J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

HIGH-FREQUENCY LIGHTING SUPPLIES

A gas discharge light source, such as a fluorescent or high intensity discharge (*HID*) lamp, requires a ballast to provide high initial voltage for starting the lamp, to regulate lamp current during operation, and to supply the proper lamp operating voltage. In the early 1980s, advances in solid-state technology allowed ballast manufacturers to replace the core-and-coil transformer with electronic components that operate fluorescent lamps at 20 to 60 kHz. The high-frequency operation of fluorescent lamps results in 10 to 15% increase in lamp efficacy, relative to 60 Hz operation.

As shown in Figs. 1 and 2, sales of electronic ballasts for fluorescent lamps in the United States grew rapidly from 1986 to 1996 (1). Their share by volume of the overall fluorescent lamp ballast industry has grown from 0.6% in 1986 to 31.2% in 1996, and their share by value of the overall fluorescent lamp ballast industry has grown from 2.9% in 1986 to 49.7% in 1996 (1). (The reduction shown from 1995 to 1996 was probably the result of a decrease in utility rebate programs for electronic ballasts.) Figure 3 shows that the calculated average unit price of U.S. manufactured electronic ballasts for fluorescent lamps has dropped gradually in 11 years.

Electronic ballasts are also available for low-wattage HID lamps. Electronic ballasts for HID lamps are lighter and smaller than magnetic ballasts but have higher initial costs. Although the high-frequency operation for HID lamps does not significantly increase lamp efficacy, electronic ballasts require less power to operate HID lamps because of lower ballast power loss. Magnetic ballasts operate the lamps at 60 Hz; electronic ballasts for low-wattage HID lamps operate lamps at either 60 Hz or much higher frequencies, such as 25 kHz. Because the market for HID lighting systems is much smaller than that for fluorescent lighting systems, this paper focuses on high-frequency electronic ballasts for fluorescent lamps. However, some basic issues apply to both fluorescent and HID lamp ballast systems.

As stated previously, high frequency electronic ballasts are promoted as a technology that can provide significant energy savings for fluorescent lighting systems. As the popularity of electronic ballasts has grown, manufacturers have introduced many new products. The compatibility of fluorescent lamps with electronic ballasts has become one of the major concerns among specifiers and users. This article provides basic technical information on electronic ballasts, including the issues of energy savings, ballast performance, lamp/ballast compatibility, and ballast reliability.

Types of Ballasts

Before discussing different types of ballasts and their performance, it is important to define fluorescent lamp designations. All fluorescent lamps have a designation made up of descriptive codes. Some examples of these designations and definitions of the component codes follow:

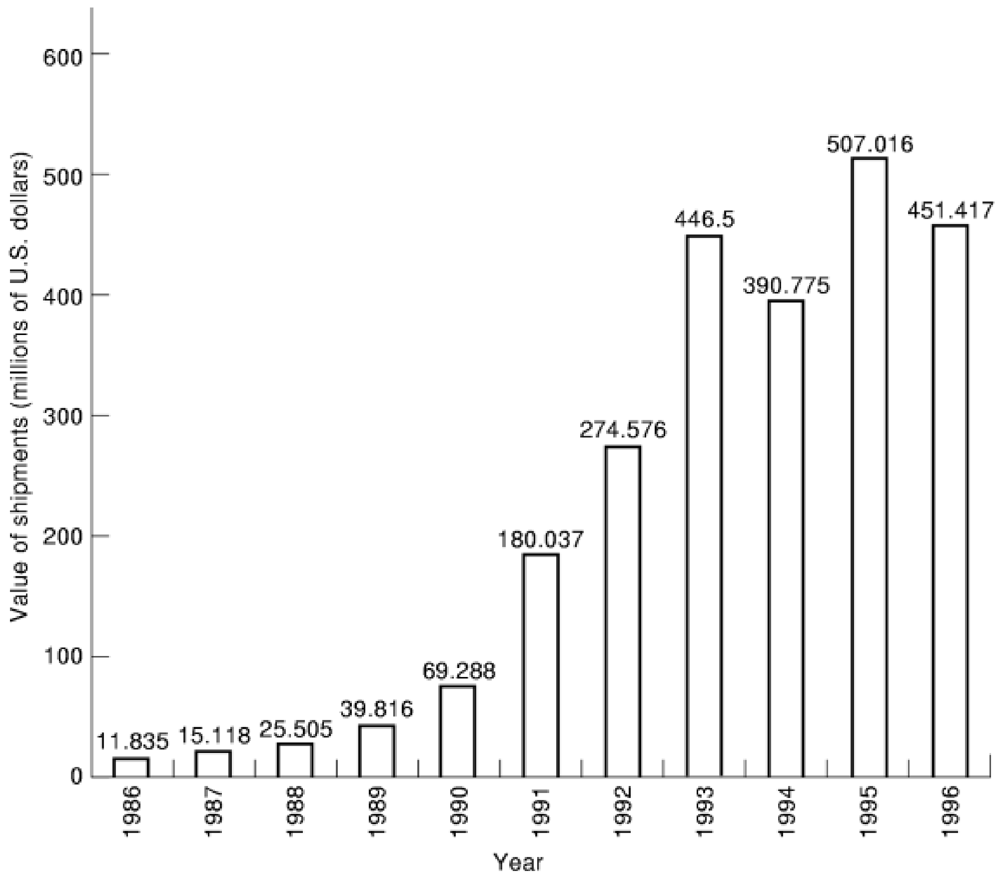

Fig. 1. Value of shipments of U.S. manufactured electronic ballasts for fluorescent lamps.

F40T12
F = fluorescent
40 = 40 W
T = tubular
12 = diameter in eighths of an inch
lamp length implied = 4 ft (1.22 m)

F40T12/ES
ES = energy-saving type, 34 W

F32T8
F = fluorescent
32 = 32 W
T = tubular
8 = diameter in eighths of an inch
lamp length implied = 4 ft (1.22 m)

