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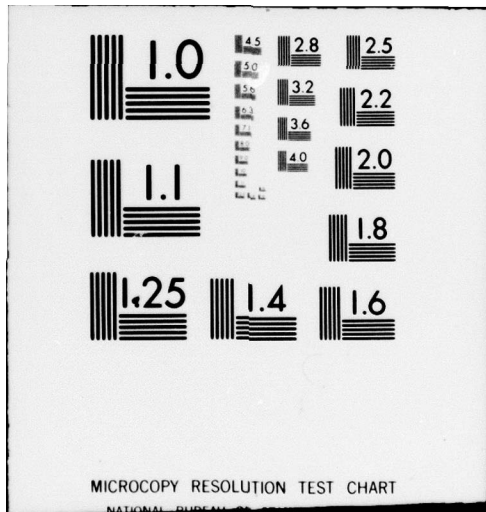
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INTRODUCTION

It is generally recognized that compared to illumination from ceiling mounted electric lighting, an equal amount of daylight illumination from windows can be about three times more effective in producing visibility.¹⁻² If this is true, then visibility based lighting controls will result in greater energy conservation than will illumination based lighting controls. It is the purpose of this technical memorandum to develop the basic principles for a control system which will simultaneously preserve visibility and conserve energy, and also to explore the magnitude of the energy savings to be achieved.

BACKGROUND

Past research into automatic lighting controls centered around on-off and equi-illumination (constant illumination) controls.³ These types of controls are now available from a number of manufacturers. The purpose of these controls is to maintain a desired level of illumination within a workspace.

The lighting literature has shown that illumination is not a very good measure of visibility.⁴⁻⁸ A better measure of visibility is the use of Equivalent Sphere Illumination (ESI) or Visibility Level (VL). Because of the complexity of visibility calculations, equi-visibility (constant visibility) lighting controls will require microprocessor intelligence. Both the theoretical and practical aspects of intelligent lighting controls are reported herein.

SYSTEM HARDWARE

The intelligent lighting control system consists of three basic hardware components. These components are the (1) sensors, (2) microprocessor, and (3) fluorescent dimming units.

The Sensors

Sensors are needed to transmit information about the luminous environment to the microprocessor. For this application, a photoconductive cell is used in a voltage divider to provide the sensor input voltage to the microprocessor (Figure 1).

POWER SUPPLY VOLTAGE (DC)

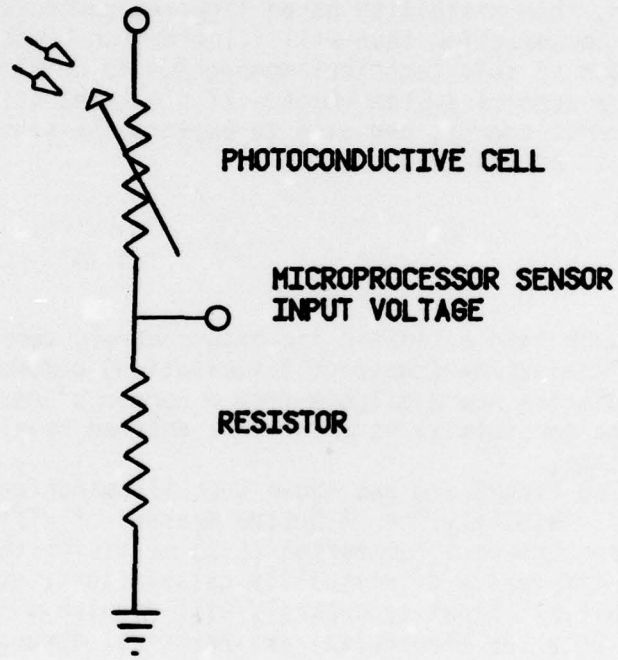


FIGURE 1 SENSOR ELECTRICAL DIAGRAM

The Microprocessor

The microprocessor is an electronic device which determines a set of output control voltages to the fluorescent dimming units based upon a set of sensor input voltages. The microprocessor may be considered to be a mathematical transfer function. The mathematical transfer algorithm is stored in the programmable read only memory (PROM). The PROM contains a sequence of instructions which the central processing unit (CPU) must follow (Figure 2). At an appropriate point in the sequence of instructions, the PROM instructs the CPU to read the sensor input voltages. At this time the analog-to-digital (A/D) converter changes the input voltage to a number and sends the number to the CPU. The next instruction tells the CPU what to do with the number. For example it may be to multiply the number by a constant. Constants and intermediate calculations may be stored in the random access memory (RAM). The PROM algorithm continues until the CPU has calculated the voltage output numerical value. At this point the digital-to-analog (D/A) converter changes the numerical value to an output voltage. The output voltage controls one or more fluorescent dimming units. Thus the microprocessor has performed its task as a mathematical transfer function.

The Dimming Units

The dimming unit is a power device which lowers or raises the light output from the fluorescent lamps in response to a control voltage from the microprocessor. Most microprocessor digital-to-analog converters provide an output voltage range of 0 to 10 volts DC. The dimming unit must be suitable for control within this range. For the purpose of discussion in this report, an ECALO (Energy Conserving Automatic Light Output, Controlled Environment Systems Inc., Rockville, Maryland) dimming unit was slightly modified to accept a microprocessor control voltage. The characteristics of the modified ECALO unit is shown in Figure 3. Empirical equations based on these characteristics are used herein.

