Performance Evaluations of Compact Fluorescent Lamps: What Does "Equivalent" Really Mean?

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Utility demand-side management (DSM) programs for residential lighting have promoted screwbase compact fluorescent lamps (CFLs) as replacements for incandescent lamps. The success of these programs depends fundamentally upon customer acceptance of CFLs. Acceptance is dependent to a large extent on accurately representing CFL wattage equivalence to the more familiar incandescent lamps. This paper provides photometric test results of both position and temperature effects on CFL light output. The paper also describes application testing in a table lamp comparing the claimed equivalence of a variety of CFLs to their measured performance.

Introduction

Stimulated largely by the residential demand-side management programs of electric utilities, the use of screwbase compact fluorescent lamp (CFL) products as direct replacements for incandescent lamps has increased dramatically in recent years. Annual shipments of screwbase CFL products in the United States have risen from 1.5 million units in 1988 to 3.2 million units in 1990; the Electric Power Research Institute forecasts shipments to reach 28.4 million units by 1995 (EPRI 1992). Because compact fluorescent lamps are higher in efficacy than incandescent lamps, they provide the opportunity for significant reductions in power demand and energy use. When selecting a CFL replacement for an incandescent lamp, however, the user or specifier is faced with a dilemma: what wattage CFL is an appropriate replacement for the particular incandescent lamp being used?

Initially, the answer to this question may seem obvious: simply select a CFL product which provides the same rated light output as the incandescent lamp. However, this answer disregards the many important light output and light distribution effects which often occur for CFL products in typical incandescent lamp applications. For example, it is well established that the light output of a CFL product is a function of its operating position, temperature, and the ballast used with the lamp (Bonwknegt 1982, Rea 1993, Roche 1993, Siminovitch & Rubinstein 1990, Serres & Taelman 1992). These effects may be further confounded by the geometry of the CFL, as different shapes vary in performance under different conditions (Barrett 1993). Because the standard measurement conditions used in determining published CFL light output ratings are limited to a single position (base up) at a single temperature (25°C ambient), the light produced by a CFL product in an application may be very different from its rated light output. Thus, matching a CFL product to an incandescent product based on rated light output is inappropriate for many applications.

Because variations from the standard test conditions for a CFL product almost always result in reduced lumen output, the end result of basing recommended "equivalences" of CFL products on rated lumens is lower illuminances than with incandescent lamps. For the electric utility, this result is of great concern, since it may lead to users removing CFL products and reverting to the higher-wattage incandescent lamps. More broadly, it may lead to an overall negative reaction of users to CFL products, further inhibiting the use of these products in the future.

In this paper, the results of three different phases of testing are presented to indicate the sources for discrepancies between claimed and actual "equivalence." The first two phases involved laboratory photometric testing of products; one in which screwbased modular and self-ballasted products ranging from 13 to 27 watts were tested (Barrett 1993) and another in which 26-watt modular quad lamps were tested (Luan 1993). The third phase involved application testing of 13- to 30-watt CFL products by installing them into a table lamp and comparing the relative performance of products purported to be "equivalent" (Ji and Davis 1993). Complete details on the methods used and the specific products tested may be found in the individual reports cited; only the results relevant to the question of equivalence are discussed in this paper.

Lab Photometry

As previously mentioned, standard testing protocols for CFL lamps (IES 1991) include testing lamps at an ambient temperature of 25°C in the base-up position. In the testing described below, both self-ballasted lamps and modular lamps and ballasts were tested under these standard conditions to directly compare measured light output (lumens) to the manufacturers' ratings. Furthermore, testing was conducted at other positions, since many CFL applications require lamps to be operated at base-down (table lamp) or horizontal (downlight, sconce) positions. Results are summarized separately for each of the different product categories tested.

Screwbased Modular Products

Light Output Ratings of Modular Lamps. In this phase, 12 lamps were tested; three lamps from each of four manufacturers. Lamps were purchased on the open market through an electrical distributor. The lamps were all 13-watt quad lamps (NEMA designation CFQ13w/GX23), and were all rated for 860 lumens. As shown in Table 1, the measured lumens under standard measurement conditions (base-up, 25°C) for all of the lamps were less than the rating, with a mean measured lumen value of 756 lumens for the 12 lamps.

Ballast Factor Ratings for Modular Ballasts. The ballast factor (BF) gives the ratio of the lumens actually produced by a specific lamp-ballast combination relative to the rated lumens for the lamp, which are measured using a reference ballast rather than a commercial ballast. Thus, BF indicates the extent to which the light output of a lamp will be reduced by a given ballast. Ten different modular magnetic ballasts from four different manufacturers were tested with one lamp, a 13-watt quad lamp. As shown in Table 2, the measured BFs for all 10 ballasts were less than the manufacturers' rated BFs, with the difference between the measured and rated values ranging from 0.05 to 0.19.

Multiplying the lamp lumens by the BF provides the actual lumens produced by the lamp-ballast system. Based on the modular lamp rating of 860 lumens and the mean BF rating of the products tested of 0.97, the predicted *rated* lumens are therefore 834 (860 X 0.97). However,

Table 1. Rated vs. Measured Light Output for Modular Lamps[(a)]

Product	Rated Lumens	Measured Lumens
A1	860	787
A2	860	752
A3	860	774
B1	860	773
B2	860	773
B3	860	773
C1	860	745
C2	860	750
C3	860	732
D1	860	745
D2	860	726
D3	860	738

(a) In the product column, manufacturers are differentiated by the letter designation. The numeral represents different products or samples from the manufacturer.

Table 2. Rated vs. Measured Ballast Factor for Modular Ballasts[(a)]

Product	Rated Ballast Factor	Measured Ballast Factor
E1	1.00	0.94
E2	0.96	0.86
E3	0.98	0.83
F1	0.93	0.88
G1	0.94	0.87
G2	0.94	0.85
G3	0.98	0.79
G4	0.98	0.81
H1	1.01	0.87
H2	1.00	0.90

(a) In the product column, manufacturers are differentiated by the letter designation. The numeral represents different products or samples from the manufacturer.

using the mean *measured* lumens of 756 and the mean *measured* BF of 0.86 yields 650 lumens, only 78% of the rated light output.

