ILLUMINATION AND THE OPTICS

OF THE EYE

by

J. H. DUBOSE

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DEFINITIONS AND UNITS.

1. LIGHT. The term is used in various ways:

a. To express the visual sensation produced normally when the radiant flux within the proper limits of wavelength, of sufficient intensity, and of sufficient duration, impinges on the retina.

b. To denote the luminous flux which produces the visual sensation.

2. INTERNATIONAL CANDLE. The unit of luminous intensity by agreement of three national standardizing laboratories; France, Great Britian, and the United States, in 1909.

3. LUMEN. The unit of light flux. It is equal to the flux through a solid angle, (Steradian) from a uniform source of 1 international candle.

4. CANDLE POWER. Luminous intensity expressed in candles.

5. FOOT-CANDLES. Using the foot as the unit of length, the foot-candle is the intensity given a square foot of surface by one lumen. Or it is the number of lumens per square foot.

PREFACE.

This Thesis is intended to be a non-technical presentation of a subject that the average person knows very little about, namely, Illumination and how our eyes see things. It is written for the non-technical mind, hence as few units of measurement and such terms have been used, as it was possible.. Many of the points have been merely touched upon, while others have been omitted as being beyond the scope of this Thesis.

This Thesis was prepared with the idea in mind that it would serve somewhat as a working manual for the numerous public schools in the stste, to check up on their illumination, and with the Bulletins named in the Bibliography, make changes in their installations that will bring them up to modern standards. Also in this Thesis is a record of a mercury-vapor installation in one of the Drafting Rooms of the University of Tennessee that has given complete satisfaction. This installation was possible through the courtesy of Mr.. Frank E. Keener, and the General Electric Vapor Lamp Co.

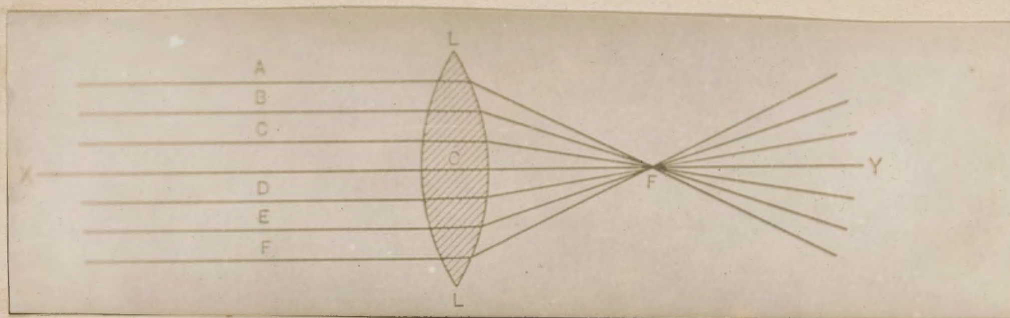


Fig. 1

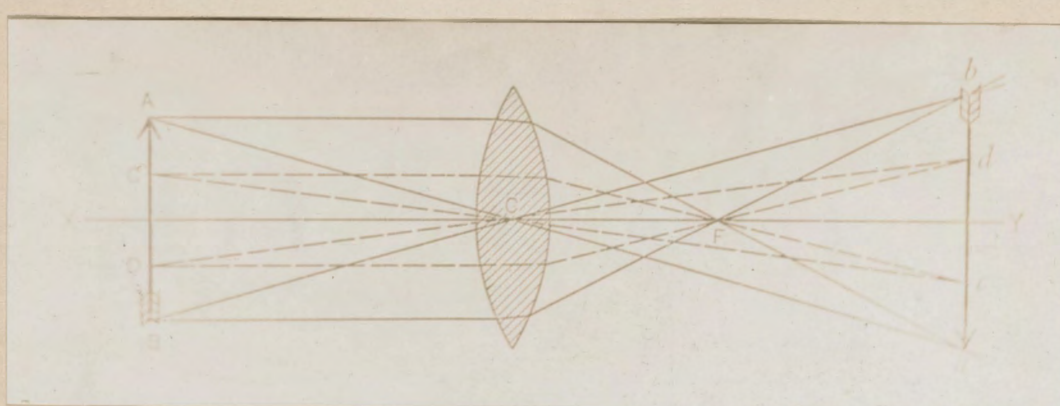


Fig. 2

FUNDAMENTALS OF VISION.

It is quite commonplace to say that sight is the most important of all senses. Therefore, in order that the eyes may work at the highest efficiency, it will be necessary for the designer of a lighting installation to have the fundamentals of the vision clearly in mind, and in order that maximum utility from the installation may be secured.

Fig. 1 shows how a simple "bull's eye" lens forms an image, or picture, as it is known in common language. The "bull's eye" lens has the property of bending, or refracting the light rays passing through it from a given point on one side, so as to bring them together at a certain point on the other side. This action is clearly shown by Fig. 1. Let L-L represent the lens in section: line x-y, drawn through the center of the lens perpendicular to the faces is the OPTICAL AXIS. Rays of light that are parallel to the axis, as A, B, C, D, will meet and cross at a certain point on the axis on the other side, as at F. This point is called the principle focus; and the distance from this point to the centre of the lens, is the focal length.

This action of a lens is familiar in its use as a "burning glass", to bring the rays of sunlight to a small spot, thereby concentrating the heat rays along with the light rays.

"The action of the lens upon rays that are not parallel is shown in Fig. 2. Rays that pass through the center keep their same course as Aa, Bb. The ray from the point A parallel to the axis will pass through the focus F, and cross the ray Ac, at the point a. All other rays coming from point A, will pass through this same point a. In the same way, all rays coming from B will cross at the point b.;and likewise rays coming from any point between A and B will cross at points between a and b, and similarly situated with reference to a and b. Thus if AB is an object reflecting light in all directions from every point on its surface, the reflected rays that pass through the lens will form a series of points on the other side in a similar manner. This similar collection of light points constitutes an image or picture of the object AB. It will be observed that the image is inverted, and therefore reversed as to right and left; and

