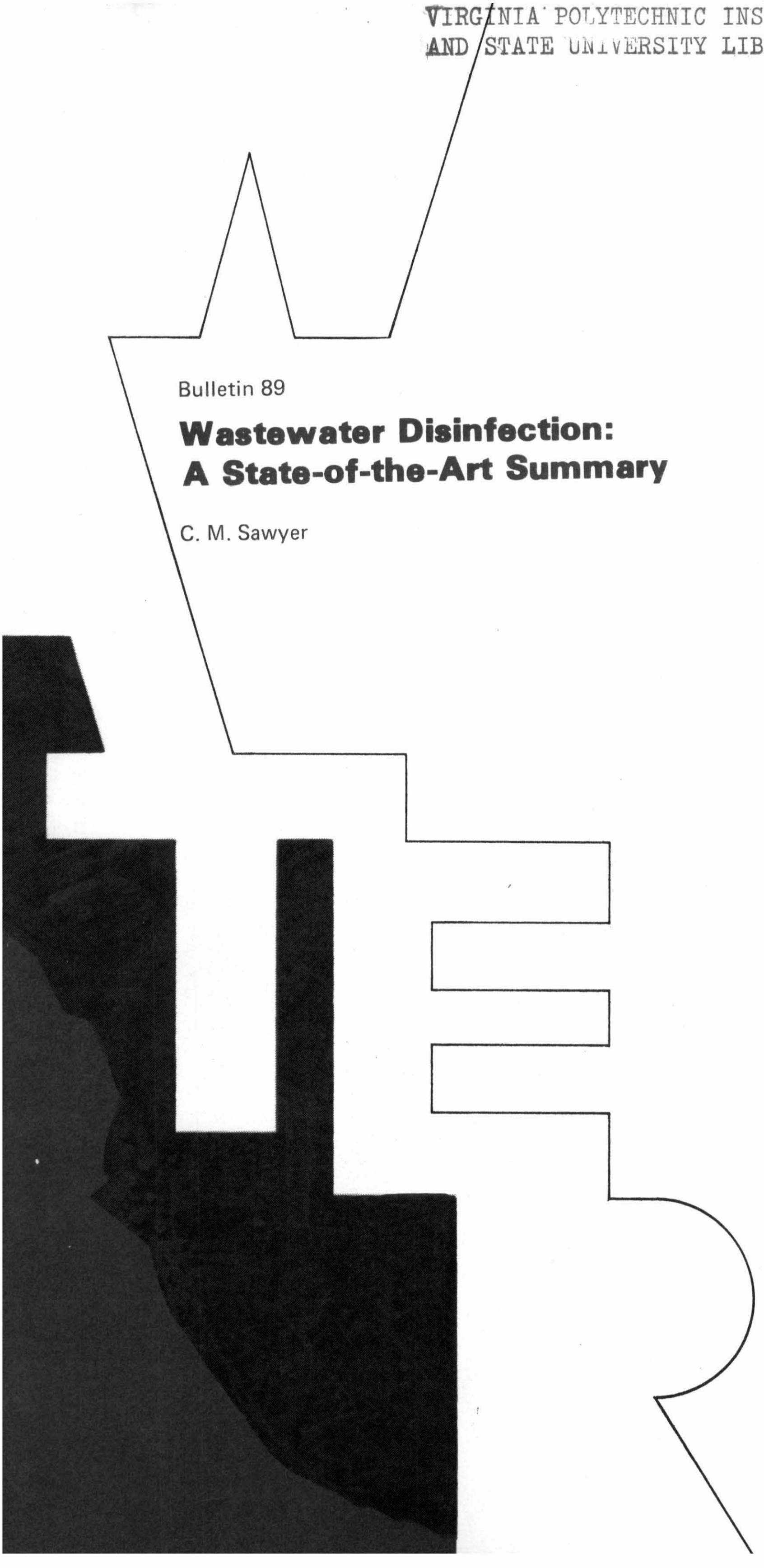

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Wastewater Disinfection: A State-of-the-Art Summary

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ABSTRACT

Disinfection often is necessary to reduce microbiological organisms in treated wastewater effluent to acceptable levels. Because of its many advantages over other methods, chlorination has become the nearly exclusive method for wastewater disinfection. Its principal advantage is economic: it is by far the lowest-cost method providing adequate disinfection of wastewater. Among other advantages of chlorination are its well-established technology, its ease of operation, and the known availability of needed materials.

It is becoming apparent, however, that chlorination also may produce undesirable consequences. Chronic toxicity effects recently have been observed in fish exposed to low concentrations of residual chlorine compounds in receiving waters. Combined chlorine-reaction products also are slow-acting viricides, requiring extended periods of exposure to achieve significant reductions of undesirable microorganisms, including viruses. Finally, chlorine has become a public-health concern because of harmful effects that may result from the presence of chlorinated organics in wastewater effluents.

The toxicity problems identified with chlorination have prompted evaluation and consideration of such various alternative disinfection methods as chlorination-dechlorination, chlorobromination, ozonation, and irradiation. Alternate disinfectants become more attractive economically if dechlorination is necessary for removal of residual toxicity. For most applications, alternate means of disinfection can offer more efficient microbial inactivation and minimal toxicity problems. However, these alternatives to chlorination require more extensive pre-treatment, effluent monitoring, dosage control, and post-treatment, than that currently practiced.

This report summarizes the advantages and disadvantages of many possible alternatives to chlorination, as reported in recent literature. It is divided into five major sections: Available Disinfection Technology, Practical Disinfection Technology, Disinfection Regulation, Summary, and Recommendations. The literature references have been organized into nine categories: Chlorination, Ozonation, Other Halogens, Irradiation, Miscellaneous Disinfectants, Indicators, Toxicity, Virology, and General Disinfection.

From the standpoint of practical technology and economics, both chlorination-dechlorination (SO_2) and the use of bromine chloride seem to be the most competitive alternatives to conventional chlorination. Additional information is needed on on viricidal efficiency and residual toxicity effects for proper evaluation of these two techniques. Tertiary treatment using effluent filtration, followed by ozonation or ultra-violet light irradiation, should provide highly efficient disinfection of wastewaters with minimal toxicity problems, although the cost will be high.

The use of alternate disinfectants should be evaluated on a case-by-case basis. In

many cases, possible trade-offs include those which might compromise the natural ecology of limited stretches of receiving waters in the higher interest of human health and life.

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INTRODUCTION

Water of high quality is necessary for drinking water supplies, ensuring survival of aquatic food chains, and recreational waters. An increasingly larger allowance of available water resources also is being used for assimilation of treated and untreated wastewaters. Municipal wastewaters carry a high concentration of pathogenic organisms—bacterial vegetative cells and spores, viruses, and protozoan cysts. Government water-quality standards specify biological characteristics for beneficial uses which hopefully, guarantee minimal possibilities of contamination.

Disinfection has become the key step for reducing the number of pathogenic organisms to a level providing the highest degree of water quality. Although this practice is critical for water and wastewater treatment, much remains uncertain about the control and optimum operation of the disinfection process. The environmental consequences of improper disinfection now may be evident in the recent apparent increases in the outbreaks of waterborne diseases and observed fish kills as reported by Craun and McCabe [F-8, F-9].

Chlorination is one of the oldest and most widely used disinfection techniques, but even now remains a poorly controlled process. The chlorination of municipal wastewater produces combined chlorine compounds from the chemical reactions between chlorine and ammonia and organic compounds present in the wastewater (Table 5). These combined chlorine compounds, found in relatively low concentrations, are poor disinfectants for many pathogenic organisms but are acutely toxic to higher forms of biological life in the aquatic food chain. Results of laboratory studies have indicated that current wastewater chlorination practice offers limited protection against viral contamination and in addition, the lack of analytical control on this process may result in accumulation of toxic compounds in receiving waters [H-18, H-33, H-34]. Addition of chlorine (breakpoint chlorination) to wastewater at levels which would eliminate interfering substances—such as ammonia—from leaving unreacted residual chlorine compounds, has been suggested as a means of providing adequate disinfection. But high dosages of chlorine in treated wastewater would greatly increase the possibility of toxicity to life in receiving streams.

The problems which recently have been identified with chlorination have prompted evaluation of alternative methods of disinfection, such as chlorination-dechlorination, ozonation, irradiation, and the use of other halogen-derived disinfectants. It would not seem likely that chlorination will drop significantly in use as a disinfection practice even with its attendant problems. In fact, probably the most viable alternative to conventional chlorination is chlorination-dechlorination to accomplish adequate disinfection and removal of toxicity effects. Dechlorination technology utilizing either sulfur compounds or activated carbon is well established. The addition of the dechlorination step in the disinfection process makes alternatives such as ozonation and the use of bromine chloride more cost competitive, and these methods in some instances can provide more efficient disinfection. Irradiation of highly treated wastewater using ultra-violet light may prove beneficial as a supplement to any disinfection alternative.

The objective of this research is to provide a brief state-of-the-art report on recent developments in the use of alternative means of wastewater disinfection. The available literature on the subject has been extensively reviewed and over fifty of the principal investigators currently working in this field have been contacted and invited to provide input to the study. The literature has been categorized into nine major areas which include: Chlorination, Ozonation, Other Halogens, Irradiation, Miscellaneous Disinfectants, Indicators, Toxicity, Virology and General Disinfection Information. The bibliographic list of references has also been divided into nine sections, although many references are somewhat difficult to categorize. The results of this study should provide a summary of information available at this time on disinfection which will allow an evaluation of the trade-offs which must be made when utilizing alternate methods of disinfection. Conclusions are drawn as to which techniques provide available, practical technology for application to a working process level.

AVAILABLE DISINFECTION TECHNOLOGY

I. Introduction

As a result of the current concern over the toxicity of chlorinated wastewater effluents (Table 1), disinfection technology and alternative means of wastewater disinfection are being reviewed and evaluated by many investigators in the United States and other countries (see Appendix). A task force report on wastewater disinfection has been developed by the U. S. Environmental Protection Agency [I-20]. The New York State Department of Environmental Conservation has published a technical report in which disinfection technology is extensively reviewed [H-28]. Recent investigations of disinfection methods and treated-effluent toxicity have been conducted at treatment plants in Michigan and results of these studies are currently being evaluated. Several textbooks include specific information concerning existing disinfection technology [A-63, C-7, I-16, I-34, I-58]. Possible use of alternate disinfectants has been discussed and reviewed by several authors [A-42, I-3, I-11, I-17, I-19, I-20, I-30, I-35, I-42, I-43, I-62].

Disinfection of wastewater may be accomplished by any physical or chemical means which can remove, or reduce to safe levels, the hazards of infectious disease transmission in receiving waters. A number of disinfectants exist which could be utilized to destroy, or inactivate to some degree, microbiological organisms (Table 2). Disinfectants may attack the individual cell in several ways, including destruction of the cell wall or membrane, denaturing of cell protein or enzymes, and attacking nucleic acids. A reliable disinfectant must be capable of destroying the disease-producing characteristics of potentially pathogenic microorganisms such as vegetative bacterial cells, bacterial spores, viruses, protozoa, and protozoan cysts (Table 3). In addition, a practical wastewater disinfectant must be able to [I-20] :

1. Accomplish acceptable disinfection within a reasonable time or contact period.
2. Remain an effective disinfectant within an expected range of variations in the physical-chemical characteristics of wastewater flows, such as temperature, pH, organics, etc.
3. Be available and attainable at reasonable costs.
4. Be safe to handle and capable of being conveniently applied in a controlled manner to wastewater flows.
5. Produce a detectable or easily measurable strength or concentration within the effluent under treatment, thus providing proper disinfection as noted by indicator organism tests.
6. Not produce compounds or reaction products within wastewater at levels which produce toxic effects in the receiving waters.

II. Physical Disinfection

Physical methods of disinfection can include heating (to the boiling point for 15 to

20 minutes), sedimentation-filtration, ultra-violet light irradiation, and the use of ionizing radiation. Heating could meet the majority of criteria established for disinfection as it destroys cell protoplasm. Heating possesses a decided advantage over other methods of disinfection in that removal efficiency is not subject to interferences from either the chemical or physical characteristics of the wastewater. A source of heat that may be applicable to wastewater treatment involves the use of high frequency sound waves (Table 25) [D-6]. Whatever method might be employed for heating wastewater, its energy requirement and subsequent cost will be extremely high. The high temperature effluent from a heating process would have to be controlled prior to discharge to prevent the adverse effects of thermal pollution.

The unit processes of sedimentation and filtration are effective for removal of spores and cysts but will not reduce to safe levels the numbers of bacteria and viruses found in municipal wastewaters. Sedimentation and filtration are used as necessary pretreatment prior to other methods of disinfection.

