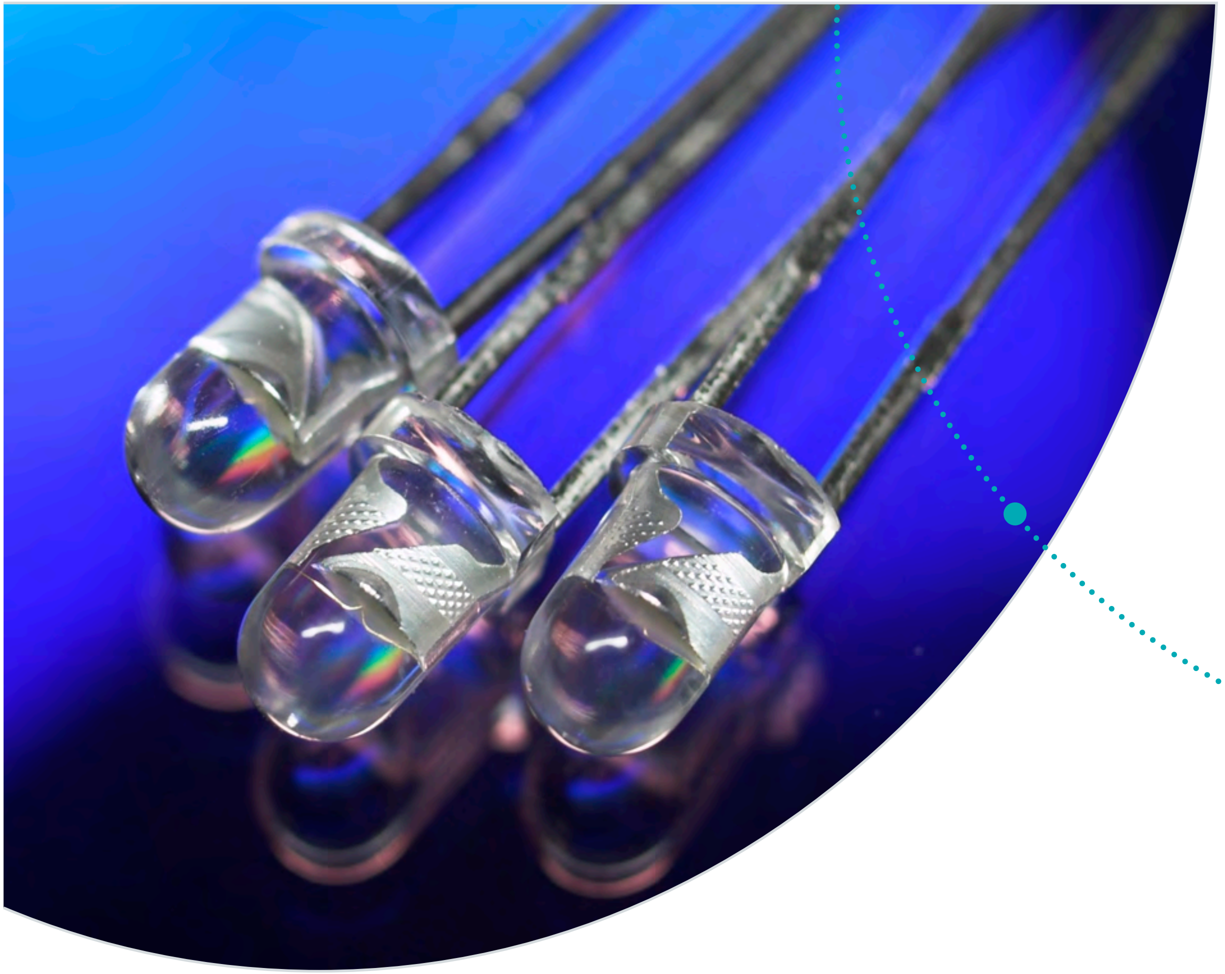

LED Curing of Light-Curable Materials: Unraveling the Myths and Realities

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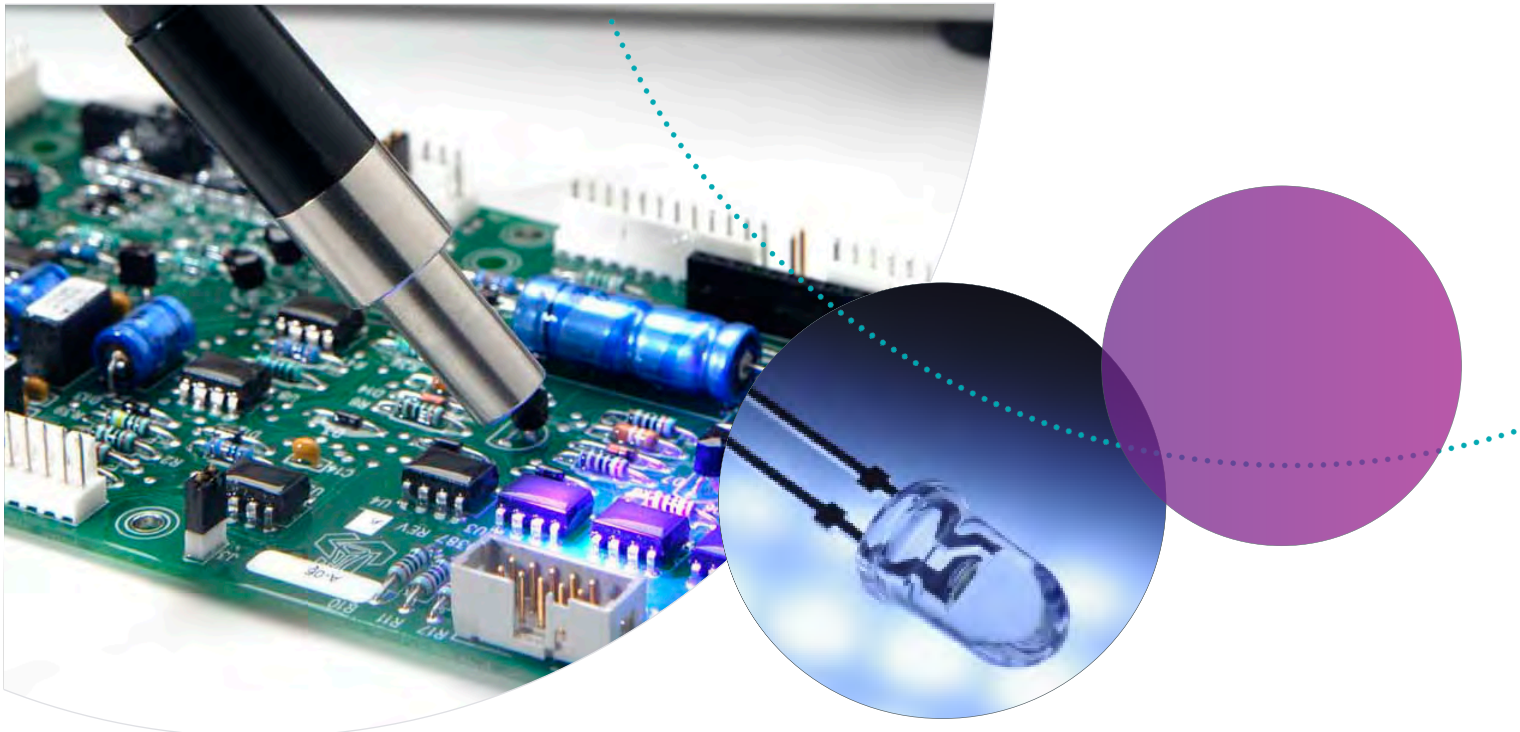


As a relative newcomer to the adhesive industry, LED curing lights continue to evolve with the goal of replacing mercury arc curing lamps, the industry standard for more than twenty-five years. The evolution of LED curing lights is driven by promises of lower operating costs and "green" attributes. Experts predict LED curing lights will evolve over time to dominate the light-curable adhesive field.

But similar to biological evolution, some technical adaptations succeed to become a permanent part of an industry, while other adaptations fail, leading to technological extinction. In the evolution of LED curing lights, performance failures in the marketplace have cost manufacturers time and money. Application failures have also spawned misinformation and apprehension in the industry.

