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A Simplified Procedure for Calculating the Direct Components of Contrast Rendition Factor and Equivalent Sphere Illumination

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ERRATUM SHEET

The following legends for the figures are reversed and should be interchanged:

Figures 3 and 4

Figures 5 and 6

Figures 7 and 8

Figures 9 and 10

Figures 11 and 12

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Contents

Abstract

A procedure is presented which enables the user to compute the direct components of contrast rendition factor (CRF) and equivalent sphere illumination (ESI) for an interior lighting design with the aid of a card-programmable hand calculator. The underlying theory and equations of CRF and ESI are discussed, including a consideration of body shadow, intensity distribution curve interpolations, bidirectional luminance factor approximating equations and Inverse Square approximations.

The procedure is designed so that the user is a participant in the computations as they progress and thus is able to modify a lighting design in "midstream" to improve CRF or ESI. A set of user instructions is included with the calculator programs.

Key Words: Body shadow; contrast rendition; hand calculator; Illuminating Engineering; light design; luminaire effectiveness; luminance factor; office lighting; sphere illumination

A SIMPLIFIED PROCEDURE FOR CALCULATING THE DIRECT COMPONENTS OF CONTRAST RENDITION FACTOR AND EQUIVALENT SPHERE ILLUMINATION

Joseph B. Murdoch

I. Introduction

The subjects of contrast rendition factor (CRF) and equivalent sphere illumination (ESI) have received considerable attention in the lighting literature in recent years.[1-6] More specifically, there has been great interest in developing methods of predicting CRF and ESI prior to the installation of a lighting system, rather than simply trying to measure these quantities after the installation is completed.

Perhaps the best known of the prediction methods is the Lumen 2 procedure developed by D. DiLaura (4). This technique relies on an extensive computer program which discretizes luminaires into source elements, formulates the luminances and illuminances produced by these elements at a task location through the Inverse Square Law, and uses a double Fourier series approximation to replace the discrete functions by continuous ones for calculation purposes. Utilization of the technique requires obtaining the Lumen 2 program and access to a computer or the services of a central computer facility.

The procedure described herein enables the user to compute the direct components of CRF and ESI quickly and simply with the aid of an inexpensive card-programmable hand calculator. Because the user is a participant in the computations as they progress, he is able to determine easily which luminaires are having the greatest effect, either positively or negatively, on CRF and ESI, and thus he is able to try different luminaire locations and orientations in "midstream". Also, again because he and the calculator are working together, he is able to understand the evaluation procedure and calculations being made -- he is more truly a "designer". And lastly, because the procedure is a simple step-by-step one, a great deal of the mystique that has unfortunately surrounded CRF and ESI in recent years is swept away.

In Section II of this report, the theoretical considerations underlying CRF and ESI are reviewed and the equations necessary for calculating each quantity are presented. In Section III four topics relating to the CRF and ESI calculations are discussed. These are body shadow, intensity distribution curve interpolations, approximating equations for bidirectional luminance factors, and Inverse Square Law approximations. In Section IV, the programmable hand calculator procedure is presented in detail, followed by the calculator programs and user instructions in Section V. The report concludes with three sample designs in Section VI.

Only the direct components of CRF and ESI are considered in this report. Development of an extension to the procedure for computing the reflected components of CRF and ESI will be the subject of future work, as well as an extension to permit the inclusion of daylighting. Also a critical comparison of the author's procedure, Lumen 2, and other procedures for calculating CRF and ESI needs to be made, and this will be dealt with in the future. Lastly, and perhaps most important of all, the issue of whether CRF, ESI or some other metric or combination of metrics, is the best measure of one's ability to perform visual work needs to be explored. It is anticipated that the procedure developed herein, the extension of the procedure to include reflected components, and the comparison with other predictive procedures will assist in answering this question.

II. CRF and ESI -- Theory and Equations

The geometry which will be used in this section and throughout the report is shown in Figure 1. The task is located at the origin of an x, y coordinate system such that the +y direction is always the direction of viewing. A typical source element is shown, whose center is at x_e, y_e. It is also useful to describe its location in terms of the azimuth angle ϕ and the polar angle θ. ϕ is 0° in the direction of viewing and positive ϕ is measured clockwise from that direction. Thus ϕ can range from 0° to $\pm$ 180°. θ is 0° when the source element center is directly over the task and its range is from 0° to +90°.

Contrast rendition factor (CRF) is defined as the contrast produced by the actual lighting system divided by the contrast produced by the standard reference lighting system -- an illuminated sphere providing equal luminous intensity from all directions. Thus CRF is clearly a measure of the effects caused by the geometric distribution of the light flux from the actual lighting system.

CRF is always defined for a specific task. The only task for which published complete reflectance data as a function of both ϕ and θ are available is the concentric ring pencil task (5). Hence the procedure developed in this report is currently limited to this task, although there is nothing inherent in either procedure that precludes other tasks once the appropriate reflectance data become available.

To obtain CRF, one must first obtain contrast, or, more correctly, luminance contrast[1], defined as the difference between the luminance of the object (task detail) and its immediate background divided by the background luminance. Generally the magnitude of this quantity is taken, so that contrast is positive. In equation form

$$C = \left| \frac{L_b - L_t}{L_b} \right| \qquad (1)$$

where "b" denotes background and "t" task. Then

$$CRF = \frac{C\ \text{actual}}{C\ \text{sphere}} \qquad (2)$$

C sphere has been calculated as .1675 for the concentric ring pencil task when viewed at 25° from the vertical, the standard viewing angle[5]. Thus, the problem of predicting CRF reduces to the problem of predicting values of L_t and L_b under the proposed lighting system for the pencil task.

Luminances are obtained as products of illuminances and reflectances. As mentioned previously, reflectance data for the pencil task are available.[5] These data are in the form of tables of bidirectional luminance factors (B) for both the pencil task and its background. Luminance factor is defined as the luminance of a surface at a certain viewing angle and illuminance divided by the luminance of a perfectly reflecting and diffusing surface under the same conditions of viewing and illuminance. Bidirectional simply means that a given B factor is for a particular pair of azimuth and polar angles. We can write

$$B = \frac{L_a}{L_{rd}} = \frac{L_a}{E} \qquad (3)$$

where "a" refers to the actual surface and "rd" to the perfectly reflecting and diffusing surface. The second form of Equation 3 arises because the luminance in footlamberts of a perfectly reflecting and diffusing surface is identical to the illuminance in footcandles on that surface.

To obtain measured values of luminance factors as functions of source and viewer locations (with respect to a task location), it is necessary to place a collimated source of light at location Ø, θ with respect to the task and place a receiver (photometer) at the chosen 25° task polar viewing angle and at Ø = 180°. Then Equation 3 can be rewritten in the forms:

$$B_{ti}(\phi, \theta) = \frac{L_{ti}(\phi, \theta)}{E_i} \quad (4)$$

$$B_{bi}(\phi, \theta) = \frac{L_{bi}(\phi, \theta)}{E_i} \quad (5)$$

If we know B_{ti} and B_{bi} (which, as mentioned earlier, we do), then we can calculate L_{ti} and L_{bi} if we know E_i. Thus, the problem of calculating CRF has now been further reduced to the problem of calculating E_i, the horizontal illuminance at the task location produced by the ith source element. (If we were including the reflected component as well, we would also need the illuminance at the task from the jth reflective surface element).

To obtain the horizontal illuminance produced by each source element, we use the Inverse Square Law:

$$E_i = \frac{I_i(\phi,\theta) \cos \theta_i}{{d_i}^2} \quad (6)$$

where I_i is the intensity of the ith source element in the direction of the task, θ_i is its angle of incidence (angle with the vertical) at the task and d_i is the distance from the center of the ith element to the task. Recognizing that $h = d_i \cos\theta_i$, a more convenient form of Equation (6) is

$$E_i = \frac{I_i(\phi,\theta) \cos^3 \theta_i}{h^2} \quad (7)$$

where h is the mounting height of the luminaire above the task.

To use Equation (7), we must first separate each luminaire into elements, such that the largest dimension of each element is small compared with the distance from the element to the task. This is necessary because the Inverse Square Law holds exactly only for point sources and thus we must choose small enough source elements so that each can be treated as a point source.

Having done this, we compute E_i for each source element, using Equation (7). With the known values of B_{ti} and B_{bi}, we use Equations (4) and (5) to compute L_{ti} and L_{bi}, again for each source element. Next we sum to obtain $L_t = \Sigma L_{ti}$ and $L_b = \Sigma L_{bi}$ and use Equation (1) to obtain C. Then Equation (2) yields the direct component of CRF, since C sphere is known for the pencil task. If we desire the total direct illuminance on the task (the "raw" lux or footcandles), we sum the values of E_i from Equation (7).

We turn now to the calculation of Equivalent Sphere Illumination (ESI), defined as the illuminance from a uniform intensity sphere which would produce a task visibility equivalent to that produced by the actual lighting system.

With CRF in hand, it is not difficult to compute ESI. First, it is necessary to determine relative contrast sensitivity (RCS).[1, 2] RCS is the normalized inverse of the VL1 (threshold) Visibility Reference Function and is obtained from the latter by writing

$$RCS = \frac{5.74}{C_1} \qquad (8)$$

where C_1 is task contrast at threshold. For each value of background luminance, a value of C_1 may be obtained from the VL1 curve. This has been done, and values of RCS as a function of background luminance are presented in tabular form in Figure 3-32 of (1) and Table 1 of (2). From these tabular values, an empirical equation for RCS has been developed[4]:

$$RCS = 10^{\left[\frac{2.195721}{1 + \frac{1}{2.25(L_b)^{.2}}}\right]} \qquad (9)$$

Equation (9) is accurate within one percent for background luminance values between 10 and 1600 footlamberts (35 and 5500 candelas per square meter).

With RCS and CRF known, the next step is to obtain effective contrast sensitivity, defined by

$$RCS_e = CRF \times RCS \qquad (10)$$

RCS_e is the relative contrast sensitivity the task would have under sphere lighting. Corresponding to RCS_e is an effective background luminance L_{be} in the sphere, which may be obtained by reentering Figure 3-32 of (1) or Table 1 of (2) with the known value of RCS_e. Or L_{be} may be calculated, within the same range of background luminances as before, from the inverse of Equation (9).

$$L_{be} = \left[\frac{1}{2.25\left(\frac{2.195721}{\text{Log } RCS_e} - 1\right)}\right]^5 \qquad (11)$$

The illumination in the sphere corresponding to L_{be} is found by dividing L_{be} by the overall luminance factor B for the 25° viewing angle. The latter is obtained from Equation (3), with $L_a = \Sigma L_{bi}$ and $E = \Sigma E_i$. Then

$$E_e = \frac{L_{be}}{B_b} \qquad (12)$$

E_e is, by definition, equivalent sphere illumination (ESI). It is the illuminance under sphere lighting which produces the same task visibility as is provided by the illuminance E from the actual lighting system.

The ratio of the two illuminances, sphere and actual, is defined as the lighting effectiveness factor (LEF). It is simply a measure of how closely the actual lighting system approximates sphere lighting. In equation form

$$LEF = \frac{E_e}{E} \qquad (13)$$

III. Four Precalculation Matters

Although a general procedure for calculating the direct components of CRF and ESI has now been described, there are four matters which need to be addressed before actual calculations can begin.

A. Body Shadow

The effect of the viewer's head and body is to shield certain source elements from the task. Body shadow has been investigated at length in the literature.[3,7] An "average" head size, upper body size, head tilt and head and body location with respect to the task have been postulated for the 25° viewing angle. These "average" conditions may be summarized in terms of ϕ and θ by noting that a source element will be shielded from the task by the viewer if

$$145° < |\phi| < 165° \text{ and } \theta > 52°$$
$$\text{or } 165° < |\phi| < 180° \text{ and } \theta > 18° \qquad (14)$$

Any source element whose center lies in the shadow defined by these angles is neglected in the calculations of luminance and illuminance. A diagram of body shadow projection onto the luminaire plane for three values of h is shown in Figure 2.

One final point should be made about body shadow. The viewer is assumed to be "zero reflective", so that no luminous flux reaches the task after reflecting from the viewer's head and body. This assumption is certainly questionable, especially for viewers wearing lightcolored clothing.

B. Intensity Distribution Curve Interpolations

Luminaire manufacturers generally present intensity distribution data in 5° or 10° increments in polar angle θ for three values of luminaire azimuth angle ψ*-parallel (0°) perpendicular (90°) and at 45° to the luminaire axis. It is thus necessary to develop interpolation procedures for obtaining intensity values at other θ and ψ angles.

First degree polynomial interpolations, while easy to perform, are quite inaccurate. Second and third degree polynomial interpolations, on the other hand, have been widely used with good results. In this report we will use a second degree polynomial for ψ interpolations (since only three values of intensity are available for each θ) and a third degree polynomial for those in θ. For the ψ interpolation, we have

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*ϕ and ψ are not necessarily the same angles. ϕ is the azimuth angle at the task with respect to the viewing direction whereas ψ is the azimuth angle at the luminaire with respect to the luminaire axis. See Figure 1.

$$I_{(\theta)} = a_o + a_1\psi + a_2\psi^2 \tag{15}$$

where

$$a_o = I_o$$

$$a_1 = \frac{-3I_o + 4I_{45} - I_{90}}{90}$$

$$a_2 = \frac{I_o - 2I_{45} + I_{90}}{4050} \tag{16}$$

For each value of θ, this interpolation passes a parabola through the intensity values at $\Psi = 0°$, 45° and 90°, resulting in three coefficients which are then used to calculate I(θ) for the given value of Ψ. This interpolation is done prior to the θ interpolation, and must be repeated four times for each intensity determination, yielding intensity values labeled I_1, I_2, I_3 and I_4 at four consecutive θ angles, each Δθ apart with two on each side of the given θ value. The procedure is illustrated in Table 1 where it is desired to obtain the intensity at $\Psi = 56.9°$ and $\theta = 43.9°$. Here $\Delta\theta = 5°$ and it is necessary to perform the Ψ interpolation at θ = 35°, 40°, 45° and 50°. The resulting intensity values are $I_1 = 947$cd, $I_2 = 857$cd, $I_3 = 699$cd and $I_4 = 505$cd.

