Lighting*Answers*

Thermal Effects in 2´×4´ Fluorescent Lighting Systems

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NATIONAL LIGHTING PRODUCT INFORMATION PROGRAM

Introduction

Statistics from the United States Bureau of the Census (1991) and the National Electrical Manufacturers Association (NEMA 1993) indicate that the 2-foot by 4-foot (2´×4´) recessed *luminaire** is the most common luminaire used for fluorescent lamps in the United States. Fluorescent lamps consume approximately 50% of the electricity used for lighting in the United States, or approximately 10 to 15% of the nation's total electricity (Lovins 1988). Fluorescent lighting systems, as a result, have been examined repeatedly as part of energy conservation efforts.

Manufacturers usually publish luminaire performance data for given lamp-ballast-luminaire combinations operating at 25°C (77°F) ambient temperature. However, a fluorescent lamp's light output, *active power*, and *efficacy* depend on the lamp's operating temperature. Thus, the performance of a 2´×4´ luminaire when it is installed may be very different from its rating. As a result, the manufacturers' ratings do not predict energy savings and light output accurately for many applications.

In this issue of *Lighting Answers*, the National Lighting Product Information Program (NLPIP)

- summarizes information on thermal effects in 2´×4´ fluorescent lamp luminaire systems
- reports the results of testing two types of recessed 2´×4´ luminaires with different combinations of fluorescent lamps and ballasts at different *plenum* temperatures
- describes how to account for the thermal effects in calculations of light output and energy use.

How does temperature affect the performance of a luminaire?

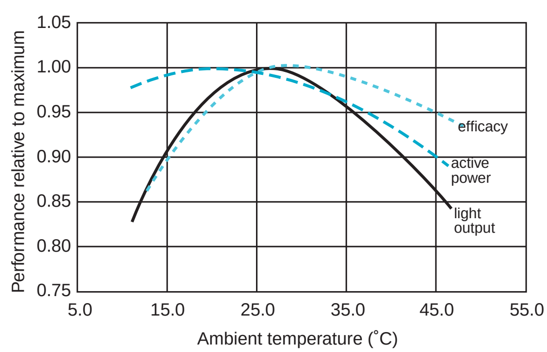
Fluorescent lamps produce their maximum light output at approximately 25°C. Any change in ambient temperature is likely to change the temperature at the coldest spot on the lamp wall. Such a change would alter the pressure of the mercury vapor inside the fluorescent lamp, which would reduce light output. Figure 1 illustrates how ambient temperature affects light output, active power, and system efficacy. The temperature near the lamps in a luminaire is almost always greater than 25°C, so the light output and the active power of the lamp-ballast system are less than those that result from manufacturers' testing, which is done at 25°C. The temperature in a ceiling plenum can also affect the total active power, light output, and *luminaire efficiency* of a luminaire.

Manufacturer-reported luminaire efficiency and *coefficient of utilization (CU)* values incorporate the reductions in light output that are caused by the luminaire itself. However, these values do not incorporate the reductions in light output that are caused by plenum temperatures greater than 25°C. Specifiers and users should also adjust the active power for thermal effects when predicting electricity use and energy savings of a fluorescent lighting system.

How did NLPIP quantify temperature effects?

NLPIP measured the effects of temperature changes on light output and active power for two of the most popular 2´×4´ luminaires: a four-lamp luminaire with a prismatic lens and

Figure 1
Performance of an F32T8 lamp
(Adapted from Bleeker and Veenstra 1990)



* Terms in *italics* are defined in the glossary on p. 7.

a three-lamp parabolic luminaire. Both were non-air-return (static) luminaires (see the sidebar "Air-return vs. non-air-return luminaires"). Table 1 on p. 4 presents active power data and estimated annual energy costs for different combinations of lamps and ballasts, at different plenum temperatures. Using the results of these measurements, NLPIP established a "first thermal factor for power" (TF_{P1}), which is defined as the ratio of the active power of the lamp-ballast system in a luminaire operated in a 25° C ambient environment to the active power of the lamp-ballast system operated in an open-air 25° C ambient environment.