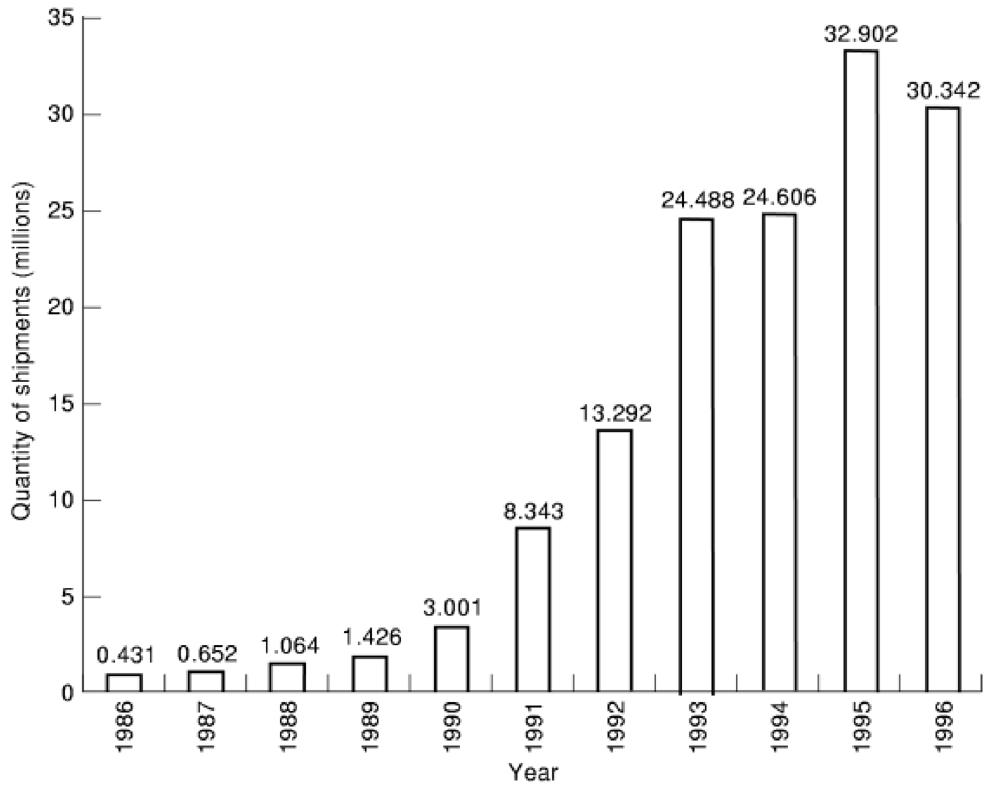

Fig. 2. Quantity of shipments of U.S. manufactured electronic ballasts for fluorescent lamps.

The 1990 National Appliance Energy Conservation Act eliminated older high-power loss magnetic ballasts by requiring all ballasts sold in the United States for commercial fluorescent lighting systems to have efficiencies greater than or equal to those of energy-efficient magnetic ballasts. As a result, only three types of ballasts presently are sold for commercial applications in the United States: energy-efficient magnetic ballasts, cathode-disconnect ballasts, and high-frequency electronic ballasts.

Energy-efficient Magnetic Ballasts. Energy-efficient magnetic ballasts are core-and-coil electromagnetic ballasts operating lamps at a frequency of 60 Hz. They contain a magnetic core of several laminated, high-grade steel plates wrapped with copper windings. By using higher-quality materials, they save about 8 W when operating two 40 W T12 lamps, compared with the older, high-loss magnetic ballasts.

Cathode-disconnect Ballasts. Cathode-disconnect ballasts, often called hybrid or low-frequency electronic ballasts, also use a magnetic core-and-coil transformer that operates lamps at 60 Hz. However, cathode-disconnect ballasts use an electronic switch to disconnect the electrode-heating circuit after the lamps are started. They save approximately 6 to 8 W when operating two 40 W T12 lamps, compared with energy-efficient magnetic ballasts. Cathode-disconnect ballasts are only available for 4-ft (1.22 m) fluorescent lamps.

Electronic Ballasts. Electronic ballasts use electronic components that operate lamps at 20 to 60 kHz. A basic electronic ballast design consists of a rectifier that converts the 60 Hz ac voltage into dc voltage; an inverter that converts the rectified dc voltage into 20 to 60 kHz high-frequency ac voltage; and an output circuit that provides proper lamp starting voltage and limits lamp current during lamp operation. Electronic ballasts offer a twofold energy advantage: the high-frequency operation increases lamp efficacy by approximately 10 to 15%, and the ballast power loss is 10% lower than that of magnetic ballasts. The increased lamp efficacy

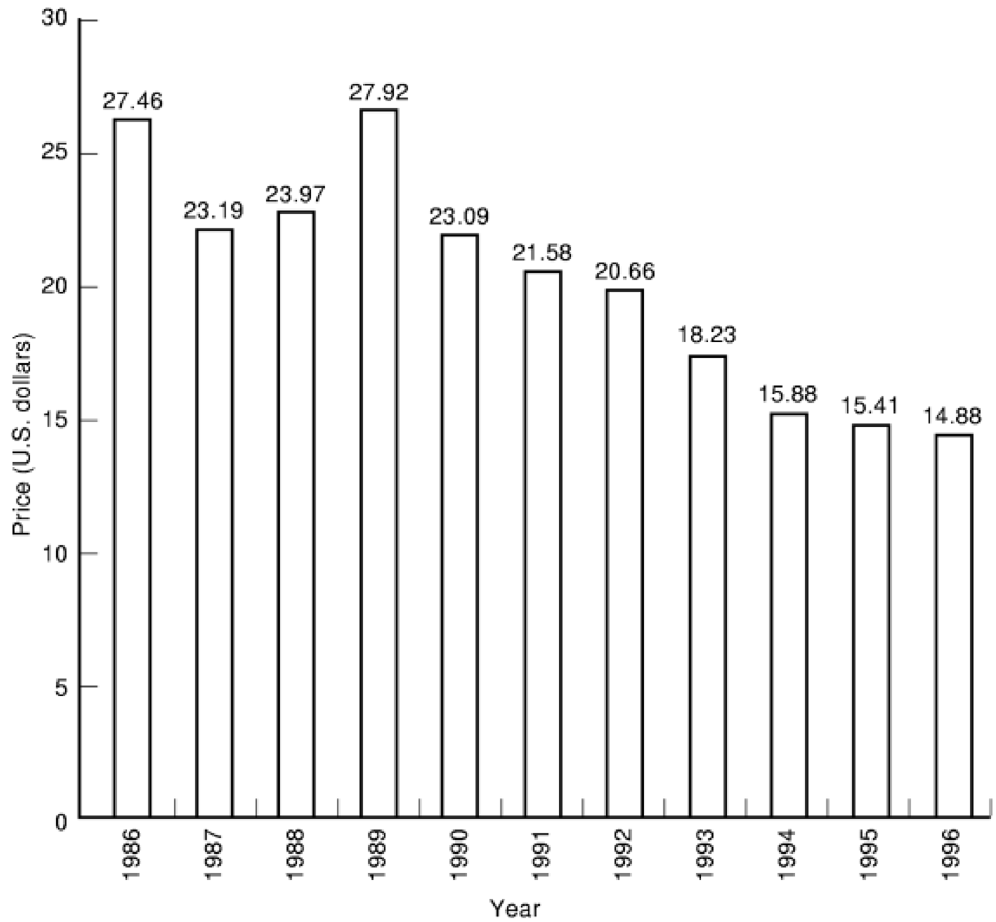

Fig. 3. Calculated average unit price of U.S. manufactured electronic ballasts for fluorescent lamps.

at high-frequency operation is shown in Fig. 4. Electronic ballasts save approximately 16 W when operating two 40-W T12 lamps, compared with energy-efficient magnetic ballasts. Table 1 shows the comparison of energy-efficient magnetic ballasts, cathode-disconnect ballasts, and high-frequency electronic ballasts.

Starting Methods

Ballasts use three main methods to start fluorescent lamps: preheat, rapid-start, and instant-start.

Preheat. In preheat starting, the lamp electrodes are preheated for several seconds to approximately 700 to 1000 °C. After the electrode is preheated, the starter switch opens to allow a voltage of approximately 200 to 300 V to be applied across the lamp to strike the arc. Preheat operation is characterized by the lamp's flashing on and off for a few seconds before finally staying lit.