Screwbased Self-Ballasted Products

Light Output Ratings for Self-Ballasted Lamps. For self-ballasted CFL products, lumen ratings and measurements already include the ballast factor. A total of 20 different self-ballasted products from eight manufacturers were tested. These products represented a range of wattages and light output ratings; both bare lamp and capsule types; both magnetic and electronic ballasts. Table 3 describes the various products tested and summarizes the results.

A comparison of the "Rated Lumens" column in Table 3 with the "Measured Lumens" column shows that seven of the 20 products met or exceeded their lumen ratings, while the measured light output for 13 of the products was less than the rated light output. Those that produced less light than rated ranged from providing 0.7% less to providing 25.9% less; the mean was 8.7% less.

Position Effects for Self-Ballasted Lamps. Whether or not a CFL product provides its rated light output, that rating is still based on the lamps being operated in the base-up position. However, since screwbased self-ballasted lamps are commonly used in table lamps, their light output when operated in the base-down position is also important. Although operating

Table 3. Rated vs. Measured Light Output for Self-Ballasted Lamps[(a)]

Product	Wattage	Ballast Type	Lamp Type	Rated Lumens	Measured Lumens	Position Factor
J1	15.0	electronic	bare	780	590	0.96
K1	18.0	magnetic	bare	700	615	0.87
K2	20.4	electronic	bare	1350	1001	0.80
L1	15.0	magnetic	capsule	700	714	0.98
L2	15.0	magnetic	capsule	700	687	1.00
L3	26.0	electronic	bare	1500	1525	0.79
L4	20.0	electronic	bare	1200	1256	0.75
M1	16.0	magnetic	bare	900	746	0.70
N1	15.0	electronic	bare	900	988	0.76
N2	20.0	electronic	bare	1200	1216	0.75
N3	15.0	electronic	capsule	700	701	0.77
P1	15.0	magnetic	capsule	720	701	1.00
P2	15.0	magnetic	capsule	720	709	1.00
P3	20.0	electronic	bare	1100	1079	0.85
P4	27.0	electronic	bare	1550	1363	0.81
P5	18.0	electronic	capsule	1100	1023	0.99
Q1	17.0	electronic	capsule	950	957	0.98
Q2	18.0	electronic	capsule	1100	1047	0.98
R1	15.0	magnetic	capsule	700	695	1.01
R2	18.0	electronic	bare	1100	1047	0.90

(a) In the product column, manufacturers are differentiated by the letter designation. The numeral represents different products or samples from the manufacturer.

position does not affect the light output of an incandescent lamp, it can have an impact on CFL light output. Industry-accepted standard test methods do not include testing in other than the base-up position (because the lamps take much longer to reach photometric stability), however, photometric measurements can be taken to estimate the magnitude of the effects of operating lamps in the base-down position.

Table 3 shows the "position factor" for the self-ballasted lamps tested. The position factor expresses the ratio of the measured light output in the base-down position to the measured light output in the base-up position. As the table shows, there was a distinct difference in the results for bare lamps compared to the results for capsule lamps. The light output for all of the 11 bare lamp products was reduced in the base-down position, with a mean position factor for these products of 0.81 (or, a 19% reduction in light output). For the nine capsule products, one had a very low position factor of 0.77, but the other eight had factors of 0.98 or above. Thus, operating position had much less of an impact on the light output of the capsule products than it did on the bare lamp products.

26-Watt Modular Quad Lamps

Because 26-watt quad lamps are commonly used in CFL downlights, testing was performed to document their performance at different operating positions and at different temperatures. In this testing, three samples each of two lamp geometries were tested, hereafter referred to as "H" and "U" lamps (see Figure 1). Furthermore, two preproduction engineering samples of an amalgam version of the "U" type lamp were tested. (These CFL products use a mercury amalgam in the lamp to maintain their light output better at high temperatures.) Specific details on the testing methods have been reported by Luan (1993). Although the 26-watt quad lamp is not commonly used in residential applications as a direct replacement for an incandescent lamp, the general effects observed should be true for other wattages as well.

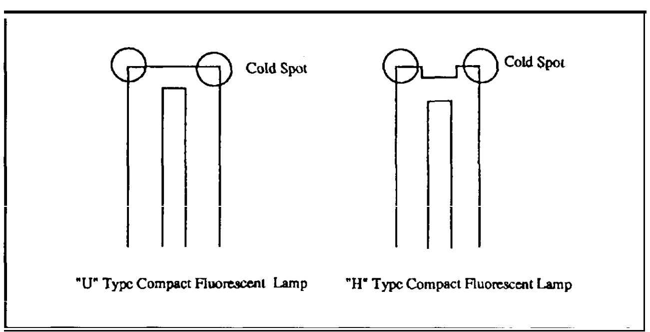

Figure 1. "U" Type and "H" Type Compact Fluorescent Lamp

Position and Temperature Effects. Figures 2, 3, and 4 show the impacts on measured light output of these lamps for the base-up, horizontal, and base-down positions as the ambient temperature was varied from 25°C to 65°C. As shown, the light output for both the "H" and the "U" type lamps decreases as temperature increases. However, the light output of the "H" type lamp was much less affected by operating position.

