Differences Between Calculated and Biodosimetrically Measured Fluences in UV Plants for Drinking Water Disinfection – Practical Experiences with the Austrian National Standard M 5873-1

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OVERVIEW

Austria has a long tradition in using UV-253.7 nm radiation for drinking water disinfection purposes. The main advantages are: (I) no chemicals must be added to the water, (II) no change of the water composition is to be expected and (III) no additional reaction time is needed (18). Nevertheless, there is one disadvantage: it is not possible to measure or calculate the applied microbiocidal fluence directly. This is because the microbiocidal efficacy depends on the intensity of the lamps, the flow and the UV transmittance-253.7 nm of the water being irradiated as well as on the hydraulic properties of the UV device. Due to inhomogeneous irradiation geometries and individual, unpredictable hydraulic behaviors in flow through systems, fluence distributions occur (6).

For a sufficient UV disinfection of drinking water a microbiocidal fluence of 400 J/m² is necessary, as stated in the Codex Austriacus in 1993 (2), based on data about the UV sensitivity of pathogenic, water-transmittable microorganisms (4,7,8,11,12,20). The only possible method to measure the UV fluence delivered by UV flow through systems, so far, is biodosimetry (1,3,5,6,9,10,13,14,19). The result of such measurements is expressed as Reduction Equivalent Fluence REF (6). The REF is influenced by two functions, namely the fluence distribution among the microorganisms passing the irradiation plant (f) and the survival function of the biodosimeter (g) as can be clearly seen by the following equation:

$$REF\left(\frac{N}{N_0}\right) = g^{-1}\left(\int_0^{\infty} g(H_0)\cdot f(H_0)\cdot dH_0\right)$$

REF: Reduction Equivalent Fluence, N: number of surviving microorganisms, N_0: number of microorganisms before irradiation, $g(H_0)$: survival function of the biodosimeter, $g^{-1}(N/N_0)$ inverse function of $g(H_0)$, $f(H_0)$: density function of fluence distribution among microorganisms after passing the irradiation plant, H_0: fluence.

We developed a combined standard procedure consisting of a biodosimetric test and physical measurements of the radiation for type-testing of commercial UV plants. In February 1996, this method was incorporated in the Austrian National Standard M 5873 "Plants for disinfection of drinking water using UV radiation" (1). Moreover we established a test stand to perform type-testing of commercial UV plants. Since that time we have tested more than 30 UV devices from Austrian, German, Swiss and Dutch manufacturers in a flow range from 0.2 m³/h up to 500 m³/h. UV plants which have fulfilled all the requirements of the standard M 5873 may be certified by the Austrian Water Association (ÖVGW). Consequently, a variety of UV plants is available with such a certificate.

BIODOSIMETRIC METHOD ACCORDING TO THE AUSTRIAN STANDARD (1)

Biodosimeter

Spores of *Bacillus subtilis* (ATCC 6633) are irradiated in a standard laboratory batch apparatus (wavelength 253.7 nm) and reduction in the number of the spores is determined as a function of the UV fluence in order to calibrate the sensitivity of the spores (13,14,15).

Test Stand

The test stand was established at the Austrian Research and Test Center "Arsenal Research" in Vienna.

Adjustment of Measurements

The UV plants are installed at the test stand. After an operating time of around 100 hours, the lamp output is reduced to a level which is equivalent to the value at the end of the lamp's operating time. Each UV disinfection device has to be tested at three flows (maximum, minimum and one in between) and the corresponding water transmittances (253.7 nm; 100 mm) according to the manufacturer's calculation for a fluence of 400 J/m². The transmittance of the water is adjusted by pumping sodium thiosulfate-solution in the inflow and is continuously monitored by a flow-through spectrophotometer.