Several manufacturers have developed prototype fluorescent dimming units which can operate within the microprocessor control voltage range. The manufacturers have projected different values for unit efficiency, cost, and availability. These factors will affect the utility of a microprocessor-based lighting control system. Since these factors are not well established, the sensitivity of lighting controls to these factors will not be discussed at this time.

SYSTEM SOFTWARE

The calculation and measurement of visibility metrics, particularly equivalent sphere illumination (ESI) and visibility level (VL), have been discussed in great detail in the lighting literature.⁴⁻⁸ This literature should be reviewed if one is not familiar with basic visibility terms and concepts.

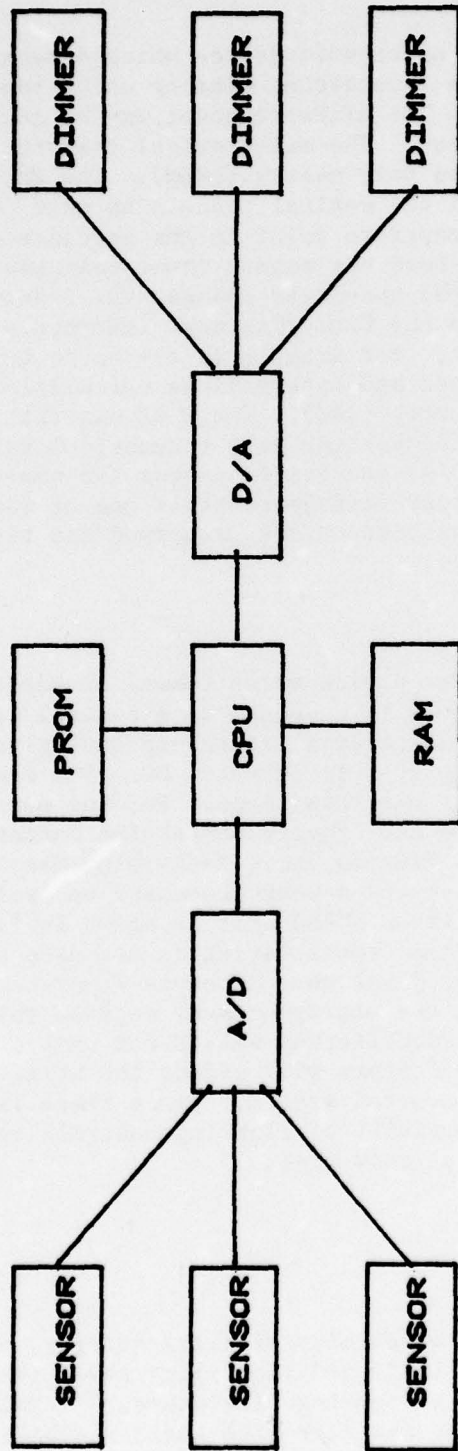
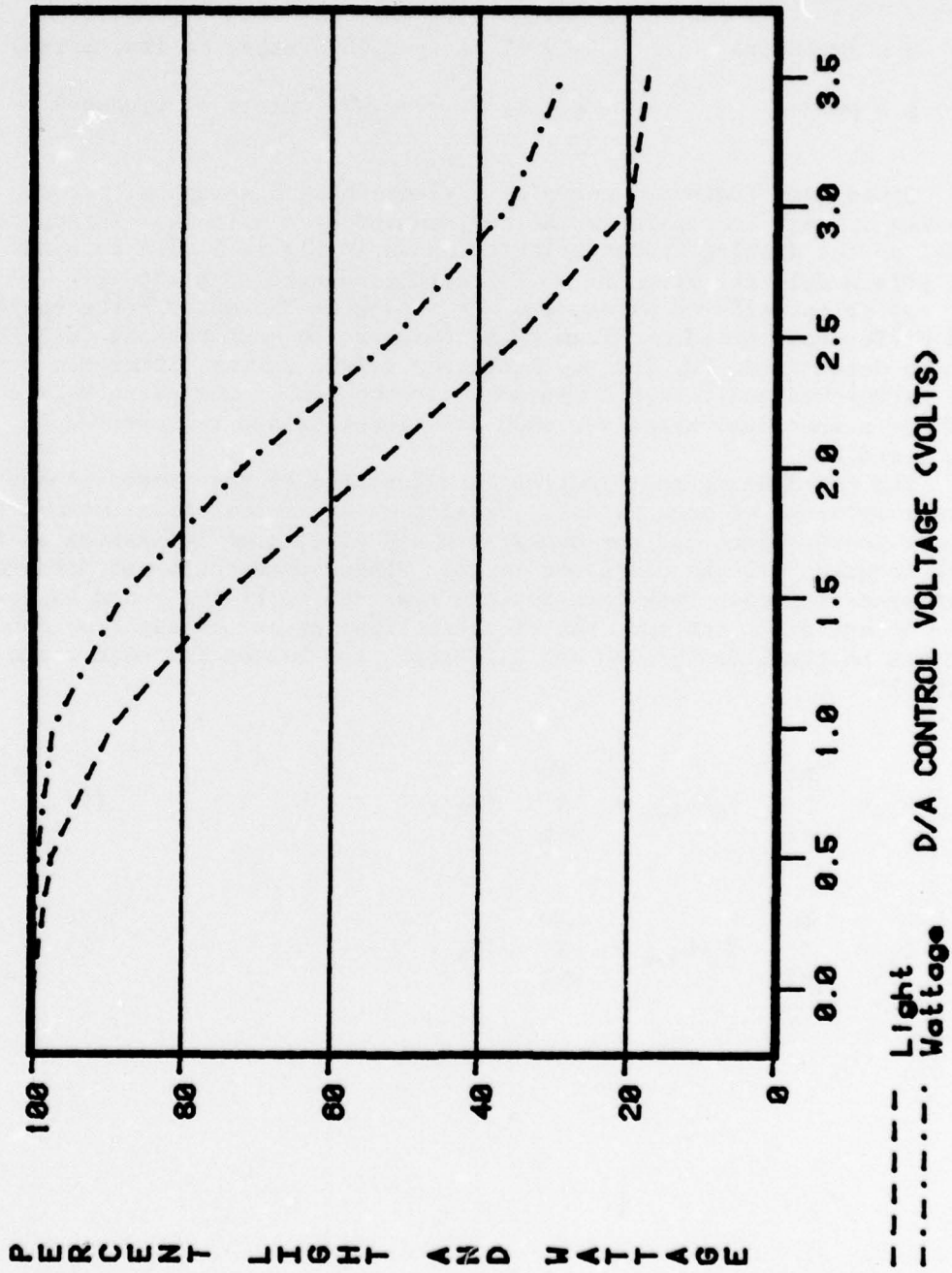