For the θ interpolation we have two cases, namely $\Delta\theta = 5°$ and $\Delta\theta = 10°$. The pertinent equations are:

for $\Delta\theta = 5°$

$$I\ (\psi,\theta) = A_o + A_1\ \theta' + A_2\ \theta'^2 + A_3\ \theta'^3 \tag{17}$$

Table 1: Illustrating Double Interpolation to Obtain $I(\psi,\theta)$

θ	$I_{o°}$	$I_{45°}$	$I_{56.9°}$	$I_{90°}$
35°	290	860	(I_1)947	1050
40°	260	780	(I_2)857	940
43.9°			(I) 738	
45°	220	650	(I_3)699	690
50°	180	490	(I_4)505	400

First Interpolation: $\psi = 56.9°$

θ	a_o	a_1	a_2	
35°	290	16.89	-.09383	I_1 = 947
40°	260	15.56	-.08889	I_2 = 857
45°	220	13.89	-.09630	I_3 = 699
50°	180	11.33	-.09877	I_4 = 505

Second Interpolation: $\theta = 43.9°$, $\theta' = 8.9°$

θ	A_o	A_1	A_2	A_3	I
43.9°	947	-9.067	-2.000	.0427	738

$$A_0 = I_1$$

$$A_1 = \frac{-11I_1 + 18I_2 - 9I_3 + 2I_4}{30} \qquad (18)$$

$$A_2 = \frac{2I_1 - 5I_2 + 4I_3 - I_4}{50}$$

$$A_3 = \frac{-I_1 + 3I_2 - 3I_3 + I_4}{750}$$

and for $\Delta\theta = 10°$

$$I\ (\psi,\ \theta) = A'_o + A'_1\theta' + A'_2\theta'^2 + A'_3\theta'^3 \qquad (19)$$

where $A'_o = A_o,\ A'_1 = 1/2\ A_1$

$$A'_2 = 1/4\ A_2,\ A'_3 = 1/8\ A_3 \qquad (20)$$

The use of θ' requires explanation. To avoid large numbers in the calculation of $I(\Psi,\ \theta)$, it is necessary to shift the $\theta = 0°$ axis to the value of θ at I_1. Thus in the example, $\theta' = 0$ at $\theta = 35°$. This yields values of θ' between 5° and 10° for $\Delta\theta =$ 5° and between 10° and 20° for $\Delta\theta = 10°$ in Equations 17 and 19, respectively. Referring again to Table 1, for $\theta = 43.9°$, $\theta' = 8.9°$ (43.9 - 35).

C. Approximating Equations for Bidirectional Luminance Factors

There is a confusion in the literature over what the visual task actually is in the definition of contrast. The Illuminating Engineering Society Handbook (1) uses the word "object" and defines luminance contrast in terms of object and background luminances. RQQ5(3), on the other hand, chooses to use flux contrast, and defines this quantity in terms of "target" and background luminances. One might logically assume that the words "object" and "target" mean the same thing, and thus conclude that luminance contrast and flux contrast are identical. Such is not the case however, for by "target", RQQ5 states that it means the task detail and its very immediate background.

The bidirectional luminance factors for the concentric ring pencil task[5] are based on flux contrast, rather than luminance contrast. Specifically the authors (5) state " . . . task detail consisting of concentric pencil rings and paper spaces . . . ". The same general statement appears in RQQ5.

It is not our purpose here to debate the merits of the two definitions of contrast, although they should be debated. Rather it is our purpose to inform the reader that the only bidirectional luminance factors available are for the pencil task under the conditions stated, that these are being used by others in calculating CRF and ESI, and that they will be used in the computational procedure presented in this report.

Values of B_t and B_b, including polarization effects, are available in the literature in tabular form[3,5]. The perpendicular and parallel polarized values have been averaged and plotted for the 25° viewing angle and are shown in Figures 3 and 4.

In order to permit calculations of CRF on a programmable hand calculator, it was necessary to develop approximating equations for B_t and B_b.* Several mathematical models were tried and evaluated for a least squares fit to the data. Ultimately a third degree polynomial in $\ell n\ \theta$, including a ϕ variation proportional to $\sqrt{\phi}$, was chosen.

$$B = k + (a_o + a_1\sqrt{\phi})\ \ell n\theta + (b_o + b_1\sqrt{\phi})\ (\ell n\theta)^2 + (c_o + c_1\sqrt{\phi})\ (\ell n\theta)^3 \qquad (21)$$

*These were derived by J. R. Rosenblatt and D. M. Maxwell of the Statistical Engineering Section, National Bureau of Standards.

Values of the constants in this equation were derived for the standard concentric ring pencil task and its background, using a least squares curve fitting computer program. The results are:

	Task	Background
k	.73586	.85206
a_o	-.21398	-.12521
a_1	.014979	.0059725
b_o	.18815	.10455
b_1	-.013542	-.0053031
c_o	-.030878	-.014888
c_1	.0020351	.000524257

Equation (21) and the coefficients above are used to obtain B_t and B_b values for each source element location. They yield B values within a magnitude of .05 of the published data for all values of θ and ϕ except the following:

Task

$\phi = 0°$ and $10° < \theta < 15°$, $45° < \theta < 90°$

$\theta = 30°$ and $10° < \phi < 20°$ (22)

Background

$\phi = 0°$ and $\theta = 15°$, $45° < \theta < 90°$

$\theta = 85°$ and $110° < \phi < 135°$

The maximum error in B_t is .07; in B_b .10, the latter occurring at $\theta = 85°$ (a relatively unimportant angle).

D. Inverse Square Law Approximations

If Equation (7) is multiplied by the appropriate bidirectional luminance factor, we obtain the luminance of the task or its background

$$L_i = \frac{I_i(\phi,\theta)\ B_i(\phi,\theta)\ \cos^3\theta_i}{h^2} \tag{23}$$

where B_{ti} is used if task luminance L_{ti} is desired and B_{bi} for L_{bi}.

In using Equation (23) it is important to choose luminaire element size small enough so that I_i, B_i and θ_i do not vary significantly over the element surface. RQQ5(3) suggests that to accomplish this the angles δ_1 and δ_2 in Figure 5 should not exceed 10°.

The angles used in this study to describe the location of a source element are not taken in the planes of δ_1 and δ_2. Rather, as previously discussed, ϕ and θ are used, as shown in Figure 1. The reasons for choosing ϕ and θ are several:

1) They are more physically meaningful.
2) Luminaire intensity distributions are given in terms of these angles.
3) Bidirectional luminance factors are given in terms of these angles.
4) Cosine correction of the Inverse Square Law is done in terms of one of these angles (θ).

The choice of angles having been made, the next problem is to determine acceptable luminaire element sizes and relate them to the chosen angles. Luminaires can be placed in three general categories, namely points, strips and rectangles. A point luminaire is one whose largest source dimension may be considered small with respect to the distance of the source from the task. As a practical matter, in offices and schools, sources 18 inches (45 cm) or less in maximum source dimension may be considered as points, permitting the entire source to be considered as a single element.

A strip luminaire is one having one dimension small (less than 18 inches) with respect to the distance from source to task, but not the other. Rows of fluorescent lamps fall into this category. For a strip luminaire, it is necessary to divide the luminaire into elemental lengths such that each element may be considered a point luminaire. Figures 6 and 7 illustrate how this should be done for a typical mounting height above the work plane of h = 7 ft (2.13 m). Figure 6 presents the situation when the rows of luminaires are parallel to the viewing direction; Figure 7 when they are perpendicular.

Before describing the rationale behind Figures 6 and 7, let us discuss how to use them. Assume a row of fluorescent luminaires parallel to the viewing direction and located at x = 0 (directly over the task). Figure 6 shows the luminaire element lengths that would be used. The first element in the + y direction is 1.2 ft (.37 m) in length. Successive elements are 1.3 ft (.40 m), 1.5 ft (.46 m), 1.8 ft (.55 m), 2.2 ft (.67 m), 4 ft (1.22 m) and 8 ft (2.44 m) long. In the -y direction, the sizes are the same but we stop at y = -2.5 ft (-.76 m) because the body shadow blocks elements beyond that point. If we now consider a row at x = 8 ft (2.44 m), longer elements can be used because the row is farther from the task. Thus less elements are needed - two 4-ft (1.22-m) elements and one 8-ft (2.44-m) element in the +y direction and three 4-ft (1.22-m) elements in the -y direction. If there were a row at x = 5 ft (1.52 m), we could use the element lengths for either x = 4 ft (1.22 m) or 6 ft (1.83 m) but would probably choose the former to be a bit more accurate.

Next let us turn 90° so that we are facing the rows. Figure 7 applies and we again read off the element lengths for each row of luminaires present. The element lengths are symmetrical about the y axis; therefore we need consider only those for +x and eventually weight each of them by a factor of 2.

Figures 6 and 7 were developed from the following guidelines: First, element lengths were chosen to fit the customary 4-ft (1.22-m) luminaire (there is no element extending between, say, y = 6 ft (1.83 m) and y = 10 ft (3.05 m). Second a row was placed directly over the task and parallel to the direction of viewing. The elements in such a row have no variation with ϕ, except in switching from $\phi = 0°$ in front of the task to $\phi = 180°$ behind it. Element lengths in this row were chosen so that $\Delta\theta \approx 10°$ for each element when h = 7 ft (2.13 m). For example, the element between y = 4 ft (1.22 m) and y = 5.8 ft (1.77 m) has θ values of 29.7° and 39.6°, giving $\Delta\theta = 9.9°$.* Third, it was decided that the change in B_t in traversing an element should be no more than .10 (the change in B_t is greater than the change in B_b for the same change in θ or ϕ). An examination of the overhead row, with the element lengths chosen as indicated, shows that ΔB_t meets this criterion (when the overhead row is turned 90°, changes in B_t are less and the criterion is easily met). Fourth, rows displaced at intervals of 2 ft (.61 m) from the overhead row were examined. For each row, the $\Delta\theta$ and ΔB_t criteria were imposed in selecting element lengths. In addition, $\Delta\phi$ (the change in azimuth angle) was limited to $\approx$ 22.5°.** This seems justifiable when it is realized that

*7 ft (2.13 m) was chosen as an "average" mounting height above the work plane for offices. For a given element size and location, as h increases, $\Delta\theta$ decreases.

**One value of $\Delta\phi$ for d = 2 ft (.61 m) exceeds this limit, but $\Delta\theta$ and ΔB_t are very small for this particular element.

published intensity distribution curves are generally given in only three azimuth planes separated by 45°.

We turn now to the rectangular luminaire and define it as one in which neither luminaire dimension is small compared with the distance from luminaire to task. Such a luminaire must be broken into rectangular elements, in much the same fashion and using the same criteria as in the strip luminaire case. The results, for a 3 ft (.91 m) by 3 ft (.91 m) luminaire are shown in Figure 8, again based on a 7-ft (2.1 m) mounting height. In that figure, each square luminaire is divided into 1, 2, 4 or 6 parts, depending on its distance from the task. For example, a 3 x 3 square luminaire centered at x = 4 ft (1.22 m) and y = 5 ft. (1.52 m) should be represented by four square elements, each 1.5 ft (.46 m) on a side. A luminaire centered at x = 2 ft (.61 m) and y = o should be represented by six rectangular elements, each 1 ft (.30 m) by 1.5 ft (.46 m).

IV. Calculation Procedure

In this section, a systematic procedure for computing the direct components of CRF and ESI for the concentric ring pencil task using a card-programmable hand calculator is presented. The procedure may be outlined as follows: First, the room layout is drawn and task and luminaire location are noted on an xy grid. Second, each luminaire is divided into one or more elements, according to the guidelines in Section IV and Figures 6 through 8. Third, the angular locations (polar and azimuth) of the center of each element are calculated and, from these, the luminous intensity of each element in the direction of the task is obtained. Fourth, bidirectional luminance factors are calculated for the task and its background for each element. Fifth, the illuminance on the task produced by each element is calculated and the results summed to obtain overall illuminance. Sixth, task and background luminances produced by each element are obtained, and these are summed to obtain overall task luminance and background luminance. Seventh, the direct components of contrast rendition factor (CRF) and equivalent sphere illumination (ESI) for the pencil task are calculated.

The procedure will now be presented in a step-by-step manner in six parts, a preliminary part and a part for each of the five program cards necessary for its execution. The actual programs and user instructions will be presented in Section V.

A. Preliminary Steps

1) Sketch a top view of the room layout to approximate scale, showing luminaire and task locations (an example of a typical room and luminaire layout is shown in Figure 9). Orient the diagram so that the viewing direction is toward the top of the page. Draw an xy coordinate system on the layout, with +y in the direction of viewing, +x to the right, and the task at the origin (o, o).

2) Divide each strip and square luminaire into elements according to Figures 6 through 8. Give each element a number designation and each strip and square luminaire a letter designation. Refer to Figure 9 for an example of dividing, lettering and numbering. For example, in that figure, elements 1 through 7 are 2.5 ft (.76 m), 1.5 ft (.46 m), 1.8 ft (.55 m), 2.2 ft (.67 m), 4 ft (1.22 m) and 8 ft (2.44 m) long, respectively, as obtained from Figure 6. Note symmetry about the viewing direction and identify those elements, and entire luminaires, that will produce equal luminances at the task. For example, corresponding elements

Table 2

Intensity Worksheet

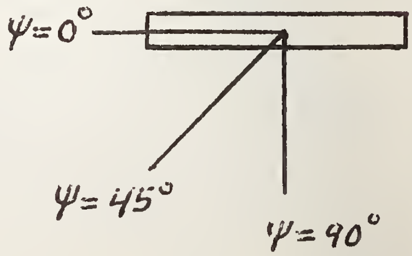
θ in deg. $\Delta\theta = 5^{o}$	θ in deg. $\Delta\theta = 10^{o}$	θ row No. n	Symmetric: I_{o} or I_{90}	Asymmetric: Intensity Format I_{o} I_{45} I_{90}
5	15	1		.
0	5	2		.
5	5	3		.
10	15	4		.
15	25	5		.
20	35	6		.
25	45	7		.
30	55	8		.
35	65	9		.
40	75	10		.
45	85	11		.
50	95	12		.
55	105	13		.
60		14		.
65		15		.
70		16		.
75		17		.

Luminaire Description:

____

____

____



in rows A and A' in Figure 9 produce identical luminances in the calculations and the luminances it produces doubled. Also, use Figure 2 or Figures 6 through 8 to ascertain those elements shielded from the task by the viewer. Omit such elements from further consideration.

3) Use the luminaire manufacturer's intensity data to fill out the Intensity Worksheet in Table 2. In that table, I_o is the intensity distribution in a vertical plane along the luminaire axis, I_{90} perpendicular to the luminaire axis, and I_{45} midway between.

If the luminaire is symmetric (no variation of intensity with azimuth angle), it is necessary to fill in only one I value for each θ. The symmetric column in Table 2 is used for this purpose. For an asymmetric luminaire, the intensity format column must be completed. The only exception to this latter statement is when a row of asymmetric luminaires passes directly over the task location so that the intensity is always either I_o or I_{90}. Then I_o values are inserted into the symmetric column if the row is parallel to the direction of viewing and I_{90} values if it is perpendicular to it.

Manufacturer's intensity data is given in either 5° or 10° increments in polar angle θ, and the appropriate Δθ column should be noted in Table 2. Each row of intensity data is given a row number n so that it may be readily identified by the calculator.

There are 17 entries* for each intensity distribution curve (some entries appear twice in each column because of the manner in which interpolations are done for small values of θ). Each entry in the intensity

*Because of calculator storage limitations, intensity data for θ > 75° (Δθ = 5°) are excluded. This limitation is minor.

format column must be of the form xxx.xxxxxx so that all intensity data may be stored at one time in the calculator. Also each intensity value must be less than 10,000c. The first three x's represent the value of $I_o/10$ rounded to the nearest 10 candelas. Thus, an intensity of 4876 candelas would be entered as 488; an intensity of 876 candelas as 088. Next, a decimal point is inserted, followed by three x's representing the value of $I_{45}/10$ to the nearest 10 candelas and, lastly, by three x's representing $I_{90}/10$ to the nearest 10 candelas. No decimal point is used between these last two entries.

As an example, suppose I_o = 3756cd, I_{45} = 976cd and I_{90} = 85cd for a particular value of θ. Then the entry in the intensity format column is 376.098009.

The reader should note that the 3-digit representation of intensity is used only when completing the intensity format column for asymmetric luminaires. Actual values of intensity should be used when completing the symmetric luminaire column.

