The photometric connection —Part 2

Lamp operation, goniophotometers and their implications in lighting design are considered

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Lamp operation

At a given line voltage, the operating watts and lumens of an incandescent lamp are set by the electrical characteristics of the lamp itself. However, the watts and lumens of a discharge lamp are determined by the ballast. Although nominal values are assigned to the lamp, they are not realized unless so driven by the ballast.

For consistency of ratings, fluorescent lamps are tested using standard circuits with closely specified electrical parameters. On the ballast used for normal lamp operation, the lumen value will differ, and it is virtually always less than the rated value. CBM ballasts* deliver at least 92-1/2 percent of rated lamp output. Some non-certified ballasts deliver as low as 60 percent of rated lamp lumens.

The output of a fluorescent lamp depends on the mercury vapor pressure which is determined by the temperature of the coldest point on the bulb wall. Lamp ratings are established in still air at 25°C. The output is maximum for a specific cold spot temperature and decreases at higher and lower temperatures. As an example, the optimum cold spot temperature for most lamps is about 40°C; this is realized at the 25°C test condition for many lamps of standard current loading. In this vicinity, the lumen output de-

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* Ballast conforming to standards established by the Certified Ballast Manufacturers Association.

creases about 1-1/2 percent for each degree (C) increase or decrease with a more rapid change for large variation.

In fluorescent luminaire photometry, calibration is established with the bare lamps in still air at 25°C before using the same ballasts to photometer the fixture. Thus, any light reduction due to lamp temperature changes caused by enclosing the lamps in the luminaire is incorporated in the luminaire photometric data. Note that the effect of light reduction due to ballast operation (ballast factor) is cancelled and does not appear in the results of relative photometry. The effects of low ballast operation and of environmentally induced lamp temperature changes (including air handling luminaires) are incorporated by correction factors (light loss factors) in the lighting design process.

The separation of parameters between the photometric test and the design process was simple and clear-cut, at least in theory, until recently. Now with the increasing number of "energy conserving" types of lamps and ballasts which are used interchangeably with each other or with standard components, an unresolved uncertainty has been introduced into the design process. The photometric test results for a luminaire are no longer independent of lamp type and ballast due to changes in luminaire heating[7] and the interaction of some lamp-ballast combinations. In general, ballast factors may either increase or decrease. Some rough guidelines have been established[8] on an interim basis to aid the lighting designer. However, until general methods are developed

and standardized, the only way to eliminate this uncertainty in the design of lighting systems with such components is to photometer the luminaire with the particular lamp-ballast combination of interest unless it is known that standard test results apply for that particular combination.

As with fluorescent lamps, an HID lamp is rated for lumens under highly standardized conditions, but the operating ballast rarely drives the lamp at this value. For HID lamps there is no ballast standardization analogous to CBM certification; ANSI standards for lamps and ballasts do insure operational compatibility. There is a strong electrical interaction between the lamp and the ballast such that the specific combination determines operation.[9] Another source of variability is that many HID ballasts are not a single package. If the coil and core and the capacitor are obtained independently rather than as a matched unit, the tolerances between the two can add to operational uncertainty. Finally, there are many types of circuits commonly used for HID ballasts.

For reasons such as these, it is difficult to quantify the range of differences between rated lamp lumens and the initial operating lumens on a ballast. Looking at the American National Standards Institute (ANSI) lamp specifications on permitted voltage variation and the variation in lamp lumens due to the corresponding change in lamp power, the range might be estimated about ±10 percent for mercury lamps, ±15 percent for metal halide lamps, and ±20 percent for high pressure sodium lamps.

HID lamps are not sensitive to ambient temperature, but other environmental factors can influence operation. Power reflected back to the arc tube by a portion of the reflector can modify performance. In the mercury lamp, all of the mercury is in the vapor phase. Reflected power may affect lamp life if the arc tube temperature becomes excessive, but the effect on luminous operation is negligible. Metal halide lamps operate as a saturated system with condensed iodides on the arc tube. Reflected power can change the condensates and affect both magnitude and spatial distribution of flux in a manner analogous to that of operating

position. A small change in arc voltage may occur thus affecting electrical characteristics.

