Designing Liquid Crystal Display Backlighting Systems With Cold Cathode Fluorescent Lamps

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Display systems development requires a working knowledge of cold cathode fluorescent lamp (CCFL) technology. To successfully implement a backlight design, the systems integrator needs to understand what defines the performance envelope of CCFLs. Parameters like starting voltage, operating voltage, lamp life, tube current and operating frequency are just some of the metrics found in lamp specifications.

This application note addresses the general operating principals of CCFLs. Issues like temperature and age effects on lamp electrical performance, system considerations like inverter selection, dimming circuit implementation, wiring layout and backlight optical design are discussed within the context of display applications.

Introduction

Liquid Crystal Displays (LCDs) are successful in the portable computing marketplace due to their small form factor, low power and high reliability features. The key to achieving a reliable low-power display design is proper integration of the backlight system.

Cold cathode fluorescent lamps (CCFLs) convert the ultraviolet light emission of mercury atoms into visible light by means of phosphor emissions. By choosing from a wide variety of available phosphor materials, different color temperature lamps can be produced. This is an important advantage over LED, incandescent or EL lamps when the application requires backlighting full color displays.

General Principles of CCFL Backlights

Differences Between CCFLs and HCFLs

CCFLs work on the principles of glow discharge, and thus require less current and dissipate less heat than hot cathode fluorescent lamps (HCFLs). In addition, the cathode construction of CCFLs are inherently more robust than HCFLs.

CCFL cathodes are composed of two relatively heavy nickel-plated iron rectangular tabs forming a "V." The size and shape of the tabs provide a robust cathode which helps confine discharge and reduce sputtering. This allows CCFLs to achieve lifetimes in excess of 25,000 hrs. HCFLs employ filament style cathodes which require preheating to achieve full operation. Though HCFL preheat circuits add to the complexity and cost of the drive electronics, they provide an advantage in allowing deeper levels of dimming and cold temperature starting performance.

Fundamentals of Emission and Lamp Construction

Three main energy conversions occur during the light generation process in a fluorescent lamp. Initially, electrical energy is converted into kinetic energy by accelerated charged particles. These in turn yield their energy during particle collisions to electromagnetic radiation in the UV region of the spectrum. This UV energy is converted to visible energy by the lamp phosphor. During each conversion, some energy is lost so that only a percentage of the input energy is converted into usable light output. Figure 2 depicts a typical energy balance for a 4mm diameter CCFL in which 85 percent of the energy is lost to either conducted or radiated heat.

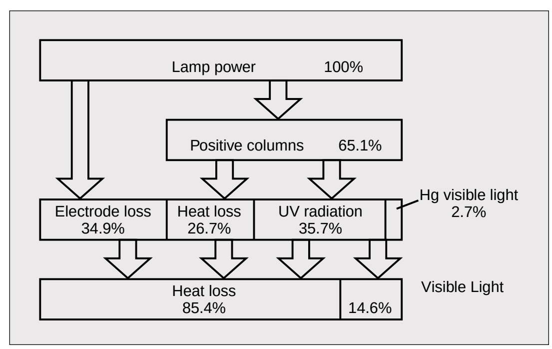

Figure 2: Energy balance for a 4mm outside diameter (OD) CCFL.

Two important parameters that effect lamp life are the electrode surface area and the tube wall thickness. An insufficient electrode surface area with respect to the lamp current will increase the sputtering of the electrode material leading to early blackening of the ends and a reduced life. Likewise, the lamp wall thickness is key to ensuring that higher fill pressures can be maintained, thus securing the appropriate mercury content in the tube.

