

# Lagrangian Actinometry's Role in UV Reactor Validation and Optimization

**Ernest R. Blatchley III<sup>1</sup>, O. Karl Scheible<sup>2</sup>, and Chengyue Shen<sup>2</sup>**

<sup>1</sup>School of Civil Engineering, Purdue University, West Lafayette, IN

<sup>2</sup>HydroQual, Inc., Mahwah, NJ

## BACKGROUND

The performance of ultraviolet (UV) reactors is known to be governed by the combined effects of the UV dose distribution and the “dose-response” behavior (i.e., photochemical kinetics) of the target chemical(s) or microorganism(s). If the dose distribution delivered by a reactor system is known, then it should be possible to develop accurate predictions of the performance to be expected from that reactor system relative to any photochemical endpoint, so long as the photochemical kinetics are known or can be measured.

While measurement of dose-response behavior is conceptually simple, methods for measurement or simulation of the dose distribution delivered by a photochemical reactor are less well-developed and have a much shorter history of application. As such, these methods (both numerical and experimental) are less familiar to the engineering and regulatory communities than are traditional methods of reactor analysis and validation.

Validation of UV reactors is an established practice, which until recently has relied exclusively on biosimetry to define the reduction equivalent dose (RED) delivered across a targeted operating range. This validation concept is driven by regulatory- and owner-related requirements and is used in both water and wastewater disinfection applications. In particular, the USEPA's newly released *Ultraviolet Disinfection Guidance Manual* (UVDGM) prescribes full-scale validation of UV reactors installed for *Cryptosporidium*, *Giardia* and viral disinfection credit. The UVDGM provides protocols for validation testing and the determination of credited RED and corresponding log inactivation. The biosimetry protocol definitions provided by the UVDGM are conceptually similar to those provided by other organizations (e.g., ÖNORM, 2001, 2003; DVGW, 2003; NWRI/AWWARF, 2003).

In most cases, the results of biosimetry are presented in the form of RED. It should be recognized that the RED is an artificial construct that was developed as a means of applying and comparing the results of biosimetry. RED was developed at a time when biosimetry was (essentially) the only measurement-based method available to characterize or validate a reactor design; in concept, it provides a means for comparison of the results of tests across operating conditions and reactor types.

The primary advantages of biosimetry as a validation method for reactors are its history of use and the fact that inactivation of a microbial target organism is measured. However, an important drawback of biosimetry is the inability of the method to yield a measurement of the dose distribution. In the absence of a reliable dose distribution measurement (or estimate), it is not possible to provide an accurate prediction of the inactivation response to be expected by a reactor, unless the organism of interest has UV dose-response behavior that is similar to that of the challenge organism. Therefore, the use of biosimetry test results for prediction of inactivation response (or inactivation “credits”) must be performed using conservative approaches.

As an example of this conservatism, the UVDGM employs a concept of a “RED bias factor” ( $B_{RED}$ ) as a safety factor for prediction of inactivation responses of microbial pathogens. The value of  $B_{RED}$  is estimated based on the implied assumption of a default dose-distribution, representative of a poorly designed UV unit. This default dose distribution, which may not be at all representative of the system in question, was selected as a means of assuring that the use of a less-sensitive challenge microbe (such as coliphage MS-2, which has become an industry “standard” surrogate) in biosimetry would not mask hydraulic inefficiencies when the observed RED data are used to predict “credit” for the inactivation of more-sensitive target pathogens (such as *Cryptosporidium*).  $B_{RED}$  accounts for a large part of the “validation” factor applied to observed MS-2 validation results.

## OVERVIEW OF LAGRANGIAN ACTINOMETRY

Lagrangian actinometry is a newly developed test method that uses dyed microspheres to measure the dose distribution delivered by a UV reactor. In this method, a photosensitive compound, (*E*)-5-[2-(methoxycarbonyl)ethenyl]cytidine (hereafter referred to as *S*), is conjugated to synthetic microspheres. When subjected to germicidal UV radiation, *S* undergoes photoisomerization, followed by spontaneous decomposition to yield 3-b-D-ribofuranosyl-2,7-dioxypyrido[2,3-*d*]pyrimidine (hereafter referred to as *P*) (Bergstrom *et al.*, 1982). The basic chemistry of this process is illustrated in Figure 1.

