THE ROLE OF UNCERTAINTY IN BALANCING BIOLOGICAL AND CHEMICAL
HEALTH RISKS IN DRINKING WATER CHLORINATION

by

Jennifer E. Slickers

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University of Virginia
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Submitted to the Department of Civil
and Environmental Engineering in Partial
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Signature of Author

Department of Civil and Environmental Engineering
January 13, 1995

Certified by

David H. Marks
James Mason Crafts Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by

Joseph M. Sussman
Chairman, Departmental Committee on Graduate Students

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ABSTRACT

Drinking water quality is threatened by health risks of both biological and chemical origin. Biological risks arise from waterborne pathogens while chemical risks are introduced during drinking water disinfection by the generation of Disinfectant By-Products (DBPs). These risks are competitive, in that, while both must be minimized to protect public health, measures taken to reduce one may increase the other. Scientific uncertainties, associated with both data and system complexity sources, present complications to the quantification of both biological and chemical risks. A conservative approach to accounting for these uncertainties results in severely narrowing the treatment options available to drinking water treatment utilities. Uncertainty regarding the effectiveness and the associated risks of treatment adaptations and of alternative disinfectant options to chlorine poses decision-making difficulties to both regulators and utility operators. Such significant scientific uncertainty amplifies the importance of non-scientific, or value-based, judgments. A corresponding uncertainty accompanies value judgments, due to the lack of consensus that surrounds them. Scientific uncertainties, because of their influence on risk-based regulations, are likely to significantly increase the cost of regulatory compliance, and, accompanied by the uncertainty of treatment alternatives, could result in a net increase of risk to human health. The prevalence of non-scientific uncertainties has already generated a new approach to regulatory decision-making, and may exert further influence on the choices made regarding drinking water treatment priorities.

Thesis Supervisor: Dr. David H. Marks

Title: James Mason Crafts Professor of Civil and Environmental Engineering
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1. INTRODUCTION

1.1 GENERAL INTRODUCTION

The drinking water treatment industry is currently faced with finding a solution to a problem of balancing two competing risks. For nearly a century, drinking water disinfection has been the key component in reducing the risk to human health introduced by waterborne pathogenic protozoa, bacteria, and viruses. These elements together comprise what is known as the "biological risk" to human health in drinking water consumption. Until the mid-1970's, minimizing biological risk through drinking water treatment was the focus of drinking water treatment and treatment regulations. Since this time however, the presence of an additional risk to human health has become more prevalently recognized. Oxidizing agents, used for destroying dangerous waterborne microbes, react with natural and synthetic organics entering with the influent and produce disinfection by-products, or DBPs. These chemicals, some of which are known or potential carcinogens and mutagens, comprise what is called the "chemical risk" to human health in drinking water consumption. Biological and chemical risks are not independent. The reliance built upon disinfection to relieve biological risk is now the generator of chemical risk; and, consequently, the reduction of one risk is likely to increase the other when the linking factor, the disinfectant or disinfection practice, is altered. Uncertainties that influence the characterization of both biological and chemical risks further obscure the precision with which this situation can be addressed.

The disinfectant used most frequently in the U.S. is chlorine. When potentially harmful DBPs were first discovered, two crucial events took place: (1) the first DBP limits were imposed, placing for the first time, an upper regulatory bound on the level of chlorination that could be conducted in a treatment stream, and (2) alternative disinfectants were sought to evade concerns over regulations on chemical risk, unlike maintaining the ability to meet regulatory standards regulating the biological risk of drinking water. At the time, DBPs were generally associated with chlorine only, so
alternative powerful oxidizing agents were pursued with the expectation that their application would sidestep chemical risk altogether. When it was established that alternative disinfectants generated their own DBPs and that these are also likely to present a health threat, the issue of mutually minimizing both biological and chemical health risks in drinking water reopened, and expanded beyond replacing the disinfectant as the exclusive solution.

The recognition that the chemical risk cannot be avoided by merely employing alternative chemical oxidants in the treatment process has initiated investigation into many different general solutions to the problem. Figure 1 presents a schematic of the relevant features in the drinking water treatment process. The source water possesses not only microbes, but also organic precursors that can react with the disinfectant during treatment, adding DBPs while lowering microbial concentrations in the effluent. Initial approaches took into consideration only a change in the disinfectant within the treatment process. Alternate solutions are now being targeted:

- prior to treatment, through the removal of precursors,
- within the treatment process with not only changes to disinfectant application, but also to peripheral treatment activities including filtration, coagulation, flocculation, and softening, and
- after treatment by removing generated by-products.

Determination of the best alternative to minimize both biological and chemical risks is dependent upon source water characteristics, as well as the economic limitations surrounding a particular treatment facility and the community it serves. Uncertainties accompanying these changes to treatment further obscure the resolution with which both biological and chemical risk can be quantified and mutually minimized.

This situation presents not only a serious engineering dilemma to utility designers and operators, but to regulators as well. Variability in both source water quality and socio-economic considerations that exist throughout the country has motivated regulators
FIGURE 1. Treatment Options.
Alternate solutions to chlorination by-product formation are now being targeted within each of the treatment stages. Source protection, precursor removal, changes in disinfectant and/or additional treatment steps, and removal of by-products all represent potential measures to reduce chemical risks while preserving disinfection benefits.
to specify concentration limits for potentially dangerous by-products, rather than specifying a particular treatment technology that is universally appropriate. However, regulators are acutely faced with the additional problem of uncertainty, present not only in characterizing both biological and chemical risks, but in assessing the safety of alternatives that treatment utilities may undertake to comply with more stringent regulations.

When regulatory efforts focused only on biological risk, the question of uncertainty was addressed in a conservative, protective fashion. Where information was lacking and uncertainty existed, "safety factors" were employed. Expert and scientific judgment provided estimates of what constituted absolute worst case scenarios, and protective limits were set as though the worst case were present. By setting regulatory limits higher than was thought to be necessitated by reality, the threat to human health was considered to be minimized. Uncertainty was by no means absent, but the additional risk presented by it could be minimized by accounting for its estimated maximum effect. The result appeared to be a benefit of over-protection from microbials with usually only a cost of a moderate increase in expenditure. This is likely to be acceptable to most people, so the existence of uncertainty did not present an urgent concern.

The addition of an opposing risk in an over-protective scheme however, added to the cost of conservatism a corresponding component of increased health risk. Consequently, a conservative approach to protection against biological risk could unnecessarily raise the chemical risk, or *vice-versa*. By regulating both risks independently, and both in a conservative manner, the flexibility needed to enable compliance with either is reduced. The practical implication of this approach to drinking water regulations is to greatly narrow the options available to drinking water treatment utilities for achieving compliance and protecting against the total human health risk. Furthermore, the uncertainty in risk characterization generates overly conservative regulations that greatly restrict the options available to drinking water treatment utilities, and therefore imposes a greater burden on them than may be necessary.
Uncertainty's role is not limited to the characterization of risk. It also extends to the options currently available for compliance. Little is known of the by-products generated by alternative disinfectants and of the potential health threats they may present. Consequently, few regulations exist that would discourage drinking water utilities from employing these less understood alternatives rather than pursuing more expensive methods of compliance that are more likely to reduce the actual chemical risk. The challenge presented to regulators by this form of uncertainty is to regulate in such a way as to discourage utilities from changing to treatment procedures that may unnecessarily expose communities to other harmful products, and to protect utilities from having to alter their treatment processes more than once simply to comply with changing regulations. This uncertainty regarding treatment alternatives and future regulations challenges treatment utilities to likewise anticipate these changing regulations, and to alter their treatment processes for current and future compliance.

The road to balancing biological and chemical risks is impeded by many factors, and uncertainty is prevalent among them. Uncertainties that arise from informational needs are great, and research should to be selectively pursued to eliminate uncertainties according to some priority. Furthermore, despite uncertainty, decisions regarding drinking water treatment and regulation must continue to be made. This introduces a component of value judgment into the decision-making process, which carries with it a corresponding uncertainty. Value judgments reflect the values of the stakeholders, and it is unlikely that the varied interests and values of affected parties can be fully represented by a single value judgment. Thus, the decision-making process has an element analogous to scientific uncertainty, a "non-scientific" uncertainty, representing non-consensus, that amplifies in the presence of scientific uncertainty. In the risk-balancing equation, it is necessary to compare two risks that are manifested in very different manners. Biological and chemical risks are not equivalent, and consequently, human judgments must be made regarding how the negative health effects of these risks are equated. In situations where it is not
technologically or economically feasible to simultaneously reduce both risks to within acceptable limits, a judgment must be made as to which to minimize preferentially. Uncertainty, as it influences the representation of community values, contributes a third major component to the risk balancing equation.

1.2 EVOLUTION OF DRINKING WATER TREATMENT

The existence of naturally occurring potential negative health effects from drinking water has been recognized for at least several millennia. The biological origin of these health effects was not uniformly accepted until the nineteenth century, but 4000 year old Sanskrit writings indicate that water standards were of concern even then, requiring that water of specified poor quality be boiled prior to its consumption (Cotruvo, et al., 1990). Filtration of turbid or otherwise unappealing water was common practice by the eighteenth century, and the first municipal drinking water filtration plant was established in 1832 in Scotland (Cotruvo, et al., 1990). Throughout the 1800's, concern over water quality grew, and in 1849 Dr. John Snow, an epidemiologist, postulated that epidemics could be transmitted through drinking water (White, 1992). Several years later Dr. Snow uncovered the source of the 1854 cholera epidemic in London, where a water pump was contaminated by a sewage leak coming from the residence of a recently returned soldier who acquired cholera while serving in India. By prevented further conveyance of the contaminated water, Snow ended the cholera epidemic and proved his theory (White, 1992 and Cotruvo, et al., 1990).

Following Snow's discovery, efforts to improve drinking water sanitation were undertaken, and filtration and coagulation techniques were developed and improved. By this time, it was recognized that biological content and turbidity were both indicators of potential negative health effects from water. Despite the success filtration found in reducing turbidity, the process of "artificial filtration" was not uniformly accepted, as demonstrated by a statement offered by MIT Professor Ripley Nichols in 1884, in which
he argued that the benefits of such processes were not worth the associated costs (Clark, 1984, 1993a). Nearing the turn of the century, however, the manner in which waterborne microbial risks were approached advanced drastically with the introduction of an electrolytic water treatment method (White, 1992). This process involves the application of the gas generated during decomposition of an acid (or salt) and water solution to the water needing purifying, and marks the first chemical disinfection procedure (White, 1992). Hypochloric acid or sodium chloride salts were thought to be the best materials for this procedure, and this was confirmed with the success of the first, full-scale disinfection installation applying chlorine to contaminated water in Chicago in 1908 (White, 1992, and Cotruvo, et al., 1990).

In the U.S., water quality standards were first promulgated in 1914, setting the first maximum contamination levels for bacteria at 2 coliforms per 100 mL for water transported between the states (Cotruvo, et al., 1990). In 1942, biological concentration limits became more stringent, and the first monitoring requirements for water treatment facilities were introduced along with the first maximum concentration levels for a number of minerals such as lead and arsenic (Cotruvo, et al., 1990). It wasn't until the 1962 standards that synthetic contaminants in surface water were addressed. Then in 1974, the Safe Drinking Water Act (SDWA) was promulgated primarily in response to concern regarding organic chemical contamination in drinking water (Cotruvo, et al., 1990). The SDWA gave the EPA the responsibility of setting and maintaining drinking water quality standards with respect to both biological and chemical contaminants. The passing of the SDWA, and the discovery that drinking water chlorination introduced a recognized carcinogenic substance, chloroform, marked a turning point in drinking water regulation and research. Research emphasis began to shift from improving microbiological quality of drinking water to reducing chemical contaminants in drinking water (AWWARF, 1993). Nevertheless, biological risk is currently recognized as a problem far from fully addressed,
as further microbiological standards were implemented in the 1980's and 90's (described in Chapter Four).

1.3 UNCERTAINTY

Before launching into a discussion of how uncertainty affects decisions regarding balancing microbial and chemical risks, it is worthwhile to discuss the nature of uncertainty, and to establish the variety of "types" or "categories" of uncertainty that are pertinent to the problem (refer to Figure 2). Uncertainties can be divided into two broad categories: (1) technical, or scientific uncertainties and (2) non-technical, or non-scientific uncertainties. The former category is highly quantitative, and deals with the acquisition (or lack) of specific information from measurement. These are the uncertainties arising from experiments or observations, and they differ widely within this category. The latter category of uncertainty deals with elements of decision-making that relate to values and interpretations, and the role of these uncertainties is generally amplified by the presence of scientific uncertainty.

In this paper, scientific uncertainties are initially divided into those associated with data and those associated with system complexities. The data uncertainties might arise from lack of research (resulting in the absence of data, or "data gaps"), or from technological limitations. Uncertainties associated with technology relate largely to measurements, and may result from limits of detection (and the subsequent need to use representative measurements or extrapolation) or from imprecision. The contributions of system complexities are numerous and varied. In this thesis, they are subdivided into five categories designated as: (1) distributional effects, (2) synergism, (3) confounding variables, (4) mechanism, and (5) extrapolation. The presence of a distribution of a particular element in a system, or of system heterogeneity, adds uncertainty when a single representative value, or point estimate, of that element must be used for analysis. Consequently, there is an uncertainty associated with the simplification of a system in this
FIGURE 2. Outline of Uncertainties for Biological and Chemical Risks.
Uncertainties in biological and chemical risks are divided into scientific and non-scientific uncertainties, each of which has its own components. Scientific uncertainty is associated with informational gaps, while non-scientific uncertainty accompanies value judgments made during policy and regulatory formation. Although it is not shown on this diagram, the presence of scientific uncertainty forces a reliance upon value judgments in policy and regulatory decision-making, and therefore exaggerates the significance and influence of non-scientific uncertainty.
manner. Synergism, which makes the whole greater than the sum of its parts, adds an
uncertainty, particularly when the interactions between those parts are unquantified. The
presence of confounding variables, and the inability to accurately account for their action,
adds an uncertainty associated with the quantification of an observation in their presence.
The inability to precisely quantify the presence of mechanisms or mechanistic pathways
within a system also contributes uncertainty. Finally, extrapolation from one system (or
one species) to another, when the specific interactions within each independent system are
unknown, carries an associated uncertainty. In general, the system complexity
uncertainties deal with interactions between elements that complicate quantification, while
data uncertainties arise from the process of obtaining information.

Scientific uncertainties have previously been categorized by Klapp into four
divisions: data, extrapolative, model, and parametric (Klapp, 1992). Data uncertainties
are associated with the quality and presence of information, and are generally recognized
by discrepancies in the conclusions drawn from different studies. Extrapolative
uncertainties arise through the extension of the results of one system to those of another,
such as using conclusions from toxicological data obtained with experimental animal
studies to estimate human health risks. Model uncertainties are generated by questions
regarding the inclusion of particular variables to estimate the generation of risk in a
system. Finally, parametric uncertainties occur when there is disagreement about how to
measure specific parameters.

Klapp's divisions are accommodated by the categorization scheme used in this
paper in the following manner. The data uncertainties of Figure 2 incorporate Klapp's
data and parametric uncertainties, while the system complexity uncertainties account for
Klapp's model and extrapolation uncertainties. Klapp's model uncertainty arises from
unknown characterization of a system, which amounts to determining parameters that
contribute to the system (identification of relevant variables and their mechanistic
pathways), their complete representation (accounting for heterogeneities), unwanted
variables (confounders), and in a situation where direct system measurement is impractical, the ability to represent the system with a comparable system (extrapolation). This final element, which is considered an entirely separate uncertainty by Klapp, also hinges on the unknown elements of a second system, and in this way does differ from the other elements. For the purposes of this thesis however, extrapolative uncertainty will be generalized under system complexities because it will also embody uncertainties that do not involve a second system. The categorization represented in Figure 2 highlights some of the more subtle differences within and interdependencies among Klapp's uncertainty divisions.

Non-scientific uncertainty arises from the necessity to make representative value judgments for a population of individuals with diverse interests. Value judgments in policy-making may fall into the category of risk management, rather than risk analysis, and such uncertainties might analogously be considered "risk management uncertainties." The non-scientific uncertainty associated with value judgment is essentially lack of consensus. The arising divergence from consensus is present among members of a community (who have different value systems), among scientists (whose interpretation of scientific uncertainty will to some degree correspond with their personal values), and among parties who will be affected differently by the outcomes of decisions (whose desires exist in accordance with their own best interest).

Non-scientific, value-based uncertainties are categorized into three divisions in this paper: (1) interpretation of scientific uncertainty, (2) determination of acceptable risk limits, and (3) valuation of risks for comparison. In the presence of great scientific uncertainty, judgments from a purely scientific basis are difficult, if not impossible, and are not well-founded. As a consequence, value judgments begin to take on a more significant role in the decision-making process (Graham, 1991). Environmental and health policy decisions also inherently involve value judgments simply in the determination of risk levels that will be acceptable to the majority of people affected by that policy. Risk avoidance
always comes at some cost, and not everyone is willing to accept the same cost or perceives the same risk. In balancing biological and chemical risk, this predicament is taken one step further: the cost associated with reducing one risk simultaneously can increase another risk. This leads to the third non-scientific uncertainty, the valuation of competing risks to provide a basis for their comparison, or to find a common denominator. In doing so, manifold value judgments must be made, and subsequently, this element contributes significantly to non-scientific uncertainty.

The problem of balancing biological and chemical risk is subject to uncertainties in all of these areas, and presents a tremendous challenge to all parties involved. Drinking water treatment regulators are particularly burdened with resolving or accounting for these uncertainties, and the methods they previously relied upon are proving to be insufficient for regulating competing risks. Furthermore, the exaggerated role of non-scientific uncertainty that has arisen in this situation has prompted their need and pursuit of "outside" contribution to the regulatory process from the stakeholders. The immense uncertainty in the risk balance equation has introduced a host of new questions regarding health policy, and has instigated a new regulatory decision-making process for its determination.

1.4 EPA TREATMENT OF UNCERTAINTY

The Safe Drinking Water Act passed in 1974 mandated that the National Academy of Sciences (NAS) provide, among other things, specific guidelines regarding the classification of contaminants in drinking water, and the treatment of uncertainty when determining limits to substances that pose a risk (USEPA, 1985). The NAS incorporated both a formalized procedure for classifying contaminants and a formalized method for treating uncertainty in its 1977 publication of Drinking Water and Health. Since publication, the procedures set for both of these processes have been implemented as standard practice by the EPA.
The determination of Maximum Contaminant Level Goals (MCLGs) for chemical contaminants in drinking water exemplifies a specific application of the formalized procedure. A substance is classified either as a carcinogen, or non-carcinogen, and the carcinogen-labeled substances are subdivided into categories representing the level of existing evidence that implicates the substance (this is part of the EPA's "weight-of-evidence" approach to risk assessment). Where there is strong evidence, the MCLG is automatically set at zero, invoking an assumption that no threshold concentration exists below which the substance imparts no carcinogenic effects (USEPA, 1985). The intermediate category of carcinogenic risk accommodates substances with limited evidence of carcinogenicity, and the final category contains substances for which there is inadequate evidence to substantiate carcinogenicity. MCLGs for substances in the latter two categories of carcinogenicity and for non-carcinogenic substances are calculated from Reference Doses (RfDs), in which uncertainties are taken into account.

An RfD for a substance is determined from another value, either a no- or lowest-observed-adverse-effect-level (NOAEL and LOAEL, respectively), which is taken from either human or animal studies of the chemical's health effects. The emerging RfD value is further reduced by dividing by a series of uncertainty factors (also called safety factors), intended to safely extend the NOAEL or LOAEL to the heterogeneous human population. The following uncertainty factors (which can amount to more than five orders of magnitude in impact) are applied when appropriate:

- a factor of between 1 and 10 for the distribution of population sensitivity
- a factor of 10 for extrapolation of data on experimental animals to humans
- a factor of 10 for extrapolating data from short-term studies to approximate long-term effects
- a factor of 10 when an LOAEL is used because an NOAEL is unavailable
- an additional factor of unspecified amount, when scientific judgment deems appropriate
- an additional uncertainty factor, called a Modifying Factor (MF), ranging from 1 to 10, based on professional judgment of the existing scientific uncertainties that are not addressed specifically above.

After the NOAEL or LOAEL has been divided by the appropriate uncertainty factors, the resulting RfD is prorated to a representative body weight (usually 70 kg), and adjusted by a relative source contribution factor (RSC), and is divided by a representative amount of water consumed per day (approximated at 2 L) to yield the MCLG. Intermediate carcinogen category substances are also subject to further margins of safety, depending on the information available. This procedure, taken directly from the Disinfectant/Disinfection By-Product (D/DBP) Rule (USEPA, 1994b) represents the typical manner in which uncertainty is incorporated into the formation of tolerance level goals for chemical substances.

In determining MCLGs for microorganisms, these safety factors are not explicitly applied, presumably because the extrapolative techniques necessary for characterizing chemical risks are not as necessary in characterizing biological risk. Data on human infectivity and illness are available for most pathogens, and dose-response curves are determined directly from these. In many instances, because infectivity has been clearly demonstrated, and is therefore not uncertain, the MCLG is set at zero (USEPA, 1994d).

Although these safety factors have been employed as recently as the proposed rules in July of 1994, their suitability has been questioned. Both the Scientific Advisory Board and the Chlorine Institute have expressed concern that the EPA's "default assumptions on cancer risk assessment for chlorinated by-products may greatly overestimate the actual cancer risks associated with chlorination by-products that are being considered for regulation" (quote from SAB correspondence appearing in Chlorine Institute, 1993). Specifically, the Institute points out that the conservative approach to accounting for uncertainty is unsafe (in its affect on biological risk), and potentially exaggerates chemical risk estimates greatly (Chlorine Institute, 1993). The EPA has also
discussed this point, but in the opposite direction, noting that the previously accepted "worst-case dose-response and exposure assessments are not appropriate to describe the situation where treatment to decrease exposure to microbial pathogens in drinking water may increase exposure to chemical contaminants" (Macler, et al., 1992). The potential for trading one risk for another in both directions has been acknowledged, but a modification to uncertainty treatment in a competing risk situation has not yet been proposed.

1.5 STATEMENT OF HYPOTHESIS

Balancing biological and chemical risks in drinking water disinfection is highly influenced by uncertainty. Scientific uncertainties, emerging from data sources and complex systems, have a direct impact on risk characterization, while non-scientific uncertainties, associated with non-consensus of interests, permeate risk management and decision-making. The purpose of this thesis is to support the following observations regarding uncertainty's role in the risk balancing problem, and to explore the possible ramifications of these issues:

- Scientific uncertainty contributes imprecision to biological and chemical risk quantification, which is subsequently reflected in regulatory limits, as well as the costs and benefits to stakeholders.
- A strictly conservative representation of scientific uncertainty in safety factors applied in regulatory development reduces the options to drinking water treatment utilities for mutual minimization of biological and chemical risks.
- Uncertainty surrounding the performance and the associated risks of alternative treatment options generates a risk of raising the overall risk to human health and of increasing drinking water utility and consumer expenditures.
- Competing risks inherently possess non-scientific uncertainty, and the prevalence of scientific uncertainty amplifies the role of non-scientific uncertainty, requiring a greater dependence on value judgments in policy and regulatory decision-making.
2. ROLE OF SCIENTIFIC UNCERTAINTY IN RISKS

2.1 BIOLOGICAL RISK

2.1.1 DEFINITION OF BIOLOGICAL RISK

The risk of disease from waterborne pathogens defines biological risk. The ability of drinking water to carry health-threatening microbial agents has long been recognized, and was among the first motivating forces initiating drinking water treatment and disinfection. Among the early known pathogenic microorganisms are *Salmonella typhi* (causing typhoid fever), *Vibrio cholerae* (causing cholera), and *Entamoeba hystolytica* (causing amoebic dysentery), all capable of generating widespread epidemics throughout the world. *S. typhi* is capable of withstanding extremely low temperatures and traveling very long distances over considerable time before infecting its human host; without drinking water treatment measures, it is vulnerable only to extreme heat. The virulence of *E. hystolica* can be reduced 99% when the organisms are not exposed to a host within a week's time, but when exposed to humans sooner than that they have an extremely high attack rate (White, 1992). However, both of these organisms are easily destroyed by chlorine disinfection. *E. hystolica* organisms form cysts, and are therefore highly resistant to disinfection, requiring more vigorous treatment procedures including longer periods of contact with chlorine as well as higher chlorine concentrations. The *E. hystolica* cysts are large, and are therefore easily trapped during sand filtration. The apparent near eradication of these organisms and their associated epidemics in North America brought great acclaim to chlorine usage in disinfection. As time and technology have progressed, however, the number of harmful waterborne organisms detected has increased, and their resistance to treatment procedures varies from virtually none to extreme, contributing to the current microbial risk.