To avoid failure in specifying new light-curable adhesive, coating, or pottings processes—given the rate of change in the technology—current, authoritative information is required for sound purchasing decisions. Select LED curing lights for which the natural selection process is moving in the right direction. You want to avoid purchasing equipment headed for extinction.

Since LED curing-light performance is inseparable from light-curable chemistry characteristics, complete solution providers (companies advancing the LED curing light AND formulation evolutionary paths) are strongly positioned to provide dependable information and robust products.

In this paper, we will attempt to bust the myths, demonstrate the realities, and provide the latest information about LED curing-light technology. In busting the myths, we will highlight the technical variables to consider when evaluating LED curing lights, and provide a informed basis for evaluating LED technology performance claims.

Scope of Discussion

Our discussion centers on spot-cure LED curing lights in the UV and visible ranges (Figure 1). Some of the myth-busting realities presented here may also apply to other types of LED curing systems that are under development.

Figure 1. LED Spot Curing System

Why Natural Selection Will Favor LED Curing Lights

Again, similar to biological natural selection, the beneficial traits of LED curing lights will make these curing lights more commonplace in the market. Some long-touted features and benefits of LED curing lights include:

- High electrical efficiency and instant on/off capability for lower operational costs
- Long service life eliminates bulb replacement and reduces maintenance costs
- Compactness that reduces the size and cost of light-curing systems
- "Cool" light radiation extends curing capabilities for thermal-sensitive substrates
- Green attributes eliminate mercury and ozone safety risks and handling costs
- Narrow wavelength-spectrum emission minimizes substrate thermal rise

These beneficial traits help make manufacturing more efficient. These offerings are also driving the divergence from metal-doped arc lamps to LED semiconductors as a light source for adhesive spot curing. Natural selection is at work in the adhesive industry.

Why Myths Exists In The Marketplace

Unsubstantiated claims on the aforementioned benefits are an underlying cause for misinformation in the marketplace. These claims include:

- Mercury arc lamp performance, long the industry standard, is improperly applied to LED technology. The two light sources differ substantially.
- LED curing-equipment manufacturers may ignore the light/adhesive interdependence. Curing light and adhesive performance are relational .
- LED technology, as it applies to light-based curing, is still in the early stages of commercial and volume applications. LED manufacturers continue to develop LED technology for curing applications. In the meantime, myths have developed due to an absence of historical performance data.

So let's look at some myths that have been adopted and bring the realities into focus. From there, if applicable, you can move successfully to LED curing technology and reap the benefits it offers.

Myths and Realities

Myth No. 1—LED light sources can seamlessly replace arc lamps in most curing processes.

Reality

The belief in this myth resulted in many application problems for manufacturers.

As a consequence, particularly in Europe and North America, sales of LED curing lights have slowed. Manufacturers want proof of compatibility.

The good news is that LED curing lights can work well while offering savings and efficiencies, but changing from arc lamp to LED curing lights may not be a simple, direct conversion. Many details must be considered, the most important of which are differences in the wavelength distribution of LED and arc-lamp light sources.