Ultraviolet light irradiation with high frequency wavelengths of 200 to 300 nanometers, in the far UV range, is an effective means of disinfection requiring only a short contact period. The most effective germicidal wavelengths appear to be in the vicinity of 250 to 260 nanometers. Absorbed ultraviolet light can excite organic molecules, disrupting unsaturated bonds which can produce progressive chain breakages [D-14, D-16]. The site of ultraviolet light action on microorganisms is thought to be in the nucleic acids [D-15]. Quartz mercury-vapor arc lamps are available for ultraviolet light production with low pressure mercury lamps producing 85 percent of emitted energy at 253.7 nanometers [I-20]. The disinfection performance of ultraviolet light is greatly affected by lamp temperature and voltage and the type of organic solids contained in the wastewater. Extensive pretreatment of the wastewater and continuous monitoring of lamp emissions would be necessary for reliable disinfection performance using an ultraviolet light process.

Ionizing radiation is capable of initiating oxidation of organic molecules and interfering with the metabolic processes of microorganisms, thus accomplishing a high degree of disinfection (Table 25). Ionizing radiation may be in the form of beta radiation, involving a stream of negatively charged particles, or gamma radiation, involving an electromagnetic energy field. Gamma rays are more suitable for wastewater disinfection because of their greater penetrating power and the fact that no residual radioactivity is left in the treated flow. Gamma radiation may be highly effective against many organisms which resist disinfection by chlorination, such as viruses [D-10]. The level of gamma radiation killing power may be seriously affected by the dissolved gas concentration [D-36]. Sources of gamma radiation include isotopes (cobalt-60 and cesium-137), electron accelerators, closed reactor loops, nuclear fuel elements, and mixed fission products. Currently, the use of nuclear fuel elements and electron accelerators appear to be the only cost-competitive sources of gamma rays. Nuclear fuel elements are now extremely scarce and the outlook for their future availability is not promising. An electron accelerator facility requires a large quantity of electric is not promising. An electron accelerator facility requires a large quantity of electric power to generate a sufficient quantity of gamma rays. Ionizing radiation is at a significant economical-technical disadvantage in comparison to other means of wastewater disinfection due to the expense and limited availability of its sources and the necessary strict control over the process operation. The most feasible use of gamma radiation would seem to be in combination with another type of disinfectant [D-37]. Gamma rays may be used for ozone generation or dechlorination and, in combination with these disinfectants, significantly reduce the dosage required to meet disinfection standards [D-17]. However, the use of gamma radiation is not thought to be practical due to the absence of a demonstrated synergistic effect in combination with chlorination and the presence of organic scavengers of free radicals in wastewater which limits the disinfection efficiency of the ionizing radiation [E-26, D-37].

III. Chemical Disinfection

Chemical disinfection methods are the most often used for treating water and wastewater. Oxidizing chemicals such as the halogens (chlorine, bromine, and iodine), ozone, and potassium permanganate can be used as disinfectants. Metal salts have been utilized to some extent, with silver and copper ions demonstrating disinfecting powers. Acids and alkalies may be used to produce pH changes which can destroy certain pathogenic organisms. Lime has been previously employed in water and wastewater treatment over many years as a coagulant aid and also as a means of controlling biological growth. Surface-active chemicals may be used to disinfect, as certain cationic detergents are strongly germicidal [E-4].

IV. Chlorination

Chlorine is essentially the exclusive disinfectant utilized for wastewater treatment due to the ability of the chlorination process to meet disinfection standards more economically than any alternative. Thus, a competitive market exists for supplying chlorine, chlorination equipment, and monitoring units for application and control of this treatment process. Chlorine may be purchased as liquified chlorine gas or as sodium hypochlorite (NaOCl). Chlorine gas is less expensive and demonstrates more stable disinfecting power when stored for lengthy periods as compared to NaOCl; but liquified chlorine gas is extremely dangerous to handle. Chlorine gas is usually produced by electrolysis of brine with a by-product of sodium hydroxide. Sodium hypochlorite can be produced by recombining the gas with sodium hydroxide. Sodium hypochlorite is available as a liquid concentrate with approximately 15 percent chlorine, a solution which should not be subjected to extreme temperatures. Storage of NaOCl at 75° F will result in a 50 percent loss of activity in a period of 100 days [I-20].

Chlorine gas is soluble in water (7,160 mg/l or 61 pounds per 1000 gallons, at 20° C and 2 ATM) and hydrolyzes rapidly to hypochlorous acid (HOCl). At the nearly neutral pH of most municipal wastewaters, the hydrolysis is virtually complete. Other halogens, such as bromine and iodine, also form hypohalous acids (Table 5). Hypochlorous acid can ionize to yield a proton (H^+) and the hypochlorite ion (OCl^-), but at pH values below 7.5, HOCl predominates briefly as the form of chlorine disinfectant. Hypochlorous acid and the hypochlorite ion are referred to as "free available chlorine." Secondary effluents will typically contain 5 to 14 mg/l of ammonia nitrogen, and the reaction between ammonia and free available chlorine produces "combined available chlorine" in the form of monochloramine (NH_2Cl) and dichloramine ($NHCl_2$), which do not disinfect as efficiently as does free available chlorine [A-32]. Hypochlorous acid may also react with other wastewater constituents to form chloramines which possess little or no disinfecting power. The sum of the concentrations eventually formed of free and combined available chlorine is referred to as the "total residual chlorine" (TRC).

The germicidal action of the various forms of chlorine in solution appear to result from their oxidizing power on the chemical structure of the cell, denaturing cell protein and destroying the key enzymatic processes necessary for cell metabolism. With the possible exception of some viruses, hypochlorous acid appears to be the most efficient form of chlorine for disinfection (Table 3). Apparently HOCl penetrates the bacterial cell more readily than does OCl^-. To insure adequate disinfection, long-term exposure (hours) of wastewater effluent to combined-chlorine forms is necessary, and therefore the addition of sufficient quantities of chlorine to insure the presence of free available chlorine within the TRC has been recommended [A-59]. The combined chlorine compounds are poor disinfectants, requiring extended periods of exposure to achieve significant microbiological reductions, with slow-acting viricidal effects [Table 4].

Previous studies have established the fact that both free and combined forms of residual chlorine in wastewater effluents are toxic to fish [H-12, H-16, H-21]. Fish normally will avoid plumes of wastewater effluents containing a toxic concentration of residual chlorine as treated effluent disperses into receiving waters. If sufficient dilution is available, residual chlorine dispersed into the receiving water should present minimal problems. However, chloramines may persist in aquatic environments for periods of sufficient length to become toxic to fish at low concentrations [H-49].

Chronic toxicity effects in which the normal functions of aquatic life may be impaired, have been observed in fish at extremely low levels of TRC. Studies using caged fish positioned below wastewater outfalls, have indicated that TRC levels above 0.01 mg/l and 0.002 mg/l can have adverse effects on freshwater populations of warm water and cold water fish, respectively [H-34]. In addition, limited data suggest that TRC levels above 0.01 mg/l may pose a serious hazard to marine and estuarine life [I-20].

Thus, the predominant forms of disinfectant which eventually result from chlorination of domestic wastewater, chloramines, are undesirable for two reasons of concern: (1) poor removal of viruses in the wastewater and (2) toxicity effects in the receiving stream. The use of "breakpoint" chlorination has been advocated, using chlorine dosages several times those applied in wastewater, in order to yield free chlorine residuals that are effective viricides [G-15]. High levels of TRC in heavily chlorinated wastewaters must be removed by a dechlorination process to prevent toxicity effects in the receiving waters. Results of several studies have shown that dechlorination of municipal wastewater reduces or nearly eliminates the toxicity effects associated with residual chlorine [I-20].

V. Dechlorination

Dechlorination treatment of chlorinated wastewater can be accomplished with the addition of sulfur compounds or by filtration through activated carbon. For dechlorination with sulfur compounds, sulfur in the "plus-four" (+IV) valence state is employed, with sulfur dioxide being the most popular in usage. Sulfur dioxide (SO_2) is commercially available as a liquified gas and can be applied to wastewater using chlorination equipment. Sulfur dioxide gas is highly soluble in water (1.0 lb/gal at 60° F), dissolving into a weak solution of sulfurous acid (H_2SO_3). The chemical reactions of sulfurous acid with both free and combined residual chlorine, reduces all chlorine to the chloride ion. The reaction weight relationship for conversion of chlorine to chloride ion requires 0.9 mg of sulfur dioxide per mg of chlorine. In addition, 2.8 mg/l of alkalinity is required to react with protons formed in the various reactions. The reaction kinetics of dechlorination with sulfur dioxide are very rapid, being nearly instantaneous for the conversion of free chlorine to chloride and taking only minutes to strip out the remaining combined chlorine. Thus, contact time for dechlorination with SO_2 is not of extreme importance, but rapid and complete mixing at the point of application is a highly important provision of the process efficiency. Because sulfur dioxide is a reducing agent, it can also strip dissolved oxygen from the wastewater and, therefore, reaeration may be necessary to meet effluent standards. Strict control over the amounts of SO_2 added for dechlorination may eliminate or lower the reaeration requirement.

Dechlorination with activated carbon is a physical process in which chlorine compounds are stripped from the wastewater by sorption at surface active sites on carbon particles. Surface oxides are formed in the subsequent reactions in which chlorine forms are reduced to the chloride ion. Additional advantages of dechlorination with activated carbon are the removal of ammonia and COD from municipal wastewaters. It is a very expensive process, however, and difficult to operate properly.

Dechlorination can eliminate many of the problems associated with residual chlorine effects, but some drawbacks to this process deserve further study. Because the removal of chlorine will halt disinfection, adequate prior contact between residual chlorine and microorganisms must be insured. Large influent doses of chlorine may result in the formation of chlorinated organic compounds that are toxic to both fish and man. Dechlorination with sulfur compounds may double the cost of conventional chlorination if reaeration is required, and the use of activated carbon beds for dechlorination could increase chlorination costs by a factor of five.

VI. Ozonation

Ozonation can be cost competitive with chlorination-dechlorination as an alternate means of wastewater disinfection and is currently in use as a water disinfectant in Europe. Ozone (O_3) is a pale blue gas in concentrated form with a pungent odor that can be detected at concentrations below 1.0 ppm. It has a very high oxidation potential. Ozone is generated by conversion of the O_2 molecule to O_3 by the addition of energy to a stream of dehydrated air or pure oxygen. Disassociation of the O_2 molecule may be brought about by electric discharge, ultraviolet irradiation (1500 to 1900 angstroms), gamma radiation, or heat [C-7]. The use of electric discharge has been established as the most practical way to generate ozone. Because the gas is very unstable and cannot be stored, it is generated on-site, prior to use. The ozonated air or oxygen stream will normally contain only a small percent of ozone by weight [C-10].

Ozone retains its strong oxidizing potential in solution and is usually mixed with a liquid prior to a downward flow into the bottom of a baffled contractor. Maximum oxidation of compounds within the liquid flow is accomplished by arranging the contactors in series or stages, with ozone injected into the effluent from each state. Although ozone is more than teen times as soluble as oxygen in water, only a few mg/l are dissolved into a liquid flow during actual operating conditions due to the low weight fraction of ozone in ozonated air or oxygen and the low available partial pressure of ozone. Ozone appears to decompose or break down into molecular oxygen and atomic, or nascent, oxygen (O) in solution. Nascent oxygen is highly reactive and capable of oxidizing a variety of organic and inorganic compounds, reducing levels of BOD, COD, color, taste, and odors as well as achieving destruction of microorganisms. The disinfecting power of ozone results from oxidation, which may affect the cell protoplasm in general or certain components of the cell wall or membrane [C-15]. Ozone as a disinfectant demonstrates an "all or nothing" effect, in that inactivation of microorganisms does not occur until a threshold level of ozone is reached [C-2]. After the threshold concentration of ozone is applied, efficient disinfection is attained very rapidly, achieving bactericidal effects hundreds of times faster than similar levels of bacterial destruction caused by HOCl. Reportedly,ozone is also a much more effective viricide and cysticide than is chlorine [C-24].

A major disadvantage of ozonation is that no long lasting residual disinfection is possible, as natural decay and oxidation reactions quickly dissipate dissolved ozone. Ozone residuals of up to 1.0 mg/l may persist for a few minutes. Ozone has a high affinity for organic matter, and large dosages may be necessary to overcome organic interferences to achieve the threshold level needed for adequate disinfection. Extensive treatment of municipal wastewater to a tertiary level may be necessary prior to ozonation. The on-site generation of ozone will produce operation problems in adjusting the dose to variations in organic content. However, an ozone dose of 8 mg/l has achieved adequate disinfection of municipal wastewater [C-16]. As ozonated organics may be more amenable to biochemical oxidation, algal slime growth may occur in the treated effluent. The cost of an ozonation process may be three times that for conventional chlorination. The energy requirement for production of ozone will be four to sixteen times that required for production of chlorine (Table 9). Information concerning the possible toxic effects of ozonated organics is now being obtained, but ozonated wastewater has not produced measurable toxicity to fish at the levels observed from chlorinated effluent [I-20].