Rapid-start. Rapid-start ballasts have a separate set of windings that provides a low voltage (about 3.5 V) to the electrodes, heating them to approximately 700 to 1000°C in 1 to 2 s. Then the starting voltage of 200 to 300 V is applied to strike the arc. Most rapid-start ballasts continue to supply the electrode heating voltage even after the lamp has started, which results in power losses of approximately 2 to 4 W for each lamp. The

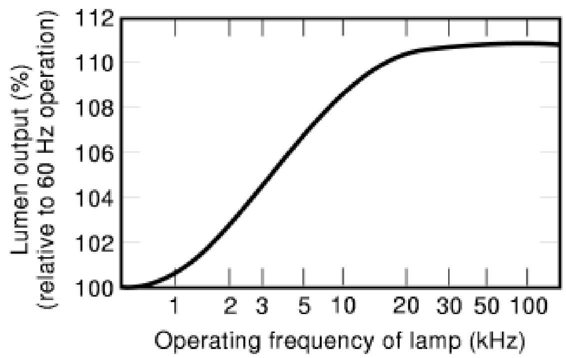

Fig. 4. Lamp efficacy gain at constant lumen output vs. operating frequency for a 40 W, T12 rapid-start lamp. Reprinted with permission from Ref. 2. © 1993.

cathode-disconnect ballasts described earlier disconnect the electrode heating voltage and are categorized as modified rapid-start. Rapid-start ballasts start lamps with a brief delay, but without flashing.

Instant-start. Instead of heating the electrodes prior to starting, instant-start ballasts supply a high initial voltage (over 400 V) to strike the arc. The high voltage is required to initiate the discharge between the unheated electrodes. The electrodes are not heated either before or during operating, so instant-start ballast systems have lower power losses than rapid-start ballast systems. However, the lack of electrode heating during starting and operating increases the damage to the lamp electrodes. Because of this, lamp manufacturers often reduce their lamp life rating for instant-start operation relative to rapid-start operation, usually by 25%. Instant-start ballasts start lamps without delay or flashing.

Performance Characteristics

Energy-saving Impacts.

System Efficacy. The system efficacy (lumen per watt) of a lamp/ballast system is the ratio of the light output (lumen) produced by the lamps when operated by the test ballast to the lamp/ballast system active power (watt). For fluorescent lighting systems, the system efficacy ranges from approximately 60 to 100 lm/W.

Table 2 lists the testing results of different types of fluorescent lamp ballasts when operating F32T8 lamps. It includes active power, ballast factor, and the calculated average system efficacy for each ballast. The results show that magnetic ballasts had the lowest system efficacies and that the system efficacies of the rapid-start electronic ballasts and the cathode-disconnect ballast were similar. For instant-start electronic ballasts, the system efficacies were about 7% higher than those of rapid-start ballasts, due to their lower active power that results from not heating the electrodes during lamp starting and operation.

Ballast Factor. Ballast factor (*BF*) is the ratio of the light output of a lamp or lamps operated by a specific ballast to the light output of the same lamp(s) operated by a reference ballast. Magnetic ballasts usually have BFs between 0.925 and 0.975. Most electronic ballasts have BFs less than 1.0, although some electronic ballasts have BFs greater than 1.0 to provide high light output. Ballasts with high BFs (>1.2) may reduce lamp life because of high lamp current. High BF also may accelerate lumen depreciation. Some electronic ballasts are designed with BFs as low as 0.75; they produce low light output but use low system power to save energy. These ballasts also may reduce lamp life because their reduced lamp current can result in low electrode temperatures.

BF is dependent upon both the ballast and the lamp type; a single ballast can have several BFs depending upon the specific type of lamp that it is operating. Thus, BFs of different ballasts should be compared only if the

Table 1. Comparison of Three Types of Ballasts for 4 ft (1.22 m) Lamps

	Energy-Efficient Magnetic Ballast	Cathode-Disconnect Ballast	Electronic Ballast
Number of lamps operated	1–3	2–3	1–4
Starting mode[a]	IS, RS	RS	IS, RS
Weight (lb)[c]	3.5	3.5–3.7	1.0–2.9
Operating frequency	60 Hz	60 Hz	20–60 kHz
System efficacy	Lowest[b]	Higher	Highest
Ballast factor	>0.925	0.79–0.95	0.73–1.3
Ballast efficacy factor (for two-lamp system)	1.1	1.1–1.37	1.15–1.56
Total harmonic distortion (%)	20–35	11–20	most <20, some <5, some >20
Power factor	>0.9	>0.9	>0.9
Current crest factor	<1.7	<1.7	<1.7
Flicker index	0.04–0.07	0.04–0.07	<0.01
Operating electrode voltage (V) (rapid-start T12 only)	2.5–4.0	0	2.5–4.0
Rated life (years)	10–12	10–20	10–20
Sound rating	A–D	A	A
Typical price ($US)	$10–15	$12–17	$18–30
Dimming available	Yes	No	Yes

[a] IS = instant-start; RS = rapid-start.
[b] Lowest of the three types shown. High-loss magnetic ballasts have lower efficacy.
[c] 1 lb = 0.45 kg.
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ballasts are operating the same lamp type. BF is used in calculations for fluorescent lighting system designs to obtain the actual light output of a specific lamp/ballast combination.

The Certified Ballast Manufacturers Association (*CBM*) uses American National Standards Institute (*ANSI*) standards to certify ballasts. Magnetic ballasts that carry the CBM seal have a minimum BF of 0.925 for F40T12 lamps, 0.90 for F40T10 lamps, and 0.85 for F40T12/ES (34 W) lamps (5). The minimum BF required by ANSI for electronic ballasts for 4 ft (1.22 m) and 8 ft (2.44 m) fluorescent lamps is 0.85 (6).

Ballast Efficacy Factor. Ballast efficacy factor (*BEF*) is a ratio of ballast factor in percent to active power in watts. BEF is used as a relative measurement of the system efficacy of the fluorescent lamp/ballast combination. BEF comparisons should be made only among ballasts operating the same type and number of lamps because BEF depends on the type and number of fluorescent lamps that a ballast is operating.

Table 2. Comparison of System Efficacy for Different Types of Ballasts for T8 Lamps[a]

Manufacturers	Type	Starting Method	System Active Power (W)	Ballast Factor	System Efficacy (lm/W)	Ballast Efficacy Factor
Manufacturer 1	Electronic	Rapid-start	60	0.87	85	1.44
Manufacturer 2	Electronic	Rapid-start	60	0.86	85	1.44
Manufacturer 3	Electronic	Rapid-start	62	0.88	84	1.42
Manufacturer 1	Electronic	Instart-start	58	0.89	90	1.53
Manufacturer 3	Electronic	Instart-start	59	0.90	91	1.54
Manufacturer 2	Magnetic	Rapid-start	71	0.97	81	1.37
Manufacturer 3	Magnetic	Rapid-start	72	0.98	80	1.36
Manufacturer 2	Cathode-disconnect	Rapid-start	60	0.87	86	1.45

Both the U.S. and Canadian governments have set minimum standards for BEF of some ballasts for 4 ft (1.22 m) and 8 ft (2.44 m) fluorescent lamps. These standards are summarized in Table 3.

