IUVA NEWS

ISSN 1528-2017
VOLUME 8/NO. 1 MARCH 2006

FEATURES

ARTICLES

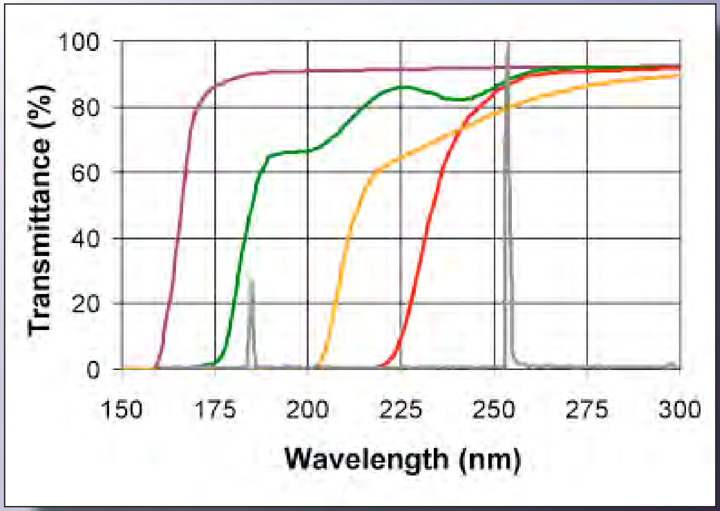
Optimum UV Disinfection Location in a Large Water Treatment Plant

Ozone and UV Disinfection Processes at the Greater Vancouver Water Source

UV Lamps for Disinfection and Advanced Oxidation

UV Dose Tables for Viruses, Bacteria and Protozoa

Linda Gowman, IUVA's new President-Elect - *see p.6*



Transmission Spectra of Various Quartzes - *see p.32*

Join IUVA!
now on line at
www.iuva.org

in the next issue . . .
more exciting UV articles

CONTENTS

4 President's Message
4 Editorial
5 Hot UV News
5 UV Industry News
6 News from IUVA
7 Application Notes
8 Report on the USEPA LT2 Rules

ARTICLES

11 Finding the Optimum UV Disinfection Location in a Large Water Treatment Plant
Jamal Awad, Ramesh Kashinkunti, Nicholas Winnike and Jim Malley

20 Integrating Ozone and UV Disinfection Processes at the Greater Vancouver Water District's Coquitlam Source
Lawrence Benjamin, Lynn Landry and Paul Wobma

32 UV-Lamps for Disinfection and Advanced Oxidation - Lamp Types, Technologies and Applications
Sven Schalk, Volker Adam, Erich Arnold, Kari Brieden, Alex Voronov and Hans-Dieter Witzke

38 UV Dose Required to Achieve Incremental Log Inactivation of Bacteria, Protozoa and Viruses
Gabriel Chevrefils, Éric Caron, Harold Wright, Gail Sakamoto, Pierre Payment, Benoit Barbeau and Bill Cairns

Printed by Quality Color an RR Donnelley Company

INDEX OF ADVERTISERS

10 *American Air and Water*
46 *American Ultraviolet*
18 *American Water Works Assoc.*
19 *Black & Veatch*
10 *Brightwell Technologies*
Inside Front Cover *Calgon Carbon*
19 *Camp, Dresser & McKee*
46 *ETA Plus*
31 *Hanovia Ltd.*
31 *Hazen & Sawyer*
37 *Heraeus Noblelight*
31 *HF Scientific*
17 *Light-Sources*
19 *Malcolm Pirnie, Inc.*
Back Cover *Philips Lighting*
10 *Real Tech Inc.*
19 *SITA*
46 *Severn Trent Services*
Inside Back Cover *Trojan Technologies*
45 *UV Systec*

Editor in Chief: *Dr. James R Bolton*

IUVA News (print version) (ISSN 1528-2017) is published quarterly by the International Ultraviolet Association, Inc. (IUVA) and is provided free to IUVA Members.

Editorial Office: Department of Civil and Enviornmental Engineering,
University of Alberta
Edmonton, AB, Canada T6G 2G8
Tel: (780) 439-4709 Fax: (780) 439-7792
Email: jim.bolton@iuva.org

For IUVA membership information, go to the IUVA Web Site http://www.iuva.org/ or contact **Kathy Harvey** *(see below)*

For advertising in IUVA News,
contact **Jim Bolton** (jim.bolton@iuva.org)
Tel: (780) 439-4709

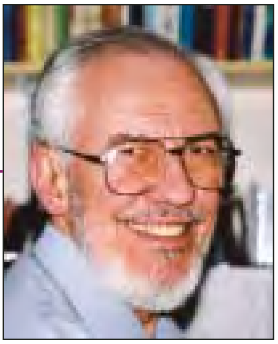
For other IUVA matters, contact:
Dr. James Bolton, Executive Director
(jim.bolton@iuva.org) or **Kathy Harvey**
Manager IUVA Head Office
(kathy.harvey@iuva.org) at the International Headquarters Office
PO Box 1110, Ayr, ON, Canada N0B 1E0
Tel: (519) 632-8190 Fax: (519) 632-9827

IUVA's Web Page: www.IUVA.org

EDITORIAL

by Jim Bolton

Editor-in-Chief



Much has happened in IUVA since the last issue of IUVA News went out in December.

This will be the first issue of IUVA News to be published in both the traditional print form and the new "electronic" form. Most IUVA Members have opted for the latter format, so hopefully you are reading this message now on your monitor, after you have "clicked through" to the issue in the Member Zone of the IUVA Web Site.

You will note that IUVA News has a 'new look'. Our publisher, Quality Color in Edmonton, is now managing the workup of each issue and took the initiative to 'redsign' the style. I like it – I hope you do too!

The IUVA Web Site has undergone a complete internal rebuilding with a new web site administrator. The "look and feel" of the Web Site has not changed, except for the addition of a new page called "What is UV?", but the site should function much more smoothly.

We have "automated" the UV Buyer's Guide on the IUVA Web Site (this is the most popular page on the web site, other than the Home page). This will allow vendors to enter their listings, edit or update them and pay online for the charges. We anticipate that this will be a considerable revenue source for IUVA.

The IUVA Board has elected a new President Elect – Linda Gowman of Trojan Technologies (see article later in this issue) – congratulations, Linda!

The 4th UV Congress, in parallel with the 18th World Ozone Congress, will take place 26 – 30 august 2007 in Los Angeles. This is the first time that IUVA and the IOA have collaborated on joint Congresses. Mark these important dates on your calendar – this will be an event you will not want to miss!

We continue to receive high quality articles, as this issue demonstrates. If you would like to write an article, or can recommend someone who should write an article for IUVA News, please let me know (jim.bolton@iuva.org) and I'll send you the "Instructions to Authors".

Let me end by paying a tribute to Kathy Harvey, the Manager of IUVA's Head Office. The smooth operation of IUVA would not be possible without her efficient management of Membership administration, financial bookkeeping and accounting, event management and responding to many inquiries every day. Thank you Kathy – it is a joy to work with you!

A MESSAGE

from the president

Andreas Kolch

I hope that everyone had a good start into the New Year. Actually IUVA had. We are glad to be able to announce that we started into the year as budgeted and we are still on budget.

This first issue of IUVA news in 2006 is at the same time the first electronic version of the news, which most of you agreed to be a good alternative to the printed version. As a result, we are also able to announce that we are not making a loss with this issue, which has been the case for a long time. Our workshops and seminars face good interest and with that background I am positive about turning the IUVA into financially healthy situation, which will allows us to build the future of the association on a solid ground.

On the activity side of things, our Manufacturers' Council has been almost reached its initial setup, with a starting group of 16 manufacturers. This illustrates the large interest of the UV industry in having their voice recognized. It will be for sure one of the most activities of considerable impact in the next couple of months.

The UV Air Treatment Group had their 3rd Conference and generated a lot of interest. Lively discussions are following these activities, and I personally think that this is a positive signal of being an active association. IUVA is a platform for all kinds of different UV applications and technologies, and it is a good forum for experts to help them sharing their knowledge and different views, This is exactly what the IUVA can and should offer.

The 4th UV Congress, with our partner the International Ozone Association (IOA) is on the way. At this time a group consisting of IOA and IUVA members are evaluating different sites in Los Angeles to get us the best place and arrangements. Again, the synergies of both organizations working together are something which we can transfer into a fantastic venue in 2007. I think that the membership fees should be looked at as giving the "biggest bang for the buck", so that everybody knows that the money one is spending in terms of membership and conference fees is invested as effectively as possible.

At this point I want to thank once again all of you who are willing to contribute time and work into activities without any charge. Without that, we would not be able to get things done. To be able to recognize those members, we have started the process of creating a new committee responsible for award recommendations to the board.

Last but not least, coming back from New Delhi, India last week where our first Indian UV workshop took place, it is fascinating to see how many people around the globe are interested in UV technology and applications and how IUVA can guide and help these activities. On the other hand, IUVA can benefit from those events reaching out for new members.

I hope you see that a lot of efforts are being spent in activities that should make IUVA an attractive association to be in. But the ones who know best of all what an attractive association should do or not do are you, the members. So if you feel something should be changed, started, not be done, etc., please do not hesitate to contact me and give me your input. We will all do our best to make it your Association.

Have a great year!

Andreas

HOT UV NEWS

The following are some of the more interesting items from the UV News page on the IUVA Web Site (http://iuva.org/public/uv_news.htm). Some of these items have been provided by IUVA Board Member, **Joan Oppenheimer**, from MWH Applied Research Dept. in Pasadena, CA who has volunteered to help with selecting items for UV News. Thank you, Joan!

19 January 2006: City to take part in ultraviolet water study, The Chronotype, Rice Lake, WI
http://www.chronotype.com/newarticle.asp?T=L&ArticleID=9628
Rice Lake and Cameron are among 14 Wisconsin communities selected for a study of the effects of **ultraviolet light** on drinking water. The study, conducted by Marshfield Clinic Research Foundation, is funded through a federal Environmental Protection Agency grant. Rice Lake Utilities general manager Scott Reimer emphasized that there is no current problem with the Rice Lake water system. He said the study was approved in December by the Utilities Commission. Under the study, **ultraviolet lights** will be installed at every city well in seven communities. The other seven communities will serve as a control group…

26 February 2006: Japanese Companies Develop Air-Purifying Paper, Great News Network.
http://www.greatnewsnetwork.org/index.php/news/article/japanese_companies_develop_air_purifying_paper/?source=rss
Nippon Paper Industries Co. has partnered with Japanese newspaper Yomiuri Shimbun to developed newsprint coated with photocatalytic titanium oxide. When the paper is exposed to the sun's **ultraviolet rays**, it works to eliminate everyday odors such as tobacco smoke, sweat and pet odors. The companies say it is the world's first application of photocatalytic compounds to newspaper…

4 March 2006: 'Ultraviolet' is Over the Top, by Peter Hartlaub, San Francisco Chronicle (http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2006/03/04/DDG8GHI8044.DTL&feed=rss.entertainment)
"Ultraviolet" is a movie so overwhelmingly computer animated, that it's maybe two light cycles away from qualifying as a "Tron" sequel. You can see how action heroine Milla Jovovich might have been attracted to the starring role – paint one wall green and she could have done most of the acting from her living room.

UV INDUSTRY NEWS

The following are some of the more interesting items from the UV Industry Announcements page on the IUVA Web Site (https://secure.nelixstore.com/iuva/public/uv_industry_announcements.htm).

If your company would like an announcement posted here or on the IUVA web site, send it to Jim Bolton (jim.bolton@iuva.org).

8 December 2005: Calgon Carbon Wins Appeal in Canadian *Cryptosporidium* Patent Dispute, Calgon Carbon Corporation announced today that the Canadian Federal Court of Appeal allowed its appeal and set aside a decision rendered by a lower court in June 2005 that declared invalid the company's patent for the use of ultraviolet light to prevent infection from *Cryptosporidium* in drinking water. As a result of the appeal court's decision, the case will move forward to trial in April 2006 to determine the merits of Calgon Carbon's claim that the City of North Bay, Ontario, Canada infringed its patent and Trojan Technologies, Inc. induced that infringement… Contact Jim Sullivan (jsullivan@calgoncarbon-us.com)

9 February 2006: Balba Technologies launches new era in UV water disinfection – "Out of the Water" UV Light for Water Disinfection, http://www.edie.net/news/news_story.asp?id=11055&channel=0#

Kings Lynn, Norfolk: Balba Technologies, a rising 'name' for the supply of innovative solutions for water treatment and purification, has announced the UK launch of the revolutionary **Atlantium Rayo** system. The system, which has been developed by the Israeli company Atlantium Limited, is non-toxic and uses advanced technologies and fiber optic principles to overcome the significant drawbacks associated with traditional methods of water disinfection…

10 March 2006: NEW DUO-SENSOR UV HAZARD METER, Gigahertz-Optik, Inc.

Four-channel microprocessor technology enables Gigahertz-Optiks' new X1-1 hand-held meter to operate and display separate UV-C/B, UV-A detector measurements as well as calculate and display the sum of the two detector readings for more accurate UV hazard assessment per ACGIH / ICNIRP guidelines… Contact Bob Angelo (b.angelo@gigahertz-optik.com).

NEWS FROM *IUVA*

IUVA Board has Elected a New President Elect, Linda Gowman

Dr. Linda Gowman is Vice President of Research at Trojan Technologies Inc. in London, ON, Canada. Dr. Gowman leads a team of scientists and researchers focused in areas of microbiology, environmental chemistry, fluid dynamics, photonics, photochemistry and disinfection modeling. Linda is a Professional Engineer (Ontario) and holds a B.A.Sc. in Mechanical Engineering from the University of Toronto, a M.Sc. in Biophysics from the University of Western Ontario and a Ph.D. in Mechanical Engineering from the University of Toronto. Linda will take over as IUVA's President at the next UV Congress in August 2007.

Membership Renewal and Wire or Check Payments: Kathy Harvey asks a favor of you our members to help make her job a little easier and get your membership renewal processed a little faster. We prefer you to use the online renewal system to renew your membership for fast efficient service. We do recognize however that some companies prefer to pay by check or wire transfer. If this is the case a certain procedure must be followed:

When you receive the email reminder that your membership is about to expire, click on the link which will take you to your membership profile. Make any updates, print this page and send it with your check or write on it the date the wire payment was sent and send it to IUVA.

The reason this process is very important is that Kathy receives a lot of payments in a week for different things including membership, advertising, conference fees etc. If a wire payment shows up on her bank statement or she receives a check with no indication re what it is for, it makes it very difficult. In the case of the wire payments she sometimes don't even know who they are from.

Your help in this matter would be greatly appreciated.

Problems with a Virus/Worm: Recently many IUVA Members have been receiving 'messages' that appear to come from IUVA Members (even Andreas Kolch!). These messages are possibly linked to a virus/worm infected computer belonging to an IUVA Member, which is sending out infected messages to the person's email address list. Please adopt the following protocol if you receive such messages:

Do NOT under any circumstances open an attachment that looks suspicious ('photos' are particularly bad)
Make sure that you have a good antivirus program installed on your computer, do a hard disk scan at least once per week and make sure that the software definitions are "up-to-date".

IUVA Web Site

The IUVA Web Site is now being managed by Kaizen Denki Inc. and the new webmaster is Kevin Wright – welcome on board, Kevin! Kevin has implemented several changes:

- All email addresses on the site are now in "graphic mode", which should prevent "spiders" from harvesting email addresses.
- The email addresses for Jim Bolton and Kathy Harvey have been changed to **Jim.Bolton@iuva.org** and **Kathy.Harvey@iuva.org** to avoid problems with excessive SPAM. Please note these changed email addresses.

Upcoming IUVA-sponsored Conferences and Workshops

28 March – 1 April 2006: WQA Aquatech USA 2006, Chicago, IL. IUVA will be sponsoring a UV Workshop (organized by Jim Malley). IUVA Members can get a free registration to the Exhibition – the VIP Code is VIPIUVA06. See www.wqa.org for more details

May 17-19, 2006: 3rd IUVA-NYSERDA Northeast-Midatlantic Ultraviolet Technology Conference, Albany, NY – Brochure and registration info available on the IUVA web site (www.iuva.org). Organizers: Kathleen O'Connor, Dave Dziewulski, Jim Malley

24 May 2006: Mid-South Ultraviolet Technology Conference Houston, Texas – Brochure and registration information will be available soon. Organizers: Jason Christensen, Karl Linden

25-30 August 2007: World UV/Ozone Congress, Los Angeles, CA – A Call for Papers will be issued soon.

As always, comments on the web Site are most welcome – send either to **Jim Bolton** (jim.bolton@iuva.org) or the Webmaster **Kevin Wright** (ask@iuva.org).

A NEW UV BOOK

The book "La Radiazione UV Nel Trattamento Delle Acque Destinate Al Consumo Umano" (UV Radiation for the Treatment of Waters Destined for Human Consumption) by **Giorgio Temporelli** and **Roberto Porro** has recently been published in Italian by FrancoAngeli s.r.l., Milan, Italy. This book covers the features, properties and start-up of UV reactors, determination of the disinfection effectiveness and certification tests and application standards for UV technologies.

APPLICATION NOTES

***Editor:** UV companies are welcome to submit "Application Notes" for this column. Send to **jim.bolton@iuva.org**.*

Danish Sludge Dewatering Plant

from Hanovia Ltd., Slough, UK
(www.hanovia.com).

To ensure wastewater is effectively disinfected before being mixed with a polymer for subsequent sludge decantation (separation) and dewatering, the Stege Kommune municipality in Denmark has installed a Hanovia medium pressure UV disinfection system.

The wastewater/polymer mixture decants the sludge into two phases as part of the dewatering process. The sludge, is disinfected by heat treatment prior to decantation, so the wastewater/polymer mixture needs to be completely free from bacteria, viruses and other microbial contaminants. The treated wastewater is also used to clean the sludge decanter at the end of the process.

To ensure optimum performance, the Hanovia UV system is fitted with a hand-operated wiper. This keeps the quartz sleeve surrounding the UV lamp free from fouling and means UV output is always at its maximum. The system has a flow rate of 10.8 m^3/h.

UV is widely used to inactivate harmful pathogens from drinking water and wastewater. It is a completely clean technology which does not rely on the use of chemicals and leaves no unwanted residues or by-products.

Recent research suggests medium pressure UV is more effective at complete and permanent inactivation of microorganisms than low pressure UV.

According to Hanovia's Danish distributor, the Stege Kommune is very satisfied with the performance of the Hanovia system, which was chosen for its quality and fast pay-back time.

For further information, contact Duncan Ockendon (duncan.ockendon@hanovia.com).

New Surface Discharge Pulsed UV Light Source

from Phoenix Science & Technology, Inc.
(www.PhoenixSandT.com).

Pulsed lamps based on electric discharges in xenon are of interest for water treatment because they are free of mercury, turn on instantly and provide enhanced treatment rates due to the high irradiance of pulses or spectral differences. Our Surface Discharge (SD) lamp is a new pulsed lamp with higher UV efficiency and peak irradiance than mercury lamps or conventional pulsed flashlamps. At the Third International Congress on UV Technologies we presented four papers on UV performance,[1] evaluating pulsed effects[2] and results of treatment of atrazine,[3] MS-2 bacteriophage and *Bacillus subtilis* spores.[4]

In an SD lamp, a high power electrical pulse discharges along the outer surface of a dielectric tube inside a larger tube (envelope). The electrical discharge produces a plasma along the surface of the dielectric. The outer envelope serves to contain the xenon, and plays no role in the plasma formation and evolution, unlike flashlamps.

A comparison of the SD lamp with a xenon flashlamp and a conventional medium pressure (MP) lamp shows that the SD has the highest UV efficiency (about 17%), defined as the ratio of light energy in 200-300 nm, to the electrical energy consumed.

Water treatment tests in a collimated beam set-up, conducted with Prof. Karl Linden and his group at Duke, showed higher dose based rates with the SD in comparison to the MP lamp. For atrazine the SD photolysis rate was 1.3 times greater, and with hydrogen peroxide 2.4 times greater than with the MP lamp[4]. For MS-2 the inactivation rate was 2.0 times greater and for *B. subtilis* 1.6 times greater than with the MP lamp.[2]

Currently we are investigating further water treatment effects of pulsed light, conducting inactivation tests on Adenovirus, conducting reactor tests with SD lamps on microbes and organic chemicals, and pursuing commercialization of the SD lamp.

For further information, contact Ray Schaefer (rschaefer@phoenixsandt.com).

All of the following references are from the CDROM Proceedings of the 3rd International conference on Ultraviolet Technologies, Whistler, BC, Canada, May, 2005. The CDROM amy be obtained from The International Ultraviolet Association, PO Box 1110, Ayr, ON, Canada N0B 1E0.

1. Schaefer, Raymond, Michael Grapperhaus, Karl Linden, New Surface Discharge Pulsed UV Light Source.
2. Grapperhaus, Michael, Schaefer, Raymond B. and Linden, Karl. Modeling of a new UV test cell for evaluation of lamp intensity effects on water treatment.
3. Bohrerova, Zuzana, Mamane-Gravetz, Hadas, Linden, Karl, Grapperhaus, Michael and Schaefer, Raymond B. Comparative inactivation of *Bacillus subtilis* spores and MS-2 bacteriophage using standard mercury laps and a new, pulsed, Surface Discharge Lamp.
4. Shemer, Hilla, Linden, Karl, Grapperhaus, Michael and Schaefer, Raymond B. Pulsed UV enhance photodegradation of atrazine in drinking water.

OVERVIEW OF RECENTLY FINALIZED LT2ESWTR & STAGE 2 D/DBPR

James Collins, Christine Cotton, and Laurel Passantino, Malcolm Pirnie, Inc.

The US Environmental Protection Agency has recently promulgated the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) and the Stage 2 Disinfectants and Disinfection Byproduct Rule (Stage 2 DBPR). These regulations were developed through a stakeholder regulatory negotiation process that started in 1992. The objective of the LT2ESWTR is to provide the public with increased protection from illnesses related to microbial contamination of drinking water. The objective of the Stage 2 DBPR is to build upon current DBP regulations to provide the public with increased protection against harmful DBPs. The Stage 2 DBPR and LT2ESWTR were published in the Federal Register on January 4, 2006 and January 5, 2006 respectively. The compliance timelines for each rule is shown in the tables below. In addition, several guidance manuals, including the UV Disinfection Guidance Manual, already have or will be published to assist utilities with compliance with these new rules.