FIGURE 2 CONTROL SYSTEM BLOCK DIAGRAM

FIGURE 3 DIMMING UNIT CHARACTERISTICS



Relative Visibility

The visibility at each task location is affected by the light supplied from windows and luminaires. The following subscripts will be used for identification:

i = task location $i = 1, 2, \dots, NT$ (number of task locations)
 j = luminaire $j = 1, 2, \dots, NL$ (number of luminaires)
 k = window $k = 1, 2, \dots, NW$ (number of windows)

Since each luminaire contains a fluorescent dimming unit, the dimming of each luminaire can be represented by a gain G_j . An empirical model of the dimming characteristics shown in Figure 3 will be used. For this model, the range of G_j is restricted such that $.2 \leq G_j \leq 1$.

By calculation or by measurements using an ESI meter,⁹ the background and difference luminances from each luminaire to each task at full gain can be determined. Difference luminance refers to the difference between the background and target luminances for the task. Luminaire Background and Difference luminances for each task location are represented by $BL_{j,i}$ and $DL_{j,i}$.

The daylighting contribution is calculated by the microprocessor from sensor readings at each window. Details on the correlation between the sensor measurements and the background and difference luminances at each task location will be discussed later. Window Background and Difference luminances for each task location are represented by $BW_{k,i}$ and $DW_{k,i}$.

At any given instant, the electric lighting and daylighting contributions to total Background and Difference luminances for task i are given by:

$$B_i = \sum_{j=1}^{NL} G_j BL_{j,i} + \sum_{k=1}^{NW} BW_{k,i} \quad (1)$$

$$D_i = \sum_{j=1}^{NL} G_j DL_{j,i} + \sum_{k=1}^{NW} DW_{k,i} \quad (2)$$

Relative Visibility (RV) is defined as the Contrast (C) of the task in the real environment times the Relative Contrast Sensitivity (RCS) of the eye adapted to the background luminance. Since $C = D/B$, relative visibility for task i is:

$$RV_i = \frac{D_i}{B_i} \times RCS(B_i) \quad (3)$$

Relative Contrast Sensitivity

Modern microprocessors have hardware functions only for addition, subtraction, multiplication, and division. Any other function, such as the RCS function, must be approximated by an expression which contains only the four basic functions. For simplicity, functions which can be easily expressed in terms of the four basic functions, such as raising a number to an integer power, shall be described in their original form.

Relative Contrast Sensitivity is a function of background luminance B. An approximation is given by:

$$RCS = a_0 + a_1 X - a_2 X^2 + a_3 X^3 \quad (4)$$

where $X = \frac{B}{(\sqrt{10})^n} - 1$

and

B	n	a ₀	a ₁	a ₂	a ₃
1 - 3.16	0	13.5	7.14	2.03	.343
3.16 - 10	1	22.9	8.85	1.45	.0898
10 - 31.6	2	36.2	12.8	4.93	.960
31.6 - 100	3	50.4	10.3	3.69	.663
100 - 316	4	62.2	8.57	2.60	.415
316 - 1000	5	72.8	8.55	2.60	.411
1000 - 3162	6	83.3	8.27	2.28	.300
3162 - 10000	7	93.5	7.42	3.00	.446

This RCS approximation has the following properties:

