BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	
WATER QUALITY STANDARDS AND	)	
EFFLUENT LIMITATIONS FOR THE	)	R08-9
CHICAGO AREA WATERWAY SYSTEM	)	(Rulemaking - Water)
AND THE LOWER DES PLAINES RIVER:	)	
PROPOSED AMENDMENTS TO 35 Ill.	)	
Adm. Code Parts 301, 302, 303 and 304	)	

PRE-FILED TESTIMONY OF ERNEST R. BLATCHLEY III

PROFESSIONAL BACKGROUND AND QUALIFICATIONS

My name is Ernest R. Blatchley III. I am a Professor of Civil (Environmental) Engineering at Purdue University. My educational background includes a Bachelor of Science in Civil Engineering from Purdue University; a Master of Science in Civil Engineering from the University of California, Berkeley; and a Ph.D. in Civil Engineering, also from the University of California, Berkeley. I have more than 20 years of professional experience in the field of environmental engineering. My technical expertise is in the area of physico/chemical processes of environmental engineering, with particular emphasis on disinfection processes. I am a licensed Professional Engineer in the State of Indiana, and I am a Board Certified Environmental Engineer (American Academy of Environmental Engineers) in the area of Water Supply/Wastewater Engineering. Awards I have received include the Harold Munson Teaching Award, School of Civil Engineering, Purdue University; the Roy E. and Myrna G. Wansik Research Leadership Award, School of Civil Engineering, Purdue University; and the William Edgar Award for Pioneering Research in Disinfection, Water Environment Federation.

The focus of research efforts within my group has been on disinfection processes based on ultraviolet (UV) radiation and chlorine. I have published more than 50 papers in refereed journals, and more than 60 papers in proceedings of conferences that pertain to my research. My

group has made fundamental contributions regarding the behavior of UV reactors, including the development of basic photochemical reactor theory, as well as the development of numerical models and diagnostic methods based on that theory. In the area of chlorine-based disinfection processes, we have defined the kinetics and mechanisms of several important reactions involving chlorine, as well as some relevant toxicological endpoints. We have also developed analytical methods that are relevant to chlorine-based disinfection processes.

My group has conducted research to address the specific implications of disinfection processes, as applied to municipal wastewater. The focus of our work in this area has been on the human health implications of wastewater disinfection.

My complete qualifications are provided in my curriculum vitae, which is provided as an attachment to this testimony.

INTRODUCTION

The Illinois Environmental Protection Agency (IEPA) has proposed a set of standards to the Illinois Pollution Control Board (IPCB) that were developed with the objective of improving water quality in the Chicago Area Waterways System (CAWS). Included in these proposed standards is an effluent limitation of 400 cfu/100 mL for fecal coliform bacteria. The rationale for this effluent standard, as defined by IEPA, is that it will provide assurance that "active disinfection" will be included as an element of wastewater treatment, and that the disinfection systems function properly. The limit is also motivated by the increasing recreational value of the CAWS, and by the fact that "Technology-based disinfection has been a long standing requirement applied to numerous wastewater facilities throughout the State, dating back to the original 1970s Board regulations."

The purpose of my testimony is to provide evidence against the proposed effluent limitation for fecal coliform bacteria, and the implied requirement of an active disinfection

system to meet such a standard. I contend that the imposition of this standard will yield minimal benefit to water quality in the CAWS, and minimal reduction in the risk of disease transmission.

PROBLEMS WITH PROPOSED EFFLUENT BACTERIAL LIMIT

At least three key issues dictate that the proposed effluent bacterial limit will not substantially improve the microbiological quality in the CAWS, as well as the risk of disease transmission associated with its use. Each of these issues will be described briefly below. Additional information pertaining to these issues is presented in the attached documents.

Coliform Bacteria are Poor Indicators of Disinfection Efficacy

Untreated municipal wastewater can contain a wide range of microbial pathogens, including many bacterial, viral, and protozoan species. For some common pathogens, analytical methods for measurement of their concentration do not exist or are difficult to perform. The large number of microbial species that can be found in municipal wastewater also complicates quantification of potential microbial pathogens. From a practical perspective, it is impossible to measure the concentrations of all pathogens present in water. As an alternative, it is common to measure the concentration of viable and/or infective "indicator organisms" in water. Indicator organisms should be common in waters that contain fecal contributions, and they should be more resistant to disinfectants than relevant microbial pathogens.

The effluent limitation proposed by IEPA is based on measurements of the concentration of viable fecal coliform bacteria in the effluents of the District's wastewater treatment facilities. Coliform bacteria are commonly used as indicator organisms in wastewater settings; however, there is considerable evidence to indicate that the use of coliforms as an indicator organism provides potentially misleading information regarding the performance of disinfection systems.

Although coliform bacteria are usually plentiful in untreated municipal wastewater, they are easily inactivated by wastewater disinfectants such as chlorine, ozone, and ultraviolet (UV)

radiation, as compared with many microbial pathogens. As a result, the conditions of disinfection that are required to yield a low concentration of viable coliform bacteria will not guarantee a low concentration of microbial pathogens.

A common impression among the lay public is that a wastewater effluent that has been "disinfected" (*i.e.*, is in compliance with an effluent discharge limitation for coliform bacteria) is "safe", in terms of potential exposure to waterborne microbial pathogens. However, systems that are in compliance with coliform limitations similar to those that have been proposed for the District's facilities may still contain viable and/or infective microbial pathogens.

Proposed Coliform Limit will Call for Modest Conditions of Disinfectant Exposure

It is important to understand that disinfection does not imply sterilization. Therefore, disinfected wastewaters will contain viable and/or infective microorganisms, some of which may be pathogenic. By extension, this implies that the risk of disease transmission associated with exposure to municipal wastewater will always be non-zero, regardless of the form of disinfection applied.

Having said this, it is also clear that the extent to which the risk of disease transmission is reduced is dependent on a number of factors, including the nature of the disinfectant and the degree of disinfectant exposure delivered by the disinfection system. In municipal wastewater disinfection practices, the characteristics of the disinfection system will be determined by the limitations of the discharge permit.

Disinfection systems used in municipal wastewater treatment applications range from no disinfection at all, to conditions that accomplish extensive inactivation of nearly all microbial pathogens. For purposes of this testimony, the term "conventional disinfection" will be used to describe municipal wastewater disinfection systems that are designed to limit viable coliform

concentrations to several hundred cfu/100 mL. On the spectrum of disinfection systems used for treatment of municipal wastewater, these systems deliver modest disinfectant doses, and accomplish modest microbial inactivation.

The proposed effluent limit of 400 cfu/100 mL for coliform bacteria is consistent with this definition of "conventional disinfection". As such, the conditions of disinfectant exposure that will be required to reach compliance with the proposed effluent limitation will also be fairly modest. While it is clear that chlorine- or UV-based disinfection will accomplish an immediate decrease in the concentration of viable bacteria, it appears that the long-term effects of chlorination/dechlorination or UV irradiation may actually be detrimental to water quality, in terms of bacterial composition

Recent research has demonstrated that "conventional disinfection" systems yield localized, i.e. zone near effluent outfall, improvements in bacterial quality in receiving waters. Perhaps more importantly, these same conditions also lead to minimal improvements in viral composition of the treated water; control of protozoan pathogens may also be quite minimal, depending on the disinfectant used. Control of viruses is particularly important because previous research has indicated that viruses represent the greatest threat to human health among microbes present in municipal wastewater effluents; protozoa may also represent a significant health risk in some situations.

Because viable and/or infective microorganisms will remain in the water post-disinfection, and because the microbial community will adapt to the post-disinfection environment, the population of microbes in disinfected water will change with time. Many microbes have the ability to repair sub-lethal damage, and therefore can recover post-disinfection. Repair and recovery will take place following any disinfection process.

To put these facts in proper perspective, it is also useful to consider the range of municipal wastewater disinfection practices that are applied in developed countries of the world. For example, in most countries of western Europe, wastewater disinfection is practiced only at facilities where effluent discharge is to a public swimming area, or where other opportunities for direct human contact are likely (*e.g.*, shellfish breeding grounds). Despite the fact that effluent disinfection is uncommon in Europe, the incidence of diseases associated with waterborne pathogens among the residents of these countries does not appear to be substantially different than in the U.S.

It is also useful to consider disinfection practices at the other end of the spectrum of available applications. Specifically, in circumstances where wastewater effluent reuse is practiced, such as in some areas of the U.S. southwest, conditions of disinfectant exposure are far more extensive than those that accompany conventional disinfection. For example, the conditions of disinfectant exposure that are mandated by *Title 22* of the California Administrative Code are roughly 10 times greater than those that are applied in conventional disinfection systems. These requirements are met through the use of reactors that are substantially larger than those that would be required for conventional disinfection, and with substantially greater quantities of disinfectant than would otherwise be required.

In reuse applications, the effluent from the facility will represent the entire source of water, and direct human contact with the treated water is likely to occur. The fact that the water distributed to a reuse system is entirely comprised of effluent means that the disinfection system must accomplish effective inactivation of microbial pathogens. It also means that the effluent is likely to represent the only source of microbial pathogens in the reused water.

Inputs from Other Sources will Affect CAWS Microbial Quality

Water quality, as measured by microbial and chemical constituents, will be influenced by inputs from point sources and non-point sources. Clearly, the release of treated wastewater from the treatment facilities of the District can have an important influence on CAWS water quality. By extension, wastewater treatment processes at District facilities will play an important role in water quality. However, it is also clear that water quality in the CAWS will be influenced by inputs from other sources, including combined sewer overflows (CSOs) and non-point sources.

The system defined by the Tunnel and Reservoir Plan (TARP) has yielded substantial improvements in water quality within the CAWS. It is likely that additional water quality improvements will result from the completion of TARP. However, even when completed, this facility will not accomplish complete capture of wastewater from CSOs; therefore, CSO events will continue to take place in the Greater Chicago Area. Moreover, non-point source contributions to the CAWS will be largely unaffected by TARP.

Therefore, irrespective of the effluent disinfection constraints that are imposed on the District facilities, the potential for inputs of microbial pathogens from other sources will still remain. These inputs to the system will limit the extent to which risk of disease transmission from microbial pathogens can be reduced in the CAWS.

A related point is that the development of disinfection processes for CSOs and non-point sources represents a difficult engineering challenge. CSO treatment systems have been developed, including systems that incorporate disinfection. To my knowledge, most of these systems are based on application of chlorine or UV radiation. Regardless of the disinfectant, engineers who design these systems are faced with a difficult challenge, in that water quality from these sources is generally poor as compared with the effluent from a municipal wastewater treatment facility.

For chlorine-based disinfection systems, the poor quality of water from a CSO will dictate that the chlorine residual will probably be in the form of chloramines (inorganic and organic), which generally are less-effective than equivalent concentrations of free chlorine. Also, the relatively high concentration of reduced compounds that are likely to be present in water from a CSO system will translate to high chlorine demand in the water. Moreover, wastewater containing chloramines often yields treated water with relatively high concentrations of disinfection by-products, some of which represent important sources of toxicity in receiving waters.

For UV-based disinfection systems, the relatively high concentration of particles and low UV transmittance of water from a CSO will adversely affect their performance. Although UV-based disinfection systems for CSOs (and waters of similar quality) have been developed, their performance will be limited by water quality. It is unlikely that disinfection processes applied to CSOs or non-point source contributions will yield substantial reductions in the risk of disease transmission associated with waterborne microbial pathogens.

CONCLUSION

The proposed effluent bacterial limit is intended to reduce the risk of disease transmission associated with use of the CAWS. While the goal is well-intended, several technical issues will limit the extent to which the risk of disease transmission may be mitigated. These issues include the facts that:

1. Coliform bacteria are poor indicators of the effectiveness of disinfection systems. Relative to most microbial pathogens, coliform bacteria are sensitive to disinfectant exposure, and as a result, conditions that accomplish effective inactivation of coliform bacteria will not necessarily translate to effective control of microbial pathogens.

2. Disinfection systems used in wastewater reuse applications with potential of direct human contact, have been demonstrated to accomplish reliable, effective control of microbial pathogens; however, these systems call for roughly an order of magnitude greater disinfectant exposure than would be required to comply with the proposed effluent bacterial limitation for incidental (limited) human contact. The proposed effluent limit of 400 cfu/100 mL for coliform bacteria is modest, as the conditions of disinfectant exposure that will be required are unlikely to lead to effective control of microbial pathogens. The response of the bacterial community to the post-disinfection environment will be influenced by bacterial repair, recovery, and re-growth; collectively, these processes may yield diminished water quality relative to a situation in which disinfection is not practiced.
3. A range of disinfection applications exists for municipal wastewater effluents in the United States. However, in many other developed countries, wastewater disinfection is not practiced, and it appears that the frequency of disease transmission associated with water contact is not substantially different that in the U.S., where wastewater disinfection is common.
4. Irrespective of any measures that are used to control microbial inputs to the CAWS from municipal wastewater treatment facilities, inputs from other sources (*e.g.*, CSOs and non-point sources) will remain. Moreover, it would be extremely difficult to implement control measures that would effectively mitigate against transport of microbial pathogens to the CAWS from these sources. These inputs will limit possible reductions in the risk of exposure to waterborne microbial pathogens.

Collectively, these issues dictate that wastewater disinfection, as required to comply with the proposed effluent bacterial limit, will yield little or no decrease in the risk of disease transmission associated with use of the CAWS.

Respectfully submitted,

By: Ernest R. Blatchley III
Purdue University

Testimony Attachments

1. Curriculum Vitae
2. Longer Report: Extended Testimony of Ernest R. Blatchley III
3. Blatchley III, E.R.; Gong, W.; Alleman, J.E.; Rose, J.B.; Huffman, D.E.; Otaki, M.; Lisle, J.T. (2007) "Effects of Wastewater Disinfection on Waterborne Bacteria and Viruses," *Water Environment Research*, Vol 79, No. 1, pgs. 81-92.

Attachment 1

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Education

Ph.D.	University of California, Berkeley Civil (Environmental) Engineering	1988
M.S.	University of California, Berkeley Civil (Environmental) Engineering	1983
B.S.	Purdue University Civil (Environmental) Engineering	1981

Academic Appointments

August 1999 – Present:	Professor, School of Civil Engineering, Environmental Engineering Group, Purdue University. Teaching and research in physico/chemical processes of environmental engineering.
July 1994 – August 1999:	Associate Professor, School of Civil Engineering, Environmental and Hydraulic Engineering Area, Purdue University. Teaching and research in physico/chemical processes of environmental engineering.
August 1995 - June 1996:	Visiting Scientist (Sabbatical Leave), CIRSEE, Lyonnaise des Eaux, Le Pecq, France. Direction of research team investigating improvements in the process theory and performance of ultraviolet disinfection systems.
September 1988 - June 1994:	Assistant Professor, School of Civil Engineering, Environmental and Hydraulic Engineering Area, Purdue University. Teaching and research in physico/chemical processes of environmental engineering.
August 1986 - December 1986:	Teaching Assistant, School of Civil Engineering, Sanitary, Environmental, Coastal, and Hydraulic Engineering Area, University of California, Berkeley. Assisted in teaching a graduate class in physico/chemical treatment processes for water and wastewater.
September 1983 - June 1988:	Graduate Student Research Assistant, Lawrence Berkeley Laboratories. Conducted research to define the atmospheric chemical behavior of organic emissions from oil shale development areas.

Non-Academic Positions

January 2003 - 2005:	Fellow, Northeast-Midwest Institute, Washington, DC. Participation in a research team developing treatment methods and management practices for ballast water on commercial ships, with a goal of minimizing the potential for invasions of non-indigenous species.
September 1992 - 1996:	Concurrent Appointment as Research Engineer, Department of the Army, Waterways Experiment Station, Vicksburg, MS. Research on remediation process alternatives for contaminated military sites.
Summer 1992:	Summer Faculty Research and Engineering Program, Department of the Army, Waterways Experiment Station, Vicksburg, MS. Evaluated solidification/ stabilization processes for remediation of contaminated soils.
August 1981 - September 1982:	Environmental Engineer, Howard, Needles, Tammen & Bergendoff, Indianapolis, IN. Modeled the effects of combined sewer overflow control and wastewater treatment alternatives on receiving streams.

Licenses, Registrations, and Certifications

Professional Engineer, State of Indiana, Registration No. PE60900120
Board Certified Environmental Engineer, BCEE, American Academy of Environmental Engineers

Awards, Recognition, and Honors

EPA Training Fellowship, University of California, Berkeley, 1982 - 1983
Chi Epsilon, 1994 - present
Harold Munson Outstanding Teacher Award, School of Civil Engineering, Purdue University, 1997
Roy E. and Myrna G. Wansik Research Leadership Award, School of Civil Engineering, Purdue University, 1998
William Edgar Award for Pioneering Research in Disinfection, Water Environment Federation, 2005
Diplomate Environmental Engineer (DEE) (*aka*, Board Certified Environmental Engineer, BCEE), American Academy of Environmental Engineers, by Eminence in the Specialty of Water Supply and Wastewater, 2006-
Sigma Xi, 2007 - present
Aquatics International 2008 "Power 25" – Annual list of the 25 most influential aquatics professionals (see http://www.aquaticsintl.com/2008/feb/0802_power.html)

Inventions and Patents

Apparatus for Improving UV Dosage Applied to Fluids in Open Channel UV Disinfection Systems, Ernest R. Blatchley III, Kuang-Ping Chiu, E. Ronald Magee, James M. Kallio, Zdravka Do-Quang, Dennis A. Lyn, U.S. Patent Number 5,952,663; issued 14 September 1999.
Dyed Microspheres for Quantification of Dose Distributions in Photochemical Reactors, Ernest R. Blatchley III, Donald E. Bergstrom, J. Paul Robinson, Chengyue Shen, Lian-Shin Lin, Shiyue Fang, Kathryn E. Ragheb, Patent Pending.

Membership in Professional and Scholarly Societies

American Academy of Environmental Engineers, American Chemical Society, American Society of Civil Engineers, Association of Environmental Engineering Professors, Indiana Water Pollution Control Association, International Ultraviolet Association, International Water Association, Water Environment Federation

Published Work (last 10 years)

a. Book Chapters

- Blatchley III, E.R. and Thompson, J.E. (1998) "Groundwater Contaminants," Chapter 13 in *GroundwaterEngineering Handbook*, (J.W. Delleur, ed.), CRC Press, Boca Raton, FL, pp. 13-1 to 13-30.
- Blatchley III, E.R. and Peel, M. (2001) "Disinfection by Ultraviolet Irradiation" Chapter 41 in *Disinfection, Sterilization, and Preservation, 5th Edition*, S. Block (ed.), Lippincott, Williams & Wilkins, Philadelphia, pp. 823-851.
- Blatchley III, E.R. (2001) "Non-Ideal Reactor Behavior" Chapter 1.2.3 in *Environmental Engineering Processes Laboratory Manual*, Association of Environmental Engineering and Science Professors (S.E. Powers, J.J. Bisogni, Jr., J.G. Burken, K. Pagilla, eds.).
- Blatchley III, E.R. (2001) "Process Behavior in Ultraviolet Disinfection Systems" Chapter 2.1.3 in *Environmental Engineering Processes Laboratory Manual*, Association of Environmental Engineering and Science Professors Professors (S.E. Powers, J.J. Bisogni, Jr., J.G. Burken, K. Pagilla, eds.).
- Blatchley III, E.R. and Hunt, N.K. (2002) "Ozone Disinfection of Drinking Water," Chapter 15 in *Control of Microbes in Water*, ASCE, Reston, VA.
- Blatchley III, E.R. and Thompson, J.E. (2006) "Groundwater Contaminants," Chapter 17 in *Groundwater Engineering Handbook*, 2nd Edition (J.W. Delleur, ed.), CRC Press, Boca Raton, FL, pp. 17-1 to 17-30.

b. Articles in Refereed Archival Journals

- Janex, M.-L., Savoye, P., Do-Quang, Z., Blatchley III, E. and Laîné, J.-M. (1998) "Impact of Water Quality and Reactor Hydrodynamics on Wastewater Disinfection by UV - Use of CFD Modeling for Performance Optimization," *Water Science and Technology*, **38**, 6, 71-78.

- Blatchley III, E.R., Do-Quang, Z., Janex, M.-L. and Laîné, J.-M. (1998) "Process Modeling of Ultraviolet Disinfection," *Water Science and Technology*, **38**, 6, 63-69.
- Chiu, K., Lyn, D.A., Savoye, P. and Blatchley III, E.R. (1999) "An Integrated UV Disinfection Model Based on Particle Tracking," *Journal of Environmental Engineering, ASCE*, **125**, 1, 7-16.
- Lyn, D.A., Chiu, K. and Blatchley III, E.R. (1999) "Numerical Modelling of Flow and Disinfection in UV Disinfection Channels," *Journal of Environmental Engineering, ASCE*, **125**, 1, 17-26.
- Thompson, J.E. and Blatchley III, E.R. (1999) "Toxicity Effects of Gamma Irradiated Wastewater Effluents," *Water Research*, **33**, 9, 2053-2058.
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- Lin, L., Johnston, C.T. and Blatchley III, E.R. (1999a) "Inorganic Fouling at Quartz:Water Interfaces in Ultraviolet Photoreactors I: Chemical Characterization," *Water Research*, **33**, 15, 3321-3329.
- Lin, L., Johnston, C.T. and Blatchley III, E.R. (1999b) "Inorganic Fouling at Quartz:Water Interfaces in Ultraviolet Photoreactors II: Temporal and Spatial Distributions," *Water Research*, **33**, 15, 3330-3338.
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- Blatchley III, E.R.; Shen, C.; Naunovic, Z.; Lin, L.; Lyn, D.A.; Robinson, J.P.; Ragheb, K.; Grégori, G.; Bergstrom, D.E.; Fang, S.; Guan, Y.; Jennings, K.; Gunaratna, N. (2006) "Dyed Microspheres for Quantification of UV Dose Distributions: Photochemical Reactor Characterization by Lagrangian Actinometry," *Journal of Environmental Engineering, ASCE*, **132**, 11, 1390-1403.
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- Li, J.; Blatchley III, E.R. (2007) "Volatile Disinfection Byproduct Formation Resulting from Chlorination of Organic-Nitrogen Precursors in Swimming Pools," *Environmental Science & Technology*, **41**, 19, 6732 - 6739 (**Cover Article, October 1, 2007**).
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- Pennell, K. G., Z. Z. Naunovic, and E. R. Blatchley III (2008) "Sequential Inactivation of *Bacillus subtilis* Spores with UV Radiation and Iodine," accepted for publication in *Journal of Environmental Engineering*, ASCE.
- Fang, S.; Guan, Y.; Blatchley III, E.R.; Shen, C.; Bergstrom, D.E. (2008) "Conjugation of (*E*)-5-[2-(Methoxycarbonyl)ethenyl]cytidine to Hydrophilic Microspheres: Development of a Mobile Microscale UV Light Actinometer," *Bioconjugate Chemistry*, **19**, 592-597.

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- "Modelling Tools for Use in the Design of Ultraviolet Disinfection Systems," presented as part of a pre-conference workshop at WEFTEC, Orlando, FL, 3 October 1998.
- "Analysis and Prediction of Process Performance in UV Disinfection Systems," presented as part of US EPA Workshop on UV Disinfection of Drinking Water, Washington, DC, 28 April 1999.
- "Dose Distribution Model for UV Disinfection Systems," presented as part of Electric Power Research Institute Municipal Water and Wastewater Program Meeting, Vancouver, British Columbia, CANADA, 27 June 1999.
- "Dose Distribution Model for UV Disinfection Systems," presented as part of Electric Power Research Institute Municipal Water and Wastewater Program Meeting, Nashville, Tennessee, 21 October 1999.
- "Dose Distribution Model for Ultraviolet Disinfection Systems," presented to Environmental Engineering Group, Norwegian University of Science and Technology, Trondheim, Norway, 11 November 1999.
- "Dose Distribution Model for UV Disinfection Systems," presented to U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Water Supply and Water Resources Division, Cincinnati, OH, 4 January 2000.
- "UV Process Modeling Based on the Dose Distribution Approach: Application and Scale-Up Issues," presented at *UV 2000: A Technical Symposium*, Costa Mesa, CA, 28 January 2000.
- "Chlorination of Aqueous Solutions Containing Organic-N: Analysis and Detection with the Application of MIMS," presented at Indiana Mass Spec Discussion Group, West Lafayette, IN, 22 March 2000.
- "Process Performance in UV Disinfection Systems," Presented at Pre-Conference Workshop for Water Quality Technology Conference, 5 November 2000.
- "Chlorination of Aqueous Solutions Containing Organic-N: Analysis and Detection with the Application of MIMS," presented at International Symposium on Waterborne Pathogens, IWA/AWWA, Cascais/Lisbon, Portugal, 22 September 2002.

- "UV Irradiation as a Ballast Water Treatment Process," presented at *International Workshop on Technical Aspects of Ballast Water Treatment Standards*, Jointly Sponsored by National Science Foundation, U.S. Department of State, and U.S. Coast Guard, Arlington, VA, 12 February 2003.
- "UV-Based Processes for Ballast Water Treatment: Research Needs," presented at *Ballast Water Workshop*, sponsored by the National Science Foundation, Seattle, Washington, 28 April 2003.
- "Optimization of Physical and Chemical Disinfection Processes Subject to Extended Space Travel Constraints," presented to Water Quality and Microbiology Laboratories, Johnson Space Center, Houston, TX, 24 June 2003.
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- "Fouling of Quartz Surfaces in UV Disinfection Systems: Causes, Effects, Methods of Characterization, and Future Research," Presented at International Ultraviolet Association (IUVA) Meeting, Hosted by US EPA, Cincinnati, OH, 20 October 2005.
- "Case Against Disinfection of Municipal Wastewater Effluents and CSOs," Presented to Indiana Association of Cities and Towns, Indianapolis, IN, 3 November 2005.
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- "Case Against Disinfection of Municipal Wastewater Effluents and CSOs," Presented to Maumee River Basin Partnership of Local Governments, Defiance, OH, 19 January 2006.
- "Validation of UV Disinfection Systems Using Dyed Microspheres," Presented to AWWARF TAC Meeting, Johnstown, NY, 17 May 2006.
- "Analysis of UV Reactors Using Dyed Microspheres," Presented at IUVA Meeting, Albany, NY, 18 May 2006.
- "Photochemical Reactor Design and Analysis," Presented at DuPont Experimental Station, Wilmington, DE, 24 may 2006.
- "New Tools for Analysis of UV Reactors," Presented to Trojan Technologies, London, Ontario, Canada, 27 June 2006.
- "A Case Against Conventional Wastewater Disinfection," Presented to Indiana Water Environment Association, Indianapolis, IN, 15 November 2006.
- "Tools for Design, Analysis and Validation of UV Disinfection Systems," Presented to Indiana Water Environment Association, Indianapolis, IN, 15 November 2006.
- "Tools for Design, Analysis, and Validation of UV Disinfection Systems," Presented to Indiana Section, American Water Works Association, 20 February 2007, Indianapolis, IN.
- "Application of Dyed Microspheres for Validation of Field-Scale Reactors," Presented at International Ultraviolet Association, Ultraviolet Disinfection Conference, Albany, NY, 18 May 2006.
- "Dyed Microspheres as an Alternative to Conventional Biodosimetry" (2007) Pre-Conference Workshop, Disinfection 2007, Pittsburgh, PA, 4 February 2007.
- "Process Theory and Applications of Photochemical Reactors," Institute of Chemistry, Chinese Academy of Sciences, Beijing, China, 8 June 2007.
- "Process Theory and Applications of Photochemical Reactors," Institute of Nuclear and New Energy Technology (INET), Division of Environmental Science and Technology, Tsinghua University, Beijing, China, 11 June 2007.
- "Lagrangian Actinometry's Role in UV Reactor Validation and Optimization," World Congress on Ozone and Ultraviolet Technologies, Los Angeles, CA, August 2007 (Keynote Address).
- "Volatile DBP Formation in Chlorinated Recreational Water," presented at World Aquatic Health Conference, National Swimming Pool Foundation, 3 October 2007, Cincinnati, OH.
- "UV Photolysis of DBPs in Chlorinated Recreational Water," presented at World Aquatic Health Conference, National Swimming Pool Foundation, 3 October 2007, Cincinnati, OH.
- "Process Theory and Applications of Photochemical Reactors," CDM Webmeeting, 7 November 2007.

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- "Application of Fundamental Photochemical Reactor Theory in Design and Analysis of UV Reactors," The Croucher Foundation Advanced Study Institute, Hong Kong University of Science & Technology, Hong Kong, China, 23-27 June 2008.

Attachment 2

Extended Testimony of Ernest R. Blatchley III

PROFESSIONAL BACKGROUND AND QUALIFICATIONS

I am a Professor of Civil (Environmental) Engineering at Purdue University. My educational background includes a BS in Civil Engineering from Purdue University; a MS in Civil Engineering from the University of California, Berkeley; and a Ph.D. in Civil Engineering, also from the University of California, Berkeley. I have more than 20 years of professional experience in the field of environmental engineering. My specific expertise is in the area of physico/chemical processes of environmental engineering, with particular emphasis on disinfection processes. I am a licensed Professional Engineer in the State of Indiana, and I am a Board Certified Environmental Engineer (American Academy of Environmental Engineers) in the area of Water Supply/Wastewater Engineering. Awards I have received include the Harold Munson Teaching Award, School of Civil Engineering, Purdue University; the Roy E. and Myrna G. Wansik Research Leadership Award, School of Civil Engineering, Purdue University; and the William Edgar Award for Pioneering Research in Disinfection, Water Environment Federation.

The focus of research efforts within my group and collaborators has been on disinfection processes based on ultraviolet (UV) radiation and chlorine. I have published more than 50 papers in refereed journals, and more than 60 papers in proceedings of conferences that pertain to my research. My group has made fundamental contributions regarding the behavior of UV reactors, including the development of basic photochemical reactor theory, as well as the development of numerical models and diagnostic methods based on that theory. In the area of chlorine-based disinfection processes, we have defined the kinetics and mechanisms of several important reactions involving chlorine, as well as some relevant toxicological endpoints. We have also developed analytical methods that are relevant to chlorine-based disinfection processes.

My group has conducted research to address the specific implications of disinfection processes, as applied to municipal wastewater. The focus of our work in this area has been on the human health implications of wastewater disinfection.

INTRODUCTION

The Illinois Environmental Protection Agency (IEPA) has proposed a set of standards to the Illinois Pollution Control Board (IPCB) that were developed with the objective of improving water quality in the Chicago Area Waterways System (CAWS). Included in these proposed standards is an effluent limitation of 400 cfu/100 mL for fecal coliform bacteria. The rationale for this effluent standard, as defined by IEPA, is that it will provide assurance that "active disinfection" will be included as an element of wastewater treatment, and that the disinfection systems function properly. Specifically, IEPA has proposed that the Metropolitan Water Reclamation District of Great Chicago (MWRDGC) should disinfect the effluent from its three largest water reclamation plants, North Side, Stickney and Calumet. The limit is also motivated, in part, by the increasing recreational value of the CAWS, and by the fact that "Technology-based disinfection has been a long standing requirement applied to numerous wastewater facilities throughout the State, dating back to the original 1970s Board regulations."

The purpose of this report is to provide evidence against the proposed effluent limitation for fecal coliform bacteria, and the implied requirement of an active disinfection system to meet such a standard. I contend that the imposition of this standard will yield minimal benefit to water quality in the CAWS, and minimal reduction in the risk of disease transmission.

