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DETERMINING LAMP/BALLAST SYSTEM PERFORMANCE WITH A TEMPERATURE-CONTROLLED INTEGRATING CHAMBER

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ABSTRACT

This paper describes an experimental integrating chamber for measuring the photometric and electrical performance of fluorescent light sources over a wide range of bulb-wall temperatures. The system was used to measure the relative light output and system efficacy of various solid-state ballasted fluorescent lighting systems for minimum bulb-wall temperatures between 20° and $65^{\circ}C$. For lamp-wall temperatures between 30 and $60^{\circ}C$, the relative efficacies of the solid-state ballasted systems were found to be less sensitive to changes in bulb-wall temperatures than standard or efficient (low-loss) core-coil ballasted systems.

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INTRODUCTION

Lighting designers are often faced with the task of furnishing a precise design illumination level while minimizing the electric power required to provide it. To meet these requirements, the temperature and ballast factors, which characterize the light output properties and impact the electrical performance of the fluorescent lighting system, must be considered in the design process [1,2]. In the past, precise lighting design, though rarely required because of higher prevailing light levels, was made easier by the dominance of standard fluorescent lighting components (viz CBM-certified ballasts and standard lamps) whose electrical and photometric properties as a function of temperature were well-standardized and understood [3,4]. Today, many new lighting products are being introduced in response to increased energy costs, and, while serving similar functions as conventional components, may have different capabilities and overall performance. Several reports have been published on the thermal behavior of various energy-efficient lamps operated by efficient core-coil ballasts [1,5]. However, little data has been published on the thermal performance of solid-state ballasted systems even though these ballasts have been shown to operate fluorescent lamps 20-25% more efficaciously than standard core-coil fluorescent ballasts [6,7]. This report is concerned with characterizing the relative light output and system efficacy of various solid-state ballasted fluorescent lighting systems as a function of bulb-wall temperature.

A temperature-controlled integrating chamber was constructed for measuring the photometric and electrical properties of fluorescent lamps driven by various ballasts as a function of minimum lamp-wall temperature. The apparatus permits the air temperature surrounding the lamps to be carefully controlled and varied between 10^o and 60^oC, covering the entire range of most interior lighting applications.

This paper describes the function and operation of the temperature-controlled integrating chamber and presents measurements made on several fluorescent lamp/ballast systems. The temperature-dependencies of two solid-state ballasted systems driving standard F40 and 35-watt lamps are measured for bulb-wall temperatures between 15 and 65^oC and are compared with the performance of standard and low-loss core-coil ballasted systems.

TECHNICAL APPROACH

The temperature-controlled integrating chamber and its associated equipment fulfills two major functions:

1. It permits the ambient air temperature surrounding the lamps to be carefully monitored and controlled between 10 and 60^oC.

2. It permits precise measurement of relative light output, system (lamp and ballast) power input, and minimum bulb-wall temperature.

The minimum bulb-wall temperature is the critical variable in measuring the thermal performance of lamp/ballast systems because the coldspot temperature determines the mercury vapor pressure within the discharge, and therefore the input watts and light output [1].

Description of System

The interrelationships between the major components of the experimental apparatus are shown schematically in Figure 1.

Integrating Chamber. The integrator is an insulated rectangular chamber having an internal volume of 0.68 m^3. Figure 2 shows a) longitudinal and b) transverse cross sections through the integrating chamber, indicating the appropriate scale and major components. Four-foot fluorescent lamps are mounted horizontally and symmetrically within the chamber, as shown. The interior walls of the integrating chamber are coated with a spectrally non-selective photometric sphere paint of 80% reflectivity. The photometric errors normally associated with measuring the luminous flux of lamps in an integrating chamber of non-spherical geometry [8] are minimized by comparing only lamps of similar spatial distributions.

Photometric Instrumentation. Luminous flux is measured by a color-corrected photometer that is protected from detecting direct light from the lamps by a baffle interposed between the lamp ends and the photometer. The photometer head is located in an auxiliary chamber that is thermally isolated from the main chamber (Figure 2). By circulating room air at 25°C (77°F) through the photometer chamber, errors due to the temperature-sensitivity of the silicon-based photometer are eliminated.

Ambient Air Temperature Control. The air temperature within the integrating chamber is controlled by a fan that re-circulates air at a fixed rate through the chamber and passes the air across a heat exchanger located in a second auxiliary chamber, as shown in Figure 2. The amount of heat added or subtracted from the air passing across the heat exchanger can be varied by controlling the temperature of the fluid flowing through the heat exchanger. The use of the air diffuser in conjunction with a low air flow rate reduces stratification within the chamber.

In typical operation, a glycol solution, cooled to 0°C by a 6000-Btu/hr chiller, is circulated through the heat exchanger to bring the initial air temperature within the chamber down to the minimum desired temperature (10°C). The air temperature within the chamber is then gradually raised at any desired rate using a 1000-watt heater to selectively heat the fluid circulating through the heat exchanger.

