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Maximizing the Economic Benefits of Compact Fluorescent Lamps

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ABSTRACT

Energy efficient lighting greatly reduces the demand for electricity and its associated environmental impacts. The compact fluorescent lamp is a high efficiency alternative with a long life in continuous service. This paper examines the impact of on/off cycling on compact fluorescent lamp life. Experimental data and manufacturers' ratings determine a linear life function that includes both lamps' run times and on/off cycling. The paper develops economic cost functions and a maximum benefit optimization formulation to examine how lamp cycling and run time affects potential savings. Numerical examples test the formulation using various combinations of energy costs, lamp purchase prices, and on/off cycling.

INTRODUCTION

Energy efficiency and the impact of energy consumption on the environment are current topics discussed and researched widely. Increasing the efficiency of illumination world-wide can reduce electricity consumption and the associated production of green house gases. Many countries have already phased out the production of low-wattage incandescent bulbs (IBs) in an effort to increase energy efficiency in lighting (Waide, 2010). The U.S. government mandates that all incandescent bulbs from 40 to 100 watts be phased out by 2014 (Ramroth, 2008). Improvements in lightning technology have made higher efficiency alternatives such as Compact Fluorescent Lamps (CFLs) available. These devices use a quarter of the power of comparable IBs. The wide use CFLs will reduce greatly the electric energy required for commercial and residential lighting. Widespread utilization of CFLs will reduce stress on the power grid, improve national energy efficiency, and lower the emission of pollutants associated with energy production.

Along with the increased efficiency, CFL manufacturers claim average lamp lives that are eight to ten times longer than standard incandescent bulbs. They also project energy cost savings based on specific operating conditions and energy costs. Studies using average life times and costs show that consumers adopting CFLs can generally reduce consumer energy consumption and life-cycle costs (Ramroth, 2008). This large difference in lifetimes gives consumers the economic trade-off of purchasing high-cost, high efficiency lamps less frequently or low cost, low efficiency lamps more frequently, which adds economic discounting to the decision process (Kooreman, 1996).

Manufacturers' and independent testing agencies use a number of testing procedures to determine the expected CFL life. Consumer use of CFLs rarely conforms to manufacturers' laboratory conditions resulting in shorter than advertised life times and reduced cost benefits.

Consumers see different CFL performance when compared to controlled studies and manufacturers' life estimates due to a number of factors. Past studies show that standard fluorescent lamps have long lives in continuous service but their useful lives shorten considerably when subjected to on/off cycling (O'Rourke, & Figueiro, 2001). CFLs also exhibit this characteristic (Sullivan, & Drescher, 1993). The CFL starting method is a significant factor in determining the number of on/off cycles a CFL can withstand before failure (Chondrakis, & Topalis, 2009). Incandescent lamps have a different failure process that does not produce rapid aging due to on/off cycles. Incandescent bulbs fail due to filament hot spots formed from the uneven reduction of filament diameter caused by tungsten boil-off during operation (Agrawal, & Menon, 1998).

Soon consumers will have no choice but to adopt CFLs (Waide, 2010). The economic benefits of adopting CFLs depend on factors that include lamp life time and energy costs. A more realistic lamp life model that includes the life-shorting effects of on/off cycling will provide better economic benefit projections. Defining both CFL break-even time and maximum benefits more accurately during the transition period from IBs to CFLs will help energy managers and consumers make informed decisions about energy consumption for lighting and determine the optimum application for these lamps.

This paper presents experimental data and an economic model that quantifies the maximum economic benefit of CFLs utilized under different operating conditions. It examines how on/off cycling of CFLs impacts lamp lifetime and economic benefits. The goal is to determine what circumstances maximize the economic benefit of a CFL. This paper presents economic models for IB and CFL operation that include replacement costs and depletion of CFL lifetime due to on/off cycling. The paper proposes a benefit maximization formulation that includes a break-even constraint and linear lifetime function that includes the impact of lamp runtime and on/off cycling.

COMPACT FLUORESCENT LAMP LIFE UNDER HIGH-CYCLE RATES

Fluorescent lamps fail from two mechanisms both related to the lamps' filaments. CFLs operate by applying a voltage to filaments enclosed at the ends of the lamp. Emissive coatings on the filaments lower their work functions and allow electrons to disassociate from them at lower temperatures and voltage potentials (Hilscher, 2002). CFLs fail when the emissive coatings on the filaments evaporate to a minimum level (Haverlag, e*t. al*., 2002). Evaporation takes place at a slow rate in steady-state operation due to the lower temperature required to free electrons using the emissive coatings. This accounts for the long lives associated with standard fluorescent lamps in continuous service. The blackening at the ends of lamp tubes comes from tungsten evaporation and emissive coating deposits that indicate lamp aging.