VII. Use of Other Halogens

Although chlorine has been used nearly exclusively as a disinfectant, other halogens have been examined, such as bromine, iodine, bromine-chloride and chlorine dioxide. Bromine, available primarily in bromide form, and iodine are widely distributed in nature and are difficult to obtain in large quantities. Bromine and iodine are produced domestically from brine wells, with extensive use of chlorine in the separation processes. Over one-half of the approximately 450 million tons yearly of bromine production in the United States was used as a component in antiknock fluid for gasoline. Removal of lead compounds from gasoline should make bromine more available for use as a disinfectant. Less than 20 million pounds of iodine are processed worldwide each year. The market price of bromine is three to four times the market price of chlorine. The price of iodine is approximately 40 times that of chlorine. The production of a pound of bromine and iodine may require two to three times the energy needed to produce a pound of chlorine.

Bromine chloride may be prepared by adding an equivalent amount of chlorine (gas or liquid) to bromine until the solution has increased in weight by 44.8 percent [B-22, I-34]. Bromine chloride may be formed in either the gas phase or in aqueous hydrochloric acid solution. Both bromine and iodine can be handled more safely and fed into wastewater more easily than chlorine. Bromine remains a liquid at atmospheric pressure and iodine is available in a very stable solid form, although each of these forms can be corrosive and toxic and must be handled carefully. Bromine chloride is less corrosive than bromine and may be shipped in steel containers, but care must be exercised in handling similar to that taken with chlorine. The cost of disinfection of wastewater with bromine chloride is comparable to the cost of ozonation.

Iodine is the least reactive of the halogens and stable residuals of molecular iodine and hypoiodus acid (HOI) become the primary forms in solution. At neutral pH, approximately 50 percent of iodine in solution will be in the HOI form. Iodine possesses the advantage as a wastewater disinfectant of not normally reacting with nitrogenous compounds such as ammonia, and therefore does not lose disinfecting power by forming iodoamines. The disinfection action of iodine has been identified with iodination of sulfhydral (—SH) groups in bacteria and amino acid iodination in viruses [B-14]. The hydrated, cationic species of iodine (H_2OI^+) has been postulated as the active disinfectant agent for aqueous iodine [I-36] . Iodine has been shown to be effective as a bactericide, cysticide, and also as a viricide, although the cellular nucleic acids apparently are not affected [G-21]. Dosages of iodine may be higher than those required to achieve similar levels of disinfection by chlorine [B-2]. Iodine also retains good disinfecting power at high pH values. The physiological activity of iodine is known to be beneficial to the formation of the thyroid hormone. The effect of its use as a disinfectant on body functions is not thought to be detrimental, as iodine has been successfully used to disinfect swimming pool water with no apparent health effects [B-3]. Economics may be a major factor in limiting its use.

Bromine is a strong disinfecting agent and when applied to municipal wastewaters at normal pH values, a predominance of hypobromous acid (HOBr) is formed [B-11]. Hypobromous acid has been noted to be the most effective disinfecting form of bromine and has demonstrated bactericidal and virucidal properties equal to those of HOCl [B-11, B-14, B-19, B-22]. Ionization of HOBr to greater than 50 percent of the less effective disinfectant, hypobromite ion (OBr^-), occurs only when the pH exceeds 8.5, about one unit higher than the pH at which the concentration of hypochlorite ion exceeds that of HOCl. Bromine is a more efficient disinfectant at pH values above neutral as compared to chlorine, since a relatively higher level of HOBr exists. Bromine also reacts with ammonia in solution to form bromamines. Unlike chloramines, combined bromine forms essentially are as germicidal as HOBr, with both forms showing similar cysticidal properties [B-27]. Bromine forms in solution can inactivate the nucleic acids of microorganisms, but it is suspected that bromine does not penetrate the protein coat of viruses [B-15].

Bromine is very susceptible to demand effects from reducing agents in wastewater, and bromamines are somewhat unstable, especially dibromamine [B-22]. Careful control over bromine dosages is necessary to maintain the proper residuals for adequate disinfection, as a portion of the dose will be quickly lost as bromides, thus providing no germicidal action. Prechlorination has been shown to reduce the required bromine dosage necessary to obtain a given level of disinfection [B-19]. An advantage of the rapid conversion of bromine to bromides is that it removes potentially toxic products from the wastewater discharge.

A variety of interhalogen compounds, formed from two different halogens, exist as possible disinfectants, such as bromine chloride, iodine monochloride, and iodine bromine [B-22]. These compounds seem to offer more stable disinfection residuals than other halogens. Of these compounds, bromine chloride [BrCl) seems to be the most likely possible replacement for chlorine in instances where toxicity to fish in receiving waters is of concern. The toxicity characteristics of BrCl become negligible in a matter of minutes as compared to residual chlorine toxicity which may last for many hours [B-21]. Iodine interhalogens apparently demonstrate disinfection characteristics similar to iodine, but are not as effective [B-22].

Bromine chloride exists in an equilibrium mixture with molecular bromine and chlorine and it is about 40 percent disassociated into Br_2 and Cl_2 in most solvents [I-34]. In water, BrCl has a solubility of eleven times that of chlorine and 2.5 times the solubility of bromine. Bromine chloride solubility increases in the presence of the chloride ion. The high reactivity of bromine chloride, coupled with rapid equilibrium adjustments, can produce disinfectant products containing bromine resulting almost exclusively from BrCl [B-22]. Bromine chloride appears to hydrolyze exclusively to HOBr in water. Thus, the disinfecting characteristics of BrCl are similar to those of bromine. Approximately 69 percent reactive bromine is available from bromine chloride, which is 40 percent higher than the bromine contributed from molecular bromine for substitution reactions [B-21]. Bromine chloride reacts with organics in wastewater to form brominated organics, but these compounds have not been identified with the suspected toxic effects of chlorinated organics. Apparently, the major portion of BrCl added to wastewater is ultimately reduced to inorganic bromides and chlorides. Results of preliminary studies have verified the postulated lack of significant toxicity in wastewater effluents treated with bromine chloride [I-34].

Chlorine dioxide (ClO_2) is a powerful oxidizing agent with excellent germicidal properties similar to those of HOCl [A-40]. Chlorine dioxide gas is unstable, corrosive, and explosive, requiring very competent handling. The ClO_2 gas is generated on-site from the reaction between sodium chlorite [$NaClO_2$] solution and chlorine in contact with water to assure that the gas remains in solution. Chlorine dioxide does not react with ammonia, as does chlorine, and thus retains a high degree of germicidal effectiveness in wastewater over a normal range of pH values. However, organic wastewater exerts a high ClO_2 demand and high dosages may be necessary to accomplish disinfection. Currently, no adequate method exists for determining low residual concentrations of ClO_2. The possible formation of chlorinated organics resulting from the use of ClO_2 has not been studied at this time. A major disadvantage, which may limit ClO_2 use, is the significant cost of generation, as the oxidant costs 13 times more than the current price for producing chlorine.

VIII. Miscellaneous Disinfectants

The use of metal salts, permanganate, and quaternary ammonium compounds does not seem to have any application to disinfection of wastewater due to extreme costs and losses in disinfection power due to the interferences from wastewater constituents.

Lime has been used to help remove colloidal solids from wastewater for many years. Lime also can act as a germicide at high pH values (above 11.5) and in addition, its flocculating capabilities can effect cyst and spore removal. Effective reductions in bacterial count have been established with lime treatment of domestic wastewater, using contact periods of 30 minutes or less [E-12, E-19]. Lime treatment at high pH also accomplishes phosphorus removal. Although a lime treatment process in itself would be relatively easy to operate at a reasonable cost, handling and disposing of the lime sludge would be difficult and expensive. The use of lime as a disinfectant may be a possible alternative to chlorine in advanced wastewater treatment where phosphorus removal is incorporated in the process design.

Economics has played a major role in the dominance of chlorine usage as a wastewater disinfectant. With the possible need for dechlorination to remove toxicity effects and growing possibilities of viral contamination of receiving waters, the use of alternate disinfectants to help alleviate these problems should be pursued. Perhaps the optimum solution will involve combinations of disinfection processes used alternately or in successive stages.

PRACTICAL DISINFECTION TECHNOLOGY

I. Process Efficiency

A number of factors may establish the performance efficiency of a particular disinfection process. Microorganisms have different levels of resistance to germicidal agents, which vary with the physical, chemical, or biological nature of the wastewater. Wastewater characteristics, such as temperature and pH, can influence both chemical and biological activity. Organic material in the wastewater may react with the disinfectant and lower its germicidal action, while other solid fractions may act as a shield to protect the cell. Microorganisms may exist in resistant forms, such as spores or cysts, or they may persist in masses or clumps of cells in which internal microorganisms are protected by surrounding cells.

The provision of a sufficient contact period to accomplish disinfection may also depend on the method of application of the disinfectant and the hydraulics of the flow through the contact unit [A-11, A-25, A-26, A-32]. Uniform and rapid dispersion of the disinfectant into the wastewater must be achieved for efficient disinfection. Hydraulic inefficiencies, such as high velocity currents, can severely limit the contact between cells and levels of disinfectants necessary to inactivate the organism [A-12, A-18, A-20].

Disinfection efficiency is commonly determined by biological enumeration tests for indicator organisms. The tests are based on the assumption that a significant reduction in indicator organisms parallels a similar reduction in pathogenic species. The coliform group of bacteria is used most often as an indicator of the presence of the wastes of a warm blooded animal. Growth results in fermentation tubes inoculated with a series dilution of a wastewater sample can be interpreted statistically to yield the most probable number (MPN). The MPN is a quantitative estimate of the number of coliform cells within a 100 ml volume of sample. A TRC level of 1 mg/l maintained within the wastewater for a period of at least 30 minutes is expected to accomplish a high (over 90) percent coliform reduction within the contact unit although the inactivation level will be dependent on the wastewater characteristics. The total coliform removal should be in excess of 99.9 percent for secondary treatment with chlorination, which may leave an effluent MPN of 1,000 to 10,000 total coliforms and correspondingly, 1 to 1,000 fecal coliforms per one hundred milliliters of sample [A-32, 1-8].

Although coliform inactivation may parallel the destruction of most pathogenic bacteria, more resistant pathogens, such as streptococci and staphylococci and some viruses, may not be as severely affected [F-14]. Inefficient inactivation of viruses could be a serious, epidemiological problem in that disease could result from infection by a single virulent cell. Disease symptoms may be delayed or the disease transmitted to another person before it is observed [G-7].

Disinfection process efficiency and control problems may be related to a lack of known disinfectant dosage-residual values. As chlorination has been the primary means of wastewater disinfection, accurate dosage-residual relationships should exist for this disinfectant, but this is not the case. Apparently, due to many interrelated factors, such as wastewater quality, chlorine application, and laboratory techniques, correlation between disinfectant dose and residual for different plants has not been established [A-31]. However, the absence of dosage-residual relationships may have originated from the lack of simple testing techniques for precise determination of disinfectant residuals. A number of analytical tests are available for measurement of residual chlorine and are outlined in American Public Health Association's *Standard Methods for the Examination of Water and Wastewater.* The most popular methods are the two colorimetric techniques, orthotolidine and DPD. Analytical testing problems do exist as the orthotolidine method is subject to a high level of interference in wastewater and underestimates actual TRC levels, which may result in severe toxicity problems from treated effluents [H-16, H-28, H-34]. The iodometric method has been shown to yield more precise results than the DPD test for chlorine residual determination [I-61]. The iodometric test end point may be determined with a high degree of accuracy by amperometric titration, or by starch-iodide titration. Iodometric measurements of chlorine residual consistently have shown higher values than orthotolidine measurements [A-19]. A proper value of residual TRC for adequate wastewater disinfection as measured iodometrically may be three mg/l or more with provision of proper contact periods [A-17].

Iodometric analytical tests should be used for close control of chlorination processes but will require proper lab equipment and trained personnel. As problems exist for chlorination residual control, many more difficult problems can be expected for alternate disinfection processes, in which only brief, or even no residual is maintained.

Accurate determination of disinfectant residuals will be necessary for optimum control of certain alternate disinfection processes. Breakpoint chlorination control will require accurate determination of free chlorine residuals which may be found using iodometric methods. Optimization of both breakpoint chlorination and ozonation will require continuous residual monitoring with loop controls on disinfectant dosages. Electrodes can be used to provide continuous residual monitoring for both processes, but proper maintenance and experienced operation is required for dependable service [I-36]. Because irradiation with ultraviolet light and gamma radiation leave no residuals, irradiation intensity must be continuously monitored to control disinfection. Dechlorination with sulfur dioxide will require that control systems balance dosages in order to prevent toxic excesses of chlorine in the process effluent. Although the methods for application of SO_2 for dechlorination differ only slightly from that of chlorine, use of the same equipment for application of each is not recommended [I-36]. The control system for optimum balancing of SO_2-Cl_2 dosages should be of the feed-forward type [I-62].