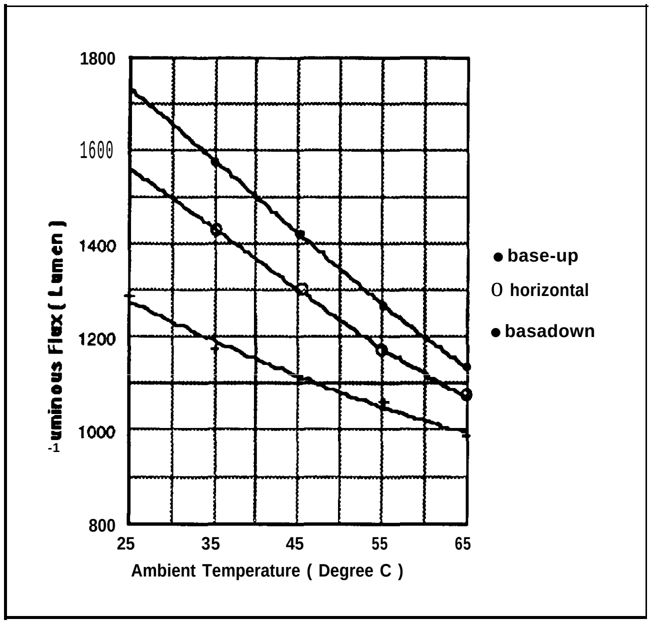

Figure 2. Light Output Measurements for 26-watt "U" Type Lamps

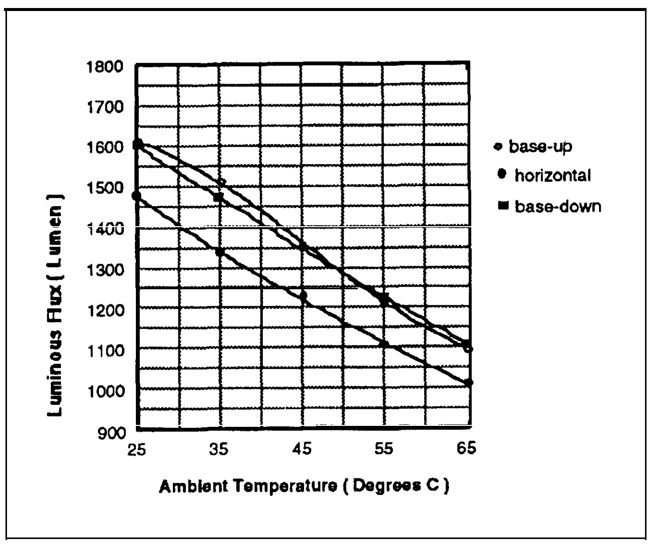

Figure 3. Light Output Measurements for 26-watt "H" Type Lamps

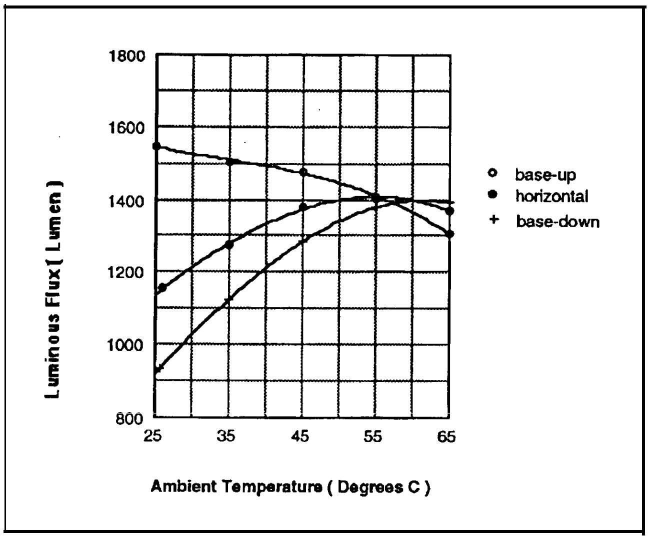

Figure 4. Light Output Measurements for 26-watt Amalgam Lamps

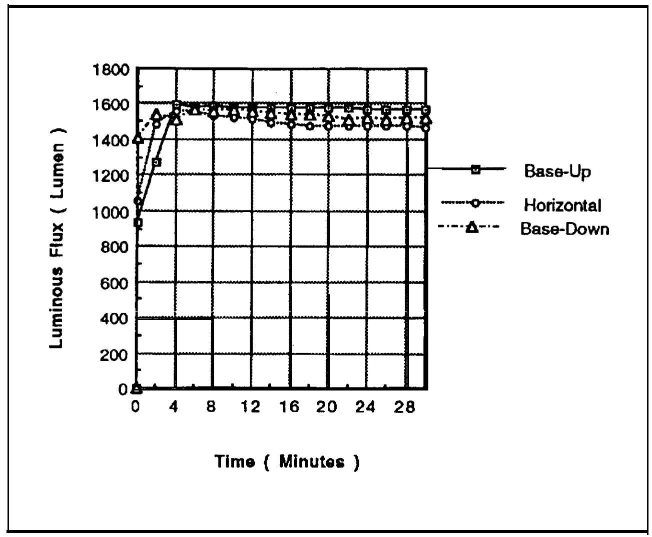

Figure 5. Warm-Up Time Tests for "H" Type Lamp

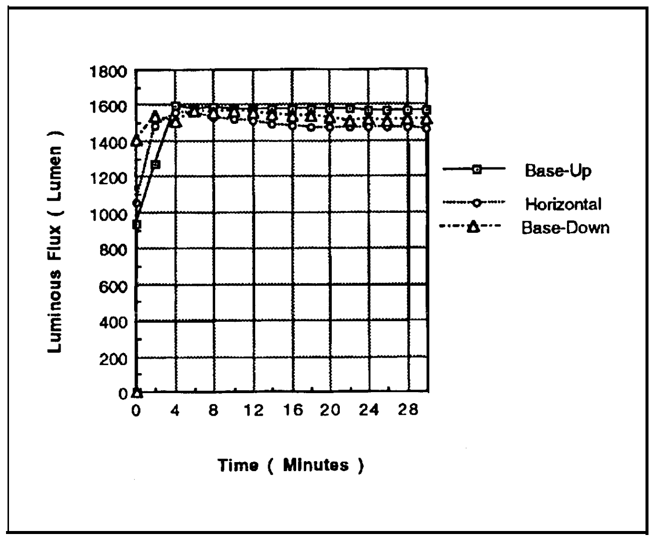

Figure 6. Warm-Up Time Tests for "U" Type Lamp

The light output of the amalgam lamp type remained relatively constant at various temperatures in the base-up position. At the 25°C condition, the light output of this lamp type was greatly reduced for the horizontal and base-down positions, but increased at higher temperatures in these positions.

Warm-up Time Measurements. In addition to the stabilized light output readings for the 26-watt lamps, warm-up time tests were conducted. In these tests, lamps were started from a "cold" condition (room temperature and at least 10 minutes after the last operation), and their light output was monitored until it stabilized. Figures 5, 6, and 7 show the results. As shown, both the "H" and "U" type lamps were relatively bright soon after being started and reached stable light output after two minutes. The amalgam type lamp, however, took much longer to reach full light output, particularly in the base-down position, where full light output was still not achieved after 40 minutes.

Application Testing

Methods

Figure 8 shows the testing setup for the table lamp application testing. Illuminances (light levels) were measured on the table surface, a wall surface, and on a horizontal plane above the table lamp. Results of the wall measurements led to similar conclusions as the horizontal plane measurements; only the horizontal plane measures are included here. Descriptions of the 26 lamps tested (4 regular incandescent lamps, 1 tungsten-halogen lamp, and 21 compact fluorescent lamps) are given in Table 4. The compact fluorescent lamp products have been differentiated by the claimed incandescent wattage equivalent, the ballast type, the lamp/ballast configuration (modular or self-ballasted), and the lamp type (quad, twin, bullet, globe, or circular).