Starting a CFL subjects the filaments to high potential differences that accelerate the loss of emissive material from the lamp filaments (Hilscher, 2002). This potential difference causes mercury atoms that are part of the gases inside the lamp to bombard the filaments causing the emissive coatings to sputter off at a high rate. Preheating filaments and limiting the currents after lamps start reduce the loss of coatings on start up. Severe lamp start damage occurs with instant-start electronic ballasts because they do not preheat lamp filaments (Haverlag, e*t. al*., 2002).

Many test procedures exist for determining the lifetime of standard and compact fluorescent lamps (O'Rourke, & Figueiro, 2001). Experimental data is time-consuming and costly to acquire due to the long lamp life and intensive labor required to monitor and maintain the test apparatus. Previous work conducted on linear lamps indicates that cycling lamps shortens lamp life, but this was conducted over 60 years ago and does not account for recent improvements in lamp construction. CFL manufacturers give consumers estimates of lamp life based on daily operating times of four hours per day but do not include the impact of life reduction due to starting.

Field use of CFLs subjects the lamps to a number of operating conditions. These operating conditions have variable lamp run times and on/off cycle frequencies that correspond to consumer habits. Table 1 summarizes three possible modes of CFL operation. Manufacturers do not publish data regarding the lifetimes of CFLs under various combinations of lamp runtime and cycles.

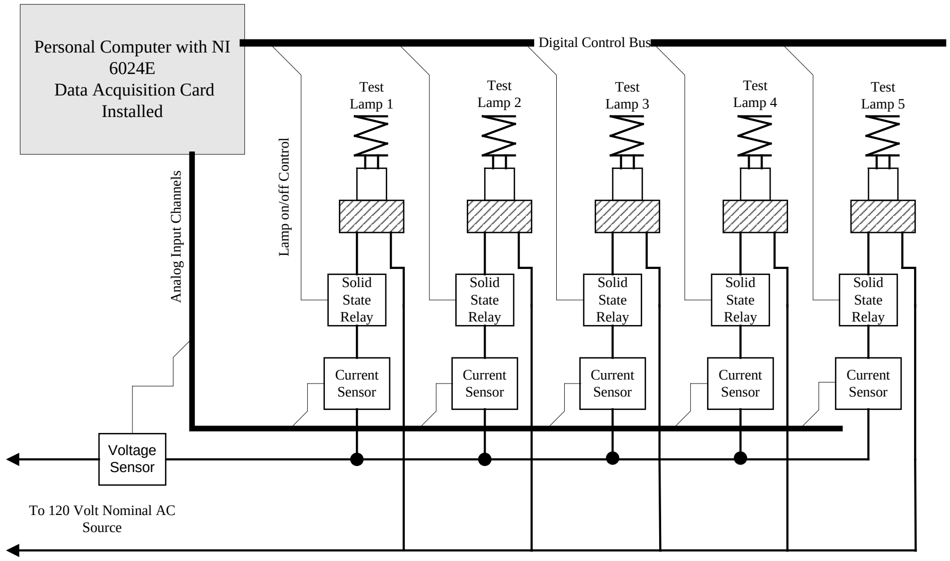
Figure 1 shows experimental apparatus for gathering data on lamp life using a computer controlled testing system to time and count lamp runtime and on/off cycles. This test setup was used to find the number of on/off cycles CFLs could survive by powering on the lamp and measuring its current flow to determine if it had successfully started. The apparatus tallied the total number of cycles until all lamps in the test failed. Lamps were sequenced on for two seconds and remained off for eight seconds. The apparatus monitored and recorded the lamp terminal voltage to verify that it remained within manufacturers' specifications. Initial tests included an incandescent bulb of equivalent light output to determine how on/off cycling affected the life of this type of lamp. The test sample consisted of 35, 26-watt GE Energy Smart$_{TM}$ lamps. Table A-1 in the Appendix lists the data and lamp ratings.

Figure 2 shows the compiled results of all experiments. The data were fitted to a Weibull distribution using

Table 1. Compact Fluorescent Lamp Usage Modes

Mode	On/Off Cycles	Lamp Run Time	Residential Usage Examples
1	Low	Low	Rooms and spaces entered very infrequently (closets, attics, etc.).
2	Low	High	Lamps and fixtures operating for several hours per day, (living, family or TV rooms).
3	High	Low	Frequently occupied rooms for short durations. (bathrooms etc.)

Figure 1. Computer Controlled CFL Experimental Apparatus.