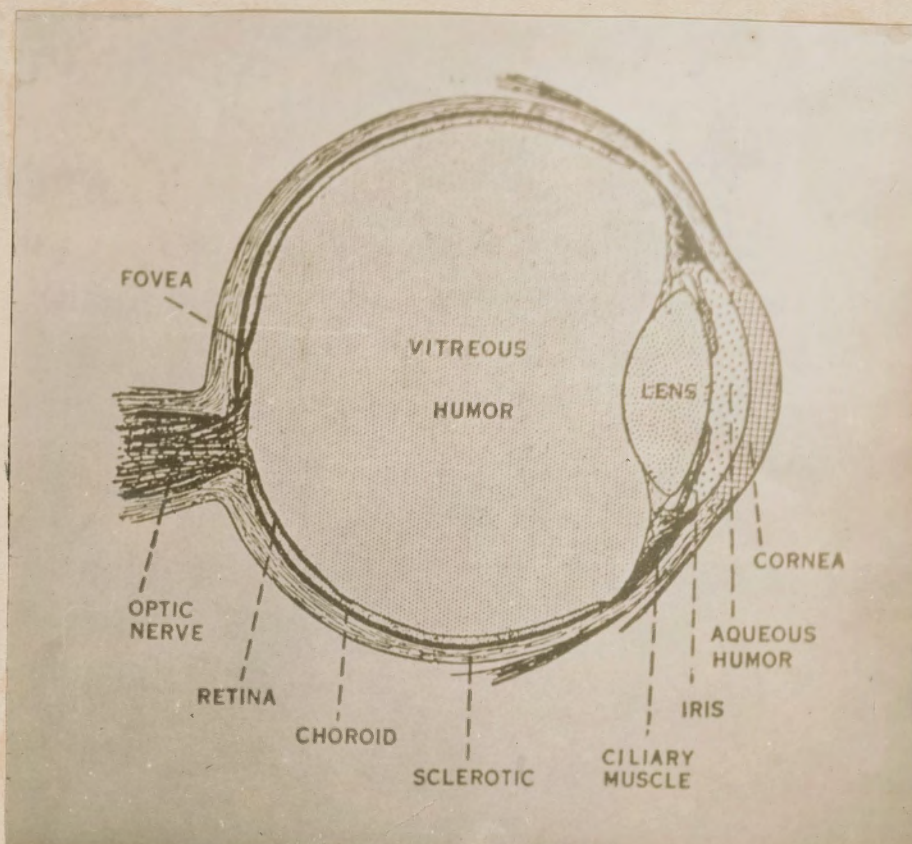

FOVEA
VITREOUS
HUMOR
LENS
CORNEA
OPTIC
NERVE
AQUEOUS
HUMOR
RETINA
IRIS
CHOROID
CILIARY
MUSCLE
SCLEROTIC

FIG. 3

it may be larger or smaller than the original object. (1)

Now, let a camera considered to be constructed around the lens of Fig. 2. A light-tight box houses the lens and the image ab is formed on the back of the box, as in Fig. 2. If a piece of film is placed against the back of the box and the proper exposure given, the film, on developing, the picture of AB will be on the film. In other words, the image of AB was formed on the film, and the light sensitive emulsion on the film gives a permanent record of this image.

Fig. 3 is a cross section of the eye horizontally through the center. The eye-ball is, roughly speaking a globular sac filled with a rather thick fluid. The sac is made of a tough, leathery fabric, called the SCLEROTIC, lined with a thin, nearly black tissue called the CHOROID, against which lies the light-sensitive mass of specially formed nerve terminals, called the RETINA. At the front of the exposed portion, the sclerotic becomes horny and transparent over a small circular area, called the CORNEA, which forms part of the lens system. Back of this is a real

(1) Elliott, E.L. "How We See".

double convex lens, called the CRYSTALLINE LENS, which is held in position by a set of muscles, called the CILLIARY MUSCLES. Lying against the front of the lens is a circular membrane made up of two sets of muscle fibers, one running radially and the other in concentric circles, leaving a circular opening at the center, which is called the IRIS. The two sets of muscle-fibers enable the opening of the iris, called the PUPIL, to be varied in diameter through a range of about four to one. When the circular fibers contract, the pupil becomes smaller; and when the radial fibers contract, it becomes larger. This muscular action is entirely automatic, or "reflex" as the physiologist would say.

There is a small space between the cornea and the lens, which is filled with a liquid called the AQUEOUS HUMOR, which is nearly pure brine. The fluid filling the larger spaces back of the lens is called the VITREOUS HUMOR, and serves to keep the several parts of the eyeball in position. The retina covers more than half of the inner surface of the containing sac, as shown. The nerve terminals in the retina connect with nerve fibers, which are gathered into a single bundle, like a telephone cable, which passes out to the brain through an opening in the sac a little towards the inner or nasal side. This is called the OPTIC NERVE or TRACT.

The similarity of construction between the eyeball and camera is now apparent. The sac is the body of the camera, which is lined with the black Choroid to prevent internal reflection. The cornea, crystalline lens, and aqueous humor, constitute the combination lens. The iris is the stop. The retina is the sensitive film. In the focusing mechanism, the eye and the camera differ; the eye focuses by changing the curvature of the crystalline lens, thereby changing its focal length, instead of varying the distance of the film from the lens, as in the camera. This change in shape of the lens is accomplished by the Cilliary, or focusing muscles". (2)

"It is plain that a photograph can be no better than the image which produces it. It is equally obvious that the character of the picture can be marred, even to the extent of complete ruination, by the quality of the photographic film, and the manner in which it is exposed and developed.

(2). Elliott, E.L. "How we See" pp. 3-5 .

The photographic film of the eye is called the RETINA. It is a transparent tissue, corresponding to the gelatin of the photographic emulsion, through which is distributed a great number of microscopically small nerves Cells containing chemical substances that are acted upon by the light, and which thus perform the same functions as the particles of silver salts in the photo emulsion. These nerve-cells are of two different kinds, called respectively RODS, and CONES, from their general shape. The cones are distributed most thickly over the central part of the retina, occupying a small area in this region exclusively. The rods are distributed spareely at the center, increasing in numbers towards the periphera, and occupy the outer part of the retina exclusively".(3)

The retina thus comprises two different photographic films. The cone film is adapted to taking pictures where the sharpness of detail and full representation of all colors is required. As in color photography, the film is relatively "slow", and requires a fairly

(3)Elliott, E.L. "How We See" p.12.

high intensity of illumination to produce a visible picture. The cones, being located almost entirely in the central portion of the retina, naturally receive the highest intensity of illumination, because the pupil contracts in very bright light so as to allow just the correct amount of light to strike the retina. This is the normal condition of vision in daylight, and corresponds somewhat to the position of "High Gear" in an automobile. The position of "Low Gear" to the eye, is when the pupil has expanded under low intensity illumination, and the light strikes the rods that are located more thickly towards the periphera of the retina, and exclusively at the outer part. The rod film is extremely rapid, but is incapable of producing sharp definitions, or of showing colors. The rods come into play when we see objects under very low intensities, such as moon-light, star-light, or feeble artificial light. Their insensitiveness to color is evidenced by the colorless appearance of colored objects under low intensities of illumination.

