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PROBLEMS IN BUILDING ILLUMINATION

BY

JOHN O. KRAEHENBUEHL

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PROBLEMS IN BUILDING ILLUMINATION*

I. INTRODUCTION

1. *Introduction.*—The building illumination problems of a university or college are general problems similar to those met with in the industrial, commercial, and public building fields. Educational building illumination presents problems ranging from the provision of proper intensities of light on the operating table to lighting fast moving machinery, with a large portion of the floor area devoted to tasks which are classified as visually difficult. This paper will not deal with specific problems in any one division of the illumination field, but with the general principles that underlie the necessity for good lighting and the problems presented in obtaining such lighting.

The problem of "seeing" is a human one and is as closely associated with personal hygiene as any other sanitary or health problem. Though for a long time the eye specialist and the physician have recognized the effect of faulty vision upon the human body, it has been largely considered a problem of physiological correction little thought being given to the fundamental cause. Heretofore both of these specialists have entered into the problem after the damage has been done, and seldom if ever have they prescribed a lighting system which would correct the basic cause. A sequence of events has placed the problem of illumination, which is essentially one of psychology and physiology, into the hands of the electrical engineer, and demands have also been made upon the science of optics and physics.

In the last five years there has been a rapid improvement in providing the much-needed higher levels of illumination. The publicity which has been given the matter of proper illumination, however, has carried in its wake much faulty information and many half-statements. The illumination specialist must use an unusual amount of judgment, as well as basic knowledge, to be able to differentiate between that which is worth while, and that which is purely propaganda, (often designed to increase monthly energy consumption). That much information is propaganda is apparent in the number of articles written pointing to the benefits of load increase derived by selling various articles of illuminating equipment, and increasing the commercial and domestic load requirements. There is a second danger in this mass of publicity and propaganda, for, when faulty material is published, and statements are made for purely selfish reasons, a whole

*Presented as a paper before the yearly meeting of the Association of Superintendents of Buildings and Grounds of Universities and Colleges, May 11, 1936, and printed by permission of that organization.

movement falls under a cloud of suspicion which hampers its rapid progress. Those prescribing the amount and the proper type of illumination should not only be well informed in the basic principles involved, but should be entirely free from commercial interests.

There is enough reliable information, based upon scientific research and experience, to justify much higher levels of illumination than are now in general use, and to show that many of the lighting units used are a real detriment, rather than an aid, to seeing. This research proves that foot-candle measurements are merely an index to the problem, and not a final answer in any analysis. Each illumination problem must be studied individually as to the severity of the task involved and the conditions under which that task must be performed.

Besides the human problem, which should be considered paramount, there is the economic problem. Seldom, particularly in an educational institution, can the lighting specialist arbitrarily condemn the equipment in use and specify a complete change requiring, in many instances, four or five times the previous wattage, for few, if any, of the wiring systems have been installed with capacity sufficient to carry this additional load. Every practical problem must be approached with an open mind in order to obtain the best "seeing" results with due consideration to the problem of financing.

II. Seeing

2. *Factors Involved in Seeing.*—The term "Seeing" as applied to artificial illumination is a term coined by Dr. M. Luckiesh and Frank K. Moss,* two scientists who have been driving forces in attempting to gather, correlate, and develop, through exacting research, the fundamental relationships between vision and lighting, a subject which has been ever changing and growing, since the advent of the relatively efficient incandescent lamp as a source of illumination. Little of their work has had scientific confirmation, because such research is very costly, and painstaking efforts are necessary to determine effects upon such a specimen as the human being; however, experience with lighting installations has, in many instances, confirmed their findings.

To understand the requirements for a good system of illumination it is necessary to study the conditions under which our vision developed and the requirements of the mechanism of vision. The human eye developed under daylight conditions, where the eyes were used

*Members of the Lighting Research Laboratory of the General Electric Company, Nela Park Engineering Department, Cleveland, Ohio.

for seeing distant objects, and for centuries there was little need for doing close work or for artificial light in performing visual tasks.

In tracing the development of man and the conditions under which the eye was evolved, the first sure ground of information is available in three human skulls, one dating back to about 500 000 years ago. This may be accepted as the beginning of the human race. At that time, life in its crudest form, without even the most primitive weapons, certainly required no close vision or artificial light. After this early beginning, there passed a period of 450 000 years before there was a trace of the first definite tools of chipped stone, the beginning of manual arts, and the first indication of close attention to detail, probably carried out under the open sky. After another period of 45 000 years, in which progress was made in artistry, came the first form of writing, and, in another 4200 years, the first printing, another 350 years elapsing before Europe developed the art. Even at this time close work was confined to artistry, and that under natural lighting. General use of printed material reaching all walks of life and the general mass of the people hardly predates the 20th century, or, conservatively, the last 50 years. For only 0.01 per cent of man's development have there been tasks other than those of distant vision and crude artistry performed under natural light, the medium in which the eye developed.

Now, except in the very unusual case, there is a great demand for close work under artificial light, and frequently the individual spends practically all of his time under this light at close work during either an eight-hour period of gainful work and an evening of reading, or, as a student, a day period of notes and blackboards with an evening of study. The eye, which was designed for long distance vision and high illumination, works now under low illumination at very close range. Under the conditions of evolution, the eye developed so that it should be used on detailed objects that could be seen at 17 feet and under illumination levels of 500 foot-candles, or more.

