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ENERGY AND LIGHTING DECISIONS

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Introduction

This report reviews the fundamental principles of lighting and uses them to evaluate energy-conserving lighting equipment and techniques. The primary goal is to demonstrate that today the selection of the proper lighting components and systems is complex. It requires a knowledge of the characteristics of light sources and their interactions with the auxiliary equipment and the environment. Furthermore, there are subjective aspects of lighting that affect comfort and moods and thus productivity, and are difficult to quantify.

Thus, before we list the energy-conserving lighting equipment presently available, we discuss selected lighting topics. We first address the simplistic way in which lighting is commonly approached. Then we present an argument as to the critical nature of the lighting decision. We briefly review the history of light sources and discuss the important performance characteristics of light sources and auxiliary equipment. In the final sections we discuss and evaluate lighting equipment in terms of its applications and characteristics. Familiarity with the fundamental characteristics of the elements of lighting equipment will also permit more judicious appraisal and use of lighting concepts that may be introduced in the future.

Traditional Lamp Descriptions

Of all the common products we may purchase, light bulbs are about the only ones that we think of in terms of a single input characteristic. That is, we require a 100-watt bulb for reading, a 25-watt bulb for the hallway, etc. This direct association between the lamp's output function and its input power was perfectly adequate in the early days of electric lighting when there was only one type of electric lamp. Today, however, with the host of different light sources there is no single relationship between input power and light output. Persisting in thinking this way subjects one to errors is judgement that are magnified by the limited specifications and descriptions of lighting products found in catalogs. Furthermore, even if both input power and light output are considered it is still not sufficient information for selecting a lighting system.

Critical Value of Lighting

The value of lighting transcends its initial and operating costs. In the workplace, one installs a lighting system to illuminate visual tasks in order to maintain workers' productivity. The annual cost of lighting a space is about one dollar per square foot, only a hundredth of the annual cost of a worker at over on hundred dollars per square foot. Thus, any lighting system that reduces energy consumption is not cost effective if it reduces productivity more than a few percent. Though difficult to quantify, the relationship between lighting parameters, visual performance, and productivity does exist. The goal is to reduce energy consumption and to increase productivity, or at least to maintain it.

Lighting History

Table I lists the light sources in use today, the year they were introduced, and an efficacy value typically associated with each (efficacy varies with the input power of the source light). It is evident that gas-discharge lamps are more efficacious than incandescent lamps. By 1969 only six new sources had been introduced since the advent of electrical lighting which reflects the conservative nature of the lighting industry. After 1973 the rate of introductiôn of new products increased in response to the rising cost of electrical energy (see Table II).

To better understand present and future lighting application trends, an examination of the use of light sources over the years is useful. Table III lists the six light sources and their proportional use in the residential, commercial, industrial, and outdoor lighting sectors.

Our estimate of each sector's use of each light source is denoted by a number from 1 to 10; 1 representing 10% and 10, 100%. For example, in 1960 the commercial sector used 20% incandescents and 80% fluorescents.

Use of the incandescent lamp in all lighting sectors has decreased as new light sources have become available. The incandescent will continue to dominate in the residential sector, but the use of fluorescents will grow. The compact fluorescent lamp with good color-rendering phosphors will stimulate this market penetration for applications that have long hours of annual use. Use of MH lamps will grow in both the industrial sector and outdoor applications where good color rendering is important, such as stadiums where there is TV coverage of events. HPS lamps will be used less in the industrial sector, particularly manufacturing sites, but more in roadways and parking areas. The MV lamps will gradually be replaced by either the MH or HPS lamps, primarily due to the MV lamps low efficacy; its use as a general illumination source will be very limited. The LPS source is used for roadways, parking areas, and security lighting, though not widely in the U.S. because of its low color-rendering index.

An interesting relationship is illustrated in Figure 1, which plots the efficacy of light sources and the highest recommended illumination levels for a visually difficult office task from 1910 to 1980. As more efficient light sources became available higher illumination levels were recommended until 1970 when this trend was reversed. These trends reflect the controversy and confusion that still exists in the professional organizations in establishing recommended lighting levels.

As yet, there are no scientifically verifiable techniques for establishing optimum lighting levels, but the IES has relied on the consensus of lighting experts who have based their recommendations on considerable experience and knowledge gained over the years. We should be skeptical of recommendations of others less experienced. Too often reductions in illumination levels are justified based on the lack of a negative response by workers or building occupants. Surprisingly, the human eye is a poor judge of light levels since the pupil size adjusts to the quantity of light to regulate the amount entering the eye. However, changing light levels can adversely affect productivity.

Lamp Characteristics

Table IV lists characteristics of light sources that are important when selecting equipment for a particular application. The six different light sources are evaluated with respect to each other in terms of the characteristics, defined as follows:

Efficacy - The amount of visible light produced per input power (lm/W).

Intensity - A measure of the light flux emanating in a solid angle from a point on a light source.

Color Temperature - A measure of the color of a light source. Color temperature is expressed as the temperature (°K) of a black body having the same color as the light source.

Color Rendering - A measure of how well a light source renders the color of a set of references relative to a black body at the equivalent color temperature. The color-rendering index (CRI) runs from 0 to 100.

Glare - Discomfort-causing brightness or intensity of a source or surface.

Source Geometry - The physical shape and size of the light source.

Dimmability - The ease and practical range of dimming a light source.

The range of values for some of the characteristics indicates that lamp designers can control that particular lamp characteristic. The color characteristics for the fluorescent and MH lamps can be altered by the type of phosphors and gases employed, respectively. None of the light sources have all of the most desirable attributes for a particular application; one must weigh the characteristics based on their importance in the application. For example, color rendition is very important, in some retail shops but less important in offices and outdoor lighting.

Another important parameter of the fluorescent lamp is its minimum lamp wall temperature (MLWT). The MLWT determines the mercury vapor pressure and affects the lamp's light output, input power, and efficacy. Figure 2 shows the change in the three parameters for a standard magnetic ballast and 40-watt F40 lamp. Lamps are designed to operate at an MLWT of about 40°C for maximum efficacy. Two-lamp air-handling fixtures operate at this temperature while in four-lamp enclosed fixtures the MLWT can approach 55-60°C, which can decrease the light output of each lamp by 20-25% (Figure 2). Figures 3 and 4 compare sensitivity to MLWT of different types of lamps and ballasts, respectively. The 35-watts krypton-filled lamps are more sensitive to MLWT than the standard argon-filled 40-watt lamps. Some solid-state ballast regulate the lamp power and reduce sensitivity of the lamps to MLWT better than the core-coil ballasts, as shown in Figure 4.

