UV Drinking Water Disinfection – Requirements, Testing and Surveillance: Exemplified by the Austrian National Standards M 5873-1 and M 5873-2

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ABSTRACT

The increased acceptance of UV drinking water disinfection is attributed, amongst other things, to the better understanding of the process and the higher quality assurance of the UV disinfection plants. Establishment of quality standards on the requirements, as well as validation testing and certification of commercial UV plants, have provided the basis for the safe application of drinking water disinfection by UV irradiation. Two different techniques of UV irradiation are used for water disinfection: low pressure lamps with quasi monochromatic emission at 253.7 nm and medium pressure lamps with polychromatic emission. Due to the differences in lamp emission and the consequences thereof, it is advisable to deal with these two techniques separately. To describe the requirements on UV disinfection of water a three-step approach has been proven to be useful: (1) the knowledge of the UV resistance of health related microorganisms transmittable by water; (2) an objective careful evaluation of commercial UV plants and (3) the surveillance during practical application by means of defined alarm points and a calibrated UV sensor, which allows checks against official specifications. The latter provides the possibility of an independent, objective inspection, as, for example, demanded by certain health authorities.

We introduce in the following text the Austrian National Standards ÖNORM M 5873-1, low pressure systems (ÖNORM 2001) and ÖNORM M 5873-2, medium pressure systems (ÖNORM 2003) as an example for standards in which these aspects have been successfully included. In 1996 we established in Vienna, Austria, a test facility to validate UV reactors (a cooperation of Arsenal Research, the University of Veterinary Medicine Vienna and the Medical University Vienna). To document its reliability, our testing facility is internationally accredited according to ISO 17025.

KEYWORDS: drinking water disinfection; UV-irradiation; biodosimetry; low pressure UV systems, medium pressure UV systems, spectral sensitivity

INTRODUCTION

In the past few decades, UV irradiation for drinking water disinfection has gained remarkable popularity especially in Europe but also throughout the world. A survey predicts for the development of the application of UV water disinfection (worldwide) that in the time span from 1997 to 2005 the application of UV disinfection will increase from 10% to 30%, whereas the use of chlorine will decrease from 87% to 55% expressed as numbers of disinfection installations.

Remarkable arguments in favor of the use of UV water disinfection are:

- no addition of chemicals
- very short reaction time (parts of a second), therefore no need for a reaction vessel
- neither pH- nor temperature-dependent
- specific inactivation mechanism
- effective against parasites (e.g. *Cryptosporidia*)

Besides these advantages of the UV technology, it became evident that to date the UV fluence (dose) delivered by UV systems cannot yet be directly measured nor can it be calculated. This is because during UV irradiation in flow-through systems, several factors act in complex combination: the output of the UV lamps, the water flow, the transmittance of the water being irradiated and – especially important – the hydraulic properties of the UV device. As a consequence of inhomogeneous irradiation geometries and individual, unpredictable hydraulic behaviors, the fluence received by microorganisms exhibits a broad distribution. These facts make it still impossible to measure directly the disinfection performance of a specific UV plant.

Two principal UV technologies are in general use: low pressure systems with quasi monochromatic 253.7 nm emission and medium pressure systems emitting polychromatic radiation. In the latter case, it is even more complex to determine the microbicidal UV fluence, since the wavelengths account differently for the inactivation of microorganisms.

In view of the above factors, it was necessary to develop and establish standard protocols for testing the efficiency of UV disinfection systems. This has now been carried out by the Austrian Standards Institute (ÖNORM M 5873-1, low pressure systems 1996; (ÖNORM 2001) and ÖNORM M 5873-2, medium pressure systems (ÖNORM 2003), the US Environmental Protection Agency (USEPA 2003) and the German Association for Gas and Water (DVGW) (DVGW draft 2003).

The use of biodosimetry to evaluate commercial UV disinfection reactors is common to all three standards and testing protocols. Biodosimetry is included in a validation test, which is performed as a full scale test of a (commercial) UV disinfection plant either at a test stand or on site in the water work.