Ambient Air Temperature Instrumentation. The ambient air temperature is measured by a three-dimensional array of 15 thermistors suspended on monofilaments spanning the length of the integrating chamber. The thermistors are accurate to ± 1°C; the locations of the thermistors are shown in Figure 2.

Minimum Bulb-Wall Temperature. Empirical testing revealed that the minimum bulb-wall temperature consistently occurred along the underside of the lamps near the lamp center. Since the coldspot was found to migrate slightly, the minimum bulb-wall temperature was measured with three thermistors on 30-cm centers attached symmetrically about the lamp center along the bottom of one lamp. These thermistors are accurate to ± $1^{\circ}C$.

Electrical Instrumentation. Input watts for lamps and ballast are measured with a calibrated watt transducer. The input voltage is monitored and held constant at 120 VAC with a voltage stabilizer.

Data-Acquisition System. The photometric, electrical, and temperature data are taken at regular intervals with an automatic data-acquisition system. The system is programmed to provide the necessary current to the thermistor array only during the measurement time to minimize errors due to thermistor self-heating.

System Operation

An initial series of calibration tests was run with a standard CBM ballast and standard lamps in the integrating chamber. The chamber was initially cooled to $10^{\circ}C$; light output and power input measurements were taken for temperature change rates between 2° and $10^{\circ}C/hr$. The thermistor array data showed that at any given time a fairly constant air temperature was maintained around the lamps. The thermistors in the upper row measured temperatures averaging $1^{\circ}C$ higher than the center thermistor row while the lower row averaged $0.5^{\circ}C$ lower. Within each row, the thermistors typically agreed to within about $1^{\circ}C$.

Comparison of the photometric and electrical data for different temperature rates showed little or no differences even at ~~10~~ 20°C/hr. For the tests described below, a temperature rate of 5°C/hr was used.

Lamp/ballast Systems Tested

Eight lamp/ballast combinations were initially selected for testing. (A larger number of advanced lamp/ballast combinations are currently being tested; results will be reported later). The combinations discussed here consist of two lamp types: a 40-watt argon-filled lamp (F40CW) and a 35-watt krypton-filled lamp (F40LW), and four ballast types: 1) a standard CBM coil-core, 2) an efficient (low-loss) core-coil, 3) a high-frequency solid-state dimming ballast, and 4) a high-frequency solid state non-dimming ballast. All tested ballasts were designed for two-lamp operation at 120 VAC input.

Lamps and ballasts were procured through standard commercial channels; individual ballasts and lamps were selected from these samples for testing. The components selected for testing displayed typical values but the small sample size precludes a statistically significant analysis. The fluorescent lamps used in these tests were aged for 1000 hours.

Analysis of Data

Relative light output (RLO) for each lamp/ballast combination tested is expressed as a percentage of the light output of either the 40 or the 35-watt lamps with the standard core-coil ballast at standard photometric conditions (i.e. 25°C). This is described by the following relationship:

$$\text{RLO} = \frac{\text{light output (test lamp/ballast, variable temperature)}}{\text{light output (test lamp/CBM ballast @ }25^{\circ}\text{C)}} \times 100$$

Relative efficacy for the range of lamp/ballast combinations tested is also expressed in terms of a percent of the performance achieved with a standard core ballast at standard photometric conditions. This is described by the following relationship:

$$\text{Relative efficacy} = \frac{\frac{\text{light output}}{\text{system Power}}\ \text{(test lamp/ballast, variable temperature)}}{\frac{\text{light output}}{\text{system power}}\ \text{(test lamp/CBMballast @ }25^{\circ}\text{C)}} \times 100$$

RESULTS

Figure 3 shows the change in relative light output as a function of lamp-wall temperature for two F40CW lamps operated with the four test ballasts. Light output is expressed as a percentage of the light output obtained when the lamps are operated in a 25°C ambient temperature by the standard core-coil ballast. For all ballasts tested, the lamps reach maximum light output between 35 and 37°C minimum lamp-wall temperature. At this temperature, there is an 8% difference in light output between the ballast providing highest output (low-loss core-coil) and the ballast with the lowest outout (non-dimmable high-frequency). Increased lamp-wall temperatures produced similar relative changes in light output for all the ballasts tested, with light output dropping to 90% of maximum at 50°C lamp-wall temperature.

Changes in efficacy as a function of minimum lamp-wall temperature are shown in Figure 4 for the same lamps and ballasts. Efficacy is expressed as a percentage of the efficacy obtained when the lamps are operated at reference air temperature (25°C) by the standard core-coil ballast. The data show that lamp-wall temperature has a less pronounced effect on efficacy than it does on light output. Nonetheless, there are noticeable differences in performance as a result of using different ballasts. The non-dimmable high-frequency ballast was at least 10% more efficacious than any other ballast (20% relative to the standard core-coil) for lamp-wall temperatures above 35°C. The dimmable high-frequency ballast was less efficacious than the low-loss core-coil ballast for bulb-wall temperatures below 50°C but was more efficacious at higher temperatures. Both high-frequency ballasts provided maximum efficacies at lamp-wall temperatures roughly 5°C warmer than the core-coil ballasts. In addition, for a lamp-wall temperature range between 30 and 60°C, the relative efficacies of the high-frequency ballasts were less sensitive to changes in lamp-wall temperature than were the core-coil ballasts.

