

APPENDIX A

UVCAT USER MANUAL

INTRODUCTION

The NYSERDA UV System Cost Analysis Tool (UVCAT) is an Excel[®] spreadsheet with embedded Visual Basic[®] software designed for analyzing UV system life-cycle costs and performance. UVCAT uses the spreadsheet as a user interface to enter data, initiate the software algorithms, and view the outputs. UVCAT is designed to conduct the following analyses:

- Standard Life-Cycle Cost (LCA) Analysis
- Lamp Replacement Interval Cost Analysis
- Advanced Life-Cycle Cost Analysis

Standard Life-Cycle Cost Analysis. The Standard Life-cycle Cost Analysis tool determines UV system O&M and present worth costs assuming the UV system operates under average conditions of flow rate, water UV transmittance (UVT), lamp aging, and fouling.

Lamp Replacement-Interval Cost Analysis. The Lamp Replacement Interval Cost Analysis tool estimates O&M and present worth costs for a UV system as a function of various lamp replacement intervals. The O&M costs are estimated assuming the UV system operates under average conditions of flow rate, UVT, lamp aging, and fouling.

Advanced Life-Cycle Cost Analysis. The Advanced Life-Cycle Cost Analysis tool simulates UV system operation over time as a function of flow rate, UVT, lamp aging, fouling, power quality, and UV system component failure. UV system operation is estimated using the UV dose monitoring and control algorithm specific to the UV system. The tool predicts the number of reactors and lamps, their power setting, UV dose delivery by each reactor, log inactivation of a target pathogen, and the associated public health protection. The tool predicts O&M costs by integrating power consumption, labor, and UV system component replacement over the time.

UVCAT INPUTS

Table A.1 lists the worksheets within UVCAT that are used to input data used by UVCAT. The following sections provides a description of the data entered into each worksheet.

Table A.1 UVCAT worksheets used for Input

Analysis	Input Worksheets
Standard life-cycle cost analysis	STANDARD LCA
Lamp replacement interval cost analysis	LAMP AGE LCA TOOL
Advanced life-cycle cost analysis	ADVANCED LCA WQ RED MODEL RISK MODEL

UV System Data Inputs

The UVCAT user enters data describing the UV system into the worksheets entitled STANDARD LCA, LAMP AGE LCA TOOL, and ADVANCED LCA. The user enters the UV system data as columns of data, where each column represents one UV system. Table A.2 summarizes the type of information entered in these worksheets.

The data inputs for each parameter in Table A.2 is described as follows:

UV System Sizing Criteria

This section is used to enter information on UV system sizing and operation as follows:

- Maximum flow - flow rate used to size the UV system.
- Average flow - average flow rate treated by the UV system.
- Average UVT - average UVT of the water passed through the UV system.
- Design UVT - water UVT (254 nm, 1-cm pathlength) used to size the UV system.
- Design UV Dose - required UV dose for treatment.
- Minimum Number of Trains - minimum number of UV reactor trains in operation.

Reactor Configuration

UV vendors and consultants often work together to define the configuration of the UV system for a given disinfection application. Often the engineer specifies the number of UV reactor trains in parallel and the number of UV reactors per train. The UV vendor often specifies the number of banks of UV lamps in each reactor and the number of UV lamps per bank. The UV vendor also defines the number of ballasts and UV sensors used per reactor. This section of the spreadsheet is used to enter the following information on the UV reactor configuration.

Table A.2 Data inputs into UVCAT

Parameter	Rows where data is entered:		
	STANDARD LCA	LAMP AGE LCA	ADVANCED LCA
Descriptive Information	15 - 18	19 - 21	15 - 18
UV System Sizing Criteria	41 - 45	25 - 29	42 - 47
Reactor Configuration	48 - 54	32 - 38	52 - 58
Redundancy	56 - 57	40 - 41	60 - 61
Lamp Data	59 - 72	43 - 56	63 - 76
Sleeve Data	74 - 80	58 - 64	78 - 84
Ballast Data	83 - 85	67 - 69	87 - 89
UV Sensor Data	87 - 92	71 - 76	91 - 96
Dose Model and Pacing	97 - 101	81 - 85	100 - 101
Failure Data	Not used	Not used	103 - 115
WTP Inputs	104 - 108	88 - 92	119 - 125
Capital Cost Inputs	113 - 141	97 - 125	128 - 160
Dose Delivery	149 - 165	133 - 149	Not used
Ballast Power Settings	Not used	Not used	164 - 187

- Max Flow per Reactor - the maximum flow per reactor as defined by headloss or validation limitations.
- Trains - number of UV reactor trains, including redundant reactor trains, installed in parallel and used to treat the flow through the UV system. As a special case, if one UV reactor is installed on each filter at a water treatment plant, the number of reactor trains is set to equal the number of filters. In this case, UV system redundancy is defined by the redundancy of the filters.
- Reactors/Train - number of UV reactors in series in each treatment train.
- Banks/Reactor - number of banks of UV lamps in each reactor. A bank of lamps can be defined as a group of lamps oriented across the reactor cross-section perpendicular to the flow through the UV reactor. In a multi-bank reactor, this configuration of lamps is repeated in the direction of flow. With the Advanced LCA tool, the banks per reactor are defined by the RED equation (see section 1.1.3).
- Lamps/Bank - number of lamps in each bank.
- Lamps/Ballast - number of lamps operated by each lamp ballast assembly. Ballast assemblies typically drive either one or two lamps.
- UV Sensors/Bank - number of duty UV sensors used per bank to monitor the UV lamps. LPHO and amalgam UV systems used in drinking water and wastewater reactors often use one UV sensor per bank of lamps. MP UV systems used in drinking water systems often use one UV sensor per lamp. MP UV systems used in wastewater systems use either one sensor per bank of lamps or do not use UV sensors.

Redundancy

Redundant UV reactors or trains are used to ensure the UV system provides the required UV dose when a UV reactor or train is out of service for maintenance or service. While UV systems used to treat secondary wastewaters typically do not use redundant reactors, UV systems used to treat re-use wastewaters (e.g. Title 22 applications) typically use one redundant reactor per train and UV systems used in drinking water applications typically use one redundant train. This section of the spreadsheet is used to enter the number of redundant trains and reactors per train used by the UV system.

Lamp Data

The most significant operating costs of a UV system are due to lamp replacement and power consumption. UV systems are sized to deliver the required UV dose with the degree of lamp aging that occurs when the lamps are replaced. Lamp aging data is typically provided by the UV vendors. This section of the spreadsheet is used to enter the following information on the lamps.

- Lamp 100% Power - electrical consumption of the UV lamp and ballast assembly when the UV lamp is operating at the 100% ballast power setting. The value can be estimated as the total power of the UV system operating at 100% power divided by the total number of UV lamps.