NLPIP also developed two other factors from these data, "second thermal factor for power" (TF_{P2}) and "thermal factor for light output" (TF_L), to quantify the in-plenum thermal effects. TF_{P2} is defined as the ratio of the active power of the luminaire at a certain plenum temperature (for example 35° C) to its active power at 25° C. TF_L is defined as the ratio of light output of the luminaire at a certain plenum temperature to its light output at 25° C.

Table 2 on p. 5 presents TF_{P1}, TF_{P2}, and TF_L data. The testing conditions are described in the sidebar on p. 6.

How can a specifier account for thermal effects?

A specifier can use NLPIP's TF_{P1}, TF_{P2}, and TF_L to adjust initial estimates of a lamp-ballast-luminaire system's active power and light output as follows.

Active power. Specifiers may obtain either the benchtop (or ANSI) active power value from the ballast manufacturer or an active power value from a luminaire photometric report. If specifiers use benchtop active power, they should

1) Look up TF_{P1} in Table 2 for the lamp-ballast-luminaire combination being evaluated.
2) Multiply benchtop active power by TF_{P1} to correct for the in-luminaire thermal effects.
3) Determine the plenum temperature for the site. For a retrofit, the temperature can simply be measured on site; for a new installation being designed, the specifier should consult the architect or mechanical engineer for the project. A typical plenum temperature is approximately 35° C; some luminaires may operate at 45° C or even higher for special applications such as greenhouses or industrial environments.

Air-return vs. non-air-return luminaires

Approximately 75% of 2´×4´ recessed luminaires presently in use are non-air-return (static) luminaires (Bureau of the Census 1991); the other 25% are air-return (or air-handling) luminaires that provide an airflow over the lamps inside the luminaire. Air-return luminaires can extract room air through the luminaire and carry the heat of the luminaire into the plenum. Integrating an air-return luminaire into a building's air conditioning system reduces the lamp ambient temperature and can improve performance of the luminaire (Siminovitch et al. 1988).

Correcting active power for thermal effects

In this example of how to use TF_{P1} and TF_{P2}, assume a specifier is calculating the power and energy cost savings of replacing four F40T12 lamps with four F40T12/ES lamps, using the same energy-efficient magnetic ballasts and the same lensed, static luminaire. The table at right lists the benchtop active power measured by NLPIP, the active power after applying TF_{P1}, and the active power after applying TF_{P2} for a 35°C plenum.

Using benchtop data, the specifier would calculate power savings of 26 watts (W) per luminaire. After correcting for in-luminaire thermal effects by applying TF_{P1}, the specifier would calculate power savings of only 20 W per luminaire. Once the specifier corrects for in-plenum thermal effects, power savings drops to 19 W per luminaire.

If the specifier does not correct for thermal effects, he or she will overestimate annual energy savings by approximately 30% ($9.10 using benchtop active power compared with $6.65 after correcting for thermal effects). The magnitude of this error increases as the plenum temperature increases. Such overestimates yield errors in such economic analyses as simple payback and return on investment.

Power and annual energy cost compared for F40T12 lamps and F40T12/ES lamps

	Benchtop		In Luminaire at 25°C		In Plenum at 35°C	
	Active Power (W)	Annual Energy Cost ($)[a]	Active Power (W)	Annual Energy Cost ($)[a]	Active Power (W)	Annual Energy Cost ($)[a]
Four F40T12 lamps	179	62.65	170	59.50	165	57.75
Four F40T12/ES lamps	153	53.55	150	52.50	146	51.10
Savings[b]	26	9.10	20	7.00	19	6.65

[a] Annual energy costs assume 3500 operating hours per year and energy cost of $0.10/kWh. No lamp replacement or other maintenance costs are included.

[b] Savings is calculated as the value for F40T12 lamps (active power or annual energy cost) minus the value for F40T12/ES lamps.

4) Look up TF_{P2} in Table 2 for the proper lamp-ballast-luminaire combination and plenum temperature.
5) Multiply the active power by TF_{P2} to correct for in-plenum thermal effects.

The sidebar on p. 2 gives an example of these calculations.