Both bacteria and viruses contribute the waterborne disease outbreaks currently observed, many of which belong to the genera of the organisms first detected in drinking water. Such organisms include at least 1000 members of the *Salmonella* genus causing
salmonellosis (actually a variety of diseases caused by these organisms), not discovered until the mid 1960's, and enterotoxigenic *Entamoeba coli*, an organism contributing significantly to modern rates of disease and death from diarrhea, especially in Third World countries. Opportunistic pathogens, such as *Psuedomonas aeruginosa*, are also becoming a greater threat due to increased usage of antibiotics, thereby increasing the range of conditions under which such organisms acquire pathogenic capabilities, making them overall more virulent (White, 1992). Among the most troublesome waterborne organisms faced today are two parasitic protozoa that are carried as highly resistant cysts and oocysts, *Giardia lamblia* and *Cryptosporidium parvum*, respectively. Outbreaks of disease from waterborne parasites have been increasing since 1970. This trend is emphasized by the fact that from 1971 to 1985, more waterborne disease outbreaks were reported than for any other 15-year period in the U.S. since 1920 (White, 1992). Nearly 20% of the reported outbreaks are attributable to *Giardia* alone, making it the leading cause of waterborne disease in the U.S. (White, 1992). *Cryptosporidium* is even more resistant to treatment than *Giardia*, since the dormant oocyst stage of this microorganism is only half the size of a *Giardia* cyst, and therefore escapes many filtration efforts. Cryptosporidiosis was first recognized as a human disease in 1976, and reports of such outbreaks have continued to increase since then. In April 1993, *Cryptosporidium* was responsible for the largest outbreak of waterborne illness in the history of the U.S., causing approximately 400,000 illnesses, and 112 deaths (Miller, 1994). This disease is especially harmful to immunocompromised populations such as the elderly and individuals infected with the AIDS virus, and was named as the major cause of death in AIDS patients at the beginning of the 1980's (White, 1992). There is currently no cure to cryptosporidiosis, and an infected individual is therefore a lifetime carrier susceptible to relapse. These examples of waterborne bacterial or protozoan pathogens are a small fraction of known waterborne pathogens, but represent some of the most troublesome.
Additionally, there are likely to be substantial numbers of as yet undetected and unidentified microorganisms contributing to waterborne disease.

Viruses comprise another active component of microbial risk. Our understanding of the waterborne contribution to viral infection is limited, owing to a number of contributing factors. First, viral infection is by no means limited to the waterborne route, so the degree to which drinking water contributes to the spread of viruses is difficult to differentiate. Furthermore, viral infections do not always reveal themselves symptomatically, making the specification of an infectivity rate difficult. Many viruses are undetectable by current culture methods (Payment, 1993). The absence of a reliable viral indicator species, an easily detectable organism (or water quality characteristic as an indicator) used to estimate the concentration of viruses in the water, makes determination of viral concentration and drinking water treatment efficiency difficult. The primary waterborne viruses include adenoviruses (highly susceptible to chlorination), some enteroviruses (most of which are highly resistant to disinfection, have low minimal infectivity doses and which result in severe or highly fatal diseases), Hepatitis A (a still relatively unknown organism), the Norwalk virus, and Rotavirus (both of which result in outbreaks of acute gastrointestinal illness (AGI) in the U.S. and Europe) (White, 1992). In light of the difficulties surrounding viral detection, it has been estimated that the viral concentration in drinking water is currently underestimated by several orders of magnitude (Payment, 1993).

2.1.2 UNCERTAINTIES IN BIOLOGICAL RISK

The uncertainties of biological risk fall into the realm of scientific, or information-based uncertainties, as described in section 1.3, "Uncertainty," of the thesis (refer to Figure 2). They are largely data uncertainties, owing to technological limitations, but are also influenced by system complexities. The uncertainties discussed in this section are
summarized with chemical risk uncertainties in Table 2, appearing later in the thesis, according to their influence on the process of risk assessment.

Identifying and characterizing all waterborne pathogens, as well as establishing their nationwide distribution, is uncertain owing to technological limitations as well as to particular system complexities. The causal microbial agent in approximately half of recently reported outbreaks of waterborne illnesses in the U.S. remains unknown (AWWARF, 1993). Although significant research has been conducted on waterborne microorganisms, much of the data on microbial occurrence was collected long ago with less sensitive methods and is potentially obsolete or misleading (Sobsey, et al., 1993). Current methods of measurement and detection are also a source of uncertainty. For instance, most analytical techniques cannot discern microbes that take on aggregated form, or that adhere to other particles in the water (Sobsey, et al., 1993). This under-estimation that arises from such technological limitations is in contrast to the over-estimation resulting from an inability to account for viability (Haas, 1994). These two opposing uncertainties arising from measurement limitations are assumed to "cancel," and are, for purposes of practicality, disregarded without quantification by regulators (personal communication with Stig Regli, October, 1994). Furthermore, the detection of microorganisms as small as viruses is still beyond scientific capabilities. Even if indicator species are found that could represent the concentrations of these agents, this would also result in an uncertainty arising from indirect measurement (Payment, 1993). *Giardia* and *Cryptosporidium* are typically measured indirectly through correlations with turbidity, potentially adding the same kind of uncertainty (LeChevallier, et al., 1993). Research and measurement processes, however, may not be entirely responsible for the uncertainties surrounding the presence of waterborne pathogens.

Observational evidence indicates that the number of waterborne pathogens is increasing (AWWARF, 1993). The growing number of pathogens detected is in part due to advancement of detection methods, but there is also evidence supporting an
augmentation in the number of pathogenic waterborne microorganisms. One explanation of this is that the use of disinfectants preferentially eliminates organisms that are easily removable, simultaneously selecting for those that are resistant to disinfection. The removed species may previously have competed with disinfection-resistant species that now, in the absence of competition, have expanded their population. Consequently, disinfection may actually enhance the populations of previously less prevalent pathogens. In a sense, disinfection imposes an artificial evolutionary selectivity, presenting a source of system complexity uncertainty owing to evolutionary mechanisms. This could account for the recent detection of pathogenicity in a long-recognized, non-pathogenic species, as was experienced with *Cryptosporidium* in 1976 (AWWARF, 1993, and White, 1992). Entirely new strains of resistant microorganisms have been discovered, such as *Mycobacterium tuberculosis* (Chlorine Institute, 1993), and a new species of pathogen for which the name *Cyclospora* has recently been proposed (Craun, et al., 1994).

The determination of infectivity rates for different microorganisms is also uncertain based primarily on system complexity. These infectivity uncertainties arise from the varying immune response throughout the heterogeneous population, as well as the variation within the microbial population (Rose, et al., 1991). Unknown elements of the mechanistic behavior of microorganisms within a human host after ingestion, as well as the varying host immune system responses, contribute system complexity uncertainties of mechanistic and distributional type, respectively. The determination of dose-response curves, which reflect infectivity, is also dependent upon data from treatment efficiency and distribution system maintenance. Consequently, uncertainties in these areas constitute data uncertainties for the determination of infectivity rates as well.

The effectiveness of treatment/disinfection and the maintenance of the distribution system are primarily due to data uncertainties. The inability to precisely quantify microbial concentrations before and after treatment, and the presence of detection limits for various microorganisms, are clearly technological inability uncertainties. Determination of residual
treatment effectiveness throughout the distribution system is uncertain due in large part to lack of research. The distribution system is the "final barrier" against waterborne disease, however its role as such is often overlooked (Clark, et al., 1993). Monitoring of the distribution system is not sufficiently employed in many areas, subsequently adding a large data uncertainty from lack of information. These uncertainties, in turn, are reflected in the estimations of microbial concentrations, which make distribution and occurrence estimations uncertain, thereby making exposure and infectivity estimations uncertain. The interdependence of these uncertainties is unquestionable, and their separation somewhat artificial. However, acknowledging the manner in which these uncertainties interact may allow focusing on the uncertainties whose resolution would have the most far-reaching positive effects.

Before it was recognized that disinfection contributed a potential chemical risk to human health, these uncertainties were treated in a strictly conservative manner. The foremost goal of the EPA in formulating drinking water regulations in response to the Safe Drinking Water Act (SDWA) is to protect the public from unacceptable health risks arising from drinking water; and, in the absence of any additional risk, a conservative, worst-case scenario approach to accounting for uncertainties was deemed appropriate to achieve this motive (Macler, et al., 1992). The question of how to account for uncertainty now, in light of competing risks, is the preeminent question scientists, policy-makers, and all the people involved with this issue are facing today. Furthermore, it appears from research conducted by Payment (Payment, et al., 1991), that current microbial concentration standards based on known pathogen concentrations are not sufficient to protect consumers from harm; this may primarily reflect undetected pathogens. This study, considered alongside the apparent growing population of pathogenic waterborne microorganisms, suggests that the microbial risk uncertainties may, in fact, result in an under-estimation of the biological risk, rather than its over-estimation, as should be the case with the conservative "worst-case" approximations. This possibility merits further
investigation in the relative weighing of biological and chemical risks. The scenario is further complicated by the even more significant uncertainties that exist in the competing, chemical risk.

2.2 CHEMICAL RISK

2.2.1 DEFINITION OF CHEMICAL RISK

The use of chemical oxidants for drinking water disinfection is responsible for the additional generation of by-products during the disinfection process. These by-products are formed because organic substances, or precursors, present in the source water enter the treatment system and react with the disinfectant. Different disinfection by-products (DBPs) are associated with each disinfectant, and these DBPs vary widely in composition, character, behavior, detectability, and nearly every other chemical property.

The generation of DBPs was not recognized as a problem until 1974, when J. J. Rook and T.A. Bellar, et al. published their findings that organohalides and haloforms are generated in chlorinated drinking water (Singer, 1993). Shortly thereafter, the EPA detected the presence of chloroform, a known carcinogen in animals, and several brominated organic by-products in chlorinated drinking water. These chemicals belong to the trihalomethane (THM) class of compounds, the predominant class of DBPs generated by chlorination. Since 1974, considerable research has been conducted to identify other by-products formed during chlorination, and hundreds have been identified. THMs remain the most abundant, followed by haloacetic acids (HAAs). Both halogenated and non-halogenated, organic and inorganic compounds comprise the remaining detected DBPs. Despite the large number of identified DBPs, evidence indicates that many remain to be identified. DBP formation data for alternatives to chlorine are even more incomplete than for chlorine, owing to the briefer amount of time they have been emphasized in research.

The health effects of the multitude of DBPs added to drinking water are varied, and in most cases, as yet unknown. It is possible that many of these chemicals may be
carcinogenic, mutagenic, or teratogenic, and therein lies the chemical risk to human health. Toxicological data for DBPs are sparse, however, and although a number of DBPs are potentially toxic (e.g., chloroform in particular is a highly suspected human carcinogen), this chemical risk has not yet been confirmed for any specific chemical. However, epidemiological studies have shown correlations between chlorination and negative health effects.

2.2.2 EVIDENCE OF CHEMICAL RISK

Many epidemiological studies have been conducted to investigate the negative health effects of by-products arising from chlorination, most of which investigate their potential carcinogenicity. However, the results of these studies are often contradictory or inconclusive, and at best allow one to substantiate a correlation, not derive a cause and effect relationship. The ability to correctly ascertain the degree of DBP exposure experienced by study subjects, as well as the potential confounding factors such as smoking, dietary habits, or working conditions, often contribute greatly to the indeterminacy of epidemiological studies. Nevertheless, the correlations continue to appear consistently enough to perpetuate the concern over the potential carcinogenicity of DBPs. These results, coupled with increasing toxicological evidence supporting that some DBPs might be carcinogens, have elevated concern over the theoretical chemical risk. However, it should be emphasized that no evidence has been obtained to date that unquestionably verifies any known DBP as a human carcinogen. Furthermore, much of the toxicological data showing negative health effects from specific DBPs emerged from studies on laboratory animals subjected to much higher exposures than are present in drinking water (Bull, 1993a).

Table 1 highlights the results of 16 epidemiological studies published between 1978 and 1993. This compilation of studies is an expansion of a survey of 12 key
### TABLE 1: Results from Epidemiological Studies Investigating Carcinogenicity of Chlorinated Drinking Water at Specific Endpoints

<table>
<thead>
<tr>
<th>Bladder</th>
<th>Brain</th>
<th>Breast</th>
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<tbody>
<tr>
<td>+ SS (Alvanja, 1978)</td>
<td>+ mSS (Young, 1981)*</td>
<td>0 (Young, 1981)</td>
</tr>
<tr>
<td>0 (Young, 1981)</td>
<td>0 (Gottlieb, 1982)</td>
<td>+ SS (Gottlieb, 1982)</td>
</tr>
<tr>
<td>+ IN (Wilkins, 1981)</td>
<td></td>
<td>0 (Zierler, 1986)</td>
</tr>
<tr>
<td>0 (Gottlieb, 1982)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ SS (Cantor, 1984)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ mSS (Zierler, 1986)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ SS (Cantor, 1987)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ SS (Zierler, 1988)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ IN (Flaten, 1992)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ SS (McGeehin, 1993)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ SS (Vena, 1993)*</td>
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<tr>
<th>Colon</th>
<th>Esophagus</th>
<th>Kidney</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ mSS (Brenniman 1980)</td>
<td>0 (Young, 1981)</td>
<td>0 (Young, 1981)</td>
</tr>
<tr>
<td>+ SS (Young, 1981)</td>
<td>0 (Gottlieb, 1982)</td>
<td>0 (Gottlieb, 1982)</td>
</tr>
<tr>
<td>0 (Gottlieb, 1982)</td>
<td>0 (Gottlieb, 1982)</td>
<td>0 (Zierler, 1986)</td>
</tr>
<tr>
<td>+ IN (Lawrence, 1984)</td>
<td></td>
<td></td>
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<tr>
<td>+ SS (Cragle, 1985)*</td>
<td></td>
<td></td>
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<tr>
<td>0 (Zierler, 1986)</td>
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<td></td>
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<tr>
<td>0 (Young, 1987)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ SS (Flaten, 1992)</td>
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</table>

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<thead>
<tr>
<th>Liver</th>
<th>Lung</th>
<th>Pancreas</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Young, 1981)</td>
<td>+ SS (Alvanja, 1978)</td>
<td>+ SS (Alvanja, 1978)</td>
</tr>
<tr>
<td>+ IN (Wilkins, 1981)</td>
<td>0 (Young, 1981)</td>
<td>0 (Young, 1981)</td>
</tr>
<tr>
<td>0 (Gottlieb, 1982)</td>
<td>0 (Gottlieb, 1982)</td>
<td>0 (Gottlieb, 1982)</td>
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<td></td>
<td>0 (Zierler, 1986)</td>
<td>0 (Zierler, 1986)</td>
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<tr>
<td></td>
<td>+ SS (Isselmuinder, 1992)*</td>
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<table>
<thead>
<tr>
<th>Prostate</th>
<th>Rectum</th>
<th>Stomach</th>
</tr>
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<tbody>
<tr>
<td>0 (Gottlieb, 1982)</td>
<td>+ SS (Alvanja, 1978)</td>
<td>+ mSS (Young, 1981)</td>
</tr>
<tr>
<td></td>
<td>+ mSS (Brenniman 1980)*</td>
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<tr>
<td></td>
<td>0 (Young, 1981)</td>
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<tr>
<td></td>
<td>+ SS (Gottlieb, 1982)*</td>
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<td></td>
<td>+ IN (Lawrence, 1984)</td>
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<tr>
<td></td>
<td>0 (Zierler, 1986)</td>
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</tr>
<tr>
<td></td>
<td>+ SS (Flaten, 1992)</td>
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</tbody>
</table>

"+" and "0" indicate, respectively, a positive correlation and no correlation between chlorinated water and cancer occurrence.

"SS," "mSS" & "IN" indicate statistically significant, moderately statistically significant, and statistically insignificant correlations, respectively.

* Occurrence ratio or relative risk is greater than 2.0

✓ Included in Morris' 1992 meta-analysis
epidemiological studies assembled by Alceon Corporation for the EPA's use in regulating disinfectants and disinfection by-products (Alceon, 1993). Here, the results are grouped according to target organs or endpoints, to identify the areas for which there is the greatest cause for concern. The study results are represented by "+" or "0" (indicating positive or no correlation, respectively), followed by "SS," "mSS" or "IN" (to indicate statistical significance, marginal statistical significance, or insignificance of correlation), followed by the year and primary author of each study. It is important to realize that there are significant variations in how these studies were conducted, and that the confounders taken into account in each study vary as well. The table is intended to emphasize the inconsistencies that arise in epidemiological studies, and to uncover trends that persist despite inconsistency.

The data presented here indicate that correlations between chlorinated water and the incidence of bladder, colon, rectal, and pancreatic cancers are somewhat frequent, having appeared significantly in more than one study. This table neglects the occurrence ratios (ORs) and relative risks (RRs) determined for the positive correlations found. The OR and RR values typically fall between 1.1 and 2.0. Those values exceeding 2.0 are marked by asterisks in Table 1.

The checked (✓) items in Table 1 indicate the results of the 11 epidemiological studies that were represented in a highly controversial meta-analysis (Morris, et al., 1992). Morris' meta-analysis is the source of much current debate, and exemplifies the difficulties present in using epidemiological data. Epidemiological studies are especially difficult to use, owing to their tremendous vulnerability to misinterpretation.

"It must be recognized that all epidemiological data are imperfect, no matter what their source or how they were collected...decisions as to the utility of the data are generally based on an independent process that is primarily political."

(Craun, 1984, p. 141)
By applying a meta-analysis technique to the highly incongruous results of these studies, Morris attempted to minimize the element of subjectivity that accompanies epidemiological studies, and to replace it with a statistically supportable conclusion (personal communication, Morris, October 1994). Morris obtained a statistically significant relative risk (RR) values of 1.21 for bladder cancer, and 1.38 for rectal cancer. These values correspond to as many as 10,700 additional cases of cancer per year. For the remaining 10 cancer sites, the RR values were between 1.01 and 1.29, but were not statistically significant. Although the application of meta-analysis to data collected under such varied conditions is still questionable, the areas indicated to be of primary concern by Morris' study are consistent with observation on a qualitative basis. It is important to point out that even though a correlation can be made between chlorination and these cancers, (a) a causative relationship cannot be derived, and (b) the correlation cannot be isolated to a particular by-product or to the chlorine residual.

Toxicological investigations have been conducted for chlorine and its major by-products including various trihalomethanes and halogenated acids. Chlorine, although a demonstrated, potentially lethal respiratory irritant, has not shown any particular carcinogenic response in rats and mice administered large doses of chlorine (Bull, 1991). There has been toxicological support for the carcinogenicity of several trihalomethanes, including chloroform, producing kidney tumors in rats, chlorodibromomethane, producing liver tumors in mice and rats, and bromoform, producing intestinal tumors in rats (Bull, 1991). Similarly, toxicological evidence supports the ability of selected haloacids to induce negative health effects in animals. For example, dichloroacetic acid, generated in high concentrations during chlorination when fulvic acids are present in source water, has demonstrated the ability to induce neuropathological and teratogenic effects in rats and dogs, and liver damage in rats and mice (Bull, 1991). For both trihalomethanes and haloacids, toxicological evidence indicates that further investigations should be conducted to determine the mechanisms by which these chemicals induce negative health effects.
Toxicological studies have been conducted on other groups of chlorinated by-products such as haloacetonitriles, halogenated aldehydes, halogenated ketones, chloropicrin and chlorinated phenols, the latter two of which are considered to be generated in insufficiently high concentrations to be of concern, and the others for which more basic information must be acquired before conclusions can be drawn (Bull, 1991).

Several reviews of multiple studies have been conducted in an effort to determine the overall substantiation of chemical risk introduced by chlorinated drinking water. Both the International Agency for Research on Cancer and the National Research Council conducted comprehensive reviews of the majority of toxicological and epidemiological studies reported prior to 1991 and 1987, respectively, investigating the carcinogenicity of chlorinated drinking water (Tardiff, 1993b). In both cases, applying the internationally accepted criteria for judging the sufficiency of such data to establish a threat to human health, organizations reached the same conclusion: although the studies to date provide sufficient evidence that several DBPs are classifiable as animal carcinogens, the data are insufficient to implicate chlorinated drinking water as a human carcinogen (WHO IARC, 1990). Based on a summary of these results by EA Engineering, Science, & Technology in which distributional information was obtained from the EPA, the estimated upper bound value for the combined additional cancer rate from three chlorination by-products that present the greatest potential for carcinogenicity (chloroform, bromoform, and bromodichloromethane) is two additional cancer cases per year in a population of 162 million (Tardiff, 1993b). A similar review was conducted by EA Engineering, Science, & Technology, Inc., in which the same criteria were applied to judge studies prior to 1993 regarding chronic and reproductive toxicity of chlorinated drinking water (Tardiff, 1993a). These reviewers concluded that significant evidence exists for chronic toxicity, but not reproductive toxicity. Furthermore, the review determined that evidence supporting the chronic toxicity of the DBPs chloroform, dichloroacetic acid, trichloroacetaldehyde, and
chlorate was also sufficient, and found that the first three could also be classified as possible sources of reproductive toxicity.

The immense discrepancy between Morris' conclusions, leading to a possible addition of 10,700 cancer cases per year, and the results of the reviews discussed above, estimating a possible addition of two cancer cases per year, demonstrates the uncertainty surrounding chemical risk of drinking water chlorination. The same body of evidence can lead to vastly different conclusions, depending upon the form of analysis conducted. So it is little wonder that authorities in toxicology, epidemiology, human health, and drinking water treatment are arriving at disparate conclusions regarding the actual chemical risk. The discrepancy brought out above is merely a representative example of this phenomenon. Such disagreement may also be an indication of uncertainty arising from identification of the correct carcinogenic agent, or the result of exposure and complexity uncertainties interfering with epidemiological correlations. However, the existence of any support for chemical risk must be addressed, according to the principles set by the EPA, and any effort that can be made to further protect human health from the addition of chemical risk must be undertaken (USEPA, 1985).

2.2.3 UNCERTAINTIES IN CHEMICAL RISK

The chemical risk presented by disinfectants and disinfection by-products is, as noted in the above discussion, even more uncertain. Unlike microbial risk, which is substantiated by history and modern world regions that don't employ drinking water treatment, chemical risk is still hypothetical, and relies on epidemiological correlations and toxicological extrapolations for its confirmation. Consequently, there is significant added uncertainty in the quantification of chemical risks.

The areas contributing to uncertainty in chemical risk, like those of microbial risk, are scientific uncertainties. These uncertainties are divided between those surrounding DBP formation, and those surrounding the potential negative effects of DBPs on the
human population. Uncertainties associated with DBP formation and occurrence are
categorized mostly as data uncertainties. Although considerable attention has been paid to
particular DBPs such as the trihalomethanes and haloacetic acids, there are numerous
DBPs about which no health effects' data are yet available, and there are undoubtedly even
more DBPs that have not yet been discovered. Research is still in the primary stages to
determine the correlations between treatment process, the presence of various precursors,
and the resulting DBPs, and although some correlations have been made, only TTHMs
and HAAs can be somewhat reliably predicted (Regli, et al., 1993b). These data
uncertainties do not appear to be generated by technological inability, but are due more to
the limited time in which such research has been conducted, and therefore the extent to
which it has advanced. The uncertainties in quantifications of the presence of DBPs are
somewhat comparable to the biological risk uncertainties regarding the presence of
microbial agents.

Also analogous to biological risk uncertainties are the chemical risk uncertainties
of mechanistic behavior of foreign agents within the human body. The exact metabolic
pathways that chemical agents follow after ingestion are highly uncertain owing to the
complex nature of the human body-chemical system, and the presence of other potentially
influential factors. Pharmacokinetic processes take place, and in order to quantify
chemical risks, must be identified. For example, chlorinated furinone (MX) may be
responsible for as much as 40-60% of the total mutagenicity in chlorinated drinking water.
However, it is suspected that it could potentially be detoxified within mammalian systems,
thus reducing, if not eliminating, a tremendous chemical risk that would be estimated
purely from experimental evidence (Singer, 1993). Biologically based models are
currently being developed to account for such processes in the prediction of DBP-human
interactions (Bull, et al., 1993b). Also in analogy to biological risk uncertainties, the
variation in health condition that exists among members of a population contributes
uncertainty regarding the prediction of negative health effects of chemical risks. Protecting sensitive populations creates uncertainty in both risk quantifications.

Beyond these commonalities, chemical risk diverges greatly from biological risk where the uncertainty of its potential health effects is concerned. The chemical risk of chlorinated drinking water is largely dependent upon correlations with elevated cancer occurrences indicated by epidemiological studies and laboratory animal toxicological studies, while biological risks are supported by direct confirmation through human exposure. By relying on these indirect expressions of effects, chemical risk is subject to numerous system complexities arising from these associations.

Epidemiological data are subject to complications from behavioral variations among individual members of the population. The effects that are correlated with chlorinated drinking water are presumed to occur after long-term exposure to DBPs. The establishment of the nature and extent of exposure over a prolonged period of time is difficult owing to the variety of water supplies an individual might be exposed to in the normal course of his or her life (accounting for water ingested at places of employment, travel, etc.). Furthermore, there are system complications added by confounding variables in people's lives, such as smoking, diet, employment conditions, alcohol consumption, and other behavioral differences, that also make the correlation between observed health effects and drinking water uncertain.