- Lamp Life - the average operating life of the lamp. In the UV literature, the life of LP, LPHO, and amalgam lamps is stated between 8,000 and 12,000 hours and the life of MP lamps is stated between 3,000 and 5,000 hours. Often, the UV vendor guarantees a lamp life and provides a pro-rata warranty. Typically, the guaranteed lamp life is used to assess operating costs.
- Lamp Aging Factor - the relative UV output of the lamp under end of Lamp Life conditions. Traditionally, an aging factor of 65 or 70% has been specified as design criteria for wastewater UV systems. However, the NWRI/AwwaRF UV Guidelines specify using a 50% aging factor for both drinking water and reuse applications. Recently, UV vendors have been reporting aging factors ranging from 80 to 95 % with both amalgam and MP lamp technologies used for drinking water and wastewater applications.
- Lamp Cost - purchase price of a new UV lamp.
- Lamp Replacement Time - operator time required to replace one lamp.
- Fit Type (MMF, EXP, LIN, CUSTOM) - the type of mathematical equation that describes lamp aging as a function of operating time. The equation must predict the lamp aging factor used for the design at the specified lamp replacement interval. The equations for each Fit Type are:

$$\text{MMF: Lamp Aging Factor} = \frac{A \times B + C \times \text{Hours}^D}{B + \text{Hours}^D}$$

$$\text{EXP: Lamp Aging Factor} = A \times \exp(B \times \text{Hours})$$

$$\text{LIN: Lamp Aging Factor} = A \times \text{Hours} + B$$

CUSTOM: The user enters a custom equation in the field “Lamp Aging Equation.”

- Coefficients A through F - the equation coefficients for the fit types MMF, EXP, LIN, and CUSTOM. If a coefficient is not used, enter “0”.
- Lamp Power - lamp aging equations can be defined as a function of the lamp operating power. The CUSTOM lamp aging model can use this field as a model coefficient.
- Lamp Aging Equation - the field contains an equation that calculates the lamp-aging factor for the lamp life entered in the Lamp Life field. The calculated value should equal the value entered into the Lamp Aging Factor field. If the two values are not equal, the equation predicting lamp aging factor as a function of lamp hours is not valid and must be corrected. If the fit type is MMF, EXP, or LIN, the contents of the column B cell contains an equation that can be copied and used. If the fit type is CUSTOM, the user must enter an equation. That equation must reference one or more of the coefficients A, B, C, D, E, F, and Lamp Power. For example, for the entered data in column C of the Standard LCA tool, the user could enter:

$$= C65 * \exp(C66 * C60) + C67$$

as a custom equation. The coefficients A, B, and C would be user defined and entered into cells C65, C66, and C67. Cells C68, C69, C70, and C71 would be set to zero since those coefficients are not used by the equation.

Sleeve Data

UV lamps used within UV reactors are housed within quartz sleeves. The quartz sleeves protect the lamp from the water flow through the reactor and control heat transfer from the lamp to the water. With operation of the UV system, the UV transmittance of the quartz sleeve will decrease due to external and internal fouling of the sleeve surfaces and aging of the quartz material. UV systems are equipped with cleaning mechanisms that remove foulant from the external surfaces of the sleeves. Typically, automatic wipers are used by MP and LPHO UV systems used in wastewater applications and MP UV systems used in drinking water applications. Manual or automatic off-line acid washes are used by LPHO used in drinking water applications. Manual wiping or off-line acid baths are used with LP systems used in both drinking water and wastewater applications. This section of the spreadsheet is used to enter the following information on the lamp sleeves.

- Sleeve Life - the average operating life of the lamp sleeves. UV vendors typically state sleeve lives that range from 5 to 10 years. Typically, the guaranteed sleeve life is used to assess operating costs.
- Sleeve Cost - purchase price of a new sleeve.
- Sleeve Replacement Time - operator time required to replace one sleeve.
- Sleeve Cleaning Type (Rinse, Wiper) - the type of cleaning mechanism used by the UV system.
- Sleeve Cleaning Period - the time period between sleeve cleaning.
- Sleeve Cleaning Time/Reactor - the operator time required to clean the sleeves of one UV reactor in the system.
- Fouling Factor - the ratio of the UV transmittance of an aged and fouled UV sleeve to the UV transmittance of a new and clean sleeve. This ratio is often termed the design fouling factor and is used to size the UV system.

Ballast Data

Many UV systems use electronic ballasts that power and control one or two UV lamps. Some UV systems use electromagnetic ballasts that consist of transformers to adjust the operating voltage and a network of capacitors to control lamp current. This section of the spreadsheet is used to enter the following information on the lamp ballasts.

- Ballast Life - the average operating life of the ballast. UV vendors typically state ballast life that ranges from 5 to 10 years. Typically, the guaranteed ballast life is used to assess operating costs.
- Ballast Cost - purchase price of a new ballast.
- Ballast Replacement - operator time required to replace a ballast.

UV Sensor Data

Drinking water UV systems are all equipped with UV sensors that are used for performance monitoring. Often the duty UV sensors used to monitor performance are regularly checked using an independent reference sensor. The duty sensors are either calibrated by a calibration lab or calibrated by the operator through comparison with a calibrated reference sensor. While many wastewater systems are equipped with UV sensors, they may or may not be used for performance monitoring and their readings are typically not checked with a reference sensor. This section of the spreadsheet is used to enter the following information on the UV sensors.

- Sensor Life - the average operating life of the duty UV sensor. UV vendors typically state UV sensor life that ranges from 3 to 5 years. Typically, the guaranteed sensor life is used to assess operating costs.
- Sensor Cost - purchase price of a new duty UV sensor.
- Sensor Replacement - operator time required to replace one duty UV sensor.
- Sensor Calibration Period - the time period between calibration of the duty UV sensor.
- Sensor Calibration Cost - cost to calibrate a new duty sensor excluding operator labor.
- Sensor Calibration - operator time required to calibrate one duty UV sensor. If the UV sensor is sent to the calibration lab, the cost is the time required to facilitate that.

Dose Pacing

While UV systems are sized to deliver the required UV dose under design conditions of flow rate, water UVT, lamp aging, and sleeve fouling, they typically operate at lower flow rate and higher water UVT with lamps and sleeves that are not as aged and fouled as the design conditions. Under these conditions, if the UV system operated with all lamps on at 100% power, the UV system would overdose. To prevent overdosing and minimize costs, UV systems turn on and off banks of lamps and reduce ballast power to ensure UV dose meets requirements without excessive overdosing. Dose-pacing strategies vary from UV reactor to reactor and from installation to installation. The UV system can turn on and off banks of lamps or adjust lamp power in response to one or more of the following measured parameters:

- Flow rate.
- Predicted lamp output based on lamp operating hours.
- UVT.
- UV intensity.

When measured intensity is used for dose pacing, it accounts for lamp aging and sleeve aging and fouling. In some cases, the measured intensity also accounts for UV transmittance and a UVT monitor is not required for monitoring UV system performance.