The approach I will use in developing my arguments is to first define some of the basic aspects of disinfection processes, as they relate to wastewater applications. From there, I will address specific concerns I have with the proposed regulations.

BACKGROUND

Fundamental Aspects of Disinfection Systems

Disinfection is practiced with the objective of inactivating and/or removing pathogenic microorganisms, so as to reduce the risk of disease transmission. For municipal wastewater applications in North America, chlorine- and UV-based disinfection systems have emerged as the most common disinfection alternatives, largely on the basis of their history of use and system costs. However, it should be recognized that other disinfection processes have been successfully implemented, including systems based on the application of other disinfectant chemicals (*e.g.*, ozone) or physical separation (*e.g.*, granular media filtration or membranes).

Disinfection systems that are properly designed and operated will yield substantial decreases in the concentrations of (viable or infective) microbial pathogens and other microorganisms; however, disinfection should not be confused with sterilization. In other words, disinfected wastewater will contain viable or infective microorganisms, but at a lower concentration than the same water prior to disinfection. This attribute of disinfection systems is important for at least two reasons. First, it should be recognized that the risk of disease transmission associated with human use of wastewater effluents or receiving streams will never be zero. Second, because viable/infective microorganisms will remain in the water post-disinfection, and because the microbial community will adapt to the post-disinfection environment, the population of microbes in disinfected water will change with time. Many microbes have the ability to repair sub-lethal damage, and therefore can recover post-disinfection. Repair and recovery will take place following any disinfection process.

The microbial pathogens that are the target of disinfection processes include bacteria, viruses and protozoa. Although bacterial pathogens are common in wastewater effluents, it is generally believed that enteric viruses represent the greatest risk to human health of all waterborne pathogens; enteroviruses are the cause of the most common wastewater-related diseases in developed countries (Cabelli, 1983). The (oo)cysts of waterborne protozoan pathogens can also represent a substantial risk to humans. The diseases associated with waterborne pathogens are generally acute in nature.

Given the diverse nature of microbial pathogens, and the complexity of some of the viability/infectivity assays associated with these pathogens, it is not practical to monitor water for the presence or concentration of all pathogens. As a substitute for this approach, so-called "indicator" organisms are generally used as an index of microbial quality.

The concept of an indicator organism is that its presence should be indicative of the presence of microbial pathogens, while its absence should be indicative of the absence of microbial pathogens. Ideally, the concentration of viable indicator organisms should correlate strongly with the concentration of viable (or infective) microbial pathogens. Based on this objective, a number of important characteristics of indicator organisms may be identified, including:

- The indicator should be present when microbial pathogens are present,
- The indicator should be absent when microbial pathogens are absent,
- The indicator should be non-pathogenic to humans,
- Viability/infectivity assays for the indicator should be quantitative, rapid, inexpensive, and simple to conduct.

Although no organism has been identified that ideally or completely satisfies these criteria, a number of bacterial species have been proposed to satisfy this function. Commonly used indicators include coliform bacteria (fecal coliforms or *E. coli*) and enterococci.

Implicit in the characteristics listed above is the requirement that indicator organisms be common in a water supply, and that they be more resistant to disinfection than the microbial pathogens of interest. Commonly-used microbial indicators, such as coliform bacteria, are plentiful in municipal wastewaters, and as such they can be a good indicator of the *presence* of enteric microbes in untreated wastewater, including some pathogens. However, coliform bacteria are easily inactivated by common disinfectants, including chlorine (in its various forms), ozone, and UV radiation. Therefore, coliform bacteria are poor indicators of the effectiveness of a disinfection process. The conditions that accomplish effective inactivation of coliform bacteria do not necessarily accomplish effective inactivation of microbial pathogens.

Principles of Reactor Design – Microbial Dose-Response Behavior
The effectiveness of disinfection systems is determined by the combined effects of reactor design (*i.e.*, geometry, size), disinfectant delivery, and the kinetics of the reactions that lead to microbial inactivation. The principles of reactor design are well-established, and are widely used in the design, construction, and operation of disinfection systems.

In the cases of chlorine- and UV-based disinfection systems, a goal of reactor design is the delivery of (roughly) the same quantity of disinfectant to all microorganisms. If we assume that this objective has been met, then the effectiveness of a disinfection system will be governed by the concentration of microbial pathogens that enter the system and the "dose-response" behavior of the target pathogens. It is important to recognize that dose-response behavior will be different for each combination of disinfectant and target microorganism. Microbial dose-response behavior may also be influenced by characteristics of the water being disinfected, including temperature, pH, and the presence of particles that may shelter microbes from disinfectant exposure.

Many models of disinfection kinetics have been developed. Although differences in these models are evident among the many combinations of disinfectant and target microbe, these models share some important features. For the sake of this discussion, it is sufficient to examine

the most basic disinfection model, as it illustrates important principles that are common to all disinfection kinetics models.

In the case of chemical disinfection systems, the simplest model is "Chick's law", which states that the rate of microbial inactivation is directly proportional to the concentration of the disinfectant and the concentration of viable microbes. Mathematically, this leads to an expression of the following form:

$$log_{10}\left(\frac{N}{N_0}\right) = -kCt \quad (1)$$

where,

N	=	concentration of viable organisms after disinfectant exposure
N_0	=	concentration of viable organisms before disinfectant exposure
k	=	inactivation rate constant
C	=	disinfectant concentration
t	=	contact time with disinfectant.

The left-hand side of equation (1) describes the extent to which a microbial population has been inactivated by disinfectant exposure. It is common to express this in $\log_{10}$ form because disinfection systems generally are required to accomplish extensive inactivation of target organisms; it is common for disinfection systems to accomplish 3-5 $\log_{10}$ units of inactivation.

The product C·t describes the extent of chemical disinfectant exposure in a reactor. As described previously, Chick's law is the most basic model of disinfection kinetics. Other, more complex models have been developed to describe the kinetics of disinfection, and in some cases the use of these more complex models is justified. However, the term C·t appears in all models of chemical disinfection kinetics, and may be viewed as the "master variable" to describe the behavior of a chemical disinfection system.

Equation (1) also provides a clear illustration of the so-called "Ct concept", which is fundamental to the design, analysis, and regulation of disinfection systems. The Ct concept implies that the extent of microbial inactivation is controlled by the extent of disinfectant exposure (Ct). Therefore, chemical disinfection systems must be designed to deliver an appropriate quantity of disinfectant (as measured by "C") for an appropriate period of exposure (as defined by "t") to achieve the desired degree of microbial inactivation.

The inactivation rate constant (k) is different for each combination of disinfectant and target microbe. For chemical disinfectants, the value of k may also be affected by temperature and pH. Because k is different for every organism, the quantity of disinfectant exposure (Ct) required to achieve effective disinfection is different for each potential target organism. As an illustration of this behavior, consider the reported inactivation behavior of coliform bacteria, enteric viruses, and protozoan parasites for chlorine-based disinfection (see Table 1). In general, the extent of microbial inactivation accomplished by a disinfectant will depend on the amount of disinfectant used. In the case of chemical disinfectants, the amount of disinfectant exposure required to accomplish disinfection will depend on the disinfectant and the target organism(s).

Table 1. Ct values (mg·min/L) for 99% inactivation (2.0 $\log_{10}$ units of inactivation) at 5°C based on microbial exposure to chemical disinfectants (from Health Canada).

Disinfectant	pH	Target Microbe		
		E. coli	*Giardia lamblia*[*]	*Poliovirus 1*
Free Chlorine	6-7	0.034-0.05	32-46	1.1-2.5
Chloramines	8-9	95-180	1470	768-3740
Ozone	6-7	0.02	1.3	0.1-0.2

[*]90% inactivation (1.0 $\log_{10}$ units of inactivation).

The data presented in Table 1 illustrates some important facts about the responses of microorganisms to chemical disinfectants. First, *E. coli* are far more sensitive to disinfectant exposure than *G. lamblia* or *Poliovirus*. More generally, coliform bacteria are more sensitive to chemical disinfectants than most microbial pathogens. Second, it is evident that of the three chemical disinfectants listed in Table 1, ozone is the most effective against all of the microbes listed. For any given microorganism, it is possible to identify an order of sensitivity to disinfectants. For the microbes listed in this table, the order of sensitivity is ozone > free chlorine > chloramines. This order applies to many waterborne microbes.

Equation (1) is an example of a mathematical model used to define the sensitivity of waterborne microorganisms to chemical disinfectants. Similar mathematical relationships have been developed for UV-based disinfection systems. The most basic model of UV disinfection kinetics is a mathematical analog of equation (1):

$$log_{10}\left(\frac{N}{N_0}\right) = -k\cdot I\cdot t \qquad (2)$$

where,

N	=	concentration of viable organisms after disinfectant exposure
N_0	=	concentration of viable organisms before disinfectant exposure
k	=	inactivation rate constant
I	=	intensity of UV radiation imposed on bacteria
t	=	contact time with disinfectant.

The product I·t is defined as the UV dose delivered by a system. UV dose is the master variable in defining the performance of a UV disinfection system. As with chemical disinfection systems, the performance of a UV system relative to any given microorganism depends on the UV dose delivered to the organisms by the system, as well as the relative sensitivity of the microorganism to UV exposure. If a Chick's law type expression is applicable to the microorganism of interest, then the relative sensitivity of the organism to UV radiation can be defined by the magnitude of the inactivation rate constant.

For UV-based systems, several compilations of microbial dose-response behavior have been assembled. Table 2 is a summary of reported UV doses required to accomplish 2.0 $\log_{10}$ units of inactivation. In general, vegetative bacteria are quite sensitive to UV exposure, as are common

protozoan parasites (*e.g.*, *Cryptosporidium parvum* and *Giardia lamblia*); however, some species of virus appear to be fairly resistant to UV exposure (*e.g.*, *Adenovirus*).

Table 2. UV doses required for 99% inactivation (2.0 $\log_{10}$ units of inactivation) of waterborne microorganisms (from Chevrefils *et al.*, 2006).

UV Dose (mJ/cm^2)	Target Microbe
E. coli	0.7-8
Legionella pneumophila	3.2-5
Salmonella typhimurium	3.5
Vibrio cholerae	1.4
Cryptosporidium parvum	1-10
Giardia lamblia	2-10
Calicivirus feline	9-16
Adenovirus (various types)	45-105
Poliovirus	7-17
Hepatitis A Virus	8.2-13.7

The information presented in Table 2 indicates similar trends to those that were evident in Table 1. Namely, coliform bacteria are generally more sensitive to UV exposure than are most microbial pathogens, and not all microbes respond the same to disinfectant exposure, including UV irradiation.

For wastewater disinfection systems, the extent of disinfectant exposure required will depend on the treatment objective. In the case of MWRDGC systems, "disinfection" will be represented by a system that reliably produces a treated effluent with fewer than 400 cfu/100 mL of fecal coliform bacteria. By comparing the rate constants for inactivation of microbial pathogens with those of fecal coliform bacteria, it is evident that coliform bacteria are relatively sensitive to chlorine, UV and most other disinfectants. Therefore, the conditions that are required to inactivate fecal coliform bacteria are relatively mild, and should not be expected to accomplish extensive inactivation of most microbial pathogens. This statement will hold true among all commonly used wastewater disinfectants, including chlorine (in its various forms), ozone, or UV radiation.

An implication of this behavior is that the application of disinfection, as required by the proposed effluent discharge limit for coliform bacteria, will yield only a modest reduction in the risk to human health posed by microbial pathogens in MWRDGC municipal wastewater effluents.

RANGE OF DISINFECTION APPLICATIONS

It is clear that the proper application of disinfectants can lead to removal or inactivation of microbial pathogens; however, a number of issues complicate the application of disinfection, including the ineffectiveness of conventional disinfectants against some important pathogens, and the generation of disinfection by-products (DBPs). As a result, there is some question as to whether disinfection of municipal wastewater effluents should be applied in all cases.

In many developed countries outside North America, wastewater disinfection is practiced only in situations where a direct, clear threat to human health is evident, such as discharges to bathing

areas or shellfish breeding grounds. The frequency of occurrence of diseases associated with waterborne pathogens does not appear to be substantially different from that of North America, where wastewater disinfection is commonly practiced. However, even within the U.S., many states have chosen to require disinfection only on a seasonal basis.

A range of possible options exist for disinfection of municipal wastewaters, from no disinfection at all, to systems in which conditions of disinfectant exposure are such that the concentration of viable microorganisms present in the treated water becomes difficult to measure by conventional means. This entire range of disinfection conditions is being used today among wastewater treatment facilities in the United States.

Within the range of municipal wastewater disinfection practices described above, the most aggressive processes tend to be those associated with water reuse applications where there is potential of direct human contact. Reuse of wastewater effluents is important in arid areas, such as the U.S. southwest. While recovery and reuse of municipal wastewaters has important implications with regard to the issue of sustainable water supplies in arid areas, it also represents a potentially important means of human exposure to wastewater pathogens. Therefore, treatment of wastewater effluents prior to reuse is a critical issue, particularly as it relates to disinfection processes.

The Los Angeles County Sanitation Districts (LACSD) initiated a study to examine process alternatives that could allow compliance with *Title 22* of the California Administrative Code, which represents the California State Health Department's Wastewater Reclamation Criteria. At the time the study was initiated, the default "Title 22 System" of tertiary treatment was alum coagulation, flocculation, sedimentation, filtration, and disinfection by chlorination. This system was effective for inactivation of viruses and compliance with the *Title 22* coliform criterion of less than 2.2 cfu/100 mL (the limit of detection based on the multiple fermentation tube method), but was expensive to implement. Therefore, an incentive existed to find less-expensive treatment approaches that would reliably satisfy the constraints of *Title 22*.

LACSD, in conjunction with the US EPA and the California State Water Resources Control Board, initiated a study, later identified as the "Pomona Virus Study" (Parkhurst, 1977), with the objective of providing data regarding alternative tertiary treatment approaches that could satisfy *Title 22* limits. The study involved operation of four pilot-scale tertiary treatment processes, one of which was the "Title 22 System", which served as a standard for comparison with other processes. Disinfectants included in these four systems were inorganic combined chlorine, free chlorine, and ozone. At the time of this investigation, UV irradiation was not viewed as a viable alternative to chlorine.

The pilot-scale experiments conducted as part of their research were largely focused on the ability of these various treatment options to remove or inactivate seeded *Poliovirus*. However, coliform counts were also part of the routine monitoring, and a limited number of experiments were conducted with (enteric) viruses that existed naturally in the wastewaters being treated.

While this landmark study was relevant for a number of reasons, perhaps the most tangible outcome of this study with regard to the issue of the need for municipal wastewater disinfection

was their definition of the conditions of chlorine-based disinfection that are required to achieve acceptable treatment in a reuse setting. Specifically, the conditions of chlorination required to accomplish reliable compliance with *Title 22* were:

- combined chlorine residual $\geq$ 10 mg/L (as Cl_2) with contact time $\geq$ 2 hours,
- free chlorine residual $\geq$ 4 mg/L (as Cl_2) with contact time $\geq$ 2 hours.

These disinfection conditions accomplished roughly 4 $\log_{10}$ inactivation of seeded virus, and were consistently in compliance with the coliform regulation. When used in conjunction with other appropriate physico/chemical processes, treatment consistently accomplished overall virus inactivation (or removal) of roughly 5 $\log_{10}$ units. The authors also noted that less aggressive chlorine-based disinfection (residual concentration of 5 mg/L combined chlorine as Cl_2, with a 2-hour contact time) also allowed compliance with virus limitations, but overall process reliability was somewhat diminished as compared with the cases listed above.

By comparison with most conventional wastewater disinfection[1] practices in use today, the conditions of chlorination defined by the *Pomona Virus Study* can be characterized as extreme. The regulatory constraints that are imposed for most scenarios involving conventional disinfection are substantially less severe than those imposed by *Title 22*. As an example, the effluent limits that have been proposed for MWRDGC facilities require less than 400 cfu/100 mL of fecal coliforms. This limit is similar to "conventional disinfection" limits that have been proposed in other states. In practical terms, this bacterial limit is met in well-run municipal wastewater treatment facilities by maintaining a chlorine residual of 1-2 mg/L (as Cl_2) for a retention time of 20-40 minutes, followed by S(IV)-based dechlorination.

To put these treatment conditions in perspective, it is useful to characterize the conditions of chlorination used in each system. A "conventional disinfection" operation may accomplish disinfection based on a Ct value (defined as the product of residual chlorine concentration and mean hydraulic detention time) of 40-80 mg·min/L, whereas a disinfection system that is implemented to satisfy the constraints of *Title 22* is likely to require chlorine exposure of roughly an order of magnitude more than is required for "conventional disinfection". Clearly, this range of possible chlorination conditions will yield a corresponding range of antimicrobial and DBP effects.

In the time since the completion of the *Pomona Virus Study* and related research on the subject of chlorine-based wastewater disinfection, UV irradiation practices have been adopted to meet the constraints imposed by wastewater treatment objectives. As one might expect, the conditions of UV irradiation required to satisfy *Title 22* constraints (and similar reuse constraints in other areas) are substantially more severe than those required to meet the constraints of "conventional disinfection". Similarly, ozone-based disinfection systems used to meet reuse criteria will be substantially larger than those used to meet conventional disinfection criteria.

More generally, one can expect that the conditions of disinfectant exposure that will be required to meet a reuse standard for effluent disinfection will be substantially more severe than those

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[1] For purposes of this document, the term "conventional disinfection" will refer to disinfection operations that are commonly used for facilities that do not represent opportunities for water reuse, and therefore are not subject to reuse criteria.

required for conventional disinfection, irrespective of the disinfectant. This implies that disinfection systems that are required to prevent disease transmission for reuse applications, where human contact is likely, will be considerably larger and more expensive than those required for conventional disinfection applications.

EFFECTS OF CONVENTIONAL DISINFECTION ON MICROBIAL PATHOGENS

As illustrated above, the effectiveness of a disinfectant will vary among the various microorganisms that are present in a water supply. For disinfection to be effective, it is necessary to accomplish inactivation of a broad range of microbial pathogens. However, the performance of a disinfection system is generally monitored through measurements of indicator organism viability.

The Water Environment Research Foundation sponsored a research project that was aimed at assessing the effects of municipal wastewater disinfection on human health (Blatchley *et al.*, 2005, 2007). To address this issue, two central questions were posed:

1. Should municipal wastewater effluents be disinfected prior to discharge?, and
2. Under circumstances where disinfection is necessary, how should it be accomplished?

Undisinfected effluent samples were collected from a number of municipal wastewater treatment facilities. Some relevant characteristics of these facilities are listed in Table 3.

Table 3. Characteristics of municipal wastewater treatment facilities from which undisinfected effluent samples were collected as part of WERF study 99-HHE-1.

Facility	Treatment Processes
A	Primary Sedimentation, Activated Sludge with Nitrification
B	Primary Sedimentation, Activated Sludge without Nitrification
C	Primary Sedimentation, Activated Sludge with Nitrification and Denitrification
D	Primary Sedimentation, Activated Sludge without Nitrification, Sand Filtration
E	Primary Sedimentation, Activated Sludge with Nitrification

Effluent samples were shipped to laboratories of the researchers who participated in the study, where they were subjected to conditions of disinfectant exposure (in bench-scale disinfection experiments) that were shown to yield water that was consistently in compliance with conventional disinfection standards. All experiments were conducted using chlorine and UV radiation as the disinfectants. Chlorination involved addition of 2.0 mg/L (as Cl_2) of free chlorine, followed by dechlorination after 40-60 minutes of exposure. UV irradiation involved exposure of effluent samples to UV doses of 10 mJ/cm^2 or 20 mJ/cm^2.

The disinfected samples were then subjected to an array of analyses to define the responses of the microbial community to disinfectant exposure, including an assay to measure the post-

disinfection responses of the bacterial community, and assays that were used to define the responses of waterborne viruses (bacteriophage) to the bench-scale disinfection procedures.

Responses of Waterborne Bacteria to Disinfectant Exposure - The response of the bacterial community to disinfectant exposure was characterized using a long-term (144 hr) respirometry test, in which O_2 uptake and bacterial community composition were measured over the 6-day period of the test. Given that disinfection processes do not accomplish complete inactivation of waterborne microorganisms (*i.e.*, sterilization is not accomplished), it is important to define the ability of the bacterial community to recover following disinfectant exposure. For every effluent sample collected, four sub-samples were tested. A partially-reduced substrate (acetic acid) was added to the disinfected samples and a non-disinfected sample prior to initiating the respirometry assay; this substrate was added to mimic the substrates that are likely to be present in receiving waters. An undisinfected sample without substrate was also included in the test as a control.

Figure 1 lists nine possible scenarios that could develop among wastewater bacteria following disinfection. From this figure, one can judge the effectiveness of a disinfection process by variations in the total bacterial community, and the pathogenic fraction. For example, cases (c), (g) and (i) may be judged to represent a positive effect of disinfection since they imply a reduction in pathogenic bacteria; on the other hand, cases (a), (b), (d) and (e) have an adverse effect since pathogenic bacterial concentrations are not reduced. It is also interesting to note that in cases (f) and (h), it is difficult to judge disinfection efficacy. For these two cases, judgment of antibacterial efficacy requires additional information, such as the concentration of pathogenic bacteria or indicator microorganisms. Cases for which disinfection is effective in reducing pathogenic microorganisms are indicated by green color. Cases for which disinfection is not effective against pathogenic bacteria are indicated by red color. Cases for which disinfection efficacy is not clear are indicated by gray color. Yellow color indicates no effect.

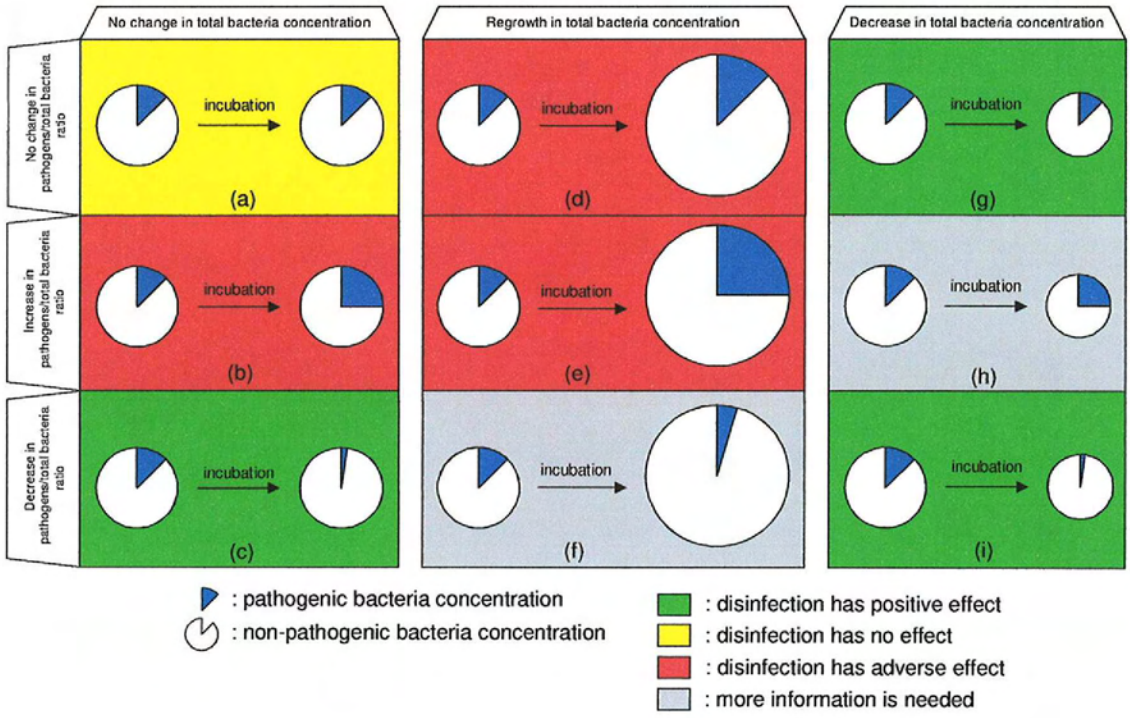

Figure 1. Conceptual representation of the possible fates of bacteria following disinfectant exposure. Disinfection is considered to be antibacterially "effective" when the risk of human exposure to bacteria is reduced. Moving from left to right, the columns represent circumstances of no regrowth, regrowth, and decline in the total bacterial population, respectively. Moving from top to bottom, the rows represent circumstances in which the fraction of the bacterial population comprised of pathogenic bacteria does not change, increases, and decreases, respectively. Together, these two attributes (regrowth of the total bacterial population, and changes in the fraction of pathogenic bacteria) will determine the effectiveness of disinfection relative to human exposure to bacteria.

To answer the question "is a disinfection process effective?" from the standpoint of bacterial risk, it is necessary to consider both regrowth and the pathogen ratio. To do this, it is necessary to investigate the impacts of upstream treatment processes, disinfection, and receiving waters on regrowth and the pathogen ratio. Under conditions of abundant substrate supply, rapid-growing microorganisms usually dominate populations. This is true in municipal wastewater treatment facilities where the abundance of available organic substrates favors the growth of rapidly dividing bacteria, such as coliforms and pseudomonads. These dominant microbial populations in municipal wastewater, which gain a competitive advantage because of their high intrinsic growth rates, are rapidly displaced in competition with other microbial populations of receiving waters as the concentration of organic compounds diminishes, owing to decomposition and dilution; under lower nutrient conditions a more diverse community of slow-growing bacteria is favored.

For interpretation of the results of these experiments, several assumptions were made, including:

- Fecal coliform bacteria can be used as an indicator microorganism for pathogenic bacteria in disinfected wastewater effluent. This implies that fecal coliforms can be characterized as having (a) similar susceptibility to disinfection processes, (b) similar intrinsic growth rates, and (c) similar requirements for nutrients as pathogenic bacteria.
- The substrate (acetic acid) used in this study can represent the substrate condition of receiving waters.
- The addition of substrate does not affect microbial ecology relationships during incubation.

It is clear that these assumptions are not entirely valid, because:

- Susceptibility to disinfection processes, intrinsic growth rates and nutrient requirements for fecal coliform and pathogenic bacteria will be different; they are different even between two pathogenic bacteria. Coliform bacteria are commonly used as an "indicator" of microbial quality; however, it is clear that no single microbial species can truly represent the broad range of waterborne pathogens that could be present in a municipal wastewater effluent.
- The nutrient conditions of receiving waters are site-specific, so it is impossible to find a substrate that can be representative of all situations.
- Acetic acid can be biodegraded easily; this will benefit those bacteria with high intrinsic growth rates. The composition of easily biodegradable compounds in receiving waters will vary.

Despite the limitations of the assumptions described above, the conditions used in these experiments provided a common basis for examination of the behavior of municipal wastewater effluents from several different facilities. As such, it was possible to compare the long-term behavior of multiple samples collected from each of the four facilities. The conditions of these experiments were believed to be representative of actual conditions in receiving waters; however, it is not reasonable to expect direct translation of these results to conditions in the respective receiving waters.

Assessments of disinfection efficacy have traditionally been based on the inactivation or removal of fecal indicators such as total coliforms, fecal coliforms and fecal streptococci. However, there is little information about correlation between these indicator organisms and real pathogens. Although the assumptions listed above are not entirely justified, it is necessary to use this approach because relatively little information has been obtained regarding the ecological relationships between fecal coliform and pathogenic bacteria (many of which are not culturable). Fecal coliforms were also selected as the target microorganism because they represent a common indicator microorganism for wastewater effluent regulation.

As described previously, the effectiveness of disinfection treatment processes was assessed based on an index test in which the dynamic behavior of fecal coliforms and total bacterial counts were examined throughout the course of incubation used in the long-term respirometry assays. Based on 16 experimental runs (four treatment facilities, 4 replicates/facility), four different treatments were applied; fecal coliform and total bacteria concentrations were recorded for each case from

the beginning of the experiment (t=0 hr) to t=144 hr. Since there were four replicates involved in each treatment facility, an average value of the four replicates was used for representation of the total bacteria concentration and fecal to total bacteria ratio. Based on this information, classification of disinfection process proceeded using Figure 1. Table 4 provides an abridged summary of the results of these measurements for all four facilities, and all four exposure scenarios (treatments).

Table 4. Summary of bacterial community responses to disinfection treatments.

Treatment	Facility	Incubation Time (hours)					
		24	48	72	96	120	144
Original without substrate addition (control)	B	i	i	c	f (-)	i	i
	D	f (-)	f (-)	c,i	c,i	i	i
	A	f (+)	i	i	i	i	i
	C	i	i	i	i	i	i
Original with substrate addition	B	i	i	c,f (-)	f (-)	c,i	c,i
	D	f (-)	f (-)	f (-)	i	c,i	i
	A	e	i	i	i	i	i
	C	i	i	i	i	i	i
UV	B	e	b	h (+)	h (+)	h (+)	i
	D	e	e	e	e	a	h (+)
	A	f (-)	f (-)	f (-)	f (-)	i	i
	C	e	e	h (+)	h (+)	h (+)	h (±)
Chlorination / Dechlorination	B	e	e	e	e	e	e
	D	e	e	e	f (+)	e	e
	A	f (-)	f (-)	f (-)	f (-)	f (-)	e
	C	f (-)	e	e	f (-)	e	f (-)

The summary presented in Table 4 reveals several interesting characteristics of the responses of the bacterial community to these four treatments. In general, the treatments involving no disinfection resulted in an improvement in bacterial quality over the course of the six-day incubation procedure. In contrast, overall bacterial quality remained essentially unchanged or degraded following the disinfection procedures.

The decreases in bacterial quality were most evident in the application of chlorination/dechlorination to the effluent samples from the non-nitrified effluents (Facilities B and D), where +1-valent chlorine would have been present predominantly in the form of inorganic chloramines (mostly NH_2Cl, with small quantities of $NHCl_2$ and perhaps NCl_3).

While it is clear that chlorine- or UV-based disinfection will accomplish an immediate decrease in the concentration of viable bacteria, it appears that the long-term effects of chlorination/dechlorination or UV irradiation may actually be detrimental to water quality, in terms of bacterial composition.

It is important to recognize that the changes among the bacterial populations were all normalized against the bacterial composition at t=0, corresponding with the time at which disinfectant

exposure was terminated. This method of normalization can provide a misleading representation of bacterial population dynamics, in that the basis of normalization was different for all samples.

Responses of Waterborne Viruses (Bacteriophage) to Disinfectant Exposure – Traditionally, assessments of antimicrobial efficacy in disinfection operations used for treatment of municipal wastewater have been based on measurements of the concentration of viable indicator bacteria. While these organisms satisfy some of the basic requirements of indicators, several important shortcomings of their application for this purpose have been identified (see preceding discussion). Among the most important of these limitations are the relative ease with which common bacterial indicators are inactivated by the disinfectants of interest, and the fact that enteric viruses generally represent the most serious risk to human health among wastewater microorganisms.

Unfortunately, the assays used to assess viability (or infectivity) among human enteric viruses are time-consuming and expensive to conduct. In most situations, it is not practical to monitor for human enteric viruses. However, several indigenous phage have been identified that are structurally or otherwise similar to human viruses. Assays of phage viability (infectivity) are comparatively easy to conduct. Therefore, a series of experiments was conducted to assess the effects of common wastewater disinfectants on the concentrations of viable (infective) indigenous phage.