Under present conditions, work is performed at a distance of about eighteen inches from the eyes using from three to ten foot-candles, and accompanied by considerable reflected, and often direct, glare. The resultant effect is a strain on the muscles of convergence (occular muscles) and accommodation (ciliary muscles), with fatigue of the muscles operating the iris (contractile membrane). The symptoms of such a strain are either local or reflex, and often are a combination of both. Local symptoms include smarting, itching, burning, watering of the eyes, and styes, while reflex symptoms are headaches, nausea, obstinate indigestion, general nervousness, and many remote reflex disturbances. Some of the conditions that exist when artificial light is used on close work cannot be corrected, for it is, of course, impossible to make drawings at 17 feet, or to read books at this distance, though some relief in reading may be furnished in the future through the projection of printed matter or by audible reproduction.

Seeing, under our present abnormal conditions, may be improved both by corrections in vision and by correct illumination. Once the eye is damaged, little can be done to correct the actual damage, but the strain on the eye may be relieved by the use of lenses, which partially restore the faulty vision. The medical divisions of our universities and colleges are always alert to these defects and advise the students accordingly. It seems reasonable that good or corrected vision should be one of the requisites for entrance into a type of work where so much depends upon vision. Conservative estimates place a figure of 80 to 85 per cent on the amount of knowledge gained through the eye. Comprehensive surveys show that 40 per cent of students in colleges have defective vision, with only 18 per cent corrected. Of the faculty age group about 70 per cent have defective vision, and, since so large a portion of their time is devoted to reading, and, what is worse, to reading hand-written material, it is safe to assume that this figure is low. Considering this high percentage of faulty vision, the person responsible for the proper lighting of study surfaces, for both faculty and students, is devoting his interest to a group needing the best that science can offer.

After realizing how the eye developed, a study of natural light would be the proper starting point in the determination of illumination requirements. A low average for natural illumination would be 500 foot-candles. A comfortable condition exists in mid-summer under a shade tree with about 1000 foot-candles; the relative brightness of the sky is very low, however, as compared with some of our artificial lighting equipment. Seldom does this brightness exceed three candle power per square inch, and the averages given in handbooks are below this value. A recent survey (1933) shows that the average in June and July ranges from 4.2 to 2.8 candles per square inch, and in September, October, and November the average is approximately 1.7 candles per square inch. This same survey shows a lower brightness near the horizon (that portion of the sky that is in the range of usual vision).

Besides the relative low brightness level, the whole surroundings are illuminated with a specific quality of light approximately the same in all regions of the sky. Fortunately, up to the present, light color has not been a factor in artificial illumination, for levels of illumination that have been utilized indoors were far too low to make this an important factor. Nature, in her wisdom, has placed a great amount of green, a very absorbing color, within the range of the eye, for its restful effect. In summary, it may be said that natural light has a high foot-candle illumination, is relatively free from glare, either direct or reflected, is general and uniform, and has the proper color contrast.

An investigation of the artificial lighting systems in general use shows low surface illumination with not much consideration given to contrast or the lighting of the surroundings. It is these conditions which are at fault in the lighting of educational institutions and which should be given immediate attention.

There are limitations to the duplication of the conditions of natural light under which the eye developed, the foremost being the control of reflected and direct glare. Lighting equipment cannot be designed, with our present knowledge, to utilize the higher levels of illumination, but moderate values (30 foot-candles or less) do not produce objectionable direct glare. Reflected glare is more difficult to control and should be reduced by proper diffusion.

The functioning of the eye under the effect of glare has been the subject of considerable study, and is a problem that will require a great deal more study for a complete answer. The effect of a glaring source may be eliminated by merely raising the general illumination without changing the glaring source. This demonstrates a differential action between the retinal image and the iris opening. The iris reacts to the relative intensity of the light source, while the vision, as interpreted by the retina, depends upon the foot-candle illumination upon it. Thus, even if the illumination on the work surface is sufficient, the directing of a beam of light into the eye will at once produce a closing of the iris to a point where it is impossible to see; however, with the beam still directed into the eye, seeing may be restored by increasing the illumination of the surface. At this point comes a limitation to the usefulness of foot-candle measurements, for the foot-candle meter interprets surface illumination without taking account of the contrast and glare that may be present. A new "Visibility Meter"* makes possible an adjustment for contrast, but the problem of glare must be treated by the proper equipment, and the *best equipment* has definite limits of application.

*General Electric Company.

There are definite factors in seeing that may be used as criteria in the study of lighting requirements. These are (1) the size of the object, (2) the contrast between the object and the background, (3) the brightness of the object, and (4) the time allowed for doing the task. Items (2) and (3) are the only ones over which there is appreciable control, as usually the size and the time elements are established, and frequently also the contrast is established. By the use of the foot-candle meter and the visibility meter it is possible to analyze these factors in a practical installation if the problem is approached with proper knowledge.

III. Illumination

3. *Systems of Lighting.*—The first portion of this paper has presented the relationship of seeing to vision and illumination, pointing out the necessity for treating the lighting of work surfaces with an understanding of visual needs, together with the necessity for economy in the installation. Unfortunately, the proper amount of light for human welfare is proportionately more expensive as a more perfect illumination is approached. The subject of costs will be discussed in the last part of the paper.

