

## Disinfection with Flash Lamps

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**ABSTRACT:** The analysis of published and new data on a pulsed disinfection is presented. It allows the conclusion that the pulsed disinfection mechanism includes both germicidal action of UVC light and a rupture of bacteria due to thermal stress, caused primarily by all UV components of the light pulse. The role of simultaneous cooling and heating of bacteria during a flash lamp pulse has been estimated and a direct detection of such a mechanism is proposed. It is suggested that an optimum pulsed light source for disinfection must have as much percentile content of a broad UV spectrum and a high peak power as is technically justified. Two new applications for pharmaceuticals and medicine are suggested.

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### Introduction

Basics on flash lamps and their major applications for the past seven decades are found on the website of the International Pulsed Power Association e.V. (1). The flash lamp industry became mature with many choices of flash lamps and associated hardware systems in the 1960s and '70s. The first work on disinfection with a flash lamp was started in late 1970s in Japan and was patented in 1984 (2). Disinfection data suggests that both the pulsed UVC line radiation and perhaps visible radiation are responsible for the disinfection effect. It is not clear (2) if one should rely on the UVC line radiation or on light pulses containing mostly visible spectra. One could not do both due to restrictions in generating flash lamp radiation (1). This work was noticed by Maxwell Laboratories, Inc. of San Diego, Ca., which, in 1986–1987, in cooperation with the California startup company Alwek Corp., investigated applications of the high-power plasma-dynamic UVC source, built by the author of this presentation. A similar improved system was recently proposed in Germany (3).

The Alwek-Maxwell tests included an inactivation of various biological agents. These data are introduced below for the first time, along with respective UVC and full deposited energies, Table 1. At about the same time, Maxwell bought the Hiromoto patent and started Purepulse Inc. in 1988, having Tetra Pak as a major investor and R&D partner. During the past decade, Purepulse Inc. has lead this approach with many patents and publications (4, 5, 6). Alwek became UVERG, Inc. in 1988 and worked on flash lamp systems for decontamination and disinfection of water, air, and surfaces with respective patents and publications (7-9). Some results on disinfection with a flash lamp were obtained during 1993-96 in Russia (10, 11). All published results showed a high-efficiency both for disinfection and decontamination, nonetheless, flash lamp systems have not spread into environmental or packaging industries due to their high costs. Some costs have now decreased and have been reviewed along with differences between Purepulse Inc. and Wek-Tec systems, patents and publications (12). On the basis of published and new data, the following analysis specifies the inactivation mechanism during a flash lamp disinfection, outlines characteristics for the optimum pulsed light source for disinfection and offers two new applications.

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**Table 1: Summary of published and new data for the disinfection with one pulse of a high loaded pulsed light source.**

Bacteria	Reduction in logs per 1 pulse	Test conditions	Used system, place, date, reference	UVC/ UV in % of all emitted flux E(f) in J/cm <sup>2</sup>
<i>E. coli</i>	2	in a UV water reactor, 1 liter	UVERG, Ca., 1989 - 90, (7)	E(f) = 0.2 J/cm <sup>2</sup> 15%; 40%
<i>E. coli</i>	12	a surface sample	Alwek UV-Blaster at Maxwells, Ca., 1986 - 87, first pres.	E(f) = 10 J/cm <sup>2</sup> ca. 40%; 70% (pulse 30 μsec.)
<i>Bacillus subtilis</i>	9	same as above.	same as above	same as above
<i>Staphylococcus</i> spp.	12	same as above	same as above	same as above
<i>Aspergillus Niger spores</i>	12	same as above	same as above	same as above
<i>Aspergillus Niger spores</i>	1	a surface sample	PureBright, Ca., 1999 (6)	0.12 J/cm <sup>2</sup> (13%; 40%.-est.)
<i>Bacillus subtilis spores</i>	1	a surface sample	PureBright, Ca., 1999 (6)	0.28 J/cm <sup>2</sup> (13%; 40%.-est.)
<i>Water-borne Criptosporidium parvum</i>	4.6	UV reactor, drinking water	one flash lamp, PureBright, Ca., 1999 (6)	E(9 = 0.25 J/cm <sup>2</sup> (Cum., a few Hz) (13%;40%.-est.)
Poliovirus Type 1	6.2	same as above	same as above	same as above
<i>E. coli</i>	3 (estimate)	UV reactor, industrial water	one flash lamp, Russia, 1995(10, 11)	E(f) = 0.3 J/cm <sup>2</sup> (7%; 25%.-est.)

### Spectral efficiency of a flash lamp

The matching of lamp emission spectra with an absorption spectra of a target is a regular procedure established to find or to optimize a photolytic mechanism of an interest (14). Such a procedure was also used to find absorption properties of various bacteria, nucleic acids, proteins, etc., (15). These data were obtained in the 1970s using low intensity mercury and deuterium lamps and will be used further for our analysis. There are no similar data for a flash lamp spectrum. Therefore, an analysis of a flash lamp spectrum is very important for using these data and for understanding the inactivation mechanism during the flash lamp disinfection. It is known that a flash lamp is usually associated with a dense

polychromatic spectrum somewhat similar to the sun spectrum. Let us closely examine both these spectra.