Currently, many operational problems exist for all disinfection processes. One such problem is the provision of a uniform exposure of efficient disinfecting agents to microorganisms in order to produce optimum inactivation. Results of many past studies have indicated that uniform injection and intense mixing of the chlorine dose followed by adequate detention within a contact basin, are more important to disinfection efficiency than is an arbitrary increase in chlorine dosage [A-12, A-18, A-32, G-9, I-11]. Results of in-plant modifications have demonstrated that uniform dispersion of chlorine with violent mixing upstream of the contact basin will increase disinfection efficiency without an increase in chlorine dosage [A-32]. Uniform application of dosage may be achieved with grid injectors or perforated plates to disperse the flow. Apparently, uniform injection and rapid mixing of the chlorine dose exposes a large number of microorganisms to the disinfectant [A-9]. Upstream mixing may be provided by hydraulic jumps, step-down drops, tubular reactors, and high velocity flows in pipeline bends. Adequate contact to residual chloramines will be necessary for inactivation of cells and will be extremely important to a chlorination-dechlorination process where breakpoint chlorination is not used. Problems related to adequate exposure or contact times may exist with other disinfection processes. Many existing contact tank designs are subject to severe short-circuiting, which allows flow to leave the basin after short residence periods [A-25]. Contact basins should be designed to achieve a plug flow condition for maximum flow retention. Horizontal baffles or a series of longitudinal end-around baffles provide the longest retention times in a basin and are more effective against thermal currents than are single longitudinal or several over-under baffles.

The short half-life of ozone and bromine in wastewater requires that care be taken in applying these disinfectants [B-22, C-35]. Ozone injection and contacting methods are well established for water treatment and similar techniques could be applied to wastewater disinfection [C-7]. However, ozone spargers would not be practical for disinfection of secondary effluent, as a large fraction of the ozone may be consumed for oxidation of organics. Provisions for handling foam from the contacting units will be necessary; however, foaming will provide additional suspended solids removal. Although bromine chloride can be handled and applied in a manner similar to chlorine, improved methods of uniform injection and pre-mixing prior to contact detention will be necessary for its use.

Many alternate disinfection processes may require exposure times somewhat less than chlorination; contact periods will vary for these other processes. Pretreatment requirements and control of influent quality will be important for each disinfectant used. Efficient disinfection performance will require minimum influent levels of solids content, BOD, COD, pH, organic and ammonia nitrogen, etc. Effluent monitoring will be necessary for operational control of all methods of disinfection. Pretreatment of secondary effluent for solids removal may be necessary to optimize the effectiveness of ozone and ultraviolet light. Pretreatment may also be employed to enhance disinfection by chlorine and bromine chloride. Lowering wastewater pH by acid addition will improve the disinfection efficiency of chlorine by increasing the level of HOCl [A-9]. Addition of chlorine prior to the injection of bromine chloride will help remove some of the bromine demand, enabling a higher residual concentration [B-9].

Temperature control may be necessary with the use of a UV system as light intensity declines as operating temperature decreases [I-11]. UV light intensity is greatly affected by voltage fluctuations, and continuous monitoring of light transmission must be designed into the system with automatic alarms to note a loss of proper intensity. An ultraviolet light dose of 5×10^{-8} Einsteins per milliliter has been shown to produce effective inactivation of many types of microorganisms [D-23]. Only brief contact periods are required for UV disinfection, but a shallow flow depth is necessary, which will require proper velocity control for depth-exposure time balance.

Pretreatment requirements for gamma radiation are not as stringent as those for other disinfectants although disinfection efficiency is greatly improved when dissolved oxygen is present [D-30]. Contacting requirements for gamma radiation have been established on a pilot-scale basis, and these could be used to design larger units [D-32]. Improving the level of wastewater treatment prior to disinfection will greatly enhance disinfection efficiency. Disinfection of tertiary or advanced treatment plant effluents would provide maximum removal of microorganisms and cause minimal problems related to process operation and effluent toxicity. Possibly, in-plant modifications or upgrading of treatment at points upstream from a conventional chlorination unit could serve the same purpose as an alternate means of disinfection.

Consideration of advanced treatment possibilities could make dechlorination with activated carbon cost competitive with some advanced treatment systems. Activated carbon columns are now used to remove dissolved organics from wastewater and that technology may be used for dechlorination purposes. As the affinity of activated carbon for combined chlorine is much less than its affinity for free chlorine, dechlorination of sewage effluent may be troublesome. Previous studies have indicated that loading rates of two to three gallons per square foot of carbon surface with 15 to 20 minutes of contact could remove three mg/l of TRC, with an expected bed life of two to three years [I-34]. Discoloration of column effluent indicates the need for replacement of the activated carbon. Post chlorination, pH adjustment and post-aeration may be required for column effluent due to acid production and biological growth within the column [I-20].

II. Comparison of Methods and Costs

Existing technology and economics favor chlorination as the most practical means of disinfecting wastewater. Chlorination of wastewaters is effective in reducing the hazards of waterborne disease outbreaks resulting from effluent discharges into recreational and food supply waters. Although chlorination can reliably meet present bacteriological standards for secondary treatment, serious deficiencies and disadvantages are inherent in current practices. These include:

1. Low MPN counts may not correlate with adequate level of disinfection.
2. Interfering substances, such as ammonia nitrogen, limit the effectiveness of a given chlorine dose.
3. Chlorine residual levels and contact periods now employed for disinfection may not adequately remove viruses (1 mg/l of TRC for 30 minutes).
4. Discharges of residual chlorine compounds may be toxic to fish in receiving waters at low concentrations (above 0.01 mg/l) for extended periods.
5. Chlorination of certain wastewaters may result in the formation of halogenated organic compounds that are potentially toxic to man [I-20].

From the estimated 100,000 tons of chlorine used annually in the United States for disinfection of wastewater, approximately 5,000 tons of chlorine-containing organic compounds may be discharged into receiving waters [H-33]. The long-term, ecological effects of these man-made compounds are largely unknown, but some identifiable forms are suspect carcinogens [H-36].

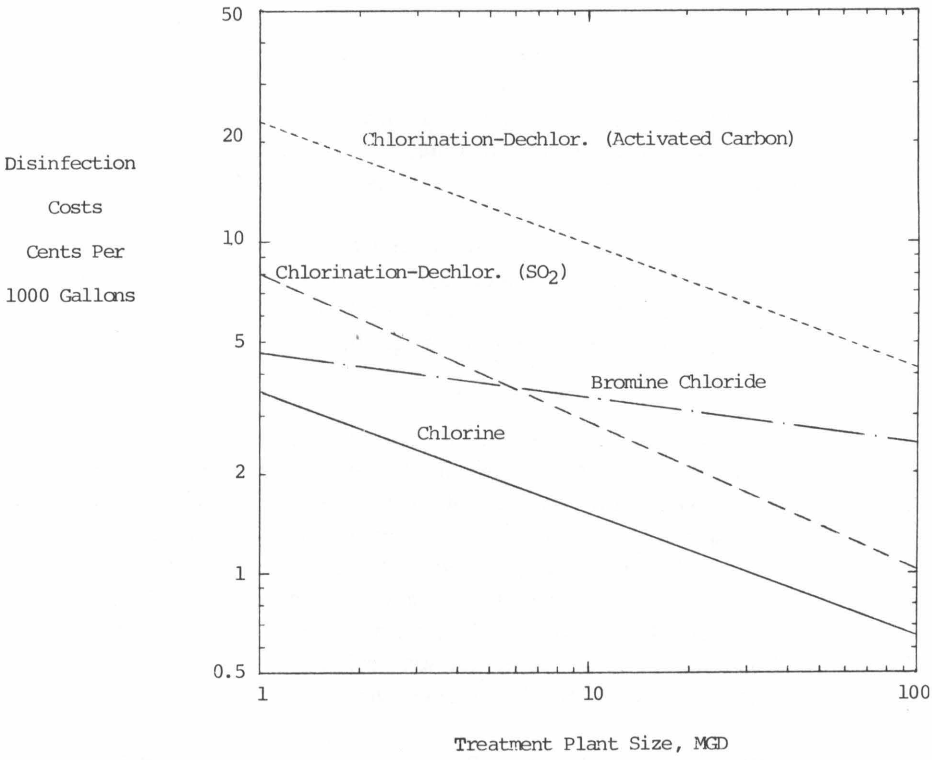
Terminal disinfection of vegetative bacteria and viruses can be obtained with breakpoint chlorination and adequate contact time. The increased dosage (above 25 mg/l) used to produce a free-chlorine residual in the effluent will intensify residual toxicity and increase the quantity of chlorinated organics released to receiving waters. Dechlorination with sulfur dioxide can remove such toxic residual chlorine as chloramines to protect aquatic and marine life, but may not effect removal of other chlorinated organics. Activated carbon dechlorination could result in removal of both organics and ammonia, but the ability of such a process to remove halogenated organics from chlorinated effluents has not been verified [I-20].

The use of ozone, bromine chloride, bromine, and iodine can reduce the problems associated with toxicity of residual chlorine, but the interactions of these disinfectants with organic matter have not been completely revealed. Thus, little is known about either the short or long-term ecological effects of reaction products formed during use of these disinfecting agents. Irradiation of wastewater may also initiate undesirable side reactions resulting in the formation of compounds that have adverse effects on receiving waters [I-20].

Chlorine is a somewhat more available resource than either bromine or iodine and requires less power for production of an equivalent quantity [Table 9]. The outlook for future availability of bromine chloride appears good [B-21]. Improvements in methods of generating and contacting ozone could reduce significantly the power requirements for its production and lower dosage requirements [C-34]. A larger use of ultraviolet lamps may result in the development of more efficient units which would consume less power than existing models [D-23]. Currently, a 65 watt bulb yields from 10 to 20 watts of UV light energy. Alternate means of disinfection will

FIGURE 1

Relative Costs of Alternate Disinfection Methods Using Halogens Applied to Secondary Wastewater Effluent

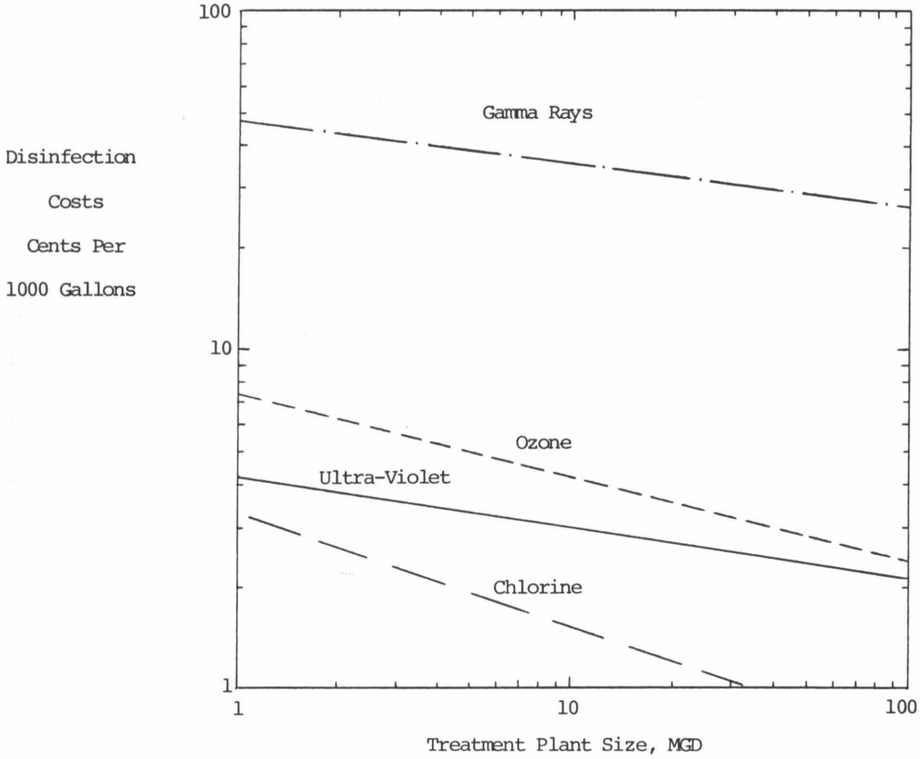


consume more energy as a whole than will conventional chlorination. Hopefully, technical improvements will narrow the current differences in energy usage if alternate disinfection techniques are utilized in the future.