REQUIREMENTS FOR SAFE UV WATER DISINFECTION

The aim of drinking water disinfection is to prevent people from getting infected by pathogenic microorganisms that are transmitted through the water route. In water disinfection the microorganisms are inactivated; this means that these inactivated microorganisms have lost their infectivity and no longer pose a threat to humans. Techniques for water disinfection are: treatment with chlorine, ozone, heat (boiling) and by UV irradiation. The goal of sufficient drinking water disinfection has been set as a 4 log reduction of the concentration (99.99%) of bacterial and viral pathogens as well as a reduction of 3 log (99.9%) of protozoa (USEPA 1989).

To answer the question as to which conditions have to be fulfilled for a successful UV irradiation, a three-step approach has been proven to be useful:

1. **Knowledge of the UV resistance of health related microorganisms transmittable by water:** These investigations can only be performed under strictly controlled laboratory batch conditions; an example for a UV laboratory device is given in Figure 1. The irradiation equipment was evaluated for reliability in an international laboratory trial (Sommer et al. 1995). Data obtained from flow-through irradiation systems are not reliable in this respect since the conditions are not well controlled (occurrence of fluence distributions). For an overview on the UV-253.7 nm resistance of water relevant microorganisms see USEPA (2003).

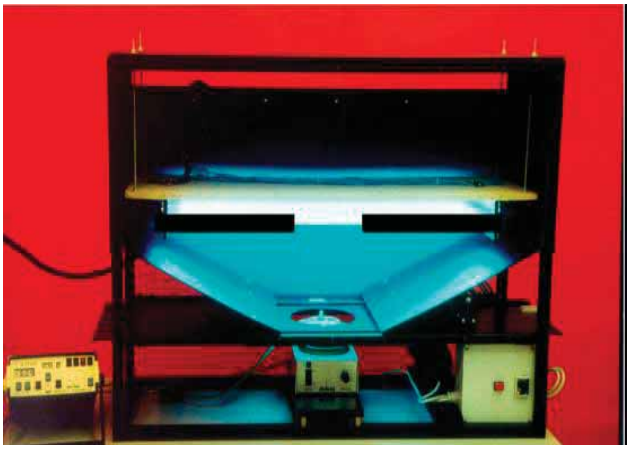

Figure 1: Laboratory batch irradiation device according to the requirements of Austrian National Standard M 5873 (safety front shield removed).

Checking solely the presence of *Escherichia coli* and enterococci in 100 mL water volume – as is done in routine bacteriological water monitoring – has to be regarded as insufficient for the surveillance of disinfected waters. This is because these bacteria are much more sensitive to disinfection measures (UV, chlorine, ozone) compared to most of the water related pathogens (e.g., viruses). Therefore the surveillance of the disinfection process has to be carried out by checking the defined technical parameters (flow, reference irradiance, water transmittance) obtained during the validation test of the UV plant.

2. **An objective evaluation of commercial UV plants:** Due to the lack of a method for the direct measurement of the microbicidal UV fluence in commercial water disinfection plants, it is necessary to establish a standardized procedure for the testing and evaluation of such plants to guarantee that only well functioning UV plants are on the market. Numerous microbiological investigations have been undertaken to evaluate the performance of commercial UV disinfection plants. Since most of these tests were not performed under standardized conditions, especially with respect to the test organisms used, different assessments were obtained, sometimes even for one and the same UV plant. Thus an objective evaluation of the microbicidal efficacy of UV

systems is the prerequisite for their reliable application in water disinfection.

3. **The surveillance during practical application:** from the data of the type test, admissible ranges of operation and alarm points are determined. Due to regular controls during the practical operation of the UV plant in the water works, it is assured that these parameters are complied with. To measure the reference irradiance, commercial UV plants have to be equipped with a calibrated UV sensor fixed at a standardized measuring window at a reference position in the irradiation chamber (sensor reading in W/m²). The sensor has to be removable during operation of the UV plant to enable a check against official specifications providing an independent, objective inspection, often demanded by health authorities.

We introduce in the following text the Austrian National Standards ÖNORM M 5873-1, low pressure systems (ÖNORM 2001) and ÖNORM M 5873-2, medium pressure systems (ÖNORM 2003) as an example for standard protocols in which these aspects have been successfully implemented.