High-pressure sodium lamps are by far the most sensitive to returned radiant power. Mercury lamps, for example, have a transparent arc tube, and the arc is semitransparent to its own radiation. The high-pressure sodium lamp is essentially opaque to its own radiation; the arc tube, end caps, and dark end deposits of evaporated electrode material also absorb power. Since the lamp operates with an excess of sodium-mercury amalgam, the partial pressures are sensitive to the cold spot temperature of the arc tube. As a result, reflector returned radiant power causes an increase in arc voltage drop changing the operating point on the ballast characteristic curve. Because the arc tube is long but of small diameter, the magnitude of returned radiation, and thus of lamp output, is critically sensitive to arc tube position within some reflectors. Whether this effect is realized in practice is completely dependent on the specific reflector design.

Goniophotometers

Luminaire photometry may be relative or absolute. In absolute photometry, the lumen output of the lamps in the luminaire must be independently established, possibly by sphere photometry, and the goniophotometer has an absolute calibration. This approach introduces the uncertainty between the absolute calibration of two measuring instruments. Establishing absolute calibrations to better than five percent is a non-trivial problem. Absolute photometry is most frequently used when the goniophotometer is unsuitable for measuring lamp lumens.

Relative photometry determines the luminaire output with respect to that of the lamp, both being measured on the same goniophotometer with the lamp operated on the luminaire ballast. Since the luminaire values are normally related to the lamp output, this avoids the problem of errors between the absolute calibration of two measuring instruments. It also permits compensation for aspects such as the ballast factor of discharge lamps. If it is necessary to move a luminaire with respect to the horizontal during pho-

tometry due to physical constraints of the goniometer, at least a partial correction can be made for some sources such as the fluorescent lamp,[10] but correction cannot be made for other source types such as the metal halide lamp.

Many goniophotometers designed for luminaires do present some problems with measuring bare lamps for calibration. For example, shadowing by or reflections from lamp supporting structures can introduce errors. Also, the control of stray light becomes more difficult since lamp emission is generally somewhat uniform through 4π steradians while most luminaires have their principal emission through much smaller regions. Black absorbing surfaces have a reflectance on the order of three to four percent with much larger values near grazing angles or when dirty. Light traps can do significantly better, but this is rarely a convenient approach over large areas.

As another problem, intensity is defined as a directional property at large distances from the source.[11] Traditional wisdom has suggested that the photometric distance should be at least five times the maximum source dimension** for an error of less than one-half to one percent.[12,13] This thinking is based on calculations for the normal direction to a lambertian surface. The error increases for certain other directions from the lambertian surface and can increase radically as the luminaire departs from a lambertian surface either as a function of position or local direction.[14] Further, this error is not self-cancelling when the bare lamp(s) is used to calibrate relative goniophotometry even for the long fluorescent lamp.

Certain factors can reduce the ultimate effect of the geometric induced errors. Unlike intensity, the total flux is independent of the test distance. It can be proved[14] that the intensity error must change sign and integrate to zero when determining total flux. If the lamp flux (as well as the luminaire flux) is determined by integration

** Luminaires for general lighting as opposed to searchlights, signal devices, etc.

rather than a single intensity reading and a lamp constant (as generally done for fluorescent lamps), the luminaire efficiency will be correct at any test distance. The intensity for interior luminaires frequently is used for point illuminance calculations by the inverse square law at distances comparable to the photometric test distance. In such cases, the *equivalent intensity of an extended source at a specified distance*[15] as measured and reported for the luminaire is the intensity of choice rather than true intensity (*i.e.*, at a large distance). The photometrically determined intensity is basically an illuminance determined at the test distance multiplied by the square of the test distance. This actual illuminance is properly recovered *in the vicinity of the test distance* using *equivalent intensity*, not true intensity.

