CHAPTER 27

ILLUMINATION

John E. Kaufman

INTRODUCTION

Lighting of the industrial environment provides for the visibility of objects and awareness of space needed for man to perform in a productive and secure manner. Not only should the lighting be properly designed and coordinated with the thermal, spatial and sonic designs, but it should be maintained through planned servicing procedures. The only means for determining whether a particular environment has been properly designed and is correctly maintained is to perform periodic evaluations or surveys.

In evaluating the lighting in any environment it is important to know how to make an effective meaningful survey and this can only be done with a basic understanding of lighting terminology, established recommendations for quantity and quality of lighting, types of lighting equipment and design procedures, and finally survey methods and instruments to be used.

LIGHTING TERMINOLOGY

The lighting terms most often used in design and evaluation of illuminated spaces include: intensity, illumination level, luminance, reflectance, lamp and luminaire. Most often used units of measurement are: candela, lumen, footcandle and footlambert. For a more complete list of terms with their definitions see Section 1 of reference 1.

Intensity

Intensity, or more correctly luminous intensity, is an indication of how much light a source gives off in a given direction. The unit of luminous intensity is the *candela* (formerly "candle"). It is sometimes referred to as "candlepower."

Lumen

The lumen is the unit of light output from a light source. For example, a 100-watt incandescent lamp emits about 1700 lumens initially in all directions, whereas a 40-watt cool-white fluorescent lamp emits about 3200 lumens initially. By definition, a light source of one candela produces 4π lumens.

Illumination Level

Illumination level is the amount or quantity of light falling on a surface and is measured in *footcandles*. If, for example, 100 lumens from a light source falls on one square foot of a table top, the illumination level on the table would be 100 footcandles. Also, a surface one foot from a source with an intensity of 100 candelas would have an illumination level of 100 footcandles.

If the unit of surface area is in square meters rather than square feet, the illumination is measured in *lux*.

Luminance

Luminance, or photometric brightness, is a measure of the amount of light emitted or reflected from a certain area of a surface. Its unit is *footlamberts* when the area of surface is square feet. A surface emitting one lumen per square foot of surface has a luminance of one footlambert. A bare 40-watt fluorescent lamp has a luminance of about 2400 footlamberts, whereas the moon has a luminance of nearly 1170 footlamberts.

If the unit of surface area is in square meters rather than square feet luminance is measured in candelas/square meter.

Reflectance

Reflectance is a measure of how much light is reflected from a surface. Actually it is the ratio of the luminance of a surface to the illumination on the surface (i.e., reflectance = luminance/illumination). A completely black surface has a 0 percent reflectance. A perfectly white surface has a reflectance of nearly 1.0 or 100 percent. Most surface finishes have reflectances of between 5 to 95 percent.

Lamp

Lamp is the term used for man-made light sources. Incandescent lamps are also called "bulbs" and fluorescent lamps, "tubes." "Lamp" is also used for the name of a complete lighting device consisting of a lamp, shade, reflector, housing, etc.

Luminaire

A luminaire is a complete lighting device consisting of one or more lamps together with parts to distribute the light, to position and protect the lamps and to connect the lamps to the power supply.

PURPOSE OF LIGHTING

The purpose of lighting in industry is to provide efficient, comfortable seeing of industrial visual tasks and to help provide a safe working environment. Advantages derived from good lighting include: fewer mistakes, increased production, reduction in accidents, improved morale and improved housekeeping.

Lighting for Task Performance

Visual tasks in industry vary in degree of difficulty depending on their size, their contrast (between detail and surround), their luminance and the time available for seeing. The smaller a task size the more difficult it is to see — for equal illumination a very small letter identification on a printed circuit board is harder to see than the type on this page. Tasks of low contrast, such as a gray stain on gray cloth are more difficult to see than higher contrast tasks such as a dark gray stain on white cloth. Also, it usually is easier to see an inspection task if more time is available for viewing.

The factors of size, contrast and in many cases time, are inherent in a visual task. On the other hand task luminance is variable and can easily affect task visibility — the higher the luminance (the greater the illumination) the more visible the task. This is due to an increase in eye sensitivity with increased luminance.

