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Performance of Electronic Ballast and Controls with 34 and 40 watt F40 Fluorescent Lamps

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PERFORMANCE OF ELECTRONIC BALLAST AND CONTROLS WITH 34 AND 40 WATT F40 FLUORESCENT LAMPS

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of modulation, the flicker can vary between 0 and 33%.

Flicker can cause discomfort and may reduce productivity in a small portion of the population. Some preliminary evidence suggests that lamp flicker may affect some people working with video display terminals, due to the interference with the display's refresh rate.[3] Reduction of flicker is another benefit of operating fluorescent lamps at high frequencies.

F. Light Output

Input power alone does not assess the performance of a lamp-ballast system. The ballast factor is another important system parameter. It is the ratio of the light output of a lamp-ballast system with respect to the light output specified by the lamp manufacturer, i.e., the light output listed in the catalogue. The specified light output is measured under ANSI conditions in open air with a reference ballast. Ballasts approved by the Certified Ballast Manufacturers (CBM) have a ballast factor of at least 95 ± 2.5%. This rating for ballasts is obtained only with ANSI specified lamps.

Ballast factors for each ballast-lamp system should always be specified. For example, the CBM core-coil ballast has a ballast factor of 95 ± 2.5% when used with a 40W argon filled lamp, but is only about 87% operating a 34W krypton filled lamp.

G. Regulation

Ballasts are designed to properly operate lamps over a voltage range of ±10% about the center design input voltage. As the voltage changes, there is a change in the light output. Lighting designs, should account for the changes in light output such that the proper illumination is always available. Highly regulated ballasts provide constant light output over the allowable voltage range. Loosely regulated systems require higher average light levels to compensate for input voltages below the center design voltage. However, if the supply voltage can be controlled, loosely regulated ballasts can be used to dim fluorescent lamps over a limited range.

H. Starting Characteristics

The maximum starting voltage (360 volts) for the 40W, F40 lamp is specified by ANSI. If lamps are started above this voltage, the lamp life will be decreased. High starting voltages increase the acceleration of the ions striking the cathode too forcefully, removing excessive amounts of the low work function coating off the filament.

The open circuit voltage is a measure of the maximum voltage that can be applied to the lamps by the ballast. Good ballast designs feature heated filaments and limit the open circuit voltage to less than the ANSI standard.

I. Power Factor

The phase relationship between the voltage, the current and the wave shape determines the line power factor. ANSI defines that a "high power factor ballast" must have a power factor greater than 90%. Core-coil ballasts achieve a high power factor by employing a suitably sized capacitor to compensate for the inductive chokes that limit the lamp current.

Some ballasts produce non-sinusoidal wave shapes that also reduce the line power factor. The primary concern of utilities for three phase systems is the out-of-phase current-voltage relationship because this factor is reflected back to the generating source. The "shape" power factor generally causes a higher circulating current in some three-phase systems, increasing line losses but does not effect the generating source.

J. Filament Power

The heated electrodes (filaments) of a rapid start fluorescent lamp permit starting at a lower voltage, injecting electrons by thermionic emission. The tungsten filaments are coated with a low work function alkali earth material to achieve thermal emission at lower filament temperatures. When there is no longer any low work function material remaining on the filament, the lamps will rapidly fail. Filament heating is one reason why rapid start lamps have a longer life than instant start or preheat start lamps. ANSI specifies that 2.5 to 4.1 volts should be applied to the filaments at all times.

Some ballast designs remove or reduce the filament power after they are started. This will save about 4W for a two-lamp system, but it is achieved at the expense of lamp life. The lamps are then derated to 15,000 hours and in some cases may be a cost effective trade-off. However, removing filament power for lamps operated at high frequency will result in a greater reduction in lamp life than when operated at 60 Hz.[4]

When a lamp is operated in the dimmed mode, removing filament power greatly reduces lamp life. Studies[5] have observed lamp lives as low as 100 to 200 hours when lamps are operated at 30% of full light output without any filament power.

III. EXPERIMENTAL PROCEDURE

A. Electrical/Photometric Measurements

The measurements of the equipment (ballasts, static and dynamic controllers) were made operating two lamp systems (40W, F40 T-12, rapid start, cool white, and 34W, F40 T-12, rapid start, lite white). Ballasts designed to operate 32W, F40 T-8 or 28W, F40 T-12 type lamps are included in this study.

Standard methods were used to measure the electrical and photometric parameters necessary to characterize these systems and have been described in detail in a previous report.[6]

B. Three-Phase Delta-Wye Circuits

Figure 1 shows a schematic of the circuit used to measure the effects of current voltage phase shifts and

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Abstract - The electric and photometric characteristics have been compared for 40 watt (40W) and 34 watt (34W), F40 T-12 fluorescent lamps by operating them with electronic ballasts, static controls and dynamic controls of different designs. The energy savings krypton filled 34W lamp system is, at best, slightly more efficacious than the standard 40W argon filled lamp system by virtue of the use of lite white phosphor. The 34W system has limitations that include higher starting voltages, reduced temperature range of operation, smaller dimming range and poorer color rendering than the standard cool white 40W lamp system.

I. INTRODUCTION

During the past several years many new products have been introduced that operate fluorescent lamps in a manner to increasing their efficacy and/or to control their light output. These devices affect the electric and photometric properties of lamps and influence the source of the supplied electrical power. This report presents the electrical and illumination measurements of several new commercially available products operating two 34W or 40W, F40 T-12 rapid start fluorescent lamps. The equipment includes electronic ballasts, static controls and dynamic controls. This report is to provide end users with the important parameters that should be considered in selecting a lighting system. The report will show the range of performances that each type of equipment can provide including the trade-offs between particular parameters. These measurements have been accumulated over the past few years; thus, some devices cited may no longer be on the market or represent early commercial products that have since been modified.

The second section describes some performance parameters and discusses how these parameters affect the lamp or the electrical supply line. The next section references the measuring techniques and describes the setup for examining harmonics through a delta-wye, three phase system. The fourth section presents the results for the three types of equipment followed by a discussion of the results. The final section summarizes the highlights of the report.

II. PERFORMANCE PARAMETERS

A. System Efficacy

Efficacy is the term used for describing how effectively a system converts electrical energy into visible light. It has dimensions of lumens per watt (lm/W) and is determined by measuring the input power to the lamp-ballast system and the light output from the lamps. The lamp-ballast system efficacy is a function of the lamp wall temperature. In practice lamps in luminaires will be found to operate at temperatures between 35°C and 60°C. System efficacy is a key parameter for determining a system's operating cost since it determines how much power is needed to supply a specified light level.

B. Lamp Input Current Wave Shapes

Measuring the current wave shapes into the lamp allows calculation of the lamp current crest factor; peak current divided by the rms current. American National Standards Institute (ANSI) specifications recommend that the current crest factor be equal to or less than 1.7; a sine wave has a crest factor of 1.4. Higher crest factors will adversely affect lamp life.

