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Advantages of LED Lighting in Vision Inspection Systems

How LED lighting can achieve consistent output, lower operational costs and provide sustainability

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Executive Summary

Light-emitting diode (LED) technology has been in use since the early 1960s, but the technology has changed quite a bit since then. Early LEDs emitted only low-intensity red light and were used primarily as indicator lamps for many devices. Today, LED technology cuts across the visible, ultraviolet and infrared wavelengths, is very bright and can achieve consistent output, as well as offer energy efficiency and very long service life.

That's why you see LED leading the way in a range of uses from interior and exterior building lighting to HD televisions to the printing industry. LED lighting solutions, especially temperature controlled LED lighting, provides many advantages over other traditional lighting options such as fluorescent and tungsten halogen.

Advantages of LED Compared to Other Lighting Options

As a leader in offering inspection solutions to the printing industry, QuadTech began to see first-hand, in 2003-2004, how systems with LED lighting offer better control of light intensity and consistency than fluorescent and tungsten halogen technologies, all while increasing intensity, reducing energy consumption and offering substantially longer life.

Let's review the primary technologies currently used for print inspection:

Fluorescent

A fluorescent lamp consists of a glass tube filled with a gas containing low pressure mercury vapor and argon, xenon, neon or krypton. Metal electrodes at each end are coated with an alkaline earth oxide that gives off electrons easily. When current flows through the gas between the electrodes, the gas is ionized and emits ultraviolet radiation. The inside of the tube is coated with varying blends of metallic and rare-earth phosphor salts; substances that absorb ultraviolet radiation and fluoresce (re-radiate the energy as visible light).

Fluorescent lighting is becoming obsolete and losing prominence to LED lighting for many reasons. Fluorescent provides very low light intensity and inconsistent output in comparison to the other lighting sources. It is difficult to control light intensity levels because of the unstable nature of the gas inside fluorescent tubes, which is affected by ambient temperature and its electrical power supply. Fluorescent lamps used in the inspection process use a high frequency electronic ballast (2 kHz to 200 kHz), which continuously runs the risk of interference with line-scan camera frequencies. This results in fluctuations not only with light output but color temperature as well. For fluorescent, it is blue color dominant. These factors have a negative effect on the inspection process. When the frequency is close to a multiple of the camera line frequency, the result is horizontal image banding. Despite attempts to smooth out the ripple effect, the interference is still visible.

Fluorescent lamps do not have a very long life and generally need to be replaced every six months.

Tungsten Halogen

A halogen lamp is an incandescent lamp with a tungsten filament contained within an inert gas and a small amount of a halogen such as iodine or bromine. The combination of the halogen gas and the tungsten filament produces a chemical reaction known as a halogen cycle that increases the lifetime of the bulb (over a traditional incandescent bulb) and prevents its darkening by redepositing tungsten from the inside of the bulb back onto the filament.

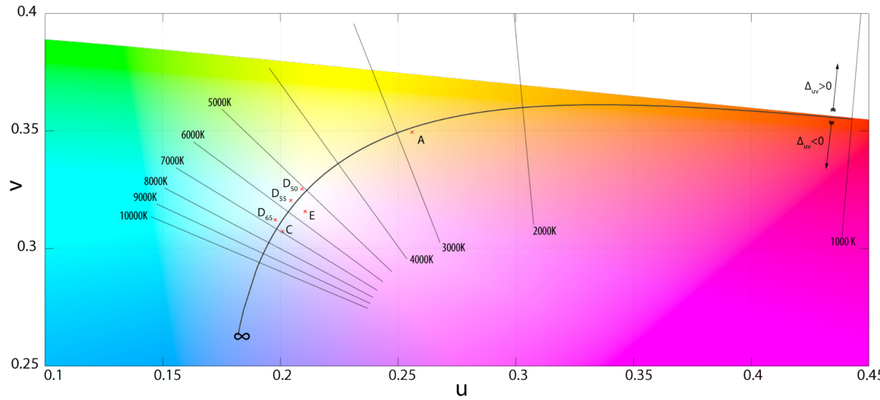
Although tungsten halogen systems have gained in popularity and offer an improvement over fluorescent in terms of light intensity, the technology has its drawbacks. The light output, while better than fluorescent, is quite non-uniform when compared to LED. It can only be used as a main top light, and control boxes are not easily linked together to provide intensity control via an operator console. From an inspection-performance standpoint, the color of light output is about 3,500k, which represents a very high dominance of red. With the higher levels of red and green, this requires the blue gain levels to be doubled. Because both blue noise levels and threshold levels can be increased, this can cause significant issues when looking for defects with significant blue components. An additional factor that affects performance is the reality that the color temperature changes when intensity changes. Another limitation of tungsten halogen is that it can only be used with the aid of a custom-made fiber optic assembly that allows the light to be formed into a single line.

