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Publisher's version / Version de l'éditeur:

IEEE Transactions on Industry Applications, 24, 3, pp. 370-379, 1988-05

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Economics of Switching Fluorescent Lamps

by L.A. Carrière and M.S. Rea

Reprinted from
IEEE Transactions on Industry Applications
Vol. 24, No. 3, May/June 1988
p. 370-379
(IRC Paper No. 1562)

ANALYZED

NRCC 29415

RÉSUMÉ

En se basant sur une étude comparative du coût de différentes options de commutation, dont une combinaison de paramètres témoignant de préjugés contre la commutation fréquente, les auteurs confirment qu'il est économique de fermer les lampes fluorescentes lorsqu'on n'en a pas besoin. Ils expliquent les méthodes de calcul utilisées et présentent une analyse de sensibilité.

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Economics of Switching Fluorescent Lamps

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**Reprinted from
IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS
Vol. 24, No. 3, May/June 1988**

Economics of Switching Fluorescent Lamps

LOUIS A. CARRIÈRE AND MARK S. REA

Abstract—Based on side-by-side cost comparison of different switching options, including a combination of parameters biased against frequent switching, this study reinforces the idea that it is economical to turn fluorescent lamps off when they are not needed. Background information to explain the calculation procedures and a sensitivity analysis are included.

I. INTRODUCTION

AS A LARGE fraction of the energy used in commercial buildings is for lighting, it should be possible to reduce energy consumption by switching lamps off. It is known, however, that the life of fluorescent lamps is affected by switching. Many believe that switching fluorescent lamps, the most common type of lighting in commercial buildings, is not economical because replacement will be necessary sooner.

The economic value of switching fluorescent lamps depends upon a variety of factors, among them rated lamp life and energy cost, both of which have grown. Examination of the various editions of the *IES Lighting Handbook*, for example, reveals that the rated lamp life for a standard fluorescent lamp (e.g., 48-in T-12, Med. Bipin) has increased over the years: 12 000 h in 1966 [1], 18 000 h in 1972 [2], and 20 000 h in 1981 [3]. Depending upon location, electricity rates have risen substantially to become quite important in economic analyses of building management. These changes, among other important considerations, necessitate a close reexamination of the economics of switching fluorescent lamps.

Several studies have addressed the subject [4]–[12], but the present paper explains in greater detail the various steps involved. Unlike previous studies, it includes the costs of lamp ballasts in the economic analysis. A sensitivity analysis is also provided to delineate more clearly the significance of the various factors in the economics of switching fluorescent lamps.

The report demonstrates that both money and energy will be saved if standard or energy-efficient fluorescent lamps are turned off at night, at lunch, during coffee breaks, and, in general, whenever they are not needed. Money will be saved, although burning life will actually be reduced by more frequent switching, because lamps will not have to be replaced

for periods much longer than those recommended at present (e.g., three years for group relamping [13]).

These conclusions are based upon a calculation procedure developed for this report. Several cost comparisons were performed for different switching scenarios, including some in which the combination of parameters in the cost equation were systematically biased *against* frequent switching (i.e., high lamp cost combined with low ballast and energy costs). The economics of switching fluorescent lamps with different purchase costs or rated lives, or for switching scenarios other than those used in this report, can be readily examined using the simple calculation procedure.

II. BACKGROUND INFORMATION

A. Starting Current

Contrary to popular belief, starting a fluorescent lamp does not take very much additional energy. The Naval Civil Engineering Laboratory (USA) [4] has demonstrated that although the “in-rush” current is five times larger for starting a fluorescent lamp than for normal operation, it lasts only half a cycle (1/120 s). The extra energy consumption is therefore negligible and need not be considered in the economic analysis. For example, a 40-W standard fluorescent lamp with a standard twin-lamp ballast burning 5.5 h/day would consume 0.256 kWh/day. If the lamp were to be started ten times during the day, the energy consumption would increase by only 0.002 percent (i.e., 5.4×10^{-6} kWh/day).

B. Lamp Life

1) *Burning Time*: Fluorescent lamp life ends after a given number of starts [14] and burning hours [15], [16], when the emissive material on one or both electrodes is exhausted and fails to produce enough electrons to enable the lamp to strike [17]. At the end of its life, the lamp will typically glow at a much reduced brightness or abruptly fail to start, depending on the ballast circuit involved [16]. The rate at which the emissive coating leaves the electrodes during starting and operation depends on many factors [15], [16], [18], including filling gas pressure, electrode characteristics, lamp operating current, waveshape of lamp current, direct-current operation, lamp operating voltage, surrounding air temperature, type of starter (quality of start), type of ballast, ballast/lamp combination, high-frequency operation, and new/old lamp combination [19].

These factors and others inherent in the lamp materials and manufacturing make it very unlikely that every lamp will operate for the same length of time. Estimates of lamp life are based on the average life of many lamps operated under controlled testing conditions [20]. A typical mortality curve

Paper IUSD 87-43, approved by the Production and Application of Light Committee of the IEEE Industry Applications Society for presentation at the 1986 Industry Applications Society Annual Meeting, Denver, CO, September 28–October 3. This work carried out on behalf of the National Research Council of Canada. Manuscript released for publication August 21, 1987.

