Technical Note

Pulsed Sterilization of Substrates in the Food and Beverage Industry

David Collins
Senior Director, Product Management
Excelitas®

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Introduction

This technical note focuses on pulsed light disinfection systems for food and beverage processing. It provides context within the broader landscape of UV-based technologies and explains the multi-mechanism microbial inactivation unique to xenon flashlamp systems.

It also outlines key engineering considerations for implementing pulsed light systems and optimization for production environments.

Pulsed UV Sources for Disinfection

For over three decades, pulsed xenon flashlamps have been used as an effective method for disinfecting surfaces, packaging materials, and food products. These systems operate by storing electrical energy in high-capacitance circuits and then discharging it in extremely short pulses that typically last only a few microseconds. The rapid release of energy produces intense broadband light that spans from the deep UV region through the visible spectrum. A significant portion of this output lies within the 200 – 400 nm UVC range, which is known for its strong germicidal activity.

Example of a pulsed xenon flashlamp.

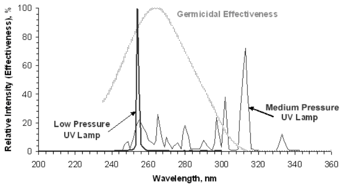
Although the UVC component typically represents only 10-20% of the total emitted energy, pulsed xenon systems achieve overall radiative efficiencies that often exceed 60%. This means that a large fraction of the stored electrical energy is converted into useful optical radiation.

Continuous UV Light Sources

Low-pressure mercury lamps
Strong, nearly monochromatic output at 254 nm, which is close to the peak germicidal wavelength. These lamps have been widely used in water treatment facilities, hospitals, and laboratories.

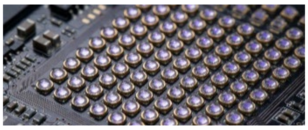
UV mercury amalgam lamps in a water treatment application.

Medium-pressure mercury lamps
Operate at higher power with a broader UV spectrum, enabling faster treatment of larger volumes, but with lower efficiency and more heat, so they are often used in industrial applications.



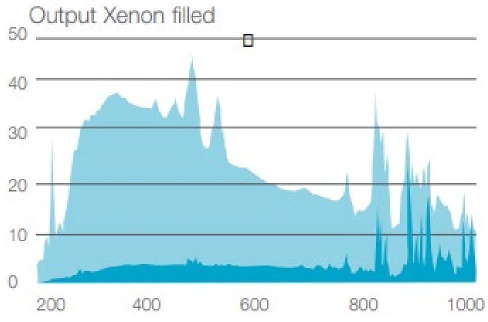
Germicidal effectiveness by UV lamp type.

UVC LEDs
UVC LEDs are improving in efficiency, cost, and reliability but remain limited for many applications. Their compact, durable design suits point-of-use systems, but lower germicidal effectiveness and output restrict use in high-power or large-area industrial processes.



LED Array

The combination of high instantaneous power and broad-spectrum emission allows these systems to deliver very high fluence levels at the surface of treated materials. As a result, they are capable of rapid microbial inactivation, often within seconds, which makes them highly suitable for applications that require fast throughput or minimal thermal impact on the product.



Lamp current verses UV output at different wavelengths.

The pulsed nature of the light also produces extremely high peak irradiances that are difficult to achieve with continuous UV sources. These short, intense bursts can disrupt microbial DNA and cellular structures more effectively than lower-intensity continuous exposure, particularly for pathogens that exhibit some UV resistance. For this reason, pulsed xenon technology has become a valuable tool in food processing, pharmaceutical packaging, and cleanroom environments where rapid, nonthermal disinfection is essential.

Mechanisms of Microbial Inactivation

Flashlamp systems are unique in their mode of disinfection by combining multiple inactivation mechanisms within a single, high-intensity pulse.