The results of photometric testing of luminaires obviously is critically sensitive to the lamp and its position in the luminaire for many types of luminaires. There are so many independent parameters characterizing the optical properties of lamps that it is difficult to conceive of the average lamp. Good practice requires that each parameter should be near its nominal value, a practice that can be achieved by lamp selection. This applies not only to obvious factors such as light center length and phosphor density, but to less obvious factors such as the life of incandescent lamps.[¶] Careful positioning of the lamp is essential if the base-socket system does not insure that the source is at the nominal position. Ideally, photometric tests should be performed for the practical range of variations in lamp characteristics. Such multiple testing is not realistic for the same reasons discussed earlier in regard to multiple testing over the range of luminaire variations. However, during the development stage, luminaire manufacturers should be expected to make such studies to prevent luminaires from being overly sensitive to the practical range of lamp variation.

Lighting design

In floodlighting and roadway lighting, analysis is usually by point

illuminance calculations using the inverse square law. When the incident light is not near the normal at the point, small errors in the angle can produce large errors in predicted illuminance. A one degree error in angle of incidence will cause a five percent error at 70° and a 10 percent error at 80°. An angular error might be caused by an uncertainty in the exact mounting location, but a more likely cause would be due to the difficulty of precisely locating and aligning a luminaire in the field.

When determining the direct component of illuminance due to physically large interior luminaires, one is limited to the photometric data taken on the luminaire as a whole. Using the best current procedure, the luminaire area is subdivided into n component luminaires. Each has the same spatial intensity distribution as the entire luminaire, but each component distribution has an intensity (1/n) times that of the full luminaire. Since this is only approximately true even at the best of times, a residual error remains in the calculations; but this error is less than that of neglecting the finite size of the luminaire altogether.

There are many problem areas in calculating the interflected component[†] of flux within a room (cavity) whether it is to determine average work plane illuminance, average surface luminances, or the contribution of surfaces to illuminance at a point. There are three underlying assumptions used in all common mathematical models. The first is that room surfaces are perfectly diffuse, *i.e.*, lambertian. This is almost always satisfactory, but, in any event, there is no viable alternative.

The remaining two assumptions are not necessary, but they are extremely convenient. It is assumed that room surfaces are spectrally neutral, *i.e.*, the reflectance is the same for all wavelengths. This is adequate for most real situations where saturated colors infrequently constitute large percentages of a room area, at least for those cases where accurate calculations are desired. There is a conceptually simple alternative. Divide the lamp output and the reflectances into spectral bands, analyze the room for each band,

and determine the final result by superposition of the individual components. It would be difficult to justify this work, especially in view of the potentially larger uncertainties of the entire analysis scheme.

The third assumption is that the room surfaces can be divided into a finite number of elements each of which can be adequately described by assuming uniform reflectance and uniform exitance (or luminance) and each of which receives a uniform illuminance. Then analysis is by algebraic flux transfer techniques.

These three factors are the only basic assumptions underlying most computer analysis programs. Generally, for reasons of computer capacity and computation time, there are limits on the number of elements used to model the room surfaces. Also, the effects of objects within the room such as furniture are handled by non-specific approximations although current interest exists toward developing specific inclusion of such elements.

The zonal cavity method[16] is an extension of the flux transfer analysis with additional assumptions. Most important, the luminaires are taken to be uniformly distributed throughout the room[17] although not necessarily in an ordered array; their distance from the walls is considered to be on the order of one-third to one-half of the typical spacing between luminaires. Further, it is taken that the initial luminaire flux incident on each surface, *i.e.*, before reflections, is uniformly distributed on that surface.

Only three surfaces are used for the standard zonal cavity method: a plane for the ceiling cavity, a plane for the floor cavity, and all of the walls taken collectively as a single surface. The room cavity is characterized by a single dimensionless parameter, the room cavity ratio. Although two parameters are necessary to completely specify the room cavity, it can be shown[17] that the room cavity ratio is a nearly complete description of the enclosure. Finally, the room is considered to be empty. Altogether, these assumptions appear overwhelmingly restrictive, but the inaccuracy caused by them is usually small if they are not radically violated.