The concentration of indigenous bacteriophage in effluent samples from the five wastewater treatment facilities varied considerably, with the highest phage concentrations isolated from facility B. The phage population for this facility was comprised of both somatic and F-specific phage, with facility B possessing the highest concentration of F-specific phages of all the facilities examined. In decreasing order of initial phage concentration, the facilities were ranked as: $B > A > D \approx E > C$. The samples containing the highest concentration of phage surviving either chlorine or UV disinfection appeared to reflect the ranking of the facilities with regard to initial phage concentration.

Although samples from all five facilities were analyzed for phage composition and dose-response behavior, the vast majority of useable data came from the analysis of samples collected from facilities A and B. Samples collected from facilities C and D had extremely low phage concentrations, such that it was difficult to assess their dose-response behavior or nucleic acid content. The samples collected from facility E had quantifiable concentrations of viable phage; however, both disinfection schemes yielded samples in which F+ phage concentrations were below the limit of detection. One of the UV irradiated samples yielded a measureable concentration of somatic phage (see below).

Figure 2 illustrates representative examples of phage responses to exposure to UV and chlorine in samples collected from facilities A and B. The data in this figure illustrates several of the important trends that were observed in the data from the experiments focused on phage inactivation. First, the concentration of viable phage present in the samples was variable and low. Some evidence of seasonal effects was apparent in samples collected from winter and spring months at these two facilities, with summer phage concentrations being substantially

higher than those observed in winter. Second, the assay based on *E. coli* C-3000 consistently yielded higher concentrations of viable phage that the assay based on *E. coli* F_{amp}.

Of particular importance in this work were the abilities of residual chlorine and UV radiation to accomplish inactivation of the indigenous phage. In the case of samples from facility A, residual chlorine existed largely in the form of free chlorine. Exposure to chlorine under conditions that were shown to be capable of complying with discharge limitations generally yielded poor phage inactivation.

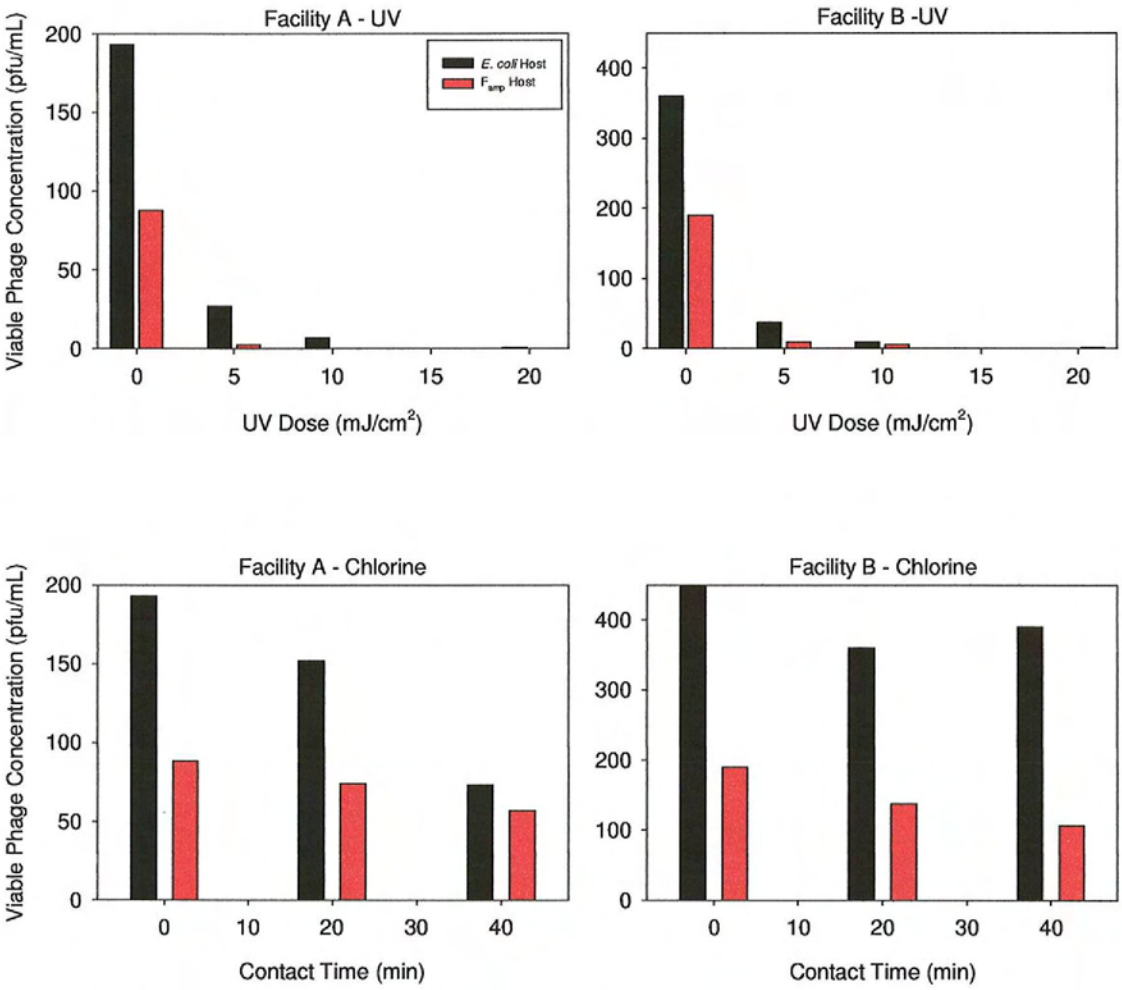

Figure 2. Representative dose-response curves for indigenous phage from wastewater effluent samples collected from facilities A and B. Samples were subjected to UV irradiation or chlorination in bench-scale reactors.

In the case of samples collected from the facility B, where residual chlorine was present largely in the form of NH_2Cl, phage inactivation was less effective. Again, it is important to recognize

that the conditions of chlorination used in these exposures were shown to be adequate to comply with existing discharge regulations based on coliform bacteria as indicators.

For samples that were subjected to UV irradiation from facilities A and B, phage inactivation was generally good. Specifically, application of a UV dose of 20 mJ/cm^2 to phage in a well-mixed, batch reactor under a collimated beam yielded phage low phage concentrations. For the examples illustrated in Figure 2, which contained some of the highest initial phage concentrations among the samples collected in this research, exposure to a UV dose of 20 mJ/cm^2 resulted in viable phage concentrations that were at or below the limit of detection.

Measurements of nucleic acid content were used as an index of phage diversity in disinfected samples. Table 5 provides a summary of nucleic acid composition measurements for surviving phage from selected samples from this portion of the research. In general terms, UV irradiation yielded much less diverse phage populations than did chlorination for the conditions of disinfection used in these experiments.

Table 5. Nucleic acid content of post-disinfection viable phage in samples that had been subjected to bench-scale disinfection.

Facility	Disinfection Exposure Scenario	Host Strain	Number of DNA Isolates	Number of RNA Isolates
A	40 min contact time; 2.0 mg/L as Cl_2	*E. coli* C-3000	7	4
	40 min contact time; 2.0 mg/L as Cl_2	*E. coli* F_{amp}	3	2
	20 mJ/cm^2 UV	*E. coli* C-3000	0	0
	20 mJ/cm^2 UV	*E. coli* F_{amp}	0	3
B	40 min contact time; 2.0 mg/L as Cl_2	*E. coli* C-3000	6	0
	40 min contact time; 2.0 mg/L as Cl_2	*E. coli* F_{amp}	4	2
	20 mJ/cm^2 UV	*E. coli* C-3000	0	0
	20 mJ/cm^2 UV	*E. coli* F_{amp}	0	0
E	40 min contact time; 2.0 mg/L as Cl_2	*E. coli* C-3000	0	0
	20 mJ/cm^2 UV	*E. coli* C-3000	2	2

In general terms, the results of these experiments indicate that the conditions of disinfection (based on chlorination with either combined chlorine or free chlorine, or UV irradiation) that are needed to accomplish compliance with discharge regulations used in conventional disinfection

operations yield incomplete inactivation of phage. Phage inactivation responses by UV irradiation were on the order of 2 $\log_{10}$ units; phage inactivation by chlorine was less than this value. By extension, this suggests that these conditions of disinfection used for compliance with conventional disinfection may yield poor inactivation of enteric viruses.

INPUTS OF MICROBIAL PATHOGENS FROM NON-EFFLUENT SOURCES

Water quality, as measured by microbial and chemical constituents, will be influenced by inputs from point sources and non-point sources. Clearly, the release of treated wastewater from the treatment facilities of the MWRDGC will have an important influence on CAWS water quality. By extension, effluent disinfection processes at MWRDGC facilities will play an important role in water quality. However, it is also clear that water quality in the CAWS will be influenced by inputs from other sources, including combined sewer overflows (CSOs) and non-point sources.

The system defined by the Tunnel and Reservoir Plan (TARP) has yielded substantial improvements in water quality within the CAWS. It is likely that additional water quality improvements will result from the completion of TARP. However, even when completed, this facility will not accomplish complete capture of wastewater from CSOs; therefore, CSO events will continue take place in the Greater Chicago Area. Moreover, non-point source contributions to the CAWS will be largely unaffected by TARP.

Therefore, irrespective of the effluent disinfection constraints that are imposed on MWRDGC facilities, the potential for inputs of microbial pathogens from other sources will still remain. These inputs to the system will limit the extent to which risk of disease transmission from microbial pathogens can be reduced in the CAWS.

A related point is that the development of disinfection processes for CSOs and non-point sources represents a difficult engineering challenge. CSO treatment systems have been developed, including systems that incorporate disinfection. However, these disinfection processes are faced with an extremely difficult challenge, in that water quality from these sources is generally poor as compared with the effluent from a municipal wastewater treatment facility.

For chlorine-based disinfection systems, the poor quality of water from a CSO will dictate that the chlorine residual will probably be in the form of chloramines (inorganic and organic), which generally are less-effective than equivalent concentrations of free chlorine. Moreover, wastewater containing chloramines often yields treated water with relatively high concentrations of disinfection byproducts.

For UV-based disinfection systems, the relatively high concentration of particles and low UV transmittance of water will adversely affect their performance. Although UV-based disinfection systems for CSOs (and waters of similar quality) have been developed, their performance will be limited by water quality. It is unlikely that disinfection processes applied to CSOs or non-point source contributions will yield substantial reductions in the risk of disease transmission associated with waterborne microbial pathogens.

SUMMARY

The proposed effluent bacterial limit is intended to reduce the risk of disease transmission associated with use of the CAWS. While the goal is well-intended, several technical issues will limit the extent to which the risk of disease transmission may be mitigated. These issues include:

1. Coliform bacteria are poor indicators of the effectiveness of disinfection systems. Relative to most microbial pathogens, coliform bacteria are sensitive to disinfectant exposure, and as a result, conditions that accomplish effective inactivation of coliform bacteria will not necessarily translate to effective control of microbial pathogens.
2. Disinfection systems used in wastewater reuse applications with potential of direct human contact, have been demonstrated to accomplish reliable, effective control of microbial pathogens; however, these systems call for roughly an order of magnitude greater disinfectant exposure than would be required to comply with the proposed effluent bacterial limitation for incidental (limited) human contact. The proposed effluent limit of 400 cfu/100 mL for coliform bacteria is modest, as the conditions of disinfectant exposure that will be required are unlikely to lead to effective control of microbial pathogens. The response of the bacterial community to the post-disinfection environment will be influenced by bacterial repair, recovery, and re-growth; collectively, these processes may yield diminished water quality relative to a situation in which disinfection is not practiced.
3. A range of disinfection applications exists for municipal wastewater effluents in the United States. However, in many other developed countries, wastewater disinfection is not practiced, and it appears that the frequency of disease transmission associated with water contact is not substantially different that in the U.S., where wastewater disinfection is common.
4. Irrespective of any measures that are used to control microbial inputs to the CAWS from municipal wastewater treatment facilities, inputs from other sources (*e.g.*, CSOs and non-point sources) will remain. Moreover, it would be extremely difficult to implement control measures that would effectively mitigate against transport of microbial pathogens to the CAWS from these sources. These inputs will limit possible reductions in the risk of exposure to waterborne microbial pathogens.

Collectively, these issues dictate that wastewater disinfection, as required to comply with the proposed effluent bacterial limit, will yield only modest decreases in the risk of disease transmission associated with use of the CAWS.

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Attachment 3

Effects of Wastewater Disinfection on Waterborne Bacteria and Viruses

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ABSTRACT: Wastewater disinfection is practiced with the goal of reducing risks of human exposure to pathogenic microorganisms. In most circumstances, the efficacy of a wastewater disinfection process is regulated and monitored based on measurements of the responses of indicator bacteria. However, inactivation of indicator bacteria does not guarantee an acceptable degree of inactivation among other waterborne microorganisms (e.g., microbial pathogens).

Undisinfected effluent samples from several municipal wastewater treatment facilities were collected for analysis. Facilities were selected to provide a broad spectrum of effluent quality, particularly as related to nitrogenous compounds. Samples were subjected to bench-scale chlorination and dechlorination and UV irradiation under conditions that allowed compliance with relevant discharge regulations and such that disinfectant exposures could be accurately quantified. Disinfected samples were subjected to a battery of assays to assess the immediate and long-term effects of wastewater disinfection on waterborne bacteria and viruses.

In general, (viable) bacterial populations showed an immediate decline as a result of disinfectant exposure; however, incubation of disinfected samples under conditions that were designed to mimic the conditions in a receiving stream resulted in substantial recovery of the total bacterial community. The bacterial groups that are commonly used as indicators do not provide an accurate representation of the response of the bacterial community to disinfectant exposure and subsequent recovery in the environment. UV irradiation and chlorination/dechlorination both accomplished measurable inactivation of indigenous phage; however, the extent of inactivation was fairly modest under the conditions of disinfection used in this study. UV irradiation was consistently more effective as a virucide than chlorination/dechlorination under the conditions of application, based on measurements of virus (phage) diversity and concentration.

Taken together, and when considered in conjunction with previously published research, the results of these experiments illustrate several important limitations of common disinfection processes as applied in the treatment of municipal wastewaters. In general, it is not clear that conventional disinfection processes, as commonly implemented, are effective for control of the risks of disease transmission, particularly those associated with viral pathogens. Microbial quality in receiving streams may not be substantially improved by the application of these disinfection processes; under some circumstances, an argument can be made that disinfection may actually yield a decrease in effluent and receiving water quality. Decisions regarding the need for effluent disinfection must account for site-specific characteristics, but it is not clear that disinfection of municipal wastewater effluents is necessary or beneficial for all facilities. When direct human contact or ingestion of municipal wastewater effluents is likely, disinfection may be necessary. Under these circumstances, UV irradiation appears to be superior to chlorination in terms of microbial quality and chemistry and toxicology. This advantage is particularly evident in effluents that contain appreciable quantities of ammonia-nitrogen or organic nitrogen. *Water Environ. Res.*, 79, 81 (2007).

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Introduction

Wastewater disinfection has been practiced in the United States for approximately 100 years with the goal of providing protection to human populations from exposure to pathogenic waterborne microorganisms. Undisinfected wastewater effluents represent a potentially important source of pathogenic microorganisms in the environment and a possible vector for transmission of disease among human populations. Although bacterial pathogens are present in wastewater effluents, it is generally believed that enteric viruses represent the greatest risk to human health of all waterborne pathogens. The (oo)cysts of waterborne protozoan pathogens can also represent a substantial risk to humans. The risks of disease associated with waterborne pathogens are generally acute in nature.

Human contact with municipal wastewater effluents can occur through ingestion, swimming, direct or indirect contact with water from water reuse applications, or ingestion of seafood. Beyond these circumstances of direct contact, it is important to consider also that municipal wastewater effluents become a part of the hydrologic cycle. As such, wastewater effluents represent potentially important sources of biological and chemical constituents in water supplies; in a very real sense, "we all live downstream".

Historically, most wastewater disinfection operations have used chlorine as the disinfectant. Chlorine is known to be effective for inactivation of common bacterial indicator organisms; however, several important drawbacks to chlorine-based disinfection have been identified, including its relative ineffectiveness against some microbial pathogens (e.g., bacterial spores, enteric viruses, and protozoan [oo]cysts) and repair or regrowth of pathogens postdisinfection. Therefore, conditions that accomplish acceptable inactivation of indicator bacteria by chlorine-based disinfection strategies do not necessarily guarantee safety of a treated water supply.

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UV irradiation is widely recognized as an alternative to chlorination/dechlorination for disinfection of municipal wastewaters. UV radiation is a broad-spectrum antimicrobial agent. However, some viral pathogens are known to be resistant to UV radiation, and the issue of repair and recovery of the exposed microbial community is also a potential drawback of UV-based disinfection processes. Therefore, as in the case of chlorination, conditions of UV irradiation that prove to be sufficient for inactivation of indicator bacteria do not guarantee an acceptable level of treatment for all microbial pathogens.

It is clear that the proper application of disinfectants can lead to removal or inactivation of microbial pathogens; however, given the drawbacks listed above, there is some question as to whether disinfection of municipal wastewater effluents should be applied in all cases. In many developed countries outside North America, wastewater disinfection is practiced only in situations where a direct, clear threat to human health is evident, such as discharges to bathing areas or shellfish breeding grounds. The occurrence of waterborne diseases in these areas is not substantially different from that of North America, where wastewater disinfection is required in the vast majority of cases. However, even within the United States, many states have chosen to require disinfection only on a seasonal basis. These attributes have prompted a reevaluation of the assignment of disinfection as a default application.

A broad range of possible options exist for disinfection of municipal wastewaters, from no disinfection at all to aggressive operations that accomplish extensive inactivation of recalcitrant waterborne microorganisms. The following sections present summaries of investigations that were performed in the mid1970s that have become classics in the disinfection field. These summaries provide useful illustrations of the range of treatment objectives and wastewater disinfection operations in place in the United States today.

Sanitation Districts of Los Angeles County, California (Pomona Virus Study [Parkhurst, 1977]). The Los Angeles County Sanitation District, in conjunction with the U.S. Environmental Protection Agency (U.S. EPA) (Washington, D.C.) and the California State Water Resources Control Board (Sacramento, California), conducted a study with the objective of providing data regarding alternative tertiary treatment approaches for water reuse applications that could allow compliance with Title 22 of the California Administrative Code. Title 22 represents the California State Health Department's Wastewater Reclamation Criteria. The study involved operation of four pilot-scale tertiary treatment processes. Disinfectants included in these four systems were inorganic combined chlorine, free chlorine, and ozone. At the time of this investigation, UV irradiation was not viewed as a viable alternative to chlorine.

While this landmark study was relevant for a number of reasons, perhaps the most tangible outcome of this study with regard to the issue of the need for municipal wastewater disinfection was the definition of the conditions of chlorine-based disinfection that are required to achieve acceptable treatment in a reuse setting. Specifically, the conditions of chlorination required to accomplish reliable compliance with Title 22 were as follows:

- Combined chlorine residual of at least 10 mg/L (as chlorine [Cl_2]) for a contact time of at least 2 hours, or
- Free chlorine residual of at least 4 mg/L (as Cl_2) for a contact time of at least 2 hours.

These disinfection conditions accomplished roughly 4 $\log_{10}$ inactivation of seeded virus and were consistently in compliance with the coliform regulation. When used in conjunction with other appropriate physicochemical processes, treatment consistently accomplished overall virus inactivation (or removal) of roughly 5 $\log_{10}$ units.

Metropolitan Water Reclamation District of Greater Chicago, Illinois. Leadership within the Metropolitan Water Reclamation District of Greater Chicago, Illinois (MWRDGC), has often challenged conventional thinking on topics relating to municipal wastewater treatment; in several cases, the approaches taken by the MWRDGC to solve water treatment and water quality problems have resulted in important innovations that have subsequently been adopted by other municipalities. An example is the MWRDGC's approach to disinfection, which is described in great detail in a series MWRDGC publications (Lue-Hing et al., 1976; Sedita, Lue-hing, and Haas, 1987; Sedita, Zenz, Lue-Hing, and O'Brien, 1987).

Beginning in July 1972, the MWRDGC implemented continuous chlorination of the effluents from all of its facilities. Soon thereafter, the district initiated testimony before the Illinois Pollution Control Board questioning the wisdom of chlorine-based disinfection. To support this effort, the MWRDGC began an extensive investigation of the advantages and disadvantages of chlorination. In general terms, the MWRDGC demonstrated that water quality in the receiving waters downstream of their facilities, which at times contained as much as 90% effluent (therefore, very little dilution), was the same or better when chlorine-based disinfection was terminated than when chlorination was practiced. Chlorination was observed to result in an improvement in bacterial quality in their effluent only within a short reach of receiving stream (roughly 16 to 22 km [10 to 15 river miles] downstream of the outfall). Viable enteric viruses in receiving streams were not significantly affected by chlorination, as practiced at the district's facilities. It is important to note that this conclusion was reached for a system that was based on a nitrified effluent. Therefore, the chlorine residual would probably have been present in the form of free chlorine, which is generally regarded as the most effective form of chlorine for inactivation of planktonic microorganisms. Chlorination also resulted in a substantial reduction in fish populations in receiving streams. In addition, the absence of fish allowed for increased populations of nuisance insects in and around Chicago waterways.

Based on their findings, MWRDGC presented a compelling argument that chlorination did not yield the benefits that were typically ascribed to disinfection practices; the risks of microbial exposure were not substantially affected by chlorination. Moreover, MWRDGC argued that the practice of chlorination was actually detrimental to water quality, based on measurements of aquatic life and other water quality parameters. It is noteworthy that these observations were made in receiving streams that, at times, were essentially undiluted municipal wastewater effluent from wastewater treatment facilities that used fairly conventional, though effective, treatment operations.

Based on the evidence presented to them, the Illinois EPA granted MWRDGC's request to discontinue disinfection at its largest facilities (Stickney, Northside, Calumet, and Lemont water reclamation plants [WRPs]). Subsequent monitoring of effluents and receiving streams demonstrated improvements in water quality. Disinfection by chlorination/dechlorination continues at the three other district facilities (Egan, Kirie, and Hanover Park WRPs) on a seasonal basis.

Table 1—Typical NPDES limitations for publicly owned treatment works in Indiana relevant to disinfection.

Parameter	Limit	Limit type
Fecal coliform	<200 cfu/100 mL	Monthly geometric mean
	<400 cfu/100 mL	Weekly geometric mean
E. coli	<235 cfu/100 mL	Daily maximum
	<125 cfu/100 mL	Monthly geometric mean
Total residual chlorine	<0.02 mg/L (as Cl_2)	Daily maximum
	<0.01 mg/L (as Cl_2)	Monthly arithmetic mean
pH	6 to 9	
Ammonia-nitrogen	Water-quality-based limitation	

By comparison with most conventional disinfection practices in use today (for purposes of this manuscript, the term *conventional disinfection* will refer to disinfection operations that do not represent opportunities for water reuse, and therefore are not subject to reuse criteria), such as those that were in place in MWRDGC facilities at the time of their studies, the conditions of chlorination defined by the Pomona Virus Study can be characterized as extreme. The regulatory constraints that are imposed for most scenarios involving conventional disinfection are substantially less severe than those imposed by Title 22. As an example, Table 1 lists typical National Pollutant Discharge Elimination System (NPDES) permit limitations issued by the Indiana Department of Environmental Management (Indianapolis) that are relevant to disinfection operations. Similar discharge limitations are imposed by regulatory agencies in other states.

In practical terms, these constraints are met in well-run municipal wastewater treatment facilities by maintaining a chlorine residual of 1 to 2 mg/L (as Cl_2) for a detention time of 20 to 40 minutes, followed by tetravalent sulfur [S(IV)]-based dechlorination. When relevant, ammonia-nitrogen (NH_3-N) limitations are generally met by biochemical nitrification.

To put these treatment conditions into perspective, it is useful to characterize the conditions of chlorination used in each system. A "conventional disinfection" operation may accomplish disinfection based on a *CT* value (defined as the product of residual chlorine concentration and mean hydraulic detention time) of 40 to 80 mg · min/L, whereas a disinfection system that is implemented to satisfy the constraints of Title 22 may require chlorine exposure of more than 1000 mg · min/L.

Clearly, this range of possible chlorination conditions will yield a corresponding range of antimicrobial (and other) effects. In the time since the completion of the Pomona Virus Study and MWRDGC's research on the subject of chlorine-based wastewater disinfection, UV irradiation practices have been adopted to meet the constraints imposed by wastewater treatment objectives. The conditions of UV irradiation required to satisfy Title 22 constraints (and similar reuse constraints in other areas) are substantially more severe than those required to meet the constraints of "conventional disinfection".

Project Objectives

The examples described above illustrate a broad range of disinfection practices that are being applied across the United States. This range of practices brings with it a range of water quality issues that are relevant to human health. To address this range of issues, a research project was initiated to address the following two basic questions:

(1) Should wastewater disinfection be practiced?
(2) Under circumstances where the answer to question (1) is yes, how should disinfection be accomplished?

Because they represent the disinfectants of choice for municipal wastewaters in the vast majority of circumstances today, chlorination/dechlorination and UV irradiation were chosen for investigation in this research. Both disinfectants were applied in bench-scale systems to effluent samples collected from several municipal wastewater treatment facilities. Facilities were selected to provide a spectrum of effluent quality, particularly as related to effluent ammonia-nitrogen and organic nitrogen. Reduced nitrogen (in the forms of ammonia-nitrogen and organic nitrogen) was viewed as a critical factor relative to chlorine-based disinfection because of the formation of inorganic and organic chloramines, respectively. In general, inorganic chloramines are less effective than free chlorine for inactivation of planktonic microorganisms, while organic chloramines have little or no antimicrobial character (Donnermair and Blatchley, 2003), but may represent sources of effluent toxicity (Gong et al., 2004).

Disinfectants were applied under conditions that were sufficient to accomplish compliance with relevant effluent discharge regulations based on microbial quality and chemistry. Bacterial and viral responses to disinfectants were then characterized. All compliance limits used as targets in this research corresponded with conventional disinfection, as defined above.

Materials and Methods

A complete description of methods and the results and conclusions of this research can be found in the final report for Water Environment Research Foundation (Alexandria, Virginia) project 99-HHE-1. Undisinfected effluent samples were collected at five municipal wastewater treatment facilities, designated herein as facilities A to E for purposes of providing anonymity to the facilities. After collection, samples were packed in ice and shipped by express courier to participating laboratories for experimentation and analysis.

Facility A uses conventional primary clarification and activated sludge (with nitrification); effluent from this facility consistently displays high quality in terms of conventional bulk parameters such as five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), and ammonia-nitrogen. At the time of this research, facility B used conventional primary settling and activated sludge treatment without nitrification. Effluent quality for samples collected during this research was typically poorer than from the other facilities in terms of BOD_5, TSS, and ammonia-nitrogen. Facility C was somewhat unusual in that effluent was subjected to nitrification and denitrification before discharge. Facility D, which subjects the effluent to conventional secondary treatment (without nitrification) and filtration, produces a high quality effluent in terms of BOD_5 and TSS, but with a relatively high concentration of ammonia-nitrogen. Facility E uses conventional primary settling and activated sludge with nitrification.

Range-finding experiments were conducted with samples from each facility to determine bench-scale conditions of disinfection that would allow compliance with relevant discharge regulations, based on concentrations of viable indicator bacteria and residual chlorine. Based on these experiments, the conditions of disinfection required for each disinfectant were defined.

Chlorination/dechlorination was conducted in well-mixed batch reactors using an initial chlorine concentration of 2.0 mg/L (as Cl_2) and a contact time of 40 to 60 minutes. The forms of residual chlorine that were generated in solution were defined by N,N-diphenyl-*p*-phenylene-diamine/ferrouos ammonium sulfate (DPD/FAS) titration (APHA et al., 1998) and by membrane introduction mass spectrometry (Shang and Blatchley, 1999). For effluent samples from the nitrifying facilities (A, C, and E), residual chlorine existed as free chlorine; for effluent samples from non-nitrifying facilities (B and D), residual chlorine was present in the form of combined chlorine, with the vast majority of the residual being present as monochloramine (NH_2Cl). Samples were dechlorinated by addition of sodium thiosulfate in slight stoichiometric excess of the chlorine residual present at the end of the exposure period.

For most experiments involving UV radiation, disinfectant exposure was accomplished in small, well-mixed, batch reactors under a monochromatic (λ = 254 nm) flat-plate collimated beam (Blatchley, 1997). For experiments requiring relatively large sample sizes (i.e., more than 1000 mL), irradiation was accomplished using a capillary-flow reactor (Gong and Blatchley, 2002). The UV dose delivered to samples examined in this research ranged from 0–20 mJ/cm^2. Disinfectant exposures were conducted at each participating laboratory immediately before initiation of experiments.

Long-Term Respirometry: Repair and Regrowth of Bacterial Communities Postdisinfection. Disinfected samples were examined by long-term respirometry for purposes of characterizing recovery of the bacterial community postdisinfection. After treatment (i.e., disinfection or control), samples were incubated at 25°C under dark conditions for 6 days in a respirometer (OO-104 system, N-CON Systems Co., Inc., Crawford, Georgia) to study the long-term respirometric behavior of the treated samples. Acetic acid was added to the disinfected samples and controls as an artificial substrate at a concentration of 14.1 mg/L (approximately 15 mg/L biochemical oxygen demand [BOD]). Artificial substrate was added at this concentration to mimic the BOD concentration of typical receiving waters. Acetic acid was selected as the substrate because acetate has characteristics that are representative of substrates that can be expected in natural receiving waters (Shuler and Kargi, 1992).

Concentrations of viable fecal coliform bacteria and total bacterial concentration (TBC) were monitored over the course of respirometry experiments as measures of the responses of the bacterial community to disinfectant exposure. These measurements were conducted daily by membrane filtration and acridine orange staining, respectively (APHA et al., 1998). The respirometer was used to monitor oxygen uptake throughout the 6-day period of each experiment.

For each treatment facility, effluent samples were collected on four different dates and subjected to the same treatments. For each sample, four treatments (original sample without substrate, original sample with substrate, UV-irradiated sample with substrate, and chlorinated/dechlorinated sample with substrate) were applied. The output variables in this study included total oxygen uptake, viable fecal coliform concentration, total bacteria concentration, and the ratio of viable fecal coliform to total bacteria concentration. Because there were orders of magnitude differences in bacterial concentrations between disinfected and undisinfected samples, viable fecal coliform concentrations were $\log_{10}$ transformed.

Other Bacterial Assays. Disinfected samples were also analyzed for viable fecal coliforms, enterococci, and total culturable bacteria. Fecal coliforms were assayed using the membrane filtration method described above. Samples from facilities C and D, both of which discharge through marine outfalls, were assayed for the presence of viable enterococci using a two-step membrane filtration method that uses the selective medium mE and EIA agars (APHA et al., 1998). Total culturable bacteria (TCB) counts were obtained by plating samples onto R2A agar (Reasoner and Geldreich, 1985).

Responses of Indigenous Bacteriophage to Conventional Disinfection. Coliphage analysis was performed by the double agar overlay method (Adams, 1959). Total coliphages (somatic and F-specific) were assayed on tryptic soy agar using a log-phase host culture of *Escherichia coli* (*E. coli*) C-3000 (ATCC #15597). The F-specific coliphages (F+ phages) were assayed using a log-phase culture of *E. coli* F_{amp}-HS (pFamp)R (ATCC #700891) on tryptic soy agar augmented with streptomycin/ampicillin, as specified by U.S. EPA (2001).

