# DRINKING WATER UV OPERATION WITHOUT ON-LINE UVT MONITORING: THE DEFAULT UVT AND SENSOR SETPOINT APPROACHES TO VALIDATION

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## ABSTRACT

UV reactors used in drinking water applications use an on-line UV dose monitoring algorithm to define disinfection performance. The USEPA UV Disinfection Guidance Manual describes two types of UV dose algorithms: the first is the calculated UV dose approach, which predicts the log inactivation or reduction equivalent UV dose (RED) as a function of flowrate through the reactor, the UV transmittance (UVT) of the water at 254 nm, the UV intensity measured by UV sensors, and lamp, row, or bank on/off status. The second is the UV intensity setpoint approach, in which case the reactor is in compliance with a required RED when the UV intensity measured by the UV sensors is greater than a required value defined as a function of flowrate through the reactor. A key benefit of the UV intensity setpoint approach is that no online UVT monitor is required, which is ideal for small or remote UV systems.

## INTRODUCTION

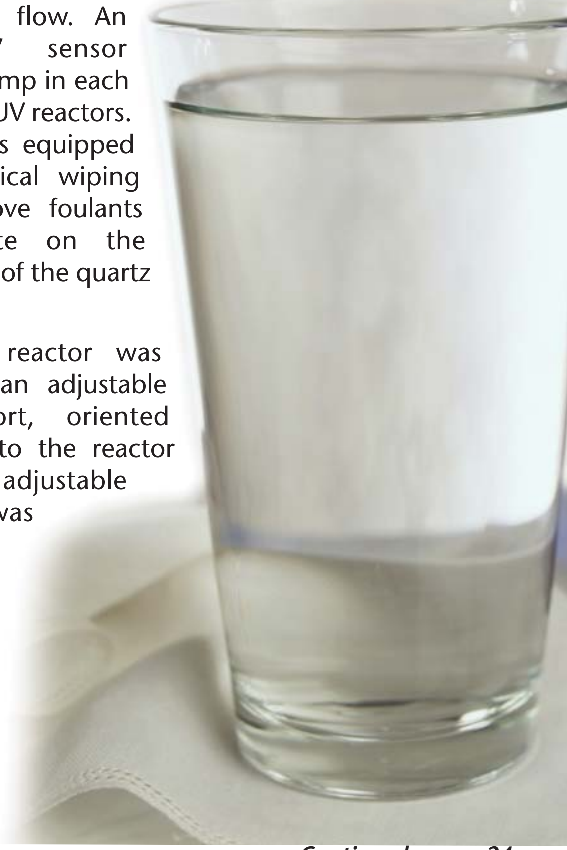
The UV intensity setpoint approach is validated by measuring the log inactivation and RED of a test microbe at various flowrates with the UVT and lamp power setting adjusted to provide specific UV sensor readings at the setpoint. Typically, the reactor is validated under two conditions of UVT and ballast power: maximum power and reduced UVT, and maximum UVT and reduced power. Depending on UV sensor position, the RED values measured at these two conditions may or may not be the same. The RED assigned to the reactor is the lower of these values.

UV vendors will often validate their reactors knowing neither the relationships between the RED and the UV sensor response nor the impact of the UV sensor position on those REDs, which can lead to expensive iterative validation as the vendor works to identify the UV sensor readings required to achieve the required RED (e.g. 40 mJ/cm$^2$) and to optimize the UV sensor position to minimize the differences between the REDs measured with the two test conditions. This approach also provides no information about REDs at UV sensor readings above and below the setpoint value or the relationship between RED and flowrate. In order to resolve these issues, Hanovia Ltd. of Berkshire, United Kingdom developed a new approach for validating their ProLine series of in-vessel UV reactors using the UV intensity setpoint approach. The approach provides a UV dose algorithm that calculates RED as a function of flowrate and UV sensor reading but does not require an online UVT monitor.

