Development of UV Disinfection - Historic Background

In Europe, especially in Germany and Austria, disinfection with UV radiation in the range of 240 to 290 nm is becoming a more and more accepted alternative to conventional chemical disinfection. It is an interesting fact that application of chlorine and UV radiation for drinking water disinfection appeared almost simultaneously in the first decade of the 20th century and, therefore, UV disinfection is not a recent invention.

It took about three decades from the discovery of microbial inactivation with UV light from the sun by Downes and Blunt in 1878 via the invention of the mercury arc by Cooper-Hewitt in 1901, and the "Original Hanau" (Quartz-Burner as the first intensive UV source by Mich in 1906) to the construction of first full-scale UV disinfection apparatus by Henri and coworkers that went into operation at Marseilles (France) on August 18, 1910. It was used to disinfect prefiltered water from the river Durance at a flow of 25 m³/h with an energy consumption of 660 Wh, and achieved a more than 3-log reduction of E. coli. Problems with the ignition of the Hg arc that afforded tilting of the lamps and the simultaneous rise of chlorine disinfection as a simple and cheap alternative ruled UV out. There remained merely some niches for UV application in the production of pharmaceuticals, food, and beverages. With the invention of the neon tubes in the 1940s, low-pressure Hg lamps became available for UV disinfection, but were only used for small capacity disinfection units for water in public transport vehicles and in small water supplies.

There were many attempts to promulgate UV disinfection, but the problems with control for proper operation and effectiveness were not solved. However, the discovery of harmful byproducts from chemical disinfectants in the 1970s supported the search for alternatives and promoted disinfection with UV-radiation in the range of 240 to 290 nm, helping UV to regain interest as an alternative to conventional chemical disinfection. In the early 1980s, the German Professor Günther Schenck (Max-Planck-Institute for Radiation Chemistry) and Professor Heinz Bernhardt (Association of Drinking Water Reservoirs, ATT) took the initiative to promote research on fundamentals for a safe, large-scale application of UV disinfection in drinking water treatment.

They launched a joint research project under the auspices of ATT, lasting from 1987 to 1993. It received financial support from the German federal government and from four manufact-

Terms (according to IEC ISO and IUPAC)

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<tr>
<th>Term</th>
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<tr>
<td>Irradiance</td>
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urers. Involved were eight German and Austrian research institutes and it was advised by a panel of 12 experts. The results stated UV disinfection to be safe with a more than 4-log inactivation of drinking water relevant bacteria and viruses at radiant exposures above 400 j/m² (40 mJ/cm²) also considering photoreactivation. Excess irradiation of surface water with natural organic matter (NOM) up to some 10 kJ/m² (which is far beyond normal application for disinfection) showed no changes in molecular weight, mutagenicity and bacterial after-growth (lab and 1 m³ model tank experiments). Irradiation experiments with chlorinated hydrocarbons and pesticides showed the need of very high UV-doses beyond normal application to cause photochemical changes in the concentration of these trace contaminants. Solely, the formation of nitrite from nitrate by UV radiation may cause problems, especially with medium-pressure lamps and high nitrate concentrations. Interference from deposits of Fe and Mn were studied as well as lamp aging and colored water.

The investigations made obvious that it is impossible to calculate performance of UV disinfection systems solely from physical data. Hydraulic movement and field of irradiation are extremely complex, especially with units for high throughput, and can be approximated only by model calculations. Actinometric measurements in the system can only quantify UV input, but are given no information on the radiation field. The only means to verify performance is to take microorganisms with known UV susceptibility (ideally, 4-log inactivation at 400 J/m²) This technique is called biodosimetry. E. Coli ATCC11229 and spores of B. subtilis ATCC 6633 were used to determine the reduction equivalent dose, simulating the worst case conditions of operation.

