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Lighting System Design and Evaluation in Federal Office Buildings

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Abstract

This report describes the results from a research project on developing methods for designing and selecting efficient and effective lighting systems for federal office buildings. It includes a review of current GSA and IES lighting design guidelines and a discussion of relevant testing and rating procedures. A comprehensive procedure for measuring and evaluating lighting components and systems was developed and used to assess the performance of a range of typical office lighting equipment. This procedure accounted for interactions between different components of a lighting system. The measurement results showed a wide range of performance characteristics related to light output and energy efficiency. The T-8 triphosphor lamps and electronic ballasts exhibited the best performance, but some of the more traditional lighting system components also performed well.

Keywords: Ballast; building technology; energy efficiency; fixture; lamp; lighting; luminaire; luminous efficacy; testing procedures.

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Disclaimer

Commercial products and trade names are provided in this report to adequately describe the procedures and equipment used and do not constitute an endorsement or recommendation by the National Institute of Standards and Technology or the General Services Administration.

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1. Introduction

Successful lighting of building interiors is an essential element in the design and operation of effective and efficient building spaces. The links between illumination conditions and occupant productivity and acceptance are myriad. The critical issue which must be faced by building designers and operators is how to provide desirable illumination conditions in an energy efficient manner. The solution to this question is complicated by the nature of lighting system performance and the fact that lighting systems are composed of several components. The interactions among the lighting system components, as well as the interactions among the lighting system, the building, and its occupants all strongly influence lighting system performance. Parameters not directly connected to lighting can create conditions which will favor one type of lighting system over another. These factors include the design of the air handling systems, the presence of plenums in the building spaces, the type of furnishings, and the room layout.

Recently, considerable attention has been focused on lighting and its contribution to the energy use within a building. The demand for more energy efficient lighting is expected to increase in future years with impetus from new state and federal regulations, energy rebates, and other incentive programs.

Achieving the objective of increased lighting efficiency is not as straight-forward as simply replacing one lamp with another. Office lighting systems are typically comprised of lamps (often fluorescent), ballasts, and optics located in a luminaire within a room. Light produced by these systems of luminaires is determined by power input to the lamp and ballast, and by electrical interactions, ballast/lamp interactions (Lewin, 1983; Siminovitch, 1989), lamp temperature (influenced by luminaire configuration and room temperature), luminaire optics, lamp location, lamp and luminaire output depreciation (due to age and dirt), surface reflectances (including luminaire, ceiling, walls, furniture, and even floors), etc. All evaluations of "lighting efficiency" must consider the effects of each component and its interaction with all other components in the system, including the room itself. Many lighting designs for more energy efficient lighting have been less successful than desired, because of failure to consider some of the complex interactions in lighting (Rubin, 1990).

In fact, the General Services Administration (GSA) has not had particularly successful experience with "energy efficient" lighting. For example, lighting designed for 2 watts/ft^2 (21.5 W/m^2) or less has resulted in numerous user complaints about unacceptable lighting, as well as measured illuminance levels well below current IES recommendations for office lighting (Ramsby, 1987). Although the design is intended to provide at least 538 lux (50 fc) on the work plane with appropriate hardware, field reports suggest that this illuminance level is rarely achieved. In addition, the use of systems furniture with fixed task lighting has also created unsatisfactory lighting for many office tasks with illuminance levels again well below current recommendations once the furniture is installed.

These experiences suggest that the existing standards, criteria, test methods, and guidelines for lighting design in GSA facilities do not appear to be adequate or effective. As a result, there is a need for accurate information on the performance of specific lighting systems and components as well as revisions to the lighting design guidelines for federal office buildings (Treado, 1991). There is also a need for detailed information on selecting and using energy efficient sources, luminaires, ballasts, and relevant office furnishings to maximize energy efficiency without sacrificing user acceptance and productivity. Finally, there is a need to develop predication procedures for accurately predicting task illuminances, surround luminances, and glare likelihood for all types of offices including those with systems furniture.

The present project was intended to determine the effectiveness of current lighting design specifications used by GSA and others; to evaluate energy-efficient lighting components and systems; and to provide an assessment for GSA to determine specific lighting component and system performance.

This report describes important aspects of lighting system performance and considerations for evaluating and selecting lighting systems. Section 2 includes a review of current GSA and IES lighting design guidelines for various applications. Section 3 discusses current test procedures used to evaluate lighting components, while Section 4 describes a more detailed, comprehensive procedure for determining lighting system performance. Section 5 lists the results of the measurements of the performance of various lighting components and systems, including those typically encountered and newly developed, high-efficiency systems. The implications of the evaluation procedures and results on lighting system design are discussed.

2. Review of GSA and IES Lighting Design Guidelines

2.1 Lighting System Characteristics

The purpose of lighting systems in buildings is to provide proper luminous conditions within building spaces. These conditions include adequate levels of illumination on working surfaces, relatively uniform surface luminances to avoid dark spots, and freedom from glare. There exists a multitude of ways to achieve the desired luminous conditions, including various lamp, ballast and fixture types, along with room and lighting system layout alternatives. Selecting and specifying a lighting system requires consideration of both the characteristics of the lighting system itself, and the requirements of the building occupants.

It is inevitable that the selection of a lighting system will involve some trade-offs, usually among cost, energy usage, and the quality of the illumination. For example, if energy usage were the only consideration, an unshielded low-pressure sodium lamp would be the obvious choice, due to its high luminous efficacy (lumens per watt). However, the glare produced by the unshielded lamp, and the monochromatic nature of the yellow light would be unacceptable for most building interior lighting applications. In general those features of a lighting system which enhance the quality of the illumination conditions, such as glare control, color and light distribution, tend to reduce energy efficiency to some extent. That is the nature of the compromise in lighting system design.

The list of lighting system performance characteristics contains a number of items related to luminous conditions, energy factors and visual performance, as shown in Table 1.

Table 1. Lighting System Performance Characteristics

1. Light output (lumens) and distribution
2. Electrical power input (watts)
3. Luminous efficacy (lumens/watt)
4. Color (Color Rendering Index, color temperature)
5. Glare
6. Life
7. Maintenance
8. Power quality (power factor, harmonic distortion)
9. Flicker

Each lighting system has a unique set of performance characteristics, so the comparison of different lighting systems involves a multi-faceted outlook and approach which considers the needs of the building occupants and the constraints on the design. Such constraints might include limits on first cost of the lighting system, minimum energy efficiency, or special color requirements.

One of the notable features of lighting systems is that they consist of a collection of components, including lamp, ballast, fixture and controls. Many times these components are produced independently and subsequently assembled into a lighting system by the designer or builder. Thus, there are a large number of potential lighting system component combinations, which are in a constant state of change as products enter and leave the marketplace. This feature of lighting systems complicates the evaluation and comparison of different lighting systems.

2.2 GSA Guidelines

PBS P 3430.1A (Feb, 1990) contains detailed specifications for electrical systems, including lighting, in GSA facilities. It refers readers to the IES Illumination Engineering Handbook[1] (1987) for specific details on lighting. The 1990 IES guidelines are currently being updated with extensive new information being provided. The provisions contained in the 02/22/91 draft are summarized below. Suggestions for modifying the revisions and comments are given in brackets following the guideline information.

Unlike the earlier guidelines, the suggested revisions provide **Specific Illumination Levels** for different types of spaces. Most offices, automated data processing (ADP), and training areas are to be lit to 538 lux[2] (50 fc), conferences rooms to 323 lux (30 fc), and internal corridors and auditoria to 215 lux (20 fc). Public areas and support spaces are to be lit to 215 lux (20 fc) (except maintenance areas which require 50 fc or 538 lux). Lighting levels for specialty areas range from 53.8 lux (5 fc) for general parking to 538 lux (50 fc) for kitchens, daycare centers, and physical fitness space. It should be pointed out that the latest version of the IES Handbook (1987) does not provide specific illuminance levels for a space. Rather, it lists a range of illuminance values for use with specific tasks. The illuminance selection procedure which is used to determine these values will be described later.

The proposed GSA revisions state explicitly that **Interior Lighting Sources** should be fluorescent, with compact fluorescent for

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1 The IESNA is currently in the process of revising the 1987 Handbook, with a new edition expected in 1993. These provisions may be modified somewhat in the new Handbook.

2 The conversion from footcandles to lux is 10.76.

downlights and HID sources for high bay lighting. Fluorescent lamps should have a color rendering index of 82 with a color temperature of 3500 K. [No provision is made in the proposed GSA guidelines for color rendering indices (CRI) greater than 82, even though they would provide better color in the space, or for warmer color temperatures for special applications such as restrooms, where more similarity to incandescent lamps might be desired.] The 1991 revisions allow incandescent lighting for dimming applications and for special architectural effects. [As yet they made no provision for metal halide lamps in office spaces, although such sources may be somewhat more efficient.]

The revisions provide for standard commercial **Fixtures**, either louvered parabolic for environments where personal computers are used, or acrylic prismatic lenses. Such lenses must be 0.125 in. (3.2 mm) thick. GSA defines the standard fixture as a 2 ft. by 2 ft. (.6m x .6m) louvered parabolic, with louvers 3-4 in. (76.2-102mm) deep. [No guidance is given on using fixtures for glare control, luminance ratios, or veiling reflections. No guidance is given on calculation methods and computational procedures either, with no mention that such information is available in the IES Handbook.]

Ballasts should be energy efficient and meet UL Class P requirements. They should have automatic reset thermal protectors and a sound rating. The revisions allow core and solid-state ballasts if illumination levels and power requirements are met.

The 1991 IES revisions describe different types of lighting for different spaces. For **Office Lighting**, they recommend generally direct fluorescent lighting, although indirect or a combined direct/indirect lighting system could be used for open plan offices. They recommend a uniform layout which provides uniform levels of illumination for ease in rearranging offices spaces. They also suggest modular or plug-in fluorescent lighting for office areas. Finally, they note that modifications must be made to the coefficient of utilization (CU) for open office areas with high partitions to take into account obstruction and reflectance of partitions. [The revisions do not explain how to make these modifications to the CU to account for obstructions - a non-trivial task.] Task lighting is recommended only where the uniform level is not sufficient for the specific task. [No guidelines are given for deciding on the type or amount of task lighting, or for when it should be used. No information is given on the use of task/ambient lighting designs for systems furniture, either.]

Lighting for **ADP** areas should be the same as for offices, although the use of dimmable incandescent lamps is suggested if there are special work stations for computer graphics. Combined fluorescent and dimmable incandescent lighting is suggested for conference facilities and training rooms. [Dimmable fluorescent lighting would appear to be another viable option that could be considered depending on the illuminance level desired.]

The revisions suggest the use of **Special** lighting design concepts for lobbies, atria, tunnels and public corridors. These concepts should be an extension of the building architecture, and may include the use of wall fixtures or combinations of wall and ceiling fixtures. For toilets and locker rooms, the guidelines suggest the use of indirect or down lighting. [No specifications are given for the type of lamp to be used or the possibility of occupancy sensors to turn off the lighting when the room is not in use.]

Industrial type fluorescent luminaires should be used for equipment rooms or closets with care taken that tall pieces of equipment do not obstruct the lighting. High bay lighting (above 4.8m or 16 ft) should be high pressure sodium, non-color corrected, with metal halide reserved for applications that require better color rendering. Daylight is suggested for use in dining areas, although incandescent or a combination of incandescent and fluorescent downlighting may be used as a supplement. [No guidelines are given on procedures for combining daylight with electric lighting or for using automatic dimming systems, or for the daylight illuminance target points.]

Lighting for **Exits** and means of egress must conform with the National Electrical Code. Provision for a backup incandescent or tungsten halogen lamp must be made for exit lighting fixtures with mercury vapor, metal halide or high pressure sodium lamps. [The NFPA requirements are not listed specifically nor is there any discussion of lamp types such as incandescent, fluorescent, electroluminescent or even tritium for exit signs, although provision is made for battery powered LED lamps.]

The proposed revisions contain extensive discussion on **Lighting Controls**. They state first that all lighting must have some form of control whether it is manual, automatic, programmable microprocessor, or computer. Selection of the type of control and its application is based on space factors such as:

- frequency of use,
- available daylighting,
- normal or extended work hours, and
- closed or open office design.

These factors are intended to reduce operating costs by permitting limited operation after working hours; taking advantage of daylight; and facilitating subdivision of space. Spaces are classified as open or enclosed and differ in the degree of flexibility that they require in a lighting control system.

For **Enclosed Areas**, lighting controls may include switches, multi-level switching, occupancy sensors, light level sensors, or microprocessors, zoned for individual or multiple spaces. The 1991 revisions recommend use of photoelectric sensors for balancing electric and natural light in small, glazed offices; use of occupancy sensors in small windowless spaces; and microprocessor control for multiple windowless spaces or for large zones. Any central system, whether microprocessor, programmable controller or central computer, should have touchtone telephone or manual override controls.

For **Open Spaces**, lighting controls may include switches, multi-level switching, light level sensors for spaces adjacent to windows, or microprocessor controls for individual zones within the space. Again, a local means for overriding microprocessor controls must be provided. The revisions call for subdividing large open spaces into zones of about 90 m^2 (1000 ft^2). Within these spaces lighting branch circuits should be arranged for 2 or 3 level switching; controls should be on permanent corridor walls, core area walls, or columns; and remote control schemes and reductions from a programmable controller, microprocessor, and central computer should be considered.

Occupancy Sensors should be considered for small enclosed office and toilet areas and should control no more than 12 fixtures. They should not be used in open office areas, corridors, or spaces with heat producing equipment. Occupancy sensors should have a label containing panel and circuit number identification information. Photoelectric sensors should be considered for areas adjacent to glazed areas or for parking facilities. [No details are given on specific operational characteristics such as delays, illumination set-points, or individual controls.]

Manual Controls should include multi-level switching wherever multiple lamp fixtures are used and should be located within the area where the lighting is used. Switches must be clearly visible and located so that the operator can easily see the fixture being switched. When interior lighting is switched in large open areas with partitions, it shall produce quadrant type illumination patterns.

Finally, the revisions provide guidance for lighting **Exterior** spaces. These include illuminance levels for building entrances, floodlit building exteriors with both bright and dark surroundings, local roadways and alleys, walkways, and outdoor parking facilities. Illuminance levels range from 5.38 lux (0.5 fc) for parking facilities and local roadways to 538 lux (50 fc) for floodlit exteriors with dark colored surfaces in bright surroundings.

The revisions recommend a 10:1 maximum to minimum ratio for parking and roadway lighting with a 4:1 average to minimum ratio. They provide for the use of high efficiency pole-mounted luminaires, with preference given to high pressure sodium lamps. All entrances and exits, including loading docks, of major structures should have lighting fixtures. Exterior lighting should have both photocell and time-clock controls for both all-night and part-night lighting. All-night (dusk to dawn) lighting should be photocell-controlled and includes lighting for life safety, egress, staff parking, and 24-hour operations. Part-night circuits should be turned on by photocells, and turned off by timers.

2.3 Guidelines from the IES Handbook

As noted above, the IES (1987) provides a range of recommendations for illuminance levels based on the visual task. The Handbook also provides a multi-step selection procedure for determining the appropriate illuminance value for these tasks. This procedure is intended to allow flexibility in setting illuminance values so that lighting systems can be tailored for specific applications. Using the procedure requires advance knowledge of the probable tasks in the lighted environment. The following elements must be considered in lighting a task:

1. *The visual display (details to be seen).*
2. *The age of the observers.*
3. *The importance of speed and/or accuracy for visual performance.*
4. *The reflectance of the task (background on which the details are seen)* (p.2-3).

Thus, the observer sees a visual display which has a certain amount of intrinsic visual difficulty and detail. One of the best predictors of the functioning of his/her visual system is the observer's age, since visual performance declines significantly with age. The importance of speed and accuracy refer to a distinction between critical, important, and casual seeing requirements. Finally, the background or task reflectance (which is produced by the task illuminance) sets the adaptation luminance for the observer's visual system.

The IES provides a four-step procedure for selecting an illuminance level for a space. The first step is to determine the visual task as well as its location in the space. The second step is to select an illuminance category based on the specific task, a generic task if the specific task is not known, or the equivalent contrast of the specific task. The third step is to determine the illuminance range, while the final step is to determine the target illuminance value from the illuminance range.

The Handbook describes nine separate illuminance categories defined by the type of visual activity performed in the space. The nine categories, which cover illuminance values from 22 to 21,500 lux (2 to 2000 fc) can be broken down into designs ranging from general lighting in the space; specific task illuminance; and combined general and local lighting. Once the visual task is selected (such as walking through a lobby or reading detailed blueprints), then the target illuminance can be selected if the observer's age, importance of speed/accuracy, and task/background reflectance are known. The IES (p.2-5) specifies the following categories for different visual tasks:

- *A* *Public spaces with dark surroundings*
- *B* *Simple orientation for short temporary visits*
- *C* *Working spaces where visual tasks are only occasionally performed*
- *D* *Performance of visual tasks of high contrast or large size*
- *E* *Performance of visual tasks of medium contrast or small size*
- *F* *Performance of visual tasks of low contrast or very small size*
- *G* *Performance of visual tasks of low contrast and very small size over a prolonged period*
- *H* *Performance of very prolonged and exacting visual tasks*
- *I* *Performance of very special visual tasks of extremely low contrast and small size*

A range of three illuminance values is given for each category. Selection of the correct illuminance value for categories A through C is based on weighing factors derived from considerations of two characteristics; namely, the design of the space (in terms of the reflectance from room surfaces), and the age of the occupant. Weighting factors can assume one of three values based on the range of room surface reflectances and occupant ages.

Weighting Factor Determination

-1 Occupants are under 40 years;
Room surface reflectance is greater than 70 percent.

0 Occupants are 40 to 55;
Room surface reflectance is between 30 and 70 percent.

+1 Occupants are over 55;
Room surface reflectance is less than 30 percent.