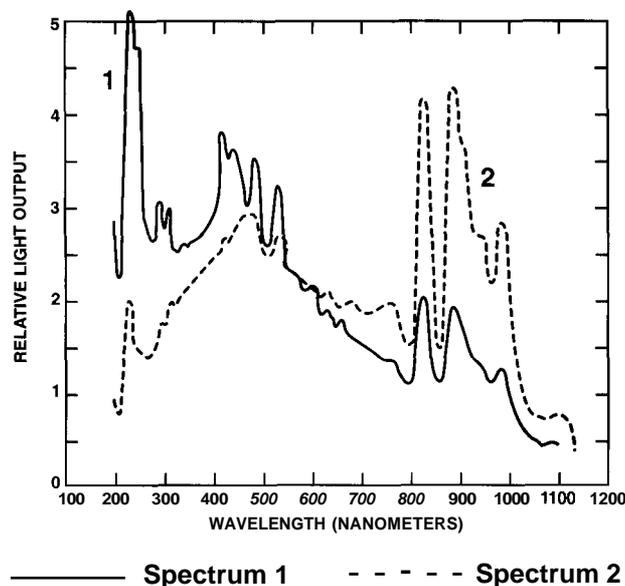
Two sample spectra of a xenon flash lamp are presented in Figure 1 (13). Both spectra are taken with a standard (a few nm) resolution, as is typical in flash lamp catalogues (13) or in relevant books (14). Note that both spectra have strong lines and a continuum. Differences between the two spectra are in the spectral density of radiated continuum and in the generated spectral lines. Spectrum 1 is for a high current density (6 to 14 kA/cm<sup>2</sup>, here it is for 6.5 kA/cm<sup>2</sup>). It has a substantial UVC component both in lines and in a continuum which constitutes about 20% of all radiated energy (13). UVB (280-320 nm) and UVA (320 and 400 nm) spectral

intervals constitute respectively about 8% and 12% of all radiation, (the spectra divisions are defined as in (14)). The total UV part of all emitted radiation here is about 40%. The position of the spectral maximum for spectra 1 is at 250 nm (or at ca. 5 eV in photon energy units). The equivalent black body temperature is about 14.000 K (or 1.7 eV in temperature energy units). To determine this equivalent temperature, tabulated data on spectral outputs from the lamp catalogue were used (13). The same temperature value can be also obtained by using a simple correlation between the black-body temperature  $T^\circ(\text{eV})$  and position of spectral maximum  $h\nu(\text{eV})_{\text{max}}$  for a black-body radiator (16):

$$\text{Equation 2.1: } h\nu(\text{eV})_{\text{max}} = 2.82 T^\circ(\text{eV})$$

The above correlation is normalized to energy units in eV for both photon energies and for 'the temperature of a radiating surface. (Correlations between units are the following: the photon energy of  $h\nu = 1 \text{ eV}$  corresponds to the temperature of 11.605 K, to the wavelength of  $\lambda = 1240 \text{ nm}$  and to the photon energy of  $\lambda = 1.6 \times 10^{-19} \text{ Joules}$  (16, 17). We used the equivalent plasma temperature in the lamp at its peak power as it is given in (13, 14).

**Figure 1: Spectra of a xenon flash lamp: 1 - at a high current density of 6500 A/cm<sup>2</sup>, 2 - at a low current density of ca 1000 A/cm<sup>2</sup> (13).**



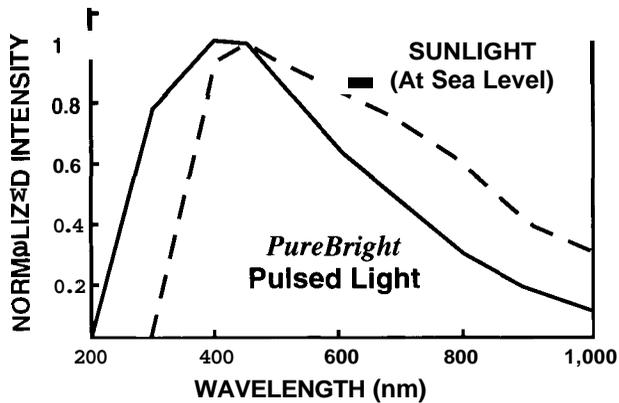
The same procedure and tabulated data for a low loaded flash lamp (spectrum 2 on Figure 1, taken for a current density of about 1 kA/cm<sup>2</sup>) shows that it has the maximum of its radiation in the visible part of a full spectra at ca. 550 nm (or at photon energy  $h\nu = 2.25 \text{ eV}$ ). It also shows that its spectrum has no UV lines but many strong and broadened IR lines between 800 nm to 1000 nm. The equivalent black-body (plasma) temperature for a low loaded flash lamp is about 9.000 K (13, 14). The real flash lamp spectrum differs from the black-body spectra due to a self-transparency of the lamp plasma to photons of higher energies, starting from about 1.5 - 2 eV (13, 14). It makes the effective lamp temperature lesser than the black-body temperature. For example, the radiative temperature for a low loaded flash lamp is in the region of ca. 7000 K (13, 14). Such lamps are usually good for photography or as light signals of any kind (1, 14).