Each light source and system is subject to a decrease in light output with operating time and is called as lumen depreciation. The total lumen depreciation is the sum of the decrease in light output of the lamp over time (lamp lumen depreciation) and a decrease in the efficiency of the fixture and room due to the accumulation of dirt and dust on the reflecting surfaces and lenses (luminaire dirt depreciation). Figures 5 shows lamp lumen depreciation for several light sources and Figure 6 shows luminaire dirt depreciation curves for one particular fixture in a clean and dirty environment. After a few thousand hours, the combined depreciation of a system can decrease the light output by 30-50%. The initial light levels can be restored by relamping and cleaning surfaces of fixtures and walls. Vendors sometimes offer to install devices and strongly recommend relamping and cleaning. However, a few vendors claim that the increase in light output is due to their devices instead of the maintenance process.

<u>Cost of Light</u>

One measure of the effectiveness of a light source is to determine the cost of producing its total flux output. One metric has been used based on the cost per one million lumen hours that includes the initial cost, the operating cost, and the labor cost to replace a lamp. The equation is:

$$\text{Cost}(\$)/10^6 \text{ lm-h} = \frac{[IC(\$) + OC(\$) + LC(\$)]}{LO(lm) \times L(h)} \times 10^6;$$

where:

IC = Initial Cost ($)
OC = Operating Cost = Power (W) x Life (L) x Electric Cost (EC) = P x L x EC
LC = Labor Cost ($)
LO = Light Output (lm)
L = Life (h)
EC = Electricity Cost($/kWh)

$$\text{Cost}/10^6 \text{ lm-h} = \frac{IC}{LO \times L} + \frac{EC}{LO/P} + \frac{LC}{LO \times L} \times 10^6 .$$

The final equation relates the light output (LO), lamp life (L), and cost of energy (EC) with the lamp efficacy (LO/P) (lm/kW). The relationship is a good measure when comparing the same types of light sources. When comparing different types light sources, one must weigh in the other qualities. We can use the equation to find the cost/10^6 lm-h for the 75-watt lamp:

$$\text{Cost}/10^6 \text{ lm-h} = \frac{\$0.70}{1190 \times 750} + \frac{\$0.75}{15{,}900} + \frac{\$5.00}{1190 \times 750} \times 10^6$$

$$\text{Cost}/10^6 \text{ lm-h} = .80 + 4.70 + 5.60 = \$11.10$$

Table V lists the parameters for some lamps and shows the cost results. Light output and life are parameters that significantly affect initial costs and labor costs. The only parameters that influence the operating cost are efficacy and the cost of energy. The operating cost of gas-discharge lamps is considerably lower than the incandescent lamps because of the greater efficacy and longer life of the gas discharge lamps.

Input Characteristics of Discharge Lamps

The incandescent lamp is a simple resistive load and its effect upon the line can be characterized by the power, voltage and current. Gas-discharge lamps, however, require auxiliary circuitry (ballasts) to properly condition the electrical input power to the lamp. The circuits employ nonlinear components and poorly designed ballasts may drastically alter the input power, which can affect the life of the lamp and/or cause serious problems in the generating source. The input characteristics that affect the line are:

• *Power Factor*	For power used, utilities must supply greater volts-amperes, increased I^2R losses in distribution system, can overload transformers.
• *Harmonics*	Increase I^2R losses in line, can overload neutral line in three-phase systems, cause interference.
• *Electromagnetic Radiation*	Interferes with other electrical systems.

The input characteristics affecting the lamp are:

• *Ballast Factor*	A manufacturing tolerance that determines the light output of a lamp relative to the manufacturer's rating found in the catalogs.
• *Regulation*	Change in light output for a change in either the input voltage or the temperature of the lamp.
• *Flicker*	Modulation of the light that may cause discomfort.
• *Filament Voltage*	Needed to heat filament to maintain rated lamp life.
• *Current Crest Factor*	The ratio of peak to rms lamp current. If too high, lamp life will be shortened.
• *Starting Voltage*	If starting requires too high a voltage, lamp life will be shortened.

Lighting Application

Table VI lists the three general types of lighting applications for which the cost of energy is a consideration. The costs that are of primary concern in each type of application are indicated.

Retrofit entails replacement of an installed system with a new system. The savings from the reduced energy consumption must exceed all of the installation costs of the new system. A retrofit lighting system must have low installation costs, and must require minimal changes in the electrical distribution system (wiring in the ceiling) and no change in the building structure.

Lighting system renovations are generally made 20 years after initial installation. Renovation implies a commitment to new fixtures and changes in the electrical distribution system, but systems that would require changes in the building structure are generally considered too costly. Hence, the major concerns in lighting renovations are the initial and operating costs of the new lighting system.

Early in the building construction process the architect, in consultation with the lighting designer, can alter the building design at a reasonably modest cost to accommodate a desirable lighting system or technique.

LIGHT SOURCES

Fluorescent Lamps

To illustrate the many types of fluorescent lamps that are available, we will describe a few of the F40, four-foot, rapid-start fluorescent lamps. Table VII lists eight different F40 lamps, along with their light output, ballast factor with a Certified Ballast Manufacturter-rated (CBM) ballast, color temperature, and color rendering index (CRI).

The first lamp is the industry standard: argon filled, 1.5 inches in diameter, with a cool-white phosphor. With a CBM-rated ballast, the ballast factor is 0.95, providing at least 2990 initial lumens, which is 5% less than the manufacturer's rated output.

Number two lamp is called an energy saving lamp and is back-filled with a krypton gas. This lamp presents a different electric load to the same CBM ballast, resulting in a lower ballast factor of 0.87. Notice that the lamp is rated to use only 34 watts. This lamp was introduced to compete with devices and methods to lower light levels in existing spaces. The lower ballast factor results in a light output decrease of 15% lower than the 40-watt F40 lamp's, instead of the 7% decrease one would expect based on the manufacturer's ratings in their catalog. The energy-saving lamp is more efficient (6%) because of the use of a litewhite phosphor with an emission spectra rich in yellow. However, the system efficacy is about the same because of increased ballast losses. Note the difference in color temperature, as well as the lower CRI. Most of the energy savings of this lamp are due to the 15% lower light output.