## BACKGROUND

Three AF3 Series UV disinfection reactors, AF3 0014, AF3 0027 and AF3 0116, manufactured by Hanovia Ltd. of Berkshire, United Kingdom, were validated at a test facility located in Portland, OR. Each reactor was equipped with one low pressure high output amalgam lamp within an L-shaped cylindrical reactor with flanged inlet and outlet openings. The nominal power ratings for the AF3 0014, AF3 0027 and AF3 0116 UV reactor lamps were 140, 270 and 500 W, respectively. Each reactor's lamp was housed within a quartz sleeve that was oriented horizontally and parallel to flow. An individual UV sensor monitored the lamp in each of the three AF3 UV reactors. Each reactor was equipped with a mechanical wiping system to remove foulants that accumulate on the external surfaces of the quartz sleeve.

Each AF3 UV reactor was equipped with an adjustable UV sensor port, oriented perpendicularly to the reactor sidewall. The adjustable sensor port was designed to accommodate spacers of various lengths to result in different water layers, i.e. the distance between the quartz sleeve



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*Continued from pg 23*

and the UV sensor port window. UV sensor performance for each AF3 UV reactor was characterized during functional testing by evaluating the dependence of the measured UV intensity on ballast power, UVT, and water layer.

The validation data from the AF3 UV reactors was analyzed to develop an online UV dose-monitoring approach that requires UVT measurement input (the 'calculated UV dose' approach), as well as one that does not require UVT measurement input (the 'UV intensity setpoint' approach). Depending on the water layer, UV dose monitoring without input of the UVT can be more conservative than the calculated UV dose approach. In order to develop efficient UV dose monitoring algorithms for the AF3 UV reactors that do not require input of UVT measurement, the 'optimal' location for the individual reactor duty UV sensors was determined using the AF3 UV reactors' biodosimetry data and UV intensity data.

To facilitate the prediction of the UV intensity for the AF3 UV reactors as a function of ballast operating power, UVT and water layer, UV intensity data was collected at three water layers with each AF3 UV reactor. The coefficients expressing UV intensity as a function of ballast operating power and UVT at each of the three water layers were then interpolated as a function of the water layer using polynomial interpolation in the Lagrange form. As a result of the interpolation, two general equations predicting the UV sensor readings for each AF3 UV reactor as a function of UVT, ballast power setting, and water layer were developed:

$$S = 10^{A_{wl}} \times B_{wl}^{UVT} \times P^{C_{wl}} \times D_{wl}^{P} \qquad [1]$$

$$A_{wl1}, B_{wl1}, C_{wl1}, D_{wl1} = a \times \left(b \times wl\right) \times \left(c \times wl^{2}\right) \qquad [2]$$

where:

$S$ = measured UV intensity (W/m$^2$)

$P$ = ballast power (W)

wl = water layer between UV sensor and quartz sleeve (mm)

$A_{wl} - D_{wl}$ = empirically-determined coefficients (see **Table 1.1**) for a given water layer

$a - c$ = empirically-determined coefficients (see **Table 1.1**)

**Fig. 1** shows the relationship between the UV intensity measured by the AF3 UV reactors' duty UV sensors, at three water layers, and the UV intensity predicted using **Equations 1 and 2**. The prediction residuals, calculated as the difference between the measured and predicted UV sensor readings divided by the predicted UV sensor reading, showed low variability, with a maximum standard deviation of 5.1 percent, and were randomly distributed around zero, with an average of 0.0 percent.

