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

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1. This compilation has been prepared for Trojan Technologies Inc. and is published here as a public service to the UV community.
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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:

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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.

Trojan Technical Bulletin #51

UV Disinfection for *Cryptosporidium* and *Giardia* in Drinking Water

Introduction

Recent research indicates that very low doses of UV light inactivate *Giardia* cysts and *Cryptosporidium* oocysts (Figure 1). In fact, animal infectivity tests have demonstrated that these protozoans are highly susceptible to UV light from low pressure, medium pressure and pulsed UV sources. These encouraging results have stimulated a worldwide interest in UV disinfection technology for drinking water applications. As a result, the U.S. Environmental Protection Agency (USEPA) is presently evaluating UV as a disinfection technology for surface water applications.

Historical Background

Chemical disinfection of drinking water supplies in North America has successfully controlled outbreaks of infectious bacterial diseases, however outbreaks of gastroenteritis are still reported. These outbreaks have been attributed to various enteric viruses and to intestinal protozoa such as *Cryptosporidium* and *Giardia*. Standard treatment processes including a combination of filtration and chemical disinfection have not been totally effective barriers for the prevention of outbreaks.

Giardia

In North America over 90 outbreaks resulting in 23,776 cases of *Giardia* infections were reported between 1965 and 1984. Investigation of individual sites indicated a combination of contributing factors including raw water quality and also process deficiencies in chemical treatment, filtration and disinfection.

In 1989, the Surface Water Treatment Rule established disinfection regulations that apply to all US public water systems using surface waters and also ground water under the direct influence of surface water. *Giardia* and pathogenic viruses were the main disinfection targets(*Cryptosporidium* was not included at this time). Primary disinfection required removal or inactivation 99.9 percent (3 log) *Giardia lamblia* cysts and 99.99 percent (4 log) viruses. At this time, a combination of filtration and chemical disinfection was considered the best available technology to achieve the desired level of protection.

Summary

Numerous research groups have demonstrated the efficacy of UV for protozoan inactivation. Animal infectivity and cell cultures have established the high sensitivity of these protozoans to UV irradiation. A 99.99% reduction in infectivity has been demonstrated for *Giardia* cysts and *Cryptosporidium* oocysts using UV doses less than 10mJ/cm^2.

Since protozoa are more sensitive to pathogenic bacteria and viruses, a resistant virus such as rotavirus has been suggested as the main target for UV disinfection.

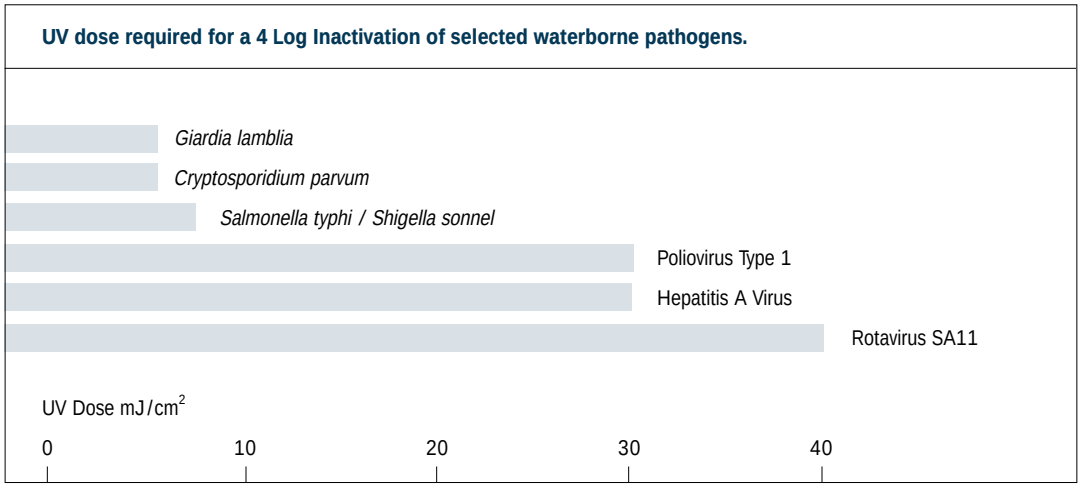

Figure 1: A 4log inactivation of *Cryptosporidium* oocysts and *Giardia* cysts requires a UV dose <10mJ/cm^2.