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IEEE Log Number 8719051.

for a large group of lamps operated under an orthodox burning cycle (3 h on and 20 min off [21]) is illustrated in Fig. 1 [22]. The distribution of values follows a normal probability curve, fully described by the mean and standard deviation [15]. In practice, lamps are replaced well before half of them are extinguished. An empirical equation can describe the first half of the standard mortality curve; the mortality ratio M is given by

$$M = 0.4228 + 0.0706(1.130 + \log(100 - SC))^2 \quad (1)$$

where SC is the survival criterion in percent ($50 \leq SC \leq 99$).

The hours of operation after which half the lamps in a large group operating under controlled testing conditions and a particular burning cycle fail to produce light are conventionally defined as the "average lamp life." The average life for a burning cycle of 3 h/start is defined as the "rated lamp life."

Fig. 2¹ gives the average lamp life (in percent of rated lamp life) as a function of different repetitive burning cycles. It can clearly be seen that shorter burning cycles u reduce the average lamp life. It must be emphasized, however, that reduced average lamp life does not necessarily mean that, in practice, a lamp will have to be replaced sooner. As will be shown later, a lamp operated for a few hours a day because of frequent switching will not need to be replaced as soon, in terms of calendar time, as a continually operated lamp, although the former has a shorter average lamp life.

To facilitate the analysis, an empirical equation based on a Weibull distribution [23] was determined to describe the curve in Fig. 2. This relation between average lamp life and burning cycle is

$$f(u) = 171(1 - \exp[-(u/3.89)^{0.505}]) \quad (2)$$

where

$f(u)$ average lamp life, percent of rated lamp life,
 u burning cycle, h/start.

Burning lamp life L_l can be defined as the total time, in hours, that a lamp will provide light. L_l depends on the rated lamp life L_r , the mortality ratio M (which depends upon the survival criterion SC), and the average lamp life for a particular burning cycle u , according to

$$L_l = L_r \times M \times f(u)/100 \quad (3)$$

where

L_r rated lamp life (given by lamp manufacturers), hours,
 M mortality ratio, (1),

and $f(u)$ is as in (2).

The longest burning life an average lamp can have is defined as its "continuous" lamp life, and according to (3) it may be

¹ The data for the curve in Fig. 2 were obtained by taking the ratio of the abscissa over the ordinate in [6, Fig. 1]. Owing to the large number of lamps and the long time involved in collecting data on lamp life, it is expensive to produce the data necessary for Fig. 2. For this reason, and because manufacturers concentrate their effort on new products constantly entering the market, such data are rare. In the absence of complete information this curve must be considered as representative of all rapid-start lamps.

Fig. 1. Typical mortality curve for statistically large group of fluorescent lamps (at 3 h/start) [22].

Fig. 2. Effect of burning cycles on average lamp life for most popular types of rapid-start fluorescent lamps [6].

found when $M = 1$ and $u \rightarrow \infty$; then $f(u)/100 = 1.71$. By using this empirical equation, the continuous lamp life is found to be 1.71 times longer than the rated lamp life L_r .

Equation (2) is strictly applicable only when the switching operation of lamps is repetitive (i.e., when lamps are turned on and off at the same regular intervals). In practice, switching is probably aperiodic (see Appendix I). Equation (2) may still be used to estimate lamp mortality by assuming that the average burning cycle $\bar{u}$ is equal to the cyclic burning cycle u in (2). Thus $f(u)$ in (3) may be defined as equal to $f(\bar{u})$,

$$f(\bar{u}) = 171(1 - \exp[-(\bar{u}/3.89)^{0.505}]) \quad (4)$$

where

$\bar{u}$ (h/s) , average burning cycle in a day, h/start,
 h daily hours of light usage,
 s number of switch operations/day.

Alternatively, one can assume that $f(u)$ can be estimated from the sum of the effects each burning cycle has on lamp life. Thus $f(u)$ may be defined as equal to $f(u)$:

$$\bar{f(u)} = \frac{\sum u}{\sum (u/f(u))} \quad (5)$$

where u is a burning cycle in h/start and $f(u)$ is as in (2).