The sun equivalent black-body temperature is 5.900 K (14, 16, 17). It is more similar to the spectrum of a low loaded flash lamp (as spectrum 2 on Figure 1) than to the spectrum 1 on Figure 1 for a high loaded flash lamp, providing that lamp spectrum are given without spectral lines. A spectrum of the PureBright flash lamp, along with the sun spectrum, are on Figure 2 (5, 6). The visual similarity of both is achieved by using wide spectral intervals of 50 nm to 100 nm between "measurement points" which hide the presence of xenon lines in the spectra of the flash lamp and distort the shape of its continuum.

Figure 2 (5, 6) cannot completely hide the fact that the spectral maximum of the PureBright lamp is at least at 400 nm (or at 3.2 eV), and according to the correlation (Equation 2.1) above, this indicates a much higher effective lamp temperature than that of the sun. This limited data allows the estimation of the effective temperature for the PureBright lamp and its approximate UV outputs. To do so, one has to redraw the same spectra from wavelength units into energy (eV) units, and then to integrate surfaces for each spectral interval, according a standard procedure (14, 16). Results

can be presented in percent parts of the full emitted energy which is a surface under the whole spectrum.

**Figure 2: Spectrum of the PureBright lamp and of the sun taken from (5, 6).**



This procedure was also done both for the PureBright spectrum and for spectra 1 and 2 of Figure 1. It revealed that the PureBright spectrum is quite identical to the spectrum 1 of Figure 1 since it has considerable energy fluxes within each UV region even with UV lines cut off by “measurement points”: UVC - 13%, UVB - 11% and in UVA - 17%. In other words, the PureBright spectrum is similar to a highly loaded flash lamp and does not match spectrum 2 on Figure 1 of the low loaded flash lamp. It comes as no surprise: the PureBright system is large.

By contrast, the same procedure on the sun spectrum (Figure 2) and published data (14, 18) show that the sun spectrum at the sea level has no UVC light (0.00%), about 0.3 % of UVB and about 8-9% of the UVA of the total sun energy at the sea level. The ratio between UVB and UVA in the sunlight is about 1 to 30, or 0.033 (18). The same ratio for the PureBright spectrum is 0.64, or twenty times higher! The ratio between UVC to UVA in the PureBright spectrum is 0.74, while for the sun it is just 0.00! Thus, the PureBright spectrum is totally different from the sun spectrum and cannot “mimic” the sun spectrum. This obvious conclusion is contrary to current working rules as described in the literature (6, 7).

These observations have strong consequences. Indeed, the UVC part of spectra has both germicidal and photolysis abilities, while UVB and UVA can cause various changes in microorganisms, nucleic acids, or in a tissue (14, 15, 18). Therefore, attempts to use a flash lamp as “sun-like source” could lead to undesirable harmful effects, similar to those from using UV line radiation from a standard mercury lamp. For example, it is known that the use of standard UV lamps for food treatment is against the law in Germany.

The works (7-9) stress just the opposite of “the mimicking the sun spectrum” – the more UV light and the higher its peak power – the better for decontamination and for disinfection. Since these works do not give an analysis on exactly how a stronger UV component would affect the disinfection, such analysis is now presented below.

## The Flash-Disinfection Mechanism

### Analysis of Flash-Disinfection Data

Tests with flash lamps have shown that even UVC-resistant bacteria such as *Cryptosporidium*, *Aspergillus Niger*, and *Bacillus subtilis* spores are effectively inactivated (4-6). Some published and newly opened data are summarized in Table 1. Specifically of interest are data on a single flash disinfection where a flash lamp light was filtered with Pyrex or with a glass: Pyrex sharply absorbs all photons with wavelengths below 300 nm, while a regular clear glass absorbs much of all UV light. Comparable data (where filtered and unfiltered data were taken at similar irradiation conditions) are selected from (4) and presented in Figure 3. These data clearly demonstrate that the UV part of the flash lamp spectra does practically all the disinfection (6 to 9 logs of the reduction is due only to the UV action!). On the other hand, the same data indicate that UVC alone (case 3 on Figure 3) is responsible for a half of the flash disinfection. The data from the Table 1 shows that the full (over 12 logs) inactivation of bacteria and spores achieved with the pulsed light have a very high ratio of UV/UVC components. These pulses also

had a very high peak power of ca.  $10^5$  wt/cm<sup>2</sup> and a rather short (for a flash lamp) pulse duration of ca. 30 microseconds. The full irradiation dose in tests with these pulses was about the same as for samples in Figure 3. Therefore, a much higher peak power with a respective greater UV content was very beneficial for the flash disinfection. Using these data let us analyze possible deactivation.

First, an overall large UVC component in all of these tests suggests that the role of the UVC light could be a plain germicidal one, just as for a steady 254 nm line from a mercury lamp. Indeed, the provided energy fluxes for data in Figure 3, in Table 1, and the spectral data above allow this conclusion to be made. Also, for the flux of 2 J/cm<sup>2</sup> the UVC part was about 250 mJ/cm<sup>2</sup>. Respectively, at 10J/cm<sup>2</sup> the UVC exposure was 1250mJ/cm<sup>2</sup>. This is sufficient to produce most of observed reduction for *E. coli* and for many other bacteria (19). Since it may not be sufficient to inactivate UV-resistant bacteria, the second deactivation mechanism was most likely present during a sample irradiation with a flash lamp pulse.

