The photometric connection—Part 1

Factors in, and the quantitative uncertainties of luminaires and photometry, lighting calculations and field measurements are examined

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If anything can go wrong, it will!

> (*Attributed to Murphy, but thought to predate him by aeons. Probably observed by Icarus . . . .who did not have time to record it due to operation of the law.*)

Introduction

Performance of an actual lighting system can be related to the original conceptual lighting system design by two alternative paths: predictive calculations and field measurements. These parallel connective paths do not necessarily lead to the same results. It is important to recognize the causes of these discrepancies and what order of magnitude of differences can be reasonably expected.

Three broad categories contribute to the potential differences between predicted and observed luminous values: luminaires and photometry, lighting calculations, and field measurements. Individual factors in the three categories will be reviewed, and the quantitative uncertainties of these factors will be discussed. It is important at the outset to recognize the classic paper by Salter[1] which so clearly presented many of the problems in the area of luminaires and photometry.

A single paper can do no more than present an overview of this subject. To limit the scope, principal emphasis will be on factors related to illuminance, but an extension to other metrics is obvious. The objective will be to show the large number of factors which affect the correlation between prediction and measurement. Considering the potential magnitudes of the individual factors, agreement between the two values is, in most cases, amazingly good. When one is aware of all of these factors, the lack of information on some of them, the precision and accuracy associated with them, and the way they interact, interpretation of design and measurement values can be placed on a realistic basis.

Specific data has been included to serve as examples of realistic conditions. These have been taken from a wide variety of sources including experiments by the author, published literature, consultation with photometrists and design engineers, etc. The only criterion for inclusion was that they represented commonly encountered values. There is no basis for assuming that they are either the average or the most commonly encountered values in current practice; because of their arbitrary selection, they certainly do not represent extremes. Consequently, these data must be considered exemplary, and it is imperative that they not be used in a predictive manner.

Photometric testing

The first problem encountered in the photometric testing of luminaires is the selection of the sample(s) to be photometered. Ideally, several luminaires would be randomly selected to establish the mean and spread of performance. Subsequently, a sampling plan

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would be developed to monitor production. While this can be done for many types of products, it is unrealistic for most luminaires. "Plain vanilla" photometry(basic tests on simple luminaires) currently is on the order of $200 to $400 at independent laboratories; ancillary costs can easily double this figure. The lighting industry cannot support the costs of multiple testing suggested by statistical concepts.

Practically, after a luminaire has been developed, one sample is photometered to establish nominal performance. Obviously, one does not want published photometric data to be based on a poor luminaire, so a "good" sample is chosen. Since this is not a statistically unbiased selection, there is little reason to believe the photometry is representative of the entire luminaire population in the sense of average or modal performance.

Hopefully, the tests establishing nominal data are based on a production luminaire since preproduction prototypes can differ in a multitude of ways involving materials, assembly tolerances, paint finishes, fabrication techniques, temporary tooling, etc. It is also well recognized that "average" performance can vary with time. A change in component vendors, minor design improvements, tool wear, introduction of more economical manufacturing processes, etc. are typical factors contributing to long term variation.

Although one accepts that projection type devices can be extremely sensitive to adjustment, this can also be true for conventional lighting luminaires. Salter[1] demonstrated the effect of a small change in lamp position as might occur when a lamp is tightened in a socket by varying amounts. The results for a deep bowl (high bay) reflector is reproduced in [1].

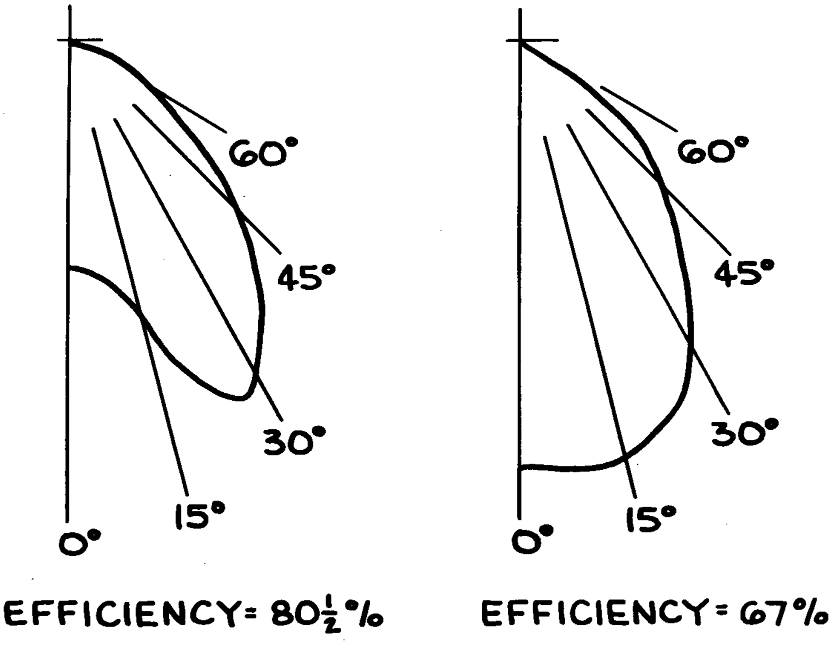
Many of the factors associated with individual components that will be discussed subsequently not only affect application performance but will reflect uncertainties in photometry. Some are controllable under test conditions; the effects of those that are not controllable must be clearly recognized.