It is convenient to base all calculations on daily usage, since activity patterns tend to be repeated in this way. Further,

annual estimates of cost are based on the number of working days in a year. This temporal demarcation in days does not affect $f(\bar{u})$, but it does affect $\bar{f}(\bar{u})$ to a small degree. If, for example, three different burning cycles ($u_1 = 1, u_2 = 3, u_3 = 4$) are repeated daily, then $\bar{u} = 2.67$ h/start, and $f(\bar{u}) = f(2.67) = 96.2$; however,

$$\bar{f}(\bar{u}) = \frac{(1 + 3 + 4)}{1/f(1) + 3/f(3) + 4/f(4)} = 98.1.$$

The estimates of $f(u)$ by either equation are very similar, but $\bar{f}(\bar{u})$ will always be slightly smaller than $\bar{f}(\bar{u})$ for practical burning cycles (i.e., for $\bar{u}$ smaller than 34.5 h/start (Appendix I)). The economic analyses in this report are based on $f(\bar{u})$ since 1) determining $\bar{f}(\bar{u})$ requires more effort than determining $f(\bar{u})$, without much change in the absolute value of $f(u)$; 2) the values of burning cycles (u) would usually be uncertain estimates based on average daily usage anyway; and 3) the cost calculations will be slightly biased *against* frequent switching.

2) *Real Time*: The real-time lamp life (lamp replacement frequency) in years L_t is the calendar time between relampings and is given by

$$L_t = \frac{\text{burning lamp life}}{\text{annual hours of light usage}} = \frac{L_l}{h \times n} \quad (6)$$

where

- L_l burning lamp life, (3),
- h daily hours of light usage,
- n total number of operational days per year.

C. Ballast Energy Consumption and Design Life

The principal function of a ballast is to limit current to a fluorescent lamp. The ballast also supplies sufficient voltage to start and operate the lamp. With rapid-start lamps, the most common type, the ballast supplies voltage to heat the lamp cathodes continuously [24].

In controlling a pair of 4-ft fluorescent lamps the standard two-lamp ballast will consume 13.2 W [21]; alternatively, 7 W will be consumed by a comparable energy-efficient ballast that has an improved iron core and a lower resistance in the copper wiring [25].

The end of ballast life occurs when the coil and the winding insulation have deteriorated to a point where the ballast fails to operate or its audible noise level is unacceptable. The rate of ballast deterioration increases as ballast temperature increases [16], [17], [22]. Because high-efficiency ballasts operate at lower temperatures, their expected lives are quoted as between 60 000 and 90 000 h; in contrast, standard ballasts are rated at 30 000 h [25].

Frequent switching may actually prolong ballast life if average operating temperatures are reduced. No benefit was given for this, however, in the calculations presented here. Consideration was given only to the extended real-time ballast life due to reduced operating hours from more frequent switching.

D. Factors Affecting Economics of Switching

1) *Heat of Lights*: In many buildings lights are a major source of heat. While this may be useful in winter, it adds to

the cooling load in summer (and sometimes also in winter for interior areas). It is usually better to have lower lighting loads unless special heat recovery systems are utilized or extensive capital expenditure is required for auxiliary heating equipment [26]. Additional savings can usually be realized by installing down-sized HVAC systems [26], but these were not considered in the present analyses.

2) *Daily Energy Cost*: Daily energy cost depends on 1) local utility rates (for energy consumption, penalties for peak demand, time of use, and poor power factor), 2) power associated with the lamp/ballast combination, and 3) daily hours of usage. Monetary saving will be realized by switching when the energy rate and the connected lighting load are high and the daily hours of light usage low. The daily energy cost for operating a lamp C_e in ¢/day/lamp is given by

$$C_e = \frac{W \times E}{1000} \times h \quad (7)$$

where

- W total wattage for lamps and ballast/number of lamps, W,
- E average energy rate, ¢/kWh,
- h daily hours of light usage, h.

3) *Daily Effective Ballast Cost*: The daily effective ballast cost is important in the same way as is daily energy cost. Greater monetary savings will be realized when ballast cost is high and daily hours of light usage are low. The cost of replacing a ballast involves labor and purchase costs, which depend in turn on local labor rates and the type and local purchase price of the ballast. The daily effective ballast cost for operating a lamp C_b in ¢/day/lamp is given by

$$C_b = \frac{R_b}{L_b} \times h \quad (8)$$

where

- R_b ballast replacement cost/number of lamps per ballast, ¢/lamp,
- L_b rated ballast life, h,
- h daily hours of light usage, h.

4) *Daily Effective Lamp Cost*: Estimating the daily effective lamp cost is especially important since relative lamp cost will be increased when the real-time lamp life is shortened by frequent switching (unlike incandescent lamps or ballasts); relative lamp cost will be decreased when the real-time lamp life is lengthened by significant reductions in hours of light usage. Effective lamp cost depends upon the purchase price of the lamp and the labor cost for replacement. Lamp cost depends upon size and type as well as local purchase price. The labor cost depends on the local rates as well as the method of relamping, i.e., group or spot relamping. For group relamping, the effective lamp cost also depends on the criterion chosen for relamping (i.e., the value of M in (1)). The daily effective lamp cost C_l in ¢/day/lamp is given by

$$C_l = \frac{R_l}{L_l} \times h$$

or, from (3),

$$C_l = \frac{R_l}{L_r \times M \times f(u)/100} \times h \quad (9)$$

where

- R_l lamp purchase and labor cost for replacement, ¢/lamp,
 L_r rated lamp life, h,
 M mortality ratio in (1),
 $f(u)$ $f(\bar{u})$ in (4),
 h daily hours of light usage, h.

