A critical evaluation of the relative visual efficiency, the relative costs of installation, and the relative costs of operation of classroom artificial lighting systems in selected elementary school buildings in Massachusetts.

Clark, William F
Boston University

http://hdl.handle.net/2144/9248
Boston University
A CRITICAL EVALUATION OF THE RELATIVE
VISUAL EFICIENCY, THE RELATIVE COSTS
OF INSTALLATION, AND THE RELATIVE COSTS
OF OPERATION OF CLASSROOM ARTIFICIAL
LIGHTING SYSTEMS IN SELECTED ELEMENTARY
SCHOOL BUILDINGS IN MASSACHUSETTS

Submitted by

William F. Clark

A. A., Tufts College, 1940

Submitted in partial fulfillment of the requirements
for the degree of

MASTER OF EDUCATION

1954

Boston University
School of Education
Library
First Reader: Dr. James F. Baker
Associate Professor of Education

Second Reader: Dr. Worcester Warren
Professor of Education
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>i-viii</td>
</tr>
<tr>
<td>I. LIGHT AND VISION</td>
<td>1</td>
</tr>
<tr>
<td>A. Structure of the Eye</td>
<td>1</td>
</tr>
<tr>
<td>1. Structure of the Human Eye</td>
<td>1</td>
</tr>
<tr>
<td>2. Accommodation of the Eye</td>
<td>2</td>
</tr>
<tr>
<td>3. The Retina</td>
<td>2</td>
</tr>
<tr>
<td>B. Function of the Human Eye</td>
<td>3</td>
</tr>
<tr>
<td>1. Central and Peripheral Vision</td>
<td>3</td>
</tr>
<tr>
<td>2. Characteristics of Foveal Vision</td>
<td>5</td>
</tr>
<tr>
<td>3. Characteristics of Peripheral Vision</td>
<td>5</td>
</tr>
<tr>
<td>4. Complementary Function of Peripheral Vision</td>
<td>6</td>
</tr>
<tr>
<td>II. BRIGHTNESS AND ITS RELATIONSHIP TO VISUAL EFFICIENCY</td>
<td>8</td>
</tr>
<tr>
<td>A. The Measurement of Brightness</td>
<td>8</td>
</tr>
<tr>
<td>1. Visual Acuity</td>
<td>8</td>
</tr>
<tr>
<td>2. Brightness</td>
<td>9</td>
</tr>
<tr>
<td>3. The Measurement of Brightness</td>
<td>10</td>
</tr>
<tr>
<td>CHAPTER</td>
<td>PAGE</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>II.</td>
<td></td>
</tr>
<tr>
<td>B. Visual Efficiency and Brightness Contrasts</td>
<td>12</td>
</tr>
<tr>
<td>1. The Importance of Brightness Control</td>
<td>12</td>
</tr>
<tr>
<td>C. Brightness Differences and Lighting Design</td>
<td>14</td>
</tr>
<tr>
<td>1. The Traditional Approach to Lighting</td>
<td>14</td>
</tr>
<tr>
<td>2. The Modern Theory of Lighting</td>
<td>16</td>
</tr>
<tr>
<td>3. Specular Reflection</td>
<td>20</td>
</tr>
<tr>
<td>4. Reflected Glare from Room Surfaces</td>
<td>21</td>
</tr>
<tr>
<td>5. Direct Glare</td>
<td>22</td>
</tr>
<tr>
<td>III. THE QUANTITY OF LIGHT - ITS RELATIONSHIP TO VISUAL EFFICIENCY</td>
<td>25</td>
</tr>
<tr>
<td>1. Footcandles and Brightness</td>
<td>25</td>
</tr>
<tr>
<td>2. Optimal Quantity of Light</td>
<td>26</td>
</tr>
<tr>
<td>3. The Quantity of Daylight Available</td>
<td>29</td>
</tr>
<tr>
<td>4. Implications of the Research</td>
<td>30</td>
</tr>
<tr>
<td>IV. THE SURVEY FORMS AND THE COMPILATION OF DATA</td>
<td>33</td>
</tr>
<tr>
<td>A. Statement of Background Research</td>
<td>33</td>
</tr>
<tr>
<td>1. Background Research</td>
<td>33</td>
</tr>
<tr>
<td>2. No Related Studies Found</td>
<td>34</td>
</tr>
<tr>
<td>CHAPTER</td>
<td>PAGE</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>IV.</td>
<td></td>
</tr>
<tr>
<td>B.</td>
<td></td>
</tr>
<tr>
<td>Construction of the Survey Forms</td>
<td>34</td>
</tr>
<tr>
<td>1. Nature of Form A</td>
<td>35</td>
</tr>
<tr>
<td>2. Nature of Form B</td>
<td>36</td>
</tr>
<tr>
<td>C.</td>
<td></td>
</tr>
<tr>
<td>Methods of Survey</td>
<td>37</td>
</tr>
<tr>
<td>1. Footcandle Measurements</td>
<td>37</td>
</tr>
<tr>
<td>2. Brightness Measurements</td>
<td>39</td>
</tr>
<tr>
<td>3. The Measurement of Reflectances</td>
<td>40</td>
</tr>
<tr>
<td>4. Determination of Color</td>
<td>41</td>
</tr>
<tr>
<td>5. Record Photographs</td>
<td>43</td>
</tr>
<tr>
<td>V.</td>
<td></td>
</tr>
<tr>
<td>VISUAL EFFICIENCY OF ARTIFICIAL LIGHTING</td>
<td>44</td>
</tr>
<tr>
<td>IN THIRTEEN SELECTED CLASSROOMS</td>
<td></td>
</tr>
<tr>
<td>A.</td>
<td></td>
</tr>
<tr>
<td>The Classification of Lighting Fixtures</td>
<td>44</td>
</tr>
<tr>
<td>1. Types of Lighting Fixtures</td>
<td>44</td>
</tr>
<tr>
<td>B.</td>
<td></td>
</tr>
<tr>
<td>Evaluation of Lighting Systems</td>
<td>46</td>
</tr>
<tr>
<td>1. Tabulation Data</td>
<td>46</td>
</tr>
<tr>
<td>2. Direct Recessed Incandescent</td>
<td>49</td>
</tr>
<tr>
<td>3. Direct Louvered Fluorescent</td>
<td>51</td>
</tr>
<tr>
<td>4. Semi-Direct Globe Lens Incandescent</td>
<td>53</td>
</tr>
<tr>
<td>5. Semi-Indirect Luminous Fluorescent</td>
<td>56</td>
</tr>
<tr>
<td>6. Concentric Three-Ring Indirect Incandescent</td>
<td>58</td>
</tr>
<tr>
<td>7. Luminous Concentric Three-Ring Incandescent</td>
<td>60</td>
</tr>
</tbody>
</table>
CHAPTER VI. COSTS OF INSTALLING AND OPERATING LIGHTING SYSTEMS IN THIRTEEN SELECTED CLASSROOMS

A. Costs of Installation
   1. Determining the Costs of Installation
   2. Construction of a Reference Guide
   3. Variations in Price Levels

B. The Costs of Operation
   1. Cost of Electrical Current
   2. Demand and Consumption Charges
   3. Annual Use in Hours
   4. Cleaning of Equipment
   5. Replacing Lamps and Starters
   6. Relative Annual Cost
   7. Comparisons of Direct and Indirect Installations
   8. Comparison of System G with Lens-Plate Installations
   9. Comparison of System G with Direct Fluorescents
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td></td>
</tr>
<tr>
<td>B.</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td></td>
</tr>
<tr>
<td>Comparison of System G with Globe Lens Incandescents</td>
<td>79</td>
</tr>
<tr>
<td>11.</td>
<td></td>
</tr>
<tr>
<td>Comparison of System G and Concentric Three-Ring Fixture</td>
<td>80</td>
</tr>
<tr>
<td>12.</td>
<td></td>
</tr>
<tr>
<td>Comparison of System G and System M</td>
<td>82</td>
</tr>
<tr>
<td>13.</td>
<td></td>
</tr>
<tr>
<td>Summary of the Chapter</td>
<td>82</td>
</tr>
<tr>
<td>VII</td>
<td>SUMMARY AND CONCLUSIONS</td>
</tr>
<tr>
<td>1.</td>
<td>Superiority of Fluorescent Fixtures</td>
</tr>
<tr>
<td>2.</td>
<td>Incandescent Systems Found Undesirable</td>
</tr>
<tr>
<td>3.</td>
<td>Initial Costs Poor Criteria for Selection</td>
</tr>
<tr>
<td>4.</td>
<td>Suggestions for Further Research</td>
</tr>
<tr>
<td>VIII</td>
<td>BIBLIOGRAPHY</td>
</tr>
<tr>
<td></td>
<td>APPENDIX &quot;A&quot;</td>
</tr>
<tr>
<td></td>
<td>Sample of the Survey Forms</td>
</tr>
<tr>
<td></td>
<td>APPENDIX &quot;B&quot;</td>
</tr>
<tr>
<td></td>
<td>Identification of the Thirteen Selected Classrooms</td>
</tr>
<tr>
<td></td>
<td>APPENDIX &quot;C&quot;</td>
</tr>
<tr>
<td></td>
<td>Photographs</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table | Recommendations for Limits of Brightness Ratios of Classroom Surfaces | Page 18
     | Desirable Minimum Reflectances of Surfaces in Classrooms               | Page 19
     | Effect of Varying the Intensity of Light Upon Percent of Maximum Performance of Reading 10 Point Type on White Paper | Page 28
     | Effect of Varying the Intensity of Light Upon Percent of Maximum Performance of Reading #2 Grade Pencil Handwriting on 70 Percent Reflectance Paper | Page 28
     | Tabulation of the Data Compiled for Each Installation and Evaluation of Visual Efficiency | Page 47
     | The Total Cost Per Classroom of Lighting Systems Installed in Thirteen Selected Massachusetts School Buildings | Page 68
     | Comparison of Actual Total Costs of Classroom Lighting Systems in the Thirteen Schools Studied, with Costs Adjusted to Labor and Material Price Levels, Together with the Rank Order of the Installations on the Basis of Adjusted Prices | Page 70
     | Cost Comparison of Owning and Operating Lighting Systems in Thirteen Selected Classrooms | Page 74
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Area of Direct and Reflected Glare Emitted by a Lighting Fixture</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>Curve of Distribution of Daylight in the Classroom on a Dark Day</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>The Graphical Representation of the Munsell Color System, With Value Units along the Vertical Axis, Chroma Units along the Radii, and Hue Units along the Periphery</td>
<td>42</td>
</tr>
<tr>
<td>4</td>
<td>The Distribution of Fixtures in Percents</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>Uneven Distribution of Light on Upper Wall, and Relative Lack of Brightness of Ceiling Characteristic of Direct-Lens Incandescent Installation</td>
<td>51</td>
</tr>
<tr>
<td>6</td>
<td>Specular Reflections from Desk and Chair Resulting from Combination of Bright Light Source and the Use of Non-Diffuse Finishes</td>
<td>55</td>
</tr>
<tr>
<td>7</td>
<td>Specular Reflection on Desk-Tops Resulting from High Brightness of the Light Source and the Use of Glossy Finishes on Classroom Furniture</td>
<td>61</td>
</tr>
</tbody>
</table>
INTRODUCTION

In June, 1950, the eighty-first Congress granted an appropriation to the United States Office of Education for the purpose of making a nation-wide survey of school housing needs. In December of 1953 the Office of Education reported that the Federal School Facilities Survey, completed in 43 of the 48 States, revealed that 325,000 additional classrooms were needed throughout the country. Of these, approximately one half are required to relieve the overcrowded classroom conditions resulting from the steadily increasing school enrollment. The remainder are needed to replace school buildings reported to be obsolete.

This need, the total cost of which has been estimated at 10 billions of dollars, exists, notwithstanding the fact that since 1947 public school systems throughout the country have been engaged in one of the largest programs of new school construction in history.

This extensive program, and the prediction of still greater need, if the ever-increasing school population is to be adequately housed, has directed a great deal of attention to all features of
the school building. A vast quantity of research is under way to determine what is the optimal physical environment for the modern program of education, as well as the most economical methods of meeting these requirements.

Sound control in the classroom, the auditorium, the playroom, and in the other special facilities of the building is being studied. The effect of classroom temperature and ventilation upon the physical condition and upon the school progress of children is being investigated. Extensive studies are being made of the design of classroom furniture and equipment.

Classroom lighting is receiving its share of attention. Practically all of the tasks of the physically normal school child involve critical seeing. Recognizing this fact, school administrators, school architects, and school plant specialists are conducting numerous investigations of artificial lighting. The Research Committee of the Illuminating Engineering Society reported that in the fall of 1949 forty-four educational institutions were conducting studies in light, vision, and the visual environment.

This manifest concern with the problems of seeing has been largely responsible for significant developments in the design of artificial lighting systems.

It is evident that we are in the midst of a lighting renaissance. The design of lamps and of lighting fixtures has been revolutionized within the past fifteen years. More important, however, is the fact that the fallacy of the traditional approach to the solution of problems of lighting has been exposed. The attitude of professional workers in the field and of educated opinion generally has changed markedly. Generally speaking, classroom lighting has improved immeasurably over the past ten years. Yet great variations exist in the visual efficiency, the original costs, and the costs of maintenance and operation even in highly similar school buildings in the same or in adjacent communities.