Lighting for Safety and Comfort

Lighting adequate for seeing production and inspection tasks usually will be more than needed for safety alone. If task lighting is not provided throughout the working space, adequate surrounding illumination is required to provide visibility of nearby objects which might be potential hazards or to see to operate emergency control equipment. In addition, lighting of ceiling and walls and the avoidance of glare will help provide a greater sense of well being and comfort.

ILLUMINATION REQUIREMENTS FOR INDUSTRY

Quantity of Illumination

The difficulty of seeing tasks, based on contrast, size and time for viewing as discussed above, is used as a basis for determining the levels of illumination for industrial areas. Research has shown that levels of illumination in the thousands of footcandles are required to see dark, low-contrast tasks as easily as light-colored tasks of high contrast under low levels. For light-colored, high-contrast tasks, the levels required for good visibility are very low. However, there are many factors in addition to visibility that affect the concept of easier seeing which suggest a minimum of 30 footcandles be used for all areas where seeing is done regularly, even for the simplest seeing tasks.[2]

The *American National Standard Practice for Industrial Lighting*[3] contains a tabulation of recommended levels of illumination for specific visual tasks and areas based on task characteristics and the visual performance requirements of young adults with normal eyes. According to the American National Standard Practice for Industrial Lighting[3] "These lighting recommendations are intended to provide guides for lighting levels desirable from an overall operational standpoint rather than from safety alone and, therefore should not be interpreted as recommendations for regulatory minimum lighting levels." Table 27-1 is a sample of the type of recommendations listed and is included here to show its form. Task areas are shown with corresponding footcandle levels recommended for the tasks in the area, these levels to be used as the minimum value on the task when the lighting system and room surface have depreciated to their lowest before maintenance procedures are effected (cleaning, relamping, painting, etc.). Also, in some cases, as denoted by a double asterisk, supplementary lighting can be used.

The levels recommended usually do not take into account the wearing of safety goggles that materially reduce the light reaching the eyes. If they are worn, the level of illumination should be increased in accordance with the absorption of the goggles used.

Quality of Illumination

By definition, quality in lighting pertains to the distribution of luminances in a visual environment and is used in a positive sense to imply that all luminances contribute favorably to comfort, safety, esthetics as well as ease of seeing. Excessively high luminances may produce glare and veiling reflections and affect eye adaptation. Improper distribution of luminances also may affect adaptation and cause shadows. Installations of very poor quality are easily recognized but those of moderately poor quality are not, even though there may be a material loss in seeing.

TABLE 27-1.
Levels of Illumination Currently Recommended[3]

Area	Footcandles on Tasks*
Clothing manufacture (men's)	
Receiving, opening, storing, shipping	30
Examining (perching)	2000**
Sponging, decating, winding, measuring	30
Piling up and marking	100
Cutting	300**
Pattern making, preparation of trimming, piping, canvas and shoulder pads	50
Fitting, bundling, shading, stitching	30
Shops	100
Inspection	500**
Pressing	300**
Sewing	500**

*Minimum on the task at any time.

**Can be obtained with a combination of general lighting plus specialized supplementary lighting. Care should be taken to keep within the recommended luminance ratios. These seeing tasks generally involve the discrimination of fine detail for long periods of time and under conditions of poor contrast. The design and installation of the combination system must not only provide a sufficient amount of light, but also the proper direction of light, diffusion, color and eye protection. As far as possible it should eliminate direct and reflected glare as well as objectionable shadows.

Glare. There are two general forms of glare — *discomfort glare* and *disability glare* — and both may be caused by bright light sources (electric and daylight) and by bright reflections in room surfaces. Glare from light sources and luminaires is known as *direct glare;* that from surfaces, as *reflected glare*.

Discomfort glare, as its name implies, produces discomfort and may affect human performance, but does not necessarily interfere with visual performance or visibility. In some cases extremely bright sources (the sun) can even cause pain. Disability glare does not cause pain, but reduces the visibility of objects to be seen. An example is the reduced visibility of objects on a roadway at night caused by the glare of bright oncoming headlights.