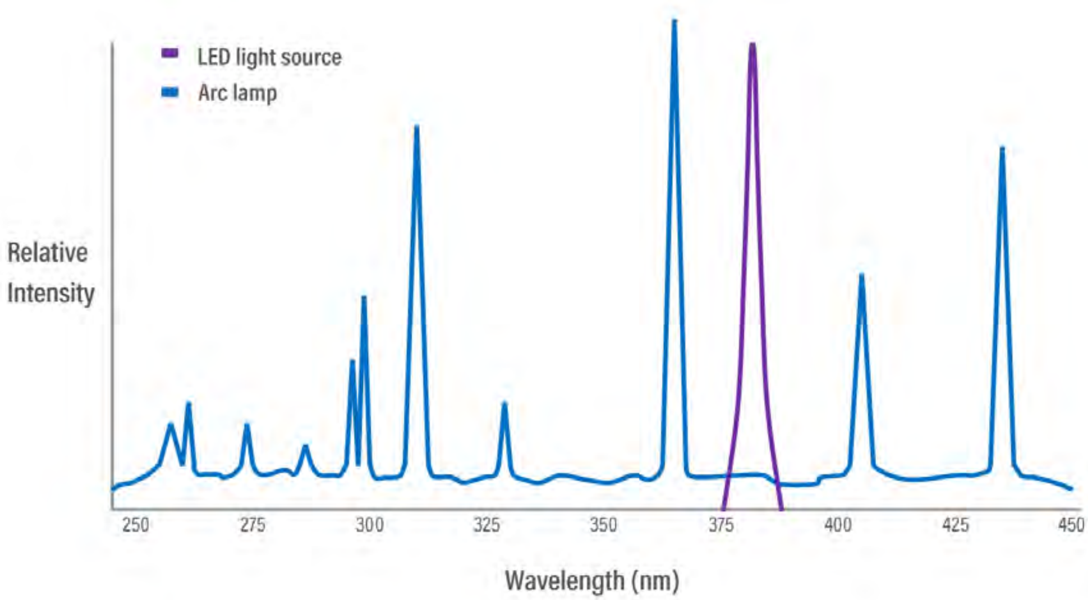
Disparate Wavelength Distributions

The wavelength distribution emitted by an arc lamp and an LED are quite different. The wavelength distribution from a LED light source is narrow and bell shaped and can peak in the UV or visible light range depending upon the selection of the LED. The wavelength distribution from an arc lamp has multiple energy peaks spread over a wide range of wavelengths (Figure 2). Arc-lamp-energy spectral distribution varies depending upon the design of the arc lamp and other components of the curing system. The disparity in the wavelength distribution curves illustrate that a light-curable chemistry optimized for an arc lamp may perform inadequately when cured with a LED light source. Replacing an arc lamp with an LED light source might be as simple as modifying curing parameters of an existing process, or more complex such as changing of the adhesive to one properly formulated for the spectral-distribution characteristics of the LED light source.

Table 1. Sample listing of various adhesive bond-performance results when cured with conventional arc lamp and LED light sources

Adhesive Type/ Description	Medical Grade	Fluorescing	UV/Visible Curable	Bond Performance Comparison			
				LED Source (385 nm)		Conventional Lamp Source (320 - 500 nm)	
				Typical Cure Time	Tensile at Break, MPa [psi]	Typical Cure Time	Tensile at Break, MPa [psi]
1161-M Needle Bonder	•	•	•	< 30s	13 [1900]	2s	13 [1900]
1162-M Low-Viscosity Needle Bonder	•	•	•	< 30s	6.1 [890]	<1s	8.3 [1200]
1187-M Plastic Bonder	•	•	•	< 30s	12 [1800]	<1s	12 [1800]
1201-M-SC See-Cure Plastic Bonder	•		•	< 30s	11 [1600]	9s	11.7 [1700]
3069-GEL Moisture-Resistant Plastic Bonder			•	< 30s	11 [1600]	1s	16 [2300]
3094 Glass, PC, Acrylic, and Metal Bonder			•	<30s	9 [1300]	<1s	11 [1600]
3030 LED-Curable Ultra-Fast Plastic Bonder			•	<2s	11 [1600]	<1 s	12 [1800]
3031 LED-Curable High-Adhesion Plastic Bonder			•	2s	10 [1500]	<1 s	11 [1600]
9001-E-V3.0 Potting Adhesive			•	< 30s	5 [730]	30s	7.6 [1100]

Figure 2. Wavelength distribution of an arc lamp and LED light source in the visible-light range



While a direct replacement of your arc lamp with an LED curing light is possible, an evaluation of many other processs parameters is essential. Furthermore, although a light- curable product that may be considered compatible with both arc lamps and LED light sources, switching to an LED light source can result in siginificant differences in post-cure bond performance (see cure-results comparisons listed in Table 1).

Myth No. 2—You can select LED spot-lamp systems and light-curable chemistries based on datasheet specifications and website information.

Reality

There are far too many variables involved in light-curable chemistry applications to use datasheet specifications and website information as the sole means for equipment and chemistry selection. Datasheet and website specifications, although useful, may lack application-specific information.

When LEDs are manufactured, each batch may yield LEDs with varying spectral output. An LED curing-light manufacturer may state in a datasheet that their LED curing lights deliver an energy peak at a specific frequency, but the question remains as to the real spectral accuracy of the LED engine. Lower-quality LED curing units may actually emit over a wider range (370 to 415 nm) of ineffective peak energies. This deviation from the required curing wavelength can result in under-cured bonds, coatings, or pottings.