Minitab software. These computations give a shape parameter, β=1.716 and a scale parameter, α=8220. The statistical distribution of operating cycles fitted to the test data is

$$f(n_{cfl}) = 3.285\times10^{-7}\, n_{cfl}^{\;0.716}\, e^{-\left(\frac{n_{cfl}}{8220}\right)^{1.716}} \quad (1)$$

Where: $f(n_{cfl})$ = probability distribution of CFL on/off cycles

n_{cfl} = number of CFL on/off cycles.

Equations (2) and (3) determine the mean and variance respectively of the distribution.

$$\mu = \alpha\Gamma\left[1+\frac{1}{\beta}\right] \quad (2)$$

$$\sigma^2 = \alpha^2\left[\Gamma\left(\frac{\beta+2}{\beta}\right) - \Gamma^2\left(\frac{\beta+1}{\beta}\right)\right] \quad (3)$$

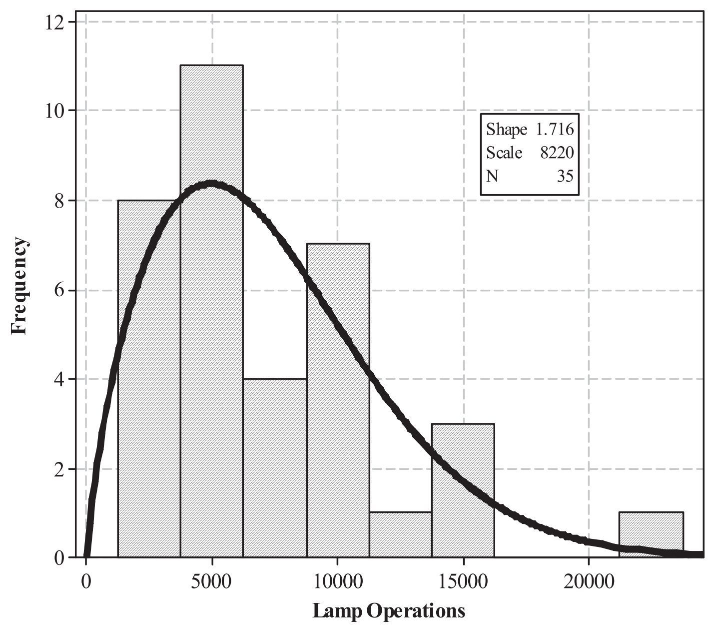
Where: $\Gamma(\,)$ = the Gamma function

μ = distribution mean

σ^2 = distribution variance

Substituting in the values of α and β from the fitted data gives a mean of μ=7329 and a variance of, σ^2 = 19,362,943. The standard deviation of the fitted distribution is σ=4400.

Figure 2. CFL On/off Operations to Failure with Weibull Fit



A chi-squared test for goodness-of-fit determines how well the proposed distribution matches the sample data. Appendix B shows the details of this calculation. The chi-squared test results support the hypothesis that the sample data come from a Weibull distribution with shape parameter β=1.716 and scale parameter α=8220 at a Type I error probability of 0.025. The calculation found a p-value of 0.059.

The mean value of the distribution represents the expected number of on/off cycles a large population of CFL's would survive before failing. The mean can be interpreted as the number of CFL-cycles/failure. Multiplying the mean number of on/off cycles by the cycle on-time of the CFL's for the test protocol gives the mean time-to-failure (MTTF) for the population. The on-time for the CFL tests was two seconds resulting in a MTTF of 4.07 CFL-hours/failure.

The variance and standard deviation of the fitted population distribution measure the population dispersion about the mean. Six standard deviations of on/off cycles will include 99.94% of the failures for the fitted CFL population distribution. After three standard deviations of on/off operations, 89.5% of the CFL population would fail while one standard deviation results in approximately 29% of the population failures.

BREAK-EVEN COST ANALYSIS OF CFLS

The lower power consumption and long lives of CFLs make them an attractive alternative to standard incandescent bulbs. Lamp manufacturers, electric utilities, and energy managers promote these facts to increase sales, reduce power demand, and increase energy efficiency. Comparing the initial costs, operating costs and depletion costs of both a CFL and a standard incandescent bulb quantifies the potential cost savings from adopting the lamps. This analysis also determines the minimum required lamp lifetime in terms of both on/off cycles and operating time to recover the higher initial cost of CFLs.