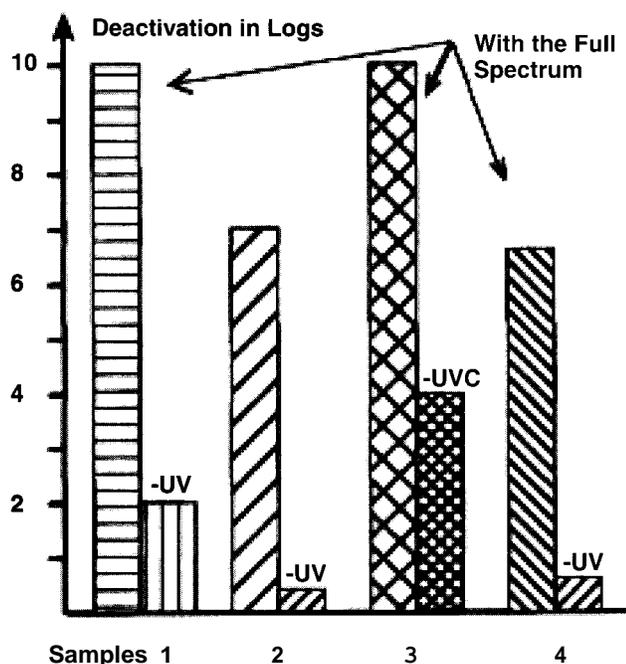
### The Flash-Disinfection Model

It is proposed here that much of flash disinfection at higher flux densities (over ca. 0.5 J/cm<sup>2</sup> at the sample level) is achieved through a rupture of bacteria during their momentous overheating caused by absorbing all UV light from a flash lamp. This overheating can be attributed to a difference in the absorption of UV light by bacteria and that of a surrounding medium. If the UV light is absorbed during a short pulse [for a flash lamp, it was ca. 20 μsec (8, 9) and for the UV-blaster in Table 1, up to 500 microseconds in (4)], then the cooling of bacteria from their surface to the surrounding medium is too small during the same heating time and cannot prevent

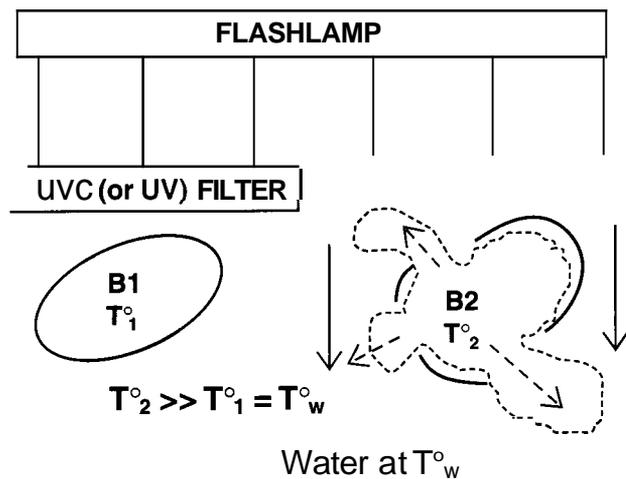
bacteria from overheating and rupturing, Figure 4. This model will not work at low flash lamp fluxes. Instead, the regular germicidal action of the lamp's UVC component should do the job unless some internal heating of bacteria is sufficient.

**Figure 3: Comparison of bacteria deactivation with a flashlamp for a full spectrum and for the UV filtered spectra (from (4)):**

- 1- *E. coli* at 8 flashes each of 12J/cm<sup>2</sup> open and 10 flashes each of 12J/cm<sup>2</sup> at the glass filtered (-W) condition,
- 2- *Bacillus subtilis* (vegetative form) for 1 flash (4 to 12) J/cm<sup>2</sup> of a full spectra and 15 flashes each of (8 - 10) J/cm<sup>2</sup> with the glass filtered (-UV) condition,
- 3- *Bacillus subtilis* (spores) at 1 flash of 8J/cm<sup>2</sup> of a full spectra and 10 flashes of same energy with the Pyrex filter (-UVC),
- 4- *Staphylococcus aureus* at 1 flash of 2 J/cm<sup>2</sup> of a full spectra and with 5 flashes at 4 J/cm<sup>2</sup> each with a glass filtered spectra (-UV).