Halogen lamps have a limited life span of 500 to 700 hours and can be very expensive, ranging from 25 Euros ($35) to 40 Euros ($55) each—currency conversion fluctuates. Because of this increased maintenance requirement inherent with the technology, it becomes necessary—and costly—to purchase and store spare light control boxes and a high quantity of spare bulbs. In some cases, a lighting source that is 1200mm long uses 4 bulbs. Besides the inherent cost, there is a concern about the light output and stability of bulbs as they are replaced, causing each to be at a different stage of their short life.

LED

A light-emitting diode (LED) is considered a semiconductor light source. When a LED is forward biased (switched on), electrons are able to recombine with holes within the device, releasing energy in the form of photons. This effect is called *electroluminescence* and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor. They are small in area (less than 1 mm2), and integrated optical components are used to shape its radiation pattern and assist in reflection, producing a bright light.

FIGURE 1: Planckian locus in the CIE 1960 UCS [MacAdam (u, v)] chromaticity diagram



International Commission on Illumination

The lighting industry currently relies on the CIE color rendering index (CRI) as a metric for ranking the color rendering abilities of white light sources, including white-light LEDs. Unfortunately, this metric was developed in the 1960s for fluorescent lamps, and is ill-suited to solid-state lighting. However, an improved metric has recently been proposed by NIST1 and the subject is currently being reviewed by the CIE.[1]

LED lighting offers the best of all worlds when it comes to print inspection systems. From a performance standpoint, LEDs, which run on DC electricity, offer high intensity with very even, stable output with no flicker, resulting in a clean, noise-free inspection of images with lower threshold levels than other technologies. Some other light sources, which usually run on AC electricity, need some sort of additional voltage regulation in an attempt to match the quality of a LED light source.

With LED production of white light, the typical light output is about 6,700k, which results in very true-to-life colors (see Figure 1) being inspected and displayed on the operator monitor. Additionally, the proportion of each color (red, green, blue) can be varied to produce a white light source with an adjustable color temperature. QuadTech Inspection Systems go a step further by utilizing this feature to optimize the lighting for each system. Since cameras vary by manufacturer, the LEDs are color matched and adjusted to achieve the best level of light for each CCD (charge coupled device) camera.

The LEDs used by QuadTech are rated for up to 100,000 hours (almost 11½ years) , and using temperature controlled (active cooled) LEDs, the life span is maximized while providing constant, stable light intensity levels.

LED lighting can be used for all lighting needs including main lighting, background lighting and reflective lighting; and combined light units are easily controlled by a PC user interface to achieve optimum inspection on different substrate types.

In addition to providing better inspection performance and being incredibly reliable, LED systems require very little maintenance. The LEDs used by QuadTech are rated for up to 100,000 hours (almost 11½ years), and using temperature controlled (active cooled) LEDs, the life span is maximized while providing constant, stable light intensity levels.

TABLE 1: Comparison of Lighting Technologies

	LED	Fluorescent	Tungsten Halogen
Light Intensity/ Color Temperature in Kelvin (K)	6,700 K +	2,700 K – 6,500 K *	3,500 K *
Light Intensity vs. Color Temperature	Stable when properly cooled	Not stable	Not stable
Output	Uniform	Non uniform	Non uniform
Power Supply Ripple (horizontal banding)	No	Yes	No
Lighting Uses	Top, Back and Foil	Top, Back and Foil	Main
Operation Control	Combined units, controlled by PC	Gas very unstable and extremely difficult to vary intensity	Can be linked, but not easy to accomplish
Bulb Life	Up to 100,000 hours	Approx 3,000 hours	500-700 hours
Green Impact	Highly energy efficient with long life	Shorter life	Shorter life

+ A typical color temperature of a LED

* During a bulb's life, for both fluorescent and halogen, there is a significant degradation in intensity and changes in color temperature

Types of Inspection Lighting

Inspection systems can use a maximum of three lighting sources. The lighting sources used depend on the substrate material type. The following are the lighting sources defined:

Main Lighting

Also known as top lighting, this is the primary lighting used during the inspection process. It is color balanced light used to illuminate non-shiny and non-transparent substrate material.

Back Lighting

This lighting is used to illuminate transparent substrate types from the back of the material.