Lamp Life Impacts. Every fluorescent lamp has two lamp electrodes, one at each end of the lamp. The electrode consists of a double- or triple-coiled tungsten wire coated with electron emissive coating (barium, strontium, and calcium oxide). The failure of fluorescent lamps is caused mainly by the loss of the electron emissive coating of the lamp electrodes, and electrode temperature directly determines the rate of loss of this emissive coating. Electrode temperatures below 700°C or above 1000°C can reduce lamp life by increasing the rate of loss of the emissive coating on the electrodes. Thus, it is important for a ballast to provide appropriate electrode heating during lamp starting and operation to reduce the damage to lamp electrodes and maintain a long lamp life.

Electrode temperature, however, is relatively difficult to measure. Instead of setting requirements on electrode temperature, the ANSI sets standards (5,6) on other starting and operating parameters such as starting voltage, electrode voltage, and lamp current, and others (see Table 4), for magnetic and electronic ballasts to ensure their compatibility with fluorescent lamps. Previous research (8,9) reported limited testing on how different ballast design parameters affected lamp life. However, the rapid pace of new product introductions means that the relevant ANSI requirements may become outdated for addressing compatibility concerns. The impacts on system performance of the newer products has not been well established.

Electrode Temperature and Electrode Voltage. Rapid-start ballasts supply electrode voltage during lamp starting and operation. This extends the electrode life and, thus, lamp life. However, very high electrode voltage causes high electrode temperature, which may reduce lamp life because of evaporation of the emissive material on the electrodes. A low electrode voltage may cause low electrode temperature, resulting in reduced lamp life because of excessive loss of emissive material by sputtering. ANSI C82.1—1985 (5) established the acceptable range of electrode voltage during starting and operation for different types of ballasts. For example, a range of 3.4 to 4.5 V is recommended for the starting electrode heating voltage for F40T12 and F32T8 rapid-start lamps. Lamp manufacturers may not warrant lamp life if the electrode voltage is not within the ANSI recommendations.

Current Crest Factor. Lamp current crest factor (*CCF*) is the ratio of peak lamp current to the rms lamp current; consequently, it is a measure of current wave shape. The CCF of a sine wave is 1.41. Lamp CCF is determined by the ballast on which a lamp operates. A high lamp CCF indicates that the current wave shape has high peaks that can reduce lamp life. Most lamp manufacturers void their warranties when lamps

Table 3. US and Canadian Standards for Ballast Efficacy Factor

Lamp Type	Ballast Input Voltage (V)	Total Nominal Lamp Active Power (W)	BEF (minimum)	
			U.S. Standard	Canadian Standard
One F40T12	120	40	1.805	1.805
	277	40	1.805	1.805
	347	40	N/A	1.750
Two F40T12	120	80	1.060	1.060
	277	80	1.050	1.050
	347	80	N/A	1.020
Two F96T12	120	150	0.570	0.570
	277	150	0.570	0.570
	347	150	N/A	0.560
Two F96T12/HO	120	220	0.390	0.390
	277	220	0.390	0.390
	347	220	N/A	0.380
Two F32T8	120	64	N/S	1.250
	277	64	N/S	1.230
	347	64	N/A	1.200

N/A = not applicable. N/S = no standard.
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are operated on ballasts with lamp CCFs greater than 1.7. ANSI Standard C82.11 recommends that for all electronic ballasts, the lamp CCF should not exceed 1.70.

Glow Current, Preheat Time, and R_h/R_c Ratio. For the starting characteristics, ANSI C82.11 (6) set requirements on glow current and preheat time for rapid-start electronic ballasts. The glow current is the lamp current during electrode preheat time and reflects the degree to which emissive material is lost during lamp starting before the electrode has reached the operating temperature. High glow current increases lamp end darkening and reduces lamp life. ANSI C82.11 established 25 mA as the maximum glow current limit for rapid-start electronic ballasts. Lamp preheat time is the length of time that a rapid-start ballast heats the electrodes before the lamp arc is initiated. A short electrode preheat time may cause insufficient heating of the electrode, which results in electrode sputtering and reduces lamp life. ANSI C82.11 established 500 ms as the minimum preheat time for rapid-start electronic ballast.

The R_h/R_c ratio is currently under discussion at ANSI as a new starting parameter for rapid-start electronic ballasts. R_c is the cold lamp electrode resistance at room temperature (25°C). R_h is the hot lamp electrode resistance at the end of the preheat period but before the glow to arc transition. Based on Mortimer (10), the average electrode temperature before the lamp glow to arc transition T_h can be calculated using the equation: $T_h = T_c * (R_h/R_c)^{0.814}$, where T_c is 25°C. This equation is based on the resistance-temperature relationship

Table 4. F40T12 and F32T8 Rapid-Start Lamp/Ballast Compatibility

	ANSI Guidelines			
	T12[a]		T8	
	Minimum	Maximum	Minimum	Maximum
	Lamp Starting			
Lamp starting voltage (one lamp) (V)	200	260	200	NA
Lamp starting voltage (two lamps in series) (V)	256	330	300[b]	NA
Lamp starting voltage (three lamps in series) (V)	395	525	NA	NA
Lamp starting electrode voltage (V)	3.4	4.5	3.4	4.5
Electrode preheat time (ms)	500	NA	500	NA
Glow current (mA)	NA	25	NA	25
	Lamp Operation			
Lamp current crest factor	NA	1.7	NA	1.7
Lamp operating electrode voltage (V)	2.5	4.0	2.5	4.4
Lamp current (% of rated value)	NA	115/107.5[c]	NA	115/107.5[c]
Ballast factor	0.925/0.85[c]	NA	0.925/0.85[c]	NA

NA = Not applicable.
[a] Also applies to T10 lamps.
[b] For starting capacitors 0.08–0.12 μf; 315 V for starting capacitors rated at 0.04–0.06 μf.
[c] First value is for low frequency (60 Hz) operation. Second value is for high frequency (20–60 Hz) operation.
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for tungsten wire. Hammer (11) indicated that approximately 700°C is needed to ensure minimum sputtering during lamp starting. This electrode temperature corresponds to an R_h/R_c ratio of approximately 4.25.

Rapid-start vs. Instant-start. For T8 fluorescent lamps, 80 to 90% of the electronic ballasts on the market are instant-start ballasts. The popularity of the instant-start electronic ballasts is primarily due to its low cost and high efficiency. Although instant-start ballasts are more energy efficient than rapid-start ballasts, it has traditionally been believed that the starting damage to the lamp electrodes is greater for instant-start ballasts because they do not preheat the electrodes. Lamp manufacturers' published data showed that at 3 h per start, instant-start ballast may reduce lamp life by 25% compared with rapid-start operation. For longer burning cycles (12 h or more per start), the difference between instant-start and rapid-start lamp life is much smaller, but at shorter cycles, it was suspected that the lamp life reduction caused by instant start operation could be greater than 25%. Thus, it is commonly recommended to avoid using instant-start ballasts in applications where lamps may be frequently switched, such as with occupancy sensors. However, only one published study (12) compares rapid-start electronic ballasts and instant-start ballasts for operating cycles less than 3 h.