**Figure 4: Bacteria B1 and B2 in water with temperature  $T^{\circ}_w$ . A high bacteria temperature during the peak of the pulsed disinfection  $T^{\circ}(B2) \gg T^{\circ}(B1)$  causes a thermal rupture of bacteria.**



**Arguments and Calculations in Support of the Flash-Disinfection Model:**

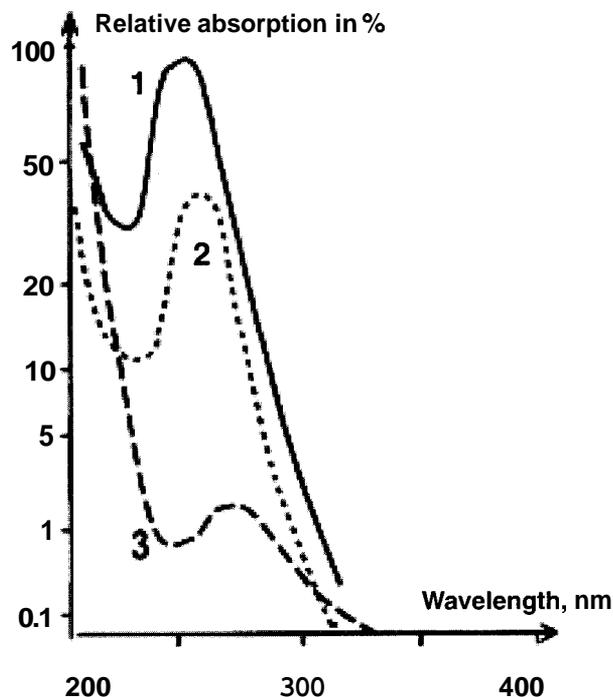
The absorption of UV light from a low-pressure mercury lamp and from a deuterium lamp by various bacteria, nucleic acids, proteins, etc. was studied (15). We will use examples from this excellent and detailed work and normalize these data on fluxes from a flash lamp to get an idea of the energy intake in each relevant case. It also will allow us to avoid an inaccuracy with our calculations of a surface/volume of bacteria or a bacteria cluster, its UV transparency, weight, etc., since such data are already available (15).

To start with, let us review absorption curves for a few important biological objects or its components. These curves are taken from (15) and are presented in Figure 5. As one can see, DNA, RNA, and nucleic acid have the highest absorption between 250 and 280 nm, which steeply falls to 300 nm, and somewhat falls towards deeper UVC wavelengths. The inactivation rate follows this absorption spectrum, rather than the absorption spectrum of protein, since these three components are more important for the inactivation than the

photolysis of the protein. The absorption spectrum of the microorganism phage T4 and its action inactivation spectrum also resembles the absorption spectrum of DNA.

**Figure 5: Data from (15) on a relative absorption for:**

1. DNA, about the same as for nucleic acid and for RNA (and the same shape x 0.25 is for the action spectrum of inactivation of *E. coli*).
2. Absorption of phage T4 (and the same shape x 0.45 is for its inactivation).
3. Absorption of protein.



The work (15) also shows a comparative table of absorption bands of the commonly occurring chromophores, which bands have about 20 nm width and cover all the spectrum from 180 nm for carbon-carbon single bonds to 380 nm for -NO. The respective analysis of numerous data (15) shows that even if absorbance properties differ somewhat for some vital live blocks of various microorganisms, the summary effect causes a full

inactivation at the UV dose sufficient to prevent any "repair work" by a bacteria after such an irradiation. Clearly, not only is the germicidal action of the 254 nm line at work, all photons in the UVC and UVB spectra contribute to the inactivation. Although it seems, from the given curves, that the UVA photons contribute much less to the inactivation, its biological consequences also are grave for a tissue, as it is shown in (18). One has to keep in mind that these data were taken with steady emitting mercury or deuterium lamps. Since a flash lamp spectrum contains from 5% to 20% of UVC light, and about 10% of UVB light, one can expect the same biological (germicidal) effects from a flash lamp. Indeed, UVC fluxes alone, as calculated above, are sufficient for the full inactivation by only this known mechanism in many tests with a flash lamp. Since the flash lamp energy dose is delivered rapidly, the effect of overheating of a bacteria must be considered. Let's estimate an overheating using available numerical data from (15) on bacteria properties.

Example: For an aqueous solution of *E. coli*. The size of this bacteria is  $(2 \times 0.8) \times 10^{-4}$  cm, its average projected (shadow) surface is  $3 \times 10^{-8}$  cm<sup>2</sup>, and its weight is  $3.3 \times 10^{-12}$  g. Its absorbency of the 254 nm light was calculated as 0.2. Its absorbency to the average UV light should be integrated on the full flash lamp spectrum (Figure 1, #1), using the calculated absorption value of 0.2 for the 254 nm line and the relative absorption properties of DNA, at Figure 5. Such estimates show that an average dosage of a full UV component from a flash lamp can be taken as  $I(\text{uv-av}) = 1 \text{ J/cm}^2$  and the average absorption coefficient as 0.05. In this case, *E. coli* bacteria will absorb  $E(b) = 1 \text{ J/cm}^2 \times 3 \times 10^{-8} \text{ cm}^2 \times 0.05 = 1.5 \times 10^{-9} \text{ J}$  or  $3.65 \times 10^{-10}$  calories. Respectively, a specific energy intake (normalized on 1 gram) for a bacteria in this case is 365 calories/gram.