**UV validation at the Portland test facility has a global impact on UV implementation**

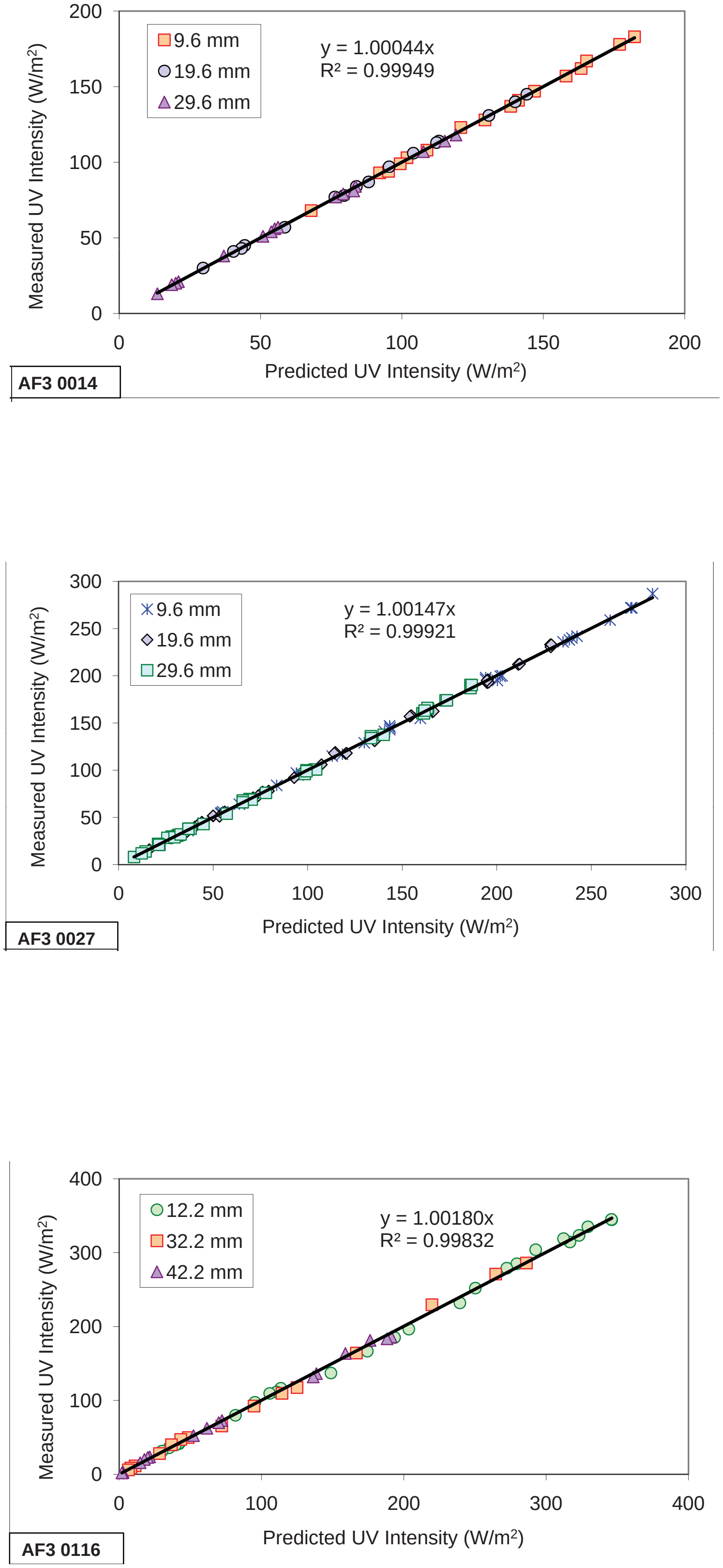

**Figure 1**: *Predicted versus measured UV Intensity for the AF3 UV reactors (the reactor number is in the lower left corner of each chart).*