4) Complete the top portion of the CRF-ESI Work Sheet for the Direct Component in Table 3. As before, h is the mounting height of the luminaires above the work plane, the latter being generally 30 inches above the floor. Δθ is either 5° or 10°. Viewing direction can be indicated by a compass direction. Row orientation (p), if rows are present, is either parallel or perpendicular to the viewing direction.*

   Row or luminaire letters are inserted according to the labeling in Step 2. For example, if the first six elements are in a square

*The procedure does not accommodate oblique viewing of rows.

Table 3

CRF-ESI Work Sheet for Direct Component

Room Location ____________ h = ____________

Luminaire ____________ $\Delta\theta$ = ____________

Lamp ____________ Viewing Direction ____________

Task Location ____________ Row Orientation (p) ____________

Row or Luminaire Letter														
			Source Element Number											
Program	Step No.	Quantity												
1	1	x_e												
	2	y_e												
	3	$\|\phi\|$												
	4	θ												
	5	Element Scaling Factor m												
	6	ψ												
2	7	θ Row Number n												
	8	$I_1(\theta)$												
	9	$I_2(\theta)$												
	10	$I_3(\theta)$												
	11	$I_4(\theta)$												
3	12	Scaled $I(\phi,\theta)$												

Row or Luminaire Letter															
			Source Element Number												
Program	Step No.	Quantity													
4	13	B_{ti}													
	14	B_{bi}													
5	15	Duplicate Element d Multiplier													
	16	ΣEi													
	17	ΣL_{ti}													
	18	ΣL_{bi}													
	19	CRF													
	20	ESI													
	21	LEF													

Table 4

Centers and Lengths of Strip Elements in ft (m)

If a Strip Element Lies Between			Its Length is	Its Center is Located at
0	and	1.2 (.37)	1.2 (.37)	.6 (.18)
1.2 (.37)	and	2.5 (.76)	1.3 (.40)	1.85 (.56)
2.5 (.76)	and	4 (1.22)	1.5 (.46)	3.25 (.99)
4 (1.22)	and	5.8 (1.77)	1.8 (.55)	4.9 (1.49)
5.8 (1.77)	and	8 (2.44)	2.2 (.67)	6.9 (2.10)
8 (2.44)	and	12 (3.66)	4 (1.22)	10 (3.05)
12 (3.66)	and	20 (6.10)	8 (2.44)	16 (4.88)

or strip luminaire A, insert the letter A in the rectangular space above elements 1-6, and place a vertical line in the space between elements 6 and 7.

B. Program 1

1) Using the luminaire location layout from Step A1, enter an x_e and y_e value in Table 3, rows 1 and 2, for each luminaire element, where x_e (y_e) is the distance perpendicular (parallel) to the viewing direction from the task to the center of the luminaire element. In entering x_e and y_e, be sure to include the sign of each. Centers and lengths of elements for strip luminaires are presented in Table 4 to assist in making these entries.

2) Program Card 1 is read into the calculator, the value of h is entered, and the values of x_e and y_e for each luminaire element are inserted. The program computes values for $|\phi|$, θ, m, and ψ for each luminaire element, prints these (if a printer is used) and shows them in the calculator display. These values should be inserted in Table 3 in rows 3 through 6. ϕ ranges from 0° to $\pm$ 180° but because of symmetry, only the magnitude of ϕ ($|\phi|$) is required, and this is calculated from

$$|\phi| = 180 - \left|\tan^{-1} \frac{x}{y}\right| \qquad \text{for } y- \qquad (24)$$

$$|\phi| = \left|\tan^{-1} \frac{x}{y}\right| \qquad \text{for } y+ \qquad (25)$$

θ is obtained from

$$\theta = \tan^{-1} \frac{\sqrt{x^2 + y^2}}{h} \qquad (26)$$

The parameter m is the element scaling factor, and is required because manufacturers' intensity distribution curves are given for entire luminaires. There are three situations to consider. In the rectangular luminaire case, the user inserts the number of subdivisions (1, 2, 4 or 6) into the calculator and obtains an element scaling factor of 1, .5, .25 or .167. For rows, the basic unit is 4 ft (1.22 m). The user inserts $\Delta\ell$, the luminaire element length, in ft and obtains the scaling factor as $\Delta\ell/4$. For point sources, the entire luminaire is always used and m = 1.

The fourth quantity computed is ψ, the angle at the source. As stated earlier, Ψ and ϕ are not necessarily the same, the former being related to the source and the latter to the task. (Refer again to Figure 1 and the diagram in Table 2). It is necessary to calculate ψ only when the source is asymmetric. The following cases exist:

	$\lvert\phi\rvert < 90°$	$\lvert\phi\rvert > 90°$
Luminaire axis parallel to viewing direction	$\psi = \lvert\phi\rvert$	$\psi = 180° - \lvert\phi\rvert$
Luminaire axis perpendicular to viewing direction	$\psi = 90° - \lvert\phi\rvert$	$\psi = \lvert\phi\rvert - 90°$

The calculator program makes these distinctions after it is given a value for "p", the row orientation factor (p=o if the rows are parallel to the viewing direction and p=1 if they are perpendicular to it).

A final feature of Program Card 1 is that it permits a calculation of body shadow factor if the user so desires. If the user has any doubt after consulting Figure 2 as to whether or not a certain luminaire element is shielded, he can ask the calculator to check. A 1 will appear if the center of the luminaire element is not shielded from the task, a 0 if it is.

C. Program 2

In Programs 2 and 3, intensity as a function of the angles (ψ, θ) is computed for each luminaire element. This is done through a single interpolation in θ if the luminaire is symmetric or if $\psi = 0°$ or $90°$ and through a double interpolation in ψ and θ for all other conditions. In the former case, the user omits Program Card 2 and goes directly to Program Card 3. In the latter case, Program Card 2 must be used first.

As mentioned earlier, interpolation in the ψ dimension is done by passing a parabola through the intensity values at $\psi = 0°$, $45°$ and $90°$ and calculating $I(\theta)$ for each of four consecutive values of θ. The user first places the appropriate θ row number n, obtained from Table 2, into row 7 of Table 3. n is the number of the row in which the first intensity interpolation (I_1) is done (in the example in Table 1, n is 9, corresponding to $\theta = 35°$). He then reads Program Card 2 into the calculator and inserts the intensity data from the format column in Table 2 and the values of ψ and n from Table 3. With these values in storage, the calculator computes I_1, I_2, I_3 and I_4, the intensities for the four consecutive θ values. These values are either available from the printer or may be observed directly in the calculator display. In either case, the user should place the four intensities in rows 8 through 11 in Table 3.

When Program 2 is omitted (for symmetric luminaires and overhead rows of asymmetric luminaires), the appropriate values of I_o or I_{90} from the symmetric column in Table 2 should be inserted in rows 8 through 11 of Table 3.

D. Program 3

Program 3 completes the double interpolation begun in Program 2 for asymmetric luminaires or conducts the single interpolation required for symmetric luminaires.

After reading Program Card 3 into the calculator, the user inserts a 0 or a 1 to indicate that the increment in θ is either 5° or 10°. He then inserts θ, m, n,* I_1, I_2, I_3 and I_4, in that order, and the calculator computes $I(\phi, \theta)$ scaled by the element scaling factor m. This value is printed and also appears in the calculator display. It should be inserted in row 12 of Table 3. The unscaled value of $I(\phi, \theta)$ is also printed, to provide a check for the user that his I value is reasonable in terms of the values of I_1 through I_4. The procedure is then repeated for each luminaire element.

E. Program 4

In Program 4, bidirectional luminance factors for the concentric ring pencil task and its background are calculated using the log cubic Equation (22). The user reads in Program Card 4, inserts the values of $|\phi|$ and θ from Table 3, and the calculator computes B_t and B_b for each luminaire element, printing and displaying each.

It should be stressed that Program 4 is applicable only to the concentric ring pencil task. However, if bidirectional luminance factor data for other tasks should become available, the program could be altered easily to accommodate them.

F. Program 5

All factors necessary for the calculation of the direct components of CRF and ESI have now been assembled except the duplicate element multiplying factor, d. Recall that in Step A2 the user was instructed to observe symmetry and note those luminaires and luminaire elements which produce

*If Program 2 was skipped, values of n should be inserted in row 7 of Table 3 prior to this step.

identical luminances at the task. In row 15 of Table 3, the user should now insert a 2 if that element's contribution is to be doubled and a 0 if it is not, making that wherever a 2 is inserted, that element's mate is not included in the calculations. Then Program Card 5 is read into the calculator, h is inserted, and θ, I, B_t, B_b and d for each luminaire element are entered, one set at a time. The calculator then computes and displays a running total of task illuminance (ΣE_i), task luminance (ΔL_{ti}) and background luminance (ΣL_{bi}). ΣE_i is also printed. These values are entered in rows 16, 17 and 18 in Table 3. Thus, the entries in column k of these rows in Table 3 give the total illuminance and luminances produced by the first k luminaire elements. If it is desired to know the contribution of luminaire element k to the illuminance and luminances, the values of these quantities in column k-1 are subtracted from those in column k.

The entries in rows, 16, 17 and 18 for the last luminaire element give the direct components of illuminance and luminances for the entire installation. Then the calculator computes and displays the direct components of CRF, ESI and LEF. It also prints these quantities, as well as the values of C, RCS, and RCS_e.

V. Calculator Program and User Instructions

A. Introduction

A Texas Instruments' SR-52 card programmable hand calculator was used in this study, but any other similar calculator would also suffice. This calculator has 224 program storage locations, 20 data storage locations and 10 user-defined labels. It is not our purpose here to describe in detail the SR-52 or any other calculator. Rather our aim is to provide sufficient information about the SR-52 so that the user can execute the five programs described in Section IV. For further details about this or other calculators, the user should consult the appropriate instruction manual.

B. Reading a Card

At Step B1 in Section V, the first program card must be read into the calculator. To do this, first press the CLR button; then press the 2ND button and the READ button and insert the program card into the lower slot on the right side of the calculator, with end A towards the calculator. The calculator motor should carry the card through to the opposite side. Next press 2ND and READ again and insert the card with end B towards the calculator. Again it should pass through. The program is now in the calculator memory and the card may be returned to its case.

C. User-Defined Labels

In order for the user to enter data into the calculator, he must be able to tell the calculator not only the data to be entered but where to go in the program to do the entering. The 10 user-defined labels, A through E and A' through E' provide this latter feature. The second set of these (primed letters) requires the user to press the 2ND button and then the letter button, much as the shift key on a typewriter causes the upper characters to be printed. Generally, an asterisk (*) is used in place of 2ND in programming instructions.

Suppose a quantity 17.6 is to be entered using label A. The user would press five buttons, namely 1, 7, ., 6, A to accomplish this. To place the entry in *A' requires six presses -- 1, 7, ., 6, 2ND, A.

Quite often labels are used to start a calculation, rather than to insert data. If so, only the buttons A or *A', for example, are pressed.

D. Readout

There are two means by which readout is accomplished, namely through the display register and through an auxiliary printer. Halt statements occur throughout the programs so that the final result of a calculation appears in the display register. The auxiliary printer, if used, will also provide the final answer, in printed form. In addition, it will provide certain intermediate answers which the calculator and its display pass by in traveling to the final answer. These printed intermediate answers are not essential to have but are useful in checking results. To repeat, the printer is not essential in carrying out the calculations, but it is convenient to have.

E. Initialization

Each of the five programs begins with an initialization instruction which is executed simply by pressing the E button. The purpose of this is to insure that the data storage and display locations (registers) are cleared before new calculations begin. Pressing E does not affect the program storage locations.

F. Inserting a Minus Number

A negative number is inserted into the calculator by first inserting the positive value of the number and then pressing the +/- button.

G. Instructions and Programs

User instructions for the five programs are given in Table 5. The instructions must be carried out in the order given, unless otherwise indicated. After entering an instruction, the user must wait until the calculator stops, as indicated by a steady display, before entering the next instruction.

Table 5 - User Instructions

Program 1

Entry	Label	Display	Print
	E	0	
h	*A'	h	
x_e	A	x_e	
y_e	B	y_e	
	C	$\|\phi\|$	$\|\phi\|$
	D	θ	θ
6,4,2 or 1	*B'	m	m
$\Delta\ell$	*C'	m	m
p(0 or 1)	*D'	ψ	ψ
	*E'	S	1 or 0

Comments

1. Pressing E clears display and data storage registers.

2. h need only be inserted once at the outset.

3. In computing m, *B' is used for square luminaires, *C' for strip luminaires.

4. In computing ψ, a 0 is inserted if luminaires are parallel to the viewing direction, a 1 if they are perpendicular. ψ need not be computed for symmetric luminaires.

5. S is an optional calculation, but cannot be done until $|\phi|$ and θ are calculated. A 0 is displayed if the viewer shields the center of the luminaire element from the task, a 1 if he does not.

Table 5 (Cont.)

Program 2

Entry	Label	Display	Print
	E	1	
xxx.xxxxxx	A	2	first I entry
xxx.xxxxxx	A	3	second I entry
.	.	.	.
.	.	.	.
.	.	.	.
xxx.xxxxxx	A	18	last I entry
ψ	B	4	
n	C	n	
	D	1	$I_1(\theta)$, $I_2(\theta)$, $I_3(\theta)$, $I_4(\theta)$
	*A'	$I_1(\theta)$	
	*B'	$I_2(\theta)$	
	*C'	$I_3(\theta)$	
	*D'	$I_4(\theta)$	

Comments

1. Pressing E clears the display register but not the data storage register. Do not press E again after the first initialization or A again after the I entries have been inserted.

2. If an error is made in an I entry prior to pressing A, press CLR and redo the I entry. If an error is made in an I entry and A has been pressed, press k STO98, where k is one less than the number in the display and then redo the I entry and push A.

3. *A', *B', *C', and *D' need not be pressed if a printer is used. Correct keying sequence in this case is EABCDBCD... .

Table 5 (Cont.)

Program 3

Entry	Label	Display	Print
	E	1	
$\Delta\theta$ (0 or 1)	A	0 or 1	
θ	B	1	
m	B	1	
n	B	1	
$I_1(\theta)$	B	1	
$I_2(\theta)$	B	1	
$I_3(\theta)$	B	1	
$I_4(\theta)$	B	1	
	C	scaled I (ϕ, θ)	θ', $I(\phi, \theta)$, scaled $I(\phi, \theta)$

Comments

1. Pressing E clears display and data storage registers.

2. Entry at A is 0 if $\Delta\theta = 5°$ and 1 if $\Delta\theta = 10°$. This is done only once.

3. Entry at B is seven items, in the order given, for each luminaire element. If an error is made in an entry prior to pressing B, press CLR and redo the entry. If an error is made in an entry and B is pressed, press k STO19 where k is the number (1-7) of the incorrect entry. Then redo the entry and press B.

3. Printer shows θ' (the transformed value of θ for calculation purposes), the unscaled value of $I_{(\phi, \theta)}$ and the value of $I_{(\phi, \theta)}$ after multiplication by m.

Table 5 (Cont.)

Program 4

Entry	Label	Display	Print
	E	0	
$\|\phi\|$	A	$\|\phi\|$	
θ	B	θ	
	C	B_t	B_t
	D	B_b	B_b

Comments

1. Pressing E clears display and data storage registers.

Table 5 (Cont.)