Datasheet and web-based information may have other shortcomings. Some adhesive manufacturers may not state the irradiance and spectral distribution requirements for optimum curing and performance. Some curing-light and adhesive, coating, and potting product formulators do not include substrate compatibility information in technical information on their website. Key information is often missing for specifying curing systems with confidence.

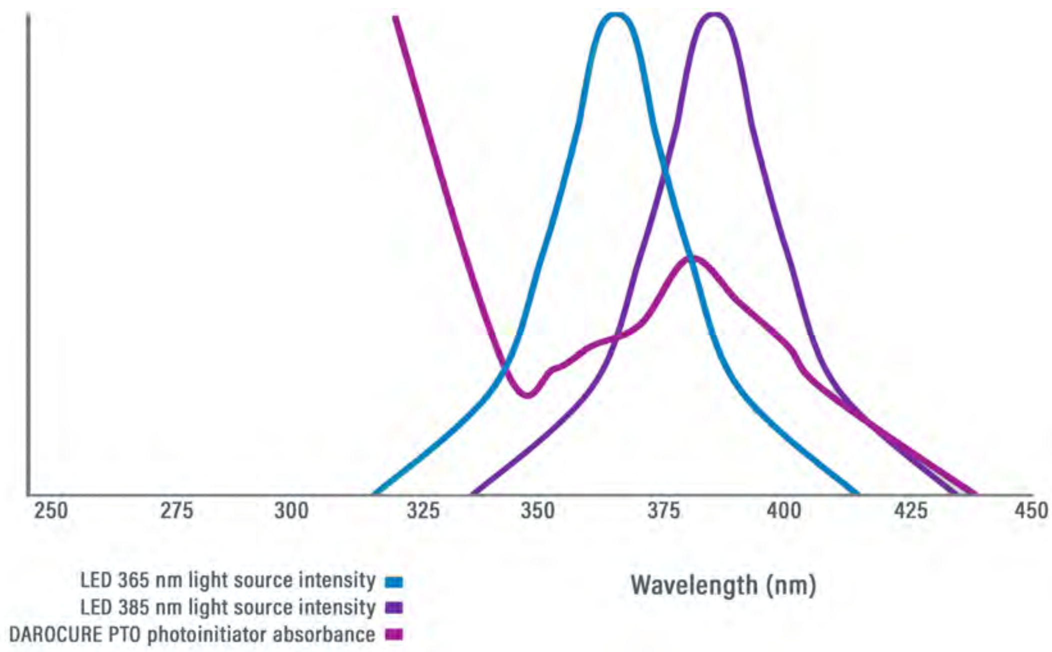
There is no shortcut to success as you consider adopting LED curing technology in a manufacturing process. Consider a total-solutions provider that can complete application studies using your substrates and process requirements. Application studies ensure the LED curing light and chemistry selection combination will work.

Myth No. 3—Bond performance is similar whether you are using an LED or a conventional lamp light source.

Reality

The direct replacement of an arc lamp spot-curing system with a LED spot-curing system—without evaluation and process adjustment—can result in substandard bond performance. Differences in LED wavelength distribution and intensity necessitates the evaluation (if not formulary modification) of the chemistry and curing-energy dosage. There are some adhesives that provide the flexibility to use both types of light sources without changes to your process. Verification is strongly recommended to ensure successful results. Table 1 (on page 6) depicts various light-curable adhesives that cure with either LED or conventional light sources, but also illustrates that the cure times and post-cure properties of the chemistry may differ.

Figure 3. Photoinitiator absorption compared to 365 nm and 385 nm LED curing - light spectral distributions



Myth No. 4—UV LED light sources best cure formulations when the wavelength peak is at 365 nm.

Reality

Traditional mercury arc lamps indeed emit a high level of energy at the wavelength peak of 365 nm. However, this does not mean that an LED light source with a 365 nm peak will provide the best performance. The reality is that many light-curable chemistries, including acrylated adhesives, use photo initiators that respond best to the narrow, bell-shaped spectral curve.

Myth No. 5—Manufacturers' LED power ratings are comparable and correspond to performance.