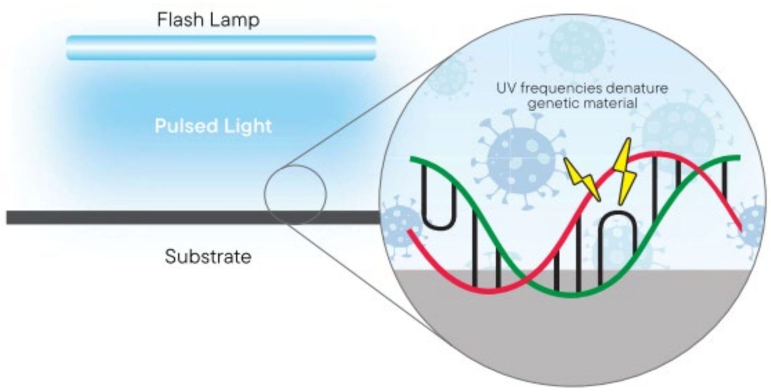
UV-Induced DNA Damage

Broadband UV energy, particularly in the UVC range, damages microbial DNA by forming cyclobutane dimers and 6-4 pyrimidine adducts, primarily between thymine and cytosine bases. Once the level of DNA damage exceeds repair capability, critical cellular processes break down, leaving the organism non-viable and unable to replicate.

Visible and Infrared Contributions

Studies using UV-blocked flashlamps still show measurable microbial reductions, indicating that visible and infrared wavelengths also play a role in pathogen inactivation.

Infrared radiation primarily contributes through localized heating. Rapid energy absorption can cause structural disruption, including protein denaturation and membrane damage. In high-intensity pulsed systems, these thermal effects can act alongside UV damage, supporting overall inactivation.

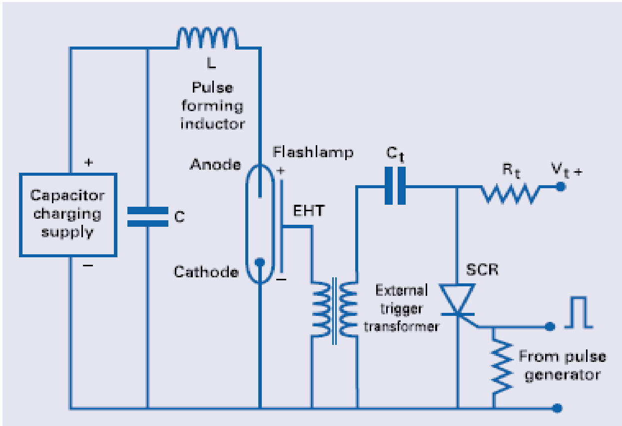


Twin-lamp UV system simulation for bottle cap disinfection.

System Operation and Engineering Considerations

Optimized pulsed light disinfection performance is strongly influenced by several engineering factors including flashlamp geometry, electrical circuit configuration, repetition rate, and thermal management. The geometry of the flashlamp determines how efficiently light is delivered to the target surface. Factors such as lamp length, diameter, reflector design, and placement relative to the substrates control the intensity distribution and the fraction of emitted UVC that reaches the surface. For conveyor-based systems, achieving uniform illumination across the full width of the moving belt is essential. Non-uniform distribution can lead to microbial survival in low-fluence regions even when the average dose appears sufficient.

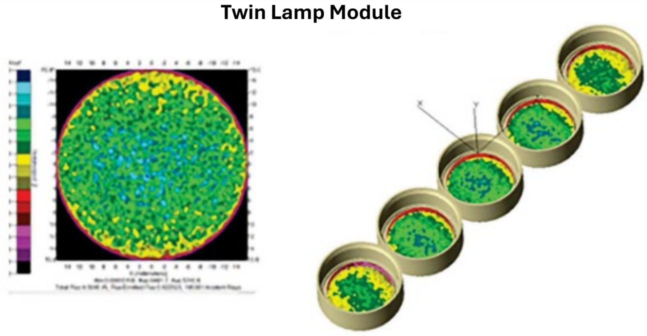
Electrical circuit design plays an equally important role. Circuits that are well designed ensure smooth repeatable pulses as the discharge is critically damped over the dynamic range of input voltages. This ensures that each flash delivers predictable spectral output and energy, which supports consistent dose delivery across millions of cycles. Underdamped circuits can introduce variation in peak currents, which can alter the spectral balance or intensity of the flash and reduce overall process reliability.