C. Harmonic Content

Non-sinusoidal wave shapes generate higher harmonics of the fundamental 60 Hz line frequency. The neutral line for a pure sinusoidal current in a balanced three-phase circuit carries no current; that is, the fundamental of each phase is 120° out of phase and the phases cancel each other in the neutral line. The third harmonic does not cancel and current will flow in the neutral line, if it is too large the line can be overloaded. Harmonics can also interfere with other electrical equipment on the circuit.

D. Conducted/Radiated Electromagnetic Energy

Electronic ballasts convert the 60 Hz input power to direct current, inverting this current to a high frequency (20 to 30 kHz) and suppling it to the lamp. The high frequency power and its higher harmonics can be reflected back into the supply power. This reflected power can interfere with other equipment on the line. Supply lines can also radiate this power into space, where it can interfere with space-radiated communications. The Federal Communication Commission (FCC) is concerned about this potential source of interference from high frequency lighting systems and appointed a subcommittee of the National Electrical Manufacturers Association (NEMA) to recommend electromagnetic interference (EMI) limits for lighting equipment. Reports from two on-site measurements of EMI from electronic ballasts[1,2] detected no adverse effects on office or communication equipment.

E. Flicker

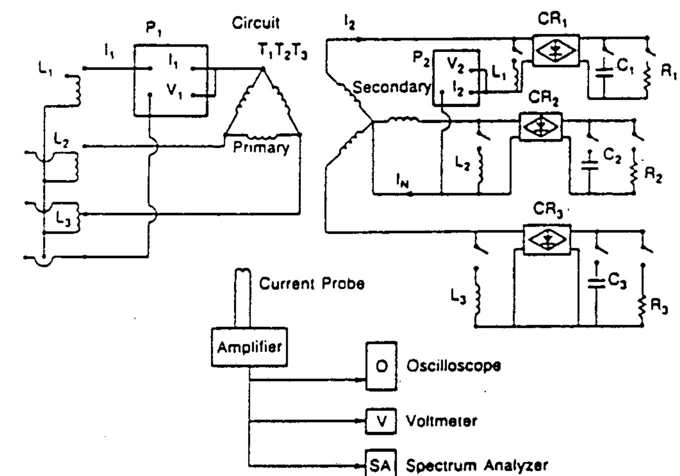
The percent flicker is a measure of the modulation of the light output. Fluorescent lamps operated at 60 Hz flicker at a rate of 120 Hz and have about 33% flicker. Lamps operated at high frequency, when unmodulated, eliminate flicker. Some electronic ballasts modulate the high frequency power at 60 Hz; depending on the degree line harmonics on the primary and secondary of a three-phase delta-wye connected system. All measurements were made with the secondary circuits balanced while measuring the current in the secondary and neutral line. The measurement of the rms current, rms voltage and power permitted the calculation of the power factor. The third and fifth harmonics were measured with a spectrum analyzer in the primary and secondary circuits. Five sets of measurements were made with different loads; a resistive, a pure inductive circuit, a saturated inductive circuit (producing harmonics), a resistor filter capacitor harmonic content and an inductor-resistor-filter capacitor harmonic content.

These experiments simulated the various electric line distortion effects from lighting systems. A balanced three-phase circuit was used to make certain that the currents measured in the neutral are only caused by wave distortions and phase relationships of the reactive components of the loads. The bridge rectifier and capacitor simulate the operation of electronic ballasts by generating harmonics with the voltage and current fundamental in phase. Measurements made with the inductor and the bridge rectifier with the capacitor, represents a circuit with the voltage and current fundamental out-of-phase with a non-sinusoidal current.

IV. RESULTS

A. Ballasts

Tables I and II show measured data for nineteen two lamp F40 electronic ballasts operating the same 40W cool white or 34W lite white fluorescent lamps, respectively. The tables include the measurement of a standard CBM core-coil ballast operating the same lamps and the ANSI standard values. Notice that the input voltages 120 or 277 volts are specified. The data was obtained from three units of each ballast design and the average of the results listed. The ballasts measured initially are specified with numbers. The more recently introduced ballasts are specified with letters.



Legend

R_1, R_2, R_3: 25W Lamp
C_1, C_2, C_3: 3000 µf, 150 VDC
L_1, L_2, L_3: 0.7h, 0.33A
T_1, T_2, T_3: 240V/120V 100 VA/ø
CR_1, CR_2, CR_3: Full-wave Bridge Rectifier
P_1: Clark-Hess Wattmeter 255
P_2: General Electric Wattmeter - WM5C

Current Probe: Tektronix P6302
Amplifier: Tektronix AM 503
Oscilloscope: Tektronix 7623A
Voltmeter: Hewlett-Packard 3400A
Spectrum Analyzer: Hewlett-Packard 3585A

Figure 1. Three-phase system test circuit

The two tables permit the comparison of different electronic ballast designs, the change of performance operating a standard and energy saving lamp, and the changes associated with ballasts operating lamps at 60 Hz and high frequency. Notice that some early electronic ballast designs (numbered) remove filament voltage after starting while all the newer designs (lettered) maintain filament voltage after ignition. Figure 2 shows the system efficacy with the electronic ballast averaged 78 to 79 lumens per watt compared to the coil-core systems at 64 to 65 lumens per watt. Notice that the system efficacy for the ballasts is at best 1% higher operating the energy saving lamps, although the energy saving lamp with the lite white phosphor is 6 to 7% more efficacious (see Table IX,) than the standard lamp. Figure 3 indicates that some electronic ballast designs result in a power factor less than 90%, the ANSI limit for a high power factor designation. The power factor with the core-coil ballast is reduced when it operates the energy saving lamps.

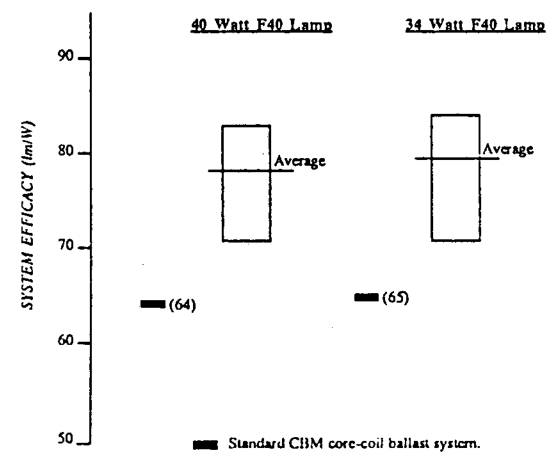


Figure 2. System efficacy for electronic ballasts operating F40 lamps

The ballast factor ranges shown in Figure 4, for the electronic designs, are lower than the standard ballast. However, recently electronic ballasts have been put on the market with a ballast factor greater than 1.0 (see Table III, 32W, F40 T-8 lamps). Figure 4 also shows operating the energy saving lamp.

Figure 5 shows the range of flicker obtained with the electronic ballasts. While some units reduce the flicker to zero, there are some units that have flicker as high as the core-coil ballast. Notice the reduction in flicker for the lite white type lamps, this is due to the longer decay time for the lite white phosphor.