Several factors have effected this situation. The writer wishes to direct attention only to three possible causes. These are:

1. The criteria for the determination of good artificial lighting has been highly technical, somewhat involved, and generally difficult for one not trained in engineering to understand.
2. The prime criterion in the selection of lighting design has in all too many instances been low first cost. As in most other things, in the purchase of lighting fixtures one gets what one pays for.

3. The confusion of claims and counter-claims of fixture manufacturers, each indicating the superiority of his own product, has tended to obscure the facts. Innovations in lighting design are coming on the market with increasing frequency. As is usually the case in a period of transition, those developments which are based upon sound psychological and physiological research will endure. Those which violate fundamental principles are, in fact, mere passing fancies.

In the opinion of the writer, a "critical evaluation of the relative visual efficiency, the relative costs of installation, and the relative costs of operation of classroom artificial lighting systems in selected elementary school buildings in Massachusetts" is justified on four grounds. These are:
1. The simplification of the engineering criteria for providing good seeing conditions so that school administrators can more readily plan visually efficient classroom lighting installations.

2. The clarification of the characteristics of the basic types of lighting fixtures found in daily use in classrooms.

3. Possible savings in the planning of lighting installations in future school buildings, as well as the lighting rehabilitation of older schools. The minimum estimate of the cost of providing adequate artificial lighting in the 325,000 classrooms which the United States Office of Education reports are needed is 95 million dollars.

4. The eventual elimination of the types of fixtures which research has shown contribute to the development of visual difficulties, muscular and skeletal strains, and in excessive demands on the energy of school children.
In this thesis, Chapters I to III are devoted to the research findings pertaining to the structure and function of the human eye and its environmental needs for optimal visual efficiency. The remaining chapters are devoted to:

1. an evaluation of the relative visual efficiency of classroom artificial lighting systems in selected elementary schools in Massachusetts in terms of the criteria for the optimal luminous environment as developed in the early chapters;

2. an evaluation of the relative costs of installation of these lighting systems;

3. an evaluation of the relative costs of operation of these lighting systems;

4. an evaluation of all factors of cost in each kind of classroom under minimum conditions desirable for visual efficiency.

The data for the determination of visual efficiency were compiled at the respective schools as a result of careful survey. Lighting measurements were taken in accordance with the procedures recommended by the recognized authorities in the field. No less than two qualified observers recorded the necessary
measurements. The forms employed for recording these data were prepared in close collaboration with recognized lighting experts.

The determination of the real costs of installations was somewhat involved. Many factors contribute to the accepted bid price of electric subcontractors on school buildings. On certain projects the contract price will include only the cost of providing and installing electrical fixtures, conduit, and switches as in residential work. On other projects the contract price may, in addition, include providing and installing oil burner controls, fire alarm, public address, and clock and bell systems. In the latter instances, the cost of providing lighting is but a fraction of the total contract, and as a result is less accurately accounted for.

The costs of installation were determined by information received from the general contractor, the electrical contractor, and through consultation with the electrical engineer who designed the system. These costs were corrected in accordance with a uniform procedure so as to eliminate the differences attributable to changes in the price levels of labor and of materials for schools built in different years.
The determination of the costs of operation involved several steps:

1. the power-rates for each community were secured;
2. the factor of frequency of cleaning of the equipment was taken into consideration;
3. the factor of maintenance (the replacement of burned-out lamps and starters) was included;
4. the cost of amortization of the equipment was given consideration.

The annual cost of operation of each system as it existed was then calculated without regard to its relative visual efficiency.

In the final chapter the several systems are equated as to minimum desirable visual efficiency, and all costs were again calculated. Direct comparisons and a critical evaluation of the real costs of the installations for each kind and size of classroom studied were then made.
CHAPTER I

LIGHT AND VISION

1. Structure of the Eye

A discussion of school lighting presupposes an understanding of the physical structure of the eye, and of the physiological process of seeing. This chapter comprises a brief description of the structure and of the process.

Structure of the human eye. -- In its structure, the human eye is frequently likened to a simple camera. Like the camera, it has a lens which focuses the image of an object upon the rear wall of the eye. This surface, the retina, corresponds to the photographic film in the camera. Like the camera, the eye also has its device, the iris, for controlling the diameter of the opening through which light is transmitted to the retina. This opening is referred to as the pupil.

Unlike the camera, the eye is spherical in shape. This shape is maintained by the toughness of the outer membraneous covering of the eye, the sclera. The interior of the eye is divided into two chambers, each filled with a transparent fluid. The
division between the two chambers is produced by the lens, the iris, and the ciliary muscle which controls both the form and the position of the lens. The iris is opaque and has two layers of muscle fibers which oppose one another, and which control the diameter of the central aperture, the pupil. The muscles of the iris are automatically controlled by the amount of light falling upon the retina, intense light producing the maximum reduction in the diameter of the pupil.

Accommodation of the eye. -- The contraction of the ciliary muscle alters the form and position of the lens so as to permit the focussing of the eye upon both near and far objects. This alteration in the lens is accompanied by a corresponding decrease or increase in the diameter of the pupil, depending upon whether the eyes are looking at near or far objects. One action complements the other in producing an image of maximum sharpness.

The retina. -- The retina comprises the inner rear surface of the eye. It is made up of layers of nerve tissue, with the surface layer composed of light-sensitive photoreceptors. These photoreceptors are made up of two kinds of nerve end structures, rods

and cones. The arrangement of the rods and cones varies over
the surface of the retina, with the proportion of cones decreasing
to the periphery of the retina. A small area at the center of the
retina contains only cones. Called the "rod-free area," it sub-
tends an angle of two degrees at the pupil. The fovea, located
in the center of the rod-free area, is the point of greater concentra-
tion of the cones.

When a person faces an object and focuses his eyes directly
upon the object, the line from the center of the object to the retina
is the "primary line of sight." In the normal eye the image of the
point of fixation of the eye will be at or near the center of the
fovea.

2. Function of the Human Eye

The field of view of each eye is divided into two distinct
kinds of vision, central vision which involves only the fovea, and
peripheral vision which involves all of the retina except the fovea.

Central and peripheral vision.-- Central and peripheral
vision differ from one another in several respects.


2/ Loc. cit.

3/ Loc. cit.
"The cones of the fovea, because of their small diameter, close packing (about 9,000,000 per square inch), and individual connections with the brain, transmit a very sharp image showing the greatest detail of which the eye is capable. Because of the sparse distribution of photoreceptors in the periphery and the fact that, in this region of the retina, each nerve cell branches to provide connection with many photoreceptors, sharp images are not transmitted to the brain, and objects appear as 'fuzzy' silhouettes."

The rod photoreceptors, acting alone, are insensitive to color, and objects appear gray when there is no stimulation of the cones. Color is seen best in the central or rod-free region of the retina, since the color response is, therefore, not diluted with the gray response of the rods. The rods, however, are more sensitive to light. When the brightness of the visual field drops below 1/100 footlambert, as at night, the cones receive no stimulation. Under these conditions, the rod-free area is completely blind, vision is limited to the peripheral area, and all objects appear gray regardless of their color. As to the effect of gradually increasing the brightness level, the I.E.S. Lighting Handbook says in part:

"...As the level of brightness is gradually increased and exceeds the threshold of cone vision, the luminosity curve for the peripheral retina undergoes a gradual transition until it becomes identical with the luminosity curve for the fovea. This means that at high levels of brightness the cones in the periphery almost completely dominate the rods.

Rods and cones differ also in the time factors associated with their activities. The rods are much slower in action than the cones (responsible for flicker fusion) and are notably slow in recovery from light adaptation (a process generally called dark adaptation)...."

Characteristics of foveal vision. -- Foveal or central vision is adapted for the perception of fine detail, as well as the identification of color. In performing most tasks the eyes move quickly from one point of fixation to another, so that things requiring critical seeing are brought within the area of central vision. In a task such as repairing a watch, central vision plays a dominant role, and peripheral vision is scarcely involved.

Characteristics of peripheral vision. -- Peripheral vision is blind to color and to detail, but is highly sensitive to brightness and to motion. The I.E.S. Handbook states:

"In a task like threading a needle, peripheral vision plays a very subordinate role, but in a task like stacking cartons in a warehouse peripheral vision is just about as important as central vision."
"Here, the worker must be aware of the spatial relationships between objects which are widely distributed in the visual field."

It is most useful in the detection of potential hazards, as in driving an automobile. One of the chief functions of peripheral vision is to send to the brain an overall picture of the location of the various objects in the field of view, providing thereby the information which guides the central vision, with its extremely narrow field of view, quickly from one point of fixation to another.

**Complementary function of peripheral vision.** -- Central vision includes an angle of approximately two degrees. While concentrating on a task within this narrow angle, the eye, however, continues to receive impressions over a very wide angle of view. This view extends approximately 60 degrees above and below the primary line of sight, and approximately 85 degrees to the right and to the left of the primary line of sight. Of the area of the field seen by peripheral vision, Sharp has this to say:

"This wide angle of perception covers a lot of territory. To a student seated in the rear of the room with gaze directed to the front chalkboard, almost two-thirds of all the room surfaces are within the visual field. With gaze directed to work on the desk or chair-arm, the space approximately 10 feet to each side and ahead will be included.

"Since it is the central field which does our useful seeing, any condition in the surrounding area which aids or hinders the central area in its work is of considerable interest."

It seems evident that to be efficient a lighting design must take into full consideration the complementary nature of peripheral vision. The fact that peripheral vision is, moreover, highly sensitive to brightness has serious implications for the treatment of the surfaces of the classroom which are within the total field of view.
CHAPTER II

BRIGHTNESS AND ITS RELATIONSHIP TO VISUAL EFFICIENCY

1. The Measurement of Brightness

Visual acuity. -- Visual acuity is the ability to perceive fine elements of detail in the object viewed. The classic research in visual acuity was undertaken many years ago by König. Disregarding the complementary function of peripheral vision, he concerned himself only with measuring the level of illumination needed on the central field. By leaving the entire surround dark, he clearly established that a relatively low level of illumination gave high acuity. Such conditions, however, never exist in practical situations of room lighting.

It was not until 1933 that the effects on visual acuity of varying levels of illumination of the surround were studied by Lythgoe. Extensive research clearly established the fact that visual acuity


Brightness. -- Brightness is the product of the quantity of light which falls upon an object, and the ability of the object itself to reflect light to the eye. An object appears light because it reflects a high percentage of light which falls upon it. Another appears dark because it absorbs or fails to reflect most of the light which is falling upon it. In discussing the relationship of brightness and vision, Sharp says:

"When the eye focuses upon an object, and thus brings the central area of the retina into action upon an object, three characteristics of the object are important: size, contrast with background, and brightness. The inter-relationship of these three factors introduces a fourth factor: time. It takes time to be aware of an object, to focus upon it, to transmit the stimulus to the brain, and to understand it. The common denominator of all these characteristics is brightness. Increasing the brightness increases the ability to distinguish size and to see finer degree of contrast. It also increases the speed with which the visual process is completed."

The level of illumination of light falling on a surface can readily be measured. The unit of measure is the footcandle, and the instrument usually employed for measurements outside of the laboratory is known as a light-meter. Brightness is the product of the light, measured in footcandles, falling upon a surface, and the ability, expressed as a percent, of that surface to reflect this light to the eye. The unit of measure of brightness is the footlambert.

A slate chalkboard has a reflectance of 10 percent. If 20 footcandles are falling upon it, it will have a brightness of 2 footlamberts. The reflectance of a printed page is 65 percent. Twenty footcandles falling upon it will produce 13 footlamberts of brightness. If this page is on a desk of 20 percent reflectance, or 4 footlamberts, the brightness between page and desk is then 1 to 3, and page to blackboard, 1 to 6. If the fixture in the room has a surface brightness of 500 footlamberts, the relationship of the page to the fixture brightness will be 1 to 38.

The measurement of brightness.-- There are two commonly used field techniques for measuring the brightness of room surfaces outside the lighting laboratory. These are:

1. the measurement by means of the light-meter of the light falling upon the respective surfaces. The reflectance expressed in a percent is derived by using the Munsell Value Scale. This is a system based on an orderly classification of over 1,000 opaque surface color samples which lend themselves to arrangement in a color solid. In the Munsell system, a color is designed according to its three psychological attributes, value, chroma, and hue. Standardized
color chips are matched with the surface to be tested, and the reflectance of the wall is read from the color chip which most perfectly matches the surface. The brightness is product of the footcandle reading and the percent.

2. The use of the Luckiesh-Taylor Brightness Meter.

This is a self-contained, battery-operated electric device which has a lens for focusing the light from the source, and an eye-piece for viewing the photometric field. The optical system presents a split field with a test field in the center and a comparison field on either side. The brightness of the comparison field is adjusted by means of a rheostat, and the reading is then taken directly from an illuminated scale. While it is a technique which is less time-consuming than that described above, it produces accurate readings only in the hands of a skilled observer.

Within the past year there has appeared on the market the first commercial, direct-reading brightness meter in history.

Known as the Spectra Spot Brightness Meter, it is an electronic device of remarkable accuracy which eliminates almost entirely the margin of error inherent in other techniques. Simple to operate, it will read with accuracy through a range of .1 to 1,000,000 footlamberts. It is operated by focussing the objective lens of the meter on the surface to be measured, pressing a button which energizes the electronic mechanism, and observing the reading directly on a logarithmic scale.

2. Visual Efficiency and Brightness Contrasts

The importance of brightness control. -- The measure of footcandles is not the measure of what the eye needs to see by.\footnote{The National Council on Schoolhouse Construction Guide states:}

"The footlambert, then, rather than the footcandle, becomes the prime factor in conditioning an environment of visual comfort and efficiency because it is the reflected brightness that we see, and not the light falling upon the task."