Equation (4) gives the total cost of purchasing and operating a CFL. This model includes the effects of both the operating time and the depletion of lamps due to on/off cycling.

$$C_{Tc}(t,n) = c_{pc} + p_c r_e t + \frac{c_{pc}}{\mu} n \quad (4)$$

Where:

$C_{Tc}(t,n)$ = total CFL cost as a function of the operating time and cycles ($)

c_{pc} = purchase price of CFL ($)

p_c = power consumed by the CFL (kW)

t = operating time of lamp (hours)

r_e = electric energy rate ($/kWh)

n = number of accumulated lamp cycles

μ = mean number of lamp cycles before failure

The first term in Equation (4) gives the initial cost of the CFL. The second and third terms define the operating cost of the lamp and the depletion of lamp value due to on/off cycling. The third term captures the impact of reduced lifetime as an additional cost due to lamp replacement based on the average number of on/off cycles. This representation assumes that the effects of lamp starting accumulate as a linear function of the number of lamp cycles.

The accumulated number of lamp cycles can be written in terms of an average number of operations per unit time to eliminate the variable n from Equation (4). Introducing the CFL cycle rate variable, θ, converts Equation (4) into the following equation.

$$C_{Tc}(t) = c_{pc} + p_c r_e t + \frac{c_{pc}}{\mu} \theta t \quad (5)$$

Where: θ = CFL on/off cycle rate in operations/hour

Equation 6 shows the incandescent bulb cost model as a function of operating time only. This equation consists of two terms; the first term represents the bulbs replacement cost while the second term gives the operating cost.

$$C_{Ti}(t) = c_{pi}\left[1 + \frac{t}{T_{Li}}\right] + p_i r_e t \quad (6)$$

Where: $C_{Ti}(t)$ = total incandescent cost as a function of the operating time ($)

c_{pi} = purchase price of incandescent lamp ($)

p_i = power consumed by the incandescent lamp (kW)

t = operating time of lamp (hours)

r_e = electric energy rate ($/kWh)

T_{Li} = Average lifetime of incandescent lamp (hours).

The incandescent bulb cost model includes multiple replacement costs because its average life is eight to ten times less than the average lifetime CFL manufacturers' claim. This equation recovers the replacement cost of the incandescent lamp linearly over the life of the bulb. This avoids discontinuities in the cost function that make optimal solutions difficult to compute.

Since rapid aging due to on/off cycles is not a factor in incandescent bulbs, its cost function does not include a term for bulb depletion. Experimental results gathered for this paper show that incandescent lamps could withstand over 50,000 on/off cycles without failure. This high cycle number coupled with the low purchase price of the incandescent lamp make the bulb depletion cost negligible.

Equating the cost functions for the CFL and the incandescent lamp and solving for t finds break-even operating time of the

CFL lamp. This is the time that a CFL must run to recover its higher initial cost from its lower energy consumption. This time varies with the electric rate and the CFL on/off cycle rate. Equation (7) gives the CFL break-even time as a function of the cycle rate for continuous recovery of incandescent bulb purchase price and constant electric rates.

$$t_{be}(\theta) = \frac{c_{pi} - c_{pc}}{r_e(p_c - p_i) + \frac{c_{pc}}{\mu}\theta - \left(\frac{c_{pi}}{T_{Li}}\right)} \qquad (7)$$

Where: $t_{be}(\theta)$ = break-even operating time of the CFL to recover purchase price.

MAXIMUM BENEFIT FORMULATION

Taking the difference between the total cost of incandescent lamps and CFL lamps finds the economic benefit of the CFL. Equation (8) shows the simplified result as a function of operating time and CFL on/off cycles.

$$B(t,n) = C_{Ti}(t) - C_{Tc}(t,n) = (c_{pi}\left(1 + \frac{t}{T_{Li}}\right) - c_{pc}) + r_e(p_i - p_c)t - \frac{c_{pc}}{\mu}n \qquad (8)$$

Where: B(t,n) = economic benefits ($).

A lifetime constraint that is a function of both the on/off cycles and the lamp runtime defines the operation limit of CFL's under various combinations of operating conditions. The experimental data collected from the on/off cycle testing and the manufacturers' lifetime estimates provide two points for an average lifetime constraint plot. This analysis assumes a linear relationship between on/off cycling and continuous operation lifetime of a CFL. The cycling test average operating time, t_c, is the product of the two second on-time and the average number of cycles a CFL survives. This point is derived from the experimental data.

Manufacturers give total operating lifetimes on the lamp packaging. This text lists the total average lifetime, in hours, and the conditions for the expected customer savings. The conditions specify the daily on-time. The average number of expected operations is the quotient of the total average lifetime and the specified daily on-time. This analysis uses an average lifetime of 8000 hours and a daily on-time of 4 hours. Table 2 lists the two data points. The variables t_m and n_m define the manufacturer's average on-time life and number of on/off cycles respectively.

