2004 EPRI/Global Ozone Handbook

Agriculture and Food Industries

Final Report

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DISCLAIMER

This report attempts to summarize some of the main research efforts pertaining to ozone's use in the agriculture and food industries. It includes experimental results from over 100 research groups and organizations and describes over two dozen specific end uses of ozone in these industries. The authors sincerely apologize for any results we may have missed. We also take no responsibility for the accuracy or methodologies of the studies presented.

REPORT SUMMARY

Background

EPRI has been extensively involved in furthering the development of ozone for use in a wide variety of applications through experimental research, demonstration projects, conferences, workshops, and dissemination of information through technical reports. Ozone is already becoming fairly established in industries such as water and wastewater treatment, but is just recently being applied to the agriculture and food industries. The progress in the agriculture and food industries is due to the work of a collaboration of many researchers and manufacturers in the U.S. and abroad, and to EPRI in particular. For example, EPRI was very instrumental in declaring ozone GRAS (Generally Recognized as Safe) in 1997 and EPRI organized the petition that led to the approval of ozone as an antimicrobial food additive in 2001. Both of these actions, coupled with participation by EPRI in a number of demonstration projects, have helped ozone achieve greater penetration in the industries. This handbook summarizes the application of ozone to various agriculture and food end-uses, ranging from food production on the farm to food processing in manufacturing plants to food preparation at home.

Objective

The primary objective of this handbook is to provide utility companies with an information source that describes ozone's implementation in many of the end-use applications related to the agriculture and food industries. Utility representatives can use the information contained herein to familiarize themselves with the benefits of ozone as a solution to numerous agriculture and food concerns.

Approach

To accomplish the stated objective, the project team:

- Summarized past and recent efforts by EPRI and others in developing and using ozone in the agriculture and food industries
- Developed a document that contains sufficient technical information about ozone to educate utility account representatives, while still being understandable by the layman
- Created stand-alone sections within the document that pertain to specific agriculture and food end-uses of ozone

Result

The result of the project is a handbook containing a technical description of ozone's use in agriculture and food applications and stand-alone descriptions of ozone applied to nine discrete areas within the agriculture and food industries, namely:

1. Ozone for Livestock and Poultry Water and Irrigation
2. Ozone for Beverage Manufacturing
3. Ozone for Sanitation of Equipment and Work Areas
4. Ozone in Pest Management
5. Ozone in the Fish and Seafood Industry
6. Ozone for Fruit and Vegetable Production and Processing
7. Ozone for the Production and Processing of Meat and Poultry Products
8. Ozone for Indoor Air Quality in Food Production and Processing
9. Ozone in Home Food Preparation and Processing

Each of the nine areas is further broken down into specific end-uses for which ozone can be employed as an alternative to conventional technologies. For each end-use, the discussion describes the main concerns associated with the end-use, the manner in which ozone can be utilized as a solution, and typical performance results of ozone.

Keywords
Agriculture
Antimicrobial
Beef
Beverages
Crops
Dairy
Equipment sanitation
Fish
Food
Fruits
Indoor air quality
Irrigation
Livestock
Pesticide
Pork
Poultry
Process water
Odor control
Ozone
Soil
Vegetables
Wastewater
Water
Wheat and grains

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1
INTRODUCTION

Ozone (O_3) is the triatomic form of oxygen. It is unstable in this form and readily breaks down to oxygen (O_2) and an oxygen atom (O). The oxygen atom is highly reactive and acts as an antimicrobial agent capable of destroying odors, fungi, bacteria, spores, cysts, and viruses. It is formed naturally in the atmosphere by photochemical reaction with solar UV radiation and by lightening. Ozone can also be generated artificially and employed in various antimicrobial applications. This handbook focuses on ozone's application in the agriculture and food industries, both on the farm and in food manufacturing plants. Specific end-uses of ozone in the agriculture and food industries range from water and process water treatment to indoor air quality to pest control to surface and equipment cleaning to food safety and shelf life extension.

1.1 History of Ozone in the Agriculture and Food Industries

Ozone was first generated and characterized by a German scientist named Schonbein in 1840. Its effectiveness in destroying microorganisms in water was then discovered in the late 1800s, and it has been used to treat potable water in France since 1906. The first continuous use of ozone in a water treatment plant in the U.S. began in 1940 and took place in Whiting, Indiana.[1] Since the first U.S. installation, ozone's use for water treatment has grown. It is one of the few disinfectants effective against *Cryptosporidium* and *Giardia,* so many plants use it for primary disinfection followed by chlorine. However, it still represents a very small market share compared to chlorine because of its higher cost and lack of residual protection. In terms of use in the food manufacturing industry, ozonation is still an emerging technology. In fact, prior to 1997, the U.S. Food and Drug Administration (FDA) only approved ozone for potable and bottled water treatment. Since the early 1990s, EPRI has been instrumental in furthering the development of ozone as an antimicrobial agent for agriculture and food processes as described below.

1.1.1 Contributions by EPRI

EPRI has been involved with a number of studies involving ozone in the agriculture and food industries. One of EPRI's primary areas of interest has been food safety. The EPRI Food Technology Alliance (FTA), which was merged with the Agriculture Technology Alliance (ATA) and is now called the Agriculture and Food Technology Alliance (AFTA), suggested in the early 1990s that EPRI investigate the use of ozone as an antimicrobial agent to enhance food

[1] *Food Industry 2000: Food Processing Opportunities, Challenges, New Technology Applications,* EPRI, Palo Alto, CA: 2000. 1000053.

safety. Discussions began in 1995 and investigation of the use of ozone started in 1996 with the convening of an expert panel that declared ozone GRAS (Generally Recognized as Safe) in 1997. Although the GRAS Declaration was deemed the proper method to legally allow the use of ozone in food processing during both the investigative period and after the 1997 GRAS affirmation, its legality became clouded due to a 1982 ruling limiting the use of GRAS Declarations for ozone uses in food processing.

In 1999, recognizing that the 1982 ruling created confusion among the food processors, the FDA encouraged EPRI's FTA to pursue the development and submission of a Food Additive Petition (FAP) that would allow the use of ozone as a contact antimicrobial agent in food. Petitioners D.M. Graham of EPRI and R.G. Rice of RICE International Consulting Enterprises completed the FAP and submitted it to the FDA in August 2000. After an expedited and rigorous review by the FDA staff, the FDA recognized ozone as an antimicrobial agent suitable for use in Food Processing and Agricultural Production. Notice of this recognition appeared in the Federal Register, June 26, 2001.

During the GRAS and FAP processes, and since the final FDA recognition of ozone as an antimicrobial agent, AFTA has spearheaded many research efforts with utility companies and their customers directed at promoting the development of ozone for food applications. The following is a list of some representative EPRI publications summarizing these efforts:

- *Ozone for the Purification of Poultry Drinking Water,* 2004, 1009527
- *2004 Food Industry Overview: Concerns, Electrotechnology Solutions and Marketing Opportunities,* 2004, 1182-3-03
- *Ozone Applications in Fish Farming,* 2002, 1006975
- *Treatment of Cut Vegetables with Aqueous Ozone: Technical Assessment*, 2002, 1007465
- *Ozone Improves Processing of Fresh-Cut Produce: TechApplication*, 2002, 1007466
- *Use of Ozone in Water on Fresh Fruit,* 2002, 1007108
- *The Use of Ozone as an Antimicrobial Agent: Agricultural and Food Processing Technical Assessment*, 2001, 1005962
- *Ozone & UV for Grain Milling Systems*, 2000, 1000591
- *Ozone Conference II: Abstract Proceedings*, 1999, GC-113975
- *Membrane Filtration and Ozonation of Poultry Chiller Overflow Water: Study of Membrane Treatment to Reduce Water Use and Ozonation*, 1999, TP-114435
- *Ozone Sanitizing for Meat Processing Equipment*, 1999, TA-114172
- *Ozone in the Food and Agricultural Industries*, 1999, TC-113814
- *Ozone Gas as a Soil Fumigant: 1998 Research Program*, 1999. TR-113751
- *Ozone Use in Agriculture and the Food Industry*, 1998, CR-110735
- *Ozone Applications in Apple Processing*, 1998, TA-112064

- *Expert Panel Report: Evaluation of the History and Safety of Ozone in Processing Food for Human Consumption*, 1997, TR-108026

1.1.2 Contributions by Others

Numerous researchers and organizations have helped further the development of ozone in the agriculture and food industries through activities ranging from laboratory-scale research to prototype development to large-scale demonstrations to commercial installations. Though there are too many contributors to mention here, Table 1 summarizes some representative groups by the type of application they contributed to. The contributions listed in the table are discussed in more detail in Chapter 3, which describes specific end-uses of ozone in the agriculture and food industries. We have attempted to include most of the prominent research groups, and sincerely apologize to those we have missed. For a more detailed list of research activities leading up to the FDA recognition of ozone as a food additive in 2001, please refer to following document: *Direct Food Additive Petition: Ozone as an Antimicrobial Agent for the Treatment, Storage and Processing of Foods in Gas and Aqueous Phases*, EPRI, Palo Alto, CA: August 2, 2000.

Table 1
Partial List of Contributors (Other than EPRI and Associates) to the Use of Ozone in the Agriculture and Food Industries

Application	Contributor
Treatment of livestock and poultry drinking water	ClearWater Tech, LLC
Treatment of livestock and poultry wastewater	Michigan State University researchers led by Masten and Yokoyama TriO3 Industries, Inc.
Treatment of irrigation water	Oxion, Inc.
Purification of water used for processing	Several bottled water plants, including Adirondack Beverages, McKesson Water, Southern Beverage, Coca-Cola Dansai, Pepsi Aquafina Several breweries, including Coors, Schmidt, Schlitz, Genessee, Molson, Sierra Nevada Brewery DEL Ozone
Treatment of fruit juice products	Tastee Apple Purdue University researchers led by P. Choi and S. Nielsen Ohio State University researchers led by J. Scheerens

Table 1
Partial List of Contributors (Other than EPRI and Associates) to the Use of Ozone in the Agriculture and Food Industries, Continued

Application	Contributor
Sanitation of equipment and work areas	Sierra Nevada Brewery Several wineries, including Kendall-Jackson, Joseph Phelps Vineyards, J Vineyards and Winery, Cakebread Cellars Several bottled water plants, including Adirondack Beverages, McKesson Water, Southern Beverage, Coca-Cola Dansai, Pepsi Aquafina Tastee Apple Plumrose USA Hanover Sea Products Delta Pride Catfish North Coast Seafood Company California State University Fresno researchers led by E. Dormedy California Polytechnic State University led by B. Hampson Ohio State University led by M. Khadre and A. Yousef North Carolina State University Seafood Laboratory led by D. Green Air Liquid America Corporation Toxicology Group, LLC NOVAZONE DEL Ozone Clean Air & Water Systems, Inc. Pure-O-Tech, Inc.
Ozone as a pesticide replacement for grains	Purdue University researchers led by Mason and Mendez Oxion, Inc.
Ozone as a pesticide replacement for fruits	USDA Agricultural Research Service
Soil fumigation	SoilZone, Inc. led by Pryor
Weed control	SoilZone, Inc. led by Pryor

Table 1
Partial List of Contributors (Other than EPRI and Associates) to the Use of Ozone in the Agriculture and Food Industries, Continued

Application	Contributor
Removal of pesticide residues	University of Minnesota researchers led by Ruan R.J. Miltner, C.A. Fronk, and T.F. Speth
Water treatment in aquaculture systems	Fingerlakes Aquaculture MinAqua Fish Farm Greifensee Hatchery LARFICO ClearWater Tech, LLC
Preservation of fish and seafood	Several fishing vessels, including *Arctic Ocean* and *Christina* Hanover Sea Products Delta Pride Catfish North Carolina State University Seafood Laboratory led by D. Green Oregon State University Seafood Laboratory led by M. Morrissey University of South Florida led by G. Rodrick DEL Ozone Clean Air & Water Systems, Inc. TriO3 Industries, Inc.
Washing fruits and vegetables	R.A. Spotts and L.A. Cervantes USDA Agricultural Research Service Strickland Produce Co. Lyons Magnus Tastee Apple Inc.
Storing fruits and vegetables	University of Idaho USDA Agricultural Research Service M.M. Barth, C. Zhou, J. Mercier, and F.A. Payne P. Sarig, T. Zahavi, Y. Zutkhi, S. Yannai, N. Lisker, and R. Ben-Arie

Table 1
Partial List of Contributors (Other than EPRI and Associates) to the Use of Ozone in the Agriculture and Food Industries, Continued

Application	Contributor
Grain storage and steeping	Harvest States Amber Milling RGF Environmental Group
Treatment of beef and pork	LSU AgCenter researchers led by McMillin and Michel South Dakota State University researchers led by Julson, Muthukumarappan, and Henning G. Kaess and J.F. Weidemann
Treatment of poultry meat	P.P.W. Yang and T.C. Chen V. Jindal, A.L. Waldroup, R.H. Forsythe, and M. Miller L. Caracciolo I-Doo Kim and Soon-Dong Kim R.W.A.W Mulder
Treatment of poultry chiller water	Y.H. Chang and B.W. Sheldon A.L. Izat, M. Adams, M. Colberg, M. Reiber M.E. Diaz and S.E. Law NovaZone Arkansas Agricultural Experiment Station FoodLabs Inc.
Poultry hatchery disinfection	Whistler, P.E., and B.W. Sheldon

Table 1
Partial List of Contributors (Other than EPRI and Associates) to the Use of Ozone in the Agriculture and Food Industries, Continued

Application	Contributor
Purification of indoor air and odor control	Metz Farms Picket Fence Farms Carrol's Foods North Carolina State University led B. Bottcher Michigan State University led by by R. D. von Bermuth Sonozaire Ozone Solutions, Inc. Envron ClearWater Tech LLC RGF Environmental BioZone Scientific NuTek International
Sanitation of food and equipment in homes	DEL Ozone Waterpik Technologies Tru-Pure Ozone Technologies Earth Safe Ozone Aqua Sun Ozone International ALAB LLC
Purification of tap drinking water	DEL Ozone Tru-Pure Ozone Technologies Earth Safe Ozone Aqua Sun Ozone International ALAB LLC Fantom Ohio State University, Dept. of Preventive Medicine and Environmental Health

Table 1
Partial List of Contributors (Other than EPRI and Associates) to the Use of Ozone in the Agriculture and Food Industries, Continued

Application	Contributor
Odor control in refrigerators and homes	BioZone Scientific NuTek International DEL Ozone RGF Environmental ClearWater Tech

In addition, the International Ozone Association (IOA) is very active in ozone applications across all sectors, including the agriculture and food industries. The IOA has worked with EPRI, G & L AgriTec, and other organizations to sponsor several ozone conferences for the agriculture and food industries. The next conference—Ozone IV—will be held March 2-4, 2005 in Fresno, CA and is sponsored by G & L AgriTec, IOA, California State University at Fresno, and the California Agricultural Technology Institute.

1.2 Relevancy of this Handbook

Food safety is of great concern to food producers and consumers. Ozone has the ability to improve food safety in a wide variety of ways through all stages of food production and processing. The intent of this handbook is to provide utility companies with sufficient information on the use of ozone in agriculture and food end-uses. Utility representatives can then use this knowledge to communicate with their agriculture and food customers about the merits of ozone. As an electrotechnology, ozone is the perfect fit for electric utilities to promote. Increased dissemination of ozone's applicability as an environmentally friendly alternative in numerous agriculture and food end-uses will help further the development of ozone, and in turn lower operational costs.

1.3 Scope

Ozone is applicable to many end-uses across all sectors of the economy. For example, it is used to treat water in residential swimming pools, control air quality in commercial buildings, clean laundry in healthcare facilities, control contaminants in metalworking fluids, treat wastewater from industrial plants, and purify drinking water, to name a few applications. It is a very effective oxidizer of pollutants and microorganisms. Ozone kills microorganisms by oxidizing organic molecules that form on cell surfaces—it lyses the cell wall. With the appropriate concentration and application, it is capable of 2-log or more reductions in microbial levels. This handbook focuses on ozone's use specifically in the agriculture and food industries. Within the context of the agriculture and food industries, the handbook explores a large range of end-uses beginning with on-farm food production and ending with home food preparation.

1.4 Handbook Organization

The handbook is designed to contain a concise but thorough treatment of ozone's utilization in agriculture and food end-uses. It begins in Chapter 2 with a technical description of ozone, including its characterization, production, and implementation. This chapter is meant to provide the reader with enough technical information to get them started. Chapter 2 also summarizes some of the hazards and current limitations of the technology. Chapter 3 contains the meat of the handbook. It is separated into nine sections based on the following general categories of agriculture and food applications:

1. Ozone for Livestock and Poultry Water and Irrigation
2. Ozone for Beverage Manufacturing
3. Ozone for Sanitation of Equipment and Work Areas
4. Ozone in Pest Management
5. Ozone in the Fish and Seafood Industry
6. Ozone for Fruit and Vegetable Production and Processing
7. Ozone for the Production and Processing of Meat and Poultry Products
8. Ozone for Indoor Air Quality in Food Production and Processing
9. Ozone in Home Food Preparation and Processing

Within each of the nine sections, the discussion is broken down further into specific end-uses. For example, in the *Ozone for Livestock and Poultry Water and Irrigation* section, there are three subsections entitled *Livestock and Poultry Drinking Water*, *Livestock and Poultry Wastewater Treatment*, and *Irrigation*. For each specific end-use, the discussion includes a description of concerns associated with the end-use, characteristics of ozone as a solution to the concerns, and performance results of ozone applied to the end-use.

2 TECHNOLOGY DESCRIPTION

Ozone is the triatomic form of oxygen (O_3) with a highly unstable molecular configuration. It is an extremely powerful oxidant because the third oxygen atom can easily detach from the ozone molecule and re-attach to molecules of other substances. Therefore, ozone lends itself very well to oxidation of pollutants and/or microorganisms, such as bacteria, viruses, mold, mildew, and odors. Ozone is a more powerful disinfectant than chlorine, chlorine dioxide, and chloramines.[1] For example, it inactivates *Giardia lamblia* approximately ten times better than chlorine, and *Cryptosporidium parvum* approximately 1000 times better than chlorine.[2] Ozone also reacts with many organic chemicals.

Dissolved ozone concentrations will drop quickly given ozone's reactivity. The speed of the oxidation process depends on environmental conditions, such as temperature, as well as the quantity of microorganisms. Ozone gas is sparingly soluble in water. It rapidly decomposes back to oxygen in aqueous solutions containing impurities. The decomposition rate is usually measurable in minutes. Consequently, it is necessary to generate ozone on-site and to apply ozone as it is generated. For example, it takes approximately 30 minutes for ozone to decompose back to oxygen in lake water but generally only a few minutes in industrial process water.[3] In high-purity water or in the gaseous phase, however, ozone decomposes more slowly. In tap water and distilled water, it takes two to five hours for ozone to decompose back to oxygen, while spontaneous decomposition of gaseous ozone occurs over a period of hours. Therefore, mold remediation of buildings using higher concentrations of gaseous ozone usually requires the buildings to be unoccupied during treatment, as well as for one to two days after treatment, to ensure all residual ozone has decomposed in the indoor air.

Ozone is formed naturally in the atmosphere by photochemical reaction with solar UV radiation and by lightening. It can also be generated artificially. Three of the most common ways of generating ozone artificially are: 1) by a corona discharge, 2) with short wave (185-nm) UV lamps, or 3) by electrolysis. All three methods for generating ozone are discussed below.

[1] Environmental Protection Agency (EPA), Jeffrey Adams and Robert Clark, *Control of Microbial Contaminants and Disinfection By-Products (DBPs): Costs and Performance,* http://www.epa.gov/ORD/NRMRL/Pubs/600R01110/600r01110chap14.pdf
[2] Ibid.
[3] *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*, EPRI, Palo Alto, CA: 1996. CR-106435

2.1 Generation of Ozone

Since ozone is an unstable gas, it must be produced on-site. Ozone generators intentionally produce ozone from oxygen or air using ultraviolet radiation or an electrical charge, such as a corona discharge. Considerably more electrical energy is required to produce a given amount of ozone by UV radiation than by corona discharge.[1] In addition, corona discharge can yield a larger quantity of ozone than UV radiation can. Because of the higher ozone concentrations required, most commercially available ozone generators for food industry applications use corona discharge to produce ozone.

With corona discharge, it is important to use air dryers to remove any moisture from the air since moist air can result in the production of nitric acid, which in turn can damage corona discharge equipment. For UV ozone generation systems, however, the dryness of the air is not a critical factor.

UV ozone generation systems have other advantages as well. For one, equipment costs with UV radiation are much lower than when generating ozone by corona discharge. Moreover, the ozone output can be better controlled in UV radiation systems, which is extremely important in indoor air purification applications as high ozone levels in the indoor air may affect humans. Therefore, some manufacturers of ozone generators for air treatment have recently switched to generating ozone with UV radiation. Another benefit of generating ozone with UV radiation is that the purification capabilities of both UV light and ozone can be used for air treatment.

2.1.1 Ozone Generated by Corona Discharge

In the corona discharge method, ozone is generated when free, energetic electrons in the corona dissociate oxygen molecules in oxygen-containing feed gas that passes through the discharge gap of the ozone generator. The electrical discharge gap is created with a dielectric material on one side of the gap and a grounded metal electrode on the other side of the gap, as is illustrated in Figure 1. The dielectric material prevents short-circuiting. Common dielectric materials are glass or ceramic. The corona cell presents a capacitive load to the power supply due to both the gas-filled gap and the dielectric material. A high voltage is applied to the electrodes while air or oxygen flows through the gap. Ozone is produced in the corona as a direct result of power dissipation in the corona. Most of the electrical energy input to the corona (85%) is dissipated primarily as heat (a by-product of the exothermic reactions that produce ozone) with smaller portions going to light, sound, and chemical reactions.[2] Therefore, the electrical efficiency of generating ozone is low. Approximately 1-2% of the oxygen that passes through the corona is converted into ozone.

Equations (2-1), (2-2), (2-3) and (2-4) show the reactions taking place:

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[1] *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*, EPRI, Palo Alto, CA: 1996. CR-106435.
[2] Ibid.

$$e^{-1} + O_2 \rightarrow 2\,O + e^{-1} \quad (2\text{-}1)$$

$$O + O_2 + M \rightarrow O_3 + M \quad (2\text{-}2)$$

where M is any other molecule in the feed gas stream

$$O + O_3 \rightarrow 2\,O_2 \quad (2\text{-}3)$$

$$e^{-1} + O_3 \rightarrow O_2 + O + e^{-1} \quad (2\text{-}4)$$

The net ozone yield is the sum of all reactions that form and discompose ozone. This yield depends on many factors, including the oxygen content and temperature of the feed gas, contaminants in the feed gas, power density of the corona, and the effectiveness of the ozone generator cooling system.

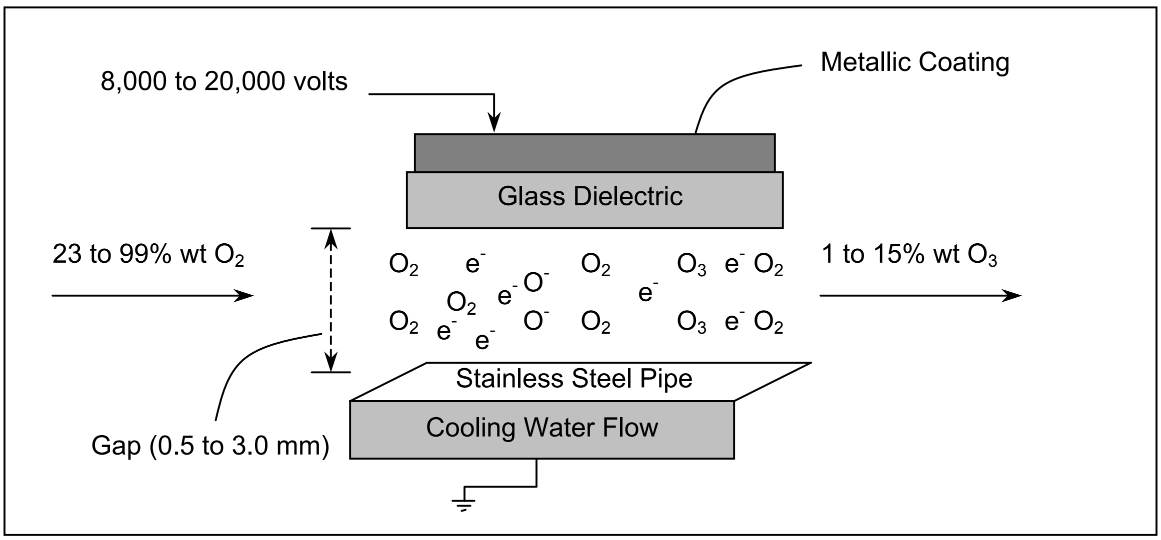

Figure 1
Schematic Diagram of Ozone Generation with Corona Discharge

Source: Redrawn from *Issues for Ozone for Drinking Water Treatment*, EPRI, Palo Alto, CA: 1999. TC-113030.

The power density of the corona is a function of the applied peak voltage, electrical frequency, and physical parameters of the discharge gap and dielectric cell. The frequency range in which they operate classifies the ozone generators: low frequency (50-60 Hz), medium frequency (60-1,000 Hz), and high frequency (> 1,000 Hz). Low frequency systems are most common in applications requiring less than 1,000 lb/day of ozone. Medium frequency systems are used in applications both smaller and larger than 1,000 lb/day. High frequency systems are generally used in applications requiring less than 100 lb/day. (However, both low and medium frequency equipment still dominate the less than 100 lb/day applications.) A few high frequency systems in operation at wastewater treatment facilities generate ozone in excess of 2,000 lb/day.[1]

In the past, most corona discharge systems for generating ozone used dried air as the feed gas. However, it is becoming increasingly more common to generate ozone from high-purity oxygen or oxygen-enriched air. This is because oxygen feed gas generates more ozone (due to the higher oxygen content) and requires less energy per unit surface area of dielectric medium to produce the same amount of ozone compared to air feed gas; this in turn translates into a tremendous economic advantage.[2] Moreover, most modern ozone systems operate unattended, making it harder to use air feed that must be dried and purified.

2.1.2 Ozone Generated by UV Light

Ozone can also be generated by UV light. The high energy UV light ruptures the oxygen molecules into oxygen atoms, and the subsequent combination of an oxygen atom with an oxygen molecule produces ozone (O_3). UV-generated ozone is produced in lower concentrations, in lower output, and at higher energy expenditure than by corona discharge.[3] Therefore, UV-generated ozone is mainly used in applications where the ozone concentration can be, or must be, low, such as purification of indoor air in occupied spaces or preservation of food, such as produce and meat, in cool storage rooms and coolers.

Early UV ozone generation systems used 254-nm lamps almost exclusively. However, UV-C of a wavelength of 185 nm has proven to be more efficient for ozone generation than the 254-nm wavelength because the latter wavelength actually destroys ozone. Thus, the most current UV lamps used for generation of ozone emit 185-nm UV light. An advantage of UV radiation over corona discharge for generating ozone is that moist ambient air can be used.

Since UV radiation has a germicidal effect, systems that use the purification effects of both UV and ozone have recently emerged for treatment of indoor air. These types of systems use UV radiation (185-nm UV) to generate ozone as well as UV radiation (254-nm UV) to disinfect the air. The UV/ozone catalytic oxidation process is discussed in greater detail in the Chapter 3 section entitled *Ozone for Indoor Air Quality in Food Production and Processing*.

2.1.3 Ozone Generated by Electrolysis

A third method for generating ozone is electrolysis, which uses water and an electrolytic cell. Specifically, electrolysis involves converting oxygen in the water to ozone by passing the water through positively and negatively charged surfaces. It is possible to use municipal water for electrolysis.

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[1] *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*, EPRI, Palo Alto, CA: 1996. CR-106435.
[2] Ibid.
[3] Ibid.

Electrolysis can produce very large quantities of ozone. Since this process uses less electricity than corona discharge and it does not require any special gases or ultra pure water, it is a less costly method of generating ozone than corona discharge. However, the capital costs of an electrolysis system for generating ozone are generally much higher than for corona discharge and UV systems. Systems utilizing electrolysis can produce sufficient amounts of ozone to give rise to worker safety hazards and should only be operated by trained personnel. Therefore, electrolysis systems are mostly used in larger operations such as municipal water systems. In Agriculture and Food applications, corona discharge systems that use high purity oxygen feed gas can usually produce sufficient ozone.

Lynntech, Inc. has patented and developed a commercial process for generating ozone with an electrolytic cell. Ozonia Ltd. of Switzerland is marketing and selling that process under the name *Membrel Systems*. Ozonia's U.S. operations are making inroads into the U.S. market through trade shows and municipal water purification applications. Due to high capital costs, the only Agriculture and Food applications that use sufficient ozone to warrant electrolysis technologies are irrigation, large scale food processing waste facilities and aquaculture units. Additional applications should become available as the technology advances.

2.2 Applications of Aqueous Ozone and Gaseous Ozone

Once generated, ozone may be used either in aqueous or gaseous form, depending on the particular application. Most of the documented applications of ozone are in aqueous form—also called ozonated water—for sanitation of equipment and work areas; purification of water used for processing, as well as livestock and poultry drinking water and tap drinking water; treatment of wastewater and recycled water; and rinsing fresh produce, meat and poultry. Gaseous ozone is mainly used for odor control and indoor air quality improvements in food production and processing facilities, including animal housing, slaughterhouses, and fish processing plants. In gaseous form, ozone can also aid in the sanitation and preservation of crops and food during storage, as well as sanitation of food-packaging materials. Table 2 summarizes all of the particular applications of aqueous and gaseous ozone that are discussed in this report.

Table 2
Applications of Aqueous and Gaseous Ozone in Food Production and Processing

Section in Report	Aqueous Ozone	Gaseous Ozone
Ozone for Livestock and Poultry Water and Irrigation	Purification of Livestock and Poultry Drinking Water Treatment of Livestock and Poultry Wastewater Recycling of Livestock and Poultry Wastewater Purification of Irrigation Water Recycling of Wastewater for Irrigation Cleaning of Irrigation Lines	
Ozone for Beverage Manufacturing	Purification of Water used for Processing Treatment of Fruit Juice Products Sanitation of Bottling Equipment, Bottles, and Storage Tanks	
Ozone for Sanitation of Equipment and Work Areas	Sanitation of Animal Housing, Trucks, Railcars, Slaughterhouses, Walls, Floors, Drains, Storage Containers, Tanks, Barrels, Filler Systems, Conveyor Belts, Knives, Tabletops, Walk-in Coolers, Packaging Material Recycling of Rinse Water Mold Control on Walls and Ceilings	
Ozone in Pest Management	Removal of Pesticides in Water Soil Fumigation	Pest Control During Crop and Food Storage Soil Fumigation
Ozone in the Fish and Seafood Industry	Water Treatment in Aquaculture Systems Preservation of Fresh Fish and Seafood Sanitation of Process Equipment	

Table 2
Applications of Aqueous and Gaseous Ozone in Food Production and Processing, Continued

Section in Report	Aqueous Ozone	Gaseous Ozone
Ozone for Fruit and Vegetable Production and Processing	Purification of Irrigation Water Cleaning of Irrigation Lines and Emitters Recycling of Wastewater for Irrigation Rinsing Fruits and Vegetables Recycling of Rinse and Flume Water Pest Control During Grain Steeping	Soil Fumigation Weed Control Pest Control During Fruit and Vegetable Storage Pest Control During Grain Storage
Ozone for Production and Processing of Meat and Poultry Products	Purification of Livestock and Poultry Drinking Water Treatment of Livestock and Poultry Wastewater Rinsing Meat Products Rinsing Poultry Treatment of Poultry Chiller Water Recycling of Rinse Water Sanitation of Equipment and Work Areas	Pest Control in Livestock and Poultry Feed Improvement of Indoor Air Quality in Animal Housing Odor Control in Animal Housing Odor Control During Meat Aging and Storage Microbial Control During Meat Aging and Storage Microbial Control in Poultry Hatcheries
Ozone for Indoor Air Quality in Food Production and Processing	Reduction of Chlorine Odors by Replacing all or a Portion of Chlorine with Ozone for Water Treatment	Improvement of Indoor Air Quality in Food Production and Processing Facilities Odor Control in Animal Housing, Dairies, Slaughterhouses, and Fish Processing Plants
Ozone in Home Food Preparation and Processing	Rinsing of Produce Sanitation of Food Preparation Equipment Purification of Tap Drinking Water	Odor Control in Kitchens Odor Control in Refrigerators

2.3 Merits and Limitations of Ozone

The specific merits of ozone in a particular application are discussed at greater length in Chapter 3. However, there are some general merits of ozone, including:

- **Powerful and Fast-Acting Antimicrobial Agent:** Ozone is the strongest oxidant and disinfectant available for oxidation of pollutants and microorganisms in aqueous solutions and gaseous mixtures. Although it is only partially soluble in water, it is sufficiently soluble and stable so that its oxidation properties can be used to full advantage. Moreover, ozone reacts with a large variety of organic compounds, including oil residues, iron, manganese, cyanides, sulfides, nitrites, as well as organically bound heavy metals, although at varying rates. The required contact time is usually only a few minutes.
- **Capable of Destroying Food Borne and Waterborne Pathogens, Pesticides and Chemical Residues:** Ozone is capable of destroying many harmful pathogens, including *E. coli*, *Cryptosporidium*, and *Giardia*. To a certain degree, ozone is also capable of destroying pesticides and chemical residues.
- **Improves Water Quality:** Ozone is highly effective in destroying a wide variety of waterborne contaminants in various types of water, including irrigation water, animal drinking water, tap drinking water, water used for processing, flume water, rinse water, and aquaculture water.
- **Effective Sanitation of Equipment and Work Areas:** Washing equipment and work areas with ozonated water is an effective way of reducing microorganisms growing on the surfaces. This reduces the risk for cross-contamination of the food:
- **Effective Water Recycling:** Because of its efficacy in oxidizing a variety of microorganisms and waterborne contaminants, ozone can be used effectively to treat recycled water.
- **Controls Odors Efficiently:** Although the reactions of ozone in the gas phase are slower than in the aqueous phase, gaseous ozone is proven effective on a variety of VOCs and organic odors, including those from animals and chemicals. Ozone offers superior performance to any other method currently in use for odor, and VOC control.
- **Extends Shelf Life and Reduces Cross-Contamination**: Ozone is effective in destroying microorganisms and mold on food, thereby reducing food spoilage, food shrinkage, and cross odor contamination. Ozone also inhibits fungal growth, sporulation, and toxin production, and odors associated with fungi.
- **No Build-Up of Resistance:** Microorganisms cannot develop a resistance to ozone, which is the case with chlorine and other chemicals.
- **Replaces or Reduces Chlorine Use:** Ozone can replace chlorine as a sanitizer. When used in conjunction with chlorine, ozone reduces the amount of chlorine required for sanitization.
- **No Harmful Residues or By-Products:** Ozone does not leave residues or by-products behind nor does it affect the taste, color, or flavor of the food or drinking water. However, ozone can produce halogenated organics if bromide ion is present.
- **No Storage and Handling:** Ozone is generated on-site, eliminating the need for chemical storage and handling.

- **Relatively Safe to Handle:** As ozone cannot be stored, it must be generated on-site, which makes it relatively safe to handle.

Although ozone has many merits, it is no panacea to all problems. There are a few limitations to ozone that also should be mentioned, including:

- **Ozone Equipment May be Costly**: In comparison with conventional oxidation and disinfection technologies, such as chlorination, ozone equipment can be expensive. This is mainly due to the requirement of generating ozone on-site, eliminating the usual economies of scale with centrally produced chemicals. A cost comparison of various technologies for disinfection of drinking water in the 100 MGD (million gallon per day) range shows ozone is approximately three to four times more expensive than chlorine.[1]
- **Ozone Equipment is Quite Complex.** An ozone system includes generator, contacting apparatus, destruction unit for the off-gases, and control equipment for the ozonation processes.
- **Corona Discharge is an Inefficient Electrical Process:** The most common method of generating ozone—by corona discharge—is a very inefficient electrical process. Therefore, electricity is the major operational cost. Even with this disadvantage however, ozone is often cost-effective over other treatment technologies.
- **Powerful Oxidizing Agent**: Since ozone is such a powerful oxidizing agent, it is also potentially dangerous to humans if they are exposed to levels beyond the permissible limit. The National Institute of Occupational Safety and Health (NIOSH) recommends the upper limit of 0.10 ppm not to be exceed at any time. Measures must be taken to prevent overexposure. In addition, because of its great oxidizing potential, ozone can oxidize sealants and gaskets. Thus, care must be taken to ensure process equipment is not unintentionally affected or ruined. This includes avoiding exposure of rubber to ozone.
- **Contact Requirement:** Ozone must come into direct contact with microorganisms to render them harmless. Thus, microbial growth on hard-to-reach surfaces or in porous material may not be inactivated, which would lower the total kill rate.
- **No Residual:** Since ozone does not leave any residual behind, it is possible for equipment surfaces or process water streams to be re-contaminated.

[1] Environmental Protection Agency (EPA), Jeffrey Adams and Robert Clark, *Control of Microbial Contaminants and Disinfection By-Products (DBPs): Costs and Performance,* http://www.epa.gov/ORD/NRMRL/Pubs/600R01110/600r01110chap14.pdf

3
SPECIFIC END-USES OF OZONE

This chapter contains descriptions of ozone's implementation in nine discrete areas of the agriculture and food industries. The descriptions are designed to be stand-alone so that they can be removed and used for interactions with customers in each of the areas. The areas are broken down further into specific end-uses. A description of the concerns associated with each end-use is provided along with an explanation of how ozone can be applied as a solution to the concerns. In addition, representative performance results for ozone applied to each end-use are summarized. The nine discrete areas evaluated are:

1. Ozone for Livestock and Poultry Water and Irrigation
2. Ozone for Beverage Manufacturing
3. Ozone for Sanitation of Equipment and Work Areas
4. Ozone in Pest Management
5. Ozone in the Fish and Seafood Industry
6. Ozone for Fruit and Vegetable Production and Processing
7. Ozone for the Production and Processing of Meat and Poultry Products
8. Ozone for Indoor Air Quality in Food Production and Processing
9. Ozone in Home Food Preparation and Processing

Because the sections are designed to be stand-alone documents, there is some overlap among the discussions. For example, treatment of livestock and poultry drinking water is applicable both to the section entitled *Ozone for Livestock and Poultry Water and Irrigation* as well as the section on *Ozone for the Production and Processing of Meat and Poultry Products*.