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Cryptosporidium

Cryptosporidium, first detected in humans in 1976, was not a public concern until 1993, when a massive outbreak involving 400,000 persons, occurred in Milwaukee WI. Subsequent outbreaks occurred in Las Vegas NV and Waterloo ON.

The threat of continuing outbreaks is large. Widespread, low-level contamination of surface waters has been reported in Europe and US. Inadequately protected groundwater supplies were implicated in half of the reported US outbreaks. Treatment deficiencies were found in some plants, however for the majority there were no water treatment irregularities, and all federal and local standards for water treatment were met. In addition, at least three outbreaks have been attributed to oocysts in drinking water supplies in which multiple barriers were used in water treatment. These outbreaks highlight the resistance of *Cryptosporidium* to the standard chlorination concentrations.

Traditional Water Treatment Strategies for Protection against Protozoa

The inactivation/removal of 99.9 percent (3log) *Giardia lamblia* and 99.99 percent (4log) viruses in surface waters was based on a combination of filtration and chemical disinfection. *Giardia* cysts are large and easily removed by filtration, however some cysts and especially the smaller *Cryptosporidium* oocysts can evade filter barriers, an occurrence that is magnified by treatment deficiencies and heavily contaminated source water. A multi-barrier approach is used by the drinking water industry to ensure high-level protection against pathogens. The combination of chlorine and filtration was successful for *Giardia* inactivation, however *Cryptosporidium* is highly resistant to chlorine-based chemicals.

The present disinfection standards and chemical doses are based on the selection of the most resistant pathogen for each specific chemical. In 1989, *Giardia* was selected as the main target for chemical disinfectants followed by a resistant virus specific for each chemical. At this time UV was not considered economical for disinfection of protozoa, however UV was considered acceptable for inactivation of viruses after *Giardia* removal by filtration.

UV Inactivates ***Cryptosporidium*** and ***Giardia***

Since 1998, the efficacy of UV for protozoan inactivation has been demonstrated by numerous research projects and equipment tests. Animal infectivity and/or cell cultures have established the high sensitivity of these protozoa to UV irradiation. A 99.99 percent reduction in infectivity of *Giardia* cysts and *Cryptosporidium* oocysts has been demonstrated using UV doses <10 mJ/cm^2. Since protozoa are more sensitive to UV than pathogenic bacteria and viruses, a resistant virus such as rotavirus has been suggested as the main target for UV disinfection.

UV Disinfection

UV disinfection is an accepted, cost effective, and increasingly popular alternative to chemicals for disinfection of drinking water, wastewater, and industrial waters. UV disinfection is an established technology, based on over sixty years of experience and fundamental research. Over 2,000 groundwater and surface drinking water installations in Europe and 1,000 groundwater installations in the United States rely on UV disinfection.

The technology is extremely versatile since disinfection systems may be custom designed to fit existing space requirements. UV is a safe technology that effectively inactivates pathogenic bacteria, viruses and protozoa. Disinfection does not give rise to any taste or odors, and is accomplished with no residual toxicity and no by-product formation. UV light energy damages the nucleic acids (DNA and RNA) in microorganisms, preventing reproduction. Pathogens that are unable to reproduce, cannot grow or cause an infection in a host. Therefore, growth or infectivity tests can be used to assess the level of inactivation.

Inactivation Doses

UV dose is a product of UV light intensity and exposure time in seconds (IT), stated in units; *mWs/cm^2 or mJ/cm^2. IT is analogous to the chemical dose or CT (concentration x time). Microbes show a range of sensitivities to UV as shown by the UV data in Table 1. *Cryptosporidium* and *Giardia* are more sensitive to UV than bacteria and viruses are more resistant than bacteria. Similar results have been obtained using low-pressure, medium-pressure and pulsed UV irradiation.

