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ANALYSIS OF POTENTIAL TRADE-OFFS IN REGULATION OF DISINFECTION BY-PRODUCTS

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Analysis of Potential Trade-offs In Regulation of Disinfection By-Products

John E. Cromwell, III & Xin Zhang
Wade Miller Associates, Inc.

Frank Letkiewicz
Abt Associates, Inc.

Stig Regli & Bruce Macler
U.S. Environmental Protection Agency

1.0 Introduction

Executive Order 12291 requires the preparation of a Regulatory Impact Analysis (RIA) on all new major federal regulations. The U.S. Environmental Protection Agency (EPA) guidelines for performing regulatory impact analysis state:

> *The goal of regulatory impact analysis is to develop and organize information on benefits, costs, and economic impacts so as to clarify trade-offs among alternative regulatory options.*[1]

Potential trade-offs between microbial and disinfection by-product risks are technically complex and fraught with uncertainties. In addition to meeting the requirement for a Regulatory Impact Analysis, the research effort reported in this paper is intended to establish a systematic analytical framework for appreciating these factors. Explicit methodology for assessing the technical potential for risk-risk trade-offs is developed (termed, the Disinfection By-Products Regulatory Analysis Model, [DBP-RAM]). The strategies used to cope with complexities and uncertainties in developing the DBP-RAM are explained. Results are presented and discussed in light of uncertainties, and in light of the analytical requirements for regulatory impact analysis.

Technical complexities stem from several competing relationships between microbial and by-product treatment objectives that are inherent in water treatment processes. These relationships are described in Section 2.

There is current exposure to both microbial and disinfection by-product risks. Neither of these is well-characterized in baseline data. Moreover, the baseline is changing. Section 3 presents an assessment of available baseline data.

Section 4 presents a statement of the specific research objectives and of the overall approach pursued in this analysis. The overall objective is to bound the range of possibilities implied by the competing treatment relationships in terms of the potential for trade-offs between microbial and by-product risks under different regulatory scenarios.

Section 5 describes the analytical approach that has been adopted in developing the DBP-RAM and the supporting rationale. Profiles of the changes in microbial and by-product risks associated with different regulatory scenarios are generated through Monte Carlo simulation of the competing treatment relationships. Specific methodology and assumptions of the DBP-RAM are presented. Section 6 presents results and discussion. Section 7 presents summary observations relevant to the research questions posed.

2.0 Competing Relationships In Microbial and By-Product Control

Exhibit 1 presents an overview of the key factors involved in the competing relationships which result in exposure to microbial contaminants and disinfection by-products at the consumer's tap. As illustrated in the diagram, these factors can be sorted into four groups:

- raw water quality;
- treatment combinations applied;
- treatment process control strategies applied; and
- distribution system characteristics.

2.1.1 Raw Water Quality

The effectiveness of treatment technologies to control pathogens and disinfection by-products is affected by the interaction of multiple influent water quality parameters. Many water quality parameters affect both microbial and by-product treatment simultaneously (e.g., TOC, UV absorbance, temperature, pH, alkalinity, and hardness). Other parameters such as bromide and pH can strongly influence the formation of one type of disinfection by-product versus another.

Chemical disinfectants are oxidants which destroy or inactivate microorganisms by oxidation. They also react with naturally occuring dissolved organics (grossly represented by TOC -- Total Organic Carbon) and with inorganics (such as bromide) to produce disinfection by-products, some of which may be carcinogenic. Higher doses of disinfectants are required in high TOC waters to achieve a desired level of microbial kill because some of the disinfectant is consumed by organic compounds comprising the TOC. But, higher disinfectant dosages lead to higher disinfection by-product formation unless TOC is removed before the disinfectant is applied. Coagulation and filtration processes, granular activated carbon, and membrane filtration remove TOC. However, such processes may also shift the chemical balance towards more brominated by-products, depending upon the bromide concentration and the amount of disinfectant applied.

The chemical reactions that kill microorganisms and those that form halogenated by-products will proceed to greater or lesser extent of completion depending upon the pH (often correlated to alkalinity and hardness); and, at a faster or slower rate depending upon the temperature of the water. Microbial kill is increased at higher temperature but so is disinfection by-product formation. At different levels of pH, different groups of by-products are favored. Trihalomethane formation is favored at high pH, while trichloroacetic acid formation is favored at low pH.

2.1.2 Treatment Processes Applied

Of the possible treatment processes indicated in the diagram in Exhibit 1, some (e.g., coagulation and filtration) are appropriate mainly in surface water systems. While there are some groundwaters that also use these treatments (e.g., in lime softening), surface waters generally present a far more complicated treatment problem where the conflict between the competing objectives (controlling for both pathogens and disinfection by-products) is much more pronounced.

Surface waters contain protozoa whereas groundwaters (that are not under the direct influence of surface waters) may only contain viruses or bacteria. Since protozoa are much more resistant to disinfection than bacteria or viruses, higher levels of disinfection are needed in surface waters than in groundwaters. Because of this feature, the analysis presented in this paper focuses exclusively on surface water systems. The number of factors involved is so great, that an excessive amount of analysis would be required to assess every conceivable type of treatment situation. By focusing on the surface water situation, which is likely to be the most highly constrained, alternative regulatory scenarios can be subjected to the toughest test. Whatever by-product control levels are achievable in surface water systems without unacceptable trade-offs are probably achievable in generally less constrained groundwaters without unacceptable trade-offs.

The nature of treatment for microbial and disinfection by-product control is complex in that several treatment steps may be added in succession to achieve successively greater levels of control. Thus, there is not a single solution to these treatment problems, but rather a menu of choices. This menu feature adds a considerable degree of complication to the evaluation of regulatory alternatives because impact assessment requires a method for forecasting these complex treatment choices.

2.1.3 Process Control Strategies Applied

The box labelled "treatment process control strategies" in Exhibit 1 is perhaps the most important part of the diagram. In striving to meet any set of microbial and by-product treatment targets, the plant operator has a broad array of choices. The following control options are available:

- control TOC
- control pH
- select type of disinfectant
- control disinfectant dose
- control contact time

In addition to influent water quality parameters such as TOC and pH, another major factor influencing the extent of microbial kill and by-product formation is the amount of time the disinfectant is in contact with the water. For any given disinfectant dose, both the level of microbial kill and the level of by-product formation will increase as the contact time is increased. Thus, the treatment process may be optimized through a combination of strategies intended to: 1) change the water quality parameters that affect the relevant reactions, 2) change the disinfectant or disinfectant dose, or 3) change the amount of contact time.

Temperature is one key variable that is beyond the operator's direct control. However, it is possible to vary winter and summer strategies to take advantage of the temperature effect. For example, a higher disinfectant residual might be needed within the plant in the winter to maintain the same level

of inactivation as in the summer. This may be possible without significant increased by-product formation since by-product formation is slowed at colder temperatures. Additional flexibility would be made available if compliance with by-product MCLs is determined on the basis of the running average of the last four quarterly samples, as under the current TTHM standard.

2.1.4 Distribution System Characteristics

A final key variable that is generally beyond the plant operator's direct control is the residence time in the distribution system -- the amount of time elapsing from the moment the water leaves the plant to when it is drawn from the consumer's tap. The residence time may vary enormously between the customer nearest to the plant and the customer farthest from the plant. The resulting microbial and by-product risk may also vary greatly between first and last customer. The plant operator must account for this additional contact time at the plant, adjusting the available controls to simultaneously assure: 1) an acceptable level of microbial kill at the first customer's tap, 2) additional microbial kill sufficient to protect the distribution system from bacterial growth and external contamination all the way to the last customer's tap, and 3) compliance with by-product MCLs on average across the total distribution system (i.e., at the average customer).

Thus, the competition between microbial and by-product control strategies is driven by performance standards that must be met in the distribution system rather than at the plant effluent. Because there are so many control options available to the plant operator, there is no unique solution to the control problem -- i.e., within each plant, there may be a number of different control strategies that can meet a given set of performance targets. Viewing the variability between plants, there is an even broader range of possible solutions since raw water and distribution system characteristics vary greatly.

2.1.5 Implications of Variability

The inherent variability in possible treatment and control configurations has two profound effects on the assessment of prospective impacts of regulatory alternatives. First, it is extraordinarily difficult to fully define the baseline, or pre-regulatory condition. This difficulty is a combined result of the fact that current microbial performance requirements are in the process of being changed through implementation of the Surface Water Treatment Rule (SWTR) and the Total Coliform Rule (TCR), and the fact that plants can meet performance standards with vastly different treatment and control strategies, depending on their individual circumstances. Also, the recent promulgation of the Lead rule will result in still further changes in water treatment that influence microbial control and disinfection by-product formation. Even if a complete characterization of baseline process settings were available, it would still be extremely difficult to predict impacts in terms of the increment of change likely to be induced by alternative by-product MCLs because the process control options are so numerous. Baseline issues are discussed further in Section 3.

The second major analytical implication is that for any set of performance targets, some plants will be driven to more extreme treatment and control strategies than others due to the inherent variability in raw water conditions. This range of strategies is significant because the competition between treatment objectives results from *side-effects* -- inadvertent increases in either microbial or by-product risks -- that are inherent in the underlying raw water chemistry. Many of these side-effects become more pronounced as control strategies become more extreme. Thus a regulatory alternative could appear to represent a happy medium between microbial and carcinogenic risks, on average (i.e., across all plants), but in fact entail significant trade-offs due to side-effects induced in the extreme cases. As a result, a complete

assessment of the *trade-offs* entailed in any set of microbial and by-product performance standards must incorporate an analysis of the downside risks that could result from side-effects at the extremes. The approach to coping with this analytical requirement is via the technique of Monte Carlo simulation as described in Section 4. In the remainder of this section, treatment and control strategies are individually characterized, including an identification of the side-effects potentially associated with each of them.

2.2 *Microbial Control*

There are two distinct objectives in controlling microbial contamination in water supplies: 1) removing or killing pathogens present in the source water, and 2) preventing contamination of the treated water during storage and distribution. The Surface Water Treatment Rule (SWTR) specifies performance targets for both of these objectives which must be met simultaneously. The Total Coliform Rule (TCR) specifies additional performance requirements that must be met in the distribution system. Both the SWTR and the TCR are currently being implemented.

2.2.1 *Source Water Treatment*

Microbial contamination in water sources presents a significant treatment challenge because the level of contamination can change sporadically and logarithmically (by several orders of magnitude). Available monitoring protocols are subject to significant sources of sampling error and measurement error, making reliable real-time process control impossible. The only effective strategy is to assure a level of over-kill sufficient to meet the most extreme condition at all times. However, this strategy conflicts with by-product control objectives.

In general, individual unit microbial treatment processes are not 100 percent effective. While coagulation/filtration processes and disinfection can each remove and inactivate a high proportion of organisms present, neither treatment is completely successful by itself (unless the source water is exceptional). The best means of assuring the necessary high degree of over-kill in microbial treatment is through the *multiple barriers approach*, combining watershed protection, coagulation/filtration processes, and disinfection. In the SWTR, the multiple barriers approach is advocated with focus on a "target organism," Giardia lamblia.

Giardia is used as a target organism in the SWTR because it has been implicated as causing the most waterborne disease outbreaks of any specific organism and Giardia cysts are much more resistant to disinfection than bacteria and viruses. Control of Giardia therefore implies significant risk reduction for bacteria and viruses that are responsible for the most notorious and lethal forms of waterborne disease (typhoid, cholera, hepatitis, etc.). Control of Giardia, however, may not provide adequate protection from Cryptosporidium. Cryptosporidium is also transmitted in the form of cysts, but these are much more resistant to disinfection than Giardia cysts.

The SWTR imposes a filtration requirement for all surface waters unless the system has an effective watershed control program and the source water is of exceptional quality. Associated with the filtration requirement are design and operating conditions specified by the state, and performance standards for effluent turbidity. In combination, these requirements are believed to represent reduction of the influent concentration of Giardia cysts by two-and-one-half orders of magnitude (2.5 "logs"). (Note: plants that do not employ a sedimentation step are assumed to achieve only a 2.0 log reduction of Giardia cysts.)

In addition to the filtration and turbidity requirements, the SWTR also specifies the need for plants with sedimentation and filtration to provide an additional half an order of magnitude reduction (0.5 "log") in Giardia cyst concentration through the provision of adequate disinfection. The adequacy of this additional disinfection is determined via equations, as follows:

Total Log Reduction = filtration removal credit + X logs of inactivation

Where: $X = f\{$disinfectant dose, contact time, temp, pH$\}$

Methods to predict the level of inactivation of Giardia achieved through disinfection (C-T calculations) have been developed. Also, a dose response function exists for Giardia (derived from human data) which has received some empirical validation through study of actual waterborne disease outbreak events.[2] Knowledge sufficient to develop comparable risk assessment methodology for Cryptosporidium does not exist, so it remains an unknown at present.

The filtration and disinfection requirements of the SWTR provide for a minimum 3-log total reduction in Giardia cyst concentrations in surface waters by the time the water reaches the first customer in the distribution system. Based on risk assessment, this level of reduction was intended to provide protection equivalent to a giardiasis incidence rate (endemic rate) of less than 1 infection per 10,000 persons per year in systems with good source water quality. The SWTR Guidance Document[3] also stipulated that systems with source waters containing higher than average levels of contamination should provide an additional log of inactivation through disinfection for each additional log of Giardia present in the source water. This guidance is difficult to implement because practical methods for measuring Giardia cysts and for determining whether they are viable or infectious to humans are not yet available. It is significant that, at this time, the criterion for achieving higher levels of treatment for poorer source water quality is not a requirement, but stipulated only as guidance. Recent Giardia occurrence data[4] indicate that many more systems may require such additional inactivation than was believed necessary at the time the SWTR was promulgated. These data are discussed further in the baseline analysis presented in section 3.