Though not specifically mentioned in the treatments contained in this chapter, the reader should keep in mind that limitations to ozone's use exist. As described in Chapter 2, the primary limitations relate to cost and safety. Carefully following manufacturer instructions and/or utilizing trained personnel in the operation of ozone equipment can ensure safety. In addition, costs should continue to lower as the technology matures.

OZONE FOR LIVESTOCK AND POULTRY WATER AND IRRIGATION

Water is used on the farm in a variety of ways. Livestock and poultry producers need reliable and clean water supplies in order to provide drinking water to animals. They also require water for other livestock and poultry operations such as misting and washing animals and cleaning facilities. In addition, livestock and poultry producers must consider methods for dealing with and treating wastewater generated from the various livestock and poultry operations. Fruit and vegetable producers need water as well, and it must be in sufficient quantity and of acceptable quality for irrigating crops.

This section deals with three primary aspects of on-farm water use, namely: 1) livestock and poultry drinking water, 2) livestock and poultry wastewater treatment, and 3) irrigation. The discussion includes the primary concerns associated with each aspect of on-farm water use that ozone can potentially mitigate. It further describes the manner in which ozone is generally applied to address the concerns and summarizes the primary benefits of ozone over other alternatives. Lastly, it provides representative performance data for ozone tested in each specific end-use.

I. Livestock and Poultry Drinking Water

Concerns

Clean drinking water is essential for the health of poultry and livestock such as cattle, sheep, and hogs. It is especially critical for at-risk animals. Poor tasting water leads to decreased consumption and, in turn, less healthy animals. Moreover, high waterborne pathogen levels in the drinking water supply can result in illness or even death. Animal health and mortality rates directly impact the producer's profit margin. Healthy animals often produce better (e.g., in the case of dairy cattle) or grow faster and larger. In addition, lower mortality rates mean higher productivity and/or more animals to reach the market.

There are many substances found on livestock and poultry farms that can and do contaminate surface and well water supplies. Examples include bacteria, nitrates, organic matter, and suspended solids. If drinking water has a high degree of suspended solids and/or objectionable taste, color, or odor, animals may avoid drinking and consume less than they should.[1]

In most cases, the current practice on farms is to give animals untreated surface or well water. In some instances, livestock and poultry producers rely on traditional chemical methods such as

[1] Pfost, D. L., C. D. Fulhage, and S. Casteel, "Water Quality for Livestock Drinking," *Environmental Quality MU Guide,* MU Extention, University of Missouri-Columbia: 2001.

chlorine to treat drinking water. Some may also use water from municipal supplies. The main concerns with current approaches are listed below.

- **Chlorine Results in By-Product Formation:** Chlorine reacts with organic substances and accelerates the production of by-products such as trihalomethanes (THMs), which are carcinogenic.
- **Chlorine Results in Disagreeable Tastes and Odors:** Chlorine reacts with substances that may be present in the water (phenol in particular) and creates compounds (e.g., chlorophenol) that have unpleasant tastes and odors.
- **Chlorine May Hurt Poultry:** Chlorine may damage the biological substances in the digestive track of poultry.
- **Chlorine Must be Stored and Handled:** Chlorine treatment often requires the storage and handling of chemicals that can be hazardous to humans and animals. In addition, it is not uncommon for storage vessels to develop leaks. All leaks must be reported to the proper agencies within a few hours.
- **Untreated Well Water May Contain Chemical and/or Organic Impurities:** Untreated well water can contain a variety of impurities including microorganisms, suspended solids, organic matter, iron, manganese, and sulfides. The impurities affect the appearance, taste, odor, and safety of drinking water. Impurities can also clog equipment and watering nipples and emitters, leading to drippy emitters and high replacement and maintenance costs to upkeep the watering system.[1]
- **Quality of Surface and Shallow Water is Unpredictable:** Surface and shallow water can also contain impurities. Moreover, their quality is unpredictable and cannot be assumed to be stable.
- **Municipal Water is Costly:** Using municipal or county water is much more costly than depending on wells or surface water. Actual costs vary with location, supplier, and season.

Ozone as a Solution

Ozone can be effectively used to treat livestock and poultry drinking water. It is generated on-site and then injected into the feed water by one of several commercially available techniques. Ozone acts as an antimicrobial agent against bacteria, viruses, and parasites, and oxidizes organic substances and suspended solids. Ozonation is also sometimes combined with filtration to remove the oxidized contaminants from the water supply and reduce turbidity. Ozonated drinking water leads to improved health, greater feed efficiency, and higher productivity in animals. Some of the main points associated with ozone as a solution are listed below.

- **Destruction of Microorganisms:** The antimicrobial ability of ozone results in cleaner, safer water. Ozone is capable of destroying many waterborne pathogens, including *Escherichia coli*, *Cryptosporidium parvum, Giardia lamblia*, and rotaviruses.

[1] *Success Stories, Hi-Grade Poultry*, www.cleanwaterozone.com/success/poultry.php.

- **Powerful and Fast-Acting:** Ozone is a more powerful oxidizer than chlorine and other chemicals, and can react with microorganisms thousands of times faster. The fact reaction rates equate to rapid destruction of contaminants and reduced treatment times. Ozone also has a very short half-life in water, which varies from nearly instantaneous to several hours, depending on the water temperature and pH; thus, it is environmentally friendly. However, since ozone reacts and decomposes so quickly, it does not leave residual protection in the water as chlorine or other chemical agents do.
- **Improved Taste and Odor:** Ozone treatment improves the color, taste, and odor of water due to its ability to react with a wide range of organic compounds, including any oil residues, plus iron, manganese, cyanides, sulfides, nitrites, as well as organically bound heavy metals. In addition, if used in place of chlorine, ozone eliminates the tastes and odors associated with chlorinated byproducts. The result is better-tasting water, and animals are more likely to consume water that tastes good.
- **May Require Filtration:** In systems where iron, manganese, and sulfur compounds are present, ozone can cause precipitation and require filtration to remove the precipitates.
- **No THMs or Other Chlorinated By-Products:** Ozonation is advantageous over chlorine in that it does not yield chlorinated by-products such as THMs. However, it can produce the bromate ion, which is a suspected carcinogen, if bromine is present in the water.
- **pH Stability:** Ozonation of water does not affect the water's pH, nor does it cause an increase in dissolved solids. In comparison, the reaction of chlorine with organic impurities in water can alter the pH of the water.
- **No Storage:** Ozone is generated on-site, eliminating the need for chemical storage and handling. However, high concentrations of residual ozone in the air can be toxic to humans. Therefore, it is very important to ensure residual ozone levels do not exceed recommended regulatory levels.
- **Cost Effective:** The use of ozone to treat surface or well water on livestock and poultry farms can be a cost effective alternative to using municipal water.[1]

Performance Results

The use of ozone for purifying livestock and poultry water can yield impressive results in terms animal health and survival rates. Healthier animals often are more productive and achieve greater weights. For example, ozone treatment systems for drinking water have resulted in increased milk production by dairy cows and increased egg production by hens. In addition, several poultry farms have seen slight gains in poultry weight since installing ozone systems.

Table 3 summarizes a specific case study in which drinking water for dairy cows was ozonated.[2] Prior to installation of the ozone system, the dairy cows were given well water with impurities such as high levels of hydrogen sulfide to drink. After ozone treatment, hydrogen sulfide levels

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[1] *Ozone for the Purification of Poultry Drinking Water,* Global Energy Partners, LLC, Palo Alto, CA: 2004. 1009527.
[2] Rice, R. G. "Ozone and Ozone/UV in Sanitation and Food Production", May 28, 2003, PowerPoint presentation.

were reduced to zero, and the odor and levels of other impurities, such as iron, manganese, and organic load, were reduced to acceptable levels. Milk production increased a sizeable amount thanks to ozone—from an average of 62 lb/day/cow prior to ozone, to 88 lb/day/cow soon after ozone, to 100 lb/day/cow after several months of ozone treatment.

Performance data for poultry given ozonated drinking water show positive results as well. Case study findings from three poultry farms show that water quality was improved after conversion to ozone purified water.[1] Specifically, iron levels dropped from a high of 3.8 ppm to less than 0.3 ppm, manganese levels dropped from a high of 0.60 ppm to less than 0.05 ppm, and total bacteria levels dropped from a high of greater than 100 ppm to less than 2 ppm. Because of the cleaner water, survival rates and average bird weights increased, although the increases were very modest. The average bird weight increased by about 2.5% across the three farms, and the percentage of live birds increased from an average of 96% to 97%. Healthier birds equate to greater profits for poultry producers.

A similar study by AFTA in which poultry drinking water and flock data were compared before and after ozonation and filtration of the water showed that poultry production data and mortality were not greatly affected by ozonation. However, the ozonation-filtration system did decrease variable water costs as well as reduce fouling of emitters.[2]

Table 3
Ozonation of Drinking Water for Dairy Cattle – Summary of a Case Study

Installation Location	Ozone Manufacturer	Application	Problems with Well Water	Results After Ozone
Dairy Farm Paulding, OH	ClearWater Tech, LLC	Treating well water used as drinking water for dairy cattle	• Odoriferous • Contained hydrogen sulfide, iron, manganese, and organic load	• Reduced hydrogen sulfide levels to zero • Reduced iron, manganese, and organic load to acceptable levels • Increased milk production from 62 lb/day/cow average before ozone to 88 lb/day/cow average soon after ozone to 100 lb/day/cow average after several months

Source: Rice, R. G. "Ozone and Ozone/UV in Sanitation and Food Production," May 28, 2003, PowerPoint presentation.

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[1] *Better Production from a Simple Idea*, Flyer Describing Ozone Water Treatment Case Studies for Poultry Producers, Earth Safe Ozone, http://www.earthsafeozone.com/pdf_docs/chicken_flyer.pdf.
[2] *Ozone for the Purification of Poultry Drinking Water,* Global Energy Partners, LLC, Palo Alto, CA: 2004. 1009527.

II. Livestock and Poultry Wastewater Treatment

Concerns

Three of the primary concerns associated with wastewater from livestock and poultry operations are summarized below.

- **Contaminated Surface and Ground Water:** Wastewater resulting from livestock and poultry operations contains a variety of contaminants such as ammonia, nitrates, phosphorus, fecal organisms, organic matter, and chemical agents. The wastewater can contaminate water supplies and the soil if it is not properly handled, stored, treated and/or utilized.
- **Odors:** Odors arising from wastewater can also present a nuisance and a health hazard to inhabitants of the farm and nearby communities.
- **Costly Consumption and Treatment:** Water is used in large quantities in some livestock and poultry operations, and much enters the waste stream. Water consumption is costly, as is treatment of wastewater.

Ozone as a Solution

Ozone can be used to mitigate some of the concerns associated with livestock and poultry wastewater, including pathogens in wastewater streams and lagoon water, odors, and costly water use and treatment. In animal wastewater applications, ozone is produced on-site and injected into the wastewater to control pathogens and oxidize other contaminants. By reducing odors and pathogens, ozone can improve the livestock and poultry living environment and the health and safety of farm personnel.

- **Lagoon Water Treatment:** Ozone is pumped into the top foot or so of the lagoon's surface to reduce pathogen levels and odors associated with the lagoon water. Figure 2 shows an ozone system applied to a lagoon. Note that it may not be cost-effective to ozonated an entire lagoon compared to using other lagoon treatment methods such as anaerobic digestion. However, it is potentially useful on a side stream or portion of the lagoon to reduce odors and pathogens.
- **Treatment of Wastewater Exiting Barns:** Water exiting barns and animal operations can also be treated prior to entry into lagoons to keep odors and pathogen levels lower in lagoons.
- **Reprocessing of Wastewater:** Water used in some livestock and poultry applications can be reused if treated with ozone. For example, water used to water and mist cattle can be recycled and reprocessed with ozone in order to lower water consumption and wastewater treatment costs.

Performance Results

Preliminary work with ozone for treating livestock and poultry wastewater has yielded encouraging results. For example, Michigan State University researchers led by Masten and

Yokoyama have shown that ozone treatment with concentrations of 1 to 3 grams per liter of waste destroys phenolics, indolics and other metabolites that are produced by bacteria in swine manure and cause odor.[1] They also found that, for the concentrations tested, ozone reduced but did not eliminate pathogenic microorganisms. Ozone's efficacy at a given concentration is affected by the contaminant loading and other characteristics of the wastewater such as pH. Lightly loaded wastewater will be cleaned more thoroughly than heavily loaded wastewater for a given concentration of ozone.

Various ozone manufacturers, livestock and poultry producers, and universities are testing the use of ozone for animal wastewater treatment with favorable results.[2,3] Odor reductions are particularly encouraging.

Figure 2
Ozone System Applied to a Lagoon Holding Waste Runoff from Hog Holding Pens

Source: TriO3 Industries, Inc., www.trio3.com. Used with permission.

[1] Watkins, B.D., S.M. Hengemuele, H.L. Person, M.T. Yokoyama, and S.J. Masten, 1997, "Ozonation of Swine Manure Wastes to Control Odors and Reduce the Concentrations of Pathogens and Toxic Fermentation Metabolites," *Ozone: Science and Engineering,* Vol. 19, No. 5, pp. 425-437.
[2] Vansickle, J., 1999, "Ozone Holds Promise for Odor Control," *National Hog Farmer,* http://nationalhogfarmer.com/ar/farming_ozone_holds_promise/index.htm.
[3] *Hog, Dairy and Poultry Farms,* TriO3 Industries Inc. webpage, on-going, http://www.trio3.com.

III. Irrigation

This section describes the use of ozone in irrigation applications. To date, ozone has been shown to work well for smaller irrigation applications such as in drip systems and for hydroponic farming. However, there is not a lot of definitive information currently available for large-scale irrigation systems. Therefore, the focus of the following discussion is on small-scale irrigation end uses.

Concerns

There are four main concerns associated with irrigation in agricultural production that can be addressed with ozone. These four concerns are summarized below.

- **Poor Water Quality:** The quality of water used to irrigate plants can affect the health and productivity of crops. High levels of impurities such as hydrogen sulfide and pH values that are either too high or too low can lead to plant stress, low yields, higher fertilizer requirements, and early plant mortality.
- **Excessive Runoff:** Irrigation water may not penetrate the soil adequately, leading to runoff, soil erosion, and insufficient water reaching plant roots.
- **Overuse of Water:** Crop production requires a significant amount of irrigation throughout the lifecycle of the crop. Losses due to evaporation before the water penetrates the soil and excessive runoff compound the problem.
- **Contaminated Irrigation Lines and Emitters:** Irrigation lines and emitters can become clogged and contaminated with microorganisms and other waterborne impurities. As a result, water flow to plants may be restricted and/or plants may be unnecessarily exposed to pathogens.

Ozone as a Solution

Ozone has the potential for dealing with some of the concerns associated with irrigation. In particular, ozone can improve water quality, help enable water recycling and reuse, and be used to clean irrigation lines and emitters. Some researchers believe it may also increase penetration of irrigation applied to crops. Ozone is currently most applicable to small-scale irrigation systems.

- **Improved Water Quality:** Ozone is highly effective in destroying a wide variety of waterborne contaminants affecting crop health. In addition to destroying microorganisms, ozone can reduce organic loading and hydrogen sulfide levels, and stabilize pH. Ozone is beneficial over chlorine for water treatment in that it does not produce trihalomethanes (THMs) and it is generated on-site, eliminating storage and handling of chemicals (see Figure 3).
- **Possibility of Increased Penetration:** Some researchers believe that ozonation of the supply water may increase the quantity of dissolved oxygen in the water. As a result, the water may

be able to penetrate the soil better. Better penetration in turn equates to improved dispersion to the root zone and less water loss.

- **Water Recycling and Reuse:** Ozone can be used effectively for treating and reusing wastewater for irrigation. Therefore, ozone can enable a reduction in water consumption.
- **Cleaning of Irrigation Lines:** Ozone is being investigated as a potential method for reducing microorganisms and other impurities that can clog or contaminate irrigation pipes and emitters.[1]

Figure 3
Use of Ozone to Treat Irrigation Water for Corn Production

Source: Oxion, Inc., www.oxion.net. Used with permission.

Performance

The efficacy of ozone for water and wastewater treatment is well known. Ozone is widely used in water treatment plants because it is such a strong oxidizer. It is one of the few disinfectants effective against *Cryptosporidium* and *Giardia,* so many plants use it when cost-effective for primary disinfection followed by chlorine. For agricultural production, ozone is advantageous because it is generated on-site and can be used to treat water supplies without the worry of chemical storage and handling. It is relative safe to use as long as measures are taken to prevent exposure to toxic levels.

One example of employing ozone for treating irrigation water involves a case study with hydroponic tomatoes.[1] In this study, ozone treatment was used to improve the quality of well

[1] National Organic Standards Board Technical Advisory Panel Review, *Ozone: Crops*, Compiled by OMRI for the USDA National Organic Program: August 14, 2002.

water for irrigating the tomatoes. Prior to ozone treatment, the well water had a hydrogen sulfide concentration of 60 ppm and a pH of 7.8. In addition, the rejection rate of tomatoes was 40% due to blossom end rot. Ozone treatment reduced the hydrogen sulfide concentration to 0 ppm, lowered the pH to 7.04 by reducing organic load and producing H_2SO_4, and reduced the rejection rate to less than 3%. The total tomato yield increased by more than 300%. By stabilizing the pH, the fertilizer consumption also decreased by 25%. Because of the tremendous benefits, the payback period for the ozone system ended up being less than 6 months.

The application of ozone for improving irrigation penetration and cleaning tubes and emitters is relatively new. Further research is required to evaluate performance.

[1] Rice, R. G. *Ozone and Ozone/UV in Sanitation and Food Production*, May 28, 2003, powerpoint presentation.

OZONE FOR BEVERAGE MANUFACTURING

The beverage manufacturing industry faces numerous challenges in producing beverages that are safe to drink and appeal to the consumer markets. Beverages, such as soft drinks,[1] reconstituted juices,[2] bottled water, and beer, are generally produced from water from regional wells or municipal taps. As local supplies are deteriorating and consumers become more sophisticated in their taste requirements, beverage manufacturers need to better control bacteria, dissolved solids, sodium, alkanity, and water hardness. Although recognized specifications are lacking, the above parameters are often set by the user-industry as opposed to regulatory agencies.

This section describes three applications of ozone in beverage manufacturing, namely: 1) purification of water used in processing, 2) treatment of fruit juice products, and 3) sanitation of bottling equipment, storage tanks, and rinse water. The discussion includes the main concerns associated with each application that ozone can potentially mitigate. It also describes how ozone is generally applied to address these concerns and summarizes the primary benefits in each specific application over other alternatives. Finally, this section provides representative performance data for ozone tested in each application.

I. Purification of Water Used in Processing

Concerns

Beverages, such as soft drinks, juices, bottled water, and beers, are produced regionally, using water from wells or from municipal taps. The quality of the water varies by region. Because of the differing water quality, the resulting beverage may not taste the same from bottling plant to bottling plant. Therefore, it is common to purify the water in an attempt to produce standardized water quality. When water is taken from municipal taps, it is first treated by prechlorination to oxidize organics and remove all traces of chloramines (a residual disinfectant used by some U.S. cities). Thereafter, lime is added to lower alkalinity and ferric chloride is added as a flocculating agent. Similar treatment methods are employed for well water, adjusted for the absence of chloramines and the presence of iron, manganese and sulfides. Since chlorine has an undesirable effect on taste, granular activated carbon (GAC) filters are used to dechlorinate the water and remove halogenated organic materials that may have formed during the prechlorination step, before the water is used for beverage manufacturing. GAC filters, however, cannot remove chlorinated organic by-products. Consequently, the beverage manufacturing industry is looking for replacements for the prechlorination step.

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[1] **Soft Drink**. A soft drink is a cold, non-alcoholic drink, such as lemonade, cola, or orange juice. Collins Cobuild English Language Dictionary, 1987.
[2] **Reconstituted**. If you reconstitute a food that is dried, you change it back to its original form by adding water to it. Collins Cobuild English Language Dictionary, 1987.

The main concerns associated with the use of water for processing in beverage manufacturing are:

- **Consistent Water Quality:** Water from different regions varies in quality. To ensure that the beverage tastes the same from bottling plant to bottling plant, the plants must purify the water used in processing.
- **Prechlorination Produces Harmful Chlorinated By-Products:** Soft drink bottlers generally treat their water by chlorination to improve water quality. The prechlorination step, however, generates harmful chlorinated organic by-products that are not easily removed.
- **Chlorination Requires GAC Filters:** Chlorine has several drawbacks, including its affect on taste and odor. Therefore, GAC filters are required to dechlorinate the water. GAC filters also remove halogenated organic by-products, such as trihalomethanes (THMs), which are carcinogenic. As discussed previously, GAC filters cannot remove chlorinated organic by-products.
- **Chlorine Storage and Handling is Involved**: Storage and handling of chlorine can be hazardous, particularly for larger systems with chlorine gas.

Ozone as a Solution

Because of pressure from many state health organizations and the FDA, proper disinfection methods, including ozone as a key component, were developed for water bottling after the many bottled water recalls in the 1970s.[1] Subsequently, ozone has quickly become the technology of choice among bottled water manufacturers because of its powerful disinfectant properties, environmentally clean treatment process, and its ability to remove unwanted tastes and odors.[2] Ozone is added to the water in an ozone contactor just prior to bottling of the water. With the application of a single ozone treatment step, ozone can disinfect the water, the bottling equipment, the bottle, the air above the water, and the sealed cap of the bottle, providing an effective barrier to microbiological contamination. Figure 4 shows a clean-in-place (CIP) sanitation system used for beverage filling. The International Bottled Water Association (IBWA) recommends an ozone level of 1.0 to 2.0 milligram per liter for a period of 4 to 10 minutes to ensure disinfection. The use of ozone also provides other benefits, such as improved taste, elimination of odors, and extention of the shelf life by two years. Water bottlers whose source water contains excessive amounts of bromide need to be careful, however, as ozone can oxidize the bromide to bromate under certain conditions. The bromate concentration must not exceed the newly established disinfection by-product (DPA) maximum contamination level.

[1] L. Joseph Bollyky, *Benefits of Ozone Treatment for Bottled Water*, Ozone News, Volume 31, No. 2. http://www.pacificozone.com/bottledwater.pdf

[2] GE Water Technologies website, http://www.gewater.com/library/tp/727_Advances_In.jsp

Figure 4
Clean-In-Place Sanitation of Beverage Filling Lines

Source: DEL Ozone. Used with permission.

Other types of beverage manufacturers can also use ozone to treat water for processing, replacing the prechlorination step and improving water quality. In this application, ozone removes foul odors as well as minerals that may affect taste thus ensuring a consistent product from one factory to another.[1] Unlike chlorine, ozone does not leave behind chemical residual aftertastes or smells. Moreover, ozonation as a replacement for the prechlorination step not only eliminates the formation of chlorinated organic byproducts, but also reduces the GAC losses because chlorine preoxidation is replaced by ozone preoxidation. For treatment of water used for soft drinks and beer, the ozone dosage required should be 5 to 15 milligram per liter, depending on the ozone demand of the water used for processing and the extent of ozonation desired.[2]

Some of the main points associated with ozone as a solution for purification of water used to manufacture beverages are listed below.

- **No Chemical Residual Aftertaste or Odor:** Unlike chlorine, ozone does not leave behind chemical residual aftertastes or odors that require removal.

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[1] *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*, EPRI, Palo Alto, CA: 1996. CR-106435.
[2] Ibid.

- **No Harmful Chlorinated Organic By-Products:** Ozone can replace chlorine in the prechlorination step of water treatment. This eliminates the formation of chlorinated organic byproducts, which are detrimental to one's health.
- **Reduced GAC Losses:** Before water is used for beverage manufacturing, the GAC filter dechlorinates the water and removes halogenated organic materials that may have formed during the prechlorination step. Since chlorine preoxidation is replaced by ozone preoxidation, the GAC losses are reduced.

Performance Results

As discussed previously, ozone for disinfecting bottled water is very common. In this application, not only the bottled water is disinfected, but also the bottling equipment, the bottle itself, and its sealed cap. Table 4 shows a few bottled water plants that use ozone. Several bottlers are also currently using ozone for sanitizing the GAC filters.[1] The table indicates that several breweries, including Coors, Schmidt, Schlitz, Genessee, and Molson, use ozone to treat water used in processing.[2] Some of the very large soft drink companies are studying ozone for pre-treating water.[3] Currently, no performance results from beer or soft drink plants are available to the public. If a brewery has already installed an ozone system for water treatment over a 16-hour period daily, then the ozone system could be used during the remaining 8 hours to reduce the biological oxygen demand (BOD) solids in the used and expelled process water.

II. Treatment of Fruit Juice Products

Concerns

Problems such as the *E. coli* outbreak in fall of 1996 due to contaminated fresh Odwalla apple juice have focused intense public concern about the safety of fresh juices, and some stores do not accept unpasteurized juices any longer. A federal probe into the Odwalla outbreak revealed that the company had stopped using chlorine to wash its apples, and also did not adequately sanitize the wooden crates used to transport the picked apples, the press bags used to squeeze the fruit, and other equipment that came in contact with the produce or its juice by-product.[4]

Typically the fruit used for juices is washed in chlorinated flume water when transported from its storage bins to a conveyor belt for further processing. Although chlorinating the flume water results in better control of microorganisms, chlorine has actually proven inefficient on *E.coli*. Washing the fruit with chlorinated water has other drawbacks as well. First, chlorine builds up in the wash water. Second, chlorine cannot break down biological oxygen demand (BOD) solids in

[1] *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*, EPRI, Palo Alto, CA: 1996. CR-106435.
[2] Ibid.
[3] Ibid.
[4] Dow Jones News, *Federal Probe-Odwalla-Findings Reported*, July 23, 1997.

Table 4
Ozone for Purification of Water Used for Processing in the Beverage Manufacturing Industry – Representative Installations

Company or Researcher	Product	Application	Method	Results
Several Bottled Water Plants, including Adirondack Beverages, McKesson Water, Southern Beverage, Coca-Cola Dansai[a], Pepsi Aquafina[b]	Bottled Water	Replaces chlorine for disinfecting water, bottle, and cap	Ozone is added to the water in an ozone contractor just prior to the bottling of water. Ozone disinfects the water (from bacteria, viruses, and parasites) and oxidizes any undesirable organic and inorganic contaminants (such as iron, manganese, and odorous materials). Residual ozone provides disinfection of the bottling equipment, the bottle, and the cap of the sealed water bottle.	• Disinfected water that tastes and smells good • Extends shelf life of bottled water by 2 years
Several Breweries[d], including Coors, Schmidt, Schlitz, Genessee, and Molson	Beer	Water treatment	Ozone purifies the water	• Consistent water quality

[a] NOVAZONE OZONE GENERATORS SELECTED FOR DANSAI WATER BY COCA-COLA, Press Release, 12/18/02

[b] *Multipurpose Pepsi bottling*, Packaging Digest, April 2003. p.30.

[c] R. Rice, *Ozone and Ozone/UV in Sanitation and Food Production*, PowerPoint Presentation, May 28, 2003.

the water. Third, chlorine residuals on the fruit and vegetables can affect the flavor of the final product. The chlorine and BOD build-up in the flume water makes it more difficult to recycle the water. Therefore, facilities are forced to replace the flume water often, sometimes on a daily basis, which is expensive. As the costs for BOD discharged to publicly owned treatment plants increases, it is becoming evermore important to lower the BOD levels prior to discharge.

To address outbreaks of pathogens in minimally processed foods, the Food and Drug Administration (FDA) mandated in 1998 a 5-log reduction of pathogenic organisms in fruit and vegetable juice products. The most common method for reduction of pathogens is thermal pasteurization. However, thermal pasteurization increases product costs and may lower nutrition, quality, and consumer acceptability of fruit juices, such as apple cider.

The main concerns of fruit juice processors are summarized below.

- **FDA Requirement of a 5-log Reduction in Microorganisms:** The FDA requires a 5-log reduction, that is 100,000-fold, in the pertinent microorganisms for the shelf life of the product. Although thermal pasteurization meets this requirement, this method is costly and may also change the desired properties of the juice.
- **Consumer Acceptability:** Consumers require a juice that is safe and "fresh-tasting." Juice processors struggle with providing a juice that is safe, but that also meets the consumers' demand for fresh looking and tasting. To ensure safe juices that have tasting quality similar to that of untreated juices, processors need to find new methods of treating the juices.
- **Replacement of Chlorine:** There are several concerns associated with washing fruit with chlorinated water, including chlorine and BOD build-ups, chlorine residuals affecting the flavor of the final beverage, and chlorine's inefficiency in destroying *E. coli*.
- **Chlorine and BOD Build-Up in Flume Water:** The build-up of chlorine and BOD in the flume water requires it to be replaced often, adding to operation costs.
- **Water and Wastewater Disposal Costs:** Replacing water and disposing wastewater is costly, particularly if the build-up of BOD and suspended solids is high.

Ozone as a Solution

Ozone is an effective method of reducing bacteria, molds, and fungi from the fruit used for juice processing. In this application, the produce is washed or sprayed with ozonated water before it is pressed. Ozone can also replace chlorine for treatment of flume water, with an ozone concentration in the flume water that is generally maintained at about 0.05 to 0.15 ppm.[1] Ozonation of flume water reduces the yeast and mold count on the produce as well as in the water, which, in turn, reduces the risk of spoilage and also extends the use of the water. Instead of replacing flume water daily, water may be reused for several days or weeks, providing substantial savings. Extending the use of flume water equates to reduced wastewater disposal

[1] EPRI Techapplication, *Ozone Applications in Apple Processing*, TA 112064, 1998.

costs because less water and lower amounts of BOD need to be disposed of. Figure 5 shows ozonated flume water transporting and rinsing apples.

Figure 5
Ozonated Flume Water Controls Microorganisms on Apples and in Water

Source: EPRI

Researchers at several U.S. universities are studying various non-thermal methods for replacement of thermal pasteurization. One such non-thermal method is ozonation. Although still in its research phase, ozone-treatment of apple cider has shown some promise. In general, the use of ozone for treatment of fruit juices is uncommon. This is because ozone decomposes to oxygen and water, resulting in a diluted beverage.

The main advantages of treating fruit juice products with ozone are:

- **Control of Microorganisms without Use of Chlorine:** Ozone is very effective at controlling the microorganisms it comes into contact with. Moreover, microorganisms cannot build up a resistance to ozone, as they do with chlorine. However, ozone must come in contact with a contaminant in order to destroy it.
- **No Chemical Residual Aftertaste or Odor:** Unlike chlorine, ozone leaves no chemical residual aftertaste or odor.
- **Conserves Water:** Flume water and rinse water are generally chlorinated to control microorganisms. Replacing chlorine with ozone in the flume water provides substantial water savings because the water does not have to be replaced as often.

- **Reduces Wastewater Disposal Costs:** The amount of BOD discharged to publicly owned treatment works is less because of a higher degree of recycled flume water. Therefore, wastewater disposal costs are lowered.

Performance Results

Table 5 shows the results from a few ozone applications in juice processing plants. In particular, the use of ozone in flume water for washing and sanitizing apples has provided great results. For example, Tastee Apple in Ohio—an apple and apple cider processor—uses ozone systems for washing and sanitizing apples on its fresh apple processing and grading line, as well as on its wash line for juice processing. These systems reduce the yeast and mold count in the water and on the apples, resulting in cleaner water and apples. Prior to the ozone equipment installation, the flume water was chlorinated to control microorganisms, and it was dumped daily because it accumulated high levels of soil and organics that washed off the apples. The apple processor now can reuse the flume water for a whole week, compared to only one day before the ozone equipment was installed. This saves the company more than 12,000 gallons of water per week.

Several researchers have studied whether ozone treatment can replace thermal pasteurization of juices and ciders. The results have been mixed. For example, researchers at the Purdue University found ozonation can meet the mandatory 5-log pathogen reduction while maintaining quality similar to that of untreated apple cider.[1] However, similar tests conducted by researchers at Ohio State University with grape juice failed.[2] In those tests, ozonation so drastically changed the flavor of grape juice that it became undrinkable. One possible explanation may be that the ozone damaged the high level of specific pigments and flavor constituents commonly present in grape juice.

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[1] Choi, *The effect of various processing treatments on the quality and nutrition of apple cider*, Paper 88E-16, IFT Food Expo 2001, 2001.
[2] Ohioline News, *Pasteurization Lends To Safer Fresh Grape Juice,* 2/04/03, http://fusion.ag.ohio-state.edu/news/story.asp?storyid=780

Table 5
Ozone Treatment of Fruit Juice Products – Summary of Representative Installations and Research Projects

Company or Researcher	Product	Application	Method	Results
Tastee Apple[a] Newscomerstown, OH	Apple Juice	Washing of apples, controlling microorganisms in flume water, and clean-in-place (CIP) sanitation of juice storage tanks	The juice processor uses three ozone systems. The first system produces ozone for the flume water, which transports and washes the apples. The ozone concentration in the flume water is maintained at about 0.05 to 0.15 ppm. In the second system, ozonated water is sprayed onto the apples before they are pressed to juice. Finally, the third system is a CIP system that sanitizes the 6,000-gallon juice storage tanks.	• Reduces the amount of microorganisms, such as yeast and mold, on apples • Flume water does not have to be replaced as often because the BOD levels are reduced. This equates to cost savings. • Clean storage tanks
P. Choi and S. Nielsen[b] Department of Food Science, Purdue University, IN	Apple Cider	Effect of ozone treatment on the quality and nutrition of apple cider	Apple cider was treated with ozone to achieve a 5-log reduction of pathogenic organisms. The quality of the ozone-treated apple cider batch was compared to one heat-treated batch and one control batch that were not treated.	• Ozonation can meet the mandatory 5-log reduction of pathogenic organisms while keeping quality similar to that of untreated apple cider • Thermal pasteurization significantly changes the quality of apple cider

Table 5
Ozone Treatment of Fruit Juice Products – Summary of Representative Installations and Research Projects, Continued

Company or Researcher	Product	Application	Method	Results
J. Scheerens et. al.[c] Agricultural Research and Development Center (OARDC), Ohio State University, OH	Grape Juice	Effect of ozone treatment on the quality of grape juice	The grape juice was inoculated with a surrogate *E. coli* bacterium (ATCC 25922) that behaves similarly to the more harmful *E. coli* O157:H7. The inoculation levels were very high — higher than would ever be present in a consumable product — in order to be able to demonstrate that treatment would result in a 5-log kill of bacteria cells	• Ozonation of the grape juice made it undrinkable • Inconsistent results in reduction of *E.coli*

[a] *Ozone Applications in Apple Processing*, EPRI, Palo Alto,TA-112064, 1998.

[b] Choi, *The effect of various processing treatments on the quality and nutrition of apple cider*, Paper 88E-16, IFT Food Expo 2001, 2001

[c] Ohioline News, *Pasteurization Lends To Safer Fresh Grape Juice,* 2/04/03, http://fusion.ag.ohio-state.edu/news/story.asp?storyid=780

III. Sanitation of Bottling Equipment, Storage Tanks, and Rinse Water

Concerns

Bacterial control is critical for the beverage manufacturing industry. In the early years of the 1970s, several bottled water recalls took place due to growth of microorganisms in the bottled water. Because of not fully developed disinfection methods and improperly sealed bottles, airborne microorganisms entered the bottles causing taste, odor, and health problems. The microbial growth sometimes commenced after weeks of storage, often on the shelves of the supermarkets. These days, consumers of all types of beverages expect a beverage that is safe, good tasting, aesthetically pleasing, storage stable, and of high quality.

Although chlorine has the capacity to efficiently sanitize process equipment and storage tanks, it leaves residuals behind that can affect the taste and odor of the beverage. Chlorine also builds up in the rinse water, making recycling of rinse water harder to complete for any longer periods of time. Frequent replacement of rinse water adds to the operation costs. Another disadvantage of chlorine over ozone is its inability to break down biological oxygen demand (BOD) solids in the water, which results in BOD charges once the water is discharged to the treatment plant.

Chemicals are also harsh on equipment. A case in point is the use of chemicals for sanitation of beer fermentation tanks and wine barrels. Chemicals wear on stainless steel equipment, such as beer fermentation tanks, and some of the commonly used chemicals for sanitation of oak barrels affect the oak essence. For example, chlorine taints the wood, and proxycarb, another chemical, strips out the oak essence. Since winemakers spend much money on oak barrels and their oak essence, they are interested in replacing these chemicals with alternative treatment technologies that can maintain the health of the wine barrels.

The following list summarizes the main concerns with sanitizing bottling equipment and storage tanks, and the associated risks with conventional chemical sanitation:

- **Control of Bacteria, Yeast, and Mold Growth:** Uncontrolled growth of bacteria, yeast, and mold on bottling equipment and in bottles and storage tanks, such as rinse water storage tanks and wine barrels, can potentially lead to inferior end-products.
- **Chlorine Leaves Residues Behind that Affect Taste and Odor:** Sanitation with chlorine affects the taste and odor of the beverage.
- **Chemicals Adversely Affect Oak Barrels:** Commonly used chemicals for sanitation of oak wine barrels, such as chlorine and proxycarb, adversely affect the oak essence.
- **Costly Water Replacement and Wastewater Disposal:** Since chlorine builds up over time, the water used for rinsing and washing has to be replaced frequently. Another drawback of chlorine is its inability to prevent the build-up of BOD and suspended solids, resulting in wastewater charges once the water is disposed of to the treatment plant.

Ozone as a Solution

Perhaps the most intriguing application of ozone in the beverage manufacturing industry is for sanitation of process equipment, storage tanks, containers, bottles, lids, and caps. It is important to remember though that ozone is neither a cleaner nor a sterilizer,[1] but a sanitizer. Ozone is very effective at destroying microorganisms. However, ozone does not destroy minerals, scale, corrosion, and tartrates. Thus, it is best to first use hot water to clean dirt and solids from the equipment, tanks, floors, and barrels, and then once the surfaces are clean, spray ozonated water onto them or let ozonated water enter into the bottles, storage tanks, or wine barrels for sanitation.