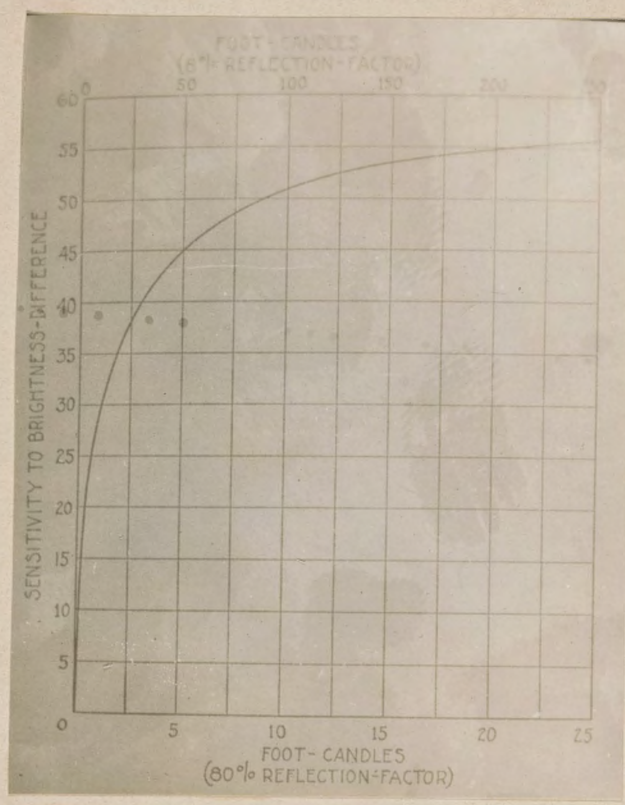
Just as an automobile is not designed to be operated continually in " low", but only in emergencies, so is it with the eye. For continuous operation the eye should be in " high ".

The difference in intensity between a bright day and a moon-light scene, may be in the order of two billion to one. The diameter of the pupil has been found to have a range of variation of about 4 to 1, which means that the variation in the amount of light entering the eye will be sixteen to one, because the area of a circle varies as the square of the diameter.

In order to have the wide range of sensitiviness dictated by the range of two billion to one in illumination intensity, the eye uses somewhat the same methods as the photographer. The photographer can obtain a variation in time of exposure by changing the size of the stop, hence the light entering the camera, and he can use films of various sensitiveness. The eye, as the camera and photographic film, can not stand over-exposure. Over-exposure of either, causes "fogging" and poor images.

The necessary variation in sensitiveness of the eye is obtained by the expansion and contraction of the pupil. This not only varies the intensity of light, as pointed out in the preceding paragraph, but in addition it brings into play the parts of the retina of different sensitiveness, the rods and the cones. When the pupil is wide open, the maximum sensitiveness is obtained by the use of the rods film which is located out towards the periphera of the retina. As the intensity of illumination increases, the pupil contracts, cutting out the more sensitive rods, and the cones begin to come into play as the intensity increases, with finally at the pupil's smallest diameter the rods are completely shielded, and only the cone film is producing the sensation of sight. There is no sharp definition between the areas of the retina occupied by the rods and the cones, and in places both are present, so that we are able to obtain a wide range of sensitiveness.

The most fundamental visual function is the distinction of brightness. It is the peculiar property of the visual sense-organ, that radiant energy between certain wavelengths, impinging upon the retina, causes the sensation of brightness. Also variations of wavelengths within this range causes sensations of certain hues. The discussion of wavelength will not be taken up here as it is of more scientific interest. Naturally there



FOOT-CANDLES
(8% REFLECTION-FACTOR)
0
50
100
150
200
SENSITIVITY TO BRIGHTNESS-DIFFERENCE
60
55
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
FOOT-CANDLES
(80% REFLECTION-FACTOR)

FIG. 4

is a brightness that is just barely visible, but this is of little concern, as in illumination work the values are much higher than this threshold value. Hence in illumination installation design the brightness-difference is the governing factor.

Fig. 4 shows a curve of Sensitivity to Brightness-Difference plotted against intensity in Foot-Candles, on a white surface of 80% reflection factor for a range of 0 to 25 Foot-Candles for the 80% reflection factor surface, and from 0 to 250 Foot-Candles for a dark gray surface of 8% reflection factor.

Inspection of Fig. 4 shows that for a sensitivity of 55% of the perceptible minimum brightness-difference (based on the greater brightness) requires an intensity of 20 Foot-Candles when this surface is white (80% Reflection Factor) and in order to obtain the same sensitivity for the 8% reflection factor surface, the required intensity would be 200 Foot-Candles. It should also be noted that the brightness of the so-called white surface is ten times that of the so-called dark gray surface. Much of our seeing is concerned with surfaces of low reflection-factor whose brightnesses are much lower than the surfaces of high reflection-factor, under the same intensity of illumination.

The data in Fig. 4 is applicable to materials that reflect 8% of the light by using the upper scale of Foot-Candles. It can be seen that the eye does not approach its maximum effectiveness within this range, until the illumination-intensity has reached the value of about 200 Foot-Candles. The same reasoning may be applied to the lower Foot-Candles scale. Also surfaces of any reflection-factor may be compared by changing the scales to suit; viz. for a 40% reflection-factor, multiply the lower scale by two, or divide the upper scale by five.

It should be remembered that the eye is called upon to distinguish brightness-differences not only of surfaces of low reflection Factor, but also when these surfaces are in a shadow. In other words, we must see under tables, and in the shadows cast by objects on the tables, etc., as well as on the table tops where full intensity may be had.

Here may be a combination of reduced illumination and low reflection factors that will make the brightness-difference low. It is quite an easy matter to determine the sensitiveness under these conditions in the laboratory where conditions are largely controllable, but in the

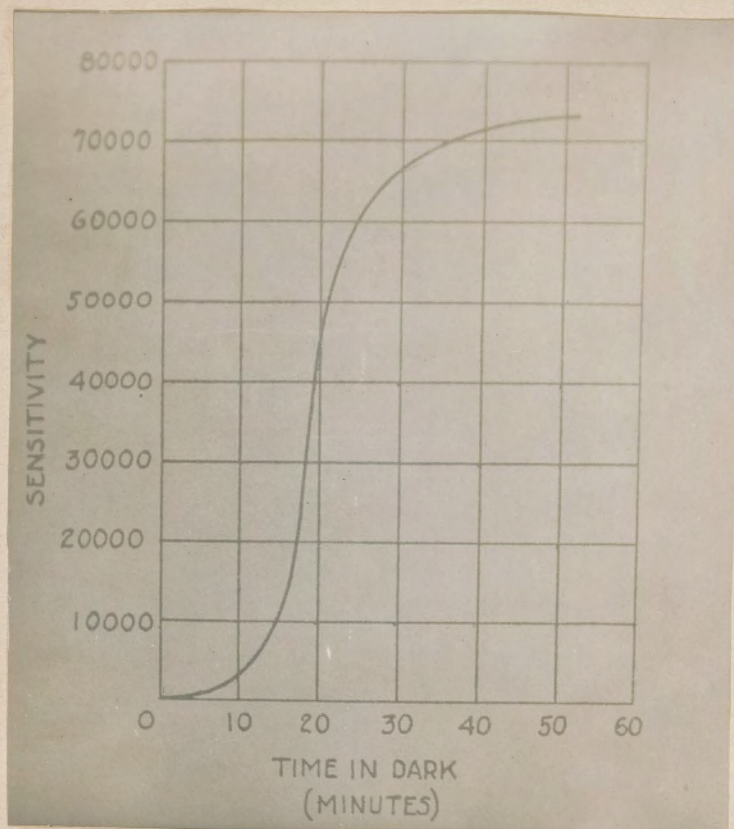

80000
70000
60000
50000
40000
30000
20000
10000
SENSITIVITY
0
10
20
30
40
50
60
TIME IN DARK
(MINUTES)

FIG. 5

actual practice it is quite a different matter for the worker. In any event, he should be given a large factor of safety; that is, the lighting installation should be such as to promote visibility, and the illumination intensity should be well up in the region of maximum visual efficiency for surfaces of widely different reflection factors.

