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BUILDING SCIENCE INSIGHT

A Systems Approach to Reducing Power Density in Office Lighting

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Introduction

Improvements in lamp and ballast technology have provided an almost baffling array of lamp and ballast combinations for use in general lighting. Narrow-diameter (T8) fluorescent lamps and high frequency electronic ballasts are among the most popular new lighting technologies employed in energy management initiatives in commercial buildings. These technologies will also play a predominant role in helping lighting specifiers design lighting systems to meet new power density criteria outlined in the ASHRAE/IES 90.1 standard being adopted by many provinces and municipalities. This standard is also the basis of the proposed National Energy Codes. A systems approach to lighting design can offer improved lighting performance and lower operating costs for the owner/user.

Sorting out the options and combining specific lamps with ballasts designed for optimum performance for a given application is often difficult; data flows from a myriad of sources and finding a common denominator for system-to-system comparison is becoming a real challenge. The systems performance approach to general fluorescent lighting equipment provides the lighting specifier with a guide to the performance characteristics of 4-foot fluorescent systems.

System Evaluation

In an effort to evaluate various 4 foot lamp and ballast systems, a typical 20" x 48" recessed troffer equipped with standard F40 lamps and a traditional magnetic ballast was electrically measured and photometered using industry accepted IES/ ANSI measurement procedures. The fixture housing was then refitted with various ballast/lamp systems and each time the resulting measurements were compared to the base F40 system. The results for each system were then tabulated to provide a simplified evaluation of each system compared to the base system under identical photometric test conditions.

Once the system performance parameters were known, a lighting analysis was conducted for various lighting layouts and ceiling configurations to determine the corresponding power density of typical lighting layouts in relation to the set limits of the proposed energy guidelines outlined in the National Energy Code for Buildings.

Fluorescent System Performance

The development of the systems concept requires that the lighting specifier review light loss and performance factors that affect lighting system performance.

Lamp bulb well temperature

The fluorescent lamp is the only major light source which is sensitive to ambient temperatures (Figure 1).

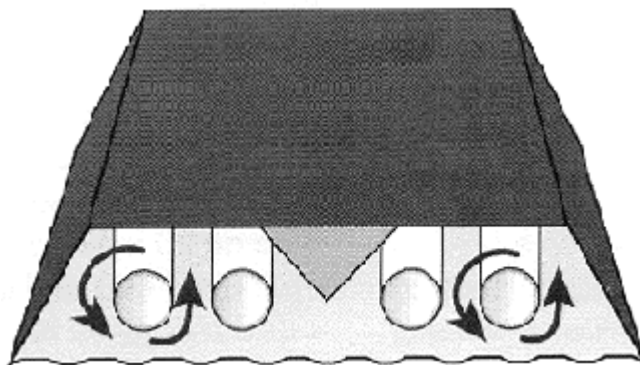


Figure 1 Lumen output is a function of bulb wall temperature. Air circulation around the lamp can have a significant impact on light output.

The general relationship between fluorescent lamp performance and temperature is shown in Figure 2. The critical area as far as the fluorescent lamp is concerned is the coldest spot on the bulb surface. This spot controls mercury vapour pressure inside the lamp, increasing or decreasing the amount of ultraviolet energy available to activate the phosphors. Most fluorescent lamps are designed to peak in light output at around 40°C (100°F) cold spot temperature. Above this value too much mercury vapour is present in the lamp and ultraviolet energy is absorbed, with a subsequent reduction in both light output and power input. This is a common mode of operation in many older installations, particularly where lamps are operated in multi-lamp recessed troffers, and it is not uncommon to find lamps under such conditions operating from 10 to 25% below rated lumen output. Temperature data do not normally appear in a luminaire manufacturers' specification sheets, since they are automatically included in the photometric tests completed under standard reference conditions and incorporated into the resulting candlepower and coefficient of utilization (CU) tables.