The final gap to close was to establish a control and monitoring concept for UV devices that maintain the conditions tested by biodosimetry during operation. This concept includes control of the electrical status of every lamp and monitoring of water quality and UV-input by a removable UV sensor placed in a sensor port with a quartz window and calibrated to irradiance in W/m² at 253.7 nm. All UV sensors must have a uniform optical characteristic and need a standardized and reproducible calibration procedure. It is necessary to allow control of the system's sensor function on-site, which is possible by replacing it with a handheld reference sensor and comparing the values. The deviation must be acceptable, otherwise the system sensor has to be replaced and recalibrated.

Based on these results, ÖNorm (Austrian Standard) M5873 and DVGW Standard W 294 were prepared and released in 1996-1997. These standards define properties of UV systems for drinking water disinfection and describe the testing and monitoring procedures. With the release of the standards, testing facilities were established in Vienna (≤ 400 m³/h) and Bonn (≤ 3,000 m³/h), which allow biodosimetric tests under selected operation conditions.

Up to now, tests in Austria predominantly have covered smaller UV-systems, while in Germany, UV-systems between 400 and 2500 m³/h have prevailed.

Successfully tested UV systems may be certified by the DVGW or DVGW. Besides the biodosimetric tests, UV sensors, command control and support documentation are validated to commit with the standard.

The German DVGW Standard W 294

DVGW Standard W 294 describes a validation/certification process involving four areas:

- **Support documentation**
- **UV sensors**
- **Command and control**
- **Biodosimetric performance test.**

**Documentation**

Support documentation supplied by the manufacturer on assembly and installation, operation and maintenance (O&M), cleaning procedures, UV lamps, sleeves, and sensors is examined.

- **UV lamp** documentation must include the lamp type, electrical operation, and UV spectral output. With UV disinfection systems using polychromatic lamps, documentation must show that UV radiation below 240 nm penetrating the water does not exceed two percent of the radiation between 240 and 290 nm.

- **Sleeve** documentation must include the sleeve material, dimensions, and UV transmittance spectrum.

- **Sensor documentation** must include the sensor's operating range in W/m², spectral selectivity, measurement uncertainty, linearity, temperature and long-term stability, and recalibration requirements.

**Standardized Irradiance Measurement – Sensor Concept**

A UV reactor must have at least one on-line sensor. On-line UV sensors must provide continuous monitoring of UV lamp output with measurements verifiable using a reference sensor. The size and properties of on-line and reference sensors are defined in detail. Most important is a nearly identical view angle with all
sensors. A sensor port with defined physical dimensions and a quartz window also is described.

If the on-line sensor provides a UV irradiance measurement that deviates from the reference sensor measurement by more than the measurement uncertainty, the on-line sensor must be either cleaned, recalibrated, or replaced. Sensors must be tested and recalibrated within 15 months.

The distance between the sensor window and the lamp being monitored must be chosen by the manufacturer to provide a similar sensitivity to changes in UV lamp output and changes in the UV absorbance of the water (see explanation below).

**On-Line Command and Control**

The UV disinfection system's on-line command and control continuously monitors water flow rate and UV sensor output, and responds to ensure UV dose delivery is maintained during system operation. UV dose delivery is ensured when the UV sensor indicates an irradiance above a set point.

The set point is defined as the sensor reading required to achieve the objective dose delivery as determined using biodosimetry plus the sensor's measurement uncertainty. The on-line command and control system must respond to lamp failure and low sensor output by activating safety devices and triggering alarms.

**Challenge Test**

German drinking water disinfection practice requires a 4-log inactivation of waterborne pathogens that is achieved using a UV dose of 40 mJ/cm². Ideally, the UV disinfection system should be challenged using a microbe that demonstrates a 4-log inactivation at a dose of 40 mJ/cm². Lacking such a microbe, Standard W 294 requires UV systems be challenged using two microbes -- *Bacillus subtilis* spores and *E. coli*. *B. subtilis* inactivation is used to demonstrate a dose of 40 mJ/cm², while *E. coli* inactivation, followed by photoreactivation, is used to demonstrate a 4-log inactivation (see Figure 1).