Due to the physics of electron emission of cold cathodes, the gas

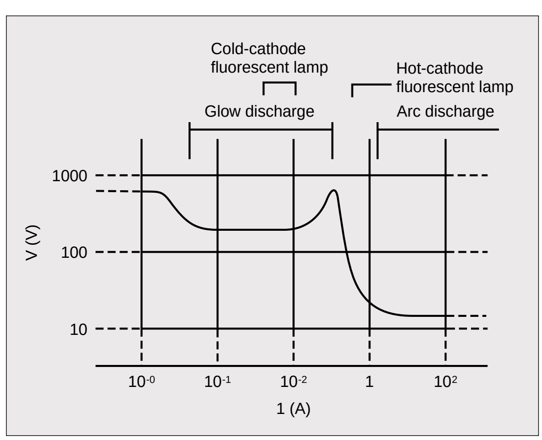

Figure 1: Glow discharge and arc discharge.

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fill pressure must be high. Cold cathodes in argon-mercury discharges emit secondary electrons from ion bombardment of their emitting surface by ions with energies equal to the cathode fall voltage. Due to the small tube diameter, a high inert gas fill-pressure is needed to reduce electrode sputtering.

Typical Lamp Performance Characteristics
Starting Voltage

Starting voltage of a CCFL varies with the lamps fill-pressure and age. Normally, a fluorescent lamp contains several thousand Pascals of argon and mercury. Because the mercury vapor pressure varies with temperature, the starting voltage varies as well. The starting voltage characteristics for a CCFL are optimized at approximately room temperature. Based on Penning effects, as the temperature changes, the ratio of argon atoms to mercury atoms becomes unbalanced, increasing the starting voltage. In addition, as a lamp ages and the mercury content is reduced, the starting voltage goes up. Lamp specifications have to take these factors into consideration and provide starting voltage ratings for a minimum operating temperature at the CCFLs end-of-life condition.

between temperature and the luminance output of 3 and 4 millimeter diameter lamps.

Although CCFLs generate very little heat, there is still a warm-up period before the luminous output is stabilized. A bare lamp at room temperature can stabilize in as few as three minutes (see figure 5). However, since the thermal mass of the lamp fixture will extend the warm-up period, it is recommended to wait 30 minutes before measuring a display's output brightness.

Because the operating temperature of the lamp is critical to the display brightness, it is important to evaluate the system in its final configuration. Sometimes practical constraints, like adding mounting brackets and forced air cooling, will lower the lamp's operating temperature and the output brightness of the display.

Drive Current Effects on Luminous Output and Life Expectancy

The most important factor governing lamp performance is drive current. There is a linear relationship between lamp current and brightness. Although higher backlight brightness can be achieved by driving CCFLs beyond the recommended current levels, the lamp life will be adversely affected. In fact, there is an approximately exponential relationship between lamp current and lamp life (see figure 6). The curves suggest that performance and reliability of the backlight system can be drastically affected by overdriving or underdriving the lamps.

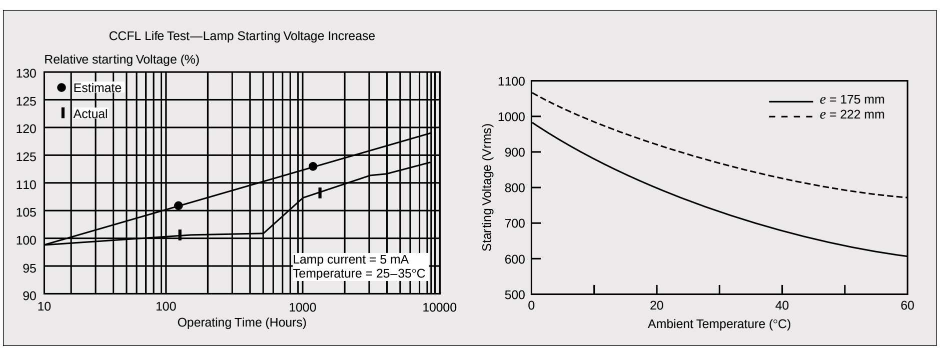

Figure 3: The effect of lamp temperature and age on the required starting voltage.