To some extent it is fortunate that multiple photometric tests cannot be routinely performed for a luminaire type since this would introduce a new problem. The photometric test involves many parameters including distribution functions. Unlike the case of a single parameter such as efficiency, there is no simple way to characterize a meaningful "average" luminaire. If a performance factor such as the intensity distribution is specified by maximum and minimum limiting curves, it is easy to overspecify. Generally, there are interactions such that a small variation in one aspect will allow larger variations elsewhere. Limiting distributions tend to be over-restrictive since they do not recognize such trade-offs. Techniques such as characteristic value analysis have been successfully used for distribution functions in lighting[2], but this would be overkill for intensity distributions in routine design applications.

Luminaires

Any experimentalist will attest to the fact that identical sequential tests on a luminaire should not be expected to produce identical results. If the individual luminaire components are taken apart and then reassembled between tests, the results generally have larger variation. If nominally identical

[1] Variation in intensity distribution of a deep bowl (high bay) luminaire when lamp is tightened in socket by varying amounts (after Reference 1).



components are interchanged, the variation in results are expected to increase further.

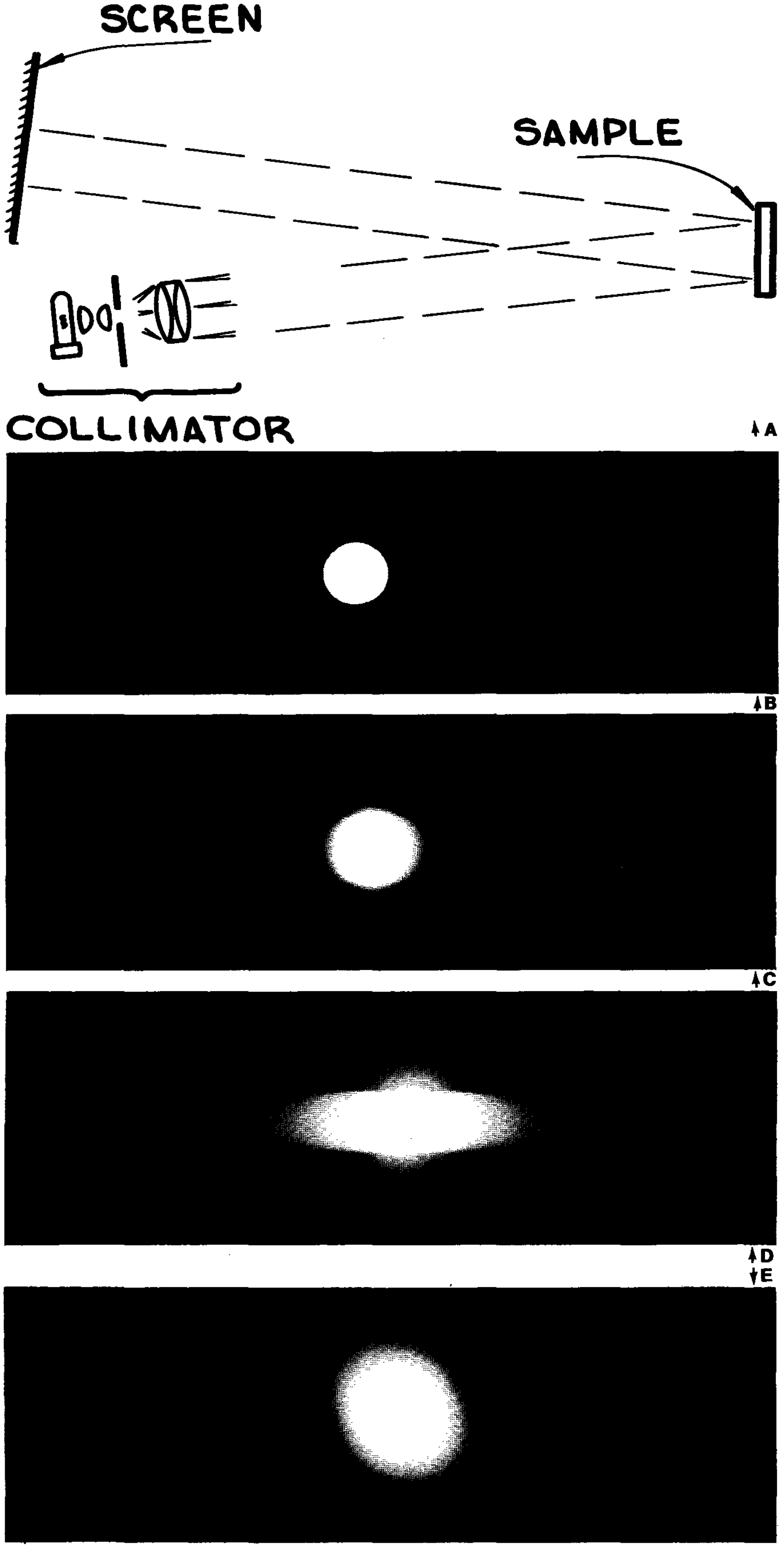
Franklin[3] assembled a roadway luminaire in a two level factorial experiment. The factors were lamp, reflector, and refractor using production components. Efficiency was the single evaluation parameter. The results were a standard deviation of 2½ percent and a range of 9 percent.