Estimated capital and operating costs for alternate disinfection methods are presented in Tables 10 through 20 and are summarized in Tables 21 and 22. Cost relationships to the hydraulic capacity of secondary treatment plants are graphically depicted in Figures 1 through 3. From an examination of the values presented in these tables and figures, it would appear that dechlorination with sulfur dioxide is relatively cheaper than other alternate means of disinfection. Post-aeration following SO_2 dechlorination would increase the cost of this process by approximately 50 percent. Ozonation and ultraviolet irradiation would appear cost competitive with chlorina-

FIGURE 2

Relative Costs of Alternate Types of Disinfection Methods Applied to Secondary Wastewater Effluent

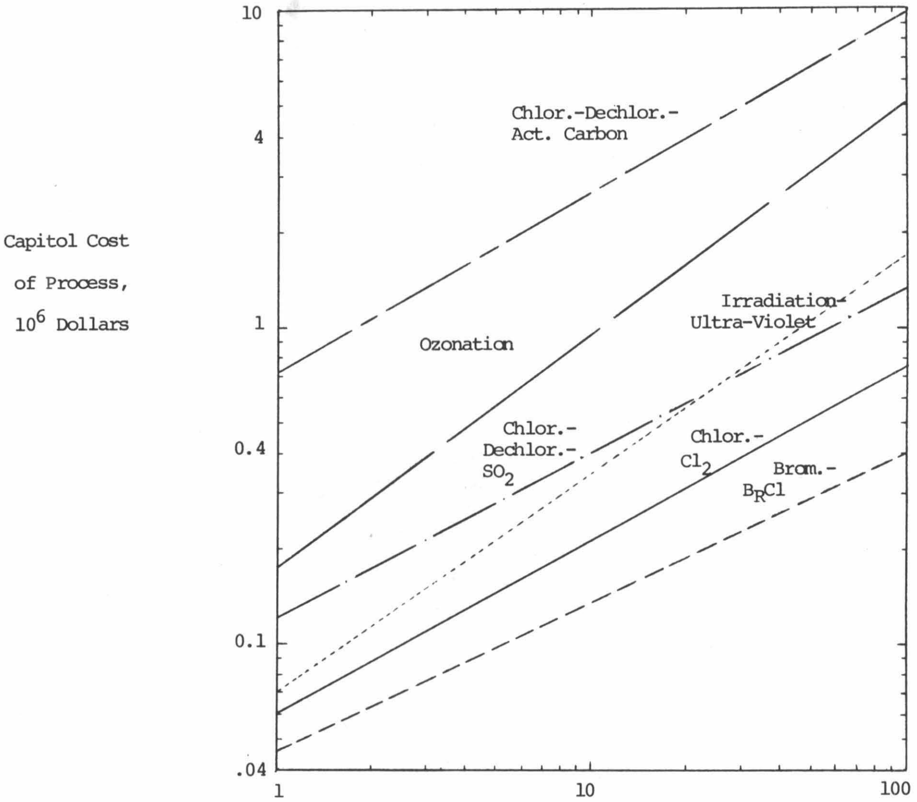


tion, dechlorination with SO_2, and post-aeration for disinfection of secondary effluent. If upgrading of treatment to a tertiary level is required for use of ozone and ultraviolet light, then the costs of these processes would go up by a factor that may range from three to five (Table 17). However, breakpoint chlorination may double chlorination costs. Thus, dechlorination with activated carbon may be cost competitive if breakpoint chlorination and the use of tertiary treatment prior to other means of disinfection are necessary. The use of bromine chloride appears to possess the most favorable economics of the alternate means of disinfection, on a cost per-gallon-treated basis.

From the standpoint of practical technology and toxicity to aquatic and marine life, both chlorination-dechlorination (with SO_2), and bromine chloride, seem to be the

FIGURE 3

Relative Capitol Costs for Possible Alternate Methods for Disinfecting Wastewater



most competitive alternatives to conventional chlorination. However, two distinct disadvantages may exist when either of these two alternate processes are used: viruses may not be removed and halogenated organics may be formed and released in the effluent. The use of ozone alone, or in combination with ultrasonics, ultraviolet light or halogens, may alleviate the disadvantages of suspect virus removal and formation of possible toxic reaction products which result from conventional chlorination. The use of alternative disinfectants should be evaluated on a case-by-case basis for any wastewater treatment process. In many cases, a trade-off of values may provide the best answer, in which the optimum natural ecology of limited stretches of receiving waters must be compromised to the higher interest of protection of human health and life [I-20].

REGULATION OF DISINFECTION

I. Current Problems

The enactment of P.L. 92-500 had the effect of requiring continuous disinfection of domestic wastewater effluents for maximum protection of human health. The Environmental Protection Agency promulgated limitations in terms of fecal coliform bacteria in section 133.102 (c) of 40 CFR Part 133, which required the following minimum levels of disinfection:

> "(1) The geometric mean of the values for effluent samples collected in a period of 30 days shall not exceed 200 per 100 milliliters (FC-MPN-200).
>
> (2) The geometric mean of the values for effluent collected in a period of seven consecutive days shall not exceed 400 per 100 milliliters."

In order to attain EPA disinfection standards, a separate unit process of disinfection was necessary as secondary treatement alone seldom accomplishes more than a 90 percent total coliform reduction. As chlorine was the only established wastewater disinfectant at that time, the use of chlorination was greatly encouraged. Although the toxicity problems resulting form chlorine residuals were well documented from past investigations, little consideration had been given to optimizing chlorination techniques to protect aquatic organisms. Recent studies emphasized the toxicity of chlorine residuals at low concentrations and potentially dangerous halogenated organics were isolated from chlorinated wastewaters. Thus, it has recently been recognized that uncontrolled and excessive use of chlorine for wastewater disinfection could pose serious threats to both human and aquatic life.

In light of these developments, the Environmental Protection Agency has proposed revisions to its secondary treatment regulations, in which the effluent limitations for fecal coliforms would be deleted and disinfection criteria would be based on water quality standards [I-56, I-57]. An assessment of state standards for wastewater disinfection conducted by EPA indicated that sufficient local regulations pertaining to disinfection of wastewater did exist which would adequately protect public health [F-1, I-21]. Disinfection requirements should provide adequate protection of the necessary water quality for the following classes of receiving waters:

1. Public water supplies;
2. Fisheries and shellfish waters;
3. Irrigation and agricultural waters;
4. Human contact waters, and
5. Interstate waters of the previously listed four classes [I-21].

In instances where the benefits derived from chlorination are greatly outweighed by ecological damage, alternate means of disinfection must be considered. If no identifiable public health hazards exist from non-disinfected discharges, then the disinfection step could be omitted from the treatment process. The omission of disinfection should be considered only when treated effluent will receive sufficient dilution in the receiving water.

The use of the coliform family of bacteria as bio-indicators of possible sewage contamination is well established. The multiple tube dilution method and the MPN parameter provide a reliable quantitative estimate of coliform density within a sample. Representative sampling is a vital aspect of the accuracy of test results. The membrane filter (MF) method has been proposed as a possible replacement for the multiple tube test because of its relative rapidity and because the procedure results in an actual bacterial count for a given sample volume. The MF procedure appears to be subject to interferences when applied to chlorinated sewage effluent [F-35]. The geometric median value of MPN obtained from tests conducted on a number of samples within a set period of time has been used as a regulatory standard by a number of state and federal agencies. Previously, a median MPN value of 1,000 total coliforms per 100 milliliters of sample was accepted as the maximum health risk value for recreational water quality. The Federal Food and Drug Administration has set a limitation of 70 total coliforms per 100 milliliters, as a median value, for shellfishing harvesting waters. Currently, fecal coliform median MPN values as regulatory standards have been proposed, such as 200 fecal coliforms per 100 milliliters for recreational waters [F-41]. The use of fecal coliform test results as the only regulatory standard is subject to many disadvantages, including [A-19]:

1. Fecal coliforms comprise only a variable portion (20 to 40 percent) of the total coliform family present in sewage contaminated waters.
2. Fecal coliforms are more susceptible to chlorine than the non-fecal coliforms.
3. Low fecal coliform MPN values may not correspond to the absence of pathogenic bacteria and viruses, due to differences in resistance.

The use of fecal coliform MPN values has the advantage of a better correlation to fecal contamination from either domestic or storm wastewaters. Assuming a normal distribution of test results, a mean MPN of 200 would indicate that a few percent of samples could show an MPN as high as 1,000 [F-22]. A definite need exists for studies concerning the relationships between fecal coliform MPN and the density of water-borne pathogenic microorganisms. Fecal coliform to fecal streptococci ratios have shown some correlation to fecal contamination from domestic wastewater [F-18, F-19]. Preliminary studies have been made on possible use of yeasts and acid-fast fast bacteria as indicators of wastewater chlorination efficiency [F-14].

Results of many studies have suggested that an examination for specific pathogens should be conducted on recreational and food supply waters for maximum health protection [F-22, F-48]. A limited number of regulatory standards have incorporated a viral limitation in the form of a maximum number of plaque-forming units (PFU) [I-61]. Viral concentration, separation, and identification techniques have been greatly modified and improved recently, but a high level of technical skill is still required to conduct viral examinations [G-2, G-28, G-34, I-34, I-49]. Destruction of at least 12 log units of a reference virus at 5° C has been recommended as a possible disinfection standard [G-8]. In view of present technology, the recommended viral standard may not be realistic as it would require improvement in present effluent monitoring and analytical testing techniques.

The possible formation of halogenated organics in chlorinated wastewaters and potentially adverse effects on public health pose serious regulatory problems. The formation of highly toxic chlorinated hydrocarbons during normal disinfection practice has been noted as highly unlikely due to the competitive reactions which exist during wastewater chlorination [H-28]. However, Jolley [H-33], has identified stable chlorine-containing organic compounds in effluents with an orthotolidine residual of 1-2 mg/l of TRC. Results indicated that one percent of the chlorine dosage could be associated with an increase in chlorinated organics. The tests involved chlorination of activated sludge effluent and a 45-minute reaction time, which left a TRC level of one mg/l (as measured by orthotolidine) [H-33]. Concentration levels of chlorinated organics in wastewater effluents have been measured in the part per billion range [H-14]. Chlorinated purines and pyrimidines have been found in chlorinated effluents at levels which could potentially exhibit some teratogenic and carcinogenic activities. [I-20]. The formation of potentially dangerous reaction products from all methods of disinfection requires additional research for proper evaluation.

II. Current Research

The Environmental Protection Agency is currently sponsoring a number of research projects concerning wastewater disinfection (Table 23). These studies include improving the chlorination process, determining viricidal properties of chlorine, comparing alternate disinfectants with parallel tests and developing new indicators of disinfection efficiency. The results of many recently completed studies have been made available (Table 24).

Four major extramural wastewater disinfection projects are now in progress. A parallel study is underway in which four methods of disinfection are being applied to wastewater effluent from the activated sludge treatment plant located in Wyoming, Michigan [I-20]. Chlorination, chlorination-dechlorination with SO_2, ozonation, and bromination with bromine chloride are used to disinfect four streams in the Michigan study, with an undisinfected fifth stream for control. Each effluent stream was evaluated for disinfection efficiency and fish toxicity. Preliminary results have indicated that the chlorinated effluent stream is the most toxic to fish life. Dechlorination with SO_2 appears to be highly successful in removing this toxicity. Ozone and bromine chloride have not exhibited significant toxicity at the levels of dosage and contact normally employed. Unfortunately, involved chemical analysis for detection and identification of reaction by-products was not included as part of this project. Thus, possible formation of halogenated and ozonated organics and the implications to public health concerns will not be addressed by this study. Results of tests at Wyoming City have verified the fact that bromine chloride is an efficient disinfectant for secondary effluent, producing residuals below those resulting from chlorination. The initial level of bromine chloride residuals was noted to dissipate rapidly and toxicity effects were not evident below a residual concentration of 0.02 mg/l. Additional data are needed to establish the optimum halogen residual required for adequate disinfection with bromine chloride. The Wyoming study has also demonstrated that it is difficult to reliably disinfect secondary effluent with ozone, using present contractor designs. Tertiary treatment, using chemical clarification followed by mixed media filtration, may be required for ozonation pretreatment. Under construction are five full-sized wastewater treatment plants which will employ ozonation for disinfection as listed in Table 23. Additional bromine chloride studies are planned for treatment plants located near shellfish harvesting areas in Maryland and Virginia.

A study of ultraviolet light disinfection of wastewater has been initiated in Dallas, Texas to evaluate operational problems, pretreatment requirements, and process economics. A 2-MGD domestic wastewater treatment plant that will use UV disinfection following filtration is under construction at Rochester, N. Y. Back-up chlorination is included in this facility. Chlorination of sand-filtered, multi-cell lagoon effluent is being investigated at Logan, Utah, to determine the chlorination requirements needed to reach a secondary treatment level. Optimization of the wastewater chlorination process to reduce toxicity emissions is being studied at Sacramento, California. A mobile, idealized chlorine-mixing and contacting unit is being tested for disinfection efficiency in parallel with existing full-scale chlorination facilities at several treatment plants. EPA-sponsored studies are also being conducted on viral inactivation by chlorine and a search is underway for new microbial indicators of disinfection efficiency [I-20]. As most of this research is relatively new or currently active, complete evaluations of study results are not available at the present time. Information obtained from this EPA-sponsored research should provide a foundation for future wastewater disinfection policy decisions.

SUMMARY

A variety of pathogenic organisms are normally present in domestic wastewater. Maximum public health protection requires the assumption that the numbers or density of pathogens is sufficient to cause a reasonable probability of infection upon ingestion of even highly diluted sewage. Indicator organisms are used to quantify the probability of contact with an infective dose of a waterborne pathogenic species. Acceptable limits for coliform density in certain waters have been established for maximum water quality protection. Proposed MPN standards of 1,000 total coliforms per 100 milliliters and 200 fecal coliforms per 100 milliliters have been previously adopted for recreational waters, based on limited epidemiological data. A limit of 70 total coliforms and 14 fecal coliforms per 100 milliliters has been established for shellfish growing waters. Outbreaks of waterborne diseases in the United States are infrequent, but reported cases of Shigella and Salmonella illnesses have occurred among swimmers, and many cases of infectious hepatitis have been related to the consumption of raw shellfish [I-20]. In several instances, outbreaks of waterborne disease occurred from contact with water contaminated by sewage [F-8, F-9].

