Innovative Approach to Validation of Ultraviolet (UV) Reactors for Disinfection in Drinking Water Systems

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Disclaimer

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Background: Evolving Use of UV for Drinking Water Disinfection in U.S.

- State credited UV systems are third-party validated for Dose-Inactivation operating range, consistent with source water, and require continuous monitoring

- 2006-UVDGM is ‘Guidance’ on recommended approach for UV Validation, installation, & monitoring but alternative approaches may be acceptable to States

- EPA not planning formal update of UVDGM or UV dose tables in near future, but issues persist with interpretation of UVDGM by State permitting agencies

- Since 2006, UV research and commercial validation experiences have provided significant lessons-learned, modified validation practices, and identified new implementation challenges

<table>
<thead>
<tr>
<th></th>
<th>UV Dose (mJ/cm²) Required for a Log Inactivation of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.0</td>
</tr>
<tr>
<td>Crypto</td>
<td>1.6  2.5  3.9  5.8  8.5  12  15  22</td>
</tr>
<tr>
<td>Giardia</td>
<td>1.5  2.1  3.0  5.2  7.7  11  15  22</td>
</tr>
<tr>
<td>Virus</td>
<td>39  58  79  100 121 143 163 186</td>
</tr>
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</table>
Evaluation Objectives of EPA Study

- Practical approach for validating LP and MP UV reactors for Adenovirus & Cryptosporidium inactivation using various test microbes, i.e., MS2, B. pumilus, AD2, T1
- Apply UV dose algorithms based on theory vs empirical that predict log-I and RED as a function of the UV sensitivity of the microbe (combined variable criteria), flow, lamp-sensor output, DL, w/wo UVT
- Assess capabilities of test microbe for predicting target pathogen, assess credibility with second test microbe vs bracketing
- Evaluate UV lamp sensor technology that accounts for germicidal contributions of low-and high-wavelength UV light within MP reactors
Evaluation Objectives of EPA Study

- Address approaches for propagating and assaying \textit{AD2}, \textit{B. pumilus}, \textit{MS2}, and methods for determining low and high wavelength ASCFs using collimated beam LP & MP UV lamps
- Determine & apply low and high wavelength ASCFs to predict \textit{Cryptosporidium} and \textit{Adenovirus} credit using \textit{MS2}, \textit{B. pumilus}, or \textit{T1} test data
- Simplify Validation-Factor (VF) analysis of uncertainties/biases
- Develop recommendations document from recent lessons learned applicable to GWR / SWTR describing alternative approaches for UV validation and implementation, and changes needed from previous UVDGM
• LPHO UV Reactor:
  ➢ 60 test conditions, MS2, Adenovirus, Bacillus pumilus
  ➢ 25-700gpm flows; UVTs 70, 80, 90, 98; Lamp power 60-100 %

• MP UV Reactor:
  ➢ 103 test conditions, MS2, AD2, B. pumilus
  ➢ 17-400gpm flows; UVTs 70, 80, 90, 98; Lamp power 0.9-2KW
  ➢ Synthetic & type 219 quartz sleeves, superhume-LSA
  ➢ Sensors: low wave 200-240nm; ONORM high wave 240-300nm
UV Dose-Response of MS2 and B. Pumilus Brackets Adenovirus
UV Dose-Response *B. pumilus*

Figure 4a UV Dose Response of *B. pumilus* spores (lab: GAP)

Figure 4b UV Dose Response of *B. pumilus* spores (lab: EPA)
UV Dose-Response Adenovirus AD2

**Figure 5a** UV Dose Response of adenovirus (lab: EPA)

**Figure 5b** UV Dose Response of adenovirus (lab: Corona)
New UV Dose Algorithm

\[
\log I = 10^A \times UVA_{254}^{B \times UVA} \times \left( \frac{S_H}{S_{0H}} \times ASCF_H \right) + 10^F \times UVA_{220}^{G \times UVA} \times \left( \frac{S_L}{S_{0L}} \times ASCF_L \right)
\]

Low wavelength UV dose monitoring component uses low wavelength UV sensor and UVT at 220 nm
At a fixed UVT, log inactivation of any microbes occurs at a similar value of $S/S_0/Q/D_L$. 