1. continuous
2. input range 1 to 10000 nits
3. maximum error = .68 percent
4. standard error of estimate = .074

Visibility Criterion

In order to maintain a specified visibility, the lighting control system must be given a criterion relative visibility. Since relative visibility is not a quantity that many lighting designers would be comfortable in specifying, it is necessary to state the relationship between relative visibility and a familiar quantity. The simplest expression is to determine the relationship between relative visibility (RV) and visibility level (VL). This relationship is:

$$RV = \frac{C_s \times 5.74 \times VL}{C_{eq}} \quad (5)$$

where C_s = sphere contrast

C_{eq} = equivalent contrast

For the standard IES office task (#2 pencil on white paper, 25° viewing angle), $C_s = .1675$ and $C_{eq} = .681$. In this case a criterion relative visibility (RVC) can be calculated from a criterion visibility level (VLC) by:

$$RVC = 1.41 VLC \quad (6)$$

Equilibrium

The microprocessor software is designed to continually evaluate the equilibrium between two opposing algorithms: the energy conservation algorithm and the visibility preservation algorithm.

The energy conservation algorithm continually reduces luminaire gain, which in turn results in less luminaire energy consumption. This can be stated as:

$$G_j(\text{new}) = G_j(\text{old}) - g \quad \text{for all } j \quad (7)$$

A determination to be made operationally is the magnitude of the decrement g . As the size of the decrement is increased, the lights will be able to dim at a faster rate. Speed is necessary so that the system does not have a considerable lag time between sensor readings and dimming adjustments. On the other hand, a smaller decrement allows for more subtle changes in light output, which is more desirable for occupant comfort, and for finer tuned energy savings.

Based on the window sensor readings and the new set of luminaire gains from the energy conservation algorithm, the relative visibility is computed from equations (1)-(3) and compared to the criterion relative visibility. If the relative visibility is less than the criterion, the gain from selected luminaires must be increased to preserve visibility. Each luminaire not at full gain is tested according to the following method.

An incremental luminaire gain q is computed from an incremental increase in wattage w . Equation (8) is an empirical approximation for this relationship based on the characteristics of Figure 3 for small incremental increases.

$$q = w / (1.54 - 1.22 G_j) \quad (8)$$

The increment w is a constant of the same order of magnitude as decrement g in equation (7). A loop is made through the luminaires, and the luminaire producing the maximum visibility increase per wattage increment is selected to have its gain increased. This can be expressed mathematically as:

$$RV_i(\text{new}) = \text{MAX} \left[\frac{(D_i + q DL_{j,i})}{(B_i + q BL_{j,i})} \text{RCS} (B_i + q BL_{j,i}) \right] \quad (9)$$

and

$$G_j(\text{new}) = G_j(\text{old}) + q \quad (10)$$

where j is the luminaire giving the maximum increase in visibility per watt.

The visibility preservation algorithm is repeated until the relative visibility meets or exceeds the criterion.

Once the energy conservation algorithm and visibility preservation algorithm for all task locations has been completed, the dimming control voltage is calculated according to another empirical approximation for Figure 3 given by:

$$V_j = 3.35 - 2.50 G_j - .77 G_j^{16} \quad (11)$$

At this point, the digital-to-analog converter can update the new control voltages calculated by equation (11).

Flow Chart

A flow chart of the processes described is shown in Figure 4. The flow chart shows the interrelationships among the various equations and algorithms. This gives a more coherent view of the overall microprocessor software.

WINDOW SENSORS

All the experimental work on window sensors was done only for the room shown in Figure 5. The first attempt to measure the daylighting contribution into the room was to use one photoconductive cell at the window. However measurements proved that two different venetian blind slat positions could produce the same sensor reading, yet the daylighting illumination levels on the desks would be substantially different. To correct this, it was necessary to place two photoconductive cells at right angles to each other as shown in Figure 6.

At each desk the following measurements were made: the resistance from each photocell using an ohmmeter, and the illumination, background luminance, and difference luminance using an ESI meter.⁹ Based on the circuit given in Figure 1, a microprocessor sensor input voltage was calculated for each photocell resistance reading. The sample of data taken was sufficient to include the effects of venetian blind slat position, time of day, and clear and cloudy conditions. The following empirical correlations were determined from the measurements:

$$BW_{k,i} = \text{EXP} (b_{0,k,i} + b_{1,k,i} VX_k + b_{2,k,i} VY_k) \quad (12)$$