Ozone has been used in the bottled water industry for several decades. In this particular application, The International Bottled Water Association (IBWA) recommends that ozone be applied at a concentration ranging from 1.0 to 2.0 milligram per liter (mg/l) for a contact period of 4 to 10 minutes to ensure disinfection of bottled water.[2] This helps maintain a 0.1 to 0.4 ppm ozone level at the time of bottling, which adds an additional safety factor because bottles can be disinfected and sanitized while filling them with water. Any type of beverage bottle, such as a beer or wine bottle, is suitable for rinsing with ozonated water. Ozone is specifically effective in the final bottle rinse to remove soap residues or pesticides that may affect the taste and odor of the beverage.

Ozone can also control microbial growth in storage tanks, such as rinse water storage tanks and fruit juice storage tanks. For example, Tastee Apple in Ohio, an apple processor, has installed an ozone system for CIP sanitation of their juice storage tank.[3] In a plant-wide ozone system at the Sierra Nevada brewery, ozone is applied at a dosage rate of about 3 ppm and the water entering the storage tank for the rinse water is maintained at a 1 ppm residual level.[4] The rinse water is used for bottle rinsing and at various CIP locations throughout the plant. In these two applications, ozone replaces chemical sanitizers.

Since the early 1990s wineries have been experimenting with ozone as an alternative to sanitizers like chlorine, proxycarb, and sulphur dioxide. It has been generally accepted to be effective for barrel and tank sanitation, CIP sanitation, and general surface sanitation. For CIP applications, larger systems providing 20 gpm of ozonated water are usually necessary, while smaller systems providing 10 gpm are satisfactory for barrel sanitation.[5] In particular, wineries have found ozone to be effective for sanitation of oak barrels because it does not taint the wood or strip the oak essence out of the oak barrels. Therefore, ozone is rapidly emerging as a replacement for the commonly used harsh chemicals and hot water for barrel sanitation. Ozonation of barrels is a two-part process, involving cleaning and sanitation. First, warm water cleans the barrel, dissolves tartrates, and opens up the wood pores in the oak. Second, cool ozonated water rinses the barrel. This sanitizes the barrel and also shrinks the wood pores. Smaller wineries usually conduct this

[1] Sterilizing implies all microbes are killed.
[2] The International Bottled Water Association (IBWA) website www.bottledwater.org
[3] EPRI Techapplication, *Ozone Applications in Apple Processing*, TA 112064, 1998.
[4] Rice, R. G., *Ozone and Ozone/UV in Sanitation and Food Production*, May 28, 2003, PowerPoint presentation.
[5] Hampson, B., *Use of ozone for winery and environmental sanitation,* Practical Winery and Vineyard Magazine, January/February 2000.

two-part process manually using a pressure washer and ozonated water from a hose connected to a mobile ozone generator. However, larger wineries have automated the process with barrel washing machines using ozonated water. Figure 6 shows a mobile ozone system used for sanitizing oak barrels at a winery.

Figure 6
Ozonated Water Sanitizes Oak Barrels at a Winery

Source: DEL Ozone. Used with permission.

The primary advantages with using ozone for sanitation of beverage bottling equipment and storage tanks include:

- **Microbial Control:** Ozone is capable of destroying bacteria, yeast, and mold. This, in turn, leads to better quality and shelf life of the beverage.
- **Lack of Residue:** Unlike sanitation with chlorine or other chemicals, ozone does not leave behind residues nor does it alter the taste or odor of the beverage.
- **Short Contact Time:** In general, the ozone concentration is high, so only a short or modest contact time is required.

- **Eliminating Wear on Stainless Steel Parts and Equipment:** Chlorine can be quite aggressive when used for sanitation of stainless steel equipment. Sanitation with ozonated water, on the other hand, eliminates this wear. However, ozone will attack and destroy any natural rubber compound, such as gaskets, fittings, pump seals, and hoses, as well as fiberglass resins. Brass and copper should also be avoided for concentrations over 1.0 ppm of ozone dissolved in water.[1]
- **Maintaining the Health of Oak Barrels:** Ozone is effective in maintaining, and even improving, the microbial health of oak barrels used in wineries. Research data have proven ozone to be effective in control of *Brettanomyces*, which is a yeast with mold-like characteristics that converts alcohols and sugar in wine into compounds causing unpleasant aromas and tastes. Some preliminary results indicate ozone may also be an effective replacement for sulphur dioxide for long-term storage of oak barrels.[2]
- **Reduced Chemical Use, Handling and Storage:** Ozone can replace many commonly used chemicals, such as chlorine, sulphur dioxide, and chlorinated trisodium phosphate (TSP), for sanitation of process equipment and storage tanks. Since ozone is produced on-site, this also reduces the risks associated with storage, handling and disposal of hazardous chemicals.
- **Not Detrimental to the Operation of Ponds, Septic Tanks, and Wastewater Plants:** Ozonated water does not pollute ponds, nor does it kill the bugs in the biomass or destroy beneficial bacteria in the septic system or wastewater plant because ozone reacts so quickly that residual quantities are not present in the waste stream.

Performance Results

The use of ozone for sanitation of equipment and surfaces in the beverage manufacturing industry has yielded impressive results in terms of control of microorganisms and savings due to less chemical handling and less maintenance. Table 6 lists some sanitation installations in the beverage manufacturing industry, including one brewery, one apple juice processor, and several wineries and bottled water plants.

At the Sierra Nevada Brewery, an ozone system was added to the plant-wide rinse water system. The rinse water is used for rinsing bottles and various CIP applications throughout the brewery. Ozone is added to the rinse water before it enters the storage tank. The target ozone residual for the rinse water in the storage tank is 0.5 ppm. The ozone system has proven efficient in maintaining a 3-log reduction in mold, yeast, and enterobacteria counts in the rinse water storage tank. The ozone system has also resulted in reduced chemical use and handling, which equates to savings for the brewery. Reduced wear on fermentation tanks and other stainless parts because of ozone replacing chemicals have provided additional savings.

Ozone systems for sanitation of equipment are becoming increasingly popular among wineries as illustrated in Table 6. Most of these ozone systems are for oak barrel maintenance and rinsing of

[1] Hampson, B. *Use of ozone for winery and environmental sanitation,* Practical Winery and Vineyard Magazine, January/February 2000.
[2] M. Coggan, *Ozone in Wineries PART 2 Barrels and Beyond*, Vineyard and Winery Management, Vol. 29 No. 2, 2003.

storage tanks, where ozone replaces commonly used chemicals. Barrel rinse times depend on the concentration of ozone in the water, and the age and degree of contamination of the barrel. For most barrels a treatment time of one and a half minute is sufficient when using the typical 2.0 to 2.5 ppm concentration. The treatment time, however, must be extended to 4 to 5 minutes for unhealthy barrels that contain wine-spoiling microorganisms, such as *Brettanomyces*, *Acetobacter*, *Lactobacillus*, or *Pedicicccus*.[1] In general, the wineries' ozone systems are either mobile or stationary. However, in larger wineries, or newly constructed wineries, a cost-efficient solution may be to install a centralized ozone system that provides ozonated water on tap. This is the approach that Cakebread Cellars has taken in their new winery. The J Vineyard and Winery uses ozonated water in a CIP system for sanitation of the filler in their bottling lines. In this particular application, the winery has been able to replace most of its use of chlorinated TSP with ozone.

[1] M. Coggan, *Ozone in Wineries PART 2 Barrels and Beyond*, Vineyard and Winery Management, Vol. 29 No. 2, 2003.

Table 6
Ozonated Water for Sanitation of Equipment in Beverage Manufacturing Operations, Breweries, and Wineries— Summary of Representative Installations and Research Projects

Company	Product	Application	Method	Results
Sierra Nevada Brewery[a] Chico, CA	Beer	Control the levels of molds, yeasts and entero-bacteria in the rinse water storage tank	An ozone system was installed in the plant-wide sterile rinse water system. The rinse water is used for bottle rinsing and various clean-in-place (CIP) locations throughout the plant. A dosage rate of 3.3 ppm provides the water entering the storage tank with a 1.0 ppm residual level, with a target ozone residual in storage tank of 0.5 ppm.	• Maintaining > 3-log reduction in molds, yeast and enterobacteria counts in rinse water storage tank • Reduced chemical use and handling, resulting in savings • Eliminated wear on fermentation tanks and other stainless steel parts
Kendall-Jackson[b] Oakville, CA	Wine	Using ozonated wash water for microbial control of wine barrels	The winery first washes the barrel for a minute and a half with hot water and then washes the barrel with cold ozonated water for three minutes. Since the ozonated water is cold it also cools the barrel.	• Replaces chlorine; reduces chemical costs • Controls the population of *Brettanomyces* on the wineries' oak barrels

Table 6
Ozonated Water for Sanitation of Equipment in Beverage Manufacturing Operations, Breweries, and Wineries— Summary of Representative Installations and Research Projects, Continued

Company	Product	Application	Method	Results
Joseph Phelps Vineyards[b] St. Helena, CA	Wine	Sanitation of barrels and tanks, and control of mold growth in barrel room	Barrels are emptied and then washed in hot water before they are rinsed in ozonated water for 1 minute Ozone is also used for sanitation of tank. First, the tank is hand-scrubbed with water. Then, the ozone system is put inside the tank for 5 to 10 minutes to rinse with ozonated water. In the past, the winery had mold problems in the barrel room. First cleaning the walls and ceiling, and thereafter spraying the surfaces with ozonated water solved the problem.	• Maintains the health of oak barrels without the use of chemicals • Replaced caustic cleaners for sanitation of tank • Destroyed mold growing on the walls and ceiling in barrel room
J Vineyards and Winery[b] Healdsburg, CA	Wine	Sanitation of barrels and CIP filler system	During bottling, the winery uses a CIP ozone system for sanitation of the filler. The filler is connected to the ozone generator in a closed loop at the end of the day and the system then runs during the night. Winery also sanitizes its oak barrels with ozone	• Ozone has replaced chlorinated TSP for filler sanitation for four out of five days. The remaining day, TSP sanitizes the filler. This has resulted in reduced chemical use. • Maintains the health of oak barrels

Table 6
Ozonated Water for Sanitation of Equipment in Beverage Manufacturing Operations, Breweries, and Wineries— Summary of Representative Installations and Research Projects, Continued

Company	Product	Application	Method	Results
Cakebread Cellars[b] Rutherford, CA	Wine	Sanitation of various equipment and surfaces, such as barrels, crush equipment, and storage tanks	A centralized ozone system provides ozonated water on tap throughout the winery. The system puts taps with ozonated water right next to hot and cold water taps.	• Building-wide ozone system provides barrel and CIP sanitation more cost effectively than stationary and mobile ozone generators since the winery uses ozone in so many locations • Maintains the health of oak barrels • Provides chemical-free sanitation of storage tanks
E. Dormedy et. al.[b] California State University Fresno	Wine	Sanitation of oak barrels	Researchers simulated two-minute barrel treatments with 1, 5, and 10 ppm ozone in water Researchers also conducted experiments with 1 cm oak blocks infected with *Brettanomyces* and treated with ozone gas	• Simulation data showed no statistically significant effect on the oak's volatile aroma compound, including vanilla, smoky and toast oak notes • Ozone gas destroyed the *Brettanomyces* organisms on the surface and inside the blocks

Table 6
Ozonated Water for Sanitation of Equipment in Beverage Manufacturing Operations, Breweries, and Wineries— Summary of Representative Installations and Research Projects, Continued

Company	Product	Application	Method	Results
Tastee Apple[c] Newscomerstown, OH	Apple Juice	Washing of apples and CIP sanitation of juice storage tanks	The juice processor uses three ozone systems. The first system produces ozone for the flume water, which transports and washes the apples. The ozone concentration in the flume water is maintained at about 0.05 to 0.15 ppm. In the second system, ozonated water is sprayed onto the apples before they are pressed into juice. Finally, the third system is a CIP system that sanitizes the 6,000-gallon juice storage tanks.	• Reduces microorganisms, such as yeast and mold, on apples • Cleaner flume water, resulting in less frequent replacement. This yielded water savings of 12,000 gal/week. • The BOD levels in flume water are reduced, which equates to reduced wastewater treatment costs • Cleaner rubber gloves for employees working with apples and cleaner juice storage tanks
Several Bottled Water Plants, including Adirondack Beverages, McKesson Water, Southern Beverage, Coca-Cola Dansai[d], Pepsi Aquafina[e]	Bottled Water	Replaces chlorine for disinfecting water, bottle, and cap	Ozone is added to the water at a 1.0 to 2.0 milligram per liter (mg/l) range for a contact period of 4 to 10 minutes to ensure disinfection of water just prior to bottling. This helps maintain a 0.1 to 0.4 ppm ozone level at the time of bottling, which adds an additional safety factor because bottles can be disinfected and sanitized while filling them with water.	• Ozone disinfects the water (from bacteria, viruses, and parasites) and oxidizes any undesirable organic and inorganic contaminants (such as iron, manganese, and odorous materials) • Residual ozone provides disinfection of the bottling equipment, the bottle, and the cap of the sealed water bottle • Extends shelf life of bottled water by 2 years

[a] R. Rice, *Ozone and Ozone/UV in Sanitation and Food Production*, PowerPoint Presentation, May 28, 2003.

[b] M. Coggan, *Ozone in Wineries PART 2 Barrels and Beyond*, Vineyard and Winery Management, Vol. 29 No. 2, 2003.

[c] *Ozone Applications in Apple Processing*, EPRI, Palo Alto,TA-112064, 1998.

[d] NOVAZONE OZONE GENERATORS SELECTED FOR DANSAI WATER BY COCA-COLA, Press Release, 12/18/02

[e] *Multipurpose Pepsi Bottling*, Packaging Digest, April 2003. p. 30.

OZONE FOR SANITATION OF EQUIPMENT AND WORK AREAS IN FOOD PRODUCTION AND PROCESSING

The food production and processing industry is facing mounting concerns about its ability to provide consistently safe food. Food borne diseases cause an estimated 6 to 33 million illnesses and up to 9,000 deaths in the U.S. every year.[1] In the past, most efforts to avoid contamination of food focused on preventing exposure to sewage or animal manure early in the production process.[2] Today, however, the entire chain of production and processing is of interest—from growing, picking, packaging, shipping, to processing—as multiple points of sanitation are necessary to avoid microbial contamination of food.

This section describes the use of ozone for sanitation of equipment and work areas as they pertain to the whole food production and processing industry. Subsequently, a vast array of equipment and work areas are included—from animal housing to trucks and slaughterhouses to storage containers and processing equipment, such as knives, saws, tabletops, and conveyor belts, and to packaging material. The discussion includes the main concerns associated with sanitation of equipment and work areas, and also describes how ozone is generally applied to address these concerns. Finally, it provides representative performance data for ozone used for sanitation of equipment and work areas in the food production and processing industry.

Concerns

It is not only important to keep food free of contamination but also critical to maintain clean equipment and work areas to prevent cross-contamination of food and the subsequent risk of food borne illness (see Figure 7). Therefore, one major concern is formation of biofilms on food processing equipment. Biofilms are simply layers of microorganisms bonded tightly to a surface, and they may consist of anything, including bacteria, yeasts, molds, algae, etc.[3] Microbes can attach themselves like glue to a surface by releasing their own biological material, exopolymeric substance (EPS).[4] This extra layer provides nutrients as well as protection against sanitizers and disinfectants. If a surface is not properly cleaned and sanitized, microorganisms can aggregate and form biofilms. More organisms will grow on the bottom because more nutrients are on the surface. Subsequent layers of organisms have fewer nutrients, and they become adapted to harsher conditions.

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[1] FoodReview, *Promoting Food Safety: An Economic Appraisal,* Vol. 22 Issue 2, 1999, http://www.ers.usda.gov/publications/foodreview/may1999/contents.htm.
[2] A. Majchrowicz, *Food Safety Technology: A Potential Role for Ozone?*, Economic Research Service/USDA, Agricultural Outlook June-July 1998.
[3] J. Yuan and S. Thakkar, *Biofilms in Food Processing Plants*, Fresh-cut™ Magazine, April 2001.
[4] Ibid.

Figure 7
Effective Sanitation Includes Washing of Processing Equipment

Source: Aramark. Used with permission.

Common cleaning and sanitation practice is to rinse equipment and work areas with chlorinated water. Although chlorine usually is effective against biofilms because it can destroy EPS and inhibit growth, microorganisms may build up resistance to chlorine. This is of particular concern with microorganisms, such as *E. coli* and *Giardia*, which may cause serious illness and may lead to deaths. Chlorine has additional drawbacks. One such drawback is that chlorine builds up in the rinse water, which reduces the water recycling potential and makes it necessary to replace the rinse water frequently. This, in turn, adds to the operation costs. Another drawback of chlorine is its inability to break down biological oxygen demand (BOD) solids in the water. The BOD build-up also adds to the operation costs because of higher BOD charges once the water is discharged to the treatment plant.

Chemicals are also harsh on equipment made of metals and wood. A case in point is the use of chemicals for sanitation of wine barrels. Commonly used chemicals for sanitation of oak barrels affect the oak essence. For example, chlorine taints the wood, and proxycarb, another chemical, strips out the oak essence. Since winemakers spend significant quantities of money on oak barrels and their oak essence, they are interested in replacing these chemicals with alternative treatment technologies that can maintain the health of the wine barrels.

The list below summarizes the main concerns associated with sanitation in food production and processing facilities that ozone can help mitigate:

- **Microbial Contamination can Cause Food Borne Illnesses:** Some types of microorganisms, such as *E. coli* and *Salmonella*, can cause food borne illnesses. If an outbreak of an illness is tracked back to a food production or processing plant, expensive recalls, damaged reputations and costly fees and litigations may be the result. Therefore, it is important to eliminate harmful microorganism from the food itself as well as any equipment or work areas that may come in contact with the food.
- **Prevent Cross-Contamination:** Food processors are especially concerned about preventing cross-contamination in their facilities. Microbial load on process equipment, such as conveyor belts, knives, and cutters, easily can transfer from the equipment surfaces to the food.
- **Microbial Contamination Shortens Shelf life and Causes Spoilage:** Microbial contamination on food, such as meat, fish, and produce, may result in shorter shelf life and spoilage. This in turn affects the bottom-line for the processing facility.
- **Replace or Limit the Use of Chemical Sanitizers:** Since commonly used sanitizers, such as caustic and hazardous chemicals, have several drawbacks, food production and processing facilities alike are investigating alternatives to replace these chemicals for sanitation. Among the more severe drawbacks are chemicals in the rinse water making water recycling more difficult, and chemicals requiring safe handling and disposal. Chlorine is also corrosive to metals, and affects the oak essence of wine barrels.
- **Costly Water and Wastewater Discharges:** Food production and processing facilities face increasingly stringent regulations and expenses in meeting strict environmental standards. Many facilities have effluent burdens because of build-up of chlorine and BOD in rinse water.
- **Resistance to Chemicals:** Microorganisms may develop a resistance to chemical sanitizers. For example, *E. coli*, *Giardia*, and *Cryptosporodium* and other new pathogens resist chlorine. There are also some microorganisms that are resistant to ammonia compounds.[1]

Ozone as a Solution

In food production and processing facilities, ozonated water can be sprayed directly onto floors, walls, drains, trucks, railcars, tanks (external and internal), and processing equipment via mobile or centralized systems with hand-held or drop-down sprayers. External surfaces are generally cleaned with mobile spray equipment. Enclosed vessels and piping systems, however, require

[1] P. Clark, *New Developments in Sanitation Help Keeps Food Plants Clean*, Food Technology, Vol. 57, No. 10, October 2003.

cleaning in place (CIP). Figure 8 shows a mobile ozone system sanitizing the interior of a commercial truck.

Figure 8
Mobile Ozone System Sanitizes the Interior of a Commercial Truck

Source: Pure-O-Tech, Inc. Used with permission.

For efficient sanitation using ozone, a two-step procedure is generally required. First, the surfaces are cleaned and the organic residues in which bacteria are embedded are removed. Thereafter, ozonated water sanitizes the surfaces by eradicating bacteria adhering to the surfaces. As ozone can destroy bacteria, viruses, fungi, and spores, no other biocide is necessary. Ozone has also proven effective in destroying many new pathogens and chemical-resistant strains of harmful microorganisms that have appeared recently. Over time, the use of ozonated water reduces overall microbial load in the facilities. It also prevents biofilms from developing on processing equipment. In addition, ozonated rinse water can be recycled easily.

Ozone for sanitation of equipment and work areas has found many applications in the food processing industry. For example, ozonated water sanitizes various types of processing equipment, including transportation racks, plastic storage tubs, conveyor belts, walk-in coolers, and cutting knives in meat and ham processing plants. Figure 9 shows transportation racks for sausages that are sanitized by ozonated water. Ozonated water also sanitizes processing equipment, walls, floors, and the fish itself in fish processing plants. Figure 10 illustrates general washing of a floor and drain using ozonated water. Another interesting application of ozone that has become increasingly popular during the last couple of years is for sanitation of oak barrels, other vineyard equipment, and general work areas in wineries. Ozone for sanitation of oak barrels is discussed in greater detail in the section entitled *Ozone for Beverage Manufacturing*.

Figure 9
Ozonated Water Sanitizes Stainless Steel Racks used for Transporting Meat Products at Plumrose USA Inc.

Source: EPRI

In food production, however, ozone's use for sanitation of equipment has not been implemented to its fullest capacity; ozone may have much broader application. For example, ozone could be used for pre-washing of poultry, swine, and calf facilities, daily washing of baby-pig operations, rinsing of swine production facilities, and washing of milking machines and milk parlors in dairy facilities.[1] As animal densities increase, the probability of disease also increases, resulting in increased use of antibiotics and mortality. Washing of animal housing with ozone may reduce the need for antibiotics and result in healthier animals.

[1] C. Sopher, *Ozone in Food Technology*, PowerPoint Presentation, October 2002.

Figure 10
Washing of Floors with Ozonated Water

Source: DEL Ozone. Used with permission.

The main merits of using ozone as a sanitizer of equipment and work areas include:

- **Powerful Microbial Control:** Ozone is capable of destroying microorganisms, including those that can cause food borne illness, such as *E. coli*, *Giardia*, and *Salmonella*.
- **Reduces Risk of Cross-Contamination:** Sanitation of process equipment and work areas with ozone reduces the risk for cross-contamination. Since ozone is safe to use on caustic-sensitive equipment it has an added advantage over caustic sanitizers.
- **No Chemical Residue that Requires Final Rinse:** Unlike chlorine or other types of chemicals, ozone is a final, no-rinse sanitation agent. Since ozone rapidly decomposes to oxygen, no final rinsing is required.
- **Ozone Replaces Harmful Chemicals:** Ozone eliminates the storage, handling, use, and disposal of caustic and hazardous chemicals that are used for sanitation. Also, chemical reporting is eliminated. This results in cost savings.
- **Maintains the Health of Oak Barrels:** Ozone is effective in maintaining, and even improving, the microbial health of oak barrels used in wineries. Research data have proven

ozone to be effective in control of *Brettanomyces*, a yeast with mold-like characteristics that converts alcohols and sugar in wine into compounds causing unpleasant aromas and tastes. Some preliminary results also indicate ozone may be an effective replacement for sulphur dioxide for long-term storage of oak barrels.[1]

- **Reduces Chemical Use, Handling and Storage:** Ozone can replace many commonly used chemicals, such as chlorine, sulphur dioxide, and chlorinated trisodium phosphate (TSP), for sanitation of process equipment and storage tanks. Since ozone is produced on-site, this also reduces the risks associated with storage, handling and disposal of hazardous chemicals.
- **Provides Water and Process Water Disposal Savings:** Rinsing equipment and surfaces with ozonated water and the subsequent ozonation of the recaptured water reduces the amount of makeup water required in the sanitation process since it can be recycled; thus, providing water savings. In addition, sanitation with ozonated water provides substantial water treatment savings on spent process water because it is free of chlorine and BOD build-ups, lowering the water disposal fees.
- **Sanitizes Water Drainage Systems in an Environmentally-Friendly Way:** Because of its short half-life, ozone reacts rapidly. Therefore, it does not lead to a harmful residual that could otherwise damage beneficial bacteria in the septic system or wastewater disposal plant. For the same reason, ozonated water does not pollute ponds.
- **Extended Hours of Operation:** Ozone is a fast and efficient sanitizing agent. In some cases, sanitation with ozone can be performed during production without comprising product or employee safety. Consequently, some of the time that previously was consumed by sanitation with chemicals may now be used for production.

Performance Results

Ozonated water has proven effective as a sanitizer for many types of surfaces in the food production and processing industry, including food processing equipment, food-packaging materials, shipping containers, wine barrels, fillers, floors, walls, ceilings, and drains as illustrated in Table 7. For example, tests, conducted in 1999, at the fruit and vegetable pilot plant at the California Polytechnic State University showed ozonated water is effective in reducing microbial load on floors, drains, tabletops, plastic shipping containers, stainless steel kettles, and shrouds. In these tests, the ozone system delivered an applied dose of 2 ppm through a hand-held spray wand. The surfaces were sprayed in a back and forth motion for about 1 minute. Since the surfaces were not cleaned prior to sanitation, only the effect of the ozone spray was measured. Table 8 presents the specific performance data for each surface tested. The first test results for the drain were inconclusive because the ozonated water washed throughout the long central drain ditch. In a second test on the drain for two minutes exposure with ozonated water provided a reduction in microbial load. The results from these tests, even without a surface cleaning prior to sanitation, indicate that ozonated water applied as a spray wash is effective in reducing microbial load, with a 60% to 99.9% reduction in plate counts.

[1] M. Coggan, *Ozone in Wineries PART 2 Barrels and Beyond*, Vineyard and Winery Management, Vol. 29 No. 2, 2003.

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects

Processing Facility or Research Site	Application	Method	Results
Plumrose USA, Inc. [a] Booneville, MS	Sanitation of meat processing equipment, including stainless transportation racks, plastic storage tubs, and stainless steel walk-in coolers.	A centrally located ozone system provides 1 ppm ozonated water on demand. The water is delivered in closed piping under low pressure to appropriate sanitation operations within the plant. One such operation is the sanitation of the stainless steel transportation racks involving a three-step process using an alkali cleaner and two ozonated water rinses.	• Ozonated water has replaced chlorinated water in the two rinses of the stainless transportation racks • Equal or better sanitation levels compared to chlorine • Final rinse water is recycled for the first rinse, which reduces water use and wastewater disposal costs • The use of cold ozonated water rather than warm chlorinated water for the final rinses provides energy savings due to reduced heating requirements and HVAC load
Meat and Sausage Processing Plant [b]	Sanitation of processing equipment	The plant experienced a *Listeria* recall. Management shut down the plant and implemented proper sanitation throughout the plant. Today, ozone is in key areas.	• Microbial results better than those obtained with caustic chemicals • Eliminates storage of hazardous materials

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
Food Processing Plant [c]	Sanitation of processing equipment	A 42,000-square foot food processing facility containing 20 processing lines operating 24 hrs/day approximately 300 days/year replaced its chemical use for surface sanitation to ozone-based mobile surface sanitation The return on investment (ROI) was calculated based on chemical cost and cost of wastewater disposal fees	• Eliminated chemical use during the sanitation process • Reduced the previous four-step sanitation process to a two-step process, including hot water wash followed by ozonated cold water rinse • On average, water usage and wastewater discharge decreased from 15,000 gal/day to 6,000 gal/day—a 60% reduction in wastewater disposal—resulting in annual savings of close to $13,000 in discharge fees alone • Return on investment for ozone implementation as a surface sanitizer can be achieved in 8.8 months
Pork Processing Plant [d]	Sanitation of processing equipment and knives	A mobile ozone system sprayed all samples with ozonated water with an ozone concentration of 1.1 to 1.4 ppm for 5 seconds	• Significant reduction in microbial load on all areas, equipment and samples tested • Ozone performed as good or better than 180^{o}F water in reducing microbial load on cutting knives, air knife, wizard knife, hook cutter, steel glove, split saw, and brisket saw • Ozone can be used as a substitution for 180^{o}F water for sanitizing purposes

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
Pork Processing Plant [e]	Sanitation of PPE equipment (gloves, apron, and arm guard), cutting knives, Mezzanine equipment (hopper and grinder), hook cutter, split saw, brisket saw, and meat cuts	A mobile ozone system sprayed all samples with ozonated water with an ozone concentration of 1.1 to 1.4 ppm for approximately 10 to 15 seconds	• Significant reduction in microbial load on all areas, equipment and samples tested • Ozone performed as good or better than 180°F water in reducing microbial load on PPE equipment, cutting knives, Mezzanine equipment, hook cutter, split saw, and brisket saw • Various meat cuts from whole carcass showed acceptable microbial reduction; however, higher ozone concentrations would be required to ensure acceptable reduction numbers on organic material, such as pig ear, feet, and hide
Hampson [f] Fruit and Vegetable Pilot Plant at the California Polytechnic State University	Sanitation of processing equipment and work areas, such as stainless steel kettle, tabletop, and shroud, floors and drains, plastic shipping container	A 10-gpm handheld ozone spray wand delivered an applied ozone dose of 2 ppm onto various surfaces in the facility. The surfaces were sprayed in a back-and-forth fashion for one minute. None of the surfaces were cleaned prior to sanitation with ozonated water.	• Ozone applied as a spray wash is effective in reducing microbial load • A 60% to 99.9% reduction in plate counts
Air Liquid America Corp. Chicago Research Center [g]	Sanitation of floor	Researchers used a mobile ozone system. Ozonated water with an ozone concentration of 0.5 ppm was sprayed onto the laboratory floor for 30 seconds.	• 3-log reduction of microbial populations on the floor surface • 4-log reduction of microbial populations in the wash water residue

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
Toxicology Group, LLC [h]	Study the efficacy of ozonated water for sanitation of surfaces	Researchers benchmarked ozonated water against EPA standards for sanitation of surfaces. Two mobile ozone surface sanitation systems were used, and many types of microorganisms were tested, including *E. coli*, *Brettanomyces*, *Listeria*, and *Salmonella*.	• Validates ozone's efficacy as a sanitizer of surfaces, including processing equipment that come in contact with food • Depending on microorganism tested, a 4-log or better reduction in microbial load
Mohammed Khadre and Ahmed Yousef [l] The Ohio State University	Study the effectiveness of ozonated water in decontaminating the surfaces of stainless steel and laminated aseptic food-packaging material	Multi-laminated aseptic food packaging material and stainless steel were treated with ozone in water of various concentrations to inactivate natural contaminants, bacterial biofilms and dried films of *Bacillus subtilis* spores and *Pseudomonas fluorescens*.	• Ozone is an effective sanitizer that can decontaminate packaging materials and equipment food-contact surfaces • The natural contaminants were eliminated from the multi-laminated packaging material when treated in 5.9 Fg/ml ozonated water for 1 minute • Dried films of spores were eliminated from the multi-laminated packaging material and stainless steel in 13 Fg/ml and 8 Fg/ml ozonated water, respectively • Ozone inactivated *Pseudomonas fluorescens* in biofilms more effectively on stainless steel than on the multi-laminated packaging material

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
Kendall-Jackson [j] Oakville, CA	Sanitation of wine barrels	The winery first washes the barrel for a minute and a half with hot water and then washes the barrel with cold ozonated water for three minutes. Since the ozonated water is cold it also cools down the barrel.	• Replaces chlorine; reduces chemical costs • Controls the population of *Brettanomyces* on the wineries' oak barrels
Joseph Phelps Vineyards [j] St. Helena, CA	Sanitation of wine barrels and tanks, and control of mold growth in barrel room	Barrels are emptied and then washed in hot water before they are rinsed in ozonated water for 1 minute Ozone is also used for sanitation of tank. First, the tank is hand-scrubbed with water. Then, the ozone system is put inside the tank for 5 to 10 minutes to rinse with ozonated water. In the past, the winery had mold problems in the barrel room. First cleaning the walls and ceiling, and thereafter spraying the surfaces with ozonated water solved the problem.	• Maintains the health of oak barrels without the use of chemicals • Replaced caustic cleaners for sanitation of tank • Destroyed mold growing on the walls and ceiling in barrel room
J Vineyards and Winery [j] Healdsburg, CA	Sanitation of wine barrels and CIP filler system	During bottling, the winery uses a CIP ozone system for sanitation of the filler. The filler is connected to the ozone generator in a closed loop at the end of the day and the system then runs during the night. The winery also sanitizes its oak barrels with ozone	• Ozone has replaced chlorinated TSP for filler sanitation for four out of five days. The remaining day, TSP sanitizes the filler. This has resulted in reduced chemical use. • Maintains the health of oak barrels

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
Cakebread Cellars [j] Rutherford, CA	Sanitation of various equipment and surfaces, such as wine barrels, crush equipment, and storage tanks	A centralized ozone system provides ozonated water on tap throughout the winery. The system puts taps with ozonated water right next to hot and cold water taps.	• Building-wide ozone system provides barrel and CIP sanitation more cost effectively than stationary and mobile ozone generators since the winery uses ozone in so many locations • Maintains the health of oak barrels • Provides chemical-free sanitation of storage tanks
E. Dormedy, et al. [j] California State University Fresno	Sanitation of wine barrels	Researchers simulated two-minute barrel treatments with 1, 5, and 10 ppm ozone in water Researchers also conducted experiments with 1 cm oak blocks infected with *Brettanomyces* and treated with ozone gas	• Simulation data showed no statistically significant effect on the oak's volatile aroma compound, including vanilla, smoky and toast oak notes • Ozone gas destroyed the *Brettanomyces* organisms on the surface and inside the blocks
Tastee Apple [k] Newscomerstown, OH	Clean-in-place sanitation of juice storage tanks	The apple juice processor uses an ozone clean-in-place system that sanitizes the 6,000-gallon juice storage tanks	• Cleaner juice storage tanks

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
Hanover Sea Products [l, m] Wilmington, NC	Sanitation of fish as well as the equipment used in the fish processing process	Ozonated water was used to wash processing equipment and rinse fish	• Sustained decrease in air- and water-borne bacteria, minimizing bacterial cross-contamination • Improved the shelf life of uncooked fish by one or two days • The appearance, color, and aroma of fresh fish was not affected
Delta Pride Catfish [n] Indianola, MS	Sanitation of catfish as well as the equipment used in fish processing Reduce the bacterial counts on the flesh of the fish and on fillet processing equipment	Processed whole fish was placed for 10 to 12 minutes in ozonated water in a 30-gallon test vessel. The test vessel included a chiller vessel and a reactor vessel. Ozone concentrations were varied from 5 to 12 ppm. Ozone was also applied at the fillet line	• Ozone was effective in reducing bacterial counts on whole fish, fillets, and fillet equipment • Shelf life increased to 14 days compared to 4-6 days for conventional treatment • A 75% reduction of bacterial counts on fillets coming off the fillet processing line when ozone was applied (compared to conventional treatment)

Table 7
Ozonated Water for Sanitation of Equipment and Work Areas in the Food Processing Industry – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
North Coast Seafood Company and other fish processing plants [b, o]	Sanitation of processing equipment, such as knives and table surfaces, and for general wash down of walls and floors	The fish processing plants use several mobile surface sanitation units. Ozonated water, with a 3-3.5 mg/l ozone level, is sprayed at 10 gallons per minute to sanitize equipment.	• A 50% increase in shelf life of white fish

[a] *Ozone Sanitizing for Meat Processing Equipment*, EPRI, Palo Alto, CA: 1999. TA-114172.

[b] Rice, R., *Ozone and Ozone/UV in Sanitation and Food Production*, PowerPoint Presentation, May 28, 2003.

[c] *DEL AGW-0500 Mobile Ozone Surface Sanitation System Food Processing Plant ROI*, 02/19/02, Product Sheet.

[d] Results from testing at a Fortune Fifty Pork Processing Plant 4/49/02, *The Effectiveness of Ozonated Water as a Sanitizer on the Kill Floor—Microbial Kill Results*, http://www.ozonecaws.com/Ozone-Knife-Report.pdf.

[e] Results from tests at a Fortune 50 Pork Processing Company, *The Effectiveness of Ozonated Water for Hard Surface Sanitation, Meat Cuts and Knife Dips—Microbial Kill Results*, http://www.ozonecaws.com/Ozone-Report-1.pdf.

[f] B. Hampson, *Use of ozone for winery and environmental sanitation*, Practical Winery and Vineyard Magazine, January/February 2000.

[g] *DEL AGW-0500 Mobile Ozone Surface Sanitizer*, Product Sheet.

[h] DEL Ozone, *AGW-1500G Mobile Recirculating Ozone Sanitation System Owner's Manual*.

[i] Khadre MA and Yousef, AE, *Decontamination of multilaminated aseptic food packaging material and stainless steel by ozone*, Journal of Food Safety,

[j] M. Coggan, *Ozone in Wineries PART 2 Barrels and Beyond*, Vineyard and Winery Management, Vol. 29, 2003.

[k] *Ozone Applications in Apple Processing*, EPRI, Palo Alto, TA-112064, 1998.

[l] *Researchers Find New Use for Ozone*, Sea Grant North Carolina, Press Release March 26, 2002, www.ncsu.edu/seagrant/Pressreleases02/Ozone.htm.

[m] *Ozone Effective in Preserving Seafood Freshness*, Sea Grant North Carolina, Marine Extension News, www.ncsu.edu/segrant/Newsletters02/MEN/Ozone.htm.

[n] Brooks, G., and Pierce, S., *Ozone Applications for Commercial Catfish Processing*, www.p2pays.org/ref/02/01251.pdf.

[o] Rice, R., Graham, D., and Lowe, M., *Recent Ozone Applications in Food Processing and Sanitation*, Food Safety Magazine, October/November 2002.

Table 8
Performance Results from Ozone Tests at the Fruit and Vegetable Pilot Plant at California Polytechnic State University

Surface	Percentage Reduction in Plate Count
Stainless Steel Kettle	89.7 to 98.2
Stainless Steel Tabletop	98.9 to 99.7
Stainless Shroud	63.1 to 99.9
High-Traffic Floor	67.0 to 95.6
Low-Traffic Floor	84.3 to 99.9
Floor Drain	----
Floor Drain 2nd Attempt	77.5
Plastic Shipping Container	96.9 to 97.2

Source: Hampson, B. *Use of ozone for winery and environmental sanitation,* Practical Winery and Vineyard Magazine, January/February 2000.