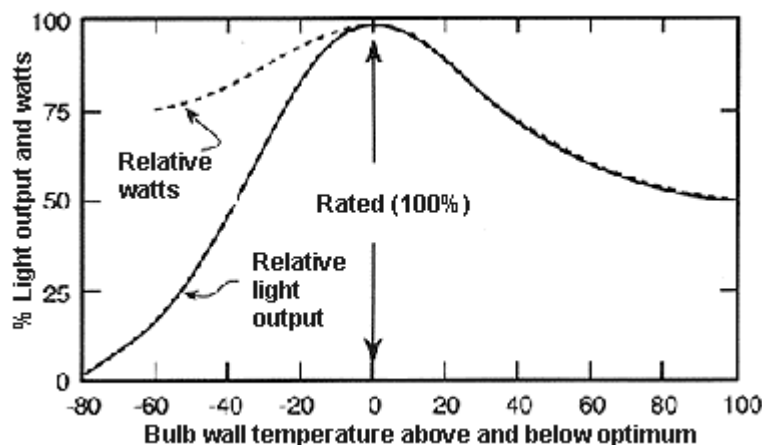


Figure 2 The fluorescent lamp is the only major light source that is sensitive to ambient temperatures. Light output decreases when the lamp is operated above or below optimum temperature.

An indication of temperature effect can readily be seen in an examination of CU tables for identical luminaire configurations; the data will show that the CU's and luminaire efficiency are lower for 4-lamp equipment than for similar 2-lamp equipment. Most of the difference is due to the higher lamp bulb wall temperature found in 4-lamp units.

As lamp temperature falls below optimum, mercury condenses at the cold spot and light output drops dramatically as the arc becomes "starved" for mercury vapour. Lamp watts remain relatively high since power is being used to heat the lamp, so there is a substantial reduction in lamp efficacy (lumens per watt) on the cold side of the curve.

While cold temperature operation has not been particularly common in interior lighting systems, it may be encountered more frequently now because:

- during the winter, lower night and weekend temperature setbacks in buildings will result in lower room temperatures when lamps are first turned on;
- as lighting system watts per fixture are reduced, in any number of ways, less heat is available to warm the lamp. Some T8 systems, for example, exhibit cold temperature characteristics of flicker and low light output when first energized.

Ballast factor

Fluorescent lamp lumen output, as defined in various manufacturers' literature, is derived from photometric measurements while the lamp is operated on a "reference" ballast. This "reference" ballast is a laboratory device, and is designed to provide "fine tuning" of lamp electrical characteristics to specific industry (ANSI) standards prior to photometry and thus a uniform measurement system for industry.

The typical commercial production ballast, however, does not provide full rated lamp lumen output. This performance differential is expressed in the lighting calculation procedure as Ballast Factor (BF).

BF = Lamp lumen output on commercial ballast / Lamp lumen output on reference ballast

Ballast factor is the ratio of actual light output of a specific lamp compared to the rated lumens of the lamp as found in manufacturers' data sheets.

Rarely do manufacturers publish ballast factor data; however, it is part of the lighting calculation process (light loss factor).

Ballast factors vary depending on the system. They may also vary in the field. For example, a standard ballast with standard lamps (F40) has a ballast factor of 0.93. However, the same ballast with energy saving 34-watt lamps will have a ballast factor of 0.87.

Ballast factors in Canada for standard F40 lamps are typically found to be 0.93. Some new magnetic ballast designs utilize a new core design and

optimum capacitor selection, resulting in improved ballast factors (up to 0.97).

Electronic ballasts

Technically, industry standards for light output and ballast factor are non-existent for electronic ballasts at this time; however, they are expected to be published shortly. Many papers have been written that describe the light output performance of lamps on electronic ballasts. Generally, electronic ballasts operate fluorescent lamps at high frequency (25 to 40 kiloHertz) resulting in favourable actual to rated lumen values, with ballast factors ranging from 0.82 to 0.97.