Adaptation of the eye is well known to everyone by experience, and, doubtless, everyone knows that it takes time for the eye to adapt itself to changes in brightness. Fig. 5 presents some quantative data as to the length of time for complete adaptation, etc. From data obtained by Hecht, it can be seen that the sensitivity of the eye increases very slowly in the first 5 or 10 minutes the subject is in the dark, and then increases rapidly for the period of 10 to 30 minutes. It continues increasing in sensetivity up to about 50 minutes.

The slow increase for the first few minutes, shows the desirability of an even intensity of illumination. Spotty illumination means that in going from one illuminated spot to another, either in person or by looking, means that the eye is in a state of continual change. In going from a spot of low intensity to one of high intensity, the pupil is open quite wide, so that the rods in the other part of the retina are subjected to the high intensity before the pupil can contract and protect them as they are too sensitive for high intensity vision. This causes what might be termed an over-exposure with its momentary pain, which, if repeated many times causes a defect of the eye. In going from the high intensity to the low intensity, there is not the pain present, yet there is a loss of time from the task in hand, and the eye is in a process of changing. The loss of time may or may not be worthy of consideration, however, the fact that the eye is changing is worthy of consideration, as previously pointed out.

THE BEST RESEARCH OF GOOD LIGHTING CONDITIONS INDICATE THAT THE EYES SHOULD NOT BE SUBJECTED TO SUDDEN CHANGES IN BRIGHTNESS , OR TO SUDDEN CHANGES IN GENERAL LEVEL OF ILLUMINATION OF GREAT MAGNITUDE.

Previous paragraphs have dealt with the fundamentals of vision as pertain to the eye itself. There are factors, external to the eye, that are equally important. Some of these factors are; direction, the diffusion, the quantity, the distribution, and the quality of light. Shadows and their complementaries, high-lights; are quite important. In order to produce the best conditions for seeing, we must aid the visual sense by giving the best conditions to these external factors.

Two eyes have a great advantage over one eye, when objects in relief are to be distinguished. Each eye sees a slightly different aspect of a three-dimensional object, and this plays an important part in giving the effect of relief. One of the most wonderful features of our vision, is that we see things out in space and not internally, where the image on the retina is. This is one of the greatest examples of learning. We have learned to interpret the various muscular stresses, such as those due to convergence of the eyes, in terms of external space. Two eyes greatly extend this interpretation of the external world. Knowledge plays an important part. When our knowledge is supposedly accurate but is actually erroneous, we misjudge or we are confronted with illusions.

The principal modes by which we perceive the third dimension of space and of objects, and other aspects of the external world are as follows:

1- Extent.
2- Perspective.
3- Elevation of objects.
4- Variation of light and shade on objects.
5- Variation of visor angle, in proportion to distance.
6- Muscular effort attending accomodation of the eyes.
7- Interference of near objects with those more distant.
8- Stereoscopic vision.
9- Clearness of brightness or color, as affected by distance (of interest only outdoors for great distances).

Shadows are that area on an object that does not receive the dominant direct light. Shadows are very important in our ability to see objects ; without them, objects would be invisible when the background was of the same color and brightness. The size of the light source determines the character of the shadow-edge. The sun causes a fairly sharp shadow; the sky a very indefinite one. The same applies for artificial light sources; small sources of light, such as bare lamps, cause sharp shadows. Larger diffusing glass units give a shadow with a softer edge. Ceilings produce effects corresponding to the sky. A good example of this is in indirect lighting; here the ceiling is considered to be the light source, and the light is diffused in every direction, so that shadows are quite light and not very sharp, if definite at all. In any event the shadows should have a minimum of 10% as much light as the adjacent surface that is under full illumination. It is impossible to adhere strictly to this ratio, but it at least represents a desirable minimum value.

Highlights, the complementaries of shadows, are important in much the same way. An object is often distinguished by its contrast between highlight and shadow, and the form by the character of the highlights, or by the modulation between highlights and shadows. There are times when we distinguish an object by its highlights. Such a case is that of a fine wire.

Our vision being based upon contrast, the control of backgrounds can be used to advantage. It is possible to make the background much lighter or darker that the object we wish to see, hence we control the contrast. The smaller the object, the greater the contrast necessary to see it. For very fine work it may be necessary to supplement the general lighting with high-intensity local illumination, well shaded from the workman's eyes. A few years ago there was the tendency to discard localized illumination entirely, and solve all problems by general lighting. It is quite obvious that such a move is not in keeping with the knowledge of light and vision.