The dependence of chemical risk quantification on toxicology studies involving effects observed in animals adds two extrapolative uncertainties that emanate from system complexities. The confidence with which one can extrapolate observed health effects from animal studies to predict human responses is uncertain as long as metabolic pathways traveled by chemical agents are unknown. This generates uncertainty from the metabolic complexities of both the experimental animal and human systems. Toxicity testing on animal subjects is conducted with large doses because of experimental constraints, and therefore must be extrapolated back along an appropriate dose-response curve to
approximate the effects of the low dosages ingested by humans. This extrapolation takes place along a dose-response curve which is established from mechanistic data characterizing the behavior of the ingested chemical agent within the human body. The absence of mechanistic data therefore contributes to both extrapolative uncertainties (metabolic/between species and dose-response) in chemical risk.

A final system complexity that contributes to chemical risk uncertainty arises from the presence of multiple DBP generation, forming a chemical mixture. Chemicals in a mixture are unlikely to maintain their individual characteristics and will usually interact, causing synergistic effects. By considering each DBP independently, the health effects that might be generated by DBPs are most likely misrepresented, generating another uncertainty in quantifying chemical risks. The potential for continued interaction between chemical agents, and the dependence upon indirect substantiation, create a much more significant total uncertainty in chemical risk.

2.3 SUMMARY OF THE ROLE OF UNCERTAINTY IN RISK ASSESSMENT

Risk assessment is inherently fraught with uncertainties. In recognition of this fact, the National Academy of Sciences (NAS) incorporates uncertainty analysis into their published guidelines for risk assessment (USEPA, 1985). According to these guidelines, risk assessment involves hazard identification, dose-response assessment, exposure assessment, and risk characterization, all to which uncertainty analysis is applied. Table 2 indicates the areas in which the individual uncertainties surrounding microbial and chemical risk have the greater influence on the risk assessment procedure.

Uncertainty contributes unequally to the different components of risk assessment in each case. In the hazard identification step of biological risk assessment, identification of waterborne pathogens is incomplete, but the major contributing pathogens have been identified. In chemical risk assessment however, very few disinfection by-products have been identified, and a causative relationship between any DBP and correlated negative
TABLE 2: Influences of Uncertainty on Biological and Chemical Risk Assessment

<table>
<thead>
<tr>
<th>BIOLOGICAL RISK UNCERTAINTY</th>
<th>CHEMICAL RISK UNCERTAINTY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hazard Identification</strong></td>
<td><strong>Hazard Identification</strong></td>
</tr>
<tr>
<td>• unknown identify and character of all waterborne pathogens</td>
<td>• unknown identity and character of all disinfectant by-products (DBPs)</td>
</tr>
<tr>
<td><strong>Dose-Response Assessment</strong></td>
<td><strong>Dose-Response Assessment</strong></td>
</tr>
<tr>
<td>• uncharacterized mechanisms by which pathogens infect</td>
<td>• uncharacterized mechanistic behavior and pharmacokinetic effects of ingested DBPs</td>
</tr>
<tr>
<td>• imprecise infectivity rates for organisms</td>
<td>• absence of appropriate dose-response curves for extrapolation from high-dose animal testing, to low-dose actual human exposures</td>
</tr>
<tr>
<td>• unknown extent to which sensitive human populations are more vulnerable</td>
<td>• undetermined metabolically appropriate animals for chemical testing of DBP toxicity to humans</td>
</tr>
<tr>
<td>• unknown and unaccounted for confounding variables in observed effects from epidemiological studies</td>
<td>• unknown synergistic effects of chemical mixtures and DBP interaction</td>
</tr>
<tr>
<td>• unknown extent to which sensitive human populations are more vulnerable</td>
<td><strong>Exposure Assessment</strong></td>
</tr>
<tr>
<td><strong>Exposure Assessment</strong></td>
<td><strong>Exposure Assessment</strong></td>
</tr>
<tr>
<td>• unknown nationwide distributions of waterborne pathogen occurrence and human exposure to waterborne pathogens</td>
<td>• imprecise approximation of long-term exposure levels to correlate with alleged chronic effects</td>
</tr>
<tr>
<td>• unknown extent of treatment effectiveness using various procedures for destroying waterborne pathogens</td>
<td>• unknown DBP formation with various treatment regimes</td>
</tr>
<tr>
<td>• undetectability of viruses or lack of reliable viral indicators</td>
<td>• unestablished influence of source water characteristics on DBP formation</td>
</tr>
<tr>
<td>• immeasurability of pathogen viability in concentration measurement</td>
<td><strong>Risk Characterization</strong></td>
</tr>
<tr>
<td>• unknown extent to which distribution systems are maintained and effective</td>
<td><strong>Risk Characterization</strong></td>
</tr>
<tr>
<td>All areas mentioned above</td>
<td>All areas mentioned above</td>
</tr>
</tbody>
</table>
health effects does not yet exist. The determination of dose and response is also more certain for biological risk than for chemical risk. More toxicological information exists for microbial infections and the mechanisms by which microbials infect humans, than has been obtained for DBPs. This is perhaps the area most affected by uncertainty in chemical risk assessment. The interactive effects of a chemical mixture of DBPs also complicates the determination of dose-response relationships. The determination of microbial exposure may be the risk assessment area most uncertain in assessing biological risk. Detection limits for measuring viable microbial concentrations, and the reliability of distribution systems for maintaining effluent quality contribute greatly to the uncertainties here. The measurement of DBP exposure for known DBPs is more certain than the comparable measurement of microbials. Risk characterization, the final step in risk assessment, is highly uncertain in both biological and chemical risk.
3. ROLE OF UNCERTAINTY IN SOLUTIONS TO RISK BALANCE

3.1 POTENTIAL SOLUTIONS

3.1.1 BALANCING BIOLOGICAL AND CHEMICAL RISKS

What exactly does it mean to "balance" the biological and chemicals health risks of drinking water treatment? For the purposes of this thesis, balancing risks means that it is not so important that an equal value of these risks be reached, but that both risks are reduced to an acceptable level determined for each. Risk reduction in water quality control is typically accomplished by isolating the waterborne agent inducing the risk, and setting a maximum limit for that agent's occurrence in the drinking water. Sometimes the concentration of the agent itself can be measured, but in other cases an indicator for the agent's concentration is more practical to measure, and therefore is regulated instead. Microbial risk has been recognized and regulated since 1914, at which time a maximum contaminant level (MCL) for coliforms was set at 2 coliforms per 100 mL of water (Cotruvo, et al., 1990). Within the last 20 years, the chemical risks to human health from disinfection by-products (DBPs) have become known, and limits for these agents were first set in 1977. The disinfectant used in at least 98% of the drinking water treatment facilities in the U.S. is chlorine, so the identified DBPs were those associated with chlorination, specifically trihalomethanes (THMs) (White, 1992). The concept of balancing these risks is to identify changes to treatment procedures that enable both of these risks to be simultaneously reduced to within acceptable limits.

What complicates the equation and forces it to become a balancing act is the interdependence of microbial reduction and DBP production. Reducing chlorine concentration or contact time during water treatment reduces DBP generation and chemical risk, but also reduces treatment efficiency and increases microbial risk. A simplified, conceptual model demonstrating the general trends with biological and chemical risks as a function of C*T, the disinfectant concentration-contact time product, is shown in Figure 3. C*T is chosen as a representation of the treatment process because
FIGURE 3. Relationship Between Treatment Process and Biological and Chemical Risks.

The agents responsible for biological and chemical risk are related in opposite directions to treatment progression. In both cases, however, uncertainty exists as to the extent of the risk imposed by the offending agents. Independently imposing regulatory limits on these agents or risks generates a *de facto* limit on the water treatment process.
treatment requirements for specific microorganisms are typically expressed in terms of this value (Clark, et al., 1993). The curves are given only as qualitative indicators of the general nature of the relationships they depict, and are not meant to be quantitative.

The areas in which uncertainty contributes are indicated as well. In Frame 1, there is an overall decrease in microbial concentration as the C*T value is increased, and an overall increase in DBP formation as the C*T value rises. The curves for these trends are dependent upon the specific microbe or DBP, and are known with varying degrees of uncertainty. However, the general directions are fairly accurate. Frame 2 represents the dose-response curves, which also vary with biological and chemical agent. As previously indicated, the dose-response curves for DBPs contributing to chemical risk are much more uncertain than those for microbial agents creating the biological risk. Frame 3 depicts the union of these two kinds of curves for each risk, allowing each risk to be expressed as a function of C*T values. The dashed lines represent a range of values arising from biological and chemical uncertainties discussed above in sections 2.1.2 and 2.2.3, respectively. Regulators decide upon acceptable levels of risk, and set maximum concentration levels corresponding to that maximum risk. In doing so, they are essentially imposing independent limitations on treatment, which translate to minimum levels of treatment for reducing biological risk, and maximum levels of treatment for introducing chemical risk. Because these regulations are made independently, a narrow window may be left between the allowable ranges of treatment. In some cases, there may not even be a window, but instead an overlap of unacceptable treatment levels for protection from both risks. This is the point from which many treatment facilities might be starting.

One solution therefore lies in finding alternative routes of DBP reduction that allow simultaneous compliance with protective microbial regulations. Numerous treatment procedures exist, spanning from various means of filtration to the application of coagulants, biological filtrants, or softening agents. However, five alternatives stand out among these options: (1) using preventative measures to protect high quality source
water, (2) moving the point of disinfectant application in the treatment process, (3) reducing the potential for DBP production by removing source water elements, organic precursors that are necessary for DBP formation, (4) removing DBPs after they form during treatment, (5) using alternative disinfectants that do not generate the DBPs that are monitored. The efficiency with which these alternatives control DBPs is highly site-specific, but some generalizations for each of these options can be made. Following their introduction there will be a discussion of the uncertainties associated with these alternatives.

3.1.2 SOURCE PROTECTION

Beginning with high quality source water is naturally desirable, and consequently, protection of such a source is the optimum manner in which to minimize DBP formation. This is a preventative approach, and although it is intuitive, the Scientific Advisory Board felt it necessary to stress among its ten primary recommendations to the EPA for reducing risk that "the EPA should emphasize pollution prevention as the preferred option for reducing risk" (SAB, 1990). Source protection is obviously a sufficient solution only for sources of high water quality, but it will still yield preventative benefits to source water of all qualities where it is an option.

3.1.3 MOVING POINT OF APPLICATION

The formation of DBPs is a function of the concentration of organic material suspended in the treatment influent. Filtration, coagulation, settling, softening, and a number of other steps typically present in the drinking water treatment process reduce the suspended material, including the total organic carbon (TOC), a representation of the organic material, present in the water. Placing the disinfectant further down the treatment stream therefore reduces the amount of organic material exposed to the disinfectant, reducing DBP formation. Moving the point-of-disinfection as a means of DBP control is
particularly appealing because it requires minimum change to the treatment process, and thus minimum costs and associated adaptations. If this approach does not sufficiently reduce DBP formation, precursor removal, essentially an extension of this procedure, may be beneficial.

3.1.4 PRECURSOR REMOVAL

Experience in the drinking water treatment industry has demonstrated that the effectiveness of disinfection is greatly improved when it follows filtration. Filtration, in addition to removing larger contaminants, also reduces the concentration of organic material, measured as total organic carbon (TOC), that would potentially react with the disinfectant. Pre-treatment filtration therefore prevents over-stressing of the disinfectant, and makes more disinfectant particles available for the intended disinfection process. This process can be taken a step further, requiring a more rigorous pre-treatment procedure to remove a great portion of the TOC, an indicator of the precursor concentration, present in the source water.

Several options have been considered for precursor removal: Granular Activated Carbon (GAC) filtration, membrane technologies (microfiltration, ultrafiltration, and nanofiltration), enhanced coagulation, and enhanced softening. Enhanced coagulation or softening are mentioned in the 1994 proposed National Primary Drinking Water Regulations Disinfection/Disinfectant By-Products Rule as methods for compliance with the proposed TOC concentration limits (USEPA, 1994b). Both GAC and membrane techniques for precursor removal are being investigated further by the EPA as specified in the Information Collection Rule (ICR) (USEPA, 1994c). The ICR requires some surface water systems serving greater than 100,000 people, and some groundwater systems serving greater than 50,000 people, to conduct pilot-scale studies of these technologies (USEPA, 1994c).
3.1.5 DBP REMOVAL

After by-products are formed, they can be removed with GAC filtration or through air stripping. Although these processes are capable of removing DBPs to within the maximum contaminant levels, they are costly, and might be less desirable in that they are not preventative; these technologies are removing DBPs rather than impeding their formation, and could therefore present additional risk in the event of a failure to remove DBPs. Consequently, it may be both safer and more economical to employ precursor removal, a more preventative approach, which adds the benefits of lowering effluent treatment needs.

3.1.6 ALTERNATIVE DISINFECTANTS

Numerous treatment alternatives are being considered for drinking water disinfectants in an effort to reduce potentially harmful DBPs. Ozone, perozone (the combination of hydrogen peroxide and ozone), Ultraviolet (UV) irradiation (used in combination with ozone), chlorine dioxide, and chloramines (chlorine with ammonia-N) are the principal alternatives under consideration in the U.S. Chlorine dioxide, chloramines, and ozone have emerged as the leading alternatives to chlorine. Several of these treatment processes are already utilized in other countries, but the need for more information to reduce the uncertainties surrounding these alternatives is critical before any of them should replace of chlorine as the leading disinfectant in the U.S.

3.1.6 (A) OZONE

Ozone is a stronger oxidant and disinfectant than chlorine, and is the only known disinfectant capable of combating the waterborne pathogen, Cryptosporidium. Ozone is used in over 40 treatment plants in the U.S., and in over 1000 treatment plants in Europe (White, 1992). Its greatest benefit, however, has been noted to be its ability to control color, odor and taste, rather than its disinfection capabilities; its lack of disinfectant
residual prevents the maintenance of post-treatment water quality, making the use of ozone alone as a disinfectant impractical for large distribution systems. Consequently, both in Europe and in the U.S., treatment facilities using ozonation as their primary treatment almost without exception back their systems with secondary chlorination to provide necessary residuals (White, 1992). Ozone is used less frequently in the U.S. for several reasons. Source water supplies in the U.S. often contain larger quantities of magnesium and iron than those in Europe, and the presence of these minerals interferes with ozone's disinfection capabilities. Ozone is also much more expensive and more difficult to generate and use than chlorine, and does not deliver as reliable or consistent of a performance as does chlorine. Furthermore, ozone produces numerous DBPs, including hydroperoxides, epoxides, aldehydes, and bromate (in the presence of bromide), some of which are at least feared to be mutagenic and carcinogenic. Despite these shortcomings, ozone has potential as a drinking water disinfectant, and several "advanced oxidation processes" utilize variations on the ozonation process.

3.1.6 (B) ADVANCED OXIDATION PROCESSES

Processes that use perozone and UV radiation as catalysts in the decomposition of ozone are considered "advanced oxidation processes" (AOPs). These processes can reduce treatment costs by accelerating disinfection, and can in many cases eliminate the by-products that would have otherwise been formed with ozone. The use of such treatment procedures may be limited, however, depending on the quality and contents of a system's source water. Pilot studies have been conducted on a number of AOPs, and their varied success has led to the conclusion that the usefulness of AOPs is highly location-specific (White, 1992). None of those techniques investigated so far will serve as sufficient alternatives for the broadly applied chlorination process.
3.1.6 (C) CHLORINE DIOXIDE

Chlorine dioxide was an exciting prospect for water treatment in the 1970's, when it was discovered that its use not only avoided THM generation, but also reduced the concentration of humic and fulvic acid, the precursors to trihalomethanes. Enthusiasm toward chlorine dioxide continued as its use provided better tasting and more aesthetically pleasing water. Unfortunately, it produces the disinfection by-products chlorite and chlorate, both suspected of presenting more serious threats to human health than the THMs, the threat that originally spurred the search for alternatives (White, 1992). Methods for removing chlorite by inducing a reaction with sulfurous compounds has met with success, but chlorate still remains an unremovable, health threatening DBP, making chlorine dioxide treatment a less favorable option.

3.1.6 (D) CHLORAMINATION

The addition of ammonia nitrogen (ammonia-N) in the chlorination process, or chloramination, is known to reduce the formation of trihalomethanes and other chlorination by-products, and is perhaps the most favorable of the alternative disinfectants for this reason. Only one additional DBP not associated with chlorine, cyanogen chloride, has been detected in significant amounts with the use of chloramines, and the health effects of this DBP are unknown (Bull, 1991). Chloramination has also been successful in minimizing negative tastes and odors associated with chlorination. However, the addition of ammonia-N introduces the risk of providing nutrients to nitrifying bacteria, and has been suspected of enhancing the nutrient content required for microorganisms to regrow in the distribution system. In Europe, ammonia-N itself is considered so dangerous and its concentration limit set so low, that chloramination cannot even be applied as a drinking water treatment (White, 1992). Chloramine residuals have also introduced problems in the U.S., affecting dialysis patients. Although this problem has been addressed by changing dialysis procedures, the suspicion surrounding chloramination has not completely
dissipated (White, 1992). Furthermore, chloramines provide weaker oxidation than chlorine, and are usually incapable of maintaining disinfection standards where poor source water quality is used.

3.1.6 (E) COMBINATIONS

With the exception of chlorine dioxide, the alternative disinfectants are by themselves insufficient to replace chlorine. Ozone, because of its extreme reactivity, maintains no residual in the treatment effluent, and requires a secondary treatment with chlorine or chloramine to provide continued protection through the distribution system. However, this approach has been known to enhance the formation of brominated compounds, which are suspected of being among the most dangerous DBPs where bromine is present in the source influent (Bull, 1991). Chloramines, on the other hand, are extremely weak oxidants, and often need an additional disinfectant to boost their efficiency of pathogen removal to required standards. Secondary chlorination, or preozonation are options that have been considered for supporting chloramines. However the enhancement of DBPs has been observed through these combinations, therefore reducing the benefit of employing chloramine. The use of ozone with chlorine dioxide has been found to be dangerous because ozone converts the removable potential carcinogen chlorite into chlorate, a hazardous and unremovable by-product (White, 1992). The results of combining disinfectant technologies are varied according to source water characteristics, and consequently it is difficult to draw broad conclusions regarding their interactions. Consequently, any favorable combination strategy for the future will require tailoring treatment to the qualities and content of the source water.

3.2 UNCERTAINTIES IN TREATMENT OPTIONS

When it was first discovered that drinking water chlorination generated trihalomethanes (THMs) and thus introduced the problem of chemical risk to drinking
water treatment, the solution was sought in the pursuit of alternate disinfectants that simply did not generate THMs (Bull, 1993a). The uncritical pursuit of this solution unfortunately delayed the realization that all disinfectants, as powerful oxidizing agents, inherently generate DBPs, and that these chemicals might also present chemical threats to human health. Owing to the delay in this realization, information pertaining to the DBPs generated by alternative disinfectants is sparse, generating a large uncertainty as to whether or not their use as a replacement for chlorine would result in a reduction in chemical risk. Furthermore, because 98% of US drinking water treatment facilities employ chlorination to purify drinking water, there is little observational or epidemiological evidence available to indicate possible negative health effects associated with alternative disinfectants. DBPs that are known to be generated by alternate disinfectants are summarized in Table 3. Comparing the DBPs listed in the table, it is difficult to say whether one disinfectant is better than another based on the DBPs they potentially generate, because of uncertainty in the identification of all DBPs, the factors governing their formation, and the toxicity of identified DBPs. Uncertainties in disinfectant alternatives are, therefore, primarily data uncertainties, arising from lack of research.

Some generalizations can be made regarding DBP formation with various disinfectants. The presence of bromine is a known element contributing to brominated by-products with all disinfectants. The formation of most halogenated DBPs is also strongly associated with the presence of humic and fulvic acids for all disinfectants. With chlorine dioxide, the formation of chlorite appears to simply accompany the generation of chlorine dioxide from sodium chlorite and chlorine, and chlorate is formed from chlorite during secondary chlorination. Chloramination appears to decrease the generation of most chlorination by-products. The addition of ammonia after chlorination stops subsequent DBPs formation, except when the chlorine to ammonia ratio is near the breakpoint, in
<table>
<thead>
<tr>
<th>DISINFECTANT</th>
<th>DISINFECTANT BY-PRODUCTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>• Trihalomethanes (specifically, chloroform, bromodichloromethane, dibromochloromethane, dibromoform)</td>
</tr>
<tr>
<td></td>
<td>• Haloacetic acids</td>
</tr>
<tr>
<td></td>
<td>• Haloacetonitriles</td>
</tr>
<tr>
<td></td>
<td>• Haloaldehydes</td>
</tr>
<tr>
<td></td>
<td>• Haloketones</td>
</tr>
<tr>
<td></td>
<td>• Halopicrin</td>
</tr>
<tr>
<td></td>
<td>• Halophenols</td>
</tr>
<tr>
<td></td>
<td>• Cyanogen chloride (low concentration)</td>
</tr>
<tr>
<td></td>
<td>• Chloral hydrate</td>
</tr>
<tr>
<td></td>
<td>• Chlorinated furanone (MX)</td>
</tr>
<tr>
<td>Chloramine</td>
<td>• An enhancement of Cyanogen chloride over chlorine's production</td>
</tr>
<tr>
<td></td>
<td>• A lesser amount of all other chlorine DBPs</td>
</tr>
<tr>
<td>Ozone</td>
<td>• Bromate, Brominated acetic acids, brominated acetonitriles, bromopicrin, &amp; bromoform (w/Br present in source)</td>
</tr>
<tr>
<td></td>
<td>• Formaldehyde</td>
</tr>
<tr>
<td></td>
<td>• Acetaldehyde</td>
</tr>
<tr>
<td></td>
<td>• Higher aldehydes</td>
</tr>
<tr>
<td></td>
<td>• Carboxylic acids</td>
</tr>
<tr>
<td></td>
<td>• Hydrogen peroxide</td>
</tr>
<tr>
<td></td>
<td>• Aldo- and ketoacids</td>
</tr>
<tr>
<td>Chlorine Dioxide</td>
<td>• Chlorite</td>
</tr>
<tr>
<td></td>
<td>• Chlorate</td>
</tr>
<tr>
<td></td>
<td>• Suspected organic DBPs similar to those generated with Ozone</td>
</tr>
</tbody>
</table>

which case ammonia may hydrolyze chlorinated intermediates, therefore enhancing DBP production (especially cyanogen chloride) (Singer, 1993).

The toxicological data on DBPs associated with alternative disinfectants is more uncertain and incomplete than for chlorine generated DBPs. Few studies have been conducted, so a comparison of the chemical risks associated with alternative disinfectants is not very enlightening. In general, it has been established that bromate, trihalomethanes, halogenated acids, chlorite, and chlorate are the DBPs that pose a significant threat, considering both toxicity data, and the concentrations in which these substances may occur (Bull, 1991). This suggests that chlorine, ozone, and chlorine dioxide all might be responsible for significant chemical risk. No animal studies investigating the toxicology of cyanogen chloride through oral administration have been conducted, so chemical risk reduction with chloramines is still uncertain (Bull, 1991).

The appropriateness of disinfectant alternatives as a function of source water characteristics will become more clear after necessary associations have been made. Until such information is available, however, there is no certainty that any alternatives will decrease the chemical risk of drinking water disinfection. Current research efforts are concentrated in this area, and the uncertainty regarding alternate disinfectants is expected to decrease significantly throughout the next decade. Consequently, regulations regarding the use of alternative disinfectants and the concentrations of their by-products are expected to increase.

The uncertainties associated with other treatment options or process changes are not as significant. Precursor removal, DBP removal, and moving the point of disinfectant application are not expected to add chemical risk to treated water, so the uncertainty surrounding them lies primarily in estimating their microbial reduction efficiency. The potential for increased biological risk should be the main consideration when entertaining these options. For instance, by removing precursors and concomitantly decreasing the turbidity and total organic carbon content of the influent, the required disinfectant
concentration is decreased. Following the C*T concept, a decrease in disinfectant concentration must be accompanied by an increase in contact time between the disinfectant and the treated water in order to ensure the same level of protection against pathogens for all consumers in the distribution system (Regli, et al., 1993b). The most certain option for addressing the risk balancing problem is, naturally, the protection of a high quality source water. In most cases, however, this is not a sufficient option.