Figure 5 shows the effect of minimum lamp-wall temperature on the relative light output of two 35-watt lamps operated with the same four ballasts described previously. Light output is expressed as a percentage of the light output obtained when the same 35-watt lamps are operated in a 25°C ambient temperature by the standard core-coil ballast. All the ballasts tested provided peak light output when the lamp-wall temperature reached 38-39°C, which corresponds to an ambient temperature of 31°C. (For the 35-watt lamps, the air temperature was typically 7°C cooler than the coldspot temperature regardless of ballast type, while for the 40-watt lamps a 10°C differential was typical (see Figure 7)). The light output of the 35-watt lamp was found to be less sensitive to changes in ballast type than was the F40 lamp; the ballast providing highest output (dimmable high-frequency) provided only 4% more light than the ballast providing least light output (non-dimming high-frequency). Regardless of ballast type, the lumen output of the 35-watt lamps was more severely affected by lamp wall temperatures below 35°C than were the 40-watt lamps.

Relative changes in efficacy as a function of minimum lamp-wall temperature are shown in Figure 6 for the same 35-watt lamps and ballasts. Efficacy is plotted as a percentage of the efficacy obtained when the 35-watt lamps are operated at reference ambient temperature (25°C) by the standard core-coil ballast. As with the F40 lamps, one finds that lamp-wall temperature has a less pronounced effect on efficacy than it does on light output. With 35-watt lamps, however, the relative efficacy for both high-frequency ballasts exceeded the efficacies achieved with the standard and low-loss core-coil ballasts for the entire temperature range. At slightly elevated lamp-wall temperatures (40-45°C), the non-dimmable high-frequency ballast was at least 25% more efficacious than the standard core-coil ballast and 15% more efficacious than the low-loss core-coil ballast. The relative efficacy for the dimming high-frequency ballast only slightly exceeded that of the low-loss core-coil ballast at 40°C lamp-wall temperature, but it was more efficacious at all other temperatures.

Figures 4 and 6 indicate that the efficacy of lamps driven by the high-frequency ballasts were less sensitive to changes in bulb-wall temperature than are the efficacies of lamps driven by the core-coil ballasts. To better quantify this effect, we examined the difference between the maximum and minimum relative efficacies of each lamp/ballast system within a specific bulb-wall temperature range using the expression below:

$$\frac{RE_{max} - RE_{min}}{(RE_{max} + RE_{min})/2} \times 100\% = \text{Efficacy variability}$$

Because the difference between the maximum and minimum efficacies is normalized in the above metric, one can directly compare the efficacy variability of the different lamp/ballast systems for a specified bulb-wall temperature range. A bulb-wall temperature range of 30-60°C was selected for this analysis because it encompasses the vast majority of applications for interior fluorescent lighting systems. Table 1 shows the efficacy variability for the eight lamp/ballast systems examined. Using this metric, it is clear that in this temperature range the efficacy variability for both high-frequency ballasts is smaller than for the core-coil ballasts. The data in Table 1 also indicate that standard F40 lamps are somewhat less susceptible to temperature-driven efficacy changes than are 35-watt lamps regardless of ballast type.

When analyzing the performance of a particular lamp/ballast system as a function of temperature, it is often useful to know the relationship between the temperature of the air surrounding the lamps and the minimum bulb-wall temperature. Minimum lamp-wall temperature as a function of ambient air temperature is shown in Figure 7 for the 35- and 40-watt lamps operated by the standard core-coil ballast. This graph shows that the relationship between ambient air temperature and minimum bulb-wall temperature is essentially linear for both lamp types tested but that at 25°C air temperature the bulb-wall temperature of the 35-watt lamp is 3 °C cooler than the 40-watt lamp.

DISCUSSION

The energy implications of using a particular lamp/ballast system can be understood only if system efficacy is considered along with relative light output. This is clearly illustrated in Figures 3 and 4, in which the relative light output of the non-dimmable high-frequency system was lower than for the other ballasts examined (i.e., the high-frequency ballast has a lower ballast factor), yet it provides this (reduced) light output much more efficaciously than the systems tested. From an applications standpoint, retrofitting these non-dimmable high-frequency ballasts in an over-lit installation would be a good energy-saving option because the resulting reduced light levels might be acceptable or desirable. On the other hand, in an installation where light levels cannot be significantly reduced, either the low-loss or the dimming high-frequency ballast would better improve system efficacy because these ballasts do not appreciably reduce light output. For new construction, different considerations apply; under these circumstances it might be advantageous to employ ballasts having a high ballast factor because this will reduce the the number of luminaires required to meet the illuminance criterion, thus reducing first costs.

