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June 1978

To the Reader:

This paper was written to promote the more widespread consideration of natural lighting in building design. The potential energy and dollar savings in new buildings and retrofitting existing buildings are tremendous. However, they are outweighed by the potential for increased human comfort and satisfaction.

This paper may, at times, seem overly harsh on lighting engineers, but the failures and criticism are directed more to the current approach to building design rather than the lighting professionals. The failure in lighting design can be attributed in large part to the increasing focus on ever narrower facets of building design. This specialization has had particularly adverse effects on the relation between architectural design and lighting. In most cases, natural lighting has been completely ignored by the lighting engineer, architect, and interior designer. The American educational system has reinforced this fragmented approach rather than the more integrated approach that is needed. The educational system, it seems, is unlikely to respond to the energy "crisis" and the many exciting opportunities for natural lighting, solar heating and natural cooling, and increased human comfort unless the practitioners in the field demand competence of this type in their future hiring.

Comments and criticism of this "draft" is desired and will be incorporated in future revisions.

Sincerely,

David A. Bainbridge

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STAFF DRAFT

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NATURAL LIGHTING

"Daylight is a gift of nature. As civilized man learns to use artificial light sources which free him from total dependence on daylight, he also learns to appreciate the value of daylight and becomes aware of its special advantages. The idea that man evolved by adapting to his natural environment is a basic feature of 20th century thought. This concept implies that human vision is adapted to daylight, and that consequently artificial light necessarily involves a certain degree of unfavorable adaptation."

R. G. Hopkinson et al
Daylighting (1966)
Heineman

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June 1, 1978

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1. INTRODUCTION

In 1972, more than 20 percent of the electricity generated in the United States was used for lighting, FEA (1975). If this energy had been widely spent to provide comfortable and safe working conditions this very high use might be justified; in fact, however, much of this energy is spent for over lighting that in many cases causes discomfort and hazard. In addition, this over lighting greatly increases the use of energy during the summer for air conditioning to offset the extra heat added by the lights. Proper lighting design incorporating as much natural lighting as possible could save considerable energy and money and would also provide more comfortable conditions for workers throughout the state.

2. SEEING AND LIGHTING

The basic goal of lighting should be the provision of a comfortable, pleasant, and safe visual environment for man. This is not as simple as one might expect because the human eye and brain are very complex and very adaptable. This complexity makes good lighting design difficult.

There are several concepts that must be understood in the discussion of lighting. The first is illumination, or the amount of light spread over a surface. This may be described in the English notation by the term foot candle or in the metric system as a lux or lumen/sq. m. [1 fc = 1 lm/sq.ft. = 10.8 lux]. Much of the discussion that follows uses fc as the sole reference; however, it is only the most convenient measurement and several other factors must also be considered in good lighting.

Brightness is a factor of the level of illumination and the reflectance of the surface we are viewing. A white surface may have a reflectance of nearly 100 percent while a dark black surface may reflect only two percent. Brightness is the product of illumination multiplied by the reflectance and is also known as "luminance." The common measurement is the foot-lambert.

Perceived brightness may vary considerably from the physically measured brightness. For example, a car headlight is apparently very bright at night yet very dull during the day even though the measured brightness is the same. Color may have a similar effect, Hopkinson (1969).

Thus, in discussing brightness we must discuss it subjectively--for what we see. The human eye can see from around .0001 to 10,000 foot candles. It is very adaptable and can be comfortable over a very broad range of lighting intensities. Research has repeatedly shown that low light levels will not cause eye damage. Variety is essential for visual comfort and must include movement, intensity, and color. The environment in which we evolved provided this stimuli and we require it for comfort and good visual performance.

Natural lighting is desirable because using the sun matches the spectrum of light our eyes evolved with exactly. The spectrum of light from incandescent lights, fluorescent lights, mercury vapor, and sodium vapor lights are considerably different and appear more and more to cause adverse psychological and/or physiological responses, Dubos (1964), Ott (1976), Clark (1974). Unfortunately, these impaacts have received very little study and remain largely speculative, Fitch (1972).