where

$BW_{k,i}$ = window background luminance

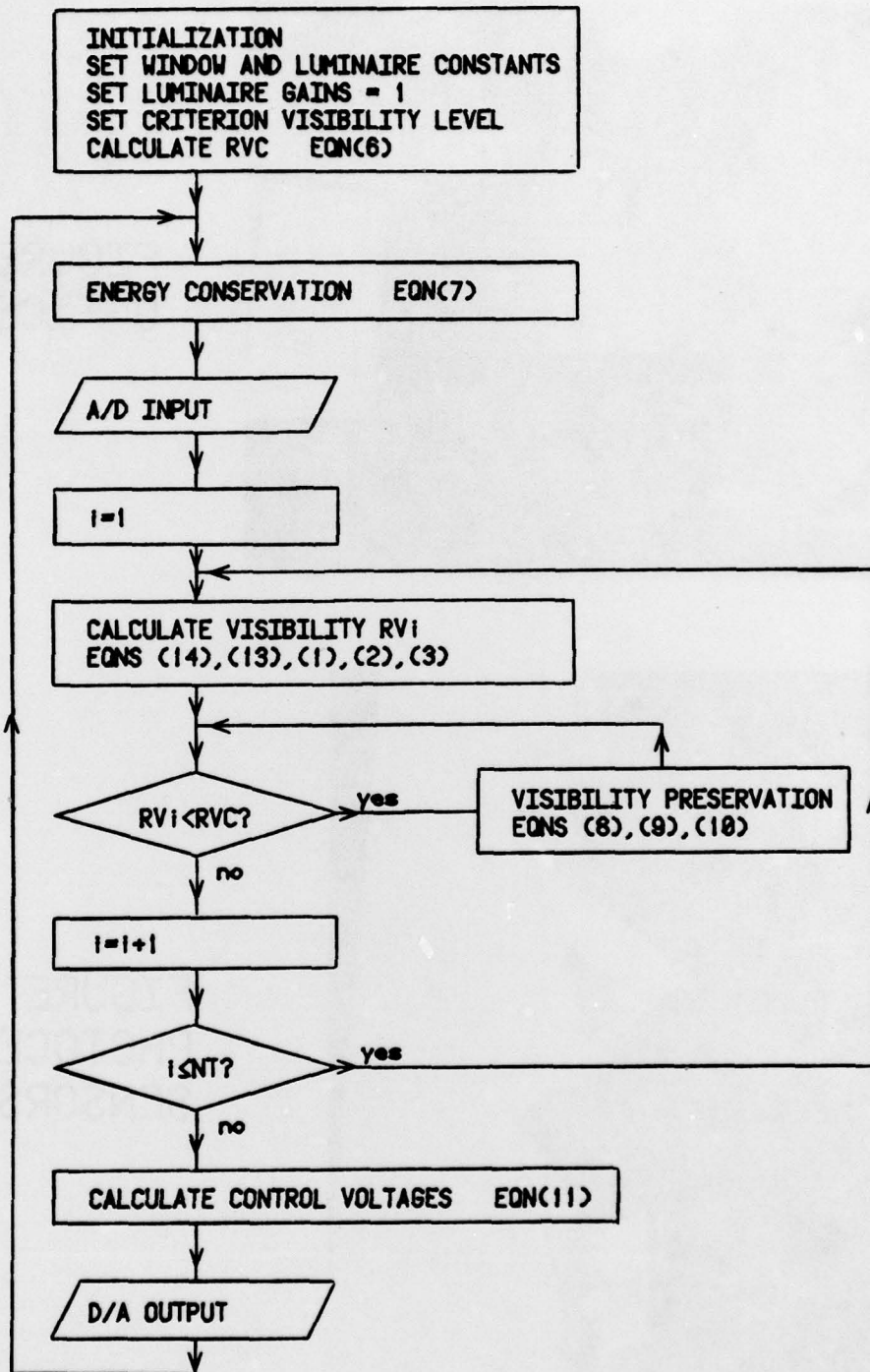
VX_k = microprocessor input voltage from upper photocell

VY_k = microprocessor input voltage from lower photocell

$b_{n,k,i}$ = correlation coefficients (n = 0, 1, and 2)

Use of a least squares multiple regression applied to equation (12) resulted in a coefficient of correlation r of .965 at desk 1 and .975 at desk 2. In Figure 5, desk 1 is in the foreground and desk 2 is nearest the window.