Let's now estimate the bacteria cooling. The above heat intake of 365 calories/gram could fully evaporate 1 cm<sup>3</sup> of water if it is delivered in a few seconds, and if the water is thermally insulated. In a case of bacteria in water, the conductive cooling

from bacteria surface to water is obviously higher than that of air. We further discuss only the condition in water, and later will correct it on a thermal conductivity in air or on a surface. The value of the cooling in water could be estimated by using an average thermal conductivity of organic compounds and of water, which are respectively about  $K(t, \text{org}) = 0.003 \text{ cal/sec.cm}^2 \times \text{grad}^\circ\text{C}$  and  $K(t, \text{water}) = 1 \text{ cal/sec.cm}^2 \times \text{grad}^\circ\text{C}$  (17). That means that the cooling from the surface of the bacteria to water is more efficient than from a bacteria volume. On the other hand, bacteria heating starts from its surface. This model is for estimates and the value for the thermal conductivity in water was used. The energy transfer  $Q$  (cool) during a cooling is proportional to the above coefficient  $K$ , to the conducting surface  $S(c)$ , to the thermal gradient  $\Delta T$  (grad) between a heated and cooling media and to the cooling time  $t(c)$ :

$$\text{Equation 3.1: } Q(\text{cool}) = K \times S(c) \times \Delta T \times t(c)$$

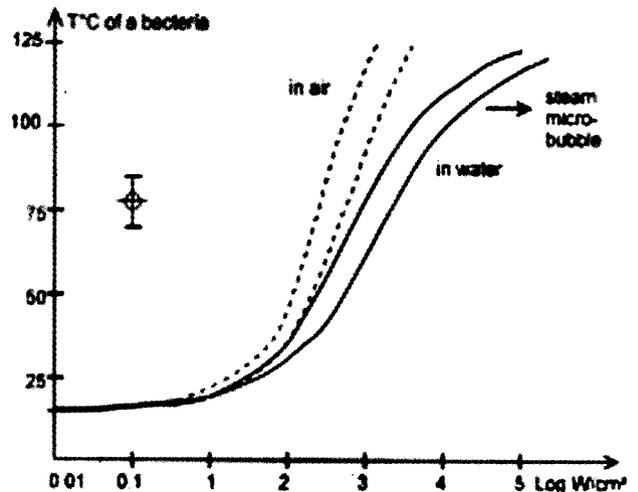
Since we are interested in the cooling during the heating of bacteria, then the cooling time is equal to the duration of the flash lamp pulse:  $t(c) = t(\text{pulse})$ . The latter was ca. 20 psec in (7- 9) and for the UV-blaster in Table 1, while 500 psec in (4) and apparently around 200 μsec in (5, 6). Assuming the maximum heating of a bacteria cannot be over  $\Delta T = 100^\circ\text{C} - 120^\circ\text{C}$  (it is limited by a creation of a steam microbubble, see further down), a heat transfer from the heated bacteria to water amounts only to 3.6 calories or to 1% for the 100 μsec ( $10^{-4}$  sec) pulse and, respectively, 36 calories (or 10%) for the 1 msec ( $10^{-3}$  sec) pulse duration. Thus, for pulse durations of flash lamps used in all cited tests, cooling losses by the bacteria could be only from 1% to 10% of the total energy intake by the bacteria. Therefore, the heating of bacteria can well be the dominant physical process during bacteria irradiation with a high loaded flash lamp.

Since bacteria cooling in water is not sufficient to offset its heating by a flash lamp fluxes, its temperature will rise to  $100^\circ\text{C}$  – much higher than

the surrounding media temperature, As with any local overheated object, bacteria will become a local vaporization center and could generate a small steam microbubble around it. The heating energy usually transfers into a steam around this center of a vaporisation at the water boiling temperature of 100°C (17). The size of a bubble around the vaporisation center will be limited by its cooling to the surrounding water and by the total energy intake as well. From these short heat fluxes and small transferred energies, these bubbles around overheated bacteria could reach sizes of a few microns and then collapse within a millisecond or so. It is technically feasible to detect such steam bubbles with laser-based photography. When the same heating conditions are applied to bacteria in air or on a transparent surface (like a polyethylene or glass), cooling will be far less and the bacteria would simply evaporate.

Various heating and cooling conditions for bacteria, such as irradiated with a flash lamp flux, are graphically presented in Figure 6 and a flash lamp with a spectrum 1 (Figure 1). The calculated dependence of the bacteria temperature is built as a function of values for fluxes from a flash lamp, in log w/cm<sup>2</sup> for the same deposited energies. One group is for water and another group is for an air or for a transparent surface. Both groups are built for a two pulse duration of the lamp – for the 100µsec (10<sup>-4</sup> sec) pulse (left curves) and, respectively, for the 1 msec (10<sup>-3</sup> sec) pulse duration (right curves). The accuracy of these calculations is in assumption that bacteria absorption of UV fluxes from a flash lamp has the same wavelength dependence as was measured in (15), and that the cooling for these microobjects is a conductive one. These may not be necessary true, however there are no other data available on this subject, neither are known strong competing mechanisms which could distort these calculations. Anyway, as the first approximation, this model satisfactorily describes observed data and allows to find optimal conditions for disinfection of bacteria with a flash lamp in many cases.