In a recent ozone study, conducted in 2001 by Toxicology Group, LLC (a division of NSF International), ozonated water was benchmarked against EPA standards for sanitation using two mobile ozone surface sanitation systems. The results from this study validate ozone's efficacy as a sanitizer for surfaces (see Table 9). As illustrated in Table 9, ozone reduces many harmful microorganisms, including *E. coli* and *Salmonella*, with a 4-log reduction or greater.

In testing of ozone's efficacy as a sanitizer, researchers at the Research Center at Air Liquid America Corporation sprayed ozonated water with an ozone concentration of 0.5 ppm onto the laboratory floor for 30 seconds. Ozone was capable of a 3-log reduction of microbial populations on the floor surface and a 4-log reduction of microbial reduction in the wash water residue. These results show ozone is effective not only in sanitizing equipment and work areas, but also effectively reduces the microbial activity in the rinse water. This, in turn, equates to water savings because more water can be recycled. In addition, the wastewater disposal fees are lowered because ozone prevents chlorine and BOD build-ups in the rinse water. A case in point is the 42,000-square foot food processing facility that replaced its chemical use for surface sanitation to ozone-based mobile surface sanitation. The previous four-step sanitation process was reduced to a two-step process, namely hot water wash followed by cold ozonated water rinse. On average, the waste usage and wastewater discharge decreased by 11,000 gallons/day, resulting in annual savings of close to $13,000 in discharge fees. The return on investment (ROI) for this specific installation was calculated, based on chemical cost and cost of wastewater disposal fees, to 8.8 months.

Table 9
Tests of Ozone's Efficacy as a Surface Sanitizer Conducted by Toxicology Group, LLC

Microorganism	Dose at Nozzle	Duration	Reduction
Escherichia coli	2.1 ppm	30 seconds	5-log (99.999%)
Aspergillus flavus	1.85-2.25 ppm	5 minutes	4-log (99.99%)
Brettanomyces bruxellensis	1.85-2.25 ppm	3 minutes	4-log (99.99%)
Campylobacter jejuni	1.85-2.25 ppm	3 minutes	4-log (99.99%)
Listeria monocytogenes	1.85-2.25 ppm	3 minutes	4-log (99.99%)
Pseudomonas aeruginosa	1.85-2.25 ppm	5 minutes	5-log (99.999%)
Salmonella choleraesuis	1.85-2.25 ppm	3 minutes	5-log (99.999%)
Staphylococcus aureus	1.85-2.25 ppm	10 minutes	6-log (99.9999%)
Trichophyton mentagropphytes	1.85-2.25 ppm	39 seconds	6-log (99.9999%)

Sources:

Rice, Graham, and Lowe. *Recent Ozone Applications in Food Processing and Sanitation,* Food Safety Magazine, October/November 2002.

DEL Ozone, *AGW-1500G Mobile Recirculating Ozone Sanitation System Owner's Manual*.

Many wineries use ozone for sanitation of oak barrels. Some wineries have also installed ozone systems, mobile as well as centralized systems or CIP systems, for sanitation of crush equipment, storage tanks, fillers, and walls and ceilings in barrel rooms. Although no detailed performance data are available from the winery installations, the wineries proclaim that ozone maintains the health of their oak barrels without the use of chemicals and in general is an effective sanitizer of many types of equipment in the operations. Wineries are particularly concerned about chemicals affecting the oak essence. They are also concerned about the wine-spoilage mold *Brettanomyces*. Some promising, but still preliminary, results from experiments at California State University Fresno show ozone gas can destroy *Brettanomyces* organisms on the surface and inside of oak blocks (see Table 7).

OZONE IN PEST MANAGEMENT

Food producers encounter pests during various stages of food production. Fungi, insects, rodents and the like attack crops prior to harvest, affecting the productivity and survival of plants and trees. Pests also infiltrate storage areas, eating and defecating on stored crops after harvest. Pests result in partially consumed and/or contaminated foods. In addition, pests in the fungal form cause odors that are readily absorbed by stored crops, affecting taste and quality. Pesticides are a valuable means of controlling pests if they are used properly; [1] however, many pesticides in current use are hazardous to humans and the environment. Therefore, measures to remove pesticides from food products and from the waste stream are of importance.

This section describes the use of ozone as a pesticide replacement in food storage and soil fumigation. It also discusses pesticide removal with ozone. The discussion includes the primary concerns associated with each aspect of pesticide use that ozone can potentially mitigate. It further describes the manner in which ozone is generally applied to address the concerns and summarizes the primary benefits of ozone over other alternatives. Lastly, it provides representative performance data for ozone tested in each specific end-use.

I. Food Storage

Concerns

Pesticides are widely used in food storage to control insects, fungi, rodents, and other pests. Pests can damage food supplies in a number of ways. For example, insects destroy stored crops by eating them and defecating on them. Defecation in turn enables fungal growth. Certain types of fungi are particularly problematic. For example, *Fusarium* and *Aspergillus* produce pathogenic mycotoxins that can harm animals or humans. Fungal growth can also ruin the taste of stored crops, as odors from the fungi are readily absorbed by food. It is estimated that 5 to 10% of the world's food production is destroyed each year by insects; in some countries the loss may be as much as 50%.[2]

In order to mitigate the effects of pests on stored crops, pesticides are commonly employed. One of the most common chemical agents is methyl bromide. Methyl bromide has been used as a fumigant for decades. However, since it damages the stratospheric ozone layer and is a suspected carcinogen, methyl bromide is in the process of being phased out for agricultural applications in industrialized countries according to the following schedule: 25% in 1999, 50% in 2001, 70% in 2003 and 100% in 2005.

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[1] Definition of a pesticide: "A material useful for the mitigation, control, or elimination of plants or animals detrimental to human health or economy" from www.accessscience.com.

[2] "Ozone may provide environmentally safe protection for grains," *Purdue News*, January 30, 2003.

The list below summarizes the main concerns associated with pests and current pest control practices.

- **Pests:** Insects, fungi, and other pests destroy stored crops. Insects and animals eat and defecate on food supplies; fungi grow in storage environments and on food supplies and can cause damage and lead to the production of pathogenic mycotoxins; and odors are absorbed by stored crops affecting taste and quality.
- **Lack of Chemical Agents for Control of Pests:** Methyl bromide, a common pesticide, is scheduled for complete phase-out by 2005 because it contributes to the destruction of the stratospheric ozone layer.

Ozone as a Solution

Ozone is currently being investigated as an alternative to chemical agents, such as methyl bromide, for pest control during crop storage. Preliminary results with ozone as a pesticide replacement show promise, but more work is necessary to determine its acute toxicity levels. Acute toxicity is often expressed in terms of the lethal dosage (LD) values LD_{50} and LD_{100}. LD_{50} is the quantity of toxicant (in this case, ozone) required to kill 50% of a test population, and LD_{100} is the quantity required to kill 100% of the test population. The units of measure for the LD values are milligrams of pesticide divided by kilograms of body weight of the test animal (mg/kg), or they can be expressed in units of parts per million (ppm). Test animals commonly used include rats, mice, and rabbits.

For pest control during food storage, gaseous ozone in air is introduced to the storage environment (see Figure 11). In experiments to date, the ozone concentration and duration of exposure have varied with application. One approach is to use high ozone concentrations for short durations. Another approach is to use a low ozone concentration for an extended period of time. For example, tests conducted with ozone to kill Indianmeal moth and diapausing codling moth larvae in crop storage required 400-500 ppm of ozone for 4 to 5 hours.[1] Other tests with confused flour beetle and saw-toothed grain beetle achieved complete mortality with 5 ppm of ozone over a 3 to 5 days period.[2] Similarly, continuous exposure to 5 ppm ozone was shown to inhibit surface growth of *A. flavus* and *F. moniliforme* as well as eliminate sporulation and aflatoxin production.[3] (Note that ozone can destroy toxin-producing microorganisms, but it cannot destroy the toxins already produced.)

The primary advantages with ozone as a pesticide replacement during food storage include:

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[1] Technical Update -- *Use of Ozone in Water on Fresh Fruit,* EPRI, Palo Alto, CA, Southern California Edison: 2002, 1007108.
[2] Mason, L.J., C.P. Woloshuk, and D. E. Maier, 1997, “Efficacy of Ozone to Control Insects, Molds, and Mycotoxins,” In *Inter. Conf. Control Atm. Fum. Stored Prod.,* E.J. Donahaye (Ed.), Cyprus, April 21-26, 1996.
[3] Mason, L.J. R. A. Rulon, and D. E. Maier, 1996, “Chilled Versus Ambient Aeration and Fumigation of Stored Popcorn – Part II. Pest Management, *J. Stored Prod. Res.*

- **May Control Insects:** Preliminary results show that ozone potentially has the ability to destroy insects in stored crops, leading to longer shelf life and reduced loss over foods stored in untreated environments.
- **Can Act as a Fungicide:** Ozone potentially inhibits fungal growth, sporulation, toxin production, and odors associated with fungi. These effects in turn can lead to increased shelf life and better product quality, as well as limit the spread of contamination to other foods.
- **Lack of Residue:** Unlike other chemical pesticides, ozone does not leave behind chemical residues nor does it alter the taste of stored foods.
- **On-Site Production:** The fact that ozone is produced on-site eliminates storage, handling, and disposal of hazardous chemicals and chemical containers. In addition, because ozone is generated at the site of use and is not stored, it is not regulated by the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) as a pesticide.[1]

Figure 11
Use of Ozone to Control Fungi During Grain Storage

Source: Oxion, Inc., www.oxion.net. Used with permission.

Although ozone has been shown to be an effective pesticide in certain food storage applications and in laboratory environments, more research is necessary to further its development in this arena. For example, LD_{50} and LD_{100} values need to be developed. Moreover, it is important to note that ozone must have direct contact with insects and fungi in order to react with them. Therefore, techniques to ensure adequate mixing throughout the environment and exposure to surfaces where the pests reside are critical.

[1] http://www.epa.gov/pesticides/regulating/laws.htm.

Performance Results

Preliminary work with ozone as a pesticide replacement for stored foods has yielded interesting findings. Table 10 summarizes some recent research efforts. The results show that with high enough concentrations and/or contact times, ozone can kill certain types and stages of insects. In addition, ozone can inhibit fungal growth, sporulation, and toxin production. Factors that affect the efficacy of ozone as a pesticide replacement include ozone concentration, contact time, and exposure to pests.

Table 10
Ozone as a Pesticide Replacement in Food Storage — Summary of Representative Research Efforts

Research Group(s)	Product(s)	Application	Method	Results
USDA Agricultural Research Service EPRI Southern California Edison	Fresh and dried fruits [a]	Post-harvest fumigation of fruit to control insects	Larvae of Indianmeal moth and diapausing codling moth in cages of monel were exposed to controlled concentrations of ozone in air for differing periods of time	• Ozone concentrations of 300 to 500 ppm for 4 to 6 hours were required to kill the larvae • In order to use these high concentrations in practice, fumigation would need to be carried out in chambers that could withstand the corrosive action of ozone
Mendez et al.	Grains [b]	Fumigation of grain to control insects and fungi	Ozone was applied to storage bins containing various types of grain and a known number of insects The grains tested were rice, popcorn, soft red winter wheat, hard red winter wheat, soybeans and corn Ozone was applied in two applications to ensure that a sufficient quantity of reactions would take place to kill insects The quality of food products made with ozone-treated grain was evaluated	• All species of insects were destroyed by ozone treatment, except immature weevils, who hide within kernels • Ozonated grains were found to have essentially the same features as non-ozonated grains in terms of milling, making flour, and being used in bread • No significant differences were found in the nutritional and metabolic values of amino acids and essential fatty acids in the grains
Mason et al.	Grain [c]	Fumigation of grain to control insects	Insects associated with grain were exposed to relatively low concentrations of ozone for long time durations	• An ozone concentration of 5 ppm in air for 3 to 5 days was sufficient to achieve 100% mortality of confused flour beetle and saw-toothed grain beetle

Table 10
Ozone as a Pesticide Replacement in Food Storage — Summary of Representative Research Efforts, Continued

Research Group(s)	Product(s)	Application	Method	Results
Mason et al.	Grain [d]	Fumigation of grain to control fungi	Fungi were exposed to an ozone concentration of 5 ppm	• Surface growth of *A. flavus* and *F. moniliforme* was inhibited for two days, after which growth was the same as that of the non-ozone environment • Sporulation and aflatoxin production were eliminated in 5 ppm ozone environment

[a] *Use of Ozone in Water on Fresh Fruit,* EPRI, Palo Alto, CA, Southern California Edison, Rancho Cucamonga, CA: 2002, 1007108.

[b] Mendez, F., D.E. Maier, L. Mason, C.P. Woloshuk, "Penetration of Ozone into Columns of Stored Grains and Effects on Chemical Composition and Processing Performance" Elsevier Science Ltd., 2002.

[c] Mason, L.J., C.P. Woloshuk, and D. E. Maier, 1997, "Efficacy of Ozone to Control Insects, Molds, and Mycotoxins," In *Inter. Conf. Control Atm. Fum. Stored Prod.,* E.J. Donahaye (Ed.), Cyprus, April 21-26, 1996.

[d] Mason, L.J. R. A. Rulon, and D. E. Maier, 1996, "Chilled Versus Ambient Aeration and Fumigation of Stored Popcorn – Part II. Pest Management, *J. Stored Prod. Res.*

II. Soil Fumigation

Concerns

Pests in soil such as weeds, insects, nematodes and fungi affect plant health and yields. One common approach to fumigate soil relies on methyl bromide. As mentioned in the previous section, methyl bromide damages the stratospheric ozone layer and is a suspected carcinogen. Therefore it is in the process of being phased out for agricultural applications in industrialized countries according to the following schedule: 25% in 1999, 50% in 2001, 70% in 2003 and 100% in 2005. Environmentally friendly alternatives to methyl bromide and other hazardous chemical agents are in need. In short:

- **Soilborne Pests Affect Plant Health and Productivity**
- **Alternatives to Methyl Bromide are Needed**

Ozone as a Solution

Ozone is currently being evaluated as an alternative to methyl bromide for soil fumigation. It is applied to the soil by injection through devices such as buried drip tubes or injection probes. It has been tested at rates of 50-400 lbs per acre to control soil pathogens. It may also be applicable in combination with plastic mulch for weed control. The list below summarizes the main advantages of ozone.

- **Pathogen Destruction:** Ozone injection has been found to decrease soilborne pathogens, thus improving plant growth and yield.
- **Possible Increase in Nutrient Availability:** Some research results suggest that by oxidizing organic compounds in soil, ozone may increase nutrient availability to plants.[1]
- **Lack of Residue:** Unlike other chemical fumigants, ozone does not leave behind chemical residues in soil or ground water.
- **On-Site Production:** The fact that ozone is produced on-site eliminates storage, handling, and disposal of hazardous chemicals and chemical containers. In addition, because ozone is generated at the site of use and is not stored, it is not regulated by the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) as a pesticide.[2]
- **Potential for Controlling Weeds:** Work by Pryor has shown that ozone injection under plastic mulch may be capable of controlling weeds with multiple pre-plant applications of 2 lbs per acre.[3,1]

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[1] *Ozone Gas as a Soil Fumigant: 1998 Research Program*, EPRI, Palo Alto, CA: 1999. TR-113751.
[2] http://www.epa.gov/pesticides/regulating/laws.htm.
[3] Pryor, A., 2001, *Petition for the Inclusion of Ozone Gas Used for Weed Control in the National List*, Submitted to National Organic Program, USDA.

Performance Results

Research into the use of ozone as a soil fumigant is still in its early stages. Much of the work to date has been conducted by Pryor of SoilZone, Inc.[2,3,4] In 1998, Pryor worked with EPRI and the California Energy Commission's Public Interest Research Program (PIER) to conduct field trials of ozone treatment for a variety of crop and soil types under a range of climatic conditions.[5] The types of crops fumigated with ozone included tomatoes, carrots, strawberries, sugar beets, broccoli, prunes, sweet potatoes, and peaches. The results show that application of 50 to 400 lbs of ozone per acre through either drip tube emitters (for row crops) or probes (for orchard replants) generally reduced negative impacts from soil pathogens and increased plant yields. The results further indicate that the ozone may increase nutrient availability to the plants due to its oxidation of soil organics; however, more work is required to verify this effect. Pryor has since extended his work to include the evaluation of ozone for weed control.[6]

[1] National Organic Standards Board Technical Advisory Panel Review, *Ozone: Crops*, Compiled by OMRI for the USDA National Organic Program: August 14, 2002.
[2] Pryor, A., 1996, Method and Apparatus for Ozone Treatment of Soil to Kill Living Organisms, US Patent #5,566,627.
[3] Pryor, A., 1997, Method and Apparatus for Ozone Treatment of Soil, US Patent #5,624,635.
[4] Pryor, A., 2001, "Field Trials for the Combined Use of Ozone Gas and Beneficial Microorganisms as a Preplant Soil Treatment for Tomatoes and Strawberries," *Pest Management Grants Final Report.* Contract No. 99-0220 California Dept. Pesticide Regulation.
[5] *Ozone Gas as a Soil Fumigant: 1998 Research Program*, EPRI, Palo Alto, CA: 1999. TR-113751.
[6] Pryor, A., 2001, *Petition for the Inclusion of Ozone Gas Used for Weed Control in the National List*, Submitted to National Organic Program, USDA.

III. Removal of Pesticides

Concerns

There is much debate over the health effects of pesticides, the exact levels of toxicity, and the role of organic farming in reducing a person's overall pesticide exposure. However, it is widely accepted that pesticide residues in drinking water or on the surfaces of fruits and vegetables can be hazardous if consumed in large enough quantities. Pesticide residues are particularly problematic for children since they are developing at a rapid rate, and their immature metabolisms may not be strong enough to withstand the toxic effects. At the same time, pesticides serve a very useful function in ensuring the quality and quantity of the nation's food supply. If it is not feasible to eliminate pesticide use, the next best alternatives are to replace hazardous pesticides with more benign alternatives such as ozone where applicable and remove pesticides from water sources and surfaces of fruits and vegetables. Some of the primary concerns with pesticide removal are summarized below.

- **Pesticides are Potentially Toxic to Humans if Consumed in Sufficient Quantities:** In toxic quantities, pesticide residues can lead to health effects such as headache, nervous system disorder, and heart and brain damage.[1]
- **Conventional Water Treatment Methods Have Little Effect on Pesticide Removal:** Water treatment practices such as flocculation, coagulation, sedimentation, and filtration are not effective in removing mobile pesticides.[2]
- **Chemical Disinfection of Pesticides May Create Toxic By-Products:** Chemical disinfectants such as chlorine and chlorine dioxide can cause hazardous by-products as they react with pesticides.
- **Adsorption Processes Are Effective But Costly:** Adsorption processes using granular activated carbon (GAC) or powdered activated carbon (PAC) are effective for removing pesticides from drinking water; however, they are costly to implement, especially in smaller water treatment systems.[3]

Ozone as a Solution

As well as acting as a pesticide itself, ozone is also capable of degrading residues from other pesticides on food surfaces and in drinking water. Moreover, advanced oxidation processes that utilize ozone in combination with either ultraviolet germicidal irradiation or hydrogen peroxide

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[1] The Pesticide Management Education Program, Cornell University, *Pesticide Health Effects on Humans*, Webpage, http://pmep.cce.cornell.edu/facts-slides-self/facts/gen-posaf-health.html.
[2] United States Environmental Protection Agency, *The Incorporation of Water Treatment Effects on Pesticide Removal and Transformation in Food Quality Protections Act (FGPA) Drinking Water Assessments*, Office of Pesticide Programs, United States Environmental Protection Agency, Washington D.C.: October 25, 2001.
[3] Ibid.

are especially effective at treating hard to oxidize pesticides in drinking water.[1] The primary merits of ozone include:

- **Ozone is Effective on a Range of Pesticides:** Experimental results have shown that ozone can oxidize a variety of pesticides in water including imazalil, thiabendazole, sodium ortho-phenyl phenate, malathion, and alachlor to name a few.[2,3,4]
- **Ozone is a More Powerful Oxidizer than Other Oxidants:** Ozone has been found to remove a greater percentage of pesticides, such as the herbicide alachlor, from water than oxidants such as chlorine or chlorine dioxide.[5]
- **Reduces By-Product Formation:** Ozone is recommended as an alternative water treatment method over chlorine and chlorine dioxide to reduce concentrations of disinfection by-products.

Performance

The application of ozone for pesticide removal is still in its early stages. More research and testing with various pesticides is necessary in order to further development. To date, several studies have demonstrated ozone's efficacy in destroying pesticides in water. For example, performance data comparing ozone with other chemical oxidants, such as chlorine and chlorine dioxide, show that ozone is more effective and rapid in removing the herbicide alachlor from water. [6] Specifically, ozone (with concentrations of 2.3 to 13.7 ppm) removed 75 to 97% of alachlor in water (with original alachlor concentrations of 0.39 to 139 ppb) in 0.22 hours. In comparison, chlorine (with concentrations of 4.0 to 6.0 ppm) only removed 0 to 5% of alachlor in water (with original alachlor concentrations of 31 to 61 ppb) in 2.5 to 5.83 hours. Similarly, chlorine dioxide (with concentrations of 3.0 to 10.0 ppm) only removed 0 to 9% of alachlor (with original concentration of 61 ppb) in 2.5 to 22.3 hours.

Ozone has also been shown to remove the postharvest fungicides imazalil, thiabendazole, and sodium ortho-phenyl phenate from tank water.[7] After 30 minutes of exposure to 170.5 g of ozone in 2000 L of water, levels of imazalil in the water decreased from 50.3 g to 2.4 g, levels of thiabendazole decreased from 20.0 g to 0 g, and levels of sodium ortho-phenyl phenate decreased from 20.3 to 1.1 g. Therefore, more than 95% of the fungicides in the water were destroyed in 30 minutes or less.

Ozone can also degrade malathion. Laboratory results comparing ozone and 50 ppm chlorine treatment in pH 7 water showed that ozone degraded nearly 80% of malathion (4 ppm original

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[1] *Issues for Ozone for Drinking Water Treatment,* EPRI, Palo Alto, CA: 1999. TR-113030.
[2] *Use of Ozone in Water on Fresh Fruit,* EPRI, Palo Alto, CA, Southern California Edison: 2002, 1007108.
[3] Ruan, R., "Ozone Treatment to Reduce or Remove Pesticides in Fruits and Vegetables," *2002 Annual Report,* Description of Research Project, University of Minnesota, Biosystems and Agricultural Engineering.
[4] Miltner, R.J., C.A. Fronk, and T.F. Speth, 1987, "Removal of Alachor from Drinking Water," *Proc. National Conference on Environmental Engineering,* ASCE, Orlando, FL, July 1987.
[5] Ibid.
[6] Ibid.
[7] *Use of Ozone in Water on Fresh Fruit,* EPRI, Palo Alto, CA, Southern California Edison: 2002, 1007108.

concentration) in under 30 minutes, while chlorine degraded only 55% in the same amount of time.[1]

[1] Ruan, R., "Ozone Treatment to Reduce or Remove Pesticides in Fruits and Vegetables," *2002 Annual Report,* Description of Research Project, University of Minnesota, Biosystems and Agricultural Engineering.

OZONE IN THE FISH AND SEAFOOD INDUSTRY

Water is used in the fish and seafood industry in a variety of ways. Commercial fishermen and operators of hatcheries[1] and fish farms[2] rely on clean water systems for the production of fish and seafood. They also require water or ice for preserving and storing the fish until it can be delivered to the fish market or the processing plant. Once there, the processors use water for preserving, rinsing, cleaning, cooking, and freezing of the processed fish product. Fish processing facilities also require rinse water for sanitation of processing equipment and for general wash down of floors and walls.

This section describes three applications of ozone in the fish and seafood industry, namely: 1) water treatment in aquaculture systems, 2) preservation of fresh fish and seafood, and 3) sanitation of processing equipment. The discussion includes the main concerns associated with each application that ozone can potentially mitigate. It also describes how ozone is generally applied to address these concerns and summarizes the primary benefits in each specific application over other alternatives. Finally, this section provides representative performance data for ozone tested in each application.

I. Water Treatment in Aquaculture Systems

Concerns

Hatcheries and fish farms use water systems for production of fish and seafood. Increased demands for maintaining indigenous fish populations and game fish have placed extreme pressures on hatcheries and farms already operating with limited facilities. One way to increase production, without spending vast capital, is to increase the number of fish and seafood being reared. However, that will also increase the risk of infection and lead to higher mortality rates. To maintain or raise the survival rates, hatcheries and fish farms are increasingly studying ways to improve water quality.

In hatcheries, the quality of the water is of primary concern during the time the eyed eggs are incubated until hatching. Depending on the type of fish, the eyed eggs are placed either in hatching flasks, or on hatching trays. Not only is this critical stage important for the actual number of eggs hatched but also for the quality of the fry produced. Similarly, water quality affects production rates at fish and seafood farms. It is essential influent waters are very clean and free from contaminants and microorganisms that can infect and wipe out a whole hatching of fry or damage the fish stock being reared. For example, bacterial gill disease caused by

[1] A hatchery is a place where people control the hatching of fish eggs.
[2] Also called fish farming, fish culture, or mariculture. Aquaculture is the science, art, and business of cultivating marine or freshwater food fish or shellfish, such as oysters, clams, salmon, and trout, under controlled conditions using ponds, pools, barricaded coastal waters, or cages suspended in open waters.

heterotrophic bacteria is a common problem among newly stocked fish. These disease outbreaks normally require several costly chemical treatments to prevent high mortality.

Recirculated aquaculture systems—also called fish farms—offer higher production intensities and also provide several advantages over ponds and cages, including flexibility in site selection, reduced water usage, and lower effluent volumes.[1] However, increased stock densities result in wastes accumulating more rapidly and the quality of water degrading, which may impact mortality rates. Increasing the daily water exchange rates would solve the problem, but would also increase water, heating, and cooling costs. Conventional means of solids removal, such as microscreen filters and sedimentation tanks, remove coarse, settleable and filterable solids, but do not remove fine, colloidal solids. Similarly, biofilters remove dissolved ammonia and nitrite, but not other dissolved wastes. As the organic loading increases with production intensity, the bacteria that convert nitrite to nitrate in the biofilter operate less efficiently, resulting in increased nitrite levels. The accumulation of fine colloidal solids, dissolved organics, and nitrite impair biofilter efficiency, increase biochemical oxygen demand, and stress cultured fish. This organic waste results in a less productive aquaculture systems.

Thus, operators of hatcheries and aquaculture systems need sophisticated systems that can remove both particulates and dissolved organic wastes as well as control microbial activity. This applies to recirculating as well as single pass systems. The two main concerns with water systems for production of fish and seafood are:

- **Control of Microorganisms**: It is critical to ensure microorganisms, such as bacteria and viruses, are not entering into the hatcheries and aquaculture systems as these may cause diseases, higher mortality rates, and lower production rates.
- **Removal of Organic Waste:** Organic waste, such as fine and colloidal solids, dissolved organics, and nitrite, impair biofilter nitrification and stress fish stocks. Therefore, operators of hatcheries and aquaculture systems want to remove or break down these organic wastes.

Ozone as a Solution

Ozone in the aquaculture industry was first used in the 1970s by researchers to evaluate its potential to maintain aquarium systems by reducing microbial growth. These systems had low fish densities and low feeding rates. Since then, ozone has been applied to all types of aquaculture production systems; from flow-through raceways to near complete recirculation systems to improve the quality of aquaculture production water by reducing microbial activity and helping improve solids settling. Ozone is a very powerful antimicrobial agent, and unlike other agents, it leaves no undesirable residues in the production systems. Thus, aqueous ozone can improve the water quality of the production systems in hatcheries and fish farms. However, ozone must be applied properly because living creatures are exposed to ozonated water more or less immediately after the water has been treated. Two potential problems are high levels of residual ozone and over-aeration of the water, leading to mortality of fish and seafood. Another potential problem is bromides. Bromides naturally occur in seawater at a concentration of

[1] *Use of Ozone in Recirculating Aquaculture Systems*, www.fisheries.nsw.hov.au/aqu/extension/Ozone.htm

approximately 65 ppm.[1] Ozone may react with some forms of bromide, creating a toxic situation for the fish. Therefore, operators of aquaculture systems have to be particularly careful how they introduce ozone to their systems.

Because of higher levels of dissolved organics in fish farms, complete ozone treatment of water, including control of microbial activity and removal of solids, color, and odor, requires large quantities of ozone. The associated high costs and risks with such complete systems are typically not justified by food-fish-producing re-circulating aquaculture systems. Therefore, ozone is generally used as a pre-treatment for influent water in fish farms. In such an application, the influent water is pumped directly into one or several contact chambers for ozonation. In the chamber(s), ozone inactivates microorganisms in the water and oxidizes particulates and protein, thereby improving water quality, color, and odor. The easiest way to apply ozone to an aquaculture system is generally through the existing oxygen transfer device (assuming one currently exists). To avoid undue stress on the fish, residual ozone should be removed outside of the aquaculture production system.

Ozone as part of a larger treatment system also maximizes its treatment effectiveness (less loading on the ozone) and cost effectiveness. Design and application of ozone in aquaculture systems are somewhat hard because of so many site-specific parameters affecting the outcome. Therefore, the design and application of ozone systems are normally based on empirical evidence observed in operating systems and trial-and-error methodology. Because of its oxidation powers, ozone can oxidize material generally perceived as non-corrosive or corrosion resistant. Ozone has not been very effective in reducing ammonia nitrogen at normal application levels.

A typical contact system for hatchery application has three chambers.[2] The first chamber is a counter flow diffusion chamber where the ozone is introduced, and the fast oxidation processes, i.e. the oxidation of dissolved matter such as iron and manganese, take place. The second chamber is designed for disinfection and slow chemical reactions. In the third chamber, the slow reactions complete and a major portion of the residual ozone decomposes.

Some of the main reasons for using ozone in water treatment of aquaculture systems and hatcheries are:

- **Reduces Microbial Activity in Water:** Ozone can effectively inactivate bacterial, viral, fungal, and protozoan fish pathogens. In general, it is the influent water that is treated by ozone in aquaculture systems. This is because effluent, re-circulated, and resident water has higher levels of organic matter requiring a greater ozone demand, with associated higher costs and limited microbial inactivation effect.
- **Increases Fish and Seafood Survival Rates**: The decreased levels of microbial activity in the water and improved solids removal results in fewer diseases and better survival rates.

[1] AquaCraft website, http://www.aquacraft.net/s9905.html
[2] Eugster and Stanley, *The Use of Ozone as a Disinfectant in Fish Hatcheries and Fish Farms*. http://midwest.fws.gov/ashland/mtan/mtan_21.html.

- **Improves Solids Settling and Separation:** The accumulation of fine and colloidal solids can impair biofilter nitrification and stress fish. Ozone removes fine and colloidal solids by causing microflocculation, which in turn, facilitates removal by foam-fractionation, filtration, and sedimentation.
- **Removes Dissolved Organic Compounds:** High levels of dissolved organic compounds (DOCs) can stress fish and reduce nitrification efficiencies of the biofilter. Ozone removes DOCs in two ways: 1) by oxidation of DOCs into products that are more readily nitrified in the biofilter, and 2) by precipitation, which enables removal of waste particles by filtration and sedimentation.
- **Reduces Color:** Color is generally an unwanted characteristic of aquaculture systems because it decreases visibility. Since DOCs give water a tea-colored stain and ozone removes DOCs, ozone has the capability of reducing color.
- **Few Harmful By-Products:** Unlike chlorine or any of its derivatives, oxidation with ozone generally leaves no harmful residues. The only exception is if bromine is present in the water. Then, ozone will produce bromate ions, which are toxic to fish and seafood. However, the bromate ions can be removed by sand and activated carbon filters.
- **Removes Nitrite Nitrogen:** Nitrite nitrogen is toxic to most fish species at low concentrations. Nitrite nitrogen is a by-product of the biological oxidation of ammonia (“nitrification”) by bacteria. Bacteria that process ammonia into nitrite operate more efficiently under high organic loading than bacteria that process nitrite to nitrate. Ozone removes nitrite nitrogen in two ways: 1) by direct oxidation to nitrate, and 2) by reducing organic loading, which improves biofiltration efficiencies and nitrification.
- **Removes Algae and Other Plankton Species:** Ozone can effectively remove many algae and plankton species.[1] This improves visibility and provides better control of odors and taste.
- **Removes Odors and Taste:** Some algae and bacteria produce metabolites that impart objectionable odors and taste to fish and seafood produced in intensive aquaculture systems. Ozone removes odors and taste from water.
- **Less Need for Chemical Treatments:** Ozone inactivates microorganisms in water, resulting in fewer diseases and better survival rates among fish and seafood. This, in turn, means less need for costly, chemical treatments.
- **Rapid Reaction Rates:** Ozone is a powerful antimicrobial agent and oxidizer. The fast reaction rates equate to reduced treatment times.
- **Faster Growth Rates:** Applications in hatcheries have shown ozone treatment of water may decrease the required time for molting and reduce the total growth cycle.
- **No Storage and Handling:** Ozone is generated on-site, eliminating the need for chemical storage and handling.

[1] Hundley, *Ozone use in recirc systems*. Systems Engineering, www.aquasales.com/techinfo/ozone.pdf.

Performance Results

Several hatcheries have installed ozone systems within the past ten years, however very little public material has been developed as to their success.[1,2] For example, Greifensee Hatchery in Switzerland has used ozone for treatment of its hatchery water for many years with excellent results, but no public data are available. One larval shrimp hatchery in Ecuador uses ozone to treat seawater before entering the larval tanks. In this application, ozonation of the seawater has eliminated the disease-causing *Vibrio* bacteria, resulting in increased survival rates of larval shrimp and reduced total growth cycle by three days. This, in turn, has equated to one additional growth cycle per year and fewer antibiotic treatments, both positively affecting the bottom-line. As illustrated in Table 11, studies of rinsing eggs from Japanese flounder and striped jack with ozonated water have been undertaken in Japan. The results from these studies show embryos remained alive longer and viruses were inactivated. In hatcheries, only small ozone concentrations of 0.2 to 0.5 mg/L are required to assure purification of the normally clean stream or river water, but since the volume of water flowing through a fish hatchery can be very high, the size of the ozone system also can be high.[3] The cost effectiveness of such large ozone systems may be a limiting factor to their success in treatment of hatchery waters.

Performance results are available from several installations of ozone systems at aquaculture sites producing shrimp, rainbow trout, and tilapia (see Table 11). For several years, a large ozone system has been controlling bacteria in the ocean water before entering a 250,000-gallon shrimp farm lagoon in Belize, South America. In Minnesota, the MinAqua Fishfarm, which raises tilapia, treats its aquaculture system with ozone. Table 11 also shows ozonation of the water just before entering the culture tanks at a recirculating aquaculture system producing rainbow trout resulted in several positive outcomes. Specifically, the use of ozone reduced bacterial gill disease outbreaks, resulting in lower mortality rates and less need for chemical treatments. Ozone also improved water quality and microscreen filtration.

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[1] *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*, EPRI, Palo Alto, CA: 1996. CR-106435.

[2] Eugster and Stanley, *The Use of Ozone as a Disinfectant in Fish Hatcheries and Fish Farms*. http://midwest.fws.gov/ashland/mtan/mtan_21.html.

[3] *Ozone Reference Guide: An Overview of Ozone Fundamentals and Municipal and Industrial Ozone Applications*, EPRI, Palo Alto, CA: 1996. CR-106435.

In-depth data from installation of a full-scale ozone system at Fingerlakes Aquaculture is available.[1] This tilapia fish farm, in collaboration with EPRI, studied the effects of ozone on water quality and fish health on one of its six 250,000-lb per year fish production systems. Results from this demonstration effort showed ozone improves water quality by effectively removing color and foam; however ozone was ineffective in removing nitrogen nitrate. The EPRI study concluded that to ensure maximum effectiveness, ozone should be added at the end of a full-system treatment train.

Interest is growing in the therapeutic application of ozone based on daily feed ration to enhance particulate removal efficiencies and to remove color in re-circulating aquaculture systems.[2] Preliminary data also indicate ozone treatment of water in aquaculture tanks greatly reduces foaming even without purifying the water.[3]

Figure 12
Ozonation of Aquaculture System at Fingerlakes Aquaculture

Source : EPRI. Used with permission.

[1] *Ozone Applications in Fish Farming*, EPRI, Palo Alto, CA: 2002.1006975.
[2] Hundley. *Ozone use in recirc systems*. Systems Engineering, www.aquasales.com/techinfo/ozone.pdf.
[3] *The Use of Ozone as an Antimicrobial Agent: Agricultural and Food Processing Technical Assessment*, EPRI, Palo Alto, CA: 2001. 10005962.