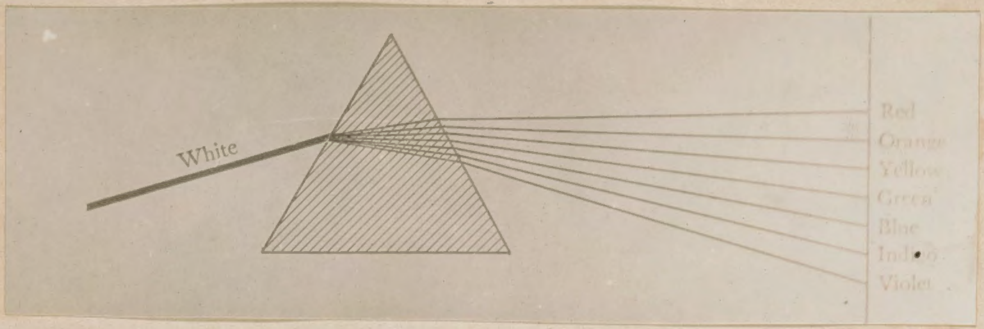


FIG. 6

FIG. 7

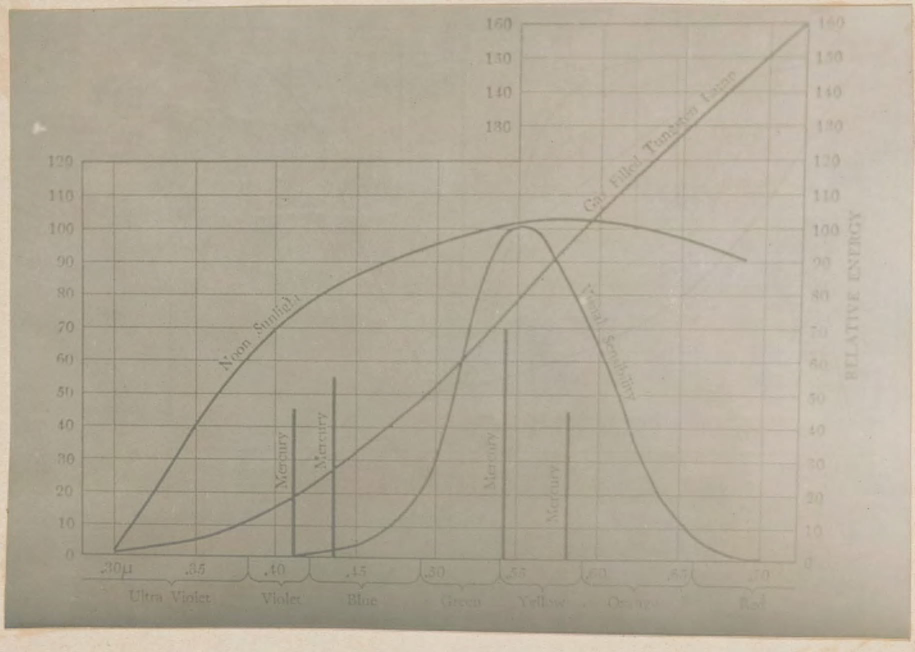


FIG. 8

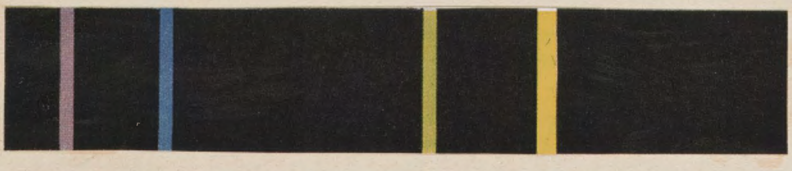


FIG. 9

In the previous discussion, the matter of wavelength has been merely mentioned, and the light under discussion has been assumed to be similar to sunlight in composition. Also a normal eye has been assumed. In the following paragraphs the variation of visual sensibility and radiant energy present in the different colors of sunlight will be taken up.

Fig. 6 shows how a triangular prism of glass breaks up the sunlight into its component colors. This is because the glass bends the different colors to different angles. The violet is bent the most, and the red the least; with the others in between as shown. Fig. 7 shows the appearance of the spectrum as near as color printing processes will permit. The violet is the shortest wavelength, and red is the longest. Such a spectrum is continuous. Fig. 8 shows the spectrum as the base of a set of curves, the vertical units being relative energy. The four vertical lines, labled Mercury, are the lines belonging to the spectrum of the Mercury-Vapor light, as produced by a mercury-light unit. The appearance of the spectrum is shown in Fig. 9.. The spectrum is not continuous, as indicated by the black spaces between the colors.

Fig. 8 shows the relative energy contained in the light from noon sunlight, ~~and~~ a gas-filled Tungsten lamp, and the Mercury-vapor unit. The Visual-Sensibility curve is plotted on this sheet to show how the vision varies with the different wavelengths, or color of light. The maximum visual sensibility comes on the lower wavelengths of yellow where, incidentally, the greatest amount of any one color of light is present in the mercury-vapor light.. In as much as the other curves represent the amount of radiant energy present in the light from different light-sources, it can be seen that those light-sources containing the greatest amount of red in their radiations, have the greatest amount of radiant energy present also. In other words, that for a given intensity of illumination, mercury-vapor light will have the less radiant energy in the light than any of the other light-sources plotted. This means that for the same visual sensibility the eye does not have to absorb as much radiant energy under the mercury-vapor lighting as under light from some other light-source.

LIGHT SOURCES.

Aside from the natural, or day light, we have two important sources of light that are used for general illumination purposes. These are the incandescent lamp and the mercury-vapor lamp. Neon tubes are quite extensively used for advertising purposes and display lighting, but as yet it is relatively unimportant from the standpoint of general illumination.

As was pointed out in Fig. 8, the incandescent lamp gives a continuous spectra, and the light is white. This type of lighting appeals to human beings more than the band-spectra light, such as that produced by mercury-vapor units, under the white light things appear more nearly in their natural colors, or as they would appear under daylight. Hence we find this type of lighting in the homes, stores, and industrial plants. While incandescent lighting contains more of the red than sun light, it does not cause "off color" appearance of things enough to bother. Where strict matching of colors is necessary, a special unit with a bluish ground glass plate gives a light that very closely approaches day-light. Also day-light lamps made of blue glass can be used in place of the regular.

clear glass lamps, and an approximate day-light effect will be obtained. In the use of any incandescent lamp, care must be taken to avoid having the high intensity light source in the direct line of vision. At all times the light from such light-sources should be well diffused, in order to reduce the surface brilliancy. A further discussion of this appears in the section on GLARE.

In the discussion of the curves of Fig. 8, it was noted that mercury-vapor light was made up of only four colors, hence has a band spectra. The spectral composition of the light is such as to promote the highest seeing ability with the least amount of radiant energy. One thing that highly favors the mercury-vapor unit is that the surface brilliancy of the light source is low because of the combination of the violet counter-balancing the glaring effect of the yellow. Also the light source is quite large, and the light is well diffused. For certain classes of work, particularly industrial application, the mercury-vapor lamp is one of the best solutions to the problem. When it is necessary to distinguish colors, the mercury-vapor lamp is out of the question because the lack of red in the light causes red to look black under this type of illumination. There is also a psychological effect to this "off color" illumination, because persons look "ashey" or "sick" under it. This effect soon disappears when those affected have become used to it; only in extreme cases is the contrary true. In general, it is best to have the services of an illuminating engineer in the designing of mercury-vapor installations, as the flexibility of these units is not as great as the incandescent unit, and greater care must be exercised in order that the maximum illumination for the money may be had.

COLORED LIGHTS.

The study of color and lighting is a subject all to itself in extent; however the following paragraphs give the fundamental ideas of color and color combinations. "The word color is used in three different senses; the color of light depends upon the relative powers of the different wavelengths which the light contains. The color of a surface depends upon its reflectivity for the different wavelengths. The color seen depends upon the kind of sensation produced in the visual centers in the brain.

For practical purposes, colored light may be resolved into three components; red, yellow, and blue. Any given visual color can be produced by mixing of light of these three colors.

Visual or psychological color is the result of four different sensations which we know as green, red, yellow, and blue. These are commonly called PLAIN COLORS.

