Fifteen years of experience with standardized reference radiometers for controlling low-pressure UV disinfection plants for drinking water

A. W. Schmalwieser

ABSTRACT

The only practicable way to control the disinfection capability of a UV disinfection plant for drinking water all the time is to use a UV radiometer. According to the Austrian Standard M5873, this plant radiometer is a standardized part of each plant. The standard defines a so-called reference radiometer (RRM) as well. This is necessary because a plant radiometer has to be controlled periodically. A RRM is a hand-held device which has to fulfil high-quality criteria and must be almost insensitive to environmental conditions. In this paper the principles of the concept behind the RRM are explained together with the requirements of such a device. Further on, the test methods are presented as well as a summary of test results from all RRMs developed during the past 15 years. It is shown that the radiation monitoring concept of the Austrian Standard has been successfully practicable and that the international acceptance of the Austrian Standard is justified.

Key words | Austrian Standard M5873, drinking water, properties, reference radiometer, UV disinfection

A. W. Schmalwieser
Institute of Physiology and Biophysics,
University of Veterinary Medicine,
Vienna,
Austria
and
UV-Team-Austria,
Water Test Centre Wiental,
Untertullnerbach,
Austria
E-mail: *alois.schmalwieser@vetmeduni.ac.at*

ABBREVIATIONS

ALPHO	amalgam low-pressure high output
AS	Austrian Standard
RRM	reference radiometer
UV	ultraviolet

INTRODUCTION

Disinfection of municipal drinking water using UV radiation has a long history in Austria. Austrian drinking water comes from mountain springs, backwater and ground water. As most waters contain a large amount of minerals, the quality of drinking water is ranked high by the Austrian population and is regarded as a very important topic. Additionally, drinking water is counted among basic foods by Austrian law. Therefore, disinfection using chlorine was always mistrusted. This was maybe the main reason that the first plants for UV disinfection of municipal drinking water were already established in Austria in 1955 (Kruithof & van der Leer 1990). The number of UV disinfection plants increased rapidly within the first decades, up to a few hundred. This led to the establishment of the first standard for UV disinfection of drinking water (ÖNORM M5873 1983) in the world in 1983. Standardization and design went along with research so that UV disinfection efficiency was ensured (Sommer *et al.* 1996) by evaluation (Sommer & Cabaj 1993) using biodosimetry (Cabaj *et al.* 1996) in conjunction with radiation measurements. In 1996 an expanded version of the Austrian Standard was established (ÖNORM M5873 1996), in which a biodosimetric test of plants was required to guarantee a reduction equivalent fluence of at least 400 J/m^2. Further on, requirements on UV sensor systems for constant monitoring and control were stated. During the subsequent years, UV disinfection of drinking water became even more popular. Around the year 2000, over 6,000 plants were installed in Europe

doi: 10.2166/ws.2016.197

(Sommer *et al.* 2002) but without any regulation in most countries (Sommer *et al.* 2008). At this time the Austrian Standard was divided into two parts separating low pressure (ÖNORM M5873-1 2001) and medium pressure application (ÖNORM M5873-2 2003).

A key task of this standard has been the definition of requirements on UV radiation monitoring and control. A table is available for each plant which provides the permissible difference between the plant radiometer and a reference radiometer (RRM). The deviation is in the range of ±15% and is taken into account when the permissible flow rate of the plant is calculated. If the plant radiometer deviates more, it has to be exchanged. Shortly after publication, plant radiometers (for monitoring) and RRMs (for control) were commercially available. Nowadays this Austrian Standard is accepted in several countries, such as the USA (USEPA 2006), France and others.

As RRMs according to ÖNORM M 5873-1 (2001) were available from the beginning and as our institute was the first test facility for plant radiometers and RRMs according to this standard, a lot of experience could be gained. In the following, the requirements on a RRM are described and explained together with recommended test methods (It should be noted that not all specifications from ÖNORM M5873-1 are given here, to avoid conflicts of interests with the Austrian Institute of Standards.) Further, final results from tests of all RRMs which have been on the market within the past 15 years are presented and discussed.

MATERIALS AND METHODS

RRMs according to ÖNORM M5873-1 have to fulfil a variety of quality criteria that have to be tested. In this chapter, the requirements are described together with the recommended test methods. For consistency, all tests are done with amalgam low-pressure high output (ALPHO) lamps. Before executing a test, it has to be ensured that the lamp has reached its thermal equilibrium and that short-term variability is below 1%. The reference temperature for all tests is 20 °C.