Surface water systems meeting the requirements of the SWTR are typically not expected to experience epidemic outbreaks of giardiasis or of any other waterborne disease. However, recent data on Giardia occurrence[5] indicate that plants having extremely poor source water quality, and only meeting the minimal requirements of the SWTR (i.e., not providing treatment according to the guidance) may still be vulnerable to outbreaks or significant levels of endemic illness. Another key point is that provision of additional logs of disinfection in accordance with the SWTR guidance (e.g., replacing chloramine contact time with chlorine contact time) can result in significant by-product formation when there is also a high level of TOC in the water.

2.2.2 Protection from Contamination During Distribution and Storage

The SWTR specifies that at least a trace level of disinfectant residual be maintained in the distribution system to contain "colonization" and "regrowth" of bacteria which might have survived the multiple treatment barriers. Even if less than one-in-a-million bacteria survives, it can conceivably attach to the wall of a pipe in an area where deposits -- potentially containing trace nutrients -- have collected. Such colonization can ultimately result in the presence of significant numbers of bacteria in localized areas. The disinfectant residual is intended, in-part, to limit such growth.

The other function of the disinfectant residual is to kill microorganisms that may enter the distribution system through breaks, leaks, cross connections, or other violations of its integrity. The absence of a residual indicates when such contamination may be occurring. This requirement to maintain a disinfectant residual complements the Total Coliform Rule (TCR) which specifies a monitoring protocol that must be followed to regularly sample the distribution system for coliform bacteria -- an indicator of either inadequate disinfection or a violation of system integrity. Under the SWTR, monitoring for disinfectant residual is required at the same locations where coliform samples are taken. The TCR, promulgated in 1989 and currently being implemented, imposes more stringent coliform monitoring than previous requirements and a more sensitive threshold for determining a violation. Many systems are expected to compensate by increasing the level of disinfectant residual they maintain in the distribution system, with a likely side effect of some increased by-product formation.

Like source water microbial treatment, protection from contamination during distribution and storage is not an exact science. Several competing relationships enter into the picture. First, the extent to which the disinfectant can remain active all the way to the ends of the distribution system is, in part, a function of the amount of TOC in the water. The higher the TOC, the higher the disinfectant dose required. The higher the disinfectant dose, in the presence of high TOC, the greater will be the by-product formation. Secondly, as described earlier, chlorine -- the most commonly used disinfectant -- is more effective at low pH, whereas corrosion control treatment required to comply with the lead rule results in higher pH in distributed water. Higher disinfectant dosages are required to compensate for higher pH, increasing formation of certain by-products such as trihalomethanes.

Adding to the significance of these potential side effects, there is some evidence which suggests that levels of over-kill implied by the SWTR and TCR distribution system requirements may not be as protective as had previously been believed. Recent epidemiological evidence on this topic is reviewed in the baseline discussion presented in section 3.

2.3 Disinfection By-Product Control

The chemistry of disinfection by-product formation has been theoretically defined and empirically described for trihalomethanes and haloacetic acids with equations[6] of the following form:

$$\text{DBPs} = f\{[Cl_2], \text{contact time}, [\text{TOC}], \text{UV absorbance}, [Br^-], \text{temp}, \text{pH}, \text{alkalinity}, \text{hardness}\}$$

All disinfection by-product control strategies have potential side effects which pose certain risks, some more than others. The most practical strategy is to limit formation through precursor removal and/or through the use of alternatives to chlorine disinfection.

2.3.1 Adjusting Pre-Disinfection Practices

A first instinct in attempting to lower DBP formation is to relocate the point of disinfection, or to discontinue the practice of pre-disinfection -- disinfection prior to settling or filtration. Such relocation permits the coagulation and filtration steps of the treatment process to remove a substantial amount of the TOC in the water before the introduction of chlorine. The extent of such removal and its significance for reducing by-product formation will largely depend upon the water quality characteristic to the plant and the extent to which clarification processes are optimized.

There are compromises in moving the first point of disinfection further into the treatment train. Abandonment of pre-disinfection may reduce the disinfectant contact time prior to the first customer and make it necessary to add storage to the end of the treatment process as a means of making up the lost contact time under the SWTR, especially if the guidance formula is followed. Plant operators also may be reluctant to give up pre-disinfection because of its benefit of sometimes improving coagulation or taste and odor control, and of keeping the filter from becoming fouled with microbial growths.

2.3.2 Use of Chloramines

In complying with the present Total Trihalomethanes MCL of 100 ug/l, it appears that many plant operators opted to switch to chloramines in lieu of abandoning pre-disinfection. It is estimated that as many as one-third of the large surface water systems (>10,000 population) that are subject to the TTHM standard use chloramines. Prior to the TTHM standard as few as five percent of these systems are believed to have used chloramines. The low cost of making such a change, the effectiveness of chloramines in reducing TTHMs and their ability to persist as a residual in the distribution system makes this an attractive option.

Chloramines are formed through the addition of ammonia which suppresses many of the by-product formation reactions while preserving some, albeit weaker, disinfecting capability. When by-product control problems are only moderately constraining, ammonia may be added after a brief period of contact with the free chlorine. Allowing the free contact time preserves some of the benefits of pre-disinfection. In more severely constrained cases, ammonia is added from the start. A side effect of the switch to chloramines is that the weaker disinfectant may not be capable of providing the level of log reduction required at the first customer under the SWTR and/or recommended in the SWTR guidance. Some plants may have to re-evaluate their use of chloramines in complying with the SWTR.

Use of chloramines also entails potential side effects on microbial protection of distributed water. Through chemical interactions, the ammonia may eventually become a source of nitrogen for bacterial growth and may promote nitrification which can lead to poor tasting water. Chloramines may also offset the need to remove TOC to some extent, leaving some available carbon in the water. If corrosion control happens to involve iron pipes and the addition of phosphate inhibitors, the biochemical setting for microbial growth in the distribution system may be further established. Coupled with an inherently weaker disinfectant, there is potential for negative side effects of a chloramines DBP control strategy on microbial control in distributed water. However, the fact that the chloramine residual may be more persistent in some systems holds the possibility that chloramines may provide more bacterial protection than chlorine where maintenance of residual is a problem. Microbial regrowth is a known problem in many systems using chloramines presently. To compensate, some systems have increased chloramine residuals to the point where they may not meet potential MCLs for chloramines.

2.3.3 Optimization of Precursor Removal

In the succession of likely treatments available for by-product control, the plant operator will probably turn next to optimization of TOC removal through fine-tuning of the coagulation and filtration processes. Removal of TOC directly reduces the potential for by-product formation. Coagulation and filtration are very effective, and depending on source water quality, may be relatively inexpensive compared to other treatments such as addition of granular activated carbon (GAC) or membrane filtration. Much of the added expense is due to increased sludge disposal. In some plants, high alkalinity could make enhanced precursor removal very expensive due to the need for pH reduction.

Optimized precursor removal has two potentially significant side effects. First, the lower TOC makes it possible to meet the disinfectant residual requirement of the SWTR with much lower free chlorine concentrations leaving the plant. However, the reduction in TOC may have a perverse effect of allowing the system to have less C-T (less inactivation) prior to the first customer, conceivably increasing the risk from Giardia in poorer source waters, unless additional inactivation is provided as recommended in the SWTR guidance document. Under the minimum requirements of the SWTR, attainment of a level of log-reduction at the first customer greater than or equal to the 1/10,000 risk level may be resulting incidentally from the need to overcome the competing effect of TOC in meeting the residual requirement.

The second potential side effect of optimizing TOC removal is a change in the chemical balances with respect to the different classes of by-products. Removal of organic precursors does not reduce bromide concentrations. As TOC removal increases, the formation of brominated by-products, some of which may be more carcinogenic, may be favored depending upon the molar ratios of bromide, free chlorine, and organic precursors.

2.3.4 Use of Ozone

Modifying pre-disinfection practice, adding ammonia, and optimizing TOC removal are relatively inexpensive, conventional technologies that are likely to be tried first. The next threshold is switching to alternative technologies that are relatively novel and relatively more expensive. The first of these is the use of ozone as a primary disinfectant. Ozone is an extremely powerful oxidant. From a process perspective, it can be very beneficial (depending on source water quality) in achieving a high level of microbial kill and in enhancing the performance of coagulation processes, sometimes with enhanced precursor removal. Because ozone is so reactive, however, it does not leave a detectable trace residual in the distributed water. To provide a measurable residual, chloramines or chlorine are generally added at the end of the plant.

There are numerous potential side effects associated with the use of ozone. First, ozone is so powerful an oxidant that it produces very small organic fragments that can evade coagulation and filtration processes, ending up in the distribution system in a form that is readily assimilable to bacteria. The increase in assimilable organic carbon (AOC) can lead to significant baterial growth in distribution systems. Some of these bacteria may be pathogenic and especially harmful to immune compromised individuals. The biochemical setting for bacterial growth may be further enhanced with the addition of ammonia as a nitrogen source.

In addition to the microbial side effects, the oxidizing properties of ozone also result in the formation of entirely different mixes of other chemical by-products which could be carcinogenic. Toxicological research on ozone by-products is in infancy; many unknowns remain in this area. A potential remedy to minimize these side effects, employed in Europe, is to follow ozone treatment with a biological activated carbon filter. This provides a means of biologically removing AOC while simultaneously removing organic precursors to by-product formation. It represents another technology shift, however, as well as another level of expense.

Another concern of ozonation is the extent to which bromate is formed. Bromate appears to be a potent carcinogen. At the moment, there is insufficient understanding of the rate at which it is formed during ozonation and the extent to which its formation can be controlled by chemical treatment processes such as pH adjustment or ammonia addition. Occurrence data are also slight due to limitations in present analytical methods of detection.

2.3.5 Use of Chlorine Dioxide

Another alternative disinfectant is chlorine dioxide. Although there is concern about health effects caused by exposure to chlorine dioxide and its by-products (chlorite and chlorate), its use in preventing or limiting other disinfection by-products may make it attractive in certain water quality situations. Unlike chlorine, chlorine dioxide is a very effective disinfectant at high pH. It does not react by itself with organics to form trihalomethanes or haloacetic acids. Also, it apparently does not react with bromide to form bromate. Systems with high levels of pathogens, TOC, and bromide in their source water which also have high hardness and alkalinity and use lime softening, may have difficulty in simultaneously achieving low by-product levels and compliance with the SWTR guidance. Use of reducing agents such as ferrous chloride, to convert chlorine dioxide to chloride may make use of chlorine dioxide a possible means of controlling disinfection by-products in such systems.

2.3.6 Use of Granular Activated Carbon or Membrane Filtration

Depending upon the source water quality, attainment of low levels of disinfection by-products may ultimately require deep bed Granular Activated Carbon (GAC) (following conventional filtration processes and the use of alternate disinfectants) or membrane filtration. Due to the expense of GAC and membrane filtration, these treatments are likely to be selected as a last resort compliance option.

When GAC is used, application of chlorine as a residual disinfectant for the distribution system should be delayed until after the water's passage through the GAC filter. This strategy optimizes the efficiency of biological removal of by-product precursors and prevents desorption of chlorinated by-products that might otherwise be formed if chlorine were added prior to GAC. Although GAC can remove by-products by adsorption, the frequency of carbon regeneration required would not be practical. Chlorine, if used, should therefore be added after GAC. Ozone, on the other hand, can be used prior to GAC to enhance removal of by-product precursors and AOC, and to provide substantial disinfection (depending upon the ozone demand in the water).

There are, however, several side effects of GAC. Deep bed carbon following conventional filtration processes may not remove significant levels of pathogens still remaining. Thus plants with high pathogen levels in their source water and currently predisinfecting prior to sedimentation may need to install substantial disinfectant contact time following GAC to prevent significant increases in risks from protozoa to populations near the first customer. Since GAC will significantly reduce disinfectant demand, a plant would be able to have very low levels of disinfectant dose and still maintain a residual in the distribution system. While use of GAC would likely decrease risk from pathogenic bacteria that could grow in the distribution system, it could increase risk from pathogens in the source water if less disinfectant or contact time is used prior to the first customer.

Membrane technologies can remove greater than 90 percent of disinfection by-product precursors and essentially all pathogens which might be present in the source water. Thus, there is little or no downside risk concerning pathogens with this by-product control technology. It is however, the most expensive approach. Solid waste and water wastage could increase costs even more. In surface waters, membrane technology would have to follow other filtration processes in most cases to prevent clogging of the membranes.

Both GAC and membranes are subject to the same uncertainties as previously mentioned for optimized coagulation/filtration precursor removal. Depending largely upon the bromide concentration,

there is potential for a shift in the mix of resulting by-products towards more brominated and more carcinogenic compounds. The shift is likely to be considerably less significant in terms of overall risk for most waters, however, because of the much greater levels of precursor removal achieved by these technologies, especially membrane filtration.

3.0 Baseline Assessment of Microbial and By-Product Exposures And Risks

The existing exposure to microbial and by-product risks is shaped by microbial performance requirements (applicable to all systems) and an MCL of 100 ug/l for Total Trihalomethanes (applicable to systems serving more than 10,000 persons) which have both been in place for over a decade. In addition, as noted in the foregoing, the SWTR and TCR, promulgated in 1989, have begun to set changes in motion in the level of microbial control being achieved from the first customer to the last. Inescapable changes in by-product exposures are also occurring as a result of these changes.

As discussed above, it is virtually impossible to predict the precise nature of the process adaptations that are presently taking place due to the enormous variability from one case to the next and the broad range of process control strategies available. It is possible to develop some characterization of the baseline that existed before these changes were put in motion, however, from data collected prior to these latest adaptations.

3.1 Microbial Contaminant Exposure And Risk

As mentioned in Section 2, the analysis presented in this paper focuses on surface water systems, since these systems are believed to be the group most highly constrained by the competing relationships between microbial and by-product control. More specifically, the analysis in this paper will focus on filtered surface water systems for which there are more data with which to characterize influent levels of contamination with the target organism, Giardia.