It is obvious that the (spatially) total luminous reflectance of reflector components will affect luminaire performance. For quality control, total reflectance can be monitored successfully by several types of reflectometers, and this metric is adequate for diffuse types of reflectors such as generally used in fluorescent luminaires. It is less obvious that the reflectance characteristics of specular reflector materials such as aluminum are not equivalent even when the total reflectance is the same. Small variations in the degree of specularity[4] can significantly affect the photometric performance with some forms of luminaires. These reflectance differences may not be obvious under casual inspection and can be difficult to quantify in a simple manner.

[2] illustrates some types of differences for nominally specular aluminum lighting reflector sheet. A quasi-collimated beam is directed to the sample, and the reflected beam is intercepted by a screen under a fixed geometry as illustrated schematically in [**2a**]. [**2b**] shows the reflection from a first surface mirror representing complete specularity from a lighting standpoint. [**2c**] is a good sample of reflector sheet while [**2d**] is for a sample with excessive "grain" structure from the forming process causing a highly directional spread. [**2e**] is a sample with virtually imperceptible diffusion under direct visual examination. Unless great care is taken to monitor such factors, it is equally likely that any of these variations might be supplied under a manufacturing specification calling for specular aluminum reflector sheet. The result could be significant performance variations between production lots of luminaires.

The problem of specifying and monitoring metallic reflectors with varying degrees of diffusion due to etching, peens, or similar treatments is

[2] Illustration of differences in nominally specular aluminum lighting reflector sheet. (a) Schematic of arrangement for photography. (b) Reflection from a first surface mirror for reference. (c-e) Samples of "specular" reflector sheet.



analogous to that for degree of specularity. The effect of a carefully controlled chemical etching process on an aluminum reflector can change if variations occur in the aluminum. Gross configurations such as peens to spread light are normally produced while forming the reflector. Tool wear can progressively change the surface characteristics of the reflector with effects much more significant than due to the slight corresponding change in the underlying curvature. Progressive tool wear is an equally important problem with lighting lenses. The effect on variation in luminaire performance cannot be generalized since it depends on the type of luminaire, the performance parameter under consideration, and the amount of wear tolerated by the manufacturer before reworking the tooling. It is important to note that these causes of performance change are often extremely subtile and difficult to identify.

A test has been reported[1] for simple industrial types of incandescent and fluorescent luminaires. Sample fixtures were selected periodically. Individual fixtures in each group of approximately eight luminaires were nominally identical but manufactured at different times. A summary of the variation in luminaire efficiency and reflector reflectance is given in **Table 1.** The original data for individual luminaires within each group shows inconsistent correlation between efficiency and reflectance confirming that multiple factors strongly influence luminaire performance.