This work also shows the importance of including temperature effects in designing lighting layouts and specifying lighting equipment. This is most clearly demonstrated by comparing the relative efficacy of the low-loss core-coil and the dimming high-frequency ballast shown in

Figure 4. Although the low-loss ballast provides both higher lamp output and greater efficacy near standard photometric conditions, at bulb-wall temperatures of 55°C (commonly found in 4-lamp troffers and 2-lamp wrap-around fixtures), the high-frequency ballast supplies the same light output with greater efficacy.

Using the integrator to create ambient temperatures below as well as above standard photometric temperature (25°C) increases our understanding of the performance of fluorescent lighting systems at colder temperatures. This is particularly important in energy-efficient buildings and luminaires that can provide cooler lamp environments than traditionally encountered. In this regard, the data would tend to caution against using 35-watt lamps in applications where the bulb-wall temperature is cooler, i.e. 22°-32°C, corresponding to ambient temperatures of roughly 15°-25°C, because of the degradation of light output.

Although the lamp/ballast systems tested above represent only a small subset of the possible combinations, the results demonstrate the usefulness of the temperature-controlled integrating chamber as a tool for generating precise light output and electrical performance data on lamp/ballast systems over a wide temperature range. While we did not attempt to minimize the time required to test each lamp/ballast combination, we believe that, with a streamlined test procedure, each combination could be tested in two hours. The actual number of man-hours required for each test would be less, though, because the data collection process is essentially automatic.

To fully understand the combined performance capabilities of advanced lamp/ballast/luminaire systems, future research efforts will be directed at measuring the lamp-wall temperatures obtained in the luminaire under variable application conditions.

CONCLUSION

A precise and relatively rapid technique has been developed to measure the total light output and electrical properties of various lamp/ballast systems over a wide temperature range. The performance results obtained with the temperature-controlled integrating chamber underscore the importance of understanding how changes in ballast type and bulb-wall temperature affect the lumen output and efficacy of the lamp/ballast system. For a lamp-wall temperature between 30 and 60°C, the high-frequency ballasted systems showed less sensitivity to changes in lamp-wall temperatures than did the core-coil ballasted systems. The differences in performance of the lamp/ballast systems tested here clearly indicate that specific illuminance requirements will be met only if the lighting designer includes the effect of temperature and ballast factor in the calculations.

ACKNOWLEDGEMENT

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TABLE 1

EFFICACY VARIABILITY FOR BULB-WALL TEMPERATURE BETWEEN 30 AND 60°C

	40-watt F40 Lamps	35-watt F40 Lamps
Standard Core-Coil	10.0	14.0
Low-Loss Core-Coil	10.6	15.2
Dimmable High-Frequency	6.0	7.8
Non-Dimming High-Frequency	6.2	11.6