Design and composition

The RRM consists of a sensor and an electronic unit which enables measurements expressed in units of W/m^2. The sensor is a cylindrical metal shaft with an entrance optic followed by a photodetector. The dimensions of the shaft are standardized as it has to fit in any disinfection plant. Vice versa, each disinfection plant has a standardized sensor attachment system where UV radiation from inside the disinfection chamber can be measured. The entrance optic consists of a protective layer and a diffusor. The protective layer has to protect the diffusor from pollution (and must be easy to clean) as well as from damage. The diffusor has to ensure that radiation falling on the entrance optic from all directions strikes the photodetector. Such an entrance optic can be realized by a transmissible quartz plate followed by a thin diffusor of polytetrafluoroethylene (PTFE) or a similar material. It can also be realized by an opaque quartz plate that takes over the function of both. There is also a certain distance defined between the diffusor and photodetector. This distance ensures that all of the radiation entering the diffusor is detected. If the photodetector is too close to the entrance optic, some of the radiation could pass aside the detector as the diameter(s) of photodiodes are rather small.

Working range, resolution and linearity

An RRM must be able to measure irradiance at least between 0.1 W/m^2 and 250 W/m^2. The lower limit is caused by irradiances available in the laboratory for measurements of quasi-parallel radiation (see below). The upper limit was set to 250 W/m^2 as this is on the order of the highest irradiance that can be gained in the laboratory (with a single lamp). Irradiance higher than 250 W/m^2 is difficult to measure with the necessary accuracy. The resolution of a RRM must be higher than or equal to 1%.

It must be ensured that the relation between incoming photons (irradiance) and displayed irradiance stays constant independently of irradiance over the whole working range of the RRM. With that given, deviation from linearity must be small. The Austrian Standard demands that deviation from linearity is ≤5%.

There are several methods to prove linearity (e.g. Kostkowski 1997). A simple and cheap method is inserting neutral absorption filters with known transmission between the entrance optic and the lamp.

Angular response

RRMs must be able to detect radiation from a 160 ° field of view. This field of view results from the RRM's standardized position within the sensor attachment system. The angular response of a RRM must be within a certain range. This range is the same for the plant radiometers, so that measurements of both radiometers are comparable. The range is given by an upper and a lower limit expressed as analytical formulas. The angular response and its specification in the Austrian Standard result mainly from the design of the sensor, and especially from the design of the entrance optic. The angular response does not need to be close to the cosine response (as in many other fields where biologically effective radiation is measured). Microorganisms can be regarded in a first approximation as spherical objects so that the fluence from all directions causes the disinfection effect. The standardized biodosimetric test procedure for UV disinfection plants allows relating the reduction equivalent fluence (Sommer *et al.* 2004) to measurements of irradiance at the measuring window of the sensor attachment system. Hence it is only important that the angular response of radiometers is as similar as possible. A field of view of 160 ° allows (in principle) the monitoring of the whole radiation field within the disinfection chamber. The ideal angular response would be a constant one.

The angular response is tested by irradiating the sensor's entrance optic stepwise with quasi-parallel radiation inclined from 0 ° to 80 °. All measured signals are normalized to the signal at 0 °.

In Figure 1 the allowed range of the angular response is shown. This way of representation pretends an apparently small difference between the upper and the lower limit. However, the angular response is the main source of differences in measurements between RRMs.

The angular response becomes important when the radiation is not parallel. This is the case in the UV disinfection plant as the sensor attachment system as well as the sensor is rather close to the lamp. Therefore, the measurements of two RRM differ in dependence of their angular response.

In this study, the differences in measurements between a RRM that has the highest allowed angular response and a RRM that has the lowest allowed angular response were estimated by a simple model. For this a single lamp is assumed with length 2·l and a distance d between the lamp and the entrance optic of the sensor. The emittance along the length is homogeneous so that every part dx emits the same amount E_0. Further on, the water possesses a certain transmission $T_{100mm} \leq 85\%$ at 254 nm and irradiance decreases with r^2. Irradiance E received by the sensor having the angular response $s(\alpha)$ can be calculated as:

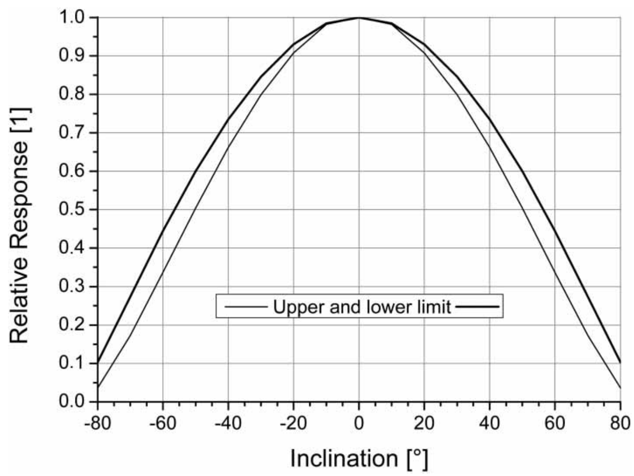

Figure 1 | Angular response as demanded by ÖNORM M5873-1:2001 (2001).

$$E = \int_{x=0}^{l} E_0 \cdot T_{100\text{mm}} \cdot 1/r_x^2 \cdot s(\alpha) \cdot dx \quad (1)$$

in which $\alpha = \arctan(x/d)$ and $r = (d^2 + x^2)^{0.5}$.