Research studies show a high percentage of visual defects in youth of high-school and immediate post-high-school age. In a\footnote{Guide for Planning School Plants, National Council on Schoolhouse Construction, Nashville, 1949, p.150.}
study of eye defects, Henderson and Rowell found that 23 out of every 100 persons under 20 years of age suffer from defective vision.

A series of research studies dealing with the influence of adequate lighting on the conservation of sight, and on school achievement, have been undertaken during the past fifteen years.

The most significant of these were long-range studies conducted in Texas. These revealed that visual stresses are important factors in the development not only of visual difficulties but also in the development of muscular and skeletal strains, and in excessive demands on energy which can directly affect both the physical growth and the classroom performance of school children. Studies in over 4,000 elementary school classrooms in the state revealed that 59 percent of the Anglo-American children had refractive eye defects or other conditions adversely affecting their vision. These ranged from 18 percent in Grade 1 to 82 percent in the last year of elementary school. Controlled experiments


were conducted in a 21-classroom school. The classrooms were redecorated so as to improve the distribution of natural and artificial light. Diffusing screens were installed at the windows so as to control ground and sky reflectance. The differences in brightness within the rooms were reduced, and shadows on the working surfaces were eliminated.

The re-examination of the pupils at the end of six months indicated a reduction of -

1. 57.1 percent in refractive eye defects;
2. 90.1 percent in non-refractive eye defects;
3. 44.5 percent in nutritional problems;
4. 30.9 percent in evidences of chronic infection.

Educationally, the experimental group was found on standardized achievement tests to have advanced 10.2 months, as compared with 6.8 months for the control group.

3. Brightness Differences and Lighting Design

The traditional approach to lighting. -- The traditional method of lighting a classroom consisted of the installation of concentrated light sources of high intensity which, in fact, directed a stream of light downward upon the desk-tops. The sole criterion
of excellence was the quantity of light upon the working plane. If the light-meter indicated a high reading, the installation was considered successful regardless of the glare, the strong contrasts, and the heavy shadows. It disregarded also the inevitable eye-strain and the possible muscular and skeletal strains which such installations frequently produce.

A measure of footcandles is not a measure of what the eye needs to see by. The true measure is the absolute brightness of the objects and surfaces of the room, as well as the differences in brightness between them. The National Council on Schoolhouse Construction \(^1/\) says in part: "Brightness-balance is the key to visual comfort and efficiency. Brightness-balance is controlled by the brightness-differences that are maintained within the total visual field."

Classical methods of light calculations are simply adaptations of the formula commonly known as the inverse-square law. This states that the intensity of light is inversely proportional to the distance from the source. It is, to be sure, a simple, direct, easily understood relationship. The inherent defect is that it has

absolutely no bearing on modern room lighting.

In the first place, it applies rigorously only to a light source that is a mathematical point. By no stretch of the imagination is it possible to consider an eight-foot, or a four-foot fluorescent lamp as a mathematical point. Furthermore, it and all other classical methods of calculating light derived from it assume that the light commits suicide when it strikes a surface. Actually, light is alive and bounces from one surface to another. This is evidenced by the fact that the predetermination of the brightness and brightness differences in planning light installations can be calculated readily.

The technique developed by Luckiesh of calculating brightness and brightness differences by means of the interreflections of light among surfaces of known reflectances is used by lighting engineers in solving highly complex problems of interior light distribution.

The modern theory of lighting.--The newer theory of lighting holds that lighting design should involve the creation of luminous environment. It maintains that a lighting system should be installed

---

1/ Mathew Luckiesh (Chairman), Committee on Standards of Quality and Quantity for Interior Illumination, Illuminating Engineering Society, "The Interreflection Method of Predetermining Brightness and Brightness-Ratios," Illuminating Engineering (May, 1946), 41: 361-385.
for human beings, not for light-meters. It recognizes the fact that vision, rather than being a simple process, is an intricate, highly complex physiological function. It recognizes also that the solution of a lighting problem is not ideal unless it satisfies all the complex human requirements associated with the luminous environment.

This concept holds that every surface in the room is important, the walls, the ceiling, the floor, and the furniture. All these surfaces interreflect between one another and send light to the eye. The color and the distribution of this light determines the human effectiveness of the lighting design. Despite the general acceptance of this concept of lighting, many fixtures being manufactured today do not satisfy these criteria.

The American Standards Association indicates the specific brightness differences which should not be exceeded.

Table 1. Recommendations for Limits of Brightness Ratios of Classroom Surfaces

<table>
<thead>
<tr>
<th>Classroom Surfaces</th>
<th>Brightness Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central visual field and immediately adjacent surfaces such as the desk</td>
<td>1 to 1/3</td>
</tr>
<tr>
<td>Central visual field and more remote darker surfaces in surrounding field such as the desk</td>
<td>1 to 1/10</td>
</tr>
<tr>
<td>Central visual field and more remote brighter surfaces in surrounding field such as walls and ceiling</td>
<td>1 to 10</td>
</tr>
<tr>
<td>Fixtures and surfaces adjacent to them in the visual field</td>
<td>20 to 1</td>
</tr>
</tbody>
</table>

These ratios can be attained if the minimum reflectances of the surfaces of the rooms recommended by the American Standard Practice for School Lighting are observed.

Table 2. Desirable Minimum Reflectances of Surfaces in Classrooms

<table>
<thead>
<tr>
<th>Classroom Surfaces</th>
<th>Minimum Reflectances in Percents</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Ceiling</td>
<td>80</td>
</tr>
<tr>
<td>Walls</td>
<td>50</td>
</tr>
<tr>
<td>Desks</td>
<td>35</td>
</tr>
<tr>
<td>Floors</td>
<td>15</td>
</tr>
<tr>
<td>Woodwork</td>
<td>30</td>
</tr>
<tr>
<td>Chalkboards</td>
<td>15</td>
</tr>
</tbody>
</table>

Two areas of the lighting zone emitted by the fixture must be considered in terms of brightness. The zone of 45 to 90 degrees with the perpendicular represents the area ordinarily seen both by peripheral vision and by direct view. The brightness in the 0 to 45 degree zone is seldom seen except by a deliberate attempt. It is, however, seen by the work since the latter reflects an image of the fixture to the eye.

![Figure 1. Area of direct and reflected glare emitted by a lighting fixture.](image-url)
The foregoing has been devoted to the consideration of the several surfaces of the room. We must now consider the brightest object in the room, the fixture itself. The fixture is almost always in the peripheral field of view and is the object of direct view many times during the day.

**Specular reflection.** Specular reflection is the reflection of the light source itself from a glossy surface. The clarity and the intensity of the image of the fixture as reflected to the eye is in direct proportion to the degree of gloss or shininess of the surface. Some degree of specular reflection is encountered in all tasks of reading, printing, or writing on the usual range of school papers. The lowering of visual acuity under conditions of high specular reflection results from the reduction in contrast between the paper and the ink which the reflected glare produces. The most objectionable papers, insofar as specular reflection is concerned, are the highly calendered pages of illustrated magazines.

Since the angle of incidence is equal to the angle of reflection, the location of the glare-course can readily be plotted. In situations where the furniture is fixed to the floor, as in most drafting rooms, reflected glare on the working surfaces can often be overcome by careful positioning of the light sources. However, in the modern
elementary school the learning process itself makes the provision of movable furniture mandatory. The program calls for a flexible kind of furniture which can readily be arranged and rearranged into a variety of groupings in accordance with the needs of the learning workshop. This means that in schools the brightness of the light source itself must be carefully controlled if harmful glare is to be avoided.

**Reflected glare from room surfaces.** -- In addition to the reflected glare from the task, the reflected glare from the several surfaces of the room must be given serious consideration. It has been established that peripheral vision is highly sensitive to brightness. It is evident, then, that attention must be given not only to the reflectances of the several surfaces of the room, but also to the degree of gloss or shininess of those surfaces.

Optimal conditions of seeing are achieved when the minimum reflectances of the room are maintained approximately as outlined in Table 2, and when these surfaces are finished in a dull, non-glossy manner. Diffused, matte surfaces reduce reflected glare to a point where even persons most sensitive to glare can perform visual tasks in comfort.
Direct glare. -- Direct glare is the result of a high brightness light source in the normal field of view, the 45 to 90 degree zone. Considerable variation of opinion exists as to the upper limit of fixture-brightness which the child of normal or near-normal vision can tolerate without visual shock, and with a minimum of discomfort. At least two studies have been made of the shock effect, and of the comfort-discomfort threshold of adults on being subjected to varying degrees of direct glare. Attempts have been made to apply these findings to the limiting of the surface brightness of fixtures in school classrooms.

In the opinion of the writer, no relationship has been established between the ability of adults on the one hand, and elementary children on the other, to adapt to levels of fixture brightness. Many questions need to be answered before such data compiled for adults can be related to children. It is commonly accepted that children vary widely in the physical rate of maturation. It is known that in most children the muscular accommodation of the eyes has matured sufficiently by the age of six that they can then begin the process of learning to read. Yet some children have difficulty in focussing on the reading task as late as eight years of age.
The maximum aperture of the pupil of the eye of an adult is very different from that of a child. Furthermore, the range in diameter of the pupil decreases with each passing year.

A large percentage of adults wear glasses to correct visual defects. Of these, a goodly proportion wear tinted lenses so as to compensate for more than ordinary sensitivity to brightness. These are but two of the ways in which the eyes of adults and of children differ. In the opinion of the writer, the question of maximum allowable fixture-brightness in elementary school classrooms cannot be answered categorically until norms for the different age groups of elementary school children are established.

The brightness limits of fixtures recommended by the American Standards Association are as follows:

1. 1,000 footlamberts in the 0-45 degree zone;
2. 450 footlamberts in the 45 degree zone;
3. 225 footlamberts in the 60-90 degree zone.

In each instance, 0 degrees is the point directly below the fixture.

1/ Leonard V. James (Chairman), op. cit., p. 32.
There is a considerable body of educated opinion \(^1\) which holds that fixture-brightness should not appreciably exceed 300 footlamberts in the 45-90 degree zone. This limit makes certain that the brightness of the fixture will not greatly exceed that of the ceiling. The rule of thumb in designing a lighting system for optimal visual efficiency is that maximum contrast is needed between the task, the print, and the immediate background, the page of the book, and minimum contrast between the immediate background and all other surfaces of the room. Until such time as studies can be made, it is the opinion of the writer that the use of fixtures with surface brightnesses appreciably exceeding 300 footlamberts in the 45-90 degree zone should be avoided.

\(^1\) Howard M. Sharp, op. cit., p.186.
CHAPTER III
THE QUANTITY OF LIGHT - ITS RELATIONSHIP TO
VISUAL EFFICIENCY

Footcandles and brightness. -- The relationship of brightness and visual efficiency has been discussed in the preceding chapter. The brightness of the task or of any other object or surface is the product of the quantity of light falling on it, and its ability to reflect this light to the eye. The quantity of light is then a factor, but only a factor, in the determination of brightness. The discussions in Chapters II and III were not intended to minimize the need for an adequate intensity of light, but to indicate that the emphasis should be on quality rather than on quantity.

Despite the fact that for many years the footcandle was the only criterion for the determination of lighting efficiency, complete agreement as to the optimal quantity of light for classrooms is lacking at the present time. There is no known optimum intensity of light suitable for all people under all conditions, and upward
revision of the standards of the level of illumination has made
school lighting one of the more controversial issues in the school
plant field.

Optimal quantity of light.--In discussing the level of illumina-
tion needed, Luckiesh and Moss hold that there are two cardinal
levels of illumination: (1) footcandles for barely seeing, and
(2) footcandles for easiest seeing. They report that for many
visual tasks, less than a footcandle is necessary for barely seeing.
All research which has dealt with the ease of seeing has found
that for easiest seeing even for relatively simple tasks, the level
is above 100 footcandles.

Luckiesh and Moss recommend the following illumination
levels:

"50 to 100 footcandles for severe and prolonged
tasks, such as proofreading, difficult reading, etc.

20 to 50 footcandles for moderately critical
and prolonged tasks, such as clerical work, ordinary
reading, etc.

10 to 20 footcandles for moderate and prolonged
tasks of office and factory and, when not prolonged,
ordinary reading, etc."

1/ Mathew Luckiesh, and F. K. Moss, The Science of Seeing,
The National Council on Schoolhouse Construction holds that "... for tasks common to schoolrooms, intensities of from 20 to 40 footcandles are practical and available today and are considered to satisfy visual environments in a balanced brightness environment."

Both of the foregoing authorities recommend a minimum of 20 footcandles for classrooms. The American Standard Practice for School Lighting recommends a minimum of 30 footcandles on the working plane.

Research studies have been conducted in order to determine the effect of varying the level of illumination upon performance efficiency while engaged in typical classroom tasks.

The following table indicates the research findings of Weston of the effect upon maximum performance of varying the level of illumination on the task of reading 10 point printers type on a white page. This is a common classroom task in the elementary school.


2/ Leonard V. James (Chairman), op. cit., p. 13.

Table 3. Effect of Varying the Intensity of Light Upon Percent of Maximum Performance of Reading 10 Point Type on White Paper

<table>
<thead>
<tr>
<th>Intensity in Footcandles</th>
<th>Percent of Maximum Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>2.5</td>
<td>90 percent</td>
</tr>
<tr>
<td>4.0</td>
<td>95 percent</td>
</tr>
<tr>
<td>6.0</td>
<td>98 percent</td>
</tr>
</tbody>
</table>

Another common elementary school task is the reading of handwriting in pencil on white paper.