The individual values for R_l and M in (9) will largely depend on the method of relamping, but it is less important for C_l because of the ratio R_l/M . For group relamping, $R_l = \$2.10$ and $M = 0.7$; for example, $R_l/M = \$3$. Similarly, for spot relamping, if $R_l = \$3$ and $M = 1$, then $R_l/M = \$3$. Thus the daily effective lamp cost (C_l) is less dependent on relamping method than might be supposed, although R_l is less with group relamping [13], [27]. This is because lamps must be replaced sooner ($M = 0.7$) with group relamping than with spot relamping ($M = 1.0$).

E. Daily Operating Cost per Lamp

The total daily operating cost (C_t) in ¢/day/lamp is defined here as

$$C_t = C_e + C_b + C_l$$

or, from (7)–(9),

$$C_t = \frac{W \times E}{1000} \times h + \frac{R_b}{L_b} \times h + \frac{100 \times R_l}{L_r \times M \times 171(1 - \exp[-(\bar{u}/3.89)^{0.505}])} \times h. \quad (10)$$

It is necessary to emphasize that relamping costs are built into this equation. Thus, when comparing two situations the lower total daily operating cost will always be more economical.

III. ASSUMED LIGHTING OPTIONS AND CASES

An appropriate way to determine the cost effectiveness of fluorescent switching is to examine the effects of switching on lamp life and daily operating costs for different situations. Suppose, for a 21-story office building with individual offices, that 10 000 4-ft fluorescent lamps are to be group-relamped. Working hours are from 8:00 A.M. to 4:15 P.M. and janitorial services are carried out during the day. Six options and two cases were considered (Appendix II gives justifications for the values used). The options considered are as follows.

- Lights are on 24 h/day, 365 days/yr: 8760 h/yr.
- Lights are on 15 h/day (e.g., 6:00 A.M.–9:00 P.M.), 230 working days/yr: 3450 h/yr.
- Lights in offices are turned on individually in the morning when occupants arrive and off when they leave at night (e.g., 8:00 A.M.–4:15 P.M.), 8.25 h/day, 230 working days/yr: 1897.5 h/yr.

- Same as C except that lights are turned off when occupants leave for lunch (e.g., 12:15 P.M.–1:00 P.M.), 7.5 h/day: two switch operations per day: 1725 h/yr.
- Same as D except that lights are turned off when occupants leave for coffee breaks (e.g., 10:00 A.M.–10:15 A.M. and 3:00 P.M.–3:15 P.M.), 7 h/day, four switch operations per day: 1610 h/yr.
- Lights in offices are turned on individually in the morning as occupants arrive and turned off whenever they leave the office. Here the lights are estimated to be on for 5.5 h/day, 1265 h/yr, with ten switch operations per day.

A. Cases

The economics of fluorescent switching will depend on the parameter values in (10). The parameters for Case I were representative of an existing situation in which standard 40-W lamps and ballasts subject to high-energy prices were used. This is favorable for switching since it creates a low effective lamp cost C_l , a high energy cost C_e , and a high effective ballast cost C_b (10). The parameters for Case II were biased against switching; in relation to Case I the effective lamp cost C_l is higher, the energy cost C_e is lower, and the effective ballast cost C_b is lower.

Case I (Favorable for Switching)—Parameters (10):

$$C_e = \text{energy cost} = 0.466 \text{ ¢/h/lamp} \times \text{usage},$$

(Equation (7)), where $W = 46.6$ W and $E = 10$ ¢/kWh;

$$C_b = \text{effective ballast cost} = 0.024 \text{ ¢/h/lamp} \times \text{usage}$$

(Equation (8)), where $R_b = 1200$ ¢/lamp and $L_b = 50$ 000 h;

$$C_l = \text{effective lamp cost} = \frac{0.015 \text{ ¢/h/lamp} \times \text{usage}}{f(u)/100}$$

(Equation (9)), where $R_l = 210$ ¢/lamp, $M = 0.7$, and $L_r = 20$ 000 h.

Case II (Biased Against Switching)—Parameters (10):

$$C_e = \text{energy cost} = 0.101 \text{ ¢/h/lamp} \times \text{usage}$$

(Equation (7)), where $W = 33.5$ W and $E = 3$ ¢/kWh;

$$C_b = \text{effective ballast cost} = 0.017 \text{ ¢/h/lamp} \times \text{usage}$$

(Equation (8)), where $R_b = 1500$ ¢/lamp and $L_b = 90$ 000 h;

$$C_l = \text{effective lamp cost} = \frac{0.028 \text{ ¢/h/lamp} \times \text{usage}}{f(u)/100}$$

(Equation (9)), where $R_l = 350$ ¢/lamp, $M = 0.7$, and $L_r = 18$ 000 h.

Note: Options A–F define usage u in hours per day for all cost calculations.

