COMPARISON between Continuous and Pulsed UV Sources:

Ultraviolet (UV) belongs to the electromagnetic waves with wavelengths below the darkest visible violet region (<400 nm, >3 eV), but longer than that of soft X-rays which start at <10 nm, >120 eV and is divided into 5 sub-regions:

- 100 -- 170 nm (120-8 eV): vacuum UV, a fused quartz border (170 nm)
- 170 - 200 nm (8-5.8 eV): deep UVC, or ozone generating UV;
- 200 - 280 nm (5.8–4.4 eV): UVC, or germicidal region,
- 280 - 310 nm (4.4-3.9 eV): UVB, limited sterile actions, bio effects,
- 310 - 400 nm (3.9-3.1 eV): UVA, bio-effects, medical applications, UV curing, a small part of the solar UV at the sea level.

1 eV = 1.6 x 10⁻⁹ Joule

Conventional gas discharge mercury vapor lamps:

Introduced and widely used since 1920’s

The major UV emission has only one of a few fixed UV spectral lines.

Medium or high pressure lamps have to be air cooled: its surface T°C is 200-600°C.

<table>
<thead>
<tr>
<th>Type of Mercury lamp</th>
<th>Lamp load in w/cm</th>
<th>UVC output in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pressure (the major usage, 254 nm):</td>
<td>1 - 5</td>
<td>15-35</td>
</tr>
<tr>
<td>254 nm):</td>
<td>10-50</td>
<td>8- 12</td>
</tr>
<tr>
<td>Middle pressure:</td>
<td>50 10</td>
<td>5 - 8</td>
</tr>
<tr>
<td>High pressure:</td>
<td>10-50</td>
<td>5 - 8</td>
</tr>
<tr>
<td>Excimer UV (non-mercury) lamps</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Spectra depends on both the vapor pressure and energy load w/cm:
Operation of Mercury vapor lamps:

Power controls for CWUV Sources includes DC or CW Power Supply and a ballast, or an electronic ballast which is also a power supply plus a switch for both cases:

Advantages of CWUV lamps:
- Simple, low cost,
- the 254 nm line output is 20 to 35% for the best performing (low pressure) lamps,
- hardware/operational costs are satisfactory for many applications.
- lamps life-time up to one year non-stop operation for low pressure lamps, and up to 3 months for medium pressure lamps.

Limitations of CWUV lamps:
- Low 4% - 8 few % UV output for all except HPLP lamps,
- Mercury is a hazard if a lamp is broken plus to pay the disposal cost (ca. 1.5€/L)
- UV power is insufficient for sterilization on conveyor lines, but only for sanitation to 4 logs,
- Warm-up time and dependence on ambient temperature,
- Fixed UV line spectra which do not allow to sterilize through many packaging materials,
- Inability to fully inactivate UV resistant micro-organisms.

Flash lamps were introduced and widely used since 1930’s

The main feature:
A pulsed discharge with a broad spectral output, which shape solely depends on a lamp circuit and a gas type and pressure.

Two major types of UV emissions:
1- Bremsschtrahlung- the UV continuum by electrons decelerated in electrical fields of ions; a position of its maximum spectral output can be adjusted by PFN (see below), and
2) recombination (wide) lines by electrons, converting ions to neutral atoms or molecules, these line positions are fixed.

Above Right: Flash lamp emission spectra at: 1) 7 kA/cm²; 2) 1.5 kA/cm²
Flashlamps have to be air or water cooled.

UV flashlamp electrical loads vary from 10 to 50 Joules / pulse / 1 cm of a flash lamp length, resulting in intense PUV emission with UVC+UVB from 15% to 35%, whereas 75% to 85% of the lamp output is a white (sun-like) light.

**Operation:**

Generation of a pulsed discharge (plasma) by a high compression of the electrical energy with a Pulse Forming Network (PFN) in two basic cycles:

A. Capacitor is charged through $S_1=\text{On}, S_2=\text{Off},$
B. Release of a stored energy in to a flash lamp, $S_2=\text{On}, S_1=\text{Off}.$

PFN provides pulses of electrical current from a few 100`s Amp to a few kAmp with a duration from sec (10\(^{-6}\)) to msec (10\(^{-3}\)) sec. Respectively the plasma temperature during the peak of the current pulse can be from about 6000 °K to about 20,000°K.

**Advantages PUV:**

- **High - up to 30% - UV output ,**
- **Adjustable UV output** - by a pulse forming network,
- **Highest UV intensities - in kw/cm\(^2\)** during a pulse, providing for
- **up to 6 logs (99,9999%) sterilization,** not possible with conventional Mercury vapor or excimer lamps,
- **No warm ups:** an instant action adjustable to a product flow,
- **well fit to high speed production conveyers,**
- **No Mercury!** Environmentaly friendly!
- **Low operating costs.**

**Limitations PUV:**

- Its live depends on its operating parameters - the lower those from the "one pulse limit", the longer it lasts, usually from 1 ww at 1 Hz to 12-16 ww which is about an average life of medium and high pressure CWUV lamps.
- A sophisticated and costly design of a lamp and its circuit to reach both a long lamp life and its high UV output.
- Prices are a few times and for it´s driving circuits are 10 to 100 times as much as those for CWUV Mercury lamps.