Table 2. Compact Fluorescent Lamp Life Data

Data Point	Average On-time (Hr)	On/off Cycles
1 (Experimental Results)	t_c=4.1	μ=7329
2 (Manufacturer's Claim)	t_m=8000	n_m=2000

Entering these values into the point-slope form of the line gives a linear expression for CFL life.
Equations (9a-c) show the development of this equation.

$$n - \mu = \frac{(n_m - \mu)}{(t_m - t_c)}(t - t_c) \qquad \text{(a)}$$

$$n - 7329 = \frac{(2000 - 7329)}{(8000 - 4.1)}(t - 4.1) \qquad \text{(b)} \qquad (9)$$

$$n = -\,0.6665t - 7332 \qquad \text{(c)}$$

Equation (10) gives the normalized CFL life based on the two data points in Table 2.

$$\left(\frac{1}{N_{ic}}\right) \cdot n + \left(\frac{1}{T_{ic}}\right) \cdot t \le 1 \qquad (10)$$

$$1.364\times10^{-4} \cdot n - 9.092\times10^{-5} \cdot t \le 1$$

Where: N_{ic} = n intercept of CFL life line
T_{ic} = t intercept of CFL life line

The values of N_{ic} and T_{ic} derive from Equation (9c). Equation (10) is a linear expression for the decay of CFLs' due to continuous operation and on/off cycling. The equation assumes that a CFL will fail after a certain combination of operating hours and on/off cycles accumulate.

A parametric equation in θ plots the break-even cost line on the t-n axis. Equation 11 gives the expressions for the t-n points.

$$t = t_{be}(\theta) \qquad (11)$$

$$n = \theta \cdot t_{be}(\theta)$$

This line shifts left for lower and right for higher energy rates. Lower energy rates increase the operating hours required to recover the higher initial cost of the CFL.

Figure 3 shows the CFL lifeline and the break-even cost plots on the t-n graph along with upper and lower on/off cycles. Table 3 lists all the data points plotted on this figure.

These constraints form the solution set for the benefit maximization problem defined below. Any point to the right of the break-even line produces a positive benefit. The figure also plots manufacturers' average on-time, t_m and on/off cycles n_m as two dashed lines. This is the second data point given in Table 2.

The break-even cost line, the CFL life line, and a minimum number of operations shown in Figure 3 form the constraints of a benefit maximization problem. Equations (12a-d) define

Table 3. Plot Data for Feasible CFL Operating Region.

Break Even Line			Life Line		Upper Cycle Limit		Lower Cycle Limit	
θ	t (hrs.)	n	t (hrs.)	n	t (hrs.)	n	t (hrs.)	n
0.167	568	95	0	7,332	0	4,850	0	2,000
0.333	576	192	4.1	7,329	8,000	4,850	8,000	2,000
0.500	584	292	8,000	2,000				
0.625	591	369	11,000	0				
0.750	597	448						
0.875	604	528						
1.000	610	610						
1.125	618	695						
2.000	671	1,342						
3.000	744	2,232						
5.750	1,064	6,118						
6.000	1,107	6,644						

this problem. The objective function of the formulation is the monetary benefit of operating a CFL and is given by Equation (12a-e). Equation (12b) is the break-even constraint for a positive benefit from purchasing and operating a CFL. Equation (12c) is the CFL life line that is assumed to be a linear function of the CFL operation time and the number of on/off cycles. The inequality (12d) defines a minimum and maximum number of operations for a given CFL application. The inequalities in (12e) are the non-negativity constraints for the variables.

$$\max\ B(t,n) = \left(c_{pi}\left(1+\frac{t}{T_{Li}}\right) - c_{pc}\right) + r_e\left(p_i - p_c\right)t - \frac{c_{pc}}{\mu}n \quad \text{(a)}$$

Subject to:

$$\left[\left(p_c - p_i\right)r_e - \frac{c_{pi}}{T_{Li}}\right]t + \left(\frac{c_{pc}}{\mu}\right)n \le c_{pi} - c_{pc} \quad \text{(b)}$$

$$\left(\frac{1}{N_{Lc}}\right)n + \left(\frac{1}{T_{Lc}}\right)t \le 1 \quad \text{(c)} \qquad \text{(12)}$$

$$n_{max} \ge n \ge n_{min} \quad \text{(d)}$$

$$n \ge 0,\ t \ge 0 \quad \text{(e)}$$

This is a two dimensional linear optimization problem easily solved using a number of algorithms (Bazaraa, & Jarvis, 1977).

NUMERICAL EXAMPLES AND DISCUSSION

The following numerical example utilizes the previous experimental and theoretical results. This example assumes that a 100 W incandescent lamp is replaced with a CFL that has an equivalent light output. Manufacturers suggest a 26 W CFL to replace a 100 W incandescent lamp. Table 4 lists the values

Figure 3. Constraints for CFL Operation and Benefit Maximization.