**Figure 6:** Calculated dependence of a bacteria temperature as a function of fluxes from a flash lamp, in log w/cm<sup>2</sup>. One group is for water (solid curves) and another group is for air (or a transparent surface) – dashed curves. Both groups have build for a two pulse durations of the lamp – for the 100µsec (10<sup>-4</sup> sec) pulse (left curves) and, respectively, for 1 msec (10<sup>-3</sup> sec) pulse duration (right curves). These fluxes are for a high loaded flashlamp (like 1 on Figure 1).



### *Consistency Between the Rupture-Model and Available Data*

It appears from Figure 6, at light fluxes of 2-10 kw/cm<sup>2</sup> (or at energy doses of 2-10J/cm<sup>2</sup>) from a flash lamp in (4) or from UV- bluster (Table 1), that bacteria on a transparent surface will evaporate. This is in accordance with data in Figure 3 and for the UV-bluster in Table 1. Therefore, the model does not contradict data taken with given power fluxes and energy and doses. At lower energy doses, in the range of 0.1-0.5 J/cm<sup>2</sup> (and for respective energy fluxes from 1 to 5 kw/cm<sup>2</sup>), Figure 3 shows that bacteria temperature in air or on a transparent surface will reach 100°C. This fits data on the 1 log reduction, taken recently with PureBright system for 1 pulse (6), and is listed also in Table 1.

Available data on water listed in Table 1 suggests that the model also fits all this data. Indeed, data for the disinfection of *Cryptosporidium* and other bacteria in water (6), shows that at the energy dose of 0.25 J/cm<sup>2</sup> was sufficient to reduce a population of this and many other microorganisms for 4 to 6 logs. For these comparative estimations we assumed that this energy was delivered within 100-500 psec. It could even be accumulated during a few repetitive pulses such as at 5 Hz, a repetition rate which was not indicated in (6), however, it is shown in (8) and (10, 11). In any case, it is sufficient to estimate that in all three cases the flux was sufficient to heat a bacteria to about 90°C, however, it was too small to generate steam microbubbles around the bacteria. Thus, data for water in the table support the model reasonably well.

For flash lamp fluxes below 100 w/cm<sup>2</sup> and at the respective energy absorbed by a bacteria below 0.1 J/cm<sup>2</sup> bacteria will be heated to about 10-20°C, see Figure 6. Let us compare this calculated result to available data (0.1 J/cm<sup>2</sup>) as listed in (4). It shows only one log reduction for bacillus subtilis, and 2.5 log reduction for *Saccharomyces cerevisiae*. It seems that in this case, the reduction was only due to germicidal action of the UVC+UVB components in the flash lamp. Indeed, according to data given earlier in this article, the used flash lamp should have UVB and UVC component of 24%, or 240 mJ/cm<sup>2</sup>. This is well sufficient to get the observed reduction due to the UV germicidal action alone (19).

As to the flash lamp irradiation of an opaque surface with bacteria on it, the disinfection effect depends on absorption properties of the surface. If the surface absorbs most of the broad irradiated spectrum, then a thin layer of the surface could be heated by a flash lamp to a temperature sufficient to “cook” all the bacteria on it. This was suggested as a means to preserve foodstuffs (4). For this purpose, it would be better to use a flash lamp with a glass filter to prevent harmful effects of the UV radiation on foodstuffs.

If the thermal conductivity of an irradiated surface is high (e.g., metals) and its reflection is also high, the heating of bacteria will depend on how strong a thermal contact the bacteria has with the surface. A thin layer of moisture or air will help to heat the bacteria, just as the reflected light will. Since we do not have data on it, we cannot discuss further flash lamp disinfection on an opaque surface.

### *Selecting Optimal Disinfection Conditions Using the Rupture-Model.*

It should be clear from Figure 6 and the discussed data that shorter lamp pulses will reduce the effect of cooling, and provide the necessary energy that is sufficient to heat the bacteria (its specific energy consumption must be well above 100 ca./g). The pulses longer than one or a few milliseconds, respectively, will result in more cooling in the water. To offset such cooling, the “cooking” temperature could be achieved with a pulse of a respectively larger energy. By contrast, a longer pulse duration (like .one millisecond instead of 100μsec) of the same energy will not reduce the bacteria’s overheating in air since the thermal conductivity in air is a small fraction of that in water.

Based on such data and approach, one can select optimal irradiation conditions for each type of bacteria, its population, and a surrounding media. By doing so, one has to take into account that lower energy fluxes from a flash lamp (with respective doses per each flash of 0.01 -0.1 J/cm<sup>2</sup>), a cumulative germicidal effect of the UVC part of the spectra perhaps plays the major role.

One can use Figure 6 to find possible irradiation conditions as soon as one has data on the pulse duration of the flash lamp and on the full radiated energy. Then, using Figure 1 data, one can determine if this flash lamp is high or low loaded, and, respectively, has a larger or smaller UV component. If the UV component is small, one has to change the lamp parameters to fit spectra 1, Figure 1. Then one has to find a geometry of

irradiation which could satisfy flux conditions in  $\text{kw/cm}^2$  in Figure 6 to achieve a rupture of bacteria due to its overheating ("its cooking").