Before the testing, the incandescent and tungsten-halogen lamps were seasoned for 10 hours; the compact fluorescent lamps were seasoned for 100 hours. Lamps were seasoned in the base-up operating position. For the incandescent and tungsten-halogen lamps, the lamps were placed in the table lamps and operated for 15 minutes immediately prior to testing. Because compact fluorescent lamps can require long time periods to reach stable light output in a base-down position, each lamp was operated for a minimum of 15 hours in the base-down position prior to testing, then moved to the table lamp and

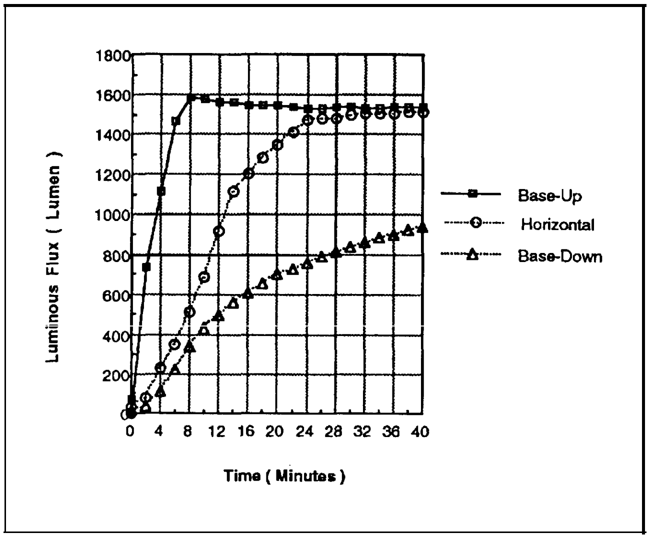

Figure 7. Warm-Up Time Tests for Amalgam Lamp

operated for an additional 20 minutes before data were collected. The same table lamp was used throughout the testing.

Results

Table 4 presents a summary of the table lamp testing results. Of particular interest is the performance of compact fluorescent lamp products relative to the incandescent lamp for which they are claimed to be equivalent.

To facilitate direct comparisons, Figures 9 through 14 were developed. The designations used in these figures to indicate specific lamps are the same as those in Table 4.

As shown in Figure 9, the compact fluorescent lamps which are claimed to be equivalent to a 60-watt incandescent lamp produced illuminances which are much less than those produced by a 60-watt A19 inside frosted incandescent lamp but greater than those produced by a 40-watt A19 inside frosted incandescent lamp. As shown in Figure 10, the capsule type compact fluorescent lamps (bullet or globe shape) produced illuminances above the table lamp which are similar to the 60-watt incandescent lamps. The bare compact fluorescent lamps, however, produced illuminances directly above the table lamp which are much less than those produced by the 60-watt incandescent lamp.

Figures 11 and 12 show that the bare and capsule compact fluorescent lamps which are claimed to be equivalent to a 75-watt incandescent lamp produced illuminances on the table which are much less than those produced by the 75-watt A19 inside frosted incandescent lamp. In fact, the performance of these products does not even match that of the 60-watt incandescent lamp. The exception is one circular product, which produced illuminances on the table which were between those produced by a 60-watt and a