IV. SIDE-BY-SIDE COMPARISONS

Only Section IV-B is required in the following economic determinations for fluorescent switching under the various

TABLE I
COMPARISON OF BURNING LAMP LIFE L_b AND REAL-TIME LAMP LIFE L_r FOR DIFFERENT SWITCHING SCENARIOS

Assumption ^a	A	B	C	Options D	E	F
h daily hours of light usage, h	24	15	8.25	7.5	7.0	5.5
s number of daily switch operations	0	1	1	2	4	10
n number of operational days	365	230	230	230	230	230
$\bar{u}$ average burning cycle per day, h	—	15.0	8.25	3.25	1.75	0.550
Case I ($L_r = 20\,000$ h, $M = 0.7$ (93-percent survival))						
L_b burning lamp life, h	23 900	20 600	18 400	15 000	11 700	7400
L_r real-time lamp life, yr	2.7	6.0	9.7	8.7	7.2	5.9
Case II ($L_r = 18\,000$ h, $M = 0.7$ (93-percent survival))						
L_b burning lamp life, h	21 500	18 600	16 600	13 500	10 500	6700
L_r real-time lamp life, yr	2.5	5.3	8.7	7.8	6.5	5.3

^a $\bar{u}$ = equation (4); L_b = equation (3); L_r = equation (6). Note: Values of L_b and L_r for spot relamping may be obtained by dividing existing values by 0.7, thus setting $M = 1$.

lighting options. Sections IV-A, V, and VI contain supplementary information.

A. Lamp Life

Examination of burning lamp life L_b (i.e., number of hours of light production) and real-time lamp life L_r (i.e., calendar time between replacements) can help one to understand the economics of on-off switching of fluorescent lamps. Table I gives values of L_b and L_r for various lighting options and for Cases I and II defined in Section III; the following observations are pertinent.

Case II follows the same pattern as Case I except that lamp life (both L_b and L_r) is shorter, owing to the smaller rated lamp life L_r . The real-time lamp life L_r is shortest for option A (Section III) since both the daily hours of light usage h and the number of operational days per year n are maximum. Still, it is about the same length of time as the conventional group relamping time, i.e., three years [13].

Burning lamp life L_b always decreases with shorter burning cycles $\bar{u}$, but real-time lamp life L_r has an optimum length associated with the value of $\bar{u}$ in option C. Clearly, the reduced burning lamp life is not always associated with reductions in real-time lamp life. Further, even without an economic analysis it is obvious that short hours of light usage (option B) and one switch per day (option C) will be cost effective since relamping has been delayed. It is not clear, however, where more frequent switching (options D-F) are cost effective without a complete economic analysis.

B. Cost

As stated in Section IV-A, operating costs have to be computed for options D-F to determine whether it is economical to switch more frequently. Table II gives the operating costs for both cases and for all the options; the following observations can be made from this table.

Both Case I and Case II show the same trends; only the

absolute values differ. The daily effective ballast cost C_b is a significant parameter in the cost equations; many times it was greater than the corresponding daily effective lamp cost C_l .

C_l has an optimum cost associated with option C, and except for option A, which is based on 365 days instead of 230 days, is inversely proportional to the real-time lamp life L_r in Table I. Nevertheless, daily operational costs C_l and annual lighting costs C_a continue to decrease for those options having more frequent switching.

It is expensive to leave lights on all the time (option A). More than half the annual lighting cost C_a can be saved by reducing the daily hours of light usage from continuous operation (option A) to 15 h (option B). Another 45 percent of the annual lighting cost can be saved by reducing the daily hours of light usage from 15 h (option B) to 8.25 h (option C). Turning lights off at lunch and coffee breaks brings additional savings. The most economical option, however, is to turn fluorescent lamps off whenever they are not needed (option F).

An important point to note is that all such savings may be realized at no additional cost to the building operator where localized switching already exists. Savings are possible simply by changing the switching attitudes of the occupants [28]. The economics of retrofitting a building with another switching arrangement are beyond the scope of this paper.

V. SENSITIVITY ANALYSIS

All examples in Section IV demonstrate that it is economical to switch off unneeded fluorescent lamps. The results depend, of course, upon the specific parameters chosen for (10). It is unnecessary to compare options A, B, and C since L_r is extended the longer the lamp is off. Table III presents the results of a sensitivity analysis, comparing options D-F for both cases. The hours of light usage and each lamp, energy, and ballast parameter (left side of Table III) are changed individually for each case. Thus 1) the daily operating cost of option F was set to equal option E (column labeled F = E), 2)