### **Further Tests, Selecting Pulsed Light Sources and Two New Applications**

#### ***To Check the Role of Each UV Part of a Flashlamp Spectra for Disinfection***

Additional data with a flash lamp on similar microorganisms using various filters will allow to effectively select the optimal light source or its operating parameters for each desirable application. Specifically, it is important to get more data on the differences between using the whole UV spectra and then cutting first UVC with a Pyrex filter, and then UVC with UVB with a selected glass filter. Screening visible and IR light and allowing only a certain UV component through would directly show its contribution. Such filters are offered in product sections of various optical-laser journals.

#### ***To Observe and to Detect a Bacteria (or a Bacteria Cluster) Overheating***

It would provide direct evidence of a rupture and of "cooking" of bacteria. It is possible to detect microbubbles of steam around overheated bacteria in water under flash lamp fluxes. The laser-based photography is a useful tool since it also allows filtering out scattered light from a flash lamp, leaving images in coherent laser light. Such images could be magnified optically so micron-sized objects could be seen even in their dynamics. This method has been used for photographing rapid microobjects in plasma where a general light from plasma had to be filtered out. Equipment for such tests are widely offered in product sections of all optic-laser journals.

#### ***To Use a UV-Blaster***

It should also be clear that this technique could be the most efficient when a single light pulse of a high peak power and of a high UV content is

applied to a treated sample with bacteria. In some cases, it would be better to use a plasma-dynamic UV lamp instead of a flash lamp, since such a system is specially designed to generate high light pulses with peak power of ca.  $10^5 \text{ wt/cm}^2$  during its ca. 20-50 microsecond pulses and can deliver energies up to  $10 \text{ J/cm}^2$  with the UV/UVC content of about 70/40% (3). Regular, or even specially designed UV flash lamps, cannot reach such values due to specific physical limitations (3, 13, 20). Therefore, the use of a system as suggested in (3) could be a solution.

#### ***Where to Get Test Units, etc.***

The author of this presentation offers help for all suggested tests by supplying necessary test systems with flash lamp or UV-blaster. These systems could be equipped with filters to vary the UV content on a sample. We also offer to select test equipment for the laser photography and design the necessary experiments, with the use of established light diagnostic techniques, etc. Also, the author has been invited to the large German Program BMBF to study disinfection mechanisms of an interest to the packaging industry. **Your** inquiries are welcome while visiting our website at [www.wektec.com](http://www.wektec.com).

#### ***Proposed Application I: To Disinfect Medical Solutions Filled into Vials for Internal Injections***

Medical personnel in hospitals routinely prepare F18-FDG solutions containing a prescribed medicine and refrigerate those vials until use. A standard vial is a cylindrical bottle with the diameter of 20 mm and a height of 180 mm, and is made from Pyrex. The problem with sterilization comes during filling the vials, since this is a manual procedure in the open air. Disinfecting vials after filling and sealing can be made with a flash lamp system, specially made for this purpose. Such disinfection will assure that no airborne bacteria or viruses are injected into the patient. Since Pyrex does not allow UVC, these solutions cannot be subjected to undesirable chemical transformations through UVC-photolysis. It is known that UVB and UVA

photons ,do not have sufficient energy for such transformations and therefore they could be used for the flash-disinfection of sealed medical solutions.

### ***Proposed Application 2: Acceleration of a Wound Healing After Surgical Procedures in Hospitals***

Clinical trials in Russia (11) have shown a remarkable (up to three-to-five times) reduction in the healing time for wounds for surgical procedures which were performed while a flash lamp system disinfected open surgical areas with about 1 flash per 30 seconds. The lamp had a Pyrex envelope to effectively screen harmful UVC radiation which otherwise would cause cancer-like cells through photolysis. The lamp power could be selected below a level where it could inflict any damage on open tissue, yet high enough to deactivate all bacteria coming onto the wound surface from the air during a surgery procedure.

### **Conclusion**

The available data suggests that bacteria inactivation during the irradiation with a flash lamp is due to both a UVC germicidal action of the UVC component in a flash lamp, and to a bacteria rupture

through a momentous overheating by the UV part of a flash lamp spectrum. The dependence of bacteria overheating ( $T^{\circ}\text{C}$ ) has been calculated and graphically presented as a function of energy fluxes deposited to a sample (in  $\text{kW}/\text{cm}^2$ ) at a fixed pulse duration from a flash lamp. This dependence correlates well with available data. It is proposed that overheating of bacteria during flash disinfection with a high peak of power could be diagnosed with a laser-based photography of steam microbubbles, possibly generated around overheated (“cooked”) bacteria. Provided analysis shows that two currently used “working rules” are no longer valid: one was that the use of all parts of a flash lamp spectrum are important for disinfection, and the other was that a highly loaded flash lamp “mimics the sun spectrum”. Both cannot be supported by available data. Just the opposite is supported by available data – getting a flash lamp with a higher UV output will be beneficial for this method while varying its content of UVC, UVB, and UVA will allow a flexibility in applications. It has been shown that for user it is important to get the best performing UV pulsed source, not just a flash lamp system. Recommendations are provided on how to achieve the optimal flash lamp disinfection for various media and where to get respective systems.

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