Plain colors mixed with white form TINTS; mixed with black they are called SHADES; and mixed with one another HUES. Hues may be lighter or darker according as they are mixed with white or black.

Color, as a general term, means any kind of light sensation other than black or white.

Color is always used with reference to a surface, unless otherwise specified.

WHITE LIGHT is light containing all of the wavelengths found in sunlight, and of the same relative powers.

A WHITE SURFACE is one that reflects all wavelengths equally well.

SEEING WHITE is the sensation produced by sunlight of average intensity.

It is not necessary to have all the wavelengths contained in sun-light in order to SEE WHITE; the same visual sensation can be produced by light containing only two wavelengths, or any other number of wavelengths, provided their relative powers be of a certain order. Two colored lights which produce the sensation of SEEING WHITE are COMPLEMENTRY or CONTRASTING COLORS.

At high intensities all colors tend to become white, and at very low intensities black.

Two colors MATCH when they look exactly alike. In practice colors are always compound, both in respect of visual sensation and of light wavelengths.

The NATURAL COLOR of a surface is its color as seen by white light.

Light of different wavelength composition from white, will produce a different color sensation when reflected from a given surface; this is the APPARENT COLOR of the surface.

Colors which match by white light may or may not match by light of other composition. Thus colors that match by day light may not match by electric light. This is due to the fact that the same color sensation may be produced by a number of different combinations of light colors, or wavelengths. Thus, suppose a given visual color is produced by light colors A, B, C, and D, and also by colors A and C; and supposed two fabrics so dyed that they reflect these rays in white light, in such proportions as to produce the same visual color. The two pieces will then match by day light. Now suppose that the two pieces are illuminated by electric light, which contains much less of the light color D than sunlight, the piece reflecting rays A, B, C, D, will then appear of different color from the pieces reflecting rays A and B, and the two pieces will not match in color." (4)

(4). Elliott, E.L. "How We See" pp. 28-29.

GLARE.

Glare may be divided into two kinds; the first is a reduction in visual perception because light is coming directly from the light-source to the eye, causing the pupil to contract thus cutting down the brightness of the retinal image. Light reflected from a surface, as that reflected from very smoothe paper, has the same effect. The second kind of glare is physiological action which leads to discomfort, pain, and inflamation. In both cases the physical cause is photographic over-exposure. The over-exposure may be local, or general. Local over-exposure is caused by excessive contrast in brightness in different parts of the retinal image. General over-exposure is caused by excessive brightness over the whole retina. Local over-exposure of the cone film reduces visual perception. Local over-exposure on the rod film produces uncomfortable, or injurious physiological effects.

There are five principal causes of glare:

1. Brightness of light source. The source may have too high surface brilliancy, that is too many light units or Foot-Candles per square inch.
2. Total volume of light. The light source may be too powerful for comfort, or as mentioned

above, there may be too great a total candle-power in the direction of the eye.

3. The location in the field of vision. A light source may be located too close to the eye, or be too near the center of the field of vision, for comfort. This dictates that the mounting height for units must not be too low, and those that must be low should be well screened from the eye.
4. Contrast with backgrounds. The contrast between the light source and the darker surroundings may be too great. Common experience shows that a lamp viewed against a dark background is far more trying on the eyes than when the background is lighter. Again this points to the fact that local lights must be well planned, and their intensity just right, else the resulting contrasts in intensity between the local and the general illuminating system will be too great.
5. Time of exposure. The time of exposure may be too great, that is, the eye may be subjected to the stress caused by a light source of given strength within the field of vision for too long a time. Where work is being done for several hours at a time by one person, the image formed on one part of the retina is

likely to cause discomfort, particularly if the light sources are too bright. Hence, for these conditions more units of lower wattage per unit must be used.

TYPES OF LIGHTING SYSTEMS.

For interior illumination there are three general systems of illumination:

1. DIRECT SYSTEM. The direct system, as the name implies, is one in which the light from the light-source goes directly to the working plane. The lamp may or may not be equipped with a reflector, shades, or diffusing media. An unprotected system has the advantage of a high light efficiency, or in other words a greater percentage of the light from the light-source may reach the working plane, yet the glare from such a system is very detrimental to the eye. Such a system has its applications, and in the case of the mercury-vapor installation the low surface brilliancy of the unit, allows it to be hung lower than would be permissible with the incandescent unit.

For high mounting, such as over crane-ways, in factories, the direct unit is about the only thing that can be used, and as far as covering the light-source is concerned; it is an unprotected system, yet the exceedingly high mounting heighth reduces the glare to a safe minimum in a properly designed system.

The protected direct system is by far the most popular because of its relative high efficiency. For residence, commercial, and office lighting, the opalescent glass bowl around a clear lamp gives the sufficient diffusion so that the surface brilliancy is not too great for general purposes. The shape of the glassware determines the distribution curve of light flux.

For industrial application, what is known as a R.L.M. Standard Dome Reflector is used with bowl-enameled lamps. R.L.M. Standard means Reflector and Lamp Manafacturers Standard reflector, and is an enameled steel reflector of standard shape as designed for maximum utility. The bowl-white lamp reduces the glare from the bright filmament, which is a considerable factor where mounting heights are moderate. R.L.M. reflectors are not for high mounting, even though many are used for such service, as over crane-ways. A special unit, of either prismatic glass or a deep bowl focusing type, should be used as the efficiency will be higher.

An R.L.M. reflector fitted with opalescent glass bowl is known as a Glassteel Diffuser, and it makes a very excellent general purpose unit that has a very much less glare than the R.L.M. Reflector bowl-white lamp combination. The Glassteel

Diffuser may be used in interiors where the R.L.M. Reflector would be entirely out of keeping with the rest of the furnishings.

The mercury-vapor lamp for industrial work is hardly surpassed by the direct system, on account of the high diffusion inherent in the mercury-vapor unit, and for industrial installations in general, it represents the best illumination, although a carefully designed incandescent system approaches it.

2. SEMI-INDIRECT SYSTEM. This system has the light-sources fitted with inverted translucent glassware so that some of the light passes directly to the working plane, while the rest goes to the ceiling and is reflected back to the working plane.

Such a system is not so economical as the direct system, as part of the light is absorbed in the translucent glass and a still larger part by the ceiling, but the quality of light reaching the working plane is far better because of the higher diffusion, and the fact that the ceiling is a secondary light source. Also the surface brilliancy of the units is not bothersome. Semi-indirect installations are unsuited for general industrial work although certain classes of industrial interiors may be lighted by such an installation.

3. TOTALLY INDIRECT SYSTEM. This system lets no direct light get to the working plane, but directs the entire output of the light-source to the ceiling, from whence it is reflected back to the working plane. The character of the light is excellent, and as the ceiling is the light source for the room, the diffusion is of the highest order. The units may or may not be luminous, hence there is no surface brilliancy to bother. However, it is not advisable to have the ceiling intensity too high as the same effect will be obtained. As a rule this item does not cause trouble.