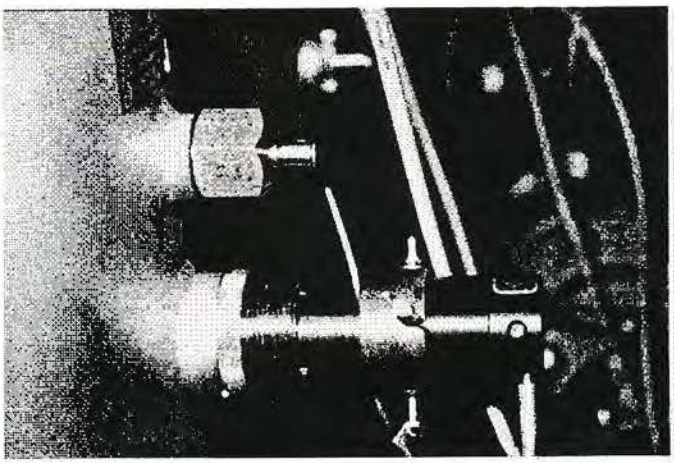

Figure 1. Measurement of the UV irradiance (W/m²) at a reference point at the wall of the irradiation chamber using a calibrated selective detector with adapter.

Biodosimetric Test Procedure

A stock solution of the UV calibrated spores is pumped into the inflow of the disinfection device in order to achieve a spore concentration of about 1 x 10^7/L in the water to be irradiated. The survival rate of the spores expressed as N/No is used to calculate the Reduction Equivalent Fluence by applying the following equation:

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

where k means the UV-sensitivity of the biodosimeter (m²/J) and d is the parameter which describes the shoulder broadness of the calibration curve of the biodosimeter.

Physical Measurements of the Radiation

During the biodosimetric tests the UV irradiance (W/m²) is measured continuously at a reference point at a standardized measuring window in the wall of the irradiation chamber using a calibrated selective detector (SED 240, International Light) as well as the UV detector installed by the manufacturer of the UV plant (Figure 1). This parameter is called reference irradiance (E_{REF}, W/m²).

UV Disinfection Devices

More than 30 commercial water disinfection plants, single lamp and multiple lamp systems, were tested (Figure 2). The devices were equipped with either 1, 3, 4, 5, 6, 8, 9, 12, 28 low pressure mercury lamps of different wattage. The standard measuring window made of quartz glass according to ÖNORM M 5873 was installed in each device.

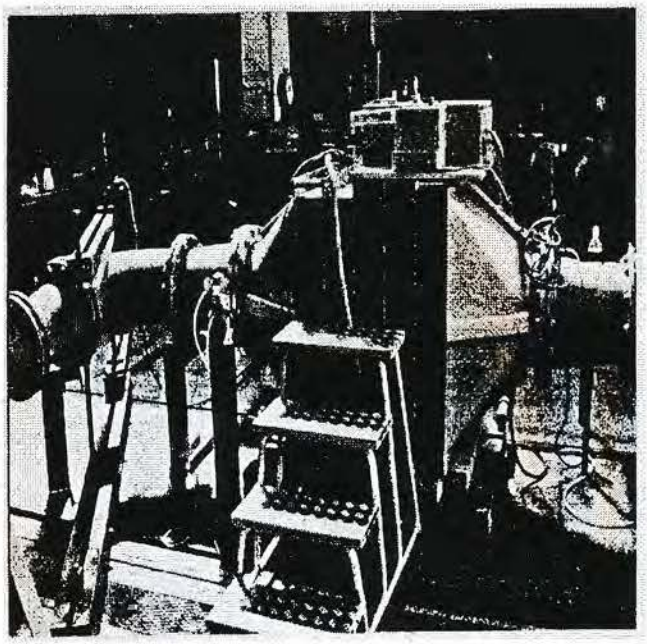

Figure 2. Commercial UV plant for water disinfection at the test stand in Vienna.

RESULTS

Some representative biodosimetric results of commercial single and multiple lamp systems (A-F) produced by different manufacturers are listed in Table 1. We compared our measured data with the fluence values as calculated by the manufacturer.

In general we found significantly lower microbicidal fluences than expected by the manufacturer. This difference between estimation and measurement increased with decreasing water transmittance. However, one single lamp system showed higher fluences than predicted by the calculation. This has been proven to be caused by reflection of the UV radiation at the wall of the irradiation chamber, as we reported previously (16).

The results of the type-test establish an approved range of application for each UV plant. Keeping to the three operating parameters (water flow, reference irradiance and UV-253.7 nm transmittance of the water) -- given by this approved range -- ensures a REF of 400 J/m² during operation and therefore a safe drinking water disinfection.