Referring again to Figure 3, the treatment options discussed above are focused on modifying the first frame of the chemical risk, where DBP concentration increases as a function of treatment (they would also have a corresponding influence on the third frame, which will be specifically addressed later). Many of the options will also modify the first frame of the biological risk, consequently changing both final frames. The challenge to treatment utility operators is to determine options that allow them to mutually satisfy the acceptable regulatory risk limits on both final risk curves (Frame 3). However, there is another challenge for the utility operators, and this is one of anticipation. The regulatory situation is very tenuous, and although compliance with current regulatory limits is mandatory, the state of these regulations is one of flux. Consequently, operators must choose wisely to avoid having to make costly future treatment changes as regulations evolve. Furthermore, the uncertainty of the effectiveness of these options in reducing overall risk to human health must be considered.
4. ROLE OF UNCERTAINTY IN REGULATORY DEVELOPMENT

4.1 REGULATORY DEVELOPMENT

When the MCL for THMs was introduced at 0.1 mg/L, this value was chosen based more upon its attainability than its risk-reduction ability; consequently, most utilities required only minimal changes for compliance (often achieved through changing the point of chlorine application) (Bull, 1993a). However, further reduction will demand more sophisticated and costly changes to many treatment facilities. In recognition of the uncertainties present in reducing both biological and chemical risks through drinking water treatment regulations and the significant impact and potential investment that further regulation will impose on the water treatment industry, the EPA undertook a new regulatory strategy (Macier, 1994). The Agency created a negotiating team in November 1992, to involve representatives of interested parties in the determination of the best regulatory approach to these competing concerns. A negotiated rule making process, or "REG-NEG" process, was employed in response to the EPA's decision that the inadequacy and unavailability of relevant information necessitated "all stakeholders to participate in the decision-making on setting proposed [water quality] standards" (USEPA, 1994b). The negotiating committee members included representatives from public water systems, state and local health agencies, environmental organizations, consumer groups, and all levels of government (USEPA, 1994a). The public water suppliers comprise the largest subgroup of the committee, reflective of their stakeholding in the drinking water risk balance issue (personal communication, Tom Grubbs of EPA, January, 1995).

A mediation firm, independent of the EPA, was contracted to create the negotiations committee. This group interviewed the stakeholders interested in participating in the REG-NEG process, and attempted to poll their views on relevant issues and to ascertain their desire to act as a member of a group aiming to reach consensus. The committee formation was constrained by the necessity to maintain a small
enough group to reach consensus, and therefore, not all stakeholders were able to gain representation. For instance, Greenpeace, a very vocal opponent of any chlorine usage, was not represented on the negotiating team. Representatives from the chemical (including chlorine) and equipment industries were also not appointed. A single seat on the committee was offered to represent these industries, but their interests were so varied that a consensus could not be reached among them regarding who would occupy the seat (personal communication, Tom Grubbs of EPA, January, 1995). In an effort to include these stakeholders in the process, the EPA formed the Technologies Working Group (TWG), in which the Chlorine Institute, the Chemical Manufacturing Association (CMA), the International Ozone Association, equipment manufacturers, and technical experts from the EPA, environmental organizations (including Greenpeace), and other research organizations participated (personal communication, Tom Grubbs of EPA, January, 1995). The TWG provides a forum in which its members can submit any scientific information to support their interest, and is based on the basic tenet that all technological information is relevant and will be considered by the negotiations committee during the REG-NEG process (personal communication, Tom Grubbs of EPA, January, 1995). In this way, members not represented on the negotiations committee were involved in the REG-NEG process.

After agreeing that further information was necessary to simultaneously minimize the chemical risks introduced through disinfection and the microbial risk from waterborne pathogens, the negotiating committee formed a three-part plan to address the problem in its present context, to generate an information database through long-term research upon which future decisions can be made, and to specify a time at which current decisions will be reevaluated. The first part of the plan sets interim controls on both disinfectant/disinfection by-product and microbial effluent concentrations based on existing data, and was proposed on July 29, 1994, in the form of the National Primary Drinking Water Regulations; Disinfectants and Disinfection By-Products (D/DBP) rule,
and accompanying Enhanced Surface Water Treatment (ESWT) rule (USEPA, 1994b and 1994d). The D/DBP Rule, applicable to all treatment utilities regardless of size, specifies new Maximum Contaminant Level Goals (MCLGs) and Maximum Contaminant Levels (MCLs) for both organic DBPs (specifically, total trihalomethanes (TTHMs) and five haloacetic acids (HAA5s)), and inorganic DBPs (chlorite and bromate). The D/DBP Rule also sets Maximum Residual Disinfectant Level Goals (MRDLGs) and Maximum Residual Disinfectant Levels (MRDLs) for chlorine, chloramines and chlorine dioxide. The MCLGs and MRDLGs are modifications to the levels at which no observed negative health effects have occurred, which allow an "adequate margin of safety," as specified by the Safe Drinking Water Act (SDWA) amendments in 1986. The MCLs and MRDLs represent the values that are as close to the corresponding goals as possible while considered to be attainable using the current Best Available Technology (BAT). The D/DBP Rule also describes what is considered to be the BAT. The values given for the MCLs and MRDLs in this proposal are Stage 1 values. Table 4 summarizes the values for these regulations.

Accompanying the D/DBP rule is the Enhanced Surface Water Treatment (ESWT) rule, applicable primarily to treatment systems serving more than 10,000 people (only the requirement to conduct a 5 year sanitary survey applies to smaller systems), that focuses on minimizing the microbial risks specifically from Giardia, Cryptosporidium and viruses in treated drinking water (USEPA, 1994d). Prior NPDWRs, namely, the Total Coliform Rule (TCR) and the Surface Water Treatment Rule (SWTR), specify removal requirements for total coliforms, enteric viruses and Giardia, but neglect Cryptosporidium owing to lack of data substantiating the necessity (USEPA, 1994d). Supporting data have now been obtained, and the ESWT rule introduces the first regulation of Cryptosporidium concentration. To protect against an undermining of protection against pathogens by compliance with the D/DBP rule, the ESWT rule requires higher treatment levels for systems with poor source water quality. The introduction of the ESWT rule is intended to
TABLE 4: Proposed (July 1994) Disinfectant/Disinfection By-Product (D/DBP) Maximum Residual Disinfectant Levels/Maximum Contaminant Levels (MRDL/MCL) for National Primary Drinking Water Regulations (NPDWR)

<table>
<thead>
<tr>
<th>COMPOUND/BAT</th>
<th>STAGE 1 MCL/MRDL (mg/L)</th>
<th>STAGE 2 MCL/MRDL (mg/L)</th>
<th>Disinfectant with which Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTHM</td>
<td>0.080</td>
<td>0.040</td>
<td>All</td>
</tr>
<tr>
<td>HAA5</td>
<td>0.060</td>
<td>0.030</td>
<td>All</td>
</tr>
<tr>
<td>Bromate</td>
<td>0.010</td>
<td>(none proposed)</td>
<td>Ozone</td>
</tr>
<tr>
<td>Chlorite</td>
<td>1.0</td>
<td>(none proposed)</td>
<td>Chlorine Dioxide</td>
</tr>
<tr>
<td>Chlorine</td>
<td>4.0</td>
<td>(none proposed)</td>
<td>Chlorine</td>
</tr>
<tr>
<td>Chloramines</td>
<td>4.0</td>
<td>(none proposed)</td>
<td>Chloramine</td>
</tr>
<tr>
<td>Chlorine Dioxide</td>
<td>0.8</td>
<td>(none proposed)</td>
<td>Chlorine Dioxide</td>
</tr>
<tr>
<td>BAT for organic by-products</td>
<td>Chlorine as primary &amp; residual disinfectant with GAC10 or Enhanced Coagulation</td>
<td>Chlorine as primary &amp; residual disinfectant with GAC10 and Enhanced Coagulation, or GAC20</td>
<td>N/A</td>
</tr>
</tbody>
</table>

BAT: Best Available Technology  
MCL: Maximum Contaminant Level (applied to disinfection by-products)  
MRDL: Maximum Residual Disinfectant Level (applied to disinfectants)  
TTHM: Total Trihalomethanes  
HAA5: Haloacetic Acids (five included)  
Stage 1: Interim Values  
Stage 2: Placeholder Values
prevent an increase in biological risk by changes in treatment process initiated by the D/DBP Rule (USEPA, 1994d).

The second part of the negotiating team's program is represented by the Information Collection Rule (ICR) (USEPA, 1994c). The ICR sets occurrence and treatment data collection requirements for systems serving at least 10,000 people. Specifically, the ICR demands the collection of monitoring data indicating the source water and within-treatment conditions as well as the ultimate effluent quality with respect to disinfectant, disinfection by-product, and pathogen concentrations. Additionally, the ICR requires that surface water systems serving at least 100,000 people and ground water systems serving at least 50,000 people complete pilot studies of DBP precursor removal efficiency by Granular Activated Carbon (GAC) or membrane technology. The ICR is unique in that it will be implemented directly by the EPA, rather than through the states (Macler, 1994). The information generated from the ICR, coupled with new information obtained from research conducted independent of these NPDWRs, will provide the foundation for the third part of the negotiating teams program from drinking water treatment regulation.

With a greater database, the EPA negotiating team will meet again to evaluate the interim Stage 1 MCL, MCLG, MRDL, and MRDLG values, and will recommend to the EPA appropriate long-term regulations. Already, Stage 2 values for the MCLs for organic chlorine by-products have been proposed in the D/DBP rule, accompanied by a proposal for the Stage 2 BAT. These values are "placeholder values," and have been proposed as indicators of future regulatory change in an effort to appease particular members of the negotiations committee who advocate tighter regulations for these DBPs (personal communication, Tom Grubbs of EPA, January, 1995). The Stage 1 values, and the proposed Stage 2 values are listed in Table 4, as well as the disinfectants with which the MCLs are applicable. The Stage 1 and 2 BAT for organic DBPs are also listed.
The assurance that the implementation of these new regulations will result in a
decreased overall risk under the current uncertainties is extremely difficult. First, one
must consider the new strategies undertaken by drinking water treatment utilities to obtain
a decreased DBP concentration, and determine if they might be accompanied by an
increased microbial concentration. For example, precursor removal lowers the organic
material of the source water, subsequently increasing the disinfection efficiency, and
decreasing the necessary disinfectant dose. However, at lower concentrations of
disinfection, the effluent may not have been sufficiently treated to achieve protection
against microbials for users at the beginning of the distribution system without additional
changes to the system (Regli, et al., 1993b). Switching to a different disinfectant might
also raise the microbial risk. Depending upon source water characteristics, chloramination
or ozone and secondary chloramination have been known to enhance the nutrient level of
the treatment effluent, ultimately promoting microbial regrowth (Regli, et al., 1993b).
Another potential problem with alternative disinfectants is the introduction of alternative
chemical risks. Concern has specifically been raised by the Scientific Advisory Board that
the D/DBP regulations should not encourage treatment facilities to shift to alternative
disinfectants with unknown quantified chemical risk relative to chlorine (SAB, 1992a). It
has been suggested that setting MCLs for DBPs associated primarily with one particular
disinfectant so that they present the same estimated risk level (typically $10^{-4}$) would assist
in this effort (Occidental Chemical Corporation, 1993). However, the interim MCLs set
are not commensurate with this concept, primarily based on technological limitations
(personal communications, Tom Grubbs of EPA, January, 1995). Although the interim
regulations represent the best current knowledge regarding DBPs, the information about
alternative disinfectants is extremely limited, and it is uncertain whether or not they will
result in a net reduced human health risk. It is because of these uncertainties that the EPA
pursued the consensus-seeking, REG-NEG approach to making decisions in this area.
The EPA and Wade Miller Associates, Inc. conducted an extensive regulatory impact analysis in an effort to determine the regulatory scenario that would result in the greatest reduction in both chemical and biological risks (WMA, 1994 and Regli, et al., 1993b). To aid in this endeavor, a DBP regulatory analysis model (DBPRAM) was used to estimate the formation of DBPs under different treatment schemes that might be initiated for compliance (judgments were made regarding the treatment options that would be encouraged by various regulatory scenarios). The model uses source water characteristics (including microbial occurrence and TOC) estimated to be representative of the country's drinking water sources, and estimates the resulting concentration of *Giardia*, TTHMs, and THAAs (Regli, et al., 1993b). Chlorinated by-products are the only DBPs about which enough is known to empirically estimate their formation. The Scientific Advisory Board, although they support the development and future use of the DBPRAM, recommended that it not be used in the forming the NPDWRs because the model inflicts an unjust bias against chlorine (SAB, 1992a and 1992b). The model's shortcomings are primarily due to large uncertainties and informational gaps, and the results, used to help determine the MCLs and BATs in the Stage I regulations discussed above, are still considered tentative by the EPA in this light (Regli, et al., 1993b).

Although the risk outcome of the proposed Stage 1 values is yet unknown, the influence uncertainty has had on regulatory development is immense. The scientific uncertainties inhibiting the quantification of both biological and chemical risk, and the EPA's continued use of conservative "safety factors" could potentially raise the overall risk to public health. The EPA has clearly maintained, among its primary objectives and basic tenets, that any measures taken to reduce chemical risk should not increase biological risk. However, in the presence of uncertainties, many of the changes to the drinking water treatment system could contradict that objective. Furthermore, the continued use of safety factors, as described in section 1.4, "EPA's Treatment of Uncertainty," allows the disproportionate amount of uncertainty surrounding the hypothetical chemical risk to
greatly reduce the MCL values corresponding to a particular elevated chemical risk value. This is tantamount to ignoring the relative certainty of biological risk in the risk characterization step. If this occurs, the uncertainty of producing a greater chemical risk might be allowed to overshadow the reality of producing greater biological risk.

4.2 IMPACT OF REGULATORY DEVELOPMENT ON UNCERTAINTY

The REG-NEG process in itself, as well as the result of the negotiators efforts, are both unique regulatory efforts directed at dealing with scientific and non-scientific uncertainty. The negotiators make an attempt through the multiphase plan to not only pursue the information necessary to reduce scientific uncertainty, but also to implement interim regulations based upon the current state of knowledge. The large-scale research endeavor undertaken by the ICR will undoubtedly result in an improvement of the knowledge base upon which drinking water regulations are built, provided that the procedural outline presented in the ICR for standardized monitoring and reliable incorporation is enforced.

Ten years ago, it was acknowledged by Davis and Roberts that in light of the uncertainties in minimizing both biological and chemical risks, "progress can be achieved through open dialogue and development of conceptual approaches and decisions, " and that "the absence of such dialogue could be the most crucial gap in our continued well being, much less our survival" (Davis, et al, 1984). Policy-makers, with the REG-NEG process, are addressing this issue by making an effort to include the stakeholders in a decision-making process that involves significant value judgments. In doing so, they are confronting the amplified role of non-scientific uncertainty, and allowing the responsibility for resulting changes in the net risk to human health to be shared among the stakeholders.
5. ROLE OF NON-SCIENTIFIC UNCERTAINTY IN VALUE JUDGMENTS

As indicated in Figure 1, there are three relevant roles non-scientific uncertainty plays in the risk balance situation: interpretation of scientific uncertainty, determination of acceptable risk limits, and valuation of disparate demonstrations of risks.

5.1 INTERPRETATION OF SCIENTIFIC UNCERTAINTY

Despite the presence of scientific uncertainty, decisions regarding the interpretation of unknowns, and the role given to the representations of scientific uncertainty must still be made. The use of safety factors as discussed above is one example of how to make such a decision. It is not always clearly indicated by the scientific evidence, how important specific parameters are in the determination of risk, and subsequently, the uncertainties surrounding them will be weighted differently depending upon who makes the decision. These decisions vary among individuals with different interests, and in the absence of scientific evidence, there may be no "correct" representation. Such decisions vary even among experts, depending on their own personal biases and their experiences in a given field. The associated non-scientific uncertainty emanates from the inability to confirm a correct judgment, or to attain consensus among all parties. Evans, et al., have suggested the use of probability distributions to represent not only variations in scientific uncertainties, but the weight of the different areas of uncertainty as judged by experts (Evans, et al, 1993). By allowing such weighting by a number of individuals, the non-scientific uncertainty discussed here is reduced. In the risk balance situation, this particular non-scientific uncertainty is clearly a large contributor to the equation.

5.2 RISK ACCEPTABILITY

The non-scientific uncertainty associated with determining acceptable limits of risk is not dependent upon the presence of scientific uncertainty. Non-scientific uncertainty
typically accompanies risk-management decisions. In the case of balancing biological and chemical risks, the acceptability of each type of risk must be established in some kind of relative manner. To do so, considerable attention has been given to the establishment of conceptual frameworks under which relevant characteristics of a given society are considered.

Where changes to drinking water treatment are technologically and economically feasible, the cost-intensive search for mutual minimization of biological and chemical risks appears to be justified by the weight of evidence that has been collected (admittedly this also involves a value judgment). However, in areas where drinking water treatment is currently insufficient to protect against microbial pathogens, or where drinking water treatment is non-existent, any concern regarding chemical risk may be detrimental. For instance, after the 1991 outbreak of cholera in Trujillo, Peru, drinking water officials announced that they had not disinfected the water because of their concern over the harmful effects of disinfection by-products (Salazar-Lindo, et al., 1993). As a result, nearly 15,000 people were infected with cholera. Similarly, there are regions within more technologically advanced countries that may not have the economic resources to implement changes that would enable their treatment systems to meet drinking water standards. This is especially relevant for smaller systems that, for the first time with the currently proposed D/DBP Rule, will be required to comply with DBP regulations. These systems typically serve smaller, more rural areas, with fewer economic resources available. Furthermore, because these systems serve fewer people, the cost of changes is likely to be significantly higher per household than in more densely populated regions.

The consensus appears to be among official representatives of the EPA (Regli, et al., 1993a) as well as the World Health Organization (WHO, 1993), that biological risk far exceeds that of chemical risk in magnitude. In 1991, the WHO documented 1.2 billion cases annually of water-related illness in developing nations, resulting in 5 million deaths each year (Pike, et al., 1993). No estimates of chemical risk to these populations come
near these within several orders of magnitude. One analysis performed on occurrence data
determined that the risk of death from waterborne pathogens in untreated water is at least
100 to 1000 times greater than death from known chlorination DBPs, and the risk of
illness from waterborne microorganisms is 10,000 to 1,000,000 times greater than the risk
of cancer from known chlorination DBPs (Regli, et al., 1993a). Such statistics emphasize
that priority should be given to the reduction of biological risk over chemical risk, and
correspondingly, health officials have judged the consideration of chemical risk to be
inappropriate for developing countries (Regli, et al., 1993a and WHO, 1993).

In recognition that many communities may not have the resources necessary to
pursue the mutual reduction of biological and chemical risks, or that communities may
have other, more pressing necessities, decision trees to guide balancing biological and
chemical risks have been developed by members of the EPA and the Environmental
Studies Institute (Regli, et al., 1993a). The decision trees incorporate community
priorities and socioeconomics into the decision-making process. In essence, in
communities where infant mortality is high and life expectancy is low, reduction in
biological risk should be the focus of drinking water treatment efforts. Only where
technology is available, economies are stable, and public health is maintained at a high
level, should reduction of chemical risk be considered; but even here, the reduction of
biological risk maintains first priority. The decision trees provide questions that guide the
expansion of treatment according to these considerations and priorities, as well as
considerations regarding the specific characteristics of a treatment scenario.

The involvement of community factors in the risk balancing problem is meaningful.
The incorporation of socioeconomic factors is critical to assist in decision-making in as
much as they impose actual limitations on the options available to that community.
However, another community factor perhaps should also play a role in the decision
making process.
5.3 RISK VALUATION

The negative health manifestations that arise from biological and chemical health risks are very different. The types of diseases that occur, the degree of incidence, the severity, the timing, the affected populations, and the certainty of biological and chemical risks vary greatly. The decisions made with regard to equating these risks for the purpose of decision-making incorporate a large degree of judgment that is not scientifically-based, but purely value-based, thus they bring with them an associated amount of disagreement among members of the communities whose judgments these decisions reflect.

Table 5 highlights the ways in which biological and chemical risks differ. The vehicle through which these disparate risks are generally compared is cost-benefit analysis. However, the morbidity and mortality that arises from each risk is not equivalent on a qualitative basis. The representations used commonly for mortality and morbidity in cost-benefit analysis are generally not appropriate for this situation. For example, a simple total of estimated number of lives lost neglects morbidity, which plays an especially large role in the biological risk. The use of number of life-years lost accounts for the delayed effects of chemical risk, but is still not representative of morbidity. Putnam and Graham (Putnam, et al., 1993) suggest the use of Quality-Adjusted Life-Years (QALYs) lost to represent the decrease in quality of life during illness, or life-years lost to death. This allows morbidity to be compared with mortality on a population scale. Even with QALYs, however, the dissimilar characteristics with respect to timing and affected populations involve judgments based on individual preferences, and the assignment of "quality" factors bears much uncertainty (e.g., How does the value of a brief, acute illness caused by a waterborne pathogen compare to that of a chronic debilitation from DBPs?). Furthermore, the issue of uncertainty complicates the equating of biological and chemical risks. The matter of how much and what type of risk people in a community are willing to accept will influence their opinions on the manner in which these risks should be
**TABLE 5: Qualitative Differences Between Biological and Chemical Risks**

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>BIOLOGICAL RISK</th>
<th>CHEMICAL RISK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Disease</td>
<td>• Acute: G-I, neurological</td>
<td>• Acute: none (possibly developmental)</td>
</tr>
<tr>
<td></td>
<td>• Chronic: immunological, neurological</td>
<td>• Chronic: cancer, chronic liver toxicity, hematopoietic damage</td>
</tr>
<tr>
<td>Incidence Rate</td>
<td>• $10^{-3}$ illness/year from bacteria, virus, or protozoa</td>
<td>• $10^{-8}$ chance of cancer/year</td>
</tr>
<tr>
<td>Severity</td>
<td>• Acute: large % debilitating, small % death</td>
<td>• Acute: none</td>
</tr>
<tr>
<td></td>
<td>• Chronic: small % debilitating, small % death</td>
<td>• Chronic: large % debilitation, small to moderation % death</td>
</tr>
<tr>
<td>Timing</td>
<td>• Usually hours to days, occasionally weeks to years (primarily acute)</td>
<td>• At least 10-30 years (primarily chronic)</td>
</tr>
<tr>
<td>Affected Population</td>
<td>• Vulnerable populations: the very young, the very old, and those already suffering from medical problems</td>
<td>• Less discriminating: carcinogenicity is not as selective, also latency period makes onset occur in mid to late life, younger populations not as affected</td>
</tr>
<tr>
<td>Likelihood</td>
<td>• Highly probable</td>
<td>• Less probable</td>
</tr>
</tbody>
</table>

(Information compiled from Putnam, et al., 1993 and Tardiff, 1993c)
addressed. Biological risk is readily demonstrable and can be related to the here and now. Chemical risk, on the other hand, is more esoteric and obscure, has delayed effects, and is still a hypothetical risk. A given community will have an opinion regarding how such issues of uncertainty should be approached in decisions regarding their drinking water. Conveying these issues to the public, and incorporating the preference of those populations served by treatment facilities, should also be part of the decision-making process. The adaptations to drinking water treatment necessary to protect against the more certain biological risk and the less certain chemical risk will present significant costs to many communities. The inability to eliminate scientific uncertainty therefore yields a lack of consensus, and an increased uncertainty in policy. The implementation of regulations that may demand such changes in light of significant uncertainty should incorporate the judgments of the society served by the regulations. The REG-NEG process, in combination with the TWG, is a move in this direction.

The potential for such a significant role by non-scientific uncertainty makes the question of whether public values are being represented critical. The population served should be adequately represented in decisions regarding competing risks that demand value judgments pertaining to the comparison of these risks, as well as to the role uncertainty should play in comparing those risks.

Figure 4 more explicitly depicts how non-scientific uncertainty plays a role in balancing biological and chemical risk. Equating the biological and chemical risks is in essence merging the final two frames of Figure 3, and forcing biological and chemical risks to fit the same axis, representing total risk to human health. By setting independent limits for biological and chemical risks, regulators have in effect already made the risk acceptability judgments discussed above. By attempting to eliminate chemical risk in the same way that biological risk is eliminated, regulators have decided that for all communities affected by these regulations (now extending to utilities of all sizes) the highly uncertain chemical risk should be avoided at whatever cost of investment necessary.
**Figure 4. Combining and Equating Risks from Biological and Chemical Origins.**

Biological and chemical risks must be combined through value judgments to reach an acceptable limit of total human health risk. "Common denominators," determined non-scientifically, enable the chemical and biological axes to be merged, ideally to define a mutually acceptable treatment range. Where this merging leads to a non-existent acceptable treatment range, alternate treatment options must be used to alter the risk functions, and subsequently, to produce the acceptable range of treatment.
6. INFLUENCE OF UNCERTAINTY ON COSTS AND BENEFITS

Perhaps the most direct consideration of uncertainty's influence on society is its effects on estimates of costs and benefits both to drinking water treatment utilities and to consumers as an indication of the relative importance of biological and chemical uncertainties in drinking water treatment. The choice of how scientific uncertainty is represented has a significant effect on regulatory limits such as MCLs. By taking a conservative approach to accounting for uncertainty in the assessment of human health risks from waterborne agents, drinking water regulations are necessarily more stringent and require greater efforts by drinking water treatment utilities to achieve regulatory compliance. These greater efforts are likely to be accompanied by greater costs.