Adequate water-quality criteria can be maintained for health protection if pathogens are removed or destroyed by physical or chemical means prior to discharge so that natural die-off and dilution eliminates possible contact with an infective dose. However, in the case of viruses, virtual elimination may be necessary as infection may result from exposure to one virulent organism. Primary and secondary treatment systems do not possess the necessary microorganism removal efficiency to meet adopted water-quality standards, unless a separate unit operation, designed specifically for wastewater disinfection is added. Total treatment with a disinfection unit should be able to meet the standards set for indicator microorganisms when the receiving waters are used for water supply, recreation, and food supply.

"Disinfection of secondary effluent with chlorine can reliably meet present bacteriological standards for secondary treatment." [I-20] But, present bacteriological standards based on the coliform bacteria MPN may not provide maximum health protection, as more resistant pathogens, such as viruses, can survive when coliforms cannot. In addition, the process of chlorination can result in the formation of residual chlorine levels in receiving waters that are toxic to fish. Dechlorination with sulfur compounds is a practical method of removing toxic residual chlorine, but it will require extensive operational control and possible post-treatment.

The unlikely, but conceivable, formation of halogenated organic compounds that are potentially toxic to man, from chlorination of wastewaters, is an area of special public health concern. The use of high chlorination doses for breakpoint chlorination may result in the production of significant amounts of halogenated organics which, although they are usually unstable, may be detrimental to environmental quality [H-2].

Uncontrolled and indiscriminate use of chlorine for disinfection should not be permitted. In-plant modifications to provide proper contact periods, with accurate residual monitoring and control, should eliminate many of the operational and toxicity problems associated with present chlorination practices. Alternate means of disinfection may possess certain advantages that favor their use in some instances, but a proper evaluation of the ecological-health-resource trade offs should proceed the selection of any one method of disinfection (Table 8).

The use of either chlorination-dechlorination or chlorobromination (BrCl) may eliminate aquatic life toxicity problems but may not completely eliminate the problems of the viruses and hazardous reaction by-products that may be discharged to receiving waters. Breakpoint chlorination should be a highly effective method for viral inactivation but may intensify the potential hazards of halogenated organics. Dechlorination to remove toxic residuals could be required as post-treatment for breakpoint chlorination. Post-treatment in the form of pH adjustments and reaeration may be necessary for proper dechlorination operation and may be required for the majority of alternate disinfection processes. Bromine chloride is a very promising alternative to chlorine from the standpoint of both available technology and economics. The halogenated reaction products of chlorobromination are apparently oxidized rapidly to non-toxic compounds. Effective bacterial and viral inactivation seem to be accomplished more rapidly by BrCl as compared to similar doses of chlorine. Effective residual monitoring and control will be very important to the use of dechlorination and chlorobromination.

Ozonation and ultraviolet light are highly effective germicides if interferences are removed from the wastewater. Ozone and UV processes will require pretreatment in the form of chemical clarification and filtration in order that they meet disinfection standards. However, ozone can provide residual oxygen in the treated effluent and ultraviolet light should not produce toxic reaction by-products. The use of lime for disinfection may be feasible if provisions can be made to handle the large quantities of sludge that would be formed by this treatment.

Conventional chlorination may utilize from 7 to 15 percent of the total on-site power demand required for the operation of a secondary treatment process. Alternate means of disinfection may need from five to seven times the power normally supplied for disinfection by chlorine. Resource scarcity and a high degree of power consumption will cause most alternative means of disinfection to be at least three to five times more expensive than chlorination. Chlorine is the most readily available and inexpensive of the various practical methods that can accomplish effective disinfection.

The technology of alternate methods of disinfection is being rapidly developed. Current research should provide parameters for practical process design of dechlorination, ozonation, chlorobromination and ultraviolet light facilities. However, economics may favor trade offs between the need for maximum public health protection and the desire to maintain a natural ecological system. Disinfection must be recognized as a unit operation for which the degree of upstream pretreatment is vitally important. Continuous monitoring of effluent residuals or dosage intensity, incorporated into an automatic control system, should be designed into each disinfection unit in areas of high water-quality requirements.

RECOMMENDATIONS

Recommendations regarding the possible usage of alternate means of wastewater disinfection, summarized from available literature, include:

1. In-plant modifications should be used to develop good mixing of chlorine and influent wastewater with adequate contact periods to improve existing chlorination processes. Consideration should be given to the provision of mixing devices, baffling modifications, stage dosing of chlorine and pH-temperature adjustments.

2. In areas where protection of aquatic life is of concern, chlorine residuals should be precisely monitored and maintained below 0.01 mg/l in the receiving waters at all times. Lower residual levels may be necessary in some cases where sensitive organisms are present or other factors add to TRC toxicity.

3. If chlorine residuals in treated effluents must be reduced to trace levels, then dechlorination, which will require continuous monitoring and loop control systems, should be utilized.

4. In areas where viral contamination and halogenated organics pose a threat to public health, the use of alternate disinfectants should be considered, based on a proper evaluation of the trade offs associated with health protection versus ecological balance.

5. The use of chlorobromination should be considered as a practical, cost-competitive alternative to chlorination-dechlorination. However, additional information concerning required residual levels and reaction by-products should be obtained through research.

6. Either breakpoint chlorination of secondary effluent followed by dechlorination, or ozonation of tertiary filtered effluent, should be evaluated for conceivable usage to suppress viral contamination of receiving waters. Information concerning the potentially adverse affects on public health from toxic reaction by-products must be developed for these methods.

7. Tertiary treatment followed by ozonation or ultraviolet light irradiation should be considered in areas where protection of both public health and aquatic life are necessary.

8. Currently, the most practical alternatives to conventional chlorination appear to be:

   A. Chlorination-dechlorination with SO_2;
   B. Bromine chloride;
   C. Ozonation of filtered effluent, and
   D. Chlorine dioxide treatment of highly clarified effluent.

9. The most efficient treatment level possible must be applied to wastewater prior to the disinfection unit. In addition, pH adjustments and combinations of disinfectants may be used, such as the use of limited chlorination prior to chlorobromination, to reduce the bromine demand, or the use of ozone as post-treatment.

10. The most precise methods available should be used to monitor disinfectant dosages and residuals, such as the Iodometric-Amperometric techniques for TRC determinations. The point at which samples are withdrawn from disinfection units for residual monitoring must be carefully chosen when disinfectants have only brief residuals.

11. Identification of specific pathogens should be made periodically in areas of high water-quality requirements and related to indicator test results. Both total and fecal coliform MPN values should be used to evaluate disinfection performance and receiving water quality.

TABLES

TABLE 1

Noted Acute and Chronic Toxic Effects of Residual Chlorine on Aquatic Life (H-16)

Species	Effect Endpoint	Measured Residual Chlorine Concentration (mg/l)
Coho salmon	7-day TL_{50}*	0.083
Pink salmon	100% kill (1-2days)	0.08-0.10
Coho salmon	100% kill (1-2days)	0.13-0.20
Pink salmon	Maximum nonlethal	0.05
Coho salmon	Maximum nonlethal	0.05
Brook trout	7-day TL_{50}	0.083
Brook trout	Absent in streams	0.015
Brown trout	Absent in streams	0.015
Brook trout	67% lethality (4 days)	0.01
Brook trout	Depressed activity	0.005
Rainbow trout	96-hr TL_{50}	0.14-0.29
Rainbow trout	7-day TL_{50}	0.08
Rainbow trout	Lethal (12 days)	0.01
Trout fry	Lethal (2 days)	0.06
Yellow perch	7-day TL_{50}	0.205
Largemouth bass	7-day TL_{50}	0.261
Smallmouth bass	Absent in streams	0.1
White sucker	7-day TL_{50}	0.132
Walleye	7-day TL_{50}	0.15
Black bullhead	96-hr TL_{50}	0.099
Fathead minnow	96-hr TL_{50}	0.05-0.16
Fathead minnow	7-day TL_{50}	0.082-0.115
Fathead minnow	Safe concentration	0.0165
Golden shiner	96-hr TL_{50}	0.19
Fish species diversity	50% reduction	0.01
Scud	Safe concentration	0.0034
Scud	Safe concentration	0.012
Daphnia magna	Safe concentration	0.003
Protozoa	Lethal	0.1

*TL_{50} = median tolerance limit (50 percent survival).

TABLE 2

Possible Alternate Methods for Wastewater Disinfection

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1. Chlorination-Dechlorination
   a) Sulfur Compounds b) Activated Carbon

2. Ozonation
   a) Air Generated b) Oxygen Generation

3. Other Halogens
   a) Chlorine Dioxide b) Bromine Cloride
   c) Bromine d) Iodine

4. Irradiation
   a) Ultra-Violet Light b) Ionizing Radiation
   c) High Frequency Sound Waves

5. Miscellaneous
   a) Heat b) Acids-Alkalies c) Metal Salts
   d) Surface Active Compounds

TABLE 3
Comparison of the Relative Disinfection Efficiency of Certain Halogen Compounds (I-30)

TARGET ORGANISM	DISINFECTING AGENTS	RELATIVE EFFICIENCY	CONDITIONS
ENTERIC BACTERIA	HOBr, HOCl, I_2	HOCl ≃ HOBr > I_2	25^0 C., 10 min.
	I_2 in NH_4Cl, NH_2Br and NH_2Cl	I_2 > NH_2Br > NH_2Cl	pH 7.5, 0^0 8mg/l dose
	OCl^- and HOCl	HOCl > OCl^-	5^0 C., pH 6.0
	I_2, HOCl, HOBr	HOCl > HOBr > I_2	pH 7.0, $3\text{-}4^0$ C.
ENTERIC VIRUSES	I_2, HOCl, HOBr	HOCl ≃ HOBr ≃ I_2	25^0 C., 10 min.
	I_2 HOCl	I_2>> HOCl	5^0 C.
	HOCL, OCl^-	OCl^-> HOCl	5^0 C.
BACTERIAL VIRUSES	I_2 in NH_4Cl, NH_2Br and NH_2Cl	I_2>> NH_2Br NH_2Cl	pH 7.5, 0^0C.
	HOCl, OCl^-	HOCl > OCl^-	5^0 C.
PROTOZOAN CYSTS	I_2, HOCl, HOBr	HOCl≃HOBr ≃ I_2	25^0C., 10 min.
	I_2, HOBr, and HOCl in H_2O with glycine and NH_4Cl	I_2 > Br > Cl (Mixture of forms) &	pH 6.0
		I_2 > Cl_2 > Br_2	pH 8.0

TABLE 4

Relative Resistance of Various Organisms of Significance in Waterborne Disease Transmission to Certain Forms of Halogen Disinfectants (I-30)

DISINFECTING AGENT	RELATIVE RESISTANCE OF VRIOUS ORGANISMS	RELATIVE DOSAGES REQUIRED FOR 99% OR GREATER INACTIVATION
Hypochlorous acid, HOCl	Amoebic Cysts > Poliovirus I > Coxsackie A9 > E. coli > T2 Coliphage	175 : 40 : 30 : 1 : 0.8
Hypochlorite ion,	E. coli > Coxsackie A9 > Poliovirus I > f2 Coliphage	1 : 0.37 : 0.25 : 0.04
Monochloramine, NH_2Cl	Enteric Viruses > Amoebic Cysts > Enteric Bacteria	5 : 4.7 : 1
Hypobromous acid, HOBr	Amoebic Cysts > Enteric Viruses > Enteric Bacteria	160 : 20 : 1
Molecular Iodine, I_2	Enteric Viruses > Amoebic Cysts > Enteric Bacteria	73 : 18 : 1

TABLE 5
Reactions of Chlorine and Bromine Forms in Water

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1. $Cl_2 + H_2O = HOCl + H^+ + Cl^-$

   $BrCl + H_2O = HOBr + H^+ + Cl^-$

2. $HOX = OX^- + H^+$

3. $HOX + NH_3 = NH_2X + H_2O$

   $HOX + NH_2X = NHX_2 + H_2O$

   $HOX + NHX = NX_3 + H_2O$

Note: X Represents Either Cl or Br

TABLE 6
Comparison (1=low, 5=moderate, 10=high) of the Relative Characteristics with Halogen Disinfection of Wastewater

Relative Disinfection Characteristics	Halogen Disinfectants Chlorine	Iodine	Bromine	Bromine Chloride
Bactericidal Efficiency	7	6	7	8
Viricidal Efficiency	3	4	3	5
Cysticidal Efficiency	2	6	4	4
High pH Efficiency	2	6	7	8
Low pH Efficiency	7	6	7	8
Combined Residual Efficiency	3	N.A.	5	6
Necessary Contact Period	7	8	6	5
Temperature Effects	6	4	5	5