Xenon flashlamp triggering circuit.

Repetition rate is another key parameter since pulsed light disinfection relies on both the intensity of individual flashes and the cumulative dose delivered over time. The repetition frequency must be high enough to ensure that all substrates moving through the system receive the required dosage, especially at higher conveyor speeds. If the rate is too low, gaps between pulses can lead to insufficient dose on portions of the production line. System designers therefore balance repetition rate with energy per pulse, lamp lifetime, and thermal load.

Twin Lamp Module



Bottle cap disinfection simulation using twin-lamp system.

Cooling is important as pulsed xenon lamps generate significant heat during high-power discharges. Adequate thermal management maintains lamp stability, prolongs component life, and prevents spectral shift at elevated temperatures. Together, these factors determine the overall efficiency, uniformity, and reliability of the pulsed light disinfection process.

Disinfection Performance

Across substrates and microbial species, broadband twin lamp pulsed light systems consistently achieve 4 Log reductions or better in controlled laboratory settings.

BLUELIGHT® FLASH SMALL AREA MICROBIOLOGICAL TESTS - REAL WORLD SAMPLES

Packaging Sample / Material		Reference Germ	Inoculation Method	Distance Sample to Lamp (mm)	Avg. Log Reduction 1 Flash	Avg. Log Reduction 2 Flash
Plastic Bottle Screw Cap		Aspergillus brasiliensis ATCC 1604	Multi Dot	20	2.02	4.21
Stainless Steel disks (Ø20 mm)		Bacillus pumilus ATCC 27142	Nebulised	30	3.90	4.80
Aluminum Tin (Volume 820 ml)		Cronobacter sakazakii DSM 4485	Sprayed	20	4.50	4.80
Aluminum Lid (Ø108 mm)		Cronobacter sakazakii DSM 4485	Sprayed	20	5.00	5.20

BLUELIGHT® FLASH SMALL AREA MICROBIOLOGICAL TESTS - REFERENCE SAMPLES

Test Material	Reference Germ	Inoculation Method	Distance Sample to Lamp (mm)	Voltage Setting	Avg. Log Reduction 1 Flash	Avg. Log Reduction 2 Flash
Glass Slide *76 mm x 25 mm*	Aspergillus brasiliensis DSM 1988	Sprayed	20	Low	3.50	5.00
				High	5.90	>6.0
	Penicillium rubens DSM 848	Sprayed	20	Low	2.60	4.50
				High	4.50	5.20
Steel Foil *50 mm²*	Aspergillus brasiliensis DSM 1988	Sprayed	20	Low	4.10	4.40
				High	4.90	5.40
	Penicillium rubens DSM 848	Sprayed	20	Low	3.60	4.30
				High	4.70	4.60

Additional Considerations

The following should be considered when implementing pulsed broadband radiation for disinfection into a production line.

Line of Site Disinfection

Radiation requires a clear line of sight to the substrate, some products may need to be re-oriented or exposed from multiple angles to ensure full coverage. To maintain effectiveness, any dirt, foreign objects, or surface films that block the light path should be removed before treatment.

Water Cooling

To achieve fast throughputs or increase the dosage delivered per unit substrate, the input power to a flashlamp system can be significantly increased using water cooling. The required water-cooling loop can also be designed to remain entirely internal, simplifying integration and maintaining a compact system footprint.

Substrate Temperatures

Most targets have enough thermal mass to prevent the surface temperature of the substrate from rising more than about 10°C instantaneously, and in most cases this temperature change is difficult to detect because the absorbed energy quickly and harmlessly disperses into the bulk of the material.

Environmentally Friendly

The pulsed broadband flashlamp contains no mercury or other hazardous material. Because the disinfection process produces no harmful residue, there is no need to rinse samples post-treatment, which can significantly reduce water usage in a sterilization workflow.

Representative system setup with a flashlamp head mounted above a conveyer belt.

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