LOW PRESSURE AND MEDIUM PRESSURE SYSTEMS

Mainly two different types of UV sources are used for water disinfection: low pressure lamps with quasi monochromatic emission at 253.7 nm and medium pressure lamps with polychromatic emission. Due to the differences in lamp emission and the consequences thereof, low and medium pressure systems have to be regarded as different techniques (Table 1).

No differences in the disinfection efficacy have been found between polychromatic and monochromatic UV irradiation, provided that the UV fluence has been measured properly.

Regarding water disinfection with medium pressure systems, additional requirements have to be established due to the polychromatic UV radiation: (1) The spectral UV sensitivities of pathogenic and indicator microorganisms have to be known, (2) the spectral sensitivity of the sensor has to resemble as close as possible the spectral sensitivity of relevant microorganisms and (3) a suitable UV absorbing substance for the adjustment of the spectral transmission of the water during the type test has to be applied.

In proficiency testing of UV plants, the biodosimeters established for the testing of low pressure systems are also applied for the evaluation of medium pressure systems. In the latter case the Reduction Equivalent Fluence is related to the wavelength of 253.7 nm. For the sake of reproducibility, the spectral UV sensitivity of the biodosimeter has to be known (ÖNORM 2003).

A further important question deals with the formation of undesired by-products due to the UV irradiation of water. This indicates a significant difference between irradiation with monochromatic low pressure systems (wavelength 253.7 nm) and polychromatic medium pressure systems. Numerous investigations on low pressure radiation have proven that no changes of the characteristics of the water to be irradiated have to be expected. However, it is known that the radiation of medium pressure lamps may cause nitrite formation from nitrate (wavelengths below 240 nm). Some investigations reveal data on the generation of other undesired substances, such as an increase of the assimilable organic carbon (causing microbiological instability of the water) or the formation of genotoxic substances (Haider et al. 2001, 2003; Ijpelaar et al. 2003). However, more investigations in this field are necessary. For the reasons described the ÖNORM M 5873-2 (ÖNORM 2003), the permissible UV radiation is restricted to wavelengths above 240 nm.

***Table 1**: Some characteristics of low and medium pressure UV systems (excerpt).*

	LOW PRESSURE	MEDIUM PRESSURE
UV-radiation (spectrum)	quasi monochromatic 253.7 nm	polychromatic 200 (240) – 400 nm
Energy consumption of the lamps	low (40 – 100 W)	high (e.g. 7 kW)
Water flow	lower water flows (< 1000 m³/h)	higher water flows (>1000 m³/h)
Percentage UVC	30%	10%
Heat development	low	high
Influence on water components	so far known, no changes	Nitrite (< 240 nm) Possible changes: Assimilable organic carbon (AOC)? Gentoxic effective substances?

UV-253.7 NM RESISTANCE OF MICROORGANISMS

In the past few decades, the UV-253.7 nm resistances of many pathogenic and indicator microorganisms with significance for water quality in public health have been investigated (for an overview see USEPA 2003). Some examples are given in Figures 2 and 3. Compared with the other test organisms shown, spores of *B. subtilis* revealed the most UV resistance, closely followed by the bacteriophage

MS2. The three viruses, poliovirus, rotavirus, and phage B40-8, take an intermediate position, whereas phage PHI X 174 and *E. coli* represent the very most susceptible test organisms. The inactivation curve of *B. subtilis* spores consists of a shoulder followed by an exponential part. The latter part can be used for the quantitative measurement of the REF in the fluence range from 200 to 600 J/m² (ÖNORM 2001, 2003). Spores of *B. subtilis* and the bacteriophage MS2 have been proposed as biodosimeters for UV reactor validation.

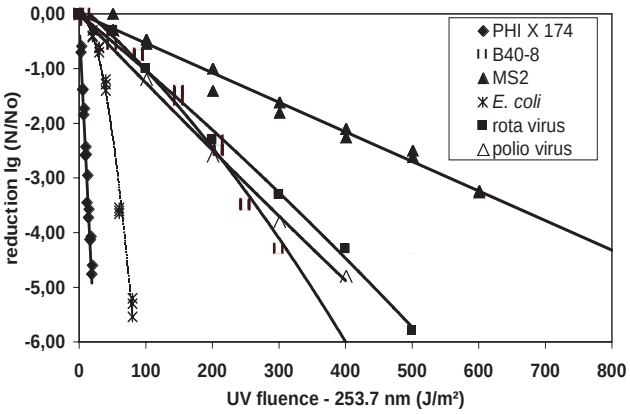

Figure 2: UV-253.7 nm inactivation of pathogenic (poliovirus, rotavirus) and indicator microorganisms (bacteriophages PHI X 174, MS2, B40-8 and bacteria E. coli) under controlled and standardized batch conditions. (Sommer et al. 1989; Sommer et al. 2001).