An industrial environment, then, will be relatively comfortable visually, if there is no glare, and seeing will be unimpaired if there is no disability glare. The effects of glare can be avoided or minimized by mounting luminaires as far above or away from normal lines of sight as possible and by limiting their luminance and quantity of light emitted toward the eyes. In general, this can be done by shielding luminaires to at least 25 degrees down from the horizontal and preferably down to 45 degrees. In other words, the brightness of bare lamps preferably should not be seen when looking in the range from straight ahead to 45 degrees above the horizontal. For critical working areas such as offices and laboratories the quality criteria of the *American National Standard Practice for Office Lighting*[4] should be followed.

Veiling Reflections. When reflected glare is produced on or within the visual task itself it becomes a veiling reflection because in most cases it will veil the task (reducing its visibility) by reducing its contrast. In some cases these losses in contrast are quite apparent; in others the losses are unnoticed yet may produce a marked reduction in visibility. The effects of veiling reflections may be reduced by increased levels of illumination and or by using layouts and luminaires designed to limit the light directed toward the task that will be reflected into the eyes. See the *IES Lighting Handbook.*[1]

Luminance Distribution. The eyes function more efficiently and comfortably when the luminances within the visual environment are not too different from that of the seeing task. While performing a task the eyes become adapted to the luminance of the task. If however, the eyes shift to view a window or floor of higher or lower luminance and then back to the task, the visibility of the seeing task will be reduced until the eyes readapt to the task luminance. To reduce this effect, maximum luminance ratios are recommended as shown in Table 27-2. As an aid in achieving these reduced luminance ratios, the reflectance of room surfaces and equipment should be as listed in Table 27-3.

Distribution, Diffusion and Shadows. In industrial areas where the locations of equipment and operations are not known, it is desirable to provide uniform illumination such that the highest and lowest levels are no more than one-sixth above or below the average. This also will help maintain desirable luminance distributions as recommended above.

Depending on the type of visual task and the operation, some tasks require directional lighting and others diffuse, but in both cases shading of the task should be avoided. Most tasks can be satisfactorily illuminated by diffuse illumination, but tasks of inherently low contrast and of a three-dimensional nature often can be seen best using directional light to produce shadows and reflections to improve contrast. Examples of such tasks are glossy black thread on matte black cloth and

TABLE 27-2

Recommended Maximum Luminance Ratios[3]

	Environmental Classification		
	A	B	C
1. Between tasks and adjacent darker surroundings	3 to 1	3 to 1	5 to 1
2. Between tasks and adjacent lighter surroundings	1 to 3	1 to 3	1 to 5
3. Between tasks and more remote darker surfaces	10 to 1	20 to 1	*
4. Between tasks and more remote lighter surfaces	1 to 10	1 to 20	*
5. Between luminaires (or windows, skylights, etc.) and surfaces adjacent to them	20 to 1	*	*
6. Anywhere within normal field of view	40 to 1	*	*

*Luminance ratio control not practical.

A—Interior areas where reflectances of entire space can be controlled in line with recommendations for optimum seeing conditions.

B—Areas where reflectances of immediate work area can be controlled, but control of remote surround is limited.

C—Areas (indoor and outdoor) where it is completely impractical to control reflectances and difficult to alter environmental conditions.

TABLE 27-3

Recommended Reflectance Values[3]
Applying to Environmental Classifications
A and B

	Reflectance* (percent)
Ceiling	80 to 90
Walls	40 to 60
Desk and bench tops, machines and equipment	25 to 45
Floors	not less than 20

*Reflectance should be maintained as near as practical to recommended values.

scratches on sheet metal. In the latter case it is especially important that the lighting be designed so that it will not produce reflected glare in the sheet metal.

Color. For equal levels of illumination variations in the color quality of currently used "white" light sources have little or no effect upon clearness or speed of seeing. However, when contrast is low and color discrimination is important, source and surrounding surface colors should be selected carefully.