Lamps

For our purposes, lamp characteristics can be divided into two categories, lamp lumens at rated operating conditions and all other factors that affect system performance, *e.g.* mechanical, optical, and causes of variation from rated lumens. The rated lumens are only of significance in design and field performance since they are the normalizing basis for luminaire photometry. The remaining factors apply throughout including photometry.

The consistency of rated lamp lumens is, to a large extent, a controllable manufacturing variable. Obviously, as variability is decreased, lamp cost increases. A reduction in variability past a certain point will not be cost-effective. The concept of zero tolerance is unrealistic, and for each basic lamp type there are inherent factors which ultimately will limit consistency.

Lumen data on several groups of general lighting lamps in each basic category, incandescent, fluorescent, and high intensity discharge (HID), were measured or taken from the literature. The samples for each group were nominally identical and from a single manufacturer. **Table 2** shows the observed variation.

Some types of lamps such as PAR, ER, and R lamps include optical con-

Table 1—Variation of individual luminaires of simple industrial types manufactured at different times (approximately 8 per group)

Ia—Luminaire Efficiency

Luminaire Type	Percent Maximum Spread	Percent Standard Deviation
Incandescent		
Group A	3	1½
Group B	6	2
Group C	12	4½
Group D	10	4
Fluorescent		
Group A	6	2
Group B	9	3
Group C	6	2½
Group D	9	3

Ib—Reflector Reflectance

Luminaire Type	Percent Maximum Spread	Percent Standard Deviation
Incandescent		
Group A	4½	1½
Group B	3½	1
Group C	9½	3½
Group D	7	2½
Fluorescent		
Group A	8	3
Group B	4½	1½
Group C	4½	2
Group D	2½	1

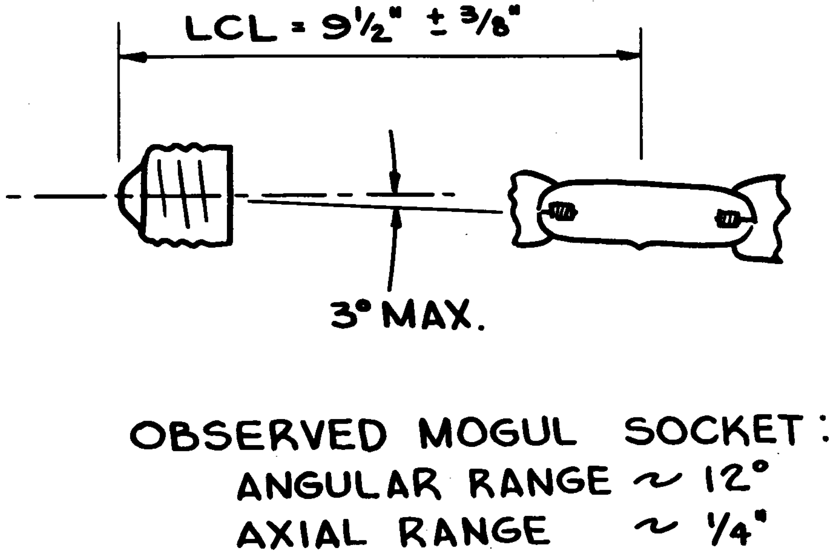
Table 2—Light output for groups of lamps (8 to 12 lamps per group)

	Percent Maximum Spread	Percent Standard Deviation
Incandescent[a]		
Group 1[b]	8½	2½
Group 2	3	1
Group 3[b]	10	2½
Group 4	6½	2
Fluorescent[a,c]		
Group 1	3½	1
Group 2	2½	1
Group 3	3	1
Group 4	1½	½
HID[c]		
Metal halide	11	4
High pressure sodium	7	1½
Phosphor mercury	7½	2

[a] Based on Reference 1.

[b] Since data unranked, the first 12 samples were used to provide comparable size groups.

[c] Operated on standard test ballast.



[3] **1000-W mercury or metal halide lamp.**

Table 3—150-W PAR 38 incandescent spot lamps

Sample	Average Central Intensity[a] (cd)	Beam Spread[b] (degrees)	Beam Flux (lm)	Total Flux (lm)
1	7810	33½	705	1600
2	10000	30	726	1710
3	9600	30	742	1680
4	8480	31	670	1620
5	9200	28½	637	1610
6	8370	29	644	1540
Mean	8910	30½	687	1630
% Standard Deviation	9½	6	6½	3½
% Range	24½	16½	15½	10½

[a] Within 5° Cone
[b] Total angle to 10 percent maximum intensity.