3. LIGHTING STANDARDS AND RESEARCH

> "It is unfortunate that American engineers do not appreciate the value of experimental checks on their computations. A system of computations might be internally consistent and still be in conflict with experience on the common sense level. In such a case it is of theoretical value only, which lighting is not.
>
> The British lighting code which, like the codes of other European countries, is more conservative than the American one has apparently taken into account much more experimental data than has the United States code. As a result, the human being figures more strongly in the British approach and is not completely eliminated in favor of the visual task as a criterion." Leslie Larson.

Lighting standards have risen drastically in the United States largely in spite of the research that has been done on human comfort. The Illuminating Engineers Society has been at the forefront of the revisions, largely in response to strong pressure from the manufacturers of lighting equipment, Clark (1974). The history of the N. Y. School lighting standards is indicative of the changes that have occurred. Before 1910 the standard was 3 fc, between 1910-1930 it was 18 fc, between 1930-1950 it jumped to 30 fc, and it has risen since then to 150 fc, Steadman (1975).

As one might expect, this is a uniquely American phenomenon. European engineers have continued to rely on the concept of human comfort rather than the idea of maximum potential performance reading very poor material. The biggest rise in standards was based on a very narrow interpretation of research by Dr. R. H. Blackwell. His research in the 1950's led to a recommendation for light levels for various purposes based on 99 percent accuracy of visual task completion. He reported that foot candle levels of only 0.60 fc were sufficient for reading a clean copy of 12 pt type (this paper). For equal accuracy reading an original typed with a very poor ribbon almost 3,000 fc were required. The I. E. S. focused on the higher levels of illumination, even though subsequent research by

Dr. M. A. Tinker found that visual performance in reading newsprint did not increase after 7 fc. Other studies have demonstrated that readers prefer much lower levels than are now prescribed, Larson (1964).

The European Standards are based more clearly on empirical studies of comfort and standards have used only 90 percent rather than 99 percent accuracy as a criterion. Their stated goal has been "lighting which would permit efficient work in a pleasant environment." A comparison of the standards in different countries is very instructive, Table 1. There seems little question that the minimum levels recommended by the I. E. S. in the U.S. are unjustified.

Table 1: RECOMMENDED LIGHTING STANDARDS

from Larson (1964)	U.S.A.	GT. BRITAIN	FRANCE	GERMANY	SWEDEN	FINLAND	BELGIUM	SWITZERLAND	AUSTRALIA
Most Difficult Seeing Tasks Finest precision work. Involving: finest detail; poor contrasts; long periods of time. Such as: extra-fine assembly; precision grading; extra-fine finishing.	926- 1852	139- 273	139- 278	370	93- 185	93- 185		over 93	over 185
Very Difficult Seeing Tasks Precision work. Involving: fine detail; fair contrasts; long periods of time. Such as: fine assembly; high-speed work; fine finishing.	463 926	65- 139	65- 139	55- 93	27- 46	46	46- 94	27- 93	65- 139
Difficult and Critical Seeing Tasks Prolonged work. Involving: fine detail; moderate contrasts; long periods of time. Such as: ordinary benchwork and assembly; machine shop work; finishing of medium-to-fine parts; office work.	463 92	28 65	28 65	23 46	28	28	23 46	14 28	28 65
Ordinary Seeing Tasks Involving: moderately fine detail; normal contrasts; intermittent periods of time. Such as: automatic machine operation; rough grading; garage work areas; switchboards; continuous processes; conference and life rooms; packing and shipping.	46- 93	14- 28	14- 28	11- 23	14	14	9- 23		14- 28
Casual Seeing Tasks Such as: stairways, reception rooms; washrooms, and other service areas; inactive storage.	18- 28	7-14	7-14	6	4-8	8	5-8	4-8	7-14
Rough Seeing Tasks Such as: hallways; corridors-passageways; inactive storage.	9-18	3-6	3-6	3	2	4	2-3		5-7

The fact that the recommended standards in the U.S. vary so widely from the rest, and that they have risen most markedly, suggests that they shouldn't be taken too seriously. The wide variation in standards also reveals the highly subjective rather than scientific nature of the standards and the standards setters.