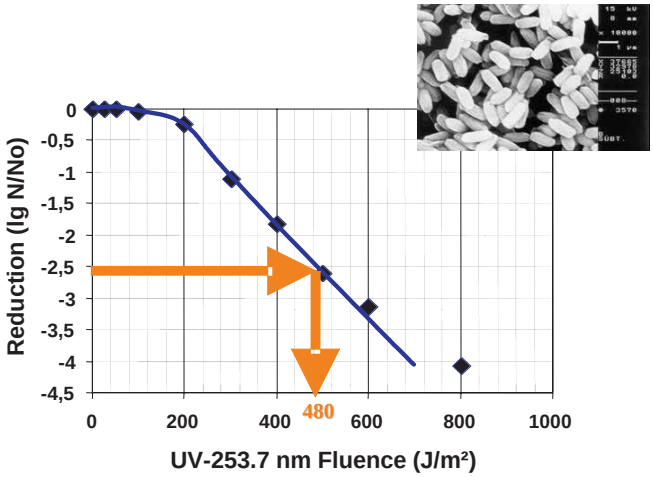

Figure 3: UV-253.7 nm inactivation of spores of Bacillus subtilis used as calibration curve of the biodosimeter. Principle of the analysis for the measurement of the Reduction Equivalent Fluence during biodosimetric test.

It has to be emphasized that some bacteria possess the ability to repair damages caused by UV irradiation, including the pathogenic *E. coli* strains which we have investigated (Sommer et al. 2000). The most potent repair pathway is photoreactivation, which is caused by the enzyme photolyase. This enzyme has to be activated by light energy in the near-UV or violet-blue spectral range. For the most UV resistant *E. Coli* strain in this study, about a 2.5-fold higher UV fluence (300 J/m²) was necessary to reduce this strain by 6 logs after photoreactivation compared with the inactivation without photoreactivation.

Considering the goal of safe water disinfection, represented by a reduction of the concentration of drinking water transmittable, relevant pathogenic viruses by 4 log, a UV fluence (253.7 nm) of 400 J/m² has to be demanded. Therefore this requirement was laid down in the Austrian National Standard M 5873-1 and -2. Recently this value was confirmed as sufficient for the inactivation of caliciviruses (De Roda Husman et al. 2004). This fluence value also covers the inactivation of human pathogenic bacteria under consideration of photo repair, such as enteropathogenic *E. coli* (Sommer et al. 2000).

UV RESISTANCE OF MICROORGANISMS AT DIFFERENT WAVELENGTHS

When polychromatic radiation is employed, knowledge about the spectral UV sensitivity of the relevant microorganisms is essential. For these investigations we have used a radiation source (400 W Cermax Xenon-lamp) together with a single monochromator (Jobin-Yvon HL). In the longer wavelength region, possible short wavelength components were filtered out by cut off filters. 20 mL of the spore suspension was added to 25 mL vessels and irradiated under continuous stirring. The spectral irradiance at the surface of the suspension was measured with a spectroradiometer (Bentham DTM300) equipped with a quartz light guide and a Teflon diffuser as entrance optics. The calibration of the spectro-radiometer was traceable to PTB (Physikalisch Technische Bundesanstalt, Braunschweig, Germany). The bandwidth of the monochromatic irradiations was 20 nm. These measurements were carried out before and after each irradiation and the mean of both spectra was used for further calculations. The resulting fluence for each experiment was calculated from the spectral irradiance by taking into account the spectral reflection of the radiation at the surface of the suspension and the spectral absorption of the suspension and the irradiation time. The spectral absorbance of the suspension was measured by means of a spectrophotometer (Hitachi U-3000).