Figure 5 (12) shows life testing results of two rapid-start (RS) magnetic ballasts (MB), three rapid-start electronic ballasts (EB), and two instant-start (IS) electronic ballasts. All life testing was conducted using two-lamp ballasts for F32T8 fluorescent lamps. These seven different ballast types were from three ballast manufacturers. For each ballast type, a sample of 36 lamps were tested on a 5 min on/5 min off cycle, representing 12 lamps from each of three major lamp manufacturers. This rapid-cycling testing method is mainly to examine how different ballast starting methods affect fluorescent lamp life. Lamps were operated

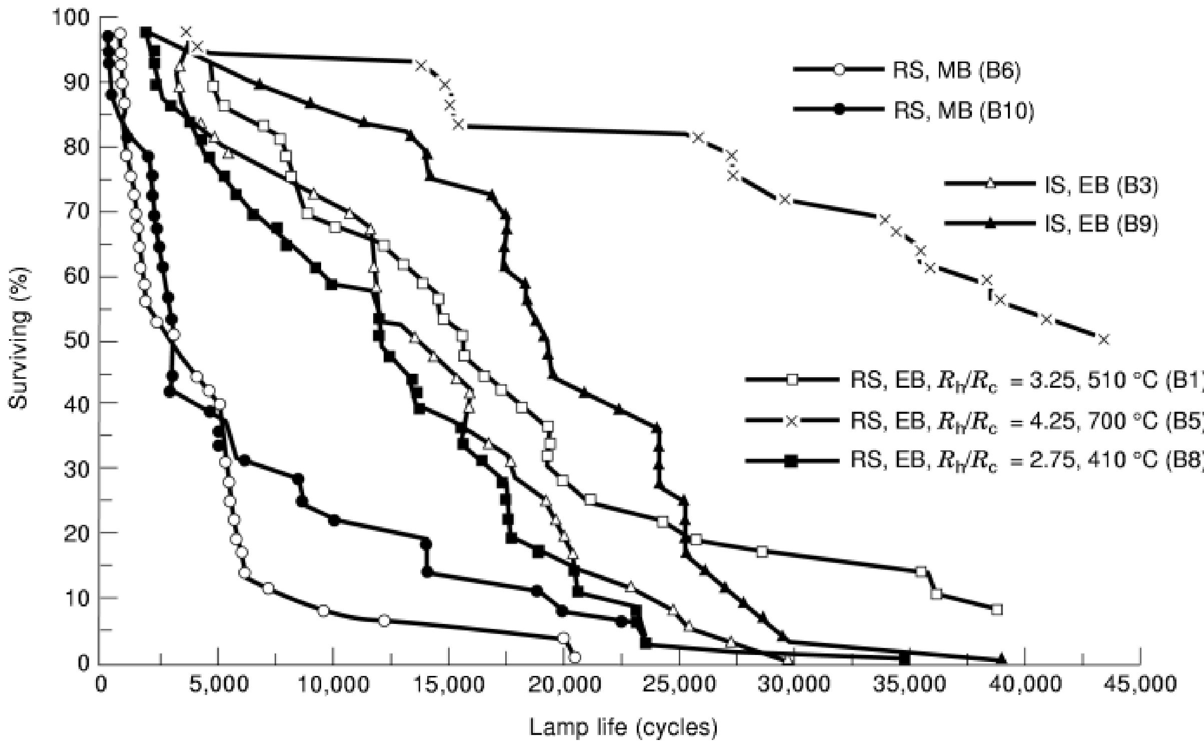

Fig. 5. Results of rapid-cycle testing for F32T8 lamp/ballast systems. Reprinted with permission from Ref. 12. © 1997.

Table 5. Compatibility Testing for Linear Fluorescent Lamps

Mfr.	Type	ID	Starting Method	Active Power (W)	Preheat Time (ms)	Glow Current (mA)	R_h/R_c Ratio	Open Circuit Voltage (V)	Lamp Current Crest Factor	Ballast Factor	Median Lamp Life (cycles) (5 min/5 min)
Mfr. 1	Electronic	B1	Rapid-start	60	637	6	3.25	430	1.42	0.87	15732
Mfr. 1	Electronic	B3	Instant-start	58	NA	NA	NA	600	1.61	0.89	13514
Mfr. 2	Electronic	B5	Rapid-start	60	1140	4	4.25	250	1.35	0.86	43274
Mfr. 2	Magnetic	B6	Rapid-start	71	716	24	NT	350	1.50	0.97	3118
Mfr. 3	Electronic	B8	Rapid-start	62	705	5	2.75	385	1.51	0.88	11977
Mfr. 3	Electronic	B9	Instant-start	59	NA	NA	NA	600	1.56	0.90	19417
Mfr. 3	Magnetic	B10	Rapid-start	72	1186	16	NT	325	1.34	0.98	2807

NA = not applicable; NT = not tested.
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until failure, and the number of cycles were recorded. The starting and operating parameters of these ballasts are listed in Table 5.

Figure 5 shows that one rapid-start electronic ballast (B5) produced the longest lamp life; the two magnetic ballasts (B6 and B10) had the shortest lamp life. However, the other two rapid-start electronic ballasts (B1 and B8) had similar lamp lives to the instant-start electronic ballasts (B3 and B9). From the starting and operating parameters tested, all the ballasts met ANSI standards. As shown in Table 5, the two rapid-start magnetic ballasts had relatively high glow current and long preheat times. This combination would be expected to be very damaging to the lamp electrodes; this in fact appears to be true based on the short lamp lives produced by these two ballasts. Table 5 also shows that all three rapid-start electronic ballasts had low glow current (4 to 6 mA), and their preheat times were all above 500 ms. Yet, the lamp life results for these three ballasts were very different.

The testing results of R_h/R_c ratio (Table 5) for the rapid-start electronic ballasts showed that ballast B5 had an R_h/R_c ratio of 4.25, which represents an average electrode temperature of 700°C; ballast B1 had an R_h/R_c ratio of 3.25 (510°C); and ballast B8 had an R_h/R_c ratio of 2.75 (410°C). Based on Hammer's (11) recommendation of a minimum temperature of 700°C, these data indicate that ballasts B1 and B8 did not provide sufficient heating to the lamp electrodes during lamp starting even though both met the ANSI standard. As a result, these ballasts did not produce longer lamp life than the instant-start ballasts tested. Ballast B5 did achieve a 700°C electrode temperature before starting the lamps and produced correspondingly longer lamp life than the other ballasts.

The two instant-start electronic ballasts (B3 and B9) started lamps very quickly (starting time around 50 ms). The damage to the lamp electrodes by the high starting voltage is minimized by such a short starting time.

These data support the belief that high glow current will reduce lamp life during lamp starting. However, low glow current does not necessarily ensure long lamp life, probably because of inadequate electrode preheating. Instead, the R_h/R_c ratio appears to be a very good predictor for lamp life based on lamp starting. A low R_h/R_c ratio indicates that the lamp electrodes have not been heated sufficiently during lamp starting, resulting in reduced lamp life. The data also showed that if a rapid-start ballast does not provide sufficient heating to the lamp electrodes, the lamp life will be similar to instant-start ballast for short operating cycles.