To select an illuminance level, the values for the weighting factors in each category are added together (including the sign). Thus if the occupants are under 40 and the room surface reflectance is greater than 70%, the weighting factor is (-1) + (-1) = "-2". If the total factor is -2, the lowest of the three target illuminances should be used. If it is +2, (meaning that the occupants are over 55 and the room surface reflectance is below

30%) then the greatest of the three targets should be used, while if it is -1, 0, or +1, the middle illuminance should be used.

For categories D through I, three parameters enter into the determination of the weighting factors. As above, occupant age is critical, but there are two new parameters; namely speed and/or accuracy of the task, and reflectance of the task background. Reflectance of the task background is used for D through I, rather than room surface reflectance as in categories A through C, because it is considered to be the portion of the task on which the visual information is displayed. These three parameters determine the weighting factors as follows:

Weighting Factor Determination

-1 Occupants are under 40 years;
Speed and/or accuracy are not important;
Reflectance of task background is greater than 70 percent.

0 Occupants are 40 to 55;
Speed and/or accuracy are important;
Reflectance of task background is between 30 and 70 percent.

+1 Occupants are over 55;
Speed and/or accuracy is critical;
Reflectance of task background is less than 30 percent.

In selecting an illuminance range for categories D through I, the weights are again summed. IES states that if the weighting factor is -3 or -2, the lowest illuminance target should be used, while if the factor is +3 or +2, the highest target should be used. The middle illuminance should be used for factors between -1 and +1.

Thus, IES provides parameters to judge the likely difficulty of the visual task in setting weighting factors. Categories D through I involve visual tasks for which speed and/or accuracy in performing the task are important; thus, task performance is included in the weighting factor determination along with age and surface reflectance. The Handbook points out that categories G though I are for *"extremely difficult visual task, and may be difficult to illuminate. For practical and economical reasons, lighting systems for these tasks may require a combination of general overall illumination and task area illumination. Because of the unusual conditions associated with tasks in Categories G through I, very careful analysis is recommended"* (p. 2-21).

Designing a new illumination system or refurbishing an existing system requires knowledge of the probable surface reflectances, the likely age of the intended occupants, and the nature of the visual task to be performed, along with the probable speed and/or accuracy requirements.

The IES Handbook provides the following illuminance values[3] for the different illuminance ranges:

Table 2. IES Target Illuminance Values

Illuminance Category	Range of Illuminances in Lux	Range of Illuminances in Footcandles
A	20-30-50	2-3-5
B	50-75-100	5-7.5-10
C	100-150-200	10-15-20
D	200-300-500	20-30-50
E	500-750-1000	50-75-100
E	1000-1500-2000	100-150-200
G	2000-3000-5000	200-300-500
H	5000-7500-10000	500-750-1000
I	10000-15000-20000	1000-1500-2000

The IES notes that the illumination selection procedure is to be used in situations where visual performance is the important consideration. It is not intended for selecting lighting levels for merchandising or display, advertising, non-visual sensors (such as cameras), artistic effects, specific emotional responses, safety, prevention of non-visual effects (such as deterioration due to ultraviolet), or a test procedure for evaluating equipment. Specific illuminance values for these types of tasks are given in the Handbook. The Handbook also describes different types of activities and their associated illuminance category. These include Commercial, Institutional, Residential, and Public Assembly interiors; Industrial; Outdoor; Sports and Recreational Areas: and Transportation Vehicles (Roadway lighting is covered separately).

The Handbook points out that illuminance values for categories A through C are intended for use in all areas in the target space. As such, they are *average maintained illuminances* and can be predicted by the lumen method using zonal-cavity calculated coefficients of utilization. Categories D through F describe tasks

[3] The Handbook uses 10 as the multiplication factor from footcandles to lux; for more precise values multiply by 10.76

which are generally fixed in one location so that each task area can be lighted individually. Because categories G through I describe very difficult visual tasks, they may require a combination of general and specific task illumination. Categories D through I describe localized values or *maintained illuminance on the task* so that point calculation methods are appropriate. Thus careful analysis of the tasks to be performed in the space is critical. If the tasks are likely to vary a great deal in lighting requirements, then the lighting designer should consider using variable controls, multiple level systems, or a mixture of lighting systems. Other factors to be considered are problems with veiling reflections or serious contrast loss - problems which often arise with displays (whether video display terminals or merchandizing; luminance ratios; visual comfort - often defined by the lack of comfort or glare; and color. Each of these is discussed in detail in the Handbook.

IES classifies lighting systems in four categories determined by the layout or location with respect to the visual task. These categories include: general, localized general, local (supplementary); and task-ambient. **General** lighting systems provide reasonably uniform luminance on the work plane within the entire area. In a **Localized** general lighting system, the luminaires are arranged with respect to a visual task or specific work area, while providing general lighting for the space. In a **Local** lighting system, lighting is only provided over the immediate task area from remote spotlights or luminaires mounted near the task. To avoid problems with glare from the fixture, or excessive changes in adaptation, local lighting should be used with general lighting. (When this occurs it is termed *supplementary* lighting.) In **Task-ambient** lighting the luminaires are typically built into the furniture in an open office plan and supplemented by indirect ambient lighting also built into the furniture and directed toward the ceiling. In these systems power is often supplied through the floor, with virtually no fixtures in the ceiling.

Following the CIE, the IES also classifies systems in terms of the type of luminaire used and the distribution of light produced - direct, semi-indirect, general diffuse (direct-indirect), semi-indirect, and indirect.

Table 3. IES Classification of Luminaires

Luminaire Type	Output **ABOVE** Horizontal	Output **BELOW** Horizontal
Direct	0-10%	90-100%
Semi-Direct	10-40%	60-90%
General Diffuse	40-60%	40-60%
Direct-Indirect	40-60%	40-60%
Semi-Indirect	60-90%	10-40%
Indirect	90-100%	0-10%

The IES Handbook notes utilization is highest for direct lighting systems, although these systems can suffer from problems of direct glare from the lamp, veiling reflections, reflected glare and shadows. The distribution for these systems can vary from concentrated to widespread depending on the finish and contour of the reflector material and the control or shielding. IES suggests that room surfaces with high reflectance are particularly important to maintain good brightness relationships, and that care should be paid to wall luminances and vertical surface illuminances. Semi-direct luminaires are similar but have a small upward component that illuminates the upper portions of the space. The amount of light upward and downward in general diffuse lighting systems is about equal, with direct-indirect systems being a special case in which very little light is emitted at angles near the horizontal. Although utilization is lower than for direct or semi-direct systems, it is quite good for rooms with high surface reflectances. With semi-indirect lighting, the luminance of the luminaire itself can approach that of the ceiling and if not controlled can produce problems of reflected or direct glare. Finally, indirect systems direct the light to the ceiling, thereby eliminating most shadows and glare. This type of system has low utilization compared with the other systems, and can have problems of excessive luminance on the ceiling (which becomes a glare source). IES provides guidelines for luminaire spacing for all these types of systems.

2.4 Review of IES Energy Management Information

Both the IES Lighting Handbook (1987) and the IES Lighting Energy Management (LEM) series provide guidance for determining lighting power limits for spaces and buildings within an entire facility. These procedures are intended first to identify the different amounts of power required for lighting different types of tasks and uses of space and to provide an indication of the amount of energy used in the facility. In this assessment, (derived from the IES Handbook, and to be updated by material from ASHRAE/IES 90.1), it is important to remember that Energy = Power x Time so that not only is the amount of power consumed by a task important, so is the amount of time spent on the task.

The procedure for determining the lighting power limits for both new and existing facilities is termed the Unit Power Density (UPD) method, and represents the sum of power "budgets" for all individual areas in a facility, as well as any related exterior areas. Although some specific types of areas such as theaters are excluded, the determination largely covers most interior and exterior spaces found in office facilities.

Criteria that are used in determining the base UPD are illuminance, flux utilization factors, light source factor, light loss factor, adjustment factor, and task area of the space. They interact as shown in the following formula:

$$BaseUPD = \frac{(F_{et} \ x \ \%T) + (F_{eg} \ x \ \%G)}{F_{cu} \ x \ F_{le} \ x \ F_{ll}} \ x \ F_{aj}$$

where:

F_{et} Illuminance for task area
F_{eg} = Illuminance for general area (usually 1/3 of F_{et})
$\%T$ = Task area of the space as percent of total
$\%G$ = General area of the space as percent of total (100 - %T)
F_{cu} = Flux utilization factor based on selection of appropriate luminaire applicable to the task or general area. This factor includes considerations such as visual performance, color rendering, control, need for modeling or sparkle, hardware availability, flicker, life, etc.
F_{u} = Light Loss Factor based on depreciation of lamps and on dirt collected on luminaires, lamps, room surfaces, etc.
F_{aj} = Adjustment factor to account for other design considerations, such as lighting vertical surfaces (stacks) in a library or reception area.

The IES Handbook provides a table of light source factors, based on color rendering and lighting geometry, which presents typical light source, uses, efficacies, and lumens/watts. For example, if the task required only minimal color rendering in storage or equipment rooms, any HID or fluorescent source could be used, with efficacies ranging from 50 to 150 and typical lumens per watt of 90. It also presents a table of light loss factors for different sources and luminaires based on assuming clean room conditions, 12-month cleaning cycle, lamp lumen depreciation (LLD) and luminaire dirt depreciation (LDD) criteria. (Other assumptions could of course be made.)

The Lighting Power Budget (LPB) is derived by multiplying the base UPD (P_b) by the Area of the Space (A) and the Area Factor (AF) (which adjusts for effect of room configuration on lighting utilization) as follows - $LPB = A \times B_b \times AF$. If a space has multiple visual task areas, the based UPD is a weighted average of individual task UPD's. It should be pointed out that lighting power budgets are an alternative way of reducing energy attributable to lighting. Ideally they will include corrections for the amount of time a system is used as well as the components that comprise the system. The present project has concentrated on determining reliable information about component and system performance which could be used as input to more accurate lighting power budget development.

The IES Handbook also provides information on the factors that contribute to light loss and which are affected by maintenance procedures. These include luminaire surfaces depreciation, room surface dirt depreciation, burnouts, lamp lumen depreciation, and luminaire dirt depreciation. Each of these factors should be evaluated in any assessment of lamp performance because of their impact on total light output.

3. Evaluation of Lighting System Energy Performance

3.1 Selecting a Lighting System

Energy efficiency continues to be a major concern throughout the building industry, and lighting is no exception. Commercial lighting is dominated by fluorescent systems because of their relatively high luminous efficacy, long lamp life and cool operating temperatures. While improvements have been achieved in fluorescent lighting systems, including lamps, ballasts and fixtures, these improved components are frequently more expensive than standard components. In the case of potential retrofits, a substantial first cost is associated with the replacement of an existing lighting system with one of a higher efficiency, making it imperative to have accurate data on system efficiency in order to determine the cost effectiveness of the retrofit.

Lighting systems are usually designed or selected based on a combination of illumination, energy, and cost considerations. The required illumination conditions are determined based on user needs and planned activities in the building space as referenced in the IES recommended design practices discussed in section 2. Once the illumination criteria are set, a pool of potential lighting systems which meet these criteria can be identified for consideration.

While each of a number of lighting systems may meet the illumination criteria, they are likely to differ in cost, efficiency, and photometric characteristics. The physical dimensions, photometric distribution, and layout may differ. Energy usage and cost considerations frequently have a strong influence on the selection of the final lighting system candidate. Either energy usage itself or first cost may be the primary consideration for the selection of a lighting system. A good compromise is the use of life cycle cost which balances first cost and energy costs over the life of the lighting system.

In the case of lighting system retrofits, the cost of the retrofit is usually compared to the savings due to increased efficiency, payback period. The savings to investment ratio is then computed.

3.2 Background on System Performance

The energy performance of a lighting system, particularly the luminaire, could in principal be assessed by measuring the total light produced by the luminaire and the total electrical power input to the luminaire. This could be done in the laboratory, for a proposed lighting system, or in the building, for an existing lighting system. However, the large number of potential lighting systems prevents the measurement of each system. Also, for an installed luminaire, these measurements may be difficult, if not impossible, and are impractical at the very least. Measuring the total light output would require a means to sense the light distributed in all directions, while measuring the power input would require access to the line feeds to the lighting system. A more useful procedure would allow the assessment and comparison of various lighting system design alternatives on the basis of component performance characteristics. However, the determination of lighting system performance based on component characteristics is complicated by the interactions between components, and the sensitivity to environmental conditions. These interactions are electrical, optical and thermal in nature. Accurate and realistic determination of lighting system performance requires adequate consideration of the effect of component interactions and environmental conditions.

3.3 Evaluating Lighting Systems

The need to have a valid basis for comparing lighting system performance has motivated the quest for improved test procedures for evaluating and rating lighting system performance. Since lighting systems are composed of components which can be assembled in various combinations, the measurement of sufficient component characteristics to enable the subsequent determination of system performance would be of great value. This would pre-empt the need for extensive testing of a never-ending procession of lighting system component combinations. Such a system must, however, be sensitive to the interactions between lighting system components, and between the lighting system and its surroundings.

Lighting component interactions fall into three categories: electrical, thermal and optical. The electrical interaction involves the lamp and ballast, while the thermal interactions include all of the components. The optical interaction relates to the lamp and fixture.

The temperature dependence of fluorescent lamps is well-known, with both light output and power input, and thus efficiency, varying with minimum lamp wall temperature, as shown in figure 1. The process of accurately determining light output, power input and efficiency for a lighting system, thus, requires knowing both lamp temperature and the temperature dependence of the lamp performance characteristics (i.e. light output, power input versus lamp temperature).

Existing test procedures are aimed toward quantifying component performance for a fixed reference condition. While this may appear to be a valid basis for comparing different components, a closer examination reveals the fallacy of this approach. The main problem with testing components at fixed reference conditions is that the resulting data are not consistent for different tests.

The inconsistencies can be illustrated by examining current procedures for testing lamps, ballasts and fixtures. Lamp light output in lumens is usually measured in an integrating sphere, and with a reference ballast, in accordance with IES LM-9. Measurements are made in still air at 25°C ambient temperature. Lamp temperature is not controlled or measured. Ballast performance is measured following the procedures given in ANSI 82.2 (1984), which determines ballast factor (the ratio of light output with the ballast to light output with a reference ballast) using a reference lamp, again in still air at 25°C ambient. However, <u>lamp</u> temperature may be different for the two tests because the lamp may be driven differently by the test ballast than by the reference ballast. Thus, part of any difference in light output could be due to lamp temperature changes, and part due to electrical properties.

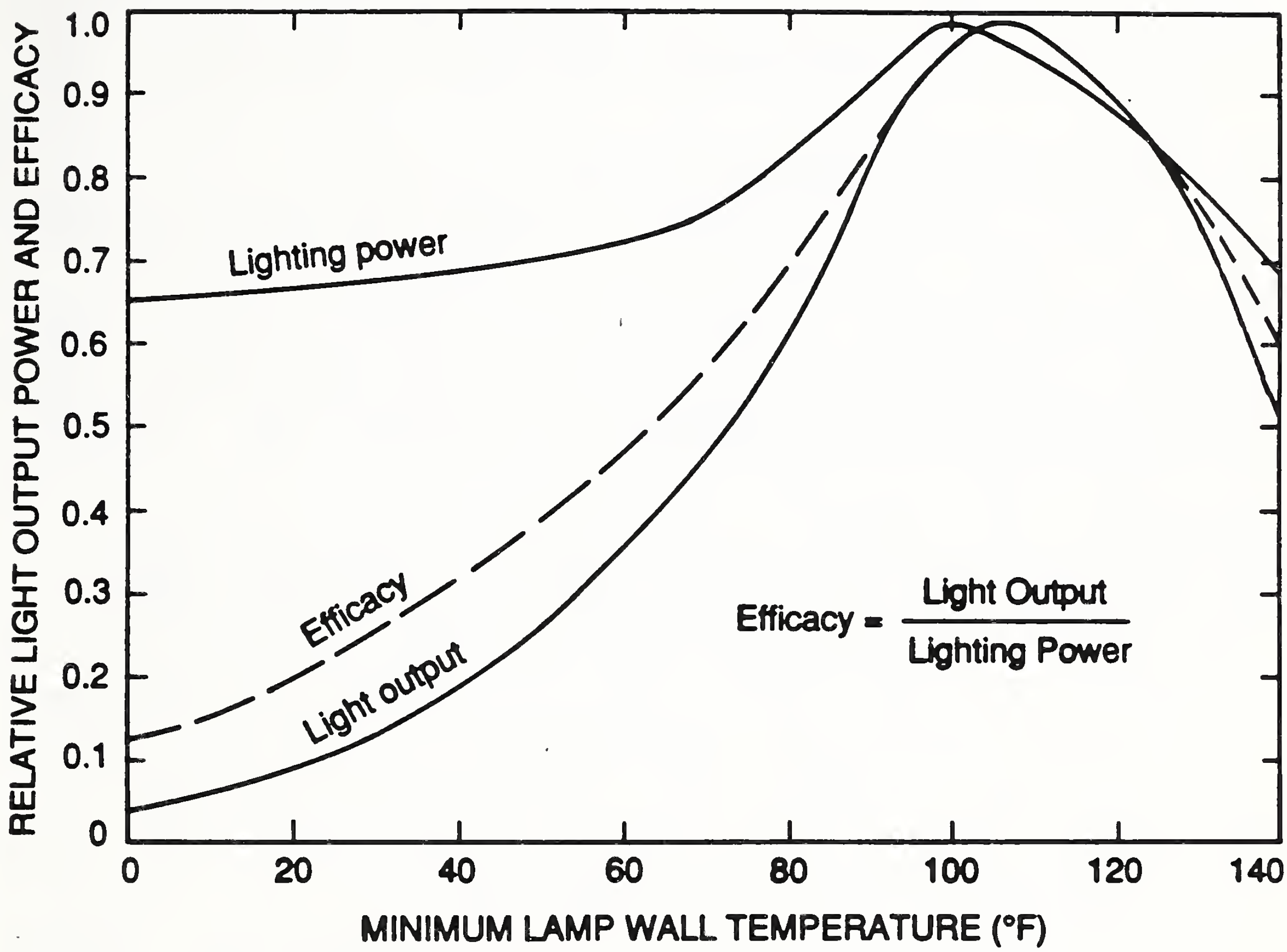

Figure 1. Dependence of Lamp Functions on Lamp Wall Temperature

Light fixtures are usually evaluated using IES LM-41 (1985) which measures the distribution of light from the luminaire using a goniophotometer or mirror photometer. If absolute photometry is used, total lumen output can also be measured. However, again lamp temperature is not controlled or measured, and room temperature is 25°C. An important point is that lamp temperature can differ significantly in the fixture compared to when the lamp is in free air, with consequent variations in lamp light output, power input, and efficacy.