A revised lighting standard prepared by the FEA is included below, Table 2, FEA (1975). Note that it is for maximum lighting level. In fact, it is still very high for most purposes.

TABLE 2: FEA'S RECOMMENDED MAXIMUM LIGHTING LEVELS

Hallways or corridors	10 ± 5 fc
Work and circulation areas surrounding work stations	30 ± 5 fc
Normal office work, such as reading and writing (on task only), store shelves, and general display areas	50 ± 10 fc
Prolonged office work which is somewhat difficult visually (on task only)	75 ± 15 fc
Prolonged office work which is visually difficult and critical in nature (on task only)	100 ± 20 fc

I have prepared a revised standard based on a review of the literature. This is included below in Table 3.

TABLE 3: RECOMMENDED LIGHTING LEVELS

Hallways or corridors	3 fc
Work and circulation areas surrounding work stations	10 fc
Normal office work	30 fc (with task light available)
Prolonged office work of detailed nature	50 fc (with task light available)

It is important to maintain a ratio of 10:3:1 for work, foreground, and background lighting levels. If background lighting levels are high, discomfort and reduced performance result because this ratio cannot be maintained.

4. NATURAL LIGHTING

> "The typical illumination specialist has a background in electrical engineering: he is thus all too prone to rely upon artificial light sources exclusively, paying little or no attention to daylighting." J. M. Fitch (1972).

Natural lighting was an integral consideration in building design and influenced building orientation and fenestration very strongly until relatively recently. It is unfortunate that it has dropped from consideration as it provides benefits other than the inestimable psychological values of daylight. Foremost is the reduction in energy use for lighting. This leads to direct dollar savings that will grow as energy prices spiral upward. In addition, natural lighting can reduce heat gain from lighting to 1/4 that obtained with fluorescent lights and as little as 1/16 that from incandescent lights. This can lead to a substantial reduction in air conditioning load and consequent energy and financial savings.

The ultimate source of all daylight is the sun, yet only a part of the light use for natural lighting is received as direct sunlight. The rest arrives as indirect or diffuse radiation reflected off dust or water particles in the atmosphere or reflected radiation bounced off other structures or features of the landscape. The proportion of each varies as a function of both building orientation, and design, variation in ground surface, and also varies as the sun's path and atmospheric clarity change.

Using natural light is not difficult, yet it has been widely ignored in the United States because of cheap electricity and a fascination with artificial lighting. Great Britain and Europe have continued to use daylight and an extensive literature is available for use in daylight design, BRS (1966), Hopkinson and Kay (1972), Walsh (1961), Hopkinson et al (1966).

Models are particularly useful in lighting design work. A scale model of a building is a true photometric analogue and is much easier and more accurate to use than any sort of calculation, Hopkinson (1958), Models of 1/20 to 1/4 scale are relatively inexpensive and easy to construct yet are large enough to provide very useful information.

5. THE TECHNIQUES OF NATURAL LIGHTING

> "Since one of these fundamental needs is for access to daylight and to the sun, the architect, when considering the general form and character of a building will have to bear in mind this requirement for daylight ..."
>
> R. G. Hopkinson

The actual design of a lighting system must meet the many objectives listed below, Table 4. The methods for meeting these objectives are varied and allow great flexibility for a sensitive and skilled designer.