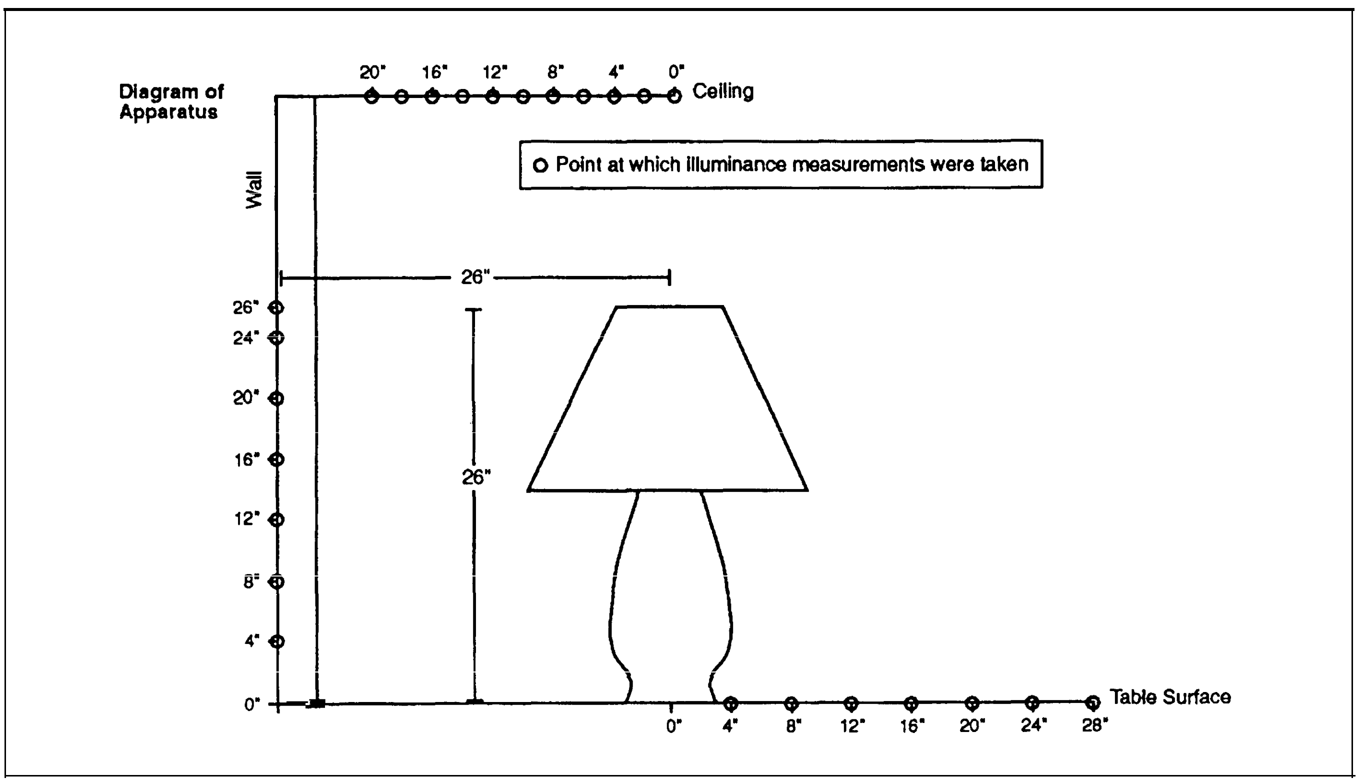

Figure 8. Table Lamp Application Testing

Table 4. Table Lamp Results

Designation	Lamp Type	Shape (for CFL type)	Actual Wattage (watt)	Claimed Equivalence (w)	Ballast type (for CFL only)	Illum. on Table (lx)*				Illum. on Ceiling (lx)*			
						20cm	30cm	40cm	50cm	0cm	10cm	20cm	30cm
I-40	Incandescent	--	40	--	--	232	187	131	91	61	167	106	51
I-60	Incandescent	--	60	--	--	484	391	283	206	202	315	186	111
I-75	Incandescent	--	75	--	--	599	494	361	261	230	353	227	138
I-100	Incandescent	--	100	--	--	920	750	544	395	352	558	339	209
TH-52	Tungsten-Halogen	--	52	--	--	427	349	257	191	101	208	159	106
CF-1T	Compact Fluorescent	Modular, Twin	12	60	Magnetic	149	121	85	55	42	51	73	66
CF-2T	Compact Fluorescent	Modular, Twin	13	60	Magnetic	253	218	151	103	73	91	131	107
CF-3T	Compact Fluorescent	Modular, Twin	13	60	Magnetic	240	205	152	91	71	146	191	115
CF-4T	Compact Fluorescent	Modular, Quad	13	60	Magnetic	329	277	198	144	108	163	214	140
CF-5T	Compact Fluorescent	Modular, Quad	13	60	Magnetic	292	246	177	129	100	147	180	104
CF-6T	Compact Fluorescent	Diffuse, Bullet	15	60	Magnetic	262	217	154	98	246	294	249	123
CF-7T	Compact Fluorescent	Diffuse, Globe	15	60	Magnetic	286	239	167	117	280	325	238	107
CF-8T	Compact Fluorescent	Diffuse, Globe	15	60	Magnetic	328	263	185	124	289	330	269	135
CF-9T	Compact Fluorescent	Integral, Twin	15	60	Electronic	351	296	220	149	102	197	226	144
CF-10T	Compact Fluorescent	Integral, Quad	16	60	Magnetic	216	184	135	110	59	132	159	89
CF-11T	Compact Fluorescent	Diffuse, Bullet	18	75	Electronic	417	341	251	162	227	296	323	224
CF-12T	Compact Fluorescent	Integral, Quad	18	75	Electronic	464	391	296	201	126	233	289	186
CF-13T	Compact Fluorescent	Integral, Quad	18	75	Electronic	405	343	252	147	158	266	335	229
CF-14T	Compact Fluorescent	Integral, Quad	20	75	Electronic	458	386	284	171	127	234	306	229
CF-15T	Compact Fluorescent	Integral, Quad	20	75	Electronic	389	328	243	148	132	236	284	196
CF-16T	Compact Fluorescent	Modular, Quad	22	75	Magnetic	495	414	297	215	217	254	336	294
CF-17T	Compact Fluorescent	Circular	27	75	Magnetic	590	501	341	239	506	328	216	186
CF-18T	Compact Fluorescent	Integral, Quad	27	100	Electronic	516	433	319	180	222	331	422	303
CF-19T	Compact Fluorescent	Integral, Quad	27	100	Electronic	543	456	337	197	215	339	422	302
CF-20T	Compact Fluorescent	Modular, Quad	28	100	Magnetic	597	501	358	249	204	272	395	333
CF-21T	Compact Fluorescent	Circular	30	150	Electronic	1154	958	645	350	886	521	375	320

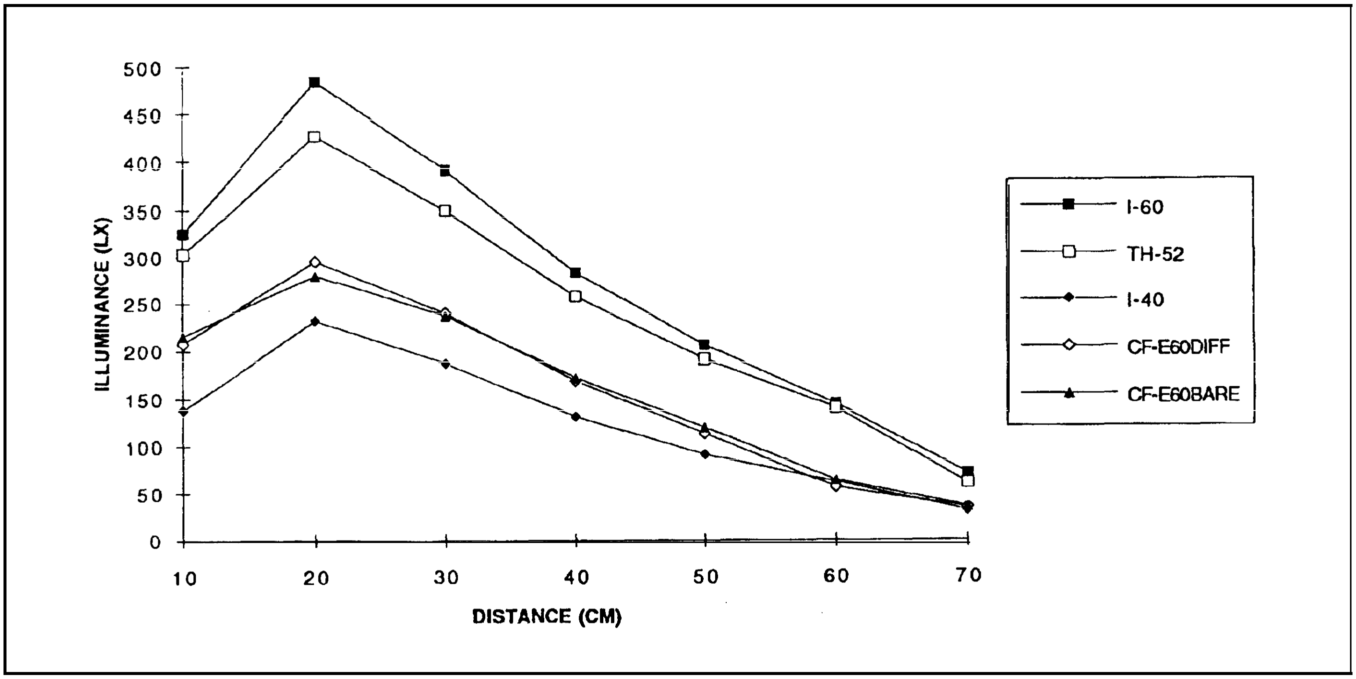

Figure 9. Illuminance Distribution on the Table for 60-w Category CF-E60DIFF is the Average of CF-6T, CF-7T, and CF-8T. CF-E60BARE is the average of CF-2T, CF-3T, CF-4T, CF-5T, CF-9T, and CF-10T. See Table 4 for explanations of lamp designations.