The typical procedure for determining lighting system light output and efficacy consists of taking the product of the lamp lumen output as measured in the sphere, the ballast factor as measured for the ballast in question, and the photometric distribution. Such a procedure assumes that the lamp is producing the same lumen output in the fixture as it did in free air, when it was likely considerably cooler, and that the ballast factor is the same for the thermal conditions in the luminaire as it was on the benchtop. To the extent that these assumptions are not valid, the resulting conclusions will be suspect.

In section 4, procedures for measuring lamp, ballast and luminaire performance under a range of more realistic operating conditions are described. These procedures were used to evaluate component and system performance as described in section 5.

4. Testing and Evaluating Lighting Systems

While the existing test procedures contain much useful information and form the basis for a more comprehensive test procedures, they suffer on two main counts. First, they are not totally consistent between tests; and second, they are somewhat vague and general rather than specific test procedures. The need exists to develop a consistent, comprehensive set of test procedures for lighting system components which would allow their direct comparison and the determination and rating of lighting system performance. As a result, this required measuring the performance characteristics of individual components in such a way that they could be combined to determine system performance for the present report.

At the same time, an important consideration was that individual lighting system components could be tested using generic versions of the other components of the lighting system, so that a large number of lighting system combinations would not have to be measured. The following is a summary of the comprehensive procedure used for evaluating lighting systems. The subsequent section contains the measurement results for a number of systems.

4.1 Lamp Measurement Approach

The light output of lamps was measured using a reference ballast and an integrating sphere. However, rather than performing the measurement only at 25°C ambient air temperature, the temperature dependence of the lamp lumen output was characterized by varying ambient temperature (is measured near the lamp) from 20 to 30°C, while also measuring minimum lamp wall temperature and lamp power. Thus, each lamp type would have a plot or table of light output and power input as functions of minimum lamp temperature. Such a plot is shown in Figure 2. Lamp temperature elevation over ambient air temperature was also calculated from these measurements and plotted. An important point is that the lamp characteristics are measured independently of any specific ballast or fixture.

This figure, and subsequent similar figures, show two or more quantities on each plot. Each quantity is indicated by a unique plot symbol, and the value of the quantity should be read from the scale labeled with the appropriate units. The fact that some axes have more than one label does not imply any correspondence between the quantities, since the actual values of the quantities are determined by the appropriate curves. Thus, light output is in lumens, lighting power in watts, temperature elevation in degrees C, and luminous efficacy in lumens per watt.

4.2 Ballast Measurement Approach

Ballast performance was characterized for each generic lamp type which the ballast is designed to operate. Ballast factor was measured, along with ballast input power and lamp temperature, for a range of ambient temperatures. This was repeated for each type of lamp, such as F40CW or energy-saving lamps, which the ballast is designed to operate. The resulting information was plotted or tabulated as a function of lamp temperature.

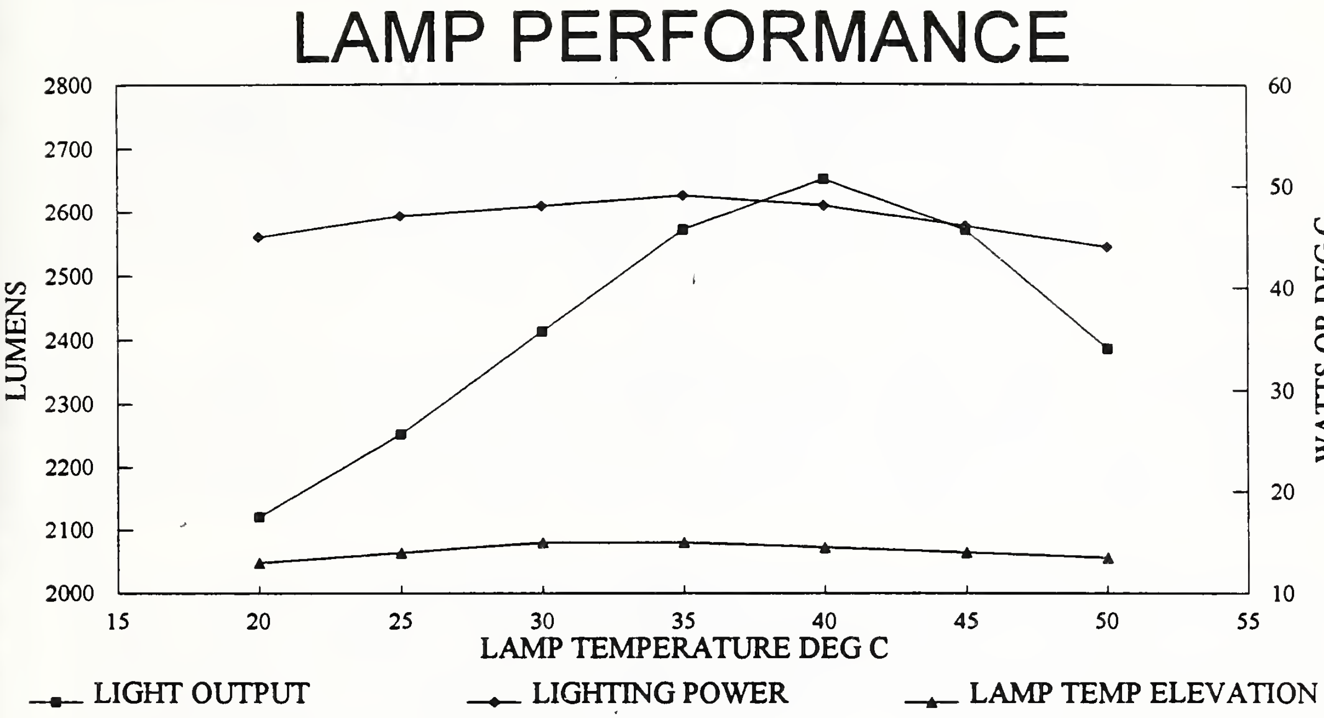

Figure 2. Typical Light Output Data at Various Ambient Temperatures.

Figure 3 shows an example of typical ballast data. Ballast factor was determined by a method similar to ANSI C82.2 (1984), as the ratio of light output with the test ballast that given in to light output with the reference ballast. The elevation of lamp temperature (specifically the minimum lampwall temperature) above ambient temperature was directly measured with contact temperature sensors (thermocouples).

A new parameter (not specified by ANSI C82.2) which is also measured was the ratio of test ballast input power to total power input under the reference condition (i.e. reference ballast and cathode heater inputs). This ratio is similar in concept to the ballast factor, except that it deals with electrical power rather than light. The quantity could be denoted as the ballast factor for power, but a less confusing, more concise name might be 'Ballast Power Ratio'.

The ballast power ratio is important because it allows for variations in lamp power to be accounted for in a manner similar to that used for lamp light output. This technique enables ballast performance to be determined using generic lamp types, rather than specific lamps, thereby reducing the number of lamp/ballast combinations to be tested.

In a similar manner, the influence of the ballast on lamp temperature elevation was accounted for by determining the ratio of lamp temperature elevation with the test ballast to lamp temperature elevation with the reference ballast. This quantity can be termed the 'Ballast Temperature Ratio', keeping in mind that it actually refers to the lamp temperature when operated by the specific ballast.

The ballast temperature ratio is a significant parameter because it accounts for the different thermal conditions which may be obtained for specific lamp and ballast combinations, primarily as the result of the electrical interactions between the lamp and ballast.

4.3 Fixture Measurement Approach

The goal of the fixture measurements was to determine fixture optical efficiency and lamp temperature for the lamps when installed in the fixture. The luminous intensity and intensity distributions of fixtures is typically measured using a goniophotometer, mirror photometer or similar apparatus. Since such photometric equipment was not available for this research effort, manufacturer's data obtained from testing by independent testing laboratories were used.

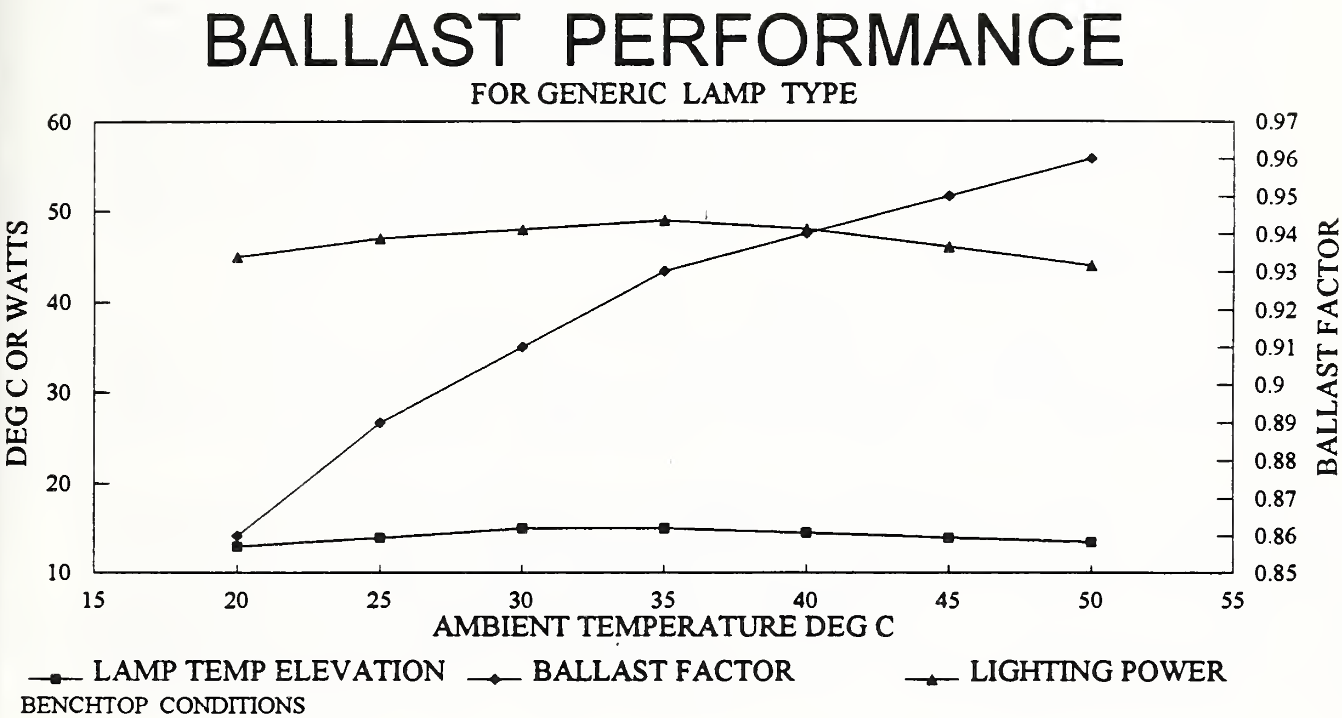

Figure 3. Typical Data for Ballast Factor, Ballast Power Ratio, and Ballast Temperature Ratio.

Optical efficiency is the ratio of light output from the fixture to the light output from the lamps, at the same thermal conditions. Thus, the effect of lamp temperature on lamp lumen output must be considered. This can be accomplished by a testing laboratory as follows:

> Measure, or have measured previously, lamp lumen output as a function of lamp temperature over a range of temperatures using a reference ballast and standard electrical conditions. Install the calibrated lamps in the fixture, and measure fixture light output and lamp temperature. Use the measured lamp temperature and the lamp calibration curves to determine actual lamp lumens for the lamp temperature in the fixture. The ratio of measured fixture lumens to lamp lumens is the optical efficiency. This parameter is purely an optical property of the fixture, and is related to absorption of light within the fixture.

The procedure for determining fixture optical efficiency is demonstrated schematically in figure 4. The upper curve is the light output of the bare lamp, while the lower curve is the light output from the fixture enclosing the lamp. The ratio of light outputs at equal lamp temperatures is the optical efficiency.

The measured lamp temperature needed to determine fixture optical efficiency is also an important property of the fixture. It should be expressed as the elevation of minimum lamp temperature above lamp temperature when the lamp is operated by the same ballast at the same electrical input (i.e. reference ballast and standard input conditions). This lamp temperature elevation is used to determine lamp light output, power input and efficiency when evaluating a luminaire.

4.4 Luminaire Measurement Approach

A luminaire, consisting of one or more lamps, ballasts and a fixture, was evaluated by suitably combining the component characteristics. The primary quantities of concern were the light output (LO), power input (LP), and luminous efficacy (LE), which are related according to:

$$LE = \frac{LO\ (lumens)}{LP\ (watts)} \qquad (1)$$

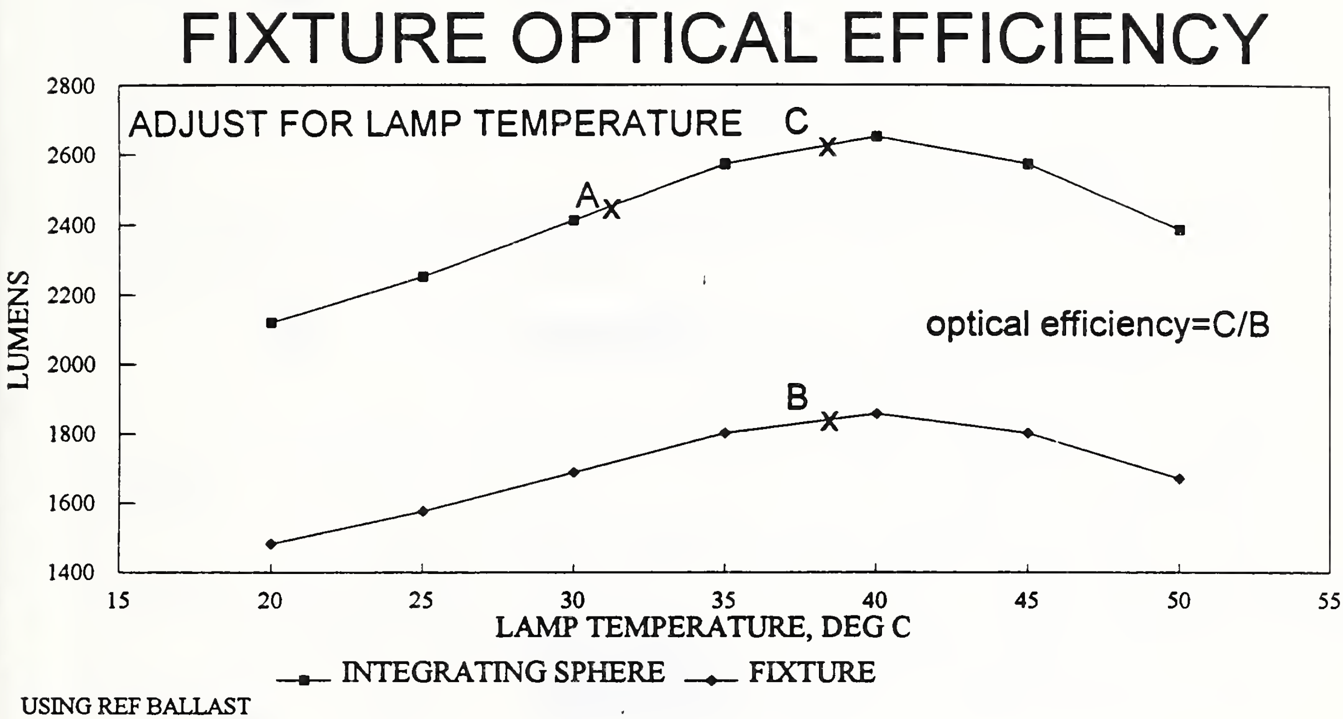

Figure 4. Procedure for Determining Fixture Optical Efficiency.

The important point is that the quantities LO and LP must be for the actual lamp/ballast/fixture combination, including optical and thermal effects. Thus, LO and LP can be expressed as:

$$LO = NL \times LL_t \times BF_t \times OE \tag{2}$$

$$LP = NL \times LW_t \times BPR_t \tag{3}$$

where:

NL = number of lamps

LL_t = lamp lumen output at actual temperature with reference ballast

BF_t = ballast factor at actual temperature

OE = fixture optical efficiency

LW_t = lighting power input at actual temperature with reference ballast

BPR_t = ballast power ratio at actual temperature

Combining equations 1,2 and 3, lighting system efficiency, or luminous efficacy given by:

$$LE = \frac{LL_t \times BF_t \times OE}{LW_t \times BPR_t} \quad \text{(lumens per watt)} \tag{4}$$

The procedure for determining the proper lamp temperature to enable the determination of the actual lamp lumen output and power input relies on the lamp temperature information recorded when testing the lamps, ballasts and fixture. Light output and power input are measured for a particular lamp as functions of lamp temperature. Actual lamp temperature is determined by taking the elevation in lamp temperature above ambient temperature for the lamp ballast combination and adding to that the rise in lamp temperature due to the lamp being installed in the fixture, and adding that sum to the actual ambient temperature. For rating purposes a fixed ambient temperature, of say 25°C, could be assumed.

Figure 5 demonstrates the sequence of four steps for determining lighting system performance and efficiency, proceeding from component measurements through the relevant interactions.