TABLE II
VARIOUS COST COMPARISONS FOR DIFFERENT SWITCHING SCENARIOS

Assumptions ^a	Options					
	A	B	C	D	E	F
<i>h</i> daily hours of light usage, h	24	15	8.25	7.5	7.0	5.5
<i>s</i> number of daily switch operations	0	1	1	2	4	10
<i>n</i> number of operational days	365	230	230	230	230	230
$\bar{u}$ average burning cycle per day, h	—	15.0	8.25	3.25	1.75	0.550
Case I ($L_r = 20\,000$ h, $M = 0.7$ (93-percent survival))						
C_e daily energy cost, ¢/lamp	11.2	6.99	3.84	3.50	3.26	2.56
C_b daily effective ballast cost, ¢/lamp	0.576	0.360	0.198	0.180	0.168	0.132
C_l daily effective lamp cost, ¢/lamp	0.211	0.153	0.094	0.105	0.126	0.155
C_i daily operating cost ¢/lamp	12.0	7.50	4.14	3.78	3.56	2.85
C_a total annual lighting cost (10 000 lamps), \$	436 000	173 000	95 100	86 900	81 800	65 600
Case II ($L_r = 18\,000$ h, $M = 0.7$ (93-percent survival))						
C_e daily energy cost, ¢/lamp	2.41	1.51	0.830	0.754	0.704	0.553
C_b daily effective ballast cost, ¢/lamp	0.400	0.250	0.138	0.125	0.117	0.092
C_l daily effective lamp cost, ¢/lamp	0.390	0.283	0.174	0.195	0.233	0.287
C_i daily operating cost, ¢/lamp	3.20	2.04	1.14	1.07	1.05	0.932
C_a total annual lighting cost (10 000 lamps), \$	117 000	46 900	26 200	24 700	24 200	21 400

^a C_e = equation (7); C_b = equation (8); C_l = equation (9); C_i = equation (10); $C_a = C_i \times n = 10\,000/100$.

the daily operating cost of option E was set to equal that for option D (column labeled E = D), and 3) the daily operating cost of option D was set to equal that for option C (column labeled D = C). Rows labeled "from" give the values assumed in the previous calculations (Appendix II); those labeled "to" give the values yielding equivalent operating costs associated with the option having more frequent switching.

Because Case I is favorable to switching, the values can be changed by a greater amount than those in Case II, which was biased against switching. The zeros in some of the columns indicate that the more frequent switching option would be economical for any values less than those assumed in Appendix II.

Table III demonstrates that exact hours of light usage need to be known for determining the economics of fluorescent lamp switching; relatively small errors in estimating the average may upset the economic analysis. Similarly, for Case II, where energy rates are low, lamp costs are high, and ballast costs low, one needs to know fairly accurately the number of switches occurring in a day. All other parameters can be estimated less precisely.

VI. BREAK-EVEN PERIOD

The break-even period is the length of "off" time for which the increase in relamping cost just offsets the decrease in ballast and energy costs. Because lamp life depends upon the number of hours per switch operation u , break-even periods will also depend upon the switching pattern (also u). It is therefore necessary to employ the "break-even period per switch operation" rather than the break-even period (in hours) when determining the proper cost balance between relamping costs and operational (ballast and energy) costs.

Using the light usage values calculated in Table III, the average break-even period per switch operation, in minutes P_s , is given by

$$\begin{aligned}
 \text{options C, D: } P_{s_{C,D}} &= \frac{h_C - h'_D}{s_C - s_D} \times 60 \\
 \text{options D, E: } P_{s_{D,E}} &= \frac{h_D - h'_E}{s_D - s_E} \times 60 \\
 \text{options E, F: } P_{s_{E,F}} &= \frac{h_E - h'_F}{s_E - s_F} \times 60
 \end{aligned} \tag{11}$$

TABLE III
SENSITIVITY ANALYSIS FOR DIFFERENT SWITCHES SCENARIOS

Operating Cost, C_i			Case I			Case II		
			D (D = C)	Options E (E = D)	F (F = E)	D (D = C)	Options E (E = D)	F (F = E)
Light usage	h	from	7.5	7.0	5.5	7.5	7.0	5.5
	h'	to	8.21	7.45	6.90	8.00	7.15	6.33
Lamp parameters	s	from	2	4	10	2	4	10
		to	79	47	402	5	5	23
	L_r	from	20 000	20 000	20 000	18 000	18 000	18 000
		to	599	1 700	795	4 170	11 800	5 530
	R_l	from	2.10	2.10	2.10	3.50	3.50	3.50
		to	70.10	24.70	52.90	15.10	5.32	11.40
Energy parameters	M	from	0.7	0.7	0.7	0.7	0.7	0.7
		to	0.02	0.06	0.03	0.18	0.47	0.22
	W	from	46.6	46.6	46.6	33.5	33.5	33.5
		to	0	1.8	0	3.5	20.1	6.5
	E	from	10	10	10	3	3	3
		to	0	0.38	0	0.31	1.8	0.58
Ballast parameters	R_b	from	12.00	12.00	12.00	15.00	15.00	15.00
		to	0	0	0	0	0	0
	L_b	from	50 000	50 000	50 000	50 000	50 000	50 000
		to	0	0	0	0	0	0

h = hour; s = pure number; L_r = hour; R_l = \$; M = pure number; W = watt; E = ¢/kWh; R_b = \$; L_b = hour.

where

- h daily hours of light usage,
- h' maximum daily hours of light usage for break-even condition,
- s number of switch operations per day.