Table 4 indicates the findings of Weston in a study of the effect of varying the level of illumination upon maximum visual performance of the task of reading handwriting done with a No. 2 grade pencil on paper of 70 percent reflectance.

Table 4. Effect of Varying the Intensity of Light Upon Percent of Maximum Performance of Reading #2 Grade Pencil Handwriting on 70 Percent Reflectance Paper

<table>
<thead>
<tr>
<th>Intensity in Footcandles</th>
<th>Percent of Maximum Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>12</td>
<td>90 percent</td>
</tr>
<tr>
<td>18</td>
<td>95 percent</td>
</tr>
<tr>
<td>27</td>
<td>98 percent</td>
</tr>
</tbody>
</table>
The two tasks in Tables 3 and 4 represent the extremes of severity of visual effort in the elementary school classroom. It should be noted that these studies were concerned only with the quantity of artificial light needed. No consideration was given to the quantity of daylight available in the classroom on even the darkest days. The studies reveal that a level of no more than 27 footcandles of artificial light is all that is really needed for the most severe visual tasks of the elementary school child. Under such an illumination level, the average child with normal or near-normal vision will perform at 98 percent of maximum efficiency.

The quantity of daylight available. -- Since some daylight is available on the desks farthest from the windows even on the darkest days of the year, the writer attempted to determine by actual study the levels of illumination on both dark and bright days. Footcandle readings were taken in three recently built school buildings in Newton, Massachusetts. This study revealed that on the 21 darkest days of the school year 1953-54, four footcandles of daylighting were available on the desks farthest from the windows. On the same days it was found that only 24 footcandles were available on the desks nearest the windows.
Implications of the research. -- The conclusion which may be drawn from the foregoing data is that for the easiest of school tasks, 95 percent of maximum visual performance could be attained without the use of the classroom lights. If the recommendations of the American Standards Association are adopted and 30 footcandles of combined daylight and artificial light are provided, the child with normal or near-normal vision will perform all tasks at better than 98 percent of maximum visual performance.
Wherein they pertain to the minimum allowable level of classroom illumination, these findings have the support of educated opinion of many experts in the field.

In a speech given before the New England School Development Council at a forum on school lighting in November, 1949, 1/ Spencer stated that no less than 20 footcandles should be provided in any school classroom.

The question of how much more than the minimum should be provided in a school has economic implications and must, then, be answered in part at least at the local level. The question is, then, how much more than the minimum can the community afford to buy, to operate, and to maintain?

It is the considered opinion of the writer and of many workers in the field of school plant planning that the installation of inadequate lighting in the name of economy in new school buildings should not be countenanced. The difference in cost between providing an adequate and an inadequate level of illumination is infinitesimal when compared to the total cost of constructing a new school. The failure to provide an adequate light level dilutes the value of the dollar spent on teachers' salaries, as

1/ Domina E. Spencer, based on notes taken at the forum.
well as on the other budget account items. Furthermore, in the light of the adverse effect on vision, in producing muscular and skeletal strains, and in excessive demands on energy of school children, the practice is indefensible.

A minimum of 27 to 30 working footcandles of combined daylight and artificial light of a balanced brightness should be provided in all elementary school classrooms.
CHAPTER IV
THE SURVEY FORMS AND THE COMPILATION
OF DATA

1. Statement of Background Research

Background research. -- Many studies have been made of the costs of installation and of operation of classroom artificial lighting systems. In the opinion of the writer, few of these can be classified as research. In some instances they have been prepared by the engineering staffs of companies manufacturing lighting fixtures. These have usually compared the costs characteristic of the types of fixtures currently manufactured by the company making the study. Comparisons have usually been made on the basis of hypothetical conditions of the (1) size of classroom; (2) height of ceiling; (3) cost of electrical current, etc.

A few careful studies of the long-term cost of a proposed program of lighting rehabilitation have been made by school systems. Rhodes ¹/ cost analysis of fluorescent and incandescent

lighting for schools of St. Louis is an example. These studies usually compare the costs of two types of fixtures as, for instance, a single type of fluorescent and a single type of incandescent fixture. For the most part, they have been prepared to assist the local board of education in determining which of two lighting fixtures should be selected.

No related studies found. -- No comparable research was found in the area of this study. The writer has been unable to discover research which evaluates the visual efficiency, the cost of installation, and the cost of operation of a variety of lighting systems in existing elementary school classrooms.

2. Construction of the Survey Forms

Two survey forms were employed in recording the data relative to the illumination level and to the brightness characteristics of the lighting systems studied. These forms were prepared in close collaboration with:

1. lighting engineers employed by manufacturers of electrical equipment;
2. a lighting engineer employed by a public utility;
3. recognized authorities in the field of lighting not included in Items 1 and 2.
Each of these persons in turn submitted copies of the finished forms to other persons in the field so as to provide a check upon validity. The validity of the form was further tested by having several qualified observers record on different occasions their impressions of a given classroom situation. It was found that in each instance the observer recorded in detail the data which the writer wished to receive. (A sample of each of these two forms is found in the Appendix.)

**Nature of Form "A".** Form "A" was designed for recording the general impressions of qualified professional observers examining classroom artificial lighting systems. The observer recorded his impressions of the degree of visual comfort and of the brightness ratios which existed on a scale listing: (1) comfortable; (2) acceptable; (3) uncomfortable; and (4) very uncomfortable. Although the observer recorded his personal impressions of the system, some degree of objectivity was effected by the requirement that he identify on the form the visual task and its relationship to the surroundings. The brightness ratios of (1) white paper to desk; (2) white paper to general surroundings; (3) fixture to surroundings, were recorded on the scale indicated above.
Form "A" was designed to be used prior to the taking of any light readings or measurements. By this means it was possible to record general impressions which had not been influenced by any actual data or specific measurements. The form was designed to provide information complementary to Form "B".

Nature of Form "B".-- Form "B" was designed for the recording of measurements. It served to complement Form "A" by providing the data needed for determining whether or not the installation met the criteria for visual efficiency which were established in the early chapters. On it were recorded:

1. name of community;
2. name of school;
3. room number;
4. room dimensions;
5. name of fixture;
6. catalog number of fixture;
7. footcandle readings;
8. surface brightnesses;
9. reflectances of room surfaces.
3. Methods of Survey

Footcandle measurements.-- Throughout the survey, no less than two observers recorded the data required on the two forms. Techniques of measurement were in strict accordance with the practices recommended by the Illuminating Engineering Society and the American Standards Association for light measurements in the field. All measurements were taken at night.

The instrument employed in the measurement of footcandles was a Weston cosine-corrected, color-corrected, three-scale light-meter. Color-correction, a feature not found on less expensive meters, permitted the accurate recording of measurements from light sources of different color temperature. This made it possible to employ the same meter in measuring light from both fluorescent and incandescent sources.

The fact that the meter was corrected for cosine error reduced to a negligible point an error inherent in certain light-meters, and which increases with the angle of incidence of the light falling upon the light cell. It is the result of one or a combination of:
1. reflection by the cover glass of the cell.
2. reflection by the photo-sensitive surface of the photo-electric cell itself.
3. obstruction of the light by the rim of the case.

The use of carefully designed plastic lenses over the light cell eliminates cosine error. The instrument was frequently calibrated so as to assure consistency in reading. Measurements were taken at desk-top height in ten carefully selected locations in the room. In addition, the mean footcandle level was calculated in accordance with the standard practice of the Illuminating Engineering Society. ¹

Careful attention was given to the need for thorough seasoning of the light source. Care was taken to determine that all fluorescent light systems had undergone a minimum of 100 hours of use before any measurements were made. Similarly, all incandescent systems underwent not less than six hours of use prior to the taking of measurements. In accordance with recommended practice, ³ an adequate warm-up was given each installation, and

² Ibid., 4. p. 5.
³ Ibid., 4. p. 5.
no measurements were taken until the system had been in opera-
tion for at least thirty minutes.

**Brightness measurements.** -- The absolute brightnesses were taken of the (1) upper wall; (2) lower wall; (3) chalkboard; (4) ceiling; (5) fixture; (6) desk-top; (7) white paper on the desk, and were recorded in spaces provided on the form. These measurements were taken by means of a Spectra Brightness Spot Meter in accordance with the practices recommended by the manufacturer. This is a completely self-contained electronic instrument which has been on the open market less than one year. It is the first direct-reading brightness meter available for use in the field, and it eliminates entirely the errors inherent in all comparison type meters. It yields accurate readings from .1 to 1,000,000 footlamberts and is simple in operation. It is necessary only to focus the instrument on the field to be tested by means of an f 1.9 objective lens. Pressing a button energizes the electronic circuit, and the measurement in footlamberts can be taken directly from a dial-type logarithmic scale mounted on the rear of the instrument below the focusing eye-piece. A new

measurement can be taken by focusing the instrument on the second field, and pressing the button.

The measurement of reflectances. -- The reflectances of the several surfaces of the room were also measured by means of the Spectra Meter. Several sheets of pure white blotting paper were used as standards of comparison for this purpose. The reflectances of these were determined by taking brightness measurements of the surface under a uniform level of lighting in comparison with the brightness measurements of a freshly scraped sample of magnesium carbonate. The latter is employed as a basic lighting standard with a known reflectance of 98 percent. The reflectance of the blotting paper was determined by means of a simple equation of proportions to be 87 percent.

These sheets of blotting paper were in turn used in determining the percent of reflectance of the (1) desk-tops; (2) furniture; (3) floor; (4) upper wall; (5) lower wall; and (6) chalkboard.

Brightness measurements were first taken on the surface to be measured. The blotting paper was then secured to the surface at the same location with a strip of masking tape and, without moving the meter, another measurement was taken.
The simple equation of proportions yields the reflectance of the surface with the blotting paper, used as the standard of 87 percent reflectance.

**Determination of color.** -- The Munsell Value Scales were used in order to determine and identify the colors of painted surfaces, and to provide a check upon the reflectance values of dark, poorly illuminated surfaces. The Munsell color designation system "...is based on an orderly classification of over 1,000 opaque surface color samples which lends itself readily to arrangement in the color solid."  

Colors were identified and reflectances were arrived at by a process of matching the surface to be tested with a color chip of known hue, chroma, value, and reflectance.

Figure 3 represents the Munsell color system in graphic form. The color is designated according to its value, hue, and chroma. The color solid is divided along its vertical axis into equally perceptible value units; along radii into equally perceptible chroma units; and radially into constant hue lines. The hue is the name of the color, the value is its lightness or darkness, and the chroma is its strength or purity as compared with a gray of the same value.

---

1/ I.E.S. Lighting Handbook, op. cit. 5 p. 8.
This classification permits ready identification of any color sample.

<table>
<thead>
<tr>
<th>NAME</th>
<th>SYMBOLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RED</td>
<td>5 R</td>
</tr>
<tr>
<td>YELLOW-RED</td>
<td>15 YR</td>
</tr>
<tr>
<td>YELLOW</td>
<td>25 Y</td>
</tr>
<tr>
<td>GREEN-YELLOW</td>
<td>35 GY</td>
</tr>
<tr>
<td>GREEN</td>
<td>45 Y</td>
</tr>
<tr>
<td>BLUE-GREEN</td>
<td>55 BG</td>
</tr>
<tr>
<td>BLUE</td>
<td>65 B</td>
</tr>
<tr>
<td>PURPLE-BLUE</td>
<td>75 PB</td>
</tr>
<tr>
<td>PURPLE</td>
<td>85 P</td>
</tr>
<tr>
<td>RED-PURPLE</td>
<td>95 RP</td>
</tr>
</tbody>
</table>

Figure 3. The Graphical Representation of the Munsell Color System, with Value Units along the Vertical Axis, Chroma Units along the Radii, and Hue Units along the Periphery.
Record photographs. -- Black-and-white photographs were taken of each classroom. In addition, photographs were also taken of conditions which either contributed to or hindered visual efficiency. Certain of these have been employed as illustrative figures in the following chapter.
CHAPTER V

VISUAL EFFICIENCY OF ARTIFICIAL LIGHTING

IN THIRTEEN SELECTED CLASSROOMS

1. The Classification of Lighting Fixtures

Types of lighting fixtures. -- Lighting fixtures are classified in terms of the proportions of light which they direct upward and downward. Fixtures which direct 90 percent or more of their light downward are referred to as direct fixtures. Those which direct 90 percent or more of their light upward against the ceiling are known as indirect fixtures. Those which direct various proportions within these two extremes are known as semi-direct, general diffuse, or semi-indirect.

In all, thirteen systems of classroom lighting were studied. They included installations of the following types: (1) direct incandescent fixtures; (2) semi-direct incandescent fixtures; (3) indirect incandescent fixtures; (4) direct fluorescent fixtures; and (5) semi-indirect fluorescent fixtures. No installations of general diffuse fixtures were found in recently built elementary school classrooms in Massachusetts, and none are reported herein.
The designations commonly referred to by the electrical trade of the particular fixtures studied are as follows:

1. the direct incandescent fixtures - "recessed, flush, lensplate incandescent";
2. semi-direct incandescent fixtures - "semi-direct prismatic enclosing globe incandescent";
3. indirect incandescent fixtures - "concentric, three-ring incandescent";
4. direct fluorescent fixtures - "direct louvered, or egg-crate, fluorescent";
5. semi-indirect fluorescent fixtures - "semi-indirect or luminous indirect fluorescent."