INDUSTRIAL LIGHTING EQUIPMENT

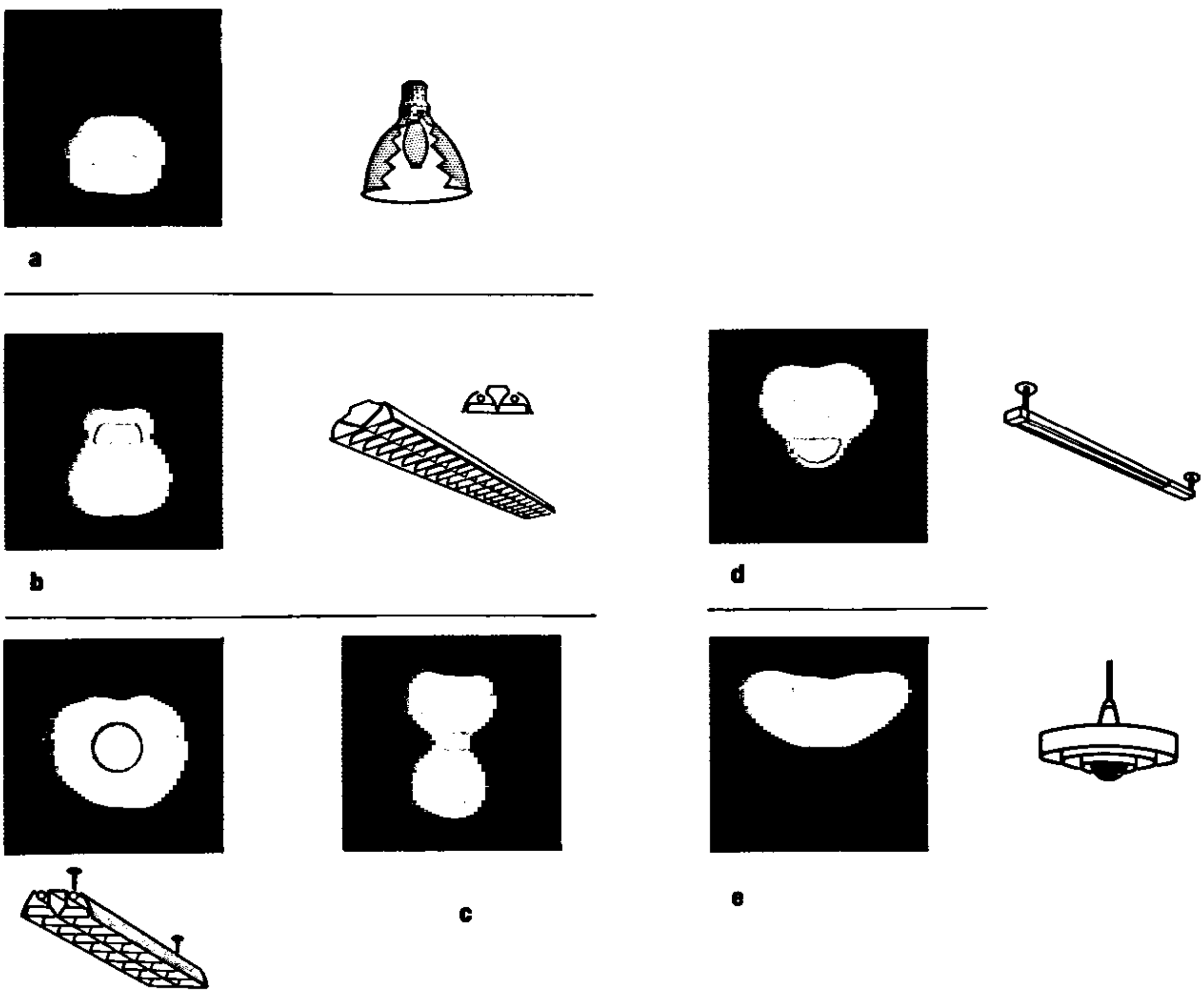
Light Sources

Daylight and electric light are the two main sources of light for industrial areas. The use of daylight depends on building design orientation and site conditions as well as the availability of daylight at the location;[5] however, because daylight is not always available electric lighting is provided.

Electric light sources used for industrial application fall into three categories: incandescent (including tungsten-halogen), fluorescent and high-intensity discharge (including mercury, metal halide and high pressure sodium). Although all types can be used, there are certain applications for which some are better suited than others. For detailed information on their physical and operating characteristics as well as industry averaged photometric data (lumen values) consult the *IES Lighting Handbook.*[1]