TABLE I
FLUORESCENT BALLASTS SYSTEM (TWO LAMP 40W F40)

Characteristic	Percent of Center Voltage	Core-Coil		Solid-State (120 Volt)												Solid-State (277 Volt)							Core Coil (277 Volt)
		ANSI	120 V	1	2	3	4	5	A	B	C	D	E	F	G	6	7	8	H	I	J	K	
Power (W)	90		89	84	65	61	64	70	62	70	58	65	61	66	60	80	61	58	65	56	65	56	87
	100		96	85	92	67	73	91	72	71	65	72	68	75	68	82	69	66	67	63	72	65	95
	110		102	86	80	75	80	116	81	71	72	78	75	82	75	83	77	74	68	69	79	73	103
Power Factor	90		.99	.99	.92	.90	.91	.96	.96	.90	.96	.93	.92	.96	.98	.95	.95	.81	.90	.95	.86	.97	.99
	100		.98	.99	.91	.89	.91	.96	.95	.89	.95	.92	.91	.95	.98	.94	.95	.80	.90	.94	.85	.97	.99
	110		.97	.98	.90	.89	.90	.97	.95	.88	.93	.91	.90	.94	.97	.93	.94	.78	.88	.93	.84	.96	.98
Harmonics 3rd (%)	100		12	9	33	20	28	16	24	36	35	17	30	26	10	13	28	22	31	34	12	8	7
Harmonics 5th (%)	100		10	1	17	11	18	15	14	16	7	20	19	16	8	13	7	14	23	7	11	5	10
Open Circuit Voltage (V)	90	256	262	294	336	380	427	-	352	430	465	384	425	360	332	298	323	497	442	465	374	333	265
	100	to	285	294	364	383	487	-	390	502	518	426	470	400	370	297	356	500	489	510	277	373	288
	110	330	307	294	380	380	536	-	431	638	568	470	520	445	410	295	375	500	537	558	272	412	310
Open Circuit Crest Factor	90		1.5	1.5	1.4	-	1.3	-	1.9	1.6	1.4	1.6	1.4	1.9	2.2	1.3	1.4	-	1.6	1.4	1.6	2.1	1.5
	100	20	1.5	1.5	1.4	-	1.3	-	1.9	1.6	1.4	1.6	1.4	1.8	2.2	1.3	1.4	-	1.6	1.4	1.6	2.1	1.5
	110		1.6	1.5	1.5	-	1.3	-	1.9	2.3	1.4	1.6	1.4	1.7	2.2	1.3	1.4	-	1.5	1.4	1.6	2.1	1.6
Filament Voltage (V)	90	2.5	3.1	3.3	3.2	0	-	-	2.8	2.8	1.3	2.0	1.7	3.2	1.6	2.8	3.1	0	2.5	1.4	2.1	1.5	3.0
	100	to	3.5	3.3	3.6	0	-	-	3.1	3.1	1.4	2.0	1.6	3.2	1.5	2.8	3.5	0	3.3	1.5	2.1	1.5	3.4
	110	4.0	3.9	3.3	4.0	0	-	-	3.5	3.5	1.4	2.0	1.6	3.1	1.5	2.8	3.5	0	3.6	1.5	2.1	1.5	3.8
Lamp Current Crest Factor	90		1.5	1.3	1.8	1.9	1.4	1.9	2.3	1.5	1.6	2.1	1.6	1.9	2.1	1.4	1.5	1.9	1.5	1.5	1.5	2.2	1.6
	100	1.7	1.7	1.4	1.8	1.9	1.5	1.8	2.2	1.6	1.6	2.0	1.6	1.9	2.1	1.4	1.6	1.9	1.5	1.5	1.5	2.1	1.6
	110		1.8	1.2	1.8	1.9	1.5	1.8	2.2	1.6	1.6	2.1	1.6	1.8	2.1	1.4	1.5	2.0	1.6	1.5	1.6	2.1	1.7
Light Output (lm)	90		5780	5630	5050	4760	5130	4740	5100	5280	4780	5150	5100	5240	4320	5740	4790	4630	5170	4590	5140	4580	5570
	100	5830	6100	5720	5590	5330	5830	6190	5870	5290	5360	5780	5100	5940	4850	5800	5320	5210	5210	5120	5850	5210	5980
	110		6290	5740	6080	5920	6420	7600	6510	5220	5850	6350	6250	6401	5240	5841	5820	5810	5180	5590	6400	5740	6300
Ballast Factor		.925	.968	.907	.887	.846	.925	.982	.932	.840	.851	.917	.905	.943	.770	.920	.845	.826	.827	.813	.929	.827	.949
Light Output Regulation (%)	90	-25	-5	-1	-10	-11	-12	-23	-13	0	-11	-11	-11	-12	-11	-1	-10	-11	-1	-10	-12	-12	-7
	110	+25	+3	0	+9	+11	+11	+23	+11	-1	+9	+10	+10	+8	+8	+1	+9	+12	-1	+9	+9	+10	+5
Flicker (%)	100		30	0	5	33	4	32	15	1	3	1	3	11	22	0	3	30	0	1	1	30	30
System Efficacy (lm/W)	90		66	68	78	79	80	64	82	75	82	80	84	79	78	72	78	79	79	82	79	82	64
	100		64	68	77	79	80	68	81	74	83	80	83	79	77	71	77	79	78	82	81	81	63
	110		64	67	77	79	80	66	80	73	82	82	83	78	76	70	76	79	76	81	81	79	61

TABLE II
FLUORESCENT BALLASTS SYSTEM (TWO LAMP 34W F40)