LT2ESWTR Background

- The LT2ESWTR requires increased microbial protection for *Cryptosporidium*.
- The level of increased protection is dependent on source water monitoring results.
- This regulation applies to all utilities using surface water or ground water under the influence of surface water.

Highlights of LT2ESWTR

- Source water monitoring for *Cryptosporidium* will determine the amount of *Cryptosporidium* removal/inactivation required (see table below).
- The Microbial Toolbox contains 15 alternatives for achieving *Cryptosporidium* credit, including options for source protection, prefiltration, treatment performance, additional filtration, and inactivation (including UV disinfection)
- Utilities with uncovered finished water reservoirs must either cover the storage facility or provide treatment for virus, *Giardia*, and *Cryptosporidium* following the reservoir.

Stage 2 DBPR Background

- The Stage 2 DBPR maintains the maximum contaminant levels for total trihalomethanes (TTHM) and haloacetic acids (HAA5) of 80 μg/L and 60 μg/L; however, compliance is based on locational running annual averages (LRAAs) at new locations in the distribution system that are representative of high TTHM and HAA5 concentrations- rather than the old system-wide running annual average.
- Consecutive water systems are also required to comply with all of the requirements of the new rule.

Highlights of Stage 2 DBPR

- All utilities are required to perform an Initial Distribution System Evaluation (IDSE) to identify new Stage 2 DBPR compliance monitoring locations
- The Stage 2 DBPR identifies granular activated carbon (GAC) and nanofiltration (NF) as Best Available Technology (BAT) to comply with the rule for systems that treat their own water.
- Chloramination and hydraulic flow and storage management to minimize water age are identified as BAT for consecutive water systems.

LT2ESWTR BIN REQUIREMENTS

Bin Number	Average Source Water *Cryptosporidium* Concentration	Additional Treatment Requirements for Systems with Conventional Treatment and in Full Compliance with IESWTR
1	0.075 oocysts/L	No action
2	0.075 to <1.0 oocysts/L	1-log treatment
3	1 to <3.0 oocysts/L	2-log treatment (at least 1-log by ozone, chlorine dioxide, UV disinfection, membranes, bag/cartridge filters, or in-bank filtration)
4	3.0 oocysts/L	2.5-log treatment (at least 1-log by ozone, chlorine dioxide, UV disinfection, membranes, bag/cartridge filters, or in-bank filtration)

LT2ESWTR COMPLIANCE TIMELINE

	Compliance Dates by System Size		
Requirement	**100,000**	**50,000 – 99,999**	**10,000 – 49,999**
Submit Sampling Plan*	1-Jul-06	1-Jan-07	1-Jan-08
Begin source water monitoring	1-Oct-06	1-Apr-07	1-Apr-08
Submit grandfathered data**	1-Dec-06	1-Jun-07	1-Jun-08
Report bin classification	1-Apr-09	1-Oct-09	1-Oct-10
Disinfection profiles/benchmarks	Prior to making changes in disinfection practices		
Comply with additional requirements	1-Apr-12	1-Oct-12	1-Oct-13
Submit Sample Plan for Round 2*	1-Jan-15	1-Jul-15	1-Jul-16
Begin Round 2 monitoring	1-Apr-15	1-Oct-15	1-Oct-16
Report new bin classification	1-Oct-17	1-Apr-18	1-Apr-19
Comply with additional requirements	On a schedule approved by the State		

** Or submit notice of intent to grandfather data or to provide maximum required treatment in lieu of monitoring.*
*** If applicable.*

STAGE 2 D/DBPR COMPLIANCE TIMELINE

	Compliance Dates by System Size			
	100,000	**50,000 – 99,999**	**10,000 – 49,999**	**< 10,000**
Submit IDSE Plan*	1-Oct-06	1-Apr-07	1-Oct-07	1-Apr-08
Complete IDSE	30-Sep-08	31-Mar-09	30-Sep-09	31-Mar-10
Submit IDSE Report	1-Jan-09	1-Jul-09	1-Jan-10	1-Jul-10
Begin Stage 2 Monitoring	1-Apr-12	1-Oct-12	1-Oct-13	1-Oct-13

** Consecutive systems follow schedule of largest system in combined distribution system.*

Classified Ad:

Regional Sales Manager

Aquionics Inc. leads the world in the design and supply of in line UV disinfection equipment. Our systems are installed across the USA for the disinfection of municipal wastewater, drinking water, as well as many other applications in well-known industrial facilities.

To support this growth we are seeking an experienced Regional Municipal Sales Manager. The ideal applicant will have experience selling capital equipment to municipal customers, consulting engineers, and contractors. While direct UV experience is not necessary, a successful track record selling specified capital equipment is essential, together with the ability to travel throughout North and South America. You will need a technical degree, preferably with a PE license or the ability to obtain. Excellent benefits package and commissionable sales.

Please send your resume and salary history to:

Aquionics Inc.
Attn: **Patrick Bollman**, P.E.
Municipal Applications Manager
21 Kenton Lands Rd.
Erlanger, KY 41018

Mark your calendar now!

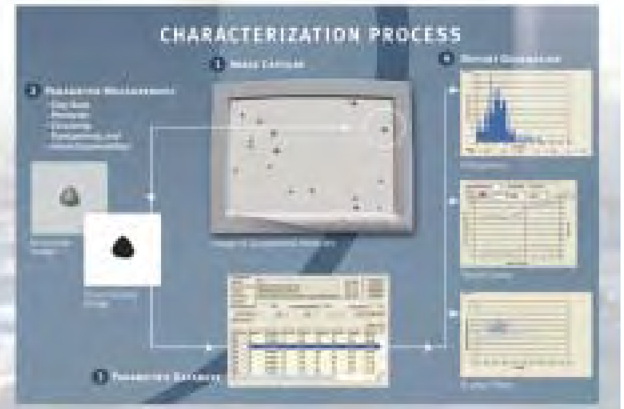
The International Ultraviolet Association
along with
NYSERDA, NYSDOH and the **University** at **Albany**
are Sponsoring the

3rd Northeast Ultraviolet Disinfection Conference

Albany, NY • May 17-19, 2006

This conference will include a day and a half of talks by experts in the field of Ultraviolet Disinfection of Drinking Water and promises to be very informative.
Brochure with full program and registration information is available on the IUVA web site www.iuva.org
Online registration is also available.

Questions? **Tel: 519-632-8190** (EDT time zone)
Fax: 519-632-9827
Email: kathy.harvey@iuva.org


CHARACTERIZATION PROCESS


Sample
Digital Camera
Optics
Flow Cell
Light Source
Detection Zone

Finding the Optimum UV Disinfection Location in a Large Water Treatment Plant

JAMAL AWAD,[1*] Ph.D., P.E., **RAMESH KASHINKUNTI**,[2] P.E., DEE, **NICHOLAS WINNIKE**,[1] P.E. and **JIM MALLEY**,[3] Ph.D.

[1] CH2M HILL, 8501 W. Higgins Rd., Suite 300, Chicago, IL 60631
[2] Greater Cincinnati Water Works, 4747 Spring Grove Ave., Cincinnati, OH 45232
[3] University of New Hampshire, Room 344, Environmental Technology Bldg., 35 Colovos Rd., Durham, NH 03824

*** Corresponding Author: Email Address: jawad@ch2m.com**

ABSTRACT

In its continuous pursuit of innovative technologies that provide the best water and service to its customers, the Greater Cincinnati Water Works (GCWW) is evaluating UV disinfection for meeting customer expectations and future regulations. The GCWW has completed extensive studies to establish the feasibility of fitting a UV system into the existing footprint and hydraulic profile of the Richard Miller Treatment Plant (RMTP).

To select the optimum UV system given the site-specific issues, analyses that were completed included hydraulic evaluations and a cost-effectiveness of alternative UV technologies for the potential locations in the plant flow. This evaluation compared the respective efficiencies of UV equipment currently available based on power usage, space requirements, and capital and O&M costs. The evaluation included both low-pressure high-output and medium-pressure systems. Among available technologies, only three proven UV units are offered in sizes suitable for installation in a facility treating up to 240 mgd (908 ML/d). A cost-benefit analysis was conducted on the three systems. The annualized cost includes equipment, facilities construction and operation/maintenance.

A benefit ranking system was developed. Evaluation criteria were identified and the relative importance established. The analysis indicated that all three UV systems evaluated could be implemented cost-effectively at RMTP. The hydraulic feasibility of adding UV technology to the existing treatment processes was addressed. Plant hydraulic conditions were analyzed using both conventional and CFD models. It was determined that a UV treatment facility could be added to the treatment train downstream of the GAC facility without the need for additional pumping.

A series of cost-benefit analyses were conducted to determine the optimum location for the UV facility in the treatment train. The benefit scoring built on the process developed for analysis of the UV technologies and was expanded to address issues related to location. Initial and life cycle costs were considered in the evaluation, along with non-economic criteria including a vast array of parameters related to water quality, operations, reliability, maintenance, and flexibility. The impact of water quality on UV equipment and operations at the different locations was also factored into the analyses. Based on the cost-benefit analysis, the alternative consisting of adding a new UV facility between the GAC facility and the clearwell was recommended for RMTP.

BACKGROUND

In its continuous pursuit of unfailing public health protection through the application of appropriate and innovative technologies, the Greater Cincinnati Water Works (GCWW) is evaluating ultraviolet (UV) disinfection as a technology for meeting customer expectations and future regulations. The GCWW has completed extensive desktop and laboratory studies of UV disinfection at the 240 mgd (908 ML/d) Richard Miller Treatment Plant (RMTP). These studies focused on scenario assessments of long-term disinfection needs, such as the inactivation of Cryptosporidium, Giardia, and other waterborne pathogens, as well as limiting the formation of disinfection byproducts (DBPs).

PURPOSE

This paper describes the cost-benefit analyses that were performed to determine the optimum location for the UV disinfection equipment in the RMTP. The analysis was performed in a series of steps to compare and evaluate location alternatives. As any alternative was eliminated from consideration the analysis was revised to compare the remaining alternatives. At each step, the cost analysis was based on increasingly detailed information.

LOCATION ALTERNATIVES

Based on site visits and a study of the RMTP, the following four location alternatives for the UV equipment were identified:

Alternative 1 – Filtered Water prior to pump station

Alternative 2 – Filtered Water on pump discharge

Alternative 3 – GAC-Contacted Water on each contactor effluent

Alternative 4 – GAC-Contacted Water prior to clear well

The four alternatives are described herein and are presented graphically in Figure 1.

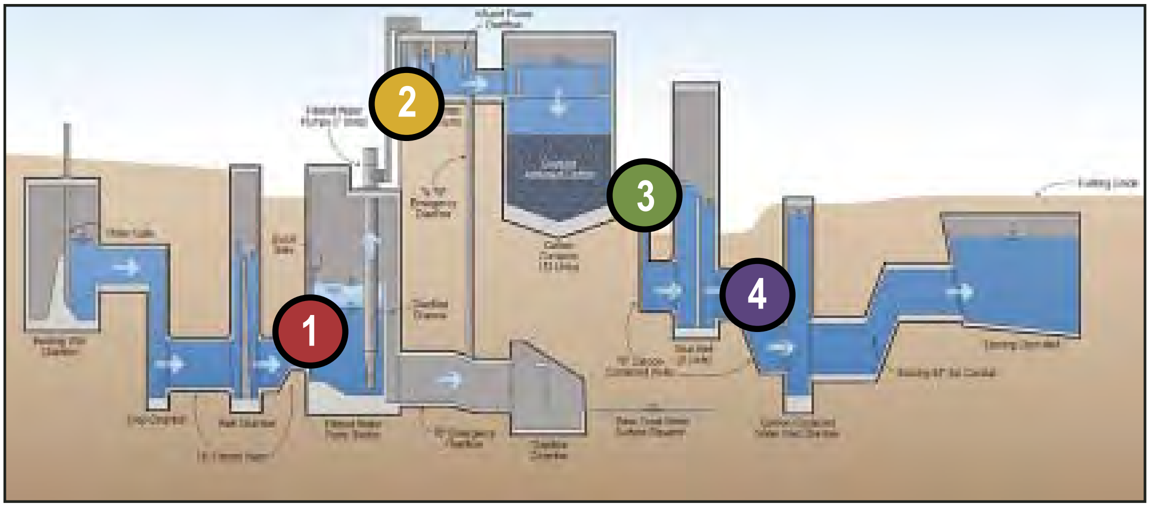


Figure 1. *UV Equipment Location Alternatives*

Alternative 1 – Filtered Water Prior to Intermediate Pump Station

The RMTP hydraulic profile indicates that it is possible to retrofit a UV facility without pumping, that is, gravity flow, between the sand filters and the GAC contactors. The UV facilities would be housed in a separate and new building. Based on a preliminary site evaluation, the new UV building would be located east of the GAC building next to the electrical substation.

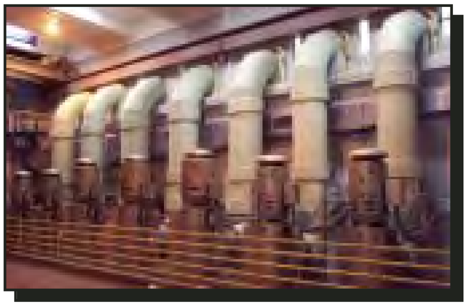
Advantages

A dedicated building would provide better facility layout, less conflict with existing structures and equipment, and easier equipment access for maintenance. The new building also would provide the opportunity to perform on-site validation of a UV full-scale reactor, if desired. Both Low Pressure High Output (LPHO) and Medium Pressure (MP) UV technologies could be implemented at this location. Housing the UV facilities in a separate building would allow the flexibility of configuring piping to routing filtered effluent through the UV facility and bypassing GAC, if desired.

Disadvantages

The design UV transmittance (UVT) for Alternative 1 would be approximately 87% compared to a minimum UVT of 96% post GAC. The lower UV transmittance would result in higher capital and operation and maintenance (O&M) costs. The larger relative size of the UV equipment might also have an impact on the power supply to the RMTP and the size of the uninterruptible power supply (UPS) system. The head loss caused by the UV facility would decrease available head on the sand filters. In addition, the total organic carbon (TOC) of the sand-filtered water is higher than that of the GAC-contacted water and would have higher potential for UV DBPs. No DPBs are known to occur with UV disinfection, but the higher organic content of the filtered effluent poses a slightly greater potential for formation of byproducts.

Alternative 2 – Filtered Water on Pump Discharge



For Alternative 2, the UV facility would be housed in the existing Filtered Water Pump Station on the discharge piping from the pumps. Effluent from the UV reactors would be routed to the GAC influent distribution channel. The UV facility would require platforms for maintenance and access to the UV reactors. Depending on the final UV reactor sizes, additional pumps and modifications of existing pumps and piping might be needed to accommodate the UV reactor, flowmeter, and isolation valves. The existing pumps and discharge piping could be modified to accommodate the additional head loss caused by the UV reactors.

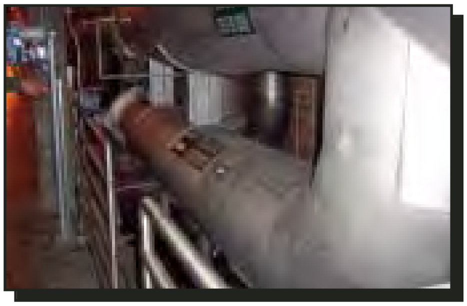
Advantages

Housing the UV facility in the existing Filtered Water Pump Station would reduce overall construction costs. As with Alternative 1, having the UV facility before GAC would provide the opportunity for bypassing GAC if desired.

Disadvantages

The design UV transmittance for Alternative 2 is the same as Alternative 1, resulting in the same need for additional lamps and associated equipment. This increases capital and operating costs. The significant pipe modifications required could result in tight space and accessibility issues. The larger relative size of the UV equipment might also have an impact on the power supply to the RMTP and the size of the UPS system. The TOC of the filtered water is higher than that of the GAC-contacted water and would have higher potential for UV DBPs. In addition, surge and water hammer analyses would be needed to evaluate pump operation on UV reactor and lamp integrity. Because of space constraints, only MP UV lamp technology would be applicable. Piping constraints make on-site UV full-scale reactor validation less feasible.

Alternative 3 – GAC-Contacted Water on Each Contactor Effluent



For Alternative 3, the UV reactors would be installed on the effluent piping of each of the GAC contactors. The GAC effluent piping diameter is 30 inches, which will readily accommodate a MP UV reactor for the 22 mgd (83 ML/d) flowrate per GAC contactor.

Advantages

At any one time, the carbon media in each of the GAC contactors have varying service lives since the last regeneration. This can result in minor differences in the water quality produced by each contactor. By placing each UV reactor on the discharge pipe from a single GAC contactor this alternative permits the reactor setting to be tailored to the specific water quality of the coupled GAC reactor, which may reduce energy demands. The GAC-contacted water has a minimum UV transmittance of 96 percent and, thus, lower capital and O&M UV equipment costs than Alternatives 1 and 2. Because each GAC contactor effluent piping is equipped with isolation valves and flow measurement that could serve both the GAC and the UV units, this option offers the least head demands. This location provides the option for a full-scale UV reactor to be thoroughly tested during the demonstration study, producing full-scale operation and maintenance data. Placing the UV reactor after GAC, as confirmed by the initial studies by the GCWW, would result in no increase in DBPs. The low number of UV lamps would also translate into lower maintenance requirements. Less UV equipment results in lower power requirements and a smaller UPS system, if desired.

Disadvantages

The flexibility to bypass the GAC or UV facility would not be possible with the existing piping arrangement. The head loss through UV reactors would reduce available head for GAC contactors. Because of space constraints, only MP UV lamp technology can be considered. Having the UV reactors in the GAC building pipe gallery could result in tight space and accessibility issues. Alternative 3 would require significant attention to locating power supply panels to mitigate electrical harmonics issues.

Alternative 4 – GAC-Contacted Water Prior to Clear Well

The UV facilities would be housed in a separate and new building. Based on a preliminary site evaluation, the new UV facility building could be located northeast of the GAC building.

Advantages

Similar to Alternative 3, the GAC-contacted water has a minimum UV transmittance of 96 percent. This high-quality water would require less UV equipment and, thus, result in lower capital and O&M costs. A dedicated building would provide better facility layout, less conflict with existing structures and equipment, and easier equipment access for maintenance. The new building would also provide the opportunity to perform on-site validation of a UV full-scale reactor, if desired. Both LPHO and MP UV technologies could be implemented at this location. Similar to Alternative 3, placing the UV reactor after GAC would result in no increases in DBPs. The hydraulic analysis of the RMTP indicates that gravity flow through the UV units in this location could be accomplished without the need for additional pumping and without the loss of clearwell storage. Finally, the flexibility to bypass the UV facility with GAC-contacted water could also be provided.

Disadvantages

The location of the UV building will need to be outside of the existing fence line, requiring considerable civil works to construct and the resulting additional capital costs.

COST-BENEFIT ANALYSES

Initial Screening of Location Alternatives

Decisions, such as selection of the location for a new UV installation, are complex and include consideration of economic, technical, and qualitative issues. Certainly, several factors influence alternative selection. The lowest-cost alternative does not necessarily provide the greatest benefit to GCWW customers. The following cost-benefit analysis is an analytical tool that comparatively assesses the costs and benefits of an alternative in support of a rational decision-making process.

The following economic criteria were used for the initial screening evaluation of the four locations:

- 20-year planning period
- 6% interest rate

For the initial screening of location alternatives, the capital and operating costs included only the major cost items and were developed for comparative (i.e., screening) purposes only. The non-economic factors are attributes of the UV location alternatives that the project team considered important.

The cost-benefit analysis undertaken involved the following steps:

1. Identifying non-monetary criteria.
2. Force ranking the non-monetary criteria.
3. Scoring alternatives in terms of their relative benefits for each of the non-monetary criteria.
4. Multiplying scores by the model weights and totaling for each alternative.
5. Developing capital and operating cost information for each alternative.
6. Comparing the relative cost and benefits for each alternative.

The following sections describe each of these steps.

Evaluation Criteria for Location Alternatives

During meetings with GCWW staff, the project team members were asked to identify all non-economic criteria that should be considered. A project workshop was conducted on October 2, 2003, to finalize primary and secondary criteria. The primary criteria and associate sub-criteria were selected and are presented in Table 1.

Table 1. *Non-economic criteria*

Primary Criteria	Example Evaluation Sub-criteria
Water Quality	DBP potential, regulatory acceptance
Operation	Construction coordination, head loss
Reliability	Testing of equipment against industry standards, performance validation
Maintenance	Potential for gravity flow, accessibility
Flexibility	Ability to accommodate MP and LP, flexibility in reactor sizing

After the primary evaluation criteria were identified and agreed on, they were force ranked in a one-on-one comparison. Following the force ranking, relative weights were assigned according to perceived importance of each criterion. The next step in the process was to conduct the non-economic evaluation of the various location alternatives based on the evaluation criteria. Scores from 1 to 5, with 5 as the highest and 1 as the lowest, were assigned to each alternative for each criteria. Table 2 shows the group consensus reached in the scoring of each alternative against the five primary criteria. These primary criteria scores are the summation of scores developed for each of the sub-criteria.

Table 2. *Ranking of UV Location alternatives*

Criterion	Weightings	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Water Quality	100	2.9	2.9	3.1	3.9
Operation	94	3.4	3.8	4.0	1.7
Reliability	86	3.9	1.7	2.9	5.0
Maintenance	73	2.7	2.0	3.7	3.7
Flexibility	59	5.0	1.5	1.0	5.0

Using the weighting for each criterion and scores, the “benefit” was calculated for each location alternative. The results are shown graphically in Figure 2.

Life Cycle Comparative Costs (Economic Evaluation)

The next step in the alternative screening was to determine the cost impacts of each of the proposed locations. Table 3 shows the life cycle costs based on the historical costs obtained for UV equipment placed in similar locations at other facilities. These costs include the annualized initial equipment (capital) costs and the yearly O&M costs based on average flow and water quality conditions at the RMTP.