Individual phage plaques surviving bench chlorination or UV irradiation were harvested and stored in 0.5-mL aliquots of phosphate buffered saline at 4°C, then regrown to high titer. Bacteriophages isolated in this manner were further characterized by their nucleic acid content. Bacteriophages containing RNA were differentiated from those containing DNA by suppressing growth of isolates in the presence of 100 µg/mL of RNAse (bovine pancreas, type I-A, Sigma, St. Louis, Missouri). Isolates that did not produce plaques in the presence of RNAse were classified as RNA phage. Bacteriophages that were able to form plaques in the presence of RNAse were classified as DNA phage.

Results and Discussion

Long-Term Respirometry: Repair and Regrowth of Bacterial Communities Postdisinfection. The goal of these experiments was to assess responses of bacterial communities in wastewater effluents to disinfectant exposure. For qualitative characterization of bacterial community responses, the following two basic factors were considered: (1) the behavior of indicator organisms (fecal coliforms, used as a surrogate for bacterial pathogens) and (2) the behavior of the total bacterial community. Based on this approach, nine possible outcomes are possible, as summarized in Figure 1. Although it is clear that this method of analysis ignores many potentially important aspects of microbial (bacterial) ecology, it does allow for simple screening of the effectiveness of disinfection processes.

From Figure 1, it is evident that not all disinfection scenarios should (necessarily) be considered effective in terms of reducing human exposure to (bacterial) pathogenic microorganisms. It should be emphasized that this illustration is aimed at a qualitative assessment of the responses of the bacterial community to disinfectant exposure. In examination of the responses of viral and protozoan organisms, the outcomes may be somewhat different in that inactivation, and repair and recovery responses are likely to be substantially different than with bacteria.

Figure 1 lists nine possible scenarios that could develop among wastewater bacteria following disinfection; the effectiveness of a disinfection process can be judged by variations in the total bacterial community and the pathogenic (indicator) fraction. For example, cases c, g, and i may be judged to represent a positive effect of disinfection because they imply a reduction in pathogenic (indicator) bacteria. On the other hand, cases a, b, d, and e have an adverse effect because pathogenic (indicator) bacteria concentrations are not reduced. It is also interesting to note that, in cases f and h, it is difficult to unambiguously judge disinfection efficacy based

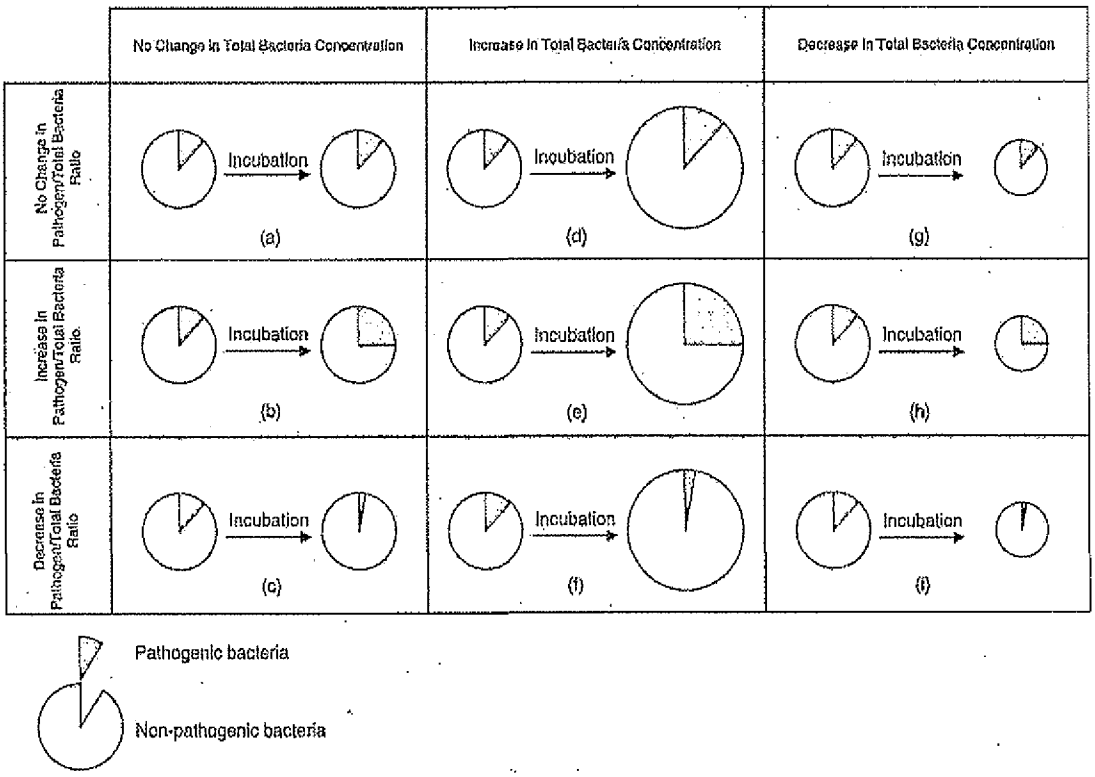

Figure 1—Conceptual representation of the possible fates of bacteria following disinfectant exposure. Disinfection is considered to be antibacterially effective when the risk of human exposure to bacteria is reduced. Moving from left to right, columns represent circumstances of no regrowth, regrowth, and decline in total bacterial population, respectively. Moving from top to bottom, rows represent circumstances in which the fraction of the bacterial population composed of pathogenic (indicator) bacteria does not change, increases, and decreases, respectively. Together, these two attributes (regrowth of the total bacterial population, and changes in the fraction of pathogenic [indicator] bacteria) can be used to represent the effectiveness of disinfection relative to human exposure to bacteria. Cases c, g, and i illustrate beneficial effects of disinfection in that risks of bacterial exposure are reduced; cases a, b, d, and e illustrate cases in which disinfection is not beneficial in that risks of bacterial exposure are not reduced; for cases f and h, additional information is required to judge the effectiveness of disinfection.

on these two criteria. For these two cases, judgment of antibacterial efficacy requires additional information, such as the absolute concentration of viable pathogenic (indicator) bacteria.

To answer the question "is a disinfection process effective?" from the standpoint of bacterial risk, it is necessary to consider both regrowth and the pathogen (indicator) ratio. To do this, it is necessary to investigate the effects of upstream treatment processes, disinfection, and receiving waters on regrowth and the pathogen ratio. Under conditions of abundant substrate supply, rapid-growing microorganisms generally dominate populations. This is true in municipal wastewater treatment facilities, where the abundance of available organic substrates favors the growth of rapidly dividing bacteria, such as coliforms and pseudomonads. These dominant microbial populations in wastewater, which gain a competitive advantage because of their high intrinsic growth rates, are rapidly displaced in competition with other microbial populations of receiving waters as the concentration of organic compounds diminishes, owing to decomposition and dilution; under lower nutrient conditions, a more diverse community of slowly growing bacteria is favored.

For interpretation of the results of these experiments, several assumptions have been made, including the following:

- Fecal coliform bacteria can be used as indicators for pathogenic bacteria in disinfected wastewater effluent. This implies that fecal coliforms can be characterized as having (a) similar susceptibility to disinfection processes, (b) similar intrinsic growth rates, and (c) similar requirements for nutrients as pathogenic bacteria.
- The substrate (acetic acid) used in this study can represent the substrate condition of receiving waters.
- The addition of substrate does not affect microbial ecology relationships during incubation.

It is clear that these assumptions are not entirely valid, because of the following:

- Susceptibility to disinfection processes, intrinsic growth rates, and nutrient requirements for fecal coliform and pathogenic bacteria will be different; they are different even between two pathogenic bacteria. Coliform bacteria are commonly used as an "indicator" of microbial quality. However, it is clear that no single species can truly represent the broad range of microbial pathogens that could be present in a municipal wastewater effluent.
- The nutrient conditions of receiving waters are site-specific, so

Table 2—Summary of bacterial community responses to disinfection treatments. Responses of the bacterial community are identified by a letter, corresponding to one of the nine possible outcomes listed in Figure 1.

Treatment	Location	Incubation time (hours)					
		24	48	72	96	120	144
Original without substrate addition (control)	B	i	i	c	f (−)	i	i
	D	f (−)	f (−)	c,i	c,i	i	i
	A	f (+)	i	i	i	i	i
	C	i	i	i	i	i	i
Original with substrate addition	B	i	i	c,f (−)	f (−)	c,i	c,i
	D	f (−)	f (−)	f (−)	i	c,i	i
	A	e	i	i	i	i	i
	C	i	i	i	i	i	i
UV	B	e	b	h (+)	h (+)	h (+)	i
	D	e	e	e	e	a	h (+)
	A	f (−)	f (−)	f (−)	f (−)	i	i
	C	e	e	h (+)	h (+)	h (+)	h (±)
Chlorination/dechlorination	B	e	e	e	e	e	e
	D	e	e	e	f (+)	e	e
	A	f (−)	f (−)	f (−)	f (−)	f (−)	e
	C	f (−)	e	e	f (−)	e	f (−)

it is impossible to find a substrate that can be representative of all situations.

- Acetic acid can be biodegraded easily; this will benefit those bacteria with high intrinsic growth rates. The composition of biodegradable compounds in receiving waters will vary.

The conditions used in these experiments provided a common basis for examination of the behavior of municipal wastewater effluents from several different facilities. As such, it was possible to compare the long-term behavior of multiple samples collected from each of the four facilities. The conditions of these experiments were believed to be generally representative of actual conditions in receiving waters; however, it is not reasonable to expect direct, quantitative translation of these results to conditions in the respective receiving waters.

Assessments of disinfection efficacy have traditionally been based on the inactivation or removal of fecal indicators, such as total coliforms, fecal coliforms, and fecal streptococci. However, there is little information to allow correlation between these indicator organisms and real pathogens, particularly in terms of their long-term behavior. Although the assumptions listed above are not entirely justified, it is necessary to use this approach because relatively little information has been obtained regarding the ecological relationships between fecal coliform and pathogenic bacteria, many of which are not culturable. Fecal coliforms have been chosen as the target microorganism because they represent a common indicator microorganism for wastewater effluent regulation.

Responses of Fecal Coliforms (Indicator) and Total Bacterial Counts. As described previously, the effectiveness of disinfection treatment processes was assessed based on an index test in which the dynamic behavior of fecal coliforms and total bacterial counts were examined throughout the course of incubation used in the long-term respirometry assays. Based on the 16 experimental runs (four treatment facilities, four replicates per facility), four different treatments were applied; fecal coliform and total bacteria concentrations were recorded for each case from $t = 0$ hours (immediately after treatment) to $t = 144$ hours. Because there were four replicates involved in each treatment facility, an average value of the four replicates was used for representation of the total bacteria concentration and fecal-to-total-bacteria ratio. Based on this information, classification of disinfection process proceeded using Figure 1. Table 2 provides a summary of the results of these measurements for all four facilities and all four exposure scenarios (treatments). Recall that effluent samples from facilities B and D were non-nitrified, whereas those from facilities A and C had been subjected to nitrification (and denitrification, in the case of facility C).

In general, the treatments involving no disinfection (designated in Table 2 as "original without substrate addition" and "original with substrate addition") resulted in an improvement in bacterial quality over the course of the 6-day incubation procedure. In contrast, overall bacterial quality remained essentially unchanged or degraded following the disinfection procedures. The decreases in bacterial quality were most evident in the application of chlorination/dechlorination to non-nitrified effluent samples, where +1-valent chlorine would have been present predominantly in the form NH_2Cl. While it is clear that chlorine- or UV-based disinfection will accomplish an immediate decrease in the concentrations of viable bacteria, it appears that the long-term effects of chlorination/dechlorination or UV irradiation may actually be detrimental to water quality, in terms of bacterial composition.

It is important to recognize that the changes among the bacterial populations were all normalized against the bacterial composition at $t = 0$, corresponding to the time at which disinfectant exposure was terminated. This method of normalization can provide a misleading representation of bacterial population dynamics, in that the basis of normalization was different for all samples. To address this issue, the data from the long-term respirometry experiments were presented in another form. Table 3 provides a summary of average total bacterial counts and average viable fecal coliform concentration for each facility and treatment. The non-normalized data in this table allow a direct comparison of bacterial changes among all of the treatments, over the period of incubation used in these experiments.

Several important trends are evident in the data presented in Table 3. First, the disinfection procedures generally accomplished

Table 3—Summary of bacterial responses to disinfection treatments for samples collected from all four facilities.

Facility	Treatment*	TBC, t = 0 (#/100 mL)	TBC, t = 144 hours (#/100 mL)	Fecal coliform, t = 0 (cfu/100 mL)	Fecal coliform, t = 144 hours (cfu/100 mL)
B	UV	6.02×10^8	4.63×10^8	495	300
	Chlorination/dechlorination	5.22×10^8	5.99×10^8	715	1133
	Ori w/	5.34×10^8	5.09×10^8	2.81×10^5	5625
	Ori w/o	5.49×10^8	3.72×10^8	2.16×10^5	7275
D	UV	9.44×10^7	7.90×10^7	640	990
	Chlorination/dechlorination	8.53×10^7	4.09×10^8	61.5	2040
	Ori w/	1.12×10^8	7.00×10^7	2.38×10^5	2718
	Ori w/o	8.54×10^7	4.25×10^7	1.95×10^5	1282
A	UV	5.63×10^7	3.69×10^7	55	0
	Chlorination/dechlorination	6.31×10^7	2.16×10^8	9	500
	Ori w/	7.16×10^7	4.54×10^7	9850	175
	Ori w/o	6.61×10^7	4.77×10^7	9350	475
C	UV	2.02×10^8	1.62×10^8	2	0
	Chlorination/dechlorination	2.28×10^8	3.99×10^8	0.25	0
	Ori w/	2.41×10^8	7.77×10^7	1925	93
	Ori w/o	2.18×10^8	1.21×10^8	2400	9

* "Ori w/" indicates original (control) sample with acetic acid substrate; "Ori w/o" indicates original (control) sample without acetic acid substrate.

effective inactivation of fecal coliform bacteria, although viable fecal coliform concentrations in some samples exceeded regulatory limits. The bacterial population that existed post-UV irradiation tended to decline over the period of incubation, as measured both by TBC and fecal coliform. In contrast, the bacterial population that existed postchlorination consistently increased, both in terms of TBC and fecal coliform. The TBC at the end of the incubation period was consistently higher in the samples that had been subjected to chlorination/dechlorination than any other treatment. In some cases, fecal coliform concentrations in the chlorinated/dechlorinated samples were higher at the end of the period of incubation than the undisinfected samples. Disinfectant exposure appears to be effective for short-term control of bacterial populations; however, the data presented in Table 3 suggest that, from the standpoint of bacterial composition in the long-term, opting to skip disinfection may yield better water quality than application of disinfection. If disinfection needs to be implemented, these data indicate an advantage of UV irradiation relative to chlorination/dechlorination.

Oxygen Uptake. Final oxygen consumption of each treatment was recorded after an incubation period of 144 hours. The resulting oxygen consumptions from each treatment were compared with initial ammonium concentrations based on 64 test samples, and the results are shown in Figure 2. The superimposed straight line represents the theoretical nitrogenous oxygen demand with a slope of 4.3 g O_2/g $[NH_4^+]$-N (Tchobanoglous and Burton, 1991). There was no clear trend between oxygen consumption and initial ammonium concentration when ammonium concentration was low (<1 mg/L), corresponding to effluent samples collected from nitrifying facilities. However, in samples collected from non-nitrifying facilities, where ammonium concentration was substantially higher, it was clear that the total oxygen consumption was strongly related to initial ammonium concentration, and higher than theoretical oxygen consumption based on ammonia oxidation was observed in most cases (except for UV irradiated samples). This suggests that most oxygen was consumed in the oxidation of ammonium (nitrification). For the range of ammonium-nitrogen concentration present in the samples that were tested in this research ($[NH_3]_0 \approx 0$ to 18 mg/L as nitrogen), the undisinfected samples, with or without substrate, typically yielded similar oxygen consumption, indicating that the artificial substrate did not cause a significant increase in overall oxygen uptake. Also, oxygen consumption in the undisinfected samples was generally higher than in the disinfected samples.

Oxygen consumption in UV-irradiated samples under high ammonium concentrations (14.35 and 18.33 mg/L as nitrogen) was substantially lower than theoretical oxygen consumption predictions based on biochemical oxidation of ammonia-nitrogen. The reason for this behavior is not clear, but it should be pointed out that these two samples were both from facility D, which uses filtration as an upstream treatment process. Guerrero and Jones (1996) indicated that exposure to visible light (400 to 475 nm) and near-UV irradiation (300 to 375 nm) will cause inhibition of nitrite oxidizers and ammonium oxidizers. Furthermore, they found that ammonium oxidizers are more sensitive to photoirradiation than nitrite oxidizers. Guerrero and Jones (1996) also investigated dark recovery of nitrifying bacteria after photoinhibition. They found that the recovery rates of *Nitrosomonas cryotolerans* and *Nitrosococcus oceanus* were slower when exposed to a short wavelength of radiation (300 nm), and the maximum recovery percentage appeared to be dependent on the wavelength of irradiation. However, no information regarding nitrifier response to UV_{254} (or other germicidally active wavelengths) was discussed in their studies, nor was the relative susceptibility of nitrifying bacteria to UV irradiation included. Therefore, similarities in observed responses of nitrifying bacteria in this research can only be made by inference of a similar set of processes being induced by solar UV radiation and the UV radiation that characterizes low-pressure mercury lamps (λ = 254 nm), as used in this research.

Other Bacterial Assays. The concentration of indicator organisms present in a water sample is often used to represent microbial quality as an index parameter. Coliform bacteria are commonly used for this purpose, but many alternative indicator organisms have been proposed and are in use today. For example, enterococci are

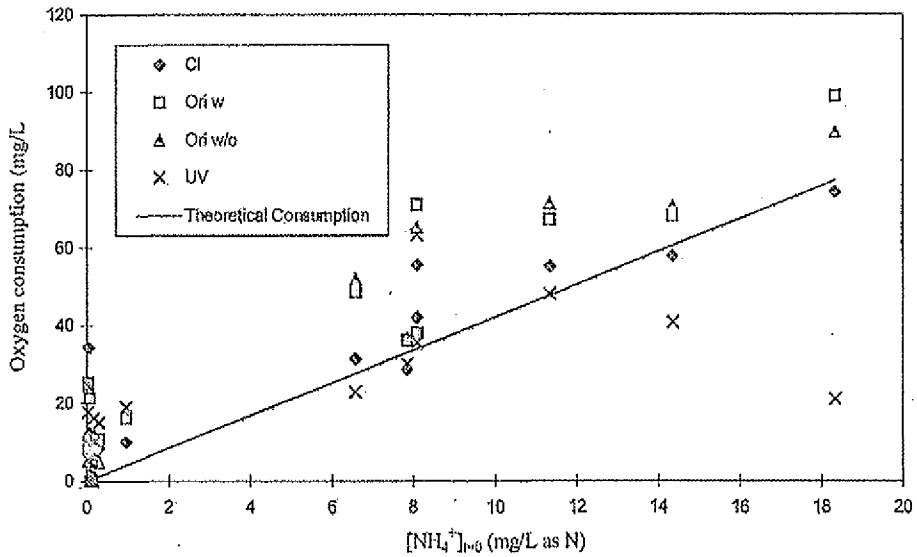

Figure 2—Results of oxygen uptake of different treatments at the end of 144-hour incubation period. Data are included for samples collected from four municipal wastewater treatment facilities; the straight line represents the theoretical oxygen consumption based on ammonium-based (nitrogenous) biochemical oxygen demand.

commonly used with facilities that discharge to a marine environment. Experiments were conducted to characterize the responses of fecal coliforms and enterococci to the bench-scale disinfection procedures used in this research. Figure 3 provides summaries of the results of these experiments for samples collected from facilities D and C.

While some variation was evident in the $\log_{10}$ inactivation responses of fecal coliform bacteria among the various samples collected, inactivation responses measured on any individual sample by the two disinfectants were quite similar. Similar conclusions can be reached with regard to the enterococcus data. Collectively, these data indicate that the conditions of disinfection by UV irradiation and chlorination/dechlorination were comparable, both in terms of coliform inactivation and enterococcus inactivation. Moreover, it appears that fecal coliforms and enterococcus are similar in terms of their behavior as indicator organisms.

These conclusions are based on effluent samples from facilities that produce effluents with substantially different residual nitrogen composition. Facility D yields an effluent that typically contains a relatively high concentration of ammonia-nitrogen, while effluent from facility C has been subjected to nitrification and denitrification. Therefore, residual chlorine composition in effluent samples from facility D was dominated by NH_2Cl, whereas the chlorinated samples of effluent from facility C were dominated by free chlorine.

The responses of TCB were also examined in disinfected samples with regard to their ability to function as an indicator group and because it represents an index of the total microbial burden to be imposed on a disinfection system. The TCB are those bacteria that can grow on laboratory media at a specific temperature during a given period of time. The assay used in this study is commonly referred to as the heterotrophic plate count assay (APHA et al., 1998). This method does not recover strict anaerobes.

The TCB made up from 4.70% (facility E) to 107.3% (facility D) of the TDC in the samples analyzed during this study. For comparison, fecal coliform comprised between 0.05% (facility C) and 39.4% (facility B) of the TCB, while enterococcus comprised between 0.01% (facility C) and 16.2% (facility D) of the TCB. These data clearly demonstrate that the conventional indicator groups of bacteria comprised only a small percentage of the total bacterial population that were present in the wastewater samples analyzed in this work. Even the most general and efficient method of culturing the total bacterial populations from these samples performed poorly. It is an established concept in microbial ecology that culture-based methods will not recover all of the bacteria from any type of sample (Amann et al., 1995; Brock, 1987).

Pooled data from all facilities were used to assess the efficacy of each disinfectant. There were no significant differences ($P = 0.052$) between TCB abundances following disinfection with chlorine and UV radiation, but both treatments were significantly different ($P < 0.001$) from TCB abundances in the untreated samples. The TCB abundances in untreated, chlorinated, and UV-irradiated samples did not correlate with the fecal coliform or enterococcus abundances in these same samples from the respective facilities. Additionally, there were significant differences ($P < 0.001$) between the TCB and the fecal coliform and enterococcus abundances in untreated, chlorinated, and UV-irradiated samples. These data indicate that the occurrence of and changes in the abundances of TCB is a dynamic process, as observed with fecal coliform and enterococcus. However, the TCB populations in the samples assayed in this study were not affected to the same extent by the actions of the disinfectants, as were the fecal coliform and enterococcus. This difference was most likely a result of significantly greater numbers of TCB than fecal coliform and enterococcus in each sample and the fact that the indigenous bacteria were inherently more resistant, based on culturability, to chlorine and UV disinfection than fecal coliform and enterococcus (Belkin et al., 1999; Matin and Harakeh, 1990; Olson and Stewart, 1987; Russell et al., 1997). Moreover, the TCB assay responds to a broader spectrum of bacteria than the fecal coliform or enterococcus assays. Consequently, it is reasonable to expect that the TCB population will display a broad range of susceptibility to externally applied stresses. The TCB assay does not

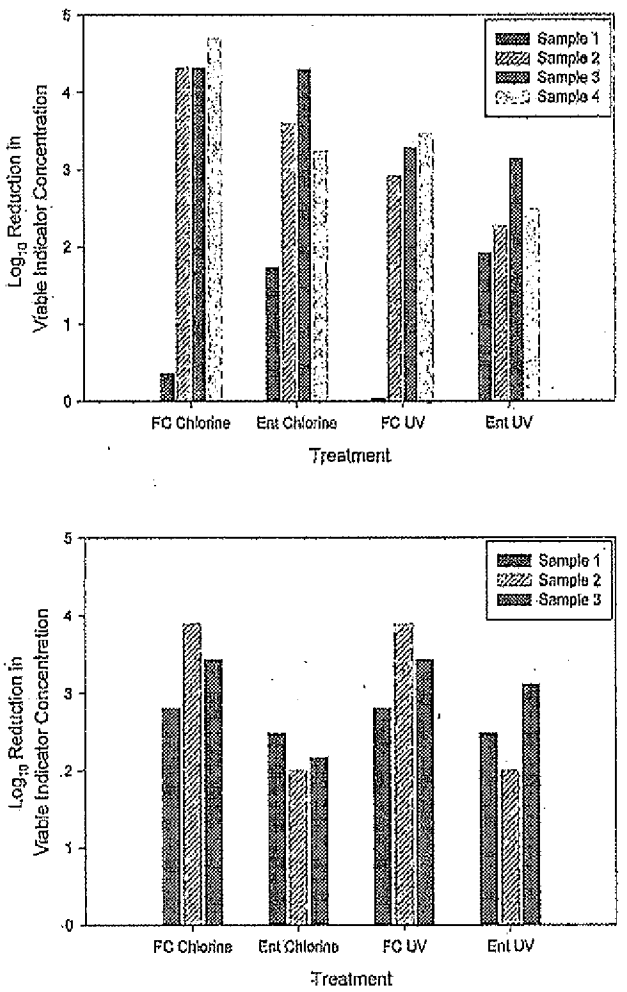

Figure 3—Summary of fecal coliform (FC) and enterococcus (Ent) inactivation by chlorine and UV for effluent samples collected from facility D (top) and facility C (bottom).

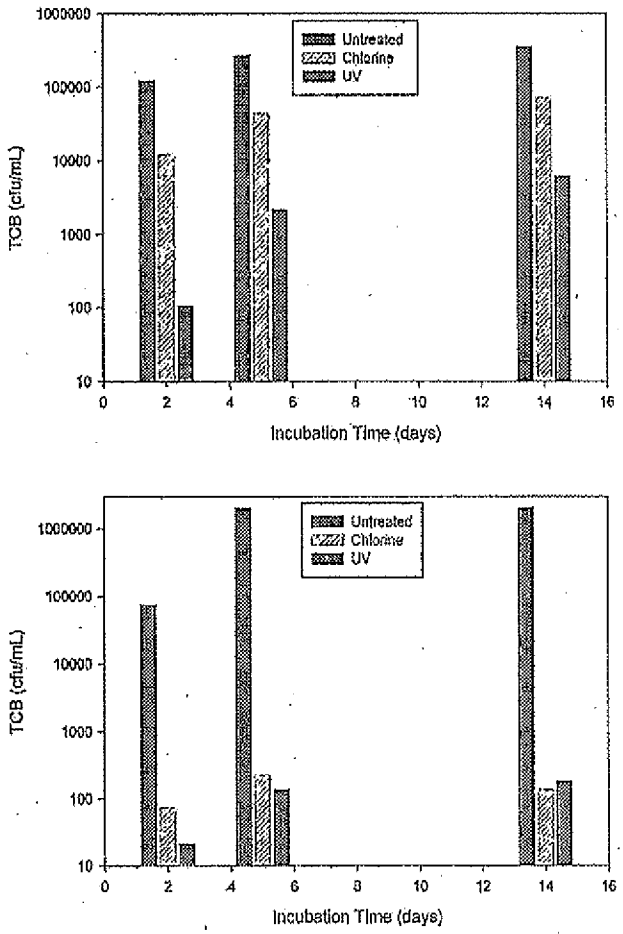

Figure 4—Summary of TCB responses as a function of time for samples collected from facility B (top) and facility C (bottom).

differentiate among bacteria based on their sensitivity to disinfectants. Therefore, the observed behavior of the population of bacteria that respond positively to the TCB assay will be heavily influenced by bacteria that display natural resistance to a form of external stress, such as a disinfectant.

Current regulations that reference the use of this method (i.e., U.S. EPA's Surface Water Treatment Rule, 40 *CFR* 141.74; U.S. EPA [2005]) recommend using a pour plate method and incubating at 35°C for 2 days. Additional guidelines for the use of this method suggest that increasing the incubation period to 5 to 7 days and lowering the incubation temperature to between 20 and 28°C will provide conditions for obtaining "the highest counts" (APHA et al., 1998). Previous work by Lisle et al. (1998 and 1999) has shown that bacterial growth rates on culture media are significantly reduced following exposure to disinfectants and that prolonged incubation at room temperatures significantly increased recovery efficiencies. It is worth noting that incubation periods for fecal coliform and enterococcus cannot be extended, as both media used in these assays would be overgrown with non-fecal coliform and non-enterococcus bacteria within 5 days. Additionally, the respective methods have been standardized for regulatory applications, and alterations to these methods invalidate any resulting data.

In this study, TCB incubation at 21 to 23°C was extended to 14 days, with counts being conducted on days 2, 5, and 14. Figure 4 illustrates TCB recovery as a function of time for samples collected from facilities B and C. Similar data were collected for samples collected from facilities A, D, and E (data not shown). Several common trends were evident among these data sets. First, the TCB concentrations for the untreated samples were consistently greater than those for the chlorinated and UV-irradiated samples throughout the incubation period. Second, there was a general increase in TCB values during the incubation period. In most, but not all cases, the samples that were subjected to UV irradiation yielded lower TCB counts than samples that had been subjected to chlorination/dechlorination.

These data indicate that the TCB assay may represent a desirable alternative as an indicator test for microbial (bacterial) composition. An important advantage of this assay over conventional indicator testing based on coliform bacteria or enterococcus is that this assay represents a larger fraction of the bacterial population than either of the conventional indicator groups. This greater diversity in testing also yields a bacterial population that is likely to display greater apparent resistance to environmental stresses (e.g., disinfectant exposure) than testing based on conventional indicators because the

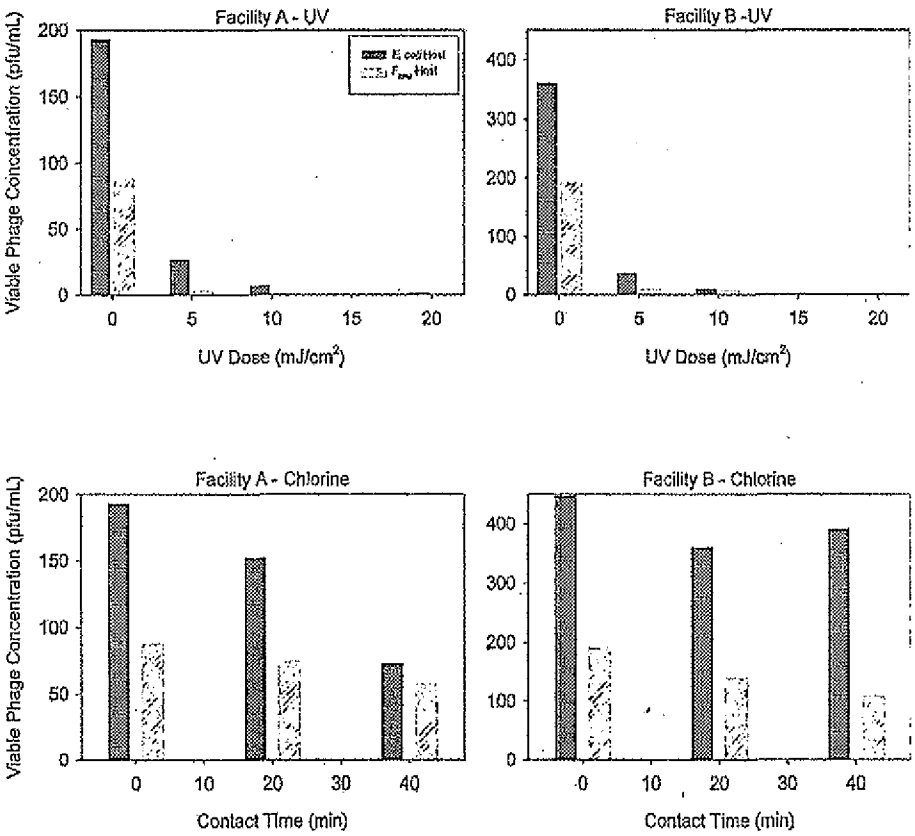

Figure 5—Representative dose-response curves for indigenous phage from wastewater effluent samples collected from facilities A and B. Samples were subjected to UV irradiation under a collimated beam or chlorination (initial chlorine concentration = 2.0 mg/L as chlorine [Cl_2]) in batch reactors. Note the use of different vertical axis scales to represent the responses of phages from facility B.

bacterial population that yields a response to the assay has a greater range of sensitivities to disinfectant exposure than do coliforms or enterococci. In addition, TCB incubation can be conducted over a relatively long period of time, thereby allowing assessment of bacterial repair and recovery.