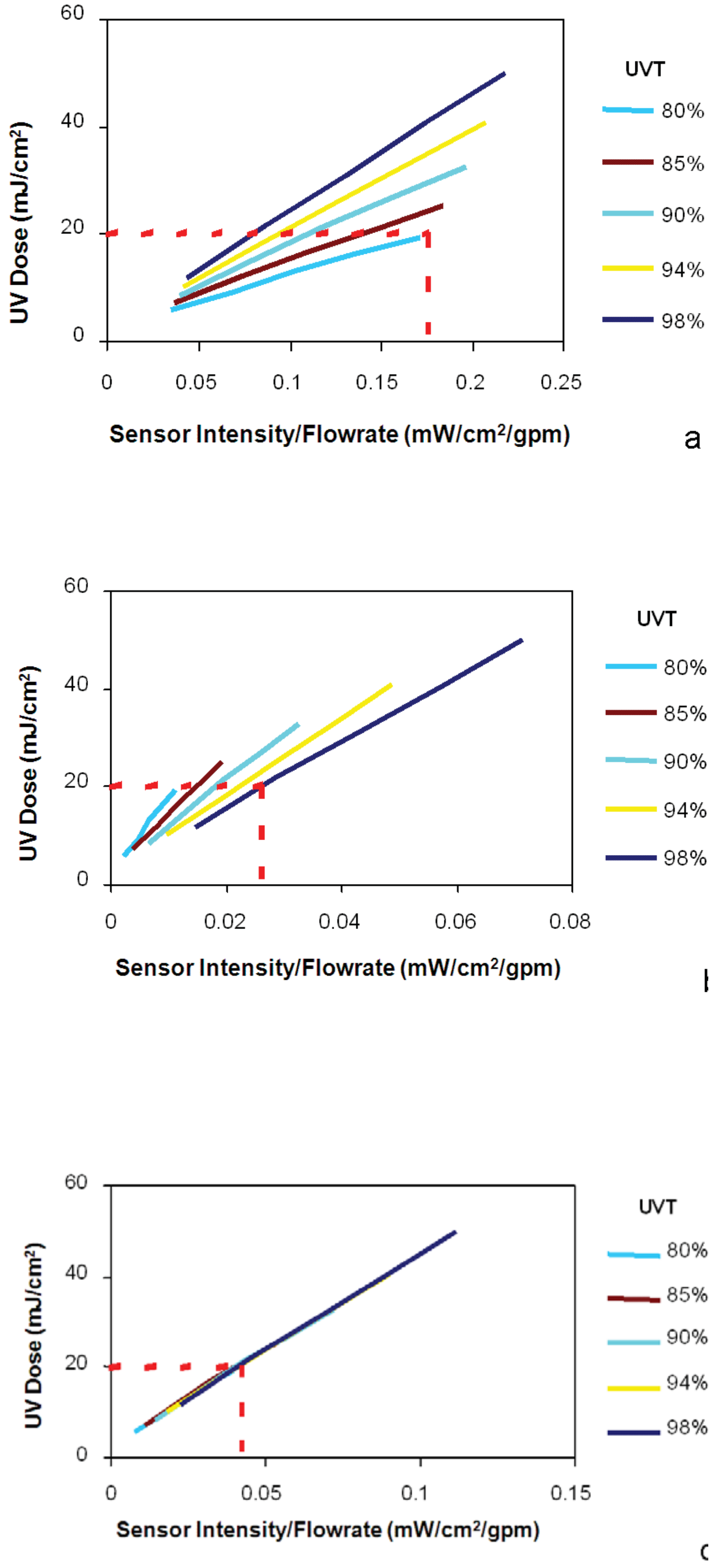

**Figure 2**: *Relationship between the MS2 RED and the measured UV intensity divided by the flowrate for three sensor positions with a hypothetical UV reactor (Wright et al., 2002); (a) sensor close to lamp; (b) sensor far from lamp; (c) optimal sensor position.*

*Continued on pg 26*

*Continued from pg 25*

# OPTIMAL WATER LAYER ANALYSIS

The relationship between the RED, UV intensity ($S$), and flowrate ($Q$) varies based on the combination of the UVT and the water layer (Wright et al., 2002). Based on the UV intensity setpoint approach, if the UV sensor is located at an 'optimal' distance from the monitored lamp, the relationship between RED and UV intensity divided by flowrate ($S/Q$) for various water UVT values will overlap (**Fig. 2**). If this is the case, the combined dataset for various UVT values can be described by a single function, which can be used for UV dose monitoring over the validated range of UVT. However, if the UV sensor is located at a water layer other than this 'optimal' position, the relationship between the RED and $S/Q$ will not overlap and will depend on UVT. If the UV sensor is located relatively close to the lamps, the RED will be proportional to the UVT. However, if the UV sensor is located relatively far from the lamps, the RED will be inversely proportional to the UVT.

The biodosimetric testing of both the AF3 0014 and AF3 0027 reactors was conducted with a water layer of 18.5 mm, while biodosimetric testing of the AF3 0116 reactor was conducted with a water layer of 32 mm. With all three reactors, the RED at a given value of $S/Q$ tended to increase proportionally with UVT, suggesting that the UV sensor was closer to the lamps than the optimized location. The increase was most notable with the AF3 0014 and less so with the AF3 0027 and AF3 0116 reactors.