Characteristic	Percent of Center Voltage	Core-Coil		Solid-State (120 Volt)												Solid-State (277 Volt)							Core Coil (277 Volt)
		ANSI	120 V	1	2	3	4	5	A	B	C	D	E	F	G	6	7	8	H	I	J	K	
Power (W)	90		75	70	54	51	55	-	56	61	51	56	54	59	52	68	53	50	57	50	57	50	75
	100		79	72	60	58	61	99	63	62	57	62	60	66	58	69	59	58	58	56	63	57	82
	110		84	73	66	69	68	-	70	62	62	68	66	73	64	71	65	68	60	61	69	64	88
Power Factor	90		.93	.99	.92	.88	.92	-	.96	.89	.95	.93	.91	.96	.97	.94	.95	.78	.88	.95	.94	.97	.95
	100		.92	.99	.92	.88	.90	.90	.93	.88	.94	.91	.90	.95	.97	.92	.94	.78	.86	.93	.94	.96	.95
	110		.92	.99	.91	.88	.90	-	.95	.87	.92	.90	.88	.94	.96	.91	.92	.78	.84	.91	.94	.95	.94
Harmonics 3rd (%)	100		20	6	31	19	14	5	24	37	38	18	34	27	15	14	32	18	32	37	12	9	16
Harmonics 5th (%)	100		14	1	18	10	13	13	13	17	8	22	21	15	4	15	8	15	25	8	13	6	13
Open Circuit Voltage (V)	90	256	262	378	328	-	418	-	352	430	465	384	425	360	332	273	311	-	442	465	374	333	265
	100	to	285	378	360	-	465	-	390	502	518	426	470	400	370	277	346	-	489	510	415	373	258
	110	330	306	378	398	-	505	-	431	638	568	470	520	445	410	272	376	-	537	558	459	412	310
Open Circuit Crest Factor	90		1.5	1.6	1.5	-	1.4	-	1.9	1.6	1.4	1.6	1.4	1.9	2.2	1.6	1.4	-	1.6	1.4	1.5	2.1	1.5
	100	2.0	1.5	1.6	1.4	-	1.4	-	1.9	1.6	1.4	1.6	1.4	1.8	2.2	1.6	1.4	-	1.6	1.4	1.5	2.1	1.5
	110		1.6	1.6	1.5	-	1.4	-	1.9	2.3	1.4	1.6	1.4	1.7	2.2	1.6	1.4	-	1.5	1.4	1.5	2.1	1.6
Filament Voltage (V)	90	2.5	3.2	2.7	3.2	0	1.4	3.4	2.8	2.8	1.3	1.9	1.5	2.7	1.3	2.8	3.5	0	2.9	1.4	1.9	1.4	3.0
	100	to	3.6	2.8	3.6	0	1.4	3.0	3.1	3.2	1.4	1.9	1.4	2.7	1.3	2.8	3.5	0	3.3	1.5	1.9	1.4	3.4
	110	4.0	4.0	2.7	4.0	0	1.4	4.3	3.4	3.4	1.8	1.9	1.4	2.7	1.3	2.8	3.9	0	3.6	1.5	1.9	1.3	3.8
Lamp Current Crest Factor	90		1.8	1.3	1.4	1.9	1.4	-	2.2	1.5	1.5	1.3	1.4	1.9	1.5	1.5	1.6	1.9	1.6	1.5	1.3	2.0	1.8
	100	1.7 max	1.9	1.4	1.4	1.8	1.4	-	2.2	1.6	1.5	1.3	1.4	1.9	1.6	1.5	1.6	1.9	1.6	1.5	1.3	2.0	1.8
	110		2.0	1.4	1.6	2.1	1.4	-	2.2	1.6	1.6	1.3	1.4	1.8	1.7	1.5	1.6	2.0	1.6	1.5	1.3	2.0	1.8
Light Output (lm)	90		5020	5040	4290	4220	4570	-	4520	4490	4120	4580	4480	4650	4330	5080	4150	4160	4390	4000	4730	4000	4900
	100		5060	5060	4750	4870	5140	6623	5060	4480	4640	5180	5040	5270	4860	5100	4610	4830	4420	4500	5310	4580	4970
	110		5290	5090	5180	5680	5650	-	5600	4490	5100	5600	5530	5800	5320	5120	5030	5580	4420	4960	5850	5100	5290
Ballast Factor		.925	.880	.865	.812	.832	.878	1.132	.865	.765	.793	.886	.862	.900	.830	.872	.788	.826	.756	.769	.908	.783	.864
Light Output Regulation (%)	90	-25	-2	0	-10	-13	-11	-	-11	0	-11	-12	-11	-12	-11	0	-10	-14	-1	-11	-11	-13	-2
	110	+25	+3	+1	+9	+17	+10	-	+11	0	+10	+[illegible]	+10	+10	+9	0	+9	+16	0	+10	+10	-11	+4
Flicker (%)	100		21	2	1	18	1	-	9	0	1	1	1	6	20	2	1	18	0	1	0	20	30
System Efficacy (lm/W)	90		67	72	80	83	83	-	81	74	81	82	83	78	84	75	78	83	77	81	83	80	65
	100		64	71	79	84	84	67	81	73	82	83	84	79	84	74	78	83	76	81	84	80	61
	110		63	70	78	83	84	-	80	72	82	82	84	80	83	73	77	83	74	81	85	79	60

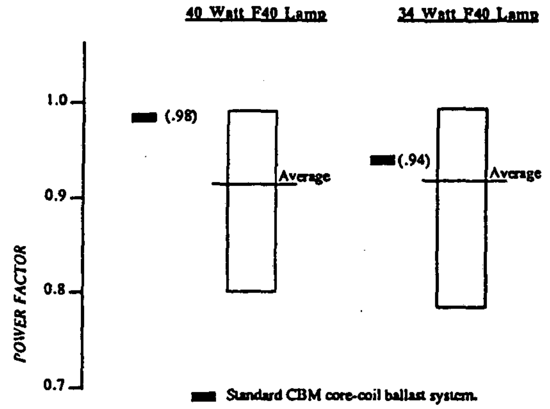


Figure 3. Power factor for electronic ballasts operating F40 lamps

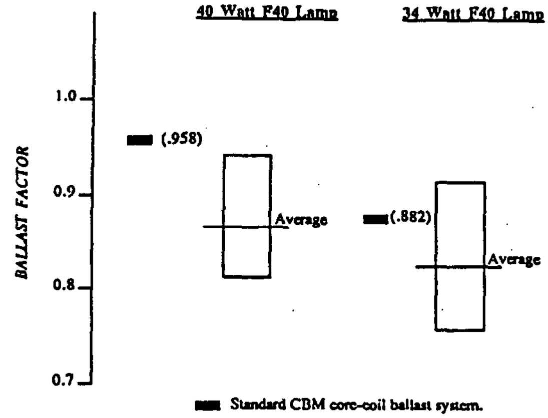


Figure 4. Ballast factor for electronic ballasts operating F40 lamps

In addition to the two lamp systems, electronic ballasts are available that operate three and four F40 lamps. The results of the measurements for these systems are listed in Table III. This table also lists measurements for ballasts systems operating two 32W, F40 T-8 lamps and a magnetic ballast designed to operate two 28W, F40 T-12 lamps. The more efficacious system uses an electronic ballast; notice the high ballast factor (1.003). The three-lamp system measured at 60 Hz used a standard two lamp and a single-lamp ballast for comparison. The four-lamp core-coil system used two, two-lamp ballasts to compare with the four lamp electronic system.