Viewed differently, diversity and incubation time can represent disadvantages of the TCB assay relative to conventional indicator assays. A drawback of diversity associated with this assay is that it provides less detailed information regarding the specific bacteria that respond to testing than do the more species-specific assays that are used for coliform or enterococcus testing. Furthermore, while extended incubation time does permit an assessment of repair and regrowth, it also represents a greater analytical burden than either of the conventional assays.

Responses of Indigenous Bacteriophage to Conventional Disinfection. Traditionally, assessments of antimicrobial efficacy in disinfection operations used for treatment of municipal wastewater have been based on measurements of the concentration of viable indicator bacteria. While these organisms satisfy some of the basic requirements of indicator organisms, several important shortcomings of their application for this purpose have been identified (see preceding discussion). Among the most important of these limitations are the relative ease with which most bacterial indicators are inactivated by common disinfectants and the fact that enteric viruses generally represent the most serious risk to human health among wastewater microorganisms.

Unfortunately, the assays used to assess viability (or infectivity) among human enteric viruses are time-consuming and expensive to conduct. In most situations, it is not practical to monitor for human enteric viruses. However, several indigenous phages have been identified that are structurally or otherwise similar to human viruses. Assays of phage viability (infectivity) are comparatively easy to conduct. Therefore, a series of experiments was conducted to assess the effects of common wastewater disinfectants on the concentrations of viable (infective) indigenous phages.

The concentration of indigenous bacteriophages in effluent samples from the five wastewater treatment facilities varied considerably, with the highest phage concentrations isolated from facility B. The phage population for this facility was comprised of both somatic and F-specific phages, with facility B displaying the highest concentration of F-specific phages of all the facilities examined. In decreasing order of initial phage concentration, the facilities were ranked as: B > A > D ≈ E > C. The samples containing the highest concentration of phages surviving either chlorine or UV disinfection generally reflected the ranking of the facilities with regard to initial phage concentration.

Although samples from all five facilities were analyzed for phage composition and dose-response behavior, the vast majority of useable data came from the analysis of samples collected from facilities A and B. Samples collected from facilities C and D had extremely low phage concentrations, such that it was difficult to assess their dose-response behavior or nucleic acid content. The

Table 4—Nucleic acid content of postdisinfection viable phages in samples that had been subjected to bench-scale disinfection.

Facility	Disinfection exposure scenario	Host strain	Number of DNA isolates	Number of RNA isolates
A	40-minute contact time; 2.0 mg/L as Cl_2	*E. coli* C-3000	7	4
	40-minute contact time; 2.0 mg/L as Cl_2	*E. coli* F_{amp}	3	2
	20 mJ/cm^2 UV	*E. coli* C-3000	0	0
	20 mJ/cm^2 UV	*E. coli* F_{amp}	0	3
B	40-minute contact time; 2.0 mg/L as Cl_2	*E. coli* C-3000	6	0
	40-minute contact time; 2.0 mg/L as Cl_2	*E. coli* F_{amp}	4	2
	20 mJ/cm^2 UV	*E. coli* C-3000	0	0
	20 mJ/cm^2 UV	*E. coli* F_{amp}	0	0
E	40-minute contact time; 2.0 mg/L as Cl_2	*E. coli* C-3000	0	0
	20 mJ/cm^2 UV	*E. coli* C-3000	2	2

samples collected from facility E had quantifiable concentrations of viable phages; however, both disinfection schemes yielded samples in which F+ phage concentrations were below the limit of detection. One of the UV irradiated samples yielded a measureable concentration of somatic phage (see below).

Figure 5 illustrates representative examples of phage responses to exposure to UV and chlorine in samples collected from facilities A and B. The data in these figures illustrate several of the important trends that were observed in the data from the experiments focused on phage inactivation. First, the concentration of viable phages present in the samples was variable and low. Some evidence of seasonal effects was apparent in samples collected from winter and spring months at these two facilities, with summer phage concentrations being substantially higher than those observed in winter. Second, the assay based on *E. coli* C-3000 consistently yielded higher concentrations of viable phages than the assay based on *E. coli* F_{amp}.

Of particular importance in this work were the abilities of residual chlorine and UV radiation to accomplish inactivation of the indigenous phage. In the case of samples from facility A (a nitrifying facility), residual chlorine existed largely in the form of free chlorine. Exposure to chlorine under conditions that were shown to be capable of complying with discharge limitations generally yielded poor phage inactivation.

For samples that were subjected to UV irradiation from facilities A and B, phage inactivation was generally good. For the examples illustrated in Figure 5, which contained some of the highest initial phage concentrations among the samples collected in this research, exposure to a UV dose of 20 mJ/cm^2 resulted in viable phage concentrations that were at or below the limit of detection.

Measurements of nucleic acid content were used as an index of phage diversity in disinfected samples. Table 4 provides a summary of nucleic acid composition measurements for surviving phages from selected samples from this portion of the research. In general terms, UV irradiation yielded much less diverse phage populations than did chlorination for the conditions of disinfection used in these experiments.

In general terms, the results of these experiments indicate that the conditions of disinfection (based on chlorination with either combined chlorine or free chlorine, or UV irradiation) that are needed to accomplish compliance with discharge regulations used in conventional disinfection operations yield incomplete inactivation of phages. Phage inactivation responses by UV irradiation were on the order of 2 $\log_{10}$ units; phage inactivation by chlorine was less than this value. By extension, this suggests that these conditions of disinfection used for compliance with conventional disinfection may yield poor inactivation of enteric viruses.

Conclusions

The first of the two central questions that formed the basis of this research was "should municipal wastewater effluents be disinfected before discharge?" It is clear that no single response can appropriately answer this important question for all circumstances. The information presented above suggests that "conventional disinfection" of municipal wastewater effluents, as commonly practiced in the United States, is probably not as effective in preventing communicable disease transmission as is generally assumed. It appears that control of bacterial populations is generally effective in receiving waters only within a relatively short distance from the point of discharge. Moreover, viral inactivation accomplished by most systems (particularly those that use chlorination) is probably minimal. Therefore, in situations where direct human contact is likely or when ingestion of indigenous microorganisms in a near-outfall area is likely, it appears that disinfection of municipal wastewater effluents may yield some direct benefits. Anecdotally, it is interesting to note that human contact does occur in many such situations, and it is not obvious that the incidence of disease associated with these situations is abnormally high. Therefore, it may be that the risks of disease transmission associated with these effluents may be less than expected. In situations where direct human contact is unlikely, it is not obvious that disinfection should be used as a default treatment process, at least not using the approaches that are common today.

With this in mind, it is also important to consider the second central question of this research, which is "under circumstances where disinfection is necessary, how should it be accomplished?" In applying any disinfectant, it is critical to strike a balance between minimizing risks associated with microbial pathogens and those associated with disinfection byproducts and related (chemical) toxicological issues. The data presented in this research indicate that UV irradiation and chlorination/dechlorination, when applied with the goal of complying with conventional effluent discharge regulations, are similar in terms of their ability to inactivate waterborne bacteria, although total bacterial populations generally recover to a greater extent in chlorinated effluents than in UV-irradiated effluents. Perhaps more importantly, the conditions that are used to accomplish bacterial (indicator) inactivation based on chlorination/

dechlorination appear to be relatively ineffective for control of waterborne viruses compared with UV irradiation. Therefore, in circumstances where wastewater disinfection is to be applied, it appears that UV irradiation is the method of choice, based on antimicrobial efficacy. However, disinfection practices that are consistent with the objectives of conventional disinfection, as defined herein, do not appear to be effective for inactivation of all pathogens. Decisions regarding the design, implementation, and operation of a disinfection system must be made on a site-specific basis taking into account these and other relevant factors.

Credits

This project was completed with the cooperation of management and operators from several municipal wastewater treatment facilities. Their participation in this project was both necessary and appreciated. This work was supported by a grant from the Water Environment Research Foundation (WERF) (Alexandria, Virginia). A complete report of the findings and recommendations of this investigation has been published and is available from WERF (project number 99-HHE-1).

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BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	
WATER QUALITY STANDARDS AND	)	
EFFLUENT LIMITATIONS FOR THE	)	R08-9
CHICAGO AREA WATERWAY SYSTEM	)	(Rulemaking - Water)
AND THE LOWER DES PLAINES RIVER:	)	
PROPOSED AMENDMENTS TO 35 Ill.	)	
Adm. Code Parts 301, 302, 303 and 304	)	

PRE-FILED TESTIMONY OF CHARLES N. HAAS

My name is Charles Haas. I have been asked by MWRDGC ("the District") to present a summary of my opinions on the risks associated with the use of chlorine as a wastewater disinfectant. For the purpose of this testimony, unless stated otherwise, "chlorine" will include the application of dissolved chlorine gas, sodium hypochlorite solution, or calcium hypochlorite (although for very large facilities such as the District, calcium hypochlorite is not a viable option). My opinions presented will focus on byproducts produced by the use of chlorine as a wastewater disinfectant, relative resistance of particular pathogens of concern in comparison with indicator organisms, and safety and security issues associated with the use of chlorine as a disinfectant.

Qualifications

I am the Betz Chair Professor of Environmental Engineering, and Head of the Department of Civil, Architectural and Environmental Engineering of Drexel University. However, my remarks present my personal opinion and not that of Drexel University. I also serve as co-Director of the Center for Advancing Microbial Risk Assessment, jointly funded by the US Department of Homeland Security and the US Environmental Protection Agency. For more than thirty years, I have worked on water disinfection topics that include experimental and modeling aspects of pathogen control in drinking water, vulnerability assessment of water

treatment plant security, risk assessment of pathogen exposure from diverse media including water. I have been familiar with disinfection issues at the District since my involvement in Illinois Pollution Control Board rulemakings on the District disinfection requirements in the early 1980's. I am author and co-author of more than 160 peer-reviewed papers and books including US EPA Municipal Wastewater Disinfection design manual, chapters on Disinfection in the America Water Works Association-supported *Water Quality and Treatment* manual, and the first book (published in 1999) on *Quantitative Microbial Risk Assessment.* I serve as a member of the Water Science and Technology Board of the National Research Council, on the Board of Directors of the Water Environment Research Foundation and as an area editor of the journal *Risk Analysis*.

Formation of Disinfection Byproducts

When chlorine is added to a treated wastewater, it has long been known that it is capable of reacting with a variety of chemical compounds present in the wastewater (Jolley 1975). Amongst these are organic materials, the reaction of which may result in chlorinated disinfection byproducts. These include trihalomethanes, haloacetic acids and other dissolved organo-halogen compounds. While the production of these can be reduced by very high reduction of organic carbon, and by avoiding complete nitrification, the formation of these byproducts at some level is inevitable (Rebhun et al. 1997).

Even in totally non-nitrified effluents, some particular byproducts of the reaction of chlorine with organic nitrogen can occur. Of particular note is N-Nitrosodimethylamine (NDMA), which is a potent carcinogen (Mitch and Sedlak 2004).

US EPA has set water quality criteria based on human health for the trihalomethanes. Based on a 1 in a million upper bound risk level, the recommended guideline water concentrations are 5.7 parts per billion for chloroform, 4.3 parts per billion for bromoform, 0.55

parts per billion for bromodichlormethane, and 0.40 parts per billion for chlorodibromomethane. Based on the USEPA IRIS (Integrated Risk Information System) (US Environmental Protection Agency) chloroform, chlorodibromomethane and bromoform are considered probable human carcinogens, and dibromochloromethane is considered a possible human carcinogen. There are a large number of other chlorination byproducts formed – not all of which have been identified -- some of which are also considered probable or possible human carcinogens.

Especially under periods of partial or complete nitrification, the chlorination of District effluents would present a high likelihood of exceeding these recommended water quality guidelines.

Although there have not been detailed investigations of the possibility that dechlorination could substantially reduce the occurrence of byproducts, studies in clean water or drinking water are not encouraging of this possibility. Morlay *et al.* (Morlay et al. 1991) chlorinated samples of aquatic humic material and measured both total organic halogen (TOX) and mutagenic activity with and without dechlorination via sodium sulfite. They observed that dechlorination, even sufficient to remove all the disinfectant residual, only partially reduced mutagenic activity and had a relatively small impact on the concentration of TOX (less than an 8% reduction). To my knowledge, there are no wastewater utilities deliberately using dechlorination to achieve disinfection byproduct control, and therefore it it unlikely that the use of dechlorination will substantially impact DBP concentrations, especially of the trihalomethanes for which EPA water quality guidelines exist.

Relative Insensitivity of Some Pathogens

It has long been known that some pathogens, such as viruses are more resistant than indicator organisms such as coliform to chlorine disinfection in wastewater (Grabow 1968;

Hejkal and al. 1979; Rippey and Watkins 1992). As a result, the attainment of satisfactory indicator levels in disinfected wastewater does not assure a low level of risk from exposure to viruses (Gerba et al. 1979) or other pathogens.

It has also been shown that indicator systems provide a poor measure of the risk from viruses, as well as protozoan pathogens (such as *Giardia* and *Cryptosporidium*) in disinfected effluents (Harwood et al. 2005).

Security and Safety Issues

The intrinsic hazards associated with gaseous chlorine at wastewater (and drinking water) disinfection facilities have long been recognized (White 1972). It is increasingly recognized that storage of large amounts of gaseous chlorine (as would occur at District facilities were gaseous chlorine to be adopted) could present a potential target for malicious activity such as by terrorists (Copeland 2007). As a result, particularly since 2001, wastewater (and drinking water) utilities have switched to sodium hypochlorite from gaseous chlorine (United States Government Accountability Office 2007), as exemplified by Portland, Oregon (Jones et al. 2007).

The use of sodium hypochlorite solutions as sources of chlorine for wastewater disinfection is not without its own risks. As a strong oxidant, the solutions must be stored and transported in chemically resistant tanks and pipeline systems, and organic matter must be prevented from entering tanks. Tanks must be vented since the solutions will decompose on a constant basis. Finally sodium hypochlorite solutions are corrosive and present potential worker safety hazards in the event of a spill or tank breach.

With respect to both chlorine gas and hypochlorite, they must be transported to wastewater treatment plants from offsite, and there will be inevitable accidents during transport

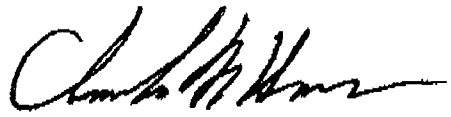
that present a hazard to off site populations, and in the event of a spill to a waterbody, to aquatic ecosystems.

Summary Opinions

On the basis of my experience, prior knowledge, and the literature – including that cited above, I conclude the following:

1. If chlorine (either as gaseous chlorine or hypochlorites) disinfection is used, there is a very high likelihood of producing organic disinfection byproducts, including those that are the subject of water quality guidelines and those that are regarded as likely carcinogens.
2. Use of chlorine as a disinfectant to achieve compliance with an indicator based standard (e.g., coliform or enterococci) will not achieve a high degree of reduction of resistant pathogens that can be present in secondary effluents, such as viruses and pathogenic protozoa.
3. The use of gaseous chlorine as a disinfectant poses a high degree of potential hazard associated with either accidental or deliberately induced releases of the gas. There is additional risk associated with transport of the gas to treatment plants from the site of container packaging.
4. If sodium hypochlorite is used as an alternative source of chlorine, there is potential risk to operators associated with handling an oxidizing material, and also there is the risk in transport of the hypochlorite solution from the site of packaging to the treatment plant.

Respectfully submitted,



By: Charles Haas

Testimony Attachments

1. *Curriculum vitae* of Charles N. Haas

References Cited

Copeland, C. (2007). "Terrorism and Security Issues Facing the Water Infrastructure Sector." Congressional Research Service.

Gerba, C. P., Goyal, S. M., LaBelle, R. L., Cech, I., and Bogdan, G. F. (1979). "Failure of Indicator Bacteria to Reflect the Occurrence of Enteroviruses in Marine Waters." *American Journal of Public Health*, 69(11), 1116-1119.

Grabow, W. (1968). "The Virology of Waste Water Treatment." *Water Research*, 2, 675.

Harwood, V. J., Levine, A. D., Scott, T. M., Chivukula, V., Lukasik, J., Farrah, S. R., and Rose, J. B. (2005). "Validity of the indicator organism paradigm for pathogen reduction in reclaimed water and public health protection." *Appl Environ Microbiol*, 71(6), 3163-3170.

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Jolley, R. L. (1975). "Chlorine-Containing Organic Constituents in Chlorinated Effluents." *Journal of the Water Pollution Control Federation*, 47(3), 601-618.

Jones, G., Stephens, H., and Ott, G. (2007). "Hypochlorite Conversion Provides Improved Disinfection Safety and Reliability in Portland, OR." *Water Practice*, 1, 1-14.

Mitch, W. A., and Sedlak, D. L. (2004). "Characterization and Fate of N-Nitrosodimethylamine Precursors in Municipal Wastewater Treatment Plants." *Environ. Sci. Technol.*, 38(5), 1445-1454.

Morlay, C., De Laat, J., Dore, M., Courtois, Y., Houel, N., and Montiel, A. (1991). "Effect of an Addition of Sodium Sulfite on the Mutagenicity of Chlorinated Solutions of Aquatic Humic Substances." *Bulletin of Environmental Contamination and Toxicology*, 47(15-22).

Rebhun, M., Heller-Grossman, L., and Manka, J. (1997). "Formation of Disinfection Byproducts During Chlorination of Secondary Effluent and Renovated Water." *Water Environment Research*, 69(6), 1154-1162.

Rippey, S. R., and Watkins, W. D. (1992). "Comparative Rates of Disinfection of Microbial Indicator Organisms in Chlorinated Sewage Effluents." *Water Science and Technology*, 26, 2185-2189.

United States Government Accountability Office. (2007). "Securing Wastewater Facilities." Washington DC.

US Environmental Protection Agency. "Integrated Risk Information System." <http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?IRIS>.

White, G. (1972). *Handbook of Chlorination*, Van Nostrand, New York.

Attachment 1

CHARLES N. HAAS

Present Position: Betz Chair Professor of Environmental Engineering & Head,
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Social Security Number: 130-38-6796
Date of Birth: December 27, 1951
Place of Birth: Bronx, New York
Citizenship: U.S.A.
Education: B.S. (Biology), Illinois Institute of Technology, 1973.
M.S. (Environmental Engineering), Illinois Institute of Technology, 1974.
Ph.D. (Environmental Engineering in the Department of Civil Engineering), University of Illinois, Urbana, Illinois, 1978.

Academic Appointments

2005-- : Head, Department of Civil, Architectural and Environmental Engineering
2003–2005: Interim Head, Department of Civil, Architectural and Environmental Engineering
2003--: Research Professor, Department of Emergency Medicine, Drexel University College of Medicine
2002–:2005 Director of Environmental Engineering and member of Department Executive Committee
1991–: : Betz Chair Professor of Environmental Engineering, Drexel University.
1989-1990: Acting Chairman, Pritzker Department of Environmental Engineering, Illinois Institute of Technology
1988-1989: Visiting Professor of Environmental Engineering, University of Illinois at Urbana-Champaign
1981-1990: Assistant Professor (1981-83), Associate Professor (1983-87), Professor (1987-90) Illinois Institute of Technology
1978-1981: Assistant Professor of Environmental Engineering in the Department of Chemical and Environmental Engineering, (1979-1981), Acting Director of Environmental Engineering Programs, Rensselaer Polytechnic Institute

Professional Memberships

American Chemical Society; American Association for the Advancement of Sciences; American Society for Engineering Education; American Statistical Association; American Society for Microbiology; American Water Works Association (Life Member); American Society of Civil Engineers ; Association of Environmental Engineering and Science Professors; International Water Association; Sigma Xi; Society for Risk Analysis; Water Environment Federation; American Academy of Environmental Engineers

ACADEMIC & PROFESSIONAL DETAILS

Honors and Awards

Recipient, 1984 AAAS-USEPA Summer Environmental Science and Engineering Fellowship.
Octave Chanute Award (Outstanding Paper), Western Society of Engineers, 1984.
Charles Ellet Award (Outstanding Young Engineer), Western Society of Engineers, 1985.
Listed in American Men and Women of Science (1994)
Listed in Who's Who in Science and Engineering (1996)
Listed in Who's Who in the East (1997)
Listed in Who's Who in Medicine and Healthcare (1997)
Listed in Who's Who in America, 51st edition (1996)
Listed in Who's Who in the World (2001)
Professional Research Award, Pennsylvania Water Environment Association (1997)
American Academy of Microbiology, Elected as Fellow (1997)
Frontiers in Research Award, Association of Environmental Engineering and Science Professors (sponsored by Malcolm Pirnie, Inc) (2002).
American Association for the Advancement of Science, Elected as Fellow (2002)
Society for Risk Analysis, Elected as Fellow (2002)
University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, Distinguished Alumnus Award (2003)
International Ozone Association, Harvey M. Rosen Memorial Award (best paper in Ozone Science and Engineering for 2001-3) (2003).
National Academies (National Academy of Sciences, National Academy of Engineering, Institute of Medicine, National Research Council): designated as a lifetime National Associate (2004).
American Water Works Association, advisor to 2nd Place Academic Achievement Award Winner (Christopher Crockett—PhD dissertation) (2005).
American Water Works Association, Water Science and Research Division, best paper award ("Risk Assessment of Waterborne Coxsackievirus") (2005).
American Academy of Environmental Engineers, Board Certified Environmental Engineering Member (BCEEM), elected by eminence (2007)

Workshops & Continuing Education Attended

American Council on Education workshop for Department/Division Chairs and Deans, February 2006, San Diego.

Funded Research Projects

Co-principal Investigator "Hazardous Waste Processing and Disposal Practices--Best Technology." New York State Environmental Facilities Corporation (1979 for $25,000).

Co-principal Investigator "The Potential for the Application of Resource Recovery Practices in the Hazardous Waste Processing and Disposal Industry." New York State Environmental Facilities Corporation (1979 for $25,000).

Principal Investigator, "Microbiological Alterations in Water Quality in Distribution Systems and Granular Activated Carbon." U.S. Environmental Protection Agency (1980-2 for $113,000).

Principal Investigator, "Trace Metal Speciation". U.S. Environmental Protection Agency--Industrial Waste Elimination Research Center (1980-1982 for $113,000).

Co-principal Investigator "Evaluation of High-Performance Phosphorus Control POTW's in the Great Lakes Basin." U.S. Environmental Protection Agency (1981-1982 for $88,850).

Principal Investigator "Preparation of a Chapter on Chlorination-Dechlorination and Miscellaneous Halogens." U.S.Environmental Protection Agency via a subcontract from Oklahoma State University (1982-1985 for $82,000).

Principal Investigator "Metal Speciation and Separation." U.S. Environmental Protection Agency--Industrial Waste Elimination Research Center (1982-1983 for $119,000).

Principal Investigator "Wastewater Treatability Study." Modine Manufacturing Company (1982-1983 for $28,000).

Principal Investigator "Evaluation of Microbial Dynamics in the Calumet River and Downstream Waters." Metropolitan Sanitary District of Greater Chicago (1983-1985 for $22,800).

Co-principal Investigator, "Metal Speciation Kinetics." U.S.Environmental Protection Agency - Industrial Waste Elimination Research Center (1984 - 1988 for $500,000).

Principal Investigator, "Indefinite Delivery Contract for Research Support in Environmental Engineering" -- US Army Corps of Engineers, Construction Engineering Research Laboratory (1985 - 1987, $1,900,000).

Co-Principal Investigator, "Characterization of Diffusion of Solutes Through Compacted Clays" -- Milligan Venture Fund Grant (IIT - 1986-1987 for $10,000).

Principal Investigator, "Wastewater Treatability Study" -- Morton Thiokol, Morton Chemical Division ($25,000 1986-1987).

Co-principal Investigator, "Waste to Energy Recovery of Refuse as an Alternative to Landfill in Illinois", Illinois Department of Energy and Natural Resources ($139,000, 1987- 1989).

Principal Investigator, "Effects of Changing Disinfection Practices on Receiving Water Quality", Metropolitan Sanitary District of Greater Chicago ($97,000, 1987-1990).

Principal Investigator, "Beneficial Co-Utilization of Solvents and Plastic Scrap Wastes", Illinois Hazardous Waste Research and Information Center ($6300, 1987).

Principal Investigator, "Disinfection of Microbial Biofilms", American Water Works Service Co., ($30,400, 1987-8).

Principal Investigator, "Analysis of Giardia Disinfection Kinetics", USEPA Office of Drinking Water ($15,000, 1987).
Co-Investigator, "Analysis of Performance of Superfund and SARA", Coalition on Superfund, (1988-89, $250,000).
Principal Investigator, "Analysis of Proposed Sludge Regulations", Metropolitan Water Reclamation District of Greater Chicago, (1989, $20,000).
Principal Investigator, "Equilibria of Mixed Metal Precipitates", IWERC (USEPA) (1990, $55,000).
Principal Investigator, "Statistical Analysis of Waste Generation by Electroplaters and Metal Finishers", Metropolitan Water Reclamation District of Greater Chicago, (1990, $9500).
Principal Investigator, "Analysis of Disinfection Survey Results", American Water Works Association, (1990, $15,000).
Principal Investigator, "Development of Novel Models for Describing Multiple Toxicity Effects", Air Force Office of Scientific Research, (1991-94, $173,925).
Principal Investigator, "Development and Validation of Rational Kinetic Approaches for Predicting Full-Scale Disinfection Performance", American Water Works Association Research Foundation (1991-1994, $260,000).
Principal Investigator, "Analysis of Groundwater Disinfection Survey Results", American Water Works Association (1991-2, $5000).
Co-Principal Investigator, "Microbial Risk Assessment", American Water Works Association Research Foundation (1993-1995, subcontract from University of South Florida, $90,000).
Principal Investigator, "Review of Factors Affecting Metal Fate and Transport in Saline Waters", Dupont Corporation (1992, $12,500).
Principal Investigator, "Effect of Level of Response on Toxicity of Mixtures", Air Force Office of Scientific Research (AASERT Program) (1993-1994, $51,000).
Principal Investigator, "Review of Models for Chemical Fate and Transport", Betz Laboratories Inc. (1993-94, $39,000)
Principal Investigator, "Disinfection of Water Mains", American Water Works Association Research Foundation (1993-1996, $250,000).
Principal Investigator, "Monitoring for Giardia and Cryptosporidium", Philadelphia Water Department (1994-95, $45,000).
Principal Investigator, "Models for Chemical Fate and Transport in Waste Treatment", Betz Laboratories Inc. (1995, $45,000).
Principal Investigator, "Inactivation of *Giardia* by Ozone and Combined Chlorine", Montgomery-Watson Americas (1995, $50,000).
Principal Investigator, "Risk Assessment from Sewage Discharges in Mamala Bay, HI", Subcontract from University of Arizona (Mamala Bay Commission), 1995, $35,000.
Principal Investigator, "Risk Assessment of Heterotrophic Organisms in Point of Use Devices", Subcontract from University of South Florida (Water Quality Association), 1995-1996, $15,000.
Principal Investigator, "Electroporation and Electroporation Aided Disinfection of Cryptosporidium and Giardia", National Science Foundation, 1995-1998, $190,000.
Principal Investigator, "Estimation of Disinfection Efficiency of Philadelphia Water Department Plants for Protozoa", Philadelphia Water Department, 1996-1997, $46,000.
Principal Investigator, "Review of Health, Environmental Effects, and Efficacy of Chlorination for Wastewater Disinfection and Cooling Water", Chlorine Institute, Inc., 1996, $45,000.

Principal Investigator, "Development of Integrated Program for Chemical Fate and Transport in Waste Treatment", Betz Laboratories Inc. (1996-1997, $45,000).

Co-Principal Investigator, "Literature Review on *Cryptosporidium* Removal in Water Treatment", Chlorine Chemistry Council, 1996, $16,000 (with Gordon Finch).

Co-Principal Investigator, "Extension of Quantitative Microbial Risk Assessment Methods to Foodborne Pathogens", International Life Sciences Institute, 1997-1998, $85,000 (with Joan Rose and Charles Gerba).

Principal Investigator, "Disinfection of Protozoa", Philadelphia Water Department, 1997-8, $50,000.

Co-Principal Investigator, "Critical Review Of Existing Data On Physical And Chemical Removal Of Cryptosporidium In Drinking Water", AWWA Research Foundation, 1997-2000 (with Gordon Finch), $150,000.

Co-Principal Investigator, Update The AWWARF Report On Experimental Methodologies For The Determination Of Disinfection Effectiveness To Include Cryptosporidium Disinfection Protocols", 1997-8 (with Gordon Finch), $25,000.

Co-Investigator, "Protocol for *Cryptosporidium* Risk Communication to Drinking Water Utilities", AWWA Research Foundation, 1998-1999 (with Mitchell Small, Baruch Fischoff *et al.*, total contract $195,843).

Co-Investigator, "Disinfection of Emerging Pathogens", AWWA Research Foundation, 1998-2000 (with J. Jacangelo, C.P. Gerba), $250,000.

Co-Investigator, "Microbial Benefits from Laundry Sanitizers", Procter & Gamble Company, 1998, $25,000.

Co-Principal Investigator, "Compilation and Kinetic Analysis of Data for Ozone Inactivation of *Cryptosporidium"*, International Ozone Association, 1998-1999 (with G. Finch, J. Jacangelo), $23,000 (Drexel share).

Principal Investigator, "Is Disinfection a Function of Initial Microorganism Concentration?", AWWA Research Foundation, 1999-2001, $127,000.

Principal Investigator, "Survey on Drinking Water Disinfection", American Water Works Association, 1998-1999, $25,000.

Co-Investigator, "Synergistic Inactivation of *Cryptosporidium* Oocysts in Natural Waters", AWWA Research Foundation, 1999-2001 (with Gordon Finch, Mike Belosevic), $77,000 (Drexel share).

Principal Investigator, Peer Review of Class A Sludge Designation Petition, Metropolitan Water Reclamation District of Greater Chicago, 1999-2000, $20,000.

Principal Investigator, Assessment of EPA Pathogen Equivalency Committee, US EPA, 2000, $15,000.

Principal Investigator, "Use of Microbial Risk Modeling to Determine the Benefits of Topical Antimicrobial Products", Soap and Detergent Association, 2000-2002 (with Joan Rose and Charles Gerba), $163,000.

Principal Investigator, "Disinfection of Protozoa", Philadelphia Water Department, 2000-2001, $50,000

Principal Investigator, "Evaluation of the Analytical Capabilities, Today and Near Future, for the Monitoring of Drinking Water for Accidental or Intentional Contamination", Philadelphia Water Department, 2002-2003, $100,000.

Principal Investigator, "Building Biodecontamination: A Process Engineering Approach", National Science Foundation, 2003-2005, $99,500 (with B. Farouk).