The relationship between the MS2 RED and the predicted $S/Q$ was used to identify a calculated estimate of the optimized UV sensor water layer based on the logistical constraints of equipment manufacturing. In practice, this calculated distance minimized the residuals between the predicted and measured REDs and resulted in optimal water layers of 23 mm for both the AF3 0014 and AF3 0027 reactors and 32 mm for the AF3 0116 reactor. In the latter case, the water layer used during biodosimetry (32 mm) was determined, after the fact, to be close to the optimal location for the duty sensor.

# CALCULATED UV DOSE MONITORING ALGORITHM ANALYSIS

For calculated UV dose monitoring with each AF3 UV reactor, the measured MS2 RED (mJ/cm$^2$) was best expressed as a function of relative lamp output (at the determined optimal water layers), flowrate (mgd) and absorbance (UVA) at 254 nm:

$$\text{MS2 RED} = e^{A} \times \text{UVA}^{B\times\text{UVA}} \times \left[\frac{S/S_0}{Q}\right]^{[C+D\times\ln(\text{UVA})]} \quad [3]$$

where

$S/S_0$ = relative lamp output, calculated as the ratio of the measured UV intensity, S (W/m$^2$), to the UV intensity predicted with the lamp operating at maximum power, given the measured UVT, with Eqs. 1 and 2, $S_0$ (W/m$^2$)

UVA = log(UVT$_{254}$/100)

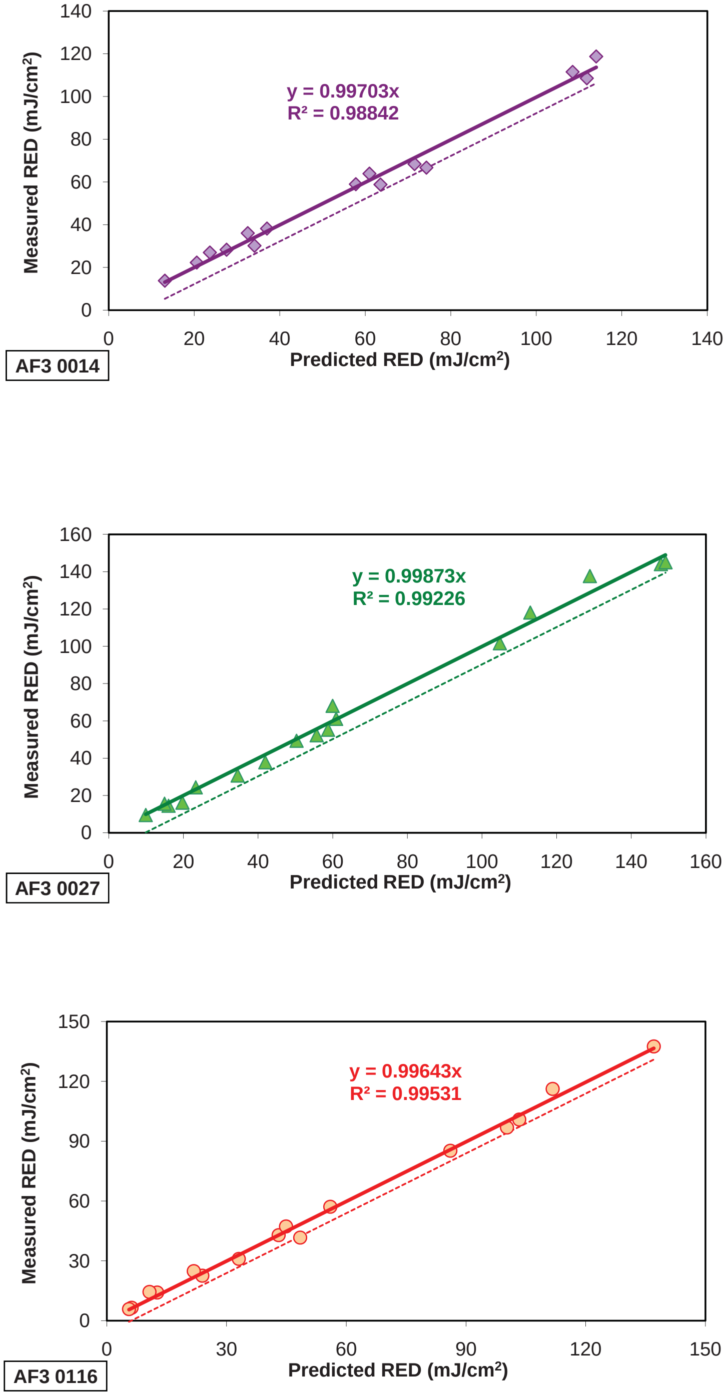

**Figure 3**: *Predicted versus measured REDs for the AF3 UV reactors: calculated UV dose approach (the reactor number is in the lower left corner of each chart).*