Figure 4: Relationship between Measured log Inactivation and $S/S_0/Q/D_L$
LP UV: Relationship between Measured log Inactivation and $S/S_0/Q/D_L$

Figure 25: Measured log inactivation as a function of $S/S_0/Q/D_L$
LP UV: algorithm calibrated with $T1$
Predicts $MS2$, $T7$, and $A. Brasilienis$

Predictions Limited to Validated Range of $S/S_0/Q/D_L$ defined by $T1$
LP UV: Measured vs. Predicted log I
Calibrated Using MS2

\[
\log i = 10^A \times UVA^{B \times UVA} \times \left( \frac{S}{S_0} \right) \left( \frac{C + D \times UVA + E \times UVA^2}{Q \times D_L} \right)
\]

\[
y = 1.0266x \\
R^2 = 0.942
\]
LP UV: Algorithm Fit to MS2 & B. Pumilus Data Predicts Adenovirus No Better Than MS2 Alone
MP Predictive Algorithm w/ high & low wavelength sensor and UVA measurements maps MS2 data well

\[ y = 0.9953x \]
\[ R^2 = 0.9935 \]

- Synthetic Quartz
- Type 219 Quartz

\[ \log i_{\text{measured}} \]
\[ \log i_{\text{predicted}} \]
**MP UV: MS2 Log I vs. $S_H/S_{0H}/Q/D_L$**

**Synthetic**

- **70%-MS2**
  - $y = 276.65x^{0.6365}$
  - $R^2 = 0.9919$
- **80%-MS2**
  - $y = 673.35x^{0.6749}$
  - $R^2 = 0.9813$
- **90%-MS2**
  - $y = 1237.4x^{0.7006}$
  - $R^2 = 0.9932$
- **95%-MS2**
  - $y = 15192x^{0.9511}$
  - $R^2 = 0.9978$
- **98%-MS2**
  - $y = 20149x^{0.9761}$
  - $R^2 = 0.9981$

**Type 219**

- **70%-MS2**
  - $y = 391.75x^{0.6655}$
  - $R^2 = 0.9464$
- **80%-MS2**
  - $y = 53.087x^{0.3886}$
  - $R^2 = 0.9979$
- **90%-MS2**
  - $y = 1550.3x^{0.7976}$
  - $R^2 = 0.9974$
- **95%-MS2**
  - $y = 3984.9x^{0.888}$
  - $R^2 = 0.9944$
- **98%-MS2**
  - $y = 8805.4x^{0.9596}$
  - $R^2 = 0.998$
**MP UV: Measured vs. Predicted log I**

Calibrated Using **MS2**

- **y = 1.0022x**  
  \[ R^2 = 0.993 \]

- **y = 0.9576x**  
  \[ R^2 = 0.8956 \]

- **y = 0.974x**  
  \[ R^2 = 0.668 \]

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**Table: ASCF Values**

<table>
<thead>
<tr>
<th></th>
<th>ASCF&lt;sub&gt;L&lt;/sub&gt;</th>
<th>ASCF&lt;sub&gt;H&lt;/sub&gt;</th>
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<tbody>
<tr>
<td>MS2</td>
<td>1.00</td>
<td>1.05</td>
</tr>
<tr>
<td>B. Pum</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Adeno</td>
<td>0.211</td>
<td>0.870</td>
</tr>
</tbody>
</table>
MP UV: 

*B. pumilus* Predicts Adenovirus
Lessons-Learned To-Date

- Use of *Adenovirus* microbes in conventional validation is impractical; if used the dataset should be large to assess high point-to-point variability/uncertainty.

- In both LP & MP analyses, *MS2* microbes alone provided good correlations and conservative predictions of *AD2* inactivation, better than *B. pumilus* alone or combined with *MS2*.

- Low-wavelength sensor paired with typical ONORM sensor can be effective for monitoring UV full germicidal range.
Lessons-Learned To-Date

- The UV industry will need to develop verification & calibration standards for low-wave sensors.

- Credit for low-wave UV contributions results show 2-3X lower REDs than LP AD2 RED=186 (4-log kill) so benefits of MP vs LP demonstrated in UV reactor scenarios.

- Combined Variable S/Q/DL algorithm variants & ASCFs, map UV reactor-validation datasets well, useful for predicting Crypto & AD2 scenarios with test microbes, and simplifies uncertainty/bias factors for VF.
Questions & Discussion

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