Table 11
Treatment of Hatchery and Aquaculture Water Systems with Ozone— Summary of Representative Installation Projects

Company	Product	Application	Method	Results
Greifensee Hatchery [a] Switzerland	Brown Trout, Powan, and Northern Pike	Improve quality of hatchery water The quality of water from any lake or river is continually changing partly due to natural causes and partly due to pollution	As the hatchery water is drawn from the lake, it is pumped directly into contact chambers. Thereafter, the water is pumped through a sand filter to remove any fine materials and precipitated or flocculated matter. Finally, the water passes through an activated carbon filter to remove residual ozone before entering the hatching trays and fry tanks.	• Hatchery water has been treated for many years with excellent results
Belize [b] South America	Shrimp	Ozone system treating a 250,000 gallon shrimp farming lagoon	Ozonation of ocean water for bacterial control	• Improved water quality • No by-products
Fingerlakes Aquaculture [c] Groton, NY	Tilapia	Ozonation of a 250,000 lb per year fish production system	Approximately 10.3 g of ozone per kilogram of feed added was used, which is the lower limit of the recommended range of 10 to 20 g ozone per kilogram of feed added	• Both color and foam were effectively removed from the production water; however nitrogen nitrate was not removed • Ozone-treated fish had lower concentrations of hematocrit, plasma sodium, chloride

Table 11
Treatment of Hatchery and Aquaculture Water Systems with Ozone— Summary of Representative Installation Projects, Continued

Company	Product	Application	Method	Results
MinAqua Fish Farm [d] Renville, MN	Tilapia	Improve water quality in eight fingerling tanks. Each fingerling tank (3,500 gallon) can hold up to 90,000 fingerlings.	Ozone is injected into two U-tubes. Each U-tube supplies water, oxygen, and ozone for four tanks.	• Improved water quality • Faster growth rates • Decreased death loss
LARFICO [e] Ayanague, Ecuador (1990-1991)	Larval Shrimp	Reduce levels of disease-causing bacteria in larval shrimp hatchery	A 1,540-liter contact tower treated seawater from the Pacific Ocean before the water entered larval tanks. The retention time was five to seven minutes, and the average ozone residual in the treated water was 0.07 ppm. Due to the success of the ozone-treated tanks, the entire 30 tank larval rearing system is now treated with ozonated seawater. The ozone residual is regulated throughout the cycle so it ranges from 0.066 to 0.250 ppm.	• Eliminated the disease-causing *Vibrio* bacteria in shrimp larval tanks • Decreased the required time for normal molting • Reduced the total growth cycle by three days, resulting in one additional growth cycle per year • Increased the survival rates of larval shrimp, indicating the oxidation effect of ozone has not diminished larval survival • Fewer antibiotic treatments needed, resulting in a reduction of antibiotics by nearly 2/3 • Ozone residual has to be kept below 0.2 ppm to ensure no damage to larvae

Table 11
Treatment of Hatchery and Aquaculture Water Systems with Ozone— Summary of Representative Installation Projects, Continued

Company	Product	Application	Method	Results
Fish Farm [e] USA	Rainbow Trout	Ozonation of a recirculating culture system to improve water quality, reduce heterophic bacteria in system water and on trout gills, and to prevent bacterial gill disease in newly stocked fingerlings	Ozone was added to the water just before it entered the culture tanks at a rate of 0.025 or 0.036-0.039 kilogram ozone per kilogram feed fed. The exposure time was 35 seconds in the contact chamber. Ozone residual at the end of contact tank ranged from 0.02 to 0.18 ppm.	• Reduced bacterial gill disease, resulting in lower mortality rates and no need for chemical treatments to control disease • Improvement in water quality entering the culture tanks by reducing suspended solids, dissolved organic compounds, and color • Supported microscreen filtration • Use of the lower ozone dosing rate was nearly as affective as the higher dosing rate; however the lower rate was less likely to produce toxic ozone residual
Arimoto et al. [f]	Striped Jack	Effect of ozone on the inactivation of striped jack nervous virus	Seawater was treated with ozone and fertilized eggs were washed with ozonated water	• An ozone residual of 0.1 mg/L and a treatment time of 2.5 minutes were necessary to inactivate striped jack nervous virus

Table 11
Treatment of Hatchery and Aquaculture Water Systems with Ozone— Summary of Representative Installation Projects, Continued

Company	Product	Application	Method	Results
Mimura et al. [f] Japan, 1998	Japanese Flounder	Effect of ozone on eggs of Japanese Flounder	Eggs of Japanese flounder were rinsed in ozonated seawater	• Delayed hatchings of eggs; however, the embryos continued to developed and remained alive for two more days • Delayed hatching increased rapidly when the ozone level increased to 2 mg/L or higher, but without any increment of dead eggs

[a] Eugster and Stanley, *The Use of Ozone as a Disinfectant in Fish Hatcheries and Fish Farms*. http://midwest.fws.gov/ashland/mtan/mtan_21.html.

[b] Ozone Solutions, Inc. website, www.ozoneapplications.com/aquaculture/aquaculture.htm.

[c] *Ozone Applications in Fish Farming*, EPRI, Palo Alto, CA: 2002. 1006975.

[d] ClearWater Tech LLC website, www.cwtozone.comagricultural.html.

[e] Summerfelt et.al. Ozonation of a recirculation rainbow trout treatment culture system. I. Effects on bacterial gill disease and hereotrophic bacteria. II. Effects on microscreen filtration and water quality. www.ozoneapplications.com/aquaculture/Ozonation_of_rainbow_trout.htm.

[f] Direct Food Additive Petition, Ozone as an Antimicrobial Agent for the Treatment, Storage and Processing of Foods in Gas and Aqueous Phases, August, 2000.

II. Preservation of Fresh Fish and Seafood

Concerns

Fresh fish and seafood do not remain fresh for any extended period of time. Bacteria residing on the surface of the fish eventually will break down the surface and cause spoilage. This breakdown can be rapid if the initial bacterial count is high and the proliferation is uncontrolled. Fishing vessels use storage tanks to hold caught fish and seafood until they can be unloaded at the processing facilities or fish markets. As a fresh-fish trawler usually spends several days at sea before returning with its catch, it is important that these onboard storage tanks maintain the freshness of the fish and seafood by suppressing microbial growth. Chilled brine can maintain the quality of the fish for about one week.[1] After that time, the fish is generally unmarketable. Once the fresh fish and seafood reaches the processing facility or markets, it is equally important to preserve the freshness until further processing. Chlorine can be used for preservation; however it may affect the taste, smell, and color of the fish and seafood. Spoiled or less appealing fish and seafood equates to less profits for fishermen, processors, and market and store owners.

Thus, there is a great demand for methods of improving the shelf life of fresh fish and seafood, without affecting the appearance, color, or aroma. The main concerns for operators of fishing vessels, fish and seafood processing plants, and markets selling fresh fish and seafood are:

- **Improving Shelf Life:** If the shelf life of raw fish and seafood can be extended by a couple of days, there will less spoilage, which equates to greater profitability. This also means fishing vessels may remain at sea longer, and can bring in larger catches.
- **Preservation of the Fresh Appearance, Color, and Aroma:** Processing plants and consumers expect to purchase fish and seafood with fresh features, including appearance, color, and aroma. As chlorine may affect taste, smell, and color, new methods for preservation are desirable.

Ozone as a Solution

Ozone is an antimicrobial agent that reduces the initial amount of microorganisms and their growth on fresh fish and seafood. It can be used in two forms: ozonated water or ozonated ice. Ozonated water is already being used for storing and maintaining fresh fish. For example, fishing vessels uses ozone in their storage tanks to maintain the quality of the fish until it is delivered to the processing plant or market (see Figure 13). In this application, ozone is generated onboard the vessel and introduced in the refrigerated sea water systems immediately after the catch to lower the initial bacterial counts on the fish surface. These initial bacteria determine the later growth and also the shape of the growth curve. Continued intermittent treatment of fish with ozone while in storage also seems to be effective as a means to extend shelf life by controlling

[1] Food Product Design, *Ozone—Another Layer of Food Safety*, February 2002, www.foodproductdesign.com/archive/2002/0202NT.html.

bacterial growth; however the intervals between treatments may have to be shortened so as not to affect the fish itself.

Figure 13
Fishing Vessels Ozonate the Water in their Refrigerated Sea Water Systems to Ensure Delivery of Fresh Fish at Shore

Source: National Oceanic & Atmospheric Administration (NOAA), NOAA Central Library

There have also been some attempts to freeze ozonated water and then store it on fishing boats for later use. The melted water is then used for washing and processing. Ozonated ice may also be used closer to consumers for storing in retail display areas. However, it is not clear whether ozonated ice retains its ozone residual for any extended period of time. Trio3 Ozone Systems is currently working with the University of Florida on a process to make ozonated ice. This ice will keep fish free from bacteria at two large supermarket chains.[1]

The main merits of using ozone for preservation of fish and seafood include:

- **Reduces Microbial Counts on Fish Surface:** Washing and rinsing in ozonated water decreases the microbial counts on fish surfaces. It has been proven effective on whole fish as well as fillets. Although ozone is highly effective against all microorganisms, each class of microorganism has its own rate of kill, or lethal dosage value.
- **Extends Shelf Life:** Ozone reduces microbial activity on the fish surface, which in turn retards spoilage. Ozone can extend the shelf life several days compared to conventional methods. This equates to improved profits for fishermen, fish processing plants, and operators of fish markets.

[1] Trio3 Ozone Systems' website, www.trio3.com.

- **Improves Fish Quality:** Ozone does not affect the appearance, color, and aroma of fresh fish. Since ozone reduces the microbial activity, it provides a fresher-looking and fresher-smelling product.
- **Few Harmful By-Products.** Unlike chlorine or any of its derivatives, oxidation with ozone generally leaves no harmful residues.
- **Odor Control:** Ozone oxidizes VOCs and organic odors, including those from fish and seafood. Because ozone controls odor so well compared to conventional preservation methods, such as hydrogen peroxide and salt solution, odor spoilage is slowed down and a better environment for workers is provided.
- **Effective Depuration[1] of Shellfish:** Depuration of mussels and clams in ozonated water has proven effective in reducing bacterial and viral counts.
- **Rapid Reaction Rates:** Ozone is a powerful antimicrobial agent and oxidizer. The fast reaction rates equate to reduced treatment times.
- **No Storage and Handling:** Ozone is generated on-site, eliminating the need for chemical storage and handling.

Performance Results

Several researchers have studied the preservation effect of ozonated water and ozonated ice on various types of fish and seafood (see Table 12). In most instances, ozonated water has proven better or equally effective in comparison to chlorine in reducing microorganisms on fresh fish surfaces, including mackerel, shimaaji, salmon, and redfish. However, results from studies with ozonated ice—that is ice made of ozonated water—are inclusive. For example, studies with shrimp and salmon indicate that ozonated ice does not work as effectively as ozonated water for rinsing and storing. This may because the ozonated ice does not contain any residual ozone at the time it is used.

Researchers at the North Carolina State University Seafood Laboratory found that treating raw fish as well as processing equipment with ozone greatly reduced the microbial populations that can potentially spoil seafood.[2] During the study, researchers also found that ozone improved the shelf life of uncooked fish by one to two days, without affecting the appearance, color, or aroma of the fresh fish.

Several fishing vessels use ozone in their refrigerated sea water systems, or holding tanks, for preservation of fresh fish. Results show an improved shell life of at least 36 hours; however

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[1] Depuration is a process of purification where filter-feeding shellfish are placed in a clean seawater environment and allowed to pump in an attempt to purge themselves of bacteria and viruses.
[2] *Researcher Find New Use for Ozone*, Press Release, March 26, 2002. www.ncsu.edu/segrant/Pressreleases0202/Ozone.htm.

several days may be possible. This means the fishing boats can remain at sea for up to 14 days.[1] In Norway, fish processors have demanded that all fish boats use ozone to maintain their catch.[2]

Ozone has also proven to be effective in depuration of mussels[3] contaminated with viruses and depuration of clams contaminated with bacteria.[4,5]

[1] Food Product Design*, Ozone—Another Layer of Food Safety*, February 2002, www.foodproductdesign.com/archive/2002/0202NT.html.
[2] Shipside Preservation, www.o3water.com/Articles/meats.htm.
[3] Schneider et. al, *Ozone Depuration of "Vibrio vulnificus" from the Southern Quahog Clam, "Mercenaria campechiensis",* Journal of Invertebrate Pathology 57:184-190,1990.
[4] Schneider, *The Use of Ozone to Disinfect Vibrio Vulnificus and Depurate the Southern Quahog Clam*, M.S. Theses, August 1997.
[5] Schneider et. al., 1990.

Table 12
Preservation of Fish and Seafood with Ozonated Water or Ozonated Ice—Summary of Representative Installations and Research Projects

Researcher or Installation Site	Product	Application	Method	Results
Fishing Vessel "Arctic Ocean" [a]	Redfish	Study the effectiveness of ozonation for controlling bacteria on redfish	The seawater in the 20 m^3 fish tank onboard the fishing vessel was ozonated up to three times a day, depending on the length of time the fish were held in storage	• Reduced initial bacterial count by 90%, but thereafter the rate of bacterial increase was the same in both ozonated and control samples • Ozone demand of dissolved organics makes it hard to maintain higher ozone residuals in fish tank • Appeared to ease the separation of slime from the surface of the fish, decreasing bacterial count • Improved shelf life by approximately 36 hours
Fishing Vessel "Christina" [b]	Fish	Improve the quality of the fish caught by the fishing vessel	The fishing vessel uses ozone in its refrigerated sea water system	• No smell on board the ship • Reduces labor costs because less maintenance required due to cleaner tanks and equipment • Improves fish quality; the toughness of the fish gills last at least 50 hours

Table 12
Preservation of Fish and Seafood with Ozonated Water or Ozonated Ice—Summary of Representative Installations and Research Projects, Continued

Researcher or Installation Site	Product	Application	Method	Results
Hanover Sea Products [c] Wilmington, NC	Fish	Treating raw fish and processing equipment with ozone	Ozonated water was used for rinsing fresh fish and washing processing equipment	• Improved the shelf life of uncooked fish by one or two days • The appearance, color, and aroma of fresh fish was not affected
Delta Pride Catfish [d] Indianola, MS	Catfish as well as the equipment used in the fish processing process	Reduce the bacterial count/content on the flesh of the fish and on fillet processing equipment	Processed whole fish was placed for 10 to 12 minutes in ozonated water in a 30-gallon test vessel. The test vessel included a chiller vessel and a reactor vessel. Ozone concentrations were varied from 5 to 12 ppm. Ozone was also applied at the fillet line	• Ozone was effective in reducing bacterial counts on whole fish, fillets, and fillet equipment • Shelf life increased to 14 days compared to 4-6 days for conventional treatment • A 75% reduction of bacterial counts on fillets coming of the fillet processing line when ozone was applied (compared to conventional treatment)
Roe Processing Facility [e] USA	Roe	Study the effect of ozone as a disinfectant for commercial processed seafood	Aqueous ozone (0.5 to 1.7 ppm) was applied in a commercial roe processing facility	• Decreased microbial load in the preprocessed samples that were ozonated with eggs in the skein (the sack containing the eggs) • No differences in the microbial loads from the non-ozonated and ozonated post-processed samples of individual eggs removed from the skein

Table 12
Preservation of Fish and Seafood with Ozonated Water or Ozonated Ice—Summary of Representative Installations and Research Projects, Continued

Researcher or Installation Site	Product	Application	Method	Results
Haraguchi et. al. [a]	Fresh Mackerel and Shimaaji	Study the preservation effect of ozone on fresh fish	The ozone-treatment solution was prepared by passing ozone-containing air through 3% NaCl in water solution, kept at 5 °C, for 30-50 minutes prior to immersion of fish in the solution, and the ozone-containing air continuously passed through the solution during the entire period of immersion. The fish was immersed in the solution every two days (60 minutes for mackerel, 30 minutes for shimaaji)	• Greatly decreased the viable bacterial counts on fish surface and also retarded fish spoilage • Killed all of the test microorganisms with the exception of spore-formers • Lengthened the storage life of the fish by 1.2 to 1.6 times • Reduced the raw fishy odor, but increased the dried fish odor. This may be due to the oxidation of fish oil by the ozone treatment.
Kim et. al. [f]	Catfish	Study the influence of ozone on microbial profile and color of channel catfish fillets	Channel catfish fillets were treated with ozonated water at 5 and 10 ppm.	• 10 ppm ozone showed odor spoilage after 10.5 days, which was 1 to 2 days better than hydrogen peroxide and salt solution

Table 12
Preservation of Fish and Seafood with Ozonated Water or Ozonated Ice—Summary of Representative Installations and Research Projects, Continued

Researcher or Installation Site	Product	Application	Method	Results
Lee and Kramer [a]	Sockeye Salmon	Study the preservation effect of ozonated ice on stored sockeye salmon	One batch of fresh sockeye salmon was washed in chlorinated water and stored in ice made from chlorinated water, while second batch was washed in ozonated water and stored on ozonated ice	• Little difference in appearance and quality among salmon stored in chlorinated or ozonated ice • However, the gills retained fresher appearance much longer in ozonated ice
Goche' and Cox [a]	Chum Salmon	Study the effect when ozone is used at pre-wash or final wash stage, or a combination of the two	An ozone spray unit treated the fish for 10 seconds. The residual ozone ranged from 0.5 to 1.5 ppm.	• Ozone is equally effective in comparison to chlorine in reducing total plate count • No advantage to applying residual levels beyond 1.0 ppm or to more than one treatment • Ozone is highly effective against all microorganisms, but each class has its own rate of kill
Chen et. al. [a]	Shrimp Meat	Study the effect of ozonated water of different conditions and in-plant ozone use on frozen fishery product	Shrimp meat was flushed with ozonated water containing 3% NaCl	• Disinfection of bacteria on the shrimp meat with ozone was ineffective • Temperature did not significantly influence the disinfection effect

Table 12
Preservation of Fish and Seafood with Ozonated Water or Ozonated Ice—Summary of Representative Installations and Research Projects, Continued

Researcher or Installation Site	Product	Application	Method	Results
DeWitt et al. [a] College Station/Corpus Christi TX	Shrimp	Study the preservation effect of ozonated ice on stored shrimp	The shrimp was pre-rinsed and then stored on ozonated ice	• Ozonated ice had no or minimal effect on the bacterial spoilage of the shrimp; possibly extending shelf life by 1-2 days only • Ozonated ice had no effect on black spots • Study was unable to distinguish whether the extension of shelf life was due to the use of ozonated water rinses or use of ozonated ice for storage • Ozonated ice in study may not have contained any residual ozone
Chen et al. [a]	Shrimp Meat Extract	Study the bactericidal effect of ozone on shrimp meat microorganisms	Shrimp meat was first washed with sterile water and dripped dry for 5 minutes. Then a bacterial suspension containing nine bacterial strains was mixed with shrimp meat. Thereafter, the bacteria-seeded shrimp meat was immersed in a 2% saline solution, which had been flushed with ozone (150 mL/min) for 30 minutes before the shrimp meat was soaked. Ozone was dispersed into saline throughout the test.	• The bactericidal effect of ozone for disinfection of shrimp meat was inefficient

Table 12
Preservation of Fish and Seafood with Ozonated Water or Ozonated Ice—Summary of Representative Installations and Research Projects, Continued

Researcher or Installation Site	Product	Application	Method	Results
Abad et. al. [a]	Mussels	Study the effect of ozone on mussels contaminated with viruses	Groups of mussels contaminated with human pathogenic enteric viruses were placed in continuous flow of ozonated marine water in 50-liter tanks	• Ozonated water was effective in decontaminating virus-contaminated mussels; the mussels purged themselves from hepatitis A virus and poliovirus after 20 hours of depuration, human rotavirus after 48 hours of depuration, and human enteric adenovirus type 40 after 96 hours of depuration.
Schneider et. al. [g]	Clams	Study ozone depuration[h] of clams.	Clams were dosed with *Vibrio vulnificus* and placed in a pilot-scale depuration systems using ozonated recirculated artificial seawater	• 24 hours of treatment with ozonated seawater (at 1 to 3 ppm) reduced bacteria counts • Shellfish pumping was not adversely affected by ozone level (up to 3 ppm)

[a] Direct Food Additive Petition, *Ozone as an Antimicrobial Agent for the Treatment, Storage and Processing of Foods in Gas and Aqueous Phases*, August, 2000.

[b] DEL Ozone website, www.delozone.com/products-fish.html.

[c] *Ozone Effective in Preserving Seafood Freshness*, Sea Grant North Carolina, Marine Extension News, www.ncsu.edu/segrant/Newsletters02/MEN/Ozone.htm.

[d] G. Brooks and S. Pierce, *Ozone Applications for Commercial Catfish Processing*, www.p2pays.org/ref/02/01251.pdf.

[e] J. Hansen, *Application of Ozone as a Disinfectant for Commercially Processes Seafood*, M.S. Thesis, ORESU-X-02-2002, Dept. of Food Science and Technology, Oregon State University, Corvallis, Oregon, 2002.

[f] Kim et. al., *Influence of Ozone, Hydrogen Peroxide, or Salt on Microbial Profile, TBARS and Color of Channel Catfish Fillets*, Journal of Food Science 65(7):1210-1213.

[g] Schneider et. al., *Ozone Depuration of "Vibrio vulnificus" from the southern quahog clam, "Mercenaria campechiensis",* Journal of Invertebrate Pathology 57:184-190,1990.

[h] Depuration is a process of purification where filter-feeding shellfish are placed in a clean seawater environment and allowed to pump in an attempt to purge themselves of bacteria and viruses.

III. Sanitation of Processing Equipment

Concerns

Fish processing facilities try very hard to limit microbial growth on processing equipment as harmful bacteria residing there could easily transfer to the processed fish and seafood causing potentially deadly disease outbreaks. Therefore, it is critical that fish processors control and keep microbial growth on processing equipment to a minimum. Although chlorine is effective in sanitizing processing equipment, it also has several disadvantages. For example, chlorine can generate harmful by-products and microorganisms can also build up resistance to chlorine. Moreover, chlorine may affect the taste, smell, and appearance of the processed fish and seafood.

The two main concerns for fish processing facilities in regard to sanitation of processing equipment are:

- **Replacing Chlorine as an Antimicrobial Agent:** Chlorine has several drawbacks when used for sanitation of processing equipment. Two critical drawbacks are chlorine generating harmful by-products and the possibility of microorganisms building up resistance to it. Chemicals are costly and with increased use to combat the resistance problem, the costs will increase too.
- **Limit Cross-Contamination:** Microorganisms that reside and grow on processing equipment can easily cross-contaminate the processed fish and seafood. Some microorganisms, such as *Listeria*, *Salmonella*, and *E.coli*, are very harmful to humans.

Ozone as a Solution

Ozone is a powerful antimicrobial agent that can replace, or complement, chlorine for sanitation of process equipment. In this application, ozonated water is used for washing and rinsing the surfaces of various process equipment, including knives, tabletops, and conveyor belts.

The main advantages of washing and rinsing processing equipment with ozonated water are:

- **Improves Sanitization without Use of Chemicals:** Washing process equipment with ozonated water is an effective way of reducing microorganisms growing on the equipment surface. Ozone is a better sanitizing agent than chlorine because it leaves no residuals and microorganism cannot build up a resistance to ozone. On the other hand, microorganisms can build up a tolerance to chlorine, requiring greater amounts of chlorine, which in turn drives up the costs.
- **Limits Cross-Contamination:** Since washing the equipment with ozone decreases the microbial levels on the equipment surface, it also reduces the risk for cross-contaminating the processed fish and seafood.

Performance Results

Table 13 summarizes representative performance results for ozone in the sanitation of fish and seafood processing equipment. At two fish processing plants, Hanover Sea Products and Delta Pride Catfish, ozonated water was used to wash down processing equipment and also to rinse the fish itself.[1] Results from these installations show a sustained decrease in bacterial counts on the fish as well as equipment surfaces. Moreover, cross-contamination was effectively controlled and shelf life of the fish was extended by several days.

Mobile ozone generators are used in several fish processing plants for sanitation of knives, table surfaces, and wash down of walls and floors. These units spray ozonated water with a 3 to 3.5 ppm concentration onto the surfaces. In general, the shelf life of the fish has been extended by 50%.

[1] *Researchers Find New Use for Ozone*, Sea Grant North Carolina, Press Release March 26, 2002, www.ncsu.edu/seagrant/Pressreleases02/Ozone.htm.

Table 13
Sanitation of Process Equipment with Ozonated Water in the Fish and Seafood Processing Industry— Summary of Representative Installations

Processing Facility	End-use	Application	Method	Results
Hanover Sea Products [a, b] Wilmington, NC	Equipment used in fish processing as well as the fish itself	Treating processing equipment and the fish itself with ozone	Ozonated water was used to wash down processing equipment and rinse fish	• Sustained decrease in airborne and waterborne bacteria, minimizing bacterial cross-contamination • Improved the shelf life of uncooked fish by one or two days • The appearance, color, and aroma of fresh fish were not affected
Delta Pride Catfish [c] Indianola, MS	Equipment used in fish processing as well as the catfish itself	Reduce the bacterial counts on the flesh of the fish and on fillet processing equipment	Processed whole fish was placed for 10 to 12 minutes in ozonated water in a 30-gallon test vessel. The test vessel included a chiller vessel and a reactor vessel. Ozone concentrations were varied from 5 to 12 ppm. Ozone was also applied at the fillet line.	• Ozone was effective in reducing bacterial counts on whole fish, fillets, and fillet equipment • Shelf life increased to 14 days compared to 4-6 days for conventional treatment • A 75% reduction in bacterial counts on fillets coming off the fillet processing line when ozone was applied (compared to conventional treatment)

Table 13
Sanitation of Process Equipment with Ozonated Water in the Fish and Seafood Processing Industry— Summary of Representative Installations, Continued

Processing Facility	End-use	Application	Method	Results
North Coast Seafood Company and other fish processing plants [d,e]	Equipment used in fish processing	Sanitize knives and table surfaces, and for general washdown of walls and floors	The fish processing plants use several mobile surface sanitation units. Ozonated water, with a 3-3.5 mg/l ozone level, is sprayed at 10 gallon per minute to sanitize equipment.	• A 50% increase in shelf life of white fish

[a] *Researchers Find New Use for Ozone*, Sea Grant North Carolina, Press Release March 26, 2002, www.ncsu.edu/seagrant/Pressreleases02/Ozone.htm.

[b] *Ozone Effective in Preserving Seafood Freshness*, Sea Grant North Carolina, Marine Extension News, www.ncsu.edu/segrant/Newsletters02/MEN/Ozone.htm.

[c] G. Brooks and S. Pierce, *Ozone Applications for Commercial Catfish Processing*, www.p2pays.org/ref/02/01251.pdf.

[d] R. Rice, *Ozone and Ozone/UV in Sanitation and Food Production*, PowerPoint Presentation, May 28, 2003.

[e] R. Rice, D. Graham, and M. Lowe, *Recent Ozone Applications in Food Processing and Sanitation*, Food Safety Magazine, October/November 2002.

OZONE FOR FRUIT AND VEGETABLE PRODUCTION AND PROCESSING

Bringing fruits and vegetables from the farm to the consumer's table involves several steps. In each step, producers face a variety of challenges. During crop production, farmers must insure that they have the necessary plant material, irrigation, nutrients, growing medium, light, and pest control for optimum plant growth and productivity. After harvest, producers and processors need to have adequate supplies of clean water, as well as appropriate processing and water treatment techniques, to wash and process fruits and vegetables. During storage, environmental conditions such as temperature and humidity, in addition to pests, microorganisms, and other contaminants must be controlled in order to maximize storage life and minimize product loss.

This section treats three main stages of fruit and vegetable production and processing, namely growing, washing and storing. It also presents the specific cases of grain storage and steeping. The discussion includes the primary concerns associated with each phase of fruit production and processing that ozone can potentially mitigate. It further describes the manner in which ozone is generally applied to address the concerns and summarizes the primary benefits of ozone over other alternatives. Lastly, it provides representative performance data for ozone tested in each specific end-use.

I. Growing Fruits and Vegetables

In general, growing fruits and vegetables requires plant material (e.g., seeds, cuttings, etc.), light, irrigation, nutrients, a growing medium (e.g, soil or a hydroponic system), as well as some sort of pest control. Ozone can contribute to the success in meeting several of these basic requirements in smaller growing applications such as in drip irrigation or hydroponic systems. For example, aqueous ozone solutions can aid the irrigation process by destroying waterborne contaminants, possibly improving water penetration into the soil, and cleaning irrigation lines and emitters. However, ozone is not likely to be practical for large-scale irrigation applications, such as those using center pivot systems. Preliminary work also indicates that ozone may be used to fumigate soil and may even control weeds.

Concerns

The main concerns associated with growing fruits and vegetables in irrigated crops that can be potentially met with ozone include:

- **Poor Water Quality:** The quality of water used to irrigate plants can affect the health and productivity of crops. High levels of impurities such as hydrogen sulfide and pH values that are either too high or too low can lead to plant stress, low yields, higher fertilizer requirements, and early plant mortality.

- **Excessive Runoff:** Irrigation water may not penetrate the soil adequately, leading to runoff, soil erosion, and insufficient water reaching plant roots.
- **Overuse of Water:** Crop production requires a significant amount of irrigation throughout the lifecycle of the crop. Losses due to evaporation before the water penetrates the soil and excessive runoff compound the problem.
- **Contaminated Irrigation Lines and Emitters:** Irrigation lines and emitters can become clogged and contaminated with microorganisms and other waterborne impurities. As a result, water flow to plants may be restricted and/or plants may be unnecessarily exposed to pathogens.
- **Effects of Pests on Plant Health and Productivity:** Pests encountered during crop production such as weeds, insects, nematodes and fungi affect plant health and yields.
- **Potentially Toxic Pesticides:** Pesticides can leave behind residues on fruits and vegetables and in water supplies. If consumed in toxic quantities, pesticide residues can lead to health effects such as headache, nervous system disorder, and heart and brain damage.[1]
- **Phasing Out of Methyl Bromide:** Methyl bromide, a common pesticide, is scheduled for complete phase-out by 2005 because it contributes to the destruction of the stratospheric ozone layer.

Ozone as a Solution

Ozone can mitigate several of the concerns addressed above. The method of ozone application for fruit and vegetable growing applications depends on the specific end-use. For improving water quality, increasing irrigation penetration, and cleaning tubes and emitters, ozone is injected into water and used as a water solution containing dissolved ozone. For fumigating soil, ozone is injected in gaseous form through emitters in buried drip tubing (for row crops) or through injection probes (for individual plants). To control weeds, ozone is injected in gaseous form under plastic mulch. The main merits of ozone in fruit and vegetable growing applications include:

- **Improved Water Quality:** Ozone is highly effective in destroying a wide variety of waterborne contaminants affecting crop health. In addition to destroying microorganisms, ozone can reduce organic loading and hydrogen sulfide levels, and stabilize pH. Ozone is beneficial over chlorine for water treatment in that it does not produce trihalomethanes (THMs) and it is generated on-site, eliminating storage and handling of chemicals.
- **Possibility of Increased Penetration:** Ozonation of the supply water increases the quantity of dissolved oxygen in the water. As a result, some researchers believe that the water is able to better penetrate the soil. Better penetration in turn equates to improved dispersion to the root zone and less water loss. More work is necessary to verify this effect.

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[1] The Pesticide Management Education Program, Cornell University, *Pesticide Health Effects on Humans*, Webpage, http://pmep.cce.cornell.edu/facts-slides-self/facts/gen-posaf-health.html.

- **Water Recycling and Reuse:** Ozone is effective for treating and reusing wastewater for irrigation. Therefore, ozone can enable a reduction in water consumption.
- **Cleaning of Irrigation Lines:** Ozone is being investigated as a potential method for reducing microorganisms and other impurities that can clog or contaminate irrigation pipes and emitters.[1]
- **Pathogen Destruction:** Ozone injection has been found to decrease soilborne pathogens, thus improving plant growth and yield.
- **Possibility of Increased Nutrient Availability:** By oxidizing organic compounds in soil, preliminary results suggest that ozone may increase nutrient availability to plants.[2] More research is needed to verify this effect.
- **Lack of Residue:** Unlike other chemical fumigants, ozone does not leave behind chemical residues in soil or ground and surface water.
- **On-Site Production:** The fact that ozone is produced on-site eliminates storage, handling, and disposal of hazardous chemical fumigants and chemical containers.
- **Not Regulated as a Pesticide:** Because ozone is generated at the site of use and degrades back to oxygen leaving no residues, it is not regulated by the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) as a pesticide.[3]
- **Potential for Controlling Weeds:** Work by Pryor has shown that ozone injection under plastic mulch may be capable of controlling weeds with multiple pre-plant applications of 2 lbs per acre.[4,5]

Performance

The efficacy of ozone for water and wastewater treatment is well known. Ozone is widely used in water treatment plants because it is such a strong oxidizer. It is one of the few disinfectants effective against *Cryptosporidium* and *Giardia,* so many plants use it, when cost-effective, for primary disinfection followed by chlorine. For agricultural production, ozone is advantageous in that it is generated on-site and can be used to treat water supplies without the worry of chemical storage and handling. It is relative safe to use as long as measures are taken to prevent exposure to toxic levels.

One case study employing ozone for treating irrigation water involves hydroponic tomatoes.[6] In this example, ozone treatment was used to improve the quality of well water for irrigating the

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[1] National Organic Standards Board Technical Advisory Panel Review, *Ozone: Crops*, Compiled by OMRI for the USDA National Organic Program: August 14, 2002.
[2] *Ozone Gas as a Soil Fumigant: 1998 Research Program*, EPRI, Palo Alto, CA: 1999. TR-113751.
[3] http://www.epa.gov/pesticides/regulating/laws.htm.
[4] Pryor, A., 2001, *Petition for the Inclusion of Ozone Gas Used for Weed Control in the National List*, Submitted to National Organic Program, USDA.
[5] National Organic Standards Board Technical Advisory Panel Review, *Ozone: Crops*, Compiled by OMRI for the USDA National Organic Program: August 14, 2002.
[6] Rice, R. G. *Ozone and Ozone/UV in Sanitation and Food Production*, May 28, 2003, powerpoint presentation.

tomatoes. Prior to ozone treatment, the well water had a hydrogen sulfide concentration of 60 ppm and a pH of 7.8. In addition, the rejection rate of tomatoes was 40% due to blossom end rot. Ozone treatment reduced the hydrogen sulfide concentration to 0 ppm, lowered the pH to 7.04 by reducing organic load and producing H_2SO_4, and reduced the rejection rate to less than 3%. The total tomato yield increased by more than 300%. By stabilizing the pH, the fertilizer consumption also decreased by 25%. Because of the tremendous benefits, the payback period for the ozone system ended up being less than 6 months.

The application of ozone for improving irrigation penetration and cleaning tubes and emitters is relatively new. Further research is required to evaluate performance.

Research into the use of ozone as a soil fumigant is also still in its early stages. Much of the work to date has been conducted by Pryor of SoilZone, Inc.[1,2,3] In 1998, Pryor worked with EPRI to conduct field trials of ozone treatment for a variety of crop and soil types under a range of climatic conditions.[4] The types of crops fumigated with ozone included tomatoes, carrots, strawberries, sugar beets, broccoli, prunes, sweet potatoes, and peaches. The results show that application of 50 to 400 lbs of ozone per acre through either drip tube emitters (for row crops) or probes (for orchard replants) generally reduced negative impacts from soil pathogens and increased plant yields. The results further indicate that the ozone increased nutrient availability to the plants due to its oxidation of soil organics. Pryor has since extended his work to include the evaluation of ozone for weed control.[5]

[1] Pryor, A., 1996, Method and Apparatus for Ozone Treatment of Soil to Kill Living Organisms, US Patent #5,566,627.
[2] Pryor, A., 1997, Method and Apparatus for Ozone Treatment of Soil, US Patent #5,624,635.
[3] Pryor, A., 2001, “Field Trials for the Combined Use of Ozone Gas and Beneficial Microorganisms as a Preplant Soil Treatment for Tomatoes and Strawberries,” *Pest Management Grants Final Report.* Contract No. 99-0220 California Dept. Pesticide Regulation.
[4] *Ozone Gas as a Soil Fumigant: 1998 Research Program*, EPRI, Palo Alto, CA: 1999. TR-113751.
[5] Pryor, A., 2001, *Petition for the Inclusion of Ozone Gas Used for Weed Control in the National List*, Submitted to National Organic Program, USDA.

II. Washing Fruits and Vegetables

Concerns

The process of washing fruits and vegetables is called "Post Harvest Physiology" and is summarized here. To wash and remove microbial contamination from produce, food producers generally use either a water spray or a flume. Flumes are also used to transport produce through the processing plant. In conventional systems, wash water is often treated by chlorination and some degree of filtration and then recycled. As the water quality degrades below acceptable limits, it is replaced with makeup water, and the degraded water enters the waste stream. The following list summarizes the main concerns with washing fruits and vegetables, and the concerns associated with conventional chlorine treatment.

- **Risk of Microbial Contamination:** Fruits and vegetables need to be cleaned after harvest and before entry to the marketplace in order to remove microorganisms. Depending on the type, microorganisms contribute to produce spoilage as well as potentially cause food borne illness.
- **Pesticide Residues:** Fruit and vegetable crops are often treated with pesticides to prevent pest damage and improve quality and increase yields. In sufficient quantities, the residues can be toxic if consumed. Moreover, the residues may enter rinse water and then be introduced into the environment via the waste stream.
- **Limitations of Chlorine:** Chlorine is widely employed as an antimicrobial agent for water treatment. However, chlorine is characterized by several downsides including the formation of THMs, the formation of by-products from reactions with pesticides, storage and handling hazards, and the inability to prevent buildup of soil and organic residues in the water.
- **Expense of Water and Wastewater Disposal:** Conventional practices to treat flume water rely on chlorine. As mentioned above, chlorine has several downsides, one of which is its inability to really clean the water. That is, although it can be effective as an antimicrobial agent with sufficient concentrations and contact times, it does not prevent soil and organic residues from building up. Thus, the water needs to be replaced frequently and the wastewater must be treated. Both replacing water and treating wastewater are costly. Waste treatment charges associated with suspended solids and biological oxygen demand are particularly expensive.

Ozone as a Solution

Ozonated water is currently used in a variety of processing plants to wash fruits and vegetables. In processing applications, ozone is often employed in conjunction with filtration to remove suspended solids and improve the effectiveness of ozonation. To ozonate flume water, generally a sidestream of water is diverted from the main flume, injected with high concentrations of ozone, and then reintroduced to the flume, maintaining a relatively steady concentration in the flume. Figure 14 shows fresh cut lettuce and vegetables being washed in ozonated flume water. In practice, ozone concentrations have been on the order of 0.05 to 0.15 ppm for flume washing and on the order of 1 to 3 ppm for spray washing.[1,2] In laboratory tests, ozone concentrations have been as high as 10 ppm to control fungal spores on fruit.[3]

The use of ozonation and filtration in the place of chlorination enables much higher water quality for a longer period of time. Thus, less water is consumed and sent into the waste stream. Ozone is also a stronger and more rapid oxidant than chlorine; however, ozone degrades very quickly in water, leaving no residual protection against contaminants. As a result, some chlorine may need to be added to the wash water in order to provide residual protection. The list below summarizes the main benefits of ozone in fruit and vegetable washing.