Table 1. Selected representative data of the biodosimetric type-testing of commercial UV plants from several manufacturers in comparison with dose values calculated by the manufacturer. UV plant A is a single lamp system, plants B, C, D, E and F are multiple lamp systems equipped with lamps of different wattage.

flow [m³/h]	water transmittance % [253.7 nm; 100 mm]	E_{REF}* at 253 nm [W/m²]	REF** [J/m²], measured	UV fluence [J/m²], calculated by the manufacturer	Difference between calculated and measured UV fluence (J/m²) %
UV PLANT A					
2.8	34	32	524 ± 10	420	+25
3.1	52	36	566 ± 13	420	+35
3.4	73	42	622 ± 12	450	+38
UV PLANT B					
16	35	24	366 ± 5	450	-18
33	74	42	393 ± 8	500	-21
57	74	42	289 ± 16	350	-17
UV PLANT C					
50	29	21	493 ± 3	700	-29
85	48	33	440 ± 15	570	-23
126	74	45	516 ± 18	570	-9
UV PLANT D					
157	25	17	392 ± 10	443	-12
203	40	28	374 ± 12	465	-20
404	90	110	450 ± 9	340	+32
UV PLANT E					
49	11	9	317 ± 7	584	-45
71	36	23	388 ± 14	529	-27
115	80	61	432 ± 5	466	-7
UV PLANT F					
25	10	15	394 ± 8	816	-52
60	50	39	411 ± 9	683	-40
90	80	65	447 ± 9	584	-23

*E_{REF} ... Reference Irradiance

**REF ... Reduction Equivalent Fluence (253.7 nm)

The described biodosimetric method is well suited to clarify further important questions such as the influence of reflection due to the material of the inner surface within the irradiation chambers (16), the influence of water transmittance and lamp intensity (17) or the influence of fluence distributions due to the hydraulic behavior of the water flow (6). Moreover, this method can be used to optimize UV disinfection plants helping to save costs of both, material and energy and to evaluate model calculations of the disinfection capacities of UV systems.

CONCLUSIONS

- Reliable data on UV fluence measurements in flow-through systems can only be obtained by biodosimetric methods and not by manufacturers' mathematical models as used so far (Table 1).
- For the safe UV disinfection of water a Reduction Equivalent Fluence REF of 400 J/m² has to be applied and three parameters have to be considered:
  - water flow (m³/h)
  - water transmittance (wavelength 253.7 nm; 100 mm)
  - reference irradiance E_{REF} (W/m²)
- For commercial UV plants the approved values for these three parameters have to be determined by a type-test and controlled during the disinfection process in the water works.
- Since February 1996 all these requirements have been fixed in the Austrian National Standard M 5873 and the first test stand for UV plants was established. The revised version "Plants for the disinfection of water using ultraviolet radiation – Requirements and Testing – Part 1: Low pressure mercury lamp plants" will be finished this year. An Austrian Standard on the use of medium pressure mercury lamps is in full progress.
- In the last 5 years we performed type testing of more than 30 commercial UV plants from several European manufacturers. Each UV plant, which meets the requirements stated above, are certified by the ÖVGW and obtains an approved range of application.

REFERENCES

[1] Anonymous (1996) "Plants and equipment for the disinfection of drinking water using ultraviolet radiations". *Austrian Standard* ÖNORM M 5873. The revised version "Plants for the disinfection of water using ultraviolet radiation – Requirements and Testing – Part 1: Low pressure mercury lamp plants" is in press (2000).

[2] Anonymous (1993) Austrian Codex Alimentarius Chapter B1 "Drinking Water".

[3] Anonymous (1997) DVGW Work Sheet W 294 "UV Disinfection devices for drinking water supply - requirements and testing".

[4] Battigelli D.A., Sobsey M.D. and Lobe D.C. (1993) "The inactivation of Hepatitis A virus and other model viruses by UV irradiation", Wat. Sci. Tech., 27 (3/4), 339-342.

[5] Blatchley III, E.R., Hunt B.A. (1994) "Bioassay for full-scale UV disinfection plants", Wat. Sci. Tech., 39 (4), 115-123.