Principal Investigator, "Workshop on Advancing the Quality of Water (AQWA)", National Science Foundation, 2003-2004, $99,000.
Principal Investigator, "Delaware Valley Water Source Tracking Effort (DeVaWaSTE)", Philadelphia Water Department, 2004-5, $25,000; 2005-6, $55,000; 2006-2007, $60,000.
Principal Investigator, "Analysis of Data on Microbial Persistence With Antimicrobial Hand Products", Soap and Detergent Association, 2004, $20,000.
Principal Investigator, "Activated Ozone for Water Disinfection", H2O3, Inc., 2004, $35,000.
Principal Investigator, "Assessment of Physical Scale Models for Development of Room Decontamination Design Criteria", funded via National Bioterrorism Civilian Medical Response Center (CIMERC), 2004-5, $55,000.
Principal Investigator, "Wastewater Disinfection Strategies for the Metropolitan Water Reclamation District of Greater Chicago", CTE Engineering, 2004-5, $75,000.
Principal Investigator, "Expert Review of EPA Recreational Water Criteria – Scientific Basis", Metropolitan Water Reclamation District of Greater Chicago, 2005, $22,500.
Co-Principal Investigator, "CLEANER Project Office", National Science Foundation, 2005-7, $200,000 (Drexel share), $2,000,000 total (lead institution: University of Illinois at Urbana-Champaign).
Co-Principal Investigator and Co-Director, "Center for Advancing Microbial Risk Assessment (CAMRA)", US EPA and US Department of Homeland Security (Cooperative Center of Excellence), 2005-2010, $2,200,000 (Drexel share), $10,000,000 total funding (lead institution: Michigan State University).
Principal Investigator, "The Drexel University GAANN Fellowship Program: Educating Renaissance Engineers", 2006-9 ($168,000 year 1).
Principal Investigator, "Risk Assessment from Wet Weather Flows", Philadelphia Water Department, 2007-, $250,000.

Publications & Presentations

Books and Other Major Works

1) Recovery, Recycle and Reuse of Industrial Waste, K. E. Noll, C.N. Haas, C. Schmidt and P. Kodukula, Lewis Publishers, Chelsea MI (1985).
2) Process Design Manual for Wastewater Disinfection, coauthored by C.N. Haas. US EPA Center For Environmental Research Information, Cincinnati (1986).
3) Experimental Methodologies for the Determination of Disinfection Effectiveness, C.N. Haas, J.C. Hornberger, U. Anmangandla, M. Heath and J. Jacangelo. AWWA Research Foundation and American Water Works Association, Denver CO (1993).
4) Hazardous and Industrial Waste Treatment, (1995) Prentice-Hall, C.N. Haas and R. Vamos.
5) Development and Validation of Rational Design Methods of Disinfection (1995), AWWA Research Foundation, C.N. Haas, J. Joffe, J.C. Hornberger, U. Anmangandla, M. Heath and J. Jacangelo.
6) Benefits and Risks of Wastewater Chlorination (1997), The Chlorine Institute Inc. (Washington DC), Pamphlet 157, 193 pages, C.N. Haas, A. Fazil and A. Khan.
7) Benefits and Risks of Cooling Water Chlorination (1997), The Chlorine Institute Inc. (Washington DC), Pamphlet 158, 188 pages, C.N. Haas, A. Fazil and A. Khan.

8) Integrated Disinfection Design Framework (1998), AWWA Research Foundation and American Water Works Association, Denver CO, W.D. Bellamy, G.R. Finch and C.N. Haas.
9) Development of Disinfection Guidelines for the Installation and Replacement of Water Mains, AWWA Research Foundation, Denver CO, C.N. Haas, R.B. Chitluru, M. Gupta, W.O. Pipes, and G.A. Burlingame. (1998)
10) Quantitative Microbial Risk Assessment, C.N. Haas, J.B. Rose and C.P. Gerba, John Wiley (NY) (1999). (translated into Japanese)
11) Methodologies for the Determination of Disinfection Effectiveness, AWWA Research Foundation, C.N. Haas and G.R. Finch, Denver CO (2001).
12) Data Review on the Physical/Chemical Removal of *Cryptosporidium*, AWWA Research Foundation, C.N. Haas, K. French, G.R. Finch and R.K. Guest, Denver CO (2001).
13) Inactivation of Waterborne Emerging Pathogens by Selected Disinfectants, AWWA Research Foundation, J.G. Jacangelo, N.L. Patania, R.R. Trussell, C.N. Haas and C. Gerba, Denver CO (2002).
14) Effect of Initial Microbial Concentration on Disinfection Efficiency, AWWA Research Foundation, C.N. Haas and B. Kaymak, Denver CO (2002).

Peer Reviewed Publications

1) "Oxygen Uptake Rate as an Activated Sludge Control Parameter." Journal of the Water Pollution Control Federation, 51, 938-943 (1979), Charles N. Haas.
2) "Physiological Alterations of Vegetative Microorganisms Resulting From Aqueous Chlorination." Journal of the Water Pollution Control Federation, 52, 1976-1989 (1980), C.N. Haas and R.S. Engelbrecht.
3) "Chlorine Dynamics During Inactivation of Coliforms, Acid-Fast Bacteria and Yeasts." Water Research, 14, 1749-1757 (1980), C.N. Haas and R.S. Engelbrecht.
4) "A Mechanistic Kinetic Model for Chlorine Disinfection." Environmental Science and Technology, 14, 339-340 (1980), C.N. Haas.
5) "Application of Predator–Prey Models to Disinfection." Journal of the Water Pollution Control Federation, 53, 378-386 (1981), C.N. Haas.
6) "Rational Approaches in the Analysis of Chemical Disinfection Kinetics." Chapter in W. Cooper (ed.) Chemistry in Water Reuse. Vol. 1, pp. 381-399. Ann Arbor Science Publishers, Inc. (1981), C.N. Haas.
7) "Practical Mixed Culture Processes." Advances in Fermentation Processes, 4, 1-29 (1980), C.N. Haas, H.R. Bungay and M.L.Bungay.
8) "Biological Process Diffusional Limitations." Journal of the Environmental Engineering Division, ASCE, 107, 269-273 (1981), C.N. Haas.
9) "Repeated Exposure of Escherichia coli to Free Chlorine: Production of Strains Possessing Altered Sensitivity." Water, Air and Soil Pollution,16, 233-242 (1981), C.N. Haas and E.C. Morrison.
10) "Sodium Alterations of Chlorine Equilibria: Quantitative Description." Environmental Science and Technology, 15, 1243-1244 (1981), C.N. Haas.
11) "Evaluation of the m-SPC Method as a Substitute for the Standard Plate Count in Water Microbiology." Journal of the American Water Works Association, 74, 322 (1982), C.N. Haas, M.A. Meyer and M.S. Paller.

12) "Enhancement of Chlorine Inactivation of E. coli by Sodium Ions." Water Chlorination Environmental Impact and Health Effects, volume 4, book 2, pp1087-96, edited by R.L. Jolley, Ann Arbor Science (1983), C.N. Haas and M. Zapkin.
13) "The Ecology of Acid-Fast Organisms in Water Supply, Treatment and Distribution Systems." Journal of the American Water Works Association, 75, 139-44 (1983), C.N. Haas, M.A. Meyer and M.S. Paller.
14) "Estimation of Risk Due to Low Doses of Microorganisms: A Comparison of Alternative Methodologies." American Journal of Epidemiology, 118,573-82 (1983), C.N. Haas.
15) "The Utility of Endotoxins as a Surrogate Indicator in Potable Water Microbiology." Water Research, 17, 803-7 (1983), C.N. Haas, M.A. Meyer,M.S. Paller and M.A. Zapkin.
16) "Effect of Effluent Disinfection on Risks of Viral Disease Transmission via Recreational Exposure." Journal of the Water Pollution Control Federation. 55, 1111-6 (1983), C.N. Haas.
17) "Engineering at the Microorganism Scale." Advances In Fermentation Processes, 6, 149-73 (1983), H.R. Bungay, M.L. Bungay and C.N. Haas.
18) "Microbial Dynamics in GAC Filtration of Potable Water." ASCE Journal of Environmental Engineering, 109, 956-61 (1983), C.N. Haas, M.A. Meyer and M.S. Paller.
19) "Application of Ion Exchangers to Recovery of Metal from Semiconductor Wastes." Reactive Polymers, 2, 61-70 (1984), C.N. Haas and V. Tare.
20) "Microbial Alterations in Water Distribution Systems and Their Relationship to Physical-Chemical Characteristics." Journal of the American Water Works Association, 75, 475-481 (1983), C.N. Haas, M.A. Meyer and Marc S. Paller.
21) "Kinetics of Wastewater Chlorine Demand Exertion," Journal of the Water Pollution Control Federation, 56, 170-3 (1984) C.N. Haas and S.B. Karra.
22) "Kinetics of Metal Removal by Chelating Resin from a Complex Synthetic Wastewaters." Water Air & Soil Pollution, 22, 429-39 (1984) V. Tare, S.B. Karra, and C.N. Haas.
23) "Estimation of Effective Intra-Particle Diffusion Coefficients with Differential Reactor Columns," Journal of the Water Pollution Control Federation, 56, 442-8 (1984) A.A. Aguwa, J.W. Patterson, C.N. Haas and K.E. Noll.
24) "Is Sodium Thiosulfate a Suitable Neutralizer For Chlorine in Microbiological Determinations?", C.N. Haas and M.A. Zapkin. Journal of Environmental Science and Health Part A: Environmental Science and Engineering, 19, 507-20 (1984).
25) "Kinetic Limitations on the Selective Precipitation Treatment of Electronics Wastes." Water Air & Soil Pollution, 24, 253-65 (1985) S.B. Karra, C.N. Haas, V. Tare and H.E. Allen.
26) "Kinetics of Microbial Inactivation By Chlorine. I. Review of Results in Demand-Free systems." Water Research, 18, 1443-1449 (1984),C.N. Haas and S.B. Karra.
27) "Kinetics of Microbial Inactivation By Chlorine. II. Kinetics in the Presence of Chlorine Demand." Water Research, In 18, 1451-4 (1984), C.N. Haas and S.B. Karra.
28) "Field Observations on the Occurrence of New Indicators of Disinfection Efficiency." Water Research, 19, 323-9 (1985), C.N. Haas, B.F. Severin, D. Roy, R.S. Engelbrecht, A. Lalchandani, and S. Farooq.
29) "Influence of Sodium, Potassium and Lithium on Hypochlorite Solution Equilibria." Water Chlorination Environmental Impact and Health Effects, volume 5, pp775-782 edited by R.L. Jolley, Lewis Publishers (1985), C.N. Haas and D.M. Brncich.

30) "Removal of New Indicators by Coagulation-Flocculation and Sand Filtration." Journal of the American Water Works Association, 77, 67-71 (1985). C.N. Haas, B.F. Severin, D. Roy, R.S. Engelbrecht, and A. Lalchandani.
31) "Direct Differential Reactor Studies on Adsorption from Concentrated Liquid and Gaseous Solutions." In Fundamentals of Adsorption Processes, A. Meyers and G. Belfort [eds.], pp411-20, United Engineering Trustees, NY (1984), K.E. Noll, C.N. Haas, J-P. Menez, A.A. Aguwa, M. Satoh, A. Belalia and P.S. Bartholomew.
32) "Sensitivity of Vegetative Protozoa to Free and Combined Chlorine. "Water Chlorination Environmental Impact and Health Effects, volume 5, pp 667-80 edited by R.L. Jolley, Lewis Publishers (1985), C.N. Haas, K. Khater and A. Wojtas.
33) "Economic Incentives for Hazardous Waste Management." Journal of Environmental Systems, C.N. Haas, 14, 373-93 (1985).
34) "Toluene-Humic Acid Association Equilibria: Isopiestic Measurements." Environmental Science and Technology, 19, 643- 5 (1985) C.N. Haas and B.M. Kaplan.
35) "Adsorption of Cadmium to Kaolinite in the Presence of Organic Materials." Water, Air and Soil Pollution, 27, 131-40 (1986) C.N. Haas and N.D. Horowitz.
36) "Revegetation Using Coal Ash Mixtures," ASCE Journal of Environmental Engineering,", 111, 559-73 (1985) C.N. Haas and J.J. Macak.
37) "Validation of the Hazard Ranking System for the Assessment of Feedstock Frequencies in Superfund Site Contaminants", Hazardous Waste and Hazardous Materials, 2, 535 (1985) G.A. Vanderlaan and C.N. Haas.
38) "Statistics of Enumerating Total Coliforms In Water Samples by Membrane Filter Procedures", Water Research, 20, 525-30 (1986) C.N. Haas and B. Heller.
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Papers Presently Under Review

1) "Effect of Initial Microbial Density on Disinfection Efficiency in a Continuous Flow System", submitted to Journal of Applied Microbiology, L. Li, B. Kaymak and C.N. Haas.
2) "Validation of Batch Disinfection Kinetics of Escherichia coli Inactivation by Monochloramine in a Continuous Flow System", submitted to Environmental Engineering Science, L. Li, B. Kaymak and C.N. Haas.
3) "Numerical simulation of biological particulate transport and inactivation in a room", Sankalp Soni, Bakhtier Farouk, Charles N. Haas, and Shamia Hoque, submitted to Environmental Science & Technology.
4) "Countercurrent Gas/Liquid Flow and Mixing: Implications for Water Disinfection", T.A. Bartrand, B. Farouk and C.N. Haas, submitted to Journal of Multiphase Flow.
5) "Dose-Response Models for Inhalation of Bacillus anthracis Spores: Interspecies Comparisons", T.A. Bartrand, M. Weir and C.N. Haas, submitted to Risk Analysis.
6) "Dose Response Model for Lassa Virus", S. Tamrakar and C.N. Haas, submitted to Human and Ecological Risk Assessment.
7) "Quantification of the Effects of Age on Dose Response of Variola major in Suckling Mice", M. Weir and C.N. Haas, submitted to Risk Analysis.
8) "The application of food microbial growth models to in vivo *Francisella tularensis* growth in laboratory animals", W McGarry, T Bartrand and CN Haas, submitted to Applied and Environmental Microbiology.

Presentations

1) "Amino Acids, Aquatic Bacteria and Diatoms: Possible Methods of Interaction." Presented at the 67th Annual Meeting of the Illinois State Academy of Sciences, Springfield, May, 1974.
2) "Physiological Alterations of Vegetative Microorganisms Resulting from Aqueous Chlorination," presented at the Research Symposium during the 51st annual meeting of the Water Pollution Control Federation, Houston, October,1978.
3) "Physiological Basis for Chlorination," presented at a seminar of the Department of Civil Engineering, Syracuse University, November, 1978.
4) "Mechanistic Aspects of Disinfection Kinetics," presented at a seminar of the Department of Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, NY, April, 1979.
5) "Mode of Microbial Inactivation by Chlorine", presented at the National Conference on Environmental Engineering, American Society of Civil Engineers, San Francisco, July, 1979.
6) "Rational Analysis of Ultraviolet Disinfection Kinetics," presented at the National Conference on Environmental Engineering, American Society of Civil Engineers, San Francisco, July, 1979.
7) "Rational Analysis of Microbial Regrowth." Presented at the 178thNational Meeting of the American Chemical Society, Division of Environmental Chemistry, Washington, DC, September, 1979.
8) "A Quantitative Model of Post-Disinfection Microbial Dynamics." Presented at the Research Symposium during the 52nd Annual Meeting of the Water Pollution Control Federation, Anaheim, October, 1979.
9) "Rational Approaches in the Analysis of Chemical Disinfection Kinetics," Presented at the 179th National Meeting of the American Chemical Society, Division of Environmental Chemistry, Symposium on Chemistry and Chemical Analysis of Water/Wastewater Intended for Reuse, Houston, March, 1980.
10) "Repeated Exposure of E. coli to Free Chlorine: Production of Strains With Differential Resistance," Presented at the 80th Annual Meeting of the American Society of Microbiology, Miami, May, 1980.
11) "Acid-Fast Bacteria and Yeast as Indicators of Disinfection Efficiency." Invited Presentation before the Interstate Seafood Seminar, Ocean City, MD, October, 1980.
12) "Theory of Alternate Disinfectants." Invited presentation at the Seminar on Current Topics in Water Supply, New York State Section of the American Water Works Association, Ossining, NY, November, 1980.
13) "The Practical Importance of Understanding Disinfection Mechanisms." Presented at the 81st Annual Meeting of the American Society for Microbiology, Dallas, March, 1981.
14) "Effects of Various Additions on the Inactivation of E. coli by Chlorine. Presented at the 81st Annual Meeting of the American Society for Microbiology, Dallas, March, 1981.
15) "Statistical Analysis of New York State Department of Environmental Conservation Lake George Bacteriological Sampling Data." Presented at the 1st Symposium of the Lake George Research Group, Lake George, NY, April, 1981.
16) "Enhancement of Chlorine Inactivation of E. coli by Sodium Ions." Presented at the 4th Water Chlorination Conference, Monterey, CA, October, 1981.
17) "Practical Considerations in the Use of Halogen Disinfectants." Invited Presentation to the Second National Symposium on Municipal Wastewater Disinfection, sponsored by the U.S. EPA, Orlando, FL, January,1982.

18) "Application of Ion Exchange to Recovery of Metals from Semiconductor Wastes." Presented at the NATO Advanced Studies Institute on Mass Transfer and Kinetics of Ion Exchange, Maratea, Italy, June, 1982.
19) "Estimation of Recreational Disease Risk due to Disinfection: Illinois–A Case Study." Presented at the 55th Annual Conference of the Water Pollution Control Federation, St. Louis, October, 1982.
20) Seminars presented during a visit to the Italian National Research Council, Water Research Institute, Bari, Italy, June, 1982:
    "Rational Analysis of Chlorination Kinetics."
    "Use of Computer Equilibrium Models for Assessment of Industrial Waste Chemistry."
    "Novel Precipitation processes for Metal Recovery from Semiconductor Wastes."
    "Application of Ion Exchange to Recovery of Metals from Semiconductor Wastes."
    "Solid Phase Differential Reactor Studies on Adsorption in Air and Water."
21) Seminar presented to the Italian National Research Council, Water Research Institute, Rome, Italy, June 1982:
    "Metal Removal and Recovery Processes: Experimental Results and Equilibrium Calculations."
22) "Relating Microbial Changes in Water distribution to Physical-Chemical Water Quality." Presented at the 74th Annual Conference, Illinois Section, American Water Works Association, Chicago, March 1983.
23) "Direct Differential Reactor Studies of Adsorption from Liquid and Gaseous Solutions." Presented at the Engineering Foundation Conference on Fundamentals of Adsorption, Upper Bavaria, West Germany, May, 1983.
24) "Water and Wastewater Disinfection." Seminar presented at IBM Corp., East Fishkill, NY, June 1983.
25) "Kinetic Limitations on the Recovery of Metals From Wastewater by Precipitation." Presented at the American Institute of Chemical Engineers National Meeting, Denver, August 1983.
26) "Microbial Risk Assessment." Invited Presentation at the Water Pollution Control Federation, Preconference Workshop on Wastewater Disinfection Alternatives, Atlanta, October, 1983.
27) "Engineering Waterborne Disease Reduction: How Much Is Enough?" Speech before the Western Society of Engineers, Chicago, November, 1983.
28) "Is Wastewater Disinfection Necessary?" Presentation to the Illinois Association of Environmental Professionals, April 1984.
29) "Sensitivity of Vegetative Protozoa to Free and Combined Chlorine." Presented at the 5th Conference on Water Chlorination: Environmental Impact and Health Effects, Williamsburg, VA, June, 1984.
30) "Influence of Sodium Potassium an Lithium on Hypochlorite Solution Equilibria." Presented at the 5th Conference on Water Chlorination: Environmental Impact and Health Effects, Williamsburg, VA, June, 1984.
31) "Scientific Principles of Disinfection" and "Need Assessments for Disinfection." Presented at the University of Wisconsin-Milwaukee Engineering Extension Program on Disinfection of Water and Wastewater, May,1984.

32) "An Engineers View of Economic Incentives for Hazardous Waste Management." Seminar presented to the Institute of Environmental Studies, Drexel University, Philadelphia, August 1984.
33) "Effect of Cessation of Chlorination on Receiving Water Microbiology." Presented at a seminar of the Research and Development Department, Metropolitan Sanitary District of Greater Chicago, October 1984.
34) "Hazardous Waste Management Challenges." Invited plenary presentation to the Annual Meeting of the Illinois Public Health Association, Peoria, April, 1985.
35) "Steps Towards a Rational Kinetic Model of Wastewater Chlorination", seminar presentation, Department of Civil and Sanitary Engineering, Michigan State University, April, 1985.
36) Presentation on potential risk avoidance due to earlier intervention in a Salmonella outbreak before the Illinois House of Representatives Committee on State Government Administration and Regulatory Reform June, 1985.
37) "Development of Acid Fast and Yeast Organisms as New Indicators of Disinfection Efficiency", seminar presented to the Department of Microbiology and Immunology, University of Arizona, Tucson, August, 1985.
38) "Is Wastewater Disinfection Worth the Cost?", seminar to the School of Civil Engineering, Purdue University, March 1986.
39) "Recovery, Recycle and Reuse of Industrial Wastes", Presented at a program on Wastewater Pretreatment and Toxicity Control, University of Wisconsin Extension at Milwaukee, March, 1986.
40) "Chlorine Residual", presented at the WPCF Conference on Analytical Techniques in Pollution Control, Denver, May 1986.
41) "On the Poisson Assumption for Analysis of MPN Results", presented at the American Water Works Association Annual Meeting, Denver, June, 1986.
42) "Kinetics of Cadmium and Copper Hydrolysis", International Association on Water Pollution Research and Control, Biennial Conference, Rio de Janeiro, Brazil, August, 1986.
43) "Wastewater Disinfection: Concepts and Practices", R.S. Engelbrecht and C.N. Haas, invited paper, Second Joint Seminar on Wastewater Treatment Technology, Japan Sewage Works Association/Water Pollution Control Federation, Hiroshima City, Japan, November, 1986.
44) "Relationship Between Disinfection Mechanism and Disinfection Kinetics", invited paper, Seminar on Water and Wastewater Disinfection, American Society of Microbiology Annual Meeting, Atlanta, GA, March 1987.
45) "Disinfection Methods and Regulatory Changes", invited presentation to the Illinois Association of Water Pollution Control Operators, Springfield, IL, April, 1987.
46) "Further Studies on Hypochlorite Ion Pair Chemistry and Disinfection Efficiency", 6th Water Chlorination Conference, Oak Ridge TN, May, 1987.
47) "Inherent Experimental Variability", invited presentation at the American Water Works Association pre-conference seminar on "Assurance of Adequate Disinfection: ct or not ct", Kansas City, June, 1987.
48) "Wastewater Chlorination and Dechlorination", invited presentation to the Michigan Section, American Water Works Association, Ann Arbor, February 1988.
49) Invited presentations before a seminar sponsored by the Michigan Water Pollution Control Association on Wastewater Disinfection: Public Health Related Issues: "Effect of Effluent Disinfection on Risks of Viral Disease Transmission via Recreational Water Exposure" and

"Water Pollution Control Federation Disinfection Committee: Report Status", Ann Arbor, May 1988.

50) Invited speaker "Comparative Aspects of Solid Waste Management", seminar on "Recycling and Solid Waste Disposal" sponsored by the University of Illinois, Rockford, June 1988.
51) "Statistics of Microbial Disinfection", International Association on Water Pollution Research and Control Biennial Meeting, Brighton, UK, July 1988.
52) "Maximum Likelihood Analysis of Giardia Disinfection by Chlorine", First Biennial Water Quality Symposium: Microbiological Aspects, Banff, Alberta, August 1988.
53) "Maximum Likelihood Analysis of Disinfection Kinetics", seminar to the Environmental Engineering Program, Department of Civil Engineering, University of Illinois at Urbana-Champaign, February 1989.
54) "Multicomponent Interactions In Environmental Engineering", seminar to the Institute of Environmental Studies, Drexel University, April 1989.
55) "Chlorination/Dechlorination for New Disinfection Criteria", invited presentation at the Water Pollution Control Federation preconference workshop, San Francisco, October 1989.
56) "Fundamental Considerations in Development of Solvent Dissolution Processes for Plastics", presented at the 6th International Conference on Solid Waste Management and Secondary Materials", Philadelphia, December 1990.
57) "Failure of Chick's Law in Batch to CSTR Extrapolation of Chlorine Disinfection of *Escherichia coli*", presented at the Annual Conference of the American Water Works Association, Philadelphia, June, 1991.
58) "Occurrence of Pathogens and their Associated Risk", invited paper, Regulating Drinking Water in the 1990's, sponsored by the Northeast Regional Environmental Public Health Center, April, 1991, Amherst MA.
59) "Status of Chlorammination", invited paper, Preconference Seminar on Water Quality Effects of Chlorammination, AWWA Annual Meeting, June 1991, Philadelphia, PA.
60) "Binary and Ternary Equilibria of Ion Exchange", 46th Purdue Industrial Waste Conference, May 1991, West Lafayette IN.
61) "Equilibrium of Mixed Solid Phases", 46th Purdue Industrial Waste Conference, May 1991, West Lafayette IN.
62) "Biological Sulfide Prestripping for Metal and COD Removal", Annual Conference of the Water Pollution Control Federation, October 1991, Toronto, Canada.
63) "Comparative Performance of Interval Estimators for Virtually Safe Dose", Annual Meeting of the Society for Risk Analysis, December 1991, Baltimore.
64) "Nonideal Interactions in Metal Separations in Environmental Engineering", seminar to the Department of Chemical Engineering, Drexel University, January 27, 1992.
65) "Risk Assessment of Infectious Disease from Waterborne Exposures", seminar to the Department of Bioscience and Biotechnology, Drexel University, April 2, 1992.
66) "New Approaches for the Analysis of Mixture Toxicity Data", presented at the 16th Biennial Conference of the International Association on Water Pollution Research and Control, Washington D.C., May 1992.
67) "Occurrence of Microorganisms", invited presentation to the Netherlands Public Health Institute, Bilthoven, June 1992.
68) "Microbial Risk Assessment", invited presentation to the Netherlands Public Health Institute, Bilthoven, June 1992.

69) "Quantifying Microbial Risk", invited presentation at the First International Conference on the Safety of Water Disinfection: Balancing Chemical and Microbial Risks, Washington D.C., August 1992.
70) "Trends in Environmental Protection", invited presentation at the 6th environmental affairs conference, Betz Laboratories Inc., Trevose PA, September 1992.
71) "Microbial Risk Assessment for Drinking Water", poster by C.P. Gerba, Joan Rose and C.N. Haas, Society for Risk Analysis Annual Conference, San Diego CA, December 1992.
72) "The Risk of Illness from Drinking Water", seminar to the Department of Civil and Architectural Engineering and the Environmental Studies Institute, Drexel University, January 1993.
73) "Microbial Risk Assessment of Drinking Water", seminar to the Department of Environmental and Occupational Health and the Department of Civil Engineering and Mechanics, University of South Florida, Tampa, March 1993.
74) "Testing for the Presence of Interactive Toxic Effects: A New Quantitative Procedure Based on Isobole Analysis", presented at the Eastern North America Regional (ENAR) Meeting of the Biometric Society/American Statistical Association/ Institute of Mathematical Statistics, Philadelphia, PA, March 1993, with Bruce A. Stirling.
75) "Nonideal Interactions in Metal Separation Processes", seminar to the Department of Civil Engineering, University of Delaware, March 1993.
76) "The Effect of Free Chlorine, Preformed Monochloramine, Chlorine+ Preammoniation and Ozone on *Giardia muris* Cyst Viability", presented at the Annual Conference of the Pennsylvania Section of AWWA, April 1993, with Joel Hornberger, Uma Anmangandla and Josh Joffe.
77) "The Necessity for Wastewater Disinfection", invited presentation at the American Society for Microbiology conference on "Water Quality in the Western Hemisphere", San Juan PR, April 1993.
78) "Modeling the Risk of *Legionella*", D.E. Friedman, C.N. Haas and J.B. Rose, poster presentation at the American Society for Microbiology conference on "Water Quality in the Western Hemisphere", San Juan PR, April 1993.
79) "What We Think We Know and What We Think We Don't Know About Chlorination and Dechlorination", presented at the Water Environment Federation Specialty Conference on Wastewater Disinfection, May 1993, Whippany NJ.
80) "Pathogen Risks and Treatment Options", presented at the AWWA Preconference Seminar on Groundwater Disinfection, San Antonio, Texas, June 1993.
81) "Monte Carlo Methods in Risk Assessment", seminar presented at Roy F. Weston Co., West Chester PA, June 1993.
82) "Application of Risk Assessment to Standard Setting for Closed Life Support Systems", C.P. Gerba, C.N. Haas and J.B. Rose, presented at the 23rd International Conference on Environmental Systems, Colorado Springs, CO, July 1993.
83) "Verification of a Mechanistic Kinetic Model for Chloroform Formation from a Model Precursor During Water Chlorination", C.N. Haas and K. Topudurti, presented at the National Meeting of the American Chemical Society, Chicago IL, August 1993.
84) Invited discussion, "Health Effects of Water Reuse", presented at the Water Environment Research Foundation Assessment Workshop on "Water Reuse Assessment", WEF Annual Conference, Anaheim CA, October 1993, C.N. Haas.

85) "Simplified Method for Microscopic Determination of *Giardia* Disinfection Efficiency", C.N. Haas, J.C. Hornberger, U. Anmangandla and J. Joffe, AWWA Water Quality Technology Conference, Miami FL, November 1993.
86) "Bench to Pilot Scale Up: Impact on Microbial Inactivation", Mark S. Heath, Joseph G. Jacangelo and C.N. Haas, AWWA Water Quality Technology Conference, Miami FL, November 1993.
87) "Microbiological Issues", invited presentation to the US EPA Federal-State Toxicology and Risk Assessment Committee, Washington DC, December 1993.
88) Invited presentations to faculty and administration at University of Texas-El Paso: "Environmental Science and Engineering at Drexel University" and "Future Trends in Environmental Protection", November 1993.
89) "Estimating Risk from Waterborne Microorganisms", presented at the Annual Meeting of the Society for Risk Analysis, Savannah GA, December 1993.
90) "Microbial Risk Assessment", seminar presented to the USDA, Agricultural Research Service, Eastern Regional Research Center, Philadelphia, February 1994.
91) "Waterborne Microbial Diseases", invited presentation to AWWA – USEPA Workshop on Information Collection Rule, Washington DC, March 1994.
92) "Relevance of UIUC Disinfection Research to Current Problems", invited presentation, UIUC-CERL Symposium on Molecular Biology in Environmental Engineering, in Honor of Richard S. Engelbrecht, Champaign-Urbana IL, March 1994.
93) "Can Chlorine be Eliminated from Water Treatment?", invited seminar, MIT Program in Technology and Public Policy, May 1994.
94) "Reconciliation of Microbial Risk Assessment and Epidemiology: The Case of the Milwaukee Outbreak", AWWA Annual Conference, June 1994, New York City.
95) "The Risk of Infectious Disease from Drinking Water", seminar to the Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, July 1994.
96) "The Relationship Between Endemic and Epidemic Disease Risk", presented at the biennial meeting of the International Association on Water Quality, Budapest Hungary, July 1994.
97) "Application of Reaction Engineering Approaches to Disinfection Process Design", seminar to the Department of Civil Engineering, University of Illinois at Urbana-Champaign, August 1994.
98) "Some Observations on Cryptosporidium Risk", invited presentation, "Water for Healthy Living: A Workshop on Public Decisions about Cryptosporidium", sponsored by AWWA, Washington DC, September 1994.
99) "Dose-Response Relationships and Community Risk", invited presentation, "Symposium on Waterborne Cryptosporidium", sponsored by the Centers for Disease Control and Prevention, Atlanta GA, September 1994.
100) "*Cryptosporidium* in Water: What is the Problem?", presented at the Pennjerdel Water Supply Committee meeting, Philadelphia, October 1994.
101) "Waterborne Diseases: Who is at Risk", presented at the AWWA Water Quality Technology Conference, San Francisco CA, November 1994, CP Gerba, JB Rose and CN Haas.
102) "Chlorine Ban Proposals from the Viewpoint of Water and Wastewater Treatment", invited presentation, Symposium on the Future Uses of Chlorine: The Role of the University, Massachusetts Institute of Technology, November 1994.