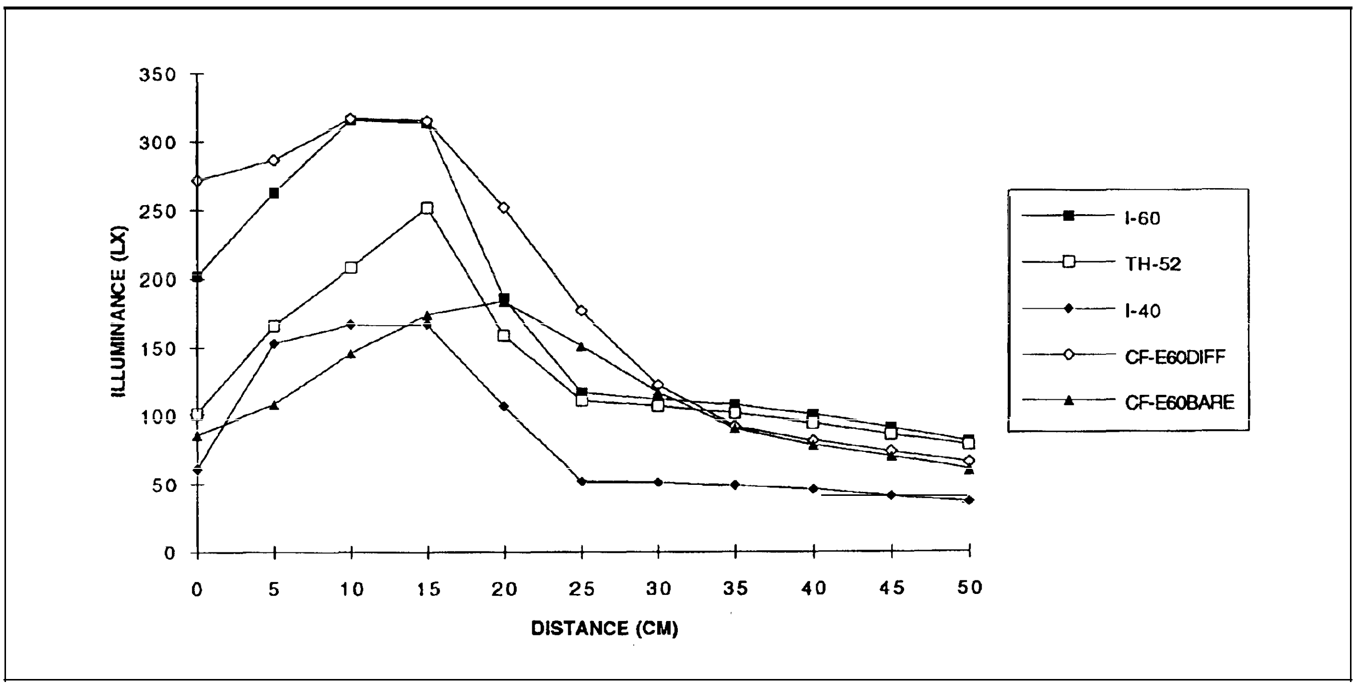

Figure 10. Illuminance Distribution on the Ceiling for 60-w Category CF-E60DIFF is the Average of CF-6T, CF-7T, and CF-8T. CF-E60BARE is the average of CF-2T, CF-3T, CF-4T, CF-5T, CF-9T, and CF-10T. See Table 4 for explanations of lamp designations.