With the STANDARD LCA and LAMP AGE LCA tool, this section of the worksheet is used to indicate which factors impacting UV dose delivery are accounted for by the dose-pacing strategy used by the UV system. This section is also used to input the Peak UV Dose defined as

the UV dose delivered by the duty UV reactors operating under design conditions of flow rate, water UVT, lamp aging, and sleeve fouling with all lamps on at the 100% power setting. This value should be equal or greater than the required UV dose if the UV system is properly sized. For example, while seven UV lamps may be required to deliver the required UV dose for a given application, the UV system provided by the UV vendor is equipped with eight lamps configured as two banks of four lamps. Thus, the peak UV dose can be estimated as 8/7 of the required UV dose.

With the ADVANCED LCA tool, this section of the worksheet is used to indicate the UV dose monitoring and control algorithm used by the UV system. This is done by entering a numeric value into the field “Dose Model.” This numeric value provides a reference to a model for UV dose monitoring and control in the worksheet RED MODEL. The second line termed “Dose Model” is set to the name of the model referred to by the numeric value specifying the UV dose model. Details on how to define the UV dose monitoring and control model in the worksheet RED MODEL is provided in section 1.1.3.

Failure Data

UV dose delivery over time by a UV system is affected by power quality and UV system component reliability. Power quality events that cause the UV lamps to extinguish include voltage sags and interruptions. Typically, the lamps extinguish when the voltage drops below a threshold voltage value for some duration. A generator is often used to provide power to the UV system during a power interruption. However, a generator does not prevent the lamps from extinguishing during a power quality event. As an alternate, a UPS can be used to provide continuous power supply to the UV system during power quality events. The time required to startup a UV system following a power quality event will depend on the lamp cool-down and warm-up times, the duration of the power quality event, and the time required to startup a generator if used. UV dose delivery is also impacted by failure of UV lamps and ballasts. UV dose monitoring is impacted by failure of UV sensor and UVT monitors. This section of the worksheet is used to enter the following information on UV system failure and response to failure:

- Supply Voltage Lower Limit - the percentage of nominal voltage that causes lamps to extinguish.
- PQ Event Duration Lower Limit - the duration of power quality event that causes lamps to extinguish.
- UPS (y,n) - indicates if an uninterruptible power system used to provide backup power.
- Generator (y,n) - indicates if a generator used to provide backup power.
- Generator Start-up Time - time required to start up the generator following the power quality event.
- Lamp Cool-down Time - time required to cool down the lamps before they can be restarted.
- Lamp Warm-up Time - time required to startup a UV lamp after cool down.
- Lamp Failure Probability - probability a single UV lamp will fail over a one day period.

- Ballast Failure Probability - probability a single lamp ballast will fail over a one day period.
- UV Sensor Failure Probability - probability a single UV intensity sensor will fail over a one day period.
- UVT Monitor Failure Probability - probability a single UVT monitor will fail over a one day period.

WTP Inputs

This section of the spreadsheet is used to enter the following site-specific data that impacts UV system O&M costs and performance:

- Labor Rate - the average labor rate including overhead of the personnel operating and maintaining the UV system.
- Electricity Cost - the cost of electricity paid by the utility.
- Patent Fees - patent royalties paid by the utility for using the UV system. Currently, the Calgon Carbon Corporation has a patent for *Cryptosporidium* and *Giardia* inactivation and requests royalty payments of \$0.015 per 1000 gallons treated.
- Interest Rate - the annual interest rate on money borrowed by the utility.
- Period - the period over which the utility pays back money borrowed to pay for the UV system. The life-cycle cost assessment is conducted over that period.
- Supply Voltage - the nominal supply voltage to the UV system.
- Population - the population served by the UV system.

Capital Cost Inputs

This section of the spreadsheet is used to enter UV system capital cost information.

- Reactor - the total capital costs of the UV reactors including the control panels.
- Install factor - the cost of installing the UV equipment.
- Validation - the cost for validating the UV reactor.
- Inlet/Outlet Piping - the capital cost including installation of all inlet and outlet piping needed for the UV system including flowmeters, valves, pipes, and channels.
- Power Supply - capital cost of providing power to the UV system including switch gear, transformers, distribution panels, generators, and UPS systems.
- Other - other costs include yard piping, chlorine contactors, and low lift pumps.
- UV Building - capital costs for demolition, civil/site work, building, and HVAC.
- Instrumentation - capital cost of all instrumentation including SCADA and on-line UVT monitors.
- HVAC - an alternate field for entering HVAC.
- Miscellaneous Electrical - a field for entering cost of any miscellaneous electrical work.
- Civil/Site Work - an alternate field for entering civil site work.
- Contingency - capital cost contingency typically set as a percent of all capital costs.

- General Conditions - includes mobilization/demobilization, major equipment, site preparation such as fences, temporary facilities for contractors, bonds/insurance, permits, supervision and engineering salaries, support systems (e.g., water), and general expense items.
- Contractor O&P - contractor overhead and profit typically set as a percent of all the above costs.
- Engineering, Legal, and Administration - the engineering costs of the UV project typically set as a percent of all the above costs.
- Total - total of all capital costs.

UV Dose Delivery

If dose pacing accounts for water UVT, the Standard LCA and the Lamp Age LCA tools use data on dose delivery as a function of UVT to estimate O&M costs. This section of the Standard LCA and the Lamp Age LCA tools is used to enter data on dose delivery as a function of specified values of water UVT. UV dose delivery by the reactor should be entered for one UV reactor operating at the design flow rate with new lamps all on and operating at 100% power, and new clean sleeves.

Ballast Power Settings

The Advanced LCA tool allows the user to enter data on ballast power settings. The Advanced LCA tool uses this data to simulate UV system operation as a function of time. Ballast typically operate at discrete power settings. Enter the discrete power settings in ascending order starting with the minimum power setting. Enter “9999” if the indicated setting does not have a value. If the UV vendor states the ballast power settings are continuous, enter values from the minimum to maximum setting at increments equal to $(\text{Max}-\text{Min})/22$.

Water Quality Data

The Advanced LCA uses the worksheet entitled WQ to enter water quality data over time as follows:

Column	Data
A	Date/time
B	Flow rate
C	UVT
D	Raw water pathogen concentration
E	Supply Voltage
F	Power quality event duration

The last entry in column C should be “9999”. Up to 10,000 datasets of date/time, flow rate, and UVT can be entered.

RED Model

The worksheet entitled RED MODEL contains equations for UV dose monitoring and control for various UV systems. The information entered into cells A3 to C23 is used as an index to identify the various models in this worksheet. Cells A3 to A23 are used to enter the name of the UV system model. Cells B3 to B23 give the model identification number. Cells C3 to C23 define the column within this worksheet where the specified model is located.