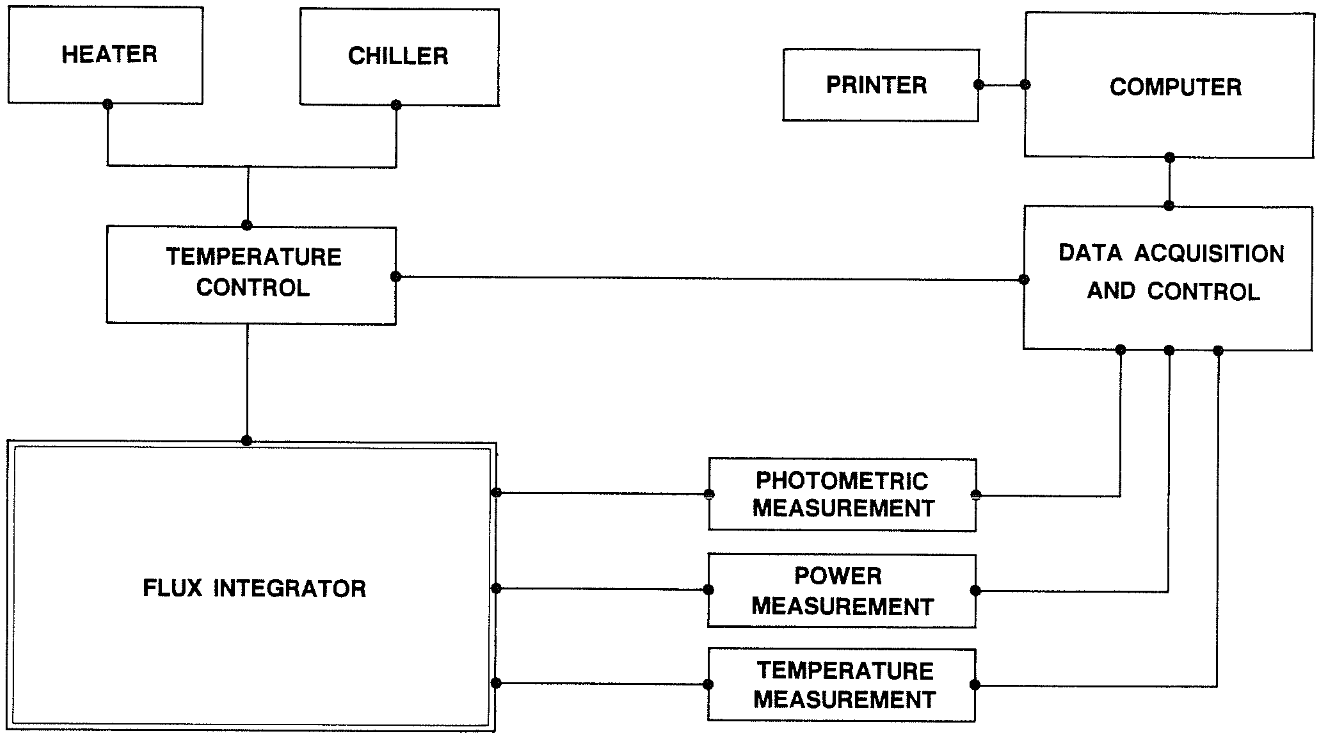

FIGURE 1: Schematic illustration of the major components of the temperature-controlled integrating chamber.

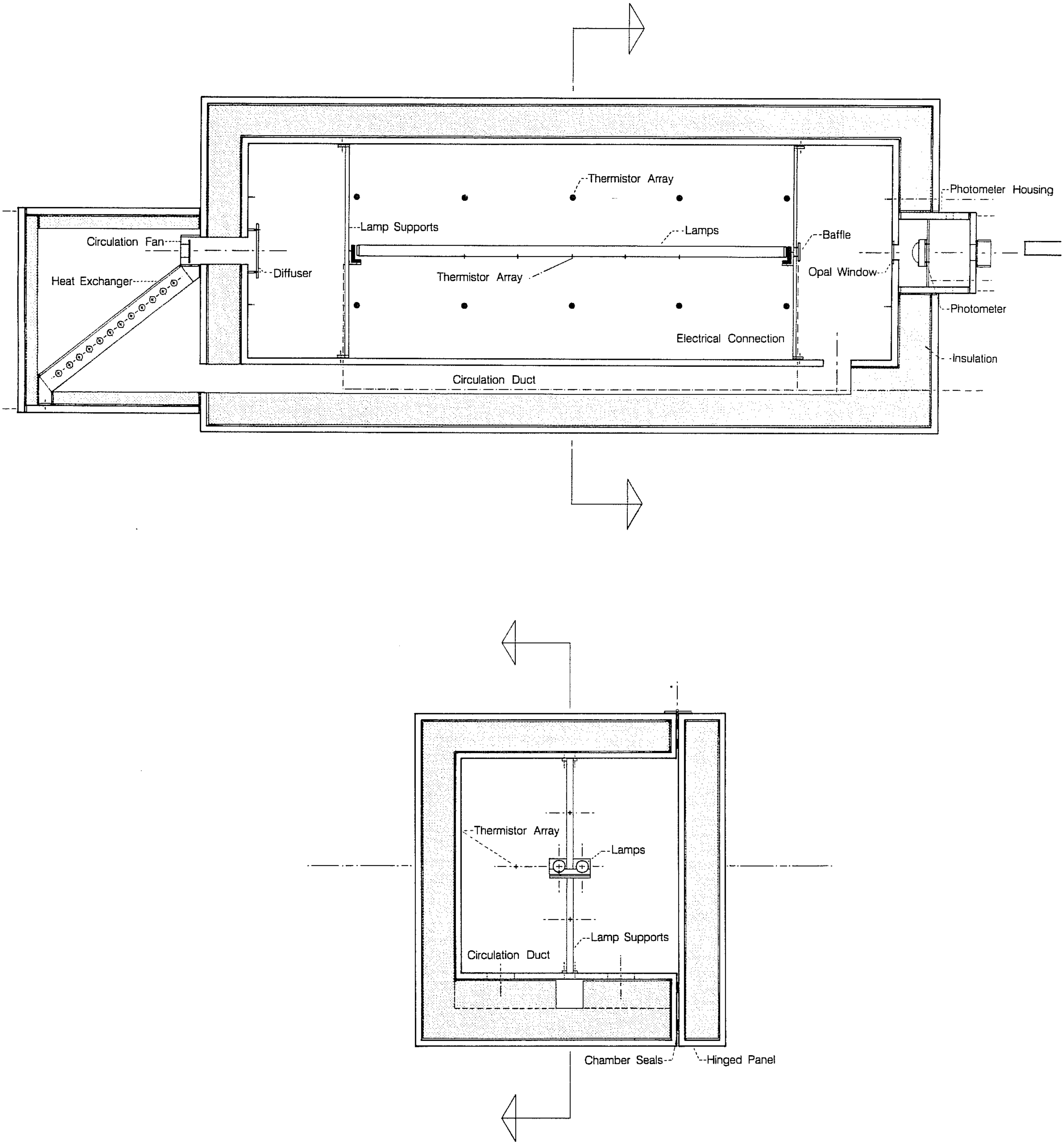

FIGURE 2: A longitudinal and transverse cross section of the integrating chamber.