Before chemical risk became an issue, the costs of drinking water regulation were simply the costs associated with pathogen removal, i.e. the treatment costs. The benefits were the improvements to human health, calculated as the mortality and morbidity avoided owing to the application of drinking water treatment. There were uncertainties associated with calculating both the costs and the benefits, in part owing to the uncertainty that guided regulation. The conservative approach taken toward drinking water regulation by setting MCLs conservatively high simply increased the monetary costs of treatment. Once chemical risk from DBPs entered the picture, the calculation of costs and benefits of treatment became significantly more complicated. The costs are no longer simply treatment costs, but now must incorporate the costs associated with the potential carcinogenic, mutagenic, and teratogenic effects of DBPs, thereby requiring estimation based on limited data of the ostensible negative health effects. Consequently, the uncertainty present in each risk has an extended effect not only on the monetary cost associated with treatment procedures, but also the costs manifested as potential carcinogenic, mutagenic, and teratogenic effects of DBPs. In some cost and benefit assessments, however, these costs have been neglected owing both to their hypothetical
nature and to indications that these costs will not be comparatively significant (Regli, et al., 1993a).

Representing both biological and chemical risk uncertainties conservatively results in additional precautionary measures demanded of drinking water utilities as they strive to fit their treatment process to the narrow window represented in Figure 4. The costs associated with fitting both independently determined risk restrictions may be extreme in many cases. Furthermore, the benefits of such investment are questionable. Although the EPA is making responsible efforts toward ensuring that regulations addressing the risk balance issue decrease the net human health risk, there is little assurance that they will in the presence of such uncertainty. Consequently, these uncertainties have a strong negative impact by increasing costs and decreasing benefits.
7. RESEARCH NEEDED TO REDUCE SCIENTIFIC UNCERTAINTY

It is overwhelmingly clear that the acquisition of more information is necessary to reduce uncertainties, simplify the risk balance problem, and provide better protection to the public from both pathogens and potentially harmful DBPs. The uncertainties contributing to biological and chemical risk naturally mark the areas in which research is necessary. Efforts have been undertaken to create research agendas by organizations and individuals, and the same areas of research are consistently identified (AWWARF, 1993, SAB, 1992c and 1993, Sobsey, et al., 1993 and Glaze, et al., 1993). The research areas fall into several categories aimed at: (1) reducing the uncertainty in biological risk, (2) reducing uncertainty in chemical risk, (3) reducing the uncertainty of alternative treatment options, (4) characterizing uncertainty in accordance with the scientific knowledge as well as with public priorities. To reduce uncertainty in biological risk, the following research needs and recommendations have been identified:

- identification and characterization of all potential waterborne pathogens
- development of a national database with occurrence data for known pathogens
- development of more accurate monitoring techniques that incorporate microbial viability
- determination of reliable indicator species or water quality parameters
- investigation of physical state of pathogens as pertains to infectivity characteristics to host and to treatment efficiency
- influence of host physiological state on infectivity rates
- establishment of epidemiological support for infection by specific waterborne pathogens
- development of dose-response curves for health-compromised populations
- identification of variations of microorganism occurrence both geographically and temporally
- the impact of various treatments on pathogens concentrations
• development of monitoring systems to estimate the effectiveness of distribution systems as the final barrier in the multiple barrier approach to protecting against waterborne microorganisms.

These research areas represent the data gaps currently contributing uncertainty to all aspects of biological risk assessment. They emphasize more specific identification and characterization of the agents responsible for biological risk, and in many cases must be geared toward attaining precision where imprecision was once technologically unavoidable or acceptable in the absence of a competing risk.

Research needs addressing chemical risk uncertainties are even more extensive, owing to the greater uncertainty in chemical risk. Areas in which research needs to be pursued include:

• development of a database of DBP occurrence correlating to precursor distribution, disinfectant, and treatment processes employed, and development of models for prediction of DBP generation

• establishment of basic toxicological research studies on all identified DBPs

• performance of long-term epidemiological studies wherein confounders are explicitly anticipated and taken into account

• development of physiologically-based pharmacokinetic models representing the fate (target organ) and transport (metabolism) of DBPs in the human body

• identification of the primary metabolic pathways followed by chemical contaminants in the human body (and subsequent toxicological investigation with metabolically appropriate animals)

• investigation of variation in chemical mechanisms in the human body with respect to dose

• determination of the effect of chemical mixtures of DBPs, and their varying toxicological behavior within the human body
determination of how chemical behavior varies with physiological well-being.

These areas emphasize not only agent identification and characterization, but the establishment of whether or not chemical risk exists, and to what extent. The present understanding of the interactions taking place between these chemical agents and all the relevant systems (treatment system, human body after ingestion, animals used in toxicology) is extremely limited, and research emphasis must be placed on elucidating the system complexities as well as collecting data on DBP occurrence.

Uncertainties that arise in both biological and chemical risk assessment provide a means of comparing the importance of research areas. Just as the EPA uses comparative measures to determine priority risks, the uncertainties contributing to risks can provide guidance for priority areas of research. The costs and benefits of proposed regulations are routinely estimated through regulatory impact analyses contracted by the EPA. The goal of such analyses is "to develop and organize information on benefits, costs, and economic impacts so as to clarify trade-offs among alternative regulatory options" (Cromwell, 1992). This objective, and the mode through which it is carried out, might provide an excellent vehicle through which the relative contributions of individual uncertainties to costs and benefits could be determined. The uncertainties, and the corresponding research that would lead to their reduction, could therefore be prioritized.

The research needs listed above for both biological and chemical risk are specifically geared toward increasing the certainty in risk assessment. Research is also needed to reduce uncertainty in treatment options. In particular, the DBP formation and disinfectant effectiveness associated with alternative disinfectants is of particular importance, and the information listed above for chemical risk must also be pursued for chemicals identified as potentially toxic. Research and development of alternative treatment options is also required to continue the investigation for treatment alternatives that do not introduce chemical risk.
The final broad area of research pertains directly to popular representation of uncertainty. The incorporation of public values in decision-making given the uncertainty that exists, requires communication of that uncertainty in risk assessment to the public, an issue that has become more prevalent in recent years. Uncertainty is often left unaddressed when it comes to concrete decisions, and decision-makers have been increasingly accused of hiding their personal preferences behind science. More important than accusation is recognition that personal values are being substituted for data in decisions where scientific uncertainty is present. As discussed above, scientific uncertainty necessitates value judgments. In efforts to balance biological and chemical risks, the actions resulting from regulations based on minimizing both these risks may be costly, may or may not reduce overall human health risk, and may or may not reflect the priorities of the communities regulations serve. Regulators, industry, and community all share the common goal of reducing human health risk, and doing so at as low a cost as possible. The manner through which each representative sees this goal being achieved undoubtedly varies. The role of both scientific and non-scientific uncertainties in the risk balance equation is to generate questions of interpretation and values. Research should be conducted to ascertain a mode through which the varying answers to these questions can be incorporated to best represent the stakeholders' priorities. This involves research into the relevant socioeconomic factors of affected communities, the development of conceptual frameworks under which these factors are incorporated into decision-making, and the expansion of community involvement in drinking water policy decision-making.
8. CONCLUSIONS

The role of uncertainty in balancing the biological and chemical risks from drinking water chlorination is extensive. The observations concerning the role of uncertainty in the risk balance equation as specified in the hypothesis are well substantiated by the evidence presented above. These observations are recalled here, accompanied by further conclusions pertaining to the specific role of uncertainty that each point addresses.

- Scientific uncertainty contributes imprecision to biological and chemical risk quantification, which is subsequently reflected in regulatory limits, as well as the costs and benefits to stakeholders.

Pursuing further information to characterize the existence, nature, and behavior of DBPs and waterborne pathogens in all relevant systems is clearly a means of reducing scientific uncertainty. The research necessary to reduce scientific uncertainties for both biological and chemical risk is extensive. The Information Collection Rule (ICR) specifically addresses this issue, and will help to build a treatment monitoring database upon which more secure regulatory decisions can be made, and the pilot studies required of larger systems by the ICR will furthermore enhance this database. Research efforts beyond the ICR must also be pursued, and decisions regarding the specific areas of study must reflect a reasonable prioritization. Uncertainties themselves may play a role in prioritizing these needs, by projecting their relative significance on cost and benefit analyses accompanying risk-based regulatory impact assessments. When uncertainty exists in the risk assessments upon which regulations are based, these uncertainties propagate through to the resulting costs and benefits estimated in the regulatory impact assessments. By individually accounting for the ambiguity induced by each uncertainty, a prioritization of research needs may be developed to most rapidly reduce the most critical
types of uncertainty. In this way, representations of uncertainty might be used to identify future research and development priorities to optimize the risk balance more expeditiously.

- A strictly conservative representation of scientific uncertainty in safety factors applied in regulatory development reduces the options to drinking water treatment utilities for mutually minimizing biological and chemical risks.

Human health regulation is traditionally accomplished under the assumption that conservative representations of uncertainties minimize risks at an acceptable level of additional expenditure. The introduction of competing risks breaks down this fundamental concept, and introduces the need for specificity and precision in quantifying each risk. Where such precision is lacking owing to scientific uncertainties in the characterization of the competing risks, the regulatory decisions that accommodate the uncertainty boundaries placed around these risks might influence the competing risk as well.

The introduction of chemical risk therefore adds complication to the minimization of biological risk. The magnitude of biological risk is evident from historical records as well as modern examples of countries not employing disinfection to their drinking water. The World Health Organization states in the Guidelines for Drinking Water Treatment, "the potential consequences of microbial contamination are such that its control must always be of paramount importance and must never be compromised" (WHO, 1993). Furthermore, the scientific uncertainties that surround the chemical risk are much more pronounced than those surrounding biological risk. These additional chemical uncertainties arise primarily from complex system sources, as well as the relative extent to which research has been conducted on both risks. Moreover, no causative relationship has been established between chlorination and the observed negative health effects of the chemical risk, nor have the by-products suspected of being responsible for these effects been positively identified. In light of the significant chemical uncertainty, and the known
magnitude of biological risks, a conservative use of safety factors for chemical risks is inappropriate.

Uncertainties arising from limited information about the occurrence of pathogenic microorganisms make it difficult to ascertain whether or not sufficient protection against biological risk is being obtained under the current practices, and evidence provided by Payment, et al. (Payment, et al., 1991) suggests that it is not. The results of the Payment study reveal that meeting the current regulatory standards for microbial concentrations in some systems is insufficient to prevent microbially induced waterborne illnesses. This indicates that the uncertainties surrounding biological risk might be causing an underestimate of the magnitude of biological risk. The recent outbreaks of waterborne illnesses caused by newly recognized pathogens such as Cryptosporidium, and the identification of new pathogens such as Cyclospora, give further indication of this possibility. Consequently, applying the same conservative principles of uncertainty representation in chemical risk regulation as in biological risk regulation might threaten the protection against microbial pathogens.

- Competing risks inherently possess non-scientific uncertainty, and the prevalence of scientific uncertainty amplifies the role of non-scientific uncertainty, requiring an acknowledgment of those uncertainties and a greater dependence on value judgments in policy and regulatory decision-making.

The nonequivalence of the manifestations of biological and chemical risks and the discrepancy in the amount of uncertainty surrounding each of them introduce the opportunity for decisions to be made based on non-scientific elements, namely, values. Such decision-making, when it potentially results in high-cost impacts on communities, should merit the involvement of community representatives in the decision-making process to incorporate various interests among community members. The EPA's implementation
of the REG-NEG process and the TWG addresses this non-scientific uncertainty, providing a forum in which stakeholders examine all available information and reach a consensus within practical limitations (not all stakeholders can be represented). The manner in which this is extended to accommodate priorities at the local level is not clear, but the need to address the lack of consensus that may exist surrounding such decisions is evident. Consequently, non-scientific uncertainty's enhancement by scientific uncertainty might continue to create additional changes to the regulatory decision-making to further incorporate public values.

- Uncertainty surrounding the performance and the associated risks of alternative treatment options generates a risk of raising the overall risk to human health and of increasing expenditures by drinking water utilities and by consumers.

An important issue that is exhibited clearly by the risk-balancing problem, is that of how much information there should be before regulation occurs. Dr. Jeffrey Harris, in a discussion of environmental policy-making (Harris, 1990), presents a point that is highly relevant to the issue of balancing drinking water disinfection risks: the issue of reversibility of consequences. In the context of environmental regulation, Dr. Harris points out that one of the key issues that should be addressed when making a regulatory decision in the presence of uncertainty is considering first, the reversibility of either implementing, or not implementing the regulation. This concept should be extended to the issue of regulating competing health risks, especially with regard to the interim regulations. The reversibility of changes to drinking water treatment and of the corresponding changes to total human health risk that could arise from the interim regulations should be compared against the reversibility of consequences arising from subjecting consumers to further risk exposure at the current levels. The present uncertainties surrounding biological and chemical risks of drinking water treatment have the potential to negatively influence both the benefits and
costs of implementing regulations. The database upon which these regulations are built will undergo rapid expansion from the ICR, and undoubtedly the uncertainty levels will decrease significantly as it does. In the meantime, the manner in which uncertainties are incorporated into the risk balance equation must be carefully weighed, and the reversibility of potential negative outcomes from the interim regulations need to be compared to the reversibility of maintaining current treatment practices until the ICR is well underway.

In summary, many of the regulatory changes that have appeared in the recent National Primary Drinking Water Regulations have been in direct response to the considerable role of uncertainty in balancing biological and chemical health risks in drinking water treatment. The REG-NEG process attempts to minimize non-scientific, value-based uncertainty. The ICR is an effort to reduce scientific, or information-based uncertainty, which influences risk quantification and risk-based regulation. The implementation of the Enhanced Surface Water Treatment Rule addresses the critical need to maintain protection against waterborne pathogens while implementing the Disinfectant/Disinfection By-Product Rule. But uncertainty's role and representation has not yet been fully addressed. The use of uncertainty to assist research prioritization, the representation of scientific uncertainty in regulatory decision-making, the optimization of tackling non-scientific uncertainty, and the full consideration of the reversibility of consequences of applying interim regulations, represent areas in which the role of uncertainty in balancing drinking water health risks warrants further consideration.
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APPENDIX A:
ANNOTATED BIBLIOGRAPHY
FOR FURTHER READINGS

This editorial expresses concern regarding the inflation of public perceptions of risks owing to inaccurate risk assessments. As an example, the author focuses on the disinfection by-product chloroform (HCCl₃). He points to the results of two laboratory studies on the negative health effects of HCCl₃; these reveal large discrepancies, apparently owing to different modes of HCCl₃ administration. In the first experiment, injecting HCCl₃ directly into the stomach of mice showed an elevated rate of tumor formation that increased with raised dosages. In the second, administration of HCCl₃ through drinking water revealed almost no tumors, and exhibited no dose-response relationship. The article points out that by discarding negative results (such as the latter experiment) public concern rises beyond reasonable, scientific justification. The author concludes that this example brings into question conventional risk assessment procedures.


This chapter examines outbreaks of waterborne disease in waters receiving various amounts of disinfection. The chapter attempts to ascertain the possibility of further outbreaks under different disinfection practices. The principal conclusion reached is that more information is needed to fully investigate the likelihood of such incidents.


This document summarizes the results of twelve "key" epidemiological studies investigating the potential correlation between drinking water chlorination and elevated cancer occurrence rates, as well as three studies investigating potential reproductive/developmental effects of drinking water chlorination. The summary includes a tabulated overview of the study objectives, conditions, controls, methods of exposure determination, methods of analysis, conclusions, and accountancy for potential confounders. A brief verbal summary precedes the tabulation, and highlights the findings of the studies in this summary.

This article discusses several difficulties associated with studying the carcinogenic effects of chlorine in drinking water. The article focuses on a meta-analysis of 10 epidemiological studies conducted by Dr. Robert D. Morris of the Medical College of Wisconsin on the correlation between cancer and drinking water chlorination. According to the article, most of the studies were conducted in the 1970’s, prior to the tightening of drinking water standards in 1979, and thus Dr. Morris’ analysis may not accurately represent today’s drinking water situation [discussion with Dr. Morris confirms this, although he also states that relevant treatment procedures have not altered significantly]. The article also discusses the difficulty of isolating the specific by-products potentially responsible for observed negative health effects.


This article is a general survey of the chlorine ban debate. It represents both sides of the debate, and describes several of the most relevant studies and reports that have contributed to the debate. The article does not directly discuss the debate’s impact on the water treatment industry, but considers its effects on the pulp and paper, plastic, solvent, and refrigerant industries. The article also points out actions taken abroad in efforts to minimize chlorine use.


This article discusses regulatory, economic, social, and political aspects of the chlorine debate, and provides a general overview of both debate positions. The article also provides a “chlorine tree,” illustrating the diversity of chlorinated compounds. The tree supports the anti-ban argument that all chlorinated compounds should not be governed under a single regulation, as they exhibit different biological and chemical behavior. As in Amato’s work referenced above, this article presents a comprehensive outline of chlorine’s present situation in the US.


This resolution highlights the collected evidence implicating various chlorinated compounds in incidents of widespread negative health effects. The resolution demonstrates the APHA’s support of the philosophy adopted by the International Joint Commission, that the best way to prevent harmful release of chlorine and chlorinated organic compounds is to avoid the use of these chemicals altogether.
The APHA recognizes that economic and technological feasibility must be assured as a chlorine phase-out progresses. The use of chlorine in drinking water treatment is singled out as a chlorine-related process for which no sufficient alternative exists, and is thereby exempt from the proposed phase-out until safe alternatives are determined.


This report describes the proceedings and conclusions of a 1992 conference, jointly sponsored by the AWWARF and the EPA. The conference aimed to establish the balance between biological and chemical risks in drinking water, and to develop regulatory priorities leading to an optimized balance. Instead, the conference generated a list of research priorities aimed at reducing uncertainty. The conference members identified four questions intended to aid in balancing microbial and chemical risks of drinking water disinfection: (1) what are the levels and distributions of both biological and chemical agents in drinking water that adversely affect the human population, (2) what diseases are caused by various agents, (3) what are the exposure sources of these hazards, and to what degree is drinking water responsible for human exposure, and (4) what are alternative strategies for providing safe drinking water to the human population, and what are their related risks, costs and benefits. Five work groups contributed to the conclusions listed in this report. These work groups focused on the areas of inorganic chemicals, microbial, synthetic organic chemicals, disinfectants and disinfection by-products, and risk assessment for chemical contaminants. The report also explains an approach to balancing biological and chemical risks from a decision science perspective [see also Putnam and Graham reference below].


This extended abstract summarizes a study examining UV disinfection, focusing both on its biocidal effectiveness and its potential for disinfection by-product (DBP) formation. The article briefly describes the experimental set up and outlines measurement procedures employed in the study. The experiment demonstrates that, despite photoreactivation and excision mechanisms employed by some bacteria, UV disinfection is capable of achieving potable water quality with no significant production of DBPs. Log removal of total coliform (representing E. coli), S. Fecalis, coliphage MS2, and poliovirus with varying UV dosage is graphically presented in the article, and raw data for DBP generation and reduction from different UV dosages are also presented.

This article presents the results of a study conducted by the AWWA Disinfection Committee. The group surveyed water treatment facilities at random, and found that the majority still used either chlorine gas or hypochlorite disinfection, but over 20 percent of these facilities also add ammonia during secondary treatment. The survey also revealed an increase in chlorine dioxide disinfection since the AWWA's 1978 survey. The report discusses the significance of process variables such as point of disinfectant application and contact time. Trihalomethane reduction schemes, and their associated negative effects, are also discussed.


This paper discusses the limitations of risk assessment and cost-benefit analyses when applied to environmental health problems. The paper addresses problems arising from the misuse of risk assessment, such as time delays accompanying further information collection, ignorance of synergistic relationships between contaminants, failure to consider the control measure benefits beyond those of immediate concern to the situation, and using risk assessment to disguise value judgments. An example of ozone contamination is presented to exhibit the occurrence of these problems. The author concludes that risk assessment is one of many tools for decision making, but that it is useful only when its limitations are recognized.


This article critiques the Environmental Protection Agency's (EPA's) decision-making policy. The EPA has begun incorporating risk assessment into regulation development, and in doing so, has encountered difficulties communicating the determined magnitudes of risks to the public. Legislators want to respond to public opinion, but public perceptions of risks often contradict the priorities set by the EPA's assessments. The EPA is further hampered by a need for more information. The decision to wait until "sufficient" knowledge is attained is often viewed as "paralysis by analysis" by environmental groups. The article explores the question of how much knowledge is enough to determine policies and regulations affecting human health.

This article discusses the EPA's approach to the rising concern over disinfection by-products (DBPs). The article introduces the EPA's two-part plan to improve disinfectant and disinfection by-product regulation, and discusses the establishment of a negotiations committee composed of representatives of parties directly affected by the new disinfection regulations. The article examines the EPA plan from a pre-implementation perspective; the plan has been initiated since the publication of the article.


This chapter addresses the uncertainty present in determining the risks and benefits of drinking water disinfection, and the subsequent need for more information. The authors identify the extent of current knowledge on the risks and benefits of chlorine, and suggest means by which decisions can be made while maintaining flexibility to enable system adaptation as new knowledge becomes available. The article discusses disinfectant alternatives, and compares their risks and benefits using results from various studies.


This report is a comprehensive review of the toxicological data on disinfectants (chlorine, ozone, chloramine and chlorine dioxide) and disinfection by-products. Suspected carcinogens, teratogens, reproductive toxins and specific target organ toxins are investigated. The author points out, however, that carcinogens are the most likely among these agents to be present in concentrations high enough to introduce substantial concern. The report outlines the mechanisms leading to each chemical's formation, and surveys the current state of knowledge regarding each chemical's human health effects. The report also examines the appropriateness of using the multistage model to extrapolate dose-response relationships for each chemical. The author concludes with projections of future regulations regarding each chemical, and enumerates obstacles that interfere with regulatory formation in this area.


This article examines available toxicological data on disinfection by-products to
establish the limits of knowledge surrounding disinfectants and their by-products, and to identify subsequent research priorities. The article emphasizes the uncertainties resulting from particular gaps in knowledge, and suggests efforts to minimize them. Several types of uncertainty are described in the article. The extent to which each type of uncertainty is present for chlorine, chloramines, chlorine dioxide, ozone, and mixed disinfection is qualitatively represented. The author highlights the by-products leading to the greatest health concerns for each disinfectant, but emphasizes that this may change as further by-products are discovered.


This article proposes a biologically based approach to risk assessment of drinking water. The approach bases the dose-response curve upon mechanistic and metabolic information regarding the behavior of individual contaminants, rather than using the linearized multistage (LMS) model. The article points out the subjectivity and arbitrary nature of the conclusions that accompany the application of uncertainty factors applied to maintain conservatism. The article describes the relevant areas of information that are incorporated into a physiologically-based pharmacokinetic (PB-PK) model, and provides examples of PB-PK models that have been completed. The development of PB-PK models is an arduous task, but the article points out that the speed with which PB-PK models are developed will accelerate as more models are completed and as the relevant mechanisms are better understood.


This article specifically addresses wastewater disinfection, but includes a broadly applicable survey of available disinfection technologies. The article discusses shipping, storage, and transport of the predominant chlorination disinfectants, and also provides an extensive discussion on UV disinfection technology, the leading alternative to chlorine disinfection in the wastewater industry.


This article summarizes the conclusions of the Society of Environmental Toxicology and Chemistry (SETAC) workshop on the environmental risks of chlorine-containing chemicals. Participants in this conference concluded the
following: (1) chlorinated compounds should not be treated as a single class of compounds, (2) current risk assessment approaches (chemical-by-chemical) are sufficient and have already improved environmental quality in some areas, (3) additional controls are necessary to eliminate the release of highly toxic and bioaccumulative chlorinated organics, and, (4) a total ban on chlorine is scientifically insupportable given current evidence.


This paper discusses a case-control study investigating the relationship between bladder cancer occurrence and both chlorination and water source (surface source vs. groundwater source). The study, taking into consideration ten different study sites, concludes that there was no overall increase in bladder cancer risk when comparing rates in areas with chlorinated surface water to areas with non-chlorinated groundwater. Among subsets of the population, however, several trends were observed and are discussed in the paper. Dose-response observations were made only in agricultural areas where the bladder cancer risk appeared to correlate with years of exposure to a treated surface source in three areas. An unusual result observed in this study is an apparently higher bladder cancer risk among cigarette smokers with a lifetime exposure to non-chlorinated groundwater than to those with a lifetime exposure to chlorinated source water. This counters the observed effects in the majority of non-smokers. The paper supports that the investigators meticulously minimized experimental bias, but points out areas in which unknown possible confounding factors could have intervened.