- **Improved Produce Quality:** Ozone treatment can improve the taste and appearance of produce over the use of chlorination alone. The antimicrobial action of ozone also helps control food borne pathogens and ensure food safety.
- **Greater Shelf Life:** Ozonation greatly reduces spoilage microorganism counts in wash water and on fruits and vegetables, thereby extending the shelf life of produce. A longer shelf life also equates to fewer discarded products and greater allowable shipping distances.
- **Lower Water Requirements:** Ozonation, particularly if combined with filtration, improves water quality significantly over chlorination alone. Since the water stays cleaner longer, less makeup replacement water is needed, and less contaminated water enters the waste stream. Water savings of 60% have been achieved in practice.[4]
- **Effective Water Recycling:** Because of its efficacy in oxidizing a variety of microorganisms and waterborne contaminants, ozone can be used quite effectively to treat recycled water.
- **No THMs or Other Chlorinated By-Products:** Ozonation is advantageous over chlorine in that it does not yield chlorinated by-products such as THMs. However, it can produce the bromate ion, which is a suspected carcinogen, if bromine is present in the water.
- **Potential Destruction of Pesticide and Chemical Residues:** To a certain degree, ozone is capable of destroying pesticide and chemical residues in wash water and on fruits and vegetables.

[1] Ozone Applications in Apple Processing, EPRI, Palo Alto, CA: 1998. TA-112064.
[2] *Direct Food Additive Petition: Ozone as an Antimicrobial Agent for the Treatment, Storage and Processing of Foods in Gas and Aqueous Phases*, EPRI, Palo Alto, CA: August 2, 2000, Section 2.4.7.
[3] *Use of Ozone in Water on Fresh Fruit,* EPRI, Palo Alto, CA, Southern California Edison, Rancho Cucamonga, CA: 2002, 1007108.
[4] Ozone Improves Processing of Fresh-Cut Produce: TechApplication, EPRI, Palo Alto, CA: 2002, 1007466.

Figure 14
Fresh Cut Lettuce and Vegetables are Washed in Ozonated Water Prior to Packaging in Bags for the Ready to Eat Market

Source: Ozone Improves Processing of Fresh-Cut Produce: TechApplication, EPRI, Palo Alto, CA: 2002, 1007466.

Performance Results

Various installations in processing plants and laboratory results have demonstrated the effectiveness of ozonated water for washing fruits and vegetables. Table 14 summarizes representative case studies in which ozone is used in practice, and Table 15 summarizes a few research efforts directed at studying ozone's efficacy under a variety of experimental conditions.

The results show that ozone can significantly reduce microbial counts in wash water and on fruit and vegetable surfaces, improving taste, appearance, and shelf life; however, ozone is more effective in treating microbes in the water than on the surfaces of produce. The results in Table 15 also show that under the conditions tested ozone does not destroy pathogens in the wounds of citrus fruit and pears. Therefore, although ozone can reduce microbial counts in wash water and produce surfaces, as well as prevent cross-contamination of fruit, it is limited in its ability to stop microbial growth in existing wounds.

Performance results also demonstrate the water savings potential of replacing conventional methods with ozonation and filtration. Savings of up to 60% have been achieved. Reduced water use also equates to lower waste treatment costs.

Table 14
Washing Fruits and Vegetables with Ozonated Water — Summary of Representative Case Studies

Manufacturer	Product	Application	Installation Year	Method	Results
Strickland Produce Co. Nashville, TN	Fresh cut vegetables and lettuce in bags for the ready-to-eat market	Replacing a flume water sanitization system that previously used only chlorine with a system combining filtration, ozonation, and chlorination [a,b]	2001	A 50 micron wedge-wire filter placed in front of the water chiller reduces suspended solids in the 200 gpm flume After the chiller, a 50 gpm side stream of water is ozonated and then returned to mix with flume water Near the end of the wash cycle, chlorine is added for residual protection	• Superior taste and appearance compared with use of chlorine or ozone alone • Plate count reduction of aerobic bacteria, resulting in longer shelf life (up to 25 days) • Clearer water over an extended period of time yielding water savings of 60% and reduced wastewater treatment costs
Lyons Magnus Fresno, CA	Strawberries and frozen strawberry toppings	Using ozonated wash water for microbial control during spraying and washing strawberries and toppings [c]	1998	2.7 ppm of ozone in water is sprayed on fresh strawberries to reduce microbial load before freezing the berries Ozonated water is also used for microbial control in the processing of frozen strawberry toppings	• Reduction of *Escherichia coli*, coliforms, standard plate count (SPC), yeasts, and molds • Specifically, SPC levels drop on average from 17,767 to 987 for raw strawberries • Yeast/mold counts drop from an average of 56,500 to 1304

Table 14
Washing Fruits and Vegetables with Ozonated Water — Summary of Representative Case Studies, Continued

Manufacturer	Product	Application	Installation Year	Method	Results
Tastee Apple Inc. Newcomerstown, OH	Caramel apples	Replacing a chlorine-based flume water sanitization system with a system combining filtration and ozonation [d]	1998	A side stream of 60 gpm from the 600 gpm flume is filtered through a 90 micron filter and then injected with gaseous ozone The side stream is returned and mixed with the flume water, where the ozone concentration is maintained between ~0.05 and 0.15 ppm Apples are exposed to ozonated flume water for about 10 minutes	• Reduction of yeast and mold counts in the water, resulting in cleaner apples and longer shelf life for caramel apples • Clearer water over an extended period of time yielding water savings of 12,000 gal/week and reduced wastewater treatment costs • Cleaner rubber gloves for employees working with apples
Company in Bakersfield, CA	Garlic cloves	Replacing a NaOCl spray washing system with an ozonated water spray system [e]	2002	Garlic cloves are spray washed with ozonated water (1.3 ppm O_3 in 13 gal/min spray) to reduce aerobic plate count (APC) levels	• Reduction of APC levels by 20 to 30% • Elimination of problems associated with NaOCl (e.g., pitting of steel rollers, and need for odor removal system) • Maintenance savings of $650-750/month

[a] *Treatment of Cut Vegetables with Aqueous Ozone: Technical Assessment,* EPRI, Palo Alto, CA, Tennessee Valley Authority, Chattanooga, TN: 2002. 1007465.

[b] *Ozone Improves Processing of Fresh-Cut Produce,* EPRI, Palo Alto, CA: 2002. 1007466.

[c] *Direct Food Additive Petition: Ozone as an Antimicrobial Agent for the Treatment, Storage and Processing of Foods in Gas and Aqueous Phases*, EPRI, Palo Alto, CA: August 2, 2000, Section 2.4.7.

[d] Ozone Applications in Apple Processing, EPRI, Palo Alto, CA: 1998. TA-112064.

[e] Rice, R. G. *Ozone and Ozone/UV in Sanitation and Food Production*, May 28, 2003, powerpoint presentation.

Table 15
Washing Fruits and Vegetables with Ozonated Water — Summary of Representative Research Efforts

Research Group(s)	Product	Application	Method	Results
USDA Agricultural Research Service EPRI Southern California Edison	Grape berries	Controlling gray mold on fruit surfaces with ozonated water [a]	The surfaces of berries were inoculated by spraying a suspension of *Botrytis cinerea* spores (~12,000 spores/mL) After 2 hours, the berries were treated in ozonated water (10 ppm, 20 ºC) for 1 to 6 minutes Ozone efficacy was compared to that of sodium hypochlorite, sodium bicarbonate, and ethanol	Ozone in water (10 ppm) for 1-2 minutes reduced gray mold disease incidence by about 50%; however, its efficacy varied and depended on the grape berry condition
USDA Agricultural Research Service EPRI Southern California Edison	Citrus fruit	Controlling postharvest pathogens in wounds with ozonated water [a]	Citrus fruit were inoculated by wounding each fruit once with spore suspensions of Penicillium digitatum or Geotrichum candidum The fruit were treated with various concentrations of ozone in water and then were stored for up to one month	• Even prolonged treatment (15 min) with high ozone concentrations (10 ppm) did not control pathogens inoculated into wounds of citrus fruit • The pathogens in the wounds appeared to be protected from ozone • Sodium hypochlorite was also ineffective for controlling pathogens in wounds
USDA Agricultural Research Service EPRI Southern California Edison	Strawberries	Controlling natural microbe populations on harvested strawberries [a]	Strawberries were treated with ozonated water with concentration varying from ~1 to 4 ppm (T = 16-20 ºC, pH = 7.6-8.1) for 10 seconds or 2 minutes Ozone efficacy was compared with sodium hypochlorite	• Yeast, mold, and aerobic bacteria counts were decreased by 50% with a contact time of 10 sec and 4 ppm ozone • A contact time of 2 minutes reduced counts by 90%

Table 15
Washing Fruits and Vegetables with Ozonated Water — Summary of Representative Research Efforts, Continued

Research Group(s)	Product	Application	Method	Results
USDA Agricultural Research Service EPRI Southern California Edison	Fruits and vegetables	Destroying fungal spores in water [a]	Spore suspensions of 8 fungi were treated with ozonated water	• 1.5 ppm ozone and a contact time of 2 minutes killed 95-100% of all fungi • No fungi survived 3 minutes of contact
Spotts and Cervantes	Pears	Controlling pathogens in wounds with ozonated water [b]	Wounds of pear fruit were inoculated with Penicillium expansum and then treated with ozonated water with concentrations up to 5.5 ppm for five minutes Efficacy was compared with water alone and chlorinated water	• Level of decay in pears treated with ozonated water were similar to pears treated in water alone—ozonated water was not effective in reducing pathogen counts in wounds • Similar levels of decay were also observed for pears treated with chlorinated water

[a] *Use of Ozone in Water on Fresh Fruit,* EPRI, Palo Alto, CA, Southern California Edison, Rancho Cucamonga, CA: 2002, 1007108.

[b] Spotts, R. A., and L. A. Cervantes, 1992, "Effects of Ozonated Water on Postharvest Pathogens of Pear in Laboratory and Packinghouse Tests," *Plant Disease,* Vol 76, pp. 256-259.

III. Storing Fruits and Vegetables

Fruits and vegetables are potentially exposed to a wide range of pests during storage that can compromise their quality and shelf life. Particularly problematic are rodents, insects, and fungal and bacterial organisms, all of which can contribute to food damage and spoilage. Rodents and insects damage fruits and vegetables by eating them and defecating on them. The defecation in turn can promote microbial growth on produce and within the storage environment. As microorganisms proliferate on food surfaces and wounds, they lead to product spoilage. Depending on the type of microorganism, they may also produce toxins that are pathogenic to humans if consumed. In addition, microorganisms such as molds are characterized by musty odors that can be readily absorbed by fruits and vegetables, thereby affecting the taste and quality of products. The main concerns encountered during fruit and vegetable storage include:

- **Pests:** Insects, fungi, bacteria and other pests destroy stored crops. Insects and animals eat and defecate on food supplies; microorganisms grow in storage environments and on food supplies and can cause damage and lead to the production of pathogenic toxins; and odors are absorbed by stored crops affecting taste and quality. Pests and their impacts can proliferate and cross-contaminate other produce in the storage environment, seriously affecting produce quality and shelf life.
- **Lack of Chemical Agents for Control of Pests:** Methyl bromide, a common pesticide, is scheduled for complete phase-out by 2005 because it contributes to the destruction of the stratospheric ozone layer.

Ozone as a Solution

In fruit and vegetable storage applications, ozone is applied in gaseous form into the storage area to control pests and oxidize odorous molecules. It acts on contaminants in the air and on surfaces. Ozone has also been shown to slow the ripening process by oxidizing metabolic products (e.g. ethylene gas) released by fruits and vegetables.[1] It may also promote wound healing and enhance resistance to infection in potatoes.[2]

The efficacy of ozone in storage applications is a function of several factors including ozone concentration, duration of exposure, organism type, and characteristics of the environment that might affect oxidation reactions such as contaminant loading in the room and/or humidity. For example, humidity causes microorganisms to swell and they are easier to destroy when swollen. Therefore, for predictable microbial efficacy humidity should be controlled.

Application can be continuous with low concentration, or it can be in bursts of high concentration. For example, tests conducted with ozone to kill Indianmeal moth and diapausing

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[1] Rice, R.G., W. Farquhar, and L.J. Bollyky, 1982, "Review of the Application of Ozone for Increasing Storage Time for Perishable Foods," *Ozone Sci. Eng.,* Vol. 4, No. 1, pp. 147-163.
[2] *Ozone and Potato Storage,* www.ozoneapplications.com/food_preservation/Ozone_And_Potato_Storage.htm.

codling moth larvae in crop storage required 400-500 ppm of ozone for 4 to 5 hours.[1] Other tests with confused flour beetle and saw-toothed grain beetle achieved complete mortality with 5 ppm of ozone over a 3 to 5 days period.[2] Similarly, continuous exposure to 5 ppm ozone was shown to inhibit surface growth of *A. flavus* and *F. moniliforme* as well as eliminate sporulation and aflatoxin production.[3] For significant fungal reduction, rather than just growth control, larger ozone concentrations must be used.

There must also be distribution and mixing of the ozone within the storage space to ensure adequate and uniform contact with the fruits and vegetables. Ozone must come in direct contact with surfaces in order to destroy microbes and organic contaminants on them.

The primary advantages with employing ozone during food storage include:

- **Insect Control:** Ozone's ability to destroy insects in stored crops can lead to longer shelf life and reduced loss over foods stored in untreated environments. Ozone coupled with temperature controls can stop the pupation of insects.
- **Antimicrobial Ability:** The fungicidal quality of ozone inhibits fungal growth, sporulation, toxin production, and odors associated with fungi. These effects in turn lead to increased shelf life and better product quality, as well as limit the spread of contamination to other foods. Ozone is also capable of destroying bacteria, but generally larger ozone concentrations are needed for the bactericidal effect than the fungicidal effect.
- **Lack of Residue:** Unlike other chemical pesticides and antimicrobial agents, ozone does not leave behind chemical residues nor does it alter the taste of stored foods.
- **On-Site Production:** The fact that ozone is produced on-site eliminates storage, handling, and disposal of hazardous chemicals and chemical containers. In addition, because ozone is generated at the site of use and is not stored, it is not regulated by the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) as a pesticide.[4]
- **Potential Metabolic Effect:** Preliminary findings indicate that ozone may slow down the ripening process by oxidizing metabolic products such as ethylene gas produced by fruits and vegetables.[5] More research is needed to verify this effect.
- **Potential Promotion of Wound Healing:** Studies with potatoes suggest that ozone gas may promote wound healing and may increase resistance to infection in produce.[6]

[1] Technical Update -- *Use of Ozone in Water on Fresh Fruit,* EPRI, Palo Alto, CA, Southern California Edison: 2002, 1007108.
[2] Mason, L.J., C.P. Woloshuk, and D. E. Maier, 1997, "Efficacy of Ozone to Control Insects, Molds, and Mycotoxins," In *Inter. Conf. Control Atm. Fum. Stored Prod.,* E.J. Donahaye (Ed.), Cyprus, April 21-26, 1996.
[3] Mason, L.J. R. A. Rulon, and D. E. Maier, 1996, "Chilled Versus Ambient Aeration and Fumigation of Stored Popcorn – Part II. Pest Management, *J. Stored Prod. Res.*
[4] http://www.epa.gov/pesticides/regulating/laws.htm.
[5] Rice, R.G., W. Farquhar, and L.J. Bollyky, 1982, "Review of the Application of Ozone for Increasing Storage Time for Perishable Foods," *Ozone Sci. Eng.,* Vol. 4, No. 1, pp. 147-163.
[6] *Ozone and Potato Storage,* www.ozoneapplications.com/food_preservation/Ozone_And_Potato_Storage.htm.

Performance Results

Although in certain food storage applications and in laboratory environments ozone has been shown to control problems such as insects, bacteria, fungi, and odors, as well as possibly slow ripening rates and promote wound healing, more research is necessary to further ozone's development in this arena. Table 16 summarizes representative experimental results with gaseous ozone to control fungi during the storage of fruits and vegetables. The products tested include onions, potatoes, oranges, blackberries, and grapes. Ozone concentrations evaluated vary widely. For example, tests with thornless blackberries implemented continuous ozone concentrations of 0.1 to 0.3 ppm, while tests with onions, potatoes, and oranges employed concentrations all the way up to 200 ppm with exposure durations ranging from 5 minutes to 72 hours. In general, the results included in the table show that continuous low concentrations of ozone inhibit fungal growth, but spore destruction necessitates higher concentrations and high humidity. Other key parameters affecting performance include product type, temperature, and exposure time.

Table 16
Storing Fruits and Vegetables in Environments Treated with Gaseous Ozone — Summary of Representative Research Efforts

Research Group(s)	Product(s)	Application(s)	Method	Results
USDA Agricultural Research Service	White onions, russet potatoes, and oranges	Controlling fungal spores in storage environments with gaseous ozone [a]	*Botrytis cinerea, Monilinia fructicola, Penicillium digitatum,* and *Rhizopus stolonifer* spores were exposed to gaseous ozone concentrations up to 200 ppm at low (35% RH) or high (95% RH) humidity at 5, 15, or 25 ºC for 5 minutes to 72 hours Spore viability was then determined by incubation on potato dextrose agar for 18 hours at 23-25 ºC and germination was measured at a magnification of 250X Kill dosages at 50% and 99% were expressed as the product of ozone concentration multiplied by exposure time (ppm-hr)	• *R. stolonifer* was more tolerant to ozone than other fungi • Ozone was ~6 times more toxic at high relative humidity • Ozone was most toxic at 25 ºC • Lower concentrations of ozone (20 ppm) stopped spore production • Higher concentrations were required to kill spores
Barth et al.	Thornless blackberries	Controlling fungi in storage with gaseous ozone [b]	Blackberries were harvested and then exposed to air with continuous ozone concentrations of 0.1 or 0.3 ppm at 2 ºC	• Fungal decay was inhibited for up to 12 days • Constant exposure is more effective in inhibiting pathogens in storage
Sarig et al.	Grape berries	Controlling fungal decay with gaseous ozone [c]	Grape berries were inoculated with Rhizopus stolonifer, placed in a Plexiglass cylinder, and then exposed to gaseous ozone for up to 30 minutes Ozone was supplied through the cylinder at a rate of 8 mg/min in an air flow of 500 mL/min	• The number of naturally present colony forming units of fungi, yeasts, and bacteria were significantly reduced by 20 minutes of ozone exposure • Decay in inoculated berries was considerably decreased for berries undergoing ozone treatment either prior to inoculation or after inoculation

Table 16
Storing Fruits and Vegetables in Environments Treated with Gaseous Ozone — Summary of Representative Research Efforts, Continued

Research Group(s)	Product(s)	Application(s)	Method	Results
University of Idaho	Potatoes	Controlling microorganism damage with gaseous ozone [d]	Russent Burbank potatoes were put in test bins and exposed to an environment of 99+% RH, 7 to 8 ºC, and 1 to 2.5 ppm ozone concentration Some of the potatoes were covered with Silver Scurf infection Potatoes were planted, harvested and graded to see the effects of ozone of seed viability	• After 5 weeks in storage, ozone eliminated any visual signs of Silver Scurf infection • Ozone aided in wound healing and reduced black spot penetration during storage • Ozone treated seed yielded 58% more U.S. #1 potatoes than non-ozone treated

[a] Margosan, D.A., and J.L. Smilanick, *Effects of Ozone Gas on Fruit and Vegetable Quality,* USDA-ARS Horticultural Crops Research, April 2000.

[b] Barth, M.M., C. Zhou, J. Mercier, and F.A. Payne, 1995, "Ozone Storage Effects on Anthocyanin Content and Fungal Growth in Blackberries," *Journal of Food Science,* Vol. 60, pp. 1286-1288.

[c] Sarig, P., T. Zahavi, Y. Zutkhi, S. Yannai, N. Lisker, and R. Ben-Arie, 1996, "Ozone for Control of Post-Harvest Decay of Table Grapes Caused by *Rhizopus stolonifer,*" Journal of Physiological and Molecular Plant Pathology, Vol 48, No 6, pp. 403-415.

[d] *Ozone and Potato Storage,* www.ozoneapplications.com/food_preservation/Ozone_And_Potato_Storage.htm.

IV. Grain Storage and Steeping

Concerns

During harvesting, transporting, and storage, grain products are exposed to a variety of contaminants, such as insects, feces, soil, bacteria and fungi. These contaminants can damage and compromise the quality of grain crops during storage. For example, insects destroy stored grains by eating them and defecating on them. Defecation in turn enables fungal growth. Certain types of fungi are particularly problematic. For example, *Fusarium* and *Aspergillus* produce pathogenic mycotoxins that can harm animals or humans consuming the grains. Fungal growth can also ruin the taste of stored grains, as odors from the fungi are readily absorbed by food. In addition, the steeping process used to hydrate grains and temper them prior to milling compounds contamination because the moisture and temperatures associated with the tempering process facilitate microbial growth.

In order to mitigate the effects of microorganisms during grain steeping, chlorinated water is often used, but chlorine may not be effective enough against all contaminants. Additionally, pesticides such as methyl bromide are commonly employed to prevent fungal growth and insect damage during grain storage. Both chlorine and methyl bromide are potentially hazardous to the environment, so alternatives to them are in need.

The list below summarizes the main concerns encountered during grain steeping and storage, as well as the concerns associated with current practices to treat steeping water and storage environments.

- **Pests:** Bacteria and mold can proliferate and contaminate grain products during steeping processes. In addition, insects, fungi, bacteria and other pests destroy stored crops. Insects and rodents eat and defecate on food supplies; fungi grow in storage environments and on food supplies and can cause damage and lead to the production of pathogenic mycotoxins; and odors are absorbed by stored crops affecting taste and quality.
- **Current Chemical Agents are Hazardous to the Environment:** Methyl bromide, a common pesticide, is scheduled for complete phase-out by 2005 because it contributes to the destruction of the stratospheric ozone layer. Chlorine, which is commonly used to treat water, produces hazardous by-products such as carcinogenic THMs, and has limited effectiveness against contaminants in steeping water. Chemical agents also present a storage and handling concern.

Ozone as a Solution

Ozone can be applied to water in place of chlorine to mitigate microbial problems during grain steeping and also prevent the negative effects of chlorine. During grain storage, gaseous ozone can be injected into the storage environment to prevent microorganisms, insects, and other pests from damaging stored grains. It can also be applied in conjunction with UV treatment to improve efficacy of microbial control (see Figure 15).[1] The primary benefits of ozone include:

- **Insect Control:** Ozone's ability to destroy insects in stored grains can lead to longer shelf life and reduced loss over foods stored in untreated environments. Ozone coupled with temperature controls can stop the pupation of insects.
- **Antimicrobial Ability:** The fungicidal quality of ozone inhibits fungal growth, sporulation, toxin production, and odors associated with fungi during grain storage. These effects in turn lead to increased shelf life and better product quality, as well as limit the spread of contamination to other foods. Ozone is also capable of destroying bacteria and fungi during grain steeping.
- **Lack of Residue:** Unlike other chemical pesticides and antimicrobial agents, ozone does not leave behind chemical residues nor does it alter the taste of stored foods.
- **On-Site Production:** The fact that ozone is produced on-site eliminates storage, handling, and disposal of hazardous chemicals and chemical containers. In addition, because ozone is generated at the site of use and is not stored, it is not regulated by the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) as a pesticide.[2]

Figure 15
Use of Ozone and UV Light in Photohydroionization Process to Reduce Bacteria During Grain Tempering

Source: RGF Environmental, www.rgf.com. Used with permission.

[1] *Ozone and UV for Grain Milling Systems,* EPRI, Palo Alto, CA: 2000. 1000591.
[2] http://www.epa.gov/pesticides/regulating/laws.htm.

Performance Results

Preliminary work with ozone in grain storage applications has yielded interesting findings. Table 17 summarizes some recent research efforts. The results show that ozone treatment can outperform chlorination in terms of bacterial control during grain steeping. It can also be used with UV light to inhibit microbial growth on hydrated wheat and grain processing equipment. In addition, with high enough concentrations and/or contact times, ozone can kill certain types and stages of insects encountered in grains during storage. Furthermore, it can inhibit fungal growth, sporulation and toxin production during storage and steeping.

Table 17
Ozone in Grain Processing — Summary of Representative Research Efforts

Research Group(s)	Product(s)	Application	Method	Results
EPRI First Energy Services Harvest States Amber Milling RGF Environmental Group	Wheat flour	Controlling bacteria and mold in grain steeping water	Ozone was injected into steeping water to control microorganisms during wheat hydration Gaseous ozone supplemented by photoionization (UV) was used to treat wheat grains and processing equipment Gaseous ozone was applied to the tempering bin and roll bin to inhibit microbial growth	• 75-80% reduction in total plate count bacteria over conventional chlorine treatment • Visible reduction in mold growth on equipment with ozone/UV system • Potential payback period of 30 months
Mendez et al.	Grains [b]	Fumigation of grain to control insects and fungi	Ozone was applied to storage bins containing various types of grain and a known number of insects The grains tested were rice, popcorn, soft red winter wheat, hard red winter wheat, soybeans and corn Ozone was applied in two applications to ensure that a sufficient quantity of reactions would take place to kill insects The quality of food products made with ozone-treated grain was evaluated	• All species of insects were destroyed by ozone treatment, except immature weevils, who hide within kernels • Ozonated grains were found to have essentially the same features in terms of milling, making flour, and being used in bread as non-ozonated grains • No significant differences were found in the nutritional and metabolic values of amino acids and essential fatty acids in the grains
Mason et al.	Grain [c]	Fumigation of grain to control insects	Insects associated with grain were exposed to relatively low concentrations of ozone for long time durations	• An ozone concentration of 5 ppm in air for 3 to 5 days was sufficient to achieve 100% mortality of confused flour beetle and saw-toothed grain beetle

Table 17
Ozone in Grain Processing — Summary of Representative Research Efforts, Continued

Research Group(s)	Product(s)	Application	Method	Results
Mason et al.	Grain [d]	Fumigation of grain to control fungi	Fungi were exposed to an ozone concentration of 5 ppm	• Surface growth of *A. flavus* and *F. moniliforme* was inhibited for two days, after which growth was the same as that of the non-ozone environment • Sporulation and aflatoxin production were eliminated in 5 ppm ozone environment

[a] *Ozone and UV for Grain Milling Systems,* EPRI, Palo Alto, CA: 2000. 1000591.

[b] Mendez, F., D.E. Maier, L. Mason, C.P. Woloshuk, "Penetration of Ozone into Columns of Stored Grains and Effects on Chemical Composition and Processing Performance" Elsevier Science Ltd., 2002.

[c] Mason, L.J., C.P. Woloshuk, and D. E. Maier, 1997, "Efficacy of Ozone to Control Insects, Molds, and Mycotoxins," In *Inter. Conf. Control Atm. Fum. Stored Prod.,* E.J. Donahaye (Ed.), Cyprus, April 21-26, 1996.

[d] Mason, L.J. R. A. Rulon, and D. E. Maier, 1996, "Chilled Versus Ambient Aeration and Fumigation of Stored Popcorn – Part II. Pest Management, *J. Stored Prod. Res.*

OZONE FOR THE PRODUCTION AND PROCESSING OF MEAT AND POULTRY PRODUCTS

Livestock and poultry producers and processors of meat and poultry products face numerous challenges in bringing products from the farm to the table. Livestock and poultry producers must feed, water, and shelter animals during the production process. Processors must slaughter animals raised for consumption and ready the carcasses for the market. Producers of processed meat and poultry products must follow stringent requirements to insure food safety and quality. In addition, waste streams from all production and processing activities require appropriate treatment in order to prevent environmental contamination.

This section deals with four aspects of the production and processing of meat and poultry products, namely 1) livestock and poultry production, 2) beef and pork processing, 3) poultry processing, and 4) sanitation of equipment and work areas to prevent contamination. The discussion includes the primary concerns associated with each aspect that ozone can potentially mitigate. It further describes the manner in which ozone is generally applied to address the concerns and summarizes the primary benefits of ozone over other alternatives. Lastly, it provides representative performance data for ozone tested in the specific end-uses.

I. Livestock and Poultry Production

There are various ways of implementing ozone to improve livestock and poultry production. This section addresses four aspects of livestock and poultry production that are particularly suitable for ozone treatment:

1. Cleaning animal drinking water
2. Treating wastewater from the farm
3. Improving air quality in barns and other indoor areas
4. Treating livestock and poultry feeds to control problems such as insects, fungi, and bacteria.

Concerns

Concerns associated with the four aspects of livestock and poultry production described above include:

- **Livestock and Poultry (Particularly At-Risk Animals) Require Clean Drinking Water:** Clean drinking water is essential for the health of poultry and livestock such as cattle, sheep, and hogs. Poor tasting water leads to decreased consumption and, in turn, less healthy animals. Moreover, high waterborne pathogen levels in the drinking water supply can result in illness or even death. Animal health and mortality rates directly impact the producer's profit margin. Healthy animals often produce better (e.g., in the case of dairy cattle) or grow faster and larger. In addition, lower mortality rates mean higher productivity and/or more animals to reach the market.

- **Untreated Well Water May Contain Chemical and/or Organic Impurities:** Giving animals untreated well water can lead to problems. Well water often contains a variety of impurities including microorganisms, suspended solids, organic matter, iron, manganese, and sulfides. The impurities affect the appearance, taste, odor, and safety of drinking water. Impurities can also clog equipment and watering nipples and emitters, leading to drippy emitters and high replacement and maintenance costs to upkeep the watering system.[1]
- **Chlorine Treatment of Drinking Water Has Limitations:** Chlorine reacts with organic substances and accelerates the production of carcinogenic trihalomethanes (THMs). Chlorine also reacts with substances such as phenol that may be present in the water to create compounds (e.g., chlorophenol) that have unpleasant tastes and odors. Furthermore, chlorine treatment requires the storage and handling of chemicals that can be hazardous to humans and animals.
- **Chlorine May Hurt Poultry:** Chlorine may damage the biological substances in the digestive track of poultry.
- **Municipal Water is a Costly Alternative:** Using municipal or county water for animal drinking water is much more costly than wells or surface water.
- **Animal Wastewater can Contaminate Water Supplies:** Wastewater resulting from livestock and poultry operations contains a variety of contaminants such as ammonia, nitrates, phosphorus, fecal organisms, organic matter, and chemical agents. The wastewater can contaminate water supplies and the soil if it is not properly handled, stored, treated and/or utilized.
- **Animal Waste is Highly Odorous:** Odors arising from livestock and poultry waste and wastewater can present a nuisance and a health hazard to humans.
- **Water Consumption and Treatment are Costly:** Water is used in large quantities in some animal operations, and much enters the waste stream. Water consumption is costly, as is treatment of wastewater.
- **Indoor Air Quality Affects the Health of Animals:** Food producers and processors need to destroy, or remove, any harmful airborne microorganisms, such as bacteria, fungi, and viruses, as well as nitrogen compounds, from the indoor air as these may cause diseases in both animals and humans.

Ozone as a Solution

Ozone can be effectively used to treat livestock and poultry drinking water, wastewater, and indoor air. For water and wastewater applications, it is generated on-site and then injected into

[1] *Success Stories, Hi-Grade Poultry*, www.cleanwaterozone.com/success/poultry.php.

the water by one of several commercially available techniques. Ozone acts as an antimicrobial agent against bacteria, viruses, and parasites, and oxidizes organic substances and suspended solids. Ozonation is also sometimes combined with filtration to remove the oxidized contaminants from the water supply and reduce turbidity. For indoor air quality applications, gaseous ozone is generated on-site and then injected into the space to control airborne contaminants and odors arising from animals and their waste materials. It also has the potential to be used in gaseous form for treating livestock and poultry feeds during storage. The primary benefits of ozone in livestock and poultry production include:

- **Destruction of Waterborne Microorganisms:** The antimicrobial ability of ozone results in cleaner, safer water. Ozone is capable of destroying many waterborne pathogens, including *Escherichia coli*, *Cryptosporidium parvum, Giardia lamblia*, and rotaviruses.
- **Powerful and Fast-Acting:** Ozone is a more powerful oxidizer than chlorine and other chemicals used to treat water, and can react with microorganisms thousands of times faster. The fact reaction rates equate to rapid destruction of contaminants and reduced treatment times. Ozone also has a very short half-life in water, which varies from nearly instantaneous to several hours, depending on the water temperature and pH; thus, it is environmentally friendly. However, since ozone reacts and decomposes so quickly, it does not leave residual protection in the water as chlorine or other chemical agents do.
- **Improved Taste and Odor:** Ozone treatment improves the color, taste, and odor of water due to its ability to react with a wide range of organic compounds, including any oil residues, plus iron, manganese, cyanides, sulfides, nitrites, as well as organically bound heavy metals. In addition, if used in place of chlorine, ozone eliminates the tastes and odors associated with chlorinated byproducts. The result is better-tasting water, and animals are more likely to consume water that tastes good.
- **May Require Filtration:** In systems where iron, manganese, and sulfur compounds are present, ozone can cause precipitation and require filtration to remove the precipitates.
- **No THMs or Other Chlorinated By-Products:** Ozonation is advantageous over chlorine in that it does not yield chlorinated by-products such as THMs. However, it can produce the bromate ion, which is a suspected carcinogen, if bromine is present in the water.
- **pH Stability:** Ozonation of water does not affect the water's pH, nor does it cause an increase in dissolved solids. In comparison, the reaction of chlorine with organic impurities in water can alter the pH of the water.
- **No Storage:** Ozone is generated on-site, eliminating the need for chemical storage and handling. However, high concentrations of residual ozone can be toxic to humans. Therefore, it is very important to ensure residual ozone levels do not exceed recommended regulatory levels.
- **Cost Effective Alternative to Municipal Water:** The use of ozone to treat surface or well water on farms can be a cost effective alternative to using municipal water.[1]

[1] *Ozone for the Purification of Poultry Drinking Water,* Global Energy Partners, LLC, Palo Alto, CA: 2004. 1009527.

- **Effective Treatment of Wastewater:** Ozone can be pumped into the top foot or so of a wastewater lagoon's surface to reduce pathogen levels and odors associated with the lagoon water (see Figure 2). It can also be used to treat water exiting barns and animal operations prior to entry into lagoons to keep odors and pathogen levels low in lagoons. Ozone also enables some of the water used in livestock and poultry operations to be reused. For example, water used to water and mist cattle can be recycled and reprocessed with ozone in order to lower water consumption and wastewater treatment costs.
- **Reduces Airborne Bacteria, Fungi, and Viruses:** Ozone oxidizes bacteria, fungi, viruses, and spores in the indoor air.
- **Eliminates Odors, VOCs and Gaseous Organic Pollutants:** Ozone oxidizes VOCs and organic odors, including those from animals.
- **Improved Health and Safety of Animals:** Ozonation of indoor air in animal housing, such as swine confinements, equates to better performance and growth because animals' immune systems are stronger and they have fewer respiratory problems.

Performance Results

The use of ozone for purifying livestock and poultry water can yield impressive results in terms of animal health and survival rates. Healthier animals often are more productive and achieve greater weights. For example, ozone treatment systems for drinking water have resulted in increased milk production by dairy cows and increased egg production by hens. A specific case study in which drinking water for dairy cows was ozonated showed that milk production increased a sizeable amount thanks to ozone—from an average of 62 lb/day/cow prior to ozone, to 88 lb/day/cow soon after ozone, to 100 lb/day/cow after several months of ozone treatment (see Table 3).[1] Prior to installation of the ozone system, the dairy cows were given well water to drink with impurities such as high levels of hydrogen sulfide. After ozone treatment, hydrogen sulfide levels were reduced to zero, and the odor and levels of other impurities, such as iron, manganese, and organic load, were reduced to acceptable levels. (Note that in systems where iron, manganese, and sulfur compounds are present, ozone can cause precipitation and require filtration to remove the precipitates.)

Preliminary work with ozone for treating animal wastewater has yielded encouraging results as well.[2,3] For example, Michigan State University researchers led by Masten and Yokoyama have shown that ozone treatment with concentrations of 1 to 3 grams per liter of waste destroys phenolics, indolics and other metabolites that are produced by bacteria in swine manure and cause odor.[4] They also found that, for the concentrations tested, ozone reduced but did not eliminate pathogenic microorganisms. Ozone's efficacy at a given concentration is affected by

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[1] Rice, R. G. "Ozone and Ozone/UV in Sanitation and Food Production, May 28, 2003, PowerPoint presentation.
[2] Vansickle, J., 1999, "Ozone Holds Promise for Odor Control," *National Hog Farmer,* http://nationalhogfarmer.com/ar/farming_ozone_holds_promise/index.htm.
[3] Watkins, B.D., S.M. Hengemuele, H.L. Person, M.T. Yokoyama, and S.J. Masten, 1997, "Ozonation of Swine Manure Wastes to Control Odors and Reduce the Concentrations of Pathogens and Toxic Fermentation Metabolites," *Ozone: Science and Engineering,* Vol. 19, No. 5, pp. 425-437.
[4] Ibid.

the contaminant loading and other characteristics of the wastewater such as pH. Lightly loaded wastewater will be cleaned more thoroughly than heavily loaded wastewater for a given concentration of ozone. Odor reductions are particularly encouraging.

Several published studies evaluate the use of ozone for odor reduction in animal production facilities (see Table 22). Most studies show ozone is effective in abating odors. For example, one case study from a swine production facility shows impressive performance results.[1] Table 23 shows the specific results. At the Picket Fence Farm, with ozonation of the indoor air, the average death loss decreased from 1.59% to 0.64%. Moreover, the pigs had a greater daily gain, resulting in an improvement of the average feed conversion by 11%.