Foil Lighting

This lighting is used to illuminate shiny substrate material.

An Illustration of Performance

The following illustrates the difference in various lighting sources during the inspection process.

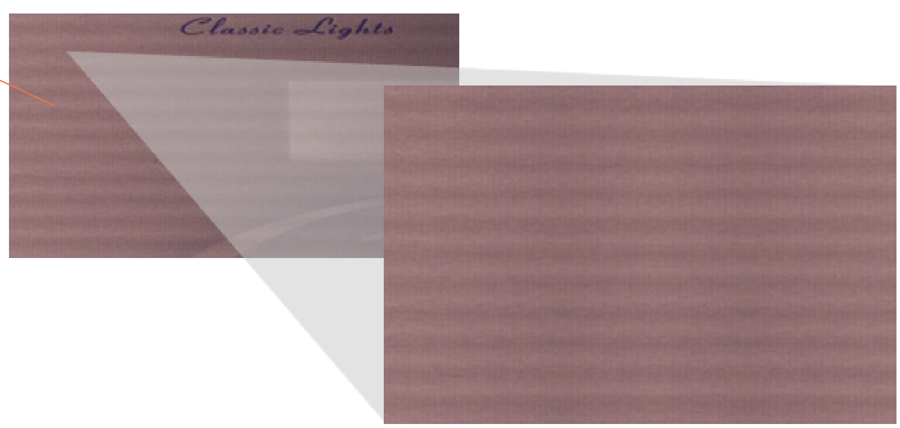
Fluorescent/Tungsten Halogen

In both examples below, there are two sources of light. The main light source is tungsten halogen. Due to the geometry of the main light, a diffusing secondary fluorescent light is used.

Foil using fluorescent and tungsten halogen light

The magnified image shows a section of the foil product. It should appear as grey, but it appears blue with alternating dark and light horizontal bands associated with the frequency of the fluorescent light. These problems impact inspection interpretation, making it difficult for the operator to identify or understand the nature of some defects.

Paperboard using fluorescent and tungsten halogen light



The magnified image shows a section of a paperboard product. In this case the blue tint is not that noticeable since the surface is not highly reflective, but the alternating dark and light horizontal bands associated with the frequency of the fluorescent light is visible. Additionally, the dominance of the tungsten halogen makes it appear as pink when it should be white. This variation in output needs to be compensated for by using lower inspection sensitivity, which is a significant compromise.

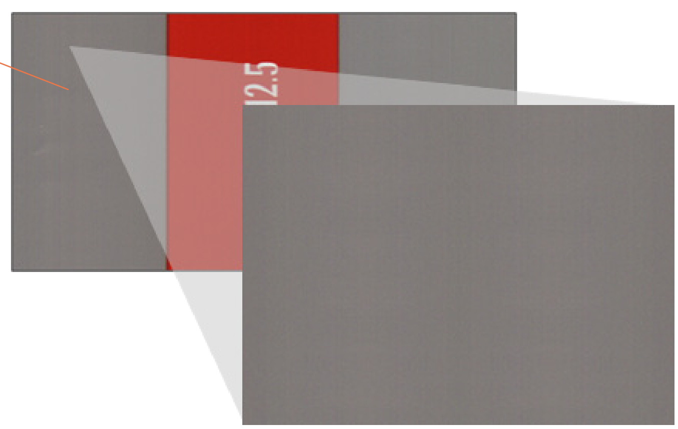
LED

In both examples below, there are two sources of light. The main light source is LED. Due to the geometry of the main light, a secondary diffusing LED light is used.

Smooth white overprint of foil using LED

The magnified image shows how the white overprint appears smooth, visually accurate with no color distortion or compromise on inspection settings.

Smooth foil using LED



The magnified image shows a section of foil product as smooth and mid-tone grey, visually accurate with no color distortion or compromise on inspection settings. Essentially, as it would appear to an operator if he held it in his hands.

The Quality of a LED Inspection System

Based on the comparison of lighting sources, LED lighting is the obvious choice for use in inspection systems. However, not all LED Inspection Systems are the same. Due to variances in LED light design and light geometry, the effective light output can vary significantly. As a result, inspection systems may compensate for this in a multitude of ways. For example, some off-the-shelf systems may focus lighting directly onto the substrate, while others use diffused lighting to illuminate the substrate. When looking into a LED inspection system, ask the following:

Can your camera acquire images at maximum press speed?