Table 4—150-W PAR 38 incandescent flood lamps

Lamp	Average Central Intensity[a] (cd)	Beam Spread[b] (degrees)	Beam Flux (lm)	Total Flux (lm)
Brand A—No. 1	3990	58	1090	1650
No. 2	3240	66	1070	1630
Brand B—No. 1	3690	56	1040	1590
No. 2	3720	56	1030	1620
Brand C—No. 1	3780	57	1100	1660
No. 2	3860	57	1130	1670
Brand D—No. 1	2770	84	1340	1690
No. 2	3280	66	1160	1700
Mean	3540	62½	1120	1650
% Standard Deviation	11½	15½	9	2
% Range	34½	45	27½	6½

[a] Within 10° cone
[b] Total angle to 10 percent maximum intensity.

trol. **Table 3** compares six 150-W PAR 38 spot lamps from a single manufacturing lot. **Table 4** compares 150-W PAR 38 flood lamps from four different manufacturers. It is observed that total lumens are reasonably consistent as might be expected for incandescent lamps. However, the optically controlled parameters have larger spreads. Since these are not precision optical devices but rather are general lighting lamps, the larger variation in the distribution related parameters should be anticipated.

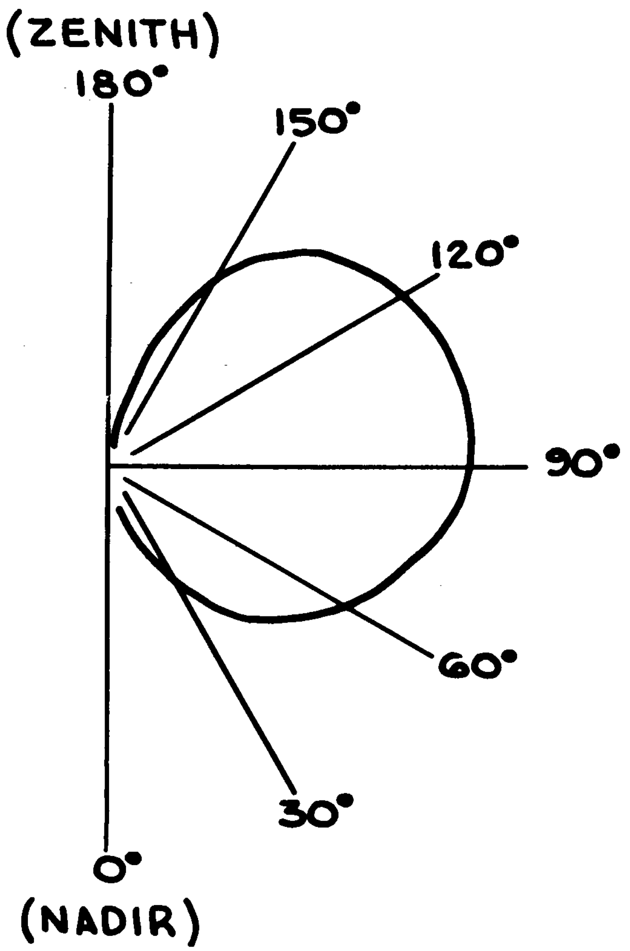
While performance of some luminaires are reasonably insensitive to lamp location, others, especially those designed to use clear bulb types whether incandescent or HID, can be exquisitely sensitive to the location of the filament or arc tube (recall [**1**]). There is, of course, the plus/minus tolerance on the light center length and on the filament dimensions or arc length.

Worse from the optical standpoint is the possible decentering from the optic axis. A large contributing factor to positioning uncertainty is the common screw type of lamp bases and sockets. As an example, consider [3] which illustrates a 1000-W mercury or metal halide lamp. Lamp specifications generally allow a ±3° variation between the axis of the base and the arc tube. At a 9½ inch LCL, this can permit a lateral displacement greater than the arc tube radius. In the absence of good data on the variability of socket positioning, a new mogul socket was randomly selected, and the range of lamp positions was observed when the lamp was inserted with various torques and in various positions with respect to the horizontal. The angular range was approximately 12°, and the axial linear range was approximately one-fourth inch. A good luminaire design is such that the fixture gives adequate performance for any possible position of the light source. Unfortunately, it is all too frequent that a luminaire is designed for a maximum performance at one position with performance seriously compromised as the lamp varies through its permitted range.