Assuming two RRM which have the lowest allowed ($s(\alpha) = s_{min}(\alpha)$) and the highest allowed angular response ($s(\alpha) = s_{max}(\alpha)$), this model predicts that the most critical situation appears at a distance $d = 99$ mm, $2{\cdot}l = 1{,}120$ mm ($=160$ °) and $T_{100mm} = 85\%$ (highest transmission for disinfection plants). In this case, the difference between these two RRMs reaches 7.65%.

Spectral response

The measurements of the RRM should be caused by radiation of 254 nm only. The Austrian Standard demands that radiation from longer wavelengths may contribute 0.1% at the most. Radiation of shorter wavelengths is absorbed by the quartz envelope of ozone-free lamps. The spectral response is examined by using a cut-off filter possessing a half-cut-off wavelength (HCW) around 280 nm. The measurement with such a filter in front of the entrance optic may not be higher than 0.1% of the measurement without this filter. A typical spectrum of an ALPHO lamp is shown in Figure 2. The emission from 254 nm contributes 91% to the total UV emission. The application of a filter with HCW = 280 nm reduces the remaining irradiance to 7%, compared with the full spectrum. Thereby the sensitivity of a RRM for wavelengths longer than 280 nm must be around 1.4% compared with that at 254 nm.

Temperature response

The sensitivity of a RRM to temperature must be low. Drinking water may have a temperature even below 4 °C (e.g. Schmalwieser *et al.* 2015) and therefore the sensor attachment should possibly as well. Hand-held instruments can have a temperature close to that of the human body. To cover this range the AS demands that within the temperature range from 0 °C to 40 °C, the change in sensitivity may be 4% at the most.

The change of sensitivity is tested within a climate chamber, where either the sensor or the hand-held electronic display unit are exposed to temperatures between 0 °C and 40 °C. If a constant amount of irradiance is brought into the chamber, the displayed irradiance allows conclusions on the temperature sensitivity of the instrument.

Calibration

The output of a photodetector is either current or voltage. This output has to be converted into units of irradiance expressed in W/m^2 by a calibration factor. Calibration is done by irradiating the entrance optic with a known irradiance. The ratio of irradiance to the signal from the photodetector gives the calibration factor. The signal of the photodetector has to be multiplied by the calibration factor to give irradiance in units of W/m^2.

In general, the angular response influences the measurements. However, if irradiance strikes the entrance optic perpendicularly, then the angular response does not matter. Therefore the calibration is done within a quasi-parallel beam. This is gained – as for testing the angular response – by a distance between the entrance optic and the aperture of the lamp which is ten times larger than the diameter of the aperture.

Total measurement uncertainty of a RRM

The total measurement uncertainty of a RRM is assumed to be the root of the sum of squared uncertainties which result from the tests above:

$$u = \sqrt{\left(u_{\text{ang}}^2 + u_{\text{lin}}^2 + u_{\text{temp}}^2 + u_{\text{spec}}^2 + u_{\text{res}}^2\right)} \quad (2)$$

The Austrian Standard demands a total measurement uncertainty $u \leq \pm 10\%$.

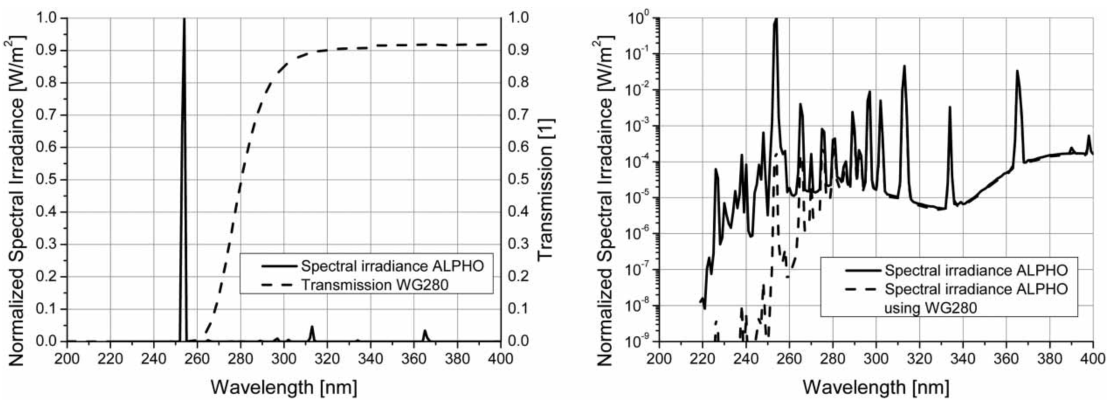

Figure 2 | Spectrum of an ALPHO lamp (left panel: linear scale, right panel: logarithmic scale) and remaining spectrum when a cut-off filter with HCW of 280 nm (left panel: transmission) is applied (right panel).