**Fig. 3** shows the relationship between measured and predicted REDs using Eq. 3 for the three AF3 UV reactors. The data was fit with a linear function forced through the origin (0,0), and the R squared coefficient of determination for the fits were all at least 0.99, indicating a strong correlation between the measured and predicted RED values. The lower 95 percent prediction intervals are shown as dashed lines, calculated as described in Section 5.9.2.2 of the UVDGM. The average and standard deviation of the prediction residuals (which were calculated as the difference between the predicted and measured RED) were 0.0 and 3.6 mJ/cm$^2$, 0.0 and 4.6 mJ/cm$^2$, and 0.0 and 2.9 mJ/cm$^2$ for the the AF3 0014, AF3 0027 and AF3 0116 reactors, respectively.

# UV DOSE MONITORING WITHOUT UVT INPUT

Nominal lamp output, $S_0$, is a function of the UVT, and, as a result, the RED (as predicted by Eq. 3) is a function of *S, Q* and *UVT*. In order to develop a UV dose monitoring approach for each AF3 UV reactor that does not require *UVT* measurement, Eq. 3 (using optimal water layers) was used to predict the MS2 REDs at discrete *S/Q* values, which spanned the validated range of *S/Q*. At each of these *S/Q* values, the RED was calculated across the validated UVT range.

In order to define a conservative UV dose monitoring approach without on-line UVT measurements, the minimum REDs predicted at each discrete *S/Q* value, across the validated UVT, were plotted as a function of the corresponding *S/Q*. The relationship between minimum predicted MS2 REDs and the *S/Q* for each AF3 UV reactor were best fit with a fifth order polynomial equation:

$$\mathrm{RED} = A \times \left[ S/_{Q} \right]^4 + B \times \left[ S/_{Q} \right]^3 + C \times \left[ S/_{Q} \right]^2 + D \times S/_{Q} + E \quad [4]$$

**Fig. 4** shows the relationship between measured and predicted REDs using Eq. 4 for the three AF3 UV reactors.

Since the RED values input into Eq. 4 are the minimum REDs for a given S/Q, they provide a conservative dose monitoring approach across the validated range of UVT (**Fig. 4**). As mentioned above, the water layers matched the optimal, calculated location to manufacturing constraints. Theory suggests that use of this equation outside the validated range of UVT, though considered an extrapolation, will still provide conservative UV dose monitoring for the AF3 UV reactors.

The UV dose monitoring approach was approximately 10, 15 and 26 percent conservative for UV dose monitoring compared to validation for the AF3 0014, AF3 0027 and AF3 0116, respectively, indicating that the water layer was more optimized for the AF3 0014 and AF3 0027 reactors than for the AF3 0116 reactor. The nominal lamp power rating of the AF3 0116 reactor was almost twice that of the AF3 0014 and AF3 0027 reactors and was validated at flows that were at least seven times greater than those of the AF3 0014 and AF3 0027 reactors. As a result, the validated range of S/Q for the AF3 0116 reactor spanned two orders of magnitude, while the same for the AF3 0014 and AF3 0027 reactors spanned only one order of magnitude. Because of this difference in validated range, the AF3 0116 reactor has potentially several optimal sensor locations, depending on the S/Q value.