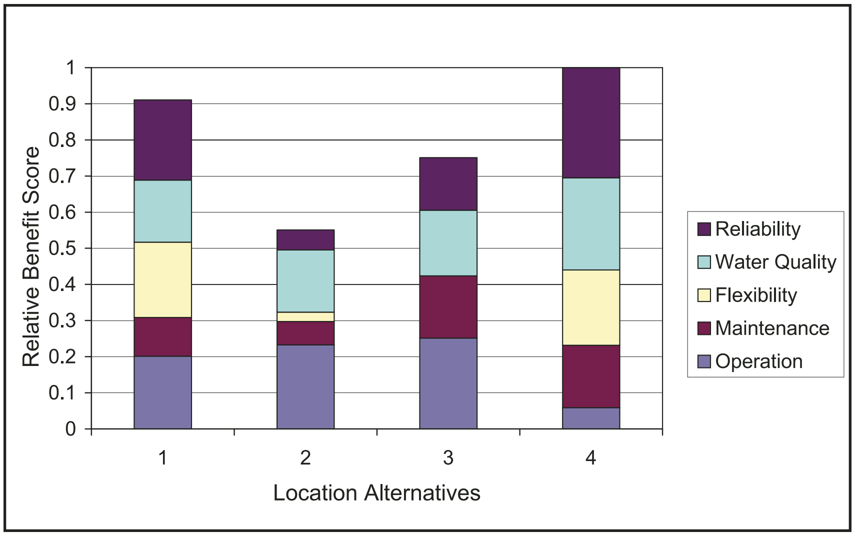


Figure 2. *Normalized Benefit Score for four UV Equipment Location Alternatives*

Table 3. *Comparative Life Cycle Costs*

Criterion	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Comparative Annualized capital cost ($M)[1,2]	0.64	0.78	0.45	0.51
Comparative Annual operating cost ($M)[3]	0.39	0.43	0.24	0.24
Comparative Total Annualized Cost ($M)[4]	1.04	1.22	0.68	0.74
Relative benefit	0.50	0.30	0.41	0.55
Cost/benefit ($M)	**2.07**	**4.06**	**1.67**	**1.35**

1. Based on comparative capital cost of UV equipment, building, valving, flow meters and 20-year amortized cost of power, maintenance, and operation. Actual costs will vary depending on final design details and other factors.
2. Note, the capital costs shown are for alternatives screening purposes only, and do not include all construction costs, which were developed in later analysis (see below).
3. Operating costs of power and O&M. Actual costs will vary depending on final design details and other factors.
4. Total annualized cost based on 20 years and 6 percent.

Figure 3 presents the relative benefits as well as the total annualized costs and the cost-benefit values for each of the four alternative locations. The cost-benefit ratio was calculated by dividing the annualized total costs by the relative benefit score. Figure 3 shows also the cost-benefit ratio, calculated as the total annualized costs over the relative benefits.

Screening Conclusions and Recommendations

Based on the results presented in Figure 3 and the discussion during the project workshop, the initial screening showed that Alternative 2 has the fewest benefits and a high cost that result in the poorest cost-benefit ratio. (Because this ratio is cost divided by benefit, low values are best.) Thus, Alternative 2 was eliminated from further analysis.

Location Alternatives 1, 3, and 4 offer cost-benefit ratios within a close range. Based on these results, it was determined to perform further hydraulic analyses and develop conceptual layouts and cost estimates for Location Alternatives 1, 3, and 4 before selecting the preferred location for the proposed UV facilities.

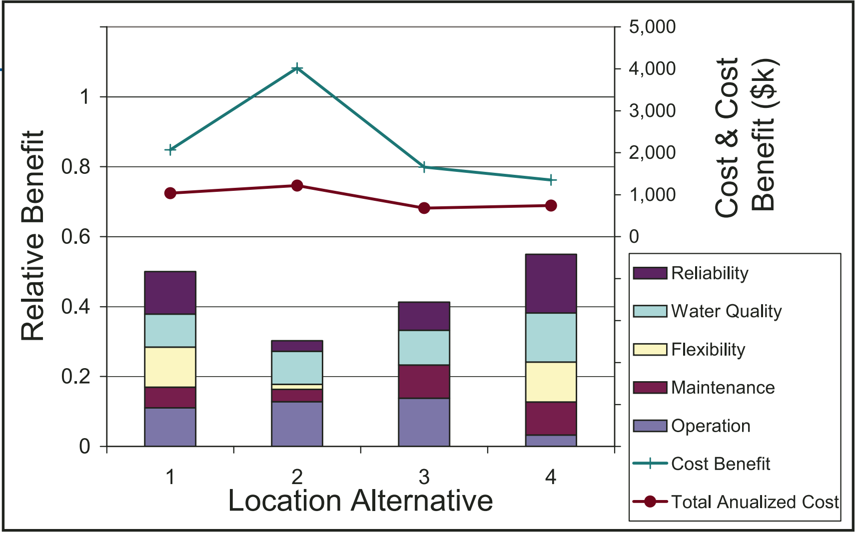


Figure 3. *Benefit, Total Annualized Cost, and Cost-Benefit Ratio for the four locations*

Conceptual Layouts and Cost Estimates

The conceptual layouts and cost estimates were developed for all three leading UV equipment suppliers – namely Trojan, Calgon, and Wedeco. A cost benefit analysis was also performed to compare these UV equipment suppliers. It should be noted that because of site constraints at Location Alternative 3, only UV equipment provided by Trojan was considered.

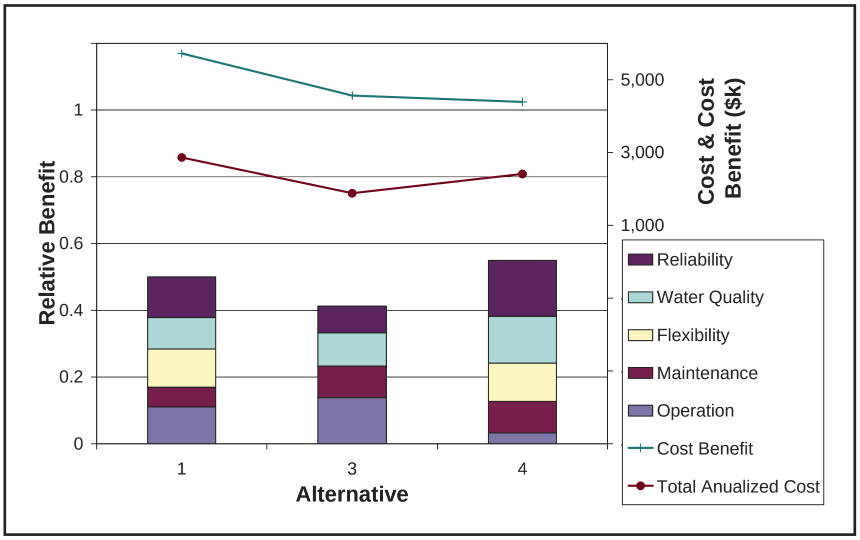
Conceptual layouts were developed for two technologies, one MP (Trojan) and one LPHO (Wedeco), at Locations 1 and 4. The size of the MP reactor offered by Calgon for RMTP falls in the range between the Trojan unit and the Wedeco LPHO unit, hence it was not necessary to develop a separate layout for Calgon. Trojan equipment was used to develop a conceptual layout at Location 3. Based on these layouts and cost estimates provided by the three UV manufacturers, order-of-magnitude cost estimates were developed for the above alternatives.

Cost Benefit Analysis for Locations 1, 3, and 4

Based on the conceptual layouts, and benefit scores developed during the initial screening of location alternatives, and the order of magnitude cost estimates, a more detailed cost-benefit analysis was performed for Locations 1, 3, and 4. By this stage of the project, vendor quotes had been obtained for the UV reactors for use in the cost-benefit analysis. The life cycle analysis had also been refined to consider that structures should be assigned a 50-year life versus 10 years for equipment.

The cost-benefit results presented in Figure 4 indicate that Location Alternatives 3 and 4 offer the GCWW the lowest cost benefit ratios (i.e., best options). Detailed hydraulic evaluations of existing facilities at the RMTP (the results of which are presented elsewhere) show that the proposed UV process can be accommodated at all locations without additional pumping. Based on the cost benefit results and the hydraulic evaluations, Location Alternatives 3 and 4 were selected for further and final comparison. Location Alternative 1 was eliminated from any subsequent analyses.

Figure 4. *Benefit, Total Annualized Cost, and Cost-Benefit Ratio for Location Alternatives 1, 3, and 4*



Cost Benefit Analysis for Locations 3 and 4

The elimination of Location Alternative 1 requires that the evaluation criteria weights and benefit scores be modified for proper comparison between Location Alternatives 3 and 4. For example, both location alternatives will treat the same water which renders the water quality benefit equal for both locations. The revised cost benefit ratios for analysis of Location Alternatives 3 and 4 are presented in Figure 5. The results indicate that Location Alternative 4 offers the better cost-benefit ratio. Location Alternative 4 is thus recommended for the proposed UV disinfection facilities. Location Alternative 4 benefits that support the decision to implement the UV at this location include:

- Increased flexibility to implement future advancements in UV technology because of improved access and retrofit capabilities.
- Increased flexibility to implement different UV technologies (Location Alternative 3 limits competition of UV bids to one manufacturer).
- Reduced GAC operating complexity because of separation of GAC and UV units; Location Alternative 3 ties the two processes together.
- Increased flexibility to bypass GAC if desired.
- Improved operability and maintainability because of improved access to equipment.
- Optimized operations performance because the new location permits optimizing flow path through the reactors.
- Provision of space for storage of spare parts and for performing maintenance (Location Alternative 3 will need additional space constructed for associated maintenance needs).

SUMMARY AND RECOMMENDED LOCATION FOR UV DISINFECTION FACILITIES

Four alternatives for the UV equipment site location were identified at the RMTP. These represented the most feasible sites for the proposed UV facilities. The four location alternatives were as follow:

Alternative 1 –
Filtered Water prior to pump station

Alternative 2 –

Filtered Water on pump discharge

Alternative 3 –
GAC-Contacted Water on each contactor effluent

Alternative 4 –
GAC-Contacted Water prior to clear well

The four alternatives are presented graphically in Figure 1. Detailed hydraulic evaluations indicated that the RMTP can accommodate the proposed UV disinfection facilities at all of these locations. No additional pumping would be required.

Cost benefit analyses were performed in three steps to reach the most cost-effective solution for the GCWW.

The results of the three cost benefit analyses are presented in Figures 3, 4, and 5. Location Alternatives 1 and 2 were eliminated in the first and second cost benefit analysis, respectively. The final cost benefit analysis between Location Alternatives 3 and 4 (Figure 5) showed that Location 4 offers the GCWW the lowest cost benefit ratio and was recommended for the proposed UV disinfection facilities at the RMTP. A sensitivity analysis of the life cycle planning period was done and showed that the time period selected did not impact the final recommendations.

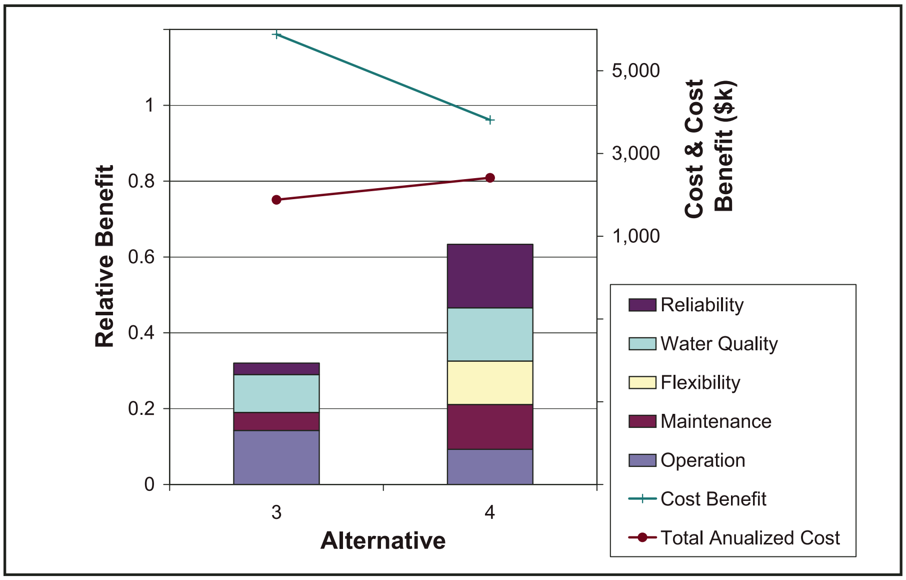
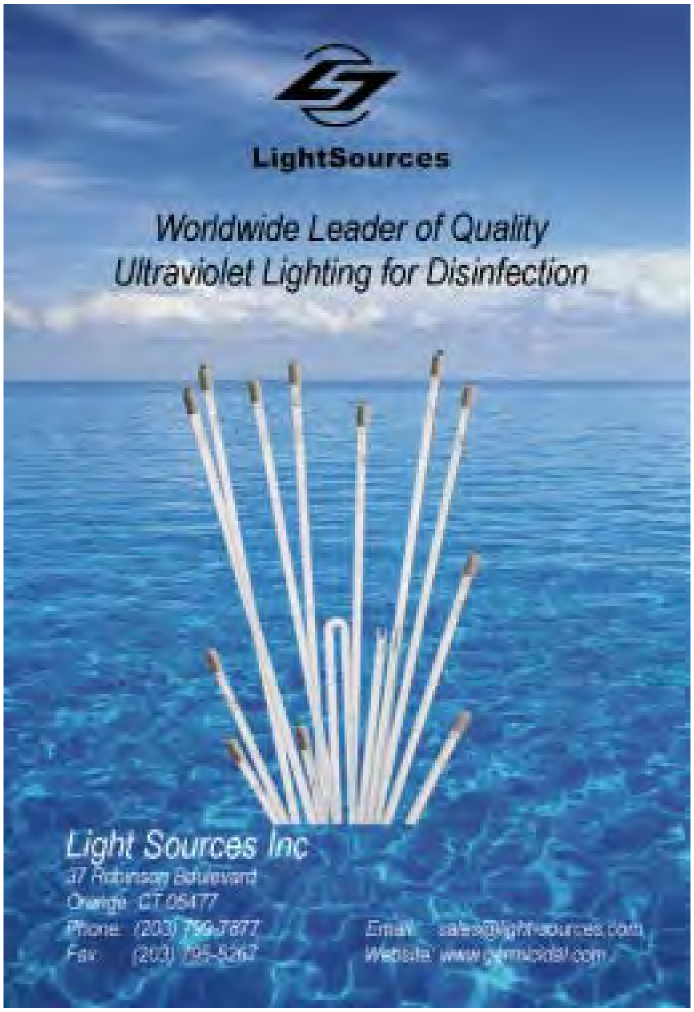


Figure 5. *Benefit, Total Annualized Cost, and Cost-Benefit Ratio for Location Alternatives 3 and 4*




Mercury vapour lamp

Integrating Ozone and UV Disinfection Processes at the Greater Vancouver Water District's Coquitlam Source

Lawrence Benjamin, P.Eng.,[1]* **Lynn Landry,** P.Eng.[2] and **Paul Wobma,** P.Eng.[3]

[1] Vice President, CH2M HILL, Burnaby, Canada
[2] Project Engineer, Greater Vancouver Regional District, Burnaby, Canada
[3] Senior Water Process Engineer, CH2M HILL, Calgary, Canada

*** Corresponding Author: Email: lawrence.benjamin@ch2m.com**

ABSTRACT

In 2004, an engineering study was completed to investigate the ramifications of adding ultraviolet (UV) treatment to the Greater Vancouver Water District's Coquitlam source. UV would replace or supplement the existing ozone and chlorine treatment. The 2004 study found that there are clear benefits to retaining ozone. Compared to UV treatment without ozone, operating with an ozone dose of 1.5 mg/L: is more economical than UV alone; reduces the formation of disinfection by-products (DBPs), with trihalomethanes (THMs) meeting the USEPA standard of 80 µg/L or less; provides some reduction in HAAs to approximately 80 µg/L; and provides an additional treatment barrier for disinfection. Increasing the ozone dose from 1.5 mg/L to 2.6 mg/L, in conjunction with UV treatment will further reduce HAA levels to the USEPA standard of 60 µg/L, has little impact on 20-year life cycle costs, but there is a significant shift from capital to operating dollars.

INTRODUCTION

The Greater Vancouver Water District (GVWD) delivers water to 18 Lower Mainland municipalities, which in turn deliver water to approximately two million people. Water is collected from three mountainous watersheds: Capilano, Seymour, and Coquitlam. The system consists of six dams and an extensive transmission system of 22 reservoirs, 15 pumping stations, and over 500 km of supply mains.

BC Hydro operates the Coquitlam Lake and dam. The GVWD has an intake tower at the south end of the lake and withdraws water in accordance with its provincial licenses and an agreement with BC Hydro. Presently the GVWD treats the Coquitlam source using ozone for primary disinfection, soda ash for corrosion control, and free chlorine for secondary disinfection.

In mid 2000, the Coquitlam ozone disinfection facility was commissioned and began treating water from the existing intake. At the time of design and construction of this facility, UV disinfection was not considered a viable technology for primary disinfection of large scale water systems. However, more recently, UV has become a viable primary disinfection option for large scale water supply systems, primarily for the inactivation of *Cryptosporidium* and *Giardia*.

While ozonation of the Coquitlam water supply provides excellent treatment for most pathogens, the GVWD recognizes that ozone may not provide adequate year-round inactivation of *Cryptosporidium*. In light of new guidelines for *Cryptosporidium* and the desire to improve water quality, the GVWD approved the addition of UV treatments as a supplement to existing ozone treatment with the approval of the Drinking Water Management Plan in September 2005. Such a change has considerable merit since it would provide a minimum 3-log inactivation of *Cryptosporidium* at all times especially during periods of low temperature water when ozone loses its effectiveness. It would also ensure compliance with future EPA regulations for *Cryptosporidium*.

In 2004 an engineering study to investigate the ramifications of adding UV treatment of the Coquitlam source was completed. A key question was whether ozone treatment should be retained when UV treatment is added, and if so, at what level. This paper is a summary of the 2004 engineering study.

EXISTING WATER SYSTEM

Coquitlam Lake currently supplies about 30% of the region's drinking water. Water is derived from a 20,000 ha mountain watershed which is closed to the public.

Water at the south end of Coquitlam Lake enters an intake tower and passes through coarse screens. It then flows through a tunnel and pipeline to an ozone treatment facility approximately 1,300 m downstream of the dam and intake.

Ozone is generated from liquid oxygen (LOX) stored in a bulk tank adjacent to the ozone facility. It is fed to a sidestream from the main flow which is then recombined with the main process flow in a long pipeline which serves as an ozone contactor. The ozone facility is designed to provide an applied ozone dose of up to 2.3 mg/L ozone at the peak hour flow of 1,200 ML/d.

At the end of the ozone pipeline contactor, the water flows to a corrosion control and chlorination facility. This facility contains four chemical feed systems: hydrogen peroxide for quenching of residual ozone, soda ash and carbon dioxide for reducing the corrosiveness of the water, and chlorine for residual disinfection (Figure 1).

WATER QUALITY

Table 1 is a summary of historic water quality data for Coquitlam Lake.

1. Units are mg/L unless otherwise noted.
2. MAC means maximum acceptable concentration, AO means aesthetic objective. There is no guideline if none shown.
3. The Canadian Drinking Water Quality Guideline for turbidity published in March 2005 allows for a waterworks system to remain unfiltered if appropriate treatment is applied and average daily source water turbidity levels measured at equal intervals, immediately prior to where the disinfectant is applied, are around 1.0 NTU but do not exceed 5.0 NTU for more than 2 days in a 12-month period.

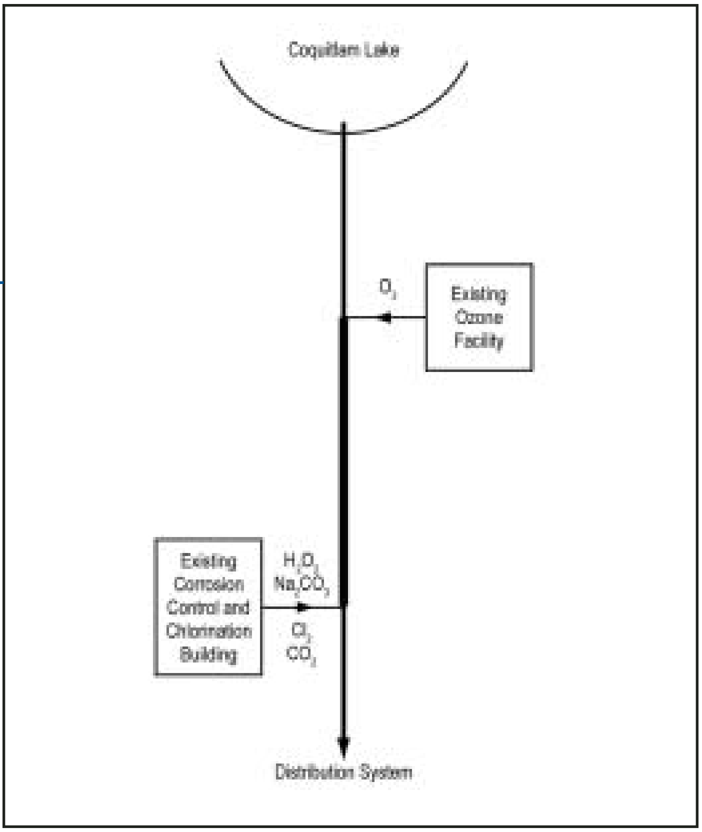


Figure 1. *Simplified Process Flow Diagram – Existing Intake*

Table 1. *Coquitlam Lake Water Quality*

Parameter[1]	**Guidelines for Canadian Drinking Water Quality[2]**		**Mean**	**Min**	**Max**	**Samples**	**Period**
	MAC	**AO**					
Physical							
UVT (filtered), % transmittance			86.6	75.7	93.5	382	1998 to 2004
UVT (apparent), % transmittance			85.8	74	91.4	63	2003 to 2004
Colour, tcu		15	11	4	22	260	1999 to 2004
pH		6.5-8.5	6.3	5.9	6.5	52	2003
Temperature °C		15		5	19	52	2003
Turbidity, NTU (daily average for an unfiltered source)	5[3]	5	0.58	0.17	**77**	3989	1993 to 2004
Inorganics							
Alkalinity, as $CaCO_3$			1.9	1.2	7.6	61	1999 to 2004
Calcium			0.96	0.74	1.08	65	1999 to 2004
Hardness, as $CaCO_3$			2.83	2.18	3.15	61	1999 to 2004
Iron		0.3	0.064	0.03	0.26	258	1999 to 2004
Manganese		0.05	0.007	0.003	0.01	64	1999 to 2004
Sodium		200	0.53	0.33	3.3	32	1999 to 2004
Total Dissolved Residue		500	11.8	10	13	6	2003
Organics							
Total Organic Carbon			1.8	1.2	2.8	297	1999 to 2004
Dissolved Organic Carbon			1.7	1.1	2.7	296	1999 to 2004

The lake water meets the Guidelines for Canadian Drinking Water Quality for all parameters listed in Table 1 except turbidity and pH. Occasionally, the colour and temperature are above the Aesthetic Objectives. The lake water turbidity is normally less than 1 NTU, but occasionally spikes to 5 NTU or greater after heavy rains. Current operation for the GVWD system is to take the Coquitlam source out of service before the turbidity exceeds 5 NTU and supply water to the system from the Capilano and Seymour sources.