This report looks at the potential economic ramifications of eliminating the industrial use of chlorine and chlorine compounds. The report calculates the cost of eliminating chlorine by determining the cost of substituting the best proven-through-use alternative technology. The report does not quantify the health benefits of such a substitution. This report was completed in response to the International Joint Commission's (IJC) recommendation to the U.S. and Canadian governments to enact a phase-out, or "sunset," of the use and generation of chlorine and chlorinated compounds. Ozonation, currently used in 1% of U.S. drinking water treatment facilities, was used as the replacement technology for drinking water chlorination. Including pre-treatment sedimentation, flocculation and filtration, and post-treatment flocculation and filtration, the estimated expense
of this treatment substitution in the United States is $3.5 billion/year for drinking water disinfection. The substitution of UV for chlorine in wastewater treatment (CRA's determination of the best available technology in wastewater treatment), brings the total to $6 billion/year. Replacement costs including all other industries are estimated at $11 billion/year. Furthermore, the report estimates that 39% of the nation's $4.5 trillion income ($1.6 trillion) is generated from chlorine-dependent industries. These industries also employ 36% of the nation's workforce. The report concludes that a chlorine phase-out would be detrimental to the nation's economy.


This report provides communication guidelines to assist governmental agencies in conveying public health risks to the public. The report was developed from information obtained from interviews with over 50 academic experts, industry representatives, citizen leaders, and agency staff members. The report summarizes the public's perceptions of different kinds of risks, and offers suggestions pertaining to timing and methods of releasing risk information. This report is intended as a very practical reference for regulatory authorities aspiring to interact effectively with the public on issues regarding public health risk.


This report surveys the status of the chlorine debate both in the U.S. and Europe, focusing primarily on its economic effects. The report gives little attention to drinking water, only mentioning that industry and the World Health Organization believe the health benefits of chlorination far outweigh the risks. The report also points out the need to standardize frequently-used terminology in the debate; according to the report, labels applied to hazardous organic compounds such as "toxicity", "bioaccumulation" and "persistence in the environment" are still vague.


This paper discusses the nature of biological and chemical risks from drinking water disinfection, as well as the nature and extent of support substantiating these risks to human health. Within the framework provided by this discussion, the paper looks at the probable risk tradeoffs resulting from using the EPA's current
approach to balancing these competing risks, and investigates the impact that regulations resulting from this strategy might have on the total risk. The paper concludes with a list of the Chlorine Institute's recommendations to the EPA's negotiations committee regarding their approach to the risk balance problem.


This statement advocates the use of chlorine in drinking water disinfection. The statement cites decreases in waterborne disease outbreak rates due to chlorination, and further points out that the majority of outbreaks occurring today occur where chlorination is not used or is conducted inappropriately. The statement also references two reports that exonerate chlorine as a plausible carcinogenic agent, conducted by the International Agency for Research on Cancer and the National Toxicity Program. The report challenges the concept of zero discharge as a target range for any disinfectant or disinfectant by-product.


This manual provides information on the chemical, physical, and biological properties of chlorine and some chlorinated compounds. It also details storage specifications, transport requirements, first-aid and emergency responses protocols for handling chlorine, and is intended to be a guide to chlorine use. The manual also provides a comprehensive list of references to other informational sources on chlorine.


This article presents a costs and benefits analysis of drinking water treatment, and establishes that the benefits of treatment exceed the costs. The article addresses the issue with a cost-per-life-saved analysis in addition to a net benefits approach, and shows that despite the "negative benefits" of trihalomethane production, the public health benefits of drinking water chlorination and chloramination outweigh the costs and negative benefits. Similar comparisons were made with the addition of GAC technology for the removal of organics, and the author concludes that the results support its application as "a socially desirable investment."


This article describes a cost and benefit analysis of drinking water treatment, and demonstrates that the benefits of drinking water disinfection and treatment far outweigh the corresponding costs. A monetary representation of disinfection benefits is calculated from: the probability of waterborne disease in the absence of treatment, a per-case cost associated with death and illness, and the attack rates for microorganisms. The article defines the analysis components and their variability, and establishes conservative estimates of a benefit to cost ratio for drinking water treatment. The analysis considers both poor and good source water quality, chlorination with and without additional treatment procedures (coagulation, flocculation, sedimentation and rapid filtration), and varying treatment population sizes. The benefit to cost ratio calculated in the article varies from 2.5 to over 50. The article also discusses the role played by the distribution system in protection against waterborne disease.


This article discusses options and estimates the associated costs for drinking water facilities to comply with the Surface Water Treatment Rule and the Disinfectant and Disinfection By-Product Rule. The article considers the following options for compliance: moving the point of disinfection in the treatment process, employing a different disinfectant, removing precursors prior to disinfection, and removing by-products after their formation. The article includes a brief cost and performance comparison for the options. When movement of the point-of-treatment is sufficient, it is likely to be the least expensive option, provided that disinfection feed capacity remains constant. Among the remaining alternatives, the article concludes that alternate disinfectant use is the lowest cost option. The most expensive treatment option is precursor removal, but this may be the most desirable choice considering its potential to achieve additional goals. The article suggests that DBP removal is the least desirable option.


This article outlines a method of studying and identifying the cause of teratogenic effects in wildlife, and of estimating the analogous risk to human health. In particular, the article concentrates on the effects observed in the Great Lakes Basin, where teratogenic effects are suspected of being caused by chlorinated-organic contamination. The article asserts that recognizing the endpoint effects of
a toxicant and identifying the exposure characteristics of affected parties are particularly difficult in teratogenic risk assessments. The author makes suggestions for overcoming these obstacles.

31. Committee on the Side Effects of Chlorination, Chlorination By-Products; Production and Control, AWWA Research Foundation, Niewegein (1986).

This report surveys a number of investigations of disinfectants and their disinfection by-products. The report comprises one the first comprehensive studies conducted in response to the discovery that disinfection by-products, such as trihalomethanes, are potentially harmful. The report differentiates between the carcinogenic, mutagenic, and acutely or chronically toxic effects of disinfectants, including chlorine, chlorine dioxide and chloramines, and their by-products.


This article emphasizes the need for more information on waterborne diseases. According to the report, not only is knowledge of the infective qualities of specific organisms insufficient, but there is little baseline information allowing the effectiveness of disinfection to be quantified. The article explains that the Information Collection Rule, promulgated in Feb. 1994, will require the collection of concentration data on the microorganism Cryptosporidium. In addition, a study is underway at the University of Texas that will supply information regarding infectivity rates of Cryptosporidium. Fact sheets for the EPA will be based upon this study.


This chapter describes the evolution of drinking water regulations, and emphasizes the gradual development of the philosophy and goals underlying the EPA's regulations. The chapter also describes how the procedures used to test substances, and the principles applied in drawing conclusions about results, have also changed. The author discusses technological and scientific assessment, public participation, and compliance monitoring in detail, and makes comparisons between regulatory development in the US and the European Community. In light of these discussions, the author asserts possible future trends in water quality regulation.

This paper describes an ecological, case-control study investigating the relationship between colon cancer incidence rates and drinking water chlorination. The study finds a strong positive correlation of elevated colon cancer with drinking water chlorination, accounting for such potential confounders as sex, age, genetics, diet, geographic region, urbanicity, smoking, alcohol consumption, education, and number of pregnancies. The relationship was found to be highly dependent upon age, but appears only in study participants over the age of 60.


This chapter explores the utility and limitations of epidemiological studies in their role as substantiation for chemical risk from disinfection by-products in drinking water disinfection. The author summarizes the types of epidemiological studies that may be performed, and discusses the characteristics of individual elements of each type of study and the circumstances under which different types of epidemiological studies are feasible or optimum. The chapter also describes other considerations that, in a thorough epidemiological study, are investigated during the interpretation of observations from a particular study. These discussions are carried out in this chapter within the context of epidemiological studies correlating drinking water chlorination with cancer incidence, and the potential biases and confounders that may be active in such studies are emphasized.


This article describes the general problem of balancing microbial and chemical risks in drinking water disinfection, and summarizes the present strategies currently undertaken to achieve this balance. The article briefly outlines the supporting evidence for each opposing risk, and overviews the microbial and chemical agents identified as or suspected of being responsible for introducing these risks. The authors conclude that although the potential carcinogenic threat from disinfection by-products must be addressed, any measures taken to this end must not
jeopardize the protection from the incontestably present microbial risk from waterborne pathogens.


This article provides an overview of epidemiological studies associating negative health effects with drinking water chlorination. The article defines the two kinds of epidemiological studies (cohort and case-control), describes the nature of conclusions that can be drawn from them, and warns against specific biases and misinterpretations that commonly arise with each. The article summarizes numerous studies, focusing primarily on cancer risks associated with drinking water chlorination. Studies investigating possible associations between chlorination and cardiovascular disease are also presented, as are studies exploring adverse reproductive effects from chlorination. Considering the inconsistency of the conclusions reached in the reviewed studies, the author concludes that new epidemiological and toxicological data must be obtained before a causal relationship can be established. Furthermore, the article states that current information is insufficient to merit abandoning chlorine as a drinking water disinfectant.


This document portrays the EPA's efforts to define a meaningful regulatory impact analysis for application to the National Primary Drinking Water Regulations (NPDWRs) that address the pathogen and disinfection by-product risk balancing issue. The document describes the uncertainties and technical complexities that complicate chemical and biological risk assessment, attempts to design a framework under which these complications are dealt during regulatory development, and investigates the manner in which the societal impact of different regulatory scenarios would vary. The document discusses at great length the use of the disinfectant by-product regulatory analysis model (DBPRAM), and explains its treatment of uncertainties and its subsequent limitations. The resulting microbial and DBP risks under different treatment alternatives with specified source conditions are explored to a limited extent. The document concentrates on defining the 'core problem' that governs the risk trade-offs arising from different drinking water treatment scenarios.

This article summarizes the available information regarding disinfection by-product (DBP) exposure in the U.S. The article lists and briefly describes a number of drinking water surveys conducted through 1991, and expounds on the information collected in two particularly relevant studies conducted by the American Water Works Association Research Foundation and the EPA. The article's summary of the information from these surveys indicates that the nation's exposure to DBPs comprises approximately 50% (by weight) from trihalomethanes, 25% from haloacetic acids, 7% from aldehydes, and 5% from haloacetamides. This distribution shifts from chlorinated toward brominated compounds when bromide is present in source water. The article examines the by-product formation accompanying chemical disinfectants including chlorine, chloramines, chlorine dioxide, ozone, as well as biological and physical disinfection processes. The authors also briefly describe options for minimizing disinfection by-products.


This chapter of Jolley's book introduces the presence of uncertainty in the maintenance of drinking water treatment that result from essentially four general research needs: (1) the development of better methods of disinfection by-product detection and analysis, (2) the minimization of chlorination to realistic rates for high-use waters, (3) the anticipation of the potential to produce chlorine-resistant pathogens, and (4) the examination of disinfection alternatives. The authors emphasize the need for designing a large-scale, conceptual plan of attack on these uncertainties through an open dialogue among stakeholders in this issue.


This chapter explores the different forms of uncertainty that accompany any planning problem. The author classifies two categories of uncertainties, those resulting from limited information, and those arising from unpredictability. Sources of the latter category of uncertainties include the presence of stochastic processes, a lack of understanding of relevant natural and technological processes, and economic and political conditions. The chapter discusses the nature and
significance of these uncertainties, and adapts a "descriptive approach" to addressing uncertainty in cost-benefit analyses.

42. deFur, Peter L., Problems with Chlorination, Health and Environment Digest, Vol. 8, No. 2, pp. 11-13 (1994).

This article focuses on the negative aspects of chlorine and chlorinated compounds, but does not suggest a complete ban of these chemicals. Instead, the article emphasizes the reverse onus principle, placing responsibility on industry to sufficiently prove a chemical is not harmful before releasing it to the environment.


These reports were provided by Sadie Willoughby, the Information Systems Manager at the Office of Hazardous Materials Planning and Analysis at the DOT. The reports include chlorine transport incidents from 1971 to the present, including both truck and rail transport. Sodium hypochlorite incidents are also included starting in 1990 (the number of reports was too great to include reports extending back to 1971). The reports support the conclusions that significantly more incidents occur with sodium hypochlorite than with chlorine, but that these incidents are much less severe than chlorine incidents. Intrastate incidents are not required to be reported (though many are), so the data in this area are not comprehensive.


This article presents the regulatory analog to balancing biological and chemical risks in drinking water disinfection: simultaneously satisfying the microbial concentration requirements of the Safe Drinking Water Treatment Rule and the chemical limits imposed by the disinfection by-products (DBPs) regulations. The article discusses the effects of various disinfectants, and discusses methods for detecting trihalomethane (THM) precursors in source water bodies, in order to determine the THM formation potential (THMFP). The THMFP can be used to indicate whether chlorine alternatives should be considered.


This article describes the proceedings of a conference sponsored jointly by the EPA and the American Water Works Association Research Foundation in order to set national priorities in the risk assessment of drinking water disinfection [see
AWWA, Drinking Water and Health in the Year 2000 reference above]. The conference generated suggestions to develop a systematic biological risk assessment method, to create a national database on inorganic chemicals and where they are found, and to form a risk analysis procedure that encompasses not only scientific information, but also value judgments regarding the inherent trade-offs in a dual risk situation. The article asserts that the final suggestion might be accomplished by employing principles of the social sciences [see Putnam and Graham reference below].


This article assesses the benefits and costs of the proposed Disinfectant/Disinfectant By-Product (D/DBP) rule. According to the article, the rule would provide increased control over negative effects of D/DBPs, reduction of exposure to D/DBPs by 20% to 30%, a decrease in outbreaks of disease induced by microbial contaminants, and regulation of Cryptosporidium. Furthermore, the accompanying Enhanced Surface Water Treatment Rule would reduce organics that can combine with disinfectants to form DBPs. The costs are estimated at $1 billion/year, resulting in 50% of households experiencing no added costs, 49% incurring less that $2/ month in added costs, and 1% of households paying at least $16/month for improvements. Costs for the enhanced surface water treatment would be in the neighborhood of $20 per year, per household.


This report surveys the proposed new standards for disinfectants and disinfection by-products, and details the types of monitoring, reporting, and public notification that are required under the Information Collection Rule. The report explains the justification and reasoning behind the formation of new maximum residual disinfectant levels (MRDLs), maximum contaminant levels (MCLs) and national primary drinking water regulations (NPDWRs). This report also describes the motivations, goals, and strategies employed by the EPA in its efforts to establish new drinking water treatment regulations, and presents the remaining concerns of legislators. The report also cites results of toxicological and epidemiological studies to support the transient conclusions drawn in this document. Proposals for future regulatory adaptations are also presented.

This document introduces three new rules proposed by the EPA's representative negotiations committee. These rules include: (1) The Information Collection Rule, which requires treatment systems over a specified size to report data on disinfectants, disinfectant by-products, and microorganisms, (2) The Interim Enhanced Surface Water Treatment Rule, which introduces new regulations to ensure protection from pathogens, specifically *Giardia* and *Cryptosporidium*, with the implementation of the D/DBP Rule, and (3) The Disinfectants/Disinfectant Byproducts (D/DBP) Rule, which (a) stipulates new maximum contaminant levels (MCLs) for previously unregulated by-products (plus lower MCLs for trihalomethanes), (b) prescribes new maximum residual disinfectant levels (MRDLs), (c) requires enhanced coagulation and softening in appropriate systems, and (d) requires compliance in all treatment systems, including smaller operations. The latter two rules will be updated in 1997, pending the results of the first rule.


This document presents the EPA's strategy in balancing the biological and chemical risks in drinking water disinfection. The EPA constructed a negotiating team in November of 1992, composed of members of consumer groups, environmentalist organizations, public water utilities, health agencies, and academia, as well as elected government officials. The committee established a plan emphasizing the need for further information, interim controls until more information is collected, and the intent to use the collected information to form improved regulations in the future. These ideas formed the basis for three new rules promulgated by the EPA.


This document describes the procedures and standards employed by the EPA for risk assessment of carcinogenic chemicals. It is one of five sets of guidelines developed by the EPA to standardize procedures, and to minimize the inconsistency of EPA decisions. These guidelines provide a four step risk assessment format consistent with the National Research Council's four component description of risk assessment. These components include hazard identification, dose-response relationship, exposure assessment, and risk characterization. The guidelines emphasize the importance of quantifying uncertainty in each risk assessment step. This document is not intended to furnish a comprehensive review of carcinogenic testing methods, but instead to provide an outline of the logical process by which carcinogens are identified.

This document details the EPA's guidelines for conducting risk assessment of mutagens. It is one of five sets of guidelines developed by the EPA to standardize procedures, and to minimize the inconsistency of the EPA's decisions. The guideline format follows that of the carcinogenic guidelines [see above]. EPA's recommendations for mutagenic risk assessment differ from those of carcinogenic risk assessment primarily in the hazard identification step. The guidelines isolate the determination of mutagenic activity and the establishment of chemical interactions in the mammalian gonad, as the dominant factors in mutagen identification. The document does not describe mutagenic mechanisms or tests for determining mutagenic activity, but explores the underlying rationale for choosing various testing methods.


This document describes the procedures and standards employed by the EPA for risk assessment of chemical mixtures. It is one of five sets of guidelines developed by the EPA to standardize procedures, and to minimize the inconsistency of the EPA's decisions. The guideline format follows that of the carcinogenic guidelines [see above]. The document characterizes the complications of predicting chemical mixture behavior, and offers approaches to problems associated with chemical mixtures. These guidelines apply to mixtures specified as combinations of two or more chemical substances, regardless of their sources or their spatial and temporal proximity. The document stresses the critical role of assumptions and limitations in chemical mixture risk assessment. Mathematical treatment methods for mixture data analysis are also suggested in this document.


This document describes the procedures and standards employed by the EPA for risk assessment of potential developmental toxicants. It is one of five sets of guidelines developed by the EPA to standardize procedures, and to minimize the inconsistency of the EPA's decisions. The guideline format follows that of the carcinogenic guidelines [see above]. Successful hazard identification of developmental toxicants is complicated by the plethora of potential endpoints, such as spontaneous abortions, stillbirths, malformations, early postnatal mortality, low
birth weight, etc. These guidelines propose methods of establishing cause and effect relationships in the presence of multiple endpoints.


This document describes the procedures and standards employed by the EPA to establish human exposure to chemical sources. It is one of five sets of guidelines developed by the EPA to standardize procedures, and to minimize the inconsistency of the EPA's decisions. The document proposes a series of questions designed to facilitate the identification of exposure sources and pathways, affected populations, and chemical exposure concentrations. Potential uncertainties in collected data and in the assumptions used for analysis are reviewed.


This proposed rule establishes Recommended Maximum Contaminant Levels (RMCLs, equivalent to currently used Maximum Contaminant Level Goals (MCLGs)) for synthetic organic chemicals and inorganic chemicals. The rule also establishes microbial parameters determined to provide sufficient protection against waterborne pathogens. The rule, mandated by the Safe Drinking Water Act (SDWA), sets a precedent for subsequent National Primary Drinking Water Regulations, and describes the calculation of Acceptable Daily Intakes (ADIs, equivalent to currently used Reference Doses (RfDs)), as well as the treatment of scientific uncertainties with the application of Uncertainty Factors (equivalent to currently used Safety Factors).


This document describes the EPA's proposed "Information Collection Rule (ICR)," under which water treatment facilities must collect data indicating source water quality, treatment procedures, and post-treatment water quality. The document is one of three rules developed by the EPA's Negotiating Committee as part of a two-phase plan to improve drinking water treatment regulations. This rule strives to develop a more solid data base for use during the second phase of regulations. The document fully details the information requirements and the methods deemed acceptable for data collection and analysis. The following ICR goals are expressed and elaborated upon in the document: (1) to identify relationships between various

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pathogens to pinpoint good indicator species, (2) to determine the removal efficiency of various treatment alternatives, (3) to establish relationships between the nature of source waters and treatment procedures, (4) to identify source water characteristics that influence disinfection by-product (DBP) formation, (5) to determine DBP formation with different treatment techniques, (6) to create accurate models for DBP formation, and, (7) to establish more effective monitoring techniques.


This article is a short synopsis of the EPA's present two-step plan to create new disinfectant and disinfectant by-product regulations. Statistics supporting the harmful effects of chlorinated organics are presented, but without specific reference [statistics appear to come from Morris' study].


This report outlines recommendations made to the EPA by the Scientific Advisory Board (SAB) toward devising a successful risk-reduction strategy. The report, constructed by the SAB's Relative Risk Reduction Strategies Committee (RRRSC), is a follow-up to the EPA's 1987 report, Unfinished Business (UB). UB was the first comprehensive comparative risk initiative taken by the EPA, and revealed the problem that regulatory prioritization corresponded to public opinion rather than to relative risks. The SAB report addresses the problem, and presents the consolidated recommendations of three subcommittees of the RRRSC. These subcommittees focus on ecology and welfare risks, human health risks, and strategic options for reducing risk. Detailed conclusions of each subcommittee are enumerated in Appendices A-C of this report. The RRRSC recommendations consider issues such as public perception of risk, optional risk-reducing tools (e.g., marketing incentives, regulatory enforcement measures), links between risk and choice, the value of the ecosystem, the role of the environment in policy decisions in other fields, and the spatial and temporal variations of risks. The RRRSC identifies research areas that would contribute information leading to minimized uncertainties. The report also includes drinking water pollutants in its list of highest potential human health risks.


This report summarizes the conclusions determined by the Ecology and Welfare Subcommittee (EWS) under the Relative Risk Reduction Strategies Committee (RRRSC). The Scientific Advisory Board (SAB) formed this subcommittee to
evaluate the conclusions of the EPA's 1987 report, Unfinished Business, regarding ecological and welfare risks. The EWS also evaluated the risk-assessment methodology employed to reach these conclusions. The EWS introduces a formalized process of ecological risk assessment in an effort to establish a firm database for future risk-based ecological decision-making. The report also proposes new parameters by which welfare impact can be assessed. These parameters include: ecological quality (addressing indirect impacts of environmental degeneration on humans), resource sustainability (looking at irreversible environmental effects such as biological depletion), direct economic effects, and direct non-economic effects (including human annoyances such as odor or noise). The report approaches welfare analysis with three of these parameters, excluding direct economic effects because of data limitations.


This report summarizes the conclusions of the Human Health Subcommittee (HHS) under the Relative Risk Reduction Strategies Committee (RRRSC). The Scientific Advisory Board (SAB) formed this subcommittee to evaluate the conclusions of the EPA's 1987 report, Unfinished Business, regarding environmental health risks. Additionally, the HHS evaluated the risk-assessment methodology employed by the EPA to obtain these conclusions. The HHS was also expected to develop an aggregate ranking of cancer and non-cancer health risks. Although the subcommittee developed two frameworks for this merging, members of the HHS judged that such a ranking was not yet appropriate owing to data deficiencies. The HHS ranks drinking water as a "moderate" carcinogenic risk, and estimates that it is responsible for 400-1000 cancer cases annually in the US (primarily caused by radon and trihalomethanes). The HHS ranks drinking water as a "high" non-cancer health risk, considering the potential threats of various illnesses caused by microbial pathogens, disinfectant by-products, nitrates, and lead. The report discusses the uncertainty surrounding risk assessment in both cancer and non-cancer risks, and recommends further research to reduce uncertainty.


This report summarizes the conclusion of the Strategic Options Subcommittee (SOS) under the Relative Risk Reduction Strategies Committee (RRRSC). The Scientific Advisory Board (SAB) formed this subcommittee to evaluate the conclusions of the EPA's 1987 report, Unfinished Business, regarding agency strategies to minimize risk through regulation. The committee recommendations to the EPA include: making pollution prevention the primary method of long-term risk reduction, providing economic incentives to the public for reducing risk,
creating a specialized governmental mechanism in the Executive Branch (such as an Environmental Policy Council or reviving the Cabinet Council on the Environment or the Council on Environmental Quality) and making the EPA responsible for developing enhanced education and training programs for both professionals and the general public. The report also reviews present regulatory strategies and identifies current system inadequacies.


This extended abstract describes a project to generate a probability distribution of risk. The project employs uncertainty analysis and expert judgment to design a probability tree that will openly express the scientific uncertainties that underlie risk evaluation. The demonstration project outlined in this abstract addresses the potential carcinogenicity of chloroform, and accounts for the scientific uncertainties of the human target organ, mode of carcinogenic action, dose scale, dose-response curve, appropriateness of animal data sets, and relative average sensitivity of humans and animals. The use of expert judgments additionally incorporates the uncertainties arising from scientific disagreement. The abstract explains how the probability tree will be created through expert analysis, and discusses advantages specific to the resulting representation of uncertainty in arriving at a distributional estimate of risk.


This article describes how chlorination became the primary control for waterborne microbial risks in the U.S., and concentrates on the present concern regarding the potential negative health effects of chlorine's disinfection by-products (DBPs). The authors discuss evidence supporting the carcinogenicity of chlorination by-products, and refer primarily to Dr. Robert Morris' meta-analysis [see Morris, et al. below]. The article identifies the need to precisely define acceptable levels of risk, and explores the role of risk assessment in meeting these levels of acceptability for competing disinfection risks.

This article addresses the controversy over the grouping of chlorinated organic compounds. The article points out that chlorinated compounds used in the pharmaceutical industry exhibit different biological behavior depending upon their individual chemical structure, not upon their common characteristic, the presence of chlorine. The author suggests that based on this idea, the investigation of chlorinated compounds is feasible by grouping according to chemical structure and attached functional groups, and that this ought to be pursued rather than passing a blanket judgment on all chlorinated compounds.