Program 5

Entry	Label	Display	Print
	E	0	
h	*E'	h	
θ	A	1	
$I(\phi, \theta)$	A	1	
B_t	A	1	
B_b	A	1	
d (0 or 2)	A	1	
	B	ΣE_i	ΣE_i
	C	ΣL_{ti}	
	D	ΣL_{bi}	
	*A'	CRF	C, CRF
	*B'	ESI	RCS, RCS_e, ESI
	*C'	LEF	LEF

Comments

1. Pressing E clears display and data storage registers.

2. h should be entered once at the outset.

3. θ, $I(\phi, \theta)$, B_t, B_b and d must be entered in order. If an error is made in an entry before A is pressed, press CLR and redo the entry. If an error is made in an entry and A is pressed, press k ST019, where k is the number (0-4) of the incorrect entry. Then redo the entry.

4. d is 0 if the luminaire element under consideration at x, y does not have a counterpart at -x, y. It is 2 if it does.

5. ΣL_{ti} and ΣL_{bi} may not be computed until ΣE_i is found.

6. Normally, calculations of ΣE_i, ΣL_{ti} and ΣL_{bi} are completed before *A' is pressed to obtain CRF. Then *B' may be pressed to obtain ESI and *C' to obtain LEF, if desired. However, if the user wishes, intermediate values of CRF and ESI may be obtained by pressing *A' and *B' earlier. This allows the user to obtain the CRF due to a single row of luminaires, for example.

7. After calculations of overall CRF and ESI are completed, intermediate values of ΣE_i, ΣL_{ti} and ΣL_{bi} may be stored by the user and then used to calculate intermediate values of CRF and ESI. For ΣE_i, enter its value and then press ST007. For ΣL_{ti}, enter its value and press ST009; for ΣL_{bi} enter its value and press ST011.

Table 6
Program 1

000	46	050	08	100	98	150	05
001	16	051	00	101	81	151	75
002	42	052	75	102	46	152	01
003	00	053	43	103	18	153	08
004	01	054	01	104	55	154	95
005	81	055	00	105	04	155	80
006	46	056	95	106	95	156	68
007	11	057	42	107	98	157	01
008	42	058	01	108	81	158	81
009	00	059	01	109	46	159	46
010	03	060	98	110	10	160	68
011	81	061	81	111	43	161	00
012	46	062	46	112	01	162	81
013	12	063	87	113	01	163	46
014	42	064	43	114	75	164	15
015	00	065	01	115	01	165	25
016	04	066	00	116	06	166	47
017	81	067	42	117	05	167	81
018	46	068	01	118	95	168	46
019	13	069	01	119	80	169	19
020	43	070	98	120	78	170	90
021	00	071	81	121	85	171	69
022	03	072	46	122	02	172	09
023	55	073	14	123	00	173	00
024	53	074	43	124	95	174	75
025	43	075	00	125	80	175	43
026	00	076	04	126	79	176	01
027	04	077	40	127	01	177	00
028	85	078	85	128	81	178	95
029	93	079	43	129	46	179	98
030	00	080	00	130	79	180	99
031	01	081	03	131	43	181	81
032	54	082	40	132	00	182	46
033	95	083	95	133	05	183	69
034	22	084	30	134	75	184	43
035	34	085	55	135	05	185	01
036	80	086	43	136	02	186	00
037	77	087	00	137	95	187	98
038	94	088	01	138	80	188	99
039	46	089	95	139	67	189	81
040	77	090	22	140	01	190	00
041	42	091	34	141	81	191	00
042	01	092	42	142	46	192	00
043	00	093	00	143	78	193	00
044	43	094	05	144	00	194	00
045	00	095	98	145	81	195	00
046	04	096	81	146	46	196	00
047	80	097	46	147	78	197	00
048	87	098	17	148	43	198	00
049	01	099	20	149	00	199	00

TABLE 6

Program 2

000	46	050	00	100	95	150	06	200	46
001	11	051	52	101	42	151	05	201	18
002	98	052	22	102	06	152	43	202	43
003	36	053	52	103	03	153	06	203	06
004	42	054	42	104	01	154	09	204	08
005	09	055	06	105	44	155	65	205	81
006	08	056	09	106	01	156	01	206	46
007	01	057	22	107	09	157	00	207	19
008	44	058	57	108	04	158	85	208	43
009	09	059	94	109	65	159	43	209	06
010	08	060	85	110	43	160	06	210	09
011	43	061	36	111	06	161	04	211	81
012	09	062	43	112	02	162	65	212	46
013	08	063	01	113	75	163	43	213	15
014	81	064	09	114	03	164	01	214	25
015	46	065	95	115	65	165	08	215	01
016	12	066	65	116	43	166	85	216	42
017	42	067	01	117	06	167	43	217	09
018	01	068	00	118	09	168	06	218	08
019	08	069	00	119	75	169	05	219	81
020	06	070	00	120	43	170	65	220	00
021	06	071	95	121	06	171	43	221	00
022	42	072	42	122	03	172	01	222	00
023	09	073	09	123	95	173	08		
024	08	074	09	124	55	174	40		
025	04	075	75	125	09	175	95		
026	42	076	93	126	95	176	98		
027	00	077	05	127	42	177	36		
028	00	078	95	128	06	178	42		
029	99	079	57	129	04	179	09		
030	81	080	00	130	43	180	08		
031	46	081	52	131	06	181	01		
032	13	082	22	132	09	182	44		
033	42	083	52	133	75	183	09		
034	01	084	42	134	02	184	08		
035	09	085	06	135	65	185	58		
036	81	086	02	136	43	186	87		
037	46	087	22	137	06	187	81		
038	14	088	57	138	02	188	46		
039	46	089	94	139	85	189	16		
040	87	090	85	140	43	190	43		
041	36	091	43	141	06	191	06		
042	43	092	09	142	03	192	06		
043	01	093	09	143	95	193	81		
044	09	094	95	144	55	194	46		
045	75	095	65	145	04	195	17		
046	93	096	01	146	00	196	43		
047	05	097	00	147	05	197	06		
048	95	098	00	148	95	198	07		
049	57	099	00	149	42	199	81		

TABLE 6

Program 3

000	46	050	55	100	08	150	43	200	46
001	15	051	03	101	90	151	00	201	17
002	25	052	00	102	87	152	03	202	43
003	47	053	95	103	02	153	75	203	00
004	01	054	42	104	22	154	02	204	04
005	42	055	00	105	49	155	54	205	56
006	01	056	09	106	00	156	95	206	46
007	09	057	02	107	09	157	98	207	18
008	81	058	65	108	04	158	42	208	43
009	46	059	17	109	22	159	01	209	00
010	11	060	75	110	49	160	02	210	05
011	42	061	05	111	01	161	46	211	56
012	00	062	65	112	00	162	88	212	46
013	08	063	18	113	08	163	45	213	19
014	81	064	85	114	22	164	03	214	43
015	46	065	04	115	49	165	65	215	00
016	12	066	65	116	01	166	43	216	06
017	36	067	19	117	01	167	01	217	56
018	42	068	75	118	43	168	01	218	46
019	01	069	10	119	00	169	85	219	10
020	09	070	95	120	01	170	43	220	43
021	01	071	55	121	75	171	01	221	00
022	44	072	05	122	01	172	02	222	07
023	01	073	00	123	00	173	40	223	56
024	09	074	95	124	65	174	65		
025	81	075	42	125	53	175	43		
026	46	076	01	126	43	176	01		
027	13	077	00	127	00	177	00		
028	01	078	10	128	03	178	85		
029	42	079	75	129	75	179	43		
030	01	080	03	130	02	180	01		
031	09	081	65	131	93	181	02		
032	02	082	19	132	05	182	65		
033	65	083	85	133	54	183	43		
034	10	084	03	134	95	184	00		
035	75	085	65	135	98	185	09		
036	09	086	18	136	42	186	85		
037	65	087	75	137	01	187	43		
038	19	088	17	138	02	188	00		
039	85	089	95	139	41	189	04		
040	01	090	55	140	88	190	95		
041	08	091	07	141	46	191	98		
042	65	092	05	142	87	192	65		
043	18	093	00	143	43	193	43		
044	75	094	95	144	00	194	00		
045	01	095	42	145	01	195	02		
046	01	096	01	146	75	196	95		
047	65	097	01	147	05	197	98		
048	17	098	43	148	65	198	99		
049	95	099	00	149	53	199	81		

Table 6
Program 4

000	46	050	93	100	03	150	75	200	02
001	11	051	00	101	85	151	93	201	23
002	42	052	01	102	93	152	00	202	45
003	00	053	03	103	07	153	00	203	03
004	01	054	05	104	03	154	05	204	85
005	81	055	04	105	05	155	03	205	93
006	46	056	02	106	08	156	00	206	08
007	12	057	65	107	06	157	03	207	05
008	42	058	43	108	95	158	01	208	02
009	00	059	00	109	99	159	65	209	00
010	02	060	01	110	98	160	43	210	06
011	81	061	30	111	81	161	00	211	95
012	46	062	54	112	46	162	01	212	98
013	13	063	65	113	14	163	30	213	99
014	53	064	43	114	53	164	54	214	81
015	93	065	00	115	93	165	65	215	46
016	02	066	02	116	01	166	43	216	15
017	01	067	23	117	02	167	00	217	25
018	03	068	40	118	05	168	02	218	47
019	09	069	85	119	02	169	23	219	81
020	08	070	53	120	01	170	40	220	00
021	94	071	93	121	94	171	85	221	00
022	85	072	00	122	85	172	53	222	00
023	93	073	03	123	93	173	93	223	00
024	00	074	00	124	00	174	00		
025	01	075	08	125	00	175	01		
026	04	076	07	126	05	176	04		
027	09	077	08	127	09	177	08		
028	07	078	94	128	07	178	08		
029	09	079	85	129	02	179	08		
030	65	080	93	130	05	180	94		
031	43	081	00	131	65	181	85		
032	00	082	00	132	43	182	93		
033	01	083	02	133	00	183	00		
034	30	084	00	134	01	184	00		
035	54	085	03	135	30	185	00		
036	65	086	05	136	54	186	05		
037	43	087	01	137	65	187	02		
038	00	088	65	138	43	188	04		
039	02	089	43	139	00	189	05		
040	23	090	00	140	02	190	07		
041	85	091	01	141	23	191	65		
042	53	092	30	142	85	192	43		
043	93	093	54	143	53	193	00		
044	01	094	65	144	93	194	01		
045	08	095	43	145	01	195	30		
046	08	096	00	146	00	196	54		
047	01	097	02	147	04	197	65		
048	05	098	23	148	05	198	43		
049	75	099	45	149	05	199	00		

Table 6
Program 5

000	46	050	42	100	00	150	01	200	05
001	10	051	00	101	09	151	02	201	55
002	42	052	06	102	55	152	95	202	43
003	01	053	44	103	43	153	98	203	00
004	08	054	00	104	01	154	42	204	07
005	81	055	07	105	01	155	01	205	95
006	46	056	43	106	95	156	03	206	98
007	11	057	00	107	98	157	53	207	81
008	36	058	07	108	55	158	04	208	46
009	42	059	98	109	93	159	55	209	87
010	01	060	81	110	01	160	09	210	02
011	09	061	46	111	06	161	55	211	93
012	01	062	13	112	07	162	53	212	01
013	44	063	43	113	05	163	51	213	09
014	01	064	00	114	95	164	87	214	05
015	09	065	06	115	98	165	55	215	07
016	81	066	65	116	42	166	43	216	02
017	46	067	43	117	01	167	01	217	01
018	12	068	00	118	02	168	03	218	56
019	00	069	02	119	81	169	28	219	46
020	42	070	95	120	46	170	75	220	15
021	01	071	44	121	17	171	01	221	25
022	09	072	00	122	01	172	95	222	47
023	43	073	09	123	00	173	45	223	81
024	00	074	43	124	45	174	05		
025	04	075	00	125	53	175	95		
026	90	076	09	126	51	176	42		
027	88	077	81	127	87	177	01		
028	02	078	46	128	55	178	04		
029	49	079	14	129	53	179	43		
030	00	080	43	130	01	180	00		
031	01	081	00	131	85	181	07		
032	46	082	06	132	01	182	55		
033	88	083	65	133	55	183	43		
034	43	084	43	134	53	184	01		
035	00	085	00	135	02	185	01		
036	01	086	03	136	93	186	65		
037	65	087	95	137	02	187	43		
038	43	088	44	138	05	188	01		
039	00	089	01	139	65	189	04		
040	00	090	01	140	43	190	95		
041	33	091	43	141	01	191	98		
042	45	092	01	142	01	192	42		
043	03	093	01	143	45	193	01		
044	55	094	81	144	93	194	05		
045	43	095	46	145	02	195	81		
046	01	096	16	146	95	196	46		
047	08	097	01	147	98	197	18		
048	40	098	75	148	65	198	43		
049	95	099	43	149	43	199	01		

The actual programs, as printed by the auxiliary printer, are given in Table 6. In each program step, the left (3-digit) entry is the program step number and the right (2-digit) number is the coded instruction.

VI. Three Design Examples

A. Point Luminaire

Consider the installation in Figure 10 and the associated intensity and CRF-ESI worksheets in Tables 7 and 8. Four high pressure sodium units are being used to light a small lobby and two task locations have been identified.

Proceeding through the steps of Section V, we first draw coordinate systems on the room layout, one for each task, with +y in the direction of viewing and each task located at the origin of its coordinate system. We consider each luminaire as a point source in this case and thus do not have to subdivide the luminaires into elements. Because the luminaires are symmetrical, we need fill in only one column on the Intensity Worksheet, noting that intensity values are given in 5 degree increments in θ. Following this, we complete the top portion of the CRF-ESI Worksheet. Because we are considering entire luminaires as elements, each element number is a luminaire number also, and we can use the luminaire letter row to designate which of the two tasks is being considered.

We are now ready to carry out Programs 1 through 5. Element scaling factors are 1 throughout, because each luminaire is a single element. Ψ need not be calculated and Program 2 may be omitted because the luminaires are symmetrical. The duplicate element multiplier is 2 for element 1 and task location 1 and 0 for all other elements. Thus the column for element 2 under task location 1 is omitted.

Table 7

Intensity Worksheet

√

			Symmetric	Asymmetric
θ in deg. Δθ = 5°	θ in deg. Δθ = 10°	θ row No. n	I_o or I_{90}	Intensity Format I_o I_{45} I_{90}
5	15	1	4857	.
0	5	2	4924	.
5	5	3	4857	.
10	15	4	4824	.
15	25	5	4765	.
20	35	6	4660	.
25	45	7	4516	.
30	55	8	4312	.
35	65	9	4003	.
40	75	10	3511	.
45	85	11	2823	.
50	95	12	2064	.
55	105	13	1396	.
60		14	826	.
65		15	448	.
70		16	235	.
75		17	175	.