In the SWTR regulatory impact analysis (RIA) prepared in 1989,[7] data available at that time[8] were used to derive an assumption of 3.3 Giardia cysts per 100 liters as an average influent concentration in filtered surface water systems. Based in part on data collected by the American Water Works Association,[9] an average of 3.33 logs of total reduction at the first customer was assumed to represent pre-SWTR treatment practices in filtered systems. Combining these two crude assumptions, via the dose/response function for Giardia infection,[10] with an estimated 133,560,000 population exposure in filtered surface water systems yielded an estimated pre-SWTR baseline incidence rate of 27,839 infections per year (2 per 10,000 population), assuming no additional inactivation is achieved in the distribution system. It was then projected that the SWTR would increase the total log reduction achieved in such systems to an average of 4.5 logs at the first customer, due mainly to improved efficiency of filtration (since average turbidities were expected to drop from 0.7 NTU to 0.3 NTU), but also due to some systems increasing their level of disinfection. EPA estimated a post-SWTR incidence rate of 1,882 infections per year in filtered systems (1 per 100,000 population).

The minimum 3-logs of total reduction required in the SWTR was believed to represent less than a 1/10,000 giardiasis risk level at the first customer for systems with good source water quality (i.e., < 1 cyst/100 liters). It is important to note that predicted infections are a worst case representation of predicted illness since many infected people are asymptomatic. The rationale supporting the use of a 1/10,000 giardiasis risk level as a regulatory target is further explored by Macler and Regli.[11]

The SWTR Guidance Document recommends an additional log of inactivation be applied for every additional log of influent Giardia in order to maintain the 1/10,000 risk level at the first customer. As indicated by the assumptions used in the SWTR RIA, it was believed that most plants would exceed the minimum requirements through improved filtration and additional disinfection. It was further believed that systems meeting a 1/10,000 endemic incidence rate would be below the threshold at which epidemic outbreaks occur. The true extent of outbreaks of giardiasis and of other forms of waterborne disease is subject to great uncertainty. The common gastrointestinal symptoms are so easily associated with other causes that it is suspected that much waterborne disease goes unreported. It is known, however, that outbreaks are not reported in systems which both filter and disinfect except when there is an identifiable failure in one of these two barriers.

In a study published in 1991, LeChevallier, et.al.[12] collected comprehensive data including measurements of influent Giardia concentrations and filter effluent Giardia concentrations, as well as computations (via CxT equations) of additional inactivation achieved through disinfection at the first customer. Eliminating results where the Giardia concentrations were estimated on the basis of the detection limit of the monitoring technique, the LeChevallier study provides 62 complete sets of data, representing 46 different plants.

The LeChevallier study employed new, state-of-the-art monitoring techniques for Giardia. Corrected for recovery efficiency (.48) and conservatively estimated cyst viability (.13) (and, dropping data points computed on the basis of the method detection limit rather than actually measured), the results indicate an average influent concentration of 203 cysts per 100 liters. The median is 89 cysts per 100 liters. These results are considerably higher than the average contamination levels of 3.3 cysts/100 liters assumed to exist in such systems in the SWTR regulatory impact analysis.

In addition to noting the generally higher level of influent Giardia implied by the results, the LeChevallier study presents an analysis computing the minimum total log reduction necessary at each plant in order to produce an effluent concentration of 0.0007 cysts/100 liters, equivalent (based on the same dose/response function employed here and in the SWTR RIA) to the 1/10,000 population risk level at the first customer sought by the SWTR. The conclusion is that the plants studied would have to achieve, *on average*, a 5-log total reduction -- compared to the 3-log minimum required in the SWTR to achieve, *on average*, the 1/10,000 risk level at the first customer. This difference is consistent with the two-log difference between the average influent Giardia concentration found by LeChevallier and the average influent concentration assumed in the SWTR RIA. An apparent contradiction is raised, however, by the fact that the average of the total (winter) log-reductions calculated to be actually achieved across the 62 data sets is 7.0 logs, whereas the average Giardia concentration at the first customer is 0.0016 cysts per 100 liters. Despite having a very high average log-reduction, the average Giardia concentration remains significantly higher than the 1/10,000 risk level.

Exhibit 2 provides some further illumination through a plot of influent Giardia versus total log reduction achieved for the 62 data sets. A critical underlying feature of the pre-SWTR baseline, made clear by the random scatter pattern in this plot, is the fact that there appears to be no correlation between the influent Giardia concentration and the total log reduction achieved. The diagonal line through the points represents the formula prescribed in the SWTR Guidance Document; points to the right are plants achieving more total log reduction than needed to meet the 1/10,000 risk target and points to the left are plants achieving less total log reduction than needed to meet the 1/10,000 risk target.

The lack of correlation between the influent Giardia concentration and the total log reduction achieved could be attributable to numerous factors: 1) the lack of monitoring capability for Giardia and appropriately adjusted treatment; 2) attempts to comply with the current TTHM MCL (Significantly, many of the plants to the left of the line are using chloramines.); 3) attempts to comply with current standards for coliforms and state chlorine residual requirements (e.g., Ten States Standards); or 4) attempts to meet other treatment objectives served by pre-disinfection. Whatever the reason, much of the 7.0 logs of total reduction that is achieved, on average, **does not** translate into reduced risk of microbial contamination.

The LeChevallier study reveals that it is the unique relationship between the influent Giardia level and the total log reduction achieved at each individual plant which matters rather than the average level across all plants. Indeed, it is made clear that such simple arithmetic as was performed in the SWTR RIA (in the absence of data such as that provided by LeChevallier) is subject to significant error.

Performing simple arithmetic based upon assumptions of average influent concentrations and average total log reductions may produce very deceiving results. For example, if the average influent concentration (203 cysts/100L) and average total log reduction (7.0) of the 62 data sets in the LeChevallier study are applied to the same exposed population used in the SWTR RIA, a pre-SWTR endemic incidence rate of 353 infections per year is the result (3 per 100,000 population).

If, in contrast, the 133,560,000 persons served by filtered surface water plants are distributed equally across the 62 pairs of influent Giardia and total log-reduction estimates, the results indicate a pre-SWTR disease incidence rate of 2,801,396 infections per year (2 per 100 population). While this rate of endemic incidence is not beyond belief, given the problems of reporting and the similarity of symptoms to those of other diseases, it is probably higher than what most knowledgeable observers would offer as a best estimate. If it is instead assumed that only the first 10 percent of customers are exposed to minimally treated water -- the rest receiving water having substantially more logs of inactivation through contact with residual disinfectant in the distribution system -- then the estimate of pre-SWTR incidence of infection would be 280,000 per year.

The clear implication of the LeCevallier data is that the minimum 3-log reduction requirement of the SWTR does not appear sufficient to reliably achieve the target 1/10,000 risk level in all systems. The higher levels of total reduction specified in the SWTR Guidance Document appear to be necessary in order to assure meeting the target risk level.

Epidemiological evidence confirms the suspicion that the extent of waterborne disease may be greater than previously realized. Bennett, et al present analysis of data collected by the Centers for Disease Control (CDC) which suggest that about 70,000 of 940,000 cases of waterborne disease per year are attributable to giardiasis.[13]

Another study published in 1991 provides evidence suggesting significantly greater incidence of waterborne disease than previously suspected. Payment[14] conducted a 15-month tracking study in Montreal comparing large samplings of families using reverse osmosis treatment units and families using tap water from a water system using very poor source water but apparently meeting the SWTR criteria. Treatment included coagulation, sedimentation, filtration, and residual disinfection. His findings indicate a 35 percent greater incidence of gastrointestinal illness among tap water users. In interpreting these results, it is impossible to determine if the increased incidence is attributable to inadequacies in source water treatment or due to inadequacies in the protection provided from contamination during storage and distribution. In either case, the results indicate more residual microbial risk than previously believed,

although the significance of these findings as they pertain to systems with different source water qualities and levels of treatment still needs to be addressed.

3.2 Disinfection By-Product Exposure And Risk

Despite the fact that an MCL for Total Trihalomethanes (TTHMs) has been in effect for over a decade, there is no resulting national data base with which to characterize exposure because the EPA Federal Reporting Data System records only compliance status, not monitoring results. Many of the large water utilities (those serving more than 10,000 persons) do have records, however, and they have been polled on several occasions by the American Water Works Association (AWWA).

In a 1987 effort sponsored by the AWWA Research Foundation, the Metropolitan Water District of Southern California (MWDSC) conducted a national mail survey of water systems serving more than 10,000 persons.[15] Completed questionnaires were received from 910 respondents. This consisted of 286 surface water systems, 243 groundwater systems, 127 purchased water systems, and 254 mixed source systems. Quarterly sampling data on TTHMs were received from over half of the respondents covering 1984, 1985, and 1986. MWDSC summarized the data in terms of the cross-utility medians (i.e., half of all utilities higher; half lower) of the maximum, minimum, and mean results obtained by individual utilities in each quarter. The summary, presented in Exhibit 3, shows that while utilities are achieving levels in a 30 to 44 ug/l range, on average, half of them have maximum values higher than 65 ug/l in the third quarter. Five percent of utilities reported having been required to make at least one public notification regarding violation of the TTHM standard. Groundwater systems had markedly lower TTHM levels, averaging around 10 ug/l.

Thirteen percent of respondents to the MWDSC survey indicated they had changed chlorine dosages to comply with the TTHM standard. Sixteen percent indicated they had moved the point of disinfection. Eleven percent of all respondents indicated use of chloramines. Among users of large lake and flowing surface sources, 25 percent reported use of chloramines. Improved clarification was reported by five percent of respondents. Very few other TTHM compliance adaptations were reported by significant proportions of the respondents.

In 1989, the AWWA Research Foundation sponsored a survey to establish the first phase of a standing Water Industry Data Base (WIDB).[16] The effort covered all utilities serving more than 50,000 persons. The Phase I WIDB contains data for 442 surface water treatment plants (a second phase of the WIDB project has extended the data base down to systems serving more than 10,000 persons and includes over a thousand records).

The Phase I WIDB data for plants that presently filter shows that 65 percent of softening plants make at least some use of alternate disinfectants (56 of the 65 percent use chloramines) compared to 37 percent for plants that do not soften (25 of the 37 percent use chloramines). For softening plants, the median of the average annual TTHM concentrations was 26 ug/l for 27 plants using chloramines versus 60 ug/l for 19 plants using chlorine. For plants that do not soften, the median of the average annual TTHM concentrations was 36 ug/l for 43 plants using chloramines versus 45 ug/l for 113 plants using chlorine. These data suggest that softening plants are more tightly constrained by the current TTHM standard than non-softening plants.

Among the filtered surface water plants which practice softening, those using chloramines answered yes to the practice of pre-disinfection 91 percent of the time while those using chlorine answered

yes only 54 percent of the time. Similarly, in filtered surface water plants which do not soften, those using chloramines answered yes to the practice of pre-disinfection 91 percent of the time compared to 80 percent for those using chlorine. These data suggest that chloramines may be being used as a means of clinging to some of the benefits of pre-disinfection while also maintaining lower levels of TTHMs than if chlorine were used.

Other noteworthy relationships in the Phase I WIDB data are that plants using chloramines have higher influent TOC concentrations, higher average temperatures, and longer distribution system residence times than plants using chlorine. All of these factors, which cause higher TTHM formation, have probably influenced the shift to chloramines.

In 1989-90, the AWWA Disinfection Committee performed a survey of disinfection practices[17] which drew responses from 283 respondents, mostly (96%) systems serving more than 10,000 persons. About half were predominantly surface water systems and the other half were predominantly groundwater systems. Of 186 respondents (surface and ground) describing measures taken to comply with the TTHM MCL of 100 ug/l, the top categories of responses were:

44% no changes needed
24% moved first point of chlorination downstream
23% ceased prechlorinating
20% decreased prechlorination dose
19% add ammonia after some contact time
16% improve coagulation by increasing pH
11% modify coagulation by other method

Of these respondents, 39 utilities reported problems as a result of modifications made to attain TTHM compliance. The top categories of modifications producing operational problems were:

56% add ammonia after some contact time
44% moved first point of chlorination downstream
36% improve coagulation by decreasing pH
36% ceased prechlorinating
28% decreased prechlorination dose
18% modify coagulation by other method

Of the systems reporting problems, the categories of problems reported were as follows:

15% increased heterotrophic plate counts in treated water
21% increased heterotrophic plate counts in tap water
13% coliforms in distribution system

For the 134 predominantly surface water systems that responded to the question regarding treatment modifications to meet the TTHM MCL of 100 ug/l, the responses were as follows:

20% moved chlorination point
19% ceased prechlorination
16% decrease prechlorination
16% add ammonia after some contact time

16% improve coagulation
13% change preoxidation

The results of the AWWA Disinfection Survey appear to confirm that compliance with the current TTHM standard can be achieved with relatively simple and inexpensive treatment modifications. However, evidence of side effects on microbial treatment objectives are also apparent.

Although the three studies discussed above provide evidence of progress made in complying with the TTHM MCL of 100 ug/l, assessment of the baseline cancer risk posed by the remaining by-product exposure requires data on the concentrations of the individual compounds, encompassing not only the individual trihalomethanes but the individual haloacetic acids as well. Such data does not exist in great abundance. The two such data sets available have been utilized to produce high and low estimates of baseline cancer incidence (computed from a toxicological perspective; i.e., assumed exposure factored by estimated dose/response relationships), summarized in Exhibit 4.

The first data set has been collected by the EPA Technical Support Division (TSD)[18] and is probably biased towards worst cases which were the original focus of the EPA investigations. Results are summarized in Exhibit 4 in the column labelled "High Case Estimate." As a point of comparison, the TSD data indicate an average TTHM concentration in systems serving more than 10,000 persons of 84 ug/l, roughly twice the average levels reported by such systems in the AWWARF survey and the WIDB survey discussed above. The high case cancer incidence estimates are therefore considered a high case, being based on this data set.