The third lamp is like the standard 40-watt argon filled lamp, but employs the litewhite phosphor to increase the light output. The fourth lamp is similar to the energy-saving lamp, but filament power is removed after the lamp is started to further increase its efficacy. Unless a sturdier filament is used there will be a reduction in lamp life. One manufacturer de-rates the lamp life by 25% when operating standard lamps in this mode. The fifth lamp is a new one-inch-diameter lamp (T-8), that uses rare-earth phosphors. The small diameter and new phosphor contribute to a higher efficacy as well as an improved CRI. This lamp employs a special ballast so no ballast factor is available to compare with the CBM ballasts. The last three lamps in the table are standard F40 lamps with rare earth phosphors. They show that rare-earth (narrow-band) phosphors with different color temperatures can be used to obtain a high CRI and maintain high efficacy.

We now have a wide range of lamps for particular applications; the choice would depend on which lamp characteristics are more important for a particular use. For example, in retrofits to lower illumination levels, one can select a lamp and ballast with a low ballast factor and less light output. In new construction and renovations one would select a lamp with high light output since fewer fixtures, lamps and ballasts would be needed. This would reduce both the initial costs as well as operating costs to meet a specified average light level. For retail applications where color rendering is sometimes important one would select the high-CRI lamps.

Incandescents and Replacements

There are several fluorescent lamps that are designed to be used in Edison-type sockets, which previously used incandescent lamps. The list of efficacious replacements now includes energy-saving incandescents, the compact and adaptive circline fluorescents, reflecting incandescents, and incandescents with selectively reflecting coatings. Table VIII lists the light output and life of several standard incandescent lamps and compact fluorescent lamps for comparing the different sources.

The energy-saving incandescents are filled with a krypton gas that reduces the rate of evaporation of tungsten from the filament. This permits operation of the filaments at higher temperatures, increasing efficacy by about 2% to 4%, and increasing lamp life.

The reflecting incandescents are coated internally with an aluminum film, which reflects the light emitted toward the rear of the fixture to the task. This does not increase lamp efficacy, but directs more of the generated light on the task by reducing the spill or misdirected light. Lamps are available that are coated with a selectively reflecting thin film that is transparent to the visible radiation and reflects the infrared radiation back onto the filament. When heated to a higher temperature in this way, the filament emits more visible radiation than it does at lower temperatures. These lamps are now available for high-ouput tungsten-halogen (10,000- and 32,000-lumen) lamps and increase their efficacy by 25%, from 25 to 33 lumens per watt. In the near future, a manufacturer will introduce a 1750-lumen lamp based on the same technology with an efficacy approaching 30 lm/W.

The most efficacious replacements for incandescent lamps are the circline and compact fluorescent lamps (Table VIII). These lamps have many commercial uses and will soon penetrate the residential market. In addition to their high efficacy, typically 40 to 60 lm/W, they have a long life (~10,000 h). They also employ the rare-earth phosphors, which gives them a high CRI and a color appearance identical to an incandescent lamp's (a color temperature of 2800°K). They are a low intensity source, limiting the maximum light output of a reasonably sized lamp to that of a 1210-lumen 75-watt incandescent lamp. A compact lamp comparable in size to an incandescent bulb requires a solid-state ballast to attain the higher light output. The compact lamps operated with magnetic ballasts provide no more light than an 890-lumen 60-watt incandescent. It is evident from the table that there is no single relationship between the power and light output of these lamps, and comparisons must be based on light output along with other characteristics.

Efficacy is a characteristic that varies with light output, and using stereotyped ideas of a light source can lead to poor choices. For example, it is common practice to associate high efficacy with HPS lamps. However, as shown in Table IX its efficacy decreases significantly for the low light output lamps. Though the 1000-W, 140,000-lm HPS lamp achieves an efficacy of 132 lm/W, the 35-watt HPS lamp is less efficacious than the 40-watt fluorescent. Comparisons of efficacy are instructive only if made between lamps of equivalent light output.

FLUORESCENT BALLASTS

One of the most significant technologies introduced in the past few years is the solid-state ballast. It performs the same function as a magnetic ballast: it starts the discharge and safely limits the current through a fluorescent lamp. The solid-state ballast operates the lamp at high frequency (~20,000 Hz), which increases lamp efficacy. High-frequency operation, coupled with the solid-state ballast's higher efficiency in transforming input power to the lamp ((87% vs. 79% for the core-coil ballast), increases system efficiency by 20 to 25%. Recent material improvements in the magnetic ballasts have further increased their efficiency to 82%. However, the ballast factors of these new ballasts from various manufacturers do vary. The ballasts with the lower input power generally have correspondingly lower lamp light output. To evaluate the product's usefulness for an application the ballast factor for the lamp-ballast system must be known, and the input characteristics affecting the line and lamp must also be evaluated.

OVER-ILLUMINATION

It is generally accepted that most buildings constructed in the past were excessively illuminated. Many new devices reduce input power and illumination levels proportionally. Some marketing literature has been less than candid in the description of the products, e.g., making false claims of increased efficacy. The performance of these devices must be carefully reviewed to assure oneself that the product is accurately represented and is suitable for the application.

Delamping

Delamping is one of the most cost effective techniques to reduce light levels. The reduction in both light and power is about 50%. One must be certain to disconnect the power to the ballasts as otherwise they will still draw current. A possible disadvantage is an even luminance pattern of the lens that may affect the aesthetics of the space.

Phantom Tube

A phantom tube is a lamp that contains a capacitor and emits no light and replaces one lamp in a two-lamp fluorescent ballast system, to convert a two-lamp a one-lamp system. The power is reduced by 67% and the light output by 75%. This is a significant reduction in light with a 10% decrease in system efficacy. The emission pattern from fixtures fitted with this device also appears uneven.

Current Limiters

The current limiter is a device that is generally hard-wired into a two-lamp F40 fluorescent system, preferably between the ballast and the lamp. Different models reduce the light output by 20, 30 or 50%. At best, the power reduction is proportional to the light reduction with no loss of efficacy. One must remember that there is an installation cost associated with these systems. Some models are wired on the input side of the ballast and reduce power factor and lower filament voltage, which may reduce lamp life. Some manufacturers claim that their devices have extraordinary performance characteristics and charge high prices for them. However, the current limiter is a simple device and any such system with proven reliability and a reasonable price should be adequate.

Low-Ballast-Factor Ballasts

Several magnetic and solid-state ballasts are designed with a 75% ballast factor, which also makes them useful for reducing lighting levels. The decrease in illumination can be determined from the ballast factor and the lamp to be used.