Figure 4. The Distribution of Fixtures in Percents
Figure 4 shows the five classifications of fixtures and their appearance in terms of the proportions of light which they direct upward and downward.

2. Evaluation of the Lighting Systems

Tabulation of data. -- Table 5 presents graphically the tabulation of the data compiled on forms A and B. A detailed analysis of these data follows, each fixture being considered in alphabetical order and in the type group to which it belongs. Columns (1), (2), and (3) are self-explanatory. Column (4) recapitulates the data compiled on form A pertaining to the observer's general impressions of the room. It is concerned more with visual comfort in terms of ease of seeing and the pleasant environment than with the level of illumination excepting as the latter effects visual comfort. The rating scale of 1 to 4 corresponds to the designations Comfortable, Acceptable, Uncomfortable, and Very Uncomfortable employed on form A.

Columns (5) to (10) inclusive comprise a tabulation of the data recorded on form B.

Column (11) is an Evaluation of the Visual Efficiency of each lighting system based upon the data recorded in Columns (3) to (10) inclusive. Each lighting system is classified Excellent,
Table 5

Table of the data compiled for each installation and Evaluation of Visual Efficiency.

<table>
<thead>
<tr>
<th>School</th>
<th>Type of Fixture</th>
<th>Mean Footcandles</th>
<th>Rating on Visual Comfort</th>
<th>Brightness in Footlamberts</th>
<th>Task &amp; Desk Top</th>
<th>Task &amp; Desk Floor</th>
<th>Task &amp; Desk Chalkboard</th>
<th>Task &amp; Desk Ceiling</th>
<th>Rating of Fixture</th>
<th>Evaluation of Visual Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Direct Lens-Plate Incandescent</td>
<td>33.8</td>
<td>4</td>
<td>40° = 7,200</td>
<td>1 to .2</td>
<td>1 to .3</td>
<td>1 to .5</td>
<td>1 to .23</td>
<td>1 to 1241</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>13.9</td>
<td>4</td>
<td>40° = 6,300</td>
<td>1 to .7</td>
<td>1 to .9</td>
<td>1 to .8</td>
<td>1 to .4</td>
<td>1 to 941</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td>C</td>
<td>Direct Lensed Fluorescent</td>
<td>51.7</td>
<td>24</td>
<td>40° = 1,950</td>
<td>1 to .8</td>
<td>1 to .4</td>
<td>1 to .5</td>
<td>1 to .3</td>
<td>1 to 8.0</td>
<td>Fair</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>51.5</td>
<td>24</td>
<td>40° = 2,120</td>
<td>1 to .8</td>
<td>1 to .4</td>
<td>1 to .5</td>
<td>1 to .3</td>
<td>1 to 8.3</td>
<td>Fair</td>
</tr>
<tr>
<td>E</td>
<td>Semi-direct Globe-lens Incandescent</td>
<td>37.8</td>
<td>4</td>
<td>40° = 28,750</td>
<td>1 to .6</td>
<td>1 to .4</td>
<td>1 to .5</td>
<td>1 to .4</td>
<td>1 to 733</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>26.3</td>
<td>4</td>
<td>40° = 8,100</td>
<td>1 to .6</td>
<td>1 to .5</td>
<td>1 to .6</td>
<td>1 to .5</td>
<td>1 to 559</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td>G</td>
<td>Semi-Indirect Fluorescent</td>
<td>41.4</td>
<td>2</td>
<td>40° = 155</td>
<td>1 to .7</td>
<td>1 to .4</td>
<td>1 to .5</td>
<td>1 to .4</td>
<td>1 to 1.9</td>
<td>Good</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td>28.3</td>
<td>2</td>
<td>40° = 155</td>
<td>1 to .7</td>
<td>1 to .4</td>
<td>1 to .5</td>
<td>1 to .4</td>
<td>1 to 1.4</td>
<td>Good</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>37.4</td>
<td>2</td>
<td>40° = 35</td>
<td>1 to .6</td>
<td>1 to .3</td>
<td>1 to .5</td>
<td>1 to .2</td>
<td>1 to 0.7</td>
<td>Good</td>
</tr>
<tr>
<td>J</td>
<td>Concentric 3-ring indirect Incandescent</td>
<td>30.4</td>
<td>3</td>
<td>45° = 16</td>
<td>1 to .6</td>
<td>1 to .2</td>
<td>1 to .3</td>
<td>1 to 10</td>
<td>1 to 10</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td>K</td>
<td></td>
<td>13.8</td>
<td>3</td>
<td>45° = 40</td>
<td>1 to .6</td>
<td>1 to .2</td>
<td>1 to .3</td>
<td>1 to 4.1</td>
<td>1 to 11</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>22.4</td>
<td>2</td>
<td>45° = 30</td>
<td>1 to .6</td>
<td>1 to .3</td>
<td>1 to .5</td>
<td>1 to 7.9</td>
<td>1 to 4.0</td>
<td>Poor</td>
</tr>
<tr>
<td>M</td>
<td>Concentric luminous 3-ring Incandescent</td>
<td>41.4</td>
<td>3</td>
<td>45° = 170</td>
<td>1 to .7</td>
<td>1 to .2</td>
<td>1 to .4</td>
<td>1 to 4.5</td>
<td>1 to 13</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>30 working照亮 compacted daylight and artificial</td>
<td>30.4</td>
<td>3</td>
<td>45° = 30</td>
<td>1 to .6</td>
<td>1 to .3</td>
<td>1 to .5</td>
<td>1 to 7.9</td>
<td>1 to 4.0</td>
</tr>
</tbody>
</table>

For convenience in comparison, the recommendations for standards wherein they apply are included in the bottom row.

* Rating on Visual Comfort, based upon data compiled on Form A. Scale 1-4 is in descending order and corresponds as follows:
1=Excellent; 2=Good; 3=Acceptable; 4=Unsatisfactory.

** The Brightness Ratios are the ratios of the surface brightness of the task and specific surfaces in the surrounding visual field, and also of the ratio of ceiling and fixture brightness. In column (6) to (10) the ratios should not exceed those indicated in row 5. In (4) for instance, the desk should not be less bright than 1.2 the task, etc.

*** Column (11) represents an evaluation of the installation based upon the data in columns (3) to (10). Installations which are seriously inadequate in footcandle level as indicated in column (3) and installations wherein the fixture brightness as indicated in column (5) are excessively high, are rated as Unsatisfactory.
Good, Fair, Poor, or Unsatisfactory, with a rating of 4 points for Excellent, 3 points for Good, 2 for Fair, 1 for Poor, and 0 for Unsatisfactory. A subtractive system was employed in assigning these classifications. One point was deducted for an inadequacy in Mean Footcandles, Column (3), not exceeding 10 percent. Two points were deducted for fixture brightnesses which were not more than four times the recommended levels in either zone. One point was also deducted for brightness ratios in Columns (6) to (10) inclusive, which were in excess of 100 percent less than or greater than recommended standards.

In all instances where a seriously inadequate level of illumination was recorded in Column (3), the system was evaluated as Unsatisfactory. This decision was based upon the research cited in the foregoing relative to the level of illumination needed for maximum visual performance. Proper brightnesses and brightness ratios become meaningless if the level of illumination is seriously inadequate.

In those instances where excessively high measurements recorded in Column (5) indicated fixture brightnesses greatly

\[1/\] H. C. Weston, op. cit.
exceeding the recommendations, the rating of Unsatisfactory was again applied. This decision was based upon the research cited in the foregoing chapters which revealed the serious effect of high brightnesses and brightness contrasts upon vision.

Direct recessed incandescent. -- Both schools A and B have fixtures of the flush recessed type with only the lens of the fixture visible from within the room. All light is directed downward. In School A twelve fixtures are installed in three rows of four fixtures each with the rows parallel to the window wall.

An adequate level of illumination was provided. This school was rated 4, or Unsatisfactory, on the Scale of Visual Comfort because of the existence of strong shadows, high direct glare, and relatively high indirect glare. Directly under the fixture, the brightnesses were 50 times as great, and in the 45-degree zone 25 times as great as the recommendation of the American Standards Association.

Careful attention was given in this room to the use of lightly highly reflective colors in dull finishes, and the ratios in Columns (6) to (8) are within acceptable limits. The ratios

1/ D. B. Harmon, op. cit.
in Columns (9) and (10), however, are excessive. School A was given a rating in Column (11) of Unsatisfactory.

As described above, School B was given a rating of Unsatisfactory because of the seriously inadequate level of illumination. It, however, was not only deficient in quantity, but also in several other respects. The surface brightness of the fixture exceeded the recommended limits. The ratio of task to floor was also greater than the acceptable limits since, contrary to generally accepted practice, the floor was a dark brown asphalt tile of very low reflectance. Similarly, while the ratio of task to ceiling was excessively low, the ratio of task to chalkboard was nearly three times as great as the recommended maximum of the American Standards Association. The direct nature of the light source which was at the same time inadequate in quantity, coupled with the existence of floors and chalkboards of very low reflectance, combined to produce heavy shadows, objectionable brightness contrasts, and a generally unsatisfactory visual environment.

Figure 5 indicates the contrast between the light and dark areas on the upper wall resulting from the downward cone of light directed by the fixtures, and the absence of illumination on the ceiling which characterizes these installations.
Figure 5. Uneven Distribution of Light on Upper Wall, and Relative Lack of Brightness of Ceiling Characteristic of Direct-Lens Incandescent Installation

Direct louvered fluorescent. -- The fixtures in schools C and D are of the suspended louvered fluorescent type installed in two rows parallel to the window wall, each 32'0" long. Plastic side panels serve to reduce the brightness of the exposed fluorescent
lamps in the 45-90 degree zone: The surface brightness of the lamps is masked by an egg-crate louver providing a visual cut-off approximately 35 degrees at right angles to the lamp and 45 degrees parallel to the lamp. Since these two rooms present highly similar conditions, they will be considered together.

The surface brightness of the fixtures in the 45-degree zone was in both instances found to be nearly four times the recommended maximum. Similarly, the brightness taken directly below the fixtures exceeded by 100 percent the recommendations of the American Standards Association. Specular reflections from the task, particularly from the page of an illustrated magazine, were noticeable and somewhat distracting. Some reflected glare was noted from the plastic surfaces of adjacent desk-tops. This indirect glare obtained despite the fact that careful attention had been given to providing light highly reflective surfaces in dull matte finishes in this school. In this connection, studies have revealed that reducing the brightness of a fixture producing specular reflection from 1200 footlamberts to 200 footlamberts has been found to have practically the same effect upon visibility as increasing the level of illumination by 60 percent.

\[1/\] Howard M. Sharp, op. cit., p.187.
A rating of 2-1/2 was given to these installations on the Scale of Visual Comfort. This corresponds to a Good rating.

In both schools, the task to chalkboard ratio was 2-2/3 of that recommended. In consideration of the degree of direct and reflected glare in these installations, and of the task to chalkboard ratio, an evaluation of Fair was assigned to both schools.

Semi-direct globe lens incandescent. -- The fixtures in schools E and F are of the suspended type, with the lamp completely enclosed within a prismatic glass globe. The globe is designed in two separate parts, an upper cone which, by means of its design, directs light against the ceiling, and a lower bowl which distributes the direct or downward component. Both these schools have square rooms with a clerestory providing natural lighting on the inner wall. The lights are installed in three rows of four fixtures with the rows parallel to the window wall.

Both installations provide an adequate level of illumination. Both were given a rating of 4, or Unsatisfactory, on the Scale of Visual Comfort, due to the fact that the fixtures present an intensely bright light source in the field of view.
School E was found to have a surface brightness in the 45 degree zone 37 times as great as recommended limits. The brightness in the zone directly under the fixture was 29 times greater than recommended limits.

In School F, which had less bright fixtures, the fixture brightnesses were found to be 27 times brighter in the 45 degree zone and 26 times brighter in the 0-degree zone than recommended.

In both installations, direct glare was so intense as to produce a sensation bordering on visual shock recorded by both observers. Reflected glare was very apparent despite the fact that much care had evidently been exercised in selecting light reflective colors in dull matte finishes.

The classroom desks, although of acceptable color, had plastic tops which provided some specular reflection. Similarly, the chair seats and structural members of the desks were finished with materials of a slight gloss.

The photograph in Figure 6 reveals the existence of reflected glare from the structural members of a classroom desk and chair.
Because of the intensely bright light sources which produced high direct and indirect glare, both schools were rated Unsatisfactory.
Semi-indirect luminous fluorescent. -- Schools G, H, and I are lighted by means of so-called luminous indirect fluorescent fixtures. These are of the suspended type installed in two continuous rows parallel to the window wall. A continuous sheet of diffusing plastic is mounted below the fixture so that the exposed lamps are not in the field of view. The major component of the light is directed against the ceiling, and the room is lighted by reflected light.

All three installations were found to provide an adequate level of illumination. The installation in school H is significant since it exemplifies an error frequently made in connection with installations of indirect and semi-indirect lighting, namely, the installation of the acoustical treatment on the ceiling.

The most efficient white paint yet developed reflects only 85 percent of the light falling upon it. This means that under optimal conditions, 15 percent of the light falling upon such a surface is absorbed and wasted. Acoustical tile, when new, has a reflectance of from 72 to 78 percent, depending upon the manufacture. As with all materials, as it ages it becomes dusty and dirty, and the reflectance drops. This particular installation was found to have a reflectance of 70 percent. Instead of having
15 percent of the light absorbed by the ceiling, in this installation 30 percent was being wasted. Moreover, research studies reveal that the practice of installing acoustical treatment on the ceiling is less efficient and more expensive than other methods.