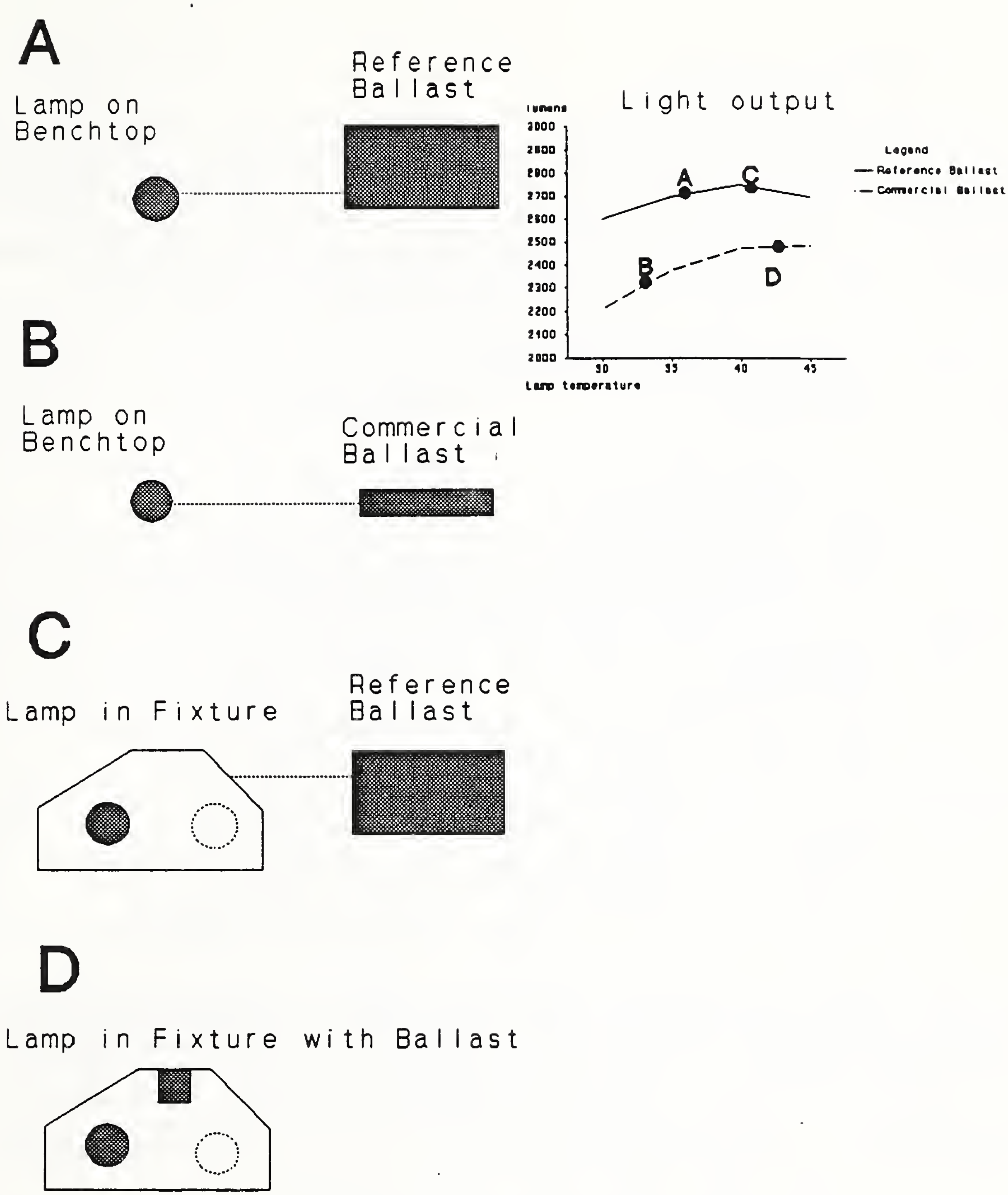

Figure 5. Sequence of Steps for Determining Lighting System Performance and Efficiency.

5. Measurement Results

5.1 Components Tested

A variety of measurements were performed on a number of lighting components and systems in a newly developed lighting system performance assessment laboratory at the National Institute of Standards and Technology. Included in the measurement program were various lamps, ballasts and fixtures, as summarized in Table 4.

Table 4. Lighting Components Tested

Type	Description	Designation	Sample #
Lamps:	T-12 Daylight	F40D 40W	1
	T-12 Energy Saving	F40CW 34W	2
	T-12 Cool White	F40CW 40W	3
	T-8 Tri-Phosphor	F32-T8, 32W (CRI of 75)	4
	T-8 Tri-Phosphor	F32-T8, 32W (CRI of 85)	5
	T-12 U-shaped	FB40CW-6 40W	6
Ballasts:	Energy Saving (core coil)	(1 lamp)	1
	Electronic	(1 lamp) T-12	2
	Standard (core coil)	(1 lamp) T-12	3
	Electronic IC	(1 lamp) T-12 or T-8	4
	Electronic Instant Start	(1 to 3 lamps) T-8	5
Fixtures:	0.6x1.2 m (2x4 ft) 2 lamp	T-8 Small cell	1
	0.3x1.2 m (1x4 ft) 2 lamp	T-12 Acrylic	2
	0.3x1.2 m (1x4 ft) 2 lamp	T-12 Acrylic Wraparound	3
	0.3x1.2 m (1x4 ft) 2 lamp	T-12 Open Cell	4
	0.3x1.2 m (1x4 ft) 2 lamp	U-shaped T-12 Acrylic	5
	0.3x1.2 m (1x4 ft) 2 lamp	U-shaped T-12 Open Cell	6

It should be noted that the particular lighting component samples tested were obtained through normal production and supply channels. It is to be expected that normal manufacturing variations and tolerances might well be responsible for some variation in performance characteristics among individual samples. As a result, the measurement data presented herein should be considered as representative of typical performance, while the actual performance of specific components might vary from these data.

The purpose of the measurements was to evaluate and compare the performance of different lighting systems, and to demonstrate the procedures used in the evaluation.

5.2 Measurement

The measurement apparatus consisted of a combination of electrical power supplies and conditioners, transducers, photometric sensors, switches and a computer-based data acquisition and control system, as described below.

<u>Electrical Power to Lamps and Ballast</u>

A regulated constant voltage power supply was used to operate the lamps and ballasts. Voltage was held at 120V within 0.1%, with RMS deviation from 60Hz sinusoidal waveshape of less than 3%. Supply voltage to the reference ballasts was adjusted to specifications using a variable transformer.

<u>Electrical Measurements</u>

Solid state transducers were used to measure electrical voltages, currents and power usages. These transducers were externally powered to minimize their influence on the measured parameters, and produced an analog output signal proportional to the quantity being measured. The transducer outputs were connected to the data acquisition system. The uncertainty of the transducer measurements was less than ±0.5%.

<u>Data Acquisition and Control System</u>

A computer-based data acquisition and control system was used to conduct the measurements, monitor the measured parameters and record the results. Solid-state relays were used to switch between the reference ballast and the test ballast configurations, under the control of the data acquisition system.

<u>Temperature Measurements</u>

Lamp, ballast, fixture and air temperatures were measured using type-T thermocouples, either affixed to the appropriate surface or suspended in the airstream. Cold junction compensation was provided by the data acquisition system. Measurement resolution was 0.1°C, while the uncertainty was ± 0.5°C.

<u>Reference Ballasts</u>

Reference ballasts, variable linear reactors, were consistent with ANSI 83.3. Impedance and power factor were set to specification for each lamp type.

<u>Integrating Sphere Photometer</u>

Lamp luminous flux was measured using a 1.65 m (65 inch) integrating sphere photometer. The sphere was calibrated to account for the effects of absorption by the sphere walls and the lamp holder, and the overall response of the filter/detector system. A spectral calibration was also completed. The procedure for this calibration is presented in Appendix A. The luminous flux data reported in this document include the spectral effects.

5.3 Fluorescent Lamp Measurement Results

The performance of various fluorescent lamps was evaluated by measuring their light output, power input and luminous efficacy. The measurements were performed in the laboratory using a reference ballast and an integrating sphere photometer, along with appropriate transducers to monitor lamp voltage, current and power. The measurement setup is shown schematically in Figure 6.

Measurements were performed at the standard temperature condition of 25°C, and at warmer and colder temperatures to evaluate the effects of ambient temperature on lamp performance. The range of ambient temperatures achieved in the laboratory ranged approximately from 20 to 30°C.

The basic measurement procedure consisted of operating the lamp while in the integrating sphere using a reference ballast and regulated power supply. The Reference ballast impedance and input voltage were set so that the lamp current matched that specified in ANSI C78.1. The Lamp current at reference conditions is specified 430mA for four foot T12 lamps and 265mA for similar T8 lamps. All electrical quantities were measured using solid state transducers and an automated data acquisition system.

Six fluorescent lamp types were measured, as listed in table 5.

Table 5. Measured Lamps

Label #	Lamp Type	Designation
1	T-12 1.2m (4 ft) daylight 40W	F40D
2	T-12 1.2m (4 ft) cool white 34W	F40 CW ES
3	T-12 1.2m (4 ft) cool white 40W	F40 CW
4	T-8 1.2m (4 ft) tri-phosphor 32W	F32 T8
5	T-8 1.2m (4 ft) tri-phosphor 32W	F32 T8
6	T-12 U-shaped cool white 40W	FB 40 CW

When operated with a reference ballast, rapid-start fluorescent lamps require an auxiliary system for providing cathode heater power. This was accomplished with a separate low voltage power supply and two small filament transformers. The details of the electrical configuration are given in ANSI 78.375.

Table 6 summarizes the measurement results obtained at the 25°C reference condition.

LAMP LUMEN OUTPUT

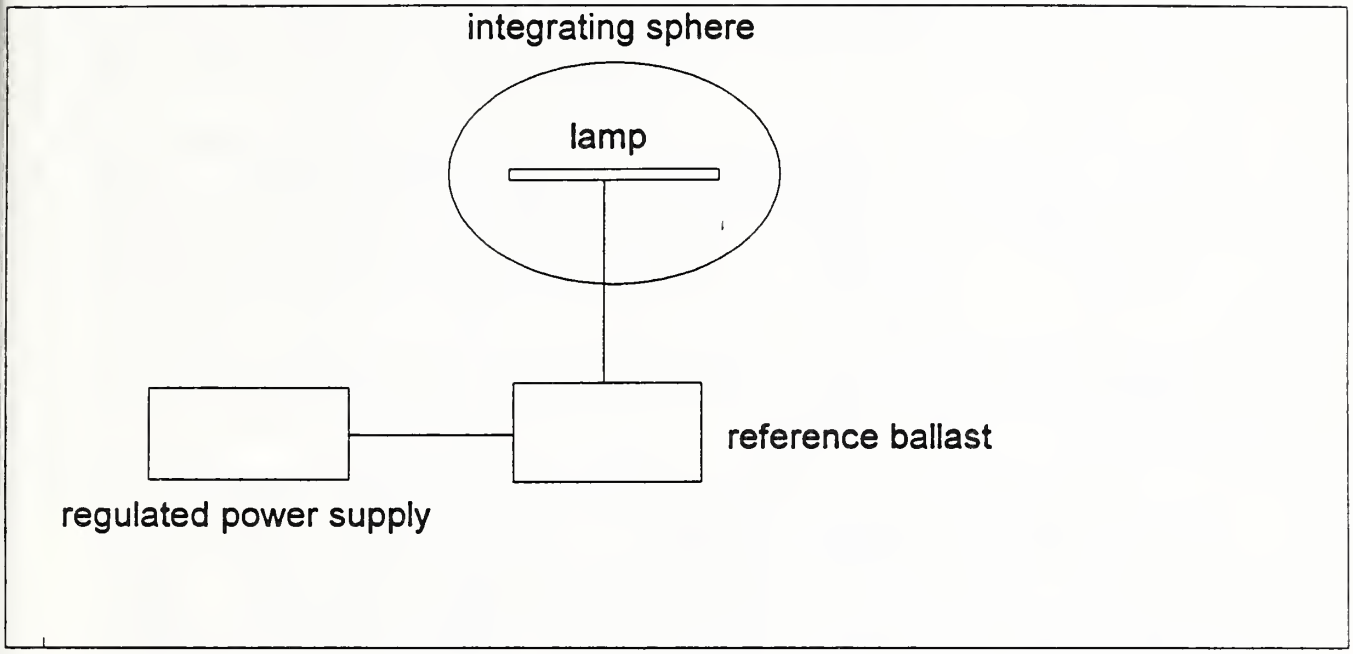

Figure 6. Schematic Approach for Measuring Lamp Output.

Table 6. Lamp Measurement Results at 25°C

Lamp #	1	2	3	4	5	6
Rated Power (watts)	40	34	40	32	32	40
Rated Lumens	2550	2650	3050	2850	3050	2900
Arc Power (watts)	37.70	30.68	38.11	30.46	30.26	38.50
Cathode Power (watts)	3.28	3.40	3.21	2.54	2.54	3.08
Lamp Power (watts)	40.98	34.08	41.32	33.00	32.80	41.58
Light Output (lumens)	2546	2415	2937	2648	2852	2852
Actual/Rated Lumens	0.998	0.911	0.963	0.929	0.935	0.983
Luminous Efficacy (lum/w)	62.13	70.86	71.08	80.24	86.95	68.59
Lamp Temperature (°C)	36.5	32.1	37.2	37.6	39.1	39.8
Lamp Temperature Elevation (°C)	11.6	6.1	12.4	11.8	13.0	14.3

Table 6 illustrates a number of points. The T-8 lamps, lamps #4 and #5 have the highest luminous efficacies, with values of 80 and 87 lumens per watt. The two T-12 cool white lamps, #2 and #3, have luminous efficacies of about 71 lumens/watt. The daylight lamp (#1) and the U-shaped lamp (#6) had luminous efficacies of about 62 and 69 lumens/watt, respectively.

The higher luminous efficacies of the T-8 lamps can be attributed to their improved phosphor coatings which alter (and improve) their spectral composition relative to that of a cool white fluorescent lamp. The lower luminous efficacy shown by the daylight lamp is a function of its spectral output, which is designed to provide more daylight-like light color at the expense of efficacy. The energy saving lamp #2 has a luminous efficacy equal to the standard cool white #3, but produces less light output at a correspondingly lower power input.

The measured lamp light outputs are in general, somewhat lower than the values published in manufacturers' catalogs and design tables. Part of the difference between measured and published values may be due to differences in measurement equipment and measurement uncertainty. The measurement uncertainty was less than 0.5% (3σ) The measurements were color corrected using a spectral power distribution measurements. The light output of lamp #1 is essentially equal to rated, while lamp #6 is within 2% of rated. The other lamps range from 4 to 9% below rated output.

While the lamp light output is reported as an absolute measurement (i.e. in lumens), it is probably best to compare lamp performance on a relative basis, since any systematic uncertainty in luminous flux measurement will drop out of this comparison. This is also true for the ballast, fixture and luminaire data presented later.

The luminous efficacy values are based on lamp power, including both arc watts and cathode watts. Efficacy values would be higher if only the arc power were used, but since the cathode power is present when the lamp is powered by the reference ballast circuit, the combined power was used.

Although lamp characteristics are normally measured and published at 25°C ambient temperature, lamps in luminaires rarely operate at that temperature. Since lamp performance varies with temperature, different ambient and operating conditions will change lamp performance and luminous efficacy. In order to quantify and account for changes in lamp performance due to operating temperature, measurements were made at ambient temperatures of 20 and 30°C. While this does not cover the extreme range of potential lamp operating conditions, it does allow for the examination of the sensitivity of lamp performance to changes in ambient temperatures.

Measurements similar to those previously described were performed with laboratory ambient temperature adjusted accordingly. The results are presented in a series of figures, one for each lamp type. Each figure shows the total measured lamp power in watts, light output in lumens, temperature elevation of the lamp above ambient temperature, and calculated luminous efficacy in lumens/watts, as functions of ambient temperature. (Ambient temperature was fixed at 20°C, 25°C and 30°C for these measures.) Lamp power, light output and temperature elevation are the three parameters which will be needed for subsequent determination of lighting system performance. Table 7 also summarizes these data and includes information on both lamp and ambient temperature.

Figure 7 shows the results for lamp #1 (F40D). Light output (lamp luminous flux) decreased with increasing temperature, as did lamp power. Calculated luminous efficacy (obtained by dividing lamp luminous flux in lumens by lamp power in watts) was greatest at the 25°C condition. Lamp temperature elevation (above the three measured ambient temperatures) ranged from 8.55 to 11.6 °C.

Figure 8 presents the measured results for lamp #2 (energy saving). Light output and luminous efficacy were greatest at the 25°C condition, as was lamp power. Lamp temperature elevation was only 6.1 to 8.8 °C, because less heat was generated by the lower wattage lamps.

Table 7. Measured Lamp performance in sphere versus ambient temperature.