DESIGN CONSIDERATIONS

For the 2004 engineering study, the GVWD specified that the overall treatment train should achieve 4 log (99.99%) virus inactivation and 3 log (99.9%) inactivation of *Cryptosporidium* and *Giardia lamblia*.

Based on the USEPA's UV Draft Disinfection Guidance Manual, the required UV dose for unfiltered water to achieve the 3-log inactivation of *Cryptosporidium* and *Giardia lamblia* is 42 mJ/cm^2 (420 J/m^2) for medium pressure UV or 36 mJ/cm^2 (360 J/m^2) for low pressure high output UV. Ozone and/or chlorine treatment will achieve 4-log virus inactivation.

The average day and peak hour flows are 450 ML/d and 1,200 ML/d respectively.

OZONE EVALUATION

In considering a switch to UV treatment, the benefits of ozone needed to be assessed. Previous research has shown that ozone treatment increases the ultraviolet transmittance (UVT) (1 cm path length) of the water and may decrease disinfection by-products (DBP) formation when applying free chlorine downstream of the ozone process.

Since the Coquitlam ozone system began operation, the increase in UVT and reduction in DBPs has also been seen by the GVWD. Data on total trihalomethane (THM) levels in the water distribution system indicates that treated water from the Coquitlam source has lower THM levels than treated water from the other GVWD sources. Data for haloacetic acid (HAA) levels also seems to show lower HAA levels in treated water from the Coquitlam source.

UV Transmittance (UVT)

Normal laboratory analysis of UVT includes filtering of the sample to remove suspended materials. For the design of UV systems, what is important is the 'apparent' UVT. The apparent UVT is the actual UVT of the water passing through the UV reactor. For unfiltered water systems such as Coquitlam, it is appropriate to measure UVT without filtration of the sample.

Figure 2 shows the apparent UVT of the Coquitlam intake and treated water, from June 2003 to August 2004.

It can be seen that ozone treatment of the water has historically increased the apparent UVT value by 5 to 11%, with the greatest increases (9 to 11%) occurring when the incoming UVT was lowest (< 85%).

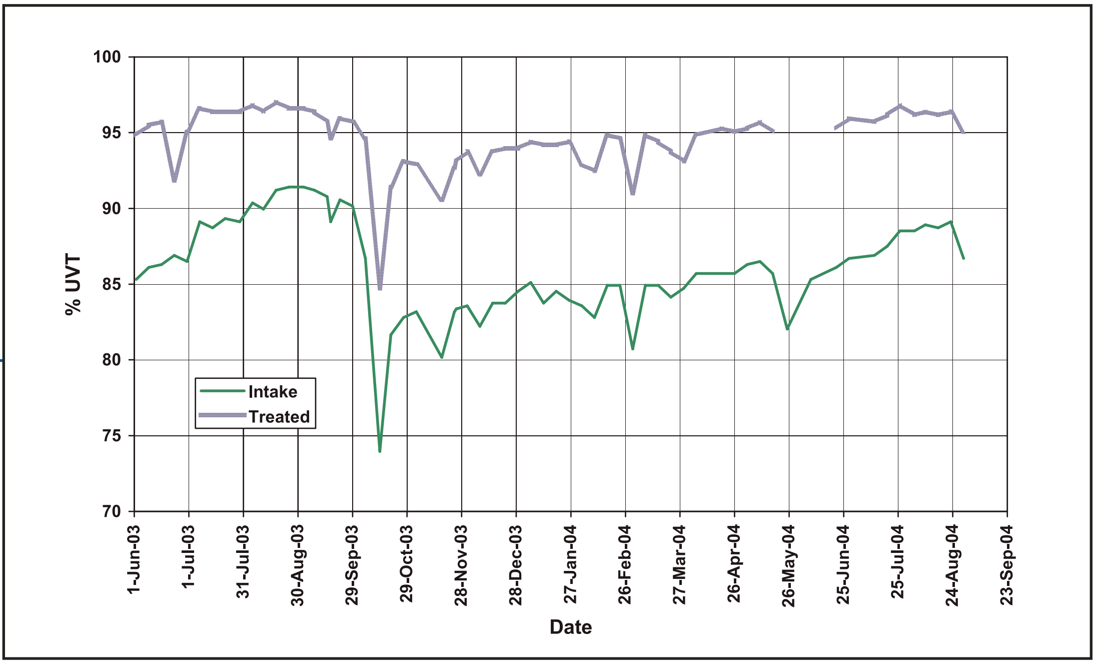
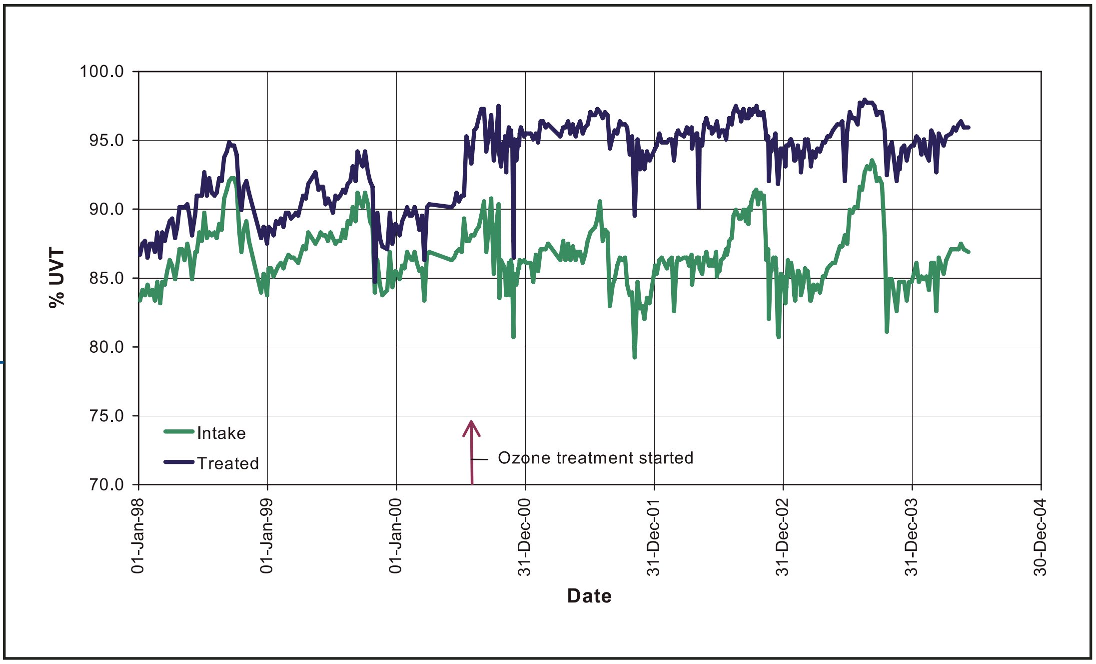


Figure 2. *Apparent UVT of Coquitlam Water (2003 – 2004)*

Figure 3 shows UVT over a longer period of time. In this plot, the UVT is the 'filtered' UVT.

Figure 3. *Filtered UVT of Coquitlam Water (1998 to June 2004)*



The filtered UVT of the intake water increases over the summer months then dips sharply when the fall rains commence.

For raw and treated Coquitlam water, the filtered UVT data is 0.6 to 3% higher than the apparent UVT when turbidities are low (< 2 NTU). During periods of higher turbidity (e.g. 20 October 2003, treated water turbidity 7.9 NTU), the filtered UVT was 8% higher than the apparent UVT in the treated water. The jump in treated water UVT in mid 2000 is due to the commissioning of the ozone treatment system.

From June 2003 to June 2004 the average apparent UVT for intake water was 86% and 94% for treated water. The minimum values were 74% UVT for intake water and 85% UVT for treated water (October 20, 2003).

Organics

NOM in the source water can adversely affect UVT levels and can include precursors available for DBP formation after chlorination.

Currently THMs are the only DBPs with guidelines in Canada. The interim maximum acceptable concentration for total THMs is 100 μg/L as a running annual average. DBPs regulated in the U.S. include THMs and HAAs. The current USEPA maximum concentrations are 80 μg/L for total THMs and 60 μg/L for total HAAs (yearly running averages). For comparison, the European Union (EU) standard is 100 μg/L total THMs. The World Health Organization (WHO) guideline for THMs is that "the sum of the ratio of the concentration of each [THM] to its respective guideline value should not exceed 1" where the individual THM acceptable maximum concentrations are: bromodichloromethane 60 μg/L, chlorodibromomethane 100 μg/L, bromoform 100 μg/L, and chloroform 200 μg/L.

Historically in the GVWD system, the levels of THMs and HAAs have increased since the implementation of secondary disinfection in the distribution system in 1998. Figure 4 shows the level and occurrence of THMs in the distribution system. A similar comparison for HAAs in the distribution system is shown in Figure 5.

For the Coquitlam source, treatment with ozone has lowered the levels of DBPs in the distribution system in comparison to waters from non-Coquitlam sources, that is, the Capilano and Seymour watersheds or water which is a blend of these two sources.

For the period shown, the total THMs measured in Coquitlam water treated with ozone do not exceed 80 μg/L. On average the levels are 41% less than the total THMs in the system from non-Coquitlam water which has not been treated with ozone. Similarly, the total HAAs in Coquitlam water treated with ozone are, on average, 31% less than the total HAAs detected in non-Coquitlam waters in the distribution system. The maximum total HAA level measured in the distribution system in single samples of Coquitlam water treated with ozone exceeds 60 μg/L, however, the yearly running average does not exceed the USEPA standard of 60 μg/L. These observations are supported by specific laboratory testing done on Coquitlam source water for the GVWD in September 2004. The testing found that ozone treatment reduced the level of total THMs by an average of 46% and the level of total HAAs by 33%. Research conducted by the University of British Columbia on Seymour water showed total THM and HAA3 reduction of more than 50% at an ozone dose of approximately 2.5 mg/L.

Coquitlam source water has dissolved organic carbon (DOC) at an average level of 1.7 mg/L and total organic carbon (TOC) at an average level of 1.8 mg/L. Ozone treatment does not significantly change the DOC and TOC levels but likely changes the molecular structure, which can make it less reactive with free chlorine. In 2003, ozonation reduced the true colour from an average of 10 tcu to 2 tcu.

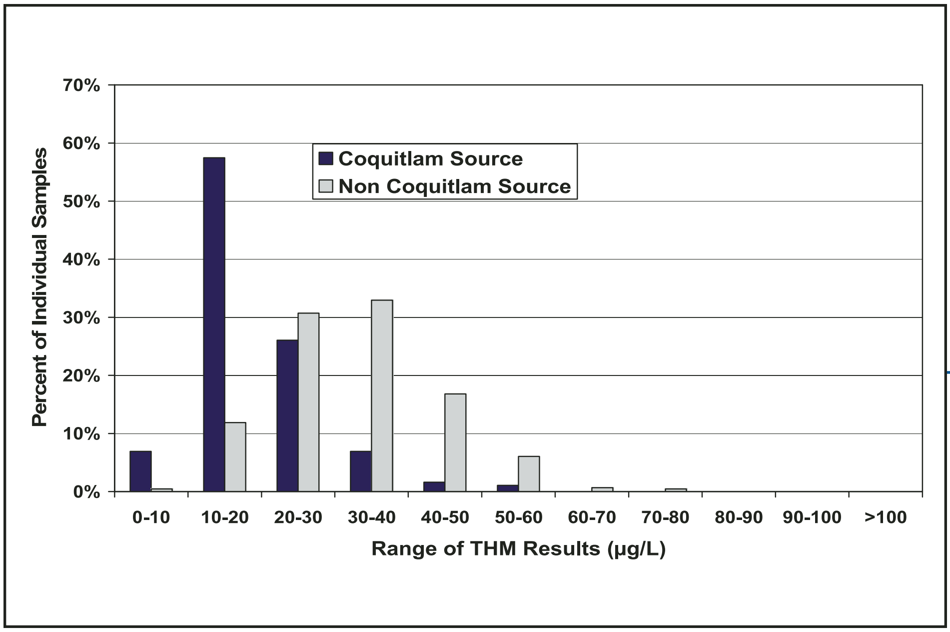


Figure 4. *GVWD THM Data (January 2000 to June 2004)*

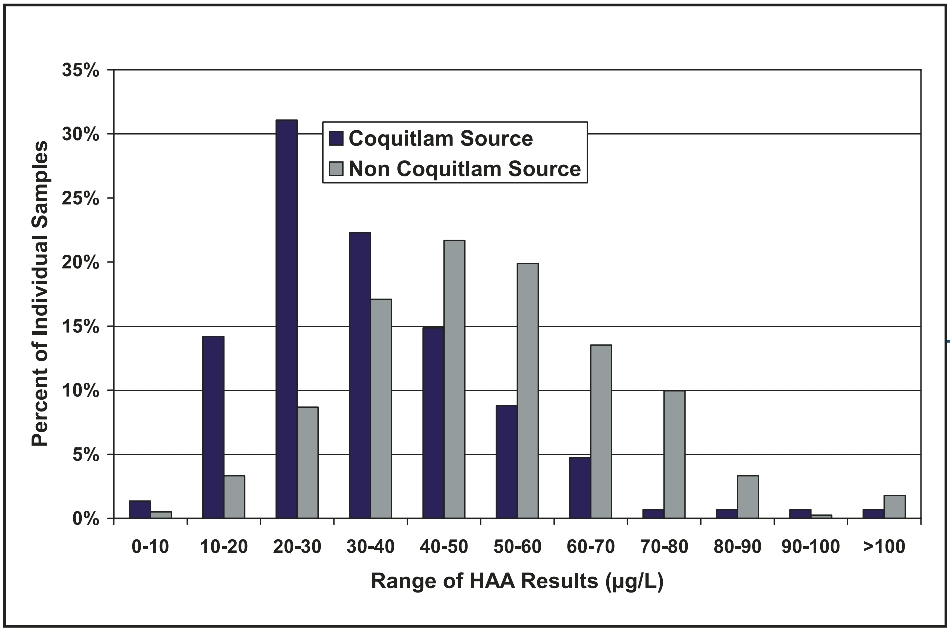


Figure 5. *GVWD HAA Data (January 2000 to June 2004)*

TURBIDITY

Table 2 shows the historical turbidity levels for the Coquitlam source for the period 1992 to 2004.

Table 2. *Coquitlam Turbidity Data, January 1, 1992 to December 7, 2004, Daily Grab Samples*

Turbidity (NTU)	Percentage of samples in range (%)	Cumulative Percentage less than Criteria (%)
≤ 1.0	94.8	94.8
> 1.0 – ≤ 2.0	4.0	98.8
> 2.0 – ≤ 3.0	0.6	99.4
> 3.0 – ≤ 4.0	0.2	99.6
> 4.0 – ≤ 5.0	0.2	99.8
>5.0	0.2	100.0

Turbidity measurements are less than or equal to 1 NTU for 94.8% of daily grab samples, and less than or equal to 5 NTU for 99.8% of daily grab samples collected from the existing Coquitlam intake prior to treatment (raw water).

PROCESS TESTING

To help with the ozone evaluation, testing of Coquitlam raw water was carried out in the CH2M HILL process laboratory in Corvallis, Oregon. Although this was only a snapshot based on one sample of intake water, the testing was required to quantify the effects of ozone addition at various dosages on the treated water UVT and distribution system DBP levels. Systematic testing at different ozone doses had not been carried out previously. Simulated distribution system (SDS) testing of the ozonated water for levels of THMs and HAAs present after 96 hours was also performed.

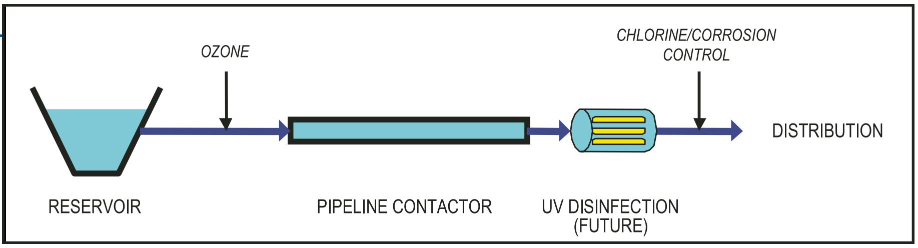


Figure 6. *Test System Simulated*

Treatment Process

Figure 6 shows the process diagram for the proposed UV disinfection system, to be added after ozonation. The test system in the process lab simulated the existing treatment system.

The pipeline contactor provides a contact time of 9.7 min at the maximum design flow of 1,200 ML/d. At a typical flow of 450 ML/d, the contactor provides a contact time of 26 min.

TEST PLAN

The scope of the testing conducted at the process lab was as follows:

- Characterize raw water as received:
  - Apparent UVT, TOC, alkalinity, hardness, pH, turbidity, SDS THMs, SDS HAAs
- Perform baseline run:
  - Simulate design dose (2.2 mg/L ozone, 26 minutes contact time)
  - Measure finished water apparent UVT, SDS THM, SDS HAAs
- Simulate ozonation at differing doses (1 run each): 0.5 mg/L, 1 mg/L, 2.2 mg/L, and 3 mg/L
  - Measure apparent UVT, SDS THM, SDS HAAs

The GVWD advised that a SDS testing time of 96 hours should be used for the Coquitlam water.

TEST RESULTS

Effect of Ozone on UVT

Figure 7 shows the effect of ozone dose on apparent UVT. The results show that for ozone doses of 0.94 to 2.84 mg/L, ozone increases the apparent UVT by 5 to 10%.

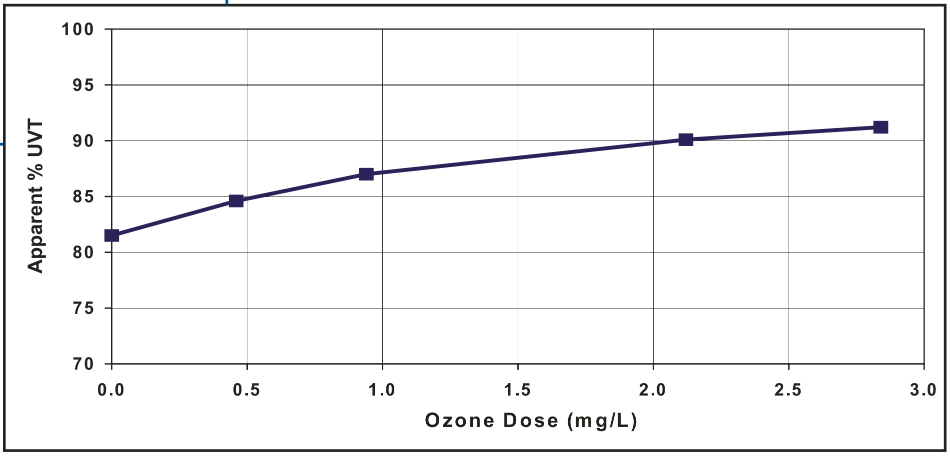


Figure 7. *Effect of Ozone Dose on UVT*

Effects of Ozone Dose on DBP Formation

Figure 8 shows the effects of ozone dose on the levels of THM and HAA formation. The results show that in comparison to non-ozonated water, for ozone doses of 0.94 to 2.84 mg/L, THMs levels decrease by 19 to 53%, and HAAs levels decrease by 20 to 51%.

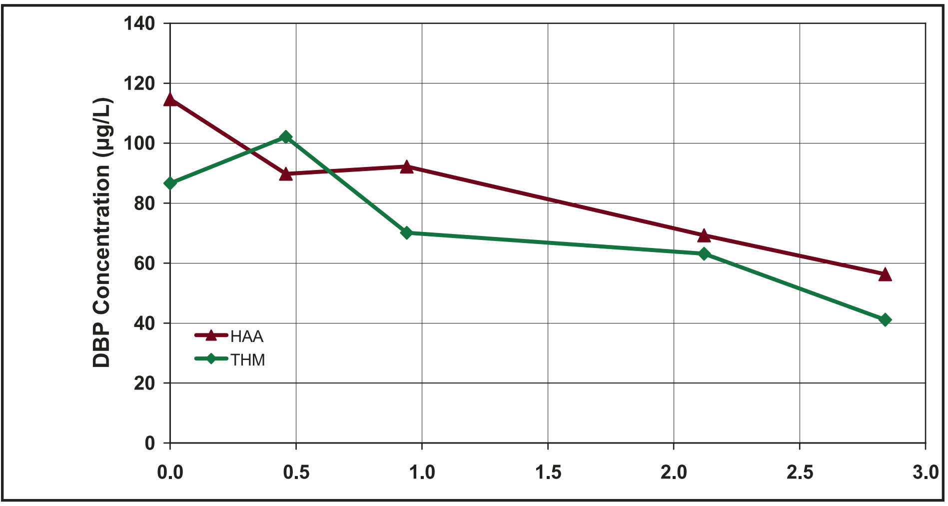


Figure 8. *Effect of Ozone on SDS DBPs*

Of note, the THM levels at an ozone dose of 0.5 mg/L are higher than with no ozone (raw water). At higher ozone doses, the THMs levels are below raw water levels and continue to decrease with an increase in ozone dose. Normally, there is a predictable and linear trend with both the levels of THM and of HAA samples from SDS testing. The 0.5 mg/L ozone sample was re-analyzed and confirmed the test results. Possibly for GVWD water, a low ozone dose creates more precursor material, and a higher ozone dose eliminates or breaks up the precursors. Another possibility is that the atypically higher turbidity Coquitlam water sample used in the test may have had higher levels of DBP precursors.