TABLE III
OTHER FLUORESCENT BALLAST SYSTEMS

CHARACTERISTIC	Percent of Center Volts	Two Lamp T-8 32W Lamp Core-Coil	Two Lamp T-8 32W Lamp Solid-State	Two Lamp 60 Hz Ø Filament Ballast 28W Lamp	Three Lamp F40 Ballast Core-Coil 40	Three Lamp F40 Ballast Core-Coil 34	Three Lamp F40 Ballast Solid-State 40	Three Lamp F40 Ballast Solid-State 34	Four Lamp F40 120V Core-Coil 40	Four Lamp F40 120V Core-Coil 34	Four Lamp F40 120V Solid-State 40	Four Lamp F40 120V Solid-State 34	Four Lamp F40 277V Core-Coil 40	Four Lamp F40 277V Core-Coil 34	Four Lamp F40 277V Solid-State 40	Four Lamp F40 277V Solid-State 34
SYSTEM INPUT																
Power (W)	90	63	60	56	136	120	118	101	171	148	122	106	169	151	126	108
	100	71	65	60	148	129	121	103	184	148	136	110	187	162	138	113
	110	77	72	64	160	139	124	105	196	168	135	109	203	176	138	114
Power Factor	90	88	93	.99	99	97	.96	96	98	93	95	96	100	97	93	93
	100	86	89	.97	98	97	95	95	97	93	94	94	100	96	92	92
	110	80	88	.92	96	95	95	94	96	93	94	92	99	96	91	90
Harmonics - 3rd (%)	100	7	43	15	4	13	10	10	12	17	17	17	7	15	12	12
- 5th (%)	100	6	6	14	8	10	12	14	9	14	14	15	9	12	20	23
LAMP INPUT																
Open Circuit Voltage (V)	90	300	498	225	265	265	461	428	262	262	696	696	266	266	776	776
	100	322	548	242	287	287	461	425	284	284	768	768	288	288	867	867
	110	344	600	258	310	310	462	428	306	306	845	845	310	310	957	957
Open Circuit Crest Factor	90	1.6	1.4	1.6	1.3	1.5	1.3	1.5	1.5	1.5	1.3	1.3	1.5	1.5	1.5	1.5
	100	1.7	1.4	1.5	1.3	1.5	1.3	1.5	1.5	1.5	1.4	1.4	1.5	1.5	1.5	1.5
	110	1.7	1.4	1.6	1.3	1.6	1.3	1.5	1.6	1.6	1.3	1.3	1.6	1.6	1.5	1.5
Filament Voltage (V)	90	3.5	0	0	3.1	3.1	2.0	2.0	3.2	3.2	2.1	1.7	3.0	3.0	2.0	1.8
	100	3.9	0	0	3.5	3.5	2.1	2.1	3.6	3.6	2.0	1.6	3.4	3.4	2.0	1.7
	110	4.3	0	0	3.9	3.9	2.0	2.0	4.1	4.1	2.0	1.6	3.8	3.8	2.0	1.6
Lamp Current Crest Factor	90	1.4	1.6	1.5	1.8	1.8	1.5	1.5	1.5	1.8	1.6	1.6	1.6	1.7	1.7	1.7
	100	1.3	1.5	1.6	1.8	1.8	1.5	1.4	1.6	1.9	1.7	1.6	1.6	1.8	1.7	1.7
	110	1.4	1.6	1.7	1.9	1.9	1.5	1.4	1.7	1.9	1.7	1.7	1.6	1.8	1.7	1.8
Light Output (lm)	90	4840	5330	4570	8470	7470	9080	8030	11540	9990	9780	8840	11160	9880	10140	8910
	100	5360	5820	4820	8970	7780	9250	8090	12200	10300	11110	9250	11930	10320	11200	9350
	110	5700	6280	5020	9350	8050	9340	8160	12620	10560	11140	9200	12560	10750	11170	9380
Ballast Factor	100	.924	1.003	.824	.949	.887	.978	.922	.968	880	.882	791	.947	882	889	799
Light Regulation (%)	90	-10	-8	-5	-6	-4	-2	-1	-5	-3	-12	-4	-6	-4	-10	-5
	110	+6	+8	+4	+4	+4	+1	+1	+4	+3	0	-1	+5	+4	0	0
Percent Flicker (%)	100	25	1	18	28	20	4	2	30	22	1	0	28	20	0	0
System Efficacy	90	76	89	82	62	62	77	80	67	67	80	83	66	65	80	82
	100	76	90	81	61	60	76	78	66	65	82	84	64	64	81	63
	110	74	87	78	58	58	75	78	65	63	82	85	62	61	81	82
Lamp Wall Temperature (°C)	90	36	36	35	36	36	36	35	40	38	39	37	42	37	40	37
	100	37	39	35	36	36	36	35	40	38	39	37	42	37	40	37
	110	38	39	36	36	36	36	35	40	38	39	37	42	37	40	37

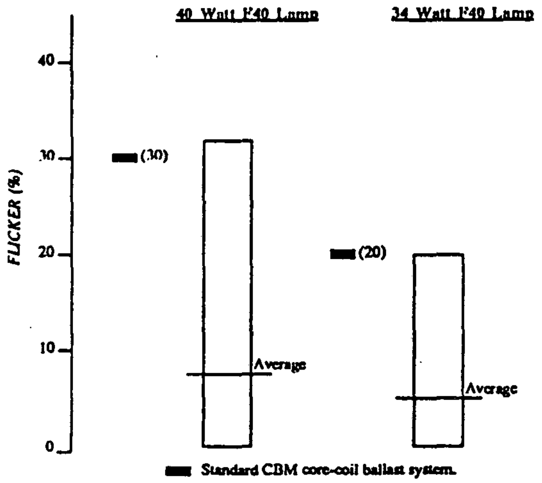


Figure 5. Flicker for electronic ballasts operating F40 lamps

Since fluorescent lamp systems, in practice, operate at different minimum lamp wall temperatures (MLWT), their thermal characteristics should be known to determine the light output in a particular luminaire. Figure 6 plots the change in light output for the standard system and an electronic ballasted system, operating 40W and 34W lamps. At a MLWT of 60°C, typical in a four lamp wrap around fixture, the light output is decreased by 25% and the efficacy is reduced by 14%. The change in light output for an electronically ballasted system is less sensitive to lamp temperature.

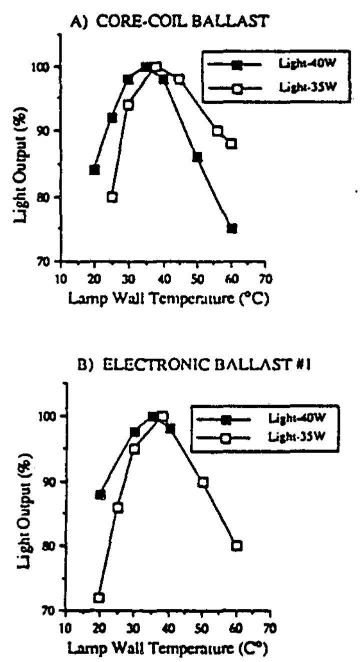


Figure 6. Effect of lamp wall temperature on the light output of 40W and 34W lamps

B. Static Controllers

The static controllers are used in conjunction with core-coil ballasts to reduce the light output of fluorescent lamp systems. They provide the proper voltage but limit the current to reduce the power to the lamps; thus, they are also called current limiters. Tables IV and V list the results of the electrical and light output measurements for the two lamp 40W and the two lamp 34W systems. Devices 1, 2, 3 and 7 reduce the light output by 30% and 4, 5 and 6 reduce light output by 50%. The design of device numbers 1 and 4 differ from the rest in that they are installed on the line side of the ballast while the other devices are connected between the ballast and the lamp. They are the only type to show a slight increase in system efficacy. However, devices 1 and 4 achieve this at the expense of power factor and a reduction in the filament voltage. As discussed earlier, reducing filament voltage at lower lamp currents will generally reduce lamp life. The third harmonic is also generally increased. Operating energy saving lamps with these devices results in a large decrease in system efficacy, an increase in flicker by a factor of three and a large increase in the second harmonic. Some of these units increase the current crest factor when operating the 34W lamp which