Pathogen	UV dose mJ/cm^2 4 log inactivation
Cryptosporidium parvum oocysts	<10
Giardia lamblia cysts	<10
Vibrio cholerae	2.9
Salmonella typhi	8.2
Shigella sonnei	8.2
Hepatitis A virus	30
Poliovirus Type 1	30
Rotavirus SA11	36

Table 1: UV dose required for a 4 log inactivation of selected waterborne pathogens.

*Note: 1 mWs/cm^2 = 1 mJ/cm^2 = 1000µWs/cm^2

Evaluation of Disinfection Performance

Inactivation of *Cryptosporidium* and *Giardia* has been attempted using UV and various chemical disinfectants. In order to save time and money, the degree of inactivation was previously measured using excystation tests and viability stains rather than the animal infectivity tests. Recent work (1998-2000) indicates that excystation is not an accurate method for measuring UV inactivation. Excystation merely determines the response of the oocyst to external chemical stimuli and does not measure the potential ability to cause an infection in a susceptible host. The Gold Standard for measuring protozoan inactivation is animal or human infectivity. Animal infectivity tests require neonatal mice for *Cryptosporidium* and gerbils for *Giardia* testing. These infectivity tests are expensive and time consuming and were not used routinely; as a result early studies testing the efficacy of UV relied on excystation tests that grossly overestimated the UV doses required for inactivation. Evaluation of chemical disinfectants was based on a combination of excystation and infectivity tests. Recently, cell culture techniques have been developed to provide a rapid and more economical method for evaluating *Cryptosporidium* infectivity. A review of the UV research to date (Table 2) compares the results after UV irradiation using in-vitro *Cryptosporidium* assay methods, animal infectivity and cell cultures. Viability tests (in-vitro tests) consistently overestimated the UV doses required to prevent oocyst infection in cell cultures or live mice.

Giardia muris and *Giardia lamblia* cysts have also been irradiated with low and medium pressure lamps. Gerbil infectivity results indicate that *Giardia* is also inactivated by very low doses of UV.

Conclusion

The high susceptibility of protozoa to low UV doses has provided the water treatment industry with an economical non-chemical disinfectant. These findings will have a profound influence on the selection of future disinfection targets, disinfection strategies and disinfection technologies.

References available on request.

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Assay Method	Low Pressure UV	Medium Pressure UV	Pulsed UV
Vital dye	+ Viable	+ Viable	+ Viable
Excystation	+ Viable	+ Viable	+ Viable
Mouse infectivity	– Non-infective	– Non-infective	– Non-infective
Cell culture	– Non-infective	– Non-infective	– Non-infective

Table 2: A comparison of four assay methods for UV irradiated *Cryptosporidium* oocysts.

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UV DISINFECTION FOR DRINKING WATER: CANDIDATE FOR BEST AVAILABLE TECHNOLOGY

Introduction

Ultraviolet (UV) disinfection is a flexible, safe and cost-effective technology that effectively inactivates pathogenic viruses, bacteria and protozoa but produces negligible disinfection byproducts. Accordingly, UV is a strong candidate for Best Available Technology for the disinfection of drinking water, wastewater, reclaimed wastewater, and industrial process water. As part of a multiple barrier strategy for protection of public health, UV is a significant component.

Mechanism of Inactivation

The absorption of UV energy by microbes results in photochemical damage to nucleic acids (DNA and RNA). Nucleic acid damage interferes with normal cell processes such as protein synthesis and cell division. Since UV irradiated pathogens cannot replicate they cannot overwhelm the host's immunalogical system and the pathogens eventually die, or are destroyed by the hosts defenses.

Effective Against a Range Pathogens

Growth and infectivity assay methods are used to assess the degree of disinfection achieved. UV is effective against a wide variety of pathogenic viruses, bacteria, and protozoa.

Animal and tissue assay methods have recently demonstrated that low doses of UV inactivate *Giardia* cysts and *Cryptosporidium* oocysts by several orders of magnitude. These low doses are a fraction of the design dose currently specified in most UV disinfection applications indicating that UV is extremely effective against these waterborne protozoa.