There are four systems of lighting; the direct, the semi-direct, the semi-indirect, and the indirect, and when properly installed they rank in the order given from poorest to best for the task of seeing. Table 1 shows the relative rating of three types of lighting systems. Lighting systems may be classed under these heads regardless of the nature of the equipment or the type of installation. The final selection of a lighting system involves a compromise between cost and effectiveness.

It is possible to obtain the proper number of foot-candles for any visual task with any of the systems listed and the designs will show the same average foot-candles; however, there will be a pronounced difference in distribution, for direct lighting will give high ratios of maximum to minimum illumination, while the indirect light will give a more uniform illumination. Therefore, with a recognition of the principles of good illumination in mind, it is well to investigate the minimum rather than the average.

The direct or semi-direct light is essentially an industrial light and a secondary light to be used in corridors, wash rooms, and places where there is no severe visual task, and where the light source is in the range of vision only a short time. This type of unit has a high efficiency, but is also very high in direct glare when lamped to the

TABLE 1

RELATIVE RATING OF DIFFERENT SYSTEMS OF ILLUMINATION

Type	Relative Cost*	Glare		Shadow	Maintenance	Distribution
		Direct	Reflected			
Semi-direct	Low	Considerable	Considerable	Harsh	Low	Poor
Semi-indirect	Medium	Some	Little	Some	Medium	Fair
Indirect	High	None	None	None	High	Excellent

*This includes first and operating costs.

manufacturers' specifications, even the better types of glassware having points with from three to four candles per square inch. When, with outdoor levels of illumination of 500 foot-candles, the sky has only 3 candles per square inch, how can three or four candles per square inch be justified with illuminations very rarely equivalent to 30 foot-candles? It has been pointed out that glare must be minimized by increasing the general illumination without a corresponding increase of the glare source. By increasing the size of the glassware for a specific lamp size, it is possible to reduce the brightness of the unit so that it will be as comfortable as a semi-indirect unit, but this is expensive, and the results do not approach the distribution possible with even the semi-indirect unit. The direct type of unit delivers 50 per cent or more of its light directly to the surface.

The semi-indirect and the indirect units deliver a portion or the whole of their light to a reflecting surface. The semi-indirect light delivers more than 10 per cent of its light directly to the work surface, and more than 50 per cent to the reflecting surface, while the indirect unit delivers less than 10 per cent directly, and more than 50 per cent to the reflecting surface.

The semi-indirect and indirect units are for use where high levels of illumination are necessary and the glare from large lamps must be removed from the range of vision. In using semi-indirect units it is necessary to guard against too much surface brightness, and with indirect lighting it is easily possible to increase the reflecting surface brightness to a point where the discomfort is as severe as that caused by a direct lighting unit. There have been office installations where, in attempting to increase the illumination on work surfaces, proper recognition was not given to ceiling brightness, which resulted in so much discomfort that the lighting units were fitted with smaller incandescent lamps.

When it is necessary to obtain higher levels of illumination, that is, above 30 foot-candles, in long low rooms, supplementary lighting must be used with the surrounding illumination raised to levels of from 10 to 20 per cent of the surface illumination; in such an installation general illumination of the indirect type is preferred.

There is no fixed formula for specifying the type of light and the equipment to use. Where expense is not a factor and the visual task is close and exacting, indirect lighting should be specified, and, for very high illumination levels, indirect lighting with some type of supplementary lighting should be used. If expense is a factor, the next choice is a semi-indirect system, with a tendency to use that system which most closely approaches the indirect; but if this still proves too expensive, then a semi-direct system with glassware of such a size as to reduce the surface brightness of the unit to at least 1.5 candles per square inch may be recommended. In corridors and recreation centers, where no severe visual tasks occur, direct units with levels of from two to three candles per square inch would be satisfactory. In shops and industrial laboratories various types of industrial units may be used, the glass-steel unit being preferred because it has less glare than other direct units. Special rooms, such as drill floors and large test floors, may be satisfactorily and economically lighted by the new high-intensity mercury-vapor type of gaseous equipment used in combination with incandescent lamps in equal lumen proportions.

4. *Illumination Requirements.*—Regardless of the type of system that is used, there should be present a sufficient amount of illumination so that the task can be performed with the minimum consumption of nervous energy; there must also be enough light on the surroundings, not for detail-vision, but for eye relaxation without severe adaptations, and there should be freedom from harsh shadows and glare. These requirements in an exacting lighting task must be observed to the most minute details. Every task should be studied as an individual problem, and recommendations should be made that will approximate most closely the average requirements.

The visual tasks in a university or a college may range from reading large type to reading handwriting, to reading scales on fine instruments, to drafting, and to sewing, often on dark cloth with black thread. On a scale of visual difficulty these tasks may run from the lowest to the highest. The requirements for these tasks will range from a few to several hundred foot-candles, yet it is possible that several of these tasks will be performed in the same room. No general scheme or type of lighting will satisfy these varying requirements. To

TABLE 2

FOOT-CANDLE REQUIREMENTS FOR SCHOOLS

Class	Description	I.E.S.* Requirement	I.E.S.* Minimum Requirement	Nela Park† Recommendation
A	Sewing rooms, drafting rooms, art rooms, and rooms where fine detail work is to be done.	15-20	8	30-50
B	Classrooms, study halls, libraries, offices, shops, laboratories, and all rooms where class work or study is done.	12-8	5	15-20
C	Gymnasia, main exercising floor, basketball, handball, wrestling, playrooms, swimming pools.	12-8	3	15
D	Auditoriums, assembly rooms, cafeterias and other rooms in which pupils congregate for extended periods, but not used for study.	5-3	2	10
E	Recreation areas, locker rooms, corridors, stairs, passage ways, toilets.	4-2	1	5