The result of the spectral investigation of the ÖNORM biodosimeter is shown in Figure 4, where the UV fluence is given in a logarithmic scale. A 2-log reduction at a wavelength of 254 nm (low pressure) was reached at a fluence of 400 J/m², whereas for the same effect at a wavelength of 352 nm 8.0 million J/m² was needed.

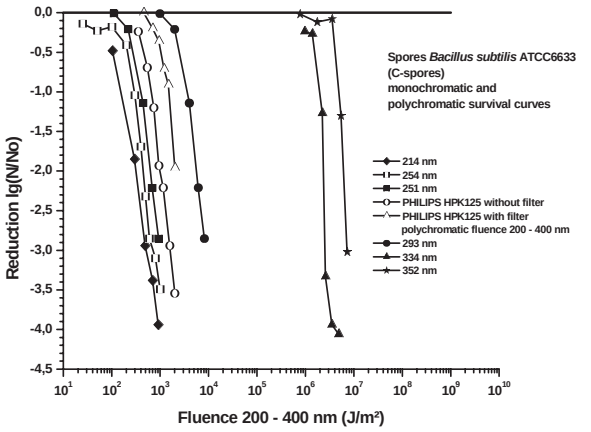

Figure 4: UV Inactivation of the ÖNORM biodosimeter (spores of B. subtilis ATCC 6633) at different wavelengths (Cabaj et al. 2002).

The inactivation data obtained at all the single wavelengths can be used to create the spectral sensitivity of a microorganism. Figure 5 represents the spectral sensitivity expressed by the UV sensitivity coefficient *k* and the shoulder broadness coefficient *d*.

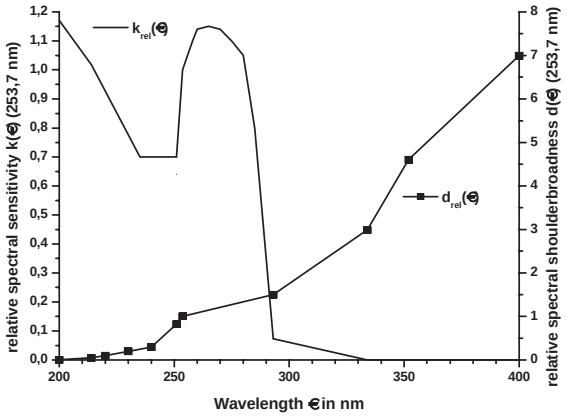

Figure 5: Spectral sensitivity (relative to the wavelength of 253.7 nm) of Bacillus subtilis spores used as biodosimeter in the ÖNORM (2001, 2003) expressed as wavelength dependence of *k*, the UV sensitivity coefficient, and *d*, the shoulder breadth coefficient (Cabaj et al. 2002).

BIODOSIMETRY

Biodosimetry is defined as a method involving the application of a test microorganism for the measurement of the UV fluence in a UV plant. This method is already in wide use in the field of UV radiation. It has been proven useful for the measurement of solar radiation as well as for technical UV sources (Cabaj and Sommer 2000; Calkins and Barcelot 1979; Munakata et al. 1996; Qualls and Johnson 1983; Quintern et al. 1992; Ronto et al. 1994; Sommer and Cabaj 1993; Sommer et al. 1999; Tyrell 1995).

The principle of UV biodosimetry is the use of carefully UV-253.7 nm calibrated microorganisms. *Bacillus subtilis* spores (bacterial spores) are typically used for UV reactor validation in Europe, while MS2 coliphage (f-RNA virus) is typically used for validation testing in the North America. Both microorganisms are non-pathogenic allowing their use in the field and they possess a sufficiently high UV resistance to be suitable as "biological UV radiometers".

Calibration of the biodosimeter at the wavelength 253.7 nm (low pressure lamp)

An inactivation curve of the biodosimeter is performed under controlled laboratory batch conditions (fluences from 100 to 800 J/m²). Subsequently the reduction log (N/N_0) of the microorganism is calculated as a function of the UV fluence. The inactivation curve of microorganisms in semi-logarithmic presentation (decadic) can be expressed by using the following formula:

[1] $$\log \frac{N}{N_0} = \lg\left[1 - \left(1 - 10^{-k \cdot H'}\right)^{10^d}\right]$$

where N/N_0 is the survival ratio

k is the slope of the linear part of the survival curve in m²/J (UV-sensitivity)

H' is the fluence in J/m²

d is the distance between the intercept of the linear part with the ordinate and the origin

Since the fluence measured by biodosimetry can be affected by the UV sensitivity of the biodosimeter used it is necessary to define its calibration curve to enable traceability.