[1] Ozone Solutions Inc., *Ozone and Swine Operations Manual*, www.mtcnet.net/~jdhogg/ozone/oznmanual.html#Application%20of%20Ozone%20in%20Swine

II. Beef and Pork Processing

Concerns

As with the production of all foods, food safety and shelf life are of the utmost importance for beef and pork processing. Contamination from microorganisms during slaughter, handling, transportation, and storage can result in premature spoilage and/or food borne illness. In response to highly publicized outbreaks of illness due mainly to *Escherichia coli* and *Listeria monocytogenes*, the USDA and Food Safety and Inspection Service have developed new regulatory requirements for meat packers since the mid 1990s.[1] The technologies implemented to prevent microbiological contamination include cleaning animals, dehairing animals at slaughter with chemical means, knife-trimming contaminated areas, steam or hot water vacuuming, washing carcasses with water, steam, hot water, chemicals, or ozonated water, and using irradiation. A combination of techniques seems to be the most effective.[2]

In raw meat products, adequate heating by the end-user (in addition to proper storage and handling) prior to serving can mitigate most food borne pathogens in beef and pork products, as heating can destroy microorganisms if lethal temperatures and heating times are achieved. However, ready-to-eat cooked cured products such as ham are often served without being re-heated. Therefore, ready to eat products must be delivered to customers with an especially high degree of food safety. The following list summarizes the main concerns associated with beef and pork processing in terms of food safety and shelf life.

- **Microbial Contamination can Cause Food Borne Illness:** Microorganisms encountered during slaughter, transportation, handling and storage can proliferate in products such as cured ham, ground beef, and beef carcasses under certain conditions. Food borne illnesses that are traced back to food producers, grocery stores, restaurants, etc. can result in damaged reputations, costly litigations, or worse for the accused. Moreover, they can result in serious illness or even death for the victims.
- **Microbial Contamination Hastens Spoilage:** Proliferation of spoilage microorganisms during beef aging and general meat processing activities leads to rapid decay of meat products. In addition, the presence of microorganisms reduces shelf lives. Shorter shelf lives mean that travel distances are more limited, and stores must move the products more quickly than for products having longer shelf lives. The result is a loss in profits for food producers and suppliers, as well as leaving the producers and suppliers open to litigation and complaints by consumers.
- **Odors Can be Absorbed During Meat Aging and Storage:** Environments used to age and store meat products must be treated to control contaminants and odors from affecting the taste and quality of stored products.

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[1] Belk, K.E., "Beef Decontamination Technologies," *Beef Facts,* Research and Technical Services, National Cattlemen's Beef Association, Centennial, CO: 2001, www.beef.org.
[2] Ibid.

- **Improved Treatment Alternatives are Always in Need:** As mentioned above, there is a variety of alternatives currently employed or under development for decontaminating meat products. As with most technologies, they are characterized by merits and limitations. Further research into effective alternatives and using combinations of technologies to achieve added benefits is needed.

Ozone as a Solution

The application of ozone to the beef and pork processing industry is expanding rapidly. However, more research is needed to further development. Preliminary results show that ozonated water can be an effective alternative for washing and removing contaminants from meat carcasses and products under certain conditions. In gaseous form, ozone can be injected into storage environments to control odors and other airborne contaminants, as well as contaminants on surfaces. It can also be injected into airtight packages of meat to inhibit pathogens and extend shelf live. Concentrations of ozone tested in meat applications have ranged from 0.2 to 5000 ppm. The main merits of ozone for beef and pork processing applications include:

- **Powerful Antimicrobial Ability:** In gaseous or water applications, ozone can potentially destroy a variety of microorganisms on beef and pork products, including *E. coli* and *L. monocytogenes* bacteria, which are of particular concern. However, ozone must come in contact with an organism in order to inactivate it, and is less effective in crevices where microbes can hide.
- **Useful in Combination with Other Antimicrobial Actions:** Ozone can be combined with other decontamination alternatives to enhance microbial destruction. For example, spray washing meat with plain water and then rinsing with ozonated water has been shown to be more effective under certain conditions than either spray washing alone or using other types of chemical rinses (including trisodium phosphate, acetic acid, and commercial sanitizers) after spray washing.[1]
- **Improved Indoor Air Quality:** By destroying microorganisms and other contaminants in indoor aging and storage environments, gaseous ozone helps prevents cross-contamination, microbial growth, and odors from affecting meat products.
- **Lack of Residue:** Ozone will not leave behind chemical residues on meat washed with ozonated water, nor will it leave residues in the wastewater, as other chemical cleaning agents may.
- **No Storage:** Ozone is generated on-site, eliminating the need for chemical storage and handling. However, high concentrations of residual ozone can be toxic to humans. Therefore, it is very important to ensure residual ozone levels do not exceed recommended regulatory levels.

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[1] Gorman, B.M., J.N. Sofos, J.B. Morgan, G.R. Schmidt, G.C. Smith, 1995, "Evaluation of Hand-Trimming, Various Sanitizing Agents, and Hot Water Spray-Washing as Decontamination Interventions for Beef Brisket Adipose Tissue," *J. Food Protection,* Vol. 58, No. 8, pp. 899-907.

Performance Results

Results from experimental work with ozone in beef and pork processing show that ozone is capable of reducing microbial counts on meat surfaces and in meat storage environments. Actual microbial destruction efficiencies vary widely with application, and depend on experimental parameters such as ozone concentration, exposure time, humidity, temperature, type of microorganism, and the presence or lack of other decontamination measures used in combination with ozone. In general, both gaseous ozone and ozonated water can contribute to microbial control during meat processing and storage. However, decontamination of meat may be most effective when ozone is combined with other measures to provide multiple protection strategies. Table 18 summarizes findings from a few representative studies. Research is continuing to better quantify ozone's application in beef and pork processing.

Table 18
Use of Ozone as an Antimicrobial Agent for Beef and Pork — Summary of Representative Research Efforts

Research Group(s)	Product(s)	Application(s)	Method	Results
Kaess and Weidemann [a]	Beef	Control of *Pseudomonas, Candida, Penicillium* and *Thamnidium* organisms on muscle slices with gaseous ozone	Beef muscle slices were contaminated with *Pseudomonas, Candida, Penicillium* and *Thamnidium* Samples were subjected to continuous ozone with concentrations of 0.13 to 5 mg/m^3, equilibrium relative humidity (EH) values of 98.0 to 99.3%, and at a temperature 0.3 ºC In two experiments, 0.6 mg/m^3 ozone in air with 11% CO_2 was tested	• An ozone concentration of 0.6 mg/m^3 and EH value of 98.5% was optimal for preventing color changes in meat due to oxidation while at the same time slightly delaying surface growth of some of the microorganisms • Ozone (0.6 mg/m^3) increased the point of manifestation of bacteria in air “the slime point” from a surface population of 10^8 cells/cm^2 to a population of 10^9 cells/cm^2 • Introducing CO_2 or lowering the humidity further delayed “the slime point”
Gorman et al. [b]	Beef brisket	Reduction of bacterial contamination on beef brisket fat by a variety of alternatives	Treatment alternatives including hand trimming, hot and cool water wash, various chemical rinses and combinations of the above were compared for efficacy in removing fecal material and reducing bacterial contamination on beef brisket fat samples The samples were inoculated with fecal paste containing *E. coli*	• In cases where the samples were first sprayed with 16 or 35 ºC water and then treated with a chemical rinse, 0.5% ozone and 5% hydrogen peroxide were superior to other chemical rinses tested and achieved total plate count reductions ranging from 2.72 to 2.86 log CFU/cm^2 for ozone and 2.60 to 2.87 log CFU/cm^2 for hydrogen peroxide

Research Group(s)	Product(s)	Application(s)	Method	Results
McMillin and Michel [c]	Ground beef	Flushing of gaseous ozone into airtight packages of ground beef to inhibit pathogens such as *E. coli*	Ground beef was inoculated with *E. coli* Airtight packages of beef patties were flushed with ozone concentrations of 500, 3500 and 5000 ppm Concentrations of *E coli* were determined after 24 hours of storage at 4.4 ºC with the ozone	• Ozone modestly reduced *E coli* concentrations by about 5 to 16% depending on the level of ozone concentration and the humidity of the gas • The level of reduction increased with concentration

Table 18
Use of Ozone as an Antimicrobial Agent for Beef and Pork — Summary of Representative Research Efforts, Continued

Research Group(s)	Product(s)	Application(s)	Method	Results
Julson et al. [d]	Ready to eat cured ham	Treatment of cured ham with ozone to control *L. monocytogenes*	The effectiveness of ozone in gaseous, aqueous, and humid (>90%) environments on destroying *L. monocytogenes* on cured ham was investigated Concentrations of ozone tested were 0.2, 0.5 and 1 ppm, with exposure times of 1, 15 and 30 minutes, and temperatures of 10 and 20 ºC	• The maximum level of inactivation of *L. monocytogenes* achieved was equal to 99.7%, which is less than 1-log cycle reduction • The gaseous environment was most effective, followed by the aqueous and then the humid environments • Effectiveness increased with ozone concentration, exposure time, and temperature

[a] Kaess, G., and J.F. Weidemann, 1968, "Ozone Treatment of Chilled Beef," *J. Food Technology,* Vol. 3, pp. 325-334.

[b] Gorman, B.M., J.N. Sofos, J.B. Morgan, G.R. Schmidt, G.C. Smith, 1995, "Evaluation of Hand-Trimming, Various Sanitizing Agents, and Hot Water Spray-Washing as Decontamination Interventions for Beef Brisket Adipose Tissue," *J. Food Protection,* Vol. 58, No. 8, pp. 899-907.

[c] McMillin, K.W., and M.E. Michel, Department of Animal Science, LSU AgCenter, 2000, "Reduction of E. coli in Ground Beef with Gaseous Ozone," *Louisiana Agriculture,* Vol. 43, No. 4.

[d] Julson, J.L., K. Muthukumarappan, and D. Henning, "Effectiveness of Ozone for Controlling Listeria monocytogenes in Ready to Eat Cured Ham," NPPC Project #99-221, South Dakota State University.

III. Poultry Processing

Concerns

Contamination of raw and ready to eat poultry products with microorganisms, as well as with chemical residues, is a major concern for poultry processors and consumers. Live poultry is potentially exposed to hazardous contaminants from feeds, living environments, and cross-contamination with infected birds. In addition, shell eggs can become contaminated (most often with *Salmonella spp.*) during transovarian passage from an infected mother, or from contact with contaminated environments in the hatchery or during processing. During slaughter, poultry meat can become contaminated by exposure to feces or contaminated equipment or surfaces. It is also subject to cross-contamination during processing activities such as chilling.

Microbial contaminants are of particular concern in terms of food safety and product shelf live. Three of the most worrisome pathogens are *Salmonella spp, E. coli* and *Listeria spp.* Spoilage organisms are also undesirable because they limit the shelf life of poultry products.

Some of the conventional antimicrobial agents or methods used for decontamination have limitations. For example, chemical disinfectants can leave behind residues on products, are potentially hazardous to live poultry, and may adversely impact the environment. In addition, the use of chemicals such as chlorine to control microorganisms in poultry chiller water is characterized by the downsides of chemical residues in wastewater including high treatment costs. Moreover, chlorine is unable to adequately clarify the water, and so chiller water must be replenished often.

The list below summarizes the main concerns related to poultry processing that ozone can help in mitigating.

- **Contaminated Poultry can Cause Food Borne Illness:** Illnesses attributed to microbial species such as *S. enteritidis, L. monocytogene* and *E. coli* have caused outbreaks of food borne illness in consumers, and resulted in product recalls by food producers, loss in profits, and litigation exposure for responsible parties.
- **Spoilage Bacteria Limit Shelf Life:** Shelf life is determined by measuring psychrotroph counts. (For broiler carcasses the acceptable shelf life count is 7.0/cm^2.)[1] Higher counts of spoilage bacteria result in shorter shelf lives, thus limiting travel distances, and requiring that products be moved from store shelves more quickly.
- **Poultry Chiller Water Gets Contaminated:** Poultry chiller water becomes readily contaminated by microorganisms, suspended solids, and organic matter and must be replenished or treated. Conventional chemical treatments such as chlorine kill microorganisms in chiller water, but do not clean the water.

[1] *Direct Food Additive Petition: Ozone as an Antimicrobial Agent for the Treatment, Storage and Processing of Foods in Gas and Aqueous Phases*, EPRI, Palo Alto, CA: August 2, 2000, Section 2.1.1.2.

- **Water Consumption and Treatment are Costly:** In conventional poultry chiller systems, water is used in large quantities and much enters the waste stream. Water consumption is costly, as is treatment of wastewater.
- **Poultry Hatchery Equipment Requires Decontamination:** Antimicrobial agents are needed to clean hatchery equipment in order to prevent contamination of poultry. Formaldehyde is commonly used for this application, but it is facing restricted use because it can cause adverse health effects in humans.

Ozone as a Solution

In the poultry processing arena, ozone has primarily been investigated for rinsing poultry (see Figure 16), treating poultry chiller water, and as a gaseous antimicrobial agent in poultry hatcheries. In aqueous applications, ozone kills pathogens and oxidizes impurities in water. It is a more powerful oxidant than chlorine and therefore is an effective replacement for chlorine as an antimicrobial agent in rinsing poultry and treating chiller water. Although ozonated water can reduce microbial counts on poultry surfaces, it is most effective in killing suspended microorganisms in water. By controlling waterborne microorganisms, ozone prevents cross-contamination in chiller water and extends the usefulness of the water. Ozone can also oxidize other waterborne impurities, so it is quite effective for recycling water, particularly in combination with filtration and other additives, such as UV or hydrogen peroxide.

Figure 16
Use of Ozonated Water to Rinse Poultry

Source: Clean Air and Water Systems, Charter, Inc., www.charter-inc.com.

In gaseous form, ozone can replace formaldehyde as an antimicrobial agent for poultry hatchery equipment. Studies have shown that formadehyde may be more effective, but in sufficient concentrations, ozone is effective enough (with microbial reductions on the order of 99.9 to 99.99% for many bacteria) to be a replacement should formaldehyde use become restricted.

The main merits of implementing ozone in poultry processing include:

- **Powerful Antimicrobial Ability:** Ozonation reduces microbial counts in poultry wash water and on surfaces of poultry products. It is effective in destroying a variety of pathogenic microorganisms, including *S. enteritidis, L. monocytogene* and *E. coli,* as well as spoilage organisms. Because of its antimicrobial ability, ozone is capable of improving food safety and extending the shelf life of products.
- **Lower Water Requirements:** Ozonation, particularly if combined with filtration and other additives such as UV or hydrogen peroxide, improves water quality significantly over chlorination alone. Since the water stays cleaner longer, less makeup water is needed, and less contaminated water enters the waste stream. This can equate to substantial monetary savings for the poultry producer due to water and water treatment costs reductions.
- **Effective Water Recycling:** Because of its efficacy in oxidizing a variety of microorganisms and waterborne contaminants, ozone can be used quite effectively to treat recycled water.
- **No THMs or Other Chlorinated By-Products:** Ozonation is advantageous over chlorine in that it does not yield chlorinated by-products such as THMs. However, it can produce the bromate ion, which is a suspected carcinogen, if bromine is present in the water.
- **Potential Destruction of Pesticide and Chemical Residues:** To a certain degree, ozone is capable of destroying pesticide and chemical residues in wash water. In addition, ozone will not leave behind chemical residues on poultry washed with ozonated water, nor will it leave residues in the wastewater.
- **No Storage:** Ozone is generated on-site, eliminating the need for chemical storage and handling. However, high concentrations of residual ozone in the air can be toxic to humans. Therefore, it is very important to ensure residual ozone levels do not exceed recommended regulatory levels.

Performance Results

Numerous studies have shown the potential for ozone as an antimicrobial agent in poultry processing. Studies have focused on three main areas: direct treatment of poultry products with ozonated water, treatment and recycling of poultry chiller water with ozone, and treatment of poultry hatcheries with gaseous ozone. Table 19 summarizes a few representative research projects. Other reseach efforts investigating poultry applications of ozone include but are not limited to work by Kim and Kim[1], Mulder,[2] Diaz and Law,[3] Sheldon and Chang,[1,2] and Izat et al.[3]

[1] Kim, I-D, and S-D Kim, 1991, "Ozone Treatment for Circulation of Fresh Country Meat," *Journal of Korean Soc. Food Nutrition*, Vol. 20, No. 5, pp. 483-487.
[2] Mulder, R.W.A.W, 1995, "Decontamination of Broiler Carcasses," *World Poultry-Misset*, Vol. 11, No. 3, pp. 39-43.
[3] Diaz, M.E., and S. E. Law, 1999, "UV-Enhanced Ozonation for Reduction of Pathogenic Microorganisms and Turbidity in Poultry-Processing Chiller Water for Recycling," in *Proc 14th Ozone World Congress,* Dearborn, MI, USA, Vol. 2, pp. 391-403.

The results indicate that rinsing poultry in ozonated water can reduce microbial counts on poultry surfaces. In addition, ozonation of poultry chiller water is highly efficacious in destroying microorganisms and reconditioning water for reuse, particularly if combined with filtration to remove particulates and additives such as UV radiation or hydrogen peroxide to enhance oxidation efficiency. Lastly, gaseous ozone has the potential to replace formaldehyde as an antimicrobial agent in hatcheries.

[1] Sheldon, B.W., and Y.H. Chang, 1986, “Efficacy of Ozone as a Disinfectant for Poultry Carcasses and Chill Water,” *Journal of Food Science*, Vol. 51, No. 2, pp. 305-309.
[2] Chang, Y.H., and B.W. Sheldon, 1989, “Effects of Chilling Boiler Carcasses with Reconditioned Poultry Prechiller Water,” *Poultry Science,* Vol. 68, pp. 656-662.
[3] Izat, A.L., M. Adams, M. Colberg, and M. Reiber, 1990, “Effects of Ozonated Chill Water on Microbiological Quality and Clarity of Boiler Processing Water,” *Arkansas Farm Research,* Vol. 39, No. 2, pp. 9.

Table 19
Use of Ozone as an Antimicrobial Agent for Poultry — Summary of Representative Research Efforts

Research Group(s)	Product(s)	Application(s)	Method	Results
Yang and Chen	Thigh and breast broiler parts	Reducing microorganism counts and extending shelf life of poultry parts by washing poultry with ozonated water [a]	Cutup broiler parts were weighed and soaked in ice cold water Then, using a washing bottle dispenser, they were treated with 3.88 ppm ozone under a flow rate of 2050 mL/min for 20 minutes Controlled samples were treated with compressed air After treatment, microbial samples were taken with cotton swabs	• Ozone treated parts had consistently lower microbial counts than control samples • Immediately after treatment, counts were 90.5, 90.5, and 86% lower than for controls at 37, 20, and 7 ºC, respectively • Results indicate that shelf life of the poultry was extended by 2.4 days with the use of ozonation
Jindel et al	Broiler drumsticks	Reducing microorganism counts and extending shelf life of poultry parts by treating chiller water with ozone [b]	Pre-chill drumsticks were treated with ozone (0.44 to 0.54 ppm) or air (control) during immersion chilling for 45 minutes at 0 to 4 ºC Select drumsticks and chiller water samples were evaluated for microbial counts on day 0 Other drumsticks were individually wrapped and stored at 1 to 3 ºC and then were evaluated on different days, ranging from day 2 to day 14	• Ozonation extended shelf life of drumsticks by 1 to 2 days over control samples • Microbial counts were lower for ozonated drumsticks, but the difference in counts between ozonated samples and control samples decrease with storage time • Microbes in ozonated chiller water were significantly reduced or eliminated, depending on the type of organism

Table 19
Use of Ozone as an Antimicrobial Agent for Poultry — Summary of Representative Research Efforts, Continued

Research Group(s)	Product(s)	Application(s)	Method	Results
EPRI Public Interest Energy Research Program, California Energy Commission, Energy Efficiency Division NovaZone	Poultry carcasses	Reconditioning chiller water with membrane ultrafiltration, ozonation, and hydrogen peroxide [c]	Chiller overflow flow water was treated with an ultrafiltration membrane and then ozonated with a concentration of 1 to 2 ppm ozone Pre-chiller poultry carcasses were rinsed with the ozonated ultrafiltrate for 30 seconds and then placed in a contactor tank for soaking 3% hydrogen peroxide (0.05 ppm) was added to the tank as a secondary oxidizer and the poultry soaked for 30 minutes	• 30 minutes of treatment in the tank reduced E. coli counts from an average of 568 (for the control) to 45 • Membranes can effectively reduce chiller water use • Ozone with proper additives can replace chlorine treatment
Whistler and Sheldon	Poultry	Replacing form-aldehyde with gaseous ozone for microbial control in poultry hatcheries[d]	*E. coli, Pseudomonas fluorescens, Salmonella typhimurium* and *Proteus spp.* were inoculated onto open petri plates of filter paper strips and exposed to ozone or formaldehyde in a poultry setter	• Ozone (1.41 to 1.68% by weight) resulted in >4-log bacterial reductions on the open plates and >3-log reductions on filter strips • Formaldehyde (triple strength) was more lethal than ozone, but ozone may be an effective alternative in the event that formaldehyde use is restricted

[a] Yang, P.P.W., and T.C. Chen, 1979, “Effects of Ozone Treatment on Microflora of Poultry Meat,” *Journal of Food Processing and Preservation,* Vol. 3, pp. 177-185.

[b] Jindal, V., A.L. Waldroup, R.H. Forsythe, and M. Miller, 1995, “Ozone and Improvement of Quality and Shelflife of Poultry Products,” *Journal of Applied Poultry Research*, Vol. 4, pp. 239-248.

[c] *Membrane Filtration and Ozonation of Poultry Chiller Overflow Water: Study of Membrane Treatment to Reduce Water Use and Ozonation for Sanitation at a Poultry Processing Plant in California,* EPRI, Palo Alto, CA: 1999. TR-114435.

[d] Whistler, P.E., and B.W. Sheldon, 1989, “Comparison of Ozone and Formaldehyde as poultry hatchery disinfectants,” *Poultry Science,* Vol. 68, pp. 1345-1350.

IV. Sanitation of Equipment and Work Areas

Concerns

It is critical to maintain clean equipment and work areas to prevent cross-contamination of meat and poultry products and the subsequent risk of food borne illness. Therefore, one major concern is formation of biofilms on food processing equipment. Biofilms are simply layers of microorganisms bonded tightly to a surface, and they may consist of anything, including bacteria, yeasts, molds, algae, etc.[1] Microbes can attach themselves like glue to a surface by releasing their own biological material, exopolymeric substance (EPS).[2] This extra layer provides nutrients as well as protection against sanitizers and disinfectants. If a surface is not properly cleaned and sanitized, microorganisms can aggregate and form biofilms. More organisms will grow on the bottom because more nutrients are on the surface. Subsequent layers of organisms have fewer nutrients, and they become adapted to harsher conditions.

Common cleaning and sanitation practice is to rinse equipment and work areas with chlorinated water. Although chlorine usually is effective against biofilms because it can destroy EPS and inhibit growth, microorganisms may build up resistance to chlorine. This is of particular concern with microorganisms, such as *E. coli* and *Giardia*, which may cause serious illness and may lead to deaths. Chlorine has additional drawbacks. One such drawback is that chlorine builds up in the rinse water, which reduces the water recycling potential and makes it necessary to replace the rinse water frequently. This, in turn, adds to the operation costs. Another drawback of chlorine is its inability to break down biological oxygen demand (BOD) solids in the water. The BOD build-up also adds to the operation costs because of higher BOD charges once the water is discharged to the treatment plant. Chemicals are also harsh on equipment made of metals and wood.

The list below summarizes the main concerns associated with sanitation of equipment and work areas in meat and poultry processing that ozone can help mitigate:

- **Microbial Contamination can Cause Food Borne Illnesses:** Some types of microorganisms, such as *E. coli* and *Salmonella*, can cause food borne illnesses. If an outbreak of an illness is tracked back to a food production or processing plant, damaged reputations and costly fees and litigations may be the result. Therefore, it is important to eliminate harmful microorganism from the food itself as well as any equipment or work areas that may come in contact with the food.
- **Prevent Cross-Contamination:** Food processors are especially concerned about preventing cross-contamination in their facilities. Microbial load on process equipment, such as conveyor belts, knives, and cutters, easily can transfer from the equipment surfaces to the food.

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[1] J. Yuan and S. Thakkar, *Biofilms in Food Processing Plants*, Fresh-cut™ Magazine, April 2001.
[2] Ibid.

- **Microbial Contamination Shortens Shelf life and Causes Spoilage:** Microbial contamination on meat and poultry products may result in shorter shelf life and spoilage. This in turn affects the bottom-line for the processing facility.
- **Replace or Limit the Use of Chemical Sanitizers:** Since commonly used sanitizers, such as caustic and hazardous chemicals, have several drawbacks, food production and processing facilities alike are investigating alternatives to replace these chemicals for sanitation. Among the more severe drawbacks are chemicals in the rinse water making water recycling more difficult, and chemicals requiring safe handling and disposal. Chlorine is also corrosive to metals.
- **Costly Water and Wastewater Discharges:** Food production and processing facilities face increasingly stringent regulations and expenses in meeting strict environmental standards. Many facilities have effluent burdens because of build-up of chlorine and BOD in rinse water.
- **Resistance to Chemicals:** Microorganisms may develop a resistance to chemical sanitizers. For example, *E. coli*, *Giardia*, and *Cryptosporodium* and other new pathogens resist chlorine. There are also some microorganisms that are resistant to ammonia compounds.[1]

Ozone as a Solution

During the production and processing of meat and poultry products, ozonated water can be sprayed directly onto floors, walls, drains, trucks, railcars, tanks (external and internal), and processing equipment via mobile or centralized systems with hand-held or drop-down sprayers. External surfaces are generally cleaned with mobile spray equipment. Enclosed vessels and piping systems, however, require cleaning in place (CIP). Figure 17 shows the use of ozonated water for washing processing equipment.

For efficient sanitation using ozone, a two-step procedure is generally required. First, the surfaces are cleaned and the organic residues in which bacteria are embedded are removed. Thereafter, ozonated water sanitizes the surfaces by eradicating bacteria adhering to the surfaces. As ozone can destroy bacteria, viruses, fungi, and spores, no other biocide is necessary. Ozone has also proven effective in destroying many new pathogens and chemical-resistant strains of harmful microorganisms that have appeared recently. Over time, the use of ozonated water reduces overall microbial load in the facilities. It also prevents biofilms from developing on processing equipment. In addition, ozonated rinse water can be recycled easily.

To date, ozone's use for sanitation of equipment in meat and poultry production has not been implemented to its fullest capacity; it may have much broader application here. For example, ozone could be used for pre-washing of poultry, swine, and calf facilities, daily washing of baby-pig operations, rinsing of swine production facilities, and washing of milking machines and milk parlors in dairy facilities.[2] As animal densities increase, the probability of disease also increases,

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[1] P. Clark, *New Developments in Sanitation Help Keeps Food Plants Clean*, Food Technology, Vol. 57, No. 10, October 2003.
[2] C. Sopher, *Ozone in Food Technology*, PowerPoint Presentation, October, 2002.

resulting in increased use of antibiotics and mortality. Washing of animal housing with ozone may reduce the need for antibiotics and result in healthier animals.

Figure 17
Use of Ozonated Water for Washing Food Processing Equipment

Source: Clean Air and Water Systems, Charter, Inc., www.charter-inc.com.

The main merits of using ozone as a sanitizer of equipment and work areas include:

- **Powerful Microbial Control:** Ozone is capable of destroying microorganisms, including those that can cause food borne illness, such as *E. coli*, *Giardia*, and *Salmonella*.
- **Reduces Risk of Cross-Contamination:** Sanitation of process equipment and work areas with ozone reduces the risk for cross-contamination. Since ozone is safe to use on caustic-sensitive equipment it has an added advantage over caustic sanitizers.
- **Reduces Chemical Use, Handling and Storage:** Ozone can replace many commonly used chemicals, such as chlorine, sulphur dioxide, and chlorinated trisodium phosphate (TSP), for sanitation of process equipment and storage tanks. Therefore it reduces or eliminates the storage, handling, use, disposal, and chemical reporting of caustic and hazardous chemicals. This also results in cost savings.
- **No Chemical Residue that Requires Final Rinse:** Unlike chlorine or other types of chemicals, ozone is a final, no-rinse sanitation agent. Since ozone rapidly decomposes to oxygen, no final rinsing is required.
- **Not Corrosive to Equipment:** Unlike chemicals, ozone does not corrode stainless steel equipment.

- **Provides Water and Wastewater Savings:** Rinsing equipment and surfaces with ozonated water and the subsequent ozonation of the recaptured water reduces the amount of water required in the sanitation process since it can be recycled; thus, providing water savings. In addition, sanitation with ozonated water provides substantial wastewater savings because the wastewater is free of chlorine and BOD build-ups, lowering the wastewater disposal fees.
- **Sanitizes Water Drainage Systems in an Environmentally-Friendly Way:** Because of its short half-life, ozone reacts rapidly. Therefore, it does not lead to a harmful residual that could otherwise damage beneficial bacteria in the septic system or wastewater disposal plant. For the same reason, ozonated water does not pollute ponds.
- **Extended Hours of Operation:** Ozone is a fast and efficient sanitizing agent. In some cases, sanitation with ozone can be performed during production without comprising product or employee safety. Consequently, some of the time that previously was consumed by sanitation with chemicals may now be used for production.

Performance Results

Ozonated water has proven effective as a sanitizer for many types of surfaces in the production and processing of meat and poultry products, including meat processing equipment, stainless steel transportation racks, plastic storage tubs, walk-in coolers, knifes, and worker apparel (e.g., gloves, aprons, arm guards), as summarized in Table 20. In general, results show that concentrations of 1 to 1.4 ppm of ozone in water, and contact times on the order of 5 to 15 seconds, can effectively replace chlorinated water and/or 180 °F water in the sanitation applications tested. The performance of ozone is often equal or superior. Ozone also reduces water and wastewater costs as well as lowers water heating energy requirements (since cooler ozonated water can replace hot water).

For a complete description of ozone for the sanitation of equipment and surfaces in all aspects of the food industry, please refer to the section entitled *Ozone for Sanitation of Equipment and Work Areas in Food Production and Processing.*

Table 20
Ozonated Water for Sanitation of Equipment and Work Areas in the Meat and Poultry Industries – Representative Installations and Research Projects

Processing Facility or Research Site	Application	Method	Results
Plumrose USA, Inc. [a] Booneville, MS	Sanitation of meat processing equipment, including stainless transportation racks, plastic storage tubs, and stainless steel walk-in coolers.	A centrally located ozone system provides 1 ppm ozonated water on demand. The water is delivered in closed piping under low pressure to appropriate sanitation operations within the plant. One such operation is the sanitation of the stainless steel transportation racks involving a three-step process using an alkali cleaner and two ozonated water rinses.	• Ozonated water has replaced chlorinated water in the two rinses of the stainless transportation racks • Equal or better sanitation levels compared to chlorine • Final rinse water is recycled for the first rinse, which reduces water use and wastewater disposal costs • The use of cold ozonated water rather than warm chlorinated water for the final rinses provides energy savings due to reduced heating requirements and HVAC load
Meat and Sausage Processing Plant [b]	Sanitation of processing equipment	The plant experienced a *Listeria* recall. Management shut down the plant and implemented proper sanitation throughout the plant. Today, ozone is in key areas.	• Microbial results better than those obtained with caustic chemicals • Eliminates storage of hazardous materials

Table 20
Ozonated Water for Sanitation of Equipment and Work Areas in the Meat and Poultry Industries – Representative Installations and Research Projects, Continued

Processing Facility or Research Site	Application	Method	Results
Pork Processing Plant [c]	Sanitation of processing equipment and knives	A mobile ozone system sprayed all samples with ozonated water with an ozone concentration of 1.1 to 1.4 ppm for 5 seconds	• Significant reduction in microbial load on all areas, equipment and samples tested • Ozone performed as good or better than 180°F water in reducing microbial load on cutting knives, air knife, wizard knife, hook cutter, steel glove, split saw, and brisket saw • Ozone can be used as a substitution for 180°F water for sanitizing purposes
Pork Processing Plant [d]	Sanitation of PPE equipment (gloves, apron, and arm guard), cutting knives, Mezzanine equipment (hopper and grinder), hook cutter, split saw, brisket saw, and meat cuts.	A mobile ozone system sprayed all samples with ozonated water with an ozone concentration of 1.1 to 1.4 ppm for approximately 10 to 15 seconds	• Significant reduction in microbial load on all areas, equipment and samples tested • Ozone performed as good or better than 180°F water in reducing microbial load on PPE equipment, cutting knives, Mezzanine equipment, hook cutter, split saw, and brisket saw • Various meat cuts from whole carcass showed acceptable microbial reduction; however, higher ozone concentrations would be required to ensure acceptable reduction numbers on organic material, such as pig ear, feet, and hide

[a] *Ozone Sanitizing for Meat Processing Equipment*, EPRI, Palo Alto, CA: 1999. TA-114172.

[b] Rice, R., *Ozone and Ozone/UV in Sanitation and Food Production*, PowerPoint Presentation, May 28, 2003.

[c] Results from testing at a Fortune 50 Pork Processing Plant 4/49/02, *The Effectiveness of Ozonated Water as a Sanitizer on the Kill Floor—Microbial Kill Results*, http://www.ozonecaws.com/Ozone-Knife-Report.pdf.

[d] Results from tests at a Fortune 50 Pork Processing Company, *The Effectiveness of Ozonated Water for Hard Surface Sanitation, Meat Cuts and Knife Dips—Microbial Kill Results*, http://www.ozonecaws.com/Ozone-Report-1.pdf.

OZONE FOR INDOOR AIR QUALITY IN FOOD PRODUCTION AND PROCESSING

The food production and processing industry is concerned about indoor air quality because poor indoor quality may cause problems ranging from allergic reactions to infection to cancer and death in humans and animals. In particular, livestock and poultry producers struggle with providing better indoor air quality for their animals in an attempt to raise healthier and more productive animals. Livestock and poultry producers also face increasingly stringent environmental standards related to odor abatement as volatile organic compounds (VOCs) released by animal housing affects neighbors. For food processors, harmful airborne contaminants that can contaminate the food can also potentially reach consumers causing illness. Poor indoor air quality also impedes worker productivity, and results in higher absenteeism. Moreover, allergens common in some types of food production facilities, such as bakeries and peanut packing facilities, may cause allergic reactions in those people exposed to the allergens.[1]

This section describes the use of ozone for improving indoor air quality and controlling odors in food production and processing facilities. The discussion includes the main concerns associated with poor indoor air quality, and also describes how ozone is generally applied to improve indoor air quality. Finally, it provides representative performance data for ozone used in indoor air quality applications in the food production and processing industry.

Concerns

There are two types of contaminants found in the indoor air: particulates and gases. Some of the more troublesome particulates in the food production and processing industries include fungi, bacteria, viruses, and spores. For example, poor indoor air quality in animal production facilities may result in animals becoming sickly and not producing as well. In food processing facilities, harmful airborne bacteria and viruses can potentially contaminate the processed food and eventually reach consumers causing diseases and deaths. Gaseous contaminants can also be worrisome. A case in point are VOCs released by certain types of food operations, such as animal farms, diaries, slaughterhouses, and fish processing plants as they may cause odor problems for neighbors and visitors. In an effort to meet increasingly stringent regulations for odors, these operations need to improve odor control practices. As poor indoor air quality and odors may impede worker productivity and result in higher absenteeism, food producers and processors are interested in improving the indoor air quality in general.

The list below summarizes the main concerns associated with poor indoor air quality and current practices to address these indoor air quality problems:

[1] C. Sopher, *Ozone in Food Technology*, PowerPoint Presentation, October, 2002.

- **Remove or Destroy Harmful Airborne Organisms:** Food producers and food processors alike need to destroy, or remove, any harmful airborne microorganisms, such as bacteria and viruses, from the indoor air as these may cause diseases in both animals and humans.
- **Remove Allergens:** The removal of allergens from indoor air may also be necessary to limit allergic reactions.
- **Increase Productivity and Less Absenteeism:** Poor indoor air quality affects the productivity of humans and animals. Although hard to quantify, improved indoor air quality, in general, results in lower rates of sickness, mortality, and absenteeism.
- **Control Odors Efficiently:** Animal housing for swine, cattle, and poultry usually cause extreme odors that may be unpleasant to visitors and neighbors. Also, fish processing industries generate odors that may require abatement. However, most air purification technologies, including filters and electrostatic precipitators, cannot effectively control odors, VOCs, and other gases.

Ozone as a Solution

Ozone in the gaseous phase is effective in purifying indoor air by destroying VOCs and controlling odors. Subsequently, ozone generators may be used in livestock, poultry, and fish production facilities and processing plants to control odors. Ozone also works well for cleaning and disinfecting HVAC ducts, where it controls the growth of mold and bacteria and the spread of odors and Legionnaire's disease. Ozone generators have also been installed at restaurants, meat lockers and food storage facilities to extend the shelf life of meats, cheeses, fruits, eggs, vegetables etc. by retarding bacterial growth and ethylene production. Ozone for storing fruits and vegetables is discussed in greater detail in the section entitled *Ozone for Fruit and Vegetable Production and Processing*.

In the simplest method of treating indoor air, ozone systems operate at periods when the building or rooms are unoccupied, such as at nights or weekends, generating ozone for mold remediation or odor removal purposes. When people and animals are present ozone levels should be maintained at safe residual ozone levels. There are no federal agencies that approve ozone systems for use in occupied space, but there are several federal agencies that have established health standards or recommendations to limit human exposure to ozone. Table 21 summarizes these ozone exposure limits. The American Lung Association suggests that ozone generators not be used at all in occupied buildings.[1]

[1] American Lung Association, *Air Cleaning Devices*, February 2000, www.lungusa.org/air/air00_aircleaners.html.

Table 21
Ozone Health Standards

Federal Agency	Ozone Exposure Limit (ppm=parts per million)
Food and Drug Administration (FDA)	Requires indoor medical devices to produce less than 0.05 ppm
Environmental Protection Agency (EPA)	Requires a maximum 8-hour average *outdoor* concentration of 0.08 ppm (National Ambient Air Quality Standard)
Occupational Safety and Health Administration (OSHA)	Requires that workers not be exposed to an average concentration of more than 0.10 ppm for 8 hours or more than 0.3 ppm for 15 minutes
National Institute of Occupational Safety and Health (NIOSH)	Recommends an upper limit of 0.10 ppm not to be exceeded at any time

Source: Environmental Protection Agency, *Ozone Generators that are Sold as Air Cleaners: An Assessment of Effectiveness and Health Consequences*, Fact Sheet, www.epa.gov/iaq/pubs/ozonegen.html.