Recent findings demonstrate the beneficial effect of the shoulder of the inactivation kinetic curve of *B. subtilis* spores that give sufficient safe results without *E. coli* challenge (see below).

The challenge test involves seeding the challenge microbe into the UV disinfection unit and measuring the inactivation achieved by the reactor (see Figure 2). Static mixers are used upstream and downstream of the unit to ensure that seeded microbes are properly mixed and that microbial samples are represented. Challenge tests are performed at the minimum and maximum flow through the UV unit with the UV sensor reading at the set point.

To determine the set point value of the UV sensor, UV lamp intensity is reduced to the level expected at the end of its useful service life (e.g., 70 percent) and UV absorbance of the water is adjusted to the maximum value for operation (e.g., 8 m⁻¹) (see Figure 3).

For the challenge the set point is achieved using two methods:

- By lowering the lamp output with low UV absorbance water (≤ 1.0 m⁻¹).
- By increasing the water UV absorbance with the lamps at maximum output.

A UV dose equivalent is assigned to the UV reactor by comparing the inactivation achieved by the reactor to a UV dose-response curve for the challenge microbe obtained using a laboratory irradiation apparatus. In this collimated beam apparatus, the inactivation of a challenge microbe is measured as a function of applied UV dose under controlled laboratory conditions.

In the German standard, the laboratory irradiation apparatus (a low-pressure mercury arc lamp) is used as the standard source. Furthermore, the microbial suspension irradiated must not be stirred and must be sampled from the center of the suspension using a small volume.

All tests are performed at a facility capable of evaluating sensors, performing challenge tests, and evaluating one-line command and control strategies. Validated UV disinfection systems are certified with a registration number and a period of validity.

**Some Details**

A 4-log-reduction requires a 99.99 percent homogeneous UV radiant exposure of 400 J/m² to all water volume elements passing the UV system and depends on radiation field and flow pattern. The optical path and intensity are influenced from diffraction through the quartz glass sleeves, reflectance from glass and steel walls, and absorbance of the water. The complex intensity pattern may be modeled, but cannot be calculated from physical measurement. Superimposed on the radiation field is the pattern of hydraulic movement. Ideally, complete mixing should be achieved, but the real intensity pattern and hydraulics may cause severe mismatch between calculation and reality.
Figure 1. E. coli is not a suitable organism to test for 400 J/m², but B. subtilis spores are.

Figure 2. Test facility for UV systems according to German DVGW standard W-294.

A performance of 400 J/m² and a 4-log reduction has to be verified by biodosimetric testing of prototypes using suspensions of germs with a known UV susceptibility. The UV susceptibility is determined with inactivation kinetics in a standardized laboratory apparatus with Hg low pressure lamps at 253.7 nm. The standard organisms are B. subtilis spores and the radiant exposure is adjusted in steps of 100 J/m² between 0 and 800 J/m² (see Figure 1). The kinetics show a shoulder curve with already no effect below 100 J/m², followed by a semilogarithmic linear slope above 200 J/m². As partial deficiencies in fluence cause no inactivation when below 100 J/m², shoulder curve kinetics enhance the detection of partial insufficient fluence (see Figure 3).

On its way passing a UV-unit, each water volume element, which may carry a microorganism, must collect sufficient UV-radiation so that the integral of the differential product of irradiance dE₀ over time dt sums up to a radiant exposure H = \int dE₀ x dt of at least 400 J/m². It is obvious that inhomo-geneities of flow pattern and radiation field have strong effects on the disinfection result. A mismatch of 0.1 percent may cause insufficient disinfection to only 99.90 percent instead of 99.99 percent inactivation, as required.

As linear increase of UV radiant exposure causes logarithmic decrease in numbers of surviving microorganisms (see Figure 1), survivors in a portion of insufficiently irradiated water will dominate the result while partial super-irradiated portions have no survivors and cannot compensate for insufficiently irradiated portions with surviving organisms.