*Standards of School Lighting—Approved September 15, 1932, by American Standards Association.
†Recommended Standards of Illumination—August, 1934, Incandescent Lamp Department, General Electric Company, Nela Park, Cleveland, Ohio.

buy lighting equipment in mass and then install it because of the ease with which standardization may be accomplished, is a violation of all logical and scientific procedure in the field of illumination. It is just as great a fault to establish a standard of foot-candles regardless of the task and to use the foot-candle meter as the sole index in lighting designs. The foot-candle meter is the instrument through which a light analysis begins, and, as a guide for its use, Table 2 is given.

Lighting equipment, though very important, is not the only factor in obtaining the proper seeing conditions. The color of the walls and ceiling and the dimensions of the room, as well as the maintenance of the lighting system, affect the lighting and the maintaining of the illumination at its initial level.

By proper choice of wall and ceiling color, more efficient use of the light may be made. Colors containing blue or red tend to absorb light. Colors should be chosen so that little light is absorbed and the greater portion is reflected without specular reflection. For this reason the matte colors are more desirable. Recently there has been marketed a paint with casein as a basic binder for which there is claimed a 90 per cent reflection factor, and no yellowing of a matte color with age. This is a remarkable claim, and, if justified, will institute a new era in painting for lighting. The room dimensions enter into the efficiency of light utilization only as a factor over which there is no control, for the room height and dimensions are established by the design.

Artificial lighting is one of the most inefficient types of energy transfer known to engineering. Only about 0.012 per cent of the sun's energy is converted into light. In an incandescent lamp, only about ten per cent of the wattage delivered is converted into light energy. The inside frosting of the lamp absorbs two per cent of the light emitted, the glassware, when clean, is not more than 80 per cent efficient, dust darkening the walls and the glassware takes from 20 to 35 per cent of the light, while the wall covering, at the best, is hardly more than 85 per cent efficient in returning light. These facts are mentioned because of the cost of adequate illumination with our present equipment. It is hoped that at some future date, when researchers have devoted as much energy to the lighting equipment as they have in proving that the human being needs more foot-candles, each of these items will be brought into line with an engineering conception of efficiency. If this becomes true, the proper illumination will then be obtained with no more expenditure of energy than with present lighting systems.

The use of natural lighting in a classroom is a subject by itself, but, since it is often necessary to combine natural and artificial light, two methods of control of natural light will be mentioned, for the neglect of this control may defeat the efficiency of the whole lighting installation. The natural light entering a room may be controlled by two methods, the use of lens control windows, or Venetian blinds, both of which are used to redirect the light to the ceiling where a good reflecting surface may diffuse it evenly in the room, and thereby eliminate peaks and valleys in the lighting.

Lens glass with the proper prisms merely changes the course of the light, and Venetian blinds must be painted white and so tilted that the natural light is caught on the surface of the slat and redirected to the ceiling from which it is reflected.

Any person responsible for lighting installations may test the facts outlined in discussing good lighting. The best test as to the desirability of an adequate lighting installation is to choose some room frequented for reading or study (probably a reading room in a library) and equip it with totally indirect lighting having a level of illumination of from 30 to 50 foot-candles. The walls should be light and without any glare. The comments of the users, as well as the increase in the number of users, will be an answer to any question as to the desirability of good lighting. An experiment of this type will necessarily bring

TABLE 3
WATTAGE REQUIREMENTS FOR SCHOOLS*

Class†	Watts per Square Foot	Class†	Watts per Square Foot
A	5	D	1½
B	3	E	1
C	3		

*Standards of School Lighting—Approved September 15, 1932, by American Standards Association.
†Classification same as in Table 2.

demands for better lighting at all points, and should only be undertaken with a clear understanding of this consequence.

5. *Wiring.*—Illumination and electrical wiring in the building are so closely associated that it is impossible to consider one without taking account of the other. The requirements for wattage allowance in school building lighting are given in Table 3.

In spite of all the information available as to the necessity for good lighting and the power needed to obtain this lighting, designs made today by even the more advanced architectural offices fall far short of meeting adequate specifications, and fail to consider future demands which continued research in illumination may make on the wiring system. The extra cost of a conduit a size or two larger is relatively small, and its use will permit considerable load increase by the installation of wires up to the capacity of the conduit. Never should conduit for feeders and sub-feeders be installed without allowing for future installation of wire of at least two sizes larger than that used for the original installation.

The National Electric Code specifies wiring that is adequate from a safety standpoint, but not necessarily from an operating standpoint. If the current requirements are fulfilled, the code is satisfied, because the fire hazard is removed, but, from an illumination standpoint, the voltage lost may represent an appreciable lighting loss; and, as the system becomes overloaded by the addition of more load to meet new illumination requirements, the whole lighting system will suffer accordingly. Table 4 shows the effect of low voltage on the operating efficiency of an incandescent lamp. Since this follows not a linear but a geometric law, the loss increases very rapidly with a lowering of voltage. For good practice the allowances for voltage drop on lighting systems should not exceed 2 per cent on minor distribution or 3 per cent

TABLE 4*
EFFECT OF VOLTAGE ON THE QUALITY AND QUANTITY OF LIGHT

Voltage per cent	Total Light per cent	Percentage of Total Light	
		White	"Sunset"
110	139.0	86	14
105	119.0	79	21
100	100.0	71	29
95	83.5	64	36
90	68.5	56	44
80	45.0	36	64

*From "Modernization Limited" by L. V. James—Skyscraper Management, October, 1932. Chosen for its conciseness, this information can be obtained in very elaborate form.