Temporal stability

The AS demands that all the properties described above must be guaranteed by the manufacturer for at least 1 year. The RRM has to be calibrated every 12 months.

RESULTS

Not many RRMs have been developed since 2001. In this paper the results of all those which passed the test according the Austrian Standard ÖNORM M5873-1:2001, referred to as the AS, are shown.

Development of the RRM

The core instrument of the first RRM was a research radiometer IL 1700 with a sensor type SED240, an interference filter NS254 and a diffusor type W (International Light, USA). A standardized adapter was set on this sensor to make it suitable for the measuring window. This combination was in use from the beginning of standardization onward (e.g. M5873:1996) but had a less robust entrance optic at first. In 2001 (ÖNORM M5873-1:2001) a new entrance optic that has a protective layer on the top was demanded. This combination is still the most accurate RRM today and should be chosen for laboratory work. Disadvantages are its costs and its size.

Despite that, it took a few years until a cheaper and handy lightweight device became available. In 2004 this RRM got its final design and passed the tests. Such instruments are still in use whereas the original manufacturer does not exist anymore. The general design of this RRM was overtaken later by other companies, whose RRMs look very similar. However, these RRMs have never been tested. That is the reason why there is no guarantee that these fulfil the requirements according to ÖNORM.

Another two RRMs were developed in 2007. One was manufactured by a company which produces UV sensors. This RRM was produced in two versions containing either a SiC-photodiode, or an AlGaN-photodiode. The other RRM came from a manufacturer of UV disinfection plants and was distributed to its own service staff only. A couple of years later (2011 and 2012) two additional RRMs from this manufacturer were developed because the range of products in respect to sensors had changed and was expanded. In 2015 another plant manufacturer developed a RRM and in 2016 a sensor manufacturer did as well. All in all, nine different RRMs have been developed and tested since the Austrian Standard M5873-1:2001 was published.

Working range, resolution and linearity

Most of the RRMs were developed for measurements of irradiance higher than 250 W/m^2. The highest working range, specified by a manufacturer, was 20,000 W/m^2. However, at this time such irradiances cannot be produced by ALPHO lamps. Recent ALPHO lamps emit up to 700 W/m^2 at the surface. In disinfection plants, measured irradiance is up to 500 W/m^2.

The lowest measureable values were either 0.001 W/m^2, or 0.01 W/m^2 or 0.1 W/m^2. A measuring limit of at least 0.1 W/m^2, as demanded by the AS, restricts the working range to irradiance $\geq$10 W/m^2 because resolution must be at least 1%. This affects testing. With this measuring limit, linearity can be tested theoretically from 2 W/m^2 (uncertainty ±2.5%) upwards, but only measurements of irradiances $\geq$10 W/m^2 deliver satisfying accuracy (±1%). This causes additional efforts as the angular response has to be tested by quasi-parallel radiation whereas irradiance values gained in the laboratory are even lower than 1 W/m^2 (see below) and deviation from linearity has to be known.

Linearity up to 300 W/m^2 can be tested straightforwardly in front of an ALPHO lamp. Linearity up to 600 W/m^2 can be tested by sensor manipulation. For this, the entrance optic of the sensor was removed to eliminate absorption by the diffusor. During the test, the position of the sensor was always the same. With that, any influences from angular response could be avoided. Incremental absorption filters were set in front of the sensor.

Angular response

The angular response is tested by irradiating the sensor with quasi-parallel radiation. Quasi-parallel radiation is gained only beyond a certain distance from the radiation source.

The distance depends on the geometry of the radiation source. ALPHO lamps are tube lamps with diameters in the range of 20 mm to 40 mm and lengths of 1 m and more. For testing, radiation escapes through a circular aperture in the lamp cover. To get the highest output, the diameter of the aperture should be no more than half of the diameter of the lamp. In this configuration, the distance has to be ten times larger than the aperture of the lamp. If the diameter of the aperture is equal to the diameter of the entrance optic, then the inclination of the irradiance is within 0 ° and ±5.7 °. With such a setup, irradiance is on the order of 1 W/m^2. The distance is crucial for the result. The shorter the distance, the higher appears the angular response, especially at inclinations larger than 20 °. This effect is shown in Figure 3 (open circles). After reaching the critical distance, the measured angular response does not change anymore with distance. Interestingly, this distance is larger for RRMs equipped with an opaque quartz plate and shorter for RRMs equipped with a transparent quartz plate and a thin diffusor of PTFE. The test results show (Figure 3, filled circles) that the angular response is generally close to the upper limit at inclinations ≤40 °. It should be noted that the angular response according to the AS is calculated in respect to an ideal cosine response (as depicted in Figure 3). As mentioned above, an angular response of a RRM that cannot display values less than 0.1 W/m^2 cannot be tested straightforwardly. There was