A specifier may obtain the active power for a lamp-ballast-luminaire combination from a luminaire's photometric report. That value frequently is called "input power" and is specific to the lamp-ballast combination that was tested, so the specifier should be sure this lamp-ballast combination is the one being considered. The input power value from a photometric report already incorporates TF_{P1}, so the specifier need only

1) Determine the plenum temperature.
2) Look up TF_{P2} in Table 2.
3) Multiply the input power from the photometric report by TF_{P2} to correct for in-plenum thermal effects.

Light output. The light output of a lamp-ballast-luminaire combination in a particular space is used to predict the amount of light delivered to the workplane (*illuminance*). Specifiers typically

1) Multiply the bare-lamp light output published by the lamp manufacturer by the *ballast factor* from the ballast manufacturer.
2) Multiply this value by the CU from the luminaire's photometric report.

This adjusted light output does not correct for in-plenum thermal effects.

To correct for in-plenum thermal effects, a specifier should do steps 1 and 2 above, then

3) Determine the plenum temperature.
4) Look up TF_L in Table 2 for the appropriate lamp-ballast-luminaire combination and plenum temperature.
5) Multiply the adjusted light output from step 2 by TF_L.

The sidebar below gives an example of these calculations.

Correcting light output for thermal effects

In this example of how to use TF_L, assume a specifier is calculating the light output of a lensed, static luminaire with four F32T8 lamps and an electronic ballast. The table at right lists the light output as each factor is applied. If the specifier stopped after applying the CU, which is the value typically used by specifiers for new installations, the predicted light output would be 6902 lumens (lm). For a 35°C plenum, however, applying TF_L yields light output of 6626 lm, a reduction of 4%. In a 45°C plenum, applying TF_L yields light output of 6281 lm, a reduction of 9%. A specifier who did not account for thermal effects while performing lighting calculations would thus predict higher illuminances than the lighting system actually produces.

Light output changes as adjustment factors are applied

	Adjustment Factors	Light Output (lm)
Bare lamps	1.0	11,600
Ballast factor	0.85	9,860
CU	0.70*	6,902
TF_L for 35°C plenum	0.96	6,626
TF_L for 45°C plenum	0.91	6,281

* This CU is representative of luminaires of this type, but each luminaire is different. Specifiers should use the CU of the specific luminaire that they are evaluating.

Table 1
NLPIP-measured active power at different plenum temperatures

Luminaire Type	Lamp Type	Ballast Type[a]	BF[b]	Benchtop Power (W)[c]	Luminaire Active Power (W)[d]					Annual Energy Cost per Luminaire ($)[e]			
					25°C	30°C[f]	35°C	45°C	55°C	ANSI	25°C	35°C	45°C
four-lamp, lensed troffer, non-air-return	F40T12	MB	0.95	179	170	167	165	160	155	62.65	59.50	57.75	56.00
		CDB	0.93	163	155	152	150	146	141	57.05	54.25	52.50	51.10
		EB	0.73	121	117	115	114	110	107	42.35	40.95	39.90	38.50
		EB	0.87	146	141	138	135	130	126	51.10	49.35	47.25	45.50
		EB	1.05	171	164	160	158	153	149	59.85	57.40	55.30	53.55
	F40T12/ES	MB	0.88	153	151	149	147	143	140	53.55	52.85	51.45	50.05
		CDB	0.91	140	137	135	134	131	128	49.00	47.95	46.90	45.85
		EB	0.73	106	105	104	102	99	97	37.10	36.75	35.70	34.65
		EB	0.87	126	125	123	121	117	113	44.10	43.75	42.35	40.95
		EB	1.05	149	145	143	141	136	133	52.15	50.75	49.35	47.60
	F32T8	MB	0.95	151	150	148	146	142	139	52.85	52.50	51.10	49.70
		CDB	0.87	122	120	119	117	114	111	42.70	42.00	40.95	39.90
		EB	0.85	105	101	99	97	92	88	36.75	35.35	33.95	32.20
three-lamp, parabolic louver, non-air-return, 18-cell	F40T12	MB	0.95	139	137	135	134	131	129	48.65	47.95	46.90	45.85
		EB	0.87	104	103	102	101	100	98	36.40	36.05	35.35	35.00
	F40T12/ES	MB	0.88	120	120	119	118	117	115	42.00	42.00	41.30	40.95
		EB	0.87	94	93	93	92	91	89	32.90	32.55	32.20	31.85
	F32T8	MB	0.95	118	118	117	116	114	111	41.30	41.30	40.60	39.90
		EB	0.87	95	92	90	89	86	82	33.25	32.20	31.15	30.10