Lamp	T amb C	T lamp C	lumens	watts	lum eff[4]
#4	20.6	29.0	2569	41.7	61.6
#1	24.9	39.5	2545	41.0	62.1
#1	29.7	39.8	2412	39.5	61.1
#2	20.5	2813	2267	39.8	67.9
#2	26.1	32.1	20.6	33.1	70.8
#2	30.1	37.7	2390	33.7	70.8
#3	21.3	32.0	2974	41.9	70.0
#3	24.8	30.2	2937	41.3	71.1
#3	30.2	40.8	2813	39.9	77.5
#4	21.7	41.6	2539	33.1	86.7
#4	20.6	37.6	2649	39.0	80.3
#3	29.9	40.9	2433	31.4	77.5
#5	22.5	35.2	2816	33.3	86.7
#5	26.1	39.1	2851	32.0	68.5
#5	20.6	40.8	24.8	32.0	87.9
#6	21.7	37.2	2816	41.1	68.5
#6	29.9	39.8	2857	41.6	68.7
#6	30.6	45.7	2804	41.5	67.6

[4] Luminous efficacy in lumens per watt

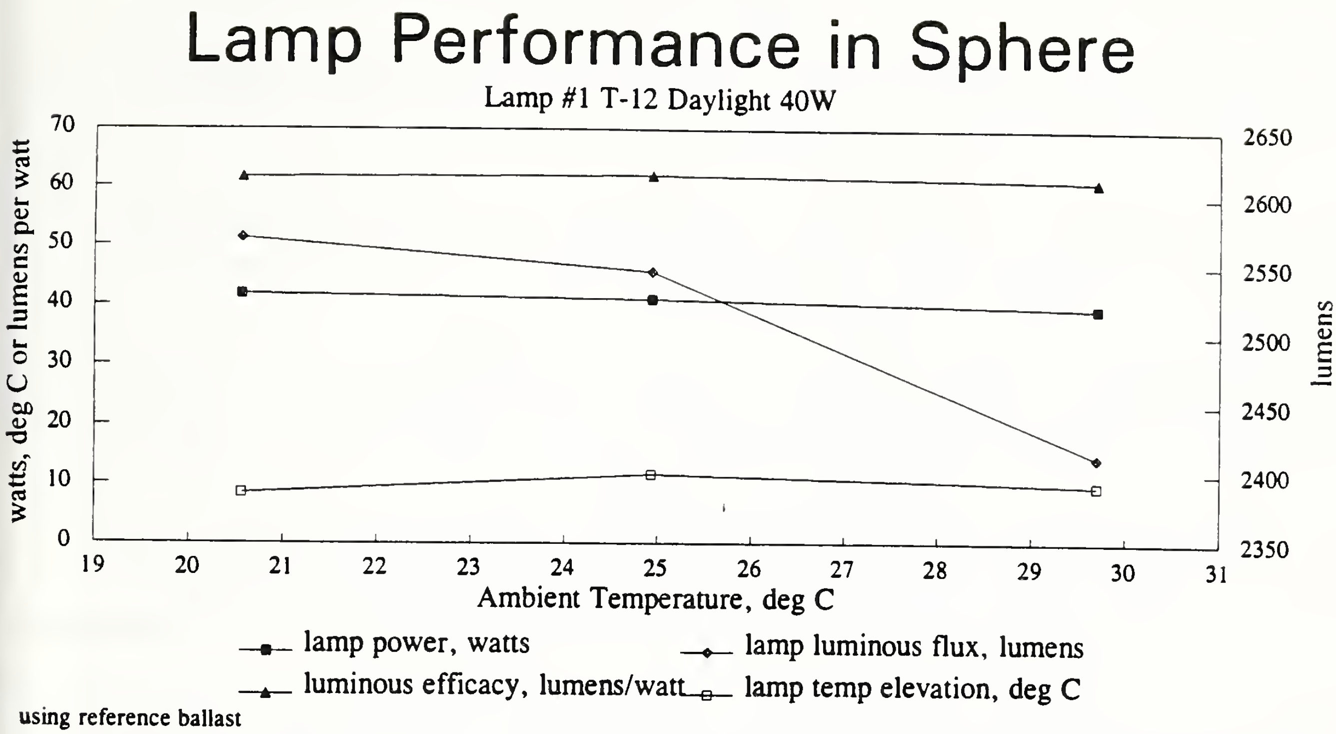

Figure 7. Measured Performance versus Ambient Temperature for Lamp #1.

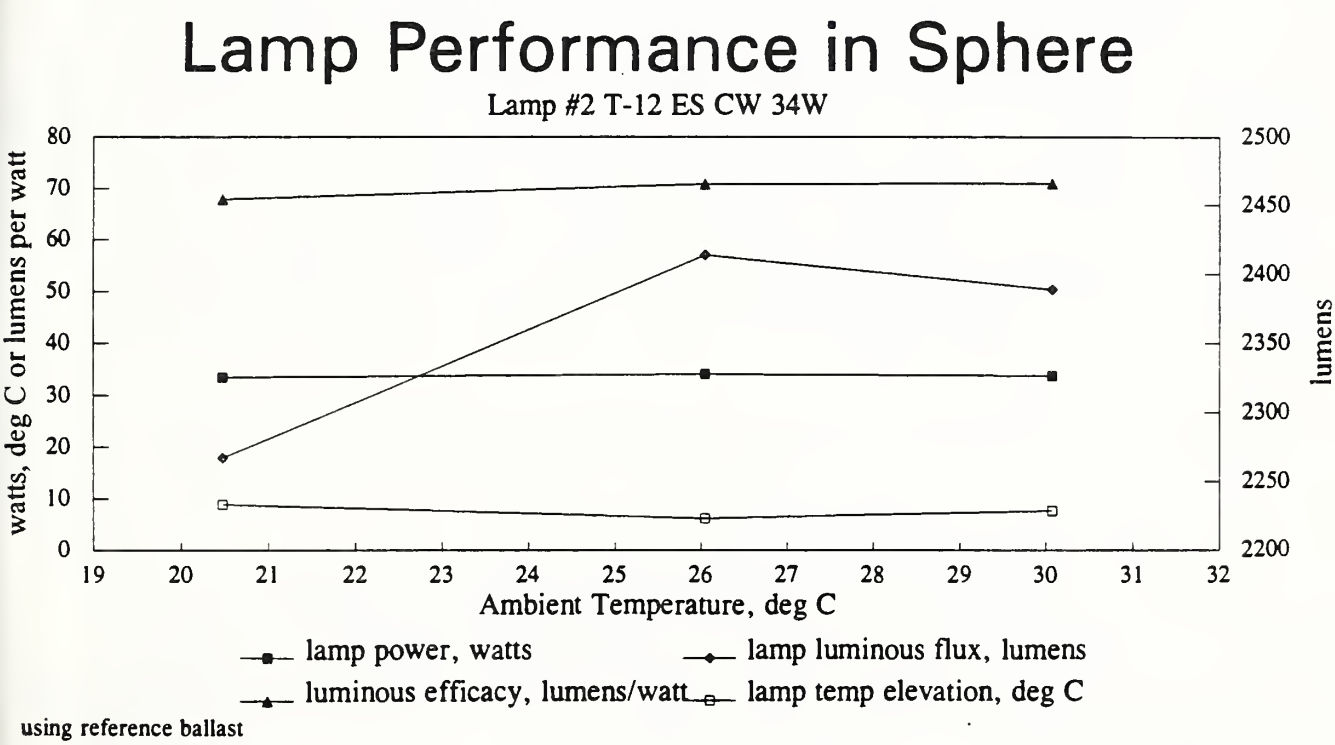

Figure 8. Measured Performance versus Ambient Temperature for Lamp #2.

The measured results for lamp #3 (F40CW) are shown in figure 11. Light output and lamp power were greatest at the coolest ambient temperature, while luminous efficacy peaked at the 25°C condition. Lamp temperature elevation ranged from 10.6 to 12.4 °C.

Figure 10 shows the results for lamp #4 (T8). Light output and efficacy were maximum at the 25°C condition, while lamp power was greatest for the coolest lamp temperature. Lamp temperature elevation ranged from 11.0 to 12.9 °C.

The results for lamp #5 (T8) are shown in figure 11. This lamp provided maximum light output at the coolest condition, but greatest luminous efficacy at the warmest condition. Lamp temperature elevation ranged from 11.2 to 13.0 °C.

The results for the U-shaped lamp, lamp #6, are shown in figure 14. This lamp achieved the greatest light output, and power input at the 25°C condition. Lamp temperature elevation ranged from 12.6 to 15.1°C. Data for a 20°C condition were not available for this lamp, due to changes in the laboratory cooling system.

Inspection of figures 7 through 12 reveals that lamp light output varied among the different lamps as a function of temperature with no consistent patterns emerging, although most showed a decline in output at the warmest ambient temperature (29-30°C). Lamps 4 and 6 had lower outputs at the coolest temperature, while 3 and 5 had higher outputs. The impact on luminous efficacy appears minimal, largely because of the compression of the ordinate by the lumen output scale. Inspection of table 7 reveals changes in luminous efficacy as a function of temperature, although the differences between lamps are greater than the temperature effect. It is important to realize that the absolute light output is markedly reduced for all the lamps at the higher temperatures. The foregoing measurement results are useful for characterizing the intrinsic performance of the different lamp types, and providing lamp data for use in determining lighting system performance such as would be achieved using commercial ballasts rather than a laboratory reference ballast.

The performance characteristics of commercial ballasts, and their link to lamp performance, are discussed in the following section.

5.4 Fluorescent Ballast Measurements

While lamps are measured and characterized while operated by a reference ballast, in actual practice, fluorescent lamps are always operated in conjunction with a commercial ballast. The characteristics of the ballast will affect the performance of the lamp/ballast system, including the light output, power input and luminous efficacy.

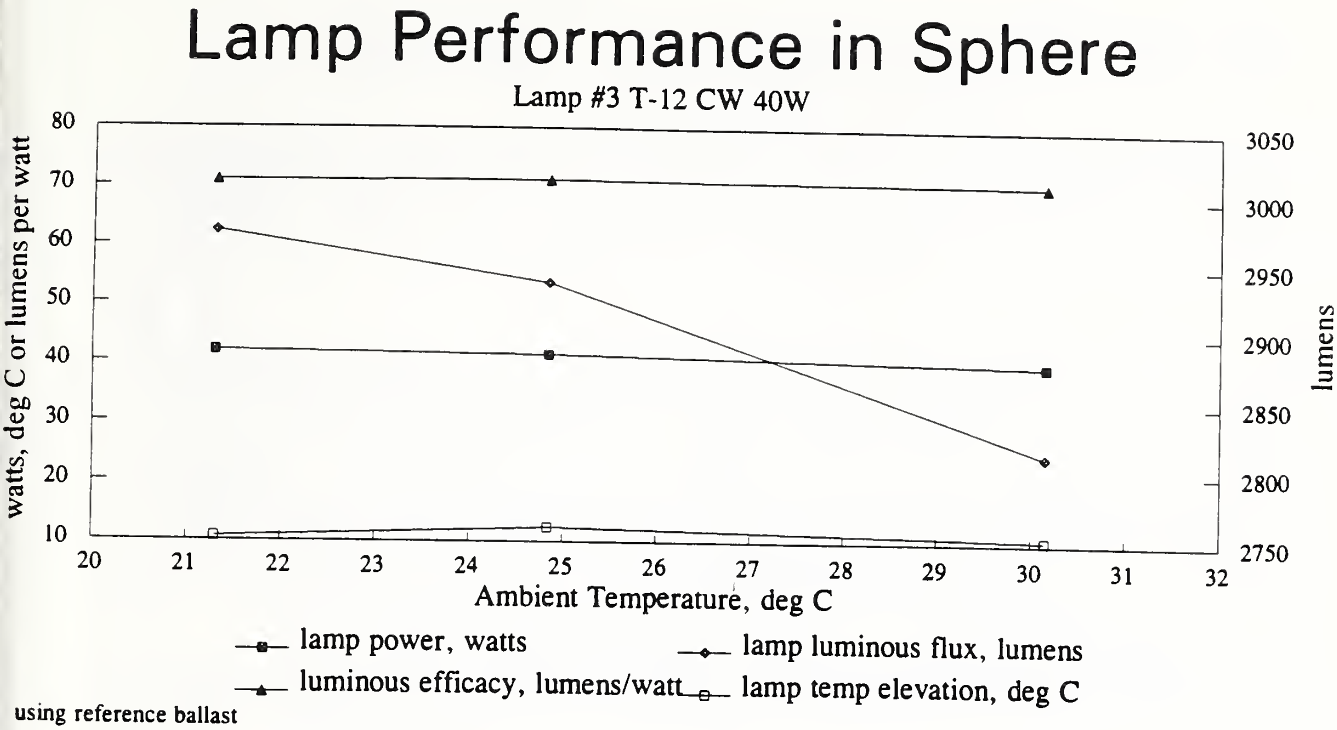

Figure 9. Measured Performance versus Ambient Temperature for Lamp #3.

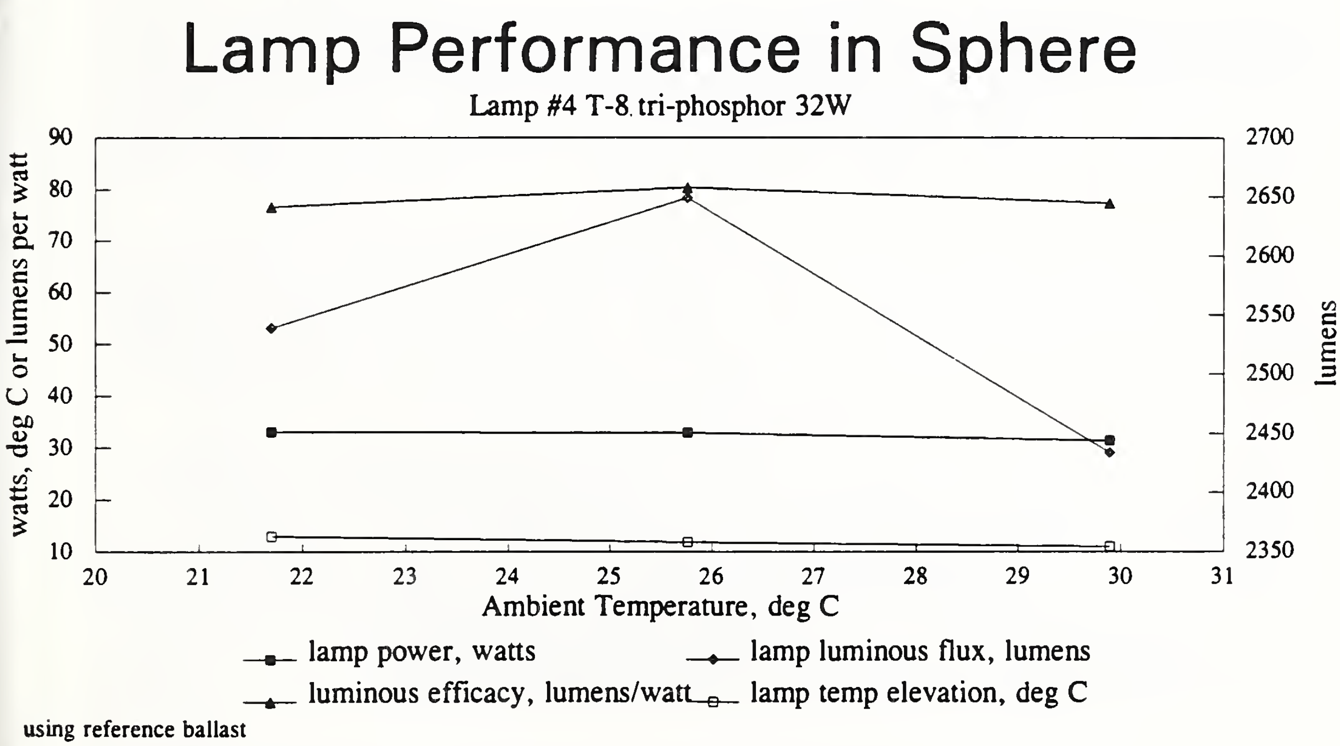

Figure 10. Measured Performance versus Ambient Temperature for Lamp #4.

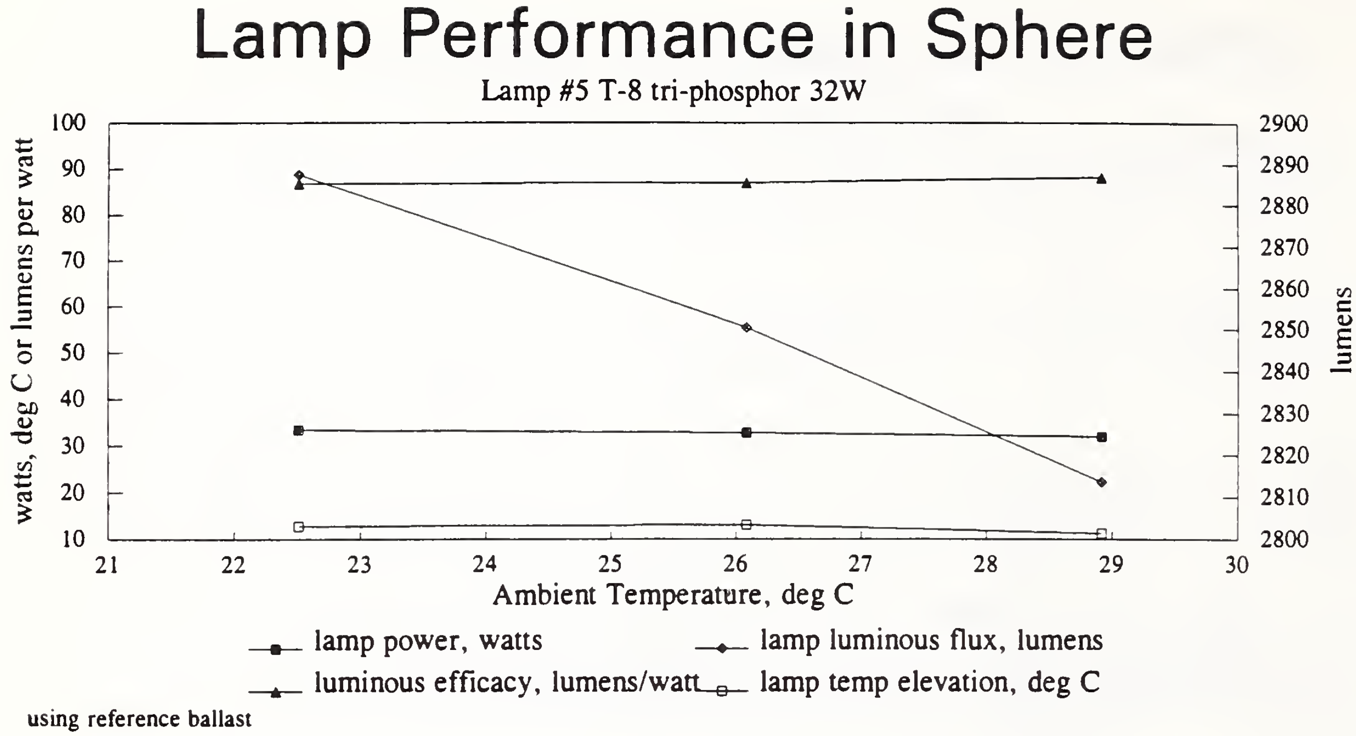

Figure 11. Measured Performance versus Ambient Temperature for Lamp #5.