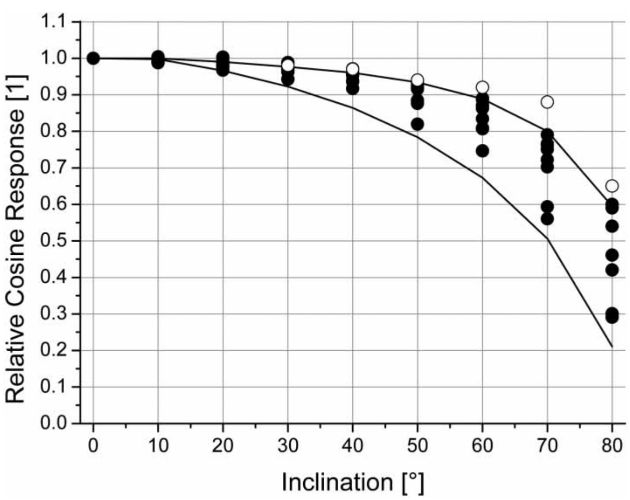

Figure 3 | Angular response of RRMs in relation to the cosine (filled circles). The open circles indicate the response at shorter distance.

only one RRM having this limit. It was tested after building in a special signal amplifier.

The tests showed that the angular response of all RRMs is noticeable higher than the lower limit given by the AS. With that, the calculated worst-case uncertainty of 7.65% is larger than those found in practice. Therefore, the lower limit could be raised without losing a RRM. By taking the lowest measured values (minus uncertainties of measurements) as the lower limit, the measurement uncertainty can be reduced significantly. This new limit can be described by the following formula:

$$s_{\min}(\alpha) = \frac{(a + c \cdot \alpha^2)}{1 + b \cdot \alpha^2}$$

in which $a = 0.99789$, $b = -0.000080345$, $c = -0.0001332$.

Inputting $s_{\min}$ in Equation (1) delivers a possible maximum difference of 5.3%.

Spectral response

Testing the spectral response is a rather easy task. Cut-off filters of type WG 280 with a thickness between 1 mm (HCW = 270 nm) and 3 mm (HCW = 290 nm) can be used. However, the transmission has to have been controlled, because the HCW may vary by a few nm due to the production process. The filter with HCW = 270 nm reduces the remaining UV irradiance to 8.6% while a filter with HCW = 290 nm reduces it to 6.7%. This denotes that the spectral sensitivity of a RRM at longer wavelengths is in any case less than 0.1/6.7 = 1.5%.

Temperature stability

The change of response caused by a change of temperature was tested within a climate chamber (Heraeus HC 4020, Vötsch, Germany). Temperature and humidity inside the chamber could be controlled. An ALPHO lamp was mounted outside. UV radiation was transmitted into the chamber by an optical quartz fibre.

In the case of analogue sensors, the sensor and the electronic unit have to be tested separately. In the case of digital sensors only the sensor has to be tested because the conversion electronics are in the sensor and the digital output is not influenced by temperature.

To evaluate the temperature response of the sensor, it was placed inside the climate chamber and the monitoring unit was placed outside. The temperature outside was nearly constant at 20 °C. The temperature inside the chamber was increased from 0 °C to 40 °C in steps of 10 °C under almost constant relative humidity of 80%. After reaching a certain temperature level there was a wait of, 30 minutes until measurements were made to ensure temperature equalization. The sensor tested was connected to the outlet of the quartz fibre by a coupler that enabled air circulation to avoid fogging. All tested sensors were stored during the whole test within the climate chamber.

The emission from the lamp was controlled by using another RRM. This RRM was stored outside the chamber at constant temperature and plugged only for the control measurement to the fibre inside the chamber. This procedure enabled measuring and correcting possible variability in the emission of the lamp.

