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Abstract Energy-efficient light bulbs are being developed to replace the incandescent lamp where they can satisfy the design criteria and be used in sockets that have long hours of annual use. The four technologies discussed here include the compact fluorescent lamp, coated-filament lamp, electrodeless fluorescent lamp, and compact high-intensity discharge lamp. The systems demonstrate efficacy improvements of two to four times that of their incandescent counterparts. These new lamps have required considerable advances in lamp technology. They offer the potential for achieving efficacies close to 80 lumens per watt.

These new lamps will reduce the energy used annually by incandescent lamps (190 BkWh) by more than 50% in the 1990s, at which times they will be commonly employed.

1 INTRODUCTION

Several light sources are being developed as potential replacements for the incandescent lamp in Edison-type sockets. This paper presents the characteristics of these new energy-efficient light bulbs (EELBs), their potential, and their present state of development.

Since its introduction in 1879, the incandescent lamp has been a major source of electrical illumination. It is a satisfactory product in form and function; its only deficiency is the efficiacy with which it converts electrical energy into visible light. The energy consumed in the United States by the incandescent lamp is about 190 BkWh, or about 42% of the total amount used for lighting. Yet in terms of lumen-hours, it provides only 16% of the illumination. Energy shortages, reflected by rising costs for electrical energy, dictate the development of a more efficient source of illumination that can be used in place of the incandescent lamp.

In 1976, the Department of Energy (DOE) supported an effort to develop a more efficient fluorescent lamp, the electrodeless fluorescent. The effort was expanded in 1979 to consider other promising technologies. In this second program, the Lawrence Berkeley Laboratory (LBL) staff and lamp manufacturers prepared a list of characteristics that an EELB should possess in order to successfully replace an incandescent lamp. Two lists were needed, one for gas-discharge type lamps and one for filament type lamps. These lists appear in the second and third columns of Table I. The first column in this table describes the performance of a 75-watt incandescent lamp.

The initial performance of six types of EELBs measured at the LBL lighting laboratory will be compared to these targeted characteristics. The number of each of type EELB tested is small because they are either advanced prototypes or samples from limited production runs. Some of the light sources were developed outside of the DOE program and provided to LBL by the manufacturers.

2.0 EELB TECHNOLOGIES

2.1 Adaptive Circline Fluorescent Lamp

An adaptive circline fluorescent lamp that is packaged with a ballast and a medium-sized Edison-type base has been on the market for several years.[1] This lamp system provides from 35 to 40 lumens per watt (1/W) and is well suited for use in portable lamp fixtures. The cost of these lamps varies from $6 to $20; they have been moderately successful in the marketplace. While they are technically a suitable efficient light source, the fact that they have a large diameter (8 to 12 inches) and weigh as much as two pounds limits their general application and appeal. This lamp system will not be considered in this report.

2.2 Coated-Filament Lamp

This is an incandescent lamp whose efficacy has been increased by reflecting the non-visible infrared radiation emitted by the heated filament onto itself.[2] This characteristic is produced by coating a spherical lamp envelope with a thin multilayer of selectively reflecting film and positioning the filament at the focal point. The thin film is designed to be transparent to the visible wavelength and highly reflective to infrared radiation. This lamp applies the technology of coating thin optical interference films onto spherical surfaces. Manufacturers must develop economical means to produce spherical glass envelopes of near optical quality and to accurately position the filament at the envelope's focal point.

2.3 Electrodeless Fluorescent Lamp

One approach to reducing the size of a fluorescent lamp while maintaining its efficacy is to eliminate the electrodes.[3,4] This can be done by operating the lamp above 100 kHz. This requires developing a switching power supply (ballast) that efficiently converts the power line frequency of 60 Hz to a lamp power frequency of 100 kHz or more. In order to obtain a suitably high luminous output (1000 to 2000 lumens), the lamp must be operated highly loaded (with a high ratio of arc watts per phosphor area), at about 3 watts per square inch. For comparison, a medium loaded four-foot fluorescent lamp is operated at 0.3 watts per square inch. Thus, efficient phosphors must be developed that will maintain lumen output at those power densitites, as well as be capable of providing suitable color rendition and color temperature.