To make up for low light output, some systems run at lower press speeds so the camera has a longer exposure time. Low camera speeds may also be used to accommodate intensity difference, but the result is lower resolution, which impacts inspection performance and image quality.

What is the camera lens aperture size?

A typical aperture setting for an inspection system camera lens is f/2.8. This aperture setting provides a reasonable balance between sharpness and total light entering the camera's charge coupled device (CCD) image sensor. When light intensity increases, it is possible to use a higher f-stop position to achieve greater image sharpness; with a higher brightness level using f/4.0, more of the image is in focus. However, if the brightness is not sufficient, the homogeneity of inspection is impacted, resulting in lower quality and inconsistent inspection. Additionally, if the aperture setting is reduced to f/1.8 due to insufficient light, the reduced aperture setting causes a loss of contrast in the image, also resulting in bad inspection.

Is the camera image digitally enhanced?

Although this sounds like a good thing, it is not. Increasing camera digital gains may result in a bright image, but as it amplifies the image signal, it also amplifies the noise within the image. Therefore, if the image had a base noise level of 10 and the gain is set to 2 the resulting image will have a noise level of 20. To accommodate the digital noise, inspection tolerances have to be lowered, resulting in reduced sensitivity to color variation and low contrast defects during inspection.

TABLE 2: LED Inspection System Comparison

Attribute	System A – QuadTech	System B - Futec
Light Intensity	400,000 Lux+	120,000 Lux*
Light Consistency	97%	70%
Camera Speed	80 MHz	60 MHz (Easy Max GS) 40 MHz (Easy Max MC)

+ Measurement taken at surface of substrate.

* Measurement taken at light - Lux value at surface of substrate is expected to be significantly lower than value quoted here.

Controlling Temperatures to Achieve Tighter Inspection Tolerances and Repeatability

While LED has been proven to be the best option for print-inspection applications compared to fluorescent and tungsten halogen, controlling LED temperature is very important to get the best performance from your LED lighting.

The Science of LED and Heat

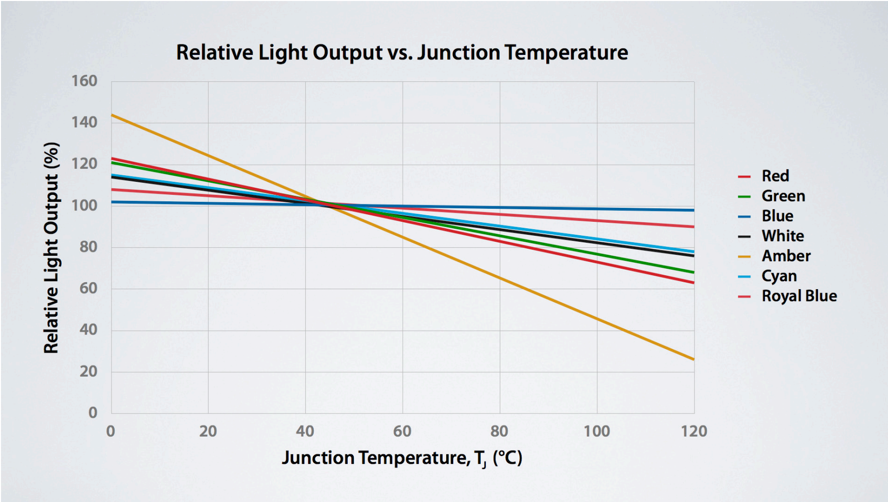
According to information published on the Web site of the Lighting Research Institute at Rensselaer Polytechnic Institute in Troy, NY:

> *In general, the cooler the environment, the higher an LED's light output will be. Higher temperatures generally reduce light output. Warmer environments and higher currents can increase the temperature of the semiconducting element. The light output of an LED for a constant current varies as a function of its junction temperature. The temperature dependence is much less for InGaN LEDs (e.g., blue, green, white) than for AlGaInP LEDs (e.g., red and yellow).*
>
> *Prolonged heat can significantly shorten the useful life of many LED systems. Higher ambient temperature leads to higher junction temperatures, which can increase the degradation rate of the LED junction element, possibly causing the light output of an LED to irreversibly decrease over the long term at a faster rate than at lower temperatures.*
>
> *Controlling the temperature of an LED is, therefore, one of the most important aspects of optimum performance of LED systems.*[2]

It is also important to note that the LED luminaries themselves generate heat; the heat generated by the LED is overwhelming compared with the ambient temperature. The junction temperature can easily exceed 150 degrees C just from the LED. Without adequate temperature management, that heat can degrade the LED's life span and affect light intensity and color output.[3]