To evaluate the temperature response of the display unit, it was placed inside the climate chamber, while the sensor was placed outside and kept under constant environmental conditions. Temperature was increased in steps of 10 °C from 0 °C to 40 °C. Relative humidity was chosen to be around 80%. Measurements of irradiance were made 30 minutes after reaching the certain temperate level inside the chamber. The sensor was mounted outside, in front of the lamp. To correct for changes in the emittance of the light source, irradiance was also measured outside by another RRM in parallel. Figure 4 demonstrates the typical

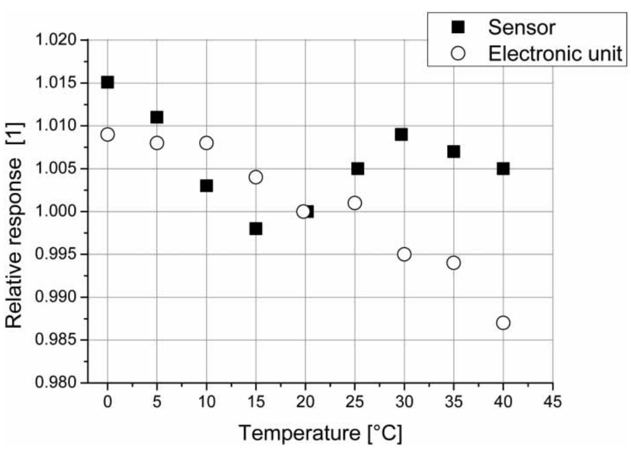

Figure 4 | Typical temperature sensitivity of sensors possessing a PTFE diffusor (filled squares) and of an electronic unit (open circles) normalized to 20 °C.

temperature sensitivity of a sensor possessing a PTFE diffusor and an electronic unit that measures voltage output from the sensor. A combination of both gives the highest temperature drift. A few RRMs did not show any statistically significant temperature drift.

Calibration

The calibration is done by measuring the quasi-parallel radiation ($r \geq 10\,d$) from the emission line at 253.7 nm by a spectroradiometer after the lamp has reached its thermal equilibrium. Band width is 1 nm and the step width is 0.1 nm. These spectral measurements (with signal-to-noise ratio >1,000) are taken from 250 nm to 259 nm and integrated to gain the irradiance E. Afterwards the sensor of the RRM is set at the same position and the signal S is measured. The ratio of E to S delivers the calibration factor. Nowadays ALPHO deliver around 1 W/m^2 at $r = 10\,d$.

The spectroradiometer is calibrated in the UV range by a 1,000 W FEL lamp and a 30 W deuterium lamp. Spectral emittance of both lamps came from PTB (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany). The calibration uncertainty at 254 nm is currently ±4.4%.

Calibration is not very sensitive to the range of integration. Irradiance from an interval of ±5 nm around the emission line at 253.7 nm is only 0.3% larger than from an interval of ±2 nm. However, calibration is sensitive to the distance and to linearity. The shorter the distance, the more variation can be seen in the calibration factor (after correction for linearity).

Temporal stability

At our institute RRMs have been available since the early days of standardization. Calibration of our RRMs has been done periodically in the same manner since 1999 when the most recent version of the AS was worked out. With that, the change in sensitivity of our RRMs can be followed over the years. Figure 5 shows the relative response of four different types of RRMs since their first calibration at our institute. These RRMs are used frequently in the laboratory (e.g. Schmalwieser *et al.* 2014) and in water works (e.g. Schmalwieser *et al.* 2015). It can be seen that these devices

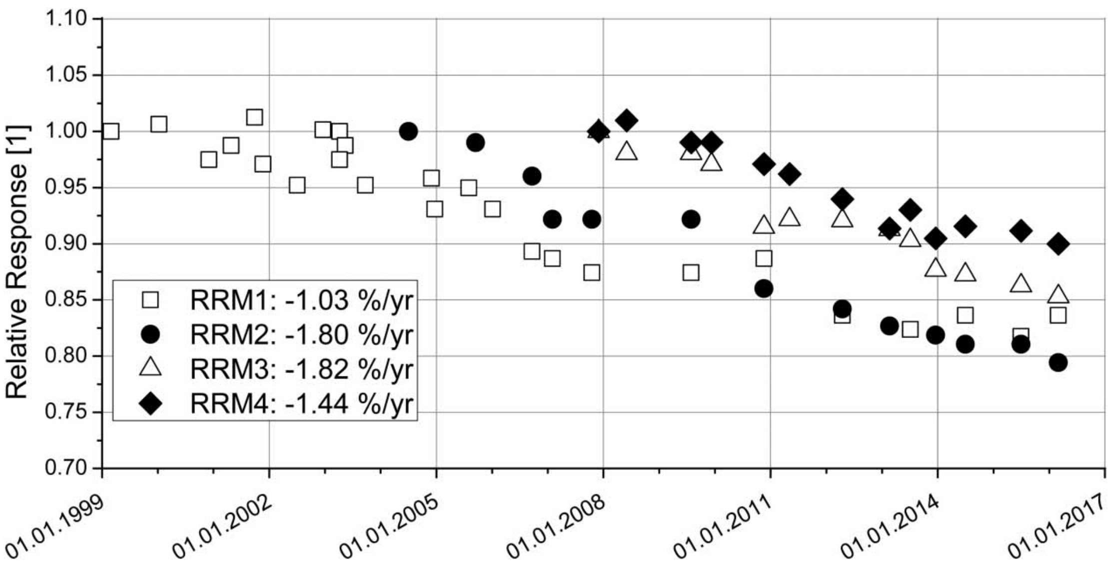

Figure 5 | Relative response of four different types of RRMs.