2.4 Compact Fluorescent Lamp

This lamp is based on the multiple bending of a long thin gas-discharge tube in order to minimize any single dimension of the lamp.[4,5] The lamp system incorporates the ballast (magnetic or solid-state) in the same package, which is connected to a medium-sized Edison-type socket. The advances in technology required for this lamp are new phosphors that can be highly loaded and can provide the proper color rendition and color temperature; development of suitably small, lightweight ballasts; and a manufacturing method for economically producing multiple bent phosphor-coated tubes.

2.5 Compact High-Intensity Discharge Lamp

These are metal halide, high-intensity discharge (HID) lamps designed to be operated at a low wattage. This lamp system includes the circuitry to initiate and maintain the discharge in a small, compact package. Instant light is provided by an internal incandescent filament that extinguishes once the gas discharge is completely ionized. Technological advances were required to design a suitably small arc tube that could be gas-filled to consistently produce a particular color rendition and color temperature. The starting and operating circuitry had to be developed to fit in the small space allocated and to withstand the operating temperatures. Gas mixes were studied to obtain the warm color temperatures and color rendition required for residential applications.

3 EXPERIMENTAL PROCEDURES

Standard Illuminating Engineering Society testing procedures were used to measure the input-output performance of all lamps. Test data for the gas-discharge lamps are reported after a 100-hour burn-in period. Measurements of the light output of the lamps were made in a six-foot-diameter integrating sphere calibrated with an NBS-certified incandescent lamp. Prior to being measured, each lamp was stabilized by being operated for 30 minutes at its rated voltage.

The spectral power distribution of each lamp was measured with a spectroradiometer; the color rendition index (CRI) and color temperature were computed from the measured spectral data using standard methods. If the retail cost of a lamp was not available, it was estimated based on projected cost at a suitable level of production. The total cost for 10^6 lumen-hours is determined by the relation:

$$\text{total cost} = (\text{initial cost} + \text{operating cost})\,(10^6) \tag{1}$$

$$= \frac{\text{product cost}(\$) \times 10^6}{\text{initial flux (lumens)} \times \text{life(hr)}} + \frac{\text{cost of energy}(\$\ \text{kWh}) \times 10^6}{10^3 \times \text{efficacy (lumens/watt)}},$$

for a cost of energy of $0.07 per kWh.

4.0 RESULTS AND DISCUSSION

4.1 Coated-Filament Lamp

Table I lists the average results of initial measurements for 10 advanced prototypes of a coated-filament lamp. The most significant achievement is the demonstration of an average lamp efficacy of 29 lumens per watt (l/W), which is twice the efficacy of these lamps without the selective reflecting coating. The most efficacious lamp had a light output of 1640 lumens and an efficacy of 30 (l/W). These lamps deviated significantly in performance from the target criteria only in their reduced power factor. The lower power factor is due to a diode in series with the lamp, which permits the use of a long-life high-efficiency filament.

Initial results show that it is technically possible to use this design for the entire product mix of existing single-filament lamps; i.e, it can produce light output from 400 to 2800 lumens. While this lamp has lower efficacy than the gas-discharge type EELBs, its technology is already accepted in residential applications.

The major challenge will be to manufacture these lamps to meet the five-dollar retail price. When this is achieved, the lamps will be cost-effective, as evidenced by the $3.71 total cost for 10^6 lumen-hours.

4.2 Electrodeless Fluorescent Lamp

This was one of the most efficient EELBs, averaging 53 l/W at 1665 lumens output. The most efficacious lamp tested achieved 61 l/W at an output of 1870 lumens. These laboratory prototypes met virtually all the target criteria. However, the CRI and color temperature were out of specification, but phosphor technology exists that will satisfy this shortcoming without reducing lamp efficacy. Subsequent systems delivered to LBL had improved CRIs of 57 and color temperatures of 4100°K with the same efficacies.