TABLE 5
ILLUMINATION BRANCH CIRCUIT SPECIFICATIONS

Run—Distance from First Outlet to Cabinet	Size Wire	Run—Distance from First Outlet to Cabinet	Size Wire
Less than 30 feet............	No. 14	70 to 110 feet...............	No. 8
30 to 50 feet................	No. 12	110 to 170 feet..............	No. 6
50 to 70 feet................	No. 10	170 to 270 feet..............	No. 4

from the service panel, with proper allowances for expansion as previously noted. The use of demand factors should be based upon rather accurate knowledge as to how the building is to be used.

The branch circuit is often neglected, being installed with No. 14 wire without respect to length of run. The code permits the use of this size wire, which is more than adequate from safety considerations, but may be very deficient in the delivery of voltage. Table 5 suggests adequate provisions for 1200-watt branch circuits.

On runs of more than 100 feet it is better to relocate the cabinets than to use the increased wire sizes.

An individual study of the allowable expenditure for an adequate wiring system for lighting is a difficult economical problem. This matter was given consideration by a committee* which selected a floor plan (9600 sq. ft.) from a building and submitted the problem in all its variations to contractors in various sections of the United States. The bids were carefully scrutinized and submitted to a statistical study, with the following conclusions:

*Report of Adequate Wiring Sub-committee "Lighting Service Manual," Part III, National Electric Light Association, August, 1928, p. 17.

(1) Reduced wiring specifications represent a false economy, and the difference in investment will be offset in a year or two.

(2) The investment does not increase in direct proportion with the increased wattage capacity.

(3) To double the wattage capacity increases the investment 33 per cent, and a 50 per cent increase in wattage capacity adds only from 15 to 18 per cent to the investment.

Since this task was undertaken by a committee whose impartiality could not be questioned, there being no reason for misrepresenting the facts, it would be well to use the findings as a starting point in a consideration of additional original investment in adequate wiring for lighting.

Too often new buildings are erected, their life estimated at fifty years of useful service, yet lacking adequate wiring systems at the time of construction, and, at the end of a year or two of service, they are full of make-shift wiring having conduit and molding placed on exposed surfaces. With our present knowledge, such buildings can be considered nothing but evidences of neglect or ignorance on the part of those responsible for regulating the financing and construction of the building. It seems rather absurd to spend large sums of money in reproducing some period scheme in a building and then, for a relatively small difference in cost, to neglect the interior appearance and usefulness of this same structure.

IV. Specific Problems in Illumination*

6. *Analysis of Illumination Problems.*—To show more clearly the relationship between the theoretical and practical aspects of the lighting problem, several specific examples will be analyzed. These studies are divided into four parts, and will be considered as follows:

(1) Comparison of design
(2) Maintenance and Replacement
(3) General Renovation for Better Lighting
(4) Building Study as to Adequacy of Lighting

Costs will necessarily vary from community to community, and such cost estimates as have been given represent costs at the location where the problems were analyzed.

*Data as presented in these problems were furnished from studies made by the Physical Plant Department, of which Mr. C. S. Havens is Director. The actual experiments were supervised by Mr. John Doak. Other data were from studies made by the Electrical Engineering Department under allotments from the N.Y.A.

TABLE 6

ANALYSIS OF HYPOTHETICAL INSTALLATION OF THREE TYPES OF LIGHTING

Type of Fixture	Luminaire Efficiency per cent	Light Distribution		Brightness, candles per sq. in. Mfg. Lamping			Average Foot-candles		Equipment Cost Dollars		Watts per Square Foot		Watts per Average Foot-candle		Operating Cost per cent†		Operating Cost per cent¶	
		Down per cent	Up per cent	Max.	Min.	Av.	300-watt lamps	500-watt lamps	300-watt lamps	500-watt lamps	300-watt lamps	500-watt lamps	300-watt lamps	500-watt lamps	300-watt lamps	500-watt lamps	300-watt lamps	500-watt lamps
Semi-direct............	85	47	38	3.7	2.0	2.6	10.7	19.3	75‡	..*	2.13	..*	28.0	..*	100	..*	100	167
Semi-indirect..........	80	28	52	2.1	1.0	1.3	10.0	18.0	51	68	2.13	3.56	30.0	27.8	107	99.4	100	167
Indirect...............	80	0	80	0	0	0	7.69	13.8	99	100	2.13	3.56	39.0	36.2	139	129	100	167

*Proper glassware too costly.
†Based on watts per foot-candle with 300-watt lamps, direct lighting, as 100 per cent.
‡20-in. glassware (1.3 candles per sq. in.)
¶Based on watt-hours with 300 watts per hour as 100 per cent.