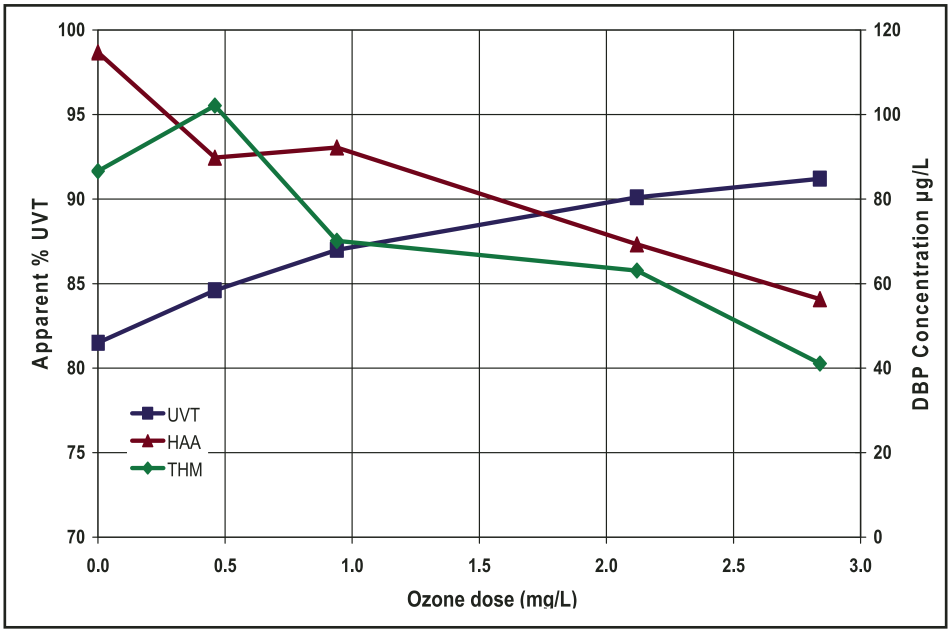


Figure 9. *Summary of Effects of Ozone Dose on UVT and DBPs*

A summary of the effects of ozone on apparent UVT, THMs, and HAAs is presented in Figure 9.

For the sample tested, an ozone dose of 1.5 mg/L resulted in a UVT of 88% or higher and a total THM level of less than 70 μg/L which meets the USEPA standard of 80 μg/L (yearly running average). To meet the U.S. standard of 60 μg/L or less (yearly running average) for total HAA levels, an ozone dose of approximately 2.6 mg/L was required for this sample. This raised the apparent UVT to 90%. The sample tested had a turbidity of 3.5 NTU.

ECONOMICS

The cost of adding UV treatment with and without ozone pretreatment was evaluated. Table 3 shows three treatment scenarios considered.

Table 3. *Design UVT and Ozone Dose*

Treatment Scenario	Ozone Dose (mg/L)	Apparent UVT (%)
Intake water, no ozone pretreatment	0	75
Intake water, low ozone dose	1.5	85
Intake water, higher ozone dose	2.6[1]	90

[1] This is a preliminary dose based on a single laboratory test. Additional testing is required to confirm this dosage.

The raw water apparent UVT of 75% is taken as being a worst-case scenario, based on the available records. Given this incoming UVT, a low ozone dose scenario is chosen to achieve an apparent UVT of 85%. This scenario also meets the USEPA standard of 80 μg/L (yearly running average) for THMs. The higher ozone dose is to meet the USEPA standard of 60 μg/L for HAAs in the distribution system (yearly running average).

The GVWD's treatment goal for the 2004 study for Cryptosporidium and Giardia was 3-log inactivation or higher to meet the requirements of the USEPA Long Term 2 Enhanced Surface Water Treatment Rule. Based on the draft USEPA Guidance Manual for UV Disinfection, the required UV dose is 42 mJ/cm^2 (420 J/m^2) for medium pressure UV and 36 mJ/cm^2 (360 J/m^2) for low pressure UV.

The Health Canada Turbidity Guideline which was published in March 2005 indicates that for unfiltered source waters, disinfection should reliably achieve at least 2-log reduction of *Cryptosporidium* oocysts and 3-log reduction of *Giardia lamblia* cysts. If mean source water cyst/oocyst levels are above 10/1000L, more than 2-log reduction of *Cryptosporidium* oocysts and 3-log reduction of *Giardia lamblia* cysts should be achieved. Overall inactivation should be met using a minimum of two disinfectants. Coquitlam has a mean cyst/oocyst concentration above 10/1000 L and would therefore be subject to the more stringent guideline criteria.

UV Equipment and Operating Costs

Preliminary UV equipment sizing and cost information was obtained from three vendors of validated UV equipment. A summary of this information is presented in Table 4.

Table 4. *UV Equipment Summary*

Equipment and Costs[1]	Calgon	Trojan	Wedeco
75% UVT			
Number of reactors	25	35	12
Lamp type	Medium pressure	Medium pressure	Low pressure
Number of lamps per reactor	9	10	252
Equipment capital cost[2]	$9,140,000	$11,600,000	$8,420,000
Annual O&M cost[3]	$ 890,000	$ 940,000	$ 370,000
85% UVT			
Number of reactors	11	17	9
Lamp type	Medium pressure	Medium pressure	Low pressure
Number of lamps per reactor	9	10	192
Equipment capital cost[2]	$4,020,000	$5,980,000	$5,150,000
Annual O&M costs[3]	$ 410,000	$ 450,000	$ 210,000
90% UVT			
Number of reactors	11	12	9
Lamp type	Medium pressure	Medium pressure	Low pressure
Number of lamps per reactor	6	10	168
Equipment capital cost[2]	$2,820,000	$4,200,000	$4,680,000
Annual O&M costs[3]	$ 250,000	$ 310,000	$ 184,000

1. Costs in Canadian dollars, December 2004.
2. For capital costs a peak flow (1,200 MLD) was used.
3. O&M costs include power and lamp replacements at an average flow of 450 ML/d.

The data indicates that the UV costs (capital and O&M) can be reduced by approximately 40% or more by increasing the apparent UVT from 75% to 85%.

A medium pressure UV system designed for a 90% apparent UVT reduces UV costs (capital and O&M) an additional 30% in comparison to a system designed for an apparent UVT of 85%. For a low pressure system, increasing the apparent UVT from 85% to 90% reduces the capital cost by 9% and O&M costs by 14%.

Ozone Operational Costs

The major operating costs associated with producing ozone are power and liquid oxygen (LOX). Based on actual operating data for 2003, the annual operating costs of the ozone system for a dose of 1.5 mg/L and a typical flow of 450 ML/d is $600,000 per year. Increasing the ozone dose to 2.6 mg/L would increase the annual operating costs to $1,040,000.

Total UV System Life Cycle Costs

Total UV system costs are the sum of the UV equipment costs, building costs, and the UV and ozone operational costs. Table 5 shows the 20-year life cycle costs for the three UV scenarios: no ozone pretreatment, 1.5 mg/L ozone pretreatment, and 2.6 mg/L ozone pretreatment. Note that the estimates are preliminary in nature but are suitable for comparing the three treatment scenarios.

Table 5. *Summary of Estimated UV System Costs*[1]

	UV Systems Costs in $1,000's		
	Calgon Carbon	**Trojan Technologies**	**Wedeco**
75% UVT, no ozone pretreatment			
UV equipment cost (1200 ML/d)	9,140	11,600	8,420
Building area, m^2	1,816	1,989	1,213
Building cost	29,060	31,830	19,410
Total capital cost	38,200	43,430	27,830
Annual O&M cost (450 ML/d)[2]	890	940	370
NPV[3] of O&M	10,220	10,770	4,210
20-year life cycle cost	**48,420**	**54,200**	**32,040**
85% UVT, 1.5 mg/L ozone pretreatment			
UV equipment cost (1,200 ML/d)	4,020	5,980	5,150
Building area, m^2	900	1064	900
Building cost	14,400	17,020	14,400
Total capital cost	18,420	23,000	19,550
Annual O&M cost (450 ML/d)[2]	1,010	1,050	810
NPV[3] of O&M	11,570	12,090	9,290
20-year life cycle cost	**29,990**	**35,090**	**28,840**
90% UVT, 2.6 mg/L ozone pretreatment			
UV equipment cost (1,200 ML/d)	2,820	4,200	4,680
Building area, m^2	863	807	869
Building cost	13,810	12,910	13,900
Total capital cost	16,630	17,110	18,580
Annual O&M Cost (450 ML/d)[2]	1,290	1,350	1,220
NPV[3] of O&M	14,820	15,520	14,030
20-year life cycle cost	**31,450**	**32,630**	**32,610**

1. Excludes standby power and power supply.
2. O&M cost includes cost of LOX and power for UV and ozone, and UV lamp replacement, but excludes labor.
3. NPV is net present value of annual operating costs. It assumes a 6% interest rate and a 20 year life cycle.

Compared to UV treatment without ozone, operating with an ozone dose of 1.5 mg/L is more economical than UV alone on a 20-year life cycle cost basis. Increasing the ozone dose from 1.5 mg/L to 2.6 mg/L in conjunction with UV treatment to meet USEPA standards for HAAs has little impact on 20-year life cycle costs, but there is a shift from capital to operating dollars.

EFFECT OF TURBIDITY ON UV INACTIVATION

A concern when designing UV treatment systems for unfiltered sources is the potential impact of turbidity events on UV disinfection.

The turbidity of Coquitlam source water grab samples collected from the existing intake is less than or equal to 1 NTU for 94.8% of grab samples, and less than or equal to 5 NTU for 99.8% of grab samples (Table 3-1). The system is usually taken off line when turbidity is greater than 5 NTU.

Figure 10. *Effect of Turbidity on UV Absorption (from 2002 AwwaRF Study)*

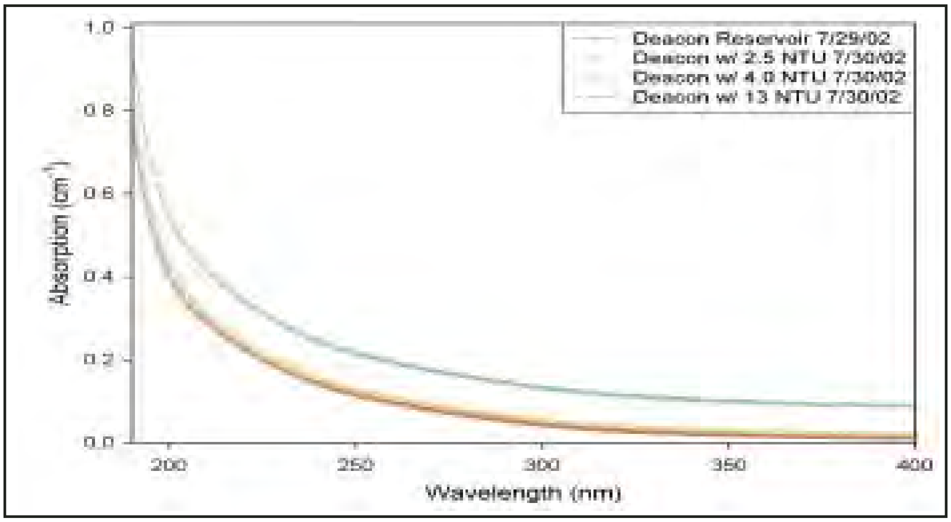


Figure 10 presents UV absorption data taken from the 2002 AwwaRF Study “UV Disinfection and DBP Characterization of an Unfiltered Water Supply”. The data shows UV absorption levels for the same source water at four different turbidity levels. It shows that there is little effect on UV absorption up to a turbidity of 4 NTU. An effect can be seen at a turbidity level of 13 NTU.

Table 6 presents the effects of turbidity on UV dose taken from the same AwwaRF study.

Table 6. *Effect of Turbidity on UV Dose (2002 AwwaRF Study)*

	Challenge Test 4			**Challenge Test 5**			
Lamp Type and UV Dose	**3/12/02 Pre-clean**	**3/13/02 Post-clean**	**3/13/02 4.0 NTU**	**7/29/02 Post-clean**	**7/30/02 2.5 NTU**	**7/30/02 4.0 NT**	**7/30/02 13 NTU**
Medium Pressure UV							
Reduction Equivalent Dose (mJ/cm^2)	37.9	56.8	54.0	36.7	36.7	32.2	26.5
Low Pressure High Output UV							
Reduction Equivalent Dose (mJ/cm^2)	31.0	54.9	45.2	40.4	42.9	39.2	33.2

The data shows that for turbidities of up to 4 NTU there is little reduction in the effective UV dose. At 13 NTU, the turbidity reduced the UV dose by 18 to 28%. Research elsewhere for unfiltered waters shows minor UV dose effects up to a turbidity of 20 NTU, and that turbidity up to these levels does not effectively shield pathogens from UV, and UV intensity can be adjusted to compensate and achieve disinfection targets. Work done by the University of Alberta for the City of Kelowna indicates that a UV dose of 40 mJ/cm^2 (400 J/m^2) achieves 3.7 log inactivation of *Cryptosporidium* at 20 NTU compared to 4.48 log inactivation at 1 NTU.

In full-scale operation, adjustments can easily be made to compensate for the reduction in UV effectiveness. For example, reducing the plant flow by half while maintaining the full power to the UV will double the applied UV dose. Of note, the UV dose is not an issue for consumers since UV does not affect the aesthetics of the water. In contrast, doubling the chlorine dose would likely be noticed and be a concern to consumers.

In summary, the effect of turbidity on UV disinfection should not be a concern for treating Coquitlam Lake water if it continues to be operated with a maximum turbidity of 5 NTU, and even operating at 10 NTU or slightly higher should not be a concern, except flows may need to be reduced from peak design flows.

NON-MONETARY OZONE BENEFITS

Maintaining ozonation in addition to UV treatment and free chlorination will enhance the robustness of the treatment system with the multiple barrier approach to disinfection. Target disinfection organisms such as *Giardia*, *Cryptosporidium*, and viruses will be inactivated by two or three of the treatment methods.

UV disinfection, designed for 3-log inactivation of *Cryptosporidium*, will also provide more than 3-log inactivation of *Giardia*, and inactivate bacteria. Ozonation at doses in the 1.5 mg/L range, with 9.7 minutes contact time (ultimate capacity) will provide inactivation of bacteria, viruses, and varying levels of *Cryptosporidium* and *Giardia* inactivation depending on seasonal water temperatures. Free chlorine is very effective at virus disinfection, and, due to the long contact times in the distribution system, will also achieve a measure of *Giardia* disinfection. The synergistic effects of using three methods for disinfection may allow lower levels of free chlorine to be used, again aiding in reducing the formation of DBPs in the distribution system.

SUMMARY

The key findings are summarized as follows:

UV Transmittance

- Ozone treatment has historically increased the apparent UVT of Coquitlam water by 5 to 10%. This increase in UVT is significant since increasing the apparent UVT from 75% to 85% reduces the UV equipment and power requirements by 40% or more.
- From the historical data and initial laboratory testing done for this project, minimum apparent UVTs of 85% and 90% can be expected at ozone doses of 1.5 mg/L and 2.6 mg/L respectively.

DBPs

- Ozone reduces the level of THMs and HAAs in the distribution system.
- THM levels measured in the distribution system from Coquitlam water treated with ozone are on average 41% less than those from non-Coquitlam water which has not been treated with ozone. The maximum THM level detected in all GVWD water including Coquitlam is less than the Canadian guideline of 100 μg/L.
- HAA levels measured in the distribution system from Coquitlam water treated with ozone are on average 31% less than those from non-Coquitlam water which has not been treated with ozone. The maximum HAA level measured in the distribution system in single samples of Coquitlam water treated with ozone exceeds 60 μg/L, however the yearly running average does not exceed the USEPA standard of 60 μg/L. There is no current Canadian guideline for HAA levels.
- Based on the available laboratory data on DBP formation potential for Coquitlam source water and HAA levels measured in the system for the Seymour and Capilano sources, the yearly running average for HAAs would exceed the USEPA standard of 60 μg/L (yearly running average) if Coquitlam water was not treated with ozone.
- From the initial laboratory testing, an ozone dose of 1.5 mg/L achieved a THM level of less than 70 μg/L, which meets the USEPA standard of 80 μg/L (yearly running average) and an HAA level of approximately 80 μg/L which does not meet the USEPA requirement of 60 μg/L (yearly running average).
- From the initial laboratory testing, an ozone dose of 2.6 mg/L can be expected to achieve distribution system HAA levels of less than 60 μg/L and THM levels of less than 50 μg/L, which meets the USEPA requirements for both HAAs and THMs.

Additional Testing

Further work will be done during the UV pre-design phase.

UV Dose

The required UV dose to meet the GVWD's treatment goal of 3-log inactivation of *Cryptosporidium* and *Giardia* is 42 mJ/cm^2 (420 J/m^2) for medium pressure UV and 36 mJ/cm^2 (360 J/m^2) for low pressure UV.

Costs

The costs of adding UV treatment to the Coquitlam source are:

Treatment Scenario	Preliminary Cost Estimates		
	Capital	O&M	Life Cycle
No ozone pretreatment, 75% UVT, THMs <100 μg/L	\$27M – \$43M	\$0.37M – \$0.94M	\$32M – \$54M
1.5 mg/L ozone pretreatment, 85% UVT, THMs $\leq$ 70 μg/L and some HAA reduction $\leq\sim$ 80 μg/L	\$18M – \$23M	\$0.81M – \$1.1M	\$29M – \$35M
2.6 mg/L ozone pretreatment, 90% UVT, THMs $\leq$ 50 μg/L, HAAs $\leq$ 60 μg/L	\$17M – \$19M	\$1.22M – \$1.35	\$31.5M – \$32.6M

Turbidity

- Turbidity measurements are less than or equal to 5 NTU for 99.8% of daily grab samples, collected from the existing Coquitlam intake prior to treatment (raw water).
- The effect of turbidity on UV disinfection should not be a concern if Coquitlam is operated with a maximum turbidity of 5 NTU, and even operating at 10 NTU or slightly higher should not be a concern, except flows may need to be reduced from peak design flows.

Ozone Benefits

- There are clear benefits to retaining ozone when UV treatment is added to the Coquitlam source.
- Compared to UV treatment without ozone, operating with an ozone dose of 1.5 mg/L:
    - is more economical than UV alone on a 20-year life cycle cost basis
    - reduces the formation of DBPs in the distribution system, with THMs meeting the USEPA standard of 80 μg/L or less (yearly running average)
    - provides some reduction in HAAs to approximately 80 μg/L
    - provides an additional treatment barrier for disinfection
    - Increasing the ozone dose from 1.5 mg/L to 2.6 mg/L, in conjunction with UV treatment:
        - will further reduce HAA levels to USEPA standards of 60 μg/L (yearly running average)
        - has little impact on 20-year life cycle costs, but there is a significant shift from capital to operating dollars.

REFERENCES

Belosevic, M., and Stafford, J. 2002. Development of Design and Operational Criteria for Encysted Parasite Control in Drinking Water Using Medium Pressure Ultraviolet Radiation, Department of Civil and Environmental Engineering, University of Alberta, November 2002.

Chin, A. 2003. Evaluation of the Removal of By-Product Precursors in Seymour Water with Ozone and the Advanced Oxidation Process Ozone-UV, Masters Thesis, University of British Columbia, Department of Civil Engineering, December 2003.

Guidelines for Drinking Water Quality, WHO. 2004. Vol. 1, 3rd ed., Annex 4: Chemical Summary Tables, Geneva.

Ozone Primary Disinfection and Corrosion Control Facilities Design Brief, Coquitlam Water Supply, 1998. SSBV Consultants, July.

Passantino, L., and Malley, J.P. 2001. Impacts of Turbidity and Algal Content of Unfiltered Drinking Water Supplies on the Ultraviolet Disinfection Process, Proceedings of the American Water Works Association Annual Conference, Denver, CO.

Preliminary Design Report. 2003. Seymour-Capilano Filtration Plant, SSBV Consultants, September.

Ultraviolet Disinfection Guidance Manual, USEPA, June 2003 draft.

Womba, P.C., Bellamy, W.D. and Malley, J.P., Recknow, D.A. UV Disinfection and DBP Characterization of an Unfiltered Water Supply. 2002, AWWARF Report No. 2757.

UV-Lamps for Disinfection and Advanced Oxidation - Lamp Types, Technologies and Applications

Sven Schalk,* **Volker Adam, Erich Arnold, Karl Brieden, Alex Voronov**
and **Hans-Dieter Witzke**

Heraeus Noblelight GmbH, Heraeusstraße 12-14, 63450 Hanau, Germany

*** Corresponding author: E-Mail: sven.schalk@heraeus.com**

Note: This article comes from a presentation made in the "Novel Lamps, Sleeves and Reactors" Session by Sven Schalk at the UV Congress in Whistler, BC, Canada in May 2005.

ABSTRACT

An overview on state of the art of UV Lamps for disinfection and Advanced Oxidation applications is given. The different types of Low Pressure Lamps, such as Standard Low Pressure, Low Pressure High Output and Amalgam Lamps, are characterized and compared. Inner wall coating, essential for extended lifetime and excellent UV maintenance of Amalgam Lamps, is discussed and the latest developments in this field are presented. Background information on lamp envelope materials (Fused Silica, Softglass) are given and it is shown how tailored transmission properties of Fused Quartz materials can help to optimize lamp performance for disinfection or oxidation applications. Differences between Low Pressure and Medium Pressure Lamps are outlined and main application fields of the various lamp types are discussed.