Lamp Life Testing Methods. The traditional method of life testing for fluorescent lamps is to determine the median operating hours until failure for a large sample of lamps, when operated on a 3 h on/20 min off cycle (13). Some researchers and manufacturers use rapid-cycle testing methods (14,15,16) to reduce the testing time required. However, the results of rapid-cycle testing are difficult to interpret because the relationship between the damage done to the lamp electrodes during rapid-cycling and the damage that occurs in the standard method is not known.

One concern with rapid-cycle methods is the duration of the off-time. If the purpose is to simulate a cold start with each cycle, then the off-time must be long enough for the lamp electrodes to stabilize at their normal off temperature. To assess this, the authors measured temporal changes in electrode resistance after extinguishing a lamp for five 4 ft (1.22 m) fluorescent lamps (16). Because electrode resistance relates directly to electrode temperature, the results show how long it takes the temperature of the electrode to stabilize. Almost all the decrease in electrode resistance occurred during the first 5 min—of the average total decrease of 6.85 Ω within 20 min for the five lamps, 93% occurred during the first minute and 99% during the first 5 min. Figure 6 (16) shows an example of the measured electrode resistance data over time. The resistance data were normalized to the maximum value, and time was plotted on a log scale. The authors also conducted similar testing on five different screwbase compact fluorescent lamps (*CFL*s). The results showed that, for CFLs, the continuing decrease after 1 min was more substantial—for an average total decrease of 14.22 Ω, 81% occurred during the first minute and 93% during the first 5 min (16).

The results demonstrate that, if the lamp off-time is less than 1 min, the electrode has not cooled completely. This can reduce the damage to the electrodes during lamp starting and may result in overestimating the number of cycles that would normally occur before the end of life. This finding was confirmed by life testing of 13 W twin-tube CFLs with modular magnetic ballasts (preheat start) (16). In this experiment, four different operating cycles were used: 40 s on/20 s off; 40 s on/5 min off; 5 min on/5 min off; and 5 min on/20 s off. The results showed that lamps on operating cycles with 5 min off-time had much shorter lamp life (in number of cycles) than lamps on operating cycles with 20 s off-time (Fig. 7).

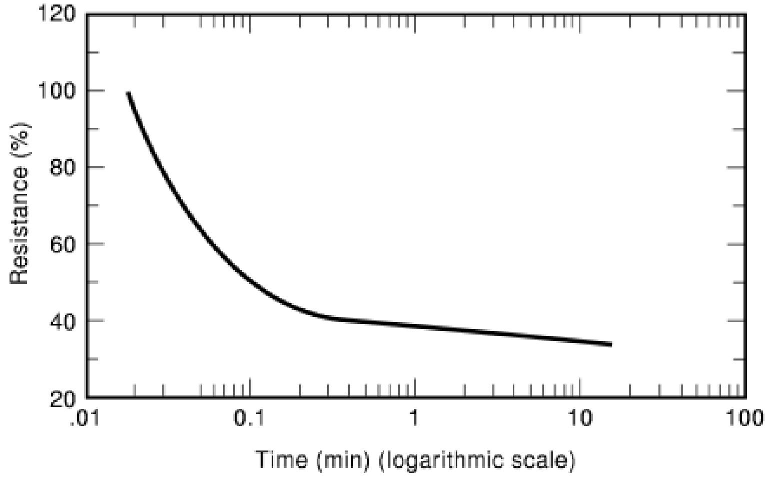

Fig. 6. Electrode resistance of F32T8 lamp after lamp is turned off. Reprinted with permission from Ref. 16. © 1996.

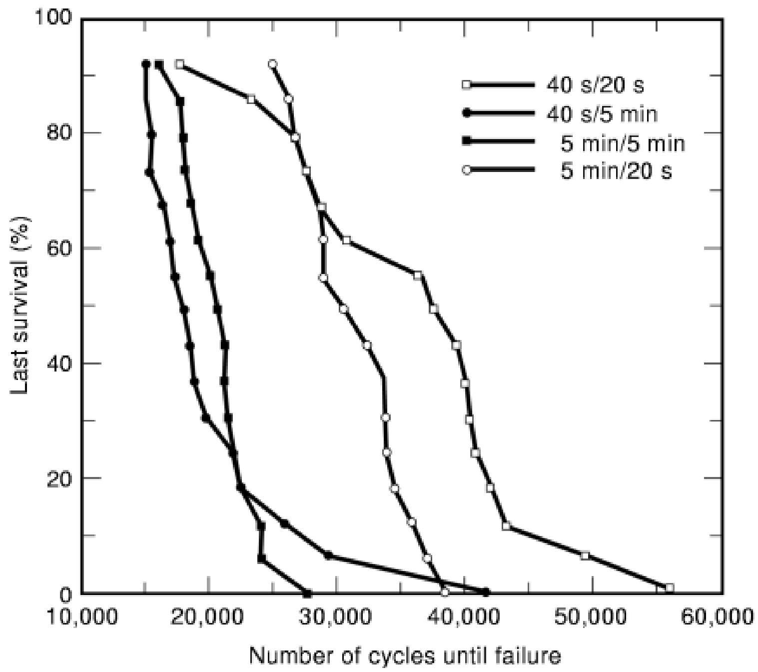

Fig. 7. Results from rapid cycle testing for preheat CFLs. Reprinted with permission from Ref. 16. © 1996.

Based on these findings, the authors recommend a 5 min on/5 min off cycle for rapid-cycle testing. A 5 min on-time is needed to help "cure" the electrodes so that the sputtering during the next lamp start is minimized. However, rapid-cycle testing only evaluates how different ballast starting parameters, such as glow current and R_h/R_c ratio, affect lamp life. To examine how ballast operating parameters, such as CCF and lamp current, affect lamp life, the standard life testing method of 3 h on/20 min off should be used.

Power Quality Impacts.

Power Factor. Power factor is defined as the ratio of active power to apparent power, which is the product of root-mean-square (*rms*) voltage and rms current; power factor ranges from zero to 1.0. A power factor of 1.0 means that the volt-amperes supplied are equal to the watts used and indicates that the voltage and current waveforms are sinusoidal and in phase. A device is said to have a high power factor (*HPF*) if the power factor is 0.9 or greater. A power factor between 0.5 and 0.9 is called a normal power factor (*NPF*). Most electronic ballasts for fluorescent lamps have HPF.

Power factor is reduced if there is a phase shift between current and voltage or if there is distortion of the sinusoidal wave shapes. A phase shift between the current and voltage is the primary cause of power factor reductions in magnetic ballasts and can be corrected by using an appropriate capacitor. Power factor reductions in electronic ballasts primarily are caused by distortions in the current wave shape, which are more difficult and expensive to correct. These distortions usually are expressed by a measure called total harmonic distortion (*THD*). The relationship between power factor and THD with no voltage-current phase shift may be determined as follows:

$$\text{Power factor} = \sqrt{\frac{1}{1+\text{THD}^2}}$$

Standards organizations have not set power factor limits for lighting products, except for the requirement that power factor must meet or exceed 0.90 for manufacturers to claim that a product has a high power factor. Lighting designers, architects, and other lighting specifiers often specify HPF ballasts for buildings with sensitive equipment, such as hospitals.