Each of these three schools was rated 2, or Good, on the Scale of Visual Comfort. In each case, the surface brightnesses of the fixtures are within acceptable limits. With two exceptions, those of the tasks to chalkboards in Schools G and I, the brightness contrasts of the room surfaces are also within approved limits. In school G, the task-to-chalkboard ratio was one-third higher than recommended, and in school I was two-thirds higher than recommended. In each instance there was found to be very little contrast between fixture and ceiling.

In school G, however, a continuous dark band one inch wide at the bottom of the fixture, and running its entire length, contrasted sharply with the brightness of the luminous plastic it served to support. The elimination of the metal band would improve the visual continuity of the luminous plastic surface and would help in blending the fixture in an unobtrusive manner with the brightly illuminated ceiling.

In school H, the fixtures are joined together to provide continuous runs by means of bands of metal three and one-half inches wide running crosswise of the fixture every four feet. As in the case of school G, the elimination of these bands which appear dark when the fixture is illuminated would improve the appearance of this installation.

In school I, this cross-band ing of metal exists every two feet on the fixture as a support for the plastic diffusing shields. The elimination of these strips would improve the appearance of the installation.

All three of these installations were allotted an evaluation of Good on the Scale of Visual Efficiency.

Concentric three-ring indirect incandescent. -- Schools J, K, and L represent installations of the popular concentric, three-ring, incandescent fixture. The fixture is a simple one consisting of an incandescent lamp silvered at the bottom so as to direct all light against the ceiling, and surrounded by three concentric sheet-metal rings painted flat white. The purpose of the rings is both to reflect the light and to provide a cutoff preventing a direct view of the bright area of the lamp. This is the type of installation most commonly seen in new school buildings. In each of these three schools, two
rows of fixtures were installed with the rows parallel to the window wall. In school J, each row consisted of three fixtures, while in schools K and L each row consisted of four fixtures.

In each school the error was made of installing the acoustical tile treatment on the ceiling. In school J, the mean reflectance from this surface was only 67 percent despite the fact that the building was only fourteen months old. In school J, the use of dark natural slate chalkboards produced a task-to-chalkboard ratio three times that recommended. Schools J and K were rated 3, or Uncomfortable, on the Scale of Visual Comfort because of:

1. the appearance of the fixture as an obtrusive dark center of very low brightness, surrounded by three concentric white rings 50 percent brighter than recommended levels permit.

2. the low level of illumination which affected both visual comfort and the pleasurable sensation which accompanies good seeing conditions.

In both schools J and K, Visual Efficiency was evaluated as Unsatisfactory because of the seriously inadequate level of illumination provided.
School L was given a rating of 2-1/2 on the Scale of Visual Comfort. Despite the fact that the light level in this school is 10 percent below the minimum recommended, all brightness ratios were well within acceptable limits. The surface brightness of the fixture presented contrasts similar to those described in schools J and K. The central portion of the fixture appears as a dark spot surrounded by concentric rings, the brightness of which approaches twice the maximum recommended. The evaluation of this installation on the basis of Visual Efficiency was Poor.

Luminous concentric three-ring incandescent.-- School M represents an installation of a fixture highly similar to that of the standard three-ring incandescent, but with concentric rings of plastic rather than of metal painted flat white. These rings are intended to diffuse the light as well as to provide a visual cutoff. The room is rectangular, located at a corner of a four-room addition, and receives natural light from two adjacent window walls. Three rows of four fixtures each are mounted with the rows parallel to the longer window wall.

The level of illumination in this school was adequate, the mean exceeding 40 footcandles. The surface brightness of the fixtures, however, was considerably above the allowable maximum.
In the 45-degree zone, the surface brightness was seven times as great as the American Standards Association recommends. In the 0-degree zone, the brightness was within desirable limits.

The high brightness of the light source produced considerable direct glare in the visual field. The photograph in Figure 7 indicates the general design of the fixture.

Figure 7. Specular Reflection on Desk-Tops Resulting from High Brightness of the Light Source and the Use of Glossy Finishes on Classroom Furniture
The use of rather glossy paints and surface finishes in the room, coupled with the absence of shades at the window, accounts for the considerable amount of reflected glare in the room. Figure 8 reveals the degree of reflected glare from window glass and from painted steel members of the window frames. A rating of 4, or Unsatisfactory, on Visual Comfort was assigned to this school.

The brightness contrast between task and chalkboard in this school was the second highest of the thirteen installations studied. Because of the presence of direct and reflected glare and the high task-to-chalkboard ratio, an evaluation of Unsatisfactory was assigned to this school.

Summary of the chapter. -- An analysis of the foregoing table reveals that of the thirteen lighting systems studied, seven were found to be unsatisfactory in terms of visual efficiency. Of these seven, three were rejected because of serious inadequacy in the level of illumination which they provided. These were:

1. school B, a Direct Lens Plate Incandescent installation.
2. schools J and K, two of the concentric, 3-ring Incandescent installations.
In addition to these three schools, A, E, F, and M were judged unsatisfactory because of high source of brightness, high brightness contrasts of the room surfaces, or both.

Of all installations tested, the three schools with the Semi-Indirect Fluorescent installations received the highest evaluation. The two schools with the Direct Fluorescent installations were evaluated as being next best in visual efficiency.

For convenience a capital letter has been used to refer to each of the Thirteen lighting installations in this chapter. This procedure will also be followed in chapters VI and VII. Each of these systems is identified in Appendix "B" as to the school system, the particular school, the room number and the grade level.
CHAPTER VI
COSTS OF INSTALLING AND OPERATING
LIGHTING SYSTEMS IN THIRTEEN SELECTED CLASSROOMS

1. Costs of Installation

Determining the costs of installation. -- The costs of installation of school lighting systems is difficult to determine. No uniform practice obtains as to what is included in the contract of the electrical subcontractor. In one school this contract will include only the labor and materials needed to provide lighting and a minimum level of electrical service in the building. In another school the contract may include also the finishing and installing of:

1. elaborate equipment for heating controls.
2. a public address system.
3. telephone intercommunication.
4. a fire-alarm system.

In these situations, the cost of the lighting installation tends to become a small proportion of the total contract price and is frequently, therefore, less carefully accounted for.
Most electrical contractors, and particularly those operating large organizations, conduct careful analyses of the costs of labor and materials for each work project. Such analyses provide them with information essential for:

1. determining the efficiency of their business operation.
2. eliminating errors and omissions, and improving generally their practices of estimating on contract work.
3. the filing of Federal business income returns.

Some contractors, usually those who operate small organizations, do not keep accurate and complete cost records. Their bid proposals are frequently made on the basis of a more or less casual inspection of the plans and specifications. Often the determining factor in the quotation they submit is the similarity of the project under consideration in terms of size and scope with some previous contract on which they have been successful.

Construction of a reference guide. -- With practices varying between these two extremes, differences in the reported costs for what apparently is the quantity and kind of work were anticipated in this study. Accordingly, a procedure was established in an attempt to eliminate the inherent possibilities of error. The
cost of the fixtures to the electrical contractor was first secured from electrical supply houses. The discount customarily extended to electrical contractors by the supply houses was taken, and the net cost of the fixture material established as a base. To this base was then added:

1. the cost of labor and materials for the necessary work in connection with wiring for the installation based upon prevailing labor rates. Reliable estimating guides prepared for such purposes were employed as guides in the determining of these unit costs.

2. a flat percentage rate to provide for overhead and profit customarily charged by the electrical contractor.

3. a percentage to provide for overhead and profit customarily charged by the general contractor.

4. the percentage established for the particular project to cover the cost of architectural fees.

With this total on file as a reference guide, the architect was in each instance then requested to ascertain the cost to the community of: (1) a typical classroom fixture hung in place,

---

(2) a fixture outlet wired and ready to receive the fixture from, but not including, the wall switches. These prices were then compared with those previously established as reference guides. Where the difference was insignificant (less than 15 percent), the figures submitted by the architect were employed in the study.

In those instances where the prices received were found to differ by more than 15 percent from the reference guide, the following procedure was then followed:

1. discussions were held with the electrical subcontractor, and with the electrical engineer who designed the installation.

2. the electrical plans and specifications for the school in question were carefully examined.

By following this procedure it was possible to isolate and to identify the variable factors responsible for the differences between the reported costs and the reference guides. In no instance was it found impossible to reconcile these differences.

Table 6 gives the analysis of the costs of installations in the thirteen schools studied.
Table 6  The Total Cost per Classroom of Lighting Systems Installed in Thirteen Selected Massachusetts School Buildings.

<table>
<thead>
<tr>
<th>School</th>
<th>Type of Fixture</th>
<th>No. of Fixtures per Classroom</th>
<th>Cost each Fixture hung in place</th>
<th>Total cost all Fixtures Col. (3) X Col. (4)</th>
<th>Cost each Wired Fixture Outlet</th>
<th>Total cost all Wired Fixtures Col. (5) X Col. (6)</th>
<th>Number Switches Required</th>
<th>Cost each Switch Installed</th>
<th>Total Cost all switches Col. (8) X Col. (9)</th>
<th>Total Installed Cost all Fixtures Col. (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Direct Lens-Plate Incand.</td>
<td>12</td>
<td>21.70</td>
<td>260.40</td>
<td>13.40</td>
<td>160.80</td>
<td>3</td>
<td>11.65</td>
<td>24.95</td>
<td>456.15</td>
</tr>
<tr>
<td>B</td>
<td>&quot; &quot;</td>
<td>12</td>
<td>20.45</td>
<td>245.40</td>
<td>10.80</td>
<td>129.60</td>
<td>3</td>
<td>9.60</td>
<td>28.80</td>
<td>403.80</td>
</tr>
<tr>
<td>C</td>
<td>Direct Louvered Fluorescent</td>
<td>8</td>
<td>58.31</td>
<td>466.48</td>
<td>19.75</td>
<td>39.50</td>
<td>2</td>
<td>11.85</td>
<td>23.70</td>
<td>529.68</td>
</tr>
<tr>
<td>D</td>
<td>&quot; &quot;</td>
<td>8</td>
<td>57.95</td>
<td>463.60</td>
<td>19.60</td>
<td>39.20</td>
<td>2</td>
<td>11.75</td>
<td>23.50</td>
<td>526.40</td>
</tr>
<tr>
<td>E</td>
<td>Semi-direct Globe-lens Incandescent</td>
<td>12</td>
<td>16.50</td>
<td>128.00</td>
<td>9.50</td>
<td>114.00</td>
<td>3</td>
<td>10.95</td>
<td>32.85</td>
<td>344.85</td>
</tr>
<tr>
<td>F</td>
<td>&quot; &quot;</td>
<td>12</td>
<td>22.10</td>
<td>265.20</td>
<td>7.80</td>
<td>23.60</td>
<td>3</td>
<td>10.10</td>
<td>30.30</td>
<td>380.10</td>
</tr>
<tr>
<td>G</td>
<td>Semi-indirect Fluorescent</td>
<td>16</td>
<td>32.16</td>
<td>514.56</td>
<td>17.76</td>
<td>35.52</td>
<td>2</td>
<td>10.85</td>
<td>21.70</td>
<td>572.78</td>
</tr>
<tr>
<td>H</td>
<td>&quot; &quot;</td>
<td>14</td>
<td>33.14</td>
<td>463.96</td>
<td>16.70</td>
<td>33.40</td>
<td>2</td>
<td>10.65</td>
<td>21.30</td>
<td>518.66</td>
</tr>
<tr>
<td>I</td>
<td>&quot; &quot;</td>
<td>8</td>
<td>65.28</td>
<td>522.24</td>
<td>18.92</td>
<td>37.84</td>
<td>2</td>
<td>11.40</td>
<td>22.80</td>
<td>582.88</td>
</tr>
<tr>
<td>J</td>
<td>Concentric 3-ring Incandescent</td>
<td>6</td>
<td>17.22</td>
<td>103.22</td>
<td>11.80</td>
<td>70.80</td>
<td>2</td>
<td>10.65</td>
<td>21.30</td>
<td>195.42</td>
</tr>
<tr>
<td>K</td>
<td>&quot; &quot;</td>
<td>8</td>
<td>15.80</td>
<td>126.40</td>
<td>11.42</td>
<td>91.36</td>
<td>2</td>
<td>10.60</td>
<td>21.20</td>
<td>238.36</td>
</tr>
<tr>
<td>L</td>
<td>&quot; &quot;</td>
<td>8</td>
<td>17.55</td>
<td>140.40</td>
<td>13.40</td>
<td>107.20</td>
<td>2</td>
<td>11.80</td>
<td>23.60</td>
<td>271.20</td>
</tr>
<tr>
<td>M</td>
<td>Incandescent 3-ring Incandescent</td>
<td>12</td>
<td>15.45</td>
<td>185.40</td>
<td>8.00</td>
<td>95.00</td>
<td>4</td>
<td>10.75</td>
<td>43.00</td>
<td>328.40</td>
</tr>
</tbody>
</table>

* The cost of each "fixture hung in place" represents the total installed price of each fixture only.
** The cost of each "fixture outlet" represents the total installed price of each ceiling fixture box required, wired from the wall switch, and ready to receive the fixture.
*** The cost of "each switch installed" represents the total installed price of the switch outlet boxes in the wall, the switches, and the switchplates complete, ready to operate the system.
Variations in price levels. -- Some variations in cost are evident in Table 6. Certain of these are the result of different structural conditions in the particular school, as well as the nature of the design of the electrical engineer. Others are due to the fact that the construction of these buildings took place from 1950 to 1953, a period during which the cost of materials and of labor increased each year. The prevailing rates of labor and the price levels of materials at the time of construction are other factors in the variances found above.