FIGURE 4 FLOW CHART



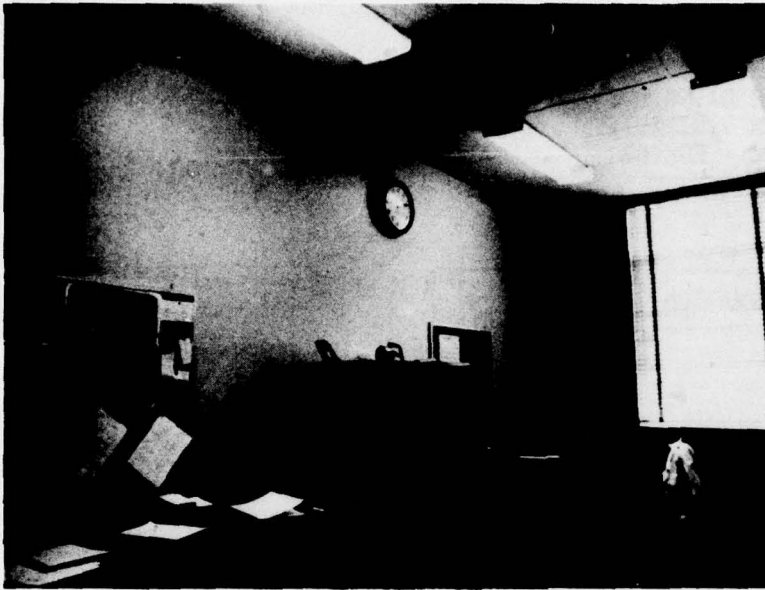


FIGURE 5
OFFICE

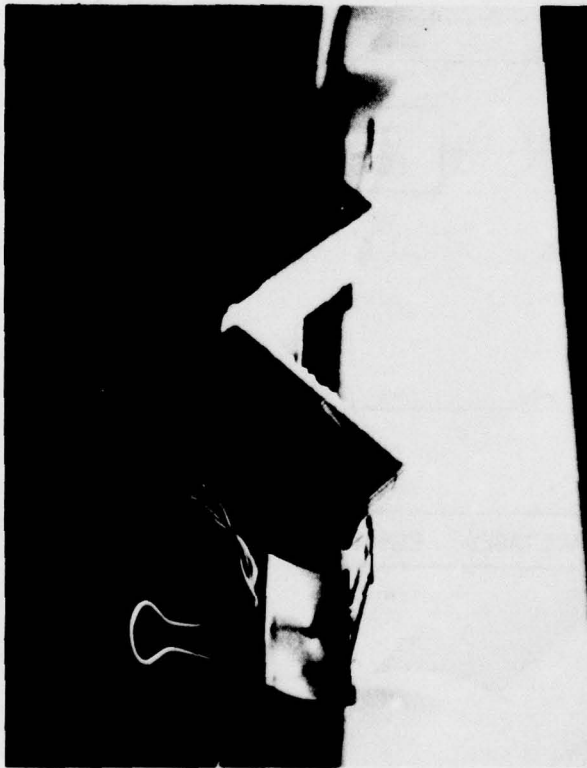


FIGURE 6
PHOTOCELL
SENSORS

Difference luminance can be predicted from equation (13):

$$DW_{k,i} = K_{k,i} BW_{k,i} \quad (13)$$

where

$DW_{k,i}$ = window difference luminance

$BW_{k,i}$ = window background luminance

$K_{k,i}$ = correlation coefficients

The error resulting from a least squares regression of equation (13) can be expressed as a standard deviation of .039 $K_{1,1}$ for desk 1 and .054 $K_{1,2}$ for desk 2. Illumination can also be expressed proportional to background luminance with similar standard deviations.

Equations (12) and (13) were developed for an east facing window and do not include the effects of seasonal variation. The effect of seasonal variation, or of sun movement across a south facing window, would probably necessitate the use of a third photocell mounted at right angles to each of the other two photocells. By inductive logic, the form of the general equation to correlate to all factors would be expected to be:

$$BW_{k,i} = \text{EXP} (b_{0,k,i} + b_{1,k,i} VX_k + b_{2,k,i} VY_k + b_{3,k,i} VZ_k) \quad (14)$$

where

$BW_{k,i}$ = window background luminance

VX_k = microprocessor input voltage from first photocell

VY_k = microprocessor input voltage from second photocell

VZ_k = microprocessor input voltage from third photocell

$b_{n,k,i}$ = correlation coefficients (n = 0, 1, 2, and 3)

Since the microprocessor can perform only the four basic functions, the exponential function must be approximated. If EXP is a function of a variable called Y, then the approximation can be given by:

$$\text{EXP} = c_n (1 + X + .500 X^2 + .218 X^3) \quad (15)$$

where

$$X = Y - n$$

and

Y	n	c_n
0-1	0	1.00
1-2	1	2.72
2-3	2	7.39
3-4	3	20.1
4-5	4	54.6
5-6	5	148.
6-7	6	403.
7-8	7	1097.
8-9	8	2981.
9-10	9	8103.

This EXP approximation has the following properties:

1. continuous
2. input range = 0-10
3. maximum error = .38 percent

EXAMPLE

For the room shown in figures 5 and 7, the following constants were measured and calculated using an ESI meter.⁹ All units are metric: illuminance in lux and luminance in nits.

Luminaire Constants

Luminaire	Task i = 1			Task i = 2		
	BL _{j,1}	DL _{j,1}	EL _{j,1}	BL _{j,2}	DL _{j,2}	EL _{j,2}
j=1	73.2	10.0	266	12.3	2.0	45
j=2	14.9	2.6	56	81.0	10.9	294
j=3	17.8	2.7	143	8.9	1.5	34
j=4	9.3	1.6	37	19.3	2.9	152