A special consideration is given to Excimer Lamps as an alternative to mercury containing UV disinfection lamps. Characteristics, such as available wavelengths, UV disinfection efficiencies and others, are shown.

KEYWORDS: UV Lamps, germicidal lamps, mercury free lamps, Quartz Glass, disinfection, Advanced Oxidation Process, water treatment, air treatment.

INTRODUCTION

In the past, the acceptance of UV disinfection in commercial applications has progressed rapidly. UV disinfection of water and air, in the food and beverage industry and in UV based Advanced Oxidation Processes (AOP) for destruction of pollutants in water and air are used either in combination with traditional methods or as a stand alone solution (Bolton 2004). In a more and more competitive market, it is important to consider all relevant aspects of the UV source, in order to exploit the full technical and economical potential of UV lamp technology that is available today and in the future.

Mercury based UV lamps

Mercury based UV lamps have a filling composed of mercury and a starting gas – typically Argon. Two major types are differentiated by the mercury vapor pressure in lamp operation. Low Pressure Lamps (LPs) work with approximately 0.01 mbar (1 Pa) and Medium Pressure Lamps (MPs) higher than 1 bar (100 kPa). Further differences like typical emission spectrum, lifetime, wall temperature, etc. will be addressed subsequently.

Low Pressure Lamps

The spectral radiation from a low pressure mercury plasma is dominated by the two ground state resonance lines at 253.7 nm and 185.0 nm (for details see Heering 2004). UV radiation (200 – 300 nm) is absorbed by DNA disrupting its structure and leading to deactivation of living cells. Lethality depends on the UV dose and the wavelength with an optimum at 265 nm. Radiation at 254 nm, however, is well suited for this direct UV disinfection process.

Radiation at 185 nm, obtained from LPs, is mainly applied for Advanced Oxidation Processes, such as the UV/O_3 or UV/H_2O_2 processes, where direct photolysis produces highly reactive radicals (·O or ·OH respectively). Since ozone is produced via 185 nm radiation in combination with oxygen from ambient air, the UV/O_3 process does not necessarily need an external ozone source. In aqueous solutions, the 185 nm radiation is absorbed almost exclusively by water, bringing about its photolysis to yield ·OH radicals and ·H atoms.

The preferred envelope material for Standard Low Pressure Lamps is Fused Quartz. Due to the generally low wall temperature, it is also possible to use Softglass (Sodium-Barium-Glass). Softglass Lamps have a similar design as Fluorescent Lamps known from general lighting. The UV-Softglass does not transmit at 185 nm, hence all these lamps are "ozone-free" lamps.

In contrast to Softglass Lamps, standard Quartz Lamps are available in both "ozone-free" (G, GPH lamps) and ozone-generating (G…VH, GPH…VH – VH stands for Very High ozone) versions. As seen in Table 1, both the specific UVC-flux per unit arc length and the UVC efficiency are higher for the Fused Quartz types. This is caused by the lower transmittance of Softglass compared to Fused Quartz at 254 nm.

A breakthrough for economic UVC generation was the introduction of LP Amalgam Lamps. They are no longer pure mercury lamps, but a mercury amalgam (typically mercury/indium) is used, that reaches the optimum mercury vapour pressure (0.01 mbar) at wall temperature close to 100°C. Thus, compared to Standard LPs, six times higher absolute electrical power can be consumed by lamps of same lengths, leading by far to the highest specific UVC-flux per unit arc length [up to 1000 mW/cm (see Table 1)] of all LP lamps.

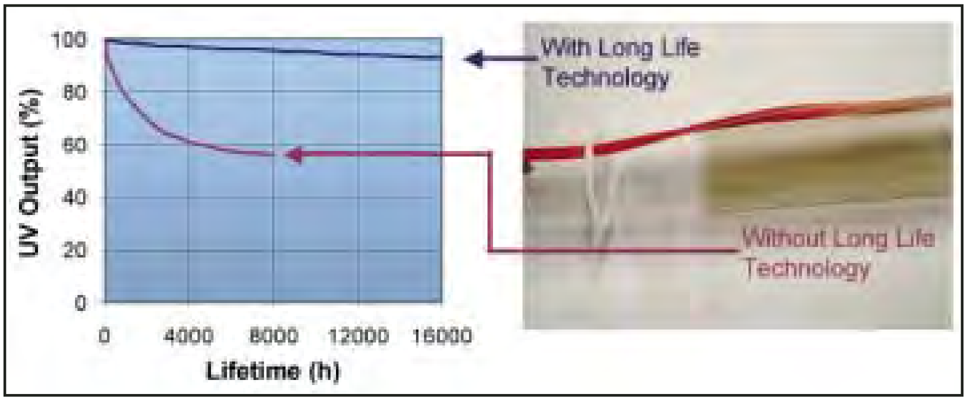
Another benefit of the higher operating temperature of Amalgam lamps is their strongly reduced dependency of UV output on the ambient temperature. While the UV output of Standard Lamps drops ~10% over a temperature range of only 25°C, Amalgam lamps are able to maintain a level above 90% over a range of ~60°C (van der Pol and Krijnen 2005).

Table 1: *Differentiation of Low Pressure Lamp Types by key physical characteristics.*

Characteristic	**Softglass**	**Fused Quartz**		**Fused Quartz**
		Standard	**High Output**	**Amalgam**
Available UV spectrum	254 nm	185, 254 nm	185, 254 nm	185, 254 nm
Wall Temperature (°C)	30-50	30-50	> 50 cold spot 40	90 -120
Electrical Power (W)	5 - 80	5 - 80	10 - 150	40 - 500
Current (A)	0.2 - 0.5	0.3 - 0.4	0.8 - 1.3	1.2 - 5.0
Specific Electrical Power* (W/cm)	0.2 - 0.5	0.3 - 0.5	0.5 - 1.0	1.0 - 3.0
Specific UVC-Flux* (mW/cm)	< 175	< 200	< 350	**< 1000**
UVC efficiency, 254 nm (%)	25 - 35	**30 - 40**	25 - 35	35
Influence of ambient temp.	High	High	High	**Low**

* *per unit arc length*

Figure 1. *Right: Amalgam Lamp partly with "Long Life Technology" coating; left: relative maintenance curve (254 nm) for coated and uncoated Amalgam Lamps.*



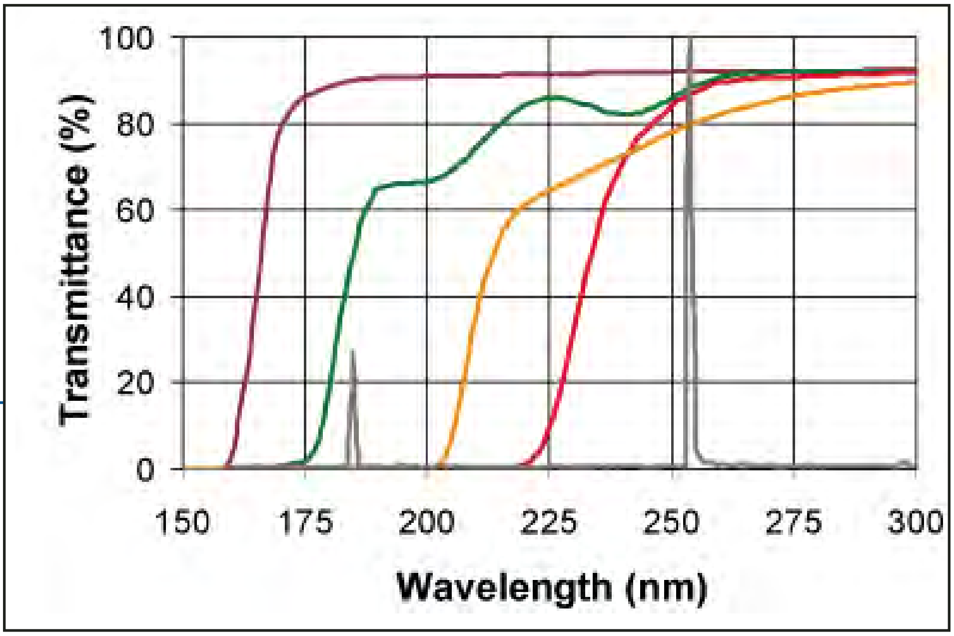
Amalgam Lamps are often categorized as Low Pressure High Output Lamps (LPHOs), also known as Germicidal High Output Lamps (GHO-lamps). However, these are merely enhanced Standard Quartz LPs. They have a long mount electrode assembly with a dead volume behind filaments. This region defines the cold spot temperature, which in turn determines the mercury vapor pressure during lamp operation. Therefore this region has to be kept at a low temperature of ~40°C to optimize the UVC generation. This design enables the lamp to operate at wall temperatures higher than 50°C between electrodes, and thus with higher electrical power consumption as can be seen in Table 1. Although, the specific UVC-flux per unit arc is slightly improved, it is still significantly below Amalgam Lamps. Thus to avoid confusion Amalgam Lamps should not be named HO-Lamps.

A particular challenge of Amalgam Lamps is to cope with a strongly UV absorbing mercury oxide layer formed on the inner wall surface of the lamp tube during operation (see brownish looking part of the tube on the right hand side of Figure 1). This layer originates from a reaction of mercury ions with oxygen in the quartz glass and is strongly dependent on the current density. Amalgam Lamps are driven with the highest current of all LPs, causing a strong decline of UV output within 8,000 h of operation (see left hand side of Figure 1).

Protective coatings can be used to diminish this effect. Commonly Al_2O_3 based coatings are used extending typical lifetimes up to 12,000 h. Voronov et al. (2003) were able to develop this coating technology to its highest level. The so called "Long Life Technology" avoids the layer formation completely and guarantees a stable optical quality of the lamp tube throughout the whole period of operation (clear part of tube in Figure 1). Amalgam lamps with Long Life Technology show almost stable UV-output (above 90%) over a lifetime period of >16,000 h. The data shown on the left side of Figure 1 are based on a lifetime test of two 300 W Amalgam Lamps at constant power and a cycling of 23 h on / 1 h off.

As mentioned earlier Standard LP quartz lamps are available as "ozone-free" and ozone generating versions, depending on different transmittance properties of quartz glass (see Figure 2). For "ozone-free" lamps Doped Fused Quartz is used (TiO_2 to cut transmittance below 235 nm).

Figure 2. *Comparison of the cut-off wavelength of different quartz glass types and softglass. (——) synthetic fused silica; (——) clear fused quartz; (——) softglass; (——) doped fused quartz. For reference a mercury low pressure spectrum (gray curve) is included.*

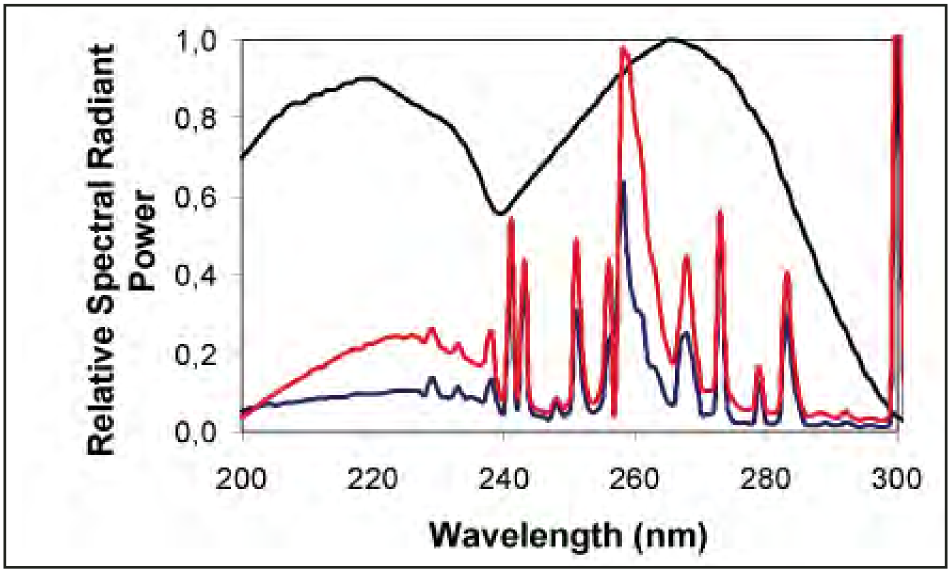


The so called Very High ozone (VH type) lamps are made from Clear Fused Quartz. This terminology is misleading, since transmittance is only ~50% at 185 nm. Lamps made from Synthetic Fused Silica (~90% transmittance at 185 nm) are by far a better option for very high ozone generation.

Generally, the grade of quartz glass depends on preparation method and starting material (Pegmatitic Quartz Sand, Synthetic Grown Crystals or Hydrolysis of $SiCl_4$). Synthetic Fused Silica is the highest grade with ultra high purity and excellent transmittance. For further information about the influence of quartz glass materials on lamp performance see Witzke (2001).

By combining the high transmittance quartz glass material with the Amalgam Lamp technology, one can achieve a fully optimized lamp with the highest possible specific flux at 185 nm for a given geometry. The 185 nm output of such a lamp is about 5 times higher (e.g. compare a G36T5VH with a NIQ 125/84 XL – same diameter, same length).

Figure 3. *Spectrum of Medium Pressure Lamps and cell deactivation curve [Deactivation of Escherichia coli Bacteria according to DIN 5031 (2000)]. (——) MP high performance; (——) MP standard; (——) cell deactivation action spectrum.*



Medium Pressure Lamps

Medium Pressure Lamps have significantly higher electrical power input compared to LPs. This results in a higher mercury vapor pressure, leading to a continuous spectrum mainly composed of broadened and partly self absorbed resonance lines (see Figure 3). A comparison of the key characteristics of LP Amalgam Lamps (as high end representative of LPs) and MPs is given in Table 2. It has to be pointed out, that the wall temperature of MPs is extremely high. It covers a range of 500°C to 950°C. This may cause problems with heat sensitive materials and may require sophisticated heat management. The biggest advantage of MPs is their very high specific UV-flux per unit arc length with up to 35 W/cm compared to Amalgam Lamps with ~1 W/cm. The benefit of high flux, however, is diminished by a far lower UVC efficiency in the range of 5 – 15% (depending on lamp type) and a significantly shorter life time of at best 5000 h, if the highest possible specific UV-flux is realized.

Table 2: *Comparison of Low Pressure and Medium Pressure Lamps*

Characteristic	**LP Amalgam**	**MP**
UV spectrum	185, 254 nm	polychromatic
Hg vapour pressure (bar)	1 x 10^{-5}	1 – 6
Surface Temperature (°C)	90 – 120	**500 – 950**
Electrical Power (W)	40 – 500	400 – 60,000
Specific Elect. Power (W/cm)	1 – 3	50 – 250
Specific UVC flux* (W/cm)	<1	**<35**
UVC efficiency (%)	**35**	5 – 15
Lifetime (h)	**<16,000**	<5,000

* *per unit arc length*

APPLICATIONS

Tables 1 and 2 show the main characteristics of the different lamp types. Lamp prices are generally higher for lamps with higher UV-fluxes. Mainly the characteristics and cost determine the optimum UV source for a specific application. Standard quartz LPs and LPHOs are used across the whole range of water applications for disinfection and/or oxidation processes (e.g. drinking water, waste water, domestic water, ground water, industrial water, ultra pure water and public pool water) with small and medium high flow rates. High UV-flux lamps, such as Amalgam and MPs, are widely used also with the exception of small residential drinking water systems. Water treatment systems with Amalgam Lamps are highly energy and cost efficient. MPs are used if space efficiency is of primary consideration. Softglass Lamps are mainly used in POE (Point Of Entry) and POU (Point Of Use) drinking water disinfection systems and domestic water treatment systems for aquaria, fishponds, private pools, etc. Small flow rates and low investment costs are key values in these markets.

Air treatment applications can be clearly separated into disinfecting and oxidizing processes. In air conditioning systems, UV lamps are used in washer tanks (encapsulated lamps), cooling coils or to disinfect the air stream directly. Light fixtures with UV lamps are installed in special locations, such as in surgeries, hospitals, clean rooms, store houses, cold rooms, etc. to disinfect the ambient air. In all of these applications, LPs are used most often. UV air oxidation is used for odor removal (in sewage plants, rest rooms, hotels, restaurants, catering, senior citizen homes, caravan trailers and cars), grease destruction in kitchen hoods and industrial exhausts. For air temperatures below 40°C, standard ozone generating LPs are utilized. For higher temperatures it is essential to use ozone generating Amalgam Lamps. They show stable operation up to 120°C ambient temperature (see Table 1).

MERCURY FREE UV-LAMPS

One of the most promising of the mercury free UV-lamp technologies for disinfection is the Excimer technology. The word Excimer originates from the expression Excited Dimer – an excited Xe_2 molecule, that forms in a dielectric barrier discharge. For this kind of discharge a modulated electrical field is applied to a quartz glass body filled with Xe gas (e.g., several hundred kHz; several kV high voltage). The quartz glass serves as a dielectric barrier and prevents the forming plasma from short-circuiting the electrodes, which are placed on the surface of the quartz body. There are Excimer lamps in planar geometries, but typically these lamps have a coaxial geometry with an inner and outer electrode and a double cylindrical quartz body (Voronov et al. 2004). In addition Excimers can be composed of a rare gas and a halogen. Two mechanisms of formation are possible: the harpoon reaction or an ionic recombination. Depending on the type of rare gas and halogen used different quasi monochromatic radiations can be obtained. Most important for disinfection are the KrCl* Excimer lamp radiating at 222 nm and XeBr* with 282 nm radiation (see Figure 4). Table 3 compares 282 nm Excimer lamps with low pressure Amalgam Lamps. Most significant is the higher specific UVC-flux per unit plasma length of the XeBr* lamps. Further, they are mercury-free and instant on lamps with no warm up time. These Excimer lamps, however, suffer from a low UVC efficiency of ~8% compared to 35% for Amalgam Lamps. Another drawback to date is the high investment costs for lamps and power supplies.

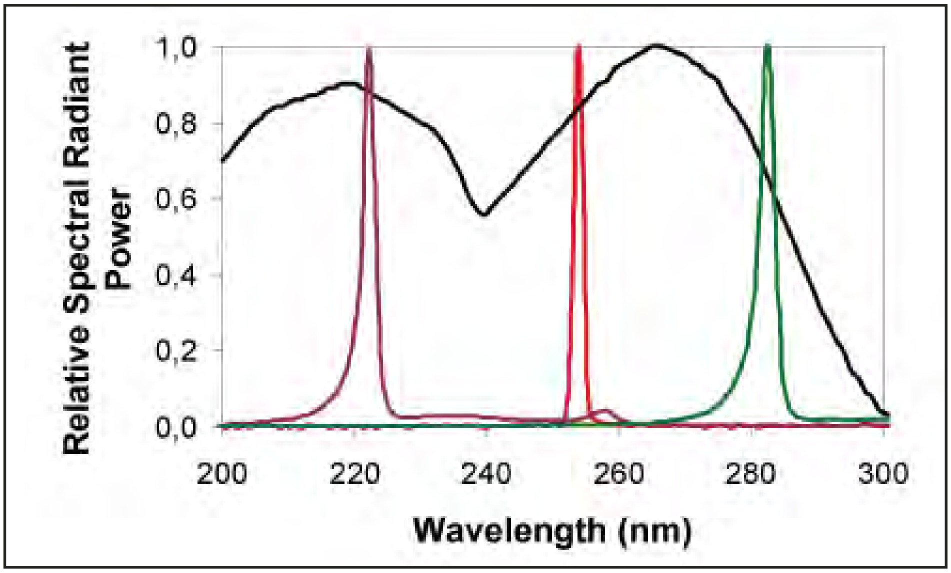


Figure 4. *Spectrum of a Low Pressure Lamp, a KrCl* and a XeBr* Excimer lamp and cell deactivation curve [Deactivation of Escherichia coli bacteria according to DIN 5031 (2000)].*
(—) Hg low pressure lamp;
(—) 222 nm Excimer lamp;
(—) 282 nm Excimer lamp.

Table 3: *Comparison of mercury based lamps and Excimer lamps*

Characteristic	LP Amalgam	Excimer XeBr
UV spectrum	185, 254 nm	282 nm
Mercury Free?	**No**	**Yes**
Surface Temperature (°C)	90-120	<100
Plasma length (cm)	20 – 150	15 – 60
Electrical Power (W)	40 – 500	60 – 2,000
Specific Elect. Power (W/cm)	1 – 3	30
Specific UVC flux* (W/cm)	<1	**<3**
UVC efficiency (%)	**35**	8

* *per unit arc length*

SUMMARY

A wide variety of state-of-the-art lamp types and lamp technologies for disinfection and Advanced Oxidation Processes is available to date. Low Pressure Lamps show the strongest diversity, amongst them the high end type in this category – the Amalgam Lamp. The notation High Output Low Pressure Lamp should be avoided in this context, since Amalgam Lamps differ in technology and key performance characteristics significantly. They offer high UVC output, excellent lifetime, good UV efficiency, high temperature stability and enable operation in high ambient temperatures. This combination makes them the right choice for compact, efficient and economic disinfection and Advanced Oxidation systems.

It was demonstrated, that the high transmitting Synthetic Fused Silica lamp body material combined with Amalgam technology results in a lamp with optimized output at 185 nm. For a given geometry the output will be up to 5 times higher compared to a standard LP Very High ozone (VH) type lamp.

Medium Pressure Lamps are applied if space efficiency is first, due to their very high UVC output and their compact lamp design.

Excimer lamps offer a future alternative for mercury free disinfection lamps with instant on operation. Until now they suffer from lower UV efficiencies and significantly higher investment costs.

REFERENCES

Bolton, J.W. 2004. Photochemical Technologies for water purification and remediation. Proceedings of the European Conference on UV-Radiation Effects and Technologies, Karlsruhe, Germany, International Ultraviolet Association, Ayr, ON, Canada.