103) "Application of Reaction Engineering Approaches to Disinfection Process Design", seminar to Texas A&M University, Department of Civil and Ocean Engineering, August 1995.
104) "Statistical Analysis of Microbial Data", presented to the AWWA Technical Action Workgroup on Disinfection and Microbials, Washington DC, September 1995.
105) "Understanding the Behavior of *Giardia* and *Cryptosporidium* in an Urban Watershed: Explanation and Application of Techniques to Collect and Evaluate Monitoring Data", presented at the AWWA Water Quality Technology Conference, New Orleans, November 1995. CS Crockett and CN Haas.
106) "Generalized Independence And Additivity: Two Approaches To Quantitatively Describing Non-Ideal Toxic Behavior Of Chemical Mixtures", presented at the Society for Risk Analysis Annual Meeting, Honolulu, December 1995, CN Haas, S. Kersten, K. Cidambi and MJ Frank.
107) "Quantitative Microbial Risk Assessment: Review of Principles and Application to Recreational Settings", seminar to the University of Hawaii Water Resources Institute, December 1995.
108) "Principles of Microbial Risk Analysis", presented to the US Department of Agriculture, Office of Risk Assessment and Cost-Benefit Analysis, April 10, 1996.
109) "Dose Response Assessment for Infectious Microorganisms", invited presentation, Annual Meeting – American Society for Microbiology, New Orleans, May 23, 1996.
110) "Risk of Chemical Mixtures: Novel Methods", seminar to Procter and Gamble Co., Cincinnati OH, November 12, 1996 (with audio feed to P&G Europe).
111) "Novel Quantitative Approaches for Chemical Mixtures", seminar to Department of Environmental Systems Engineering, Clemson University, April 4, 1997.
112) "The Role of Risk Assessment in Setting US Drinking Water Standards". Nishihara Invited Lecture delivered to:
    Hokkaido University (Japan) – Environmental Engineering program
    Tokyo University – Department of Urban and Environmental Engineering
    Nishihara Sanitation Company
    Nihon University – Department of Civil Engineering
    Japan Ministry of Health – Membrane 21 Conference
    September 1-15, 1997.
113) "What we Think We Know and What We Think We Don't Know about Chlorination-Dechlorination", presented at the preconference workshop on Disinfection, Water Environment Federation Technical Conference, October 18, 1997, Chicago.
114) "Risk of HIV to Wastewater Operators". Presentation at the 70th Annual Water Environment Federation Technical Conference, October 23, 1997, Chicago.
115) "Correlations and Copulas in Monte Carlo Analysis". Platform-Poster at the Annual Meeting of the Society for Risk Analysis, Washington DC, December 10, 1997.
116) "Risk Assessment for Household Sanitation", seminar to Procter and Gamble Co., Cincinnati OH, February 19, 1998.
117) "Risk Based Criteria for Pathogens in Drinking Water: Has the Time Come?", Seminar to the Department of Civil and Environmental Engineering, University of Delaware, March 27, 1998.
118) "Back to the Future: Engineering Safe Water and Safe Food in the 21st Century", Invited Lecture, Villanova University Chapter of Sigma Xi, April 3, 1998.

119) "Benefits of Employing a Disinfectant Residual", invited presentation at the AWWA/IWSA Conference on Disinfectant Residuals, April 26, 1998, Philadelphia PA. Also presented in Mulheim, Germany, October 2, 1998.
120) "Predicting Disinfection Performance In Continuous Flow Systems From Batch Disinfection Kinetics", presented at the biennial Conference of the International Association on Water Quality, June 1998, Vancouver BC (Canada).
121) "Frameworks for Assessing Reliability of Multiple, Independent Barriers in Potable Water Reuse", presented at the biennial Conference of the International Association on Water Quality, June 1998, Vancouver BC (Canada).
122) "A Quantitative Risk Assessment Model For *Listeria monocytogenes* And *E. coli* O157:H7", presented at the International Association of Milk, Food and Environmental Sanitarians, Nashville TN, August 1998/
123) "Epidemiology, Microbiology and Risk Assessment of Waterborne Pathogens Including *Cryptosporidium*", invited presentation – Conference on the National Food Safety Initiative: Implications for Microbial Data Collection, Analysis and Application, Arlington VA, October 15, 1998.
124) "What Is Disinfection?", presented at AWWA Preconference Workshop, November 1, 1998, San Diego CA.
125) "Risk Based Criteria for Pathogens in Drinking Water: Has the Time Come?", seminar to Department of Civil Engineering, San Diego State University, December 2, 1998, San Diego CA.
126) "Predicting Disinfection Performance in Continuous Flow Systems from Batch Disinfection Kinetics", seminar to the Department of Environmental Science and Engineering, University of North Carolina at Chapel Hill, November 11, 1998.
127) "Back to the Future: Engineering Safe Water and Safe Food in the 21st Century", presented to the Philadelphia Chapter of the Society for Risk Analysis, March 23, 1999.
128) "The Future of Drinking Water Science [and Engineering]". Invited presentation – EPA/AWWA Conference on Drinking Water: 2025. June 14, 1999, Washington DC.
129) "Watershed Management for Pathogen Control". Invited presentation – New York State Energy Research and Development Agency Conference on Management of Small Reservoirs. June 16, 1999, Albany NY.
130) "Formulation and Validation of a Dose Response Model for *Escherichia coli* O157:H7", presented at the International Symposium on Waterborne Pathogens, AWWA, Milwaukee WI, August 31, 1999.
131) "Inactivation of *Legionella pneumophila* by Free Chlorine", presented at the International Symposium on Waterborne Pathogens, AWWA, Milwaukee WI, August 31, 1999.
132) "Predicting Disinfection Performance in Continuous Flow Systems from Batch Disinfection Kinetics", seminar to the Department of Civil & Environmental Engineering, New Jersey Institute of Technology, September 22, 1999.
133) "Risk Based Criteria for Pathogens in Drinking Water: Has the Time Come?", seminar to the Department of Civil and Environmental Engineering, Princeton University, October 20, 1999.
134) "Community Level Impacts of Waterborne Infections", presented at the annual meeting of Society for Risk Analysis, Atlanta, December 7, 1999.

135) "Dermal Microbial Risk Assessment: Impact Of Germicidal Soap On Risk Of Infection From *Staphylococcus aureus*", presented at the annual meeting of the Society for Risk Analysis, Atlanta, December 6, 1999.
136) "Microbes and Monte Carlo", presented at the annual meeting of the American Association for Advancement of Science, Washington DC, February 22, 2000.
137) "Statistical Modeling in Drinking Water Production", invited presentation, IWA Workshop of Modeling Conventional Drinking Water Treatment Processes, Mar 16, 2000, Delft, The Netherlands.
138) "Dose Response Models", invited presentation, WHO-FAO Workshop on Microbial Risk Assessment, Utrecht, The Netherlands, June 13, 2000.
139) "Probabilistic Modeling of Drinking Water Treatment", seminar to the Department of Civil and Environmental Engineering, Duke University, September 7, 2000.
140) "Microbial Risk Factors: How We Got Here and Alternative Futures", invited presentation, AWWA Water Quality Technology Conference, Salt Lake City, November 7, 2000.
141) "Progress and Data Gaps in Quantitative Microbial Risk Assessment", invited presentation at the 2001 Asian Water Quality Conference, Fukuoka, Japan, September 12, 2001.
142) "Progress and Data Gaps in Quantitative Microbial Risk Assessment", invited presentation to the Department of Urban and Environmental Engineering, University of Tokyo, Japan, September 18, 2001.
143) "Decontamination Using Chlorine Dioxide", Testimony before the US House of Representatives, Committee on Science, hearing on "The Decontamination of Anthrax and Other Biological Agents", November 8, 2001, Washington DC.
144) "Bioterrorism 101", Invited presentation, Lehigh University chapter of Sigma Xi, November 28, 2001.
145) "The Role of Risk Analysis in Understanding Bioterrorism", invited plenary address, Society for Risk Analysis Annual Meeting, Seattle WA, December 3, 2001.
146) "The Risk of Inhalation Exposure to Anthrax Spores", seminar to the School of Environmental Science, Engineering and Policy, Drexel University, February 15, 2002.
147) "Disinfection Modeling", invited presentation, WEF Disinfection Specialty Conference, St. Petersburg FL, February 17, 2002.
148) "Microbial Dose-Response Models", presented at a short course on microbial risk assessment offered by the University of Ottawa to personnel from Food Canada and Health Canada, March 1, 2002, Ottawa, Canada.
149) "Chemical and Biological Terrorism and Higher Education", presented at a workshop organized by the Association of Independent Colleges and Universities of Pennsylvania, Harrisburg PA, March 7, 2002.
150) Invited Distinguished Public Health Scientist Lecture, "The Role of Risk Assessment in Responding to the Threat of Anthrax", Johns Hopkins University, Bloomberg School of Public Health, Baltimore, May 16, 2002.
151) "Risk Assessment, Bioterrorism and the Food Industry", invited presentation, First International Conference on Microbial Risk Assessment: Food, College Park MD, July 25, 2002.
152) "Quantitative Assessment Of Benefits From Using Topical Antimicrobial Hand Products: Case Study On *E. coli* Risk From Handling Raw Beef", Society for Risk Analysis Annual Meeting, New Orleans, December 9, 2002.

153) "Towards a Fourth Generation in Water (Chemical) Disinfection Process Design", seminar presented to the Department of Civil and Environmental Engineering, Tulane University, December 10, 2002.
154) "Risk Assessment, Bioterrorism and the Food Industry", seminar to the Eastern Regional Research Center, USDA, Wyndmoor PA, January 10, 2003.
155) "Pathogens: Understanding Risks and Control", invited presentation – Symposium on Drinking Water and Health, sponsored by Philadelphia Suburban Water and Drexel University, Philadelphia, March 25, 2003.
156) "Chemical and Biological Threats", presented at a workshop on Community Infrastructure Protection, Pennoni Associates, March 26, April 2, April 30 and May 7, Wilmington DE, Mt. Laurel NJ, Harrisburg PA and Philadelphia (2003).
157) "How Much is Enough to Protect Public Health: Statistical and Sampling Size Considerations for Environmental Sampling", invited presentation, Annual Meeting of the American Society for Microbiology, Washington DC, May 21, 2003.
158) "Overview of Risk Assessment Concepts and Methodologies", invited presentation, Workshop on Quantifying The Health Risk from Water Recycling Schemes, Brisbane, Australia, September 3, 2003.
159) "Quantitative Microbial Risk Assessment and Uncertainty Analysis", invited presentation, Workshop on Quantifying The Health Risk from Water Recycling Schemes, Brisbane, Australia, September 3, 2003.
160) "Numerical Investigation of the Effects of Reactor Configuration on the Efficacy of Microbial Inactivation", presented at the WEF Annual Conference, October 2003, Los Angeles CA.
161) "Quantitative microbial risk assessment+20: victories, challenges and a look forward", seminar to the Harvard Center for Risk Analysis, October 31, 2003, Boston MA.
162) "Risk Assessment", presented at workshop on "Reclaimed Water: Whose Water is it?", AWWA WQTC Conference, November 2, 2003, Philadelphia.
163) "Selection of an Appropriate Batch Inactivation Model – Why it Matters", presented at the WQTC Conference, Philadelphia, November 2003.
164) "Arrivederci "Minimal Infectious Dose": Have We Learned the Lesson Yet?:, presented at the 2003 Annual Meeting of the Society for Risk Analysis, Baltimore, December 7, 2003.
165) "Emission Rates of Biological Aerosols during the Land Application of Biosolids? Presented at the 2003 Annual Meeting of the Society for Risk Analysis, Baltimore, December 9, 2003.
166) "Disinfection 2020 (20/20)", Seminar presented to the Department of Civil Engineering, Villanova University, March 18, 2004.
167) "Disinfection 2020 (20/20)", Seminar presented to the Department of Civil and Environmental Engineering, University of Cincinnati, June 4, 2004.
168) "Quantitative Microbial Risk Assessment: An Introduction", invited presentation, 5th Annual Environmental Health Conference of the Association of Schools of Public Health, July 12, 2004 , University of Minnesota.
169) "Quantitative microbial risk assessment+20: victories, challenges and a look forward", seminar to the Department of Soil, Water and Environmental Science, University of Arizona, Tucson, October 25, 2004.

170) "Arrivederci "Minimal Infectious Dose": Have We Learned the Lesson Yet?", invited presentation – Workshop on Microbial Risk Assessment, US EPA – National Exposure Research Laboratory, Cincinnati OH, November 18, 2004.
171) "Reducing Waterborne Infectious Disease", seminar presented to the Department of Environmental Health Science, University of Michigan School of Public Health, November 29, 2004.
172) "Chemical Terrorism Against Food and Water Supplies", Symposium on Toxic Industrial Chemicals and Toxic Industrial Materials, sponsored by ATSDR and American Society for Medical Toxicology, Drexel University, June 13, 2005.
173) "Simulation of Anthrax Spore Transport and Inactivation in a Room: Scaling Analysis", S Soni, B Farouk and CN Haas, Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition, November 5-11, 2005 Orlando FL.
174) "Human and Animal Health Risks Associated With Biosolids", C.N. Haas, presented at the annual meeting of the American Society for Microbiology, Orlando FL, May 23, 2006.
175) "Thresholds: (Lack of) Evidence for their Existence, and What We Would See if They Were Significant", invited presentation – Upstate NY Chapter of the Society for Risk Assessment, October 13, 2006.
176) "Animal Dose Response Data for Predicting Risk of BT Events: Preliminary Thoughts on Validation Using the 2001 AMI Incident as a Case Study", presented at the annual meeting of the Society for Risk Analysis, December 2006.
177) "Basic Microbial Dose Response", C.N. Haas, presented at the annual meeting of the American Society for Microbiology, May 20, 2007, Toronto.
178) "Developing Unifying Principles in Microbial Risk Assessment", presented at the annual meeting of the American Society for Microbiology, May 22, 2007, Toronto.
179) "*E coli* O157:H7 -- What we Know about Assessing its Risk to Human Health", presented at the annual meeting of the American Society for Microbiology, May 23, 2007, Toronto.

Non-Reviewed Publications

1) "Chemical Basis for Interaction Between Aquatic Bacteria and Phytoplankton," Final Report to the National Science Foundation, Student Originated Studies Program (1973).
2) "Soluble Phase Chemistry of Trace Metal Transport Through Secondary Wastewater Treatment Systems," M.S. Thesis, Department of Environmental Engineering, Illinois Institute of Technology (1974).
3) "Heavy Metals Transport Through Municipal Sewage Treatment Plants." Proceedings, 2nd National Conference on Complete Water Reuse (1975). With J.W. Patterson and P. Shimada.
4) Discussion on "Temperature-Toxicity Model for Oil Refinery Waste." Journal of the Environmental Engineering Division, Proceedings ASCE, 101,446 (1975).
5) "New Microbial Indicators of Disinfection Efficiency." Annual Report to the U.S. Army Medical Research and Development Command (1975). With R.S. Engelbrecht et al.
6) "Inactivation of New Indicators of Disinfection Efficiency, Part I. Free Available Chlorine Species Kinetics." Proceedings, 96th Annual Meeting, American Water Works Association (1976). With F. Surucu.

7) Discussion on "Cyanophage Analysis as a Biological Pollution Indicator—Bacterial and Viral." Journal of the Water Pollution Control Federation, 49, 1913 (1977).
8) "Acid-Fast Bacteria and Yeasts as Disinfection Indicators: Enumeration Methodology." Proceedings, 5th Water Quality Technology Conference, AWWA. (1977). With R.S. Engelbrecht.
9) "New Microbial Indicators of Disinfection Efficiency." U.S. EPA Environmental Protection Technology Series 600/2-77- 052 (1977). With R.S. Engelbrecht et al.
10) "Mechanism of Inactivation of New Indicators of Disinfection Efficiency by Free Available Chlorine." Ph.D. Thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign (1978).
11) "Literature Review—Disinfection." Journal of the Water Pollution Control Federation, 50, 1134 (1978), with J. Gould.
12) "The Future of Chlorination." Rensselaer Fresh Water Institute at Lake George Newsletter, 8 #3 (1978).
13) "Acid-Fast Bacteria and Yeasts as Indicators of Disinfection Efficiency." US With R.S. Engelbrecht, et al.
14) Discussion on "Effects of Chlorination on Differentiated Coliform Groups." Journal of the Water Pollution Control Federation, 51, 2961(1979).
15) "Literature Review—Disinfection." Journal of the Water Pollution Control Federation, 51, 123 (1979). With J. Gould.
16) "Mode of Microbial Inactivation by Chlorine." Proceedings of the ASCE Environmental Engineering Specialty Conference, pp646-52 (1979). With R.S. Engelbrecht.
17) "Rational Analysis of Ultra-Violet Disinfection Reactors." Proceedings of the ASCE Environmental Engineering Specialty Conference, pp540-7 (1979). With G. P. Sakellaropoulos.
18) Discussion on "Kinetics of Bacterial Deactivation with Chlorine." Journal of the Environmental Engineering Division, ASCE, 105, 1198 (1979).
19) "Hazardous Waste Processing and Disposal Practices—Best Technology." Report to the New York State Environmental Facilities Corporation (1979). With W.W. Shuster, et al.
20) "The Potential for the Application of Resource Recovery Practices in the Hazardous Waste Processing and Disposal Industry." Report to the New York State Environmental Facilities Corporation (1979). With W.W. Shuster, et al.
21) "Literature Review-Disinfection." Journal of the Water Pollution Control Federation, 52, 1224 (1980 with J. Gould.
22) "Literature Review—Disinfection." Journal of the Water Pollution Control Federation, 53, 789 (1981), with J. Gould.
23) "What are Hazardous Wastes?" In R.L. Robbins (ed.) Limiting Liability for Hazardous Wastes, Chicago-Kent College of Law (1981).
24) "Technical Arguments Against the Adoption of Changes in the Illinois Wastewater Fecal Coliform Standards." Paper submitted to the Illinois Pollution Control Board (1981).
25) "Practical Considerations in the Use of Halogen Disinfectants." In A.D. Venosa (ed.), Proceedings of the Second National Symposium on Wastewater Disinfection, U.S. Environmental Protection Agency, EPA600/9-83-009 (1983).
26) "Literature Review—Disinfection." Journal of the Water Pollution Control Federation, 54, 646 (1982). With J.J. McCreary.

27) "Evaluation of High-Performance Phosphorus Control POTW's in the Great Lakes Basin." Final Report to the US EPA. With J.W. Patterson et al.(1982).
28) "Management of Hazardous Wastes: An Illinois Perspective." Report to the Illinois Institute of Natural Resources, With J.W. Patterson (1982).
29) "Microbiological Alterations in Water Quality in Distribution Systems and Granular Activated Carbon." Final Report to the US EPA. With M.A. Meyer et al. (1983).
30) "Incentives for the Treatment and Disposal of Hazardous Wastes by Alternative Methods." Report to the US EPA and the American Association for the Advancement of Sciences (1984).
31) "Wastewater Disinfection-A Review of the Technical and Legal Aspects in Illinois." Metropolitan Sanitary District of Greater Chicago, Department of Research and Development, Report 84-17 (1984). With C. Lue-Hing et al.
32) "Computer Applications to Chemical Equilibria in Modeling and Simulation of Aqueous Environment." Proceedings of the 2nd International Conference on Computer Aided Analysis and Design in Civil Engineering (1985). With V. Tare.
33) "Risks Associated with Viruses in Drinking Water", Proceedings of the Third Conference on Progress in Chemical Disinfection, p460-8 (1986), C.P. Gerba and C.N. Haas.
34) "Effects of Ceasing Chlorination on Selected Indicator Populations Downstream of Metropolitan Chicago's Major Wastewater Treatment Facilities", Metropolitan Sanitary District of Greater Chicago, Department of Research and Development, Report 87-17 (1987). With S. Sedita and C. Lue-Hing.
35) "Methods and Monitoring – Statistical Approaches", Chapter 20 in Drinking Water Microbiology: Progress and Recent Developments, G.A. McFeters[ed.], Springer-Verlag, New York (1990). C.N. Haas and B. Heller.
36) "Development and Testing of a Methodology to Identify, *ex post facto*, the Determinants of Remedial Actions at Superfund Sites", Center for Hazardous Waste Management, IIT/IITRI (1989). With G. Paulson et al.
37) "User Manual for the Computer Program WASTE (Waste Alternative Solutions to Evaluate) [and accompanying software]. Report to the Illinois Department of Energy and Natural Resources, J.W. Van Nortwick, C.N. Haas and R. Porter (1989).
38) "Editorial: Acting in the Face of Uncertainty", Journal of the Water Pollution Control Federation, 62, 2, 115 (1990).
39) Discussion on "Analysis of Inactivation of *Giardia lamblia* By Chlorine", Journal of Environmental Engineering, 115, 1, 1210-2 (1990).
40) "Editorial: Let's Surprise Rip Van Winkle", Research Journal of the Water Pollution Control Federation, 63, 5, 755 (1991).
41) "Demand Exceeds Supply for Environmental Engineers", Engineering Horizons, Fall (1992), pp27-28.
42) Invited Book Review, "Taste and Odor Problems Associated with Chlorine Dioxide", Environmental Progress,, 13(1):F10-11 (1994).
43) "The Risk of Over reliance on Risk Assessment", Water Environment Research, 67, 1, 3 (1995).
44) "Waterborne Diseases – Who is at Risk?", Proceedings of the 1994 AWWA Water Quality Technology Conference, II:57-71, CP Gerba, JB Rose and CN Haas (1995).
45) "Risk Assessment in Microbial Water Quality Criteria", Australian Water and Wastewater Association Journal, November/December, pps 18-20, CN Haas (1995).

46) "Microbial Risk Assessment: A New Tool in Water Quality Management", CP Gerba, JB Rose and CN Haas, Proceedings of the 6th International Conference for "Ecology and Environmental Quality", June/July 1996, Jerusalem.
47) "Linking Microbiological Criteria for Foods with Quantitative Risk Assessment", Chapter 14 in JJ Sheridan, RL Buchanan and TJ Montville (eds.), HAACP: An Integrated Approach to Assuring the Microbiological Safety of Meat and Poultry, Food and Nutrition Press, Trumball CT (1996).
48) "Quantitative Microbial Risk Assessment for Reclaimed Water", Proceedings – WaterTech, 1996 Annual Conference of the Australian Water and Wastewater Association, Sydney, May 1996, pp254-260. CP Gerba, JB Rose and CN Haas.
49) "Microbial Risk Assessment: A New Tool in Water Quality Management", Preservation of Our World in the Wake of Change, (Y Steinberger, ed.), VIA/B:732-735 (1996).
50) "Main Disinfection – Why Do it the Way We Do?", Opflow, 22(9):1,4 (1996), GA Burlingame, CN Haas and WO Pipes.
51) "Viewpoint: Acceptable Microbial Risk", Journal of the American Water Works Association, 88(12):8 (1996), CN Haas.
52) "Risk Assessment of HIV in Wastewater Collection and Treatment Systems", CN Haas, pages 103-108, in HIV in Wastewater, WEF Monograph (C. Lue-Hing, P. Tata and L. Casson eds.), Alexandria VA (1999).
53) "Disinfection in the 21st Century", Journal of the American Water Works Association, 92(2):72-3 (2000), C.N. Haas.
54) "Editorial: Environmental Engineering and Bioterrorism?", Journal of Environmental Engineering, 128(5):397 (2002), C.N. Haas.
55) "Toxic and Contaminant Concerns Generated by Hurricane Katrina", The Bridge (published by the National Academy of Engineering), Spring 2006, p5-13, D.D. Reible, C.N. Haas, J.H. Pardue, and W.J Walsh.
56) "WATERS Network - Transforming the Way the United States Assesses Water Quality and Manages This Valuable and Threatened Resource", submitted to WATER21 (International Water Association), Paula Estornell, Charles N. Haas, Barbara Minsker, Jerald L. Schnoor and Jami L. Montgomery.

Student Advising

Rensselaer Polytechnic Institute

Year	Degree	Student	Title
1979	M.Eng.	P.A. Sajous	Oxygen Uptake Rate as a Control of Activated Sludge Process
1979	M.Eng	E.C. Morrison	Altered Sensitivity to Chlorine in E. coli.
1980	M.S.	P.A. Hughes	Laboratory Investigation of the Activated Sludge Process with Alum Addition for the Removal of Trace Metals.
1980	M.S.	C.A. Weitz, Jr.	Ultraviolet Reactor Design Using Hydraulic Parameters.

1982	M.Eng.	M.A. Zapkin	Inactivation of Escherichia coli by Chlorine in the Presence of Various Additives.

Illinois Institute of Technology

Year	Degree	Student	Title
1981	M.S.	L.M. Mele	Surface Water Hydrology of Coal Refuse Disposal Sites.
1982	M.S.	R. Garunas	Acid Waste Gas Biodesulfurization: An Alternative to Chemical Sulfur Recovery Processes.
1982	M.S.	K.A. Lavelle	Desulfobacter Biocatalyzed Reduction of Gypsum Wastes: Applications to Phosphoric Acid Manufacturing.
1983	M.S.	S.B. Karra	Kinetic Limitations on the Recovery of Metals From Wastewater by Precipitation.
1984	M.S.	K. Khater	Inactivation of Tetrahymena pyriformis By Monochloramine.
1984	M.S.	T. Jamrock	Effect of Time and Temperature on the E.P. Toxicity Test.
1984	M.S.	A. Wojtas	Inactivation of Tetrahymena pyriformis By Free Chlorine.
1984	M.S.	D.M. Brncich	The Determination of Stability Constants for Na, Li, and K Ion Pairs with Ocl
1984	M.S.	N. Horowitz	The Effect of Organic Ligands on the Adsorption of Cadmium Onto Kaolinite.
1984	M.S.	B. Kaplan	The Influence of Humic Acid on Solubility and Air-Water Partitioning of Toluene.
1984	M.S.	J. Macak	The Use of Coal Ash Mixtures as a Final Cover in the Reclamation of Landfills.
1985	M.S.	G. Vanderlaan	Feedstock Chemicals and the Hazard Ranking System Data Base.
1985	M.S.	M. Karalius	Inactivation of Escherichia coli by Chlorine in the Presence of K^+ and Li^+ Ions.
1985	M.S.	Robert Renaud	Investigation of Thiosulfate and other Dechlorinating Agents.
1985	M.S.	John Sheerin	Magnitude and Decay of Fecal Coliforms in Chlorinated and Non Chlorinated Wastewater Discharges.
1985	M.S.	J.R. O'Donnell	Spectrophotometric Determination of K_D for the LiOCl, NaOCl and KOCl Ion Pairs.
1986	M.S.	Paul Bitter	Analysis of Five Nutrient Effects on the Growth of Microorganisms in the City of Chicago Drinking Water Supply.
1986	M.S.	Bon Mui	Distribution of Coliforms in Lake Michigan.
1986	M.S.	R. J. Vamos	Kinetics of Cadmium Complexation Reactions with

			Chloride and Hydroxide
1986	M.S.	C. D. Trivedi	Inactivation of Escherichia coli by Free Chlorine and Monochloramine in the Presence of Potassium Ions.
1986	M.S.	Andrew Kling	Energy Waste in Aeration Processes.
1986	M.S.	Angela Podesta	A Rapid Membrane Filter Technique For the Concentration of Plankton in Finished Drinking Water.
1987	M.S.	Paul Favara	Metal Removal in SBR Systems Treating Hazardous Waste Leachate.
1987	M.S.	H. D.-Markazi	Effect of Ethylene Glycol on Transport of Chloride thru Landfill Liner Material.
1988	M.S.	C. Brougnier	Co-Disposal of Plastics and Solvent Wastes as Residual Fuel.
1988	Ph.D.	K.V. Topudurti	Transfer of Chlorine from Monochloramines and Organochloramines to a THM Precursor.
1988	M.S.	Marc Bonem	Plant Deposition of Nitrogen Dioxide (co advised).
1990	Ph.D.	Yao Kouome	CSTR Microbial Inactivation by Free and Combined Chlorine.
1990	Ph.D.	C. Polprasert	Biological Sulfide Production for Heavy Metal Removal.
1990	Ph.D.	Richard Vamos	Binary and Ternary Equilibria of Cation Exchange.
1990	M.S.	Chi Lo	Assessment of Solid Waste Generation Patterns and Potential for Recycling on the IIT Campus.
1990	M.S.	P. Cunningham	Carcinogenic Risk Assessment: A Monte Carlo Study of Methods for Determining Confidence Limits on the Virtually Safe Dose
1991	Ph.D.	J. VanNortwick	Mixed Metal Precipitation
1991	M.S.	B. Bush	Carcinogenic Risk Assessment: Calculating Confidence Limits on the Virtually Safe Dose

Drexel University

Year	Degree	Student	Title
1992	M.S. (Env. Sci.)	Bruce Stirling	Biological Responses to Mixtures
1993	M.S. (Env. Eng.)	Joel Hornberger	Development of a Standard Method for the Determination of Disinfection Effectiveness Against *Giardia* Cysts
1993	M.S. (Env.Eng.)	Uma Anmangandla	Regression Analysis of Disinfection Kinetics
1994	M.S. (Env.Eng.)	Sean Kersten	Analysis Of Binary Toxic Mixtures Using A Model Of Independence
1995	M.S. (Env. Eng)	Kaushik Cidambi	Analysis Of Binary Toxic Mixtures Using A Generalized Additivity Model
1995	M.S.	Chris Crockett	Determination of Sources and Impacts of *Giardia*

	(Env.Eng)		and *Cryptosporidium* in a Major Metropolitan Watershed
1996	PhD (Env Eng)	Jin Anotai	Effect of Calcium Ion on Chemistry and Disinfection Efficiency of Free Chlorine at pH 10
1996	M.S. (Env.Eng.)	Shubhangi Desai	Kinetics of Inactivation of *G. muris* by Monochloramine
1996	M.S. (Env.Eng.)	Aamir M Fazil	A Quantitative Risk Assessment Model for *Salmonella*
1996	M.S. (Env.Eng.)	R.B. Chitluru	Chlorination Kinetics for Water Main Associated Organisms
1996	M.S. (Env Sci)	J.L. Gambetese	Fate Modeling of Organic Compounds in Wastewater Treatment Plants: A Comprehensive Analysis of WATER7 and WATER8
1996	Ph.D.(Env Eng)	James Hagan	An Examination of Acute Environmental Toxicity of Pharmaceutical Compounds Using Quantitative Structure-Activity Relationships
1996	M.S. (Env Eng)	Josh Joffe	Data Analysis for Disinfection Kinetics Modeling.
1997	M.S. (Env Eng)	Joe Nattress	Benchmarking *Giardia* and *Cryptosporidium* Inactivation at the Philadelphia Water Department
1998	M.S. (Env Eng)	Dhumal Aturaliye	Electroporation Assisted Disinfection of *Giardia* and *Cryptosporidium*
1998	M.S. (Env Sci)	Aadithya Thayyar-Madabusi	A Quantitative Risk Assessment Model for *Listeria monocytogenes* and *Escherichia coli* O157:H7.
1999	Ph.D. (Env. Eng)	Mukul Gupta	Epidemiological Modeling of Waterborne and Foodborne Outbreaks
1999	MS (Env Eng)	Kathy French	Modeling *Cryptosporidium* Removal in Drinking Water by Physical Processes
1999	MS (Env Eng)	Chad Pindar	Clostridium perfringens as an Indicator for *Cryptosporidium* During Electroporation Assisted Disinfection
1999	MS (Env Eng)	Paul Batman	Water matrix effects on protozoan inactivation in chlorine-chloramine disinfection processes
1999	MS (Env Eng)	Dora D'Andrea	Inactivation efficiency of *Mycobacterium* by free chlorine
1999	MS (Env Sci)	Joseph Dmochowski	Benchmarking and modeling the inactivation of Legionella pneumophila using chlorine and chloramines
2000	MS (Env Eng)	Jason Sites	Analysis of *Giardia* Inactivation and *Cryptosporidium* Viability/Infectivity Assays in Various Disinfection Schemes
2001	PhD (Env Eng)	Paula R. Klink	Ion exchange on a chelating resin: multicomponent equilibrium predictions using binary data
2002	MS (Env Eng)	Jason Marie	Use of Microbial Risk Modeling to Determine the

			Benefit of Topical Antimicrobial Products
2002	PhD (Env Eng)	Dennis Greene	Numerical Simulation of Chlorine Disinfection Processes in Non-Ideal Reactors
2003	PhD (Env Eng)	Baris Kaymak	Effect of Initial Microorganism Concentration on Disinfection Efficiency by Chlorine.
2004	PhD (Env Eng)	Lijie Li	Effects of Initial Microbial Density on Disinfection Efficiency in a Continuous Flow System and Validation of Disinfection Batch Kinetics in a Continuous Flow System
2004	PhD (Env Eng)	Christopher Crockett	The Concentration and Resuspension of *Cryptosporidium* Oocysts by Sediments
2005	MS (MechE)	Sankalp Soni	Simulation of Contaminant Dispersal in An Apartment Building" (co-advised with Baki Farouk)
2005	PhD (Env Eng)	Thomas W. Armstrong	A quantitative microbial risk assessment model for human inhalation exposure to *Legionella*
2006	PhD (EnvEng)	Timothy A. Bartrand	High-Resolution Experimental and Numerical Analysis of Fine Bubble Ozone Contactors (co advised with Baki Farouk)
2006	MS (EnvEng)	Bishel B. Baby	A Dose-Response Analysis for Plague bacterium: *Yersinia pestis*
2007	PhD (EnvEng) (co advised)	Lynn A Arlauskas-Dekleva	1-Hydroxyanthraquinone: Activity in *Paracoccus denitrificans* and Potential Application for Biomass Reduction in Wastewater Treatment Facilities.