The lumen output of mercury lamps varies with operating position, being greater vertically than horizontally. Lamps are normally rated for these two positions, and the output is reasonably consistent with operating position. However, not only does the lumen output of the metal halide lamps change with operating position, but the spatial distribution of flux also varies due to the condensation of halides at various locations on the arc tube. [4] shows a typical intensity distribution from a bare, vertically operated metal halide lamp; usually, the intensity is attenuated in the lower hemisphere whatever the operating position.

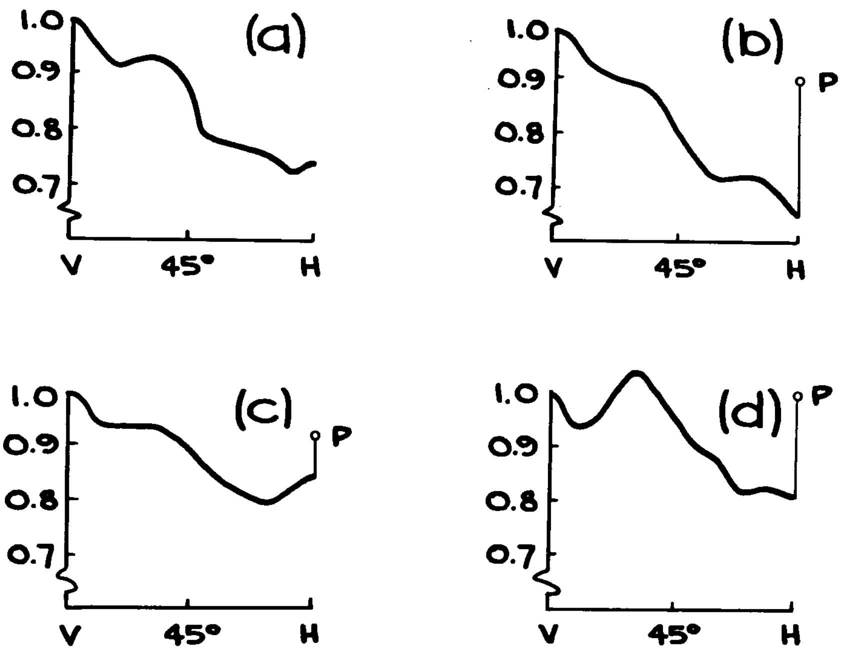
The lumen output of the metal halide lamps is not a repeatable function of operating position since the amount and location of the condensates is not consistent.[5] **[5a]** shows the relative lumen output versus operating position from vertical to horizontal of 400-W metal halide lamps averaged for a 12-lamp sample. A smoothed version of such curves is frequently used to describe lamp characteristics. Data on three of the individual lamps is shown in **[5b–d]** (lamps were fully stabilized in each operating position). After moving progressively from vertical to horizontal, the lamps were returned to the vertical position (point P). Note that the individual lamps do not return to their previous vertical lumen values and that the curves for the individual lamps are significantly different.

If the illuminance at some location has an appreciable contribution from each of several lamps, then the average lumen variation with operating position can be applied in calculations with some justification. Otherwise, it is meaningless in a specific situation although there are statistical implications in the long term. This instability of the lamp with operating position has tremendous impact on luminaire photometry. It reduces the accuracy and precision of the photometric tests and of subsequent application of the data in two ways. First, even if the lumen values are equal there is an inherent difference from lamp to lamp in spatial output due to the random variation in condensate deposition and migration. Performance of many luminaire types is sensitive to this variation in spatial distribution. Second, extreme care must be taken during photometric testing to avoid large changes from the initial lamp calibration. A partial list of controls might



[4] Intensity distribution from a vertical metal halide lamp.

[5] Relative lumen output from 400-W metal halide lamps. Operation is at various angles from vertical to horizontal (lamp stabilized at each angle). Point P is for restabilization in vertical after progressively going from vertical to horizontal. (a) Average of 12 lamps. (b-d) Three of individual lamps contributing to average.