The constants k and d shall be in the following range (spores of *Bacillus subtilis* according to ÖNORM 2003)

k = 0.0065 ± 20% m²/J (k = 0.0052 – 0.0078 m²/J)

d = 0.7 ± 30% (d = 0.49 – 0.91)

It has been found that the UV resistance of bacterial spores strongly depends on the method for the spore production (Sommer and Cabaj 1993). Therefore a suitable method – a liquid fermentation technique – has been developed for the production of sufficiently UV resistant spores (Sommer 1991).

For the measurement of the UV fluence, the biodosimeter is exposed to an unknown field or space of UV radiation. After exposition the concentration of the microorganisms still able to multiply is determined. The reduction log(N/N_0) is calculated. N represents the concentration of biodosimeter after irradiation and N_0 stands for the starting concentration. By means of the UV-253.7 nm calibration

curve the reduction is calculated back to the corresponding UV-253.7 nm fluence (J/m²). The result of the biodosimeter method is called Reduction Equivalent Fluence, $REF_{253.7}$ nm (Cabaj et al. 1996).

The conversion of the reduction to the Reduction Equivalent Fluence is carried out by using the following formula:

$$REF = -\frac{1}{k} \cdot \log\left[1 - \left(1 - 10^{\log\frac{N}{N_0}}\right)^{10^{-d}}\right]$$

where N/N_0 is the survival rate caused by the UV-disinfection plant. A schematic representation of the procedure is given in Figure 3.

The REF is affected by the fluence distributions within the suspensions due to inhomogeneous radiation fields, the UV absorption of the water and the lamp power. In the case of polychromatic UV sources (medium pressure UV lamps) the individual spectral UV sensitivity of the particular microorganism also has to be taken into account. To obtain reproducible and reliable UV validation data, the spectral sensitivity of the biodosimeter applied has to be characterized, as it was performed for the biodosimeter (spores of *Bacillus subtilis* ATCC 6633) used in the Austrian National Standard M 5873-2 (Cabaj et al. 2002).

BIODOSIMETRIC TYPE TEST ACCORDING TO THE AUSTRIAN NATIONAL STANDARD M 5873-1 AND M 5873-2

The type test at the test stand comprises five parts:

1. checking the compliance of the plant to be tested with the specifications given by the manufacturer;
2. general technical measurements during the test (flow, water temperature, electrical current, ...);
3. full scale microbiological test with the biodosimeter at a test stand under worst case conditions regarding flow and UV transmittance of the test water and lamp power (simulating aging of the lamp and fouling of the lamp sleeve); 6 defined test points
4. radiation physical measurement of the reference irradiance, test of the plant sensor;
5. evaluation of the UV disinfection plant and specification of the admissible operation range.

Adjustment of the test points

1. Determination of the relationship between the UV-transmittance of the water and the reference irradiance:

a. The radiant power of the lamp is reduced (e.g. by lowering of the voltage) so that the radiant power at the end of the lamp utilization period is simulated (e.g. 30%).

b The UV-transmittance of the test water is adjusted with a transmission reducing substance (aqueous sodium thiosulfate solution for low pressure lamps, instant coffee solution for medium pressure lamps).

c. Adjust the UV-transmittance that corresponds to the highest flow to be tested and measure the reference irradiance (E_1).

d Adjust the UV-transmittance that corresponds to the medium flow to be tested and measure the reference irradiance (E_2).

e. Adjust the UV-transmittance that corresponds to the lowest flow to be tested and measure the reference irradiance (E_3).

The water flow may be kept low for these measurements (eg lowest flow to be tested), as the flow does not influence the measurement results.

2. Test points

a. **Test point 1**: highest flow to be tested, full lamp power, adjustment of the reference irradiance E_1 by reduction of the UV-transmittance of the water.

b. **test point 2**: medium flow to be tested, full lamp power, adjustment of the reference irradiance E_2 by reduction of the UV-transmittance of the water.

c. **test point 3**: lowest flow to be tested full lamp power, adjustment of the reference irradiance E_3 by reduction of the UV-transmittance of the water.