TABLE 4: LIGHTING OBJECTIVES

visual comfort and efficiency for all users

maximum use of natural lighting

integration with other building systems

minimal lifecycle energy use and cost

low initial cost

maximum flexibility

minimal undesired heat gain

minimal use of non-renewable energy sources

automatic control of switching to reflect natural light levels

minimal glare

A. WINDOWS

Windows offer one of the better methods for providing natural lighting because they are almost always incorporated in the building design. If used properly they can provide "free" natural light. Orientation, placement, and control are essential for good natural lighting--without glare, excessive heat gain, or great variation in brightness. Proper design can also ensure that the windows also provide needed cross ventilation for natural cooling--an added bonus.

Windows should have narrow glazing bars and frames and window surrounds should be angled when possible. Diffusers can be used to reduce glare where needed. Windows should be shaded during the summer in hot areas. In very hot areas, translucent insulated shutters or shutters with light ports may be desirable to reduce conductive heat gain, Bainbridge (1976).

Effective placement of windows will yield the best light for a given window area. Thin tall windows placed near walls wash the walls with light and provide pleasant lighting without excessive contrast, Figure 1.

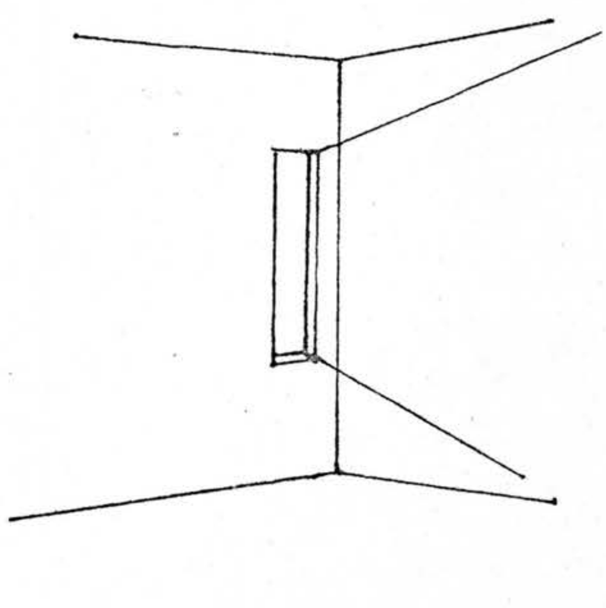

FIGURE 1: LIGHTING WITH TALL CORNER WINDOWS IS VERY EFFECTIVE

High windows admit more light and are also desirable for venting hot area. Yet disability glare will occur unless they are isolated with some form of screen. One of the best methods of screening is the use of a light shelf, Figure 2.

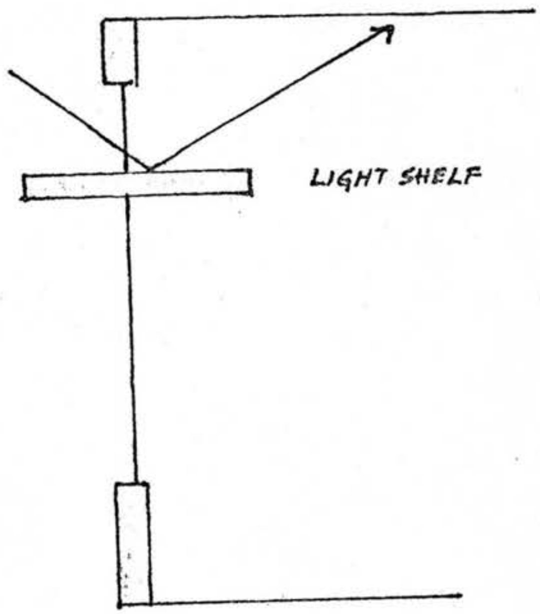

FIGURE 2: THE LIGHT SHELF IS A PROVEN AID IN NATURAL LIGHTING

The light shelf also helps spread light onto the ceiling and increases light penetration into the room. With a light shelf, adequate natural lighting can reach up to 24 feet from the window, Hopkinson and Kay (1972). The initial cost of window and light shelf will be lower than for artificial lighting if the cost of added generating capacity and transmission losses are included in cost of artificial lighting.