Table IV gives the break-even periods per switch operation for the various options and Cases I and II; from this the following observations can be made.

Because Case I is more favorable for switching, the break-even periods are smaller than those for Case II.

Even if the break-even period per switch operation is large (15 min), in comparing options C and D for Case II it is still economical to turn lights off at lunch because half an hour of a 3/4-h period constitutes a saving. Comparable arguments may be made for the other option comparisons.

Because the lamp replacement time L_r was increased in the first two columns (A, B and B, C), there are no break-even periods; it is always economical to reduce the hours of usage for the same number of switches. For the other columns (C, D; D, E; E, F), break-even periods will of course depend upon the length of time the lights are off relative to the lamp life lost by switching. The smaller the average burning cycle $\bar{u}$, the smaller the break-even period per switch operation; this is because the effect of *each* switch operation on lamp life becomes less as the frequency of switching increases, in spite of the fact that total lamp life is reduced by more frequent switching.

VII. DIMMING LAMPS

The economic analysis for dimming fluorescent lamps will be different from that for switching only because the lamp and

ballast wattages change during dimming. As long as lamps are started at full output (because they were designed to be started in this way) and the lamps, ballasts, and dimming equipment are properly matched [22], lamp life should not be affected by dimming.

VIII. DISCUSSION

Equation (10) does not provide a complete cost analysis; it does not include important factors such as occupant productivity, heat recovery or loss from lights, and lighting maintenance. Equation (10) is useful as long as 1) saving lighting energy does not compromise occupant productivity through reduced illumination levels, and 2) reducing the heat to the space by switching lights off is, in fact (usually the case), beneficial on an annual basis [26]. Given these caveats, (10) enables one to determine cost savings from turning fluorescent lamps off when they are not needed during a working day.

Short "off" times between switch operations decrease fluorescent lamp life and can potentially increase lighting operating cost. During a normal working day, however, there are very few occasions when lamps would be turned off for less than 7 min (Table IV, Option F, Case II) before being turned on again. For this reason people should be instructed to turn fluorescent lamps off when they are not needed. Occasionally there may be small losses from short off periods, but on average, savings would surely occur for most scenarios with frequent switching (e.g., Table II).

IX. CONCLUSION

Based on side-by-side cost comparison of different switching options, it is concluded that for normal working days it is economical to turn off unneeded fluorescent lamps. This is

TABLE IV
BREAK-EVEN PERIODS PER SWITCH FOR DIFFERENT SWITCHING SCENARIOS

Assumptions		A	B	Options			F
				C	D	E	
h	daily hours of light usage	24	15	8.25	7.5	7.0	5.5
s	number of daily switch operations	0	1	1	2	4	10
$\bar{u}$	average burning cycle per day, h/s	—	15	8.25	3.75	1.75	0.55
Compared Options ^a		A, B	B, C	C, D	D, E	E, F	
I	daily savings in hours of light usage, h	9	6.75	0.75	0.5	1.5	
Case I ($L_r = 20\,000$ h, $M = 0.7$ (93-percent survival))							
h'	maximum daily hours of light usage for break-even conditions, see Table III	—	—	8.21	7.45	6.90	
P_s	break-even period per switch operation, min	always	always	2.4	1.5	1.0	
Case II ($L_r = 18\,000$ h, $M = 0.7$ (93-percent survival))							
h'	maximum daily hours of light usage for break-even conditions, see Table III	—	—	8.00	7.15	6.33	
P_s	break-even period per switch operation, min	always	always	15.0	10.5	6.7	

^a P_s = equation (11).

true even for a combination of parameters biased against frequent switching (i.e., high effective lamp cost combined with low effective ballast and energy costs).

It is shown that the daily effective ballast cost can be a significant parameter in the economic analysis of fluorescent switching. Sensitivity analysis reveals that the average hours of light usage must be determined accurately when making cost calculations; and the number of switch actions must also be identified when energy rates are low.

Break-even periods for fluorescent switching depend on so many parameters that it is impossible to provide a single value. For the lighting options considered in this report, however, break-even periods per switch operation are always below 2.5 min at 10 ¢/kWh (Case I) and below 15 min at 3 ¢/kWh (Case II).

APPENDIX I

DISCUSSION OF THE DIFFERENCES BETWEEN $f(\bar{u})$ AND $\bar{f}(u)$

When the switching operation of lamps is not cyclic, as is the usual practice, the average life ratio $f(u)$ in (3) can be given by either $f(u) = \bar{f}(u)$ in (4) or by $f(u) = \bar{f}(\bar{u})$ in (5). Equation (4) includes the implicit assumption that switching actions are independent. Thus the total hours of operation and the total number of switches are divided without regard for the time between switching operations. This assumption cannot be correct; the effect of each switch action on lamp life decreases with more frequent switching. Equation (5) reflects, although

not completely, this interaction of switching operations. The effect of each switch action is weighted differentially according to (2) (see Fig. 2). (The denominator in (5) weighs each burning cycle u in the numerator relative to $u = 3$ h/start.) The real effect of mixed burning cycles on lamp life is unknown, however, because there are no lamp life data for nonrepetitive on-off cycles.