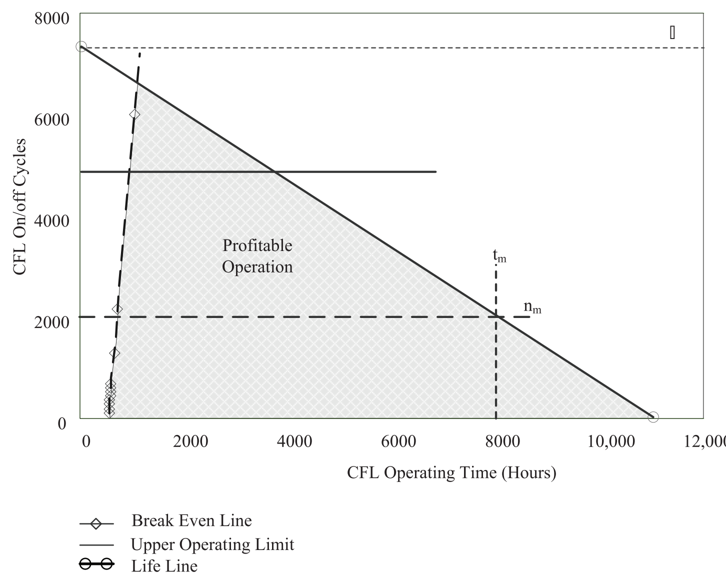


Table 4. Numerical Example Base Case Data

Parameter	CFL (GE energy smart)	Incandescent bulb
Power (kW)	0.026	0.10
Purchase Cost ($)	3.50	0.25
Average Lifetime (Hours)	8000	1000
Energy Cost ($/kWh)	0.0751	0.0751

[1]*Typical electricity costs in Midwest U.S. circa 2009*

Table 5. Optimization Results with Parameter Variation

	Parameters			Optimal Values		
Case	c_{pc} ($)	r_e ($/kWh)	n_{min} (operations)	B(n*,t*) ($)	t*[1] (hrs)	n*[1]
1	3.50	0.075	2000	43.08	8000	2000
2	2.50	0.075	2000	44.08	8000	2000
3	1.25	0.075	2000	45.33	8000	2000
4	3.50	0.100	2000	57.88	8000	2000
5	3.50	0.125	2000	72.68	8000	2000
6	3.50	0.150	2000	87.48	8000	2000
7	3.50	0.075	3000	34.34	6500	3000
8	3.50	0.075	4000	25.61	5000	4000
9	3.50	0.075	5000	16.87	3498	5000

[1]*n* and t* indicate optimal values of n and t.*

Table 6. Break-Even Operating Times

	Parameters				
Case	c_{pc} ($)	r_e ($/kWh)	n_{min} (operations)	θ=n*/t*	Break-Even Time $t_{be}(\theta)$ (hrs)
1	3.50	0.075	2000	0.25	572
2	2.50	0.075	2000	0.25	394
3	1.25	0.075	2000	0.25	174
4	3.50	0.100	2000	0.25	432
5	3.50	0.125	2000	0.25	347
6	3.50	0.150	2000	0.25	289
7	3.50	0.075	3000	0.46	583
8	3.50	0.075	4000	0.80	600
9	3.50	0.075	5000	1.43	635

of power consumption, purchase price, lamp average lifetimes, and energy price initially used in this base case example. Table 5 summarizes the results of optimization computations run with these base values and with parameters varied. The table lists nine cases that show the impact on economic benefits of varying CFL purchase price, energy costs, and minimum operating cycles. Table 6 lists the break-even times resulting from parameter change

The first three cases in Table 5 indicate that the variation of CFL purchase price does not have as strong an impact on the potential benefits of adopting it as do the variations in energy cost and operating cycles. In these three cases, a 64% reduction in CFL purchase price only results in a 5% increase in benefit. Cases four through six demonstrate that energy cost variation produces proportional increases in benefits. The benefits increase to 103% of the base case in case six. Cases seven through nine examine the relationship between the minimum number of operating cycles and CFL benefits. A 50% increase in operating cycles reduced the benefit by 20% from the base case (Case 1). The variable n_{min}, the minimum number of operating cycles, varies 67% over cases seven through nine results in a 51% change in benefits. Study cases one through six produce the same optimal operating point. Cases seven through nine have different optimal operating points determined by the intersection of the CFL life line and the minimum number of operating cycles.