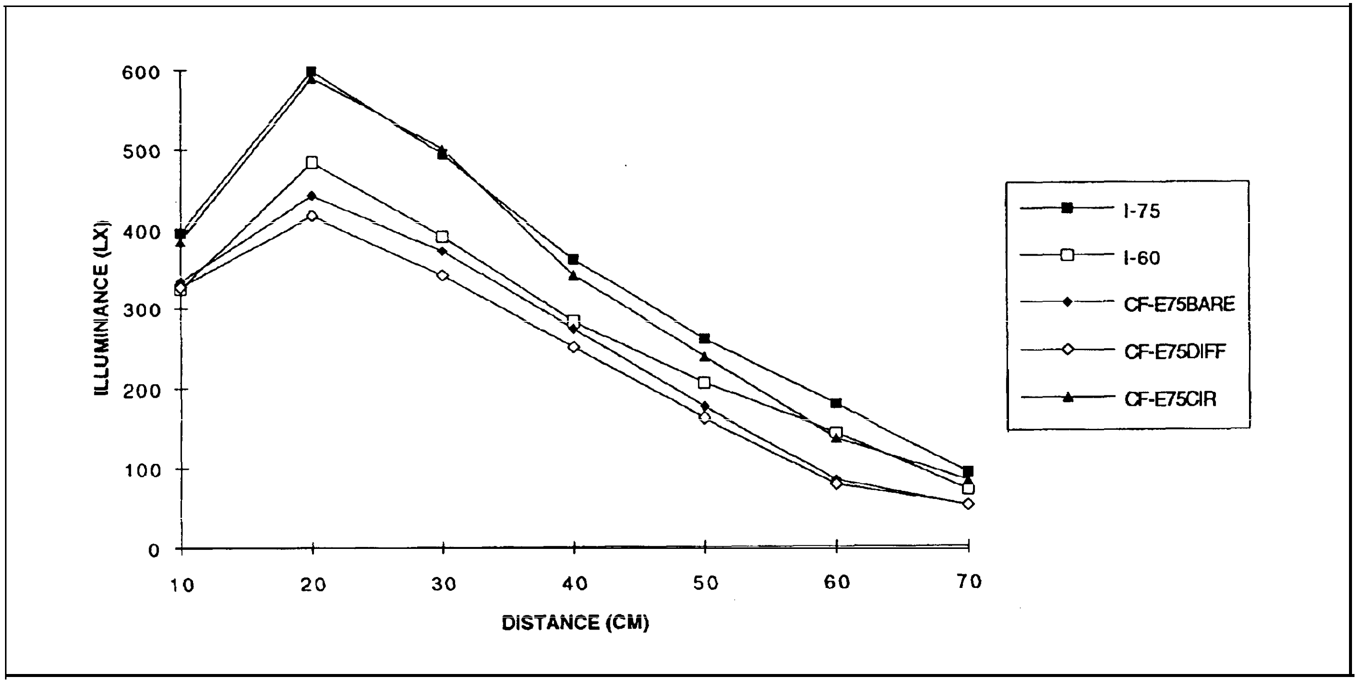

Figure 11. Illuminance Distribution on the Table for 75-w Category CF-E75BARE is the Average of CF-12T, CF-13T, CF-14T, CF-15T and CF-16T. CF-E75DIFF is the data of CF-1lT, CF-E75CIR is the data of CF-17T. See Table 4 for explanations of lamp designations.

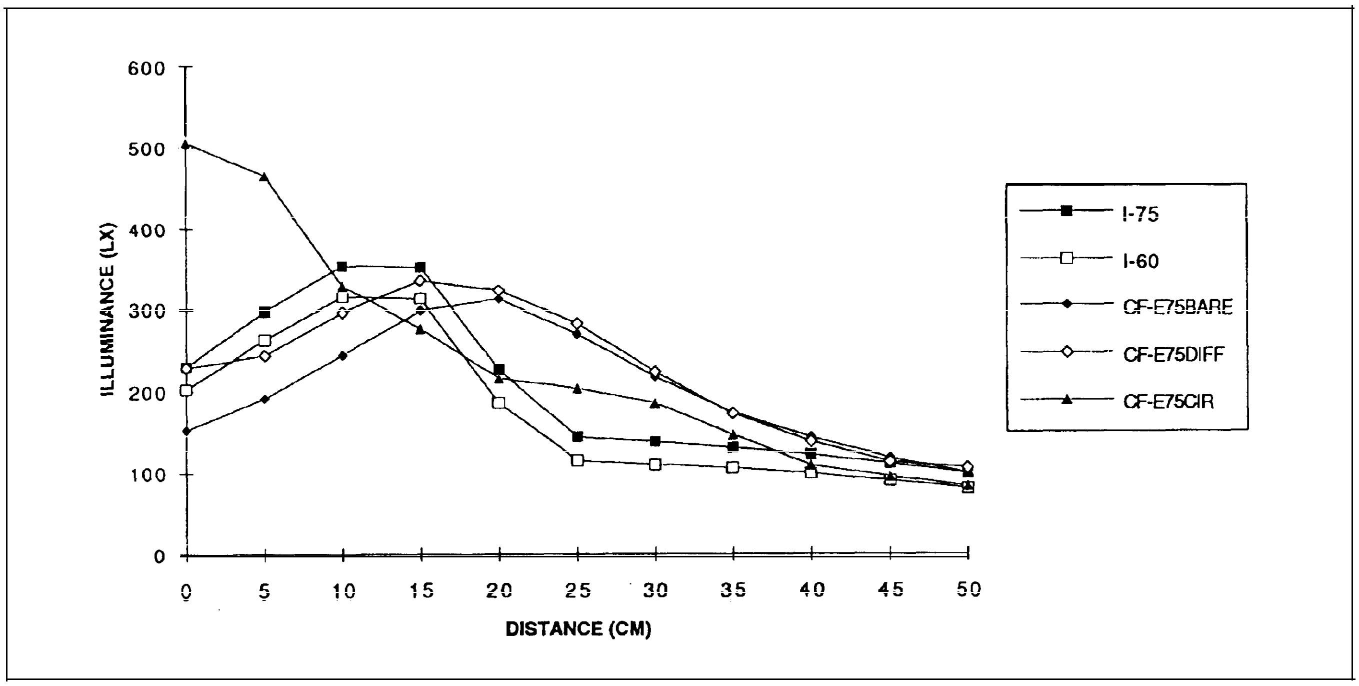

Figure 12. Illuminance Distribution on the Ceiling for 75-w Category CF-E75BARE is the Average of CF- 12T, CF-13T, CF-14T, CF-15T, and CF-16T. CF-E75DIFF is the data of CF-1lT, CF-E75CIR is the data of CF-17T. See Table 4 for explanations of lamp designations.