TABLE 7
MAXIMUM LAMPING FOR ENCLOSING GLOBES, DIRECT LIGHTING

Size of Lamp	Size of Globe		
	I.E.S.* Requirement	Manufacturers Recommendation	For Low Brightness
75	10-in.	.....	12-in. (1.5 candles per sq. in.)
100	12-in.	.....	14-in. (1.5 candles per sq. in.)
150	14-in.	12-in.	16-in. (1.5 candles per sq. in.)
200	16-in.	14-in.	18-in. (1.2 candles per sq. in.)
300	18-in.	16-in.	20-in. (1.3 candles per sq. in.)
500	.....	18-in.	....
750	.....	20-in.	....

*Standards of School Lighting—approved September 15, 1932, by American Standards Association.

(1) Comparison of Design

In this problem the relative costs and merits of the three systems of installation, that is, semi-direct, semi-indirect, and indirect lighting will be considered. A lighting system is designed for a typical classroom for the same foot-candle level, and the results compared. The data for the room are:

Room dimensions................................25 ft. x 45 ft.
Ceiling height...13 ft.
Tentative design for 12 foot-candles:
Units spaced....................................11 ft. x 12 ft.
Side wall spacing...............................6 ft. x 6½ ft.
Ceiling very light............(85 to 70 per cent reflection factor)
Side walls fairly light........(70 to 50 per cent reflection factor)
Square feet per outlet....................................140.6

The three lighting systems as calculated for this installation and the average foot-candles for the nearest standard lamp are given in Table 6.

Costs in Table 6 are considered on the lamping of glassware, not to the manufacturers' specification, but to a specification that will reduce the brightness per square inch to approximately 1.5 candles. Table 7 compares the various systems of rating glassware to lamp size.

To compare the installations in Table 6 it will be necessary to consider the semi-direct and semi-indirect systems when using 300-watt lamps, and the indirect system using 500-watt lamps. There is some difference in foot-candles which cannot be avoided because lamps come in definite sizes. The semi-indirect and semi-direct light equipments cost $68 and $75 respectively (this is for glassware and support; —wiring in all cases would be the same), while the indirect costs $100.

The semi-indirect system costs less than the semi-direct because large semi-direct glassware is more expensive; if the manufacturer's rating were taken, the semi-direct system would cost the least. When comparing costs on a foot-candle basis, the operation cost of the semi-indirect system is 7 per cent more than that of the semi-direct, and that of the indirect 29 per cent more, but, when considered from the point of consumption alone, the indirect system consumes 67 per cent more energy than do either the semi-direct or the semi-indirect. A study of Table 6 gives a comprehensive picture of the comparative costs of the three systems of lighting within the limits of the present lighting code. If this problem is considered from a strictly visual view point, then the only answer would be indirect lighting with 30 to 50 foot-candles, a standard that could not be met in an old building without extensive remodeling, and which would be excluded in even a new building from financial considerations; but the future will demand these high values of illumination and allowance should be made for the inevitable in all designs.

(2) Maintenance and Replacement

In this problem the relative improvement in lighting that may be attained by maintenance and replacement will be considered. Two identical class rooms were subjected to treatment. These rooms are 13 feet high, and the original semi-direct light units were mounted at 10 ft. 6 in. while the new semi-direct equipment was mounted at 9 ft. 6 in. (when the ceiling height is 13 feet a mounting of a minimum of 10 feet and preferably 12 feet should be used). The lowering of the equipment does not invalidate the comparative results given in Table 8.

There were three progressive steps in the study of the influence of making these changes. These may be classified as

(a) Replacement of old lamps with new
(b) Repainting of the walls and installing new lamps
(c) Repainting the walls, and replacement of obsolete equipment with new equipment using new lamps

Since these rooms had a very large window area, which acted as a black wall as regards reflection, the repainting did not show as much advantage as it would otherwise. Table 8 gives a tabulation of the results obtained with very light ceilings, fairly light side walls, and 16-inch semi-direct glassware.

Though these rooms do not represent an adequate minimum when renovated for lighting, the problem does show the possibilities in maintenance, and the gain possible in the various steps of the work.

TABLE 8
MAINTENANCE AND REPLACEMENT STUDY

		Room A Foot-candles	Room B Foot-candles	Cost per Room dollars
Original	Maximum	2.5	3.5	....
	Minimum	0.9	0.5	....
	Average	1.2	1.5	....
New Lamps	Maximum	2.8	2.9	3.00
	Minimum	1.5	1.0	....
	Average	2.2	2.3	....
Gain, per cent		83	53	....
Paint	Maximum	4.0	4.5	48.43
New Lamps	Minimum	2.0	2.3	3.00
	Average	3.4	3.4	51.43
Gain, per cent		55	48	....
Paint	Maximum	5.8	6.3	48.43
New Lamps	Minimum	2.5	2.8	3.00
New Fixture	Average	4.3	4.8	8.10
Gain, per cent		26	41	59.53
Foot-candles gained, per cent		258	220	....
Ratio Maximum to Minimum—Initial		2.78	7.00	....
Ratio Maximum to Minimum—Final		2.32	2.25	....
Gain in Seeing		2.0 units	1.8 units	....

(3) General Renovation for Better Lighting*

In this problem an over-all change attained by removing an obsolete lighting system of the early indirect type, consisting of small inefficient indirect units, and replacing the whole system by a modern semi-direct-lighting system lamped with larger and more efficient lamps will be considered. The walls and ceilings were repainted, the fixtures renewed, and new lamps installed. Table 9 gives a comparison of the lighting of the rooms before and after the change.