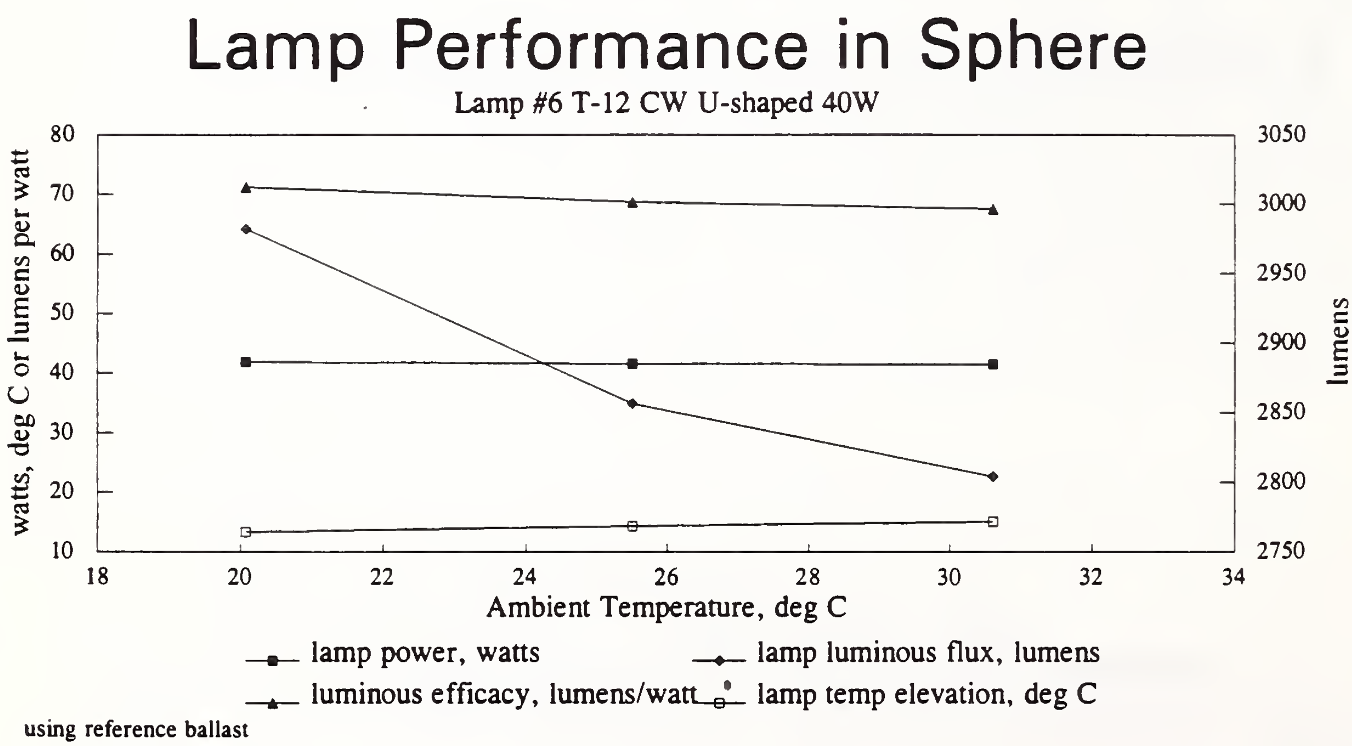

Figure 12. Measured Performance versus Ambient Temperature for Lamp #6.

The traditional method for characterizing ballast performance has been ballast factor (BF), defined as the light output produced by the lamp/ballast combination relative to that produced with the reference ballast. A related parameter is ballast efficiency factor (BEF) which is ballast factor divided by ballast input power.

Ballast factor is normally measured in accordance with ANSI 82.2 at 25°C ambient temperature by sequentially operating a reference lamp with a reference ballast and a test (commercial) ballast and comparing the respective light outputs. While ballast factor is frequently treated as a constant (for each lamp type) the possibility exists that it could vary with lamp temperature, ballast temperature or other factors. It is known that ballast factor varies with lamp type, and must be measured for each lamp type to be operated by the ballast.

Ballast factor was measured for various lamp/ballast combinations at both the 25°C standard condition and for a range of ambient and ballast temperatures. In addition, lamp/ballast power and lamp temperature elevation were also measured. These latter two parameters are needed for subsequent determination of lighting system performance.

Table 8 displays the measurement results obtained for various lamp/ballast combinations at the standard ambient condition of 25°C. The importance of these results lies in the differences in performance of the different combinations, as evidenced by different light output, ballast factor and luminous efficacies, and the similarities in performance for generically similar combinations.

Ballasts #1 and #2 were tested with each of the four T-12 lamps, while ballast #4 was tested with all six lamps, since it could operate both T-8 and T-12 lamps. Ballast #5 was tested with the two T-8 lamps (#4 and #5). Ballast #3, the standard core coil, was tested only with lamps #1, #2, and #3.

In general, the measurement results in table 8 demonstrate the wide range in performance which can be achieved with the various combinations of a relatively limited set of lamps and ballasts. The three main parameters evaluated in the table are the ability of the lamp and ballast to produce light (ballast factor, lumens), the efficiency with which the light is generated (ballast power ratio, luminous efficacy) and the effect of the ballast on lamp temperature (lamp temperature elevation, ballast temperature ratio).

A number of results stand out and can be immediately summarized. Ballast #3, the standard core-coil ballast (of low quality) did not perform well, showing low ballast factors (~0.5), low light output (~1200 lumens) and low efficacy (~45 lumens/watt).

Table 8. Ballast Measurement Results at 25°C

ballast	lamp	test bal w	test t elev	BF	BPR	BTR	lumens	lum eff l/w
1	1	46.21	12.1	0.9253	1.1170	0.8700	2355	51.0
1	2	40.34	10.7	0.8862	1.1562	1.0019	2139	53.0
1	3	46.44	13.5	0.9096	1.0957	0.9547	2671	57.5
1	6	47.75	13.6	0.8715	1.0936	0.9532	2490	52.1
2	1	35.07	10.6	0.8914	0.8400	0.8297	2269	64.7
2	2	29.64	8.9	0.8916	0.8658	0.9479	2152	72.6
2	3	36.92	13.2	0.8892	0.8585	0.8784	2611	70.7
2	6	36.26	15.2	0.8594	0.8291	0.9453	2455	67.7
3	1	27.76	11.3	0.4771	0.6722	1.0000	1214	43.7
3	2	27.56	4.3	0.5188	0.7951	0.4365	1252	45.4
3	3	28.20	12.8	0.4836	0.6666	0.8937	1420	50.4
4	1	36.42	13.3	0.8657	0.8696	0.9348	2204	60.5
4	2	33.85	11.2	0.9315	0.9702	1.0210	2249	66.4
4	3	36.57	9.6	0.8469	0.8542	0.8885	2487	68.0
4	4	38.34	15.1	1.0551	1.0329	0.9344	2795	72.9
4	5	38.05	11.7	1.0476	1.1249	0.9415	2986	78.5
4	6	36.51	13.6	0.8667	0.8492	0.8978	2476	67.8
5	4	40.48	16.6	1.1077	1.0959	1.0203	2934	72.5
5	5	40.17	12.5	1.1269	1.1904	1.0443	3212	80.0

BF-ballast factor BPR-ballast power ratio BTR-ballast temperature ratio

Luminous efficacy would have been even lower, except ballast #3 did not use much power (~28 watts). At the other extreme, ballast #5, the electronic instant start T-8 ballast, had ballast factors greater than one (1.11 to 1.13), the greatest light output (2934 to 3212 lumens) and luminous efficacies above 72 lumens/watt. It should be noted that although ballast #5 operates the lamps in the instant start mode (i.e. no cathode power), the lamps were the same rapid start types used with the other ballasts. Any potential effects of the lack of cathode heating on lamp life were not investigated, but may bear some consideration.

Ballast #4 (an electronic IC) also performed well, particularly with the T-8 lamps (#4 and #5) where ballast factors were about 1.05, light output exceeded 2800 lumens and efficacy was above 73 lumens/watt. Although ballast #1 and ballast #2 provided about the same light output, #2 used less power (due to being electronic) thus resulting in higher luminous efficacies. Ballast #2, which was electronic and intended only for T-12 lamps, provided more light at higher efficiency than ballast #4, which was also electronic, when ballast #4 was paired with the T-12 lamps.

Lamp #5, the high output T-8, provided the most light and the highest efficacies. Lamp #4 (also a T-8) was almost as good, reaching about 92% of the values for lamp #5. Lamp #1, the T-12 daylight lamp, had the lowest efficacies, a byproduct of its emphasis on daylight spectral output at the expense of efficiency. Lamp #2, the energy saving, cool white (34W) T-12 had the lowest light output as a consequence of its lower power usage, but its luminous efficacy was similar to the 40W T-12 cool white (lamp #3). Lamp #6, the U-shaped lamp, was similar to lamps 1 and 2.

In order to focus on efficiency, the measurement results were ranked according to luminous efficacy, including measurements for a range of ambient temperatures. Not all lamp/ballast combinations were tested at a range of temperatures; temperature was varied for ballast #1 with lamp #3, ballast #4 for lamps #3 and #4, and ballast #5 with lamp #4. This procedure allowed the evaluation of the sensitivity of an energy saving core coil ballast and electronic ballast to ambient temperature.

Table 9 displays the measurement results ranked by luminous efficacy. The highest efficacy, 80.0 lumens/watt, was achieved by ballast #5 with lamp #5. This performance, at an ambient temperature of 25°C, was slightly better than ballast #4. The temperature dependance of ballast performance is discussed below.

In general, table 9 shows that the electronic ballasts had the highest luminous efficacies and ballast factors, with the T-8 lamp/electronic ballasts having the highest. These combinations provided more light, used more power and frequently operated the lamp at a higher temperature than the reference ballast circuit.

Table 9. Lamp/Ballast Combinations Ranked by Luminous Efficacy

ballast	lamp	test bal w	test lamp t	test t elev	BF	BPR	BTR	lumens	lum eff
5	5	40.17	38.2	12.5	1.1269	1.1904	1.0443	3212	80.0
4	5	38.05	37.3	11.7	1.0476	1.1249	0.9415	2986	78.5
4	4	38.13	45.9	15.8	1.1008	1.0580	1.0624	2916	76.5
5	4	39.62	46.8	17.9	1.1142	1.0749	1.0953	2952	74.5
4	4	38.34	41.2	15.1	1.0551	1.0329	0.9344	2795	72.9
2	2	29.64	33.5	8.9	0.8916	0.8658	0.9479	2152	72.6
5	4	40.48	41.9	16.6	1.1077	1.0959	1.0203	2934	72.5
5	4	41.04	39.8	17.9	1.1024	1.0808	1.2344	2920	71.2
2	3	36.92	37.6	13.2	0.8892	0.8585	0.8784	2611	70.7
4	3	36.57	41.7	11.4	0.8736	0.8570	0.8249	2566	70.2
4	4	37.45	36.2	14.8	0.9883	0.9836	0.9572	2618	69.9
4	3	34.50	34.1	12.7	0.8061	0.7908	0.8666	2367	68.6
4	3	36.57	36.1	9.6	0.8469	0.8542	0.8885	2487	68.0
4	6	36.49	42.6	12.6	0.8687	0.8355	0.8037	2482	68.0
2	6	36.42	42.8	12.3	0.8656	0.8580	0.8561	2473	67.9
4	6	36.51	39.3	13.6	0.8667	0.8492	0.8978	2476	67.8
2	6	36.26	41.1	15.2	0.8594	0.8291	0.9453	2455	67.7
4	2	33.85	37.4	11.2	0.9315	0.9702	1.0210	2249	66.4
2	1	35.07	34.8	10.6	0.8914	0.8400	0.8297	2269	64.7
4	1	36.42	39.9	13.3	0.8657	0.8696	0.9348	2204	60.5
1	3	45.13	35.3	13.7	0.8888	1.0365	0.9364	2610	57.8
1	3	46.44	39.2	13.5	0.9096	1.0957	0.9547	2671	57.5
1	3	46.30	42.3	12.2	0.9035	1.0957	0.8660	2653	57.3
1	6	46.94	44.1	13.7	0.89	1.0931	0.9751	2542	54.2
1	2	40.34	36.5	10.7	0.8862	1.1562	1.0019	2139	53.0
1	6	47.75	39.2	13.6	0.8715	1.0936	0.9532	2490	52.1
1	1	46.21	37.8	12.1	0.9253	1.1170	0.8700	2355	51.0
3	3	28.20	37.9	12.8	0.4836	0.6666	0.8937	1420	50.4
3	2	27.56	29.7	4.3	0.5188	0.7951	0.4365	1252	45.4
3	1	27.76	36.6	11.3	0.4771	0.6722	1.0000	1214	43.7

BF-ballast factor BPR-ballast power ratio BTR-ballast temperature ratio

The energy saving core coil ballast (#1), while showing better performance than the standard core coil ballast (#3), had only 80% of the efficiency of a T-8 lamp with an electronic ballast, and only 70% of the efficiency of a T-12 lamp with an electronic ballast.

It should be noted that the luminous efficacy values reported here for the lamp ballast combinations are based on power input to the ballast, which includes both arc and cathode power, where appropriate, and ballast losses. This is in contrast to the luminous efficacy values reported for the lamps operated by a reference ballast, which were based only on lamp arc and cathode power.

The effect of ambient temperature on lamp ballast performance is evaluated in a series of figures, showing ballast factor, light output and luminous efficacy as functions of lamp temperature, based on measurements at different ambient temperatures. Figure 13 shows the results for ballast #1 and lamp #3. Luminous efficacy was fairly constant over the range of temperatures, while the ballast factor increased slightly with temperature. Light output, however, was greatest at the middle temperature of about 39°C.

Figure 14 presents similar results for ballast #4 with lamp #3. Both ballast factor and light output increased with temperature, although efficacy increased somewhat less due to a corresponding increase in power input.

Figure 15 shows the temperature dependence of ballast #4 with lamp #4. Luminous efficacy and ballast factor were very sensitive to temperature, varying by more than ten percent over the range of temperatures tested.

Figure 16 summarizes the results for ballast #5 with lamp #4. Light output increased with temperature, as did luminous efficacy and ballast factor, although to a lesser extent.

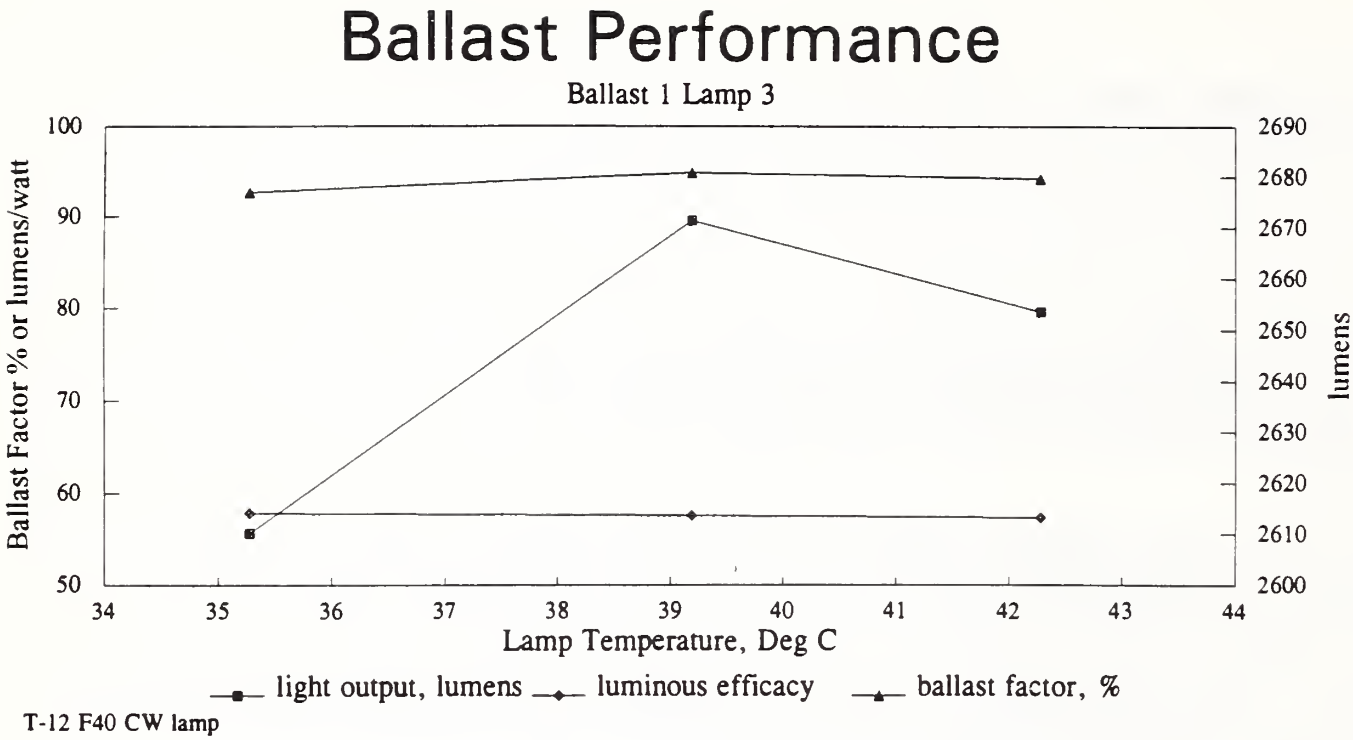

Figure 13. Measured Performance of Ballast 1 with Lamp #3.