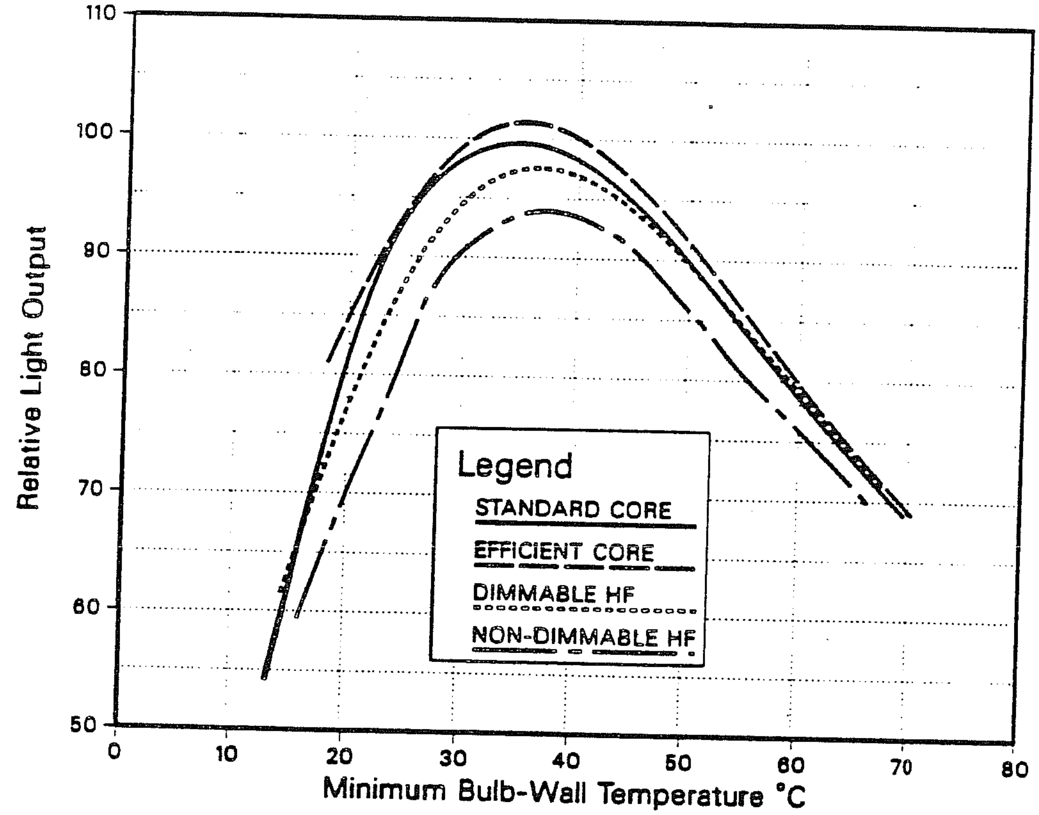

FIGURE 3: Relative light output vs. minimum lamp-wall temperature for 40-watt lamps operated by four different ballasts.