Cancer incidence estimates are presented in two forms, based on maximum likelihood estimates of the dose-response relationship and based on a 95th percentile estimate of the dose-response relationship. While the 95th percentile is the basis that has been used in most previous assessments of drinking water cancer risks, the microbial risk assessment methodology provided for assessing incidence of giardiasis infections is based upon a maximum likelihood procedure. Thus, the maximum likelihood estimates are a better basis for comparison. As shown in Exhibit 4, the total baseline cancer incidence in the high case, based on the maximum likelihood estimates, is on the order of 159 cases per year (0.4+2.4+20+136-=158.8). Several significant footnotes must accompany this result. First, it is significant that all but three of these cases are attributable not to trihalomethanes, but to haloacetic acids. The greater impact of haloacetic acids is a result of the use of the maximum likelihood procedure and the higher cancer potency factors attributed to dichloroacetic acid and trichloroacetic acid than to the THMs. On a maximum likelihood basis, the cancer risk from trihalomethanes becomes less significant. A second footnote concerns the fact that cancer risk estimates are presently available for only two of the haloacetic acids. No risk factors are available for the brominated haloacetic acids. A third footnote is that TCAA and dibromochloromethane are tentatively being classified by EPA as Class C (possible) carcinogens, rather than Class B (probable) carcinogens. As a conservative assumption, this analysis has assigned carcinogenic potential equal to that of Group B. Finally, it is noted that of the total incidence, 20 cases are projected in systems serving fewer than 10,000 persons.

The Low Case Estimates presented in Exhibit 4 are based on a study by Krasner performed by the Metropolitan Water District of Southern California (MWDSC)[19] in which data on concentrations of individual compounds were collected at the clearwell prior to entry into the distribution system. Higher concentration levels could be expected if the samples had been collected in the distribution system. The median TTHM concentration of the plants surveyed in this study was 25 ug/l, somewhat below the levels typifying the other surveys reviewed above. If these data were assumed to represent a lower bound of

exposure, the total baseline cancer incidence, as indicated in Exhibit 4, would be 40 cases per year, on a maximum likelihood basis.

A recent "meta" analysis of epidemiological data[20] has produced estimates that as many as 10,000 cases of cancer per year may be attributable to chlorinated drinking water. There is considerable controversy among epidemiologists on the appropriateness of applying "meta" analysis on the data that were used, and on the interpretation of the results. The results of the study differ significantly from the estimates yielded by the above toxicological approach (exposure/dose-response) to estimating baseline cancer risk. The analysis in this paper has been developed using the toxicological approach.

4.0 Research Objective and Approach

Clearly, assessing the impacts of alternative regulatory options for disinfection by-products is not straightforward. Additional difficulty results because the objective of this research is to devise a means of analyzing the problem in a summary form that permits drawing generalized conclusions to serve as a basis for national level analysis. At least four features of the problem contribute significant additional complications in elevating analysis to an aggregate level:

- The baseline is in motion. Water systems are presently in the process of complying with SWTR and TCR requirements subject to the existing by-product constraint embodied in the TTHM MCL of 100 ug/l. Analysis of microbial and by-product exposures under the currently defined regulatory regime indicates that -- under various interpretations -- both types of exposure have a wide range of possible risk.

- The two types of exposures are dynamically interrelated in a manner which is not completely revealed through simple intuition. Inadvertent side-effects are accentuated under various combinations of extreme conditions, making the average condition a deceiving benchmark. The central tendencies are not as important as the interactions between the tails in assessing potential trade-offs.

- There is a factorial number of combinations of raw water, treatment, process control, and distribution conditions that present an unmanageable number of conceivable "extremes" to be considered in analyzing potential interactions of the exposures. There are, in fact, many times more combinations than there are public water systems. There is also a factorial number of conceivable combinations of regulatory options to consider (e.g., TTHMs 100, SWTR 3-logs; TTHMs 50, SWTR 4-logs; etc.).

- Finally, there are significant *uncertainties* inherent in the current state-of-the-art of both exposure and risk assessment pertaining to both types of health risks. Many of the key areas of uncertainty can be addressed through "what-if" analysis to test the sensitivity of results to uncertain estimating procedures. However, such extensive "what-ifs" add to the factorial burden of analysis. Moreover, in addition to areas of uncertainty, there are several areas where so little is known of potential side-effects that even provisional quantification of exposure and risk is infeasible (e.g., formation and health risk from brominated haloacetic acids, ozone by-products, changes in bacterial populations in the distribution system, Cryptosporidium, etc.), requiring them to be treated as complete *unknowns* at this point.

Analysis of by-product regulatory options is a unique problem. Most drinking water regulations present much simpler analytical problems, where national impacts can be fully characterized in a way that is representative of the overall national exposure and risk. Because of the factorial dimensions of the by-products problem, and the extensive range of uncertainties and unknowns characterizing the available information and understanding, analysis of by-products regulation cannot be approached in the same comprehensive manner. Even if the outstanding uncertainties and unknowns were resolved, the factorial dimensions would still place practical limits on the extent of the analysis.

4.1 Defining A Manageable And Meaningful "Core Problem"

Recognizing the practical constraints, the specific research approach adopted in this analysis is to define the nature of the trade-offs by focusing on a *core problem*; a manageable segment of the problem where the most conflicting interactions and the most significant population exposures are likely to be found. A manageable and meaningful *core problem* can be defined by two means. First, some of the factorial dimensions may be collapsed into a smaller number by focusing on those relationships which are perceived to be most influential in causing trade-offs to occur. Fortunately, this approach is feasible because, although there are many dimensions conceivably involved, there is sufficient understanding to suggest which are the strongest relationships (i.e., where extreme treatments, and therefore trade-offs, are most likely).

Surface water systems are generally much more likely to have to resort to extreme treatments than groundwater systems. They also serve a much larger segment of the overall population. Though there are locations (e.g., FL, CA) characterized by high TOC or high bromide groundwaters, unless they are groundwater under the direct influence of surface water, they are not vulnerable to protozoa and therefore do not need as much disinfection. Any set of regulatory requirements achievable by most surface water systems without adverse trade-offs will probably also be achievable by most groundwater systems. Exhibit 5 illustrates the relative proportions of population exposure between surface and ground water systems.

In addition to collapsing factorial dimensions to define a manageable and meaningful *core problem*, there must also be a strategy to maintain an accurate summary representation of the variability introduced by site-specific conditions. Site-specific variability affects the analysis in two ways. First, the multidimensional baseline configuration of factors affecting microbial and by-product risks is unique in every local situation. Second, the baseline condition is changing in every local circumstance in response to implementation of the SWTR and TCR. The various conceivable combinations of site-specific conditions must be factored into the analysis in a way that is somehow representative. This site-specific variability can be analyzed statistically through the technique of Monte Carlo simulation, described in section 5.0.

4.2 Coping With Uncertainties and Unknowns: Scenarios And Place-Holders

The second part of the research strategy for defining a manageable and meaningful *core problem* is to collapse additional dimensions of complexity through the use of *scenarios* and *place-holder assumptions*. If the above-described complex of interrelated factors and processes that simultaneously contribute to by-product and microbial risks is envisioned as one great multi-dimensional matrix, the scenarios and place-holder assumptions provide a limited selection of cross-sections through it. A factorial number of other cross-sections are feasible, but the selected views are intended to offer a meaningful starting point -- a benchmark from which other "what-if" excursions can be launched.

Even within the *core problem* category of surface water systems, *the number of conceivable* combinations of microbial and by-product risk targets that could be considered is factorially large. The approach to coping with this large number of combinations is to bracket the range of microbial protection through evaluation of two scenarios: a SWTR scenario, and an Enhanced SWTR scenario (ESWTR). The SWTR scenario assumes that all surface water systems will be constrained to meet a total reduction target for Giardia of only 3-logs at the first customer. Additional log-reduction for poorer quality source water that is recommended in the SWTR Guidance Document is assumed to be ignored. The ESWTR scenario presumes an enhanced SWTR is enacted which would convert the prescription for additional total reduction presently made in guidance into a mandatory requirement. Due to lack of adequate monitoring techniques, an easily implementable enhanced SWTR does not appear to be a near-term possibility, but is nonetheless an important benchmark. Both scenarios assume the SWTR disinfectant residual requirements, the coliform rule, and the lead rule are met in the distribution system.

Another significant challenge in defining a *core problem* is presented by the fact that quantitative exposure and risk assessment is feasible for some of the microbial and by-product risks (albeit, subject to significant *uncertainties*), but is not feasible for others, leaving them as pure *unknowns*. The estimable aspects of the problem include risks associated with Giardia, trihalomethanes, dichloroacetic acid and trichloroacetic acid. Exposure and risk assessment models have been pieced together for these contaminants. The assumptions required are regarded as *place-holders*. As implied by the name, place-holder assumptions are intended to be continually refined as better information becomes available. They can also be systematically varied as the object of "what-if" analysis to examine the sensitivity of the results to *uncertainties* associated with them.

As a result of its use as a target organism in the SWTR, methods to predict the level of inactivation of Giardia achieved through disinfection (C-T calculations) have been developed. Also as a result of its recent popularity, a dose response function exists for Giardia.

Chemical equations with which to predict the formation of disinfection by-products have been the focus of much recent research effort. As a result, equations are available with which to predict formation of trihalomethanes and haloacetic acids as a function of the concentrations of organic precursors and other raw water and treatment conditions. The research in this area is far from complete. The equations utilized in the present analysis are clearly *place holders*. Although the equations have been validated within numerous individual plants, their validity when extrapolated outside the boundary conditions of those cases remains a question mark which can only be removed through broader validation studies. The equations used to predict the brominated species are particularly prone to such error. The equations utilized for haloacetic acids base predictions on concentrations of THMs rather than directly as a function of water treatment and precursor parameters. The caveats associated with all the formation equations have been documented in the users manual which accompanies the USEPA Water Treatment Plant Model.

The cancer risks attributable to three of the four trihalomethanes (chloroform, bromodichloromethane (BDCM), and bromoform) have been estimated according to standard protocols used by EPA in establishing MCLGs. The final carcinogenic status of dibromochloromethane (DBCM) is unclear at this time, however. As a conservative *place holder* assumption, the cancer risk estimate for BDCM has been used for DBCM. (NB: the estimated risk for BDCM has been increased since this analysis was finalized.)

Cancer risk estimates have been developed for the chlorinated haloacetic acids (dichloroacetic acid (DCAA) and trichloroacetic acid (TCAA)) following standard protocols used by EPA in establishing MCLGs. Although a cancer risk estimate has been developed for TCAA, its carcinogenic status has not

been finally established. As a conservative *place holder* assumption, the cancer risk estimate for TCAA has been used in the analysis as though it were a B2 carcinogen. While formation equations exist for five of the haloacetic acids (mono-, di-, and trichloroacetic acids and mono- and dibromoacetic acid), cancer risk estimates have been developed only for DCAA and TCAA (MCAA does not appear to be a carcinogen). Thus the present analysis predicts concentrations of two brominated haloacetic acids, but does not quantify associated risks. Finally, to further condense dimensions, summary results are presented in terms of hypothetical Total Trihalomethane (TTHM) MCL alternatives and hypothetical Total Haloacetic Acid (THAA) MCLs, despite the fact that calculations are performed for individual compounds. Results for individual compounds are provided in appendices.

In focusing on those contaminants for which exposures and risks are estimable, it is possible to begin to quantify the *core problem* and learn as much about the potential risk-risk trade-offs as possible given current information. Insights regarding the potential significance of yet inestimable, or *unknown*, risks can be obtained by further segmenting the analysis into two additional scenarios. Since more *unknown* risks are associated with the use of alternate disinfectants than with the use of chlorine, the analysis has been structured into two scenarios: *with* and *without* alternate disinfectants.

The *without scenario* permits evaluation of the limits of risk reduction possibilities for Giardia, trihalomethanes, and chlorinated acetic acids without introducing other unknown by-product or microbial risks associated with alternate disinfectants. The *with scenario* permits evaluation of the potential for further reductions in Giardia, trihalomethane, and chlorinated acetic acid risks at the expense of introducing other unknown risks. Results for the *with scenario* can be further subdivided to differentiate between a scenario allowing only chloramines and a scenario allowing both chloramines and ozone. Comparison of the results of *with* versus *without* scenarios should make it possible to evaluate the potential significance of the *unknowns* (i.e., how many plants might switch to alternate disinfectants as a means for meeting TTHM and THAA regulatory requirements). Cost estimates can also be made to compare complying with and without alternate disinfectants.

The guiding principle in this attempt to develop exposure and risk assessment models is the scientific method of inquiry. Models are constructed using the best information available as place-holders. Hypotheses are substituted as place-holders for missing information or understanding. Scenarios are structured to bound the range of possibilities introduced by complete unknowns. The models are exercised under a range of conditions to examine the plausibility of results and to explore sensitivity to the major uncertainties and unknowns. Using the exposure and risk assessment models in this way, significant areas of research need can be identified and prioritized in a systematic manner. The models can be refined as research results provide new information and understanding.

5.0 Analytical Methodology

There are four steps to the overall methodology for analyzing potential trade-offs.

- *step 1:* model the mix of raw water and distribution system characteristics in a manner that is representative of the variability in site-specific conditions;

- *step 2:* predict the compliance choices that plants will make in attempting to meet a given set of regulatory targets, given their raw water and distribution system characteristics;

- ***step 3:*** predict the plant effluent (1st customer) and distribution system exposures that will result from the given characteristics and compliance choices;

- ***step 4:*** predict the microbial and by-product risks that will result from these exposures.

Exhibit 6 illustrates these steps and summarizes the different analytical strategies that have been applied to each. These are discussed below.

5.1 Step 1: Characterize Raw Water and Site-Specific Variability

Step 1 requires a means of modelling influent variability that is representative of conditions nation-wide. As described in earlier sections, both microbial and by-product control techniques have side effects which are exacerbated under extreme combinations of influent water quality conditions. It is these side effects that are responsible for the existence of trade-offs between microbial and by-product treatment objectives. The analytical objective for a national exposure assessment is therefore to build a model that permits analysis of side effects resulting from treating extreme raw water conditions.