This report details an epidemiological study conducted in Norway to determine the correlations between water chlorination and various forms of cancer. The author stresses that confounding variables were difficult to minimize in this study. Furthermore, he emphasizes the importance of recognizing the differences in pretreatment water conditions between countries before applying the study results. Mild correlations between chlorination and both colorectal and breast cancer were established. No significant correlations were established for other forms of cancer, and the overall cancer-associated mortality rates, which included colorectal and breast cancer occurrences, were approximately the same for chlorinated and non-chlorinated waters. The study included partly-chlorinated systems in an attempt to establish dose-response relationships.


This article discusses toxicological studies conducted in the Great Lakes Basin, and describes how to determine the carcinogenic risk incurred from the consumption of contaminated Great Lakes fish. The article focuses on the calculation of parameters indicating exposure and risk levels, which can be used indirectly in determining water quality standards.


This article describes modifications made to the World Health Organization (WHO) Guidelines for Drinking Water Quality, which was scheduled to be published in 1993. The article explains the new goals and priorities set by the WHO, the motivations underlying the issue prioritization in the guidelines, and the goals of the guidelines. The article also briefly presents a comparison of microbial and chemical risks and stresses the conclusion of a previous evaluation by WHO
International Agency for Research on Cancer, that biological risks greatly surpass those presented by disinfection by-products. The article emphasizes how the new guidelines differ from those issued in 1984.


This article surveys research procedures used in establishing the risk to human health from drinking water disinfection. The article discusses the formation of biologically-based exposure-response models for disinfectant byproducts, and the extrapolation of these models to different species. Inter-species extrapolation demands that several points be addressed: (1) the metabolic processes of each species compared must be parallel to ensure similar by-products generation, (2) the means by which a chemical introduces its toxicity must be established as the same, and (3) the likelihood of in vivo by-product generation when chlorinated water encounters foodstuffs in humans must be considered, adding not only the complication of unknown by-products, but also presenting further difficulty to determining the amount of oxidant reaching the bloodstream in people.


This article discusses ways of minimizing the production of chlorate, a disinfection by-product, when it is generated by sodium hypochlorite. Although chlorate is typically associated with chlorine dioxide disinfection, it has also appeared as a by-product of hypochlorite disinfection. Chlorate generated by sodium hypochlorite forms during pre-treatment storage, whereas chlorate generated by chlorine dioxide appears during disinfection reactions. Modifications to storage procedures, such as lowering storage temperature and diluting sodium hypochlorite, stabilize the hypochlorite solution, and therefore reduce chlorate formation.


This paper describes the intricacies of the redox reactions taking place during disinfection with various oxidants, and aims to elucidate the mechanisms that might interfere with the expected reactions. This presentation is followed by descriptions
of different methods used to detect the presence of disinfectant residual and by-products after treatment with chlorine, chloramines, chlorine dioxide, and ozone.


This article illustrates the relative risk of cancer introduced by various environmental agents, and identifies those within the EPA's jurisdiction. The article tabulates estimates of cancer mortality risks from various exposures with the calculation methods of the EPA and the FDA. The article discusses the degree to which risks from various agents could potentially be affected by EPA regulation. The article lists the total cancer mortalities arising from drinking water exposure to be between 240 and 591 cases annually, which includes 161 cases from trihalomethanes and 60 cases from other organic sources. The article concludes that if the EPA were completely successful in regulating all carcinogenic potential under its jurisdiction, the total annual cancer deaths would only decrease by 1.3%.


This chapter investigates the relationship between environmental regulatory development and the science upon which it is based, as well as the scientific and value judgments that must be employed judiciously where science provides insufficient guidance for regulatory development. The chapter traces the evolution of the regulatory development system as it exists today, emphasizing the roles of Congress, the EPA, particular Presidential Administrations, and organizations such as the Scientific Advisory Board (SAB), the Chemical Industry Institute of Toxicology (CIIT), and the Health Effects Institute (HEI) (these organizations are discussed at length in subsequent chapters of the book). This chapter specifically discusses how uncertainty has played a role in this evolution.


This article describes reactions from Rick Hind, the legislative director of Greenpeace, and Brad Leinhart, the director of the Chlorine Chemistry Council, to the International Joint Commission's (IJC's) seventh biennial report. The biennial report reiterates (after the 1992 report) the IJC's support of a chlorine phase-out. Hind touts the report as "one of the most important statements ever made," while Leinhart holds that the philosophy backing the report "is not a sound-scientific approach to decision-making" with respect to chemical use.

This educational flyer, distributed by Greenpeace, explains the health hazards of chlorine and chlorinated compounds, and calls for phasing out the use of all chlorine-containing chemicals. The document discusses the unnatural creation of chlorine gas, the synthetic production of other chlorinated compounds, and describes the use of these materials in industry. Greenpeace suggests alternatives for many uses of chlorine, including water treatment, but does not discuss potential problems associated with switching to the alternatives. Greenpeace also asserts that phasing out chlorine will save money, and create more jobs in the U.S.


This article discusses House Representatives Bill Richardson's and Henry Waxman's proposed bill that would ban the discharge of organochlorines produced by the pulp and paper industry. Alternatives to the use of chlorine in bleaching, such as the use of oxygen and hydrogen peroxide, are presented with their advantages.


This report refutes the claims of the International Joint Commission and Greenpeace that organohalogen compounds are only synthetic, and therefore inherently harmful to the environment and its inhabitants (owing to a lack of natural means to defend against them). This report examines the natural occurrence of over 1500 chlorinated organic compounds (COCs). The report discusses examples of these compounds, the means through which they are generated, and explanations for the natural generation of toxic COCs.


This article explores how countries at different levels of development respond to the threat of toxicological risks from disinfection. Wealthier countries, such as the U.S. and Canada, respond by researching alternatives that often result in higher water treatment costs. Less developed countries, such as those in Latin America or the Caribbean, respond by abandoning disinfection. The article compares waterborne disease outbreaks in Latin America to those of the U.S. It suggests that, in light of the drastically greater number of pathogen-associated deaths, the
benefits achieved through disinfection in less developed countries greatly outweigh the negative effects of added toxicological risk. The article elaborates on this scenario, and derives an approach to decision-making for financially limited countries unable to implement more expensive means of reducing the smaller risks associated with disinfection by-products.


This article describes a process used to estimate the microbiological risk from waterborne pathogens in drinking water. The method is analogous to procedures employed to quantify risks from chemical contaminants, and is capable of yielding both point and interval risk representations. The article details each step of the procedure, including dose-response assessment, exposure assessment, and risk characterization. Both point estimates and interval estimates are determined in the article, and are compared with epidemiological data. In light of uncertainty and limited data availability, the comparison of microbiological risk quantification to epidemiological observations indicates that microbiological risk estimation is a valid procedure, and will be enhanced as further information is obtained on occurrence and dose-response characteristics of prominent pathogens.


This article describes the development and the limitations of a computer model simulating disinfection by-product (DBP) formation under treatment conditions representative of the average U.S. drinking water treatment facility. The article highlights portions of the model simulating total trihalomethane formation, total organic carbon removal, removal of substances absorbing ultraviolet light at 254 nm, and pH changes. The article presents data base sets used during the formation of the model, and discusses the formulation of equations upon which the model is built. Comparisons between model results and observed data are presented, and research areas that would facilitate improvements to the model are identified. The model is currently being used to estimate national distributions of DBP and pathogen exposure concentrations under various regulatory scenarios in order to assist the EPA in comparing the costs and public health risks of regulatory alternatives [see Regli, et al. reference below].

This paper addresses the question of timing in administering environmental regulations. The author identifies two principal issues that underlie the commonly made decision to wait for more information before regulating: the irreversibility of policy implementation, and the potentially synergistic relationship between regulation and research. The paper highlights these issues, discusses counterproductive effects that often arise from delaying regulation, and explores the potential benefits of regulating more immediately in the face of persistent uncertainty. The paper presents past experiences to illustrate the points it develops.


This article establishes the inadequacy of current microbial monitoring techniques, and suggests an alternative approach in which monitoring occurs throughout the treatment system. The suggested monitoring method is modeled after the food industry's recently adopted protection system, the Hazard Analysis Critical Control Point (HACCP) system. The article also discusses and defends direct measurement of pathogens to gain behavioral information on "aftergrowth pathogens" present in the distribution system. The article details monitoring criteria for determining concentrations of microbials in drinking water, and subsequently compares the abilities of different pathogen detection methods to meet the specified criteria.


This article is a report following a Finnish study, released August 18, 1994, in which chlorination was determined to present an elevated risk factor of between 1.2 and 1.4 for kidney cancer, and 1.2 for bladder cancer. The article points out that potential confounding variables such as smoking and poor diet were not accounted for in this study. The article concludes that this study further supports the negative health effects from chlorination by-products.


This article discusses an industrial effort to strengthen the pro-chlorine argument with scientific backing. The article introduces the "CanTox report" [see Willes, et
al. below), sponsored by the Chlorine Institute and the Chlorine Chemical Council, as a strong industrial effort to establish scientific support for the chemical industry's position on chlorine use. This article summarizes the conclusions of the CanTox report, and presents the reactions of various groups involved in the debate, to its release.


This article cites several studies in which chlorine and organic chlorinated compounds are suspected of causing adverse health effects. The article focuses on the ecological studies in the Great Lakes Basin, which possibly implicate chlorinated compounds in observed reproductive abnormalities, tumor growths, and behavioral changes. Experimental observations of organohalogenes in other studies indicate that they are capable of producing these effects, casting further suspicion on chlorinated organics. The article also provides a timeline of the chlorine ban evolution.


This article surveys studies linking organochlorides to the onset of health risks to the environment and human population. Several chlorinated organics, such as DDT and some PCBs, are capable of attaching to estrogen receptors in the body. In this position, as "estrogen mimics," they either perform the function of estrogen or inhibit estrogen-initiated processes. Estrogen mimics are often bioaccumulative, and are capable of crossing the placental barrier, interfering with fetus development. They are also suspected of causing reproductive abnormalities, feminization in men, decreased sperm counts, testicular cancer, and breast cancer. Although other causes of these effects exist, research indicates that chlorinated estrogen mimics are the most likely suspects.

86. Hirl, J. Roger, Why Society's Access to Chlorine Chemistry Must Be Protected, speech to National Chemical Credit Association, April 7, 1994.

This speech, given by the president and CEO of Occidental Chemical Corporation, represents the chlorine industry's position in the chlorine ban debate. The speaker offers a history of the opposition to chlorine, and focuses on the point at which the government joined in this opposition. To support this, the speaker refers to the EPA's and the Clinton Administration's proposal of a Clean Water Act amendment that would strive to limit national chlorine usage. The speech discusses the lack of scientific foundation underlying this proposal. The speaker cites the events surrounding Alar as a case where sound scientific reasoning was unable to
overpower public fears resulting from a calculated campaign against Alar. The speech offers two recommendations: (1) that the evaluation of a given chemical be based upon sound scientific principles, include the risk-benefit assessments to society, and consider the availability of chemical substitutes, and (2) that the EPA involve all potentially affected parties in the making of regulatory decisions.


This article provides a brief overview of the drinking water priorities established by the Centers for Disease Control and Prevention, and enumerates the infectious disease issues addressed by these priorities. The article also summarizes recent national surveillance data pertaining to waterborne disease outbreaks. Issues considered in the article include: (1) maintaining and improving waterborne disease outbreak surveillance, (2) developing new diagnostic techniques to identify etiological agents, (3) devising new treatment strategies for chlorine-resistant organisms in drinking water, and, (4) addressing the increased vulnerability of a population with a growing number of immunocompromised members. The article warns that the recent decline in reported waterborne disease outbreaks may actually be due to decreased surveillance efforts, and that the need to maintain observational efforts is demonstrated through the unpredictability of measured epidemiological patterns.


This report announces the International Joint Commission's (IJC's) recommendation that the industrial use and generation of chlorine and chlorinated-compounds be eliminated. The IJC wants the United States and Canada to meet the zero discharge goals specified in the Great Lakes Water Quality Agreement. After witnessing failed government attempts to monitor and control hazardous releases, the IJC proposed that the avoidance of hazardous chemicals is the only fail-safe means of preventing hazardous release. The IJC has determined that at least half of the over 300 contaminants detected in the Great Lakes Basin are chlorinated compounds. Consequently, the IJC advocates the phase-out, or "sunsetting," of chlorine use and generation. Water chlorination is deemed acceptable only until less harmful alternatives are determined. A public response section of the report expresses a concern that a chlorine phase-out might result in decreased drinking water quality.

The International Joint Commission (IJC) reiterates their earlier call for the "sunsetting" of chlorine chemistry, but now also emphasizes the need for altering the strategy of chemical risk assessment. The strongest recommendation made by the IJC in this report is to place the burden of proof on industry to demonstrate non-toxicity of chemicals before using them (reverse onus). The IJC also suggests the maintenance of better communications between industry and environmental protection groups such as the IJC, and the immediate phase-out of PCBs and DDT. As in the previous report, the IJC accepts drinking water chlorination only until sufficient disinfectant alternatives are found.


This section of Jolley's book on water chlorination examines studies linking drinking water chlorination with adverse health effects experienced by humans and the ecosystem. In particular, the section looks at studies on the following subjects: bladder cancer in humans, colon cancer in humans, reactions between chlorine and humic acids taking place in drinking water, and reactions that occur in the presence of hypochlorite and N-chloramines taking place in stomach fluid.


Section IV of Jolley's book on water chlorination investigates the carcinogenic, mutagenic, teratogenic, and pharmacokinetic effects of various disinfectants and their disinfection byproducts. The book describes effects arising both from disinfection byproducts, formed in the drinking water, as well as from substances formed in vivo, post-consumption. The section also discusses laboratory animal testing and techniques for extrapolating animal test observations to humans.


This article describes a computer model, the Risk Assistant, designed to estimate the degree of human exposure to a contaminant. The program allows the environment under investigation to be described through various parameters, calculates the degree of exposure and compares it to exposure limits.
corresponding to EPA standards. The program can be used to assess health risks in water disinfection, air dispersion, or skin exposure.

93. **Kirschner, Elisabeth, Chlorine: Can We Live With It, Can We Live Without It?**, *Chemical Week*, November 3 Issue, p. 31 (1993).

This article presents highlights from a debate between Brad Leinhart, director of the Chlorine Chemistry Council (CCC), and Joe Thornton, a Greenpeace toxicology researcher leading the anti-chlorine campaign. Leinhart emphasizes the need to balance the benefits of chlorine chemistry with the risks, and to apply the same kind of scrutiny when examining alternatives to chlorine. Furthermore, he points out that socioeconomic considerations must be taken into account. Thornton responds by pointing out that the economy's dependency on chlorine is unhealthy, and further asserts that the elimination of chlorine elimination would result in great savings to currently chlorine-dependent industries. He cites examples where the replacement of chlorinated products, such as PVC, has been easily achieved and resulted in savings. Thornton also expresses concern that waiting for chlorine to be "proven guilty" may cause more serious negative effects to arise.


This article discusses the Clinton Administration's position toward chlorine, as expressed in the Clean Water Act Initiative (CWAI). Although the CWAI does not include a chlorine ban, the Administration supports the use of chlorine alternatives where possible. The author points out that the easy replacements have already been made, and that those alternatives not already implemented may be economically or scientifically unfeasible.


This article provides a comprehensive introduction to the basic principles of toxicology, especially in the ability to quantify human health risk. The article describes toxicological procedures, the assumptions that accompany various procedures, and their particular utility and application to risk assessment. Among the specific areas discussed are: (1) distinctions and relationships between descriptive, (2) mechanistic and regulatory toxicology, (3) pharmacokinetic and toxicity studies, (4) experimental toxicity testing, negative health effects caused by toxicants, (5) dose-response relationships, (6) threshold concentrations versus the
one-hit theory, (7) risk quantification, and, (8) the uncertainties inherent to toxicology. The article describes toxicology's role in the risk quantification process as employed by regulatory agencies in the U.S.


This book explores the role of uncertainty in policy-making pertaining to public and environmental health. It addresses different kinds of scientific uncertainty present in the risk assessment process and the relative influence in different policy decisions these varied uncertainties can have. The concepts introduced throughout the book are applied and analyzed through a case-study approach, examining the specific effects of uncertainty that have taken place in regulatory history. The book also investigates the public's exposure to uncertainty issues, and the influence of uncertainty on interactions between the public and policy agencies, specifically on reaching consensus or "bargaining" among them.


This chapter examines the chemical risks associated with chlorine, chlorine dioxide, and ozone disinfection, and the associated disinfectant by-products. The chapter also discusses biological risks, and refers to outbreaks of waterborne disease that occurred recently in the Netherlands. The author favors the use of chlorine dioxide and ozone over chlorine, but maintains that information is too incomplete to be conclusive.


This article evaluates the relationships among *Giardia*, *Cryptosporidium*, turbidity and particle count in both raw and filtered water samples. The article summarizes the results of a case study that measures cyst and oocyst concentrations at three sites employing different treatment regimes. It compares the efficiency of treatment techniques for removing *Giardia* in particular, and identifies the best indicators of cyst and oocyst removal. The article outlines the study procedures, graphically presents measurement data, and presents conclusions regarding concentration variations, correlations, and organism viability. Recommendations are provided pertaining to sampling strategy, measurement indices, turbidity and particle count variability, and areas of further research.

This paper examines some of the mores and values underlying decisions that form environmental policies. The author recognizes that determining a common rate of exchange with which to compare different benefits and costs is among the leading problems facing environmental policy-makers. The paper describes approaches to this problem, focusing primarily on discounting for consequences predicted to occur in the future. This issue provides a springboard for a subsequent discussion of the basic, cultural values underlying this notion. The paper concludes that the values underlying different environmental policy decisions must be acknowledged to adequately represent viewpoints common to members of the affected population.


This paper presents the EPA's strategy and rationale concerning the use of biological risk assessment to support the US National Primary Drinking Water Regulations' (NPDWRs) development. The paper discusses the goals and underlying assumptions directing decision-making regarding biological and chemical risks in drinking water regulation. Contrasting characteristics of these risks are also emphasized as they affect the quantification of each risk. The EPA takes a modeling approach to estimating the level of both chemical and microbial risk under specified circumstances, and the manner in which the EPA addresses risk quantification of uncertainty during modeling is also considered. The paper also investigates the specification of acceptable human health risk, and, in light of acceptable risk limits, the policy implications of complications to balancing the competing biological and chemical risks.


This article explains the Information Collection Rule (ICR) proposed by the EPA. The article describes the current state of water treatment knowledge, and identifies the areas of greatest uncertainty in this knowledge. The article also surveys acceptable monitoring methods, and specifies the extent of the ICR's application. The author points out that the EPA will play an active role in the collection of information for future regulatory changes by directly applying this rule, rather than working only through the state governments.

This paper discusses the factors that define safe drinking water and acceptable microbial risk in drinking water, and surveys the aptitude of the EPA's current regulatory approach to maintain standards within the limits of acceptability. The paper stresses that while focus is being drawn to reducing chemical risks from disinfection by-products, there is insufficient discussion regarding levels of acceptability of microbial risks. Furthermore, considering specific uncertainties surrounding dose-response curves and sensitive subpopulations, the level of microbial risk in treated drinking water may still be greater than chemical risks introduced by disinfection by-products. The paper explores the regulatory implications of these considerations, and introduces several questions to aid in the determination of acceptable drinking water risks in a given social and economic environment.


This article offers detailed information about the ozonation process, and its use in wastewater treatment. The oxidation strength of ozone surpasses that of other known disinfectants, making ozone a powerful tool in wastewater disinfection. However, its use in other advanced oxidation processes (AOPs), such as with UV or hydrogen peroxide, provides even greater strength. The article describes other uses of ozone, and presents ozone's disadvantages, such as its cost and its non-selective oxidation.


This article announces the proposal of the Disinfectant/Disinfection By-Product (D/DBP) Rule and the Enhanced Surface Water Treatment Rule. The article estimates the impact of these rules on treatment facilities of various sizes, and anticipates the increased costs to consumers and treatment facilities. These rules require surface water filtration prior to water treatment (specifically to protect against Cryptosporidium), decrease the maximum contaminant levels (MCLs) for total trihalomethanes from 100 to 80 micrograms per liter, and stipulate new MCLs for six previously unregulated DBPs.

This paper describes a case-control study exploring the relationship between elevated bladder cancer incidence and drinking water chlorination and chloramination from surface water sources. The study accounts for the potential confounding effects of cigarette smoking, coffee drinking, and family medical history. The study determines a positive correlation between drinking water chlorination and bladder cancer that increases with exposure, and determines odds ratios less than unity for chloramination (the authors caution against concluding that this implies a protective effect; it is more likely an artifact of the replacement of chloraminated water with chlorinated water in the study region). The paper discusses the results of this study in the context of previous study results, and explores possible study limitations and biases.


This article documents a brief overview of current knowledge regarding Cryptosporidiosis and how drinking water facilities can protect against it. The article discusses the characteristics of the responsible pathogen, *Cryptosporidium*, present in all surface water sources and in approximately 25% of all filtered water in the U.S., and describes the water quality limits that are known to allow the microorganism to thrive (turbidity counts as low as 0.1 ntu). The author provides recommendations to drinking water treatment utilities regarding monitoring, public communication, and procedural changes to reduce the risk from *Cryptosporidium*.


This article investigates the use of ozone in drinking water treatment, and the formation of its harmful disinfectant by-products such as aldehydes and ketones. According to the article, the primary problem with ozone is the possibility of biological regrowth, due to ozone's lack of residuals. The article also discusses biotreatment, a process used in Europe to control color, odor, taste, and disinfectant by-product precursors (such as humic acids, which form trihalomethanes during chlorination).

This article describes the results of a meta-analysis establishing a correlation between drinking water chlorination and occurrences of bladder and colorectal cancer. The meta-analysis is an effort to consolidate the conflicting and incongruent findings of prior epidemiological studies on chlorination. Ten studies provide data for the analysis [see also Altman reference above]. The data are standardized across the studies, and confounders such as sex, age, occupation, diet, smoking, and population density are identified and controlled where possible. Morris reports a statistically significant association between exposure to chlorination by-products in drinking water and bladder and rectal cancer when the studies are combined, even though these associations are inconsistent when taken from individual subject studies. Morris' results also indicate a strong dose-response relationship between drinking water chlorination and both bladder and rectal cancer. Morris reports that there was no significant correlation between colon cancer and chlorination.


This article investigates four different approaches to estimating cancer risk from epidemiological data. Quantitative risk assessment (QRA), years of potential life lost (YPLL), meta-analysis, and the attributable fraction (AF) present possible means of expressing chemical risk from exposure to disinfection by-products (DBPs). The article provides an extensive explanation of how each approach is conducted. The author offers the following conclusions regarding the applicability of each approach for quantifying chemical risks from DBPs. QRA requires accurate information on the exposure dose to be valid. Consequently, the uncertainties surrounding actual exposure doses render QRAs less useful. YPLLs are intended to reflect premature deaths. However, because cancer occurrence distributions exhibited in epidemiological data weigh heavily toward older individuals, YPLLs actually represent the older portion of the population. Meta-analysis requires that epidemiological studies be combinable, based upon a number of criteria. However, the variability among epidemiological studies makes obtaining accurate results and well-founded implications from a meta-analysis difficult. The author presents no analogous substantial shortcomings with the AF method, and points out that AF estimates are applicable to both cohort and case-control epidemiological studies. The article concludes that AF estimates are most useful in establishing DBP exposure-risk relationships, provided that underlying assumptions, inherent problems and limitations to the process are considered.

This article briefly explores the influences on public risk perception, and the potential for rash decisions based upon these perceptions. The article presents this discussion in the context of developing regulations regarding chlorine, and emphasizes the EPA's responsibility to communicate its findings clearly to the public and to focus public attention on the "real" risks.


This extended abstract reports the results of a study comparing the risks resulting from chloramination and rechlorination as secondary disinfection processes. The abstract describes the second response to bacterial regrowth problems experienced in the Greater Vancouver Water District, and follows a 1988 study of secondary chloramination and rechlorination that resulted in two fish kills. The article describes the sampling procedures, presents the collected data, and compares the chemical, biological and environmental risks. The article concludes that chloramination is superior to rechlorination with respect to microbial risk because it distributes residuals more thoroughly. Two of the generalizations drawn are: a general preference for chloramination with respect to biological and chemical risks, and a preference for rechlorination where environmental risks are considered. However, the article concludes that neither procedure is clearly superior.


This article presents President Clinton's changes to the environmental budget for the fiscal year 1995. The EPA's budget will increase by 8%, with funds allocated largely to operating programs, water infrastructure, and multimedia efforts, which increase from the fiscal year 1994 by 13%, 6%, and 60%, respectively (note that this corresponds to an approximate increase of $360, $150 and $60 million, respectively). Research and development funds will increase by approximately 7%, but research funds toward water quality, drinking water, and toxic substances will decrease by 4%, 1%, and 2%, respectively. The article points out the discrepancy between the EPA's priority on research and the trends in the EPA's R&D funds.