With a 32-per cent reduction in wattage per square foot there is a gain of 250 per cent in illumination. In this equipment replacement, 16-inch glassware was used, but with little additional cost; the 18-inch (the recommended size for a 200-watt lamp) glassware could have been installed, and under these conditions the results, except for shadow, would have been as good as for semi-indirect lighting. With the larger glassware the surface brightness would have been 1.2 candles per square inch giving a direct glare which would not be objectionable for a class period.

Before the change was made the foot-candles ranged from 2 to 5, and after the change from 10 to 13, giving a more uniform illumination

*This is for initial conditions; only 70 per cent of this value would be possible under operating conditions.

TABLE 9
EFFECT OF GENERAL RENOVATION OF FIVE ROOMS FOR BETTER LIGHTING*

Room	Length feet	Width feet	Area sq. ft.	Out-lets	Size of Lamp		Watts		Watts per Square Foot		Coefficient of Reflection, Sidewall		Coefficient of Reflection, Ceiling		Illumination, Foot-candles						Ratio Max./Min. Foot-candles	
															Before			After				
					Before†	After†	Before	After	Before	After	Before	After	Before	After	Min.	Max.	Av.	Min.	Max.	Av.	Before	After
A	40	26	1040	6	2 100-w. 8 150-w. 2 200-w.	200-w.	1800	1200	1.7	1.2	0.42	0.70	0.88	0.80	1	3	2	6	11	10	3.0	1.8
B	45	25	1125	7	14 150-w.	200-w.	2100	1400	1.9	1.2	0.53	0.70	0.68	0.80	4	6	5	7	13	10	1.5	1.9
C	25	24	600	4	3 100-w. 5 150-w.	200-w.	1050	800	1.8	1.3	0.42	0.70	0.88	0.80	1	3	2	7	11	10	3.0	1.6
D	31	19	589	5	10 150-w.	200-w.	1500	1000	2.5	1.7	0.46	0.70	0.63	0.80	3	4	4	5	13	10	1.3	2.6
E	32	18	576	6	1 50-w. 2 100-w. 8 150-w. 1 200-w.	200-w.	1650	1200	2.9	2.1	0.56	0.70	0.56	0.80	1	2	2	11	15	13	2.0	1.4
Average (not weighted)									2.2	1.5							3			10.6		

*Classrooms with 13 foot ceilings.
†Before—obsolete indirect lighting.
After —16-in. semi-direct enclosing globe—Standards of School Lighting Specifications.

and an increase of 400 per cent in the minimum lighting. The improvement in lighting cost $127.32 for the electrical equipment and labor, and $354.93 for the painting, making a total cost of $482.25, which, if divided by five, gives $96.45 per room, an amount justified on the power saving alone.

(4) Building Study as to Adequacy of Lighting

In this problem an analysis is made of the illumination in forty-seven rooms located in one building, and also a general analysis of the adequacy of the wiring. The survey is confined to classrooms, lecture rooms, art rooms, and auditoriums, neglecting the corridors, stairs, and offices which may be handled by supplementary light, or which are adequately lighted. In Table 10 this survey is tabulated under three heads, (1) present lighting, (2) new lighting design using the old outlets, and (3) new lighting design with arrangement of outlets for best uniformity.

In the study of the building summarized under Tables 10, 11, and 12 the new designs were based on semi-direct-lighting equipment with over-size glassware to lower the brightness. As stated before, this is not the best type of classroom lighting but it has proved under the con-

TABLE 10
GENERAL INFORMATION ON LIGHTING SURVEY OF BUILDING

	50 per cent	Minimum	Maximum	Average
Reflection coefficient for sidewall	above 70 per cent	42 per cent	88 per cent	69 per cent
Reflection coefficient for ceiling	above 80 per cent	40 per cent	88 per cent	80 per cent
Lamp size	below 200-watt	50-watt	500-watt	....
Natural lighting	....	1 f.c.	500 f.c.	32 f.c.
Ratio glass to floor area	above 0.19	0.02	0.31	0.2
Artificial lighting	below 4 f.c.	1 f.c.	16 f.c.	4.8 f.c.
Watts per square foot	above 1.3	1	4.2	1.8

TABLE 11
COMPARISON OF PRESENT LIGHTING SYSTEM WITH NEW DESIGNS

	Number of Outlets	Average Area per Outlet	Average Foot-candles	Average Watts per Square Foot	Total Power Required kw.
Present lighting system	353	146	4.8	1.8	57.9
New design using old outlets	244	146	12.1	2.4	87.8
New design using new outlets	275	126	11.9	2.5	88.0

TABLE 12
COMPARISON OF PRESENT LIGHTING SYSTEM WITH NEW DESIGNS ON A PERCENTAGE BASIS

	Present Lighting	New Designs Using Old Outlets	New Designs Using New Outlets
Average area per outlet:			
50 per cent below	130 sq. ft.	130 sq. ft.	100 sq. ft.
75 per cent below	160 sq. ft.	160 sq. ft.	140 sq. ft.
90 per cent below	180 sq. ft.	180 sq. ft.	150 sq. ft.
Average foot-candles:			
50 per cent below	4	11.5	11.0
75 per cent below	7	13.5	13.0
90 per cent below	8	14.5	13.5
Watts per square foot:			
50 per cent below	1.6	2.4	2.3
75 per cent below	2.1	2.7	2.6
90 per cent below	2.9	2.8	2.9
Lamp sizes:			
Below 100-watt	3.7 per cent	0	0
Below 200-watt	69.4 per cent	0	0
Below 300-watt	97.2 per cent	7.8 per cent	26.5 per cent
Below 500-watt	97.2 per cent	85.7 per cent	94.9 per cent
Below 1000-watt	100.0 per cent	95.9 per cent	96.4 per cent