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**Sterilization with UV Flash Lamps**

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**1. Conventional CWUV sterilization.**

The conventional UV sterilization with CWUV mercury lamps (254 nm) is known as Germicidal Inactivation (UVGI):

254 nm (4.9 eV) photons at a sufficient UV Dose J/cm\(^2\) disrupt DNA chains making micro-organisms inactive. It is possible because this UV line is near the maximum of the DNA absorption and because it energy exceeds the electron binding energy in DNA:
However, DNA has a programmed ability to repair this damage with time, known as a recovery time. The recovery can be minimized both by the UV dose (in mJ/cm²) and by the UV intensity (mw/cm²). Below are data for 1 log (90%) sterilization doses (254 nm line, a CWUV Mercury lamp) for selected micro-organisms:

<table>
<thead>
<tr>
<th>Micro-organism</th>
<th>Bacteria</th>
<th>Viruses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mJ/cm²</td>
<td>mJ/cm²</td>
</tr>
<tr>
<td>Escherichia Coli</td>
<td>2 – 6</td>
<td>Phage</td>
</tr>
<tr>
<td>Salmonella</td>
<td>5 – 40</td>
<td>Hepatitis</td>
</tr>
<tr>
<td>Spores</td>
<td>20 - 36</td>
<td>Cryptosporidium</td>
</tr>
<tr>
<td>Bacillus Subtilis</td>
<td>20 – 80</td>
<td>Yeasts</td>
</tr>
<tr>
<td>Aspergillus Niger</td>
<td></td>
<td>2 – 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 – 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 – 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 - 500</td>
</tr>
</tbody>
</table>

2. Pulsed UV sterilization.

The effective temperature of a pulsed discharge in a flash lamp reaches 10,000°K to 20,000 °K! It´s maximum spectral output is in the UVC-UVB region with a visible light output similar to that of the Sun.

*pulsed UV and sun-light spectra:

The Solar UV has significantly less UV because the effective visible temperature of the Sun is also far less: 5780°K.

Sterilization actions by intense Pulsed UV Light: UVC fluxes of 1 to 3 kw/cm² at a product level far exceed those of CWUV mercury or excimer lamps and cause a massive germicidal damage, where the DNA recovery programm is no longer effective:

See details in "Our Publications: Alex Wekhof, PDA J. of Pharmaceutical Sci. & Techn. May 2000:

In UV transparent media at high photon fluxes in kw/cm² range micro-organisms are destroyed through an instant overheating:

Three Regions of Pulsed UV Sterilization:

- **PUVGI**: the same germicidal incitation (GI) as with mercury lamps.
- **PUV**: accelerated germicidal inactivation not possible with UV mercury lamps.
- **PUVD:** disintegration, possible only with intense pulsed UV from flash lamps, first described by Dr.-Wekhof in PDA (200) and then experimentally proved by a joint work with Fraunhofer (Aachen Freizing), published at Report to the 1-st IUVA Congress, 2001, USA. See INFO for downloading.

**Practical Note:** Pulsed UV sources have no advantage in the PUVG region when

- the full pulse energy is too small (e.g. 10 Joules for a 10 cm lamp)
- a pulse duration is too long (e.g. a few msec)
- samples are too far from a flash lamp (geometrical - optical losses)

*In this case the PUV action is identical to work of a simple CWUV Mercury lamp!* See our section "comparison of UV sources" for further info.

**Working with clear plastic foils as wraps (PP, PE, etc):**

on the left is a relative UV absorption by 0.5 – 1.5 mm thick materials such as (left to right:

- Clear Teflon, UV glass,
- Topas, Nylon, LDPP and PE,
- Pyrex,
- PET, standard glass,
- Plexiglass, Makrolon.
Resume: sterilization is possible with the Pulsed UV light, and it is not possible with the 254 nm line!

Moreover, it is possible to have a broad filtered UV or UVB + UVA light, where the visible and IR light are filtered out. This is very useful for many applications, where extra heating and bleaching have to be suppressed.

Examples of the Filtered “Cold” full UV (200-400 nm) and UVB + UVA (310-400 nm) light:

Unique benefits of Pulsed UV Sterilization:

- One to 3 pulses can fully (6 logs!) sterilize a product;
- Flexible adaptation to fast computerized conveyer lines;
- Sterilization through UVC / UVB transparent packaging;
- Effective both for UV- and thermal resistant micro-organisms;
- No warm-ups, an instant UV sterilization action,
- No heat or structural DAMAGES to a product;
- Low operating costs per a sterilized item;
- No Mercury - it is safe and environmentally friendly,
- FDA approved and requires no labeling unlike e-beams or cobalt gamma sources).

Wek-tec (SteriBeam) Systems also offers its expertise in the installation of any necessary diagnostic instrumentation and consultation relating to the evaluation of test studies.

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