average illumination times C_f (55.1 lm/fc) for the two-lamp luminaire.

Four-Lamp Luminaires

The results for the three types of lamp ballast systems in the four-lamp luminaire is listed in Table 3. The MLWT temperatures are within one degree of the bare lamp MLWTs and the power (sum of the two, two-lamp systems) is within one watt. The light output listed is the product of the measured average illuminance times C_f. C_f was determined to be 56.1 lm/fc for the four-lamp luminaire with the 40-watt T-12 lamps. In these measurements the outboard pair of lamps had a slightly lower MLWT.

Fixture and Optical Efficiency

Table 4 lists the light output previously listed in Tables 2 and 3. This information was used to calculate the optical efficiency for the three lamp-ballast systems in the two luminaires, and the fixture efficiency in the two luminaires for the 34-watt and 32-watt lamp-ballast system. (The manufacturers measured fixture efficiencies was used for the 40-watt lamp ballast system in order to determine C_f). The optical efficiency for the 40-watt and 34-watt lamp systems are 75.8 ± 0.4% and 78.6 ± 0.4% in the two- and four-lamp luminaires, respectively. The optical efficiency for the 32-watt T-8 lamp-ballast system in the two luminaires shows it is the same as for the T-12 lamps within the precision of the measurement.

The fixture efficiency for each type of luminaire is determined by the type of lamp-ballast system used in the measurement. The values of efficiency depends upon the different MLWT for the lamps in open air and in the luminaire. The large decrease in the fixture efficiency, as compared to the optical efficiency for the four-lamp luminaires, is primarily due to the high MLWT of the lamps in the luminaire.

The increased value for the optical efficiency of the four-lamp luminaire is not real and due to the relative nature of the measurements. The demonstration of the technique assumed the manufacturer measured the fixture efficiency under the same conditions. It is possible that the MLWT of the lamps in this study were at a higher temperature in the luminaire measurement, which could account for the larger value of optical efficiency.

Discussion

Another Determination of Optical Efficiency

If the MLWT of the lamps during the standard photometric measurements are recorded, it is possible to determine the optical efficiency by calculating the thermal factor of the lamp-ballast system used in the luminaire measurements. The relative change in the light output and system efficacy for the three types of lamp-ballast systems employed in this study are shown in Figure 3 (a, b, and c).

Table 5 lists the average MLWT for the lamps in the open air and luminaire measurements. In parenthesis in the MLWT columns is the relative light output obtained from Figure 3 based upon the measured MLWT for each lamp-ballast system. The ratio of the relative light output at the MLWT in the open air and in the luminaires, times the measured fixture efficiency is the optical efficiency. The optical efficiencies determined with this procedure are listed in the last two columns. The results demonstrate the invariance of the optical efficiency and show that the major source of the variance of the fixture efficiency is the change in the MLWT. This method also shows no increase in the optical efficiency for the T-8 lamp-ballast system.

The optical efficiencies determined from the light output - MLWT curves, are about the same as the measured optical efficiencies for the two- and four-lamp luminaires. Although the optical efficiencies measured directly (Table 4) are relative measurements due to the assumptions, there is surprisingly good agreement (within 3 %) between the two methods to attain this parameter.

Peltier Device Control

Previous applications of the Peltier devices have suggested[5,6] its use to control the light output of fluorescent in practice. The present study employs the techniques in the laboratory when testing the performance of fluorescent lamp systems. Its use would be particularly useful in laboratories that desire to make standard ANSI measurements where the ambient temperature cannot be maintained to the standard 25 ± 1°C.

The results in this study show that the Peltier device can suitably control the MLWT of a fluorescent lamp and obtain the appropriate lamp-ballast performance. When this device is used, one must be certain that the device is controlling the lamps performance. The device must cool a suitable lamp area, and one must allow the system to reach equilibrium. Depending upon the manner in which the lamps had been operated previously, the time to reach equilibrium may range from several minutes to hours. To reduce the time to achieve equilibrium, the Peltier device should be held at a temperature several degrees centigrade below the target temperature.