Current Total Harmonic Distortion. Current total harmonic distortion is a measure of the degree to which current deviates from a sinusoidal waveform. Ballast manufacturers, electric utilities, and standards organizations define THD differently, which has caused some confusion in the lighting industry. The Institute of Electrical and Electronics Engineers (*IEEE*), ballast manufacturers, utility companies, and this paper define THD as

$$\text{THD} = \frac{\sqrt{I_2^2+I_3^2+I_4^2+\cdots}}{\sqrt{I_1^2}} \times 100 \text{ (to convert to percentage)}$$

where I_1 is the rms of the fundamental current waveform, I_2 is the rms of the second-order harmonic current waveform, I_3 is the rms of the third-order harmonic current waveform, etc.

The ANSI, the Canadian Standards Association (*CSA*), and the International Electrotechnical Commission (*IEC*) use this formula as the definition of harmonic factor. ANSI does not provide a separate definition for THD, but CSA and IEC define THD as

$$\text{THD} = \frac{\sqrt{I_2^2+I_3^2+I_4^2+\cdots}}{\sqrt{I_1^2+I_2^2+I_3^2+I_4^2+\cdots}} \times 100 \text{ (to convert to percentage)}$$

where I_1 is the rms of the fundamental current waveform I_2 is the rms of the second-order harmonic current waveform, I_3 is the rms of third-order harmonic current waveform, etc.

Higher values of THD indicate greater distortion. Any distortion of the current wave shape causes distortion current to flow through the electric supply system, which reduces the power factor. Distorted currents may have other effects, including interference with the operation of electronic equipment (both nearby and remote);

Table 6. Sample Power Quality Characteristics for Different Electric Loads[a]

	Active Power (W)	Power Factor	Current THD (%)
Compact Fluorescent Lighting Systems			
13 W quad-tube compact fluorescent lamp w/NPF magnetic ballast	16	0.54	13
13 W quad-tube compact fluorescent lamp w/NPF electric ballast	13	0.5	153
16 W quad-tube compact fluorescent lamp w/HPF electronic ballast	16	0.91	20
Full-Size Fluorescent Lighting Systems (two lamps per ballast)			
T12 34 W lamps w/energy-efficient magnetic ballasts for T12 lamps	72	0.94	22
T12 34 W lamps w/electronic ballast for T12 lamps	62	0.99	5
T8 32 W lamps w/electronic ballast for T8 lamps	63	0.98	6
High-Intensity Discharge Lighting Systems			
400 W high-pressure sodium lamp w/magnetic transformer	425	0.99	14
400 W metal halide lamp w/magnetic transformer	450	0.94	19
Incandescent Lighting System			
100 W incandescent A lamp	101	1	1
Office equipment			
Desktop Computer Without Monitor	33	0.56	139
13-in. (33 cm) high-resolution color monitor for desktop computer	49	0.56	138
Laser printer while in standby	29	0.4	224
Laser printer while printing	799	0.98	15
External fax/modem	5	0.73	47
Electric pencil sharpener	85	0.41	33

[a] NLPIP measured specific products and reported their characteristics. These characteristics may vary substantially for similar products.

improper operation of power grid protective devices (fuses, circuit breakers, and relays); interference with nearby communications circuits; and overheating of motors, transformers, capacitors, and neutral conductors. Harmonics that are odd, triple multiples of the fundamental frequency (third, ninth, fifteenth, etc.) have the greatest potential impact on electrical systems because the current from these harmonics flows on the neutral conductor and may cause an overload on this conductor.

ANSI C82.11 (6) established a maximum current harmonic factor (which is called THD by IEEE, manufacturers, and utility companies) limit of 32% for electronic ballasts for full-size fluorescent lamps. The standard also specifically limits the amplitude of the third-order harmonic to 30% of the fundamental amplitude and limits the amplitude of all higher-order harmonics (greater than eleventh order) to 7% of the fundamental. CSA, IEC, and IEEE set a 20% current THD limit for electronic ballasts. Almost all electronic ballasts currently available for 4 ft (1.22 m) T12 and T8 lamps have current THD less than 20%.

Some *CFL*s have current THD greater than 100%, but they have low active power compared with other high-THD products such as personal computers. Consequently, standards organizations have not set power quality requirements for CFLs. Table 6 lists the measured power factor and current THD for several types of lighting loads and for common office equipment (17).

Inrush Current. Inrush current is a momentary surge in current that can occur when an electrical device, such as an electronic ballast, is switched on. Depending on whether the input voltage wave is at zero or at a peak when the ballast is switched on, inrush current of electronic ballasts can range from 0 to more than 70 A, compared with 0.5 A during normal operation. The duration of inrush current is typically less than 3 ms. High inrush current can trip circuit breakers, blow fuses, or overload relays. If several ballasts with high inrush current are connected to the same circuit, the effects can be cumulative.

The inrush current for the ballast must not exceed the rated inrush current for any other device in the circuit. ANSI presently does not set limits for inrush current. Some ballast manufacturers already incorporate devices in their ballasts to limit inrush current. Zero-crossing switches and relays can be used to minimize the impacts of inrush current.

Other Considerations.

Electromagnetic Interference. Electronic devices often employ power supplies that can generate electromagnetic interference (*EMI*). EMI occurs when unwanted electromagnetic signals interfere with desirable signals. EMI can take two forms: conducted or radiated. Conducted EMI occurs when electronic devices induce currents in the local power network that adversely affect an electronic device on the same power network. Radiated EMI is associated with solar flares, for example, and the electric and magnetic fields inherent in electronic devices.

In the United States, the Federal Communications Commission (*FCC*) regulates radio and wire communications, including interference. The FCC regulates conducted electromagnetic emissions with frequencies from 450 kHz to 30 MHz and radiated electromagnetic emissions with frequencies from 30 to more than 960 MHz (18). Most of the radiated electromagnetic waves from both electronic ballasts and fluorescent lamps are not covered by FCC restrictions because their frequencies are outside the regulated range (the portion below 30 MHz).

Buddenberg and Fowler (19) identified applications where EMI involving fluorescent lighting systems may cause problems and discussed methods for avoiding or resolving EMI problems. Anderson, Hammer, and Serres (20) discussed the interaction of infrared controls and electronic compact fluorescent lamps and recommended methods for avoiding or resolving these problems.

Flicker. Operating fluorescent lamps on alternating current modulates the light output. For fluorescent lamps operated at a frequency of 60 Hz, the phosphors are refreshed 120 times per second, resulting in 120 Hz light output oscillation. Although this is generally not perceptible, flicker is sometimes a suspected source of worker complaints of eyestrain and headaches. Electronic ballasts that operate lamps at a frequency of 20 kHz or higher refresh the phosphors so rapidly that flicker is imperceptible. Flicker index (2) is the industry-recognized measure for light modulation and ranges from zero to 1.0. Higher values indicate an increased possibility of perceptible flicker. Flicker indices for fluorescent lamps operated by magnetic ballasts range from approximately 0.04 to 0.07, whereas most electronic ballasts have flicker indices below 0.01.