Temperature Effects on Lamp Luminance

The peak radiation efficiency for mercury falls off as temperature increases or decreases. As such, the luminous output of a lamp varies with the temperature of the coldest spot on the lamp surface (generally the center of the lamp). Figure 4 illustrates the relationship

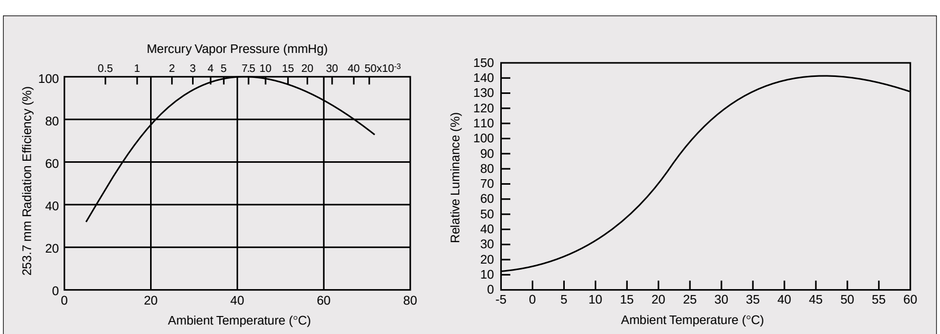

Figure 4: Effects of lamp surface temperature on luminous output for 4mm and 3mm (OD) lamps.

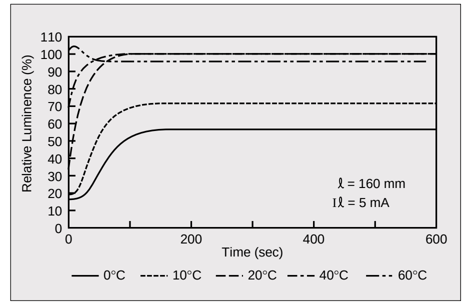

Figure 5: Lamp luminous output rise time for 4 mm (OD) lamps.

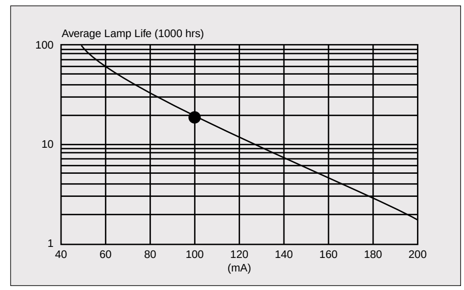

Figure 6: Lamp life versus normalized lamp current input (aggregate data for various manufacturers' lamps).

Lamp Power Consumption

Power consumption is critical in most portable applications. More than seventy-five percent of the display power budget is dissipated in the backlight system (the lamp and inverter circuit). Thus, it is important to understand the variables that affect lamp current in order to determine the worst case system power consumption.

Lamp power consumption varies in an approximately linear fashion with lamp length and ambient temperature (see fig. 7).

Lamp Life Performance for Standard and Long Life Lamps

Under nominal drive current, the typical lamp life for a standard 2 to 3 mm diameter CCFL is 10,000 hours to half-brightness. Some industrial applications require continuous operation of display units. For these ruggedized designs, Sharp recommends using high mercury-content lamps. These high fill pressure lamps reach performance levels greater than 20,000 hours to half-brightness.

Higher fill pressures have two antagonistic effects on lamp characteristics:

1) Reduced positive column efficacy as discharge energy is lost to elastic collisions within the gas; and
2) Higher positive column voltages which cause a larger fraction of the total lamp power to be used in light generation. The net loss in lamp efficacy increases power dissipation while the higher fill pressures increase start-up voltage requirements (see figure 8). The resultant performance

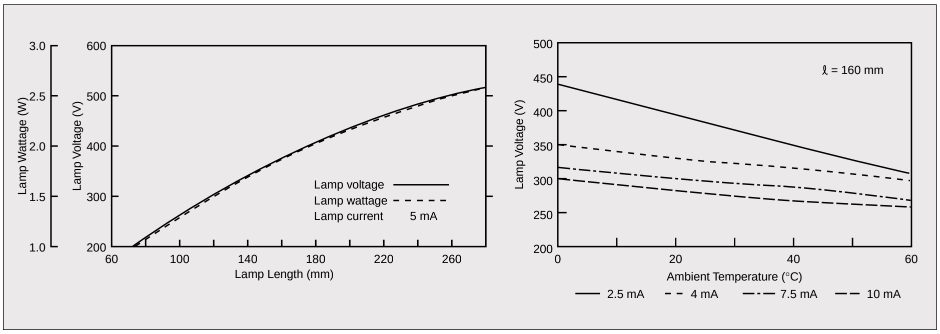

Figure 7: Lamp power as a function of lamp length and ambient temperature for 3mm (OD) lamps.