UV Dose

UV dose may be defined using IT values. IT values are the product of delivered UV intensity and the exposure time, and are analogous to CT values used to define chemical disinfectant dose. The data reported in the scientific literature, (Table 1) illustrates the UV dose required to inactivate dispersed cultures of pathogens by various orders of magnitude. The UV dose used in a specific UV application will depend on the regulatory requirements for pathogen inactivation, the target pathogens, the number of microbes present, and the association of those microbes with particles.

Table 1. UV inactivation of pathogens associated with waterborne outbreaks.

Pathogen	Representative Average UV Dose ($mWs/cm^{2)}$ Required to Inactivate			
	1log	2log	3log	4log
Cryptosporidium parvum oocysts	3.0	4.9	6.4	7.9
Giardia lamblia cysts	NA	<5	<10	<10
Giardia muris cysts	1.2	4.7	NA	NA
Vibrio cholerae	0.8	1.4	2.2	2.9
Shigella dysenteriae	0.5	1.2	2.0	3.0
Escherichia coli O157:H7	1.5	2.8	4.1	5.6
Salmonella typhi	1.8-2.7	4.1-4.8	5.5-6.4	7.1-8.2
Shigella sonnei	3.2	4.9	6.5	8.2
Legionella pneumophile	3.1	5	6.9	9.4
Salmonella enteritidis	5	7	9	10
Hepatitis A virus	4.1-5.5	8.2-14	12-22	16-30
Poliovirus Type 1	4-6	8.7-14	14-23	21-30
Coxsackie B5 virus	6.9	14	22	30
Rotavirus SA11	7.1-9.1	15-19	23-26	31-36
NA – Data not available				

Regulatory Requirements

Wastewater disinfection is the first barrier for protection of potable water sources. But regulatory disinfection requirements for wastewater and reclaimed wastewater differ from those for potable water. In wastewaters, microbes used as indicators of fecal contamination are present in sufficient numbers that UV dose-response inactivation curves can be readily measured and used to select a design dose to achieve the target level of indicator microbes specified in the regulations. In potable water, the concentration of pathogens and indicator microbes are often below the detection limits of routine assay methods. Accordingly, legislation like the Surface Water Treatment Rule specifies target doses (CT and IT values) as opposed to target microbe concentrations. With chemical disinfection, *Giardia* cysts are more resistant than bacteria and viruses; therefore *Giardia* inactivation determines the chemical design dose. In the case of UV, viruses are more resistant than bacteria, *Giardia* cysts and *Cryptosporidium oocysts*. Therefore rotavirus is proposed as a more suitable target for the UV disinfection of potable water, since it is the most UV-resistant pathogen implicated in waterborne disease outbreaks.

Minimal Sensitivity to Water Quality

While the action of chemical disinfectants varies depending on the temperature and pH of the water, pathogen inactivation by UV light is independent of these factors. Thus, while cold water inactivation of a pathogen like *Cryptosporidium* by ozone or other chemicals would require additional dose or CT, UV disinfection is equally effective at both high and low water temperatures.

Various chemical species in water may react with chemical disinfectants or absorb UV light thereby competing with the pathogens for the disinfectant. The complexity of chemical mixtures in water makes it difficult to anticipate chemical disinfectant demand and its impact on pathogen disinfection. However, the UV absorbency of water is easily measured and its impact on UV dose delivery readily predicted thereby providing confidence that a target pathogen reduction will be achieved.

Pathogens within particles are more resistant than dispersed pathogens to both chemical and UV disinfection. With potable water, particle concentrations are minimal and disinfection is assumed to follow the disinfection of dispersed microbes measured in laboratory cultures.

Chemical species such as iron and calcium in water may form fouling deposits on the quartz sleeves that protect the UV lamps. Fouling causes a reduction in the UV intensity delivered to the water. UV sensors may be used to monitor the impact of fouling and trigger cleaning cycles. For small UV systems with low fouling rates, periodic manual cleaning may be the most cost-effective approach. For larger systems and systems with rapid fouling, automatic wiping mechanisms that combine both physical and chemical cleaning may be more appropriate.