The room cavity in the basic zonal cavity procedure is assumed to be a

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[¶] At a given wattage, the filament size varies as a function filament temperature which, in turn, is a function of life.

[†] Multiply reflected as opposed to directly from the luminaire.

rectangular parallelepiped. Using the couple cavity concept,[18] non-horizontal ceilings, furniture, and even low partitions can be handled. If a non-rectangular horizontal room section contains reentrant angles, it is treated by the coupled cavity concept. Otherwise, the existence of an equivalent rectangular section is postulated, and the room cavity ratio is determined using the section perimeter and room cavity height. These approximations when the room cavity is not a simple rectangular parallelepiped are not as robust as in the basic case, but they lead to practically useful answers.

The consequences associated with mathematical modeling of the physical system cannot be quantified in the general case. However, years of experience throughout the lighting industry indicate that these methods are adequate *if applied carefully and with understanding of the limitations.* Problems frequently occur when this caveat is not observed.

There is an additional class of pragmatic problems, that of unknown parameters. At the time of initial lighting design, it is not unusual for most of the input data to be uncertain, *e.g.*, surface reflectances or even the specific luminaire type ("or equal" means one thing to a purchasing agent and another to a mathematician). A good designer frequently runs some form of error analysis. For example, if reflectances must be assumed, the effect of the uncertainty can be estimated by bracketing calculations using extreme values. It is possible to repeat the analysis after the lighting system has been built, but it still may be difficult in the field to be certain that the components meet the available photometric data. Subtle variations in factors such as the room dimensions, fixture mounting, or even something as simple as an inverted luminaire lens may go unobserved.

Collectively, the *light loss factor*[19] usually represents the single largest uncertainty in the calculation process. Some component factors may be well quantified, but others are, at best, an educated guess. Of the recoverable factors, *lamp lumen depreciation* factor, even though large, is the best documented. Although it may range from about 0.5 to 1.0 for general lighting lamps, this data is available

from lamp manufacturers.[‡] It is obviously a statistical concept for a lamp population and may depend on operating condition, *e.g.*, the operating position of a general service incandescent lamp affects lamp maintenance by varying the deposition location on the bulb of tungsten evaporated from the filament. Factors, such as *luminaire dirt depreciation, room surface dirt depreciation,* and *burnouts* are based on assumed environmental conditions and assumed maintenance practices. There are standard procedures to help in obtaining consistent values,[19] but the results can be no better than the input data. These recoverable factors do not apply to the initial lighting but only later on in life.

Of the non-recoverable factors considered next, all but the *luminaire surface depreciation* apply to initial lighting values. This factor depends on materials, processes, and operating conditions of the luminaire as well as on the environmental conditions. It is a progressive change that sometimes takes years to become observable. It is the most difficult factor to estimate since many of the contributing aspects will become obsolete in the manufacturing process by the time that sufficient history has been accumulated to quantify them.

The *luminaire ambient temperature* factor is quantifiable providing environmental conditions are known. Luminaire manufacturers frequently provide the required basic information along with other photometric data. *Voltage to the luminaire* factor is difficult to predict since it is dependent on electrical system characteristics. Power system voltage regulation is frequently limited to ±5 percent, and normal variation may be less. Voltage drop due to feeders and branch circuits plus the effects of local loads further increase the voltage variation. Depending on lamp and ballasting, a one percent change in voltage can cause anywhere from about one-fourth percent to four percent change in light. The *ballast factor*[§] can be obtained from the manufacturer, but observation indicates that it is usually just es-

timated in practice. While the normal list of light loss factors is associated with interior room lighting, those factors not directly associated with rooms apply to all lighting systems including outdoor lighting.

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20. ibid., Figure 8-83 et seq.

[‡] It also may be estimated from mean lumens in the *IES Lighting Handbook*.[20]

[§] Ratio of lamp lumens operated on the ballast to the rated lamp lumens as determined on a standard electrical test circuit.