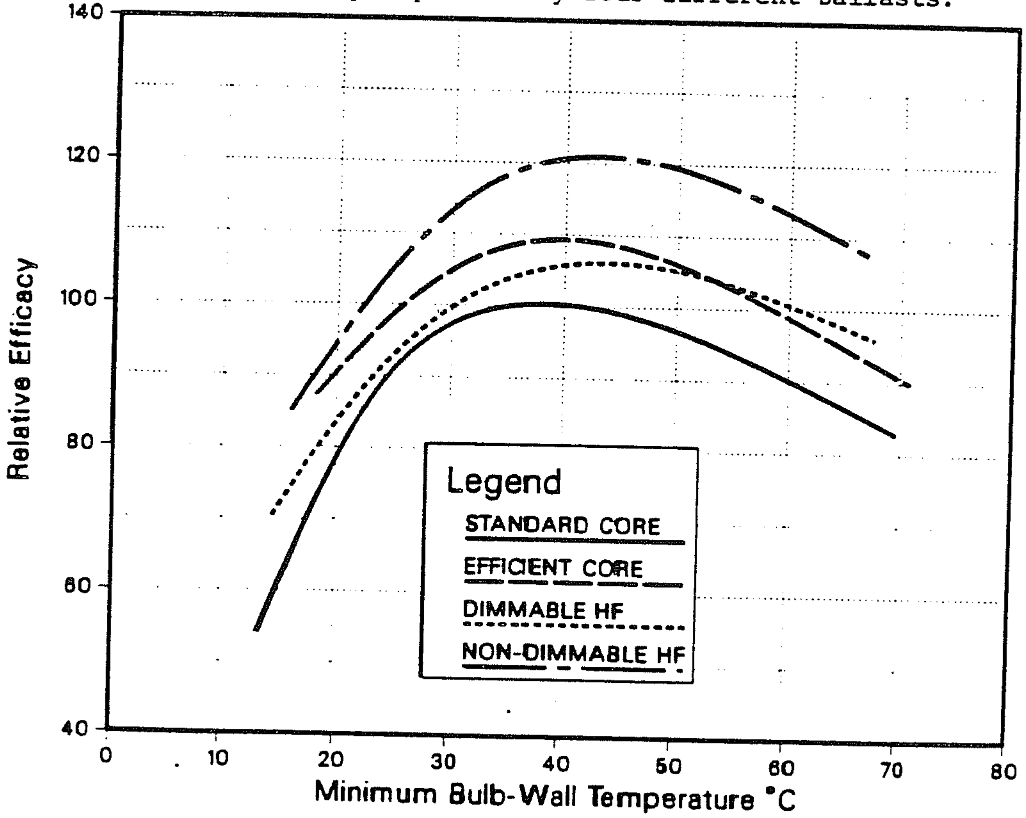

FIGURE 4: Relative efficacy vs. minimum lamp-wall temperature for 40-watt lamps operated by four different ballasts.

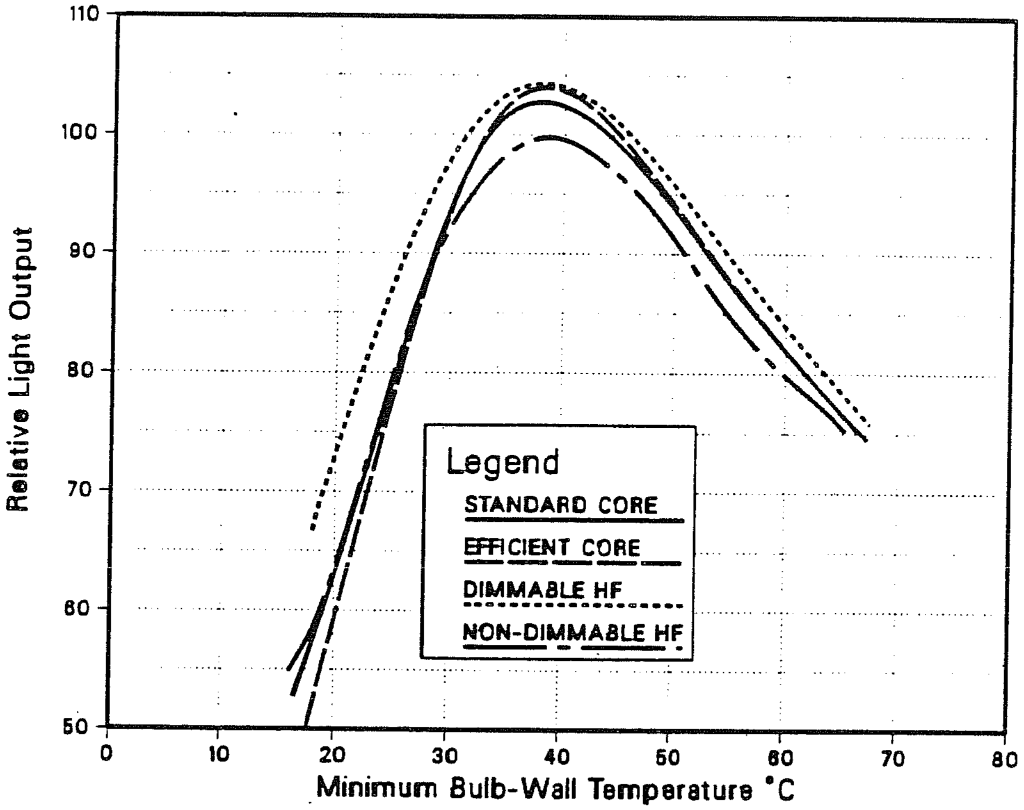

FIGURE 5: Relative light output vs. minimum lamp-wall temperature for 35-watt lamps operated by four different ballasts.