The most notable technological advance in the development of this system was the switching circuitry that transforms the 60-Hz, 120-volt line power to the desired high-frequency (13.56 MHz) lamp power for starting and maintaining the discharge. The ballast efficiency is estimated at 80%; thus the RF power to the lamp is 25.6 W. The average efficacy of the lamps excluding ballast losses is 65 l/W. The highest lamp efficacy measured was 76 l/W. Neither the power supply nor the lamp was considered to be optimized; both could be improved with further effort. In particular, the lamp design could be improved by using the more advanced phosphors developed by the major lamp manufacturers. One can conceive of the ballast nearing a 85 to 90% efficiency having a lamp efficacy of 80 to 85 l/W. This would produce a lamp having a system efficacy of between 68 and 77 l/W.

At present, the cost to manufacture these lamps would exceed the target cost to sell each lamp at a retail cost of $15. The greatest expense comes from the power field effect transistors (FET) used in the ballast circuit. These are very high-frequency transistors and are required to efficiently switch the 13.56 MHz power supplied to the lamp. They have just recently been introduced by the semiconductor industry and are more costly than the bipolar transistors. However, as users discover more applications for these devices, the increase in volume will reduce their cost. The low current and voltages in these ballast circuits require only relatively small area devices; hence, these will be one of the least costly types of power FET devices.

The operation of these lamps at megahertz frequencies creates an additional barrier to their use: possible interference with other electronic appliances. The electromagnetic (EM) energy radiated from the system and conducted back into the line must be evaluated. For the present system, the 13.56 MHz frequency was selected because it is at an ISM band, (ie., a band that is not regulated). However, the harmonics of this fundamental frequency fall into regulated regions. If the EM energy is too high, filters can be used to reduce the conducted levels and the lamp can be coated with a transparent conductive thin film to reduce the radiated EM energy. However, this would increase cost and reduce lamp efficacy.

4.3 Compact Fluorescent Lamp

Table I lists the initial characteristics of three types of compact fluorescent lamps. The most highly developed lamp employs a solid-state ballast and has a system efficacy of 56 l/W. The highest efficacy measured was 60 l/W. This particular 1000-lumen output lamp meets nearly all the target criteria. Examination of the three lamps indicates some of the limitations of this technology. To obtain a high light output lamp (2000 to 3000 lumens), the size and weight of the lamp system must increase. However, these fluorescent lamp systems can be designed with a wide variety of color temperatures. These high-efficiency light sources have been realized because of industry's advances in phosphors technology. The new phosphors have satisfactory depreciation rates under high loading and have improved efficacies in converting the ultraviolet mercury radiation to visible light. These new phosphors enable one to control the color temperature over a large range (2600°K to 5000°K) while maintaining a good CRI and high efficacy.

These types of lamps are available at a cost-effective price. They are presently being employed in sockets that have a high annual use (primarily commercial and industrial applications). Their cost can be expected to decline when the volume demand increases; they will then become more attractive for residential applications.

4.4 High-Intensity Discharge Lamp

This lamp technology satisfactorily conforms to all the target criteria. Its outstanding features are its light output, color temperature, size, and weight. It has good efficacy, CRI, life, and cost. This lamp required considerable advances in technology to produce the small low-wattage arc tube. The average system efficacy was 43 l/W. The most efficacious lamp was 46.1 l/W.

These lamps are soon to be marketed and offer the end user an option to the higher wattage incandescent lamps (1700 lumen output and above). The system efficacy can be improved because this lamp employes a resistive ballast. For at a higher cost, a magnetic or solid-state ballast could be used and would readily increase efficacy by 20 to 30%, approaching values as high as 60 l/W. Arc tube technology makes it difficult to produce lamps with very low light output (1100 lumen or less).

This lamps has an outer glass envelope coated to diffuse the light from the arc tube. This lamp could be manufactured with a clear glass envelope and would be an excellent point light source. Lighting designers prefer point light sources for exact control of the illumination in a space.

5 OVERVIEW DISCUSSION

These EELBs will not eliminate the general use of incandescent lamps. However, in many applications, particularly for sockets with high annual usage, one of these EELBs may suit the design criteria and be a cost-effective replacement. The primary factor that makes them viable is their efficacy, which ranges from 30 to 60 l/W. We have addressed this topic considering only the engineering (technical) aspects of these light sources. One must also consider the lighting design features to determine which lamp may be most appropriate.