Analyzing a *core problem* focusing on surface waters provides a practical strategy for reducing the scope of this analytical need to just one category of raw waters. The most fundamental relationship in the *core problem* is that between influent TOC, influent bromide, and influent Giardia concentrations. Although many other factors are included in the model, as described below, these three are assumed to be the fundamental influences -- the "drivers." High-TOC/high-Bromide/high-Giardia source waters are likely to be much more susceptible to adverse trade-offs than low-TOC/low-bromide/low-Giardia source waters. In addition, for any given combination of influent concentrations, the extent of the trade-offs will be a function of the interplay between influent conditions and alternative combinations of regulatory constraints. There are three different regulatory targets: a microbial target at the plant effluent (or 1st customer); a microbial target in the distribution system (the disinfectant residual requirement); and a by-products target in the distribution system. Significant trade-offs can result depending upon how the regulatory regime specified at these three points is constrained. Modelling the *core problem* under a range of assumptions about influent conditions and regulatory alternatives permits an assessment of the possible extent to which trade-offs may be encountered.

Even when limiting analysis to focus on the *core problem*, a difficulty still arises in coping with the enormous variability in site-specific conditions. A first instinct in approaching an analysis of by-product regulatory options might be to perform case studies of plants representing different types of raw water conditions. Upon closer scrutiny of the factors involved, however, it becomes apparent that an unmanageable number of different cases would be required in order to capture the diversity that exists in water supplies. Moreover, significant leaps of faith would be needed for determining the influence that individual cases should have in the overall analysis and in the ultimate selection of appropriate regulatory options.

Another approach would be to convene a panel of "experts" to render a judgement regarding the effects of different regulatory options. Experts provide a concentrated source of case studies, drawn from their collective experiences. While this feature is very efficient, it is likely that such a panel would also have difficulty weighting different cases in arriving at the type of generalized conclusion required in this unusual rulemaking. The panel of experts approach has been used in development of EPA regulatory impact analyses involving straightforward contamination problems such as Flouride, VOCs, IOCs, SOCs, and Radionuclides. It was also used -- with much greater difficulty -- in analyses of the Surface Water

Treatment Rule and the Lead and Copper Rule, since these rulemakings involved optimization of entire treatment and distribution systems as a function of variations in raw water quality. The treatment and distribution optimizations implied by the by-products regulatory options are several times more complex than previous rulemakings.

Another analytical option is to characterize site-specific variability through statistical modelling (simulation) of the variability in raw water and distribution system characteristics. The diversity of site-specific conditions is represented through the technique of Monte Carlo simulation applied to the *core problem.*

The key question is: what percent of the time can the most extreme combinations of circumstances be expected to co-occur? Monte Carlo simulation provides an explicit methodology through which the frequency of such co-occurrences can be assessed. In this procedure (fully described in a companion paper),[21] numerous parameters that are critical to predicting microbial and by-product treatment performance are characterized as probability distributions. Next, interdependencies between related parameters (e.g., TOC and UV; pH and alkalinity) are examined and joint occurrence relationships are statistically defined. A significant assumption made in this procedure is that influent Giardia occurrence is independent of all other influent parameters. (Since the approach to simulating influent Giardia levels is integral to the approach taken to the Giardia risk assessment, it is discussed under step 4, below).

In the actual simulation step, individual and joint distributions are sampled randomly to create 100 different simulated raw water quality profiles which, depending on the quality of the data and the statistical analysis, should be representative of the variability that will confront surface water systems. In other words, the critical analytical step of weighting, or assigning a frequency to different combinations of extreme raw water and distribution system conditions to form a representative composite picture is handled by this procedure, based on an explicit statistical analysis. In effect, the statistical approach provides a means of considering 100 case studies at a time, that are randomly selected via a procedure that should be broadly representative of the inherent variability between individual sites, and thus of the extent to which extreme conditions co-occur.

The characterization of influent raw water quality and distribution system residence time, was made possible through the extensiveness of the AWWA Water Industry Data Base (WIDB) for fundamental parameters such as pH, hardness, alkalinity, temperature, and many others. There are important weaknesses, however, affecting the three driving variables in the *core problem*. The WIDB contains only just enough data on TOC (84 observations), to permit a statistical approach. Furthermore, the WIDB does not provide data on bromide or Giardia. Thirty bromide observations from a national study by Krasner, et al were utilized to define a statistical distribution for influent bromide concentrations.[22] (An ongoing study by the AWWA Research Foundation is developing new data on TOC and bromide which may be used to improve current *place holder* assumptions.) The LeChevallier study of Giardia concentrations (representing 46 plants), discussed above, was utilized to model the variability in influent Giardia concentrations between plants. Another data base was used to model the day-to-day variability of Giardia cysts within individual plants (Hibler[23]). A companion paper describes these statistical analyses developed to characterize Giardia occurrence as a function of both these considerations.[24]

The provision of explicit methodology for assessing site-specific variability enables explicit inspection of the uncertainties inherent in this key contributor to the overall exposure assessment. All distributional assumptions are regarded as *place-holders* in the same sense discussed earlier. The Monte Carlo framework can support sensitivity and what-if analyses that can shed light on the potential

significance of major areas of uncertainty. Exhibit 7 presents a three-panel summary of the simulated values TOC, bromide and Giardia as compared to the respective observations in the data sets on which the simulations are based. Exhibit 8 presents plots of simulated influent TOC versus simulated influent bromide and versus simulated influent Giardia. The assumption of total independence between these "driving" variables is evident in the scatter patterns.

5.2 Step 2: Predict Compliance Choices

The second step, predicting the compliance response to individual site specific circumstances in terms of treatments deployed and process control settings, is far more troublesome. It represents another source of factorial possibilities that must somehow be contained within a manageable analytical framework. As mentioned earlier, there is often no unique solution to the treatment and process control problem. There may be several different combinations of strategies that will serve to achieve compliance in any given circumstance. As noted in Section 2.0, this feature has two profound analytical implications: 1) it is virtually impossible to construct a model that can precisely replicate the existing baseline condition; and 2) the extent to which the most extreme compliance options (e.g., GAC or membrane filtration) are relied upon depends on the extent to which less extreme options (e.g., use of alternate disinfectants) are adequate, given raw water conditions.

A baseline "calibration" of the Monte Carlo simulation procedure was undertaken during prototype development of the modelling methods employed here. Results of that effort, summarized in the next few paragraphs, are documented in more detail in a separate paper.[25] The AWWA WIDB is unique in that it enables a correlation of existing treatment practices with data on influent water quality, plant effluent quality, and distributed water quality. The uniquely comprehensive coverage of the WIDB data across the treatment train suggests the potential to obtain a baseline "calibration" of the Monte Carlo procedure. Such calibration might be achieved by adjusting treatment and process control assumptions to produce model results that replicate the statistical distributions exhibited in the WIDB finished water and distributed water data. In the end, it became clear that process control assumptions regarding factors not included in the WIDB (e.g., chlorine dosages, basin contact times, and points of chlorination) are more important to matching the observed distributions of effluent and distributed water quality than the distributional assumptions applied to the raw water parameters. It was shown to be possible to achieve a number of different calibrations through a number of different combinations of these fixed settings -- i.e., since different process control assumptions could be used to achieve the same target used for calibration, one could not conclude which assumptions would be most appropriate.

It was possible to match the means of the predicted total trihalomethane and chlorine residual distributions for 100 randomly synthesized plants to the means of the observed distributions in the WIDB data under a number of different settings. The predicted and observed distributions for chlorine residual were shown not to be statistically different as measured by a Kolomogorov-Smirnoff test. The predicted and observed distributions for total trihalomethanes did not compare favorably, however. Since the chlorine dosages were fixed by calibrating to the chlorine residual (via a chlorine decay equation), they reflected the log-normal distribution of the chlorine residual data. The total trihalomethane levels predicted from these dosages were then also log-normal. However, the observed distribution for total trihalomethanes in the WIDB data is normal -- a reflection of the fact it is a regulated parameter. In reality, the plants in the upper tail of the log-normal TTHM distribution predicted by the model would have undertaken various process refinements to meet the current TTHM standard. Such refinements were not accounted for in the model.

It was concluded that true model "calibration" could eventually require process data at such a level of detail that the exercise becomes indistinguishable from that required for case-by-case "validation" studies. The rule development process might stimulate the development of additional validation through the release of EPA's Water Treatment Plant Model and accompanying users manual.[26] Despite the inherent difficulties, some measure of calibration was achieved. The revised version of the model produces predictions that appear to approximate national occurrence data on average and that, starting from a pre-TTHM standard condition, reflect treatment changes comparable to those that actually occurred to meet the TTHM MCL of 100 ug/l. These results are discussed in section 6.0 and confirm that the Monte Carlo procedure involving distributional representation of the variability in raw water conditions is reasonable, *on average*. But, the imperfect match to observed by-product *distributions* is an important source of error inherent in the process control assumptions applied to the simulated raw waters. The tails of the distributions of chlorine dosages, chlorine residuals, and by-products are ultimately the determining influences in characterizing what percent of plants can meet a given microbial or by-product risk target. Results show that process control assumptions and model equations are over-predicting TTHMs in the upper tail of the distribution and under-predicting in the lower tail. Thus conclusions regarding the attainability of relatively less stringent TTHM MCLs are likely to be overly pessimistic while conclusions regarding the attainability of relatively more stringent MCLs are likely to be overly optimistic.

Without a baseline characterization of the configuration and performance of treatments and process controls, it is not possible to approach regulatory impact analysis in the conventional manner of comparing pre- and post-regulatory conditions. The approach adopted therefore is one of assessing the attainability of different treatment objectives as if working from a "clean slate." Microbial treatment objectives are evaluated in terms of two scenarios, as described above: 1) the SWTR scenario, assuming minimalist adherence to the existing SWTR (i.e., ignoring the advice of the Guidance Document for poorer quality source waters); and 2) the Enhanced SWTR scenario (ESWTR), assuming adherence to the SWTR Guidance as if it were a firm requirement. Both the SWTR and the ESWTR scenarios assume disinfectant dosages sufficient to meet the distribution system residual requirements of the SWTR, as well as pH conditions assumed sufficient to meet the requirements of the Lead Rule. A full range of alternative by-product MCLs are evaluated under each microbial scenario.

The answer to the question of what is ultimately attainable should be the same regardless of whether the baseline is understood. Similarly, the trade-offs between the different treatment objectives can be revealed just as clearly through the "clean slate" approach to assessing treatment performance under different regulatory scenarios. At some point it will become necessary to "net out" the treatments already applied to comply with current standards from the treatments required to comply with alternative standards in order to pinpoint the regulatory impact. Fortunately, studies such as those reviewed in Section 3.0 indicate that most of the adaptations undertaken in response to the current TTHM standard have involved simple low cost process control modifications (moving points of chlorination, adjusting dosages, etc.) that would not amount to significant costs at an aggregate level. The largest adaptation in evidence is the indication from WIDB data that perhaps as many as one-third of surface water plants are using chloramines, which is also relatively inexpensive.

The "clean slate" approach is analyzed in terms of a *With* Alternate Disinfectants Scenario and a *Without* Alternate Disinfectants Scenario (described in Section 4.0). The *Without* Scenario would not be expected to bear any resemblance to the baseline treatment configuration in any case, since chloramines and other alternate disinfectants are already in use. In both the *With* and *Without* Scenarios, a progression of successively more extreme treatment and process control adaptations is assumed with increasingly stringent MCLs. The progression of treatments follows a least-cost criteria; the less costly compliance

options being tried first before progressing to more extreme and more costly measures. This sequence is illustrated in the decision tree illustrated in Exhibit 9. As noted in Section 3.0, there appears to be a tendency of some plant operators to add ammonia as a means of preserving the use of pre-chlorination in the face of by-product control requirements. The least-cost criteria of the decision tree produces results (Section 6.0) that indicate less extensive use of chloramines in the *With* Alternate Disinfectants Scenario than the proportion shown in the WIDB and AWWARF data. Despite this divergence from reality, the least-cost sequence, as illustrated in Exhibit 9 is believed to be an intuitively sound *place holder* assumption to assess likely treatment adaptations. The decision tree is discussed further in a separate paper.[27]

A related problem arises in the "clean slate" approach regarding the need to make an assumption about the presence or absence of pre-chlorination in the starting condition. As shown in Exhibit 9, elimination of pre-chlorination is the first step in the compliance decision tree. It has the potential to greatly reduce by-product formation, but can also compromise microbial treatment under certain conditions. For this analysis, the presence or absence of pre-chlorination was simulated as a random variable based on the prevalence of the practice indicated in the AWWA WIDB which shows about 80 percent of surface water plants still practicing pre-disinfection as of 1988 (Pre-SWTR). This proportion seems high by comparison to the Disinfection Survey conducted by the AWWA Disinfection Committee in 1990 which shows, at most, two-thirds. However, the wording of the WIDB question was somewhat vague since the term "predisinfection" was not more precisely defined. Ideally, pre-TTHM standard baseline data on the extensiveness of pre-chlorination would be required in order to truly start with a clean slate. The WIDB estimate is used with the knowledge that it may be on the high side. Alternatively, it may be an accurate reflection of the fact that many plants have followed a different decision tree in their compliance choices, favoring the introduction of chloramines as a strategy for preserving the benefits of pre-chlorination.

In addition to defining the likely sequence of treatments resulting from alternative regulatory scenarios, it is also necessary to specify a wide range of specific process control assumptions. A long list of *place holder* assumptions is required here, as discussed at length in a separate paper.[28] In general, the assumptions fall into three categories: *best estimates*, *constraints*, and *bounding assumptions*. *Best estimates* are employed in places (e.g., initial dosages and unit process contact times) where the range of variability is considered reasonably estimable based on engineering judgement and experience. *Constraints* are performance requirements that relate to treatment objectives other than microbial or by-product objectives. The need to simultaneously meet these other objectives forces more extreme microbial and by-product treatment solutions in some instances. The most significant constraints are pH conditions assumed necessary to comply with the Lead Rule, and maximum disinfectant residual concentrations required to satisfy the taste constraint for chlorine and a possible MCL of 3.0 mg/l for chloramines.

Bounding assumptions were applied at several key junctures where it was deemed prudent to estimate conservatively in order to minimize the chances of under-estimating the potential for trade-offs between the competing treatment objectives. An important set of bounding assumptions concerns the engineering design margins assumed in making treatment choices (described more fully in a companion paper[29]). The CxT equations used to assess compliance with SWTR requirements for disinfection are applied with a 20 percent over-design factor. Similarly, compliance with by-product MCLs is evaluated with a 20 percent over-design factor. In combination, these two *bounding assumptions* are expected to reflect the upperbound of possibilities for conflicts between treatment objectives, minimizing the possibility that the conflicts between them will be under-estimated.