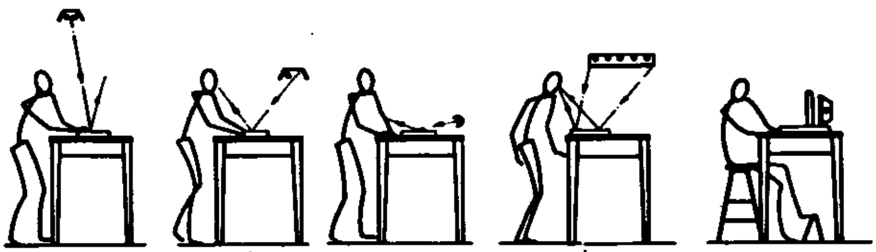
Luminaires

There are two categories of luminaires for industrial lighting — general and supplementary. *General Luminaires* are classified into five types according to their light distribution, as shown in Figure 27-1, and are used to provide general lighting throughout an area or localized general lighting, where the luminaries are located to provide higher levels at specific task locations yet provide some degree of general lighting. Each type of dis-



Illuminating Engineering Society, New York, New York.

Figure 27-1. Luminaire Classifications by Light Distribution: (a) Direct Lighting, (b) Semi-Direct Lighting, (c) General-Diffuse and Direct-Indirect Lighting, (d) Semi-Indirect Lighting and (e) Indirect Lighting.



Illuminating Engineering Society, New York, New York.

Figure 27-2. Examples of Placement of Supplementary Luminaires: (a) Luminaire Located to Prevent Reflected Glare — Reflected Light Does Not Coincide with Angle of View. (b) Reflected Light coincides with Angle of View. (c) Low-Angle Lighting to Emphasize Surface Irregularities. (d) Large-Area Surface Source and Pattern are Reflected toward the Eye. (e) Transillumination from Diffuse Sources.

tribution has an application in industrial lighting, for example: *direct* types are the most efficient (but may produce disturbing shadows and glare unless units are of large size, mounted close together and have some upward light), whereas at the other extreme *indirect* types are least efficient but produce more comfortable lighting. No one system can be recommended over all the others. Each should be evaluated based on the quantity and quality requirements of the space.

Supplementary luminaires are luminaires used along with a general lighting system but are located near the seeing task to provide the higher levels or quality of lighting not readily obtainable from the general lighting system. They are divided into five major types from Type S-I to S-V, based on their light distribution and luminance characteristics. Each has a specific group of applications and locations, as shown in Figure 27-2, to best illuminate the seeing task involved.