Optical Efficiency Metric

This work has indicated the merits of using the optical efficiency as a standard parameter for evaluating luminaires. The optical efficiency is only a function of the luminaire geometry and material characteristics (reflectivity and transmittance). The fixture efficiency is dependent upon the thermal performance of the lamp-ballast system used in the measurements, and the aim of repeatability of results between laboratory measurements, as well as the ability to compare the performance of different luminaire designs is not realized.

One could argue that the fixture efficiency best reflects a realistic application of the luminaire. However, this prevails only if the luminaire is used in the same environment (ambient temperature, plenum temperature, etc.) and with the same lamp-ballast system. Both the optical and fixture efficiencies are equally troublesome in this aspect and result in design layout errors.

To avoid some of the sources of errors, it would be helpful if photometric reports included; the luminaire optical efficiency and the MLWT of the lamps for various luminaire operating enviroments. For complete information for a lighting layout, the ballast factor and the thermal performance (relative light output vs MLWT, Figure 3) for the lamp-ballast system to be used should be available.

Conclusions

Using a Peltier device to control the MLWT of fluorescent lamps in a luminaire was found to be a useful method to experimentally correct for the thermal factor of lamps in a luminaire system under test and, provided a simple means for determining the luminaires optical efficiency. For the luminaires we tested, the optical efficiency for a given fixture was unchanged within 1% for different lamp ballast systems. The fixture efficiency varied considerably, depending on the lamp-ballast system used. This indicates that optical efficiency is an invariant parameter for a fixture and will help alleviate some of the confusion surrounding the comparison of different luminaire systems. The use of optical efficiency would permit the reproducibility of results. between different laboratories.

We also found that the smaller diameter lamps (T-8) did not improve the optical efficiency of the luminaire we tested in comparison to the T-12 lamps. However, T-8 lamps used in luminaires that focus the light source may show an improved optical efficiency with the smaller diameter lamps.

References

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TABLE 1

Bare Lamp Light Output

Lamp	MLWT (°C)	Power (W)	φ_b (lm) 1-lamp	2-lamp	4-lamp
40W F40, T-12					
1	36.7 (38.7)	92.9	2900	5800	
2	38.8 (37.6)	92.7	2900		11,650
3	36.8 (37.8)	93.4	2930	5850	
4	39.2 (38.1)	92.9	2920		
34W F40, T-12					
1	34.5 (35.7)	79.0	2450	4910	
2	36.7 (35.2)	79.0	2460		9,890
3	34.9 (35.6)	79.2	2490	4980	
4	36.8 (35.1)	78.8	2490		
32W F40, T-8					
1	38.1 (39.4)	69.7	2770	5570	
2	40.2 (38.7)	69.7	2800		11,290
3	38.4 (38.7)	70.5	2820	5720	
4	39.9 (39.1)	70.5	2900		

φ_b - Light flux for open air measurement at bare lamp MLWT.

TABLE 2

Two-Lamp Luminaire Performance

	Lamps at					
	Bare Lamp Temperature			Luminaire Temperature		
Lamps	MLWT (°C)	Power (W)	φ_{lb} (lm)	MLWT (°C)	Power (W)	Light φ_{lt} (lm)
40W F40, T-12						
1 and 2	37.4 (37.5)	93.4	4420	49.3 (49.5)	87.1	4120
3 and 4	38.0 (37.7)	93.8	4460	48.5 (48.8)	87.3	4160
34W F40, T-12						
1 and 2	35.5 (35.4)	77.6	3710	44.9 (44.7)	76.6	3680
3 and 4	35.1 (35.2)	77.7	3740	45.7 (45.8)	76.4	3700
32W F40, T-8						
1 and 2	39.0 (38.1)	68.0	4220	47.4 (47.9)	65.8	4090
3 and 4	38.5 (39.0)	69.2	4350	47.2 (47.4)	66.7	4200

φ_{lb} - Light output from luminaire, lamps at temperature b.

φ_{lt} - Light output from luminaire, lamps at temperature t.