DIN 5031 2000. German Standard, DIN 5031-10: 2000-03, Part 10. DIN Deutsches Institut für Normung e.V., Berlin, Germany

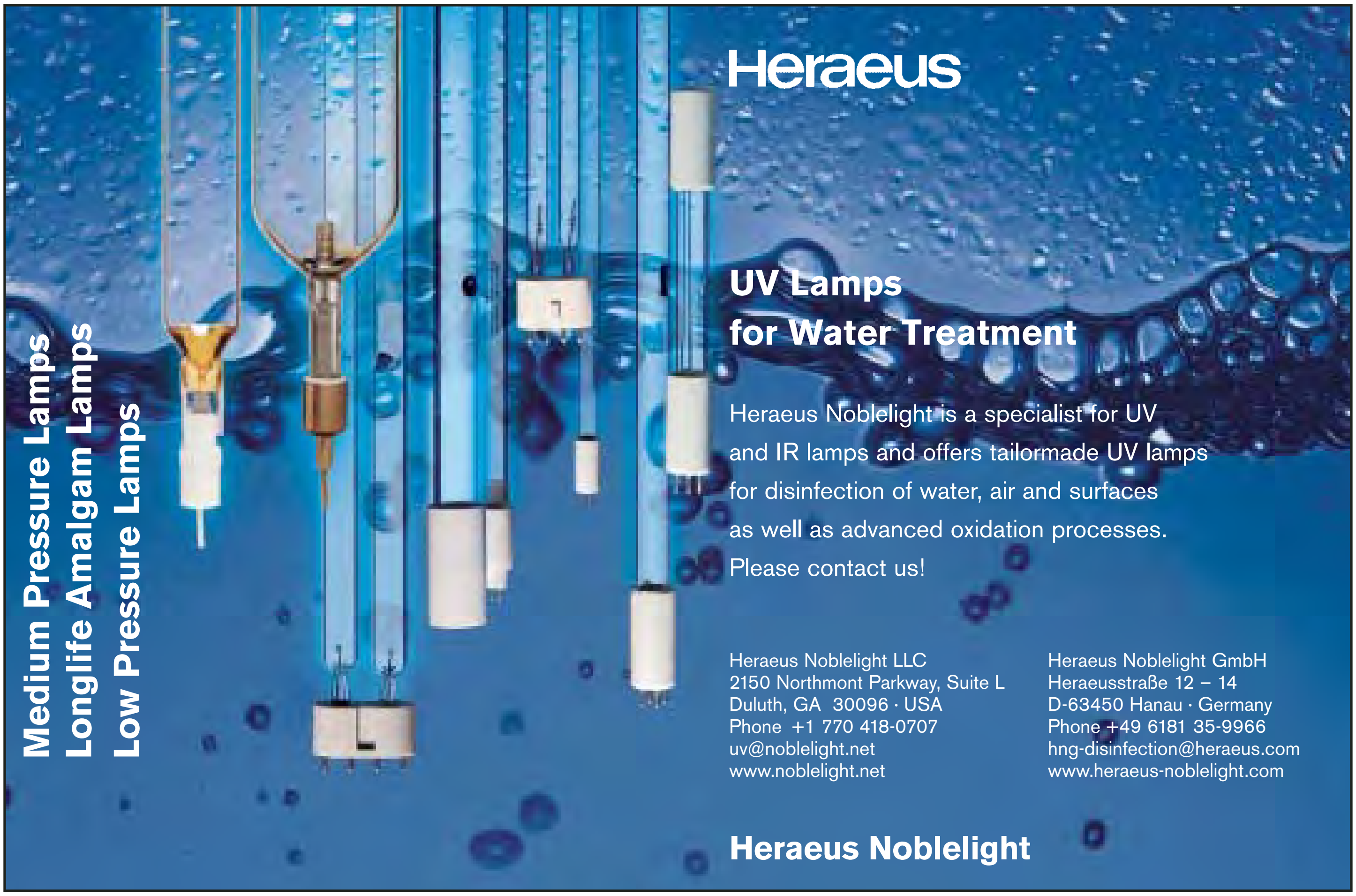
Heering, W. 2004. UV Sources – Basics, Properties and Applications, IUVA News, 6(4): 7 – 13.

Van der Pol, A.J.H.P. and Krijnen, S. 2005. Optimal UV output in different application of low-pressure UV-C lamps. Proceedings of the Third International Congress on Ultraviolet Technologies, Whistler, BC, Canada, International Ultraviolet Association, Ayr, ON, Canada.

Voronov, A., Arnold, E., Roth, E. 2003. Long Life Technology of High Power Amalgam Lamps, Proceedings of the Second International Conference on Ultraviolet Technologies, Vienna, Austria, International Ultraviolet Association, Ayr, ON, Canada.

Voronov, A.M., Reber, S., Schilling, F.J. and Arnold, E. 2004. Mercury-free UV-Light Sources: Technology and Perspectives of Excimer Lamps, Proceedings of the XV International Conference on Gas Discharges and their Applications, Toulouse, France

Witzke, H.-D. 2001. Recent Studies on Fused Quartz and Synthetic Fused Silica for Light Sources. Proceedings of 9th International Symposium on the Science and Technology of Light Sources (LS 9), Ithaca, NY, USA.



UV Dose Required to Achieve Incremental Log Inactivation of Bacteria, Protozoa and Viruses[1]

Revised and Expanded by:

Gabriel Chevrefils, B.Ing,[2] and **Éric Caron**, B.Sc.[2]

With earlier (1999) Contributions by:

Harold Wright[3] and **Gail Sakamoto**[3]

And with Peer Review by:

Pierre Payment,[4] **Benoit Barbeau**[5] and **Bill Cairns**[3]*

1. This compilation has been prepared for Trojan Technologies Inc. and is published here as a public service to the UV community.
2. Chaire de recherche en Eau Potable, École Polytechnique de Montreal
3. Trojan Technologies Inc., London, ON, Canada
4. INRS- Institut Armand-Frappier
5. École Polytechnique de Montreal

*** Corresponding Author:** bcairns@trojanuv.com

BRIEF DESCRIPTION AND SELECTION CRITERIA FOR CONTENT OF THE TABLES

Tables 1-4 present a summary of published data on the Ultraviolet (UV) dose-response of various organisms that are pathogens, indicators, or organisms encountered in the application, testing of performance, and validation of UV disinfection technologies. The tables reflect the state of knowledge, but include the variation in technique and biological response that currently exists in the absence of standardized protocols. Users of the data for their own purposes are advised to exercise critical judgment in how they use the data.

In most cases, the data are generated from low pressure (LP) monochromatic mercury arc lamp sources for which the lamp fluence rate (intensity) can be measured empirically and multiplied by exposure time to obtain a dose. Earlier data do not always contain the correction factors that are now considered standard practice (Bolton and Linden 2003). Some data are from polychromatic medium pressure (MP) mercury arc lamps, and in some cases both lamp types are used. In a few cases, filtered polychromatic UV light is used to achieve a narrow band of irradiation around 254 nm. These studies are also designated as LP.

None of the data incorporate any impact of photorepair processes. Only the response to the inactivating UV dose is documented. The references from which the data are abstracted must be carefully read to understand how the reported doses are calculated and what the assumptions and procedures are in the calculation.

At the time this table was being prepared, a parallel initiative (Hijnen et al. 2006) was ongoing and is recommended to the reader.

It is the intention of Trojan Technologies, École Polytechnique de Montreal and INRS- Institut Armand-Frappier to keep this table dynamic, with periodic updates. Recommendations for inclusion in the tables, along with the reference source, can be sent to:

Dr. Bill Cairns, Chief Scientist
Trojan Technologies Inc
3020 Gore Road
London, Ontario, Canada N5V 4T7
e-mail: bcairns@trojanuv.com

The selection criteria for inclusion are recommended as follows:

1. Data must be already published in a peer-reviewed journal or other peer-reviewed publication media;
2. The dose-response should be empirically determined in the laboratory with the assistance of a collimated beam apparatus;
3. Ideally, the fluence rate (intensity) should be measured with a recently calibrated radiometer and when this has not been done, a well-characterized organism should be run as a reference to provide a comparison with the literature values to substantiate that the radiometer is within calibration.
4. The publication from which the data is abstracted should describe the experimental procedures including collimated beam procedures, dose calculation procedures along with any assumptions made, organism culturing procedures, enumeration and preparation for experiments.
5. Responses should be determined over a range of doses; that is, a complete dose-response curve is preferred to a single dose-response measurement.

Table 1. *UV Doses for Multiple Log Reductions for Various Spores*

Spore	Lamp Type	UV Dose (Fluence) (mJ/cm^2) for a given Log Reduction without photo-reactivation							Reference
		1	2	3	4	5	6	7	
Bacillus subtilis ATCC6633	N/A	36	48.6	61	78				Chang et al. 1985
Bacillus subtilis ATCC6633	LP	24	35	47	79				Mamane-Gravetz and Linden 2004
Bacillus subtilis ATCC6633	LP	22	38	>50					Sommer et al. 1998
Bacillus subtilis ATCC6633	LP	20	39	60	81				Sommer et al. 1999
Bacillus subtilis WN626	LP	0.4	0.9	1.3	2				Marshall et al., 2003

Table 2. *UV Doses for Multiple Log Reductions for Various Bacteria*

Bacterium	Lamp Type	UV Dose (Fluence) (mJ/cm^2) for a given Log Reduction without photo-reactivation							Reference
		1	2	3	4	5	6	7	
Aeromonas hydrophila ATCC7966	LP	1.1	2.6	3.9	5	6.7	8.6		Wilson et al. 1992
Aeromonas salmonicida	LP	1.5	2.7	3.1	5.9				Liltved and Landfald 1996
Campylobacter jejuni ATCC 43429	LP	1.6	3.4	4	4.6	5.9			Wilson et al. 1992
Citrobacter diversus	LP	5	7	9	11.5	13			Giese and Darby 2000
Citrobacter freundii	LP	5	9	13					Giese and Darby 2000
Escherichia coli ATCC 11229	N/A	2.5	3	3.5	5	10	15		Harris et al. 1987
Escherichia coli ATCC 11229	N/A	3	4.8	6.7	8.4	10.5			Chang et al. 1985
Escherichia coli ATCC 11229	LP	<5	5.5	6.5	7.7	10			Zimmer et al. 2002
Escherichia coli ATCC 11229	MP	<3	<3	<3	<3	8			Zimmer et al. 2002
Escherichia coli ATCC 11229	LP	7	8	9	11	12			Hoyer 1998
Escherichia coli ATCC 11229	LP	3.5	4.7	5.5	6.5	7.5	9.6		Sommer et al. 2000
Escherichia coli ATCC 11229	LP	6	6.5	7	8	9	10		Sommer et al. 1998
Escherichia coli ATCC 11303	LP	4	6	9	10	13	15	19	Wu et al. 2005
Escherichia coli ATCC 25922	LP	6	6.5	7	8	9	10		Sommer et al. 1998
Escherichia coli C	LP	2	3	4	5.6	6.5	8	10.7	Otaki et al. 2003
Escherichia coli O157:H7	LP	1.5	3	4.5	6				Tosa and Hirata 1999
Escherichia coli O157:H7	LP	<2	<2	2.5	4	8	17		Yaun et al. 2003
Escherichia coli O157:H7 CCUG 29193	LP	3.5	4.7	5.5	7				Sommer et al. 2000
Escherichia coli O157:H7 CCUG 29197	LP	2.5	3	4.6	5	5.5			Sommer et al. 2000
Escherichia coli O157:H7 CCUG 29199	LP	0.4	0.7	1	1.1	1.3	1.4		Sommer et al. 2000
Escherichia coli O157:H7 ATCC 43894	LP	1.5	2.8	4.1	5.6	6.8			Wilson et al. 1992
Escherichia coli O25:K98:NM	LP	5	7.5	9	10	11.5			Sommer et al. 2000
Escherichia coli O26	LP	5.4	8	10.5	12.8				Tosa and Hirata 1999
Escherichia coli O50:H7	LP	2.5	3	3.5	4.5	5	6		Sommer et al. 2000
Escherichia coli O78:H11	LP	4	5	5.5	6	7			Sommer et al. 2000
Escherichia coli K-12 IFO3301	LP & MP	2	4	6	7	8.5			Oguma et al. 2002
Escherichia coli K-12 IFO3301	LP & MP	2.2	4.4	6.7	8.9	11.0			Oguma et al. 2004
Escherichia coli K-12 IFO3301	LP	1.5	2	3.5	4.2	5.5	6.2		Otaki et al. 2003
Escherichia coli Wild type	LP	4.4	6.2	7.3	8.1	9.2			Sommer et al. 1998

Table 2. *(continued)*

Bacterium	Lamp Type	UV Dose (Fluence) (mJ/cm^2) for a given Log Reduction without photo-reactivation							Reference
		1	2	3	4	5	6	7	
Halobacterium elongata ATCC33173	LP	0.4	0.7	1					Martin et al. 2000
Halobacterium salinarum ATCC43214	LP	12	15	17.5	20				Martin et al. 2000
Klebsiella pneumoniae	LP	12	15	17.5	20				Giese and Darby 2000
Klebsiella terrigena ATCC33257	LP	4.6	6.7	8.9	11				Wilson et al. 1992
Legionella pneumophila ATCC 43660	LP	3.1	5	6.9	9.4				Wilson et al. 1992
Legionella pneumophila ATCC33152	LP	1.6	3.2	4.8	6.4	8.0			Oguma et al. 2004
Legionella pneumophila ATCC33152	MP	1.9	3.8	5.8	7.7	9.6			Oguma et al. 2004
Pseudomonas stutzeri	UVB	100	150	195	230				Joux et al. 1999
RB2256	UVB	175	>300						Joux et al. 1999
Salmonella spp.	LP	<2	2	3.5	7	14	29		Yaun et al. 2003
Salmonella anatum (from human feces)	N/A	7.5	12	15					Tosa and Hirata 1998
Salmonella derby (from human feces)	N/A	3.5	7.5						Tosa and Hirata 1998
Salmonella enteritidis (from human feces)	N/A	5	7	9	10				Tosa and Hirata 1998
Salmonella infantis (from human feces)	N/A	2	4	6					Tosa and Hirata 1998
Salmonella typhi ATCC 19430	LP	1.8	4.8	6.4	8.2				Wilson et al. 1992
Salmonella typhi ATCC 6539	N/A	2.7	4.1	5.5	7.1	8.5			Chang et al. 1985
Salmonella typhimurium (from human feces)	N/A	2	3.5	5	9				Tosa and Hirata 1998
Salmonella typhimurium (from human feces)	N/A	2	3.5	5	9				Tosa and Hirata 1998
Salmonella typhimurium (in act. sludge)	LP	3	11.5	22	50				Maya et al. 2003
Salmonella typhimurium	UVB	50	100	175	210	250			Joux et al. 1999
Shigella dysenteriae ATCC29027	LP	0.5	1.2	2	3	4	5.1		Wilson et al. 1992
Shigella sonnei ATCC9290	N/A	3.2	4.9	6.5	8.2				Chang et al. 1985
Staphylococcus aureus ATCC25923	N/A	3.9	5.4	6.5	10.4				Chang et al. 1985
Streptococcus faecalis ATCC29212	N/A	6.6	8.8	9.9	11.2				Chang et al. 1985
Streptococcus faecalis (secondary effluent)	N/A	5.5	6.5	8	9	12			Harris et al. 1987
Vibrio anguillarum	LP	0.5	1.2	1.5	2				Liltved and Landfald 1996
Vibrio cholerae ATCC25872	LP	0.8	1.4	2.2	2.9	3.6	4.3		Wilson et al. 1992
Vibrio natriegens	UVB	37.5	75	100	130	150			Joux et al. 1999
Yersinia enterocolitica ATCC27729	LP	1.7	2.8	3.7	4.6				Wilson et al. 1992
Yersinia ruckeri	LP	1	2	3	5				Liltved and Landfald 1996

Table 3. *UV Doses for Multiple Log Reductions for Various Protozoa*

Protozoan	Lamp Type	UV Dose (Fluence) (mJ/cm²) for a given Log Reduction without photo-reactivation							Reference
		1	2	3	4	5	6	7	
Cryptosporidium hominis	LP & MP	3	5.8						Johnson et al. 2005
Cryptosporidium parvum, oocysts, tissue culture assay	N/A	1.3	2.3	3.2					Shin et al. 2000
Cryptosporidium parvum	LP & MP	2.4	<5	5.2	9.5				Craik et al. 2001
Cryptosporidium parvum	MP	<5	<5	<5	~6				Amoah et al. 2005
Cryptosporidium parvum	MP	<10	<10	<10					Belosevic et al. 2001
Cryptosporidium parvum	LP	1	2	<5					Shin et al. 2001
Cryptosporidium parvum	MP	1	2	2.9	4				Bukhari et al. 2004
Cryptosporidium parvum	LP	<2	<2	<2	<4	<10			Clancy et al. 2004
Cryptosporidium parvum	MP	<3	<3	3-9	<11				Clancy et al. 2000
Cryptosporidium parvum	LP	<3	<3	3-6	<16				Clancy et al. 2000
Cryptosporidium parvum	LP	0.5	1	1.4	2.2				Morita et al. 2002
Cryptosporidium parvum	LP	2	<3	<3					Zimmer et al. 2003
Cryptosporidium parvum	MP	<1	<1	<1					Zimmer et al. 2003
Encephalitozoon cuniculi, microsporidia	LP	4	9	13					Marshall et al. 2003
Encephalitozoon hellem, microsporidia	LP	8	12	18					Marshall et al. 2003
Encephalitozoon intestinalis, microsporidia	LP & MP	<3	3	<6	6				Huffman et al. 2002
Encephalitozoon intestinalis, microsporidia	LP	3	5	6					Marshall et al. 2003
Giardia lamblia, gerbil infectivity assay	LP	<0.5	<0.5	<0.5	<1				Linden et al. 2002b
Giardia lamblia	LP	<10	~10	<20					Campbell et al. 2002
Giardia lamblia	LP	<2	<2	<4					Mofidi et al. 2002
Giardia lamblia,excystation assay	N/A	> 63							Rice and Hoff 1981
Giardia lamblia, excystation assay	N/A	40	180						Karanis et al. 1992
Giardia muris, excystation assay	N/A	77	110						Carlson et al. 1985
G. muris, cysts, mouse infectivity assay	N/A	<2	<6	10 + tailing					Craik et al. 2000
Giardia muris	MP	1	4.5	28 + tailing					Craik et al. 2000
Giardia muris	MP	<10	<10	<25	~60				Belosevic et al. 2001
Giardia muris	LP	<1.9	<1.9	~2	~2.3				Hayes et al. 2003
Giardia muris	LP	<2	<2	<4					Mofidi et al. 2002
G. muris, cysts	MP	<5	<5	5					Amoah et al. 2005

Table 4. *UV Doses for Multiple Log Reductions for Various Viruses*

Virus	Host	Lamp Type	UV Dose (Fluence) (mJ/cm²) per Log Reduction						Reference
			1	2	3	4	5	6	
PRD-1 (Phage)	*S. typhimurium* Lt2	N/A	9.9	17.2	23.5	30.1			Meng and Gerba 1996
B40-8 (Phage)	*B. Fragilis*	LP	11	17	23	29	35	41	Sommer et al. 2001
B40-8 (Phage)	*B. fragilis* HSP-40	LP	12	18	23	28			Sommer et al 1998
MS2 (Phage)	*Salmonella typhimurium* WG49	N/A	16.3	35	57	83	114	152	Nieuwstad and Havelaar 1994

Table 4. *(continued)*

Virus	Host	Lamp Type	UV Dose (Fluence) (mJ/cm^2) per Log Reduction						Reference
			1	2	3	4	5	6	
MS2 DSM 5694 (Phage)	*E. coli* NCIB 9481	N/A	4	16	38	68	110		Wiedenmann et al. 1993
MS2 ATCC 15977-B1 (Phage)	*E. coli* ATCC 15977–B1	LP	15.9	34	52	71	90	109	Wilson et al. 1992
MS2 NCIMB 10108 (Phage)	*Salmonella typhimurium* WG49	N/A	12.1	30.1					Tree et al. 1997
MS2 (Phage)	*E. coli* K-12 Hfr	LP	21	36					Sommer et al. 1998
MS2 (Phage)	*E. coli* CR63	N/A	16.9	33.8					Rauth 1965
MS2 (Phage)	*E. coli* 15977	N/A	13.4	28.6	44.8	61.9	80.1		Meng and Gerba 1996
MS2 (Phage)	*E. coli* C3000	N/A	35						Battigelli et al. 1993
MS2 (Phage)	*E. coli* ATCC 15597	N/A	19	40	61				Oppenheimer et al. 1993
MS2 (Phage)	*E. coli* C3000	LP	20	42	69	92			Batch et al. 2004
MS2 (Phage)	*E. coli* ATCC 15597	LP	20	42	70	98	133		Lazarova and Savoye 2004
MS2 (Phage)	*E. coli* ATCC 15977	LP	20	50	85	120			Thurston-Enriquez et al., 2003
MS2 (Phage)	*E. coli* HS(pFamp)R	LP		45	75	100	125	155	Thompson et al. 2003
MS2 (Phage)	*E. coli* C3000	LP	20	42	68	90			Linden et al. 2002a
MS2 (Phage)	*E. coli* K-12	LP	18.5	36	55				Sommer et al. 2001
MS2 (Phage)	*E. coli* NCIMB 9481	N/A	14						Tree et al. 2005
PHI X 174 (Phage)	*E. coli* WG5	LP	2.2	5.3	7.3	10.5			Sommer et al. 1998
PHI X 174 (Phage)	*E. coli* C3000	N/A	2.1	4.2	6.4	8.5	10.6	12.7	Battigelli et al. 1993
PHI X 174 (Phage)	*E. coli* ATCC15597	N/A	4	8	12				Oppenheimer et al. 1993
PHI X 174 (Phage)	*E. coli* WG 5	LP	3	5	7.5	10	12.5	15	Sommer et al. 2001
PHI X 174 (Phage)	*E. coli* ATCC 13706	LP	2	3.5	5	7			Giese and Darby 2000
Staphylococcus aureus phage A 994 (Phage)	*Staphylococcus aureus* 994	LP	8	17	25	36	47		Sommer et al. 1989
Calicivirus canine	MDCK cell line	LP	7	15	22	30	36		Husman et al. 2004
Calicivirus feline	CRFK cell line	LP	7	16	25				Husman et al. 2004
Calicivirus feline	CRFK cell line	N/A	4	9	14				Tree et al. 2005
Calicivirus feline	CRFK cell line	LP	5	15	23	30	39		Thurston-Enriquez et al. 2003
Adenovirus type 2	A549 cell line	LP	20	45	80	110			Shin et al. 2005
Adenovirus type 2	Human lung cell line	LP	35	55	75	100			Ballester and Malley 2004
Adenovirus type 2	PLC / PRF / 5 cell line	LP	40	78	119	160	195	235	Gerba et al. 2002
Adenovirus type 15	A549 cell line (ATCC CCL-185)	LP	40	80	122	165	210		Thompson et al. 2003
Adenovirus type 40	PLC / PRF / 5 cell line	LP	55	105	155				Thurston-Enriquez et al. 2003
Adenovirus type 40	PLC / PRF / 5 cell line	LP	30	ND	ND	124			Meng and Gerba 1996
Adenovirus type 41	PLC / PRF / 5 cell line	LP	23.6	ND	ND	111.8			Meng and Gerba 1996
Poliovirus Type 1 ATCC Mahoney	N/A	N/A	6	14	23	30			Harris et al. 1987
Poliovirus Type 1 LSc2ab ()	MA104 cell	N/A	5.6	11	16.5	21.5			Chang et al. 1985