Reality

A thorough review is required to properly interpret the claimed power ratings and associated advantages of LED curing systems. LED curing-equipment manufacturers may use LED power ratings as a sales tool, claiming that a higher power rating equates to better performance. Qualifying direct comparisons of power can be achieved by focusing on the following areas:

Power Expressed as Intensity

Intensity is the measure of electromagnetic radiation of all frequencies at the surface of an object. In reference to light-curable chemistry, the electromagnetic radiation is that in the visible or UV range of frequencies or wavelengths. Standard units of measure of intensity are milliwatts per square centimeter (mW/cm^2).

Compare Intensity at the Surface of the Substrate

This measurement represents delivered power at the bond line.

Determining the intensity at the substrate surface removes process variables and misinformation such as claimed power, transmission losses, and lens variables such as divergence angle. Intensity is measured with a radiometer.

When measuring intensity with a radiometer, keep in mind that considerable variation can exist in the measurements depending upon the brand of radiometer. When comparing irradiance among prospective light-curing systems, use a radiometer that is specifically designed to measure intensity levels at the frequency(ies) emitted from the curing-light source, or, at the very least, use the same radiometer for all comparative measurements. Incorporation of a radiometer that is specifically designed and optimized to address the LED source frequencies will ensure accurate readings.

Claimed Power Versus Useable Intensity

The claimed power of LED curing lights is almost always quoted as power emitted from the lightguide. However, two factors influence how much radiation or light actually reaches the substrate surface: (1) the divergence angle of the energy emitted from the light source and (2) the inverse-square law in radiography.

Divergence Angle Decreases or Increases Power

The emitting end of the lightguide is the final optical component in the light-delivery path. The divergence angle determines the degree to which the energy spreads out after it leaves the light source. As the light diverges, the power per unit area (expressed as mW/cm^2) on the substrate surface is diminished.

Inverse-Square Law

The inverse-square law describes the transmission losses that occur due to the distance between the emitting end of the lightguide and the substrate. Less power is transmitted to the substrate surface as the emitting end moves further from the substrate. As you double the distance between the emitting end of the lightguide and your substrate, the light intensity or energy impinging on the substrate decreases by a factor of one quarter. This principle illustrates why the most valuable information is determining the intensity level at the bond-line point of cure.

Comparing Manufacturers' Power Ratings Requires Comparing Spectral Distribution

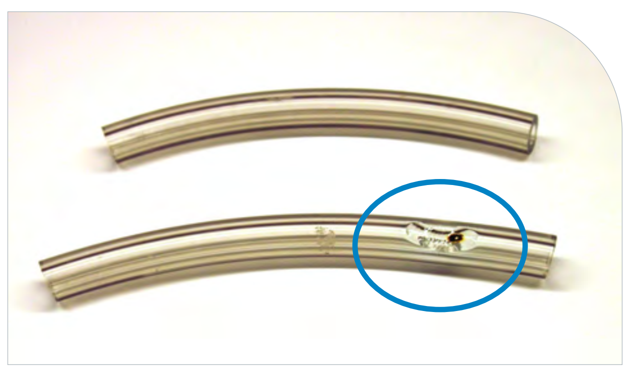
Delivered power or intensity provides only a partial comparison of LED light-curing systems. Spectral distribution of the prospective light sources must also be evaluated. Furthermore, the spectral output and intensity must be aligned with those required by the adhesive formulation. It is spectral-distribution information combined with irradiance measurements that enables a relative comparison among light-curing systems.

Myth No. 6—The energy supplied by LEDs enables you to cure heat-sensitive substrates without fear of product damage or substandard bonding.

Reality

LED sources do not generate or emit the multiple frequency irradiances across the spectrum as found in a conventional lamp. LED sources operate in a narrow spectral range that is specific for adhesive curing, resulting in "cooler" curing charicteristics. However, when energy from an LED source reaches a substrate or chemistry being exposed, it has two options. Depending on absorbtion characteristics of the irradiated materials (substrates and chemistry), the energy may be absorbed or reflected. Energy that is absorbed will genreally cause some level of thermal rise of the materials being exposed. Even under the "cool" energy supplied by an LED light source, the substrate and the chemistry can experience a thermal rise that may alter their structure and influence bond performance (Figure 4).