Indirect systems may have the light units hung from the ceiling, as the ordinary direct unit, but unlike the direct unit, the indirect unit turns its entire light output to the ceiling. Or the reflectors and lamps may be located around the edge of the ceiling, in recesses or covers, that hide the primary light source from direct view.

The indirect system is not very economical of power, on account of the high losses of light to the ceiling, but as pointed out previously the quality of light and the diffusion is the best. Shadows are reduced to a minimum, and under a properly designed installation vision is at its best. For cetain classes of work indirect lighting is the only really satisfactory solution to the problem. Drafting rooms are the biggest commercial users of indirect systems, although Mercury-Vapor illumination, for certain classes of drafting work, is excellent.

As to the reflecting equipment, mirrored and prismatic glass reflectors give the highest efficiency, although other reflecting mediums are used to some extent.

MAINTENANCE, PAINTING AND THE
COST OF ARTIFICIAL LIGHTING
vs. NATURAL LIGHTING.

A new installation always gives a higher intensity than was the designed value. This is because of the fact that everything is new and clean. After short period of service, a thin layer of dirt settles on the lamps and reflecting equipment, which materially reduces the light output. Frequent cleaning of the reflectors and lamps, will do much towards maintaining adequate illumination at all times. If the periods between cleaning are tooo long, it is necessary to add a higher depreciation factor to cover this absorption of light. In other words, it will be necessary to install lamps that are far too large for the job, in order that the intensity of illumination will be adequate when the units are dirty,. This means higher initial investment, plus the extra energy consumed by the overly large lamps. Another way of looking at dirty reflecting equipment, is that the light absorbed by the dirt represents energy wasted, for which money was paid out, and no return was received on this money because the light never reached the working plane to be utilized.

Maintenance of a proposed installation should be carefully considered, so that the proper Depreciation Factor may be applied, else the job will be a failure and unsatisfactory. Indirect and Semi-Indirect units are inherently dirt collectors, and in some cases they might be ruled out for no other reason. Maintenance of clean equipment and clean walls and ceilings pay the highest returns in the case of these two systems.

The maintenance of the direct system is less trouble than either of the others, because the reflector shields the lamp from falling dust and dirt. However, in smoky or exceedingly dirty interiors, they will require frequent cleaning.

No matter what system of illumination is used, a regular cleaning schedule, followed reasonably close, will pay in the long run by its increased illumination and reduction of energy for which no light is received on the working plane.

Along with cleaning of reflecting equipment, the maintenance of the walls and ceilings in a condition of good reflection is very important. Painting, in this discussion, will be taken to

Reflection Factors

White Paper 84%

Gray 69%

Buff Stone 35%

Ivory White 77%

Pink 50%

Gray 39%

Yellow 70%

Pale Azure - White 52%

Tan 25%

Pale Azure 39%

Fig. 10

mean the wall covering, and not to refer to paint specifically.

The discussion of the Semi-Indirect and the Totally-Indirect illumination, did not mention the color or condition of the ceiling. It is readily apparent that for the least loss of light, the ceilings and walls should be pure white. It is impossible to obtain this ideal, but it can be approached with light colors. Fig. 10 shows the reflection-factors of some of the common colors; by matching these colors, it will be possible to closely approximate the reflection-factor for a given room.

What is true of walls and ceiling for Semi-Indirect and Indirect installations, is also true for direct installations. If the walls and room furnishings are dark they will absorb light from the light-source, and in order to get a given intensity of illumination, more power will have to be expended. By repainting in a light color, the same intensity can be obtained with less power, hence the paint applied has a definite money value. Under any given set of conditions, the economical limit can be determined for painting on an illuminating basis alone. The cheerfulness of a light-colored room and the incentive for

Cleanliness, are also linked up with the illumination problem.

Glossy paints have the disadvantage of reflecting the images of the light-sources, causing glare that is troublesome. Glossy desk-tops, walls and ceilings, and various polished surfaces, are possible sources of glare. Paints with dull finish approach perfect diffuse reflection fairly closely. However, these dull finish paints are likely to have a somewhat roughened surface that will catch dirt and be hard to clean. A paint that gives a rather dull finish, with a fairly smooth surface, is desirable; as it is necessary to strike a balance between the two extremes of glossy and matte surfaces in the matter of maintenance.

"Daylight has been accepted for so long as a matter of course, that many do not realize its cost when applied to interior illumination. In general, it might be stated that natural lighting indoors costs as much as artificial lighting, and in some cases in crowded cities, it costs more.

Without regard to the psychological effects of natural light, the chief items which contribute to the initial net cost are:

a. The difference in cost of the building with and without windows and skylights.

b. The rent value of the ground area sacrificed for light courts, and in other ways, to obtain effective daylight openings.

c. The cost of extra heating equipment to supply the excess heat-losses from the glass areas, over the loss from equal areas, of walls, ceilings, etc.

The chief items which contribute to the operating cost of natural lighting equipment are:

a. Interest on initial net investment.
b. Depreciation of natural lighting equipment.
c. Repairs.
d. Cleaning glass.
e. Depreciation of extra heating equipment.
f. Extra fuel.

I Investigations relative to natural lighting in seven-room houses brought out these facts; The initial cost of natural lighting was about $600, and the total annual operating costs were about $100. These figures were closely approached by artificial lighting of a high standard, considerably above average conditions.

From the psychological standpoint light-courts and windows will always be demanded. However there are millions of persons working under artificial light throughout the day with no discomfort." (5) With the advent of ventilation systems that supply the correct amount of fresh air under the proper conditions of humidity and temperature at all times windows and light-courts are catering more to the psychological than to the practical. The extreme has been advocated that all windows and light-courts be eliminated, but such a tendency does not seem present in the construction of some of the later large structures.

(5) Luckiesh, M. "Light and Work".

APPENDIX.

Mercury-Vapor lighting has primarily been a lighting for industry. It is a different light, and has not been used in an exceedingly wide range of applications until the last few years. Its glareless illumination and low brilliancy light-source has led to its use in places heretofore unthought of.

One theory that has been advanced relative to a person's high seeing power under mercury-vapor illumination, is that being made up of only four different colors, or wavelengths, the chromatic abberation of the lens of the eye is less, hence we get a sharper retinal image than under any other light. Chromatic abberation is the property of a lens to bend one wavelenght of light more than another, as the triangular glass prism does. When an image is formed by a lens, using sun-light, the image will, in the case of the simple lens, be found to be timged with the colors of the spectrum. This tinging is the result of Chromatic Abberation. Mercury-vapor light having only the four colors in it, is freerer from Chromatic Abberation than would be the case if the image were formed by light from other light-sources.