The summary of the break-even times in Table 6 show that this value is most sensitive to changes in the purchase price of the CFL. Cases one through three exhibit a 70% decrease in the break-even time for a 64% reduction in the CFL cost. A 50% change in energy price produces a 33% change in the break-even time with a constant purchase price. Varying the number of operating cycles produces less than one percent of variation in the CFL break-even time. The ratio of the optimal operating time and on-off cycles produces the cycle rate parameter, θ, for these calculations.

The results of these optimization cases suggest some easily applied “rules of thumb” that will help consumers maximize their benefit potential from CFLs. On/off cycling of CFLs greatly reduces their lifetimes in field usage so mode 2 operation (low on/off cycling, high lamp run time from Table 1) will give the highest economic benefit. High run time also helps overcome the high initial cost of CFLs more quickly as the break-even time analysis shows. The cost models show that CFLs accrue savings as a function of the lamp run time, so the more the CFL operates in application the greater the savings potential. Lamps applied in mode 1 locations will provide economic benefits but will require a much longer time to recover the higher initial CFL cost since run time is minimal.

Although on/off cycling of CFLs can greatly reduce lamp life and potential economic benefits, most practical applications will still produce even small benefits due to low lamp break-even time. Figure 4 shows partial test data for mode 3 operation of three CFLs plotted on the lamp operating characteristic. These three data points do not achieve maximum economic benefit but still recover their initial cost. Higher energy rates and lower CFL purchase prices lower the break-even time to approximately 20% of the average incandescent bulb lifetime. CFL manufacturers' and energy conservation professionals must emphasize this point. The high initial cost coupled with premature lamp failure, (less than manufacturers' claims of 5 years typically) gives consumers a false impression of the lamps cost and energy saving potential. This can hinder the wide acceptance of the light source.

Residential consumers may fail to realize significant cost reductions in their monthly utility bills due to the small consumption associated with lighting relative to other household appliances and electricity consuming processes. Consumers should consider the application of CFLs as an easily executed, low cost method of increasing the overall energy efficiency of their homes. This should be the first step in raising consumer awareness of how and when they use energy and lead to the examination of other systems that can produce more significant reductions in electricity consumption and its associated costs.

This study adds to the performance data available on CFLs but fails to address other key factors related to lamp lifetime in field application. The collected data and the associate economic analysis do not address the impact of heat on the electronic ballast components. This factor may significantly shorten lamp lives and reduce potential economic benefits. The study also assumes that the lifeline of CFLs is linear based on only two data points. On-going tests will generate more data points for better estimates of the relationship between lamp on/off cycles and run-time. Assuming continuous accumulation of incandescent bulb replacement cost removes the discontinuity in its total cost function but overestimates its operating cost slightly.

CONCLUSION

This paper presented experimental data from rapid on/off cycling of CFLs and developed from it an economic model for determining maximum economic benefits of purchasing and operating these lamps. The collected data provided an upper limit data point for a linear CFL lifetime function. This function included the effects of on/off cycling and runtime. The paper developed a linear optimization formulation to determine the maximum economic benefit of replacing incandescent lamps with CFLs. Numerical examples tested the formulation and determined its sensitivity to parameter variations such as energy cost, CFL purchase price, and total on/off cycles.

The numerical examples show that CFL benefits are most sensitive to changes in energy price and the total number of operating cycles. The break-even times are most sensitive to lamp purchase price. The high efficiency of the CFL compared to the incandescent bulb allows the CFL to break-even at run times that are a low fraction of the average life of the lamp. This point should be emphasized when educating consumers. The break-even time becomes lower as the cost of electricity increases.

Lamp applications that require long run times and infrequent on/off cycling provide the largest benefits. This application is similar to the testing cycles adopted by most manufacturers', which should give average lifetimes closer to advertised values. Higher cycling reduces the lamp lifetime and benefits. The reduced lifetimes are still sufficiently long to recover the higher purchase price of the CFL.
More testing of the CFL life under various operating conditions will provide more data points and a better approximation of the CFL life line function.