ditions of power available and possible financing to be the best illumination available for the money expended. In this building analysis it has been found that the new designs give a gain of approximately 152 per cent in the lighting, requiring an increase of 52 per cent in power as contrasted with the analysis in Problem 3, for five rooms located in the building. Each illumination problem is an individual problem, and conclusions cannot be drawn from very restricted data. The advantages gained in Problem 3 are possible under very narrow limitations. Normally it is usual to require more power for a gain in illumination, though seldom does it require a proportionate increase. The advantage of using new outlet layouts lies in obtaining a more uniform distribution. Since the two problems give almost the same average results, they will not be considered separately. Tables 10, 11, and 12 are detailed enough to give a picture of the lighting installations, comparing the present installation with the new designs that would replace it.

The second portion of the analysis deals with the wiring requirements of the building. Table 13 compares the specifications of the "Standards of School Lighting" with the actual provisions made to take care of the lighting at the time the wiring was installed, also with the requirements for the new design.

Though the building was built when it was recognized that educational demands were advancing rapidly with tendencies to include subjects that required close detailed application, the installation, with

TABLE 13
WIRING IN BUILDING CONSIDERED IN PROBLEM 4

Class*	Area sq. ft.	Watts per† Square Foot Required	Power Required kw.	Watts per Square Foot Required for New Design	Power Required for New Design kw.
A	1 023	5	5.1	3.5	3.6
B	45 616	3	136.8	2.5	114.0
C	0	3	0	0	0
D	32 222	1½	48.3	3	96.7
E	67 558	1	67.6	1	67.6
		Total........	257.8		281.9

Present Wiring Installation
100 kv-a Transformer (connected load 188 kw.)

Feeders: 3-600 M.C.M.
3-400 M.C.M.—Stage and House Lights
(5.4 kw. house lights)

Mains: 3 No. 3/0 (Code 175a) Maximum Load Mains
3 No. 1/0 (Code 125a) 161 kw. 3 per cent drop
3 No. 8 (Code 35a)
3 No. 4/0 (Code 225a) Connected Load Mains
3 No. 2/0 (Code 150a) 114 kw.

*Class given in Table 2.
†Wattage requirements for schools as given in Table 3.

the mains fully loaded, and allowing a 3 per cent drop of voltage, would supply only 161 kw. This would be adequate if based on a 55 per cent demand as used by the Wisconsin Commission, or the measured demand of from 37 to 52 per cent determined by the same body; however, even the National Electric Code specifies a 100 per cent demand per feeder on the wattage esimates up to 10 000 square feet of floor area, and 50 per cent above this minimum (the wattage allowed for schools is 1.5 watts per square foot). The requirement for the building by the "Standards of School Lighting" is 257.8 kw., while if a new design is used as a basis for the whole with a 3 per cent drop, 291 kw. are necessary. The present transformer capacity is low by any standard of analysis; that is, 55 per cent demand for the school and 70 per cent demand for the theater requires a 115 kw. capacity, which is being supplied by a 100 kv-a. transformer. It will be seen that there is not sufficient wiring capacity in this structure to properly light the building according to modern concepts of minimum good lighting. To rewire a modern fireproof or semi-fireproof building is extremely expensive, and it is almost impossible to increase the wiring capacity without damaging the interior appearance of the building. The time to plan lighting and wiring not only for present but for future use is when the building is being constructed.

V. Summary

7. *Summary.*—In discussing the lighting of the buildings at universities and colleges, there has been some digression from the field of artificial illumination into the fields of natural lighting and wiring, but neither of these subjects has been treated adequately, for the problem of either natural lighting or wiring could be treated to good advantage as a subject by itself.

The new science which deals with seeing has pointed out the way to what may, at present, be considered adequate lighting, and what will be the probable future demands in lighting. The school will not escape the recent propaganda for better lighting, for when home lighting is improved there will be a demand for better lighting in the school. There is no such thing as going back to lower levels of illumination after working under proper levels of controlled light, for experience has shown that individuals have no desire to work under lower levels when once accustomed to the higher levels.

The pressing need is for improvement of present lighting systems, and the means available are new and more efficient equipment, paints having high reflection factors, and a reliable system of maintenance. In some instances it will be necessary to rewire portions of a building using the present installation to supply the higher wattage demand of the remaining portion. For new buildings, recognition should be given to the fact that today's lighting requirements will not be those of tomorrow, and it is reasonable to expect that before a new building completes its life of fifty years, even 100 foot-candles will not be an unusual level of illumination. It is doubtful if all the gain will be attained with improved equipment and without higher wattage requirements. Therefore, the least that can be done in a new building is to provide sufficient conduit capacity so that the only additional cost will be for larger wire, and not for damaging the interior appearance of the building.

For the specific problem of lighting, the important factors are adequate illumination for the task that is to be performed, the absence of direct or reflected glare, and the illumination of the surroundings so as to be restful to the eyes. After an adequate system has been installed to meet these requirements, then the level of illumination should be maintained by renewing the lamps when needed, by proper regulation of voltage, and by renewing the paint when the walls do not function as proper reflectors.

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