The adjustment of the further test points is performed by using test water with a UV-transmittance of 80% to 90% and by reduction of the power of the UV lamp(s):

Test point 1*: highest flow to be tested, adjustment of the reference irradiance E_1 by reduction of the lamp power.

Test point 2*: medium flow to be tested, adjustment of the reference irradiance E_2 by reduction of the lamp power.

Test point 3*: lowest flow to be tested, adjustment of the reference irradiance E_3 by reduction of the lamp power.

Biodosimetric measurement of the Reduction Equivalent Fluence

As soon as stable conditions at the test point are reached, the stock solution of the biodosimeter (spores of *B. subtilis*) is pumped to the inlet flow of the UV plant tested. Optimum mixing is achieved by a static mixer (concentration of the biodosimeter after mixing about 10^6 to 10^7 per L). The samples after UV irradiation are also taken after a static mixer. During the test, there shall be a continuous flow through the sampling cocks. Per test point and test run, 5 samples are taken before and after UV irradiation respectively and the spore concentrations are analyzed quantitatively in triplicate using pour plate method. .

This procedure results in 5 log-concentrations before and 5 log-concentrations after UV irradiation for each test point, of which the arithmetic mean is calculated (log N_0: before irradiation, log N_1: after irradiation). The standard deviation s of the 5 parallel samples shall not exceed ±0.2, otherwise the test conditions are not considered to be stable (hydraulics, dosing, mixing). By calculating log N minus log N_0, the reduction at the test point is determined.

In terms of quality control during the type test, the UV-sensitivity of the biodosimeter must be checked in the standard laboratory batch apparatus (see above) with at least two samples of the test water containing the biodosimeter, in order to verify the stability of the biodosimeter. The two samples (with and without UV absorbing substances) must be irradiated with fluences of 200, 400 and 600 J/m², respectively. The values of k and d must be within the range of the values given in the standard. The inactivation function and the results of the verification test must be included in the test report.

Admissible range of operation and surveillance during practical operation

1. For establishing the admissible operating range the lower maximum flows at the same reference irradiance (E_1, E_2, E_3) that give a REF ≥ 400 J/m² are used. The alarm points and the admissible operating range of the UV plant are determined from the data derived from flow and reference irradiance.

2. In the course of regular controls during the practical operation of the UV plant in the water works, it must be assured that these parameters comply with the specifications obtained in the validation test.

Considerations for medium pressure UV plants

Compared to low pressure systems, using almost solely monochromatic UV radiation at 253.7 nm, medium pressure UV plants with polychromatic UV sources represent a much more complex case. Therefore **additional requirements** have to be considered when testing and operating such a **medium pressure UV disinfection system**; these are:

1. **Definition of the UV fluence caused by polychromatic radiation**: three types have to be distinguished:

   a. the absolute fluence in J/m².

   b. a weighted fluence related to a certain spectrum, e.g. to the spectral sensitivity of a microorganisms or to the absorbance spectrum of the DNA.

   c. the $REF_{(253.7\ nm;\ biodosimeter)}$ as the result of biodosimetry, which is related to the UV-253.7 nm inactivation curve of the microorganism used as biodosimeter.

2. **Spectrum of the lamp**: The microbicidal effect of the UV lamp depends on the spectrum which is emitted.

3. **UV-transmittance of the water (%T_{100})**: The spectral transmission of the water influences the microbicidal efficiency of the UV radiation. This has to be taken into account when choosing a transmittance reducing substance for the biodosimeter test. For practical reasons the transmittance of the water being disinfected – as a measure of water quality – is determined at the wavelength of 253.7 nm.

4. **Spectral sensitivity of microorganisms**:
   Microorganisms possess different spectral sensitivities; therefore these data for biodosimeters, as well as for water transmittable pathogens, are necessary for the establishment of medium pressure systems.

5. **Spectral sensitivity of the reference and the plant sensor:** For the surveillance of water disinfection the spectral sensitivity of the sensors should resemble as closely as possible the spectral sensitivity of microorganisms.