[a] MB = energy-efficient magnetic ballast, CDB = cathode-disconnect ballast, EB = electronic ballast

[b] BF = ballast factor provided by ballast manufacturer

[c] Benchtop power is the active power to the bare lamp and ballast system in open air, measured by NLPIP using ANSI test conditions.

[d] Luminaire active power is the active power to the lamp-ballast-luminaire system, measured by NLPIP with the lamps and ballasts installed in the luminaire and the luminaire operated at the plenum temperatures shown. It therefore takes both TF_{P1} and TF_{P2} into account.

[e] Annual energy costs assume 3500 operating hours per year and energy cost of $0.10/kWh. No lamp replacement or other maintenance costs are included.

[f] This column of data can be compared with CEC calculated values.

Table 2
NLPIP-calculated thermal factors at different plenum temperatures

Luminaire Type	Lamp Type	Ballast Type[a]	BF[b]	TF_{P1}	TF_{P2}[c]					TF_L[c]				
					25°C	30°C	35°C	45°C	55°C	25°C	30°C[d]	35°C	45°C	55°C
four-lamp, lensed troffer, non-air-return	F40T12	MB	0.95	0.95	1.00	0.98	0.97	0.94	0.91	1.00	0.96	0.93	0.88	0.82
		CDB	0.93	0.95	1.00	0.98	0.97	0.94	0.91	1.00	0.97	0.94	0.88	0.83
		EB	0.73	0.97	1.00	0.99	0.97	0.94	0.91	1.00	0.99	0.97	0.93	0.88
		EB	0.87	0.96	1.00	0.98	0.96	0.93	0.90	1.00	0.98	0.95	0.90	0.85
		EB	1.05	0.96	1.00	0.98	0.96	0.93	0.91	1.00	0.97	0.95	0.89	0.85
	F40T12/ES	MB	0.88	0.98	1.00	0.99	0.97	0.95	0.93	1.00	0.96	0.95	0.88	0.83
		CDB	0.91	0.97	1.00	0.99	0.98	0.95	0.93	1.00	0.98	0.95	0.90	0.85
		EB	0.73	0.99	1.00	0.99	0.98	0.95	0.92	1.00	0.99	0.98	0.94	0.89
		EB	0.87	0.99	1.00	0.98	0.97	0.94	0.91	1.00	0.98	0.96	0.92	0.86
		EB	1.05	0.97	1.00	0.98	0.97	0.94	0.92	1.00	0.98	0.95	0.90	0.85
	F32T8	MB	0.95	1.00	1.00	0.99	0.97	0.95	0.92	1.00	0.97	0.94	0.89	0.83
		CDB	0.87	0.99	1.00	0.99	0.97	0.94	0.92	1.00	0.98	0.96	0.90	0.85
		EB	0.85	0.97	1.00	0.98	0.96	0.91	0.87	1.00	0.98	0.96	0.91	0.85
three-lamp, parabolic louver, non-air-return, 18-cell	F40T12	MB	0.95	0.99	1.00	0.99	0.98	0.96	0.94	1.00	0.98	0.96	0.93	0.89
		EB	0.87	0.98	1.00	0.99	0.99	0.97	0.95	1.00	1.00	1.00	0.99	0.97
	F40T12/ES	MB	0.88	0.99	1.00	0.99	0.99	0.98	0.96	1.00	0.99	0.98	0.95	0.91
		EB	0.87	0.99	1.00	0.99	0.99	0.98	0.96	1.00	1.00	1.00	0.99	0.97
	F32T8	MB	0.95	1.00	1.00	0.99	0.98	0.96	0.94	1.00	0.98	0.97	0.93	0.90
		EB	0.87	0.97	1.00	0.98	0.97	0.93	0.89	1.00	0.99	0.98	0.95	0.91

[a] MB = energy-efficient magnetic ballast, CDB = cathode-disconnect ballast, EB = electronic ballast

[b] BF = ballast factor provided by ballast manufacturer

[c] TF_{P2} and TF_L values are normalized to their respective values at 25°C.