are very stable over time. Linear regression analysis delivers a decrease of response in the range of 1% to 2% per year (RRM1: −1.03%/yr, $r^2 = 0.85$, since 1999; RRM2: −1.80%/yr, $r^2 = 0.96$, since 2004; RRM3: −1.82%/yr, $r^2 = 0.94$, since 2007; RRM4: −1.44%/yr, $r^2 = 0.93$, since 2007). Beside this steady decrease, changes result from new calibrations of the spectroradiometer or from new calibrations of the calibration lamps and are on the order of a few percent. Assuming a constant linear decrease in sensitivity, all measured relative response values (N = 62) deviate between +4.2% and −2.1% from the regression lines. The largest difference between two consecutive calibrations of a certain RRM was 6.2%. These deviations are on the order of the uncertainty of the calibration lamps (±4.4%).

Measurement uncertainty

Using the highest allowed threshold values from above one gets $u_{\text{ang}} = 7.65\%$, $u_{\text{lin}} = 5.00\%$, $u_{\text{temp}} = 4.00\%$, $u_{\text{spec}} = 0.10\%$, $u_{\text{res}} = 1.00\%$. According to these, the maximum uncertainty u is 10.0%. In the worst-case scenario, the measurements made by two RRMs, which have the opposite properties in respect to the limit values, could differ by 17.7%. The main contribution to the total measurement uncertainty comes from the allowed range of angular response that causes an uncertainty above ±7%. The total measurement uncertainty of the tested RRMs is in the range from ±8.5% to ±10%.

DISCUSSION AND CONCLUSIONS

The main source of uncertainties in measuring irradiance at 253.7 nm by a RRM is calibration. The recent accuracy by national calibration services at this wavelength is ±4.4%. Another ±2% may come from the calibration procedure of the RRM. This denotes that measurements of two calibrated RRM can differ by 12.8%. Although many efforts have been made in the past and are still ongoing, one should not expect that there will be a significant improvement in the near future.

A main contributor to total measurement uncertainty is the difference in angular response due to the allowed range. The uncertainty from this is not explicitly given by the AS. A simple model was developed to estimate the worst-case scenario. It was found that two RRMs could differ by 7.65%. The tests have shown that recent RRMs may differ by 5.2% because they do not capitalize the lower limit. With that the total measurement uncertainty is reduced to ±8.3% and most of the RRMs had a total measurement uncertainty below 7.5%.

The lower measurement limit of a RRM is required to be 0.1 W/m^2. This requires additional efforts for testing and restricts the application range of a RRM to irradiance higher than 10 W/m^2. Additionally, the uncertainty of calibration becomes high. Therefore this limit should be lowered to 0.01 W/m^2. As shown by several manufacturers, such a lower limit does not represent a technical challenge.

The RRMs have been in use over more than 15 years at our institute and changes of sensitivity are documented. From this it has been shown that the guidelines for design have enabled a temporally stable instrument. The decrease of the relative response is on the order of 1% to 2% per year.

The concept of a RRM for controlling the plant radiometer can also be found in later standards and guidelines of other countries (e.g. DVGW W294-3 2006; USEPA 2006; NWRI 2012). The properties and quality criteria are similar but practical implementation differs. The American guidelines (USEPA 2006; NWRI 2012) are less definite, especially in the design (dimensions) of the sensor and its entrance optic. Various obviously different sensors have been developed. Examples and properties of plant sensors and reference sensors in use can be found in Wright *et al.* (2009). Water works possessing different UV disinfection plants must own and care for different RRMs. This could enhance the running costs for water production. Much more critical is the fact that quality control and calibration are left as the responsibility of the manufacturers. Objective control by a third party is not intended by these guidelines and remains very difficult.

In contrast, the AS allows independent control. RRMs are available on the free market and fit in every AS-certified UV disinfection plant. Public authorities, water works and special service staff are able to prove disinfection capability all the time.

In Germany the situation is quite different. The working paper DVGW W294-3 (2006), which defines both RRMs and plant radiometers, could never be realized as the requirements for radiometers as defined are too sophisticated. Although many efforts have been made to test and certificate UV disinfection plants for drinking water according to W294 there is as yet no plant that fulfils the W294 completely as there are no proven radiometers available. It therefore cannot be guaranteed that these plants deliver the necessary reduction equivalent fluence during operation. However, to avoid running a risk, most manufacturers use RRMs according to the AS and equip their plants with corresponding radiometers.