Luminaire Description:

High Pressure Sodium Unit

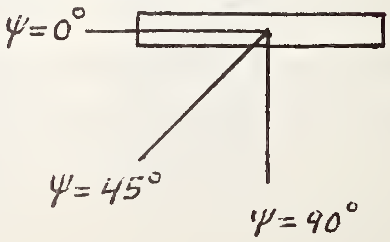


Table 8

CRF-ESI Work Sheet for Direct Component-Example A

Room Location Figure 10 h = 6.2 ft

Luminaire High Pressure Sodium Unit $\Delta\theta$ = 5°

Lamp 150-watt Viewing Direction South

Task Location T1, T2 Row Orientation (p) ____

Row or Luminaire Letter			T1				T2							
			Source Element Number											
Program	Step No.	Quantity	1		3	4	1	2	3	4				
1	1	x_e	-5.0		-5.0	10.0	-10.0	0	-10.0	5.0				
	2	y_e	5.0		-5.0	-5.0	5.0	5.0	-5.0	-5.0				
	3	$\|\phi\|$	44.9		134.9	116.5	63.4	0	116.5	134.9				
	4	θ	48.8		48.8	61.0	61.0	38.9	61.0	48.8				
	5	Element Scaling Factor m	1		1	1	1	1	1	1				
	6	ψ												
2	7	θ Row Number n	10		10	13	13	8	13	10				
	8	$I_1(\theta)$	3511		3511	1396	1396	4312	1396	3511				
	9	$I_2(\theta)$	2823		2823	826	826	4003	826	2823				
	10	$I_3(\theta)$	2064		2064	448	448	3511	448	2064				
	11	$I_4(\theta)$	1396		1396	235	235	2823	235	1396				
3	12	Scaled $I(\phi,\theta)$	2244		2244	736	736	3636	736	2244				

Row or Luminaire Letter			T1				T2							
			Source Element Number											
Program	Step No.	Quantity	1	2	3	4	1	2	3	4				
4	13	B_{ti}	.753		.621	.611	.685	.959	.611	.621				
	14	B_{bi}	.896		.767	.761	.842	1.064	.761	.767				
5	15	Duplicate Element d Multiplier	2		0	0	0	0	0	0				
	16	ΣEi	33.4		50.0	52.2	2.2	46.8	48.9	65.6				
	17	ΣL_{ti}	25.1		35.5	36.8	1.5	44.3	45.6	55.9				
	18	ΣL_{bi}	29.9		42.7	44.4	1.8	49.3	50.9	63.7				
	19	CRF	1.01				.73							
	20	ESI	57.6				8.8							
	21	LEF	1.10				.13							

Following computation of illuminance and luminances, CRF, ESI and LEF values are obtained for each task location. Note that this requires Program 5 to be run essentially twice, once for T1 and again for T2.

B. Strip Luminaire

Only the dissimilarities between this example and the previous one will be discussed. Refer to Figure 11 and the associated worksheets in Tables 9 and 10. In this instance, the luminaires are strips, fluorescent batwing units. Each row is given a letter label and elements are selected from Figure 6 and numbered. Referring to the intensity worksheet, the I_o column is used for row A, because ψ is o for this row, and Program 2 is omitted. However, for row B, the intensity format column must be completed and Program 2 used to find the four intensities, I_1 through I_4, row A has no symmetrical counterpart, but row B does. Hence d = o for row A and 2 for row B and elements in row B' are not labeled or included in the calculations. The remainder of the calculations proceed as in Example A.

C. Square Luminaire

This final example involves 3 ft x 3 ft (1.01 m x 1.01 m) crosslamp fluorescent luminaires with prismatic lenses. Figure 12 and the associated work sheets in Tables 11 and 12 apply. In this case, intensity data, given in 10 degree increments, is inserted in the I_o or I_{90} column because the luminaire is symmetrical. Thus, Program 2 may be omitted. Also ψ need not be calculated. Each luminaire is subdivided into elements according to Figure 8, and, because of the task location and viewing direction, each element has a d factor of 2 and thus one-half of the elements may be omitted from the calculations. The remainder of the calculations are as in Example A.

Table 9

Intensity Worksheet

√

θ in deg. Δθ = 5°	θ in deg. Δθ = 10°	θ row No. n	Symmetric	Asymmetric
			I_o or I_{90}	Intensity Format I_o I_{45} I_{90}
5	15	1	349	035 . 037039
0	5	2	348	035 . 035035
5	5	3	349	035 . 037039
10	15	4	351	035 . 044053
15	25	5	351	035 . 055073
20	35	6	354	035 . 070094
25	45	7	326	033 . 081105
30	55	8	307	031 . 087109
35	65	9	285	029 . 086105
40	75	10	260	026 . 078094
45	85	11	217	022 . 065069
50	95	12	179	018 . 049040
55	105	13	159	016 . 034031
60		14	146	015 . 025028
65		15	127	013 . 019025
70		16	106	011 . 016022
75		17	78	008 . 013019

Luminaire Description:

Batwing Fluorescent

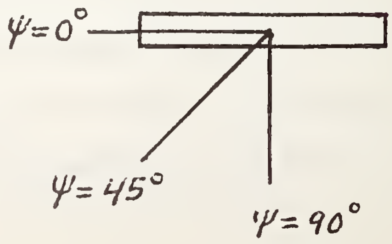


Table 10

CRF-ESI Work Sheet for Direct Component-Example B

Room Location Figure 11 — h = 6.2 ft

Luminaire Batwing Fluorescent — $\Delta\theta$ = 5 deg.

Lamp 40 CW Fluorescent — Viewing Direction North

Task Location T — Row Orientation (p) 0

Row or Luminaire Letter			A											
			Source Element Number											
Program	Step No.	Quantity	1	2	3	4	5	6	7	8	9			
1	1	x_e	0	0	0	0	0	0	0	0	0			
	2	y_e	.6	1.85	3.25	4.9	6.9	10	16	-.6	-1.85			
	3	$\|\phi\|$	0	0	0	0	0	0	0	180	180			
	4	θ	5.5	16.6	27.7	38.3	48.1	58.2	68.8	5.5	16.6			
	5	Element Scaling Factor m	.3	.325	.375	.45	.55	1	2	.3	.325			
	6	ψ	0	0	0	0	0	0	0	0	0			
2	7	θ Row Number n	2	4	6	8	10	12	14	2	4			
	8	$I_1(\theta)$	348	351	354	307	260	179	146	348	351			
	9	$I_2(\theta)$	349	351	326	285	217	159	127	349	351			
	10	$I_3(\theta)$	351	354	307	260	179	146	106	351	354			
	11	$I_4(\theta)$	351	326	285	217	159	127	78	351	326			
3	12	Scaled $I(\phi,\theta)$	105	115	118	121	106	151	223	105	115			

Row or Luminaire Letter			A											
			Source Element Number											
Program	Step No.	Quantity	1	2	3	4	5	6	7	8	9			
4	13	B_{ti}	.765	.935	.969	.960	.935	.901	.860	.715	.671			
	14	B_{bi}	.869	.995	1.044	1.064	1.070	1.071	1.066	.833	.815			
5	15	Duplicate Element d Multiplier	0	0	0	0	0	0	0	0	0			
	16	ΣEi	2.7	5.3	7.5	9.0	9.8	10.4	11.0	13.7	16.4			
	17	ΣL_{ti}	2.1	4.5	6.6	8.1	8.8	9.3	9.6	11.5	13.3			
	18	ΣL_{bi}	2.3	5.0	7.2	8.8	9.7	10.3	10.6	12.8	15.0			
	19	CRF												
	20	ESI												
	21	LEF												

Table 10

CRF-ESI Work Sheet for Direct Component - Example B

Room Location Figure 11 — $h = 6.2$ ft

Luminaire Batwing Fluorescent — $\Delta\theta = 5$ deg.

Lamp 40 CW Fluorescent — Viewing Direction North

Task Location T — Row Orientation (p) 0

Row or Luminaire Letter			B											
			Source Element Number											
Program	Step No.	Quantity	10	11	12	13	14	15	16					
1	1	x_e	5	5	5	5	5	5	5					
	2	y_e	1.25	3.25	6	10	16	-2	-6					
	3	$\lvert\phi\rvert$	75.8	56.9	39.8	26.5	17.3	111.7	140.1					
	4	θ	39.7	43.9	51.6	61.0	69.7	41.0	51.6					
	5	Element Scaling Factor m	.625	.375	1	1	2	1	1					
	6	ψ	75.8	56.9	39.8	26.5	17.3	68.3	39.9					
2	7	θ Row Number n	8	9	11	13	14	9	11					
	8	$I_1(\theta)$	1057	947	620	291	197	1006	621					
	9	$I_2(\theta)$	1031	857	475	217	153	908	475					
	10	$I_3(\theta)$	928	699	330	165	128	719	330					
	11	$I_4(\theta)$	719	505	242	138	98	493	242					
3	12	Scaled $I(\phi,\theta)$	586	277	426	205	259	876	426					

Row or Luminaire Letter			B												
			Source Element Number											
Program	Step No.	Quantity	10	11	12	13	14	15	16					
4	13	B_{ti}	.724	.744	.756	.757	.753	.670	.608					
	14	B_{bi}	.859	.881	.902	.923	.941	.812	.755					
5	15	Duplicate Element d Multiplier	2	2	2	2	2	2	2					
	16	ΣEi	30.2	35.6	40.9	42.2	42.7	62.3	67.6					
	17	ΣL_{ti}	23.3	27.3	31.3	32.3	32.7	45.8	49.0					
	18	ΣL_{bi}	26.9	31.7	36.5	37.6	38.1	54.0	58.0					
	19	CRF	.93											
	20	ESI	39.8											
	21	LEF	.59											

Table 11

Intensity Worksheet

	✓		Symmetric	Asymmetric
θ in deg. $\Delta\theta = 5^{o}$	θ in deg. $\Delta\theta = 10^{o}$	θ row No. n	I_o or I_{90}	Intensity Format I_o I_{45} I_{90}
5	15	1	1535	.
0	5	2	1575	.
5	5	3	1575	.
10	15	4	1535	.
15	25	5	1440	.
20	35	6	1270	.
25	45	7	995	.
30	55	8	600	.
35	65	9	370	.
40	75	10	210	.
45	85	11	70	.
50	95	12	0	.
55	105	13	0	.
60		14		.
65		15		.
70		16		.
75		17		.

Luminaire Description:

3x3 Crosslamp with Prismatic

Enclosure

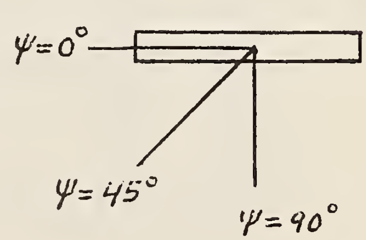


Table 12

CRF-ESI Work Sheet for Direct Component - Example C

Room Location Figure 12 h = 6.2 ft

Luminaire 3x3 Crosslamp $\Delta\theta$ = 10 deg.

Lamp 40 CW Fluorescent Viewing Direction South

Task Location T Row Orientation (p) ______

Row or Luminaire Letter			A			B				C			
			Source Element Number										
Program	Step No.	Quantity	1	2	3	4	5	6	7	8	9	10	11
1	1	x_e	.75	.75	.75	5.75	5.75	4.25	4.25	5.75	5.75	4.25	4.25
	2	y_e	-1	0	1	-5.75	-4.25	-4.25	-5.75	4.25	5.75	5.75	4.25
	3	$\lvert\phi\rvert$	142.9	89.2	36.6	135.0	126.4	135.0	143.5	53.5	45.0	36.4	45.0
	4	θ	11.4	6.9	11.4	52.7	49.1	44.1	49.1	49.1	52.7	49.1	44.1
	5	Element Scaling Factor m	.167	.167	.167	.25	.25	.25	.25	.25	.25	.25	.25
	6	ψ											
2	7	θ Row Number n	1	1	1	5	5	4	5	5	5	5	4
	8	$I_1(\theta)$	1575	1575	1575	1270	1270	1440	1270	1270	1270	1270	1440
	9	$I_2(\theta)$	1575	1575	1575	995	995	1270	995	995	995	995	1270
	10	$I_3(\theta)$	1535	1535	1535	600	600	995	600	600	600	600	995
	11	$I_4(\theta)$	1440	1440	1440	370	370	600	370	370	370	370	600
3	12	Scaled $I(\phi,\theta)$	260	262	260	172	208	256	208	208	172	208	256

Row or Luminaire Letter			A				B				C			
			Source Element Number											
Program	Step No.	Quantity	1	2	3	4	5	6	7	8	9	10	11	
4	13	B_{ti}	.712	.737	.797	.611	.631	.634	.611	.736	.742	.770	.766	
	14	B_{bi}	.841	.851	.896	.758	.776	.779	.757	.879	.890	.913	.901	
5	15	Duplicate Element d Multiplier	2	2	2	2	2	2	2	2	2	2	2	
	16	ΣE_i	12.7	26.1	38.8	40.8	43.9	48.8	51.8	54.9	56.9	59.9	64.8	
	17	ΣL_{ti}	9.1	18.9	29.1	30.3	32.2	35.3	37.2	39.4	40.9	43.2	47.0	
	18	ΣL_{bi}	10.7	22.1	33.5	35.0	37.4	41.2	43.5	46.2	47.9	50.7	55.2	
	19	CRF												
	20	ESI												
	21	LEF												

Table 12

CRF-ESI Work Sheet for Direct Component - Example C

Room Location Figure 12 h = 6.2 ft

Luminaire 3x3 Crosslamp $\Delta\theta$ = 10 deg.

Lamp 40 CW Fluorescent Viewing Direction South

Task Location T Row Orientation (p) ______

Row or Luminaire Letter			D	E										
			Source Element Number											
Program	Step No.	Quantity	12	13										
1	1	x_e	.75	5										
	2	y_e	10	15										
	3	$\lvert\phi\rvert$	4.3	18.4										
	4	θ	58.3	68.6										
	5	Element Scaling Factor m	.5	1										
	6	ψ												
2	7	θ Row Number n	6	7										
	8	$I_1(\theta)$	995	600										
	9	$I_2(\theta)$	600	370										
	10	$I_3(\theta)$	370	210										
	11	$I_4(\theta)$	210	70										
3	12	Scaled $I(\phi,\theta)$	255	307										

Row or Luminaire Letter			D	E										
			Source Element Number											
Program	Step No.	Quantity	12	13										
4	13	B_{ti}	.847	.754										
	14	B_{bi}	1.012	.938										
5	15	Duplicate Element d Multiplier	2	2										
	16	ΣEi	66.7	67.5										
	17	ΣL_{ti}	48.6	49.2										
	18	ΣL_{bi}	57.1	57.8										
	19	CRF	.89											
	20	ESI	31.0											
	21	LEF	.46											