Table 7 is a recapitulation of the total installation costs of the lighting systems in the thirteen schools, adjusted to the labor rates and material price levels of March, 1953. In order to obviate this difference due to the time of construction, the adjusted costs will be employed in the analyses following.

2. The Costs of Operation

Factors in cost analyses. -- The primary points of comparison in a cost analysis of lighting are (1) the total initial investment, and (2) the total annual lighting cost. The total initial investment is essential since it reveals the amount of money which must be raised in order to make the installation. All too often this initial
Table 7. Comparison of Actual Total Costs of Classroom Lighting Systems in the Thirteen Schools Studied with Costs Adjusted to Labor and Material Price Levels, Together with the Rank Order of the Installations on the Basis of Adjusted Prices

<table>
<thead>
<tr>
<th>School</th>
<th>Type of Fixture</th>
<th>Actual Total Costs of Lighting Systems</th>
<th>Total Costs Adjusted to Price Levels of March 1953</th>
<th>Rank Order on Basis of Adjusted Prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Direct Lens Plate Incandescent</td>
<td>456.15</td>
<td>456.15</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>&quot;</td>
<td>403.80</td>
<td>450.50</td>
<td>7</td>
</tr>
<tr>
<td>C</td>
<td>Direct Lowered Fluorescent</td>
<td>529.68</td>
<td>529.68</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>&quot;</td>
<td>526.30</td>
<td>526.30</td>
<td>9</td>
</tr>
<tr>
<td>E</td>
<td>Semi-direct Globe Lens Incandescent</td>
<td>344.85</td>
<td>385.50</td>
<td>5</td>
</tr>
<tr>
<td>F</td>
<td>&quot;</td>
<td>389.10</td>
<td>389.10</td>
<td>6</td>
</tr>
<tr>
<td>G</td>
<td>Semi-indirect Fluorescent</td>
<td>571.78</td>
<td>593.75</td>
<td>12</td>
</tr>
<tr>
<td>H</td>
<td>&quot;</td>
<td>518.66</td>
<td>543.26</td>
<td>11</td>
</tr>
<tr>
<td>I</td>
<td>&quot;</td>
<td>582.88</td>
<td>601.40</td>
<td>13</td>
</tr>
<tr>
<td>J</td>
<td>Concentric 3-ring Incandescent</td>
<td>195.42</td>
<td>216.55</td>
<td>1</td>
</tr>
<tr>
<td>K</td>
<td>&quot;</td>
<td>238.36</td>
<td>263.65</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>&quot;</td>
<td>271.20</td>
<td>278.70</td>
<td>3</td>
</tr>
<tr>
<td>M</td>
<td>Luminous 3-ring Incandescent</td>
<td>324.40</td>
<td>324.40</td>
<td>4</td>
</tr>
</tbody>
</table>
cost is used as the sole means of comparing the costs of proposed installations.

**Cost of electrical current.** -- Contrary to general opinion, the cost of electrical current varies from community to community, and from school to school. Neighboring towns which buy their electric power from the same company usually pay different net amounts for a similar consumption of electrical energy. This is due to the fact that the utility company must provide capacity in service facilities for a load which is seldom experienced. It must be equal to that needed should every light and every appliance be used at one time. The power company must provide transformers and service lines which would take care of the total load if:

1. all fan, heating and ventilating motors were operating.
2. all lights in the building were turned on.
3. every electrical outlet was being used to operate visual aid equipment, cleaning equipment, home-making or some other kind of electrical equipment.

This situation seldom obtains in a school. In New England it is most nearly approached during the months of December and January. During the dark days of these winter months the needs for lighting and for heat combine to produce a total load which
approaches the maximum possible load. Conversely, the lowest consumption is usually recorded during the months of September, October, May and June.

Demand and consumption charges. -- In view of this need for providing service to the building and facilities in the generating plant in excess of normal needs, most utility companies predicate their rates upon a so-called "demand charge." This charge is usually calculated on either a kilovoltampere or a kilowatt basis, and in terms of the maximum load for which the entrance switches to the building are fused. The basic charge for each month for each school is usually a percentage of this load. The actual monthly consumption of current is based upon the meter reading in kilowatt hours, the unit which covers the provision of 1,000 watts of current for a one-hour period. This latter rate differs from the demand rate and is usually on a sliding scale basis, so that the greater the consumption, the lower the rate.

In each of the schools examined, the rate structure and the distribution of the monthly charges were carefully studied. The median of the charges over the previous full year period was calculated. In those instances where the building had not yet been in use for a full year, the median was calculated on the
basis of the distribution made up of the known months, and the estimated charges for the remaining months of the year.

Table 8 provides a comparison of the annual costs of owning and operating each of the thirteen lighting systems studied. Four factors affect the total annual operating cost of a lighting system. They are:

1. the annual charge for amortizing the original cost of installation.
2. the annual charges for electrical current.
3. the annual cost of cleaning of the equipment.
4. the annual cost of replacing burned-out lamps and fluorescent starters.

The term of amortization was determined after careful investigation of modal practice in the state. The Massachusetts School Building Assistance Commission reports that virtually all schools constructed under the state financial assistance program were financed over a twenty-year term. Accordingly, this term was employed in the calculations of Table 8.

Annual use in hours. -- In order to determine with reasonable accuracy the actual number of hours which each system
Table 8. Cost Comparison of Owning and Operating Lighting Systems in Thirteen Selected Classrooms.

<table>
<thead>
<tr>
<th>Description of Lighting System</th>
<th>Direct Incandescent</th>
<th>Direct Incandescent</th>
<th>Direct Incandescent</th>
<th>Semi-Diffused Incandescent</th>
<th>Semi-Diffused Incandescent</th>
<th>Semi-Diffused Incandescent</th>
<th>Direct Fluorescent</th>
<th>Direct Fluorescent</th>
<th>Direct Fluorescent</th>
<th>Direct Fluorescent</th>
<th>Direct Fluorescent</th>
</tr>
</thead>
<tbody>
<tr>
<td>School</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
<td>H</td>
<td>I</td>
<td>J</td>
<td>K</td>
</tr>
<tr>
<td>Number of Fixtures</td>
<td>12</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>12</td>
<td>12</td>
<td>16</td>
<td>14</td>
<td>8</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Wattage of Lamps</td>
<td>300</td>
<td>204</td>
<td>306</td>
<td>75</td>
<td>200</td>
<td>40</td>
<td>40</td>
<td>75</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Number of Lamps Per Fixture</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total Voltage Per Classrooms</td>
<td>360</td>
<td>280</td>
<td>1600</td>
<td>1600</td>
<td>3600</td>
<td>2400</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>2400</td>
<td>2400</td>
</tr>
<tr>
<td>Mean Footcandies</td>
<td>33.8</td>
<td>13.9</td>
<td>51.7</td>
<td>51.5</td>
<td>37.8</td>
<td>26.3</td>
<td>41.4</td>
<td>28.3</td>
<td>37.4</td>
<td>14.3</td>
<td>13.8</td>
</tr>
<tr>
<td>Total Cost of Installation</td>
<td>456.15</td>
<td>403.20</td>
<td>529.68</td>
<td>526.30</td>
<td>394.85</td>
<td>571.78</td>
<td>518.66</td>
<td>582.96</td>
<td>195.42</td>
<td>238.36</td>
<td>271.20</td>
</tr>
<tr>
<td>Amortization of Total Cost over 20 yrs at 1.5% interest**</td>
<td>23.21</td>
<td>20.55</td>
<td>26.95</td>
<td>26.78</td>
<td>17.55</td>
<td>19.00</td>
<td>29.09</td>
<td>26.39</td>
<td>29.65</td>
<td>9.95</td>
<td>12.13</td>
</tr>
<tr>
<td>Lamp &amp; Starter Replacement</td>
<td>3.60</td>
<td>3.09</td>
<td>2.32</td>
<td>2.02</td>
<td>2.60</td>
<td>2.40</td>
<td>4.48</td>
<td>4.26</td>
<td>2.02</td>
<td>3.11</td>
<td>4.14</td>
</tr>
<tr>
<td>Power Cost per kW Hour</td>
<td>.047</td>
<td>.046</td>
<td>.046</td>
<td>.047</td>
<td>.038</td>
<td>.037</td>
<td>.05</td>
<td>.053</td>
<td>.049</td>
<td>.052</td>
<td>.051</td>
</tr>
<tr>
<td>Annual Operating Hour</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>530</td>
<td>530</td>
<td>530</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Annual Operating Cost for Power</td>
<td>101.53</td>
<td>82.32</td>
<td>104.16</td>
<td>65.12</td>
<td>54.72</td>
<td>35.52</td>
<td>42.40</td>
<td>39.33</td>
<td>47.04</td>
<td>56.16</td>
<td>73.44</td>
</tr>
<tr>
<td>Total Annual Operating Cost Items (7) + (9) (10)</td>
<td>128.24</td>
<td>106.77</td>
<td>73.13</td>
<td>73.92</td>
<td>74.67</td>
<td>56.26</td>
<td>75.97</td>
<td>69.98</td>
<td>78.71</td>
<td>69.22</td>
<td>89.61</td>
</tr>
<tr>
<td>Relative Annual Operating Cost</td>
<td>2.28</td>
<td>1.90</td>
<td>1.30</td>
<td>1.31</td>
<td>1.33</td>
<td>1.00</td>
<td>1.35</td>
<td>1.24</td>
<td>1.40</td>
<td>1.23</td>
<td>1.60</td>
</tr>
<tr>
<td>Annual Cost per Footcandle</td>
<td>1.60</td>
<td>1.44</td>
<td>1.62</td>
<td>1.48</td>
<td>1.68</td>
<td>1.44</td>
<td>1.98</td>
<td>1.94</td>
<td>2.47</td>
<td>2.11</td>
<td>4.86</td>
</tr>
<tr>
<td>Relative Annual Cost per Footcandle</td>
<td>2.68</td>
<td>5.41</td>
<td>1.00</td>
<td>1.81</td>
<td>1.61</td>
<td>1.30</td>
<td>1.74</td>
<td>1.49</td>
<td>3.41</td>
<td>4.57</td>
<td>2.52</td>
</tr>
</tbody>
</table>

* These figures for fluorescent lights include the wattage consumed by starters and ballasts. Consumption of current per 40 watt lamp 50 watt actual. Consumption per 75 watt lamp 100 watt actual.
** Amortization covers the annual cost of bonding the construction for 20 years at 1.5% percent interest.
*** It was assumed that burned-out lamps and starters would be replaced promptly. This item covers the cost of lamp and starter replacement based upon manufacturer's tables of "average lamp life."
**** Relative costs in (14) and (15) were derived by regarding the lowest cost in each row as unity and dividing each other cost by the lowest cost to determine the ratio.
operates, an analysis was made in these and in similar buildings during the past year. Inspections were made to determine the number of hours which each kind of school lighting system was in use in clear weather, in cloudy weather, and in stormy weather.

It was determined that in rectangular classrooms with unilateral natural lighting, the artificial lights were in use 66 percent of every school day. In buildings with natural lighting from two adjacent window walls, the lights were in use 55 percent of the school day. In buildings with bilateral natural lighting, the lights were in use 44 percent of the school day. Based upon a school-day of five hours and a school-year of 180 days, these proportions were used in the calculations of annual use.

The annual costs of electrical current were, of course, derived by multiplying the total wattage of the installation by the annual use in hours, and by the rate per kilowatt hour.

Cleaning of equipment. -- No provision was made for the cost of periodic cleaning of the fixtures so as to insure maximum or near-maximum light emission. In each instance the maintenance of fixtures is provided by the school custodial staff. Since these men are regular employees of the school system, no additional cost is incurred in the cleaning of fixtures.
Replacing lamps and starters.—As with maintenance, the labor of replacing burned-out lamps and fluorescent starters is done by the school custodians. Since no additional cost is incurred by the school system for this service, this item as included on Table 8 covers only the cost of materials.

The life of the lamps was taken from manufacturers' tables of "average lamp life."

Relative annual cost.—In order to facilitate direct comparison of the data in Table 8, the annual lighting cost has been expressed also in terms of the Relative Annual Lighting Cost. In these calculations, the least expensive installation was expressed as having a relative cost of 1.00.

It is also apparent from an inspection of Table 8 that a fallacy in comparisons of annual lighting costs exists, since some of the more expensive installations actually are providing considerably more illumination than those whose costs are apparently lower. Relating Table 8 to Table 5 reveals also that the more expensive installations are, in several instances, providing better light than those whose costs are apparently lower. In order to compare the true economics, the relative costs per footcandle for each installation have also been calculated. As
in the Relative Annual Lighting Cost, the least expensive installation was expressed as having a relative cost of 1.00.

Several facts are revealed by an analysis of Table 8. One is that low initial investment is a poor and unreliable way of judging the real cost of a lighting installation. Low cost installations which provide inadequate illumination are not only low in visual efficiency but are poor investments, since in most instances little additional money is required to provide adequate systems.

It is apparent that school F, which is globe lens incandescent, has the lowest Relative Annual Operating Cost. Study indicates, however, that the advantages of school F are not due to the efficient operation of the installation. Rather, they are the result of: (1) the existence of the lowest power rate of the schools studied, and (2) the lowest annual hourly use of the schools studied. This latter is brought about by the better distribution of daylight in buildings provided with bilateral natural lighting.