The Advanced LCA algorithm programmed into UVCAT uses the models located in REDMODEL as a calculator to determine UV dose delivery and target ballast power settings given inputs on target UV dose, flow rate, UVT, number of banks of lamps, and ballast power setting. The structure of each referenced model is organized into five color-coded sections. The first section in rows 5 to 12, color-coded yellow, represents information that the Advanced LCA algorithm transfers into the model. This information includes:

- Target RED per reactor,
- Flow rate per reactor,
- Water UVT,
- Lamp aging factor,
- Fouling factor,
- Number of operating banks per reactor, and
- Actual Power Setting of type 1 and 2 lamps in each bank

The second section in rows 13 to 14, color-coded light blue, defines how many Type 1 and Type 2 lamps are in each bank and the model calculation cells. Type 1 and 2 lamps are defined as lamps within a bank that have a specified relationship between measured UV intensity and ballast power setting. With MP lamps, the relationship between measured UV intensity and ballast power setting may differ if the lamp is monitored from different directions because of a non-uniform UV intensity field around the lamp. With LPHO lamps, the relationship between measured UV intensity and ballast power setting may differ because one sensor monitors one lamp and another monitors multiple lamps. Note that the entered number of Type 1 and Type 2 lamps must add up to the total number of lamps in a bank. Furthermore, if the relationship between measured UV intensity and ballast power setting is the same for all lamps, the Type 1 lamps is set equal to the number of lamps in a bank and Type 2 lamps is set to zero.

The field termed Model Calc in row 15, color-coded light blue, is an alphanumeric string specifying the cells where the model equations are located. UVCAT uses this alphanumeric string to identify where the UV dose monitoring model equations are located in the worksheet for a given model. For example, for a model located in column G, Model Calc may be set to "G17:G34." This tells UVCAT that the equations used in the UV dose model are located in cells G17 to G34.

The third section in the model in rows 17 to 22, color-coded dark blue, contain equations for determining UV dose delivery, sensor readings, target ballast power settings, and target UV sensor values as follows:

- Row 17 - equation for the target ballast power for Type 1 lamps
- Row 18 - equation for the target ballast power for Type 2 lamps
- Row 19 - equation for the target UV sensor readings
- Row 20 - equation for the actual sensor reading
- Row 21 - equation for the actual UV dose delivered.

- Row 22 - equation indicating if the reactor is operating off spec

The UVCAT user defines these equations, either from the validation report for the UV system or from CFD-based modeling.

The target ballast power setting is defined as the ballast power setting predicted to deliver the target UV dose given the flow rate, UVT, lamp aging, fouling, trains, reactors, and banks entered in section 1 (color coded yellow). The target power setting calculated using the equations can be above, below, or within the range of ballast power settings used by the reactor. For example, the equation may determine that the UV reactor as defined in rows 5 to 12 would have to operate at a power setting of 200 percent to deliver the required UV dose. This outcome indicates to UVCAT that the UV system needs to operate with more reactors and banks of lamps.

The fourth section of the model in rows 24 and on, color-coded peach, contains other equations that can be referenced by the equations in rows 17 to 21. As many cells and equations as necessary can be used in this section to facilitate the calculation of target ballast power and delivered UV dose. However, the field Model Calc must include both the cell in rows 17 to 22 as well as the cells in this section.

The fifth and last section of the model occurs in rows below the fourth section and is color-coded light blue. These rows contain numeric constants used by the equations entered into sections 3 and 4. Ideally, the coefficients entered into section 5 and the equations entered into section 3 and 4 by the UVCAT user are based on validation data.

The example version of UVCAT provided with this report provides eight example RED models for drinking water reactors and three example RED models for wastewater reactors. These examples should be studied and understood by the UVCAT user before using UVCAT. These models can be used as a framework for defining models for commercial reactors.

IMPORTANT NOTE: The example drinking water models entered into UVCAT were developed based on models used by the industry but are not true models of commercial UV systems. UV vendors consider their models proprietary and do not want them published in the public domain. However, engineers and utilities can obtain validation reports from UV vendors that define the models or can work with UV vendors to develop a model.

Risk Model

The worksheet RISKMODEL is used to enter the UV dose-response of the target pathogen and the risk model for human infection. The Advanced LCA algorithm programmed into UVCAT uses these models as a calculator tool to determine log inactivation credit and public health impact of a given UV dose and a raw water pathogen concentration.

The pathogen UV dose-response is located in column C. Cell C7 contains the UV dose defined as the RED calculated using the UV dose model. Cell C8 contains an equation for the log inactivation expected with that UV dose. Cell C9 contains the maximum pathogen inactivation credit that a State will grant. Cell C10 contains the credited log inactivation based on the maximum pathogen credit and the calculated log inactivation.

The risk model for human infection is located in column G. Specific cells are as follows:

- Cell G7 - raw water pathogen concentration
- Cell G8 - log removal credit through the filter
- Cell G9 - UV log inactivation credit

- Cell G10 - Chemical disinfection log inactivation credit
- Cell G11 - Human water consumption per day
- Cell G12 - Number of infections per UV dose

UVCAT ALGORITHMS

The following sections describe the software algorithms used by UVCAT.

Standard Life-Cycle Cost Analysis

The Standard Life-Cycle Cost Analysis uses two subroutines. The first determines the operation status of the UV system under average conditions. The second determines O&M costs for those conditions and calculates the present worth costs factoring in capital costs.

Determining UV System Operating Status

The following steps are incorporated into a subroutine that determines the number of banks, lamps, ballasts, and UV sensors used for the UV reactor operating under average conditions of flow rate, UVT, lamp aging, and lamp fouling given the dose-pacing strategy used by the UV system.

Step 1. Calculate the total number of lamps in each reactor:

$$\text{Total lamps/reactor} = \text{Lamps/bank} \times \text{banks/reactor}$$

Step 2. Calculate the total number of lamps required under design conditions of UV dose, flow rate, UVT, lamp aging, and fouling.

$$\text{Total duty lamps} = (\text{Trains} - \text{Parallel Redundancy}) \times (\text{Reactors/Train} - \text{Series Redundancy}) \times \text{Total lamps/reactor} \times \text{Design UV Dose} / \text{Peak UV Dose}$$

This calculation factors in the specified redundancy of the UV system and the ratio of design to peak UV dose. The ratio accounts for the fact that the UV system may have the capacity to deliver a UV dose greater than the design UV dose under design conditions of flow rate, UVT, lamp aging, and fouling.