Specular Reflectors

Specular reflectors are carefully designed, highly reflective sheets of silver or aluminum that are installed in fluorescent fixtures. Manufacturers recommend them as a retrofit in four-lamp fixtures and claim that about the same light level can be maintained by removing two lamps and installing the reflector. The reflectors tend to focus the light beneath the fixture, changing the light distribution patterns, so using a single measure of the light directly beneath the light fixture will underestimate the average light level decrease. When photometers are used to measure the total light flux from the systems they show that the total light output is decreased by 41%. Accompanied by a decrease in power of 48%, this does yield a gain in fixture efficiency of 10 to 12%, but the installed cost of these reflectors is very high. The manufacturers' claims may rely on customers' following their recommendations that the fixtures be cleaned and relamped. While this is a good idea, one should be aware that the light gained by this maintenance can be significant and should not be attributed to the specular reflectors.

Energy Button

The energy button is a diode or a thermistor that is placed in the socket of an incandescent lamp. The diode blocks one half of the duty cycle, reducing the power to the lamp by 40% and the light output by 75%, which represents a significant reduction in efficacy. For example, a diode placed in a socket of a 100-watt, 1750-lumen lamp reduces the input power to 60 watts and light output to 438 lumens. Unless the cost of replacing a light bulb is a major consideration, using a 40-watt, 480-lumen bulb would be more cost effective (see Table VII).

The thermistor is a similar device that reduces the initial surge of current and slowly heats up to operate the lamp at a slightly lower than normal voltage, but this also makes the lamp operate less efficaciously. These devices do extend bulb life by a factor of about two by reducing the initial power surge. A new bulb on the market uses a diode inside the glass envelope. Its characteristics are the same as those of a lamp in with a diode in the socket.

The selection of these types of devices should be determined by an economic analysis considering operating cost, light output, and replacement cost. Many vendors claim diodes cause little loss of light and suggest their use in higher-wattage, higher-light-output bulbs if more light is required. This will produce light less efficiently than a standard light bulb, and will generally not be cost effective unless there is a relatively high labor cost to replace a lamp.

Personnel Sensors

Personnel sensors detect the presence of motion in a space by ultrasonic, infrared, optical, or, audio techniques. If a room or space becomes occupied the sensor activates a relay to turn lights on, and if the space is vacated, after a short period (4 to 10 minutes) the lights will be switched off. These systems are relatively expensive and operate most effectively in a one- or two-person space. However, in a one-person area the device will control only a small amount of power--100 or 200 watts of lighting. In order to be cost effective the space must be vacant a considerable portion of the day. Particularly good applications of these devices are spaces that are used only occasionally, such as copying rooms and filing areas. Before installing these automatic sensors one must be certain the constant activation of the device turning the lights on and off will not disturb occupants in adjacent areas or adversely affect the aesthetics of the space.

SUMMARY

We have briefly reviewed the available lighting products for a variety of energy-saving lighting applications. Our discussion of several topics in lighting highlighted the importance and complexity of selecting an appropriate and effective lighting system. The large number of alternatives available and their interchangeability for the same application make it imperative to understand the basic characteristics of lamps and auxiliary devices in order to make a sound decision.

While the proliferation of lighting products has complicated decision making, it has increased the options available to arrive at the most cost-effective lighting decision. This flexibility is essential since there are non-lighting constraints that affect the selection process, such as available capital, which may not permit one to select the device with the fastest payback or the greatest efficiency. In all cases the devices selected and the change made in the illumination must be intended to maintain or improve productivity and comfort.

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Table I

LIGHT SOURCES

Year Introduced	Description	Efficacy (lm/W)
1879	Incandescent	17
1925	Mercury Vapor (MV)	50*
1935	Low-Pressure Sodium (LPS)	130*
1939	Fluorescent (F)	62*
1950	Tungsten Halogen Incandescent	22
1962	Metal Halide (MH)	90*
1967	High-Pressure Sodium	110*

* Efficacy values for gas-discharge lamps account for ballast losses.

Table II

NEW PRODUCTS/TECHNOLOGIES INTRODUCED SINCE 1973

Phantom Tube	Solid-State Ballasts
34-Watt Fluorescent Lamp	Compact Fluorescent Lamps
Current Limiters	Circline Conversion Lamps
Specular Reflectors	Coated Incandescent
Low Ballast Factor Ballasts	Energy Saving Plus Lamps
Rare Earth Phosphors	Small Diameter Fluorescents
Energy Efficient Core Ballast	Delamping
Energy Buttons	Personnel Sensors

Table III

USE OF LIGHT SOURCES BY LIGHTING SECTOR
1920 - Future
(10 = 100%)

Light Sources	1920				1940				1960				1980				Future			
	R	C	I	O	R	C	I	O	R	C	I	O	R	C	I	O	R	C	I	O
Inc.	10	10	10	10	10	10	10	7	9	2	2	1	8	1	1		5	1	1	
F									1	8	8	2	2	8	6	1	5	8	4	1
MV								2				6				3				
MH														1	1	1	1		4	3
HPS															2	4			1	5
LPS								1				1				1				1

C = Commercial

HPS = High-Pressure Sodium

I = Industrial

Inc = Incandescent

F = Fluorescent

LPS = Low-Pressure Sodium

MH = Metal Halide

MV = Mercury Vapor

O = Outdoor

R = Residential

Table IV

IMPORTANT CHARACTERISTICS OF LIGHT SOURCES

CHARACTERISTIC	----------LIGHT SOURCE----------					
	INC	MV	F	MH	HPS	LPS
Efficacy	Very Low	Low	Medium	Medium	High	Very High
Intensity	Medium	High	Low	High	High	Low
Color Temperature	Low	High	Low-High	Low-High	Low	Low
Color Rendering	Excellent	Medium	Poor-Good	Good-Ex.	Poor	Very Poor
Glare	Medium	High	Low	High	High	Low
Source Geometry	Point	Point	Diffuse	Point	Point	Diffuse
Dimmability	Very Good	Good	Very Good	Good	Good	Good

TABLE V

LAMP PARAMETERS

Lamp	75W, Inc	150W, Inc	40W Fl	50W, HPS
Power (W)	75	150	50*	65*
Light Out (lm)	1190	2850	3150	4000
Initial Cost ($)	.70	1.00	7.00*	40.00*
Energy Cost ($/kWh)	0.075	0.075	0.075	0.075
Labor Cost ($)	5	5	5	20
Life (h)	750	750	20,000	24,000
Efficacy (lm/kW)	15,900	19,000	63,000	61,500
Initial Cost ($/$10^6$ lm-h)	.78	.47	.10	.42
Operating Cost ($/$10^6$ lm-h)	4.70	3.90	1.10	1.20
Labor Cost ($/$10^6$ lm-h)	5.60	2.30	.08	.21
Total Cost ($/$10^6$ lm-h)	11.08	6.67	1.28	1.83