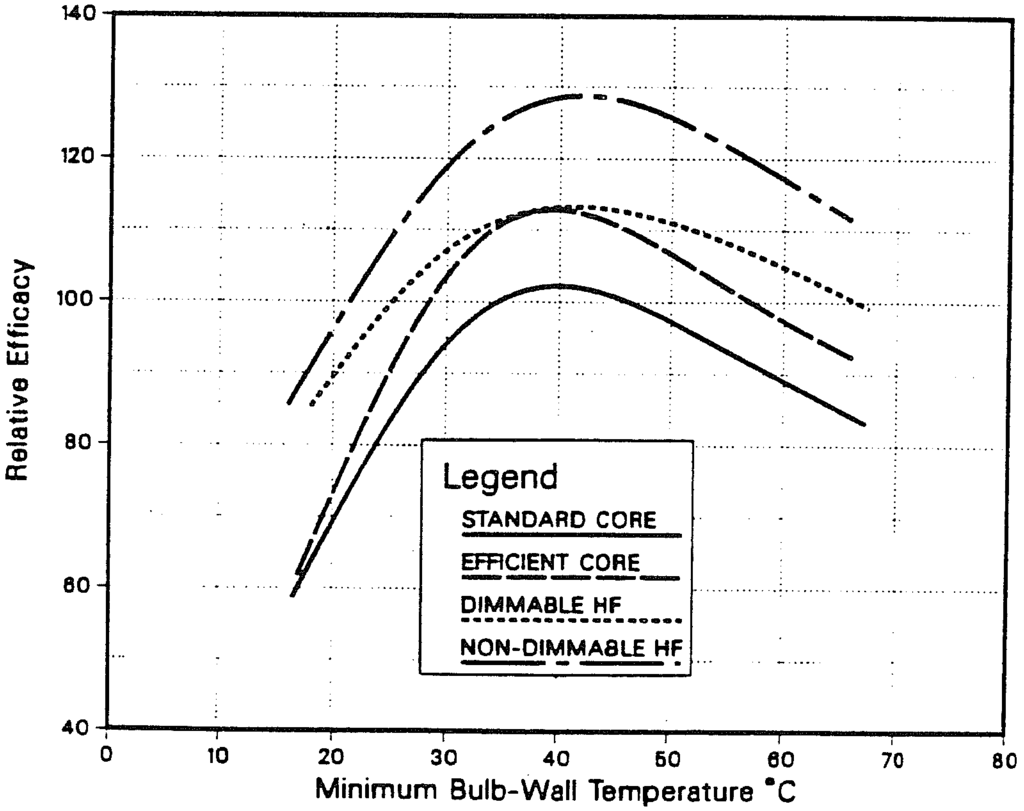

FIGURE 6: Relative efficacy vs. minimum lamp-wall temperature for 35-watt lamps operated by four different ballasts.

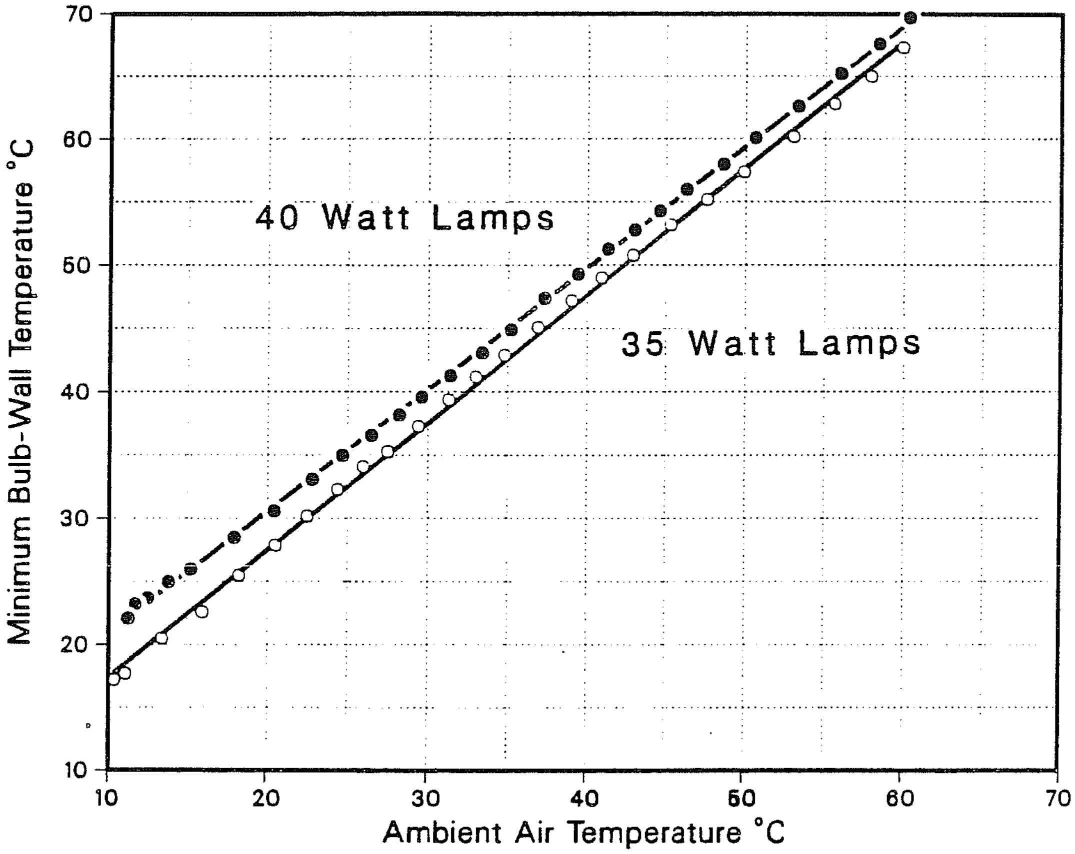

FIGURE 7: Minimum lamp-wall temperature versus ambient air temperature for 35- and 40-watt lamps operated by standard core-coil ballast.