[6] Cabaj A., Sommer R., Schoenen D. (1996) "Biodosimetry: Model calculation for UV water disinfection devices with regard to dose distributions", Wat. Res., 30 (4), 1003-1009.

[7] Chang J.C.H., Osoff S.F., Lobe D.C., Dorfman M.H., Dumais C.M., Qualls R.G. and Johnson J.D. (1985) "UV inactivation of pathogenic and indicator microorganisms", Appl. Environ. Microbiology, 49(6), 1361-1365.

[8] Harris G.D., Adams V.D,. Sorenson D.L. and Curtis M.S. (1987) "Ultraviolet inactivation of selected bacteria and virus with photoreactivation of bacteria", Wat. Res., 21, 687-692.

[9] Havelaar A.H., Nieuwstad T.H.J., Meulemans C.C.E., van Olphen M. (1991) "F-specific RNA bacteriophages as model viruses in UV disinfection of wastewater", Wat. Sci. Tech., 24 (2), 347-352.

[10] Qualls R.G., Johnson J.D. (1983) "Bioassay and dose measurement in UV disinfection", Appl. Environ. Microbiology, 45, 872-877.

[11] Sommer R., Weber G., Cabaj A., Wekerle J., Keck G., Schauberger G. (1989) "UV inactivation of microorganisms in water", Zbl. Hyg., 189, 214-224.

[12] Sommer R., Cabaj A., Weber G., Wekerle J. (1993) "Inactivation of viruses by UV irradiation", Wiener Mitteilungen Wasser Abwasser-Gewässer, 112, 69-72.

[13] Sommer R, Cabaj A (1993) "Evaluation of the efficiency of a UV plant for drinking water disinfection", Wat. Sci. Tech., 27 (3/4), 357-362.

[14] Sommer R., Cabaj A. (1993) "Prototype testing: A promising tool to proof the safety of UV disinfection plants", in Craun, G.F. (ed.): *Safety of water disinfection: Balancing chemical and microbial risks.* ILSI Press Washington D.C., 569-572.

[15] Sommer R., Cabaj A., Schoenen D., Gebel J., Kolch A., Havelaar A.H., Shets F.M. (1995) "Comparison of three laboratory devices for inactivation of microorganisms", Wat. Sci. Tech., 31 (5/6), 147-156.

[16] Sommer R., Cabaj A., Haider Th. (1996) "Microbiocidal effect of reflected UV radiation in devices for water disinfection", Wat. Sci. Tech., 34, (7/8), 173-177.

[17] Sommer R., Cabaj A., Pribil W., Haider Th. (1997) "Influence of lamp intensity and water transmittance on the UV disinfection of water", Wat. Sci. Tech., 35 (11/12), 113-118.

[18] Sommer R., Haider Th., Cabaj A., Pribil W. and Lhotsky M. (1998) "Time Dose Reciprocity in Disinfection of Water", Wat. Sci. Tech., 38 (12), 145-150.

[19] Sommer R., Cabaj A., Sandu T. and Lhotsky M. (1999) "Measurement of UV radiation using suspensions of microorganisms", J. Photochem. Photobiol. B: Biol. 53/1-3, 1-6.

[20] Sommer R., Lhotsky M., Haider Th. and Cabaj A. (2000) "UV inactivation, liquid holding recovery and photoreactivation of *Escherichia coli* O157 and other pathogenic *Escherichia coli* strains in water", J. Food. Protect. 63 (8), 1015-1020.

Recent Abstracts of UV Articles

Seeing the light -- disinfecting foods with UV. G. Shama (Dept. of Chem. Eng., Loughborough Univ., Loughborough LE11 3TU, UK. E-mail: g.shama@Lboro.ac.uk). International Food Hygiene 2000, 11(2):5-8.