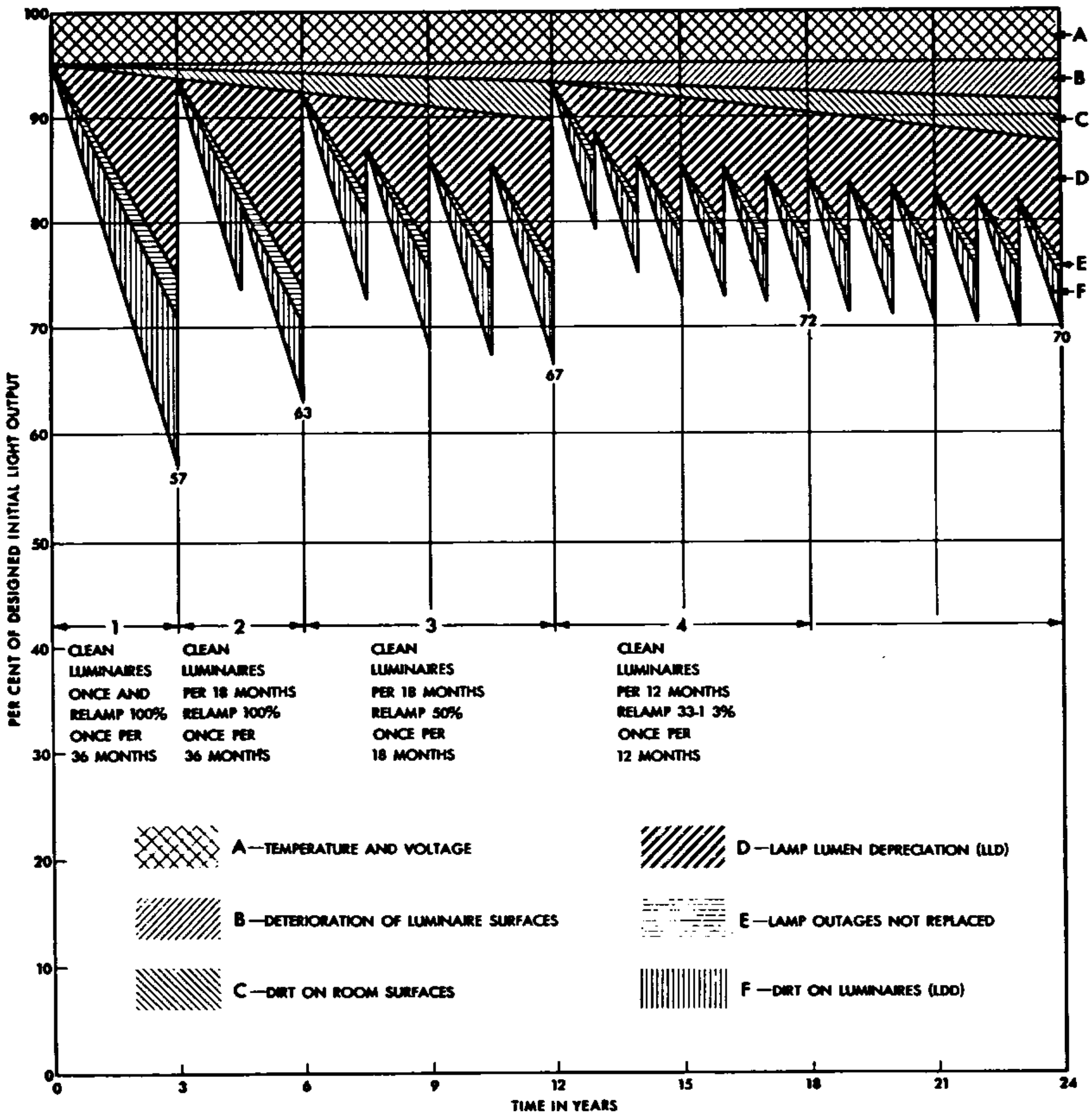
LIGHTING DESIGN

In industrial areas where the primary function of the lighting installation is to provide illumination for quick, accurate performance of visual tasks, the task itself is the starting point in the lighting design. Factors to be considered in the design process are listed below, but it should be recognized that the success of the design also depends on the accuracy of the information available to the designer.

1. Visual Task.
    a. What commonly found visual tasks are to be lighted?
    b. How should the tasks be portrayed by the lighting? Should the lighting be diffuse or directional? Are shadows important for a three dimensional effect? Will the tasks be susceptible to veiling reflections? Is color important?
    c. What level of illumination should be provided in accordance with the *American National Standard Practice for Industrial Lighting?*[8]
2. Area in Which Task Is Performed.
    a. What are the dimensions of the area and reflectances of surfaces?
    b. What should the surface luminances be to minimize eye adaptation effects without creating a bland environment?
    c. Might the surfaces produce reflected glare?
    d. Is illumination uniformity desirable (general illumination or task illumination)?
3. Luminaire Selection.
    a. What type of distribution and lamp color quality is needed to properly portray the task (for diffusion, shadows or avoiding veiling reflections) and provide a comfortable environment (visually, thermally and sonically)?
    b. What type is needed to illuminate the area surfaces (for eye adaptation, for avoiding reflected glare)?
    c. What is the area atmosphere and therefore the type of maintenance characteristics needed?
    d. What are the economics of the lighting system?
4. Calculation, Layout and Evaluation.
    a. What layout of luminaires will portray the task best (illumination level, direction of illumination, veiling reflections, disability glare)?
    b. What layout will be most comfortable (visually — direct and reflected glare, thermally)?
    c. What layout will be most pleasing esthetically?

General Illumination

When task locations are not known or a flexible arrangement of operations is desirable, lighting is usually designed to provide general illumination of the required amount throughout the area. This is also true where supplementary luminaires are used for task illumination alone. The calculation procedure for designing general illumination



Illuminating Engineering Society, New York, New York.