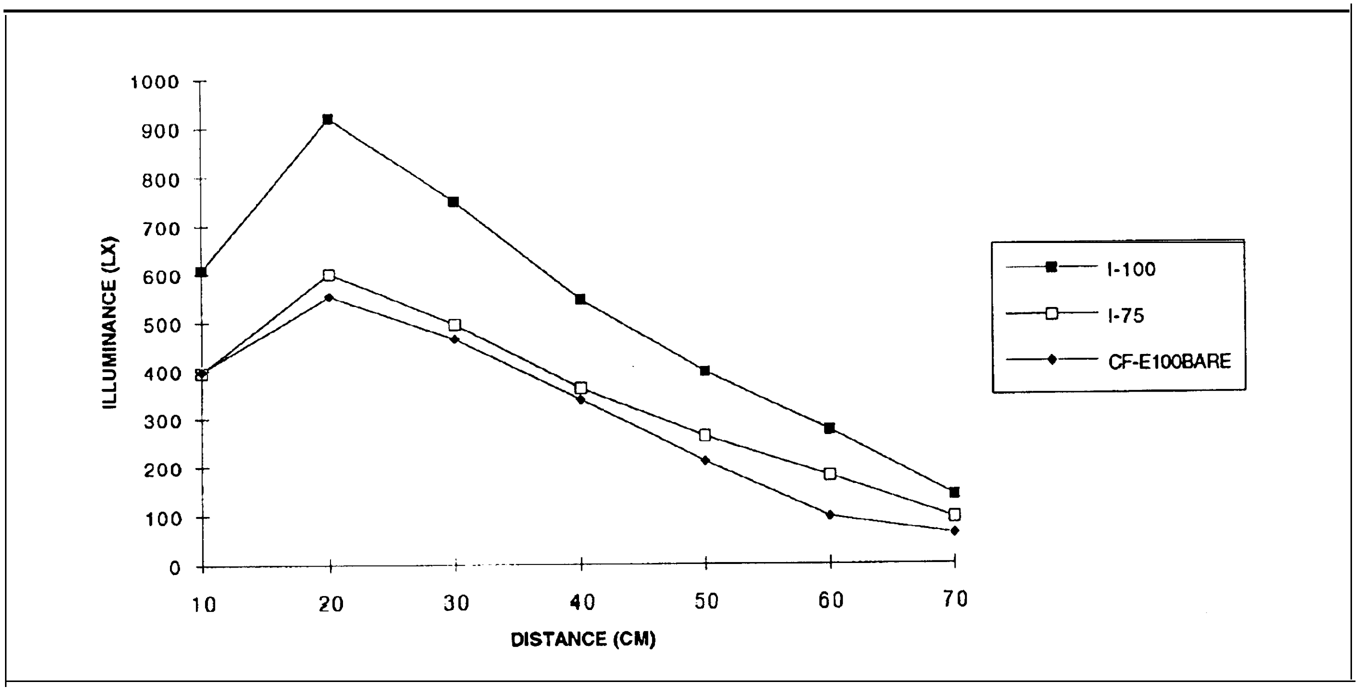

Figure 13. Illuminance Distribution on the Table for 100-W Category CF-E100BARE is the Average of CF-8T, CF-19T, and CF-20T. See Table 4 for explanations of lamp designations.

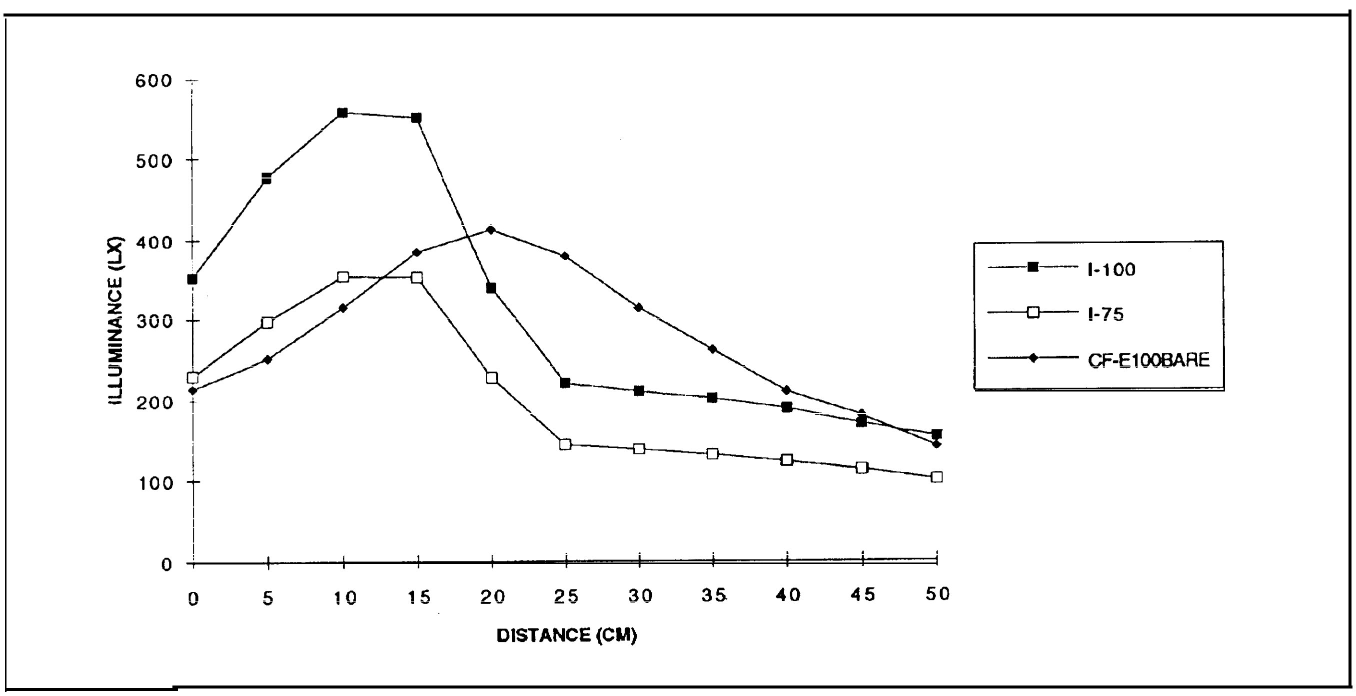

Figure 14. Illuminance Distribution on the Ceiling for 100-W Category CF-E100BARE is the Average of CF-18T, CF-19T, and CF-20T. See Table 4 for explanations of lamp designations.

75-watt incandescent lamp. The circular product also produced a very different distribution above the table lamp, as shown in Figure 12.

Figures 13 and 14 present data for lamps in the 100-watt category. The results are similar to those for the 60-watt and the 75-watt categories.

Conclusion

This paper suggests reasons why CFL products which are rated as "equivalent" to certain incandescent lamps do not produce equivalent light output in a particular application. The testing results summarized here show that in some cases products vary substantially from the manufacturers' rated light output, and that the particular conditions of the application (operating position of the lamp and temperature) often reduce CFL light output. The net result of these effects was demonstrated through the application testing, where very few CFL products were found to provide light levels similar to those provided by the "equivalent" incandescent lamp.

With these results in mind, what can the utility do to increase the probability that their customers will not complain of inadequate light output from a CFL? A number of possible actions are available. Before embarking on a large-scale promotion of any particular product, the light output of a sample of the lamps could be measured using standard methods and compared to the manufacturer's ratings. Furthermore, position factor for base-down operation could be documented, if the products will primarily be used in table lamps. If the utility is working with a customer with many products being used in a single typical application (such as all the table lamps in a large hotel), the direct application testing methods described above can be used to evaluate various CFL products in terms of their performance relative to incandescent lamps. Finally, customers need to be educated as to the longer warm-up times required with CFL products, to avoid any "instant" assessments of the light output.

CFL products offer the potential for significant energy savings, which, combined with their long rated lifetimes, can make them a cost effective measure for replacing incandescent lamps. However, residential users can become frustrated with the technology if their expectations about light output are not met. It is therefore imperative that proper information about equivalency is provided to consumers.

Acknowledgements

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