Similarly, the effect of seasonal temperature variations on compliance choices and resulting exposure estimates has been incorporated into the model via a set of ***bounding assumptions***. Partially to avoid the necessity of building a much more complex model capable of simulating seasonal treatment adaptations, and partially to minimize the possibility of under-estimating the potential for trade-offs between treatment objectives, the model equations are structured to predict Giardia concentrations on the basis of average winter temperatures and by-product concentrations on the basis of average annual temperatures. The two temperatures are simulated based on the joint distribution they exhibit in the AWWA WIDB data.

5.3 Step 3: Predict Resulting Microbial & By-Product Exposures

Step 3, predicting microbial and by-product exposures resulting from the different combinations of raw water, distribution system, and treatment characteristics, is accomplished through application of a number of chemical equations that have been brought together in a comprehensive modelling framework in the USEPA Water Treatment Plant Model.[30] Among these are the CxT equations utilized to compute disinfection requirements, trihalomethane formation equations, haloacetic acid formation equations, and chlorine decay equations.

All of these relationships are considered *place holder* assumptions. They have all received some measure of validation and yet many uncertainties remain. The major ones are as follows:

- The CxT equations were developed to assess inactivation at the first customer. In the model employed in this analysis, they are linearly extrapolated assuming first order kinetics to estimate total log inactivation through the distribution system. Thus, for a given concentration of chlorine, pH, and water temperature, if a CT of 300 achieves a 3-log inactivation of Giardia cysts, a CT of 900 (which may occur through a point in the distribution system) would be estimated to achieve a 9-log inactivation. No data are available to assess the validity of this assumption for Giardia inactivation, although for viruses there appears to be reduced inactivation efficiency relative to CT, as the level of inactivation increases.

- Giardia has been selected as the target organism for analysis. The rationale for this is described in more detail in a companion paper.[31] Since Cryptosporidium is much more resistant to disinfection than Giardia, and is ubiquitous in surface waters, it may be a more appropriate target organism, but it is not sufficiently understood to support all the analytical needs.

- The trihalomethane formation equations have been the focus of considerable research and have been empirically validated to some extent. A major source of potential error concerns use of these equations to extrapolate outside the boundaries of the raw water and treatment conditions that characterized the plants in which they were originally developed and tested. Although predicted results for total THMs seem to fall within a plausible range of occurrence, results for individual THMs, especially regarding the brominated compounds, may have large uncertainties.

- The haloacetic acid formation equations are at a less refined stage of development. The equations predict haloacetic acids as a function of predicted trihalomethane concentrations rather than as a direct function of raw water parameters and treatment conditions. Much less validation research has been performed on haloacetic acid formation equations. Although results for THAAs seem to fall within a plausible range of occurrence, there could be large uncertainties in the predictive capability for individual compounds, especially the brominated compounds. New equations have

recently been developed and are being incorporated into the DBP-RAM for future iterations of the analysis.

While the collection of equations being utilized produces results in plausible ranges, all equations are subject to error. Significantly, extrapolations outside the boundaries of the conditions where equations were estimated and verified may be most susceptible to error. Unfortunately, such results are also most likely to represent the types of extreme conditions that are critical to the analysis. Until further characterization of the error in the selected model equations or replacement with better equations, the results presented herein represent *best estimates.*

Presently, trihalomethane and haloacetic acid formation equations have been developed only for surface water plants that do not soften. Owing to the different chemical relationships that characterize a softening plant, a different set of by-product formation equations is required. EPA is currently developing such equations for incorporation into the Water Treatment Plant Model and DBP-RAM.

The initial analytical effort has focused only on large (>10,000 population) surface water systems that presently filter but do not soften. This portion of the universe represents a substantial proportion of the total population exposed to the highest microbial and by-product risk levels. They serve a total of 103 million persons, equivalent to 64 percent of the total population served by community surface water systems (162 million) and 43 percent of the total population served by all community water supplies (242 million; not including non-transient, non-community systems). Under some conditions, surface water plants which soften could be more highly constrained. This question bears further investigation. By comparison, the total population served by large (>10,000) surface water softening plants is about 20 million.

Although the initial modelling work has focused on large (>10,000 population) surface water systems that do not soften, it is believed that results of this analysis can be applied to smaller systems of the same type. The raw water characteristics of the large systems represented in the principal data source -- the AWWA WIDB -- should not be vastly different from raw water characteristics facing small water systems of the same type.

5.4 Step 4: Predict Resulting Microbial and By-Product Risks

Step 4, predicting microbial and by-product risks resulting from the projected exposures, is performed through the application of risk assessment models for Giardia and carcinogenic by-products, respectively. These models are of the nature of *best estimates.* In more precise statistical terms, the risk models are based upon "maximum likelihood" estimates of the dose-response relationships. Use of maximum likelihood estimates is a departure from EPA's usual practice in evaluating carcinogens. Carcinogenic risks in drinking water have more typically been evaluated on the basis of the upper 95-percent confidence bound of the dose-response relationship. Since risk assessment methods for Giardia are developed on a maximum likelihood basis, however, the cancer risk has been evaluated on a similar basis to facilitate comparison. Cancer risk estimates are also presented in summary print-outs for the 95-percent confidence interval in order to provide a point of comparison to other drinking water rules that have been assessed by that procedure. However, the maximum likelihood estimates are considered the *best estimates.* The methods employed in derivation of cancer risk estimates are summarized in Technical Note 1.

Risk assessment methodology for Giardia has been previously defined[32] and has received some empirical validation.[33] Exhibit 10 presents the results of previous attempts to validate the Giardia risk assessment procedure using data from epidemic outbreaks of the disease. In the analysis supporting Exhibit 10, the following assumptions were made:

- the dose-response function (developed from data on human subjects) is representative for all populations;
- all cysts recovered by the monitoring technique are viable;
- all viable cysts are infective in humans;
- a single cyst **can** cause an infection (the dose-response function estimates that only about 2 percent **will** cause an infection upon ingestion, but the point is it only takes one);
- infection = illness (i.e., all infections are symptomatic);
- cysts recovered by the analytical technique represent all cysts which are present; and
- the error caused by assuming all cysts are recoverable and infectious to humans (an under-estimate) is equivalent to the error in assuming that there is 100 percent recovery of cysts by the analytical method (an over-estimate).

These are the same assumptions that were used in the Surface Water Treatment Rule Regulatory Impact Analysis prepared in 1989.[34] At that time, they were considered to be conservative assumptions. The results of the validation studies suggest that the assumptions may not be significantly conservative since the results they generate replicate the empirical data fairly well.

In approaching the assessment of by-product regulatory alternatives, a number of refinements were made in the existing risk assessment methodology for Giardia. These refinements are fully described in a companion paper.[35] In considering analysis of waterborne disease risk within a simulation framework, there are two important dimensions of variability in influent concentrations: 1) variation between different plants, and 2) temporal (day-to-day) variation within individual plants. The first dimension is important for accurately characterizing the risk at an aggregate or national level. The second dimension is critical to assessing the risk of epidemic occurrence of giardiasis.

The SWTR endemic risk target of one case per 10,000 persons per year was believed to be equivalent to a level of outbreak risk that would be trivially small. The recent findings of LeChevallier discussed in Section 3.0, indicate that the minimum treatment requirements specified in the SWTR would not be sufficient to achieve the target risk level for many systems. If by-product regulatory alternatives further erode the level of microbial treatment provided, the threshold of significant outbreak risk may be crossed. The refinement of predictive methods for assessing outbreak risk is therefore important.

There are two primary sources of data regarding the raw water occurrence of Giardia. Both were used to support the analysis. Hibler collected data for 73 plants which includes multiple samples at the same plants to give an indication of the variation from day to day within the same plant. These data have been utilized (adjusted by a recovery efficiency factor of two) to develop a statistical characterization of the day-to-day within-plant variation in terms of a *delta* negative binomial distribution which is described

in an accompanying paper.[36] LeChevallier collected data for 46 plants using state-of-the-art monitoring methods. These data have been used to simulate the raw water variability in influent Giardia between different plants. Since LeChevallier provides empirical estimates of the recovery efficiency (48%) and percentage of viable cysts (13%), these estimates were adopted in the analysis. All the other pertinent assumptions, listed above, from previous Giardia risk modelling efforts are kept the same.

A few other *best estimate, place-holder* assumptions have been added to the Giardia risk assessment methodology. To reflect the day-to-day variability in operations, the level of Giardia present in the simulated effluents is assumed to drop by 1-log five percent of the time.[37] In addition, to the primary infections estimated by the dose-response function, a secondary infection rate of 25 percent is assumed. Finally, the outbreak threshold, the level at which outbreaks are considered to be detected and reported, resulting in a chain reaction of societal coping costs, is assumed to be the point at which 1 percent of the population is ill (defined, in this analysis, as infection of 1 percent of the population exposed in the vicinity of the first customer) within any 30-day period. The overall Giardia risk assessment methodology is illustrated in Exhibit 11.

5.5 Summary of Analytical Methodology

The overall analytical methodology is summarized in the diagram in Exhibit 12. The modelling apparatus is structured in a "batch mode." A batch of 100 simulated input profiles, characterizing influent, distribution system, and some treatment parameters are run through the EPA treatment model as a separate batch run for an initial (*clean slate* status quo) treatment benchmark and again for each treatment configuration indicated by the successive nodes of the decision tree (Exhibit 9). In this way, the same 100 input files are run as a batch through every one of the conceivable treatment configurations.

These batch results are then interpreted by a compliance sorting routine. Compliance with either the present SWTR or an Enhanced SWTR is assured by the structure of the scenarios. The compliance sorting routine evaluates the extent to which more extreme treatments are required in order to meet alternative by-product MCLs. (For economy of presentation, these are summarized in terms of hypothetical total THM MCLs and in terms of total haloacetic acid MCLs. Detailed results are also generated for each individual compound, however.)

The compliance sorting routine begins by reading the 100 effluent by-product concentrations for the initial, status quo, treatment configuration. For each alternative MCL being evaluated, it selects the records for those plants which meet the MCL and saves their output files to the master output file for that MCL. It then reads the model results at the next treatment node on the decision tree and performs the same selection routine, but working only on the remainder of the 100 plants -- i.e., those that did not achieve compliance at the previous node. Exhibit 13 presents a two-panel summary of the procedure. The flow diagram in the top panel summarizes the logic. The bottom panel summarizes the form of the output.

As illustrated in the bottom panel, the sorting routine produces a complete assessment of the *core problem*. For any given combination of microbial treatment targets and by-product MCLs, it produces an assessment of the extent to which relatively more extreme treatments will be required. These treatment deployment profiles are matched to the appropriate unit cost vectors to produce estimates of the total national treatment cost of alternative by-product MCLs for the subset of the universe being studied (large surface water plants that filter but do not soften). In addition to the treatment percentages, the output files assembled by the sorting routine provide a quantitative profile of the exposures to Giardia, trihalo-

methanes, and haloacetic acids at each benchmark. The exposures are then converted into estimates of disease incidence via the risk models described above. Taken together, these elements of methodology provide a complete basis from which to characterize the trade-offs between regulatory alternatives -- i.e., a complete basis for regulatory impact analysis.

6.0 Results & Discussion

The results generated by the above-described DBP-RAM methodology are presented in a series of tables in Appendix A. These tables present results in a form similar to the bottom panel of Exhibit 13, showing the degree of treatment required to meet a specific combination of regulatory targets. In addition, the appendix tables also present quantitative estimates of the microbial and cancer risks associated with each combination of regulatory targets.

Several different tabulations are provided, representing different scenarios. Results are summarized in terms of the SWTR Scenario With Alternate Disinfectants versus the SWTR Scenario Without Alternate Disinfectants. Equivalent summaries are provided for the Enhanced SWTR Scenario.

For each of the scenarios evaluated, two complete sets of tables are provided; one in which by-product control is dimensioned in terms of total trihalomethane (TTHM) MCLs and the other in terms of total haloacetic acid (THAA) MCLs. To facilitate comparisons between hypothetical TTHM MCLs and comparable THAA MCLs, tables comparing the two are provided in Appendix B. Appendix C presents tables which document the associated concentrations of individual trihalomethanes and individual haloacetic acids under the different scenarios.

The results are evaluated and discussed at a summary level in the remainder of this section. There are two broad questions which must be addressed in reviewing these results:

1) Are the DBP-RAM outputs a plausible representation of reality?

2) What is implied about the trade-offs between microbial and by-product risks?

The first question is covered in Section 6.1; the second in Section 6.2.

6.1 Assessment of Model Performance

Before examining model results in terms of the potential trade-offs between microbial and by-product control objectives, it is necessary to first compare model outputs to available studies of actual conditions in order to assess the realism of model predictions. Such comparisons can be made in terms of: 1) by-product occurrence, 2) treatment adaptations to meet the current trihalomethane standard, 3) cancer incidence, and 4) Giardia incidence. Given the "clean slate" approach outlined in Section 5, the SWTR With Alternate Disinfectants Scenario, evaluated at a TTHM MCL of 100 ug/l, should demonstrate a reasonable degree of replication of the pre-SWTR/TTHM MCL=100 conditions reflected in a number of available studies.