* Includes ballast

Table VI

COST FACTORS FOR LIGHTING APPLICATIONS

Application	Initial Cost	Operating Cost	Installation Cost	Supply Circuit Layout	Building Design
Retrofit	X	X	X	X	X
Renovation	X	X			X
New Construction	X	X			

TABLE VII

F40 FLUORESCENT LAMPS

Lamp	Light Output* (lm)	Ballast Factor	---Light Output--- Initial (lm)	Relative to Standard (%)	Color Temp. (°K)	CRI
1. Standard 40W F40, T12 CW RS	3150	.95	2990	0	4100	65
2. 34W F40, T12, LW, RS	2925	.87	2540	-15	3500	55
3. 40W F40, T12, LW, RS	3450	.95	3280	+10	3500	55
4. (Plus) 32W F40, T12 LW RS	2925	.87	2540	-15	3500	55
5. 32W F40, T8, 4100, RS	2900	--	--	--	4100	82
6. 40W F40, T12, 3000, RS	3230	.95	3070	+3	3000	85
7. 40W F40, T12, 3500, RS	3180	.95	3020	+1	3500	85
8. 40W F40, T12, 4100, RS	3240	.95	3080	+3	4100	85

* Manufactuter's Rated

TABLE VIII

LIGHT OUTPUT AND LIFE OF INCANDESCENT AND COMPACT FLUORESCENT LAMPS

---------INCANDESCENTS---------				------COMPACT FLUORESCENTS------			
Power (W)	Light Output (lm)	Life (hr)	Efficacy (lm/W)	Power*** (W)	Light Output (lm)	Life (hr)	Efficacy (lm/W)
150	2780	750	18.5	22*	870	9000	39.5
100	1750	750	17.5	44*	1750	9000	39.8
75	1210	750	16.1	7.0	250	10,000	35.6
60	890	1000	14.8	10	400	10,000	40.0
40	480	1500	12.0	13	600	10,000	46.2
25	238	2500	9.5	19	900	10,000	47.4
				18**	1100	7,500	61.1

* Circline (adaptive).
** With solid-state ballast.
*** Including ballast.

TABLE IX

EFFICACY OF HIGH- AND LOW-OUTPUT LIGHT SOURCES

Lamp Type	Power* (W)	Light Output (lm)	Efficacy (lm/W)
35W LPS	60	4800	80
180W LPS	220	33,000	150
35W HPS	44	2,250	51
1000W HPS	1060	140,000	132
175W MH	210	15,000	71
1000W MH	1070	125,000	116
40W F	48	3150	66
110W F	124	9200	74

* Including ballast.

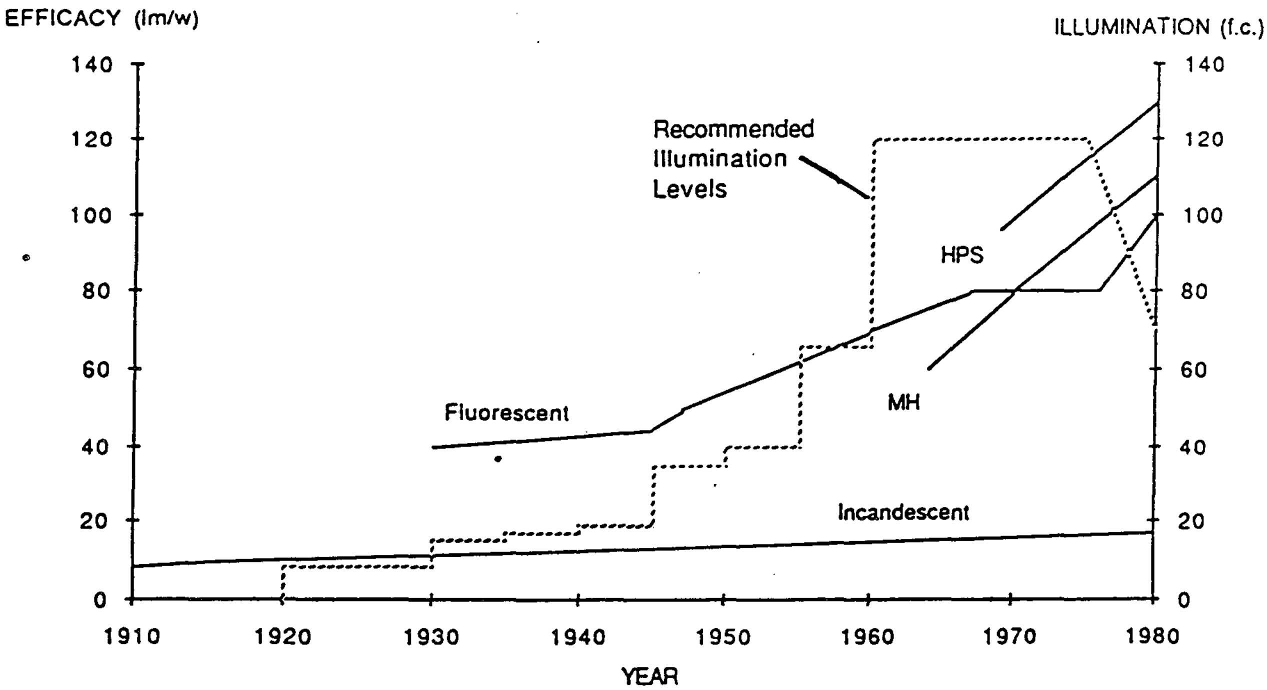


Figure 1. Comparison of light source efficacies and recommended illumination levels from 1910 to 1980.