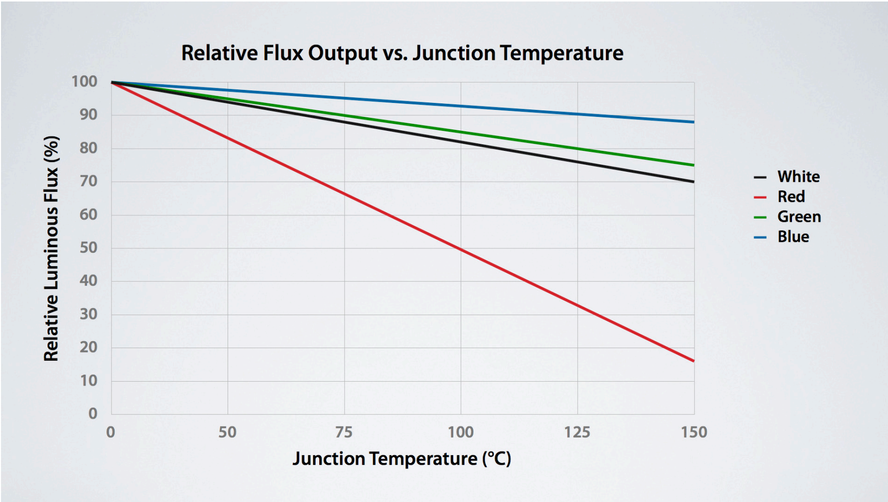
The following examples illustrate how the LEDs' relative flux output changes as the junction temperature (Tj) increases or decreases.

FIGURE 2: Relative Light Output vs. Junction Temperature[4]



As you can see in Figure 2, if the Junction temperature of Amber LEDs is reduced, it doubles the light output. Other colors are less sensitive, but still demonstrate a dramatic improvement, for instance, reducing the temperature of a white LED from 100 degrees to 45 degrees Celsius adds up to 25% in light output.

FIGURE 3: Relative Flux Output vs. Junction Temperature (IF = 350 mA)[5]



As Figure 3 illustrates, most LED data sheets list typical luminous flux at Tj = 25°C. If the application uses the LEDs at higher junction temperatures (Tj > 25°C), then a proper cooling method must be used or the luminous flux must be derated from the value listed on the LED's data sheet.

Active Cooling

With advancements in technology, active cooling (e.g. liquid-cooling) has clearly taken the lead over passive cooling (e.g. fan-cooling) in the management of Junction temperature. QuadTech, through its acquisition of Vigitek, has offered active-cooled LED lighting since 2003. The cooling method selection was made in line with the results of extensive research to determine the effects of both types of cooling on LED lighting. It was determined that the single-most-important aspect of LED light design was to ensure that the LED light output did not change in either light intensity output or color temperature. As previously discussed, we also determined that the only way to achieve this is through excellent thermal management, which is best achieved via active cooling.

Only temperature controlled LED lighting, achieved with active cooling, can create the repeatable conditions to utilize a reusable Golden Template on successive print runs of the same product. The same can be said of color monitoring algorithms, which are not reliable without the use of temperature controlled LED lighting. Active cooling not only ensures the stability of light output intensity, but it also ensures there will be no LED light color changes during a run and from one print job to the next. This is critical because LED light intensity can change with ambient temperature.

Additionally, since constant exposure to high Junction temperatures accelerates the degradation of LEDs and reduces their life and reliability[6], active cooling ensures the lifetime of the LEDS will be considerably longer than with passive cooling.

TABLE 3: Active vs. Passive Cooling

Advantages of Active Cooling	Disadvantages of Passive Cooling
Light intensity consistent over every job	Output can change with ambient temp
Color temperature of LEDs is constant	Color change can occur over time
Repeatability/Golden Template; light settings can be saved and recalled for later use since intensity and color are constant	Light intensity and temperature can shift, making it difficult to have confidence in previous settings
Lifetime of LEDs is prolonged greatly	Lifetime of LEDs can be reduced by as much as 50%

Conclusion

LED lighting for print inspection has far surpassed any other lighting options for consistency, performance values, energy efficiency, longevity and cost of operation and maintenance. Superior LED inspection systems achieve appropriate light intensity, resulting in unsurpassed inspection image quality output. When temperature controlled, LEDs offer unmatched ability to maintain standards, save and recall specific print jobs for use on later print runs, regardless of location, time and ambient temperature. Temperature controlled LEDs provide repeatability, life cycle stability and prolonged life span.

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