These facts are revealed when the annual use of system F is set at 600 hours and the rate set at the median of all the rates studied. System F then ranks eleventh rather than first in annual operating cost. Despite this, the system actually provides only a bare minimum of light of unsatisfactory quality.
Comparisons of direct and indirect installations. -- Of all the lighting systems studied, the fluorescent systems, both direct and indirect, are best in terms of relative annual cost per foot-candle. In this respect, system C ranks first. Systems C and D, however, were both evaluated on visual efficiency one rank lower than systems G, H, and I. The presence of direct and reflected glare in both C and D tend to indicate that unless the difference in cost were prohibitive, indirect fluorescent systems should be selected. Table 8 reveals that the difference in cost between the most efficient semi-indirect installation, school G, and either C or D is insignificant. In twenty years, generally considered to be the life of electrical fixtures, system G would cost only $56.80 per classroom more to own and to operate than system C. Because of its inherent superiority at only slightly higher cost, G will be used as a standard in this discussion.

Comparison of system G with Lens-Plate Installations. -- The total cost of installation of system G is some $115 more than that of A. The annual savings in operating cost of system G, however, would pay for this difference in outlay in slightly over two years of operation. Similarly, the difference in outlay between G and B can be made up in less than six years of operation,
Moreover, both A and B are installations of the direct lens-plate design which were evaluated as Unsatisfactory. It is apparent, then, that these two installations are not only undesirable from the standpoint of visual efficiency but, when considered over the life of the fixture, are also more expensive.

Comparison of system G with direct fluorescents. -- As could be expected, systems C and D yielded the lowest relative annual cost per footcandle. The presence of direct and reflected glare in both schools resulted in systems C and D being evaluated Fair as compared with G, H, and I which were evaluated as Good. The difference in costs between system G and system C over a twenty-year life period is only $56.80. In a twenty-room building, this difference in cost would total less than $1200.

Few communities would not be able to afford this insignificant added cost necessary to provide top-quality classroom lighting for its school children.

Comparison of system G and globe-lens incandescents. -- Fixtures E and F, globe-lens incandescent systems, were evaluated Unsatisfactory because of high direct and indirect glare. In spite of this, system E, which comes nearest to providing the same light as system G, costs only $2 less per year to operate. In other words,
if the life of the fixture is taken as the term of the cost evaluation, then the most efficient installation of those studied can be purchased for only $40 more than the cheaper of these two visually unsatisfactory systems.

Comparison of system G and concentric three-ring fixtures. -- Table 8 reveals that the concentric three-ring incandescent fixture, contrary to general opinion, is not the cheapest installation in the long run. Direct comparisons of system G with systems J and K are difficult for two reasons:

1. systems J and K provide only one-third the illumination of system G.

2. the existence of poor surface reflectances from both ceiling and chalkboard in the cases of J and K.

In order, therefore, to provide some direct comparison between the standard and a concentric three-ring fixture, system G is compared with system L. In order to make such a comparison possible, system L, which provides only 22.4 footcandles of light, was recalculated so as to provide the minimum 30 footcandles recommended by the American Standards Association.

This recalculation revealed the following costs:
1. $372.90 - installation
2. 18.97 - amortization
3. 83.10 - electrical current
4. 5.70 - lamp replacement
5. 107.77 - total annual operating cost

This total annual operating cost exceeds that of system G by $31.80.

This means that in slightly over six years of normal use the difference between the initial costs of systems G and L would be made up by the lower operating cost of the former. Moreover, as indicated in Chapter V, the appearance of the latter fixture is that of a dark, un-illuminated bowl surrounded by three concentric rings with surface brightnesses 50 percent higher than recommended. This merited an evaluation of Poor in the best of the three installations of concentric three-ring fixtures studied.

Contrary to popular opinion, this type of installation is, then, not a bargain but, rather, when taken over the life of the fixtures, one of the more expensive kinds of lighting commonly used in elementary schools.
Comparison of System G and System M. -- In terms of its very high consumption of current, system M is the most expensive to operate of all those studied. Although the difference in cost of installation of system M is nearly $250 less than system G, the lower operating costs of the latter will pay for its higher initial cost in only two and one half years.

Moreover, because of the high brightness of the light source in both the direct and indirect glare zones, system M was evaluated as Unsatisfactory. There can be little justification for installing a type of fixture which is both inferior from the standpoint of visual efficiency and more expensive to operate.

Summary of the chapter. -- The data in Chapter VI reveals that of all the lighting systems studied, the direct and luminous indirect fluorescent types were the least expensive over the life of the installations. Of the two types, the direct installation was found to be the least expensive to operate.

However, the slight disadvantage in operating costs were more than offset by the superior lighting characteristics of the indirect fluorescent installations. In twenty years, the net difference in cost of owning and operating the direct and indirect systems in a school of twenty classrooms would total $1100.
The inherent superior characteristics of this type of installation render this cost difference insignificant.

Analysis revealed that the lens-plate incandescent installations could not be defended on an economic basis. The additional costs of operation of these two installations as compared with the best of the luminous incandescent systems would equal the difference in initial costs in two years and in six years, respectively.

Of the two globe-lens incandescent installations, one was found to have the cheapest annual operating cost of all those studied. Examination revealed that this was due to (1) the design of the classroom; (2) the existence of a very low power rate. When compared to the best of the indirect fluorescent systems on equal terms, these two installations cannot be defended economically.

Analysis reveals that, contrary to popular opinion, the concentric three-ring fixture is not economical. Over the life of the installation it costs considerably more to operate than the inherently superior luminous indirect fluorescent. Its use cannot be defended from an economic standpoint.

Finally, the luminous concentric three-ring fixture was found to have the highest of operating costs. From the economic
standpoint, the use of this fixture as installed in this school is difficult to defend.
CHAPTER VII
SUMMARY AND CONCLUSIONS

Superiority of fluorescent fixtures. -- This study reveals clearly the superior visual efficiency inherent in the fluorescent installations. From the standpoints of adequacy of illumination, brightness contrasts of the structural parts of the fixtures, and absence of direct and reflected glare, the fluorescent installations were found to be superior to any of the incandescent systems.

Of the two types of fluorescent systems studied, the indirect luminous system was found to be superior to the direct system on the basis of visual efficiency.

Incandescent systems found undesirable. -- Three types of incandescent fixtures were revealed to possess characteristics which render them questionable for use in elementary school classrooms. These were found to have high surface brightnesses which produced either objectionable direct or reflected glare, or both.

Initial costs a poor criteria for selection. -- The study revealed that the cost of installation alone was not a sound criterion
for determining the selection of a classroom lighting installation. If, however, this criterion were to be employed, it was revealed that the difference between the best fluorescent and the best incandescent systems was only $200 per classroom. When one considers that the median cost of 20-classroom elementary schools in Massachusetts during 1952 and 1953 exceeded $600,000, the $4,000 difference in lighting costs becomes insignificant, particularly in terms of the quality of the light.

Under statute, a state grant ranging from 20 to over 50 percent of the gross cost of new school buildings is made to each community. This grant is based upon an equalized valuation formula and is designed to assist in equalizing educational opportunity throughout the state. These grants reduce the net cost of schools to the local community. The net cost of the $4,000 difference referred to above becomes, then, $3,200 for those communities most able to pay for their schools, and less than $2,000 for those least able to pay.

Moreover, the study revealed that in addition to the costs of installation, the costs of operation should be considered. The operating costs of fluorescent installations were found to be lower.
than those of the incandescent systems. Actually, the extra cost of installing the best fluorescent system, as compared with the best incandescent system, was made up in six years by the lower costs of operation of the former. When one considers that the life of a lighting fixture is some 20 years, it is apparent that the system which costs the least to install may well cost the most to own and operate over the period of its life.

This study has been concerned only with the use of elementary school buildings during the school day. The factor of community use of school buildings should be given consideration. Most cities and towns are finding that their elementary school buildings are becoming the centers of their communities, and are experiencing rapidly increasing public use.

Extensive use makes it possible to pay for the more expensive installations in an even shorter period of time. The greater the use, the more easily can the greater initial cost of the inherently superior, but more expensive, system be justified.

Those responsible for the selection of classroom lighting systems should, then, consider four criteria:
1. visual efficiency in terms of brightnesses and brightness contrasts.

2. quantity of light.

3. costs of installation.

4. costs of operation.

Suggestions for further research. -- The writer suggests that at least two areas of research in connection with school artificial lighting merit attention. Early in the thesis it was reported, in effect, that little is known about the shock effect or the comfort-discomfort level of children upon being subjected to varying degrees of direct glare. Efforts have been made to apply to children certain findings relating to adults. There is a need for a thorough research study of brightness tolerances of elementary school children.

There is presently under construction in a suburban Boston community a four-classroom addition to an elementary school which will be lighted by a so-called "luminous ceiling." This is an adaptation of the luminous indirect fluorescent fixture design. It provides for a series of fluorescent lamps mounted on the ceiling surface, with a continuous corrugated plastic material suspended some 18 inches below the lamps. This acts as a continuous
diffusing shield somewhat as in the case of the luminous indirect fixture.

The chief advantage of such a design is the very low surface brightness of the plastic surface which serves as the light source. When this building is completed, a study should be made to determine its relative visual efficiency. Cost studies will not be meaningful because of the fact that few installations of this kind of system have been made. For this reason, since the benefits of mass production cannot be realized, high material unit costs are inevitable.
CHAPTER VIII
THE BIBLIOGRAPHY


34. Simonson, Ernst and Josef Brozek, "Effects of Illumination Level on Visual Performance and Fatigue," Journal of the Optical Society of America (April, 1948), 38; P. 4.

APPENDIX "A"

Sample of the Survey Forms

In the following pages a sample of each of the two survey forms is presented.
FORM A
SCHOOL LIGHTING SURVEY
Subjective Appraisal of Quality
Artificial Lighting - Surveyed at Night
FOR PROFESSIONAL OBSERVERS

Date________________________

School______________________City______________________Room No.______Grade_____

(This form is intended for lighting engineers or others familiar with the specification of lighting.)

Please make this appraisal before taking any measurements.

How would you rate the room as a whole, from a standpoint of the pleasantness or unpleasantness, and comfort or discomfort of the surroundings?

Excellent _______ Good _______ So-so _______ Very poor _______

Grade your impression of the following brightness ratios on a scale of:

C = Comfortable
U = Uncomfortable
A = Acceptable
VU = Very Uncomfortable

<table>
<thead>
<tr>
<th>BRIGHTNESS RATIOS</th>
<th>C</th>
<th>A</th>
<th>U</th>
<th>VU</th>
</tr>
</thead>
<tbody>
<tr>
<td>White paper to desk</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White paper to general surroundings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixture to surroundings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Highest brightness in any normal field of view (please identify it).

________________________________________________________________________

Does fixture blend well with ceiling, or does it have a dark band which is conspicuous against ceiling?

________________________________________________________________________

Additional comments:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________
FORM B
SCHOOL LIGHTING SURVEY

Date ____________________

School __________________ Room No. _________ Survey by ____________________

MEASUREMENTS - ARTIFICIAL LIGHTING ONLY

FOOTCANDLE DISTRIBUTION

Front of Classroom

Record Footcandle measurements at points in circles

Show location of lighting fixtures on Room Plan

Rear Wall of Classroom

Plan View of Classroom

Sketch cross section of fixtures indicating opaque and luminous parts

BRIGHTNESS MEASUREMENTS
(Taken from a seat near center of rear wall)

Desk Top  →  White Paper

Record Brightness Values at Points in Circles

1. Brightest significant fixture area in field of view ____________________ F. L.
2. Brightest part of ceiling near fixture ____________________ F. L.
3. Darkest part of wall near fixture ____________________ F. L.

(Location readings 1, 2, and 3 on drawing above.)
APPENDIX "B"

In the following pages, the thirteen selected classrooms referred to in the body of the thesis by letter for reasons of convenience are identified as to the city or town, the school, the classroom number and the grade level.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Community</th>
<th>School</th>
<th>Room</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hanover</td>
<td>Center</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>Norwell</td>
<td>Elementary</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>Braintree</td>
<td>Lakeside</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>Braintree</td>
<td>Foster</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>Franklin</td>
<td>Parmenter</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>Lunenberg</td>
<td>Elementary</td>
<td>5c</td>
<td>5</td>
</tr>
<tr>
<td>G</td>
<td>Newton</td>
<td>Bowen</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>Newton</td>
<td>Williams</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>I</td>
<td>Newton</td>
<td>Peirce</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>J</td>
<td>Sharon</td>
<td>Cottage St,</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>K</td>
<td>Brookline</td>
<td>Baker</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>L</td>
<td>Newton</td>
<td>Claflin</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>M</td>
<td>Quincy</td>
<td>Squantum</td>
<td>A</td>
<td>4</td>
</tr>
</tbody>
</table>
APPENDIX "C"

In the following pages three photographs indicating the design and general arrangement of the fixtures in two of the classrooms are shown.
Photo #1: This photograph indicates the design and general appearance of the concentric three-ring incandescent fixture. This is the fixture most commonly used in elementary school classrooms today.
Photo #2 - This photograph indicates the design and general appearance of the globe-lens incandescent fixture.

In the photograph the intensity of the light source is evident.
Photo #3 - This is another photograph of a globe-lens incandescent installation showing the design of the clerestory arrangement.