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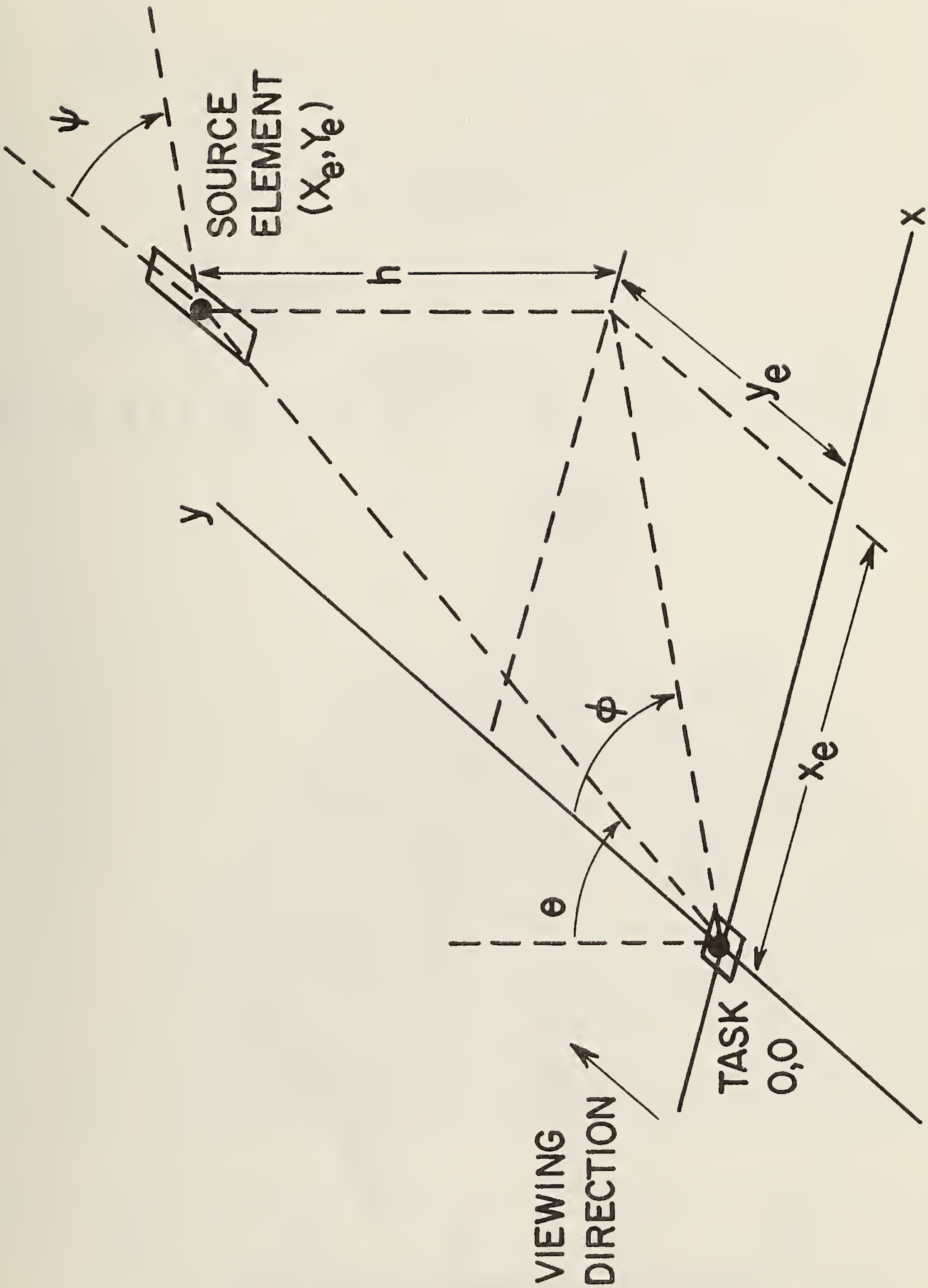

Figure 1. Geometrical Relationships Between x_e, y_e, h, ϕ, ψ and θ.

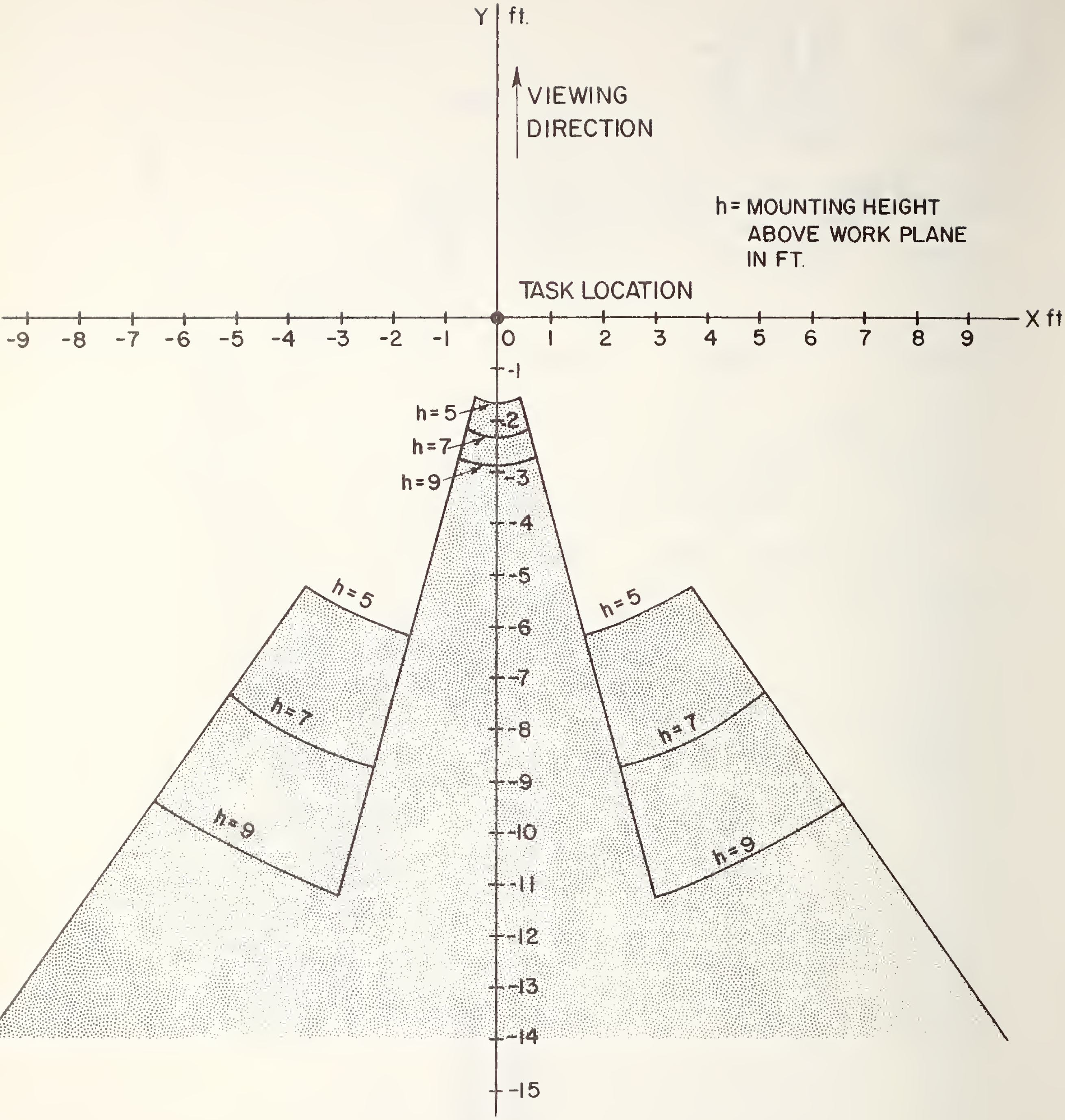

Figure 2. Body Shadow Diagram for 25° Viewing Angle.

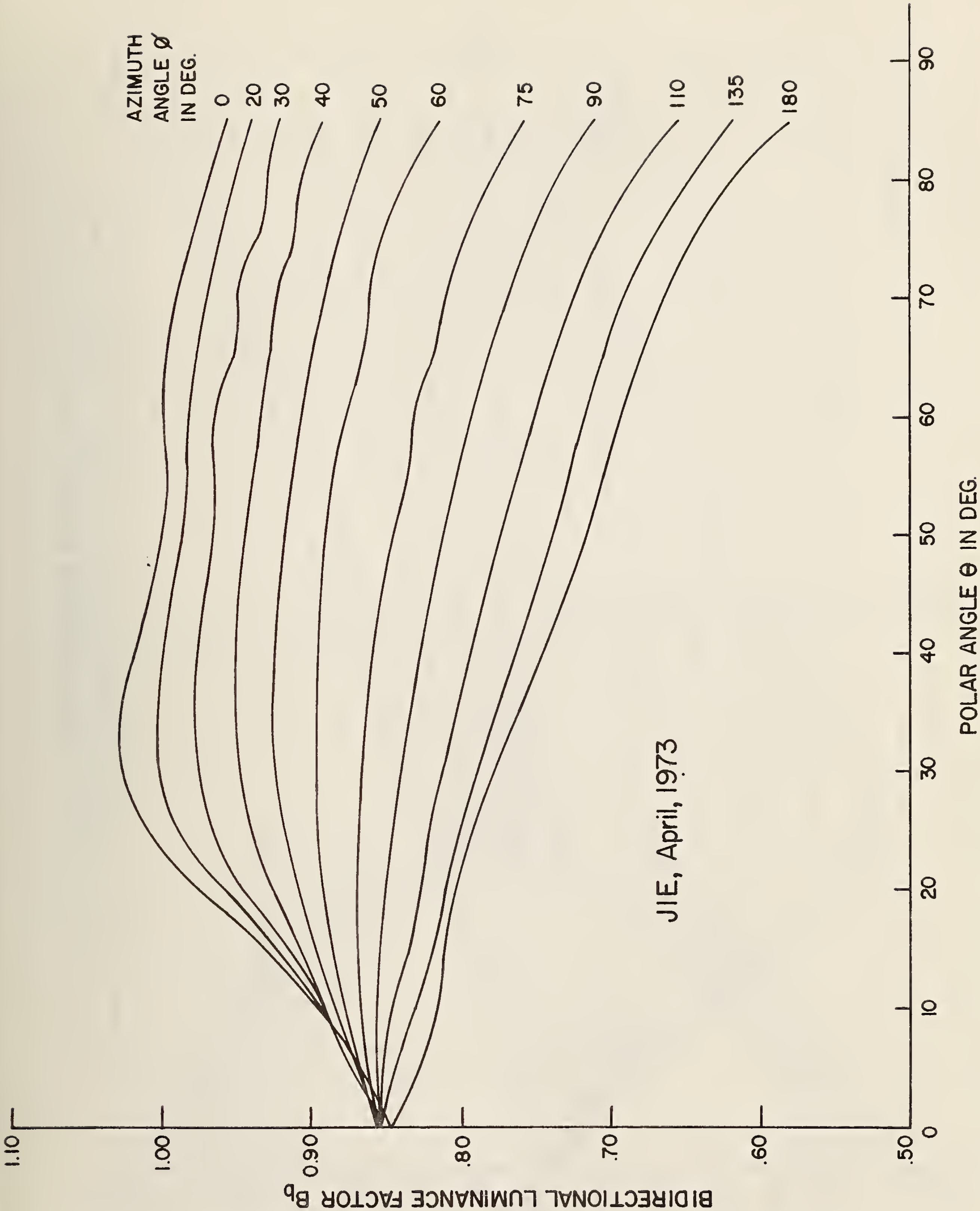

Figure 3. Bidirectional Luminance Factors for Concentric Ring Pencil Task - 25° viewing angle.

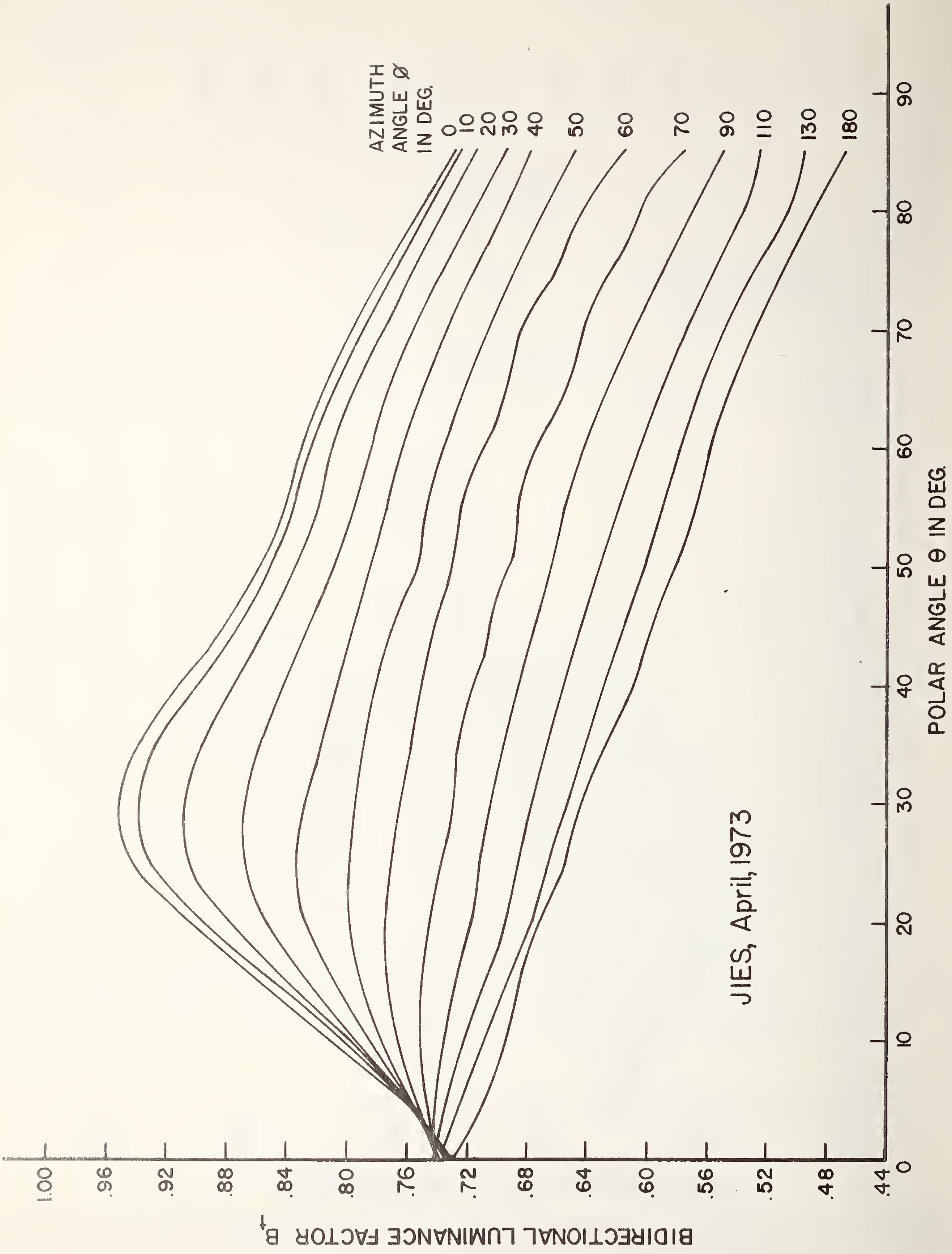

Figure 4. Bidirectional Luminance Factors for Concentric Ring Pencil Task Background - 25° Viewing Angle.