[d] This column of data can be compared with the California Energy Commission's (CEC) calculated application correction factors by multiplying TF_L by the ballast factor.

What other data are available on thermal effects?

Most researchers studying the effects of temperature on fluorescent lamps either did not collect data on lamps installed in luminaires or used testing conditions that did not necessarily represent typical applications (Bleeker et al. 1988; Hammer and Purvis 1987; Lewin and McFarlane 1993; Verderber et al. 1988).

Information about thermal effects on fluorescent lamp systems, including different combinations of lamps, ballasts, and luminaires, has been published in the California Energy Commission's (CEC) Advanced Lighting Guidelines (CEC 1993). Although the CEC's tables present values for many different lamp-ballast-luminaire combinations, few of the combinations were actually tested. Instead, the values presented are based on calculations that use the relationship between light output, power, and lamp ambient temperature published by Bleeker and Veenstra (1990) and shown in Figure 1.

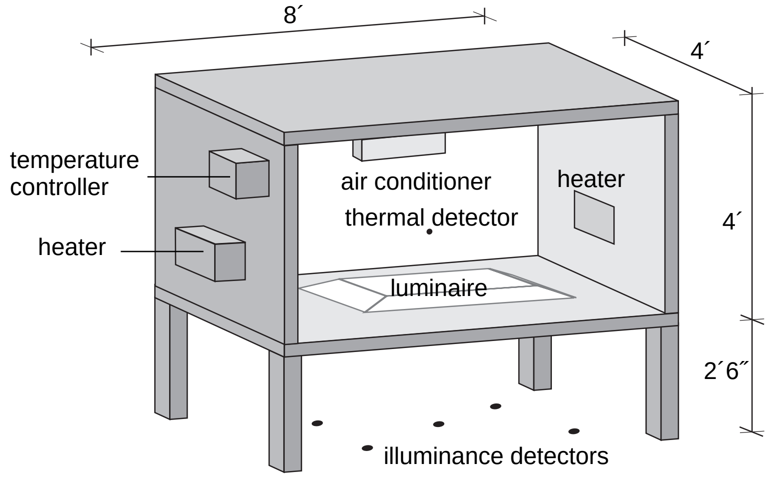
Testing conditions

Luminaire types*:	Prismatic-lensed, static, four-lamp 2´×4´ luminaire Parabolic-louvered, static, three-lamp 2´×4´ luminaire
Lamp types*:	F40T12/RE735 F40T12/RE735/ES (34 W) F32T8/RE835
Ballast types*:	Energy-efficient magnetic ballasts *Cathode-disconnect ballasts* *Electronic ballasts*: BF=1.05, BF=0.87, BF=0.73

Plenum temperatures: 25, 30, 35, 45, and 55°C

*NLPIP selected products from several manufacturers to represent typical lamp-ballast-luminaire combinations in testing. Results may vary for other products.

Testing chamber



Direct comparisons between NLPIP's testing results (Tables 1 and 2) and CEC's calculated data are difficult, because the CEC made several assumptions for their calculations. In general, the luminaire active power values calculated by the CEC assuming a 30°C plenum are lower than those measured by NLPIP at 30°C. The values reported by the CEC would thus produce lower estimates of energy costs than NLPIP's measured data. The CEC's calculated application correction factors, used to adjust estimated light output, can be compared with the product of ballast factor and TF_L. For the lamp-ballast-luminaire combinations that NLPIP tested, TF_L and the CEC's application correction factors agree to within 3%. However the CEC reports nearly 300 application correction factors and over 700 active power values, so more testing is necessary to fully evaluate the CEC's assumptions.

Does the Energy Policy Act address luminaire efficiency?