This reaction has been shown to have a high quantum yield



## DEVELOPMENT OF A STANDARD PROTOCOL

A project is underway, funded by the New York State Energy Research and Development Authority (NYSERDA), AwwaRF, NYCDEP and others, to develop protocols for the application of Lagrangian actinometry. It follows completion of extensive demonstration efforts, whereby the method was applied to medium- and low-pressure reactors, complemented by the collection of biosimetric data (MS2, Q $\beta$ , T1) and comparison to CFD-Intensity modeling and model predictions. The project's primary components are summarized below.

### Stakeholders Review Group

Representatives from the regulatory, owner, and design community will be convened periodically to review and guide the dyed-microspheres project and protocol development. The first Stakeholders meeting was held in July 2007 in Albany, NY. Presentations were made at this meeting to summarize the background of the Lagrangian actinometry method and the results of Lagrangian actinometry field trials completed to date involving LP and MP reactor systems. Based on the lessons learned from these experiments, a draft protocol has been developed; the protocol will be presented in detail for information and comment. The protocol will include methods for interpretation of the data in a manner that is consistent with the approach presented in the UVDGM. The draft protocol will be implemented in a series of full-scale validation experiments to be conducted at the UV Validation and Research Center of New York, located in Johnstown, NY. A summary of the reactors involved in these tests and the range of test conditions will be presented.

### Demonstration of the Methodology and its Correlation to Standard Biosimetric Practices

The full-scale experiments planned for the project will allow examination of the ability of the method to measure the impact of hydraulic and intensity variations in a reactor. For each reactor, a matrix of operating conditions will be examined in which flow rate, lamp output power, and transmittance are varied across the range of anticipated conditions for the reactor in question. Conventional biosimetry experiments will be conducted simultaneously, or under identical operating conditions. The results of these experiments will be compared on the basis of microbial inactivation so as to allow for a detailed examination of the ability of Lagrangian actinometry to quantify changes in the dose distribution that result from changes in operating conditions.

### Demonstration of the Calibration and Verification Process for CFD-Intensity Models Based on Dose-Distribution Measurements

In conjunction with the Lagrangian actinometry and biosimetry experiments, numerical simulations of reactor behavior based on combined CFD-I field models will be

conducted. An objective of this work will be to allow critical comparison of the results of these simulations with the results of Lagrangian actinometry and biosimetry. Lagrangian actinometry and CFD-I models are the only methods available for measurement/estimation of the dose distribution delivered by a reactor. An argument could be made that the dose distribution represents the most fundamental and comprehensive description of the performance characteristics of a photochemical reactor system, because if the dose distribution is known, then the performance of the reactor can be accurately described relative to essentially any photochemical endpoint. Therefore, Lagrangian actinometry represents the most comprehensive method for validation of a CFD-I model. This aspect of the project will address statistical (and other) methods that can be used to compare the results of Lagrangian actinometry with those of CFD-I models.

### Interpretation of Lagrangian Actinometry Results with respect to Reactor Validation

The UVDGM provides detailed guidance as to how to interpret the results of full-scale biosimetry experiments with respect to validation of reactors that could be used in water treatment settings. The goal of this phase of the project is to develop analogous methods for interpretation of the results of reactor validation by Lagrangian actinometry. In general terms, the goals of this phase of the project will be to present methods that allow for assignment of inactivation "credits" for validated reactors relative to the microbial pathogens of interest. These methods will account for the sources of variability and uncertainty that are known to characterize Lagrangian actinometry, and will be developed in a manner that is consistent with the approaches that are defined in the UVDGM.

The ability of Lagrangian actinometry to yield a measure of the dose distribution represents (perhaps) the most important attribute of this method. Because the method allows the dose distribution to be measured, it is possible to use the results of Lagrangian actinometry to predict the inactivation response of any microorganism for which reliable UV dose-response behavior exists. As such, the concept of RED becomes moot. While it is possible to translate a dose distribution measurement (or estimate) into a value of RED for any hypothetical challenge organism, this approach hides critical information regarding the performance of the reactor. Therefore, Lagrangian actinometry allows for elimination of RED and many of the sources of ambiguity associated with it.

The actinometry approach provides a resource to support a wide spectrum of uses. An obvious example is in troubleshooting a non-performing reactor; the ability to understand its dose-distribution and then to assess potential corrective measures (baffles, lamp positions, etc.) can save a considerable amount of effort. Optimization of a system is also a potential benefit, not only from the point of validation, but also after commissioning. Re-validation of a modified system can be simplified with the use of the dyed-microspheres, possibly in-place at a commissioned, operating facility.



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