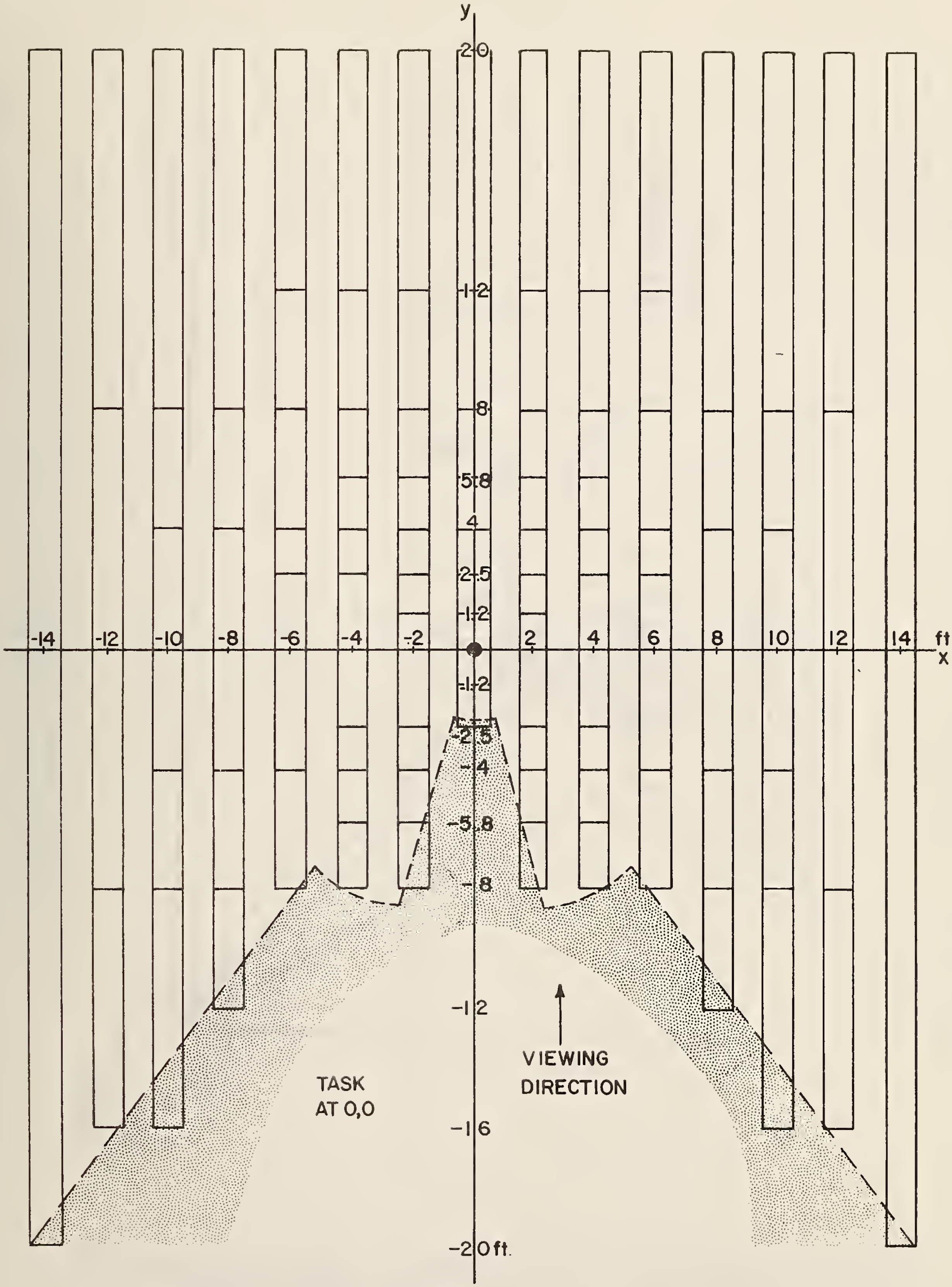

Figure 5. RQQ5(3) Source Element Angular Coordinates.

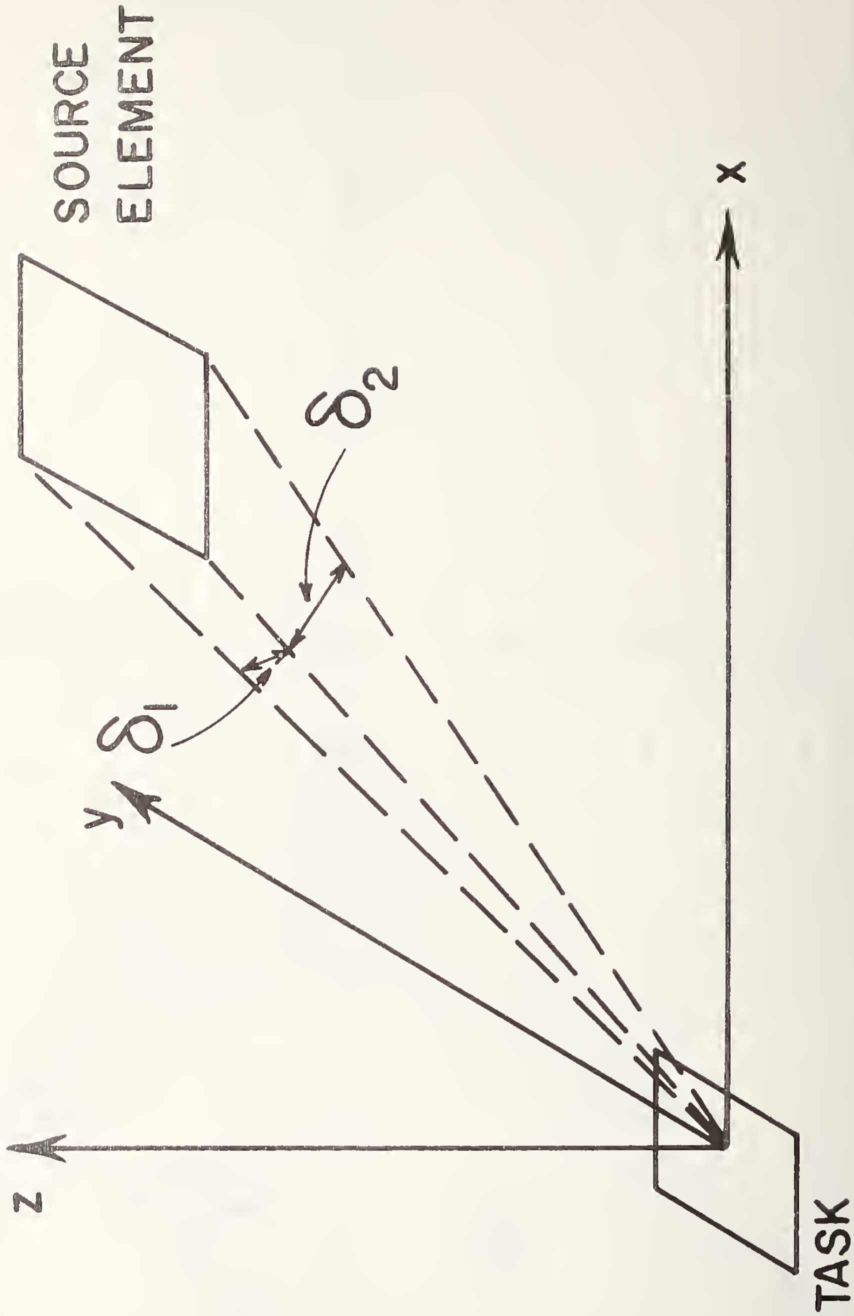

Figure 6. Strip Luminaire - Element Length vs. Location for Parallel Viewing. Dashed line denotes body shadow boundary for h = 7 ft (2.1 m). y axis numbers are locations of ends of elements.

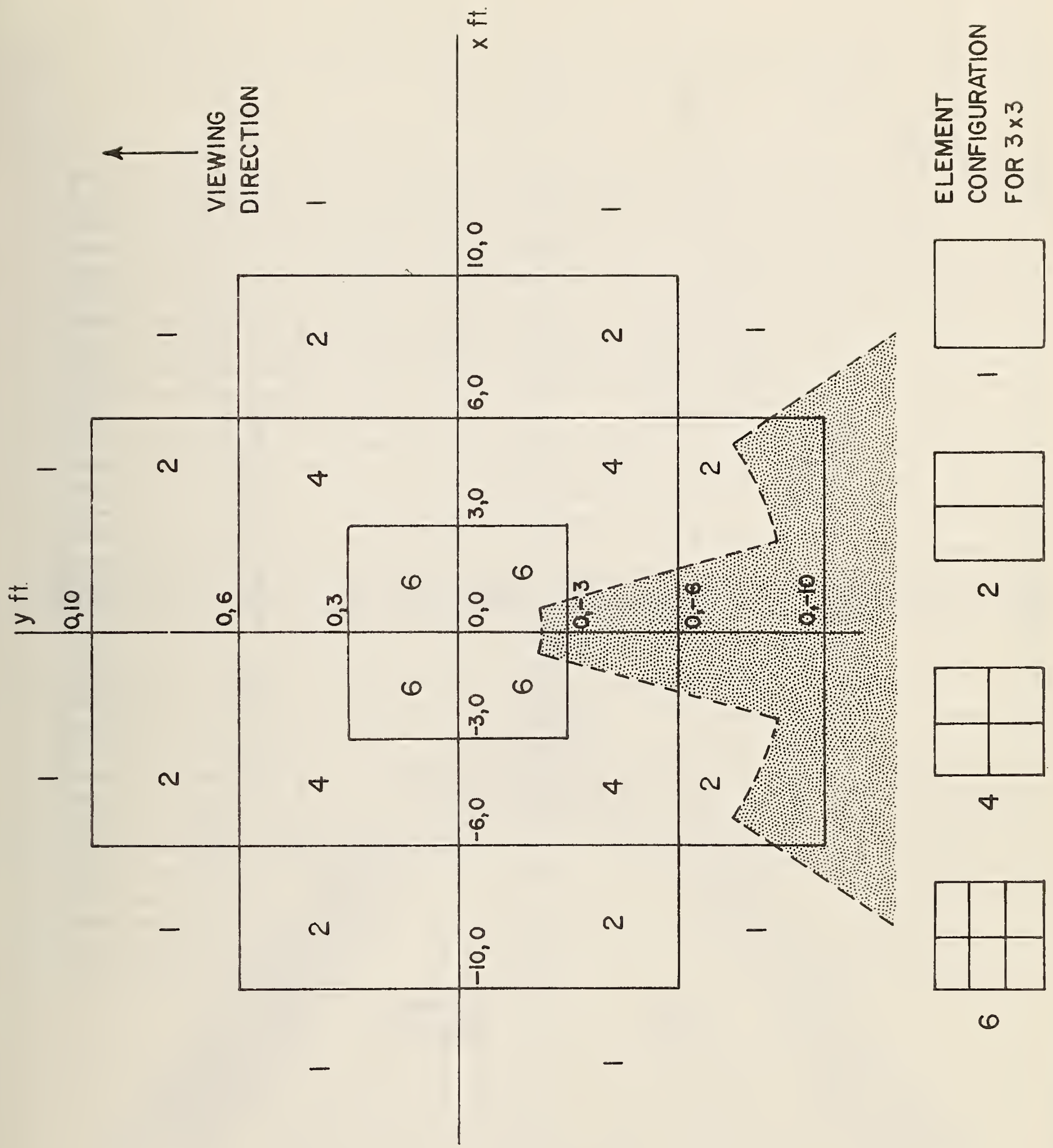

Figure 7. Strip Luminaire - Element Length vs. Location for Perpendicular Viewing. Dashed line denotes body shadow boundary for h=7 ft (2.1 m). x axis numbers are locations of ends of elements.

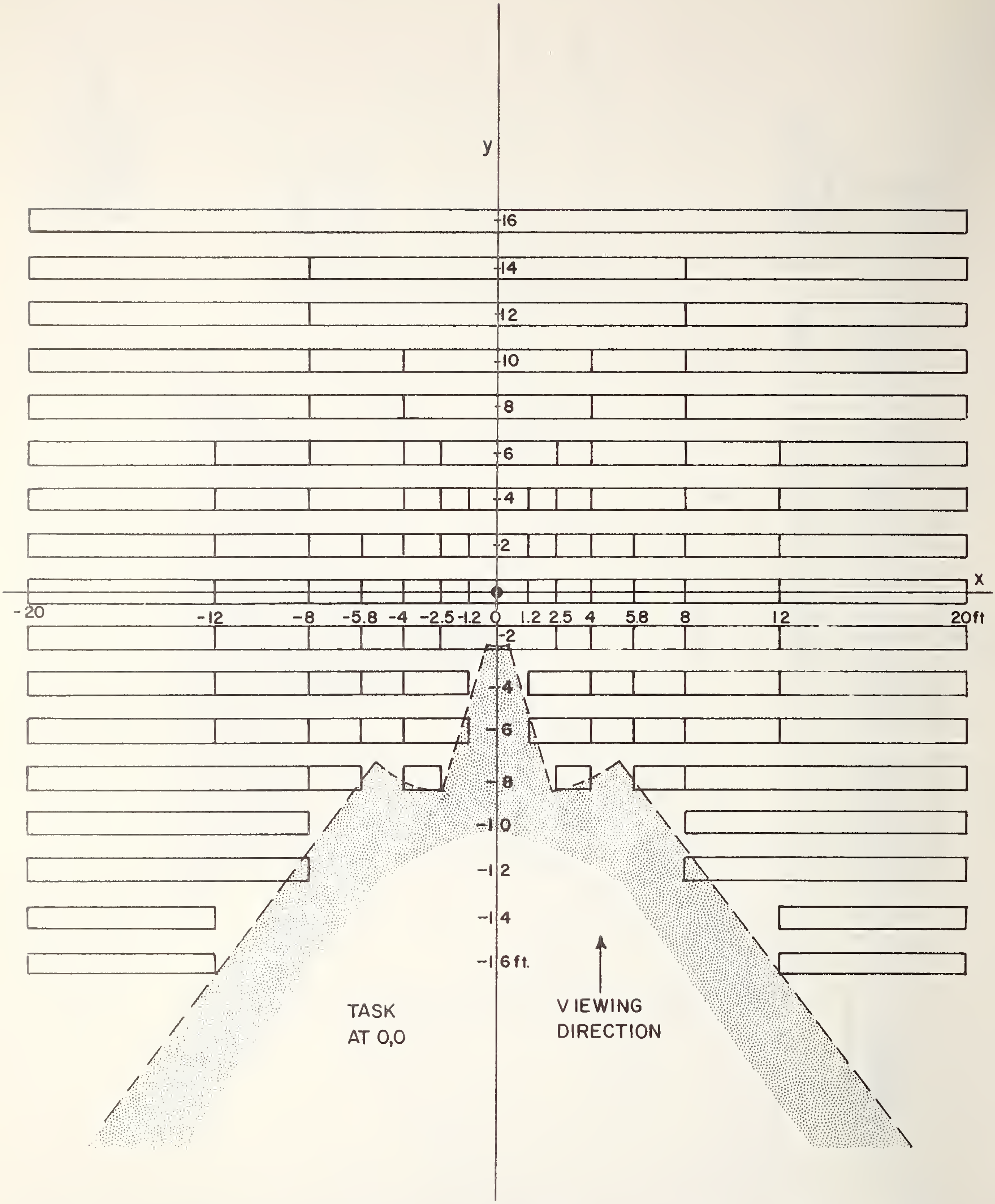

Figure 8. 3 ft (.91 m) x 3 ft (.91 m) Luminaire - Element Size and Number vs. Location. Dashed line denotes body shadow boundary for h = 7 ft (2.1 m). Number pairs are x, y coordinates.