Table 4. *(continued)*

Virus	Host	Lamp Type	UV Dose (Fluence) (mJ/cm^2) per Log Reduction						Reference
			1	2	3	4	5	6	
Poliovirus Type 1 LSc2ab	BGM cell	LP	5.7	11	17.6	23.3	32	41	Wilson et al. 1992
Poliovirus 1	BGM cell line	N/A	5	11	18	27			Tree et al. 2005
Poliovirus 1	CaCo2 cell-line (ATCC HTB37)	LP	7	17	28	37			Thompson et al. 2003
Poliovirus 1	BGM cell line	LP	8	15.5	23	31			Gerba et al. 2002
Poliovirus Type Mahoney	Monkey kidney cell line Vero	LP	3	7	14	40			Sommer et al. 1989
Coxsackievirus B5	Buffalo Green Monkey cell line	N/A	6.9	13.7	20.6				Battigelli et al. 1993
Coxsackievirus B3	BGM cell line	LP	8	16	24.5	32.5			Gerba et al. 2002
Coxsackievirus B5	BGM cell line	LP	9.5	18	27	36			Gerba et al. 2002
Reovirus-3	Mouse L-60	N/A	11.2	22.4					Rauth 1965
Reovirus Type 1 Lang strain	N/A	N/A	16	36					Harris et al. 1987
Rotavirus SA-11	Monkey kidney cell line MA 104	LP	8	15	27	38			Sommer et al. 1989
Rotavirus SA-11	MA-104 cell line	N/A	7.6	15.3	23				Battigelli et al. 1993
Rotavirus SA-11	MA-104 cell line	N/A	7.1	14.8	25				Chang et al. 1985
Rotavirus SA-11	MA-104 cell line	LP	9.1	19	26	36	48		Wilson et al. 1992
Rotavirus	MA104 cells	LP	20	80	140	200			Caballero et al. 2004
Hepatitis A HM175	FRhK-4 cell	LP	5.1	13.7	22	29.6			Wilson et al. 1992
Hepatitis A	HAV/HFS/GBM	N/A	5.5	9.8	15	21			Wiedenmann et al. 1993
Hepatitis A HM175	FRhK-4 cell	N/A	4.1	8.2	12.3	16.4			Battigelli et al. 1993
Echovirus I	BGM cell line	LP	8	16.5	25	33			Gerba et al. 2002
Echovirus II	BGM cell line	LP	7	14	20.5	28			Gerba et al. 2002

REFERENCES

Amoah, K., Craik, S., Smith, D.W. and Belosevic, M. 2005. Inactivation of *Cryptosporidium* oocysts and *Giardia* cysts by ultraviolet light in the presence of natural particulate matter, AQUA, J. Wat. Supply 54(3): 165-178.

Ballester, N.A. and Malley, J.P. 2004. Sequencial disinfection of adenovirus type 2 with UV-chlorine-chloramine, J. Amer. Wat. Works Assoc., 96(10): 97-102.

Batch, L.F., Schulz, C.R. and Linden, K.G. 2004. Evaluating water quality effects on UV disinfection of MS2 coliphage, J. Amer. Wat. Works Assoc., 96(7): 75-87.

Battigelli, D.A., Sobsey, M.D. and Lobe, D.C. 1993. The inactivation of Hepatitis A virus and other model viruses by UV irradiation, Wat. Sci. Tech., 27(3-4): 339-342.

Belosevic, M., Craik, S.A., Stafford, J.L. Neumann, N.E., Kruithof, J. and Smith, D.W. 2001. Studies on the resistance/reaction of *Giardia muris* cysts and *C. parvum* oocysts exposed to medium-pressure ultraviolet radiation, FEMS Microbiol. Lett., 204(1): 197-204.

Bolton J.R. and Linden, K.G. 2003. Standardization of methods for fluence (UV Dose) determination in bench-scale UV experiments. J. Environ. Eng. 129(3): 209-216.

Bukhari, Z., Abrams, F. and LeChevallier, M. 2004. Using ultraviolet light for disinfection of finished water, Water Sci. Tech., 50(1): 173-178.

Caballero, S., Abad, F.X., Loisy, F., Le Guyader, F.S., Cohen, J., Pinto, R.M. and Bosch, A. 2004. Rotavirus virus-like particles as surrogates in environmental persistence and inactivation studies, Appl. Env. Microbiol. 70(7): 3904-3909.

Campbell, A.T. and Wallis, P. 2002. The effect of UV irradiation on human-derived *Giardia lamblia* cysts, Wat. Res., 36(4): 963- 969.

Carlson, D.A., Seabloom, R.W., DeWalle, F.B., Wetzler, T.F., Engeset, J., Butler, R., Wangsuphachart, S. and Wang, S. 1985. Ultraviolet disinfection of water for small water supplies. US EPA Report No. EPA/600/S2-85/092.

Chang, J.C.H., Osoff, S.F., Lobe, D.C., Dorfman, M.H., Dumais, C.M., Qualls, R.G. and Johnson, J.D. 1985. UV inactivation of pathogenic and indicator microorganisms, Appl. Environ. Microbiol., 49(6): 1361-1365.

Clancy, J.L., Bukhari, Z., Hargy, T.M., Bolton, J.R., Dussert, B.W. and Marshall, M.M. 2000. Using UV to inactivate *Cryptosporidium* – Even extremely low dosages of ultraviolet light can be highly effective for inactivating *Cryptosporidium* oocysts, J. Amer. Wat. Works Assoc., 92(9): 97-104.

Clancy, J.L., Marshall, M.M., Hargy, T.M. and Korich, D.G. 2004. Susceptibility of five strains of *Cryptosporidium parvum* oocysts to UV light, J. Amer. Wat. Works Assoc., 96(3), 84-93.

Craik, S.A., Finch, G.R., Bolton, J.R. and Belosevic, M. 2000. Inactivation of *Giardia muris* cysts using medium-pressure ultraviolet radiation in filtered water, Wat. Res., 34(18): 4325-4332.

Craik, S.A., Weldon, D., Finch, G.R., Bolton, J.R. and Belosevic, M. 2001. Inactivation of *Cryptosporidium parvum* oocysts using medium- and low-pressure ultraviolet radiation, Wat. Res., 35(6): 1387-1398.

Gerba, C.P., Gramos, D.M. and Nwachuku, N. 2002. Comparative inactivation of enteroviruses and adenovirus 2 by UV light, Appl. Environ. Microbiol., 68(10): 5167-5169.

Giese, N. and Darby, J. 2000. Sensitivity of microorganisms to different wavelengths of UV light: implications on modeling of medium pressure UV systems, Wat. Res., 34(16): 4007-4013.

Harris, G.D., Adams, V.D., Sorensen, D.L. and Curtis, M.S. 1987. Ultraviolet inactivation of selected bacteria and viruses with photoreactivation of the bacteria, Wat. Res., 21(6): 687-692.

Hayes, S.L., Rice, E.W., Ware, M.W. and Schaefer III, F.W. 2003. Low pressure ultraviolet studies for inactivation of *Giardia muris* cysts, J. Appl. Microbiol., 94(1): 54-59.

Hijnen, W.A.M., Beerendonk, E.F. and Medema, G.J. 2006. Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water; a review, Wat. Res., 40(1): 3-22.

Hoyer, O. 1998. Testing performance and monitoring of UV systems for drinking water disinfection, Wat. Supply, 16(1-2): 424-429.

Huffman, D.E., Gennaccaro, A., Rose, J.B. and Dussert, B.W. 2002. Low- and medium-pressure UV inactivation of microsporidia *Encephalitozoon intestinalis*, Wat. Res., 36(12): 3161-3164.

Husman, A.M.D., Bijkerk, P., Lodder, W., Van den Berg, H., Pribil, W., Cabaj, A., Gehringer, P., Sommer, R. and Duizer, E. 2004. Calicivirus inactivation by nonionizing 253.7-nanometer-wavelength (UV) and ionizing (Gamma) radiation, Appl. Environ. Microbiol., 70(9): 5089-5093.

Johnson, A.M., Linden, K., Ciociola, K.M., De Leon, R., Widmer, G. and Rochelle, P.A. 2005. UV inactivation of *Cryptosporidium hominis* as measured in cell culture, Appl. Environ. Microbiol., 71(5): 2800-2802.

Joux, F., Jeffrey, W.H., Lebaron, P. and Mitchell, D. L. 1999. Marine bacterial isolates display diverse responses to UV-B radiation, Appl. Environ. Microbiol., 65(9): 3820-3827.

Karanis, P., Maier, W.A., Seitz, H.M. and Schoenen, D. 1992. UV sensitivity of protozoan parasites, Aqua, 41: 95-100.

Lazarova,V. and Savoye, P. 2004. Technical and sanitary aspect of wastewater disinfection by ultraviolet irradiation for landscape irrigation, Wat. Sci. Technol., 50(2): 203-209.

Liltved, H. and Landfald, B. 1996. Influence of liquid holding recovery and photoreactivation on survival of ultraviolet-irradiated fish pathogenic bacteria, Wat. Res., 30(5): 1109-1114.

Linden, K.G., Batch, L. and Schulz, C. 2002a. UV disinfection of filtered water supplies: water quality impacts on MS2 dose-response curves, Proceedings Amer. Wat. Works Assoc. Annu. Conf., Amer. Wat. Works Assoc., Denver, CO.

Linden, K.G., Shin, G.-A., Faubert, G., Cairns, W. and Sobsey, M.D. 2002b. UV disinfection of *Giardia lamblia* cysts in water, Environ. Sci. Techol., 36(11): 2519-2522.

Mamane-Gravetz, H. and Linden, K.G. 2004. UV disinfection of indigenous aerobic spores: Implications for UV reactor validation in unfiltered waters, Wat. Res., 38(12): 2898-2906.

Marshall, M.M., Hayes, S., Moffett, J., Sterling, C.R. and Nicholson, W.L. 2003. Comparison of UV inactivation of three *Encephalitozoon* species with that of spores of two DNA repair-deficient *Bacillus subtilis* biodosimetry strains, Appl. Environ. Microbiol., 69(1): 683-685.

Martin, E.L., Reinhardt, R.L., Baum, L.L., Becker, M.R., Shaffer, J.J. and Kokjohn, T.A. 2000. The effects of ultraviolet radiation on the moderate halophile *Halomonas elongata* and the extreme halophile *Halobacterium salinarum*, Can. J. Microbiol., 46(2): 180-187.

Maya, C., Beltran, N., Jimenez, B. and Bonilla, P. 2003. Evaluation of the UV disinfection process in bacteria and amphizoic amoebae inactivation, Wat. Sci. Technol.: Wat. Supply, 3(4): 285-291.

Meng, Q.S. and Gerba, C.P. 1996. Comparative inactivation of enteric adenoviruses, poliovirus and coliphages by ultraviolet irradiation, Wat. Res., 30(11): 2665-2668.

Mofidi, A.A., Meyer, E.A., Wallis, P.M., Chou, C.I., Meyer, B.P., Ramalingam, S. and Coffey, B.M. 2002. The effect of UV light on the inactivation of *Giardia lamblia* and *Giardia muris* cysts as determined by animal infectivity assay, Wat. Res., 36(8): 2098-2108.

Morita, S., Namikoshi, A., Hirata, T., Oguma, K., Katayama, H., Ohgaki, S., Motoyama, N. and Fujiwara, M. 2002. Efficacity of UV irradiation in inactivating *C. parvum* oocysts, Appl. Environ. Microbiol., 68(11): 5387-5393.

Nieuwstad, T.J. and Havelaar, A.H. 1994. The kinetics of batch ultraviolet inactivation of bacteriophage MS2 and microbiological calibration of an ultraviolet pilot plant, J. Environ. Sci. Health, A29(9): 1993-2007.

Oguma, K., Katayama, H. and Ohgaki, S. 2002. Photoreactivation of *E. coli* after low- or medium-pressure UV disinfection determined by an endonuclease sensitive site assay, Appl. Environ. Microbiol., 68(12), 6029-6035.

Oguma, K., Katayama, H. and Ohgaki, S. 2004. Photoreactivation of *Legionella pneumophila* after inactivation by low- or medium-pressure ultraviolet lamp, Wat. Res., 38(11): 2757-2763.

Oppenheimer, J.A., Hoagland, J.E., Laine, J.-M., Jacangelo, J.G. and Bhamrah, A. 1993. Microbial inactivation and charcaterization of toxicity and by-products occurring in reclaimed wastewater disinfected with UV radiation, Conf. on Planning, Design and Operation of Effluent Disinfection Systems, Whippany, NJ, May 23-25, 1993, Wat. Environ. Fed., Alexandria, VA

Otaki, M., Okuda, A., Tajima, K., Iwasaki, T., Kinoshita, S. and Ohgaki, S. 2003. Inactivation differences of microorganisms by low pressure UV and pulsed xenon lamps, Wat. Sci. Technol., 47(3): 185-190.

Rauth, A.M. 1965. The physical state of viral nucleic acid and the sensitivity of viruses to ultraviolet light, Biophys. J., 5: 257-273.

Rice, E.W. and Hoff, J.C. 1981. Inactivation of *Giardia lamblia* cysts by ultraviolet irradiation, Appl. Environ. Microbiol., 42(3): 546-547.

Shin, G.-A., Linden, K.G. and Sobsey, M.D. 2000. Comparative inactivation of *Cryptosporidium parvum* oocysts and colliphage MS2 by monochromatic UV radiation, Proceedings of Disinfection 2000: Disinfection of Wastes in the New Millennium, New Orleans, Water Environment Federation, Alexandria, VA.

Shin, G.-A., Linden, K.G., Arrowood, M.J. and Sobsey, M.D. 2001. Low-pressure UV inactivation and DNA repair potential of *C. parvum* oocysts, Appl. Environ. Microbiol., 67(7): 3029-3032.

Shin, G.A., Linden, K.G. and Sobsey, M.D. 2005. Low pressure ultraviolet inactivation of pathogenic enteric viruses and bacteriophages, J. Environ. Engr. Sci., 4: S7-S11.

Sommer, R., Weber, G., Cabaj, A., Wekerle, J., Keck, G., and Schauberger, G. 1989. UV inactivation of micro-organisms in water. Zbl. Hyg. 189: 214-224.

Sommer, R., Haider, T., Cabaj, A., Pribil, W. and Lhotsky, M. 1998. Time dose reciprocity in UV disinfection of water, Water Sci. Technol., 38(12): 145-150.

Sommer, R., Cabaj, A., Sandu, T. and Lhotsky, M. 1999. Measurement of UV radiation using suspensions of microorganisms, J. Photochem. Photobiol., 53(1-3): 1-5.

Sommer, R., Lhotsky, M., Haider, T. and Cabaj, A. 2000. UV inactivation, liquid-holding recovery, and photoreactivation of *E. coli* O157 and other pathogenic *E. coli* strains in water, J. Food Protection, 63(8): 1015-1020.

Sommer, R., Pribil, W., Appelt, S., Gehringer, P., Eschweiler, H., Leth, H., Cabaj, A. and Haider, T. 2001. Inactivation of bacteriophages in water by means of non-ionizing (UV-253.7 nm) and ionizing (gamma) radiation: A comparative approach, Wat. Res., 35(13): 3109- 3116.

Thurston-Enriquez, J.A. , Haas, C.N. , Jacangelo, J. , Riley, K. and Gerba, C.P. 2003. Inactivation of feline calcivirus and adenovirus type 40 by UV radiation, Appl. Environ. Microbiol., 69(1): 577-582.

Thompson, S.S., Jackson, J.L., Suva-Castillo, M., Yanko, W.A., Jack, Z.E., Kuo, J., Chen, C.L., Williams, F.P. and Schnurr, D.P. 2003. Detection of infectious human adenoviruses in tertiary-treated and ultraviolet-disinfected wastewater, Wat. Environ. Res., 75(2): 163-170.

Tosa, K. and Hirata, T. 1998. HRWM-39: Photoreactivation of Salmonella following UV disinfection, IAWQ 19th Biennial International Conference, Vol. 10, Health-Related Water Microbiology.

Tosa, K. and Hirata, T. 1999. Photoreactivation of enterohemorrhagic *E. coli* following UV disinfection, Wat. Res., 33(2): 361-366.

Tree, J.A., Adams, M.R. and Lees, D.N. 1997. Virus inactivation during disinfection of wastewater by chlorination and UV irradiation and the efficacy of F+ bacteriophage as a ‘viral indicator’, Wat. Sci. Technol., 35(11-12): 227-232.

Tree, J.A., Adams, M.R. and Lees, D.N. 2005. Disinfection of feline calicivirus (a surrogate for Norovirus) in wastewaters, J. Appl. Microbiol., 98: 155-162.

Wiedenmann, A. , Fischer, B., Straub, U., Wang, C.-H., Flehmig, B. and Schoenen, D. 1993. Disinfection of Hepatitis A virus and MS-2 coliphage in water by ultraviolet irradiation: Comparison of UV-susceptibility, Wat. Sci. Tech., 27(3-4): 335-338.

Wilson, B.R., Roessler, P.F., Van Dellen, E., Abbaszadegan, M. and Gerba, C.P. 1992. Coliphage MS-2 as a UV water disinfection efficacy test surrogate for bacterial and viral pathogens, Proceedings, Water Quality Technology Conference, Nov 15-19, 1992, Toronto, Canada, pp. 219-235, Amer. Wat. Works Assoc., Denver, CO.

Wu, Y., Clevenger, T. and Deng, B. 2005. Impacts of goethite particles on UV disinfection of drinking water, Appl. Environ. Microbiol., 71(7): 4140-4143.

Yaun, B.R., Sumner, S.S., Eifert, J.D. and Marcy, J.E. 2003. Response of *Salmonella* and *E. coli* O157:H7 to UV energy, J. Food Protection, 66(6): 1071-1073.

Zimmer, J.L. and Slawson, R.M. 2002. Potential repair of *E. coli* DNA following exposure to UV radiation from both medium- and low-pressure UV sources used in drinking water treatment, Appl. Environ. Microbiol., 68(7): 3293-3299.

Zimmer, J.L., Slawson, R.M. and Huck, P.M. 2003. Inactivation and potential repair of *C. parvum* following low- and medium-pressure ultraviolet irradiation, Wat. Res., 37(14): 3517-3523.

FOR ULTRAVIOLET HVAC EQUIPMENT,
EXPERIENCE MATTERS.

Since 1960, American Ultraviolet Company has manufactured quality UV equipment for the disinfection of air, liquids and surfaces around the world. We proudly serve the HVAC, healthcare, pharmaceutical, water purification, bottling, food processing and aerospace industries, among others.

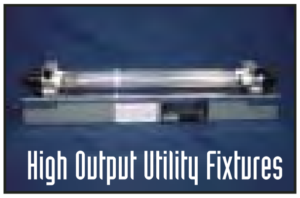
Residential and Light Commercial Applications:

- **For coil or air stream disinfection**
- **1 or 2 lamp configuration**
- **14” to 24” lamps**

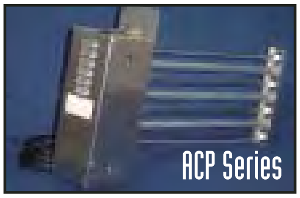
- **Coil and return air duct sterilization from one unit with one control enclosure**
- **Up to 4 remote lamps/fixture**

Commercial and Industrial Applications:

- **Custom sliding rack enclosures with multiple lamps**
- **Coil Irradiation system**



- **Duct mounted units for air stream disinfection**
- **Up to 4 lamps/fixture**



All products are made in the USA, come in standard and custom configurations for In Duct and On Coil applications, are easy to install and economical to operate. You can trust ultraviolet HVAC equipment from American Ultraviolet Company, because experience matters.

American Ultraviolet Company
Since 1960. It’s all we do.
www.americanultraviolet.com
mstines@americanultraviolet.com
(800)288-9288

eta plus – our name is our principle

Innovation in the development and production of

- efficient and powerful UV light sources
- electronic ballasts for UV lamps up to 24 kW
- electronic & electro-optical components for control and adjustment of UV installations

We manufacture according to your needs

eta plus electronic gmbh & co kg
Nuertingen/Germany
contact: Anne O’Callaghan
Tel.: +49 7022 6002 80
Fax: +49 7022 658 54
info@eta-uv.de, www.eta-uv.de

eta plus
part of the IST METZ group

SEVERN
TRENT
ULTRAVIOLET DISINFECTION
SERVICES

UltraDynamics®

Severn Trent Services offers the UltraDynamics® low pressure standard and high output UV disinfection systems ranging in capacity from 2 to 3,000 GPM. Systems are suitable for a range of applications.

- Potable
- Industrial
- High purity
- TOC reduction

For more information call 215.997.4000 today.

SEVERN
TRENT
SERVICES

www.severntrentservices.com

UV SOLUTIONS
START HERE.