TABLE IV
STATIC CONTROLS FOR 40 WATT F40 LAMPS

Characteristic	Core-Coil	Controller 1	2	3	4	5	6	7
Power (W)	94	62	62	59	46	41	45	62
Power Factor (%)	98	66	94	94	60	80	85	94
Light Output (lm)	6100	4090	4050	3820	2990	2300	2660	4000
Filament Voltage (V)	3.6	2.3	3.6	3.5	2.4	3.6	3.5	3.6
Flicker (%)	30	31	29	28	38	33	29	28
Current Crest Factor	1.6	1.7	1.7	1.7	1.9	1.8	1.8	1.7
Harmonics (%)								
2nd	2	3	1	4	3	1	3	2
3rd	11	30	25	28	38	42	37	26
5th	10	4	12	12	3	11	12	12
System Efficacy (lm/W)	65	66	65	65	65	56	59	65
Relative Change (%)								
Power	0	-34	-34	-37	-51	-56	-52	-34
Light Output	0	-33	-34	-37	-51	-62	-56	-34
Efficacy	0	+2	0	0	0	-14	-9	0
Lamp Wall Temperature (°C)	40	37	37	37	36	35	35	37

TABLE V
STATIC CONTROLS FOR 34 WATT F40 LAMPS

Characteristic	Core-Coil	Controller 1	2	3	4	5	6	7
Power (W)	77	50	53	52	37	36	38	53
Power Factor (%)	90	53	72	69	48	74	75	70
Light Output (lm)	5150	3400	3100	2900	2400	1830	2130	3040
Filament Volt (V)	3.5	1.8	3.5	3.5	2.0	3.6	3.5	3.5
Flicker (%)	13	20	46	46	29	33	36	48
Current Crest Factor	2.0	1.7	2.5	2.5	1.8	2.5	2.3	2.6
Harmonics (%)								
2nd	4	1	94	92	14	50	62	96
3rd	24	32	23	24	39	34	30	26
5th	16	2	11	10	3	8	6	12
System Efficacy (lm/W)	67	68	58	56	65	51	56	57
Relative Change (%)								
Power	0	-35	-31	-32	-52	-53	-51	-31
Light Output	0	-34	-40	-44	-53	-64	-59	-41
Efficacy	0	+1	-13	-16	-3	-24	-16	-15
Lamp Wall Temperature (°C)	34	30	29	29	28	26	26	30

will adversely affect lamp life. These effects with the energy saving lamps are due to the low lamp wall temperature (less than 35°C) obtained in a room ambient temperature of 25°C.

C. Dynamic Controllers

This section provides results of several systems that can dim fluorescent lamps. In Tables VI and VII the first five devices (1 to 5) can dim standard core-coil ballasts; 1, 2, 3, and 5 dim the lamps by reducing the duty cycle, device 4 dims lamps by reducing the input voltage to the ballast. The remaining devices are electronic ballasts designed to reduce lamp current when the ballast receives the proper low voltage signal. The characteristics of all the systems were measured at three light levels: at maximum, at the minimum and approximately half way between the light level of the two extremes.

Dimming the 40W lamps with the controllers generally reduced the input voltage to the ballast, lowered the system efficacy, reduced power factor, reduced the filament voltage and increased the third harmonic. The changes with respect to power factor and the harmonics are less with the electronic ballasts. The filament voltage, with some electronic designs, can be maintained or even increased when the light level is reduced. On the average, the dimming range with the electronic ballast is greater than the core-coil ballast system. The most notable difference with most of the dimming devices operating the energy saving lamps is the reduction in the range of light output.

D. Power Factor with Three Phase Circuits

Table VIII shows the measurements for the delta-wye system that result from high resistive, inductive and component-generating harmonics. The pure resistive load results in a unity power factor in the secondary circuit and a near unity in the primary circuit. Shown in Figure 7, the leg currents in the balanced three-phase circuit are out of phase by 120° which results in a near zero current in the neutral. The inductive loads (columns 2 and 3 of Table VIII) show an out-of-phase relationship of about 84° in the secondary. The 80 volt inductor circuit shows virtually no wave distortion, as evidenced by the low third and fifth harmonics. Increasing the voltage to 120 volts across the inductor causes saturation, resulting in some wave distortion, as evidenced by the increase in the third harmonic. The neutral current increases to about 10% of the leg current.

The bridge-rectifier capacitor circuit distorts the wave shapes and generates large third and fifth harmonics, well above those generated by electronic ballasts (Tables I and II). The current in the neutral exceeds the current in any one leg and will add to the I^2R loss.

The current components reflected through the delta-wye system to the primary are the phase shifts and the fifth harmonics. The odd triple in harmonics (third, ninth, fifteenth, etc.), are contained and circulated in the transformer primary. Therefore, they will not affect the generating source but will heat the transformer.

TABLE VI
DYNAMIC CONTROLS FOR 40 WATT F40 LAMPS

Characteristic	Light Level	Core-Coil Ballast	Controller 1	2	3	4	5	Solid-State Ballasts 6	7	8	9	10	11	12	13
SYSTEM INPUT															
Power (W)	max	94	94	100	100		105	83	82	90	121	71	136	67	138
	mid		73	80	50		73	50	47	48	59	47	93	46	100
	min		38	48	17		47	22	19	16	41	29	53	28	62
Power Factor (%)	max	97	98	91	94		96	99	93	96	96	89	94	90	92
	mid		86	52	61		89	98	89	97	93	87	94	86	90
	min		71	66	63		88	97	75	87	88	82	88	79	86
Harmonics 3rd (%)	max	12	10	35	33	12	13	9	13	16	9	36	17	31	12
	mid		35	52	54	19	31	3	24	11	21	42	17	36	12
	min		42	53	56	24	27	9	50	24	28	51	22	44	12
BALLAST INPUT															
Voltage (V)	max	120	117	119	119	120	277								
	mid		95	92	87	90	234								
	min		91	87	84	84	222								
Power (W)	max	94	91	100	98	94	104								
	mid		59	63	47	73	65								
	min		31	48	15	53	38								
Light Output (lm)	max	6100	5910	6410	6180	6100	5880	5690	5950	6210	9048	5290	11120	5210	11200
	mid		3960	4740	3390	4900	3990	2660	2780	2890	3500	3530	7270	3570	7620
	min		2010	3070	602	3560	1830	360	390	430	2060	1820	3300	1980	4000
Filament Voltage (V)	max	3.5	3.4	3.4	3.4	3.5	3.3	3.3	3.3	4.6	2.5	3.5	2.0	3.2	2.0
	mid		2.7	3.0	2.5	2.4	2.8	4.1	3.8	3.1	2.8	3.1	2.1	3.2	2.0
	min		2.7	2.4	2.5	2.5	2.8	3.0	3.1	4.5	2.8	2.7	2.2	3.0	2.1
System Efficacy (lm/W)	max	65	63	64	62	65	56	69	73	69	75	75	82	78	81
	mid		55	59	68	67	53	53	59	61	59	75	78	78	76
	min		54	65	37	66	39	16	21	27	50	63	62	71	65
Dimming Range (%)	max		100	100	100	100	100	100	100	100	100	100	100	100	100
	mid		67	74	55	80	68	47	47	47	39	67	65	69	68
	min		34	48	10	59	31	6	7	7	23	34	30	38	36