Sound. Magnetic ballasts sometimes produce a humming noise, which is caused by vibrations in the laminated magnetic core. Electronic ballasts have significantly reduced ballast noise because they use solid-state electronic rather than magnetic components and operate at high frequencies. Ballasts are sound-rated from A to F based on the level of noise (2). A-rated ballasts are for indoor applications such as offices, and noisier B-rated ballasts are intended for outdoor applications or indoor spaces such as warehouses where quietness is not as important. Most electronic ballasts have a sound rating of A.

End of Lamp Life Phenomenon. For fluorescent lamps with diameters less than T8 (e.g., T4 and T5 fluorescent lamps), operational problems can occur at the end of lamp life, especially in a small luminaire that elevates the operating temperatures. At the end of lamp life, a broken or deactivated electrode of that lamp can create a nonsymmetric lamp operating condition with high local heating. The continuous high local temperature can crack the lamps or overheat the lamp bases and sockets or the luminaire. National Electrical Manufacturers Association (*NEMA*) is currently developing information for incorporating a shut-off circuit in the ballast to avoid overheating at the end of lamp life. Some ballast manufacturers have already employed shut-off circuits in their ballasts for small diameter lamps.

Ballast Life and Reliability

Ballast life depends upon ballast operating temperature and input voltage. High temperatures or high peak voltage can damage electronic components. For fluorescent lamp ballasts operating in luminaires at an ambient temperature of 25°C, Underwriters Laboratories specifies a maximum ballast case temperature of 90°C (21). For magnetic ballasts, an increase of 10°C over this temperature may reduce ballast life by as much as 50%. Conversely, operating the ballast at a temperature 10°C below the limit may double the ballast life. For electronic ballasts, life is dependent upon the quality of the components used and the degree to which the ballast is protected from line surges and electrical transients.

Electronic ballasts use semiconductor devices such as transistors and rectifiers that are more sensitive than magnetic components to line surges. To protect these electronic components from electrical line surges, electronic ballast designs can employ filters and voltage limiters at the ballast input. Traditionally, electronic ballasts have been designed to meet their rated life with input voltage variations of ±10% at a maximum ambient temperature of 60°C.

The ballast design also should adapt to faulty operating conditions such as operating fewer lamps than the number for which the ballast was designed, operating the wrong lamp type, operating with a failed lamp in the circuit, and operating under open-circuit and short-circuit conditions. Adding protection against these conditions increases the reliability of the ballast but also increases its price. Manufacturers often must choose between better reliability or lower costs.

One published study reports the results of field testing over 30,000 electronic ballasts that were installed between 1987 and 1991 in 67 campus buildings (22). The ballasts were from three manufacturers, with at least 4000 ballasts from each manufacturer. For two of the manufacturers, the defect rate was no greater than 1.0% (1.0% and 0.5%); the defect rate for the third manufacturer was much higher (6.3%). By comparison, magnetic ballasts typically have failure rates of 0.5% (23). With over 30,000 ballasts installed, even a 1% defect rate meant that hundreds of ballasts needed to be replaced.

Dimming Electronic Ballasts

For lighting systems, dimming controls provide two primary advantages: they can save energy, and they can enhance the versatility or aesthetics of spaces. A dimming system saves energy relative to a nondimming system (assuming the same hours of use) because dimmed lamps require less input power. And, by providing a wide range of possible illuminances, dimming systems can better accommodate user needs in spaces such as conference rooms, offices, classrooms, lobbies, and residences.

Incandescent lamps are easily dimmed, and the use of manual slide or rotary dimmers for incandescent lamps is commonplace in residential and commercial buildings. Early dimming systems for fluorescent lamps used magnetic ballasts and were sometimes characterized by a limited dimming range, lamp flicker at dimmed levels, and reduced lamp life. But today, dimming electronic ballasts are available for a variety of linear and compact fluorescent lamp types; these ballasts can offer significant performance improvements over the earlier products.

Control Voltage. Most dimming electronic ballasts have two wires (usually one gray and one purple) for a low-voltage control circuit, often rated at 0 to 10 V of direct current (*dc*). The ballast supplies power to a control device, such as a manual dimmer or a photosensor, on this circuit. For full light output, the control device returns the maximum control signal (10 V) to the dimming ballast. When the control device reduces the voltage across the control wires, the ballast dims the lamps. As the control voltage approaches 0 V, the lamps will usually be dimmed to the lowest light output possible with the dimming ballast.

Some dimming electronic ballasts use a high voltage (120 V) control circuit to dim lamps. Rather than responding to a dc control voltage, these ballasts interpret digitally encoded pulse signals from the control device. Because the pulse-coding method is often proprietary, these ballasts typically require control devices made by the same manufacturer as the ballast. However, some manufacturers of high-voltage control ballasts also offer interface devices that can convert low-voltage control signals into a high-voltage digital signal.

Dimming Range. Dimming ballasts vary in the lowest light output at which they can operate lamps. Some dimming ballasts dim lamps to less than 5% of the maximum light output; most dim lamps to less than 25% of maximum. The dimming range required for a specific installation depends on the needs of the application. For example, a ballast that dims to about 20% of maximum may be adequate for many photosensor applications, whereas ballasts with a wider dimming range may be desirable for applications where dimming is needed to accommodate audio-visual needs or to create architectural effects. For some ballasts, the manufacturer can adjust the minimum light output possible to a specified level before shipping the ballasts for installation.

System Efficacy. System efficacy of a lighting system is expressed as the ratio of the light output produced by the system (in lumens) to the active power of the system (in watts). A system that produces higher light output for the same active power as another system is therefore a higher-efficacy system. In almost all cases, the authors have found that system efficacy decreases as lamps are dimmed. For example, when lamps are dimmed to about 20% of the maximum light output, the active power of the lamp/ballast system is often approximately 40% of the power at maximum light output. Thus, the system efficacy has decreased by about 50%. This decrease is partially caused by decreased lamp efficacy at dimmed levels and by the electrode heating voltage provided by many dimming ballasts at dimmed levels.

Lamp Life Considerations. Previous sections have discussed the impacts of ballast starting and operating parameters on fluorescent lamp life. Loss of electrode emissive material resulting from sputtering during operation is a particular concern for dimming ballasts because at dimmed levels the lamp electrodes may be operating at temperatures below optimum. To help minimize electrode sputtering, well-designed dimming electronic ballasts provide electrode heating voltage to the electrodes during operation, whether or not they preheat the electrodes during starting. In fact, many dimming ballasts increase the electrode heating voltage as the lamp is dimmed.

Power Factor and THD. The authors have found that the THD produced by a few dimming ballasts increases significantly at dimmed levels. This increase in THD produces a corresponding decrease in power factor for these ballasts. Because current THD is expressed as a percentage of the fundamental current, a high THD at low light output levels (and low fundamental current levels) may not be a concern, because the actual distortion current will be small. However, if THD increases sharply as lamps are dimmed, the distortion current flowing at higher light output (and active power) settings may contribute to some of the problems associated with harmonic distortion discussed earlier.

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