Figure 27-3. Six Causes of Light Loss. Example above uses 40-watt T-12 cool white rapid start lamps in enclosed surface mounted units, operated 10 hours per day, 5 days per week, 2600 hours per year. All four maintenance systems are shown on the same graph for convenience. For a relative comparison of the four systems, each should begin at the same time and cover the same period of time.

is the *Lumen Method,* where, with a uniform layout of luminaires, a relatively uniform level of illumination will be provided on a horizontal work-plane at a given distance above the floor. A detailed outline of this method can be found in *General Procedure for Calculating Maintained Illumination.*[6]

Task Illumination

When task locations are known, *Point Method* procedures are used for design. Methods are available[1] for calculating illumination levels at specific locations on horizontal, vertical and inclined surfaces, from all types of general or supplementary lighting systems. Use of these methods is the most accurate means of checking illumination levels on tasks during the design stage.

Maintenance

As mentioned above, the success of the lighting design is dependent on the accuracy of the information available to the designer, including the lighting servicing plan for maintaining the lighting from installation to end of life. Figure 27-3 illustrates the sizeable effects of various elements of light loss (temperature, voltage, dirt on luminaires and room surfaces, lamp depreciation and burnouts and deterioration of luminaire parts) on the level of illumination from initial operation (100 hours use) through various stages of servicing procedures. It is important to know or correctly assume these losses. It is equally as important to know the type of servicing plan so that minimum maintained levels can be designed for; so that during a lighting survey the surveyor will know if initial or lowest expected values are being measured, or whether the survey is somewhere between.

Guidance for the use of light loss factors in design and information on lighting maintenance can be found in the *IES Lighting Handbook*.[1]

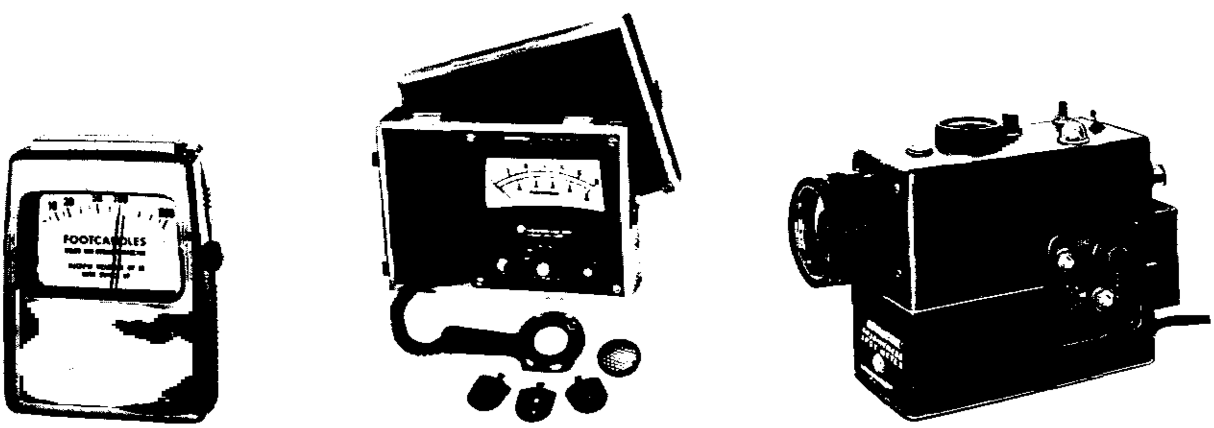
LIGHTING SURVEYS

Evaluation of the lighting in an industrial environment depends on the amount and type of information obtained during survey procedures and on the evaluator's knowledge and understanding of industrial operations and their associated lighting recommendations. The material presented so far in this chapter deals with lighting recommendations. The following deals with the survey and evaluation.

Measurable Quantities

A lighting survey can be as simple or as comprehensive as desired, but in any case three essential quantities are measured or determined: illumination (footcandles), luminance (footlamberts) and reflectance (percent). For the more comprehensive surveys, temperature and voltage are also measured.

Illumination readings are made at task locations for task lighting, at various locations on the horizontal work-plane for general lighting, and in some cases on various room surfaces to determine luminances and reflectances. *Luminance* readings are made of luminaires and room and task surfaces. *Reflectance* determinations are made of room surfaces. *Temperature* is measured in the air near luminaires. *Voltage* is measured at the luminaire input.



Illuminating Engineering Society, New York, New York.