Lamp lumen depreciation

An evaluation of system performance includes lumen depreciation, since maintained footcandles (lux) take into account phosphor degradation over time. Standard T12 systems utilizing halophosphates experience greater lumen depreciation than newer T8 lamps utilizing rare earth phosphors.

Systems Comparison and Performance

Luminaire light output and ballast input wattage are affected by the thermal operating point of the lamps. This, coupled with the total lumens available, the ability of the ballast to deliver lumens, plus the optical efficiency of the luminaire itself, determines the final lumen output of the luminaire.

A significant number of lamp/ballast/ luminaire combinations can be made today, with a wide range of system performance. To obtain some idea of this variability between 4-foot lamp and ballast combinations and systems, a single 20" x 48" 2-lamp fixture housing equipped with specific lamp and ballast configurations was thermally, electrically and photometrically measured.

System comparison

Information obtained from the tests included:

System input power - Input power was measured once the system was thermally stabilized to ANSI and IES luminaire photometry standards. Tests were conducted in a 25 °C ambient temperature.

Light output percent - Once photometry was completed, the relative light output compared to the base system was determined.

Efficiency - Using relative light output and input watts, an efficiency rating was determined compared to the base system. This evaluation of lumens per watt provides a useful comparison since all components are evaluated to the base system.

System lumens - System lumens represents total rated lumens of the lamps installed.

Luminaire efficiency - The photometric measurement of luminaire efficiency is the percentage of lumens leaving the luminaire compared to rated lumens installed. In this report it is an indicator of the gains made through the reduction of lamp diameter in this particular luminaire.

Test Summary

System 1 F40 T12/MAG (Base System)

Standard magnetic 2-lamp 120V ballast with 2 regular F40T12 cool white halophosphate 40-watt fluorescent lamps. This system is the base system (100) and other systems were compared to it. Input power was 88 watts. Luminaire efficiency was 68%.

System 2 F34ES T12/MAG

Installing energy saving 34-watt T12 lamps on this ballast changed the system thermal characteristics (lower watts = less excess heat) and ballast factor (BF), resulting in 93% light output compared to the base system and a 4% increase in system efficiency, i.e., light output relative to energy input. Luminaire efficiency remained at 68%.

System 3 F32 T8/MAG

Energy saving high performance system. Magnetic 2-lamp ballast with 2 32-watt T8 rare earth phosphor lamps.

Present day fluorescent lighting efficacies have been improved by phosphor technology that emits light in the red, blue and green portions of the visible spectrum. These new phosphors can withstand higher power loading and exhibit less depreciation over time compared to standard colour halophosphates. These improved phosphor coatings are found in small diameter (T8, T5, T4) lamps, and provide the added benefit of improved colour rendering (CRI).

Our tests indicated that system input power was 68 watts, while light output increased by 2% over the base system, even though fewer lumens were installed. This would indicate that the thermal characteristics of the lamp and luminaire system are favourable. In addition, luminaire efficiency improved by 6% due to the narrow lamp configuration. Overall system performance is 32% greater than the base system.

System 4 F032 T8/Elec- 1

High frequency electronic ballast for 1 to 4 T8 lamps. This ballast is an instant start design, used in this system with 2 F032 T8 high efficiency lamps. Fluorescent lamps become more efficient when supplied with high frequency power.

F032 T8 high efficiency lamps are primarily rapid start designs, requiring cathode heating for electron emission purposes. Lamp manufacturers' studies have shown that some two wire design (instant start) high frequency ballasts provide reliable starting and operating characteristics for 32-watt T8 lamps. They do, however, derate lamp life by 25% for these circuits.

System input power was 57 watts and light output was down by 5%. Overall system performance was 46% greater than the base system.

System 5 F032 T8/Elec - 2

Electronic high frequency integrated circuit ballast for 32- to 40-watt T8, T10 or T12 rapid start lamps. The tested system had two F032 T8 lamps

installed.