Step 3. If the UV system uses a dose-pacing strategy that responds to flow rate, adjust the total duty lamps by the ratio of average flow rate to peak flow rate.

$$\text{Total duty lamps} = \text{Total duty lamps} \times \text{Average flow rate} / \text{Peak flow rate}$$

Step 4. If the UV system uses a dose-pacing strategy that responds to UVT, adjust the total duty lamps by the ratio of UV dose delivered at design UVT to UV dose delivered at average UVT. Use interpolation of entered UV dose as a function of UVT to calculate the UV dose expected at average and design UVT.

$$\text{Total duty lamps} = \text{Total duty lamps} \times \text{UV Dose (Design UVT)} / \text{UV Dose (Average UVT)}$$

Step 5. If the UV system uses a dose-pacing strategy that responds to lamp aging, integrate the inverse of the lamp-aging curve over the lamp replacement interval. Determine the lamp age where the integrated value equals half the value over the lamp replacement interval. Adjust the total duty lamps by the lamp-aging factor that occurs at that lamp age. This approach

assumes that the increase in lamp power required to dose pace as a function of lamp aging is inversely proportional to the lamp-aging curve.

$$\text{Total duty lamps} = \text{Total duty lamps} \times \frac{\text{Output of new lamp}}{\text{Output of lamp at half of lamp-life}}$$

Step 6. If the UV system uses a dose-pacing strategy that responds to sleeve fouling, adjust the total duty lamps by the average fouling factor defined as $(1+f_f)/2$ where f_f is the design fouling factor.

$$\text{Total duty lamps} = \text{Total duty lamps} \times (1 + \text{Design fouling factor}) / 2$$

Step 7. Calculate the number of operating banks in the UV system.

$$\text{Duty Banks} = \text{Total duty lamps} / \text{Lamps/bank}$$

$$\text{If Duty Banks} > \text{Int}(\text{Duty Banks}) \text{ then Duty Banks} = \text{Duty Banks} + 1$$

The calculation assumes that the UV system always operates as multiples of a single bank.

Step 8. Calculate the power setting of the lamps in those banks.

$$\text{Power Setting} = \text{Total Duty lamps} / (\text{Duty Banks} \times \text{Lamps/bank})$$

Step 9. Calculate the number of operating lamps, ballast, and sensors in the duty banks.

$$\text{Duty Lamps} = \text{Duty Banks} \times \text{Lamps/Bank}$$

$$\text{Duty Ballasts} = \text{Duty Lamps} / \text{Lamps/Ballast}$$

$$\text{Duty UV Sensors} = \text{Duty Lamps} / \text{Lamps/Bank} \times \text{Duty UV Sensor/Bank}$$

Determining UV System Costs

The following steps are incorporated into a subroutine that determines the UV system O&M and life-cycle costs.

Step 1. Calculate the annual power costs.

$$\text{Power Costs} = \text{Power/Lamp} \times \text{Electricity Costs} \times \text{Duty Lamps} \times \text{Power Setting}$$

Step 2. Calculate the annual consumable costs.

$$\text{Lamp Costs} = \text{Duty Lamps} / \text{Lamp Life} \times \text{Lamp Cost}$$

$$\text{Sleeve Costs} = \text{Duty Lamps} / \text{Sleeve Life} \times \text{Sleeve Cost}$$

$$\text{Ballast Costs} = \text{Duty Ballasts} / \text{Ballast Life} \times \text{Ballast Cost}$$

$$\text{UV Duty Sensor Costs} = \text{Duty UV Sensors} / \text{UV Sensor Life} \times \text{UV Sensor Cost}$$

$$\text{UV Sensor Calibration Costs} = \text{Duty UV Sensors} / \text{UV Sensor Calibration Period} \times \text{Sensor Calibration Cost}$$

$$\text{Consumable Costs} = \text{Lamps Costs} + \text{Sleeve Costs} + \text{Ballast Costs} + \text{Duty UV Sensors Costs} + \text{Sensor Calibration Costs}$$

This calculation assumes that the sensor life is defined by operating time.

Step 3. Calculate annual labor costs.

$$\text{Lamp Replacement Labor} = \text{Duty Lamps} / \text{Lamp Life} \times \text{Lamp Replacement}$$

$$\text{Sleeve Replacement Labor} = \text{Duty Lamps} / \text{Duty UV Sensor Life} \times \text{Sensor Replacement}$$

If Sleeve Cleaning Type = "Rinse" then

$$\begin{aligned} \text{Cleaning Labor} &= (\text{Trains} - \text{Parallel Redundancy}) \times (\text{Reactors/Train} - \\ &\text{Series Redundancy}) / \text{Sleeve Cleaning Period} \\ &\times \text{Sleeve Cleaning Time/Reactor} \end{aligned}$$

$$\text{Ballast Replacement Labor} = \text{Duty Ballasts} / \text{Ballast Life} \times \text{Ballast Replacement}$$

$$\text{Sensor Replacement Labor} = \text{Duty Sensors} / \text{Sensor Life} \times \text{Sensor Replacement}$$

$$\text{Sensor Calibration Labor} = \text{Duty Sensors} / \text{Sensor Calibration Period} \times \text{Sensor Calibration}$$

$$\begin{aligned} \text{Labor Costs} &= \text{Lamp Replacement labor} + \text{Sleeve Replacement Labor} + \text{Cleaning Labor} \\ &+ \text{Ballast Replacement Labor} + \text{Sensor Replacement Labor} \\ &+ \text{Duty UV Sensor Calibration Labor} \end{aligned}$$

Step 4. Calculate Annual Patent Costs.

$$\text{Patent Costs} = \text{Total Flow} \times \text{Patent Cost}$$

Step 5. Calculate Total O&M Costs

$$\text{O\&M Costs} = \text{Power Costs} + \text{Consumable Costs} + \text{Labor Costs} + \text{Patent Costs}$$

Step 6. Calculate Reactor Capital Costs.

$$\text{Reactor Capital} = \text{Reactor Cost} \times \text{Reactors/Train} \times \text{Trains}$$

$$\begin{aligned} \text{Capital Costs} &= \text{Reactor Capital} + \text{Building Piping} + \text{Power Supply} + \text{Instrumentation} \\ &+ \text{Engineering} \end{aligned}$$

Step 7. Calculate Present Worth Costs.

$$\text{NPV} = 0$$

For $x = 1$ to Period

$$\text{NPV} = \text{NPV} + (1 + \text{Interest})^{-x}$$

Next x

$$\text{NPV} = \text{NPV} \times \text{O\&M Costs} + \text{Capital Costs}$$

Lamp Replacement Interval Cost Analysis

The Lamp Replacement Interval Cost Analysis determines the UV System Operating Status and UV System Costs for lamp replacement intervals from 1,000 to 20,000 hours in 1,000-hour increments. For each replacement interval, the algorithm adjusts the number of duty lamps by the ratio of the standard lamp aging factor to the lamp-aging factor associated with the interval. In other words, Step 2 of the subroutines that determines the UV System Operating Status includes:

$$\begin{aligned} \text{Total duty lamps} &= \text{Total duty lamps} \times \text{Lamp Aging Factor} \\ &/ \text{Lamp Aging Factor}(\text{Lamp Replacement Interval}) \end{aligned}$$

The Lamp Aging Factor for each interval is calculated using the entered Lamp Aging Equation.