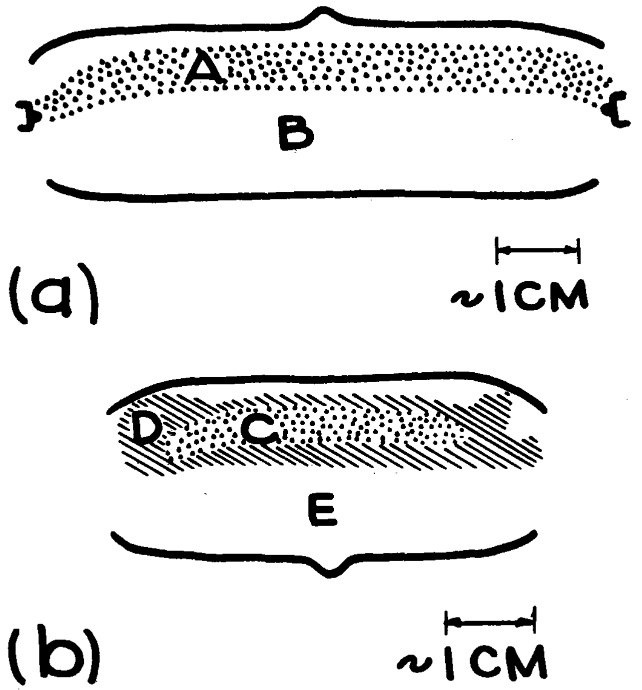


include long term stabilization, not moving the fixture during testing (especially with respect to the horizontal), never changing the operating position of the lamp (this includes rotation about its axis for a horizontal arc tube), etc. In spite of all possible precautions, the accuracy and precision of photometric tests involving metal halide lamps is poorer than for the other common types of light sources.

The luminance of the arc in mercury and metal halide discharge lamps is not uniform throughout the arc tube; [6] illustrates typical luminance gradients for such lamps. The high luminance core frequently represents about half of the total output, is about one-third of the arc tube diameter, is located above the centerline of the horizontal arc tube, and moves with operating position. Consequently, the location of the principal source component changes with operating position of luminaires such as floodlights and can cause changes in relative beam distribution.

When such arcs are operated vertically, they frequently are unstable spatially with time and wander slowly and randomly about the vertical centerline of the arc tube. [7] shows a test on a high-bay luminaire using a 400-W metal halide lamp. The lamp was stabilized for several hours, and then the intensity was photometered in one vertical plane at one minute intervals. This arc wandering can cause an apparent slight flickering of the illuminance, usually observable only if the principal light at a point is due to one luminaire and if each part of the reflector directs light in a different direction. The important consequence of such instability is that it reduces precision of photometric tests.

The density of phosphor coating on mercury and metal halide lamps and



[6] Arc luminance measured on 400-W HID lamps showing principal zones. (a) Mercury. (b) Metal halide (thorium/thallium/sodium type). Average luminance of zones in cd·cm^{-2}: A-350, B-20, C-700, D-220, E-70.

[7] Intensity trace in single vertical plane for 400 W vertically mounted metal halide lamp in high bay luminaire. Traces taken at approximately one minute intervals.