System input power was 78 watts, and light output was 25% greater than the base system; efficiency improved 56% over the base system.

System 6 F40 T10/MAG - HE

High efficiency low loss magnetic ballast fitted with 2 high lumen 40-watt T10 high efficiency lamps. This high efficiency ballast is modified to enhance lamp performance and includes an energy saving core to reduce ballast energy losses.

System input power was 90 watts, while light output was 41 % greater than the base system and system efficiency improved by 31 %. Of interest is the increase in luminaire efficiency from 68% to 71%, due to the use of the narrower T10 lamp.

System 7 F40 T8/Elec - 2

This lamp and ballast combination consisted of two 3700-lumen 40-watt T10 lamps combined with the same integrated rapid-start electronic ballast as used in System 5. This combination consumed 74 watts, while light output was 31% greater than the base system, and system efficiency increased by 56%. Luminaire efficiency remained at 71 % since lamp size characteristics were unchanged from System 6.

The summarized results for the performance of all 7 systems are presented in Table 1.

Table 1 Test Summary. All systems are compared to the base F40 2-lamp system with a standard magnetic ballast.

System	Input power (watts)	Light (%)	Efficiency (%)	System lumens	Luminaire efficiency (%)
1. F40 T12/Mag	88	100	100	6300	68
2. F34ES T12/Mag	76	93	104	5300	68
3. F32 T8/Mag	68	102	132	5800	74
4. FO32 T8/Elec-1	57	95	146	5800	74
5. FO32 T8/Elec-2	78	125	156	5800	74
6. F40 T10/Mag-HE	90	141	131	7400	71
7. F40 T10/Elec-2	74	131	156	7400	71

System Evaluation: ASHRAE/ IES 90.1

In order to evaluate the impact of the proposed new energy guidelines for lighting in commercial buildings, some typical layouts incorporating Systems 1 to 4 were evaluated. Each system was evaluated in a 9600 ft² open plan office with a 10 ft ceiling, falling into ASHRAE/IES 90.1 office category 1.

For a typical open plan office in category 1, the maximum allowed power

density is 1.8 W/ft². For this evaluation, reflectance values of 80/50/20% were chosen, and Illuminance were calculated at the work plane. Measured parameters included Illuminance (footcandles) and field power (watts), also called field watts. Power density was then calculated and compared to the maximum allowed power density of 1.8 W/ft². Systems which met the requirement are indicated by a ✓ under 'status' in Tables 2-4. The following typical layouts were used:

Table 2 Layout 1: 144 2-lamp troffers set on 8' centers in a 2' by 4' ceiling grid. All systems meet ASHRAE/IES 90.1 power density limit of 1.8 W/ft².

System	Illuminance (footcandles)	Filed Watts (watts)	Power density (W/ft ²)	Status
1. F40 T12/Mag	54	90	1.35	✓
2. F34ES T12/Mag	46	72	1.08	✓
3. F32 T8/Mag	58	70	1.05	✓
4. F032 T8/Elec-1	56	58	0.87	✓

Table 3 Layout 2: 181 2-lamp troffers set 5' by 5' ceiling modules, with one luminaire every other module (50 ft²/luminaire). All systems meet ASHRAE/EIS 90.1 power density limit of 1.8 W/ft².

System	Illuminance (footcandles)	Filed Watts (watts)	Power density (W/ft ²)	Status
1. F40 T12/Mag	68	90	1.70	✓
2. F34ES T12/Mag	60	72	1.40	✓
3. F32 T8/Mag	72	70	1.30	✓
4. F032 T8/Elec-1	70	58	1.10	✓

Table 4 Layout 3: 120 4-lamp recessed troffers set on 8' by 10' centers in a 2' by 4' ceiling grid. Systems 1 does not meet the ASHRAE/IES 90.1 power density limit of 1.8 W/ft².