Minimal Byproduct Formation

Chemical species in water can react with a disinfectant to form disinfection byproducts (DBPs). Chlorine DBPs include trihalomethanes, haloacetic acids, and high molecular weight halogenated compounds. Many of these DBPs are carcinogenic, mutagenic, capable of causing birth defects, and therefore regulated. Chlorine dioxide has chlorate and chlorite DBPs. Ozone disinfection converts large organic polymers to smaller organic molecules releasing nutrients that promote biofilm growth in distribution lines. Ozonation also converts bromide to bromate, a regulated compound.

UV disinfection in water, wastewater and reclaimed wastewater has been found to produce negligible concentrations of DBPs, even at UV doses in excess of those needed for disinfection. UV produces no measurable change in the DBPs formed when chlorine or chloramine are used as a secondary disinfectant following UV. While some UV lamp technologies produce low UV wavelengths capable of converting nitrate to nitrite. This is not a problem in North America with the regulated levels of nitrate and nitrite and conventional UV design doeses. In Europe where the nitrate and nitrite limits are more stringent, appropriate lamp technology selection or the use of optical filters can minimize the formation of nitrite.

Cost-Effectiveness

With experience in over 1000 potable water installations in the United States and over 2000 in Europe, UV is recognized as a cost-effective disinfection technology. A cost comparison by the USEPA (1996) demonstrated that for a dose of 40 mWs/cm^2, UV was cost effective compared to ozonation and chlorination over a flow range of 0.024 to 1.8MGD

Recent analysis suggests that the capital costs for UV range from $US0.02 to $0.07 per US gallon of installed capacity. Operation and maintenance costs range from $0.005 to $0.03 per thousand gallons produced.

UV technologies using low-pressure mercury lamps are most cost effective for small-scale applications. Medium-pressure mercury lamps are most cost effective for plant flows greater than 2MGD.

Safety to Operators and the Public

With proper training, UV technology is simple and safe to operate. Use of UV removes the need to transport, store, and handle dangerous disinfectant chemicals. When such practices are regulated, costs associated with chemical disinfection may increase by 30%. The Uniform Fire Code calls for accident insurance, ventilation and storage requirements, and treatment facilities capable of dealing with an accidental release of chlorine gas or a caustic liquid spill. From the public's perspective, UV offers increased protection from the broad spectrum of pathogens. UV achieves disinfection without DBPs, unpleasant taste and odors, and the need to transport chemicals through the community to the treatment plant.

Compatibility with Multiple Barrier Strategies

Because there is no ideal disinfectant, treatment processes are built around several unit operations, each of which contributes to the overall reduction in pathogens and hence a reduction in the risk to public health. Negligible DBPs, minimal space requirements, modular design, low cost, and a broad spectrum of pathogen inactivation allow UV to be combined flexibly with a variety of other physical and chemical unit operations. For example, the ability of UV to readily inactivate *Cryptosporidium* and *Giardia* would allow UV to supplement ozone to reduce the ozone required for cold waters or when bromates are a concern.
Similarly, UV could supplement disinfection achieved by other chemical disinfectants, such as chlorine which is ineffective against *Cryptosporidium*. Recent studies also indicate the *Legionella* is almost as resistant as *Giardia* to chlorine, but is sensitive to UV. Since UV does not provide a residual, UV as a primary disinfectant could be followed directly by chloramine, a secondary disinfectant for biofilm control in the distribution line, or by chlorine for a short CT followed by conversion of the chlorine to chloramines to create the better residual for biofilm control.

Summary

Ever since chemical disinfection became the primary barrier against outbreaks caused by waterborne pathogens, the search has continued for an ideal disinfectant. While the availability of chemical disinfectants has expanded from the early use of chlorine to include chloramine, chlorine dioxide, and ozone among others, chemical disinfectants have failed to satisfy the requirements of an ideal disinfectant. Ultraviolet disinfection (UV), on the other hand, has emerged after over eight decades of research and application as a strong contender. With confirmation of the recent findings on the ease of UV inactivation of *Cryptosporidium, Giardia and Legionella*, UV could qualify for designation as Best Available Technology for the primary disinfection of potable waters, wastewaters, reclaimed wastewaters and industrial process waters.

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Note: UV dose equivalent units
$1mJ/cm^2 = 1mWs/cm^2 = 1000\mu Ws/cm^2$

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