	Symbol	Standard Lamp			Long Life Lamp			Unit
		MIN	TYP	MAX	MIN	TYP	MAX	
Lamp Voltage	IL	—	480	530	—	500	550	Ta-25°C, Vrms
		—	—	690	—	—	740	Ta-0°C, Vrms
Lamp Current	VL	3.8	5.4	6	3.8	5.4	6	mA rms
Lamp Power Consumption	PL	—	2.6	—	—	2.8	—	W
Lamp Frequency	FL	20	—	50	20	—	50	Khz
Kick-off Voltage	VS	—	—	900	—	—	1,000	Ta-25°C, Vrms
		—	—	1,100	—	—	1,100	Ta-0°C, Vrms
Lamp Life	LL	—	10,000		—	23,000		h
Color		Same						

Figure 8: Lamp characteristics for Sharp's standard and long-life CCFLs.

tradeoff improves lamp life but reduces system efficiency.

Luminance Maintenance Characteristics

Luminous depreciation due to backlight aging has to be accounted for in design and maintenance of a display system. The luminous flux performance of a lamp degrades over time due to three major factors:

1) Impurities in the fill gas evident in the first 500 hours of use;
2) UV degradation of the fluorescent materials—a long term degradation with effects ranging from 1% to 5% per 1,000 hours of use;
3) Tube blackening caused by electrode materials being sputtered onto the glass envelope of the lamp. Generally, the lamp's output will degrade relatively quickly at first but then stabilize, maintaining a constant luminous depreciation over time (see fig. 9).

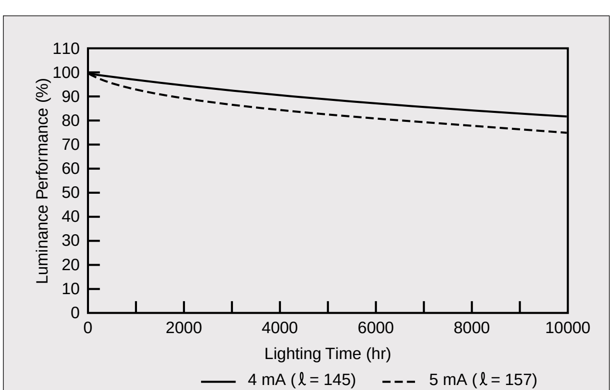

Figure 9: Luminous depreciation for 3mm diameter CCFL.

Display Backlight Systems Considerations

Inverter Selection

CCFLs require special inverter drivers to create the kick-off voltage and the high frequency sinusoidal drive current needed for proper operation. This section outlines considerations for specifying an appropriate inverter based on the lamp characteristics typically found in display specifications.

Specifying an inverter takes knowledge of four key CCFL parameters:

1) Starting voltage;
2) Operating voltage;
3) Tube current; and
4) Operating frequency.

If dimming is required, special consideration must be given to whether pulse width modulation techniques or analog dimming should be used.

Starting Voltage

The starting voltage is the minimum voltage required to fire the tube at the lowest expected operating temperature at the end of its useful life. It is important to know the worst case starting voltage, because as the tube ages and the temperature drops, the starting voltage goes up. If the inverter is not designed to address the worst case conditions, then it won't produce the minimum required discharge voltage and the tube will not light.

Operating Voltage

The operating voltage is the voltage across the tube when the lamp is functioning under the specified lamp current levels. This voltage is expressed as a steady state RMS voltage and reflects the physical characteristics of the tube. Since inverters are designed to function as constant current sources, some variation in operating voltage will be observed. Generally, lamp voltage characteristics are stable with only minor variation over temperature and time.