The field of radiation around the tubular mercury lamps mounted in sleeves from UV-transparent quartz glass depends on optical geometry (intensity decreases with distance approximately...
according to the reciprocal value of the radial distance \( d \) and on the spectral absorption coefficient at 254 nm (SAC-254) of the water (according to Beer's law):

\[
E_o \sim E_i \times \left( \frac{r_i}{r_i + d} \right) \times 10^{-SAC \times 254 \times d}
\]

Figure 3. “Shoulder-curve kinetics” are more sensitive to detect hydraulic and irradiance deficiencies than are “linear kinetics” because fractions obtaining “doses” below 100 J/m\(^2\) are not inactivated and contribute fully to lower log-reduction results. Example: 10 percent receives less than 100 J/m\(^2\).

It is obvious that an increasing number of UV lamps makes the field of radiation and hydraulics more complex. Furthermore, it is apparent that the sensor does not record only the longest light path but a continuum of paths of different length. Figure 4 shows in a simplified model with a sensor position in 3-cm distance from the sleeve and a set point of 20 W/m\(^2\) good for a SAC of 8 m\(^{-1}\) and lamp fouling to 70 percent must be tested in two ways:

- First, by lowering the lamp output to 43 percent and with low UV absorbance of the water (SAC = 1.0 m\(^{-1}\)) to obtain a reading of 20 W/m\(^2\). The irradiance between sleeve and sensor position is lower compared to SAC of 8 m\(^{-1}\) and 70 percent lamp intensity and higher at greater distances.

- Second, by increasing the water UV absorbance (SAC = 13 m\(^{-1}\)) with the lamp at maximum output to obtain again a reading of 20 W/m\(^2\). Now, the irradiance between sleeve and sensor position is higher compared to SAC of 8 m\(^{-1}\) and 70 percent lamp intensity, but lower at greater distances.

With well-designed UV reactors and well-chosen sensor position, the second setting gives a lower RED compared with the first setting.

Figure 4. Diagram to explain why a UV-System -- example: set point 20 W/m\(^2\) good for SAC = 8/m and 70 percent lamp intensity -- must be tested with two settings. In this case, ▲ SAC = 1/m, I = 43 percent. △ SAC = 13/m, I = 100 percent.

**Conclusions**

- UV systems that comply with the German DVGW Standard W 294 will be suitable for reliable use in water works as a substitute for chemical disinfectants.
- With progress in testing experience, details of procedures and requirements may change.
- Especially when applied to multi-wavelength UV sources, sensor properties may need redefinition.
- The present concept normalizes UV susceptibility to radiant exposure of monochromatic radiation at 253.7 nm, which is easily available. This concept ensures that UV sources with emission of other wavelengths (but also of microbiocidal effect) are equally evaluated.
- International cooperation on the standardization of equipment, performance, and testing of UV systems is a desirable aim upon which to focus.

**Acknowledgments**

Some parts of the text are related to a compilation on the W 294 Standard by H. B. Wright and Y. A. Lawryshyn, which eased my English writing and is gratefully acknowledged.

**References**


From UV 2000, Abstracts pp. 35-41

UV Patents

Improved UV Dosage

Inventors: Ernest Rowland Blatchley III, Kuang-Ping Chiu, E. Ronald Magee, James M. Kallio, Zdravka Do-Quang, and Dennis Anthony Lynn

Assignee: Infilco Degremont Inc. (Richmond, VA, USA)


Application No.: U.S. 898,307, filed: 7/22/97

Summary: The patent is about a portable module that may be immersed in water for exposing the water to ultraviolet (UV) radiation. The unit has two headers in which the UV lamps are placed. The headers have upstream and downstream ends and opposed sides. There are fluid flow diverters between the headers and located next to the opposite sides. The flow diverters are made in such a way as to take the water by at least some of the UV lamps.