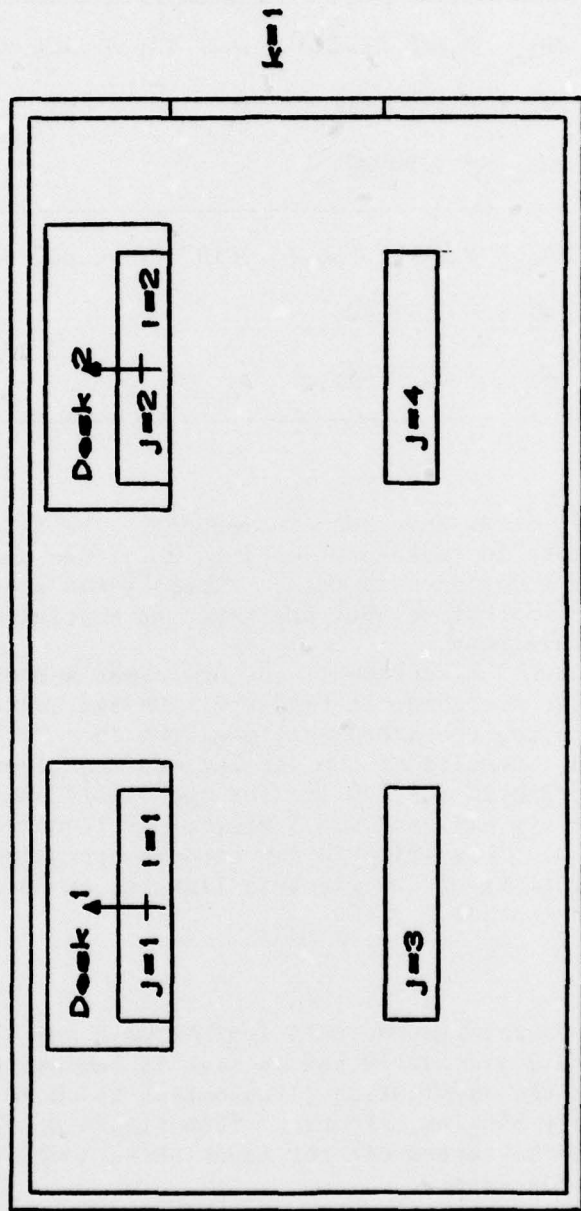


FIGURE 7 OFFICE PLAN VIEW

Window Constants

Task	Window k=1
i=1	$BW_{1,1} = \text{EXP} (-.393 + .487 VX_1 + .198 VY_1)$
	$DW_{1,1} = .173 BW_{1,1}$
	$EW_{1,1} = 3.98 BW_{1,1}$
i=2	$BW_{1,2} = \text{EXP} (.580 + .0819 VX_1 + .612 VY_1)$
	$DW_{1,2} = .173 BW_{1,2}$
	$EW_{1,2} = 3.88 BW_{1,2}$

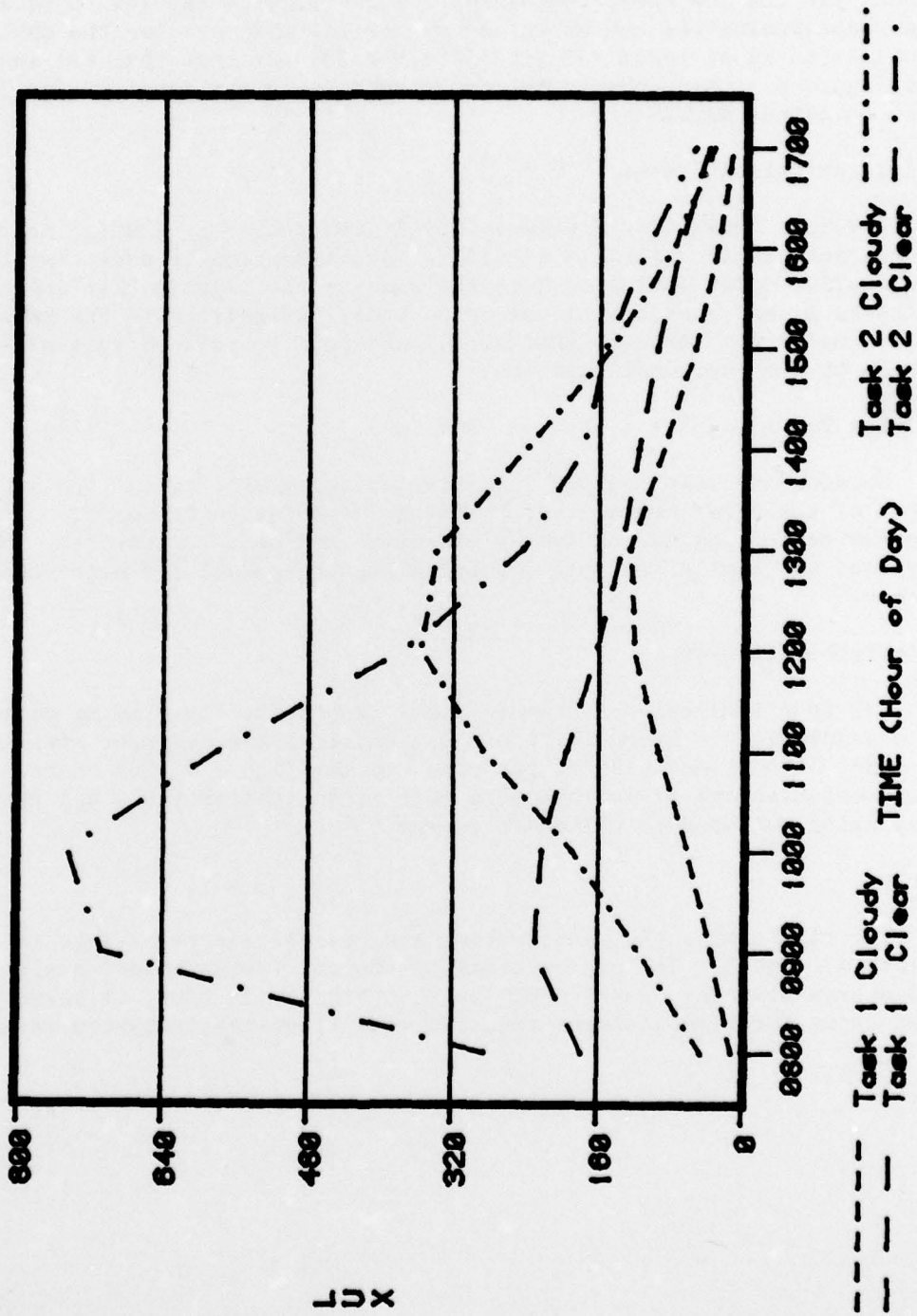
Note that two new terms have been introduced. The illumination from luminaire j at full gain to task location i is $EL_{j,i}$ and the illumination from window k to task location i is $EW_{k,i}$. These terms are not needed for relative visibility calculations, but are given as a point of reference for illumination calculations.