6.1.1 Comparison of DBP-RAM Results to By-Product Occurrence Data

In the SWTR Scenario (with alternate disinfectants) at a TTHM MCL of 100 ug/l, the 100 simulated plants exhibit a mean TTHM concentration at the average customer of 40 ug/l, with a 95th percentile of 78 ug/l. These results compare favorably with data reported by Krasner et al[38] which shows a median of 25 ug/l and a 75th percentile of 59 ug/l, measured at the plant effluent. It also compares favorably with the AWWARF TTHM survey[39] which reported the mean of quarterly distribution system samples, averaged across all plants, to be in a range of 30 to 45 ug/l. Similarly, the AWWA Water Industry Data Base shows annual means of distribution system samples to lie within a range of 30 to 60 ug/l. In contrast, data collected by EPA at plants selected to reflect more extreme conditions exhibited a mean of 84 ug/l.[40]

As noted in section 5..3, the *place holder* assumptions used to predict haloacetic acid concentrations are based on a relationship to TTHMs rather than on chemical formation relationships. It is important therefore to check the realism of THAA predictions also. Based on only dichloroactic acid and trichloroacetic acid, average customer levels predicted in the SWTR scenario (with alternate disinfectants) for a TTHM MCL of 100 ug/l exhibit means of 10 ug/l and 8 ug/l, respectively. 95th percentiles are 24 ug/l and 20 ug/l, respectively. These model results compare favorably to data reported by Krasner et al[41] which have medians of 6 ug/l and 75th percentiles of 12 to 15 ug/l, measured at the plant effluent. In contrast, data collected by EPA at plants selected to reflect more extreme conditions exhibits a mean of 39 ug/l.[42]

6.1.2 Comparison of DBP-RAM Compliance Predictions to Actual Compliance Patterns

While it is good that mean values are replicated by the modeling apparatus, the true test of validity is in the prediction of performance at the extreme ends of the range -- the interactions between the tails of the different random variables. Some indication of this critical aspect of model performance is provided by a comparison of the treatment deployment projected by the "clean slate" model results at a TTHM MCL of 100 ug/l versus the treatment deployment that actually resulted from the current TTHM standard. The need to resort to higher levels of treatment to meet a TTHM MCL is driven by the tails of the distributions -- by the more extreme conditions. The model results show the following treatment deployment required to meet a TTHM MCL of 100 ug/l in the SWTR Scenario with alternate disinfectants:

No Further Treatment	61%
Eliminate Pre-chlor	21%
Eliminate Pre-chlor & Add NH3	18%

Data on treatment changes made to comply with the TTHM MCL of 100 ug/l were collected in the AWWA Disinfection Survey[43] and in the AWWARF TTHM Survey[44]. Unfortunately, both studies tabulate the data in a manner which does not permit direct comparison because the treatment percentages (presented in section 3.2) do not sum to 100 percent. It is nonetheless possible to make some comparisons.

Compared to the model prediction that 61 percent of plants require no treatment changes to meet a TTHM MCL of 100 ug/l, the AWWA Disinfection Survey reported 44 percent. The survey included the option of moving the first point of chlorination as well as a second option of eliminating

prechlorination, versus the model algorithm which offers only elimination of prechlorination as the first option. Both surveys indicate that compliance with the present TTHM standard was achieved predominantly through changes in chlorination practice; and, at the most extreme, addition of ammonia. As in the model results, more significant treatment modifications were generally not rquired to meet TTHM MCL of 100 ug/l. The model indicates 18 percent of systems had to resort to chloramines versus survey estimates of 25 percent (AWWARF) and 16 percent (AWWA). The AWWA Water Industry Data Base provides another data point, showing 25 percent of surface water plants that filter, but do not soften, using chloramines. As discussed in Section 3.2, some plants may be using chloramines as a means of clinging to the benefits of pre-disinfection. This may account for survey estimates of chloramines usage exceeding estimates produced by the DBP-RAM algorithm.

6.1.3 Comparison of DBP-RAM Estimates of Cancer Incidence to Other Estimates

As the tables in Appendix A indicate, the model results suggest that both cancer risks and microbial risks lie in significant ranges. The potential for significant trade-offs to occur appears to be confirmed. On a maximum likelihood basis, however, the risk posed by trihalomethanes becomes very small while the cancer risk of dichloroacetic acid becomes the predominant concern. DCAA is shown to account for most of the total by-product cancer risk. In the period since the input assumptions used in the current model were fixed, the cancer risk factors that EPA believes should be used for the brominated THMs have been increased, so this result may change somewhat in the next iteration.

Within the 103 million population covered by the current model, DCAA would be responsible for 38 cases of cancer per year. Because of the widespread exposure, this would make DCAA one of the most significant carcinogens ever encountered in the SDWA regulatory program. As discussed in Section 5, the DBP-RAM predictions of cancer incidence are based on dose-response relationships derived from toxicological research. There is debate in the epidemiological literature over suggestions that cancer incidence attributable to disinfection by-products may be on the order of thousands of cases per year.[45,46,47] EPA does not believe that it is appropriate to derive quantitative cancer risk estimates from the available studies because the weight of evidence is not strong enough to indicate a causal relationship between exposure to chlorinated drinking water and cancer incidence.

6.1.4 Comparison of DBP-RAM Results to Estimates of Waterborne Disease Incidence

The Appendix A tables show significant incidence of Giardia infections at the benchmark TTHM MCL of 100 ug/l in the SWTR Scenario (with alternate disinfectants). Within the 103 million population represented by the model, 340,000 infections per year are indicated. These results are two orders of magnitude higher than the post-SWTR predictions presented in the SWTR Regulatory Impact Analysis. As discussed in section 3.1, the difference results from use of Giardia data collected recently by LeChevallier[48] which indicate occurrence levels about two orders of magnitude higher than that estimated in the SWTR RIA. As the TTHM MCL is changed from 100 ug/l to 25 ug/l, the DBP-RAM predicts a near doubling over this baseline level of Giardia infections.

In the present analysis, all predicted Giardia infections occur at the first customer which is assumed to represent 10 percent of the total 103 million population exposed in the model. The C-T equations have been extrapolated to predict additional log-kill achieved in the distribution system. The resulting log-kills are sufficiently high that Giardia infections are indicated only at the first customer. As described in an accompanying paper by Grubbs, et. al.,[49] use of the Giardia dose/response model employed in this analysis includes several new aspects of analysis beyond that developed originally by

Rose et. al.[50] The same dose/response relationship is utilized, but the daily variation in the influent concentration is simulated over 365 days rather than based on a single annual average. In addition, a treatment failure rate is incorporated by assuming a 1-log drop in the total reduction achieved five percent of the time. Also, a secondary infection rate of 25 percent is assumed. The collective result of these refinements is a model which predicts approximately twice the level of infections estimated by using only the arithmetic mean with the Rose equation.

In addition to predicting endemic incidence of giardiasis, the modelling framework developed by Grubbs et. al. also includes an outbreak simulation feature. As shown in the results in Appendix A, the outbreak risk is shown to be significant at the current TTHM MCL, a finding that does not appear to match reality. This prediction is based, however, on the conservative assumption that infection equals illness and that infection of one percent of the population at the first customer (versus the total population) would lead to community awareness of waterborne disease and formal recognition of an outbreak event.

On balance, both the endemic and epidemic predictions for Giardia risk are believed to be plausible considering that there are great uncertainties regarding accurate reporting of disease and outbreak incidence and considering the uncertainty in the relationship between infection and symptomatic illness. Reconciling the model results against epidemiological evidence on endemic incidence of waterborne disease[51], it is possible that the target organism methodology used in DBP-RAM may be a conservative estimate of the total microbial risk.

A flaw in the current Giardia modelling exists in the evaluation of the more extreme MCL scenarios where ozone is employed to obtain compliance. The present treatment model assumes that if ozone is used for primary disinfection, then Giardia inactivation will be achieved to meet only the minimum SWTR requirements in the SWTR Scenario, or the 1/10,000 risk level in the Enhanced SWTR Scenario. This must be refined in future development of the model. Due to concerns over unknown dimensions of ozone by-products and ozone decay, the current framework focuses more keenly on chlorine and chloramines. Ultimately, analysis of the "ozone paradigm"[52] will have to be fully developed to the same level of sophistication as the "chlorine paradigm."

6.2 Assessment of Potential Trade-offs

As discussed in Section 4, the analysis of trade-offs between competing risk reduction objectives presents a problem that has infinite dimensions, making it necessary to focus on a smaller *core problem* for purposes of analysis. Analysis of the *core problem* is intended to illuminate both the nature of the trade-offs involved and the potential significance of uncertainties and unknowns. There are three conceivable types of trade-offs to be evaluated:

- As by-product MCLs are imposed, the level of microbial protection may be compromised. As a result, the reduction in *known* cancer risks (THMs and HAAs) may be offset by increased microbial risk.

- If the level of microbial control is first enhanced to prevent adverse side effects on the level of microbial protection, the increased level of microbial control could result in greater by-product formation and higher costs for by-product control.

- If by-product control is pursued with the use of alternate disinfectants, the incidence of *known* cancer risks (THMs and HAAs) will be reduced, but *unknown* cancer risks (e.g., bromate, other

DBPs) and *unknown* microbial risks (e.g., bacterial growth from increased AOC with use of ozone, or reduced inactivation with use of chloramines) may be introduced. Weighing against these concerns, alternative disinfectants may be less expensive than other advanced by-product control strategies.

A structured approach to evaluating these three types of trade-offs is provided through the consideration of four scenarios:

- The SWTR Scenario evaluates the potential for increased microbial risk when by-product MCLs are imposed with the currently required level of microbial control. The decrease in *known* cancer risks may be compared to the increase in microbial risk.

- The Enhanced SWTR (ESWTR) Scenario assumes the microbial risk level is fixed at a 1/10,000 endemic incidence rate for giardiasis. Alternative by-product MCLs are evaluated with this microbial constraint. Results can be compared to the SWTR Scenario to determine 1) how much additional *known* cancer risk results from the higher level of microbial control; and, 2) how much additional treatment cost is entailed in by-product control to compensate for the higher level of microbial protection.

- Both the SWTR Scenario and the ESWTR Scenario are evaluated in two variations: 1) with alternate disinfectants; and 2) without alternate disinfectants. Comparing the results of the two variants permits an assessment of the treatment cost savings made possible by the use of alternate disinfectants. This cost savings must then be weighed against the *unknown* cancer risks and *unknown* microbial risks that may be introduced through the use of alternate disinfectants. The *unknown* risks cannot be quantified, but the comparison to cost savings provides a framework within which to consider these unknowns.

6.2.1 Potential for Increased Microbial Risks

Exhibit 14 presents a graphic illustration of the process through which by-product controls might result in inadvertent increases in microbial risks. Coagulation and filtration have the joint effect of removing Giardia and reducing TOC. Reducing TOC decreases the overall potential for by-product formation. It also decreases the chlorine demand in the water and permits the SWTR disinfectant residual requirements in the distribution system to be met with lower chlorine dosages. While the diminished use of chlorine may reduce the overall potential for by-product formation, it may also decrease the total level of Giardia inactivation achieved at the first customer, unless compensating treatment is added.

Reducing TOC may not seem like a problem since the SWTR requires a minimum of 3-logs of inactivation at the first customer. New Giardia occurrence data collected by LeChevallier, however, indicate that an average of at least 5-logs may be required by many utilities in order to meet the 1/10,000 endemic incidence goal sought by the SWTR (as discussed in Section 3). Many plants may be achieving adequate log-reduction at the first customer as an accidental result of the need to meet the distribution system residual requirement in the presence of high chlorine demand. Removal of TOC to meet by-product constraints may allow the log-reduction at the first customer to drop back to the 3-log minimum which now appears inadequate. This phenomenon is observed in the modelling results.

Exhibit 2 summarizes the LeChevallier data in terms of a plot of influent Giardia versus the total log reduction achieved. The pattern of the data indicate a complete lack of correlation between the

influent Giardia concentration and the log reduction achieved. This lack of correlation is perhaps the result of the dominant influence of the residual requirement, in addition to other factors. Model results appear to support this explanation. The Monte Carlo simulation framework established in the DBP-RAM is well-suited to analyzing the relationship between influent Giardia levels and total log-reductions achieved at each individual plant. Since the influent Giardia distribution used to drive the simulation was developed from the LeChevallier data, some direct similarities to the LeChevallier findings are to be expected in the model results. Unfortunately a complete calibration check of the model against the LeChevallier results is not possible because the LeChevallier data was collected in a pre-SWTR compliance environment whereas the model is constructed to include the SWTR requirements as initial constraints. Some similarities are evident, nonetheless, as discussed further below.

There are many possible reasons why the LeChevallier data indicate a lack of correlation between the influent Giardia level and the total log reduction achieved. In the over-simplified framework of the DBP-RAM, a few assumptions dominate this relationship. Exhibit 15 presents a plot similar to that of Exhibit 2 showing simulation results for a scenario that assumes implementation of the SWTR (with alternate disinfectants) and a TTHM standard of 100 ug/l. Of 100 simulated plants, only 39 were determined by the DBP-RAM algorithm to require treatment adjustments in order to meet a TTHM MCL of 100 ug/l. These 39 points are plotted in Exhibit 15. The plotted points reflect the relationship between influent Giardia and total log reduction after compliance with these scenario constraints.

Many of the 39 points in Exhibit 15 appear in a vertical line reflecting the SWTR requirement for a minimum of 3-logs of total reduction. In contrast to the pre-SWTR baseline reflected in the LeChevallier data in Exhibit 2, some of the points along the 3-log line in Exhibit 15 represent a higher level of total reduction than in the pre-SWTR condition while others represent a lower level. In the simplified model logic, those plants that were not previously achieving a 3-log level would have increased their level of total reduction to equal 3-logs, while some of those achieving more than a 3-log reduction would have dropped their level of total reduction to the 3-log minimum, where they could still meet the residual requirement. Notably, all the points aligned vertically along the 3-log minimum are to the left of the diagonal line that defines the 1/10,000 risk threshold that the SWTR sought to achieve, indicating that they are incurring risks greater than this target level.

The remaining points plotted in Exhibit 15 show more than 3-logs of total reduction. Some of them are above the 1/10,000 risk threshold (to the right of the diagonal) while others are below it (to the left of the diagonal). In tracing the source of this result through the model logic, it appears that the reason these plants exhibit more than the 3-log minimum is due to the additional SWTR constraint of maintaining a disinfectant residual in the distribution system. The simulated plants that are achieving more than a 3-log total reduction at the first customer in Exhibit 15 represent conditions where there is enough TOC to require elevated chlorine dosages to overcome the chlorine demand of the TOC in the distribution system, but yet where the resulting contribution to TTHM formation is not significant enough to require additional TOC removal.