TABLE VII
DYNAMIC CONTROLS FOR 34 WATT F40 LAMPS

Characteristic	Light Level	Core-Coil Ballast	Controller					Solid-State Ballasts						
			1	2	3	4	5	6	7	9	10	11	12	13
SYSTEM INPUT														
	max	80	81	92	93		94	72	69	103	62	110	58	113
Power (W)	mid		84	69	70		82	48	46	80	42	76	42	81
	min		78	37	37		68	23	21	58	27	45	25	51
	max	93	94	83	87		92	99	92	95	88	94	86	92
Power Factor (%)	mid		96	55	58		88	99	89	94	85	90	82	88
	min		93	45	50		85	96	76	92	79	86	76	85
	max	20	15	47	50	15	10	6	14	10	37	17	32	12
Harmonics 3rd (%)	mid		24	54	58	18	26	2	26	14	44	19	37	12
	min		32	57	62	22	30	8	40	14	52	24	44	12
BALLAST INPUT														
	max	120	118	120	120	120	271							
Voltage (V)	mid		97	90	92	70	242							
	min		88	74	76	66	222							
	max	80	80	92	90	79	93							
Power (W)	mid		65	66	62	50	73							
	min		55	36	33	38	58							
	max	5150	5110	5250	5410	5150	5110	5060	5100	8090	4480	9250	4420	9350
Light Output (lm)	mid		4470	3120	3690	3530	4350	2780	2830	5830	2960	6070	3000	6350
	min		3860	1950	2050	2690	3520	420	480	3570	1420	2880	1560	3220
	max	3.6	3.5	3.5	3.5	3.6	3.3	2.8	2.8	2.1	3.2	1.6	3.3	1.7
Filament Volt (V)	mid		2.8	2.6	2.6	1.9	2.9	3.1	3.1	2.2	3.1	1.7	3.3	1.6
	min		2.5	2.1	2.2	1.9	2.7	3.0	3.1	2.3	2.7	1.7	3.0	1.7
	max	64	63	57	58	65	54	70	74	79	72	84	76	83
System Efficacy (lm/W)	mid		53	52	53	71	53	58	62	73	70	80	71	78
	min		49	53	55	71	52	18	23	62	53	69	62	63
	max		100	100	100	100	100	100	100	100	100	100	100	100
Dimming Range (%)	mid		87	69	68	69	85	55	55	72	66	66	68	68
	min		76	37	38	52	69	8	9	44	32	31	35	34

TABLE VIII
WAVESHAPES AND VOLTAGE-CURRENT RELATIONSHIPS FOR INDUCTIVE (NONSATURATING) LOAD

	Types of Load				
	R	R, C	L(80-V)	L(120-V)	R,L,C
Balanced Secondary					
Primary Power Factor	0.980	0.870	0.208	0.213	0.669
Secondary Power Factor	1.0	0.667	0.102	0.107	0.562
Secondary Leg Current (A)	0.150	0.344	0.273	0.438	0.445
Secondary Neutral Current (A)	0.0079	0.61	0.007	0.044	0.60
Primary 3rd Harmonic Current (%)	0.5	2.0	0.4	1.9	2.5
Secondary 3rd Harmonic Current (%)	0.6	82.9	0.5	3.4	50.5
Primary 5th Harmonic Current (%)	2.6	47.9	1.6	3.7	28.9
Secondary 5th Harmonic Current (%)	0.4	54.7	0.3	1.7	33.0
Unbalanced Secondary					
Primary 3rd Harmonic Current (%)	1.8	77.2	1.1	4.7	43.7
Primary 5th Harmonic Current (%)	5.4	52.3	2.5	5.4	29.8

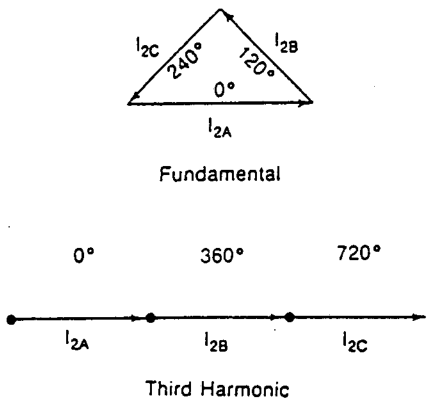


Figure 7. Vector sum of fundamental and third harmonics

V. DISCUSSION

A. History

The 34W, F40 rapid start lamp was introduced as a retrofit lamp that would lower light levels and could be operated with standard ballasts. The differences between the 34W and the 40W, F40 lamps are: 1) the 34W lamp contains krypton instead of argon, 2) the 34W has a transparent conductive coating on the bulb wall and 3) the 34W lamp uses a more efficient phosphor mix (lite white) than the 40W lamp (cool white).

The new lamp presented a different electrical load to the ballast and draws less power; 80W, compared to 95W for the 40W system, a reduction of 16%. These lamps were designated as energy-saving lamps because of the power reduction. The first energy saving lamps used the cool white phosphor and reduced the efficacy and the light output substantially. A new phosphor mix, lite white was used to increase the rated light output from 2750 to 2925 lumens but achieved it at the expense of the color rendering index (CRI) which was reduced from 65 to 55. The lite white phosphor added some yellow-emitting phosphor to the mix providing more light in the part of the spectrum where the human eye's response is most sensitive.

The krypton-filled lamps have different starting characteristics from argon-filled lamps. Specifically, the krypton lamps have a peak starting voltage of nearly 400 volts compared to the 200 volts for argon filled lamps.[7,8] To reduce this voltage, the lamps are coated with a conductive layer that reduce the peak starting voltage at 60 Hz to 150 volts. However, the rms starting voltage was increased from 130 volts to 200 volts but was considered acceptable because of the large reduction in the peak starting voltage. These voltages still exceed the starting voltages of the argon-filled lamps (125 volts rms and 140 peak volts). The difficulty of starting the 34W lamps is evident by its specifications which state the minimum operation ambient temperature is 60°F compared to 50°F for the standard F40 lamp. Both the higher peak and rms starting voltages will tend to accelerate the erosion of the electrodes, hence reduce lamp life.

At high frequency the krypton filled lamps with the conductive coating have a peak starting voltage of about 175 volts, but a high rms starting voltage of about 290 volts.[7,8] Without the conductive coating, the starting voltages will be lower (240 peak volts and 110 rms volts) which is within the ANSI specifications.