TABLE 3

Four-Lamp Luminaire Performance

	------------ Lamps at			-----------		
	Bare Lamp Temperature			Luminaire Temperature		
Lamps	MLWT (°C)	Power (W)	φ_{lb} (lm)	MLWT (°C)	Power (W)	φ_{lt} (lm)
40W F40, T-12						
1 and 2	36.8 (37.6)	186	9200	59.1 (58.8)	164	7340
3 and 4	36.7 (37.7)			57.5 (56.3)		
34W F40, T-12						
1 and 2	34.4 (35.7)	157	7720	56.6 (57.2)	147	6450
3 and 4	34.4 (35.8)			54.8 (54.6)		
32W F40, T-8						
1 and 2	38.2 (38.8)	142	8890	55.1 (55.5)	127	7710
3 and 4	38.0 (39.5)			55.3 (54.3)		

TABLE 4

Fixture and Optical Efficiency

	Light Output (lm)			Efficiency	
		--- Luminaire ---			
	φ_b	φ_{lb}	φ_{lb}	Optical	Fixture
Two-Lamp Luminaire					
40W F40, T-12					
1 and 2	5800	4420	4120	76.2	71.0
3 and 4	5850	4460	4160	76.2	71.1
34W F40, T-12					
1 and 2	4910	3710	3680	75.6	74.9
3 and 4	4980	3740	3700	75.1	74.3
32W F40, T-8					
1 and 2	5570	4220	4090	75.8	73.4
3 and 4	5720	4350	4200	76.0	73.4
Four-Lamp Luminaire					
40W F40, T-12	11,650	9200	7340	79.0	63.0
34W F40, T-12	9890	7720	6450	78.1	65.2
32W F40, T-8	11,290	8890	7710	78.7	68.3

TABLE 5

Calculation of Optical Efficiency

Lamps	MLWT (°C) Bare Lamp	MLWT (°C) --- Luminaire --- Two-Lamp.	MLWT (°C) --- Luminaire --- Four-Lamp	Optical Efficiency (%) Two-Lamp	Optical Efficiency (%) Four-Lamp
40W F40, T-12	38 (97)	49 (87)	58 (77)	79	79
34W F40, T-12	36 (98)	45 (96)	56 (83)	77	77
32W F40, T-8	39 (98)	48 (92)	55 (86)	78	77

( ) Relative light output from Figure 3.

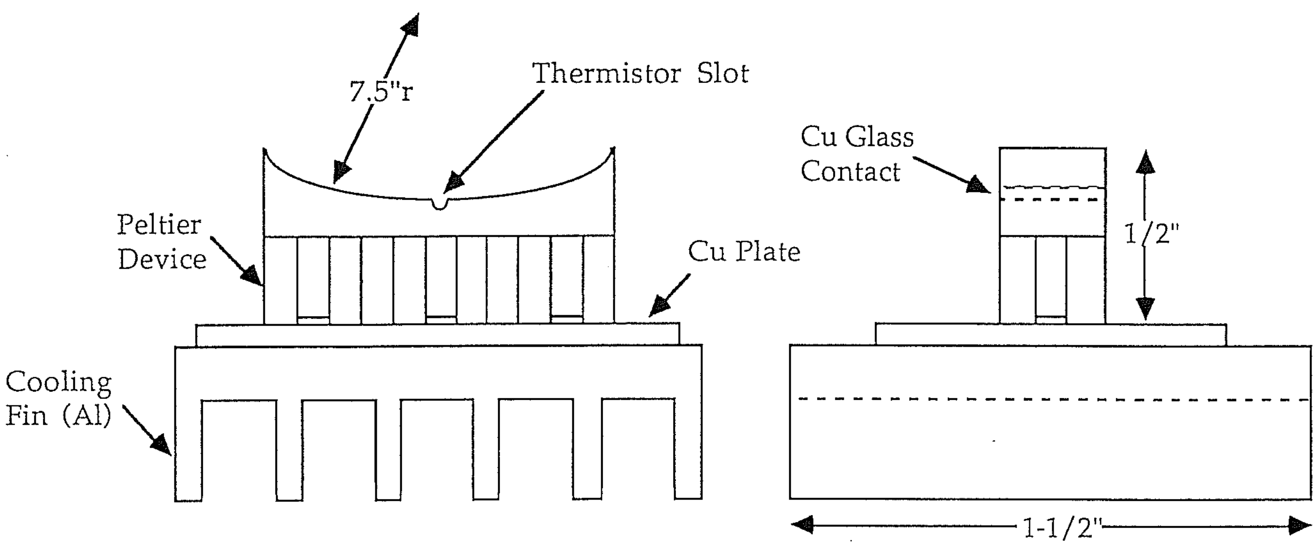


Figure 1. Peltier Device Heating and Cooling System.