If the Lamp Aging Flag is set to one, the algorithm also adjusts the capital costs by the ratio of the standard lamp aging factor to the lamp-aging factor associated with the interval.

$$\begin{aligned} \text{Capital Costs} &= \text{Capital Costs} \times \text{Lamp Aging Factor} / \\ &\text{Lamp Aging Factor}(\text{Lamp-Replacement Interval}) \end{aligned}$$

Advanced Life-Cycle Cost Analysis

The Advanced Life-Cycle Cost Analysis uses three subroutines. The first determines the operation status of the UV system for each data set of water quality data (date/time, flow rate, UVT). The second determines the impact of power quality and component failure events on UV dose delivery and provides an estimate of public health protection. The third estimate determines integrated O&M costs and calculates the present worth costs factoring in capital costs.

Determining UV System Operating Status

The following approach is used to determine the number of reactors and banks of lamps used by the UV system to deliver the target UV dose at various conditions of flow rate and UVT specified in the worksheet WQ.

Step 1. Define the first water quality data set (date/time, flow rate, UVT) as time zero data. Set lamp aging factors for each bank to 100 percent. Set fouling factors for the UV system to 100%.

Step 2. Set the number of operating reactors and operating banks equal to 1. Calculate the flow per reactor as:

$$\text{Flow per reactor} = \text{Flow} / \text{Number of Reactors}$$

Step 3. For each bank of lamps in the operating UV system, enter the flow per reactor, UVT, lamp aging factor, and fouling factor into the relevant model for UV dose monitoring and control in REDMODEL. Read the target ballast power setting needed to deliver the required UV dose. If the required ballast setting is greater than 100 percent with any bank or the UV system is off specification, increase the number of banks of lamps in the operating UV system and repeat this step. If the required ballast setting is less than 100% with all banks, then identify the ballast power setting that equals or just exceeds the target ballast power setting.

Step 4. Determine the minimum UV sensor reading per reactor accounting for ballast power setting, lamp aging, and fouling. The lamp aging factor and ballast power setting will vary from bank to bank depending on previous simulated operation. Using the model for UV dose monitoring referenced in REDMODEL, determine the UV dose delivered by each reactor using the minimum UV sensor reading.

Step 5. Read the next water quality dataset. Calculate the lamp hours with each bank of lamps based on the operation defined in Step 4. Determine the lamp age per bank using those updated numbers. Update the fouling factor based on the expected rate of fouling over that period.

Step 6. Repeat steps 3 to 5 for each combination of date/time, flow rate, UVT in the water quality dataset.

Determining the Impact of Power Quality and Component Failure Events

The following approach is used to determine the UV system response to power quality and UV system component failure.

Step 1. For each water quality dataset, if the Supply Voltage is less than the voltage threshold for a duration longer than the event duration threshold, then a power quality event has occurred that causes the lamps to extinguish.

Step 2. Determine the down time due to the power quality event as follows:

If UPS = yes then Downtime = 0

If UPS = No and Generator = Yes, Then

If PQ Event Duration > Generator Startup Time, Then

If Generator Startup Time > Lamp Cool Down Time, Then

Downtime = Generator Startup Time

Else

Downtime = Lamp Cool Down Time

End if

Else

If PQ Event Duration > Lamp Cool Down Time, Then

Downtime = PQ Event Duration

Else

Downtime = Lamp Cool Down Time

End if

End if

Downtime = Downtime + Lamp Warmup Time

End if

If UPS = No and Generator = No, then

If PQ Event Duration > Lamp Cool Down Time, Then

Downtime = PQ Event Duration

Else

Downtime = Lamp Cool Down Time

End if

Downtime = Downtime + Lamp Warmup Time

End If

If Automatic Flow Shutoff Valve = Yes and Shutoff Valve Response Time < Downtime,

Then

Downtime = Shutoff Valve Response Time

End if

Step 3. Assume zero UV dose delivery over the downtime duration.

Step 4. For each WQ dataset, determine if a lamp, ballast, or UV sensor has failed using a Monte Carlo approach. Calculate Delta Date/Time as the difference between the Date/Time of the current and previous WQ datasets:

Delta Date/Time = Date/Time (t) - Date/Time(t-1)

Determine the probability of lamp failure within that bank of lamps over the duration of Delta Date/Time:

Probability = 1 - (1 - Lamp Failure Probability per day) ^ (Lamps per Bank × Delta Date Time)

Generate a random number between 0 and 1. If the random number is less than the probability of failure for a lamp, then assume a lamp failure event has occurred:

If Probability < Random Number then Lamp Failure

Repeat these calculations using the probability of failure for ballasts and lamps.

Step 5. Assume the UV dose-monitoring algorithm cannot estimate dose delivery with a bank of lamps if a lamp, ballast, or UV sensor failure event has occurred. As such, UV dose delivery by that bank is assumed as zero. Calculate UV dose delivery by the UV reactor using the remaining number of banks of lamps. Use the minimum UV sensor reading with the various banks of lamps in the dose calculation.

Step 6. UV system will respond to the failure event by turning on a bank of lamps or a reactor. Calculate the time it takes to turn on the bank of lamps as:

$$\text{Failure time} = \text{Lamp Warmup Time}$$

Calculate the time it takes to turn on another reactor as:

$$\text{Failure Time} = \text{Automatic Valve Shut Off Time} + \text{Lamp Warmup Time}$$

Step 7. Using the pathogen UV dose response model in the worksheet RISKMODEL, determine dose delivery and log inactivation by each train of reactors for following cases:

1. Operation unaffected by power quality events or component failure,
2. Operation with zero UV dose delivery caused by the power quality event, and
3. Operation with reduced UV dose delivery caused by the component failure event.

Calculate log inactivation by the UV system over the Delta Date/Time period as follows:

$$\text{UV System Log Kill} = 0$$

For $x = 1$ to Trains

$$\text{UV System Log Kill} = \text{UV System Log Kill}$$

$$+ \text{Failure Time} / \text{Delta Date/Time} \times 10^{-(\text{Failure Log Kill})}$$

$$+ (\text{Delta Date/Time} - \text{Failure Time} - \text{Downtime}) / \text{Delta Date/Time} \times 10^{-(\text{Log Kill})}$$

Kill)

Next x

$$\text{UV System Log Kill} = -\log(\text{UV System Log Kill}/\text{Trains})$$

Step 8. Using the human infection UV dose response model in the worksheet RISKMODEL, calculate the risk of infection. Calculate the accumulated infections over time.

Step 9. Determine the monthly average off spec performance by time and by volume.

Determine Integrated O&M and Life-Cycle Costs

The following approach is used to determine the integrated O&M and life-cycle costs.