Table V compares the values for $f(\bar{u})$ and $\bar{f}(u)$ with various burning cycles (A–G). Both functions give similar results; except for average burning cycles $\bar{u}$ less than 34.5 h/start, $f(\bar{u})$ is always slightly smaller than $\bar{f}(u)$.

APPENDIX II

JUSTIFICATION FOR DATA USED

1) Fig. 1: Curve is as published in the *IES Lighting Handbook* [22].

2) Fig. 2: Curve is as published in [6]. The comparable curve in the *IES Handbook* [22] was inappropriate because of its small size and missing values for small burning cycle. No other good quality curve could be identified.

3) Building: A 21-story office building (data from a case study 21-story office building [29]) with

- 10 000 lamps (from [29]),
- daytime janitorial hours (from [29]),
- private offices (so that occupants can control their own lights),
- group relamping (group relamping is supposed to be

TABLE V
VALUES OF $f(\bar{u})$ AND $f(u)$ FOR VARIOUS BURNING CYCLES (u)

Example	u_1	u_2	u_3	$\bar{u}$	$f(\bar{u})$	$f(u)$
A	1	3	4	2.7	96.1666	98.1272
B	4	6	7	5.7	119.9686	120.2779
C	8	10	11	9.7	135.9042	135.9762
D	18	20	21	19.7	153.2767	153.2808
E	38	40	41	39.7	164.2396	164.2382
F	58	60	61	59.7	167.7735	167.7727
G	98	100	101	99.7	170.0028	170.0026

more economical than spot relamping [4], [27]),

- standard 40-W fluorescent lamps with regular two-lamp ballast (the most widely used type of fluorescent lamp/ballast combination for office purposes),
- energy-efficient 30-W fluorescent lamp with energy-efficient two-lamp ballast (this combination is replacing the standard lamp/ballast combination).

4) Daily Hours of Light Usage h :

Option	h	Explanation
A	24	lights always on
B	15	average value from case study [29]
C	8.25	daily hours paid for as government employee plus lunch time
D	7.5	daily hours paid for as government employee
E	7.0	daily hours paid for as government employee, minus two 15-min coffee breaks
F	5.5	average daily hours of light usage in first author's room (private office), taken over a 1-yr period

5) Number of Operational Days Per Year n :

n	Explanation
365	number of days per year for continuous burning
230	number of days per year that first author was in his office (1984), not including weekends, 11 statutory holidays/year, five days of vacation/year, five days/year for conference attendance (or for sick leave).

6) Daily Number of Switch Operation s :

Option	s	Explanation
A	0	none, lights always on
B	1	one on-off switching/day
C	1	one on-off switching/day
D	2	one on-off switching/day plus one extra switch for lunch
E	4	one on-off switching/day plus three extra switches, for lunch and two daily coffee breaks
F	10	average daily number of switch operations, taken over a one-year period in the first author's room (private office).

7) Parameters for (10):

Case I, Favorable to Switching:

power, W

energy rate

standard two-lamp ballast (cost)

standard two-lamp ballast design life

standard 40-W lamp (rated life)

standard 40-W lamp (cost)

group relamping

two standard 40-W lamps and a two-lamp ballast, $2W = 93.2$ W [21], $W = 46.6$ W/lamp;

$E = 10$ ¢/kWh (average in Charlottetown, PE, Canada);

$2R_b = \$24$ [30] (purchase price \$10, labor cost \$14), $R_b = \$12$ /lamp;

$L_b = 50\,000$ h [30];

$L_r = 20\,000$ h [3];

$R_l = \$2.10$ [30];

purchase price \$1.25, labor cost 85 ¢.

Case II, Biased Against Switching:

power, W

energy rate

energy-efficient two-lamp ballast (cost)

energy-efficient two-lamp ballast design life

energy-efficient 30-W lamp (rated life)

energy-efficient 30-W lamp (cost)

group relamping

two energy-efficient 30-W lamps and two-lamp ballast, $2W = 67$ W [22], $W = 33.5$ W/lamp;

$E = 3$ ¢/kWh (average in Ottawa, ON, Canada);

$2R_b = \$30$ [30] (purchase price \$16, labor cost \$14), $R_b = \$15$ /lamp;

$L_b = 60\,000$ h [25], $L_b = 90\,000$ h was used as a conservative value;

$L_r = 18\,000$ h [3];

$R_l = \$2.60$ [30] (purchase price \$1.75, labor cost 85 ¢, $R_l = \$3.50$ was used as a conservative value.

ACKNOWLEDGMENT

The authors would like to thank the members of staff at the General Electric Company, Nela Park, and those at BC Hydro, Vancouver, for comments on a previous manuscript. They gratefully acknowledge the contributions of M. Ouellette for computer assistance.

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