This article discusses the effects of drinking water regulations and the Safe Drinking Water Act (SWDA) on the drinking water treatment industry, with particular emphasis on small treatment operations. 87% of the country's public
water systems serve fewer than 3300 people, and combined serve only 11% of the population. These small operations often experience compliance difficulties due to lack of resources, and this creates problems for the states in fulfilling their primacy obligations. The article predicts that consumers will have to pay more for their drinking water if improvements are to be made at small treatment plants.

114. Occidental Chemical Corporation, Correspondence from the Occidental Chemical Corporation to AWWA - Government Affairs, March 29, 1993.

This correspondence records the Occidental Chemical Corporation's (OxyChem's) response to the American Water Works Association's (AWWA's) request for input on regulatory negotiations. The letter specifically addresses changes to Maximum Contaminant Levels (MCLs) for disinfectant by-products (DBPs), and the implications such changes might reflect. The MCLs for DBPs generated by different disinfectants are not representative of equal risk levels, and such a discrepancy might be construed as a prejudice against certain disinfectants. The existence of a larger database on chlorination by-products sets up a bias against chlorine, and the letter points out that both OxyChem and the Scientific Advisory Board are concerned that regulatory development should not prematurely reflect this bias, which might consequently direct compliance measures toward more uncertain treatment options.


This article explores possible causes for post-treatment persistence of pathogens within drinking water distribution systems. The author considers how physiochemical factors could shield microorganisms from disinfection and foster bio-propagation throughout the system. For example, methods by which pathogenic organisms survive treatment include the presence of particulate matter to which microorganisms can adhere, intersystem growth of macroinvertebrates that can act as transmission vectors, and the ability for organisms to generate a protective microbial biofilm. The author also investigates the influences on microbial growth of system variables such as temperature, pH, and nutrient levels.


This article discusses the nature of toxicity, and the scientific, political, and public perceptions of toxicity. The article discusses frequently misunderstood issues such as chronic toxicity vs. acute toxicity, naturally occurring toxic chemicals vs.
manmade toxic chemicals, and contradicting observations of human and
environmental effects of toxicants. The article also focuses on toxicity testing, and
points out the absence of a technique that conclusively proves a chemical is non-
toxic. The author discusses the causes and effects of public misconception, and
emphasizes that the public needs good information in order to understand toxic
risks.


This book explores the field of toxicology, emphasizing reproductive toxicology.
The book surveys experimental methods used in obtaining toxicological and
epidemiological data and the uncertainties arising in these methods. The author
also discusses the complications inherent in applying toxicological data to risk
assessment. The book investigates problems associated with data pertaining to
low exposure levels, identification of causal relationships, and assessing chronic
versus acute exposure effects. The author summarizes common public perceptions
of risk, and concludes that better public risk education would both improve risk
perception and reaffirm the public's faith in science.

118. Ozgo, David M., Hazardous Cargo Accidents: Rail Safer Than Truck, Competitive
Policy Reporter: An AAR/Policy and Special Projects Report, Vol. IV, No. 8
(1993).

This report analyzes statistics regarding rail and truck transport of hazardous
materials. The report concludes that railroad transport is five times safer than
truck transport of hazardous materials when measured against a criterion of
accidents per ton-mile. Only truck transport over distances greater than 200 miles
are considered, to avoid the inherent bias presented by the great number of short
transport events completed by trucks. The report does not consider the relative
severity of the incidents experienced by trucks and rail cars, the loss of product, or
the degree of harm experienced in accident events.

119. Payment, Pierre, Richardson, Leslie, Siemietycki, Jack, Dewar, Ron, Edwardes,
Michael, and Franco, Eduardo, A Randomized Trial to Evaluate the Risk of
Gastrointestinal Disease due to Consumption of Drinking Water Meeting Current

This article presents the results of a study directed at determining how effectively
current drinking water standards protect against waterborne pathogens. The
article describes the study purpose and method, and discusses the study results in
the context of drinking water standard adequacy. The investigators compare the
rates of gastrointestinal (GI) disease recorded by randomly selected consumers served by drinking water facilities maintaining adequate treatment levels. Among these study participants, a number were randomly selected to receive reverse-osmosis filters. The rates of GI illness were consistently found in all population subgroups to be approximately 50% higher among consumers without the household filters. Approximately 35% of the reported illnesses by consumers drinking the unfiltered tap water reaching drinking water standards were determined to be water-related and preventable.


This article proposes that concentration measurements of waterborne viruses are frequently underestimated, resulting in a substantial under-estimation of microbial risks to human health in drinking water. The author examines epidemiological data and detection techniques, and concludes that commonly used bacterial indicators under-represent the presence of viral activity in drinking water. The article explores the following contributors to the misrepresentation of waterborne virus behavior: limited knowledge on the occurrence and survival of viruses in water treatment systems, difficulties experienced in obtaining representative viral concentration information from current culture methods, and limited reporting of viral infections.


This paper discusses the difficulties experienced by public health agencies when communicating risk assessment results to the public. The paper identifies uncertainty and the public's perception of risk as the principal factors contributing to this communication problem. The author briefly describes the effects of these factors, and concludes that the use of risk assessment in policy development must incorporate a more honest representation of uncertainty and risk assessment limitations when speaking with the public.


This article considers the costs accompanying the alteration of drinking water
treatment procedures, in combination with the costs associated with the subsequent raising or lowering of biological or chemical risks. The article considers costs associated with the water treatment system, such as source water protection, treatment, disinfection, supervision, maintenance, and monitoring, as well as costs associated with societal effects, such as morbidity, mortality, and changes in community productivity. The latter costs are inherently more subjective. The article discusses the elements that contribute to the cost of separately attaining microbiological quality and chemical quality. The article jointly considers biological and chemical risks, by assessing the costs associated with procedural changes in treatment and estimating the accompanying changes in costs from biological- and chemical-related disease. The article stresses that limited understanding of health effects associated with different treatment procedures greatly constrains the precision of the analysis. The authors offer a number of generalizations that account for the uncertainties surrounding the topics of concern.


This article asserts that biological and chemical risks differ in terms of the severity, certainty, timing, and distribution of their associated health effects; consequently, a means of normalizing these variables is necessary in order to compare the two types of risk. In examining severity, the concept of "Quality-Adjusted Life Years," or QALYs is a means by which effects not resulting in fatalities can be incorporated into risk analysis. Severity can also be assessed in terms of the number of days per year that people are healthy, or the amount of money spent on health problems per year. Biological risk is considered more certain and better understood than chemical risk. In addition, the potential carcinogenicity of disinfectant by-products does not appear until much later than most microbial consequences. Analysts can compensate for the effects of certainty and timing by discounting, based upon public opinion of the value of future health risks. The article also suggests that differences in the certainty, timing and sociodemographic distribution of health effects can be compensated for by adopting methods from the social sciences, and incorporating human values into the comparison.


This article introduces a decision tree for managing microbial and chemical risks in drinking water disinfection. Data presented in the article indicate that the risk of
death from waterborne pathogens in untreated water is at least 100 to 1000 times greater than from carcinogenic chlorination by-products, and that the risk of microbially induced illness in untreated water is 10,000 to one million times greater than the cancer risk from chlorination. The decision tree places priority on reducing microbial risk at least until it matches the lower carcinogenic risks of disinfection by-products. The article elaborates on the significance of each step in the decision tree, explaining the framework upon which an appropriate treatment scheme can be determined. The article also discusses community factors that should influence choices in water treatment design.


This paper discusses the EPA's regulatory policy toward drinking water disinfection, identifies potential ramifications of possible regulatory scenarios, and presents the EPA's strategy to identify a regulatory implementation that minimizes risks from waterborne pathogens, disinfectants and disinfection by-products (DBPs). The paper investigates different regulatory scenarios, considering alternative specifications of maximum contaminant levels (MCLs) and best available technologies (BATS). Anticipated shifts in treatment procedures that would likely accompany particular regulatory scenarios are discussed in the article. Subsequently, the risks associated with these different treatment procedures are evaluated using the DBP risk assessment model (DBPRAM) [see Harrington, et al. reference above]. The paper presents model results from a variety of treatment schemes in which disinfectants, the presence of precursor removal, and source water qualities are varied. The paper lists a number of conclusions, and identifies areas in which additional knowledge would increase the certainty of these conclusions.


This synopsis highlights the proceedings of a conference held to discuss the EPA's use of Comparative Risks Assessment (CRA) to form regulatory judgments. The conference members discussed numerical representations of a benefit and cost analysis, and the reallocation of funding to support a risk-based system. The article expresses the members' concerns over the methodology, procedure and implementation of CRA, and describes three proposed ideas on which the CRA process could focus: pollution prevention, environmental justice, and directed innovation. The conference members didn't reach a consensus, but agreed that
public values should play a large role in the CRA process, and that the three ideas mentioned above should also be incorporated.


This article announced a recently granted patent for a drinking water disinfection procedure using iodine. This purification system, used by NASA for space missions, is also being distributed to remote or developing areas of the world. The article briefly describes the system's operation, but makes no mention of by-products other than writing that those formed by chlorination are avoided. The writer points out that the system offers further benefit by providing iodine to the consumer, thus alleviating cases of iodine deficiency common to other countries. The article reports that inventors are seeking EPA approval.


This book is a collection of papers presented at the Fifth National Conference on Drinking Water, held in Winnipeg, Manitoba in 1992. The papers address general issues regarding drinking water disinfection as well as specific drinking water problems observed in Canada. The topics explored in the book include: (1) the role of risk determination in drinking water quality guidelines, (2) the control of disinfectants and disinfection by-products, (3) the use of biological activated carbon filtration, (4) the occurrence of ozonation by-products, (5) the biological treatment of drinking water, (6) the implementation of the CT concept for disinfection optimization, (7) the underestimated health risk of enteric viruses, (8) the costs of disinfection, (8) the removal of precursor by low-pressure membrane filtration, (9) the application of potassium permanganate in water treatment, (10) the concern surrounding halocarbons and bromate as by-products of alternative disinfectants, (11) chloramination, (12) chlorine dioxide disinfection, (13) UV disinfection, and a number of topics pertaining specifically to the Canadian water system.


This article describes the determination and application of a mathematical model used to estimate the risk of Giardia infection from exposure levels. The model is based upon dose-response data from experiments with human volunteers, and is
applied in the article to determine the log reduction necessary to achieve acceptable microbial risk levels from drinking water treatment. The article discusses potential areas of uncertainty that may influence the accuracy of the dose-response curve and consequently of the mathematical model, and also establishes the merits of the model and of its application by public health agencies.


This article investigates the transmission, occurrence records, and techniques for the detection of three protozoa strongly associated with waterborne disease: *Entamoeba histolytica*, *Giardia lambia*, and *Cryptosporidium parvum*. The article expresses historical outbreak patterns of infections from these protozoa in relation to trends observed in other waterborne diseases in the U.S. Patterns observed in these data are related to varying water treatment procedures. The article also discusses the potential for risk underestimation resulting from incomplete protozoan recovery, and risk overestimation owing to inability to determine cell viability. The author identifies a number of areas on which research should focus to minimize risk from waterborne pathogens.


This paper explores the use of risk analysis as a tool for policy decision-making, and discusses the processes comprising risk analysis, specifically risk assessment and risk management. The paper stresses that these two processes are inseparable because the uncertainties of one affect the other. The author describes examples of both use-based and approach-based risk analysis techniques, and proffers factors that should influence which risk analysis method is chosen in a given particular situation. The author emphasizes that risk analysis must be approached through a decision framework that allows the structure of the analysis to fit the particular problem, as well as the intention of the analysis. The paper reveals the spectrum of options that are available for designing an appropriate analysis, and identifies the uncertainty that emerges from a risk analysis as an indicator of its appropriateness. The paper also includes a secondary discussion regarding misuse of risk information in cancer-related policy.


This letter highlights the Drinking Water Committee's (DWC's) review of the
EPA's Maximum Contaminant Level (MCL) establishment for ozone and ozonation by-products, and presents its response to specific questions asked by the EPA pertaining to the application of risk assessment to ozone by-products, inclusion of appropriate by-products for assessment, and the EPA's examination of bromate's toxicity. The DWC isolates the areas of most critical concern regarding ozone and its disinfection by-products, and recommends appropriate research areas to reduce uncertainty regarding ozonation of drinking water.

133. SAB Drinking Water Committee, Correspondence to EPA Administrator, Carol M. Browner, EPA-SAB-DWC-COM-94-002, November 8, 1993.

This letter presents a response by the Drinking Water Committee (DWC) to a briefing by EPA members, Stig Regli and Jim Elder, on the progress of the latest additions to the National Primary Drinking Water Regulations. The DWC specifically emphasizes the withstanding need to design a research program that will fill critical informational or scientific gaps that contribute to the uncertainty of risk-balancing regulations. The letter lists the DWC's priority research areas and recommendations, and provides an addendum describing uncertainties present in biological and chemical risk.

134. SAB Drinking Water Committee, Correspondence to EPA Administrator, William K. Reilly, EPA-SAB-DWC-LTR-92-008, August 18, 1992 (1992b)

This correspondence discusses the Scientific Advisory Board's (SAB's) recommendations to the EPA to regarding specific research needs. The letter emphasizes research on combined treatment methods, and on determining disinfection by-product (DBP) formation by all disinfection alternatives. The letter points out that this is especially relevant to the use of the Disinfection By-Product Regulatory Analysis Model (DBPRAM) in regulatory development. The letter specifically requests the EPA's support in establishing a credible research program in which the effects of the entire treatment train are considered, and in developing a process for uniformly accepting and analyzing DBP data from drinking water treatment utilities and research organizations such as the American Water Works Association.


This correspondence addresses the Scientific Advisory Board's (SAB's) opinion regarding the use of the Disinfection By-Product Regulatory Analysis Model (DBPRAM) in light of the significant uncertainty present in the drinking water database. The letter points out that the SAB considers the model a worthwhile endeavor and supports its future use, but warns against its premature
implementation while it still represents significant uncertainty and assumptions. The letter outlines the research needs the SAB feels will alleviate these uncertainties, and suggests that the draft Disinfection/Disinfectant By-Product regulations include only a discussion of the DBPRAM, rather than its application.


This article summarizes a case study of the 1991 and 1992 cholera epidemic in Peru. The study characterizes the outbreaks occurring in two towns, Trujillo and Iquitos, based upon weekly data collected from a variety of sources. The study also assesses changes in water treatment procedures that preceded and accompanied the epidemic, noting correlations between drinking water treatment procedures and outbreak patterns. The article provides a summary of water treatment procedures for each town, and a graphical representation of outbreak data. The authors conclude that drinking water contributed to the cholera epidemic. In both towns, treatment procedures and distribution system upkeep were insufficient to provide properly disinfected water to city inhabitants. The article points out that Trujillo did not use chlorination because of the potential negative health effects of disinfection by-products.


This book is a comprehensive text, providing information on the chemical aspects of processes such as water treatment. The properties, uses, hazards, and methods of generation of chemicals are explained in detail. The book provides a good reference for understanding chemical processes such as drinking water disinfection.


This article gives an economic perspective on the competition between the risks and benefits of drinking water disinfectants. The article reviews the current state of knowledge about disinfectant alternatives, and offers observed market trends of disinfectant chemicals as an indication of industry's preferences among treatment procedures.

This article discusses the positions held by the chemical industry and environmentalist groups in the chlorine ban debate. The article focuses on the ambiguities in scientific results that allow their dichotomous interpretations to support both sides of the debate, and points out the absence of a middle ground between the two opinions. The article also briefly summarizes potential scenarios arising from a chlorine phase-out, as described by both the chemical industry and environmentalists.


This article surveys the disinfection by-products (DBPs) formed with chlorine, chlorine dioxide, monochloramine, and ozone, and considers the factors that affect by-product formation. The article focuses primarily on chlorination by-products, reflecting the unavailability of by-product information concerning alternative disinfectants. The considered factors influencing by-product formation include pH, temperature, the concentrations of specific precursors (such as humic and fulvic acids), and the presence of other elements (especially bromine) and nutrients (particularly nitrogen). The article also presents the empirical DBP formation equation used as a predictive model by the EPA to develop drinking water treatment regulations.


This extended abstract summarizes the results of a pilot study investigating the relative negative health effects of drinking water chlorination, chloramination, ozonation postdisinfected with chlorine, and ozonation postdisinfected with chloramine. The study identifies eighteen halogenated disinfection by-products, and indicates their relative production by the disinfectants investigated. The negative health effects associated with each by-product are briefly described, and the potential overall health risk of each disinfectant is assessed and compared with the other disinfectants in the article. The article also suggests a relationship between mutagenicity data determined in the Salmonella/microsome assay (representing the entire mixture of by-products), and the potential health risks determined during risk evaluations of individual by-products.


This article introduces a conceptual framework for establishing microbial risk in drinking water, incorporating hazard identification, exposure assessment, effects assessment, risk assessment and characterization, and risk management. The article diagrams a model representing the relative roles these steps play in identifying the key issues, informational gaps, and research needs in microbial risk assessment, and the role that they play in providing a basis upon which microbial risks can be compared to chemical risks. The article extrapolates on each step of the framework, and highlights the problems currently associated with each step. In particular, the article discusses problems pertaining to the identification of etiological agents, the detection of aggregated microbes, the accurate measurement of virulence, the unknown extent to which immunocompromised populations are growing and affected by microorganisms, and the capabilities of microorganisms in different physiological states to infect the host. The need for additional research, to aid in measurement and identification processes, is also emphasized in the article.


This article investigates the implementation of rechlorination procedures in distribution systems in order to address the deterioration of residual chlorine owing to turbidity masking and disinfection stressing. The article describes a process involving the identification of locations in the distribution system suffering from bacterial regrowth, and the installation of a rechlorination system at this location. The rechlorination system operates by maintaining specific Oxidative Reduction Potential (ORP) parameters. The article discusses the utility of ORP and its ability to represent changes in the oxidant profile and disinfectant demand. The article suggests this process as an alternative to increasing residuals by over-chlorinating at the point of treatment, and compares the consequences of both options.


This document describes a framework under which the EPA and its Advisory Committee can balance the contributions of microbial and chemical agents to the total human health risk in drinking water, as well as suggestions for equating the disparate manifestations of these risks. The document outlines extensively the manners in which biological and chemical risks differ, and lends possible ways to normalize these elements for comparison. The decision framework described in
this publication considers five essential criteria: (1) the type of diseases that emerge from the responsible agents, (2) the disease incidence, (3) the disease severity, (4) the latency of disease onset, and (5) the certainty of disease onset. The authors provide estimations of these parameters regarding both biological and chemical risk.


This document summarizes the current knowledge and understanding of the nature and extent of non-cancer risks potentially resulting from chlorinated drinking water consumption, and presents the results of a "weight-of-evidence" evaluation of potentially toxic disinfection by-products. Furthermore, the document classifies these agents by principles paralleling those established by the International Agency for Cancer Research (IARC) for rating carcinogenic agents, and discusses the subsequent implications for balancing biological and chemical risks.


This document summarizes the current knowledge and understanding of the nature and extent of cancer risks potentially resulting from chlorinated drinking water consumption. Using the "weight-of-evidence" criteria employed by both the International Agency for Cancer Research (IARC) and the USEPA to evaluate the carcinogenicity of chemical agents, the author examines the epidemiological and toxicological data supporting the carcinogenicity of various chlorination by-products, and classifies them accordingly. The author concludes that under the specified criteria, the available data are inadequate to categorize chlorinated water as a human or animal carcinogen. Further conclusions regarding the carcinogenicity of various individual by-products are also described in the document.


This article represents Greenpeace's stance on the chlorine ban debate. The article provides reasons for the elimination of chlorine, including economic benefits. The article proposes the imposition of a chlorine tax to generate money for a fund to retrain workers displaced because of the ban. The report also responds to a report
completed by the Charles River Associates (CRA) consulting group, on the economic effects of a chlorine ban [see reference above]. This article points out over-estimates made in the CRA predictions. The report explains Greenpeace's step-by-step plan to phase-out chlorine, to be accomplished by providing transitional help to those employees or consumers negatively affected by the removal of chlorine, and gradually "phasing-in" chlorine alternatives.


This article describes different treatment alternatives and compares their proficiency in simultaneously minimizing disinfectant by-products and microbial levels throughout the water treatment process. The article explores existing alternatives in oxidation, precursor removal, primary pathogen removal, and distribution maintenance. For each of these treatment categories, the article summarizes the conditions under which specific alternatives are optimal, or suggests considerations that should indicate the most appropriate alternatives for the specific treatment situation being considered.


This paper describes a case-control study investigating the relationship between elevated bladder cancer and total fluid consumption. The ingestion of alcoholic beverages, bottled beverages, soda, milk, coffee, tea, all juices, and tap water comprise fluid consumption in this study. The study found that even accounting for potential confounders, the total daily fluid intake is strongly correlated with elevated bladder cancer occurrence. The paper discusses possible biological and non-biological causes for the study observations, compares the study results with those of previous investigations, and describes biases that could have influenced the study results.


This chapter discusses psychological principles for studying the public's perception of risks, and applies these principles specifically to environmental risks. The article suggests that two psychological notions, "behaviorist tendencies" and "defense
mechanisms", provide insight to the way the public reacts to information about risk. The author discusses the presentation strategies that may be used by groups such as environmental organizations or the government, and ways in which public reactions can be manipulated. The author concludes that the public should be given complete accurate, organized, unbiased information, to enable people to contribute more to risk-based decisions. The author also maintains that emotion and intuition are an important part of risk evaluation, and that these elements should not be manipulated by those presenting risk information.


This article discusses the role of chlorine and chlorinated compounds in the European Community, and emphasizes the benefits of chlorine chemistry. The article presents concerns about chlorine risks from the perspectives of industry, government, and environmental groups. The European efforts to balance the benefits and risks of the chlorine industry are also described.


This report describes the results of the regulatory impact analysis conducted for the EPA's proposed National Primary Drinking Water Regulations (NPDWRs). The report includes estimates of the costs and benefits of the proposed regulations, as they will affect not only treatment utilities, but consumer households. The use of the Disinfection By-Product Regulatory Analysis Model (DBPRAM) for this assessment is also described within the report. The report explains in detail the estimation of all relevant factors in the determination of costs and benefits, as well as the treatment of uncertainty throughout the analysis.


This book is perhaps the most comprehensive reference on chlorine available. The book gives detailed information on chlorine's chemical properties, reactions, generation, uses, hazards, and history. The book also discusses storage and transport issues, with examples of incidents and critiques of how the incidents were handled. The book describes nearly every industrial use of chlorine, and provides suggestions and strategies for improving the safety and efficiency of such use. In the area of drinking water treatment, disinfectant alternatives are discussed, including their by-products and associated risks and benefits.

This publication summarizes the conclusions and expert opinions of the International Agency for Research on Cancer (IARC) Working Group on the Evaluation of Carcinogenic Risks to Humans that met in June of 1990 in Lyon, France. The book addresses issues regarding chlorinated drinking water, chlorination by-products, other halogenated compounds, and cobalt and cobalt compounds. Pages 32-33 detail the IARC's criteria and scale for evaluating and rating agent carcinogenicity. Pages 37-39 provide a discussion of this working group's priorities regarding the maintenance of drinking water quality.


This report [commonly referred to as "the CanTox report"] suggests four principles for assessing the behavior of chlorinated organic compounds: (1) a compound's chemical structure determines its behavior, (2) a concentration threshold exists for every chemical below which no negative effects appear, (3) organisms are inherently capable of metabolizing low concentrations of some chlorinated organics, and (4) causal associations between chemical agents and observed negative effects must be "biologically plausible." The authors demonstrate the application of these principles to situations in which chlorinated organic compounds are correlated with toxic or carcinogenic effects. In addition, the authors invoke these principles to support continued use of chlorine and the majority of chlorinated compounds.


This article examines the inherent presence of uncertainty in the concept of risk, and asserts that risk comparison is required to minimize the ambiguity associated with uncertainty. The author also defines links between risk assessment and social values through the making of judgments. The article evaluates a variety of risk assessment methods, and their associated uncertainties.


This article investigates the use of ultraviolet radiation in drinking water treatment. Ultraviolet (UV) radiation, in the wavelength range of 240 to 280 nm, is capable of
killing microorganisms by damaging their nucleic acids. UV is widely used as a wastewater disinfectant, and is considered a possible disinfectant alternative for drinking water treatment. UV is reportedly used in over 2000 European communities for drinking water treatment. The article discusses the effectiveness of UV, and describes the DBPs formed during its use.


This publication describes the recommendations of the World Health Organization for the development of national drinking water quality regulations to optimally protect public health from harmful microbial and chemical agents in drinking water. The guidelines are described in detail in this publication, and are provided as a basis upon which drinking water quality can be assessed within the socioeconomic context of individual nations.