Figure 27-4. Typical Photoelectric Meters Used in Lighting Surveys: (a) Pocket-Size Illumination Meter, (b) Paddle-Type Illumination Meter with Operational Amplifier, and (c) Luminance Meter.

Instruments

Illumination (Light) Meters. Figure 27-4a and b shows two typical illumination meters — a pocket-type and a more accurate paddle-type. The degree of accuracy required dictates the type of meter to be used, but in any case, instruments should be color corrected (to account for the response of the eye to light), cosine corrected (to compensate for light reflected from the light-detecting cell surface), calibrated for accuracy and with scale ranges so that no measurements are made below one-quarter full scale. A luminance meter (see below) can be used to measure illumination if a target of known reflectance is measured (illumination = luminance ÷ reflectance).

Luminance (Brightness) Meters. Figure 27-4c shows a typical direct reading portable luminance meter. Again the degree of accuracy required dictates the type of meter to be used and its corrections, sensitivity and calibration. Luminance of surfaces also can be measured using an illumination meter if the reflectance of the surface is known (luminance = illumination × reflectance).

Reflectance can be measured directly using a Baumgartner reflectometer,[1] however in field surveys, reflectance is usually determined by visual comparison of the unknown surface with color chips of known reflectance (Munsell Value Scales[1]) or by calculation using measurements (reflectance = luminance ÷ illumination).

Survey Procedures

The publication *How to Make a Lighting Survey*,[7] developed by the Illuminating Engineering Society in cooperation with the U. S. Public Health Service, provides a uniform detailed lighting survey form along with instructions for use. The survey involves recording the following information:

1. Description of the illuminated area — room dimensions; colors, reflectances and condition of room surfaces; and temperature surrounding luminaires.
2. Description of the general lighting system — quantities, condition, wattages, lamps, distribution, spacing and mounting.
3. Description of any supplementary lighting equipment used — as in 2, above.
4. Description of instruments used — manufacturer, model and date of last calibration.
5. Illumination measurements — at specific locations, depending on type of lighting system used.
6. Luminance measurements — from specific work locations in normal viewing directions.
7. Answers to a series of questions concerning the lighting servicing procedure and a subjective evaluation of the lighting.

Evaluation of Results

The measurements and other data recorded are used to determine: (a) illumination levels (for compliance with footcandle recommendations), (b) luminance values (for compliance with luminance ratio limits for visibility and safety) and (c) an indication of the degree of comfort and pleasantness in the area (from answers to related questions). In addition, these data are useful in determining if adequate maintenance or lighting servicing procedures are in effect. Also, they can indicate if deficiencies exist and what changes can be made for improvement; (e.g., application of higher or lower surface reflectances, better use of color, different luminaire locations for uniformity and to avoid shadows and glare, more light on the ceiling and better control of the daylighting).

It should be realized, of course, that the conditions existing during the survey may not be the same as those assumed by the designer in his design procedure, and the surveyor and evaluators should be aware of this.

References

1. *IES Lighting Handbook*, fifth edition, Illuminating Engineering Society, New York, 1972.
2. IES COMMITTEE ON RECOMMENDATIONS FOR QUALITY AND QUANTITY OF ILLUMINATION: Report No. 1, *Illum. Eng.*, 53: 422 (1958).
3. *American National Standard Practice for Industrial Lighting*, A 11.1 — 1965 (R 1970), Illuminating Engineering Society, New York, 1970.
4. *American National Standard Practice for Office Lighting*, A 132.1 — 1966, Illuminating Engineering Society, New York, 1966.
5. DAYLIGHTING COMMITTEE OF THE IES: Recommended Practice of Daylighting. *Illum. Eng.*, 57: 517 (1962).
6. LIGHTING DESIGN PRACTICE COMMITTEE OF THE IES: General Procedure for Calculating Maintained Illumination. *Illum. Eng.*, 65: 602 (1970).
7. LIGHTING SURVEY COMMITTEE OF THE IES: How to Make a Lighting Survey. *Illum. Eng.*, 57: 87 (1963).

Preferred Reading

1. *Lighting Design & Application*, Illuminating Engineering Society, New York.
2. *Journal of the Illuminating Engineering Society*, Illuminating Engineering Society, New York.
3. ALLPHIN, W.: *Primer of Lamps and Lighting*, Sylvania Electric Products, Inc., 1965.