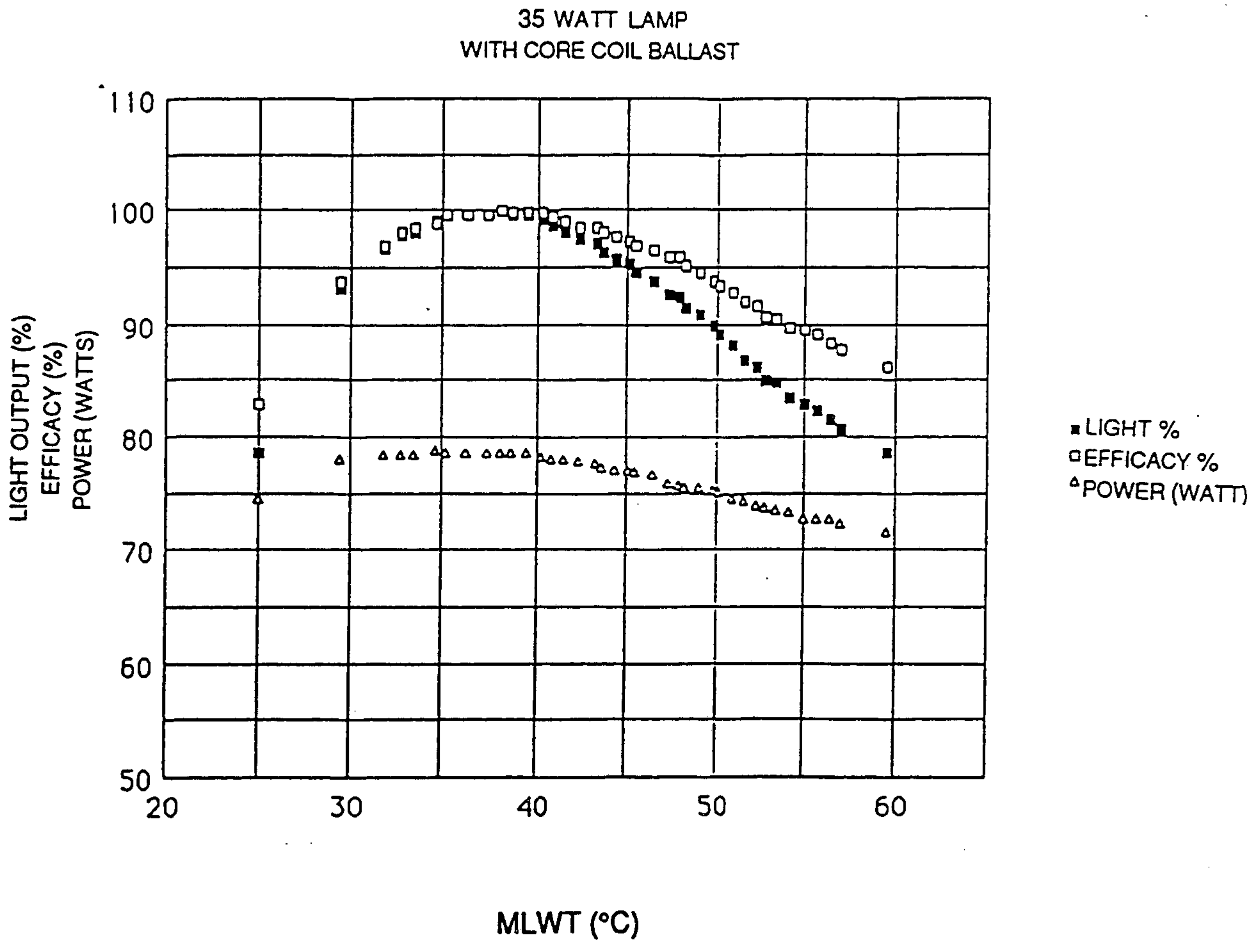
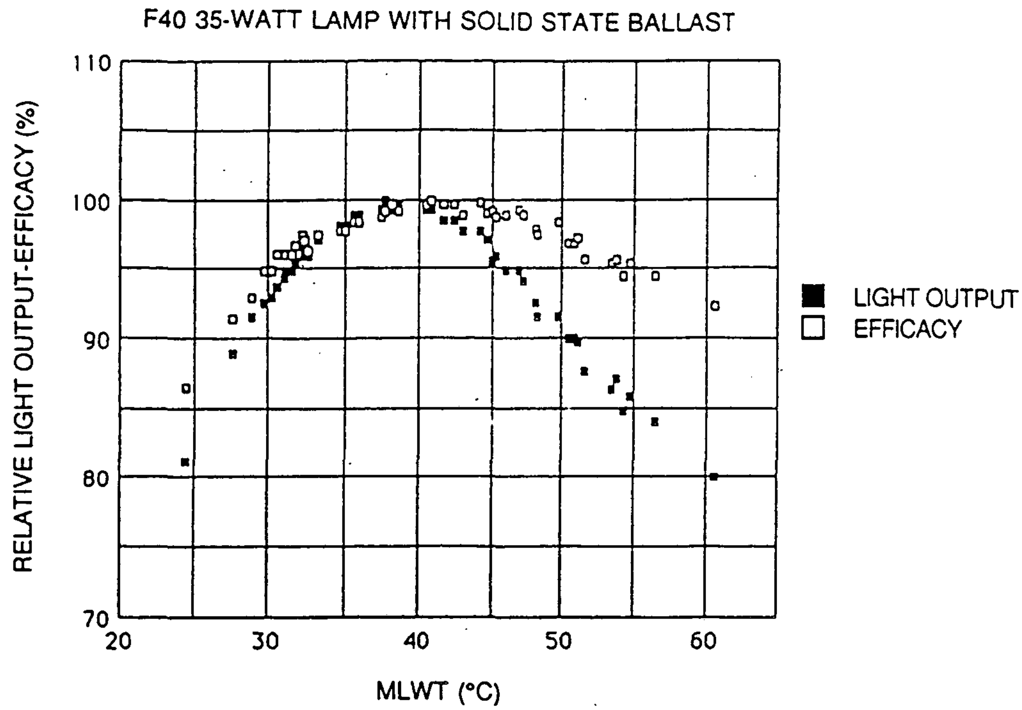


Figure 2. Change in light output, efficacy and power of an energy-saving fluorescent lamp for different minimum lamp wall temperatures (MLWT).