Step 1. After determining the operation of the UV system using the last WQ dataset, calculate the Total Bank Hours as the sum of the bank hours with each bank in each reactor:

$$\text{Total Bank Hours} = 0$$

For $x = 1$ to Trains

For $y = 1$ to Reactors

For $z = 1$ to Banks

$$\text{Total Bank Hours} = \text{Total Bank Hours} + \text{Bank Hours}(x,y,z)$$

Next z

Next y

Next x

Step 2. Calculate Total Delta Date/Time as the difference in the Date/Time of the first and last WQ datasets:

$$\text{Total Delta Date/Time} = \text{Date/Time}(\text{last}) - \text{Date/Time}(1)$$

Step 3. Calculate the average number of lamps, ballast, and UV sensors used by the UV system over the simulation as:

```

Total Power = 0
For x = 1 to Trains
  For y = 1 to Reactors
    For z = 1 to Banks
      Total Bank Hours = Total Bank Hours + Bank Hours (x,y,z)
    Next z
  Next y
Next x
Duty Lamps = Total Bank Hours × Lamps per Banks / Total Delta Date/Time
Duty Ballasts = Duty Lamps / Lamps/ballast
Duty UV Sensors = Duty Lamps / Lamps/bank × Sensors/Bank

```

Step 4. Calculate the integrated power consumed by each bank of lamps in each reactor:

```

Sum Power = 0
Do Until Last WQ Dataset
  For x = 1 to Trains
    For y = 1 to Reactors
      For z = 1 to Banks
        Sum Power = Sum Power + Power (x,y,z)
      Next z
    Next y
  Next x
Loop

```

Power Setting = Sum Power / Total Delta Date/Time / Power/Lamp / Duty lamps

Step 5. Determine O&M life-cycle costs using the Standard LCA subroutine for determining UV system costs.

UVCAT OUTPUTS

Table A.3 lists the worksheets within UVCAT that are used to output data generated by UVCAT.

Table A.3 UVCAT worksheets used for output

Analysis	Input worksheets
Standard life-cycle cost analysis	STANDARD LCA
Lamp Replacement Interval Cost Analysis	LAMP AGE LCA TOOL
Advanced life-cycle cost analysis	ADVANCED LCA WQ REACTOR DOSE TARGET POWER 1 TARGET POWER 2 POWER 1 POWER 2 LAMP HOURS LAMP AGING FACTOR

Standard Life-Cycle Cost Analysis

The outputs for the Standard Life-Cycle Cost Analysis are placed in the worksheet entitled INPUTS AND LCA in rows 19 through 30.

- Rows 19 and 20 provide the lamp life and aging factor used in the analysis. The data matches the data entered in Lamp Data and is provided for reference purposes.
- Rows 21 and 22 provide the number of duty lamps and power setting of those lamps with the UV system operating under average conditions of flow rate, UVT, lamp aging, and sleeve fouling given the dose-pacing strategy used by the UV system.
- Rows 23 through 33 provide annual O&M costs. Row 23 provides the annual power cost. Rows 25 through 29 provide annual consumables costs including lamp replacement, sleeve replacement, ballast replacement, sensor replacement, and sensor calibration, respectively. Row 30 provides the total annual consumable costs. Rows 31 and 32 provide the annual total labor and patent costs, respectively. Row 33 provides total annual O&M costs.
- Row 34 provides total capital costs. Rows 35 and 36 provides total present worth costs and present worth of O&M.
- Row 37 provides the ballast power setting the UV system operates at under design conditions. If the power setting is greater than 100%, the UV system is undersized for the design conditions of flow, UVT, lamp aging, and fouling. If the power setting is less than 100%, the UV system is oversized.

Lamp Replacement Interval Cost Analysis

The outputs for the Lamp Replacement Interval Cost Analysis are placed in the worksheet entitled LAMP AGE ANALYSIS.

Results for each case analyzed are placed in tables organized with the results for case 1 placed in rows 18 through 40, case 2 in rows 44 through 66, case 3 in rows 70 through 92, as so forth. The tables provide operating status and costs as a function of lamp replacement interval. Columns in each table are:

- Lamp Life - from 1,000 to 20,000 hours in 1,000 hour increments
- Age Factor - lamp aging factor associated with each lamp life
- Average Lamps - number of lamps that would operate under average conditions of flow rate, UVT, lamp age, and sleeve fouling.
- Power Setting - Power setting of those lamps
- Power - annual power costs
- Consumables - annual consumable costs
- Labor - annual labor costs
- Patent - annual patent costs
- Total O&M - total annual O&M costs
- Capital - total capital costs
- NPV - Net Present Value of O&M and capital costs

Information in each table can be graphed as a function of lamp replacement interval.

Advanced Life-Cycle Cost Analysis

The outputs from the advanced LCA tool are placed in the following worksheets:

- LAMP AGING FACTOR - relative output of the UV lamps in each banks of lamps as a function of time
- LAMP HOURS - number of operating hours accumulated by the lamps since lamp replacement in each bank of lamps as a function of time
- TARGET POWER 1 - target power predicted by the RED model for the type 1 lamps in each bank assuming ideal dose pacing with infinite turndown and turn up (ie, the target power could be 25 kW with lamps rated at 10 kW).
- TARGET POWER 2 - target power predicted by the RED model for the type 2 lamps in each bank
- POWER 1 - operating power setting of the type 1 lamps in each bank based the entered ballast power settings achievable
- POWER 2 - operating power setting of the type 2 lamps in each bank
- REACTOR DOSE - UV dose delivered by each reactor in the UV system as a function of time with operation not impacted by power quality events and component failure
- WQ - various measures of UV system performance as a function of time including:
 - Target RED - column I
 - Trains - column J
 - Reactors Per Train - column K
 - Banks per Reactor - column L
 - Flow rate per reactor - column M
 - Fouling Factor - column N
 - Total Power based on Power 1 and Power 2 data - column O
 - Ideal Total Power based on Target Power 1 and Target Power 2 data - column P
 - Ratio of Total Power and Ideal Total Power - column Q
 - Daily Power Costs - column R
 - Power Costs - column S
 - Sum Power Costs - column T
 - Ofspec Flag - column U
 - Percent Ofspec Time - column V
 - Percent Ofspec Volume - column W
 - UV System Log Kill - column X
 - Risk - column Y
 - Annual Risk - column Z
 - Accumulated Illness - column AA

The information placed into the above-mentioned worksheets is for the last column of analysis conducted by Advanced LCA Tool of UVCAT. Because UVCAT can conduct analysis of multiple sets of input data, the software also saves the worksheet WQ for each analysis to a user-defined file. The user can specify the filename and the directory where that file is saved in

cells B5 and B6 of the worksheet ADVANCED LCA. Examples of those output files are provided for the analysis conducted for this report.

Last, the CLEAR button in the worksheet ADVANCED LCA allows the UVCAT user to clear all output data in the above-mentioned spreadsheets. This feature is useful for removing output data from old files and minimizing the filesize of UVCAT EXCEL workbook. The example version of UVCAT provided with this report includes example output data.

QUALITY ASSURANCE/QUALITY CONTROL

The UVCAT software checks the inputs to the software and flags the user if those inputs do not meet the criteria given in Table A.4. The criteria provided in Table A.4 are broad and extend well beyond the typical range used with drinking water and wastewater reactors. The user should use Table A.4 as guidance for the values entered into UVCAT.