The introduction made mention of a mercury-vapor lighting installation in one of the Drafting Rooms and in the Machine Shop of the University of Tennessee. Figures 11, 12, and 13, are pictures taken for comparison between Mercury-Vapor, daylight, and bare incandescent lamps. No readings of intensity in any of the places have been made; however, the pictures give an idea as to what the eye sees. These pictures were made with the same length of exposure and size of stop, with an ordinary kodak, then enlarged to this size from their original size of 2 1/4 inches by 3 1/4 inches. Care has been exercised to make the handling of the pictures and negatives the same, so as to eliminate any "tricks".

Figure 11 shows a general view of the two rooms which are identical, except for the lighting. In the picture on the left, the presence of detail and the absence of heavy shadows and glare from the ceiling is an index to the utility of the installation. Compared with it is the picture on the right which shows the worst conditions. 200 Watt bowl-white lamps without reflectors are used in this room. The distribution of light on the ceiling can be seen, also the glare from the light-source can be appreciated by noting the difference between the light and dark around each lamp. The lack of detail on the desk-tops and the floor is a marked contrast to the picture on the left made under the Mercury-Vapor lamps.

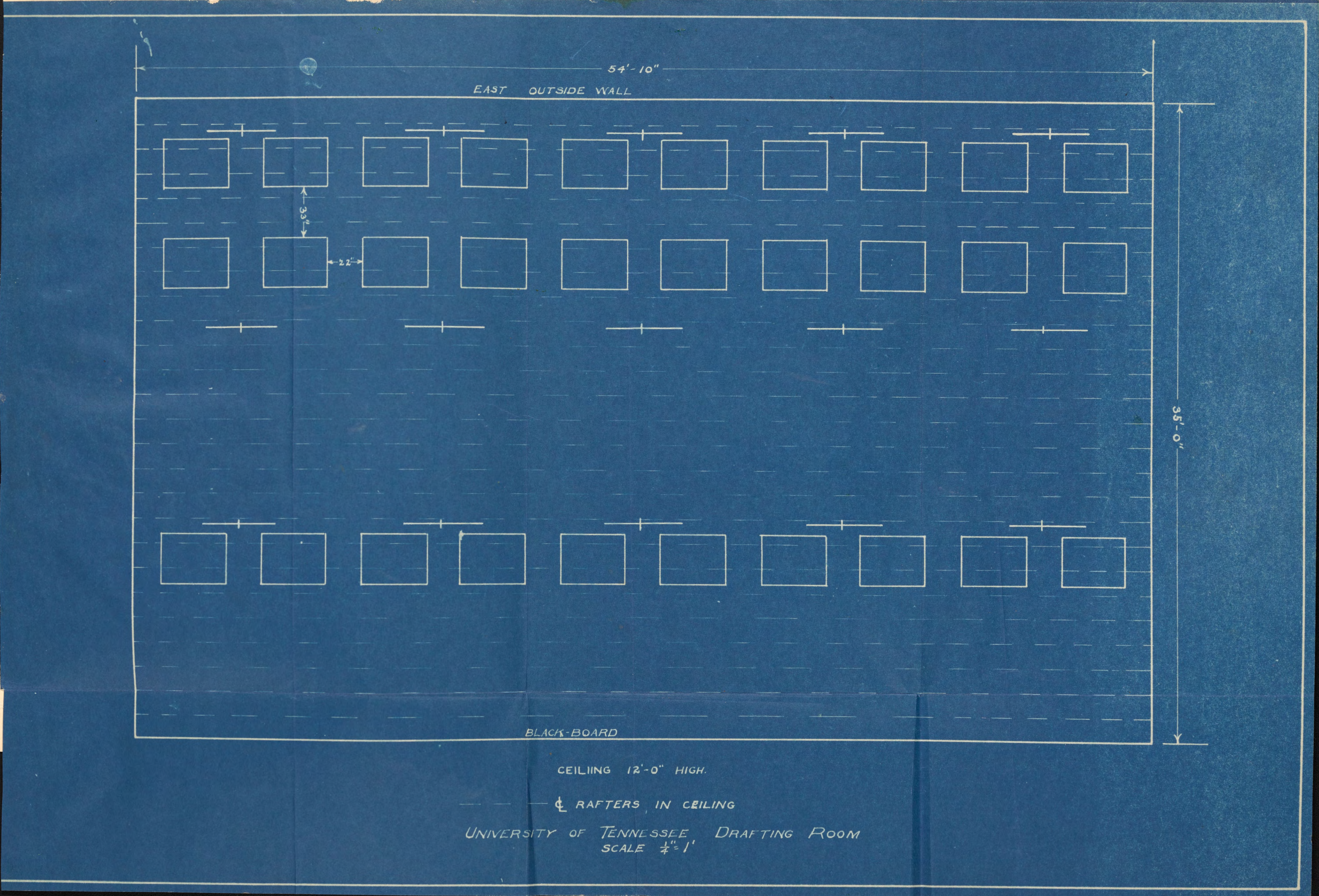
Figure 12 is to show the illumination on the vertical surfaces. In the picture on the left the reflection from the paper has gone right into the camera lens causing no detail to show up. The picture made under the bare lamps shows good detail. This is the reverse of what was expected, yet it is rather hard to account for the fact that the reflection from the paper seems to cause no glare, as shown by the detail around the paper in the picture on the left. Attention is also called to the detail present under the tables, on the floor, where ordinarily very little light finds its way.

Figure 13 shows the appearance of the machine shop under Mercury-Vapor lighting (left) and daylight (right). These pictures were made from slightly different locations, but the effect is there. They present a graphic idea of the difference in illumination between natural and artificial illumination indoors.

The blue-print shows the arrangement, etc. of the fifteen 450 Watt Mercury-Vapor units in one of the Drafting Rooms.

Throughout this comparison nothing has been said about the power consumption in the two Drafting

Rooms. The Mercury-Vapor units represent a load of 6750 Watts, or 6.75 Kilowatts, which means a power consumption of 6.750 Kilowatt-hours per hour. The other Drafting Room has eighteen 200 Watt lamps for illumination, and they represent a load of 3600 Watts, or 3.60 Kilowatts, which means a power consumption of 3.60 Kilowatt-hours per hour. The seeing ability under the Mercury-Vapor units may be estimated to be about four times that under the incandescent lamps, yet the Mercury-Vapor units use only 87.5% more energy.


54'-10"
EAST OUTSIDE WALL
33"
22"
35'-0"
BLACK-BOARD
CEILIING 12'-0" HIGH.
℄ RAFTERS IN CEILING
UNIVERSITY OF TENNESSEE DRAFTING ROOM
SCALE 1/4"=1'

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APPROVAL.

The foregoing Thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the Thesis only for the purpose for which it is submitted.

Name W. R. Woolrich

Title Prof. Mech Eng.