When the 34W lamp was first introduced as a retrofit, there were numerous reports of an abnormally large number of ballast failures. This was found to be caused by a failed capacitor for ballasts that were approaching the end of their life. Table IX lists the detailed characteristics of a standard ballast operating 40W and 34W lamps. The 34W lamps operates at a higher current and lower voltage. Thus, there is a higher voltage across the ballast and the capacitor that was found to fail. When the capacitor was new it could withstand the additional voltage stress; but after a long operating time the capacitor would experience some deterioration and the extra stress would cause premature failure. All new ballasts upgraded this capacitor that these ballasts could operate the energy saving lamps and the standard lamps.

TABLE IX
DETAILED CHARACTERISTICS
OF CORE-COIL BALLASTS
OPERATING F40 LAMPS

	40 Watt F40 Lamp	34 Watt F40 Lamp
Ballast Input		
Voltage (V)	120	120
Current (A)	0.798	0.715
Power (W)	93.4	78.9
Power Factor	0.975	0.920
Lamp Input		
Voltage (V)	9.6	81.6
Current (A)	0.416	0.460
Cathode Voltage (V)	3.5	3.5
Ballast Factor	0.97	0.88
System Output		
Light Output (lm)	5970	5160
Flicker (%)	30	21.2
Harmonics - 3rd	12.3	19.7
Harmonics - 5th	9.6	14.3
Ballast Efficiency (%)	0.804	0.762
Lamp Efficacy (lm/W)	81.2	87.4
System Efficacy (lm/W)	64	65

B. 40 Watt and 34 Watt System Efficacy

Table IX also lists the ballast efficiency, lamp efficacy and the system efficacy. The lamp efficacy of the 34W lamp is about 7% higher than the 40W lamp primarily due to the more efficient lite white phosphor, yet the efficacies of the two systems are virtually the same. Because the 34W lamp operates at a higher current, the ballast I^2R losses increase reducing ballast efficiency (76.2% compared to 80.4%). Electrically, the 34W system is about 7% less efficacious than the 40W system, if the same two lamps employed the same phosphor.

C. Design

Designers and facility managers must realize there will be a difference in the ballast factor for the same ballast operating an argon or a krypton filled lamp. The ballast factor has no bearing on efficacy or reliability but alters the initial light output from a lamp as rated by the manufacturer. For example, two 40W lamps with electronic ballast A will provide 5870 initial lumens while 34W lamps will provide 5060 initial lumens (see Tables I and II) which is a decrease of 14%. The manufacturers rated difference (6300 lumens and 5850 lumens) is only 7%. In addition, the tables show a large variation in the ballast factors for the different ballast designs. Thus, the designer must know the ballast factor for each lamp-ballast combination to properly calculate the illumination level.

D. Controls

The static and dynamic controls with both the core-coil ballasts and the dimmable electronic ballasts can function suitably with the 40W or 34W lamps. However, at lower ambient temperatures and lower light output, when the MLWT falls below 35°C, the 34W lamps may flicker excessively and generate a large second harmonic component.

The dynamic controllers of the core-coil ballasts, including the dimming electronic ballasts, have a more restricted dimming range operating the 34W lamps when compared to 40W lamp operation. The dynamic controllers decrease the filament voltage to the lamps when they are dimmed; as the arc current is lowered below 50% of full light output, lamp life could be significantly reduced. When dimming these lamps below 50% of full light output, it is best to provide full filament voltage (2.5 volts to 4.1 volts) to maintain lamp life.

E. Specification

This report has measured the major parameters that affect the generating supply, the system reliability, the lamp life and the lighting design. The large range of values for the different ballasts make it essential that the engineer, end user and designer understand his/her needs to properly specify the equipment.

The parameters that affect the electrical supply are of concern not only to the end user but to the utility companies. A recent utility study[9] has estimated that fluorescent lighting constitutes 25% of the total consumer load and often exceeds 30%. The utility was concerned with the impact on its system that would result by voltage reductions to load shed during emergencies. The test involved a core-coil ballast 34W lamp system. The line volt-amperes (VAR's) increased when the supply voltage was reduced and higher line currents were measured, although the power was reduced.

The lamp-ballast parameters affecting reliability and lamp life are open circuit crest factor, lamp current crest factor and filament voltage. Unique to the operation of lamps at high frequency is the need to supply filament voltage during operation. At 60 Hz, electrons bombard the anode providing most of the energy to heat the filaments. At high frequency, the anode fall (potential) is reduced and the externally applied filament voltage is required to maintain a suitably high filament temperature. In the dimmed mode (low arc currents), full filament voltage is required to maintain a suitable temperature at all operating frequencies.

Finally, to better meet the lighting design targets and costs demanded today, the lighting designer must know the performance parameters of the lighting system. The factors affecting the lighting design are the system efficacy, system power, ballast factor, light regulation, and percent flicker. The input power and system efficacy permit the designer to evaluate the economics of the system where the operating cost for the providing light is:

Cost ($/lm h) = Energy Cost / System Efficacy.

The above relationship indicates that the light provided by a 40W system has the same cost effectiveness as a 34W system because their system efficacies are the same. For new construction the 40W system will generally prevail since each two-lamp unit provides more illumination, reducing the number of fixtures (lamps and ballasts) needed to supply the specified light levels in a space. Additional gains could be obtained with 40W, F40 lamps with the lite white phosphor.

The results of this study show that the above factors vary between different electronic ballast manufacturers. There are also new F40 lamp ballast 60 Hz systems that have unique operating parameters. Thus, if the designers are to obtain the proper illumination features and levels, they must understand these factors to properly specify the equipment.

VI. SUMMARY

A. Electronic Ballast Status

The development and manufacture of electronic ballasts have evolved over the past eight years to a point where product reliability has been established. This is evidenced by their availability from the major ballast manufacturers and by the smaller companies that spearheaded their advance. The major lamp companies now offer energy saving lamps (krypton filled) designed for high frequency operation. The fundamental change is the removal of the conductive coating that resulted in higher peak starting voltages at high frequency operation, but necessary for 60 Hz operation.

The different design approaches result in the large variation in performance of electronic ballasts, as well as the lack of standards to guide the developers. The establishment of standards is a lengthy procedure and they should be available in the near future.

B. F40 Lamps

The 34W, F40 energy saving lamp has been a suitable retrofit for the reduction of illumination levels in overlit spaces. However, as an option for new lighting layouts or renovations, this study indicates its overall performance may not warrant its premium cost. The energy saving lamp requires a higher rms starting voltage, results in a lower power factor, a higher harmonic content and a greater current crest factor. These factors have a negative impact upon the electrical supply and lamp life. When the lamps light output is controlled, statically or dynamically, the range of dimmability with the 34W lamps is limited relative to the 40W lamps; in a slightly cool environment a large second harmonic will occur and will be accompanied by severe flickering.

Designers must consider all the factors when comparing the 40W (argon filled) lamp system with the 34W krypton (filled) lamp system (system efficacy, light output, lamp life, dimmability, color rendering, power factor, harmonics, and initial cost). For new construction and renovation applications, the 40W, F40 argon filled lamp should be preferred.

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