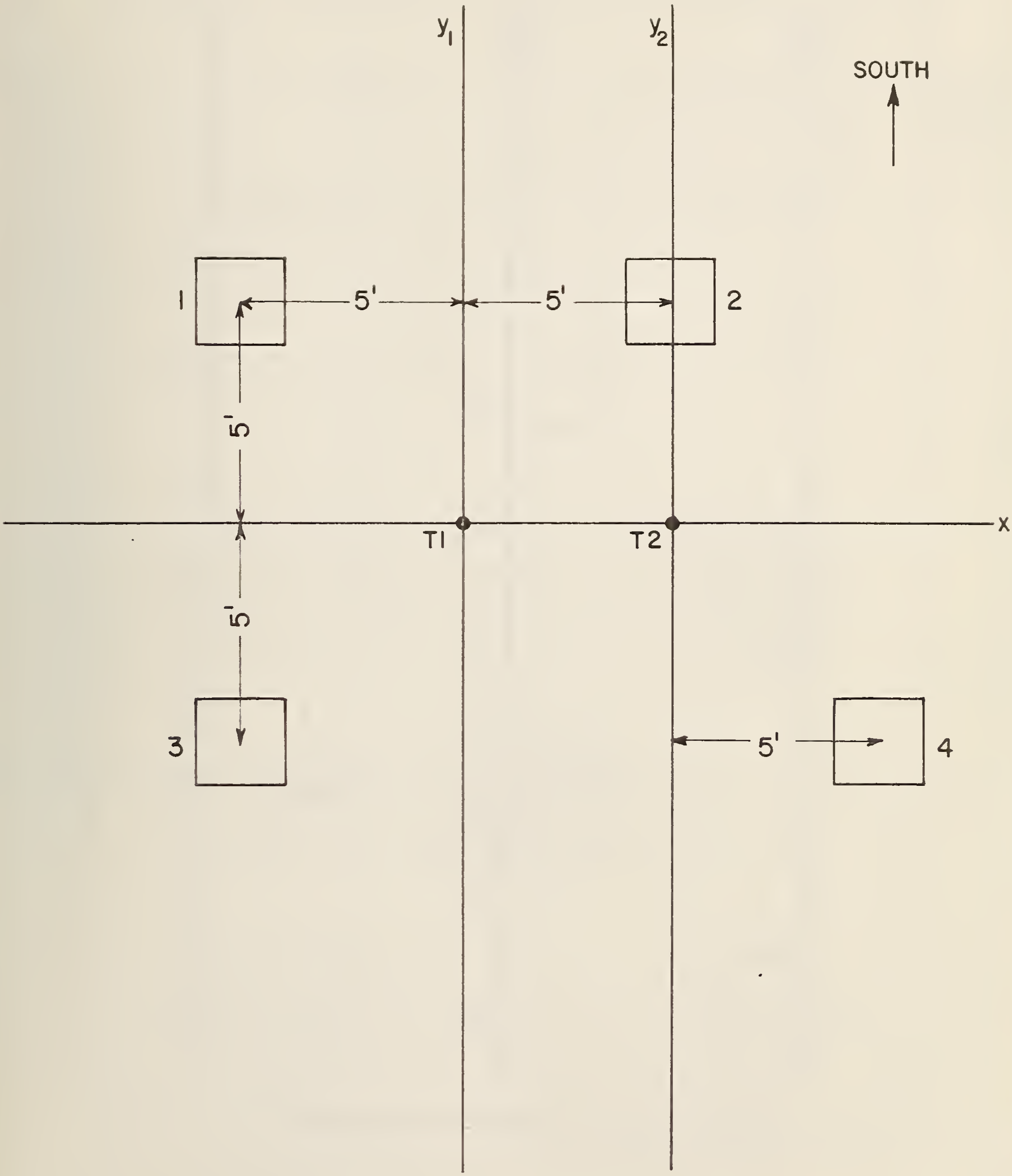

Figure 9. Typical Room and Luminaire Layout.

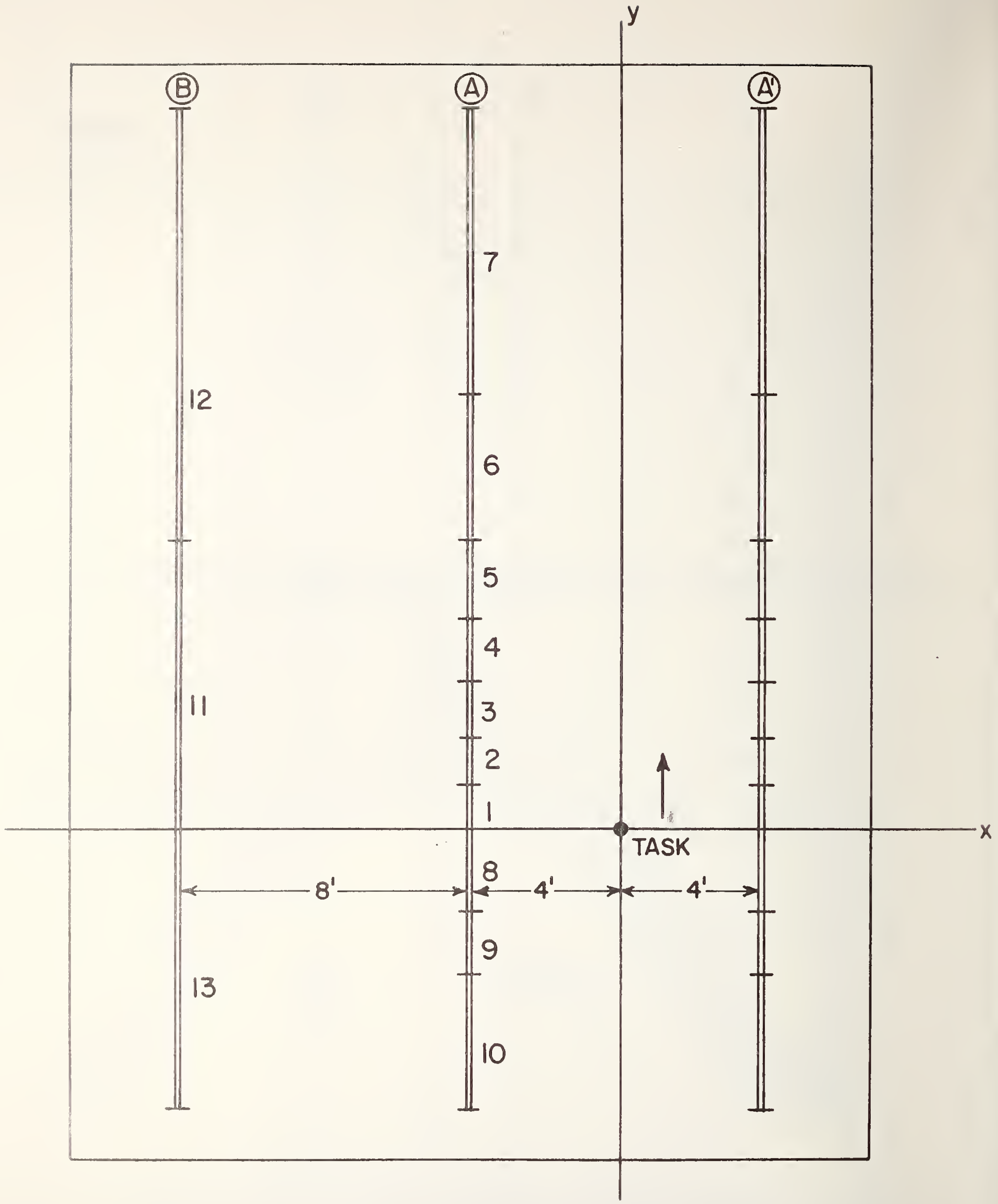

Figure 10. Lighting Layout Diagram for High Pressure Sodium Installation (Point Luminaire).

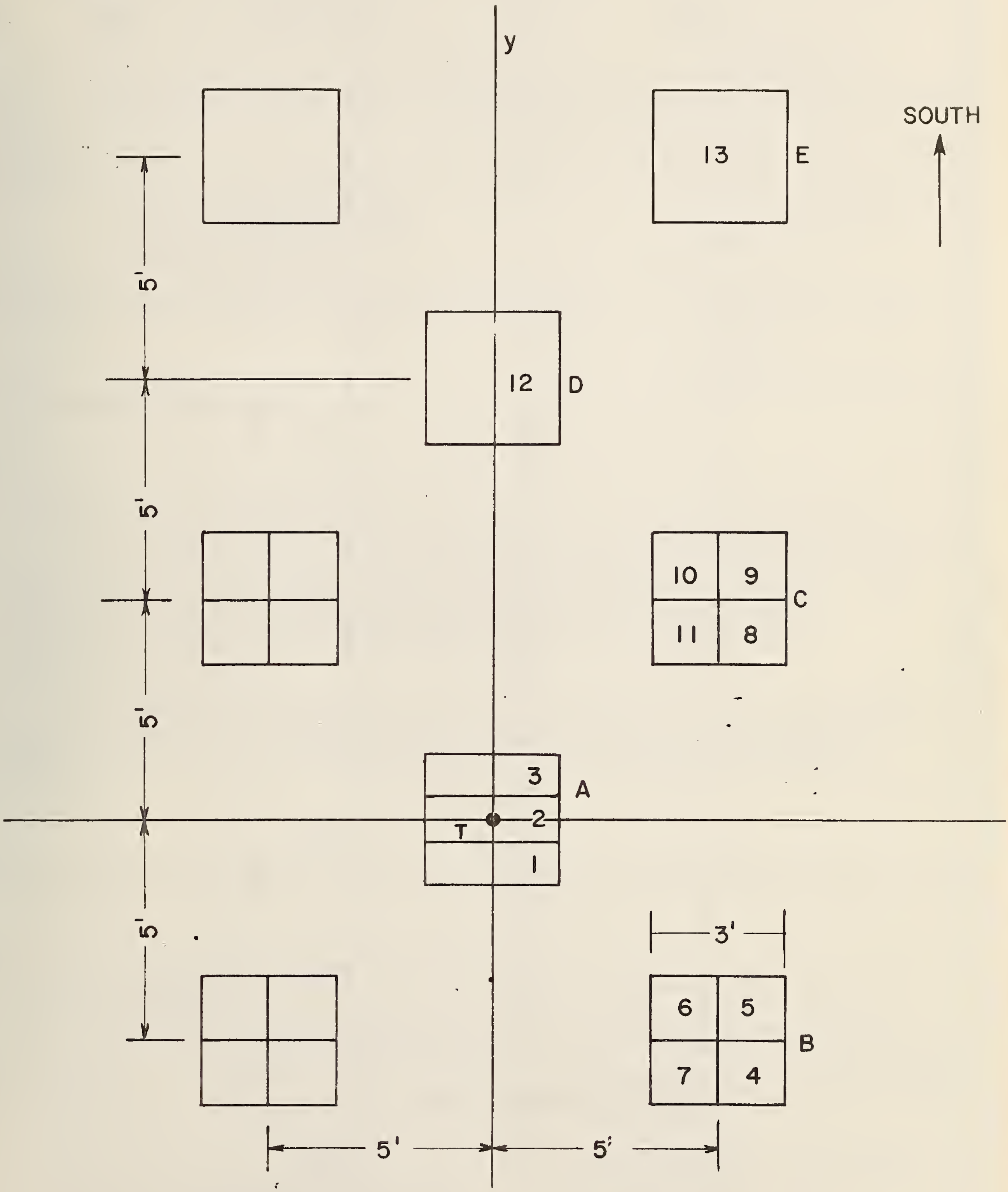

Figure 11. Lighting Layout Diagram for Fluorescent Batwing Installation (Strip Luminaire).

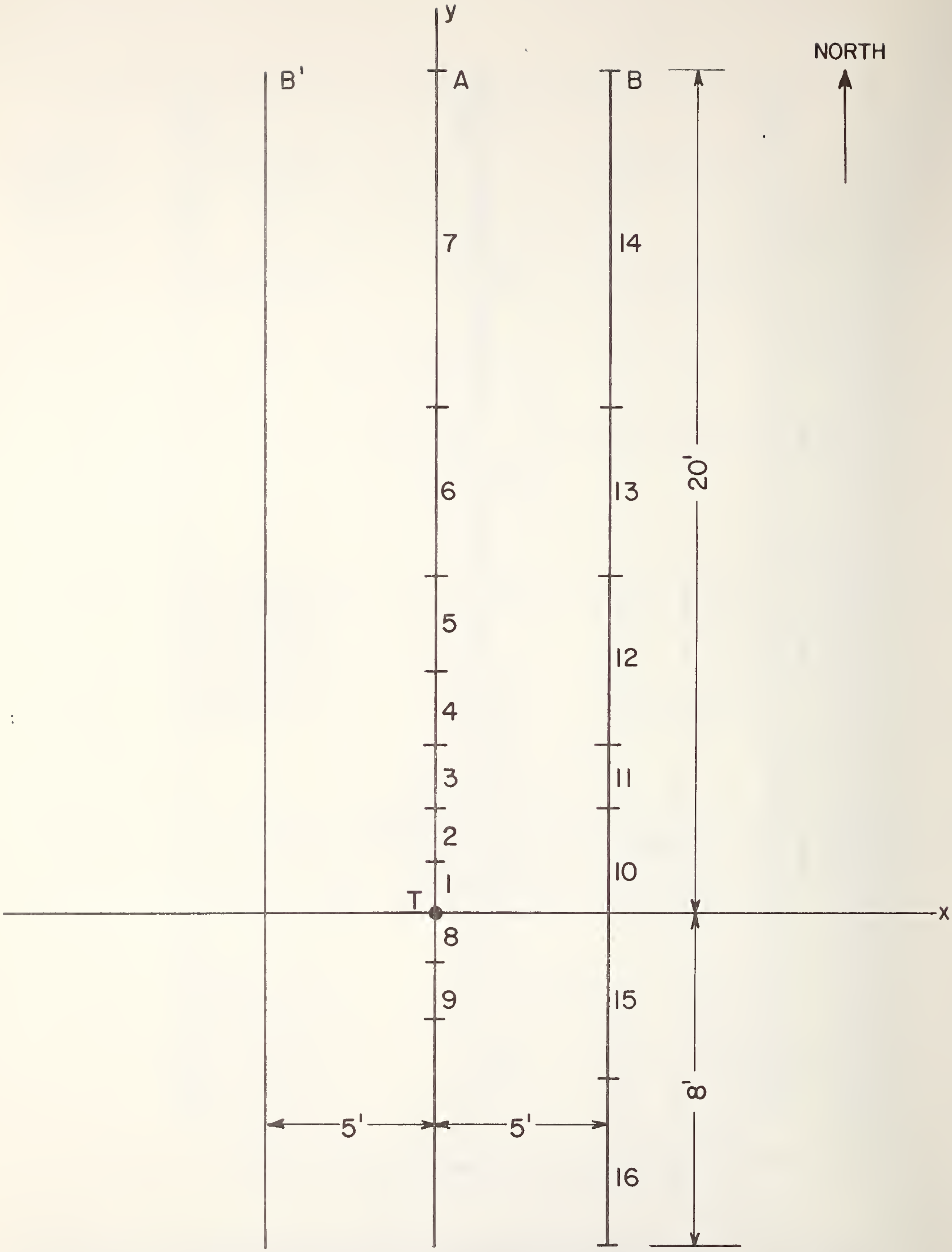

Figure 12. Lighting Layout Diagram for 3 x 3 Fluorescent Crosslamp Installation (Square Luminaire).

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A procedure is presented which enables the user to compute the direct components of contrast rendition factor (CRF) and equivalent sphere illumination (ESI) for an interior lighting design with the aid of a card-programmable hand calculator. The underlying theory and equations of CRF and ESI are discussed, including a consideration of body shadow, intensity distribution curve interpolations, bidirectional luminance factor approximating equations and Inverse Square approximations.

The procedure is designed so that the user is a participant in the computations as they progress and thus is able to modify a lighting design in "midstream" to improve CRF or ESI. A set of user instructions is included with the calculator programs.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Body shadow; contrast rendition; hand calculator; Illuminating Engineering; light design; luminaire effectiveness; luminance factor; office lighting; sphere illumination

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