Figure 4. Close-up photo of a part damaged by the heat generated during curing



The above image compares parts exposed to conventional (bottom) and LED (top) light-curing energy sources. Exposure parameters:

Intensity: 8,000 mW/cm^2
Distance: 10 mm
Exposure time: 20 seconds

Light-Curable Chemistries Can Also Produce Heat

Some formulations are exothermic and release heat during the curing process. This heat of reaction can add to the heat generated by radiation adsorption.

How to Avoid Bonding Problems Due to Heat

Consider the impact of heat in developing the bonding process for an assembly application. Applications impacted by heat generation include those involving small parts, thermally- sensitive materials, energy-absorbing materials, and adhesives, coatings, or potting materials that exhibit exothermic curing. If your substrate absorbs any frequency of energy, you may choose to use an led light source. If your application has flexibility in terms of the materials of construction, select materials which are thermally stable.

Myth No. 7—Wand-mounted LED light sources are better than using lightguides to transmit light energy from cabinet-mounted LED light sources.

Reality

Arc-lamp curing lights and some advanced LED curing lights mount the light source in the control cabinet for precision cooling. Cabinet-mounted LED light sources use standard lightguides for transmission of light. Alternatively, some cure-unit manufacturers mount the LED light source at the end of an electrical control cable.

Mounting the light source in the control cabinet offers provisions for efficient energy generation and heat dissipation. LED power output decreases with increases in temperature. LED operating temperature variation can also lead to frequency shifts in the emitted energy. The precision cooling offered by cabinet-mounted LED designs results in more consistent power output with less regulation. Furthermore, transitioning from arc lamp to cabinet-mounted LED light sources may obviate the need to replace existing lightguides or application fixturing.

Wand-mounted LEDs do have drawbacks.

- Wand-mounted LED housings heat up, making some uncomfortable to hold during production hand curing. For example, the tip of a standard liquid-filled lightguide may reach 31°C after five minutes of continuous operation. The housing of a wand-mounted LED can reach 58.1°C, which is not only uncomfortable to hold, but leads to considerable losses in light intensity that removes repeatability from your curing process (Table 2). This thermal rise can also cause a shift from optimum frequency emitted by the unit.
- Wand-mounted LEDs are susceptible to physical damage such as droppage or crushing that requires premature replacement.
- The tips of wand-mounted LED housings are larger than standard lightguides, making them more cumbersome to hold, manipulate, or integrate into fixturing, particularly if they use water- or fan-cooling systems.
- The design of wand-mounted LEDs may limit access to their emitting end, making maintainence more challenging if cleaning of accumulated adhesives and outgassing residue is required.

Conversely, cabinet-mounted light sources using standard lightguides offer: (1) cool operation and small size for comfortable and precise hand operations, (2) durability and interchangeability that reduces conversion and operating costs, (3) easy cleaning that lowers replacement and maintenance costs, and (4) consistent and dependable regulation of temperature to deliver uniform light intensity during use.

Table 2. Housing temperature and light-intensity measurements for a commercially available, wand-mounted LED light source

Wand-mounted LED Curing Light-Source Performance			
Time (min)	Housing Temperature (°C)	Light Intensity (mW/cm^2)	Light Intensity (%)
0	22.9	444	100
1	33.0	407	91.7
2	41.7	365	82.2
3	48.6	325	73.2
4	54.3	298	67.1
5	58.1	281	63.3

Conclusions

LED curing technology offers significant cost savings and efficiencies in adhesive, potting, coatings, and printing spot-cure applications. Many experts predict LED curing technology will evolve to become the industry standard, replacing arc-lamp curing systems. Manufacturing managers, process engineers, and technologists should consider LED curing equipment as a process upgrade or during new development projects where feasible and qualified.

As LED curing technology is still evolving, choosing the right equipment can be challenging due to myths and misinformation which exists in the marketplace. LED curing-light technology performance differs considerably from arc-lamp technology performance. The transition from arc lamp to LED light sources requires consideration of the many factors reviewed in this article. Selection of equipment and LED-curable chemistries should derive from real-world application studies. Total-solution providers who understand all aspects of the substrate properties, curing technology, light-curable materials, and dispensing components can enable quality decisions on LED equipment and LED-curable formulations that will ensure the full benefits of LED light-curing technology are realized.

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