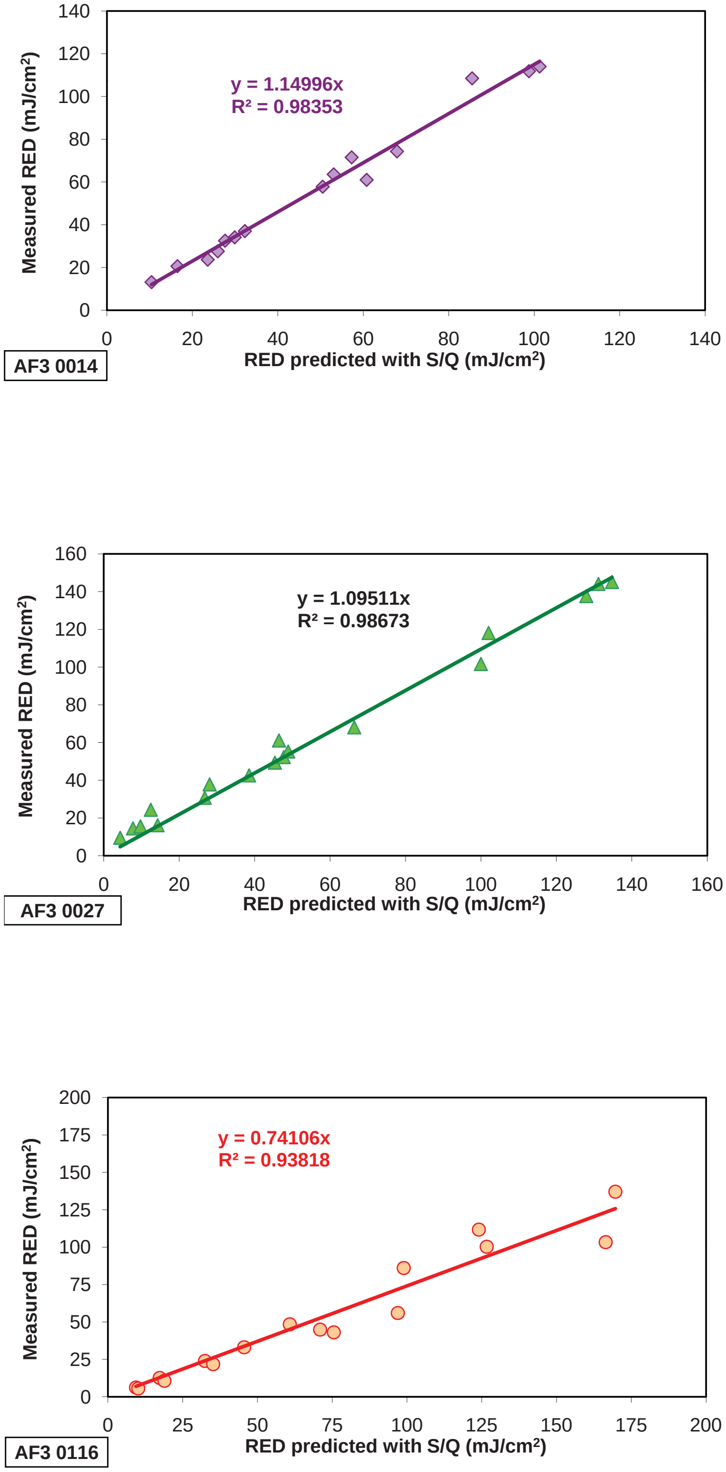

**Figure 4**: *Predicted versus measured MS2 REDs: UV dose monitoring without UVT (the reactor number is in the lower left corner of each chart).*

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*Continued from pg 27*

## SUMMARY

Validated calculated UV dose algorithms can be used to develop online UV dose monitoring strategies that do not require UVT input. The DVGW approach uses 'low' and 'high' UV intensity setpoints to develop the a UV intensity setpoint UV dose monitoring approach; however, outside of these two points, the reactor performance may no longer be consistent. The use of calculated UV dose algorithms to develop UV intensity setpoint UV dose monitoring strategies better defines UV dose delivery between the 'low' and 'high' points, as multiple data points are used in the assessment.

Online UVT monitors tend to drift over time, so their accuracy needs to be checked regularly using calibrated bench-top UV spectrophotometers. Depending on the water layer, the online UVT drift can result in significant UV dose calculation error, especially in high UVT water. As a result, algorithms that forgo UVT measurements eliminate UV dose calculation uncertainty as well as off-spec performance associated with UVT monitors, reducing UV system O&M requirements.