When an ozone system is operating directly in a room or parallel to a HVAC system, the ozone output is generally 0.5 to 2 g/hr, but may be as high as 10 g/hr. However, the residual ozone level should never exceed 0.10 ppm when people are present in a building. There are several ways to control the level of residual ozone. The most common are: 1) operating the ozone system when the facility is unoccupied, 2) generating ozone only when the duct fan is operating, 3) manually adjusting the ozone level output, 4) using ozone monitors to measure the residual ozone level and adjust ozone output accordingly, and 5) using filters to reduce the residual ozone level. The first approach is common in buildings damaged by fire, flooding, and mold, where higher ozone levels are required. The second and third approaches are the most common in smaller stand-alone units while the two latter approaches are the preferred methods in ozone systems used inside, or in parallel, with HVAC ducts. Figure 18 illustrates how an ozone system can be integrated into a building's HVAC system.

Recently, a few companies have also evaluated the combination of ultraviolet germicidal irradiation (UVGI) and ozone for indoor air purification.[1] UVGI relies on UV-C, which has a wavelength of 100 to 280 nm, for purification of the indoor air. These emerging systems are usually referred to as UV/O_3 catalytic oxidation systems, and they combine UV-C, ozone and humidity to create hydroxyl radicals, which are faster and stronger oxidizers than ozone.[2] In this application, ozone is generated by a dual UV-C lamp rather than corona discharge. The optimum ozone output using UV-C is obtained with a UV-C wavelength of 185 nm. However, 185 nm UV-C is not germicidal so UV-C with a wavelength of 254 nm is required to obtain the

[1] Companies manufacturing UV/ozone catalytic oxidation systems for indoor air purification include RGF Environmental, NuTek International, Medallion Healthy Homes of Canada, ClearWater Tech, and BioZone Scientific.

[2] R. Fink, C. Willette, and W. Ellis, RGF Environmental Group, *Air Purification By Oxidation in HVAC Systems*, www.rgf.com/hvac.com.

germicidal effects. Thus, to create the optimal purification system, a dual UV-lamp is used that emits a wavelength of 185 nm to generate ozone, while also emitting a UV-C wavelength of 254 nm for germicidal irradiation. The 254-nm UV-C, however, will break down the ozone to acceptable limits before the air is re-circulated to the rooms in the building. Figure 19 shows a dual UV-lamp. The advantages of systems combining UV-C and ozone over systems that rely on only one of the purification methods are that microorganisms can be destroyed (by UV-C and ozone) at the same time as gases, vapors, and odors are controlled (by ozone). The UV/O_3 catalytic oxidation systems require continuous movement of the air. This will enhance the ability of the systems to treat a given area by keeping the ozone moving throughout the facility and ensure no buildup of ozone residues. The ozone levels generated by the UV/O_3 catalytic oxidation systems do not exceed 0.04 ppm, and are generally below 0.02 ppm.[1]

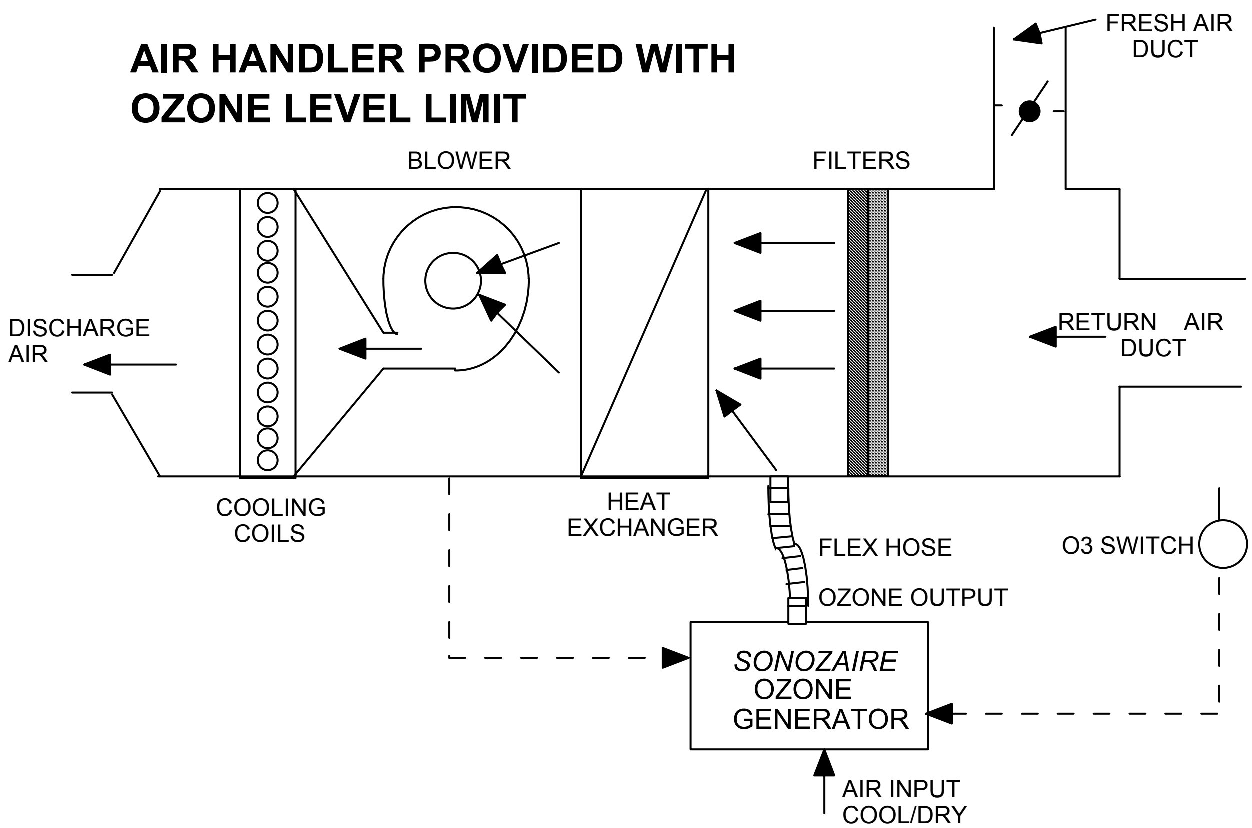

Figure 18
Ozone System Integrated into Building's Air Handler

Source: Sonozaire. Used with permission.

[1] Phone conversation with Walter Ellis, VP Advanced Oxidation Systems, RGF Environmental Group, April 14, 2003.

Figure 19
Dual Wavelength UV Lamp Generating UV-C, Ozone, and Hydroxyl Radicals for Indoor Air Purification

Source: RGF Environmental. Used with permission.

The main merits associated with purification of indoor air and controlling odors with ozone or UV/ozone catalytic oxidation include:

- **Effective and Fast-Acting Oxidant**: Ozone is one of the most effective and fact-acting oxidants, when implemented correctly. Ozone offers superior performance to any other method currently in use for odor and VOC control.
- **Reduces Bacteria and Viruses:** Ozone oxidizes bacteria and viruses in the indoor air.
- **Eliminates Odors and VOCs:** Ozone oxidizes VOCs and organic odors, including those from food, cigarettes, chemicals, mold, and animals.
- **Controls Mold**: Ozone has been used extensively for many years for whole-building remediation, and cleaning and disinfection of HVAC ducts, coils, and drain pans. In these applications, high levels of ozone output are used in unoccupied buildings. For continuous ozone output in HVAC ducts, lower ozone levels are used. These ozone levels are still sufficient to kill mold spores.
- **Extends Shelf Life and Reduces Cross Odor Contaminations of Food:** Ozone destroys mold and microorganisms, thereby reducing food shrinkage (up to 50%), spoilage (up to 85%), and cross odor contamination.[1]

[1] Product brochure, *CrispAir® A Revolution in Fresh Food Storage,* Nutek International, Inc.

- **Improves Animal Growth and Performance:** Ozonation of indoor air in animal housing, such as swine confinements, equates to better performance and growth because animals' immune systems are stronger and they have fewer respiratory problems.
- **Combination of UV-C and Ozone Has Double Purifying Power:** The germicidal effects of UV reduce the amount of microorganisms, such as bacteria and airborne viruses, that come in contact with the UV rays**,** while ozone reduces VOCs and odors.
- **Combination of UV-C and Ozone Provides Lower and Better Controlled Ozone Levels:** The UV/O_3 catalytic oxidation systems can better control the levels of ozone generated compared to conventional corona discharge ozone generators, resulting in lower and safer residual ozone levels: <0.04 ppm.

Performance Results

Several published studies evaluate the use of ozone for odor reduction in livestock and poultry production facilities (see Table 22). Most studies show ozone is effective in abating odors. Ozone has proven especially effective in reducing ammonia and hydrogen sulfide odor levels. Ozonation of the indoor air also generally results in healthier animals. For example, one case study from a hog production facility shows some impressive performance results.[1] This study recorded the hog performance over 35 days twice; it was recorded during August to September of 1996 before the ozone system was installed and then recorded again during December of 1996 to January of 1997 after the ozone system had been installed for three months. Table 23 shows the specific results at the Picket Fence Farms. As indicated in the table, the average death loss decreased from 1.59% to 0.64% with ozonation of the indoor air. The pigs also had a greater daily weight gain, resulting in an improvement of the average feed conversion by 11%. Moreover, the ventilation in the farrowing and nursery rooms was reduced after ozonation, resulting in 30% savings in heating bills.

At another hog farm (Metz Farms in New Bruinswick, Canada) ten rooms are equipped with ozone systems supplying 16 grams per hour of ozone to each room. In addition to reducing odor levels, ozone improves the well-being and health of the hogs by reducing tail biting and coughing. It also increases the daily weight gain.

Although most documented results from ozonation of animal housing are for hog facilities, ozone is also effective for odor control in other types of animal housing. For example, a poultry barn in Canada has installed ozone systems in its poultry layer and pullet barn. In addition to improved weight gain and odor control, ozonation of the indoor air improved the egg quality and eradicated *Salmonella* according to the researchers.[2]

In addition to indoor air purification of food production, ozone has also proven effective in purifying the indoor air in various processing facilities and commercial buildings. Recently, ozone systems have been integrated with the building HVAC systems, either mounted inside the

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1 Ozone Solutions Inc., *Ozone and Swine Operations Manual*, www.mtcnet.net/~jdhogg/ozone/oznmanual.html#Application%20of%20Ozone%20in%20Swine

2 Envron Inc., Case Study from Poultry Barn, http://www3.sk.sympatico.ca/envron/poultry.htm.

ductwork or in parallel with the duct. Current design and development are mainly focused on how best to control residual ozone levels. Several large projects for indoor air quality application with controlled and modulated ozone injection have been implemented.[1] The results from these projects showed fresh air intake could be reduced, resulting in reduced operating costs of HVAC systems while still remaining within the ASHRAE Ventilation Codes.[2] This is of particular interest in hot and humid climates where ambient temperature and relative humidity are high. Although ozone systems have been installed inside or in parallel with HVAC systems at several locations, only very few performance results are available.

The UV/O_3 catalytic oxidation technology is emerging as an improved alternative to pure ozone systems for ozonation of the indoor air in occupied buildings because it allows better control of the residual ozone levels. Several companies, including RGF Environmental, NuTek International, ClearWater Tech, and BioZone Scientific, are currently manufacturing UV/O_3 catalytic systems.

NuTek International has performed controlled testing of its UV/O_3 catalytic oxidation systems at several food storage and preparation applications. The company states in its marketing material that their system can reduce trim losses up to 85% and reduce shrinkage up to 50%; however, results are not publicly available from their tests.[3] BioZone Scientific has conducted testing of their system in the company's own laboratory to quantify the life extension of produce in cool storage and also provides results from a case study demonstrating the effectiveness of ozone in prolonging shelf life at a commercial retailer of produce.[4] The laboratory tests show that ozone levels of 0.6 to 2.0 ppm were effective for achieving overall improved quality (mold, color, firmness) in strawberries, raspberries, blueberries, asparagus, and white grapes. Moreover, the laboratory test results showed cross-odor contamination was eliminated. The case study including a commercial retailer of produce shows a reduction in product waste of 66%. For greater details about ozone for produce storage, see sections entitled *Ozone in Pest Management* and *Ozone for Fruit and Vegetable Production and Processing*.

RGF Environmental has field-tested its UV/O_3 catalytic oxidation systems at a rat farm and a veterinarian hospital, reducing the bacteria count by 80-95%.[5] At the veterinarian hospital, noticeable reduction in odors and pathogens were also observed.[6]

Moreover, the system's effectiveness and life cycles at various air handler installations have been tested. For example, one hospital in Virginia experiencing high levels of mold (*Aspergillius fumigatus*) and with more than 30% of the staff members complaining of upper respiratory symptoms installed UV/O_3 catalytic oxidation systems in its HVAC system supplying air to the intensive care and coronary units. After these indoor air purification units were installed, the mold levels were drastically reduced and there have been no further complaints of upper

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[1] Email correspondence with Kris Krishnan, President, Ruks Engineering, on April 17th, 2003.
[2] Ibid.
[3] NuTek International, Inc., *CrispAir® A Revolution in Fresh Food Storage*.
[4] Bryan Cecchi, John Garret, B.V. Rajmane, *Extended Shelf Life for Produce*, 2002.
[5] Ibid.
[6] Ronald G. Fink, Christopher Willette, and Walter Ellis, *Air Purification by Oxidation in HVAC Systems*, www.rgf.com/hvac.com

respiratory symptoms by the staff.[1] The UV/O_3 catalytic oxidation system systems have also been installed at a bingo hall where total VOC levels dropped by about 90% at peak load levels.[2] Other tests include installation in the return air duct of a residential building HVAC system, reducing the survival of *Serratia marscenens* by 98.9% at distances up to 39 inches from the unit within two minutes of exposure with undetectable residual ozone.[3]

[1] Indoor air quality investigations conducted by ECOSYSTEMS Environmental Services, Inc., April 3, 2003.
[2] Lawrence B. Kilham and Randall M. Dodd, *The Application of Ozone for Air Treatment (Case Study of a Bingo Hall HVAC System)*, www.ecosensors.com/pg4_2applozoneair.html.
[3] Field tests conducted by Life's Resources, Inc., *Effect of a HVAC Air Treatment Unit on the Survival of Bacteria*, 2000.

Table 22
Ozone for Improved Indoor Air Quality and Odor Control – Representative Installations in Food Production and Processing Facilities

Facility or Research Site	Facility Type	Application	Method	Results
Metz Farms [a] New Brunswick, Canada	Hog Facility	Reduce odor from air emitted from 10,000 head hog barn	Ten rooms on the farm are equipped with ozone generators. Each ozone generator supplies 16 g/hr ozone to a room through two distributor systems. Also experimenting with the ozone system as a disinfectant tool in between batches of hogs to replace chemical use	• Dramatic reduction in odors; no “pig smell” • Improved comfort levels for staff • More content animals with less tail biting, reduced coughing, and increased average daily gain • Small drop in mortality among hogs • Decrease in airborne dust particles as these settle to the ground instead of remaining airborne
Picket Fence Farms, Inc. [b] Doon, Iowa	Hog Confinements, including Farrowing, Nursery, and Finisher	24-hour operation provide constant suppression of primary hog odors, such as ammonia and hydrogen sulfide	Generated ozone is pushed in front of a distribution fan where an engineered system of PVC tubing and holes help distribute the ozone in the building. Natural air currents also circulate the ozone, oxidizing odors, bacteria, mold and viruses.	• Significant reduction in ammonia and hydrogen sulfide odor • Significantly fewer respiratory problems, which equates to better hog performance • Hogs’ immune system is stronger so they are able to combat many more diseases and viruses; death loss went from 1.6% to 0.6% • Prevents mold from growing on feed • Ventilation was reduced, resulting in 30% savings in heating bills (in farrowing nursery rooms)

Table 22
Ozone for Improved Indoor Air Quality and Odor Control – Representative Installations in Food Production and Processing Facilities, Continued

Facility or Research Site	Facility Type	Application	Method	Results
Hog Barn [c]	Hog Facility	Reduce ammonia levels	Ozone at concentrations up to 0.2 ppm were introduced into the facility	• 50% reduction in ammonia levels under winter ventilation conditions • 15% reduction in ammonia levels under summer ventilation conditions
Michigan State University Teaching and Research Farms [d]	Hog Housing Facility	Study the indoor air quality changes after ozonation in a swine housing facility including four rooms, each room containing one pen of 24 pigs Most malodorous VOCs associated with livestock operations were monitored	Ozone was injected at the rates of 0, 1.36, 2.72, and 4.10 m^3/day to produce target ozone doses of approximately 0 (control), 0.01 (low), 0.05 (medium), and 0.01 (high) ppm, respectively. PVC tubing distributed the ozone to the rooms. Every group of 24 pigs was exposed to a fixed level of ozone. Each group was moved every two weeks to another randomly selected pen.	• Odor detection threshold decreased as ozone dosage increased • However, insignificant reduction of odor offensives, suggesting VOCs were still present after ozonation or by-products caused by ozonation had an offensive odor • Odor characteristics were different from control rooms, suggesting some odorous compounds were destroyed or by-products were formed during ozonation • Reduced the levels of phenolic and indolic compounds, but volatile fatty acids (VFAs) were not reduced
Carrol's Foods in cooperation with North Carolina State University[e,f] Warzaw, NC	Hog-finishing House	Odor and dust reductions	Evaluating a commercial ozone air treatment system in a tunnel-ventilated swine-finishing house	• Decreased ammonia levels 58% compared to the control building • Decreased total dust 58% compared to the control building • Olfactometry panel, however, did not measure significantly different levels of odor parameters

Table 22
Ozone for Improved Indoor Air Quality and Odor Control – Representative Installations in Food Production and Processing Facilities, Continued

Facility or Research Site	Facility Type	Application	Method	Results
Poultry Barn [g] Canada	Poultry Layer and Pullet Facilities	Reduce ammonia levels	Ozonation of layer and pullet barn via ductwork air distribution	• 0.40 cents/bird increase in layer barn production • Ammonia levels were reduced by 60% in layer barn • Egg quality improved dramatically in layer barn • Increase in weight gain in pullet barn • Negative *Salmonella* test; never happened in the history of the pullet barn

[a] Metz Farms Ozone Installation Testimonial, Ozone Solutions, Inc. website, www.ozoneapplications.com/clients/metz_farms_ozone.htm.

[b] Ozone Solutions Inc., *Ozone and Swine Operations Manual*, www.mtcnet.net/~jdhogg/ozone/oznmanual.html#Application%20of%20Ozone%20in%20Swine.

[c] Livestock and Poultry Environmental Stewardship (LPES) Curriculum, Lesson 41 Emissions Control Strategies for Building Sources, *Minimizing Odor Generation*, www.lpes.org/Lessons/Lesson41/41_2_Odor_Generation.pdf.

[d] Kim-Yang et. al, *Effect of Ozonation on Odor and Selected odorants in Swine Housing Facilit*y, 2002 ASAE Annual International Meeting / CIGR XVth World Congress, www.ozoneapplications.com/research/MSUResearch2-Jeff%20Hill.pdf.

[e] G. Riskowski, *Overview of Methods to Reduce Odorant Emissions from Confinement Swine Buildings*, www.traill.uiuc.edu/uploads/sowm/papers/p122-128.pdf.

[f] National Hog Farmer, Ozone Holds promise for Odor Control, June 1, 1999, http://nationalhogfarmer.com/mag/farming_ozone_holds_promise/.

[g] Envron Inc., Case Study from Poultry Barn, http://www3.sk.sympatico.ca/envron/poultry.htm.

Table 23
Effect of Ozonation of Indoor Air on Hog Performance at Picket Fence Farms, Inc.

Performance Parameter	Hog Performance without Ozone [d]	Hog Performance with Ozone [d]
Average Death Loss (%)	1.59	0.64
Average Daily Consumption [a] (lbs.)	1.26	1.50
Average Daily Gain (lbs./day) [b]	0.78	1.04
Average Feed Conversion [c]	1.61	1.44

[a] Total lbs. feed per total pig days
[b] Total lbs. produced per total pig days
[c] Total lbs. feed per total lbs. produced
[d] Recorded over 35 days

Source: Ozone Solutions Inc., *Ozone and Swine Operations Manual*,
www.mtcnet.net/~jdhogg/ozone/oznmanual.html#Application%20of%20Ozone%20in%20Swine

OZONE FOR FOOD STORAGE AND PREPARATION IN HOMES

Food borne diseases cause an estimated 6 to 33 million illnesses and up to 9,000 deaths in the U.S. every year.[1] Subsequently, people preparing and consuming food at home are concerned about harmful food borne pathogens, such as *E. coli*, *Listeria*, and *Salmonella*, not being effectively destroyed before the food is consumed. Consumers of fresh fruits and vegetables are also concerned about chemicals and pesticides used in the growing process as these may still reside on the produce surfaces when purchased and brought home. Chemicals and pesticides are also a concern for residents getting their drinking water from wells. Aside from removing pathogens, chemicals, and pesticides contaminating food and drinking water, residents are also increasingly interested in removing, or controlling, odors in their homes. For example, homeowners strive for better control of unpleasant odors in refrigerators, trash bins, and sinks.

This section describes three applications of ozone in homes that pertain to food preparation, namely: 1) sanitation of food and food preparation equipment, 2) purification of tap drinking water, and 3) odor control. The discussion includes the main concerns associated with each application that ozone can potentially mitigate. It also describes how ozone is generally applied to address these concerns and summarizes the primary benefits in each specific application over other alternatives. Finally, this section discusses performance data very briefly since very little data are available from third party testing.

I. Sanitation of Food and Food Preparation Equipment

Concerns

One way to remove microorganisms from food or equipment surfaces is to wash carefully; however, this is not always effective. Another way is to use various types of sanitizers to clean the surfaces. Although these sanitizers may work well on food preparation and cooking equipment, such as tabletops and cutting boards, they generally are not applied directly on food because these chemicals themselves may be harmful to humans. A third way is to inactivate harmful microorganisms by cooking the food at high temperatures. This is an effective method for inactivating certain microorganisms, but not all. Also, cooking at high temperatures can only be used on food that is supposed to be cook, such as meat and chicken. United States Department of Agriculture provides guidelines on what cooking temperatures to use for meat and poultry. These guidelines state whole poultry should reach 180 °F, poultry breasts 170 °F; and ground

[1] FoodReview, *Promoting Food Safety: An Economic Appraisal*, Volume 22, Issue 2, released September 1999, www.ers.usda.gov/publications/foodreview/may1999/contents.htm.

poultry 165 °F, while all cuts of pork and hamburgers made of ground beef should reach 160 °F, and beef, veal, and lamb steaks, roasts and chops can be cooked to 145 °F.[1]

The main concerns for people preparing and consuming food at home are:

- **Remove Chemicals and Pesticides on Fresh Produce:** Consumers of fresh produce, such as fresh fruit and vegetables, are especially concerned about chemicals and pesticides used in the growing process. Consumers want to make sure that such chemicals are removed before the produce is ingested.
- **Inactivate Harmful Microorganisms on Food:** Other types of microorganisms, such as *E. coli* and *Salmonella*, are also a concern because they can cause diseases, and even deaths, in humans. Therefore, these microorganisms must either be removed or inactivated before or during cooking.
- **Sanitize Food Preparation and Cooking Equipment Effectively:** To limit cross-contamination, it is important to sanitize equipment used in food preparation and cooking. There is nothing to be gained in inactivating microorganisms on food if microorganisms are still residing on kitchen equipment and can easily be transferred back to the food.

Ozone as a Solution

Several companies have developed equipment that uses aqueous ozone for sanitation of food and cooking appliances in homes. Table 24 summarizes some representative products. There are several types of equipment, including countertop and under-the-counter units. Typically the equipment consist of a countertop container that first is filled with ordinary tap water, and then ozone is infused into this water at a concentration of a few ppm to several ppm. Depending on the countertop model, the ozonated water is either dispensed from a carafe or spray bottle onto the food or surface for sanitation. Another method is to fill the kitchen sink with tap water and then infuse ozone into the water. Food and equipment are then placed into the ozonated water. In either method, ozone in the water oxidizes and inactivates microorganisms on contact. Figure 20 shows ozonated water sanitizing fruits and vegetables in a kitchen sink.

The main advantages of using ozonated water for washing and rinsing food and food preparation and cooking equipment include:

- **Powerful Antimicrobial Agent:** Ozone is more powerful than chlorine in destroying microorganisms. Levels of harmful food borne bacteria, such as *E.coli*, *Listeria,* and *Salmonella*, can effectively be reduced by ozone.
- **No Build-Up of Resistance:** Unlike chlorine and other household chemicals, microorganisms cannot develop a resistance to ozone. For example, there are chlorine-resistant strains of *Giardia* and *Cryptosporidium*, both of which have caused deaths in recent years.

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[1] Food Safety and Inspection Service United States Department of Agriculture (USDA), http://www.fsis.usda.gov/OA/pubs/facts_barbecue.htm.

- **Destroys Mold and Pesticides:** Ozone can destroy molds and pesticide residues residing on fresh fruit and vegetables.
- **Replaces Chlorine and other Harmful Household Chemicals:** Ozone is extremely effective in inactivating microorganisms. Thus, there is no need for chlorine or other household chemicals in sanitizing food preparation and cooking equipment.
- **Leaves no Residuals:** Ozone does not leave residues or byproducts behind; nor is it believed to affect the taste, color, or flavor of the food.
- **Fast and Easy Sanitation:** Ozonated water sanitizes cooking equipment and food quickly. Usually, food and equipment items only need to be emerged in the ozonated water for a few minutes.

Figure 20
Sanitation of Fruit and Vegetables (left) and Chicken (right) with Portable Ozone Purifier

Source: DEL Ozone. Used with permission.

Performance Results

There are no public performance data from third party testing available that show the effectiveness of household ozone equipment in sanitizing food and preparation and cooking equipment. Although, ozone has proven effective in sanitizing food surfaces as well as equipment surfaces in the commercial food industries, the ozone output and the contact time applicable to the household units need to be evaluated better to ensure optimal performance. Table 24 shows performance results claimed by the companies that have developed these systems.

Table 24
Ozone for Sanitation of Food and Equipment in Homes – Summary of Products Commercially Available

Application	Targeted Products	Method	Stated Results	Companies Involved in R&D
Sanitization of food	Vegetables, fruit, meat, chicken, and fish	Foodstuff is either emerged into ozonated water or rinsed in ozonated water to inactivate microorganisms and oxidize pesticides and other chemicals that are residing on food surface	• Reduces contamination • Removes pesticides, herbicides, fertilizers, bacteria, viruses, fungus, and other microorganisms from foodstuff (surface only) • Food stays fresher longer because of less spoilage • No additional rinsing or soaking required as no residue is left behind • No affect on taste	DEL Ozone, Waterpik Technologies, Tru-Pure Ozone Technologies, Earth Safe Ozone, Aqua Sun Ozone International
Sanitization of food preparation and storage equipment	Knives, utensils, cutting boards, storage trays and containers, dishes, baby bottles, high-chair trays, jars for jellies, jams, and pickles	Equipment is rinsed in ozonated water to inactivate microorganisms, such as *E. coli* and bacteria, and prevent cross-contamination	• Reduces contamination • Kills bacteria, viruses, yeasts, molds, and mildew on exposed surfaces • Kills *E. coli* and *Salmonella* • Prevents cross-contamination	DEL Ozone, Waterpik Technologies, Tru-Pure Ozone Technologies, Earth Safe Ozone
Sanitization of cleaning equipment[a]	Kitchen sink, dish brushes, sponges, gloves	Equipment is rinsed in ozonated water to kill germs	• Reduces contamination • Kills bacteria, viruses, yeasts, molds, and mildew on exposed surfaces • Prevents cross-contamination	DEL Ozone, Earth Safe Ozone

Table 24
Ozone for Sanitation of Food and Equipment in Homes – Summary of Products Commercially Available, Continued

Application	Targeted Products	Method	Stated Results	Companies Involved in R&D
Sanitization of hands, mouth, and hygiene items[a]	Hands, mouth, tooth brushes, dentures, pacifiers, toys, contact lenses	Hands and personal items are either emerged into ozonated water or rinsed with ozonated water to kill microorganisms, and to prevent cross-contamination and the spread of diseases. Ozonated water may also be used as a mouth rinse.	• No publicized claims or test results available	Tru-Pure Ozone Technologies, Earth Safe Ozone, ALAB LLC

[a] R. Babyak, *Ozone Heads for Home*, Appliance Manufacturer, 06-21-2000, www.ammagazine.com/CDA/ArticleInformation/features/BNP__Features__Item/0,2606,5368,00.html.

II. Purification of Tap Drinking Water

Concerns

People are not only concerned with the food they consume, but also with the water they consume and use for cooking. In general, drinking water supplied by municipal waster treatment plants is safe as long as the treatment plants are working. However, the drinking water may have a taste, color, or odor to it that is unpleasant and which the consumer would like to remove. Households that get their drinking water from wells could potentially have more serious problems as this water may include chemicals, pesticides, or metals that are harmful when ingested.

Main concerns for consumers of tap drinking water include:

- **Impurities Affect Water Quality:** Consumers require safe tap drinking water, but they also increasingly demand a tap drinking water that tastes, smells, and looks pleasant. Impurities in tap drinking water may affect the quality of the water, and therefore, require removal.
- **Water Free of Chemicals and Pesticides:** Except for chlorine- and fluoride-residues, tap drinking water supplied by municipal water treatment plants is usually free of chemicals and pesticides. However, well water used for drinking may require treatment to ensure removal of impurities.

Ozone as a Solution

In this application, tap drinking water is ozonated to improve water quality. Ozone improves water quality by oxidizing impurities, such as iron, manganese, and hydrogen sulfide. Ozone has also proven effective in the removal of commonly used pesticides.[1] There are two types of household systems for purifying drinking water: 1) tabletop systems, and 2) under-the-counter systems. The tabletop systems consist of canisters or jars that are filled with tap water, which is then ozonated. Figure 21 illustrates such a tabletop ozone system. Under-the-counter systems are connected directly to the tap and all water flowing out of that tap is treated with ozone, as illustrated in Figure 22.

If the impurity is only a hazard or nuisance in drinking or cooking water, a point-of-use (POU) treatment device, such as a tabletop system or an under-the-counter system connected to a specific tap, is adequate. However, some contaminants, such as pesticides, are as hazardous when inhaled or absorbed through the skin as when ingested. In those instances, a point-of-entry (POE) treatment system treating all water used in the household may be required. POE treatment is also recommended for iron removal since iron is a nuisance in the laundry, bathtub, and toilet.

[1] University of Iowa, Center for Health Effects of Environmental Contamination, *Identification and toxicity of decomposition products of nitrogenous pesticides following ozonation*, http://www.cheec.uiowa.edu/seed/fy89/89c.html

Figure 21
Purification of Tap Drinking Water With Tabletop Ozone Unit

Source: ALAB, LLC. Used with permission.

Figure 22
Purification of Tap Drinking Water With Under-the-Counter Ozone Unit

Source: Tru-Pure Ozone Technologies, Inc. Used with permission.

The main advantages of household ozone systems for purification of tap drinking water include:

- **Improves Taste, Look and Smell:** Ozone removes impurities in the water by oxidation. This improves water quality by removing any foul taste or odor. It also makes the water clearer-looking.
- **Removes Pesticides:** Ozone oxidizes harmful pesticides in well water.
- **Provides Sanitization of Water Filter:** Households generally use filters for purification of tap water. These filters require frequent maintenance and replacement. An under-the-counter ozone unit would not only provide additional purification of tap water but also provide sanitation of the filter itself; thus, extending the filter life.

Performance Results

The U.S. Environmental Protection Agency, in conjunction with the Safe Drinking Water Act of 1991, confirmed that ozone was effective in ridding water of hazardous pathogens, including chlorine resistant *Cryptosporidium*. Some manufacturers of residential water purification systems provide performance results on their websites. For example, *QuickPure™* developed by ALAB LLC, was tested for *E. coli* by an independent laboratory. All 16 coliform analyses were negative, showing no growth. Table 25 shows household ozone systems for water purification.

Table 25
Ozone for Treatment of Tap Drinking Water in Homes – Summary of Representative Products and Research Projects

Application	Targeted Products	Method	Stated Results	Companies Involved in R&D
Purification of drinking water	Drinking water	Drinking water is treated with ozone to improve water quality. There are two types of systems: 1) tabletop and 2) under-the-counter that are connected to the tap water. Ozone is generated at a rate of 2.5 to 2.8 mg/L per minute of process time	• Kills up to 99.9 to 99.99999 percent of microorganisms, including bacteria, viruses, and protozoa. • Purifies a gallon of water in a few minutes	DEL Ozone, Tru-Pure Ozone Technologies, Earth Safe Ozone, Aqua Sun Ozone International, ALAB LLC, Fantom, Air-Zone
Removal of pesticides from drinking water	Drinking water	Open or closed point-of-use (POU) or point-of-entry (POE) ozone treatment systems for homes that remove common pesticides (alachor, aztracine, cyanazine, metachlor, metribuzin, and propachlor) from drinking water	• The effectiveness of ozone is closely related to the compound oxidized, the pesticide concentration, the ozone concentration, and contact times • Given a large enough concentration time, oxidation of the pesticides can be achieved through POU/POE ozone systems • These systems may also remove iron, manganese, hydrogen sulfide	Dept. of Preventive Medicine and Environmental Health, The University of Ohio

III. Control of Odors

Concerns

Preparing and cooking food usually are associated with pleasant odors in the home. Some odors, such as odors from cooking fish, cabbage, and onion, however, may turn unpleasant over time. Another odor concern in kitchens is odors in refrigerators. Here, the odors are not only causing a repugnant smell every time the refrigerator door is opened, but can also easily affect the smell and flavor of other food stored in the refrigerator, resulting in shorter shelf life.

Ozone as a Solution

Gaseous ozone is effective at purifying indoor air and controlling odors. Stand-alone ozone generators for general indoor air purification have been used in homes for several years (see Figure 23). The earlier versions of these ozone systems produced very high residual ozone levels because the ozone output levels were not controlled at all or were controlled manually. Subsequently, some ozone systems generated harmfully high residual ozone levels. The Food and Drug Administration (FDA), the Environmental Protection Agency (EPA), and several state agencies became involved to control the use of ozone systems, and several manufacturers of ozone systems that produced high levels of residual ozone were banned from the market. Because of this, ozone attained a bad reputation, even if not all ozone systems were bad. When applied correctly, and when the residual levels of ozone are acceptable, ozone is one of the better disinfectants of air. In general, commercially available ozone systems for controlling odors use a corona discharge to produce ozone. Lately, newer systems have switched to generating ozone with ultraviolet light (UV) because the ozone output can be more closely controlled. Also, the purification capabilities of both UV light and ozone can be used for air treatment.

Figure 23
Small Ozone System Purifying the Indoor Air in a Room

Source: DEL Ozone. Used with permission.

Food storage, preparation, and cooking generate odors in homes. These odors are easier to control close to where they are generated—that is, in the kitchen. In general, the odor-causing culprits are food stored in refrigerators, food wastes in trash bins and sinks, and food cooking on the stove. Thus, the optimal location for ozone systems controlling odors in the kitchen is either in the refrigerator to limit odor cross-contamination and prolong shelf life, in the waste bin or sink to limit foul odors, or in the kitchen fan to remove odors from cooking. Some companies have developed ozone systems for odor control in household refrigerators.[1] This application is quite common in Japan. In the U.S., ozone systems for food odor control, so far, have mainly been used in warehouses to extend the shelf life of fresh produce, fish, and meat. One such system from CrispAir is illustrated in Figure 24.

Figure 24
Ozone System Mounted in HVAC Ducts Controls Odors in Walk-in Coolers

Source: CrispAir. Used with permission.

The main advantages of ozone for controlling odors generated by food storage and preparation are:

- **Ozone is an Effective Oxidant**: Ozone is one of the most effective oxidants, when implemented correctly. Ozone offers superior performance to any other method currently in use for odor and VOC control.
- **Removes Odors:** Ozone oxidizes VOCs and organic odors, including those from food, pets, cigarettes, chemicals, and mold.
- **Kills Mold:** Ozone has been used extensively for many years for whole-building remediation, and cleaning and disinfection of HVAC ducts. In these applications, high levels of ozone output are used in unoccupied buildings. For continuous ozone output, such as in ozone systems placed in ventilation systems and refrigerators, lower ozone levels are used. However, the ozone levels are still sufficient to kill mold spores.

[1] Biozone Food Service Air Purifier for Double Door Refrigerator, www.shop.store.yahoo.com/air-n-water/foodserairpu.html.

- **Limits Food Spoilage:** Ozone destroys microorganisms on food surfaces, which delays food spoilage.
- **Extends Shelf life:** Since ozone delays food spoilage, the shelf life of fresh produce, meat, poultry, and fish is extended.
- **Reduces Cross Odor Contamination:** Since ozone controls odors, it also prevents odor transfer between foods stored in the refrigerators. This equates to less food spoilage.

Performance Results

Newer residential ozone systems for indoor air purification use UV light, rather than corona discharge, to generate ozone. The main reason is such systems, also called UV/ozone catalytic oxidation systems, can better control the levels of ozone generated compared to conventional corona discharge ozone generators. Table 26 summarizes representative products. For more information on the UV/ozone catalytic oxidation process for odor control, see the previous section in this chapter entitled *Ozone for Indoor Air Quality in Food Production and Processing*.

Table 26
Ozone for Odor Control in Home Food Storage and Preparation – Summary of Representative Applications

Application	Targeted Areas	Method	Stated Results	Companies Involved in R&D
Odor Control in Refrigerator	Refrigerators	Gaseous ozone is generated by UV	• Reduces food borne pathogens and spoilage microorganisms in refrigerated environments • Prevents odor cross-contamination • Reduces food spoilage • Extends shelf life of produce, meat, poultry, and fish	Biozone, CrispAir, Ozonator Inc.
General Odor Control in Homes	Kitchens, offices, bedrooms, bathrooms, closets, waste bins	Unit plugs into standard outlets. When odor control is needed, unit is tuned on for a few minutes and ozone is generated at a concentration of between 0.02 ppm to 0.06 ppm. Some systems generate ozone from UV rather than from corona discharge.	• Removes odors caused by food, beverages, tobacco smoke, mold, and mildew	Biozone, DEL Ozone