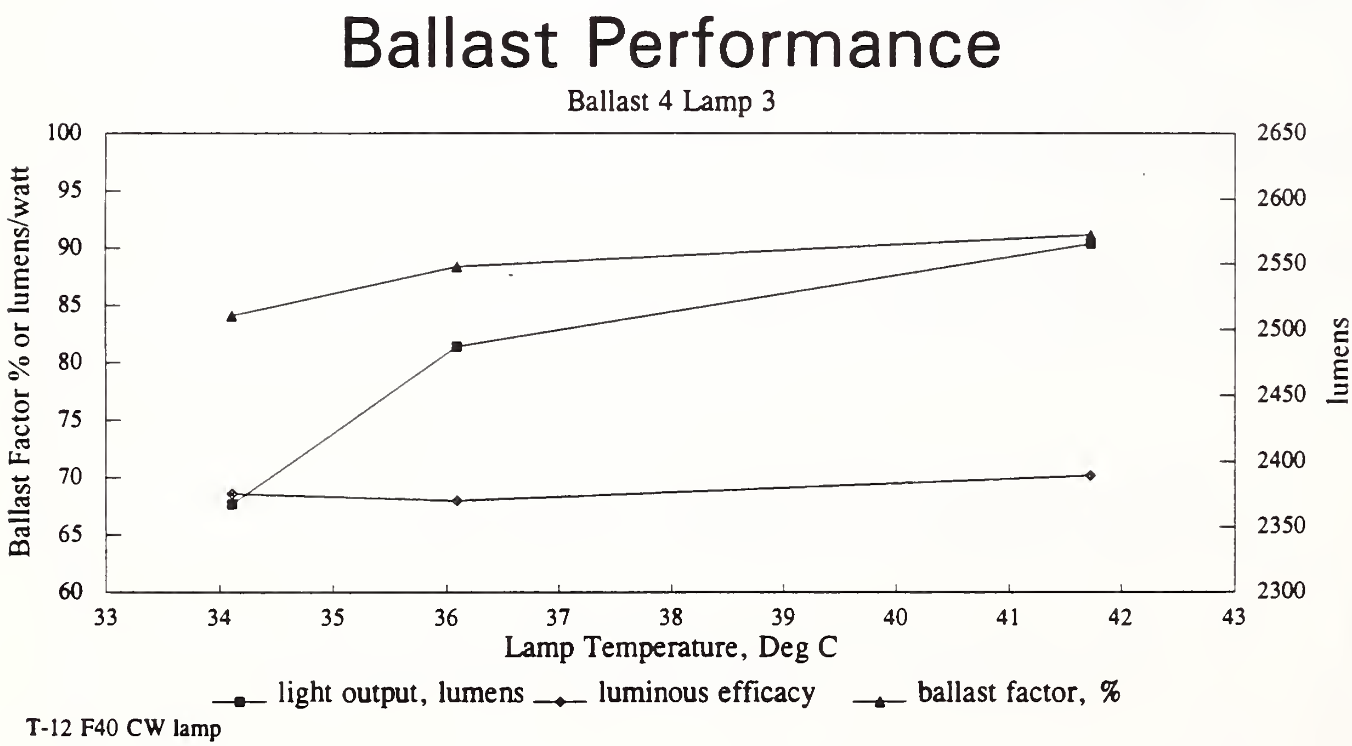

Figure 14. Measured Performance of Ballast 4 with Lamp #3.

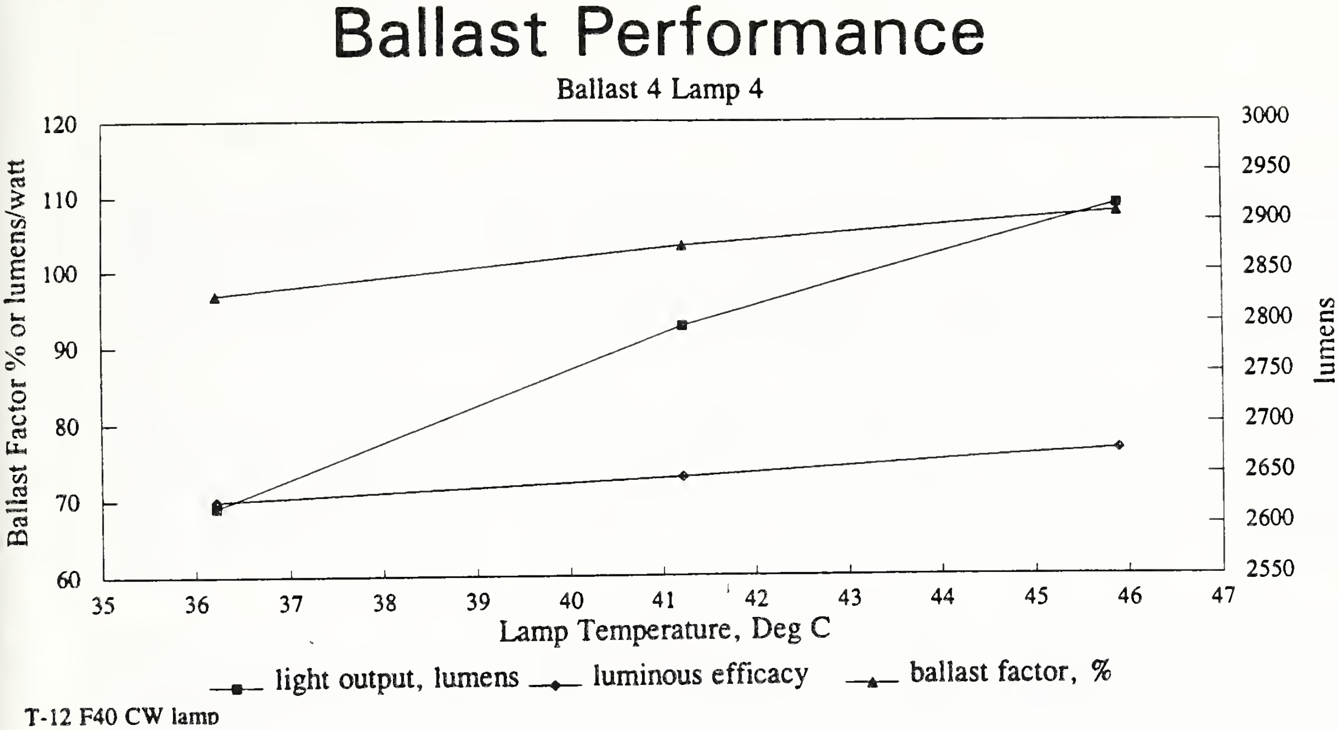

Figure 15. Measured Performance of Ballast 4 with Lamp #4.

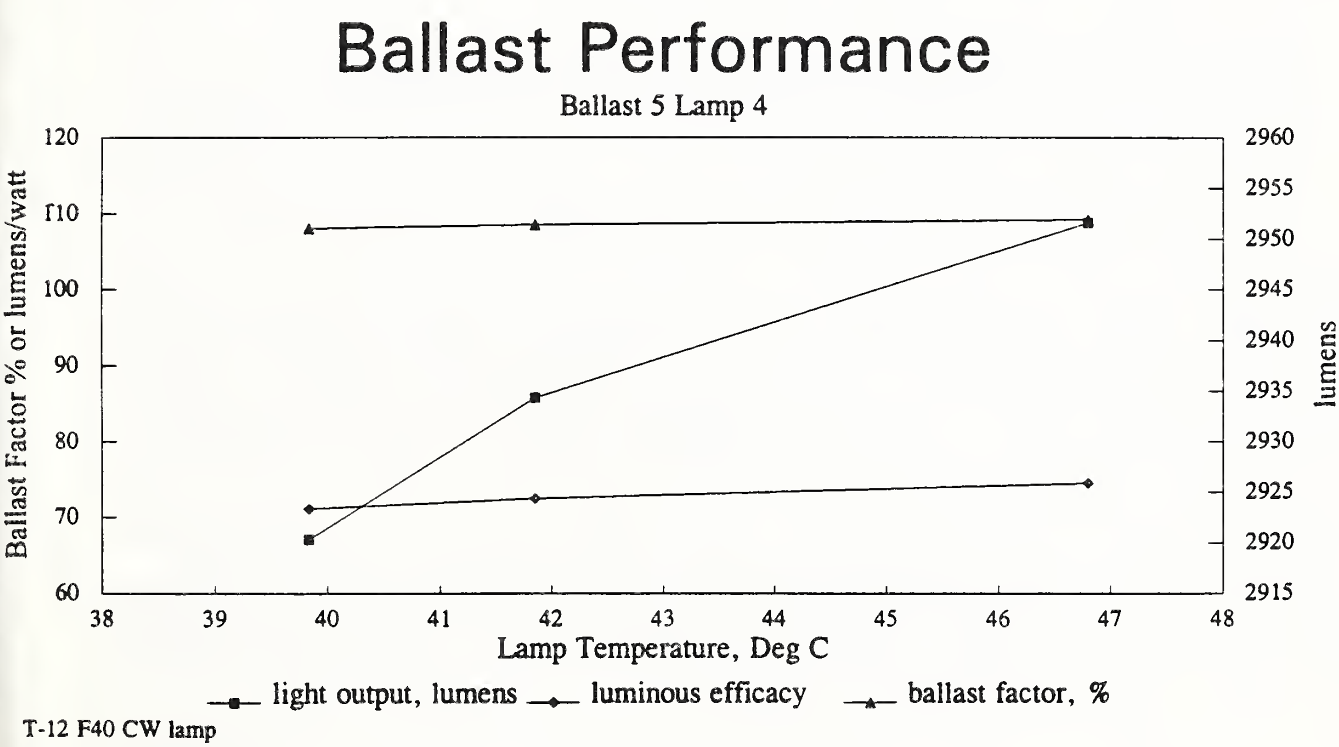

Figure 16. Measured Performance of Ballast 5 with Lamp #4.

5.5 Fixture Measurement Results

Six fixture types each having two lamps were evaluated. The influence of the fixture on lighting system performance is primarily optical, as the fixture directs the light from the lamps to the building interior space, absorbing some light in the process. The fixture also affects lamp temperature as it changes the thermal environment surrounding the lamp.

The optical performance of the fixture is characterized by its optical efficiency which can be defined as the fraction of light emitted by the lamps which is distributed by the fixture. Although the optical efficiency is high for a bare lamp, the glare is generally unacceptable. Thus, the lighting system efficiency is reduced to control glare and stray light from the fixture.

Optical efficiency is measured in a large photometry facility, such as a mirror photometer, usually in conjunction with the measurement of light distribution from the fixture. Since such a facility was not available at NIST, manufacturer's data were used. These data were determined from independent laboratory testing.

The thermal effects of the fixtures, as they influence light output, were measured in the NIST laboratory. This allowed the effect of each fixture on lamp temperature elevation to be characterized. The procedure was as follows:

> The lamps were operated under benchtop conditions at 25°C ambient and the lamp temperature was measured. Then the lamps, but not the ballast, were installed in the fixture, and the increase in lamp temperature due to the fixture was noted. (The ballast remained outside the fixture.) Finally, the ballast was also installed in the fixture and any change in lamp temperature due to ballast heat dissipation was measured.

Table 10 shows the measured temperature elevation data and optical efficiencies for each fixture. The highest optical efficiencies were obtained for fixture 1 (open cell parabolic 0.6x1.2 m (2x4 ft)) at 0.681 and fixture 3 (wrap-around prismatic lens 0.3x1.2 m (1x4 ft)) at 0.686. Optical efficiencies for the other four fixtures ranged from 0.59 to 0.63.

The acrylic lensed fixtures caused lamp temperatures to increase by 6 to 9°C, above what they would be for bare lamps. By contrast, the large cell parabolic fixtures only increased lamp temperatures by 2 to 3°C. The presence of the ballast in the fixture caused the lamps to run 0.5 to 2°C warmer than otherwise, depending on the proximity of the ballast to the lamp.

5.6 Lighting System Performance Results

The various lamps, ballasts and fixtures tested, when combined in different permutations, represent a large number of potential lighting systems. The performance of each lighting system is a function of the electrical, thermal and optical interactions between the components. In order to evaluate the performance of each of the lighting systems, the measured electrical, thermal and optical characteristics of each component were combined as described earlier in this report to determine the system performance of each potential combinations of components. Each allowable fixture/ballast/lamp combination was evaluated. Some combinations were not allowable, since a ballast might be limited to T-12 lamps, or a fixture might be designed only for U-shaped lamps.

The number of allowable lighting system combinations was 70. Table 11 lists the configuration and performance of each system. System performance is characterized by power input, light output and luminous efficacy. A wide range of lighting system performance is apparent from an inspection of table 11.

It should be noted that some of the difference in performance for the different lighting systems can be attributed to specific fixture characteristics rather than the generic fixture type. For example the luminous efficacy of a fixture with an acrylic lens is strongly dependent on the transmittance of the lens, which can vary by 10% or more, depending on the manufacturer. The two lenses measured here differed by almost 15% in transmittance, in fact. As a result, the results reported here are for the specific fixtures measured, and may not be applicable to other fixtures with different characteristics.

The various lighting systems were ranked according to luminous efficacy in table 12 and in order of light output in table 13 to enable performance to be compared more easily. Efficacy, which is based on power input to the fixture and light output from the fixture, varied from 20 to 57 lumens per watt. The T-8 lamp and ballast systems with fixture 3 showed the best performance at over 57 lumens per watt. The energy saving T-12 lamp (#2) with the electronic ballast #2 also performed well, (52 lumens/watt) as did the standard cool white lamp (#3) with electronic ballast #2 (51 lumens/watt).

The best performance for a core coil ballast was ballast #1 with lamp #3, at about 41 lumens/watt. The highest efficacy for a U-shaped lamp fixture was 48 lumens/watt with ballasts #2 and #4.

In terms of light output, the rankings were similar, although ballast #1, the energy saving core coil ballast, moved up in the rankings.

Table 10. Fixture Measurement Data

Fixture	Size	Type	Optical Eff	Fixt TE C	Bal TE C	Total TE C
1	2x4	small cell	0.461	6.83	1.54	8.37
2	1x4	prismatic	0.57	8.49	0.69	9.18
3	1x4	wraparound	0.721	9.1	0.16	9.26
4	1x4	large cell	0.556	2.83	0.97	3.8
5	2x2	prismatic	0.707	2.41	0.43	2.84
6	2x2	large cell	0.647	6.7	2.4	9.1

Fixt TE- lamp temp elev due to fixture, Bal TE-lamp temp elev due to ballast

Table 11. Lighting System Performance

system	fixture	ballast	lamp	power w	fixt lumens	efficacy
1	1	1	1	92.4	2172	23.5
2	1	1	2	80.7	1972	24.4
3	1	1	3	92.9	2463	26.5
4	1	2	1	70.1	2092	29.8
5	1	2	2	59.3	1984	33.5
6	1	2	3	73.8	2408	32.6
7	1	3	1	55.5	1120	20.2
8	1	3	2	55.1	1155	20.9
9	1	3	3	56.4	1309	23.2
10	1	4	1	72.8	2032	27.9
11	1	4	2	67.7	2073	30.6
12	1	4	3	73.1	2293	31.4
13	1	4	4	76.7	2577	33.6
14	1	4	5	76.1	2753	36.2
15	1	5	4	81.0	2705	33.4
16	1	5	5	80.3	2962	36.9
17	2	1	1	92.4	2685	29.1
18	2	1	2	80.7	2439	30.2
19	2	1	3	92.9	3045	32.8
20	2	2	1	70.1	2587	36.9
21	2	2	2	59.3	2454	41.4
22	2	2	3	73.8	2977	40.3
23	2	3	1	55.5	1384	24.9
24	2	3	2	55.1	1428	25.9
25	2	3	3	56.4	1619	28.7
26	2	4	1	72.8	2512	34.5
27	2	4	2	67.7	2564	37.9
28	2	4	3	73.1	2835	38.8
29	2	4	4	76.7	3186	41.6
30	2	4	5	76.1	3404	44.7
31	2	5	4	81.0	3345	41.3
32	2	5	5	80.3	3662	45.6
33	2	1	1	92.4	2685	29.1
34	3	1	2	80.7	3085	38.2
35	3	1	3	92.9	3852	41.5
36	3	2	1	70.1	3272	46.6
37	3	2	2	59.3	3104	52.4
38	3	2	3	73.8	3766	51.0
39	3	3	1	55.5	1751	31.5
40	3	3	2	55.1	1806	32.8
41	3	3	3	56.4	2048	36.3
42	3	4	1	72.8	3178	43.6
43	3	4	2	67.7	3243	47.9
44	3	4	3	73.1	3586	49.0
45	3	4	4	76.7	4030	52.6
46	3	4	5	76.1	4306	56.6
47	3	5	4	81.0	4231	52.3
48	3	5	5	80.3	4632	57.7
49	3	1	1	92.4	3396	36.7
50	4	1	2	80.7	2379	29.5
51	4	1	3	92.9	2970	32.0
52	4	2	1	70.1	2523	36.0
53	4	2	2	59.3	2393	40.4
54	4	2	3	73.8	2904	39.3
55	4	3	1	55.5	1350	24.3
56	4	3	2	55.1	1393	25.3
57	4	3	3	56.4	1579	28.0
58	4	4	1	72.8	2450	33.6
59	4	4	2	67.7	2501	36.9
60	4	4	3	73.1	2766	37.8
61	4	4	4	76.7	3108	40.5
62	4	4	5	76.1	3321	43.6
63	4	5	4	81.0	3263	40.3
64	4	5	5	80.3	3572	44.5
65	5	1	6	95.5	3520	36.9
66	5	2	6	72.5	3471	47.9
67	5	4	6	73.0	3501	47.9
68	6	1	6	95.5	3222	33.7
69	6	2	6	72.5	3177	43.8
70	6	4	6	73.0	3204	43.9