B. SKYLIGHTS

> "A common mistake in comparing the economy of daylight utilization with that of electric lighting is made by many air conditioning people. The person figuring the air conditioning load fails to realize that foot-candles of illumination obtained with daylighting produces less heat than equal foot-candles produced by electric light. The normal procedure is to assume a fixed electric lighting load and consider any daylighting as an additional heat load. This assumption is erroneous and does not recognize the advantages of daylight utilization."
>
> J. W. Griffith

Skylights are in many cases the best method of natural lighting. They should face north or should be shaded in the summer to reduce heat gain using the concept of the north facing shade developed by L. W. Neubauer and refined by Living Systems, Hammond et al (1976). In addition, the skylight should be double glazed, preferably with a diffusing inner surface, and should have the surroundings painted bright white, Figure 3.

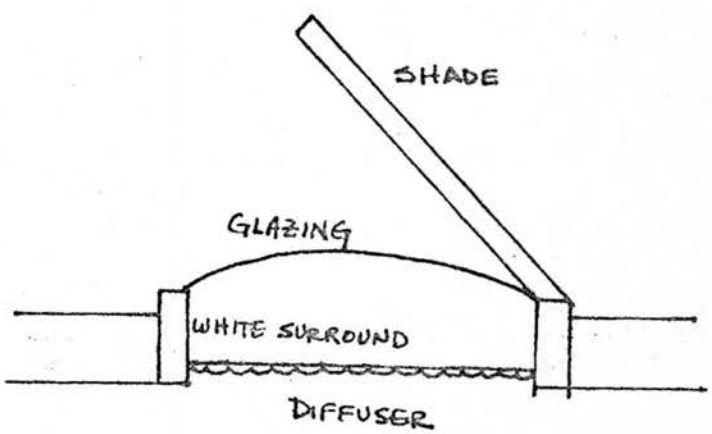

FIGURE 3: SKYLIGHTS ARE VERY EFFECTIVE FOR NATURAL LIGHTING

The following chart makes a comparison of various features of two types of lighting, skylight and fluorescent lighting, Evans (1962). Note that the cost of additional heating/cooling must be added to both systems of lighting. (Note also that the data from the chart are from 1962). All of the costs, and especially the cost of power, will continue to increase rapidly. Skylights still have no power cost. To be energy efficient, skylights must be carefully designed for lighting. Therefore, skylights intended for view or purely architectural reasons may not pay for themselves.

Although skylights are almost 100 percent efficient as the light enters, eventually that light does convert to heat and cooling may be required to offset the heat gain. Likewise, infiltration and conduction of air through skylights may call for additional heating or cooling. However, electric light has only a 20 - 50 percent initial efficiency; the other 50 - 80 percent is given off directly as heat gain that must be met with additional cooling. Electrical lighting, even with fluorescent lights, requires much more cooling than properly used skylights will.

The following comparison of the efficiency of skylights over electric systems is instructive, Table 5. Note: .033 more tons of air conditioning per 100,000 lumens of light at an outside temperature of 100 degrees and an inside temperature of 78 degress should be added to the skylight air conditioning loads.

TABLE 5: EFFICIENCY COMPARISON OF SKYLIGHTS AND ELECTRIC LIGHTING

Source of Illumination	Light Output: Lumens/ Sq.Ft.	Light Output: Lumens/ Watt	Air Conditioning Load: Tons/100,000 Lumens
Daylight through acrylic plastic, high transmission	5,270	106	.27
Daylight through acrylic plastic, medium transmission	3,110	106	.27
Incandescent light	- - -	20	1.90
Fluorescent light	- - -	60	.63

From Evans (1962)

This efficiency is reflected in reduced costs of lighting using skylights rather than artificial lights, Table 6. This is particularly important in this era of rising energy prices. A life cycle comparison of lighting cost makes natural lighting look even better.