TABLE 7

Relative Evaluation (1=low, 5=moderate, 10=high) of Various Characteristics of Alternate Methods of Wastewater Disinfection

Relative Characteristics	Chlorination-Dechlorination	Bromine Chloride	Ozonation	Ultra-Violet Light	Ionizing Radiation
Bactericidal Efficiency	6	6	7	8	6
Viricidal Efficiency	5	6	7	8	7
Cysticidal Efficiency	3	4	6	2	6
Residual Disinfection	5	4	2	0	0
Toxicity of Secondary Reactants	2	3	?	0	0
Pre-Treatment Requirement	4	4	7	8	2
Energy Requirement	3	4	9	6	10+
Costs	4	4	7	5	10+

TABLE 8
Comparison of the Status of Various Wastewater Disinfection Methods (I-20)

	State-of the Art	Health Effects	Aquatic Toxic Effects
Chlorine	Operational	Assume Chlorinated Organics	High
Sodium Hypochlorite	Operational	Assume Chlorinated Organics	High
Chlorine/Sulfur Dioxide	Operational	Assume Chlorinated Organics	Low
Chlorine/Carbon	Pilot Plant	Assume Minimal	Low
Ozone/Air	Pilot Plant	Unknown	Low
Ozone/Oxygen	Pilot Plant	Unknown	Low
Ultraviolet	Pilot Plant	Assume Minimal	Assume Low
Bromine Chloride	Pilot Plant	Halogenated Organics	Intermediate
Ionizing Radiation	Pilot Plant	Assume Minimal	Assume Low

TABLE 9
Estimated Power Consumption for Production of Possible Wastewater Disinfectants

Disinfectant	Power Consumption for Production KWH/1000 gallons
Chlorine*	0.06
Bromine*	0.15
Iodine*	0.15
UV (10,000 micrwatt-sec/cm^2)	0.20
Ozone* (from air)	0.30
Gamma Ray Accelerator (50,000 Rads)	1.45

* Based on 8 mg/l dose

TABLE 10

Estimated Costs of Disinfection of Secondary Effluent Using Chlorination (1974), (I-20)

(A)	Capital Costs	
(1)	Chlorine contact basin (30 min. contact)	$ 26,071
(2)	Feeding and storage equipment	34,617
Total		$ 60,688
(B)	Total Treatment Costs (¢/1000 gal.)	
(1)	Amortization (@ 5 7/8% for 20 years)	1.435
(2)	O. & M., materials, labor and supplies	0.740
(3)	Chlorine (@ 16¢/ lb.)	1.068
Total		3.243

*Design Flow 1 MGD - 8 mg/l Dosage.

TABLE 11

Estimated Costs for Dechlorination for 1 MGD of Secondary Wastewater Effluent Using Sulfur Dioxide (1974), (I-20)

(A)	Capital Costs	
(1)	Feeding and storage equipment	$ 10,818
Total		$ 10,818
(B)	Total Treatment Costs (¢/ 1000 gal.)	
(1)	Amortization (@5 7/8% for 20 years)	0.256
(2)	O. & M., materials, labor and supplies	0.232
(3)	Sulfur dioxide (@ 21¢/ lb.)*	0.438
Total		$ 0.926

* 2.5 mg/1 Dosage.

TABLE 12

Estimated Costs of Post-Aeration Facilities That Will Provide 5 mg/l of Dissolved Oxygen in Secondary Wastewater Effluent (1974), (I-20)

(A)	Capital Costs*	
(1)	Aeration basin	$ 13,229
(2)	Diffused air system	35,873
Total		$ 49,102
(B)	Total Treatment Costs (¢/1000 gal)	
(1)	Amortization (@ 5 7/8% for 20 years)	1.161
(2)	O. & M., materials, labor and supplies	2.148
Total		3.309

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*Based on a Dissolved Oxygen concentration of 1 mg/l in the dechlorinated effluent.

TABLE 13

Estimated Costs of a Chlorination-Dechlorination (SO_2)-Reaeration Process for Disinfection of Secondary Wastewater Effluent, (I-20)

Capital		
Chlorination-Dechlorination	$ (000)	$ (000)
Structure	376	
Equipment	674	
		1,050
Reaeration		
Structure	17	
Equipment	21	
		38
Total		$1,088
Operating	¢/1000 gal.	
Chlorination-Dechlorination		
Chemicals	3.32	
Supplies and Utilities	0.30	
O & M Labor	0.64	
		4.26
Reaeration		
Supplies and Utilities	0.07	
O & M Labor	0.64	
		0.71
Total		4.97

Basis: 6 mgd plant, Cl_2:NH_3 feed rate = 9:1, 12 mg/l NH_3

TABLE 14

Estimated Costs of Disinfection of 1 MGD of Secondary Wastewater Effluent Using an 8 mg/l Dosage of Bromine Chloride (1974), (I-20)

(A)	Capital Costs	
(1)	Contact basin (30 min. contact)	\$ 26,071
(2)	Feeding and storage	34,617
Total		\$ 60,688
(B)	Total Treatment Costs (¢/1000 gal.)	
(1)	Amortization (@ 5 7/8% for 20 years)	1.435
(2)	O. & M., materials labor and supplies	0.740
(3)	Bromine chloride (@ 35¢/lb.)	2.335
Total		4.510

TABLE 15

Estimated Costs of Disinfection of 1 MGD of Tertiary Wastewater Effluent Using an 8 mg/l Dosage of Ozone Produced from Electrical Discharge in Atmospheric Air (1974), (I-20)

(A)	Capital Costs	
(1)	Ozone generating units	$ 111,468
(2)	Ozone contacting unit	23,379
(3)	Engineering, piping, land and interest costs during construction (@ 35% of construction costs)	47,196
Total		$182,043
(B)	Total Treatment Costs (¢/1000 gal)	
(1)	Amortization (@5 7/8% for 20 years)	4.305
(2)	O. & M., materials, labor and supplies	1.784
(3)	Power costs (@ 12 kw-hr/lb O_3 used)	1.201
Total		7.290

TABLE 16

Estimated Costs of Disinfection for 1 MGD of Tertiary Wastewater by Ozonation, Using an 8 mg/l Dosage of Ozone Produced from Electrical Discharge in Pure Oxygen (1974), (I-20)

(A)	Capital Costs	
(1)	Ozone Generating unit	$ 55,743
(2)	Ozone contacting unit	23,379
(3)	Oxygen storage tank	26,402
(4)	Engineering, piping, land and interest during construction (@ 35% of construction costs)	36,930
Total		$142,445
(B)	Total Treatment Costs (¢/1000 gal)	
(1)	Amortization (@ 5 7/8% for 20 years)	3.368
(2)	O. & M., materials, labor and supplies	1.784
(3)	Power costs (@ 5 kw-hr/ lb O_3 used)	0.500
(4)	Liquid oxygen (@ 4.6¢/lb)	0.920
Total		6.572

TABLE 17

Capital Costs and Operating Costs of Ozone Treatment Plants Requiring Pretreatment, (H-34)

Item	Dollars per Million Gallons 1mgd	 10 mgd	 100 mgd
Capital Costs	440,000	227,000	130,000
Operation Costs			
Amortization 4%-15 yrs	108.2	55.7	31.8
Power	44.5	37.3	30.1
Labor	51.2	5.2	1.0
Maintenance	4.0	2.0	1.2
Oxygen	24.0	17.8	9.0
Alum- 132 mg/l	31.4	31.4	31.4
Acid- 63 mg/l	8.4	8.4	8.4
Total Operating Costs	271.7	157.8	111.9
Operating Costs cents per 1,000 gal.	27.2	15.8	11.2

TABLE 18

Estimated Costs of an Ozonation Process for Disinfection of a Mean Daily Flow of 14 MGD of Tertiary Effluent, (C-34)

Capital Costs	$ (000)
Ozone generators (585 lb./d, air feed)	150
Compressor/dryer @ 27% of ozone generator	40
Oxygen storage tank (15T)	20
Contactors (installed)	160
Building @ $25/sq. ft.	38
Controls	25
Installation (piping)	50
Engineering & contingencies	32
Total	515

Direct Operating Costs	¢/1000 gal.
Ozone generators @ ∿8.0 kwh/.b. ozone	0.51
Compressor/dryers @ 3.5 kwh/lb. ozone	0.21
Oxygen, 135T/ yr. @ $30/T (including usage and evaporation loss)	0.11
Operation and maintenance	0.24
Total	1.07

TABLE 19

Basic Assumptions Utilized for Estimating Costs of Ozonation for Wastewater Disinfection (Costs Listed in Table 18).

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1. Ten mgd flow, 23 mgd peak, <14 mgd flow 90% of time.
2. Flow distribution based on a plant in the N.E. U. S. for last three years.
3. Effluent quality to allow 5 ppm dosage to achieve 200 fecal coliform or less/100 ml.
4. Operating characteristics of Grace Ozone Generators and Contactors.
5. Power costs @1.5¢/kwh.
6. Designed for air feed to 14 mgd with liquid oxygen addition to ozonator feed for peak shaving to 23 mgd.
7. Two day supply of liquid oxygen for maximum peak usage.
8. Three psig gravity feed for wastewater to contactor.

TABLE 20
Estimated Costs of Disinfection of Tertiary Wastewater Effluents Using Ultra-Violet Light Units, (H-34)

Item	0.1 mgd	0.5 mgd	1.0 mgd
Number of Units	1.28-2.55	6.4-12.8	12.8-25.5
Cost of Units $ x 1,000, adjusted	$6.4-$12.8	$22.9-$45.7[1]	$35.2-$70.3[2]
Kilowatt Hours/Day	20-40	100-200	200-400
Cost of Power[3]			
per day	$0.20-$0.40	$1.00-$2.00	$2.00-$4.00
per year	$73-$146	$365-$730	$730-$1,460

[1] Adjustment factor 0.715
[2] Adjustment factor 0.55
[3] At $0.01 per KWH

Both relative to 0.1 mgd equipment cost.

TABLE 21

Comparison of the Estimated Costs of Alternate Disinfection Methods Applied to Secondary Wastewater Effluent (1973), (I-20)

PLANT SIZE, MGD	1	10	100
CAPITAL COST	$1000	$1000	$1000
PROCESS			
Chlorine	60	190	840
Chlorine/ SO_2	70	220	930
Chlorine/ SO_2/ Aeration	120	360	1,580
Chlorine/ Carbon	640	2,800	8,400
Ozone/ Air*	190	1,070	6,880
Ultraviolet*	70	360	1,780
Bromine Chloride	50	130	410
Activated Sludge	1,450	5,790	39,800
DISINFECTION COST	¢/ 1000 Gal.	¢/1000 Gal.	¢/1000 Gal.
PROCESS			
Chlorine	3.49	1.42	0.70
Chlorine/SO_2	4.37	1.75	0.89
Chlorine/SO_2/Aeration	7.66	2.39	1.19
Chlorine/Carbon	19.00	8.60	3.28
Ozone/Air	7.31	4.02	2.84
Ozone/Oxygen*	7.15	3.49	2.36
Ultraviolet*	4.19	2.70	2.27
Bromine Chloride	4.52	3.04	2.65
Activated Sludge	55.90	20.20	14.00

* Tertiary treatment stage is not included in these costs.

TABLE 22

Estimated Capital and Operating Costs of Alternate Disinfection Methods for Treating a 1 MGD flow of Secondary Wastewater Effluent, (I-20, I-62)

Alternate Disinfection Methods	Total Costs ¢/1000 gal.
Chlorination-Dechlorination-(8 mg/l_2, 2.5 mg/l SO_2) Post Aeration	7.478
Bromine Chloride 35¢/lb by tank cars (8 mg/l $BrCl_2$)	4.510
* Ozonation (8 mg/l O_3)	
In Atmospheric Air	7.290
In Pure Oxygen	6.572
* Ultra-Violet Light (10,000 microwatt-sec/cm^2)	4.190
Ionizing Radiation (50,000 Rad Accelerators)	100+

* Does not include Tertiary Treatment Phase

TABLE 23

A Listing of On-going Research Projects on Wastewater Disinfection Sponsored by the Environmental Protection Agency (I-20)

A. "Parallel Ozonation and Chlorination with Dechlorination of Chlorinated Effluent." Project No. 802292, City of Wyoming.

A study on disinfection effectiveness and bioassay effects of chlorine, ozone, dechlorination with sulfur dioxide and bromine chloride. Estimated completion date, Jan. 1976.

B. "Ultraviolet Disinfection of Municipal Effluents", Project No. 803292, City of Dallas.

The evaluation of ultraviolet light as a disinfectant for wastewater.

C. "Reduction of Toxicity Emission Rates from Wastewater Treatment Plants by Optimization of the Chlorination Process." Project No. 803459, State of California.

Develop cost effective design parameters for the chlorination process.

D. "Multicell Lagoons- Micro Organism Removal Efficiency and Effluent Disinfection", Project No. 803294, Utah State University.