Illuminance Test Chamber

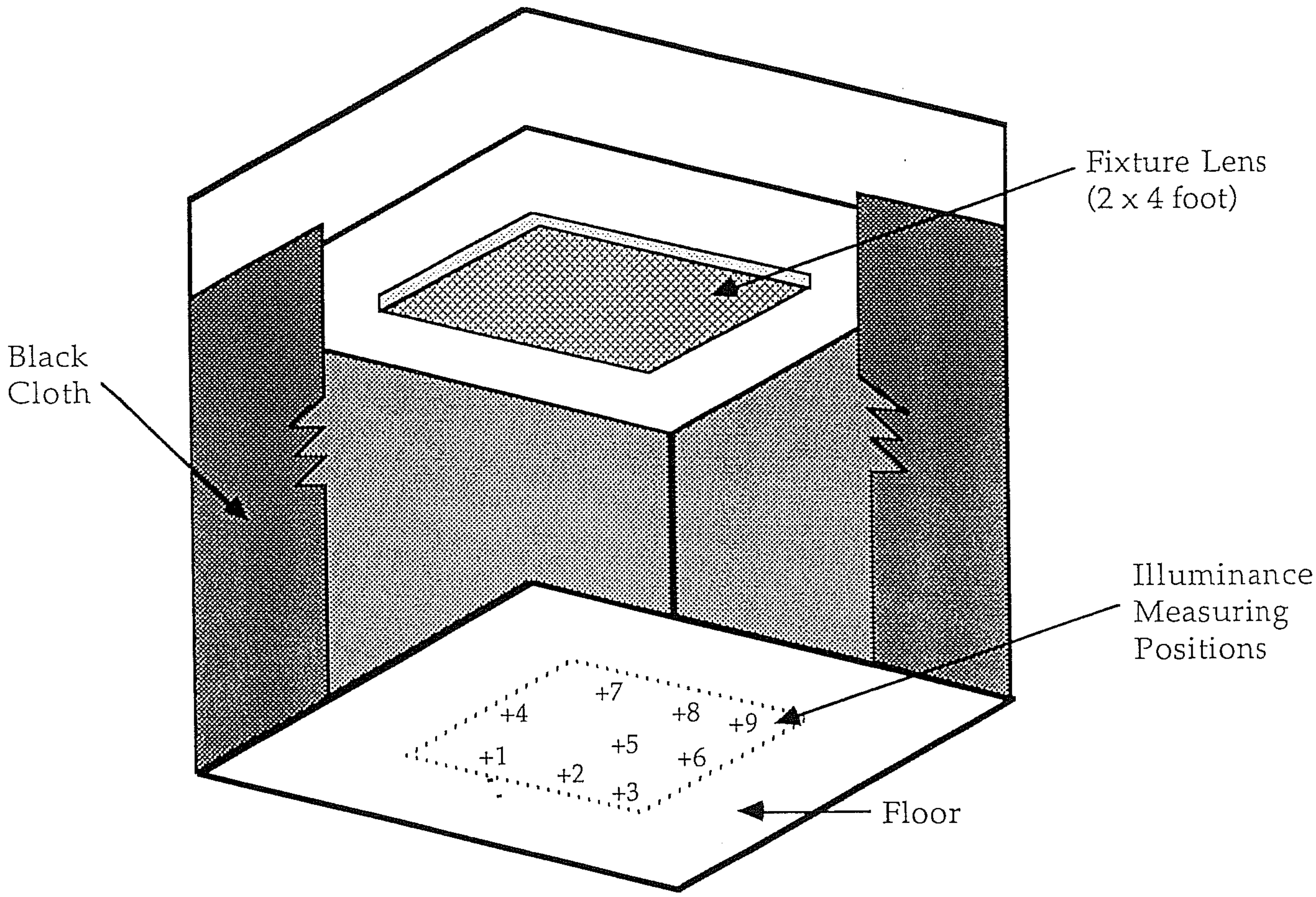
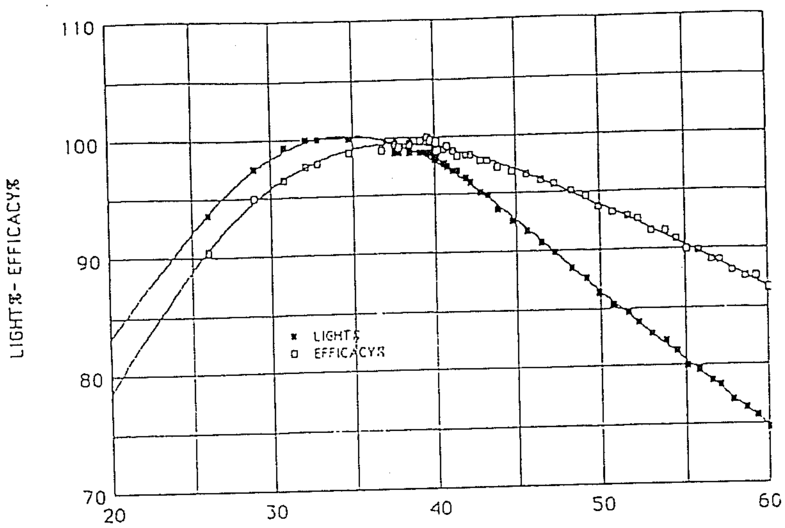
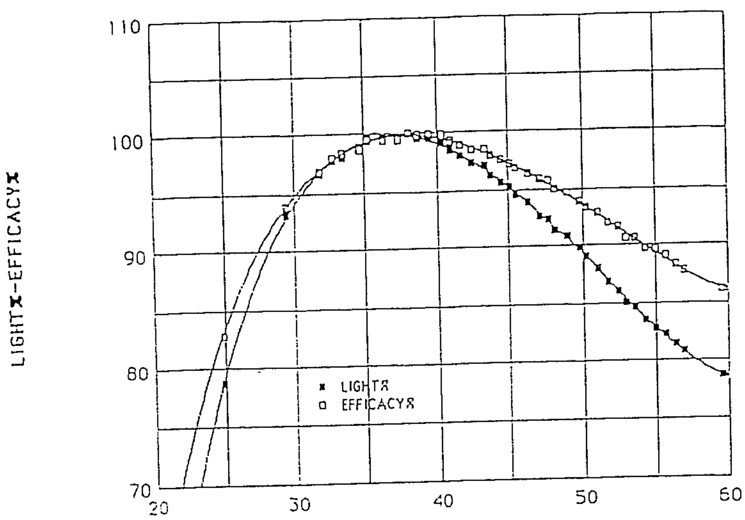