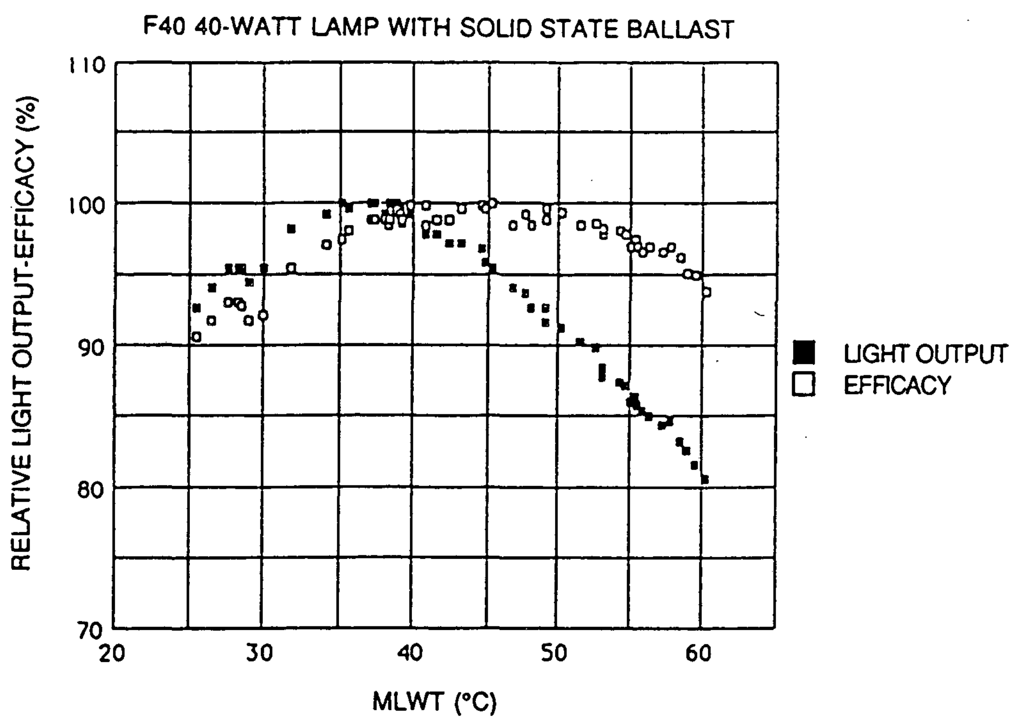


Figure 3. Comparison of the temperature dependence of standard fluorescent lamps and energy-saving fluorescent lamps operated with solid-state ballasts.

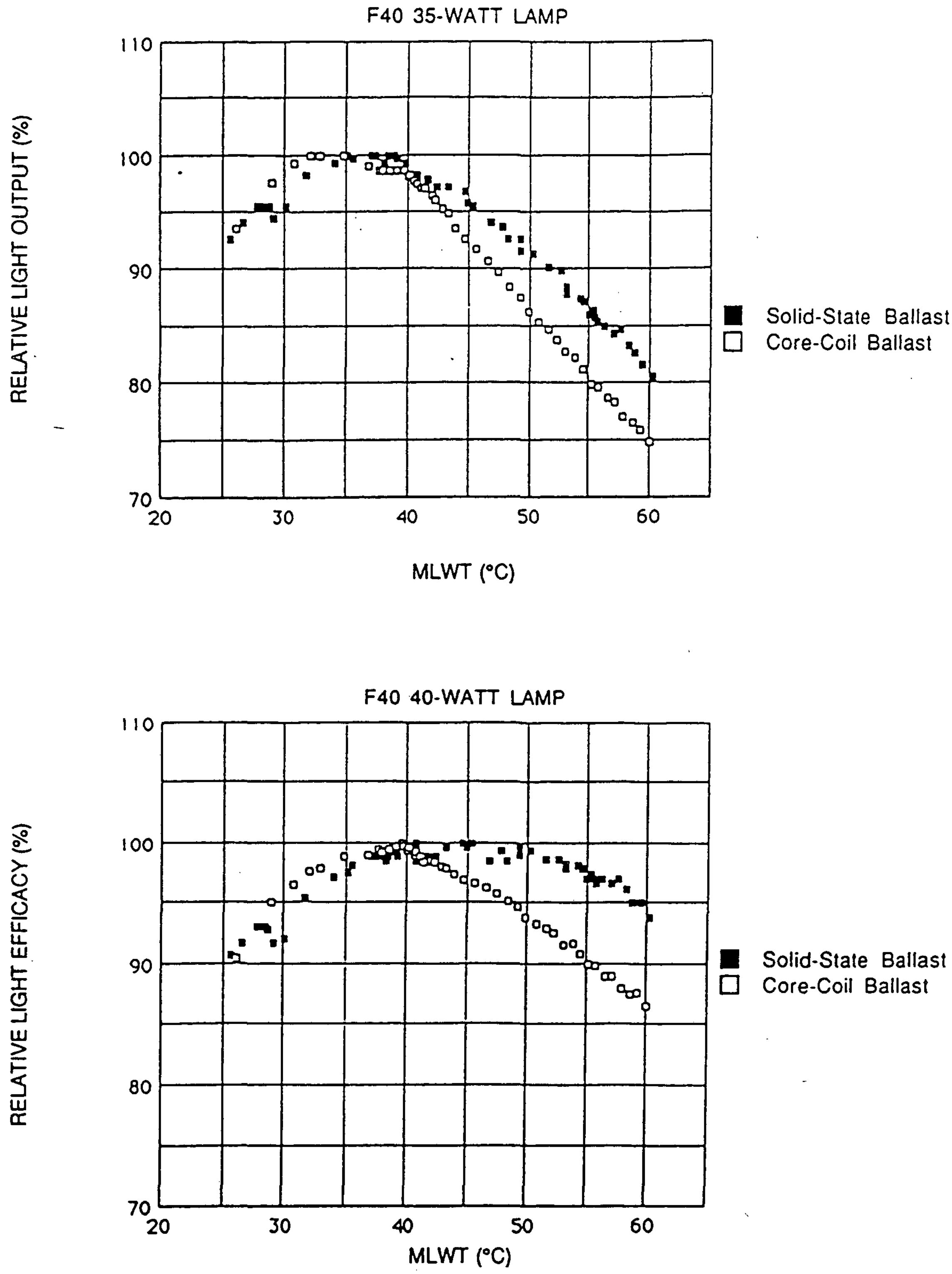


Figure 4. Comparing temperature dependence of efficacy and light output of a fluorescent lamp when operated with a core-coil and a solid-state ballast.