In the very near term, the compact fluorescent and the high-intensity discharge lamp are or will be available. Neither technology can satisfy the entire incandescent market. The compact fluorescent lamp can best meet the market for lower light output (1500 lumens and below). The compact HID lamp is best suited for the higher light outputs (above 1500 lumens). The compact fluorescent lamps cannot serve as point light sources but can provide a variety of color temperatures. However, the compact HID can provide an efficient point light source. Besides the above technical and design features of these light sources, two important attributes that affect their acceptance are their higher initial cost (negative) and their longer life (positive).

The coated-filament lamp soon will be an option for general lighting. It can satisfy the need for a point light source for lower intensities. Because it is incandescent it avoids the stigma homeowners associate with fluorescent lamps for residential use. In addition, its initial cost will be more compatible with the present cost of incandescent lamps.

In the near future, the electrodeless fluorescent lamp will be available to provide the most efficacious light source for Edison-type sockets. This technology can provide a variety of lamps, ranging in output from 400 to at least 2300 lumens, thereby meeting 95% of the incandescent market.

6 CONCLUSIONS

New EELBs are available that can meet the criteria for design, performance, and total cost as viable replacements for incandescent light bulbs from 40 to 150 watts. Their most attractive attributes include efficacy and long life. The most difficult barrier is their $5 to $15 initial cost and their stigma of "fluorescence."

Through the efforts of the lighting industry, the utility companies, and the government to provide the necessary distribution of information and incentives, by the 1990s these light sources will be in widespread use.

Their impact on the consumption of energy for illumination will be significant, reducing the present consumption of 190 BkWh by more than one-half.

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TABLE I
ENERGY-EFFICIENT LIGHT BULBS: REPLACEMENTS FOR INCANDESCENT LAMPS

		TARGET		INITIAL CHARACTERISTICS					
		ENERGY-EFFICIENT LIGHT BULB				COMPACT FLUORESCENT			
CRITERIA	INCANDESCENT (75 WATT)	Filament	Gas Discharge	COATED FILAMENT	ELECTRODELESS FLUORESCENT	High Light	Medium Light	Low Light	HIGH-INTENSITY DISCHARGE
INPUT VOLTAGE (V)	0-120	0-120	120	0-120	120	120	120	120	120
FREQUENCY (HZ)	60	60	60	60	60	50	60	60	60
POWER FACTOR (%)	100	100	50	71±1	59±0.5	75±1	62±0.3	61±0.2	59±0.6
INITIAL LIGHT (L)	1210	1000-2200	1000-2200	1550±60	1665±110	1700±60	1020±10	490±70	2410±160
POWER (W)	75	-	-	54±1	32±1	34±0.5	18±0.2	16±0.5	51±2
SYSTEM EFFICACY (L/W)	16	34	50	29±1	53±3	50±2	56±1	32±5	43±2
BURNING POSITION	any	any	any	any	any	any	any	any	base down
LIFE (HR)	750	2500	10,000	2500*	10,000*	8000*	6500*	10,000*	6500*
WEIGHT (OZ)	1	6	16	4.1	9.6	22.7	7.4	5.9	4.5
SIZE (LENGTH" X DIAMETER")	4.5 x 2.38	5 x 2.5	7.5 x 4	5.1 x 3.3	7.2 x 3.1	9.7 x 3.4	7.2 x 2.8	8.3 x 2.4	5.7 x 2.5
RETAIL COST ($)	0.70	5.00	15.00	5*	15*	17*	25 15*	15 10*	10* 15*
TOTAL COST/10^6 L/HR ($) @ $0.07/kWh	5.27	<5.27	<5.27	3.71*	2.23*	2.64*	5.03 3.52*	5.28 4.26*	2.27 2.60*
NUMBER OF UNITS TESTED				9	10	10	6	5	15
COLOR RENDERING INDEX	93	90	70	90±3	16±2	82±2	81±0.4	39±6	65±2
COLOR TEMPERATURE (°K)	2800	3000±200	3000±200	2940±50	4815±111	2620±70	2790±70	4507±240	3020±150

*Estimate