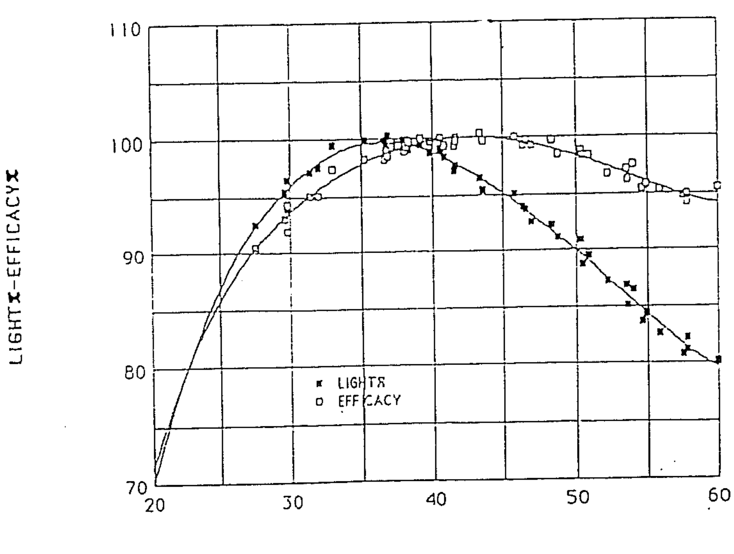
Figure 2. Experimental Arrangement for Luminaire Measurements



a) Standard CBM Ballast - 40-Watt F40 T-12 Lamps



b) Standard CBM Ballast - 34-Watt F40 T-12 Lamps, and



c) Core-Coil Ballast - 32-Watt F40 T-8 Lamps

Figure 3. Thermal Dependence of the Relative Light Output and Efficacy vs. MLWT