System	Illuminance (footcandles)	Filed Watts (watts)	Power density (W/ft ²)	Status
1. F40 T12/Mag	91	180	2.25	✗
2. F34ES T12/Mag	80	142	1.77	✓
3. F32 T8/Mag	95	140	1.75	✓
4. F032 T8/Elec-1	92	108	1.35	✓

Tables 2, 3 and 4 illustrate that significant reductions in power density can be made by adopting newer ballast and lamp systems. These systems could be used to trade off power density for other building systems requiring a higher concentration of energy than allowed in the guidelines.

System Evaluation: Economics

Tables 5, 6 and 7 provide some simple economic analyses of the various layouts, including incremental costs and payback periods of the systems discussed. For this comparison, systems 1 to 4 were again considered to be installed in the same typical layouts represented in Tables 2, 3 and 4. The analysis takes into account the typical added cost of the ballast and lamp and does not include any impact the reduced load would have on initial wiring and distribution costs or on the HVAC system. The cost analysis is a guide only, as market fluctuations in electronic ballast pricing could change calculated paybacks significantly.

Table 5 Simple economic analysis for Layout 1: 144 2-lamp troffers set on 8' by 8' centers in a 2' by 4' ceiling grid. Annual operating time is assumed to be 3500 hours; wiring and distribution costs are not included in initial costs; lamps and electricity are included in operating costs.

System	Illuminance (footcandles)	Power Density (W/ft ²)	Added Incremental Initial Cost (\$)	Annual Operating Cost Savings (\$)	Simple Payback (months)	Simple Return on Investment
1. F40 T12/Mag	54	1.35	--	--	--	--
2. F34ES T12/Mag	46	1.08	432	700	7	162%
3. F32 T8/Mag	58	1.05	1440	705	24	49%
4. FO32 T8/Elec- 1	56	0.87	3456	1189	34	35%

Table 6 Simple economic analysis for Layout 2: 181 2-lamp troffers set in 5' by 5' ceiling modules, with one luminaire every other module (50 ft² / luminaire). Annual operating time is assumed to be 3500 hours; wiring and distribution costs are not included in initial costs; lamps and electricity are included in operating costs.

System	Illuminance (footcandles)	Power Density (W/ft ²)	Added Incremental Initial Cost (\$)	Annual Operating Cost Savings (\$)	Simple Payback (months)	Simple Return on Investment
1. F40	68	1.70	--	--	--	--

T12/Mag						
2. F34ES T12/Mag	60	1.40	543	880	14	162%
3. F32 T8/Mag	72	1.30	1810	886	24	49%
4. FO32 T8/Elec- 1	70	1.10	4344	1495	34	34%

Table 7 Simple economic analysis for Layout 3: 120 4-lamp recessed troffers set on 8' by 10' centers in a 2' by 4' ceiling grid. Annual operating time is assumed to be 3500 hours; wiring and distribution costs are not included in initial costs; lamps and electricity are included in operating costs.

System	Illuminance (footcandles)	Power Density (W/ft ²)	Added Incremental Initial Cost (\$)	Annual Operating Cost Savings (\$)	Simple Payback (months)	Simple Return on Investment
1. F40 T12/Mag	91	2.25	--	--	--	--
2. F34ES T12/Mag	80	1.77	720	1167	7	162%
3. F32 T8/Mag	95	1.75	2400	1176	24	49%
4. FO32 T8/Elec- 1	92	1.35	3960	2251	21	56%

Conclusion

Our findings indicate that while the proposed minimum efficiency energy codes set maximum limits for power density in office buildings, these limits can be met using current illuminance guidelines, using standard lamps with energy saving magnetic ballasts. An exception is where older layout design techniques are used, incorporating four-lamp luminaires. Four-lamp 2' x 4' systems in general offices today produce much higher illuminances than current practices recommend. This results in power densities that exceed the proposed energy code guidelines.

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