Examples for the results of biodosimetric testing are given in Table 2. For the majority of the UV plants tested, we found significantly lower REF values than expected from the calculations made by the manufacturers (up to a factor of 2). In some rare cases we observed unexpectedly higher REF values.

***Table 2**: Results of biodosimetric type testing according to the Austrian National Standard M 5873 versus the UV fluence calculated by the manufacturer. Simultaneously performed tests with the fecal bacterial indicator enterococci are shown for comparison.*

Flow (m^3/h)	Water Transmittance % (253.7 nm; 100 mm)	Reference Irradiance (W/m^2)	REF[1)] (J/m^2) measured	UV Fluence (J/m^2) calculated by the manufacturer	Reduction $\log(N/N_0)$ of *Enterococcus faecium*
3	10	21	220	400	> 6
3	90	21	230	400	> 6
28	10	72	290	420	> 6
28	88	72	325	420	> 6
107	16	21	290	400	> 6
107	84	21	260	400	> 6
239	71	83	410	400	> 6
239	84	83	390	400	> 6

[1)] Reduction Equivalent Fluence

Microbiological testing performed simultaneously with *Enterococcus faecium* yielded reductions of > log 6 under all conditions tested, even if the REF was far below 400 J/m^2. This strongly confirms the uncertainty of microbiological testing without considering the individual UV sensitivity of the test organism used.

Biodosimetry has proven eminently suitable to investigate quantitatively influences on the performance of UV disinfection, such as the water transmittance and the lamp intensity, reflection due to reflecting materials of the inner surface of the irradiation chamber and the hydraulic behavior of the device (Sommer and Cabaj 1993; Sommer et al. 1996; Sommer et al 1997). The application of biodosimetrically tested UV plants ensures safe water disinfection and, moreover, can be used to optimize UV disinfection plants helping to save costs for energy and building material.

CONCLUSIONS

The following recommendations can be made for ensuring safe drinking water disinfection by UV irradiation:

1. A biodosimetric full scale test of UV plants using a biodosimeter (UV calibrated test organisms with a sufficient UV resistance compared to water transmittable microbial pathogens; non pathogenic; long-term UV stability) gives the Reduction Equivalent Fluences (J/m^2) under worst case conditions (flow and UV transmittance of the water, lamp power, reference irradiance given as sensor reading in W/m^2). Spores of *Bacillus subtilis* comply with all the demands for a biodosimeter.
2. If the test performance of the UV plant fulfills the microbicidal requirements alarm points and an approved range of application (maximum flow and minimum UV transmittance of the water as well as minimum reference irradiance) are fixed. These parameters serve as objective tools to check the performance of UV plants during practical operation.
3. Commercial UV plants have to be equipped with a calibrated UV sensor fixed at a standardized measuring window at a reference position in the irradiation chamber (sensor reading in W/m^2). The sensor has to be removable during operation of the UV plant to enable the objective and independent inspection against official specifications.
4. Since routinely used bacteriological parameters (*E. coli* and enterococci) are too susceptible to serve as surrogates for health related water microorganisms the surveillance of disinfected water has to be based on well evaluated technical parameters which are controlled during practical operation in the water work.
5. To establish a minimum required Reduction Equivalent Fluence for safe drinking water disinfection, accurate data on the UV resistance of health related microorganisms are needed. Such data can only be obtained under well defined and controlled conditions in laboratory batch experiments. Based on our own findings and data from the literature a Reduction Equivalent Fluence of 400 J/m^2 has been fixed in the Austrian legislation. This fluence can be regarded as sufficient for a 4 log reduction (99.99%) of the majority of health related bacteria, viruses and protozoa.
6. When applying medium pressure systems the spectral UV sensitivity of the biodosimeter, the spectral sensitivity of the sensor, the suitable UV absorbing substance for adjusting the spectral transmission of the water dur-

ing the type test have to be taken into consideration (ÖNORM 2003). Since these requirements for commercial UV plants with medium pressure lamps have to date not been completely realized medium pressure systems are not yet allowed for drinking water disinfection in Austria. More data about the spectral sensitivity of pathogenic and indicator microorganisms as well as studies on the possible formation of undesired by-products are urgently needed.

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