Use of UV radiation for disinfection of foods is discussed. Topics considered include: advantages of low vapor pressure mercury UV sources (emit most of their energy within the far UV range, relatively cheap, long service lives, run at low operating temp.); effects of germicidal UV wavelengths (253-265 nm) on cell DNA; estimation of UV doses required to achieve a desired level of disinfection; factors affecting cell survival and resistance to UV treatment; UV absorption effects; techniques for measuring UV doses; estimating UV intensity; surface shielding effects; undesirable effects of UV treatment (can reduce nutritional value or affect appearance of foods); and use of UV in combination with other treatments (such as thermal processing or ozone treatment) to achieve a synergistic disinfection effect.

Using UV to Inactivate *Cryptosporidium*. J.L. Clancy, Z. Bukhari, T.M. Hargy, J.R. Bolton, B.W. Dussert and M.M. Marshall, J. Am. Water Works Assoc. 92(9):97-104 (2000).

Recent studies have shown that *Cryptosporidium parvum* oocysts demonstrate high susceptibility to low dosages of medium-pressure ultraviolet (UV) light. These investigations have raised several questions, which include determination of minimum medium-pressure UV dosages necessary to inactivate *C. parvum* oocysts, elucidation of differences (if any) between medium- and low-pressure UV light for inactivating *C. parvum* oocysts, and evaluation of medium-pressure UV effectiveness in inactivating oocysts suspended in poorer quality water. To compare low- and medium-pressure UV, the authors exposed oocysts suspended in deionized water to UV delivered by either medium- or low-pressure UV lamps at bench scale using a collimated beam apparatus. The applied UV dosages ranged from 3 to 33 mJ.cm^2, and oocyst inactivation was assessed using the neonatal mouse infectivity assay. At 3 mJ/cm^2, medium-pressure UV showed a 3.4-log inactivation of oocysts, and low-pressure UV showed a 3.0-log inactivation, demonstrating that medium- and low-pressure UV did not differ significantly in inactivating *C. parvum* oocysts.

High survival of neustonic zoea of larvae of American lobster *Homarus americanus* following short-term exposure to ultraviolet radiation (280 to 400 nm), C.A. Rodriguez, H.I. Browman, and J.F. St-Pierre (Maurice-Lamontagne Institute, Dept. of Fisheries and Oceans Canada, Division of Ocean Sciences, P.O. Box 1000, 850 Route de la Mer, Mont-Joli, Québec G5H 3Z4, Canada; Dept. d'océanographie, Université du Québec à Rimouski, 310, allée des Ursulines, Rimouski, Québec G5L 3A1, Canada). Marine Ecology, Progress Series: (Halstenbek), 2000, 193:305-309.

Ultraviolet radiation (UV-B = 280 to 320 nm; UV-A = 320 to 400 nm) is harmful to the planktonic early life stages of some marine organisms. In the Gulf of St. Lawrence, Canada, measurements of the diffuse attenuation coefficients have indicated that the maximum depth to which 10% of the surface energy penetrates at 310 nm is 3 m. Thus, organisms residing in this surface layer are exposed to UV radiation. During the summer spawning season (May to September), the first zoeal larval stages of the American lobster *Homarus americanus* are present in the first 2 m of the water column during the day. Thus, *H. americanus* larvae are exposed to UV radiation. We incubated stage I larvae of *H. americanus* under an artificial light source that simulated the irradiance conditions measured at a depth of 1 m in the Gulf of St. Lawrence waters near solar noon. Three spectral exposure treatments were used: (1) UV-B+UV-A+PAR; (2) UV-A+PAR; (3) PAR only. Larvae were irradiated for 4 d (2 h/d) and maintained thereafter under a natural photoperiod (fluorescent lamps) until first molt. Mortality was monitored daily throughout the experiment. There were no differences in mortality amongst the 3 spectral treatments. Larvae began dying at the same time and at the same rate independently of the spectral irradiation that they received. Thus, lobster larvae appear to be tolerant of short (2 h) exposures to UV radiation.

Simulation of the effects of naturally enhanced UV radiation on photosynthesis of antarctic phytoplankton, A.U. Bracher and C. Wiencke (Alfred-Wegener-Institute for Polar and Marine Research, Postfach 120161, 27515 Bremerhaven, Germany). Marine Ecology. Progress Series : (Halstenbek), 2000, 196:127-141.

The effects of spectral exposure corresponding to normal and depleted stratospheric ozone concentrations on photosynthesis