Daylight illumination measurements for one clear and one cloudy day near the end of October are shown in Figure 8. On the basis of these illumination measurements, the energy savings from four different control systems was simulated. Results of the simulations are given in Tables 1 and 2. The control criteria was 540 lux for the on-off, high-low-off, and equi-illumination systems, and a 6.5 visibility level for the equi-visibility system. This criteria corresponds approximately to the illumination and visibility of the electric lighting at full intensity with no daylight contribution.

On-Off System

For the on-off control system, only luminaires 2 and 4 are controlled. Since luminaires 1 and 3 provide 79 lux to task 2, luminaires 2 and 4 can be turned off anytime the daylighting illumination is above 461 lux as this will meet the necessary 540 lux criteria. From figure 8, this means that luminaires 2 and 4 can be turned off for about three hours on clear days and not at all on cloudy days.

FIGURE 6 TASK ILLUMINATION



High-Low-Off System

For the high-low-off control system, only luminaires 2 and 4 are controlled. These luminaires will be turned off the same as for the on-off system. In the low mode, luminaires 2 and 4 provide 223 lux to task 2. Thus these luminaires can be turned to the low mode anytime the daylighting illumination is at least 238 lux (540-79-223), but less than 461 lux. From figure 8, this range is met for 2 hours on clear days and for 3-1/2 hours on cloudy days.

Equi-Illumination System

All four luminaires are individually controlled by dimming units with the characteristics given in figure 3. An assumption is made that the illumination under luminaire 3 is the same as the illumination under luminaire 1, and that the illumination under luminaire 4 is the same as for luminaire 2. For each luminaire, wattage W is related to luminaire gain G_j by the empirical equation:

$$W = 96. \times (.053 + 1.56 G_j - .609 G_j^2) \quad (16)$$

Because the light output from any luminaire will affect the light output of the other luminaires, an iterative solution is needed. Therefore the equi-illumination system was simulated using a computer. Methodology used was similar to that described for the on-off and high-low-off systems.

Equi-Visibility System

All four luminaires are individually controlled by dimming units with the characteristics given in figure 3. An iterative computer simulation was made which essentially corresponded to the figure 4 flow chart. Hourly calculations of wattage were made from equation (16), and trapezoidal integration was used to calculate energy.

Results

The resulting energy consumption and percent energy savings are shown in Tables 1 and 2. The equi-visibility control system saved considerably more energy than any of the other three systems. In fact, it saved about three times more energy than the equi-illumination system saved.

Table 1: ENERGY CONSUMPTION (KILOWATT-HOURS/DAY)

WEATHER	ON-OFF	HIGH-LOW-OFF	EQUI-ILLUMINATION	EQUI-VISIBILITY
Clear	2.88	2.69	2.69	1.44
Cloudy	3.46	3.12	3.00	2.07

Table 2: ENERGY SAVINGS (PERCENT)

WEATHER	ON-OFF	HIGH-LOW-OFF	EQUI-ILLUMINATION	EQUI-VISIBILITY
Clear	17	22	22	58
Cloudy	0	10	13	40

FUTURE WORK

Ongoing work in two different projects will need to be successfully completed before an intelligent lighting control system becomes a viable alternative to presently available lighting controls. First experimental intelligent lighting control systems shall be fabricated, installed, and evaluated. This is necessary not only to determine economic costs, actual energy savings, and reliability, but also to observe psychological effects. If occupants feel that the system provides insufficient lighting, they will find ways to defeat it. Secondly, an advanced lighting design computer program shall be developed which has the capability to generate the luminaire and window constants for different room geometrics. Calculation of these constants through hand calculations or measurements is too tedious to be done in practice.

CONCLUSION

It has been demonstrated that an intelligent equi-visibility lighting control system can save substantially more energy than present illumination based control systems. The amount of energy saved will depend, of course, on each application. Use of a microprocessor also offers other opportunities, such as occupant sensors, light loss control, and window management. However, a great deal of future work will need to be successfully completed before the intelligent lighting control becomes a viable alternative to existing lighting controls.

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