Operating Current

The operating current is the nominal RMS current as measured on the return side of the lamp by a current probe. This is the most important parameter of the lamp since it determines the luminous output, power consumption, and the expected life of the backlight system. The apparent brightness of the display varies linearly with operating current and the expected life varies exponentially with the operating current.

In cases where excessive drive currents are used, heat dissipation in the lamp electrodes can lead to an uneven temperature rise on the display surface. This effects both the display's contrast uniformity, and the long-term reliability. Since the inverters act as a constant current source, there will be brightness fluctuations due to lamp warm-up characteristics, ambient temperature and lamp age. If the application calls for a constant output backlight, some type of optical feedback loop is required along with a variable current inverter.

Operating Frequency

The frequency of the AC signal used in the drive circuit can impact the brightness of the tubes. Typically, the recommended operating frequency for sub-3 mm diameter CCFLs lies between 20 and 50 KHz. Higher frequencies are not converted into light output. So any high frequency spikes in the current waveform will be lost resulting in lower lumen-per-watt conversion efficiency.

High frequency losses should be included in the power budget calculations where operating power is critical. Thus, when evaluating inverters, the designer should verify the lumens-per-watt efficiency in the product's final configuration. This can be accomplished by measuring the ratio of display light out to the power into the inverter.

Dimming Considerations

Dimming may be required if a display system has to operate under a variety of lighting conditions. The simplest way to dim a backlight is to vary the amplitude of the lamp current waveform. This technique is known as analog dimming and can typically provide modulation ratios of only 3:1.

For wider dimming ratios, designers have to resort to using pulse width modulation (PWM) techniques. In PWM dimming, the current to the CCFL is switched on and off at a set frequency. The lamp's brightness varies with the duty cycle of the current "on-time." Any display implementation that requires PWM dimming should be reviewed for backlight uniformity, perceivable flicker, and EMI/RFI compatibility with the system.

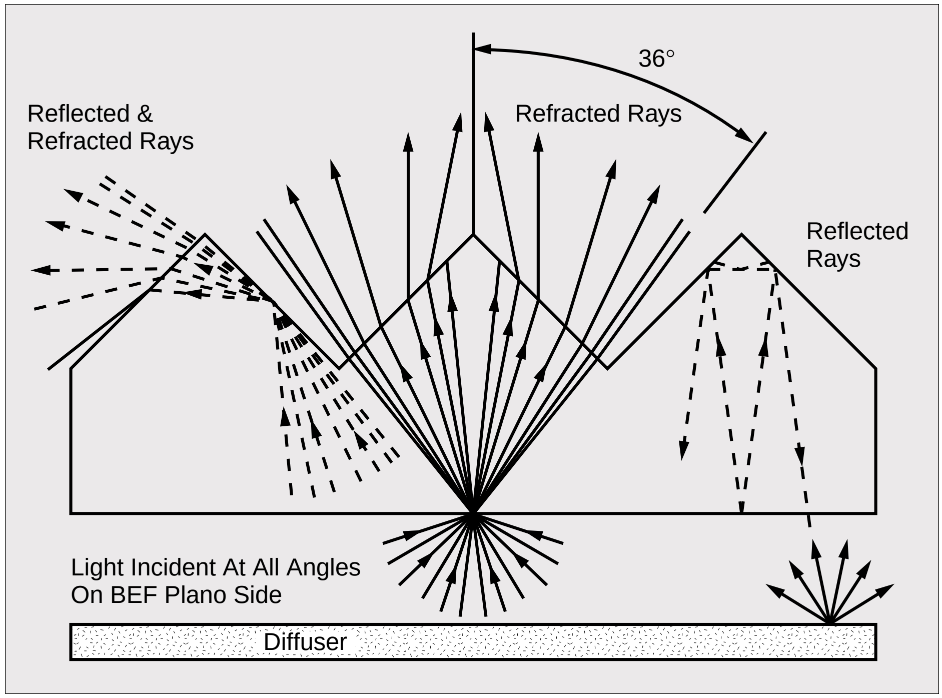

Figure 11: Principles of Brightness Enhancement Films (BEFs).