Define the lagoon equivalency to disinfection and determine whether chlorination will effect the organic content of effluent.

E. "A Comparative Study of the Inactivation of Viruses in Waste, Renovated and Other Waters by Chlorine and Chlorine Compounds". Project No. 800370, University of Cincinnati.

Determine the capability of chlorine and chlorinated compounds to destroy viruses in wastewaters.

F. "New Microbial Indicators of Wastewater Chlorination Efficiency", Project No. 800712, University of Illinois.

Develop a biological indicator that is more suitable and reliable than the coliform group. Report No. EPA 670/2-73-082.

G. "Ozone Contactor Study,",AWTRL Pilot Plant.

An evaluation of ozone contactor efficiencies.

TABLE 24
Recently Completed Research Projects Related to Wastewater Disinfection (I-20)

A. "The Detection and Inactivation of Enteric Viruses in Wastewater", Project No. 800990, Hebrew University.

Develop effective and economical procedures for the inactivation of viruses in wastewater by ozone.

B. "Batch Disinfection of Treated Wastewater with Chlorine at Less Than 1 C," Project No. 16100 GKG, Arctic Environmental Research Laboratory, Report No. EPA-660/2-73-005.

C. "Lime Disinfection of Sewage Bacteria at Low Temperature", Project 16100 PAK, Colorado State University, Report No. EPA-660/2-73-017.

D. "Hypochlorite Generator for Treatment of Combined Sewer Overflows", Report No. 11023 DAA 03/72, Ionics Incorporated.

E. "Ultraviolet Disinfection of Activated Sludge Effluent Discharging to Shellfish Waters", Project No. WPRD 139-01-68, The Town of St. Michaels.

F. "Disinfection of Sewage Effluents", Project No. 17060 DNU, University of Illinois, Bromine and Chlorine Disinfection Results.

G. "Demonstrate Effectiveness of Iodine for the Disinfection of Public Water Supplies", Project No. 19-06-68, City of Gainesville.

H. "Hypochlorination of Polluted Stormwater Pumpage at New Orleans", Report No. EPA-670/2-73-067, Pavia-Byrne Engineering Corporation, New Orleans, La.

I. Bench-Scale High-Rate Disinfection of Combined Sewer Overflows with Chlorine and Chlorine Dioxide", Project No. 802400, O'Brien and Gere Engineers, Inc., Syracuse, New York.

TABLE 25
Dimensional Factors Encountered in Irradiation Disinfection

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1. Size Prefixes:
   a) Small: milli (m) = 10^{-3}, micro (u) = 10^{-6}, nano (n) = 10^{-9}
   b) Large: Kilo (K) = 10^{3}, Mega (M) = 10^{6}, Giga (G) = 10^{9}
2. Wavelength: Distance Between Energy Peaks
   a) Angstroms (Å) = 10^{-10} meters
   b) Nanometers (nM) 10^{-9} m = 10^{-7} centimeters
3. Frequency: Cycles per second = cps = c/s
   a) Hertz (Hz) = 1 cps
   b) MHz = 10^{6} cps, GHz = 10^{9} cps
   c) Microwaves = highest radio frequencies = 30 MHz to 300 GHz
   d) UHF = ultra high frequency = frequencies higher than 300 MHz

4. Force: Mass Times Acceleration

   a) Dyne = grams-centimeters/second squared = gm-cm/sec^2

   b) Newton = 10^5 Dynes

5. Power: Force Times Distance Per Time

   a) Watt (W) = 1 amp through 1 volt

   b) Horsepower (HP) = 746 watts

6. Energy: Force Times Distance

   a) ERG = Dyne-cm = 10^{-7} watt-secs. = 2.15 x 10^{-16} einsteins at 2573 angstroms

   b) Joule = 10^7 ERGS

   c) Kilowatt-hours (KWH) = 3.6 (10^6) Joules = 1.341 HP-Hour

   d) Million Electron Volts (MeV) = 1.602 (10^{-13}) Joules

   Note: The product of wavelength in centimeters and frequency in Hertz must equal the speed of light (3 x 10^{10} cm/sec) for electromagnetic radiation.

TABLE 26

Terms Encountered in the Measurement of Ionizing Radiation

A. Definition of Radioactivity: Certain atoms are radioactive i.e., their nuclei are unstable and emit energetic particles, pulses of energy, or both in a process known as radioactive decay which continues until the nuclei reach a stable state. This process may occur in a natural state or may be artificial i.e., influenced by man.

B. Types of Radioactive Emissions

1. Alpha Particles: Identical to helium nucleus in structure, a plus two positive charge and an atomic mass of 4 (two protons) and two neutrons), the least penetrating type of radiation, can be stopped by a few centimeters of air or a thin piece of paper.

2. Beta Particles: Similar to an electron with negligable mass and a negative charge of minus one, approximately 100 times the penetrating power of Alpha Particles, require a few millimeters of aluminum to stop them, emission from nuclear structure results in neutron changing to proton.

3. Gamma Rays: Similar to X-rays in that they apparently are uncharged pulses of electromagnetic radiation that move with the speed of light and possess very short wavelengths of .001 to 1.0 Angstroms. Only stopped by several inches of lead plate.

C. Measurement: Quantity of radiation is measured by the number of emissions that take place in a unit of time.

1. Curie: The most widely used unit of radioactivity. The modern standard value is 3.7 x 10^{10} emissions per second, which is the rate of disintegration of one gram of radium.

2. Specific Activity: Curies per gram of weight of substance

   Ex. 1 Curie of (Cobalt)^{60} weighs o.9 milligrams
   1 Curie of (Uranium)^{238} weighs two metric tons

3. Roentgen: Measures relative magnitude of exposure to X-rays and Gamma radiation. The Quantity of X - or Gamma Radiations which will form 1.61 x 10^{12} ion pairs when absorbed in 1 gram of air. The absorption of one roentgen results in the release of about 87 ergs of energy per gram of air.

Table 26 (con't)

4. RAD: The absorbed dose of any nuclear radiation which is accompanied by the liberation of 100 ergs of energy per gram of absorbing material.

   Roentgens and RADS are equivalent for Gamma Radiation of water.

5. Relative Biological Effectiveness (RBE): The ratio of the absorbed dose (RADS) of Gamma Radiation (of a specified energy) to the absorbed dose of the given radiation required to produce the same biological effect.

   Ex. If an absorbed dose of 0.2 RAD of slow neutron radiation produces the same effect as an absorbed dose of 1.0 RAD of Gamma Radiation:

   $$\text{Slow Neutron RBE} = \frac{1.0}{0.2} = 5$$

6. Roentgen Equivalent Man (REM): Indicates the extent of biological injury and is determined from the following formula:

   a) Dose in REMS = (RBE) x (Dose in RADS)

   b) Natural background radiation varies from 100 to 200 millirems depending on elevation.

APPENDIX

Currently Active Researchers in Wastewater Disinfection

	Name	Affiliation	Specialty
1.	Arthur, J.W.	National Water Quality Lab. ORD-NERC-EPA	Toxicity
2.	Ballantine, D.S.	Environmental Programs, Div. of Biomed. and Envir. Research-EPA	Irradiation
3.	Berg, G.	Biol. Methods Branch, Methods Develop. and Qual. Assurance Lab. NERC-EPA	Virology
4.	Block, R.M.	Chesapeak Biological Lab University of Maryland	Halogen
5.	Brungs, W.A.	National Water Quality Lab. ORD-NERC-EPA	Toxicity
6.	Buelow, R.W.	Control Technology Branch BWH-PHS-HEW	Chlorination
7.	Burbank, N.C.	Sanitary Engr. Dept University of Hawaii	Halogens
8.	Burton, D.T.	Benedict Estuarine Research Lab Academy of Natural Sciences of Philadelphia	Halogens
9.	Carlson, R.M.	Department of Chemistry University of Minnesota	Chlorination
10.	Chambers, C.W.	Advanced Waste Treatment Res. Lab. NERC-EPA-Cincinnati	
11.	Chang, S.L.	Bureau of Water Hygiene ECA-PHS-HEW-Cincinnati	Etilogy
12.	Collins, H.F.	California State Dept. of Health-Sacremento	Chlorination
13.	Englebrecht, R.S.	Department of Civil Engr. University of Illinois	Engineering
14.	Esvelt, L.A.	Stevens, Thompson and Runyan-Engrs./ Planners-Spokane, Washington	Engineering
15.	Feng, T.H.	Department of Civil Engr. University of Massachusetts	Engineering
16.	Filvey, A. H.	Asst. Dir. Petroleum Chem. Res Ethyl Corporation Researh Labs Ferndale, Michigan	Halogens

17.	Fujiaka, R.	Department of Microbiology University of Hawaii	Halogens
18.	Geldreich, E.E.	Water Supply Research Lab. NERC-EPA-Cincinnati	Microbiology
19.	Glaze, W.H.	Department of Engineering North Texas State University	Chlorination
20.	Gordon, R.C.	Artic Environmental Res. Lab EPA-Alaska	
21.	Harr, Thomas E.	Environmental Quality Res. Div N.Y. State Department of Environ. Conserv.-Albany	Chlorination
22.	Hoehn, R.	Sanitary Engr. Department Virginia Polytechnic Institute and State University	Toxicity
23.	Hsu, Y.	Department of Environ. Health School of Hygiene and Public Health Johns Hopkins University	Halogens
24.	Huggett, R.J.	Dept. of Ecology-Pollution Virginia Institute of Marine Science	Halogens
25.	Ingols, R. S.	Engr. Experiment Station Georgia Institute of Technology	Engineering
26.	Johnson, J.D.	Department of Environ. Science and Engr. University of North Carolina	Chemistry
27.	Jolley, R.L.	Exper. Engr. Section Chemical Tech. Div. Oak Ridge National Laboratory	Toxicity
28.	Katzenelson, Eliyahy	Environmental Health Lab Hebrew University Hadassah Medical School Jerusalem	Virology
29.	Kinman, R. N.	Department of Civil and Environ. Engr. University of Cincinnati	Engineering
30.	Kothandaraman,V.	Illinois State Water Survey	Chlorination
31.	Kott, Y.	San. Engr. Lab. Israel Institute of Technology	Halogens
32.	Kruse, C.W.	Department of Environ. Health School of Hygiene and Public Health Johns Hopkins University	Halogens
33.	Kuzminski, L. N.	Department of Civil Engr. University of Illinois	Halogens

34.	Leland, H.C.	University of Illinois	Halogens
35.	Malina, J.F.	Environmental Health Engineering University of Texas at Austin	Engineering
36.	Mills, J.F.	Halogens Research Lab. Dow Chemical Co.-Michigan	Halogens
37.	Morris, J.C.	Div. of Engr. and Applied Physics Harvard University	Chemistry
38.	Netzer, A.	EPS Canada Centre for Inland Waters P.O. Box 5050 Burlinton, Ontario, Canada	Ozonation
39.	Nupen, E.M.	N.I.W.R. C.S.I.R. Pretoria, P.O. Box 395 Rep. of South Africa	Virology
40.	Oda, A.	Ministry of the Environment Toronto, Canada	Halogens
41.	Murphy, K.L.	McMaster University Toronto, Canada	Engineering
42.	Olivieri, V.P.	Dept. of Environ. Health School of Hygiene and Public Health Johns Hopkins University	Virology
43.	Pavoni, J.L.	Civil and Environmental Engineering U. of Louisville, Kentucky	Engineering
44.	Peleg, Mordechai	Environ. Health Lab Hebrew University Hadassah Medical School Jerusalem	Ozonation
45.	Rosen, H.M.	Pollution Control Systems Div. W.R. Grace and Co.-Maryland	Ozonation
46.	Rosenkranz, W. A.	Waste Management Division ORD-EPA-Washington, D.C.	Engineering
47.	Scarpino, Pasqual	639 Baldwin Hall #71 University of Cincinnati	Virology
48.	Shuval, H. I.	Department of Medical Ecology Environ. Health Lab.-Hadassah Med. School-Hebrew University	Virology
49.	Sollo, R. w.	Chemistry Section Illinois State Water Survey	Chemistry

50.	Snoeyink, V.L.	Department of Sanitary Engr. University of Illinois-Urbana	Engineering
51.	Subsey, Mark	Dept. of Environmental Engineering University of North Carolina	Virology
52.	Sung, R.D.	TRW Systems Group One Space Park, Redondo Beach California	Toxicity
53.	Trump, J.G.	Department of Electrical Engr. Massachusetts Institute of Technology	Irradiation
54.	Tsai, C,	Natural Resources Institute University of Maryland	Toxicity
55.	Venosa, A.D.	Biol. Treatment Section Municipal Environ. Res. Lab. NERC-EPA-Cincinnati	Microbiology
56.	Ward, Ronald	Grand Valley State College	Toxicity
57.	White, G.C.	556 Spruce Street San Francisco	Chlorination
58.	Woodbridge, D.D.	University Center for Pollution Research, Florida Institute of Technology	Irradiation
59.	Zillich, J. A.	Water Resources Commission Department of Natural Resources Lansing, Michigan	Toxicity

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