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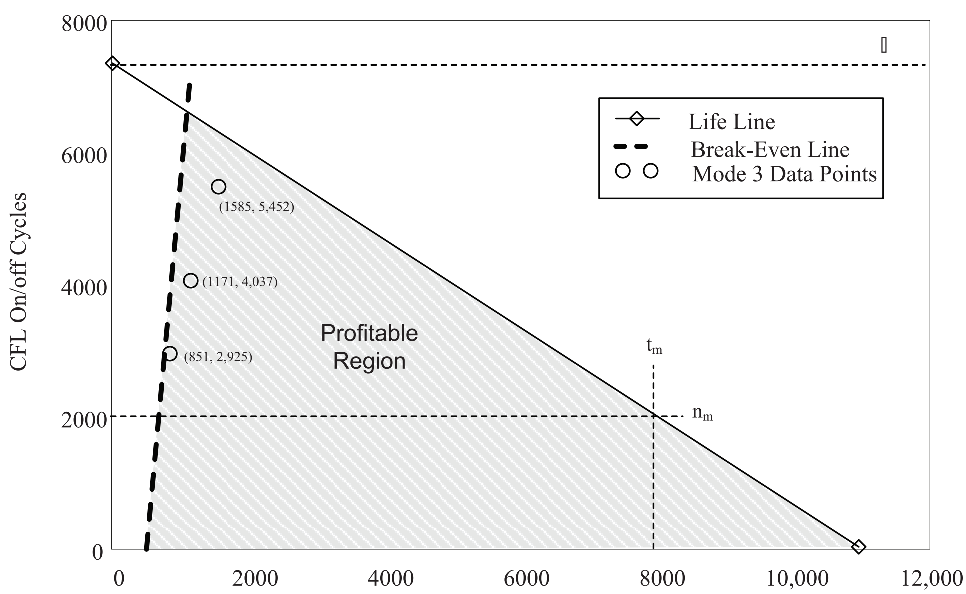
Figure 4. Mode 3 CFL Operation Data Points within Potential Benefit Area of CFL Operating Area. CFL Purchase Price =$3.50, Energy Cost=0.075 $/kWh, IB Purchase Price=$0.25.



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Appendix A: Experimental Data From On/off CFLs Tests

Table A-1 - Experimental Data from Rapid Cycling Tests

	Lamp 1		Lamp 2		Lamp 3		Lamp 4		Lamp 5	
Test Group	On/off Cycles	ET[1] (Hr)	On/off Cycles	ET (Hr)	On/off Cycles	ET (Hr)	On/off Cycles	ET (Hr)	On/off Cycles	ET (Hr)
1	6,405	3.556	12,043	6.691	5,572	3.096	5,998	3.332		
2	5,747	3.193	4,865	2.703	6,316	3.509	15,447	8.582		
3	9710	5.394	6,017	3.343	3,246	1.803	5,515	3.064		
4	6,856	3.809	10,639	5.911	10,561	5.867	10,903	6.057		
5	10,518	5.843	9,631	5.351	15,338	8.521	2,738	1.521		
6	14,262	7.918	7,796	4.331	9,577	5.321	22,141	12.30	2,867	1.593
7	2,065	1.147	2,738	1.521	5,653	3.141	3,767	2.093	2,448	1.360
8	4,786	2.659	4,429	2.461	1,838	1.021	3,947	2.193	2,495	1.386

[1]*Elapsed Time in operation.*

All tested CFLs were GE energy smart™ 26-watt lamps.
Rated voltage: 120 Vac
Rated current: 390 mA
Rated frequency: 60 Hz
Rated light output: 1750 lumens
Light temperature: 3900K

Appendix B: Chi-Squared Goodness-of-Fit Calculation Details

Sample Size: N_s=35
Number of Bins: N_b=10
Bin index: b=1… N_b
Observed Frequency in bin: N_{fb}
Cumulative probability distribution for Weibull: $F(n) = 1 - e^{\left(\frac{n}{\alpha}\right)^{\beta}}$
Bin probability found by subtracting values of F(n) found at bin limits: $P(n)_b = F(n_H) - F(n_L)$
Expected values given by: $E(n)_b = P(n)_b \, N_s$
Degrees of freedom for χ^2: DF=N_b-1-(# of parameters)

Chi-Squared value: $$\chi^2 = \sum_{b=1}^{N_b} \frac{\left(N_{fb} - E(n)_b\right)^2}{E(n)_b}$$

Table B-1. Computational Results

Bin b	Range of n (n_L-n_H)	Cumulative Probability F(n)	Bin Probability $P(n)_b$	Expected Bin Value $E(n)_b$	N_{fb}	Contribution to χ^2
1	0-1250	0.0387	0.0387	1.355	0	1.355
2	1250-3750	0.2290	0.1903	6.661	8	0.269
3	3750-6250	0.4647	0.2357	8.248	11	0.918
4	6250-8750	0.6715	0.2068	7.238	4	1.449
5	8750-11,250	0.8197	0.1483	5.189	7	0.632
6	11,250-13,750	0.9109	0.0911	3.190	1	1.503
7	13,750-16,250	0.9601	0.0492	1.721	3	0.950
8	16,250-18,750	0.9837	0.0236	0.827	0	0.827
9	18,750-21,250	0.9939	0.0102	0.358	0	0.358
10	21,250-23,750	0.9979	0.0040	0.140	1	5.283
					Total χ^2	13.544