Wiring and Layout

Due to the high frequency drive waveform employed with CCFLs, placement of the inverter circuit and wiring layout should be carefully considered. At the 20 to 50 KHz drive frequencies, impedance matching dictates that the length of the high-voltage lead wire be kept as short as possible. Parasitic capacitance can drain approximately 5% of the lamp current per inch of wire length. This leakage capacitance current does not impact the input power, but rather the lumens-per-watt conversion ratio of the backlight system. As a rule, the length of the input power lead to the lamp should be minimized. The leads should be routed as far away from ground planes as possible and never be twisted together.

Light Pipe Technology

As CCFL technology evolved to thinner tube diameters, displays changed from directly backlit to edge-lit designs. The implementation of edge lighting helped reduce the overall thickness of the display system and enabled applications in portable computing. Figure 10 shows two typical backlight designs. The single tube system is optimized for low power applications and the dual tube system addresses high brightness designs.

Edge lighting uses a CCFL source to inject light into a polycarbonate waveguide. The waveguide efficiently disperses the photons through the principles of total internal reflection. When rays hit one of the diffuser dots silk-screened on the waveguide, light scatters randomly creating a Lambertian point source. Based on the strategic spacing of the diffuser dots, a uniform backlight is created.

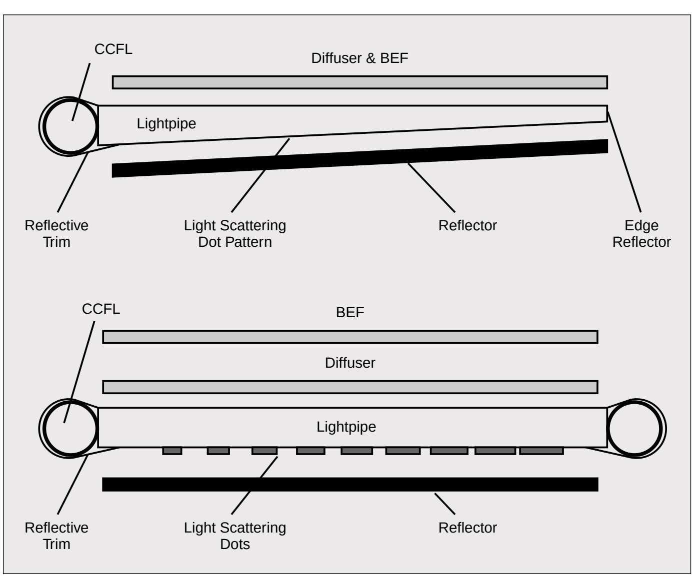

Figure 10: A single CCFL wedge-shape lightpipe and a high-bright dual CCFL lightpipe employing BEF technology.

Brightness Enhancing Films (BEFs)

Where high backlight luminance needs to be achieved, BEFs are used to direct the light inside the viewing cone of the LCD. When placed over a diffuser, BEFs take Lambertian light and, through the principles of total internal reflection and refraction, focus the light into a 72 degree cone (see figure 11). A single BEF can provide a 150% increase in brightness, while two BEF layers stacked in a crossed pattern can provide up to a 240% increase in brightness. The tradeoff is a reduction in the viewing angle. Typically, you will sacrifice +15/-15 degrees in the horizontal viewing direction by using BEFs.

Conclusions

This application note was prepared as a guideline for successful implementation of CCFT backlighting systems. Designers need to understand the performance envelope for such key lamp metrics as starting voltage, operating voltage, lamp life, tube current and operating frequency. They must also consider the effects of temperature and lamp age on the overall performance of the backlight system and the importance of inverter selection, dimming techniques and wiring layout.

References

1. IES Lighting Handbook 1994 edition.
2. Toshiba Lighting technical note titled "Cold-Cathode Fluorescent Lamps for Thin Backlight Units."
3. Ward, Dan; Information Display, Feb. 92; "Matching Inverters to CCFT Backlights."