Student Research In Progress at Drexel University:

Degree	Student	Topic
PhD (Env Eng)	Russell Green (2002-)	Biologically Assisted Corrosion
PhD(Env Eng)	Shamia Hocque (2005-)	TBD
PhD (EnvEng)	Mark Weir (2004-)	Microbial risk assessment
PhD (EnvEng)	Joanna Pope (2004-)	PCR and Antibiotic Resistance Profiling for Microbial Source Tracking in the Delaware Valley
PhD (EnvEng)	Sushil Tamrakar (2006-)	Microbial Risk Assessment
PhD (EnvEng)	Paula Estronell (2006-)	Water Policy

Teaching Experience

Rensselaer Polytechnic Institute

Course	Semester	# Enrolled	# Responses	Course I Instructor (4 point max.)	
Enve Lab II	Spring 78	29	21	2.67	2.70
Unit Processes	Spring 78	27	25	3.17	2.74
Chemistry for Env. Eng.	Fall 78	4	4	3.25	3.33
Adv. Aquatic Chemistry	Fall 78	6	6	3.67	3.50
Env.Eng.Lab.I	Fall 78	20	12	2.73	2.55
Unit Processes	Spring 79	29	25	3.50	3.58
Thermodynamics	Spring 79	47	24	2.33	3.04
Adv.Aquatic Chemistry	Spring 80	4	4	3.75	4.00
Biol. Tmt.	Spring 80	19	18	3.39	3.59
Unit Ops.	Spring 80	21	21	2.82	2.94
Biol. Tmt.	Spring 81	16	not available		

Illinois Institute of Technology

Course	Semester	# Enrolled	# Responses	Course Instructor (5 point max.)	
Environ. Chem.	Fall 1981	20	20	3.94	4.00
Water & Waste Tmt.	Fall 1981	5	5	4.20	4.40
Biochemical Eng.	Spring 1982	8	8	4.71	4.82
Physical Tmt.	Spring 1982	10	10	4.30	4.44
Environ. Chem.	Fall 1982	6	6	3.70	4.30
Biochemical Eng.	Spring1983	4	4	5.00	4.75
Sanitary Design	Spring1983	8	7	4.10	4.50
Environ. Chem.	Fall 1983	9	7	3.71	4.14
Physical Tmt.	Fall 1983	8	8	4.75	4.63
Hazardous Waste Eng.	Spring1984	20	17	4.00	4.41
Water & Waste Tmt.	Spring1984	14	13	4.00	4.40
Biochemical Engng.	Fall 1984	8	7	4.60	4.90
Water & Waste Tmt.	Fall 1984	12	10	4.30	4.50
Hazardous Waste Eng.	Spring1985	16	14	3.78	3.92
Sanitary Design	Spring1985	8	8	4.38	4.88
Water & Waste Tmt.	Fall 1985	11	11	3.91	4.30
Intro. Environ. Eng.	Fall 1985	29	18	3.39	4.19
Hazardous Waste Eng.	Spring1986	12	12	4.00	4.00
Physical Tmt.	Spring1986	11	11	4.06	4.01
Biochemical Eng.	Fall 1986	18	18	4.67	4.72
Ind. Wst. Tmt. Crit.	Fall 1986	10	10	4.30	4.40
Sanitary Design	Spring1987	5	5	4.80	4.80
Hazardous Waste Eng.	Spring1987	13	13	3.23	3.61
Groundwater Contam.	Fall 1987	13	13	4.07	
Physical Tmt.	Fall 1987	7	7	4.43	
Hazardous Waste Eng.	Spring1988	10			
Biochemical Engng.	Spring1988	8			
Intro. Env. Eng.	Fall 1989	13			
Biochemical Engng.	Fall 1989	35			
Hazardous Waste Eng.	Spring1990	12			
Data Analysis	Spring1990	30			
Physical Tmt.	Fall 1990	8			

Drexel University (* - Undergraduate Course)

Course	Term	Enrollment
Unit Ops:Biological	Winter, 1991	16
Environ. Engineering I (*)	Spring, 1991	25
Chem. Of the Environ.	Fall, 1991	80
Unit Ops. Laboratory	Winter, 1992	5
Unit Ops: Biological	Spring 1992	25
Risk Assessment	Fall 1992	12
Adv.Environ.Chem.	Winter 1993	6
Unit Ops: Biological	Spring 1993	7
Unit Ops: PhysicalChemical	Spring 1993	16 (team taught)
Environmental Chemistry I	Fall 1993	25
University Seminar (*)	Fall 1993	22
Risk Assessment	Winter 1994	23
Unit Ops: Biological	Spring 1994	12
Topics in Environmetrics	Spring 1994	6 (plus 12 audits)
Environmental Chemistry I	Fall 1994	25
Environ. Engineering I (*)	Fall 1994	45
Risk Assessment	Winter 1995	20
Adv. Environ. Chem.	Spring 1995	11
Environmental Chemistry I	Fall 1995	20
Risk Assessment	Winter 1996	17
Unit Ops: Biological	Spring 1996	17
Environmental Chemistry I	Fall 1996	22
Risk Assessment	Winter 1997	24
Unit Ops: Biological	Spring 1997	10 (team taught)
Haz.Waste & GW Tmt.	Fall 1997	6
Reaction Kin.&Mass Tr.	Winter 1998	10
Risk Assessment	Winter 1998	15
Unit Ops: Physical-Chemical	Spring 1998	7
Envir. Transport & Kinetics (*)	Fall 1998	3
Risk Assessment	Winter 1999	11
Water Infrastructure (*)	Summer 1999	25 (team taught)
Biostatistics	Fall 1999	15
Risk Assessment	Winter 2000	5
Water Infrastructure (*)	Winter 2000	23
Unit Ops: Biological	Spring 2000	4
Water Infrastructure (*)	Summer 2000	28 (team taught)
Biostatistics	Fall 2000	30
Risk Assessment	Winter 2001	7
Environmental Impacts (*)	Spring 2001	6
Biostatistics	Fall 2001	50
Bioterrorism (*)	Winter 2002	130

Freshman Design (*)	Winter 2002	8
Environmental Impacts (*)	Spring 2002	16
Unit Ops: Biological	Spring 2002	3
Intro. To Enve. Eng. (*)	Fall 2002	6
Prof.. Practice in Env.Eng.(*)	Fall 2002	9
Risk Assessment	Winter 2003	8
Intro. To Environ. Eng. (*)	Spring 2003	8
Intro. To Environ Eng (*)	Fall 2003	17
Environ Eng Lab I (*)	Winter 2004	3
Environ. Eng. Lab II (*)	Spring 2004	3
Intro to Environ Eng (*)	Spring 2004	37
Intro to Environ Eng (*)	Fall 2004	39
Risk Assessment	Winter 2005	18 (team taught)
Intro to Environ Eng (*)	Spring 2005	32
Unit Ops: Biological	Spring 2005	7
Prof. Practice in Env Eng (*)	Fall 2005	6
Mass Transfer & Kinetics in EnvE (*)	Winter 2006	8
Water & Wastewater Design III (*)	Spring 2006	7
Freshman Design I (*)	Fall 2006	23

Service on External Graduate Student Committees

Alexa Oblensky, University of North Carolina at Chapel Hill, Department of Environmental Science and Engineering (advisor – Phil Singer), 2002-present.

Benjamin Tanner,, University of Arizona, Department of Soil, Water and Environmental Sciences (advisor – Ian Pepper), 2003-2004.

James Brooks, University of Arizona, Department of Soil, Water and Environmental Sciences (advisor – Ian Pepper), 2003-2004.

Domenico Santoro, Polytechnic of Bari at Taranto (Italy), Faculty of Environmental Engineering (external examiner and collaborator; advisor – Lorenzo Liberti), 2004-2005.

Professional Activities

Editorial Boards

Founding Editor in Chief - Quantitative Microbiology (Kluwer), 1998-2001
Applied and Environmental Microbiology (Editorial Board, 1988-1994)
Water Environment Research (Board of Editorial Review, 1989-1995; Chair 1991-1995)
Ozone Science & Engineering (Editorial Board, 1999 - 2001)
Journal of Medical Risk (Editorial Board, 2003-)
Risk Analysis (Associate Editor – Microbial Risk, 2006-)

Panels and Seminars Chaired

Organized and Chaired a Seminar on "Mode of Action of Halogen Disinfectants Used in Water and Wastewater Treatment" at the Annual Meeting of the American Society for Microbiology, Dallas, March, 1981.
Organized and Chaired a Session on "Disinfection and Chemical Oxidation" at the Annual Meeting of the American Institute of Chemical Engineers, New Orleans, November, 1981.
Organized and Chaired a Session on "Potpourri: Industrial and Toxic Wastes" at the National Meeting of the American Institute of Chemical Engineers, Cleveland, August, 1982.
Organized and Co-Chaired a Session on "Recovery of Metal Values From Industrial Wastes" at the National Meeting of the American Institute of Chemical Engineers, Denver, August 1983.
Invited Chairman on "Disinfection of Wastewater Effluents" NSF State of the Art Conference on Disinfection of Wastewater Effluents and Sludges, Miami, May 1984.
Organized and Chaired a Preconference Workshop on "Alternative Wastewater Disinfection Processes: Design and Operation", WPCF, Los Angeles, October 1986.
Organized and Chaired a Preconference Workshop on "Emerging Issues in Effluent Disinfection", WPCF Preconference Workshop, Philadelphia, October 1987.
Co-Organized and Co-Chaired a Preconference Seminar on "Practical Experience with Ozone for Organics Control and Disinfection", AWWA, Cincinnati, June 1990.
Co-Organized and Co-Chaired a Preconference Seminar on "Water Quality Changes from Chloramination", AWWA, Philadelphia, June 1991.
Co-Organized and Co-Chaired a Preconference Seminar on "Meeting Disinfection Byproducts Standards", AWWA, Vancouver, June 1992.
Organized opening general session, "When is Wastewater Disinfection Necessary?" at WEF Specialty Conference on Wastewater Disinfection, Whippany NJ, May 1993.
Co-Organized Preconference Seminars on "Disinfection: The New Basics" and "When is Groundwater Disinfection Necessary", AWWA, June 1993, San Antonio.
Co-Organized Symposium on "Microbial Risk Assessment in Water and Food" at the Annual Conference, Society for Risk Analysis, Savannah GA, December 1993.
Organized a Workshop on Microbial Risk Assessment of Food, Society for Risk Analysis, Washington DC, December 1997.
Co-Organized Disinfection Specialty Conference, Water Environment Federation, Baltimore MD, April 19-22, 1998.
Program Committee, AWWA/IWSA Conference "Protecting Water Quality in the Distribution System: What is the Role of Disinfectant Residual", Philadelphia, April 26-28, 1998.
Organized NSF supported expert workshop on Advancing the Quality of Water (AQWA), Chapel Hill NC, March 10–12, 2004.
Co-Organized WEF/AWWA/IWA Disinfection Specialty Conference, Pittsburgh PA, February 4-7, 2007

Professional Society Activities

American Society of Civil Engineers, Environmental Engineering Division.
Member, Task Committee on Disinfection Risk Assessment 1981-1985.
Water Supply and Resource Management Committee

Chairman, Task Committee on Control of Microbes in Drinking Water, 1989-92

American Water Works Association

Member, Research Division Committee on Disinfection, 1980-1992.

Member, Water Quality Division Committee on Disinfection, 1982-present.; Chairman, 1989-1994

Member, Water Quality Division Committee on Organisms in Water, 1983-1987.

Member, Water Quality Division Committee on Status of Waterborne Diseases in the US and Canada, 1987-1995

Member, Student Activities Committee, 1984-1990.

Illinois Section Student Activities Committee, Member, 1981-1990; Chairman, 1983-1986.

American Water Works Association Research Foundation (AWWARF)

member, various project advisory committees (1993-current)

Association of Environmental Engineering and Science Professors

Chairman, Committee to revise recruitment brochure, 1981-1983.

Member, Board of Directors, 2001-2004

Treasurer and Member of the Executive Committee, 2002–2004

Chairman, Conference Planning Committee, 2003-present

International Water Association

USA National Committee

delegate (from ASM) 1988-2000.

Chairman 1994 - 2000

Chairman, USANC Membership Committee, 1991-1993.

Program Committee for 1998 (Vancouver), 2000 (Paris), 2001 (Berlin) and 2002 (Melbourne) Conferences,

1996-2001.

Water Environment Federation

Director-at-Large, 2004-2006.

Member, Research Committee, 1978-1982.

Member, Research Committee Task Force on Toxic Substances, 1980-1982.

Member, Committee on Disinfection, 1980-1988, 1991-present.

Vice-Chairman, 1982-1985.

Chairman, 1985-1988.

Member, Research Symposium Subcommittee of the Program Committee, 1984-1986.

Member, Illinois Association Student Activities Committee, 1981-1990.

Member, Technical Practices Committee Task Force on Disinfection, 1982-1985.

Chairman, Specialty Conference Planning Committee: Microbial Aspects of Surface Water Quality, 1988-1989.

Member, Board of Editorial Review for the Research Journal, 1989-1995.

Chairman, 1992-1995.

Co-Chairman, Third Specialty Conference on Disinfection (Baltimore, April 1998)

Water Environment Federation Research Foundation

member, Project Subcommittee (UV Disinfection) - Sept 1996-1998

member, Project Subcommittee (Water Reuse) - Oct. 1997-2001

member, Board of Directors – 2006-

Standard Methods for the Examination of Water and Wastewater
Chairman, Joint Task Group on Chlorine Residual, 1984-present.
Member, Joint Task Group on Chlorine Demand, 1988-present.
Society for Risk Analysis, Councilor (member, Board of Directors), 2000–2003
American Association for the Advancement of Science, Division Y (General Interest)
Electorate Nominating Committeee (2002-2005).
Chair-Elect (2008-9)
American Society for Microbiology
Public and Scientific Affairs Board, Committee on Environmental Microbiology, Member (2003-)

Continuing Education Programs

Seminar on Current Topics in Water Supply, New York State Section of the American Water Works Association, Ossining, NY, November, 1980.
Limiting Liability for Hazardous Wastes, a continuing education program for lawyers, sponsored by the Chicago-Kent College of Law, Chicago, November, 1981, was also a member of the program Steering Committee.
WPCF Preconference Workshop on Wastewater Disinfection Alternatives, Atlanta, October 1983, Co-organizer and participant.
University of Wisconsin-Milwaukee, Engineering Extension. Disinfection of Water and Wastewater, May 1984.
WPCF Preconference Workshop on Disinfection Risk Assessment, New Orleans, September 1984, Co- organizer and participant.
University of Wisconsin-Milwaukee, Engineering Extension. Disinfection of Wastewater, May 1985.
University of Wisconsin-Milwaukee, Engineering Extension. Wastewater Pretreatment and Toxicity Control, March, 1986.
University of Wisconsin-Milwaukee, Engineering Extension. Disinfection of Water, June 1986.
WPCF Preconference Workshop on Design and Operation of Alternative Disinfection Systems, Los Angeles, October, 1986, Organizer and participant.
WPCF Preconference Workshop on Emerging Issues in Effluent Disinfection. Philadelphia, October, 1987, Organizer and participant.
WPCF Specialty Conference on Microbial Aspects of Surface Water Quality, Chicago, May 1989, Organizer.
WPCF Preconference Workshop on Changing Standards for Effluent Disinfection, San Francisco, October 1989.
California Business Law Institute, Environmental Regulation in Illinois, participant, November 1989.
University of Wisconsin-Madison, Engineering Extension. Disinfection of Wastewater, October 1989, October 1990.
University of Wisconsin-Madison, Engineering Extension. Disinfection of Water, November 1989.
International Association of Milk, Food and Environmental Sanitarians, Co-Organized Workshop on Microbial Risk Assessment of Foods, Pittsburgh, July 1995.
WEF Specialty Conference on Disinfection, Baltimore MD, April 1998, co-organized.

AWWA/IWSA Symposium on Disinfection Residuals, Philadelphia PA, April 1998, member - planning committee.

University Service

Rensselaer Polytechnic Institute

RPI Department of Chemical and Environmental Engineering Committee on Graduate Students, Member, 1978-1981.
Planning Committee for the UPS Conference, RPI Fresh Water Institute, 1979.
Member, RPI Biohazard Safety Committee, 1979-1981.
Advised RPI Safety Manager on Chemical Waste Disposal Practices, 1980-1981.

Illinois Institute of Technology

Member, IIT Graduate Study Committee, 1981-90.
Chairman, Departmental Faculty Search Committee, 1982-1984, 1987, 1990.
Member, Armour College Committee on Promotion and Tenure, 1984-1986.
Member, Institute Library Planning Committee, 1983-88.
IIT Faculty Senate, Recording Secretary, 1984-1986.
Corresponding Secretary, 1987-1988.
Member, New Business Committee, and IIT Projects Manager, Center for Hazardous Waste Management, 1987-89.
Member, Search Committee for Dean of Armour College of Engineering, 1987-1988.
Member, Department Chairman Search Committee, 1988-9.
Member, IIT Faculty Council, 1989-90
Chairman, Academic Affairs Committee, 1989-90

Drexel University

University
Faculty Senate
Member 1991-1992, 1994-1997
Vice Chair, 1994-1995
Chair, 1995-1996
Member, University Appeals Committee, 1991-94
Member, Search Committee for Associate Director of Enrollment Management (Graduate/Part Time), 1992
Chairman, University Biosafety Committee, 1996-1998.
University Assessment Committee (preparation for Middle States visit), 1998-2001
Member
Co-chair, Research & Graduate Task Force
Chairman, Search Committee for a Director of SESEP, 2000-2002
Member, Law School Development Committee, 2004-5.

College/School

Chairman, BS Environ. Eng. Curriculum Development Committee, 1993.
Chairman, Environmental Policy Faculty Search Committee, 1997.
Member, The Drexel Engineering Curriculum Revision Committee, 2005-current.

Department
Chairman, Environmental Studies Institute Curriculum Committee, 1991-1994
Chairman, Civil and Architectural Engineering Department Graduate Committee, 1991-1992
Member, Civil and Architectural Engineering Department Committee on Laboratory Renovation, 1993-4.
Member, Search Committee, Architectural Engineering Faculty, 1993-1994.
Member, Search Committee, Environmental Engineering Faculty, 1996.
Member, Search Committee, Environmental Chemistry Faculty, 1993-1994, 1996
Chairman, SESEP Faculty Search Committee, 1997-1998.
Chairman, SESEP Curriculum Committee, 1999-2002
Chairman, ABET Preparation for Initial BS EnvE Accreditation, 1999-2002
Chair, Midterm Review Committees for Assistant Professors Lordgooei and Wartman, 2002.
Member, Departmental Promotion Committee for Associate Professor Welty, 2002.
Member, Department Head Search Committee, 2002-2003.
Member, CAEE Department Undergraduate Curriculum Committee, 2002-2005
Member CAEE Department Graduate Committee, 2003-2005
Chair, CAEE Department Faculty Search Committee, 2003-2004

Consulting Activities

Energy & Resource Recovery Corporation (Subsidiary of Alpha Portland Industries)--performed a regulatory analysis and preliminary feasibility study for the use of hazardous wastes and spent solvents as supplemental fuel in cement kilns, 1979.

New York State Department of Civil Service - served as a member of oral examination panels for the positions of Associate Sanitary Engineer and Associate Air Pollution Control Engineer, March through May, 1981.

Patterson Associates, Inc.
–preparation of a state-of-the-art report on hazardous wastes in Illinois, Illinois Institute of Natural Resources, May through October, 1981.
–determination of hazardous waste production potential and management options for the forging industry, June through October, 1981.
–analysis of a the waste management profile for a large, privately held, conglomerate, November, 1986.

K.A. Steel Chemicals, Inc. --preparation of a technical document and testimony against the proposed changes in the Illinois wastewater fecal coliform standards, October 1981 through February, 1982.

PEER Consultants, Inc. -- reviewed draft US EPA report entitled "User Guide for Evaluating Remedial Action Technologies." August, 1982.

Waste Management, Inc. --Prepared testimony on the need for additional hazardous waste disposal capacity in Will County, Illinois, October, 1982.

Katz, Friedman, Schur and Eagle/United Auto Workers-- evaluation of technical documents relating to environmental impact of cooling water discharge at Quad Cities/Cordova Generating Station, June 1983-ongoing.

Bituminous Insurance Companies--evaluation of possible mechanisms for failure of the Galesburg, IL anaerobic digestor, November 1984-1985.

Metropolitan Sanitary District of Greater Chicago--preparation of oral and written civil service examination materials and service on oral examination panels, 1981-1990.

Battelle Columbus Laboratories -- peer review of a document on feasibility of risk assessment for sludge management. August, 1985.

Hydrite Chemical Co.--Preparation of expert testimony on changes in wastewater bacteriological standards in the State of Wisconsin, December 1985 - March, 1986.

US EPA (Region VIII) -- Advised on the efficiency of and the means to improve disinfection and dechlorination at the Metro Denver Wastewater Treatment Plant, March 1986.

East Bay Municipal Utility District (Oakland, CA) -- Serve as a technical advisor on the design of an innovative stormwater overflow disinfection system, August 1986-April 1987.

E & E Hauling, Inc. -- Advised on environmental impact of an asphalt hot melting facility, January 1987.

Confidential client -- Advised on the feasibility of a proposal for a new solid waste disposal facility, March, 1987.

Peat Marwick Main, Inc. -- Preparation of examination questions for wastewater treatment plant operational personnel, November, 1987.

Metropolitan Waste Systems, Inc.

-- Preparation of testimony on need for solid waste disposal capacity in La Salle County, IL, March - May, 1988, January-May, 1989.

-- Assessment of need for a solid waste transfer station in Blue Island, IL. January 1989.

Madison (WI) Metropolitan Sanitary District -- Review of Petition for Disinfection Waiver and presentation of supporting testimony, August, 1988-February, 1989.

US EPA (Region IX)/US Department of Justice -- Expert witness regarding removal of pathogens and trace pollutants by secondary treatment processes (US and California vs. City of San Diego), October 1989 - February 1991.

James M. Montgomery Engineers -- Statistical evaluation of disinfection byproduct data, February 1990 - September 1990.

Land and Lakes Co. -- Assessment of need for additional solid waste disposal capacity in Will County, IL. December 1989 - November 1990.

Chlorine Institute -- preparation of review on chlorine fate in freshwater systems as part of FIFRA reregistration application, July-August, 1990.

Wade Miller and Associates, Inc., Cadmus Inc. -- Provided input and assistance in development of disinfection byproduct regulatory analysis in drinking water, July 1991 - 1998.

City of Philadelphia - Department of Personnel -- Served on Oral Examination Panel for Water Treatment Engineer, March 1993.

Miller, Cassidy LaRocca and Lewin; Carr Goodson and Lee; Elzufon Austin and Drexler - Expert witness on chlorination practices in water treatment (Hoechst Celanese et al. v. National Union et al.; Delaware Chancery Court), 1991-1994.

Montgomery Watson Engineers - Technical Advisory Panel Member, Multiclient Study on Disinfection of *Cryptosporidium* in Drinking Water, 1995-1999.

Carollo Engineers - Microbial Criteria Development for a Water Treatment Plant, including consideration of recycle streams and *Cryptosporidium*, 1996-1997.
Procter and Gamble Co.-Evaluate Beneficial Effects of Anti-Microbial Preparations, 1997-1999.
Procter and Gamble Co.-Analyze Kinetics of Algal Growth on Inhibitory Substrates, 1998-1999.
Holland & Knight - provide expert report and testimony regarding water and wastewater treatment (US and State of Maryland vs. Mayor and City Council of Baltimore), 1998-1999.
US Department of Justice - provide expert analysis on impact of sewage discharges on water quality (US vs. Penn Hills), 1998.
CDM, Inc. and Massachusetts Water Resources Authority - advise on novel integration approaches to evaluating disinfection "ct" values, 1998.
Foley, Hoag and Eliot (counsel for Massachusetts Water Resources Authority) -- expert in defense (US vs. Mass. Water Resources Authority) regarding necessity for filtration, 1999-2000.
Black and Veatch - Technical review and resource panel, Las Vegas Alternative Discharge Study, 2000.
McDermott, Will & Emery and Bayer Agricultural - Assistance with comments on proposed FDA withdrawal of use of fluoroquinolines in poultry rearing, 2001-2003.
Linowes And Blocher/Holland and Knight - Assistance with permit issues on limestone mining (potential groundwater impacts) in Miami-Dade, Florida, 2001-2004.
Alston and Bird - Provide expert support in administrative proceeding on behalf of Gwinnett County GA regarding defense against petition to deny effluent discharge permit modifications. (Lake Lanier Association et al. v. Georgia Environmental Protection Division). 2001-2002.
US Department of Justice - provide expert analysis on impact of microbial water quality on worker risks (John G. Abbott *et al.* vs. U.S.). 2002-2004.
Foley, Hoag and Eliot (counsel to Portland Water Bureau) – advise on regulatory issues relating to the Long Term 2 Enhanced Surface Water Treatment Rule, 2006.

Membership in Advisory Bodies

External Thesis Examiner, Indian Institute of Technology, Kanpur, 1979, 1981, 1983, 1993, 1996.
Chaired peer review panel to review the research program on "Microbial Degradation in Distribution Systems" for US EPA, June 1983.
Member, State of Illinois Hazardous Waste Task Force, 1983-4.
Member, US EPA peer review panel to review work on microbial inactivation in drinking water disinfection, March 1986.
Member, US EPA peer review panel to review program on risk assessment from microorganisms in wastewater sludges, April 1986.
Invited ad hoc reviewer for the Drinking Water Subcommittee, US EPA Science Advisory Board, June 1987.
Assisted in preparation of resource document on wastewater disinfection, US EPA, 1988.
Member, peer review panel, Oklahoma Council on Science and Technology, 1989.
Member, study section, National Institute of Environmental Health Sciences, 1991, 1994.
Invited Participant, Workshop on the Methodology for Deriving National Ambient Water Quality Criteria for the Protection of Human Health, US EPA -- Office of Science and

Technology, September 1992.
Member, City of Philadelphia, Department of Health, Advisory Committee on *Cryptosporidium*, October 1995-1999.
Member, Panel on Augmentation of Potable Water Supplies with Reclaimed Water, National Academy of Sciences, Water Science and Technology Board, 1996-1998.
Invited Participant, Workshop on Microbial Risk Assessment, hosted by NAS Committee to Review New York City Watershed Management Strategy, April 1998.
Member, Committee to Review New York City Watershed Management Strategy, National Academy of Science, Water Science and Technology Board, 1998-99.
Member, Oversight Steering Committee and Statistics Panel, EPA-George Washington University Cooperative Agreement on Risk Assessment, 1999-.
Member, Committee on Drinking Water Contaminants, National Research Council Water Science and Technology Board, 1999-2001.
Invited Participant, Consultation on "Harmonised Risk Assessment for Water-Related Microbiological Hazards", World Health Organization, Stockholm, Sweden, September 12-16, 1999.
Invited Participant, World Health Organization and Food and Agricultural Organization, joint workshop on "Hazard Characterization of Pathogens in Food and Water", Bilthoven, The Netherlands, June 13-18, 2000.
Member, Committee on Toxicants and Pathogens in Biosolid Fertilizers, National Research Council, Board on Environmental Studies and Toxicology, 2001-2002.
Member, review team for the Environmental Pollution Control MS Program, Pennsylvania State University, March 2001.
Honors examiner, Swarthmore College, May 2001.
Member, Committee on Indicators for Waterborne Pathogens, National Research Council, Board on Life Sciences, 2002-2003
Member, Panel to Review EPA Research Plan on Water Security, National Research Council, Water Science and Technology Board, 2003-.2004
Member, Committee on Standards and Policies for Decontaminating Public Facilities Affected by Exposure to Harmful Biological Agents: How Clean is Safe? National Research Council, Board on Life Sciences, 2003-2005.
Member and Vice Chair, Committee on Public Water Distribution Systems: Assessing and Reducing Risks. National Research Council, Water Science and Technology Board, 2004-2006.
Member, Water Science and Technology Board (WSTB), National Research Council, 2004-2007.
Member, Committee on Water System Security, National Research Council, Water Science and Technology Board, 2004-2006.

Community Service

Member, Philadelphia Water Department Drinking Water Quality Community Advisory Committee, August 2000-2001.