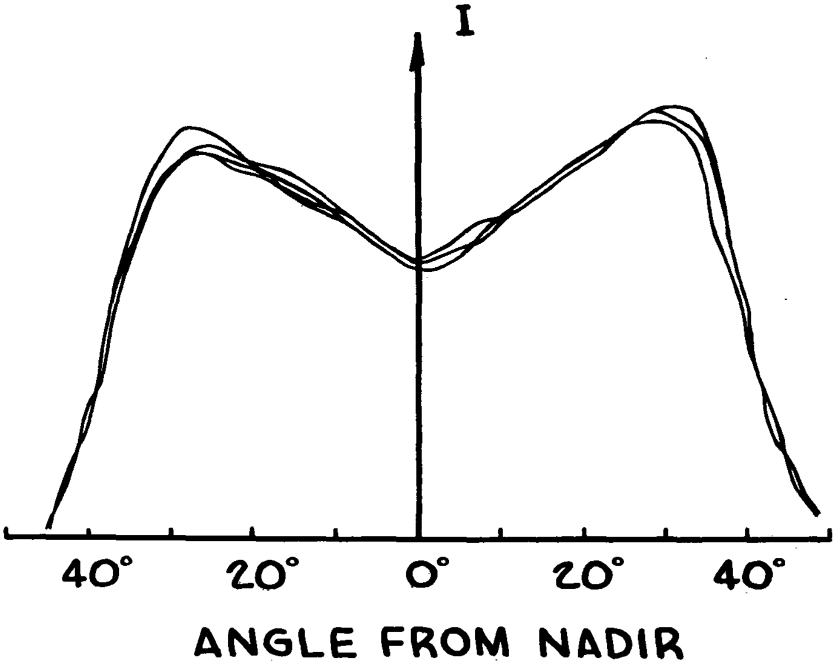


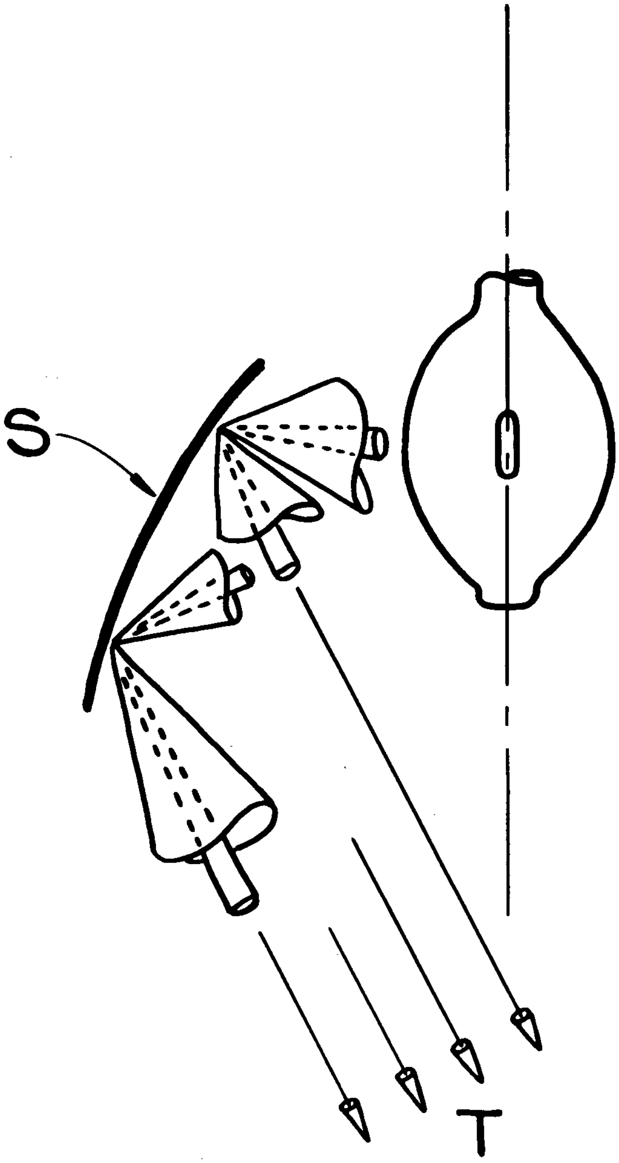
Table 5—Effect of phosphor density on enclosed HID luminaire with horizontal lamp[6]

Phosphor Density	Percent Efficiency	Intensity at Nadir (cd)
Heavy	60.2	6412
Light & uniform	65.9	7510
Light & nonuniform	67.1	7750
% Range	10½	18½

of the diffusing coating on high pressure sodium lamps will affect photometric performance of luminaires. The magnitude of this effect depends on the density variation between lamps, on the uniformity of density over the bulb, and on the optical schema of the luminaire. The average density and density range is dependent on lamp type, on manufacturer, and even on manufacturing lot.

In most cases, luminaire efficiency decreases as coating density increases. Frequently, the maximum intensity of the luminaire will decrease although this is dependent on the characteristics of the spatial change in flux distribution from the luminaire. The decrease in efficiency is not due to absorption in the denser coating. Rather, it is due to increased scattering and trapping of light within the luminaire. **Table 5** (taken from Reference 6) shows the performance for an enclosed HID luminaire with a horizontal lamp as lamps of different phosphor density are used.

A thin coating on a mercury lamp can produce an interesting effect. The spectral power distribution of light directly from the arc is principally composed of the four visible mercury lines producing a bluish-white light. The phosphor SPD is a band near the red end of the spectrum. If the phosphor is not sufficiently dense to completely diffuse the arc emission and hide the arc as a direct source, then sections of a specular reflector may preferentially focus the direct arc emission. The luminaire intensity distribution will not be homogeneous spectrally. This may produce slight, but noticeable, coloration between parts of the light field and may be observed if there is not sufficient overlap between luminaires to wash it out. **[8]** illustrates the process. ☐



[8] Schematic of how a section of a reflector (S) could concentrate arc tube flux in a direction (T) for a lamp with a thin phosphor.

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