REFERENCES

Cabaj, A., Sommer, R. & Schoenen, D. 1996 Biodosimetry: model calculations for UV water disinfection devices with regard to dose distributions. *Water Research* **30**, 1003–1009.

DVGW (Deutscher Verein des Gas- und Wasserfaches) 2006 *DVGW 294-3:2006. UV-Geräte zur Desinfektion in der Wasserversorgung, Teil 3: Messfenster und Sensoren zur radiometrischen Überwachung –Anforderungen, Prüfung und Kalibrierung*. DVGW, Bonn, Germany.

Kostkowski, H. J. 1997 *Reliable Spectroradiometry*. Spectroradiometric Consulting, La Plata, MA, USA.

Kruithof, J. C. & van der Leer, R. C. 1990 Practical experiences with UV-disinfection in the Netherlands. In: *Proceedings of the American Water Works Association Seminar on Emerging Technologies in Practice*. Annual Conference of the American Water Works Association, June 17–21. Cincinnati, OH, USA.

NWRI (National Water Research Institute) 2012 *Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse*. WRI-2012-04, National Water Research Institute, Fountain Valley, CA, USA.

ÖNORM (Österreichisches Normungsinstitut) 1983 VORNORM ÖNORM M 5873:1983. *Requirements for Plants for the Disinfection of Water by Ultra-violet-rays*. ON Österreichisches Normungsinstitut (Austrian Standards Institute), Vienna, Austria.

ÖNORM M5873 1996 ÖNORM M 5873:1996. *Requirements for Plants for the Disinfection of Water by Ultra-violet-rays*. ON Österreichisches Normungsinstitut (Austrian Standards Institute), Vienna, Austria.

ÖNORM 2001 ÖNORM M 5873-1:2001E. *Plants for Disinfection of Water Using Ultraviolet Radiation: Requirements and Testing, Part 1: Low Pressure Mercury Lamp Plants*. ON Österreichisches Normungsinstitut (Austrian Standards Institute), Vienna, Austria.

ÖNORM (Austrian Standard) 2003 VORNORM M5873-2. *Plants for Disinfection of Water Using Ultraviolet Radiation: Requirements and Testing, Part 2: Medium Pressure Mercury Lamp Plants*. Austrian Standards Institute, Vienna, Austria.

Schmalwieser, A. W., Wright, H., Cabaj, A., Heath, M., Mackay, E. D. & Schauberger, G. 2014 Aging of low pressure amalgam lamps on UV dose delivery. *Journal of Environmental Engineering and Science* **9**, 113–124.

Schmalwieser, A. W., Cabaj, A., Hirschmann, G. & Sommer, R. 2015 Ten-year monitoring of an ultraviolet disinfection plant for drinking water. *Journal of Environmental Engineering and Science* **10**, 34–39.

Sommer, R. & Cabaj, A. 1993 Evaluation of the efficiency of a UV plant for drinking water disinfection. *Water Science and Technology* **27** (3–4), 357–362.

Sommer, R., Cabaj, A. & Haider, T. 1996 Microbicidal effect of reflected UV radiation in devices for water disinfection. *Water Science and Technology* **34** (7–8), 173–177.

Sommer, R., Cabaj, A., Hirschmann, G., Pribil, W. & Haider, T. 2002 UV Disinfection of drinking water in Europe: application and regulation. In: *Proc. of the First Asia Regional Conference on Ultraviolet Technology for Water, Wastewater, and Environmental Applications*. International Ultraviolet Association, Scottsdale, AZ, USA. CD-ROM.

Sommer, R., Cabaj, A., Haider, T. & Hirschmann, G. 2004 UV drinking water disinfection – requirements, testing and surveillance: exemplified by the Austrian National Standards M 5873-1 and M 5873-2. *IUVA News* **6** (4), 27–35.

Sommer, R., Cabaj, A., Hirschmann, G. & Haider, T. 2008 Disinfection of drinking water by UV irradiation: basic principles – specific requirements – international implementations. *Ozone: Science and Engineering* **30** (1), 43–48.

USEPA (US Environmental Protection Agency) 2006 *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule*. EPA 815-R-06-007, US Environmental Protection Agency, Office of Water, Washington, DC, USA.

Wright, H., Gaithuma, D., Dzurny, T., Schulz, C., McCurdy, K., Bogan, T., Cabaj, A., Schmalwieser, A., Ohno, Y. & Larason, T. 2009 *Design and Performance Guidelines for UV Sensor Systems*. American Water Waterworks Association Research Foundation, Denver, CO, USA.

First received 30 June 2016; accepted in revised form 22 November 2016. Available online 9 December 2016