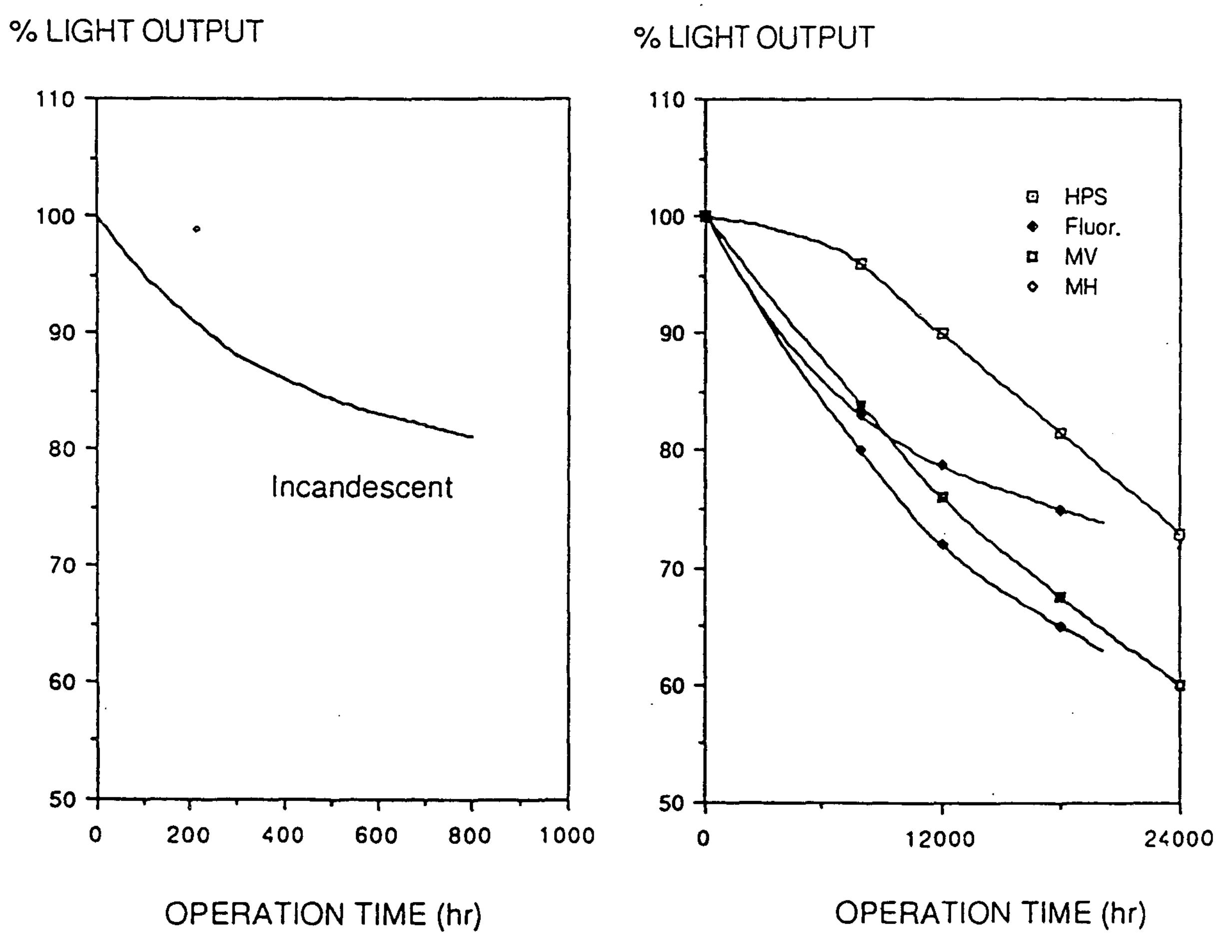
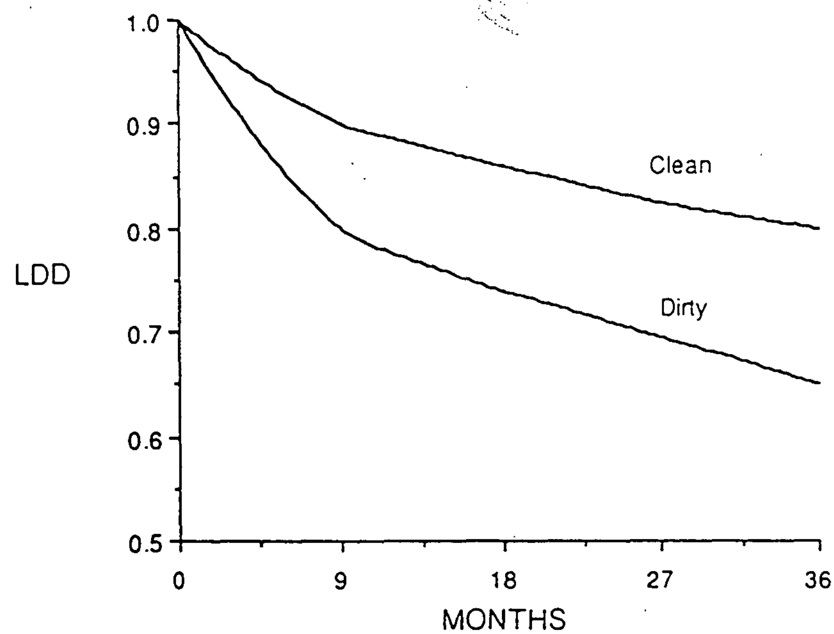


Figure 5. Lamp lumen depreciation of light sources.



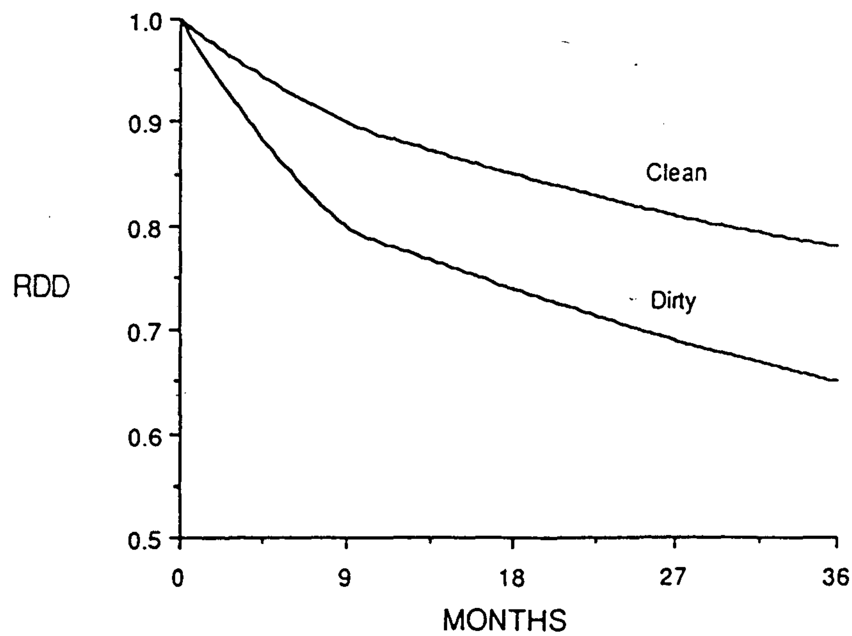


Figure 6. Lumen-depreciation factors for luminaire dirt (LDD) and room dirt (RDD) in a clean and a dirty environment.

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