As discussed, UVCAT uses various models for lamp aging, UV dose delivery, pathogen UV dose-response, and risk analysis. Those models are defined by the user. UVCAT does not check the form of those models. If the form of those models gives results that make no sense, either the outputs from UVCAT will make no sense or the model could cause a software running error. For example, if the model used results in a divide by zero taking place, the software will stop and indicate an error with the following message:

“UVCAT encountered a running error”

The user should check their models for lamp aging, UV dose delivery, pathogen UV dose-response, and risk analysis to ensure they provide valid predictions over the range of conditions simulated using UVCAT. If UVCAT does encounter a mathematical error running the Advanced LCA, the user can investigate model predictions for the combination of WQ data that caused the software error by entering that data into the respective models.

Table A.4 UVCAT QA/QC Checks on Input Parameters.

Parameter	Units	UVCAT QA/QC Criteria
Maximum Flow rate	mgd	$0 < \text{Value} \leq 9999$
Average Flow rate	mgd	$0 < \text{Value} \leq 9999$
Average UVT	%	$0 < \text{Value} < 100$
Design UVT	%	$0 < \text{Value} < 100$
Design UV Dose	mJ/cm^2	$0 < \text{Value} \leq 9999$
Minimum Number of Trains	-	$0 \leq \text{Value} \leq 40$
Max. Flow rate per reactor	mgd	$0 < \text{Value} \leq 9999$
Number of Trains	-	$0 < \text{Value} \leq 40$
Number of Reactors/Train	-	$0 < \text{Value} \leq 8$
Banks/Reactor	-	$0 < \text{Value} \leq 30$
Lamps/Bank	-	$0 < \text{Value} \leq 9999$
Lamps/Ballast	-	$0 < \text{Value} \leq \text{Lamps/Bank}$

(Continued)

Table A.4 UVCAT QA/QC Checks on Input Parameters (cont.)

Parameter	Units	UVCAT QA/QC Criteria
Sensors/bank	-	$0 < \text{Value} \leq \text{Lamps/Bank}$
No. of Redundant Trains	-	$0 \leq \text{Value} < \text{Number of Trains}$
No. of Redundant Reactors per train	-	$0 \leq \text{Value} < \text{Number of Reactors/Train}$
Lamp 100% Power	kW	$0 < \text{Value} \leq 100$
Lamp Life	hrs	$0 < \text{Value} \leq 100,000$
Lamp Aging Factor	%	$0 < \text{Value} \leq 100$
Lamp Cost	\$	$0 < \text{Value} \leq 99,999$
Lamp Replacement Time	Min.	$0 < \text{Value} \leq 500$
Fit Type (MMF, EXP, LIN, CUSTOM)	-	Enter either MMF, EXP, LIN or CUSTOM
Coefficient A	-	Any numeric value, set to 0 if not used
Coefficient B	-	Any numeric value, set to 0 if not used
Coefficient C	-	Any numeric value, set to 0 if not used
Coefficient D	-	Any numeric value, set to 0 if not used
Sleeve Life	yrs	$0 < \text{Value} \leq 100$
Sleeve Cost	\$	$0 < \text{Value} \leq 20,000$
Sleeve Replacement Time	min	$0 < \text{Value} \leq 500$
Sleeve Cleaning Type (Rinse, Wiper)	-	Enter either "Rinse" or "Wiper"
Sleeve Cleaning Period	weeks	$0 < \text{Value} \leq 99$
Sleeve Cleaning Time/Reactor	min	If Sleeve Cleaning Type = Rinse, then $0 < \text{Value} \leq 1000$ If Sleeve Cleaning Type = Wiper, then $0 \leq \text{Value} \leq 100$
Fouling Factor	%	$0 < \text{Value} \leq 100$
Ballast Life	yrs	$0 < \text{Value} \leq 100$
Ballast Costs	\$	$0 < \text{Value} \leq 100,000$
Ballast replacement	min	$0 < \text{Value} \leq 600$
Sensor life	yrs	$0 < \text{Value} \leq 100$
Sensor cost	\$	$0 < \text{Value} \leq 20,000$
Sensor replacement	min	$0 < \text{Value} \leq 300$
Sensor cal period	months	$0 < \text{Value} \leq 60$
Sensor calibration cost	\$	$0 < \text{Value} \leq 9999$
Sensor calibration	min	$0 < \text{Value} \leq 600$
Dose Model	-	$0 < \text{Value} \leq 99$
Peak UV Dose	mJ/cm ²	$0 < \text{Value} \leq 9999$

(Continued)

Table A.4 UVCAT QA/QC Checks on Input Parameters (cont.)

Parameter	Units	UVCAT QA/QC Criteria
Flow (y/n)	-	Either “y” or “n”
Lamp Age (y/n)	-	Either “y” or “n”
Lamp Age (y/n)	-	Either “y” or “n”
UVT (y/n)	-	Either “y” or “n”
Fouling (y/n)	-	Either “y” or “n”
Supply Voltage Lower Limit	% nom	0 < Value < 100
PQ Event Duration Lower Limit	s	0 < Value ≤ 100
UPS (y/n)	-	Either “y” or “n”
Generator (y/n)	-	Either “y” or “n”
Generator Startup Time	s	0 < Value ≤ 1800
Automatic Flow Shutoff Valve (y/n)	-	Either “y” or “n”
Shut Off Valve Response Time	s	0 < Value ≤ 1800
Lamp Cool-down Time	min	0 < Value ≤ 30
Lamp Warmup Time	min	0 < Value ≤ 30
Lamp Failure Probability	per day	0 ≤ Value < 1
Ballast Failure Probability	per day	0 ≤ Value < 1
UV Sensor Failure Probability	per day	0 ≤ Value < 1
UVT Monitor Failure Probability	per day	0 ≤ Value < 1
Labor rate	\$/hr	0 < Value ≤ 999
Electricity Cost	\$/kWhr	0 < Value ≤ 99
Patent fees	\$/1000 gal	0 < Value ≤ 99
Interest rate	%	0 < Value ≤ 100
Period	yrs	0 < Value ≤ 99
Supply Voltage	volts	0 < Value ≤ 9999
Population	-	0 < Value ≤ 999,999,999
Dose Delivery vs UVT	mJ/cm ²	0 < Value ≤ 9999
Ballast Power Settings	%	0 < Value ≤ 150 9999
Starting Column	-	0 < Value < 254
Ending Column	-	0 < Value < 254
Lamp Aging Analysis Type	-	0 or 1
Save Directory	-	Valid MS Windows Directory Name
Save Directory	-	Valid MS Windows File Name
Date_Time	-	Valid Excel Date/Time Formatted Values
Flow rate	mgd	0 ≤ Value ≤ 9999
UVT	%	0 < Value < 100 or 9999
Pathogen Data	per L	0 < Value < 99,999,999
Supply Voltage	V	0 ≤ Value ≤ 9999