Table 12. Lighting System Efficiency

system	fixture	ballast	lamp	power w	fixt lumens	efficacy
48	3	5	5	80.3	4632	57.7
46	3	4	5	76.1	4306	56.6
45	3	4	4	76.7	4030	52.6
37	3	2	2	59.3	3104	52.4
47	3	5	4	81.0	4231	52.3
38	3	2	3	73.8	3766	51.0
44	3	4	3	73.1	3586	49.0
67	5	4	6	73.0	3501	47.9
43	3	4	2	67.7	3243	47.9
66	5	2	6	72.5	3471	47.9
36	3	2	1	70.1	3272	46.6
32	2	5	5	80.3	3662	45.6
30	2	4	5	76.1	3404	44.7
64	4	5	5	80.3	3572	44.5
70	6	4	6	73.0	3204	43.9
69	6	2	6	72.5	3177	43.8
62	4	4	5	76.1	3321	43.6
42	3	4	1	72.8	3178	43.6
29	2	4	4	76.7	3186	41.6
35	3	1	3	92.9	3852	41.5
21	2	2	2	59.3	2454	41.4
31	2	5	4	81.0	3345	41.3
61	4	4	4	76.7	3108	40.5
53	4	2	2	59.3	2393	40.4
22	2	2	3	73.8	2977	40.3
63	4	5	4	81.0	3263	40.3
54	4	2	3	73.8	2904	39.3
28	2	4	3	73.1	2835	38.8
34	3	1	2	80.7	3085	38.2
27	2	4	2	67.7	2564	37.9
60	4	4	3	73.1	2766	37.8
59	4	4	2	67.7	2501	36.9
20	2	2	1	70.1	2587	36.9
16	1	5	5	80.3	2962	36.9
65	5	1	6	95.5	3520	36.9
49	3	1	1	92.4	3396	36.7
41	3	3	3	56.4	2048	36.3
14	1	4	5	76.1	2753	36.2
52	4	2	1	70.1	2523	36.0
26	2	4	1	72.8	2512	34.5
68	6	1	6	95.5	3222	33.7
58	4	4	1	72.8	2450	33.6
13	1	4	4	76.7	2577	33.6
5	1	2	2	59.3	1984	33.5
15	1	5	4	81.0	2705	33.4
19	2	1	3	92.9	3045	32.8
40	3	3	2	55.1	1806	32.8
6	1	2	3	73.8	2408	32.6
51	4	1	3	92.9	2970	32.0
39	3	3	1	55.5	1751	31.5
12	1	4	3	73.1	2293	31.4
11	1	4	2	67.7	2073	30.6
18	2	1	2	80.7	2439	30.2
4	1	2	1	70.1	2092	29.8
50	4	1	2	80.7	2379	29.5
33	2	1	1	92.4	2685	29.1
17	2	1	1	92.4	2685	29.1
25	2	3	3	56.4	1619	28.7
57	4	3	3	56.4	1579	28.0
10	1	4	1	72.8	2032	27.9
3	1	1	3	92.9	2463	26.5
24	2	3	2	55.1	1428	25.9
56	4	3	2	55.1	1393	25.3
23	2	3	1	55.5	1384	24.9
2	1	1	2	80.7	1972	24.4
55	4	3	1	55.5	1350	24.3
1	1	1	1	92.4	2172	23.5
9	1	3	3	56.4	1309	23.2
8	1	3	2	55.1	1155	20.9
7	1	3	1	55.5	1120	20.2

Ranked by Luminous Efficacy

Table 13. Lighting System Light Output

system	fixture	ballast	lamp	power w	fixt lumens	efficacy
48	3	5	5	80.3	4632	57.7
46	3	4	5	76.1	4306	56.6
47	3	5	4	81.0	4231	52.3
45	3	4	4	76.7	4030	52.6
35	3	1	3	92.9	3852	41.5
38	3	2	3	73.8	3766	51.0
32	2	5	5	80.3	3662	45.6
44	3	4	3	73.1	3586	49.0
64	4	5	5	80.3	3572	44.5
65	5	1	6	95.5	3520	36.9
67	5	4	6	73.0	3501	47.9
66	5	2	6	72.5	3471	47.9
30	2	4	5	76.1	3404	44.7
49	3	1	1	92.4	3396	36.7
31	2	5	4	81.0	3345	41.3
62	4	4	5	76.1	3321	43.6
36	3	2	1	70.1	3272	46.6
63	4	5	4	81.0	3263	40.3
43	3	4	2	67.7	3243	47.9
68	6	1	6	95.5	3222	33.7
70	6	4	6	73.0	3204	43.9
29	2	4	4	76.7	3186	41.6
42	3	4	1	72.8	3178	43.6
69	6	2	6	72.5	3177	43.8
61	4	4	4	76.7	3108	40.5
37	3	2	2	59.3	3104	52.4
34	3	1	2	80.7	3085	38.2
19	2	1	3	92.9	3045	32.8
22	2	2	3	73.8	2977	40.3
51	4	1	3	92.9	2970	32.0
16	1	5	5	80.3	2962	36.9
54	4	2	3	73.8	2904	39.3
28	2	4	3	73.1	2835	38.8
60	4	4	3	73.1	2766	37.8
14	1	4	5	76.1	2753	36.2
15	1	5	4	81.0	2705	33.4
33	2	1	1	92.4	2685	29.1
17	2	1	1	92.4	2685	29.1
20	2	2	1	70.1	2587	36.9
13	1	4	4	76.7	2577	33.6
27	2	4	2	67.7	2564	37.9
52	4	2	1	70.1	2523	36.0
26	2	4	1	72.8	2512	34.5
59	4	4	2	67.7	2501	36.9
3	1	1	3	92.9	2463	26.5
21	2	2	2	59.3	2454	41.4
58	4	4	1	72.8	2450	33.6
18	2	1	2	80.7	2439	30.2
6	1	2	3	73.8	2408	32.6
53	4	2	2	59.3	2393	40.4
50	4	1	2	80.7	2379	29.5
12	1	4	3	73.1	2293	31.4
1	1	1	1	92.4	2172	23.5
4	1	2	1	70.1	2092	29.8
11	1	4	2	67.7	2073	30.6
41	3	3	3	56.4	2048	36.3
10	1	4	1	72.8	2032	27.9
5	1	2	2	59.3	1984	33.5
2	1	1	2	80.7	1972	24.4
40	3	3	2	55.1	1806	32.8
39	3	3	1	55.5	1751	31.5
25	2	3	3	56.4	1619	28.7
57	4	3	3	56.4	1579	28.0
24	2	3	2	55.1	1428	25.9
56	4	3	2	55.1	1393	25.3
23	2	3	1	55.5	1384	24.9
55	4	3	1	55.5	1350	24.3
9	1	3	3	56.4	1309	23.2
8	1	3	2	55.1	1155	20.9
7	1	3	1	55.5	1120	20.2

Ranked by Lumen Output

Excluding the systems with ballast #3, the lowest light output was provided by lamps #1 and #2, the daylight and energy saving T-12 lamps, which produced only 62 percent of the light produced by the highest output systems. Fixture #3 provided the greatest light output by virtue of its high optical efficiency, while fixture #1 generally provided lower light output because its small-cell parabolic diffuser had a low effective transmittance.

The open-cell parabolic fixtures were generally less efficient than the lensed fixtures, due to their lower optical efficiency. Parabolic fixtures are, however, usually selected on the basis of their light distribution properties (such as reduced glare) rather than overall light output so these results are not particularly surprising.

6. Summary and Conclusions

This report describes the results from a research project intended to develop methods for designing and selecting efficient and effective lighting systems for federal office buildings. It includes a review of current GSA and IES lighting design guidelines and a discussion of relevant testing and rating procedures.

In addition, a comprehensive procedure for measuring and evaluating lighting components and systems was developed and used to assess the performance of a range of typical office lighting equipment. This procedure accounted for interactions between different components of a lighting system. Lighting component interactions fall into three categories: electrical, thermal and optical. The electrical interaction involves the lamp and ballast, while the thermal interactions include all of the components. The optical interaction relates to the lamp and fixture. The performance characteristics of lighting systems and their dependence on interactions between lighting system components was also discussed.

The procedure was applied to measurements of lighting system component performance and to total lighting system performance based on the component characteristics. The method for determining lighting system performance involved the prediction of lamp lumen output with a specific ballast at the lamp temperature which is likely to occur in the specific fixture, adjusted for the absorption of light by the fixture, and the prediction of system power input under the same conditions. Lighting system performance can be predicted, and therefore evaluated and rated, through knowledge of the temperature dependent characteristics of the lamp and ballast combination, the optical efficiency of the fixture and the determination of lamp temperature.

In this study, the performance of various fluorescent lamps was evaluated by measuring their light output, power input and luminous efficacy. The measurements were performed in the laboratory using a reference ballast and an integrating sphere photometer, along with appropriate transducers to monitor lamp voltage, current and power. However, rather than performing the measurement only at a 25°C ambient air temperature, the temperature dependence of the lamp lumen output was characterized by varying ambient temperature from 20 to 30°C, while also measuring minimum lamp wall temperature and lamp power. Thus, light output and power input were determined for each lamp type as functions of minimum lamp temperature. Lamp temperature elevation over ambient air temperature also was calculated from these measurements and plotted. The lamp characteristics were measured independently of any specific ballast or fixture.

Ballast performance was then characterized for each generic lamp type which the ballast was designed to operate. Ballast factor was measured, along with ballast input power and lamp temperature, for a range of ambient temperatures. This procedure was repeated for each type of lamp, such as F40CW or energy-saving lamps, which the ballast could operate. The resulting information was tabulated and plotted as a function of lamp temperature.

A new parameter which was also measured was the ratio of test ballast input power to total power input under the reference condition (i.e. reference ballast and cathode heater inputs). This ratio is similar in concept to the ballast factor, except that it deals with electrical power rather than light. The quantity could be denoted as the ballast factor for power, but a less confusing, more concise name might be 'Ballast Power Ratio'. The ballast power ratio is important because it allows for variations in lamp power to be accounted for in a manner similar to that used for lamp light output. This technique enables ballast performance to be determined using generic lamp types, rather than specific lamps, thereby reducing the number of lamp/ballast combinations to be tested.

In a similar manner, the influence of the ballast on lamp temperature elevation was accounted for by determining the ratio of lamp temperature elevation with the test ballast to lamp temperature elevation with the reference ballast. This quantity can be termed the 'Ballast Temperature Ratio', keeping in mind that it is actually referring to the lamp temperature when operated by the specific ballast. The ballast temperature ratio is a significant parameter because it accounts for the different thermal conditions which may be obtained for specific lamp and ballast combinations, primarily as the result of the electrical interactions between the lamp and ballast.

To evaluate overall lighting system performance, measurements were performed on six fluorescent lamp types, five ballasts and six fixtures. As a result, lighting system performance for 70 combinations was evaluated and compared.

The measurement results showed a wide range of performance characteristics related to light output and energy efficiency. The results showed the wide range of lighting system performance which can be obtained for various combinations of lighting system components. The combination of T-8 triphosphor lamps and electronic ballasts exhibited the best performance, but some of the more traditional lighting system components also performed well. The sensitivity of component and system performance to thermal conditions and electrical interactions was also demonstrated. The need to consider factors related to the individual application, such as light levels and distribution, and occupant requirements also was discussed.

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Appendix A. Errors in Integrating Sphere Photometry: Identifying Their Sources and Providing Correction Factors

The luminous flux output of a lamp, Φ, is generally defined as

$$\Phi = 683 \int_{380}^{760} S(\lambda)\, V(\lambda) \qquad [1]$$

where

Φ = flux generated by a light source
S(λ) = spectral power distribution of the lamp
V(λ) = spectral sensitivity of the human eye.

This computation assumes that the spectral power distribution, or spectroradiometric, data of the lamp is known and can be multiplied by respective V(λ) values to obtain the lumen output of the lamp.

It is not always the case, however, that the spectroradiometric data is available for each lamp of interest. Further, it is not a trivial task to obtain such data. Thus, a more convenient method of determining lamp lumen output is used — the integrating sphere.

An integrating sphere is a hollow sphere which has a uniform perfectly diffusing coating on its inner surface. When a light source is placed at the center of the sphere and initially turned on, it directly radiates its spectral power to the surface of the sphere. Then, because of the unique geometry of the sphere, the fact that each sub-surface can "see" every other sub-surface, the spectral energy of the lamp is inter-reflected until all surfaces are equally irradiated. Thus, the irradiance of the sphere's surface is proportional to the power output of the lamp. If a photocell, corrected to imitate the spectral sensitivity of the eye, is placed in the wall of the sphere, the spectral power at each wavelength falling on that cell is selectively attenuated according to the V_λ function (S(λ) x V(λ)) and summed across wavelengths to produce a single output that is proportional to the lumen output of the lamp. Thus, the sphere effectively performs the integration of equation [1] and hence the origin of its name (Kauffman, 1984).

The advantage of the integrating sphere is that the lumen output of a lamp can be determined with one instrument reading as compared to the hundreds of readings and multiplications required in the spectroradiometric method. While integrating spheres are convenient, one must take care that the measurements are accurate. There are two **(three)** potential sources of error and both relate to the original calibration state of the sphere. The first is commonly referred to as "self absorption" and the second is the overall relative spectral sensitivity of the sphere system (CIE, 1988).

Self Absorption. Integrating spheres can be calibrated by placing a lamp of known lumen output in the sphere and adjusting the photometer so that the observed value is equal to the lamp's rated lumen output. The resulting photometer calibration is only appropriate for similar lamps burned in the same socket as the standard lamp because, as more lamp hardware for other types of lamps is added, the additional hardware absorbs some light. The correction for this source of error is straight forward.

To begin, an auxiliary lamp is located at the interior surface of the sphere and is shield so that no light directly falls on the receptor assembly. After energizing the lamp, the amount of light inter-reflecting in the sphere is recorded as L_0. Subsequently, the standard lamp and its accompanying hardware is added to the sphere, the auxiliary lamp is again energized, and the amount of light inter-reflecting is recorded as L_S. The ratio of these two values,

$$R_1 = \frac{L_S}{L_0} \qquad [2]$$

will be less than one and will provide an indication of the amount of light absorbed by the standard lamp assembly (the standard lamp was not lighted).

Similarly, the self absorption of a test lamp can be determined. In addition to the previously collected data for the standard lamp, the amount of light not absorbed by the test lamp and its hardware must be determined. This is accomplished by replacing the standard lamp assembly with the test lamp and its hardware, energizing the auxiliary lamp, and recording the amount of light inter-reflecting in the sphere as L_T. Now, the ratio of these two numbers,

$$R_2 = \frac{L_T}{L_0} \qquad [3]$$

indicates the amount of light absorbed by the test lamp and its assembly. Thus it follows that the correction for self absorption, K_{SA}, for a lamp assembly other than the standard lamp is

$$K_{SA} = \frac{R_1}{R_2} = \frac{L_S}{L_T} \qquad [4]$$

such that

$$\Phi_T = \Phi_S K_{SA} \qquad [5]$$

Overall Relative Spectral Sensitivity. Light is a unique quantity in that it lies at the interface of the physical and psychological worlds as implied in equation [1] (CIE, 1978). Physically, light is electromagnetic energy not unlike radio waves or microwaves in that light sources produce certain amounts of power at each wavelength. This is the $S(\lambda)$ in equation [1] and is invariant for a particular lamp if the lamp is consistently operated under given voltage conditions. However, unlike radio waves or microwaves, humans are only sensitive to the small portion of the electromagnetic spectrum we call light. Unfortunately, the eye is not equally sensitive to all wavelengths of energy. For instance, if we traverse the electromagnetic spectrum from short wavelength energy to long wavelength energy, we would see that the receptiveness of the eye would be zero until about 380 nm. At 380 nm, the sensitivity gradually begins to increase until it reaches its maximum sensitivity at 555 nm before it declines back to zero at about 760 nm. Thus, the eye is not very sensitive to red or blue energy but very sensitive to green. This is the $V(\lambda)$ in equation [1]. Therefore, in order for the sphere to provide an accurate lumen output, it is important that the photometric assembly of the sphere duplicate the eye's spectral sensitivity as closely as possible.

If we consider the total integrating sphere system it is apparent there are a number of variables affecting the spectral sensitivity of the photometric assembly. These include the spectral reflectance of the sphere's inner surface $\rho(\lambda)$, the spectral transmittance of the viewing window, or port, $\tau(\lambda)$, and the relative spectral sensitivity of the photocell $D(\lambda)$. Although these three factors are independent of one another, they are typically considered as a system where $V(\lambda)$ is approximated as

$$R(\lambda) = k \frac{p(\lambda)}{1-p(\lambda)} \tau(\lambda) D(\lambda) \qquad [6]$$

where k is an arbitrary constant.

Since equation [6] is an approximation of the V_l function, it is clear that any deviation from V_l will produce an erroneous result. For example, if $R(500) << V(500)$, the measured luminous flux at 500 nm will be underestimated and require a correction factor. The necessary correction factor is called the color correction factor, or K_{CCF}, and is necessary for determining the flux output of any lamp with a spectral power distribution differing from the spectral power distribution of the calibration lamp. It is defined as:

$$K_{CCF} = \frac{\int S_T(\lambda)\, V(\lambda) d\lambda \quad \int S_S(\lambda)\, R(\lambda)\, d\lambda}{\int S_S(\lambda)\, V(\lambda)\, d\lambda \quad \int S_T(\lambda)\, R(\lambda)\, d\lambda} \qquad [7]$$

where

$S_T(\lambda)$ = spectral power distribution of the test lamp
$S_S(\lambda)$ = spectral power distribution of the standard lamp
$V(\lambda)$ = photopic spectral sensitivity of the human eye
$R(\lambda)$ = overall relative spectral sensitivity of the sphere's photometric assembly.

Note from equation [7] that the spectroradiometric data of both the standard and test lamps is necessary to determine the color correction factor. In theory, the K_{CCF} should be calculated for each test lamp but practice has shown that a K_{CCF} for a lamp representative from a spectrally similar family of lamps produces accurate results.

Applying the Correction Factors If we place a standard lamp with a known lumen output, F_S, in the sphere, it will register a numerical value on the photometer which is recorded as I_S. Then the test lamp is placed in the sphere where it, too, registers a numerical value on the photometer I_T. The flux output of the test lamp, F_T, correcting for differences in spectral composition and self absorption, is then described as follows:

$$\Phi_T = \Phi_S \frac{I_T}{I_S} K_{CCF} K_{SA} \qquad [8]$$

This expression allows the luminous flux output of a lamp to be accurately determined without performing hundreds of detailed measurements and computations required by other methods.