Although the United States Energy Policy Act of 1992 did not mandate minimum luminaire efficiency standards (U.S. Congress 1992), it did require the lighting industry to develop a rating system for luminaires subject to the approval of the Department of Energy. In response to this requirement, NEMA (1993) developed a new parameter, the luminaire efficacy rating (LER), which is defined as:

$$\text{LER} = \frac{\text{luminaire efficiency} \times \text{total lamp lumens} \times \text{ballast factor}}{\text{total luminaire active power}}$$

According to the definition, LER is the ratio of the amount of light coming from a luminaire to the luminaire's total active power, all measured at 25°C. LER rates the entire lamp-ballast-luminaire system by including ballast factor and total luminaire active power, and it accounts for NLPIP's TF_{P1}, because the total luminaire active power is measured with the lamp(s) and ballast(s) installed in the luminaire. However, LER does not account for changes to active power and light output due to in-plenum thermal effects (NLPIP's TF_{P2} and TF_L) because LER rates the luminaire at 25°C. Thus, LER values will change at different plenum temperatures.

Glossary

active power The system input power in watts for a lamp and ballast combination. When referred to as benchtop active power, the measurement procedure follows ANSI standards, which include horizontally mounted bare lamp(s) at an ambient temperature of 25° C ±1° C, and air movement less than 5 feet per minute. The lamps are seasoned 100 hours before testing, and the measurements are conducted after lamp light output stabilizes.

ballast factor (BF) The ratio of the light output of a fluorescent lamp(s) operated on a ballast to the light output of the lamp(s) operated on a standard (reference) ballast. BF is dependent upon both the ballast and the lamp type; a single ballast can have several BFs, depending on the type and number of lamps that it is operating. Thus the BFs for different ballasts should only be compared if the ballasts are operating the same lamp type.

cathode-disconnect ballast An electromagnetic ballast that disconnects the electrode-heating circuit after the lamps are started. Cathode-disconnect ballasts operate lamps at 60 hertz; they sometimes are called "hybrid" or "low-frequency electronic" ballasts. They operate lamps at lower power than other magnetic ballasts that produce similar light output.

coefficient of utilization (CU) The ratio of the luminous flux (lumens) received on a plane to the light output (lumens) of the lamps. CU depends on luminaire efficiency, distribution of light from the luminaire, size and shape of the room, and reflectances of surfaces in the room. Specifiers use the CU to evaluate how effectively a luminaire delivers light to a work plane.

efficacy The ratio of the light output of a lamp (lumens) to its active power (watts), expressed in lumens per watt.

electronic ballast A ballast that uses electronic components instead of a magnetic core and coil to regulate the voltage of fluorescent lamps. Electronic ballasts operate lamps at 20–60 kilohertz.

illuminance The luminous flux incident on a surface area. Illuminance is measured in footcandles (lumens per square foot) or lux, (lumens per square meter). One footcandle (fc) equals 10.76 lux (lx), although for convenience 10 lx commonly is used as the equivalent.

luminaire A complete lighting unit consisting of a lamp or lamps and the parts designed to distribute the light, to position and protect the lamp(s), and to connect the lamp(s) to the power supply.

luminaire efficiency The ratio of the light output of a luminaire to the light output of the luminaire's lamps. Luminaire efficiency accounts for the optical and thermal effects that occur within the luminaire under standard test conditions.

plenum Air space between a ceiling plane and the floor or roof above. This space is used for air-handling ducts, electrical wiring, and other building systems.

Resources

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Author: Yunfen Ji
Program Director: Robert Davis
Editors: Amy Fowler and Kevin Heslin
Production: Nancy Bayer and Jason Teague

Other Lighting Research Center members who contributed include Kathryn Conway, James Gross, Russell Leslie, Dorene Maniccia, Naomi Miller, Mark Rea, Paula Rodgers, Pamela Schemenaur, Robert Strobel, and Ling Tang.

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For publications ordering information, contact:

Lighting Research Center
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Telephone: (518) 276-8716
Fax: (518) 276-2999
Internet e-mail: lrc@rpi.edu

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Lighting Answers complements the National Lighting Product Information Program's (NLPIP) other serial, *Specifier Reports*. Each issue of *Lighting Answers* presents educational information about a specific topic or a particular technology. For some issues, NLPIP may perform limited testing. For this issue of *Lighting Answers*, NLPIP has summarized information about thermal effects in 2´×4´ luminaires and performed limited testing.