Exhibit 16 illustrates the effect of a tighter by-product MCL of 25 ug/l. In this scenario, 83 plants would be required to change treatment in order to comply. As shown in the graph, the result is that all the points are aligned along the 3-log minimum line. Those plants that had more than 3-logs of total reduction in Exhibit 15 have been guided by the treatment algorithm into TOC removal strategies which in turn reduced the chlorine demands that had to be overcome in order to meet the SWTR residual requirement in the distribution system. As a result, the model predicts that all plants required to change

treatment to meet a TTHM standard of 25 ug/l would reduce their total log reduction to the 3-log minimum.

As shown in Exhibit 16, the convergence to the 3-log minimum results in a risk level higher than the 1/10,000 target for all of the 83 plants compelled to modify treatment in meeting a TTHM MCL of 25 ug/l. The resulting change in endemic incidence of Giardia infections will be larger for some plants than for others. In particular, there may be some plants for which the co-occurrence of high influent TOC and high influent Giardia result in a very large increase in incidence of Giardia infections. This increase results from significant drops in chlorine dosages for compliance with SWTR residual requirement after TOC removal has been triggered by the need to meet a TTHM MCL. The increase in incidence of Giardia infections has been computed based on the change in total log-reduction between one MCL and another, as computed by the DBP-RAM model. Results of this analysis are presented in Exhibits 17 and 18.

Exhibit 17 plots the cumulative distribution of the 100 simulated plants in terms of the increase in annual Giardia infections per 1 million persons when moving from a TTHM MCL of 100 ug/l to an MCL of 75 ug/l. The plot confirms that there are a few plants that would face extreme conditions, resulting in significant increases in Giardia infection rates. Nearly 10 percent of plants could experience increases of between 1,000 and 10,000 infections per 1 million population. The top end of this range approaches outbreak proportions. Exhibit 18 shows that the impact of a shift from a TTHM MCL of 100 ug/l to a TTHM MCL of 25 ug/l would produce increases in Giardia infection rates on this same order of magnitude for over 30 percent of plants. Exhibits 19 and 20 present the same results that are plotted in Exhibits 17 and 18 in terms of bar charts that emphasize the impacts at the extreme ends of the range.

Ultimately, a comparison must be made between the increase in incidence of Giardia infections and the corresponding decrease in cancer incidence that might result from alternative MCLs. This is achieved by combining the above analysis of predicted Giardia infections with predictions of cancer incidence resulting from exposure to by-product concentrations that are simultaneously projected by the DBP-RAM. Results are summarized graphically in the log-log plots presented in Exhibits 21 and 22. Exhibit 21 plots increased incidence of Giardia infections per 1 million persons per year versus decreased cancer incidence per 1 million persons per year for the plants having to change treatment when the TTHM MCL is changed from 100 ug/l to 75 ug/l in a SWTR scenario (with alternate disinfectants).

Exhibit 22 presents the same picture for the plants that would have to change treatment if the TTHM MCL is changed from 100 ug/l to 25 ug/l. The pattern of the points plotted in these diagrams indicates that the degree of change in cancer incidence generally spans only one order of magnitude (less than one case per 1 million persons per year) while the degree of change in incidence of Giardia infections spans several orders of magnitude (from one to more than 10,000 infections per 1 million persons per year). This points to a finding that changes in microbial risk are more sensitive than changes in cancer risk to treatment changes needed to meet TTHM MCLs.

Exhibits 23 through 30 present the same series of graphs as Exhibits 15 through 22 except that the entire analysis is structured in terms of alternative MCLs for total haloacetic acids. The interpretation is identical to that described above.

6.2.2 Potential to Avoid Increased Microbial Risk

One obvious direction indicated by the above results would be to strengthen the SWTR before proceeding with requirements for additional by-product controls. An enhanced SWTR has been evaluated using the DBP-RAM. It was assumed that the portion of the SWTR Guidance Document which recommends an additional log of inactivation for each additional log of influent Giardia is converted to a mandatory requirement. If an enhanced SWTR were in place, the graphs presented in Exhibits 2, 16 and 17, would show plants lined up along the diagonal line representing the 1/10,000 target risk level rather than along the vertical line representing the 3-log minimum required by the present SWTR. By definition of the 1/10,000 risk level as the target, there would therefore be no adverse risk trade-offs in terms of Giardia. (Trade-offs with respect to other pathogens such as Cryptosporidium may still occur, depending on the efficiency of using Giardia as a target organism for defining adequate treatment.) Such an Enhanced SWTR may not be feasible due to the lack of practical monitoring protocols available for Giardia, but there is promising research in this area.[53]

The evaluation of the Enhanced SWTR with the DBP-RAM showed that adherence to the 1/10,000 risk level resulted in very little additional cancer incidence, very little modification in treatment and, therefore, very little additional cost. This minimal cost impact resulted from the model assumption that the additional inactivation requirements at the first customer would be met with additional contact time at the plant effluent. Additional contact time allows inactivation requirements to be met without significant increased chlorine dosages. While additional contact time contributes to inactivation, it does not contribute very much to additional by-product formation, because the additional increment of contact time is trivial in proportion to the total residence time in the distribution system.

6.2.3 Potential Trade-Offs Involved In The Use of Alternate Disinfectants

The most striking aspect of the cancer incidence predicted by the DBP-RAM is the order of magnitude of the results (tabulated in Exhibits A-1 through A-8). Exhibit A-1 presents an evaluation of the SWTR Scenario in the presence of alternate disinfectants. This exhibit most closely resembles the status quo. Using maximum likelihood estimates of the dose response functions, results indicate 45.5 cases of cancer per year (trihalomethanes: 0.9 cases; di- and tri- chloroacetic acids: 44.6 cases) at the current TTHM standard of 100 ug/l. Using the upper 95 percent confidence bound of the dose response functions, results indicate 163 cases of cancer per year (trihalomethanes: 24.6 cases; di- and tri-chloroacetic acids: 138.7 cases) at the current TTHM standard of 100 ug/l. About 70-85% of the total projected cancer incidence is attributable to dichloroacetic acid.

The most promising aspect of the cancer incidence results is the small difference between SWTR Scenarios and Enhanced SWTR Scenarios. Comparison of results in Exhibits A-1 and A-2 indicate that an Enhanced SWTR, versus the SWTR, would produce about 1 additional case of cancer per year at the current TTHM standard of 100 ug/l.

Exhibits 31 and 32 present an analysis of the total and incremental costs of cancer risk reduction. The analysis is presented in terms of different Total Haloacetic Acid MCLs in recognition of the fact that dichloroacetic acid accounts for most of the projected cancer risk. The tables in Appendix B permit various comparisons between THAA MCLs and comparable TTHM MCLs. The total and incremental cost analysis presented in Exhibits 31 and 32 is developed from the treatment profiles assigned by the DBP-RAM to meet different regulatory targets and from unit cost estimates derived from the Water Cost Model.[54]

Exhibits 33 and 34 present vectors of compliance percentages for the *with* and *without* alternate disinfectants variants of the SWTR and the ESWTR scenarios. Each column in each of the tables contains a compliance vector for a given THAA MCL. The percentages in each vector total 100 percent. Taken together, the percentages comprising each vector indicate the mix of treatments that are projected to be required to comply with each MCL alternative. For example, in Exhibit 34, compliance with an MCL of 60 ug/l in the *without* alternate disinfectants variant of the SWTR scenario is projected to require no further treatment by 70 percent of plants; elimination of pre-chlorination by 12 percent of plants; elimination of pre-chlorination and optimization of alum coagulation by 11 percent of plants; and elimination of pre-chlorination, optimization of alum coagulation, and installation of granular activated carbon (GAC) by 7 percent of plants.

These compliance vectors are an input to the computation of the aggregate treatment cost of each MCL alternative. The percentages are used to split the total number of plants into treatment categories. The corresponding unit costs for each treatment are then multiplied by the number of plants assigned to the category. The resulting products in each category are summed to produce the estimate of the total aggregate treatment cost. (Because of the *clean slate* approach adopted in the DBP-RAM (see Section 5), some of the costs counted by this procedure may have already been incurred by systems complying with the current TTHM standard. These costs are trivially small, however, because they involve low cost techniques such as moving the point of chlorination and adding ammonia.)

It is important to note that although the vectors of compliance percentages total 100 percent, a portion of the plants assigned to the final treatment category, involving GAC, may not actually be able to comply with the MCL. This is particularly true at the more stringent MCLs. For purposes of estimating aggregate treatment costs, it makes no difference. Once GAC is installed, the plant would either be in compliance or would be eligible for a variance. The cost computed by the DBP-RAM is the same either way. The inability to attain compliance even with GAC is taken into account, however, in the analysis of the change in by-product exposures. Appendix A presents a more detailed print-out of the modelling results which contains a graphical summary of the extent of variances that would be implied with increasing stringency of regulation.

Results in Exhibits 33 and 34 indicate that (assuming some proportion of variances is accepted) stringent by-product MCLs are technically feasible if the use of alternate disinfectants and/or GAC is accepted. In *without* alternate disinfectants scenarios, 57 to 58 percent of plants are projected to require GAC to comply with a THAA MCL of 10 ug/l. Nearly one-third of the plants driven to GAC at this MCL would not be able to meet it, but would obtain variances. In the *with* alternate disinfectants scenarios, 50 percent of plants would still require GAC to comply with a THAA MCL of 10 ug/l. About one-fifth of these plants would not meet the MCL, but would obtain variances. A THAA MCL of 10 ug/l would eliminate roughly three-quarters of the total quantifiable by-product cancer risk.

For the segment of the water industry studied (representing 103 million persons; 43 percent of the total population served by community water supplies), the aggregate treatment cost of a THAA MCL of 10 ug/l is estimated to be $957 million (SWTR Scenario) to $974 million (ESWTR Scenario) per year in the *without* alternate disinfectant scenarios and $922 million (SWTR Scenario) to $963 million (ESWTR Scenario) per year in the *with* alternate disinfectant scenarios. These results do not indicate significant cost savings from the use of alternate disinfectants because an MCL of this stringency would drive nearly the same percentage of plants to GAC, as noted above.

An alternative regulatory strategy might attempt to reduce by-product cancer incidence to the maximum extent possible without triggering irreversible and expensive technology shifts, such as switching to ozone and GAC. The results in Exhibits 33 and 34 indicate that standards equivalent to a THAA MCL of 30 ug/l would force 20 to 21 percent of systems to GAC if alternate disinfectants were not permitted (*without* scenarios). If chloramines are permitted, the *with* scenario results show that only 4 to 11 percent of systems would have to resort to ozone or GAC to meet a THAA MCL of 30 ug/l. Results for the *with* scenarios indicate 59 to 60 percent of plants could achieve a THAA MCL of 30 ug/l with either no treatment changes at all or with elimination of pre-chlorination. An additional 30 to 36 percent of plants could achieve this level with elimination of pre-chlorination, chloramines and optimization of coagulation. This proportion of chloramines usage is about equivalent to the current penetration of this technology in systems subject to the interim TTHM standard.

If alternate disinfectants are permitted (*with* scenario), the total treatment cost of a 30 ug/l MCL for the segment of the industry under study (surface water systems serving > 10,000 that filter but do not soften) would be roughly 10 percent as much as for an MCL of 10 ug/l ($71 to $120 million per year for the SWTR and ESWTR, respectively vs. $1 billion per year). If chloramines are not used (*without* scenario), a THAA MCL of 30 ug/l would cost about one-third as much as a THAA MCL of 10 ug/l ($336 to $353 million per year vs. $1 billion per year). In the *without* scenarios, a THAA MCL of 30 ug/l achieves 50 percent as much reduction in cancer incidence as a THAA MCL of 10 ug/l. In the *with* scenarios, a THAA MCL of 30 ug/l achieves 38 percent as much reduction in cancer incidence as a THAA MCL of 10 ug/l. The difference results from the reliance on GAC as a last resort in the *without* scenarios. Once use of GAC is triggered, it over-shoots a target of 30 ug/l.

6.2.4 Evaluation of Trade-Offs Within The Regulatory Impact Analysis Framework

The framework for regulatory decisionmaking is defined in the Safe Drinking Water Act. The application of that statutory framework to the problem of disinfection by-products regulation, using DBP-RAM results, is described in a companion paper.[55] A totally separate mandate, Executive Order 12291, specifies a cost-benefit framework for analyzing trade-offs during the rule development process. As stated at the outset of this paper, *the goal of regulatory impact analysis is to develop and organize information on benefits, costs, and economic impacts so as to clarify trade-offs among alternative regulatory options.*[56] EPA guidance for developing regulatory impact analyses (RIAs) specifies that the comparison of regulatory options is to be achieved by *quantifying and monetizing benefits and costs to the extent possible.*

This section presents DBP-RAM results in the context of the RIA requirement. The discussion is presented in three parts. The first part (6.2.5.1) briefly describes the conventional approach that has been followed in assessing the benefits of SDWA regulations in previous RIAs. The second part (6.2.5.2) discusses how the development of DBP regulations presents a completely different type of problem due to the trade-offs between health risks, and describes the solution that has been devised to cope with this analytical complication. The third part (6.2.5.3) presents DBP-RAM results in the context of this RIA framework.

6.2.4.1 Economic Benefits Relevant to SDWA Regulations

The benefits of SDWA regulations are usually evaluated in terms of two approaches: 1) damages avoided, and 2) willingness-to-pay. It is possible to quantify the monetary value of direct economic

damages, such as lost income and medical costs, that are associated with the incidence of adverse health effects. Such damage estimates can be combined with exposure and risk models to yield aggregate national estimates of the expected value of monetary damages that will result at alternative levels of regulation. The difference in the expected value of damages between one level of regulation and the next most stringent level (*the damages avoided*) may be compared to the difference in the associated treatment and monitoring costs. As long as the expected value of the damages avoided exceeds the difference in the treatment and monitoring costs, the aggregate net benefits of regulation are positive.

The concept of economic benefits is not merely the expected value of the avoided damages, but the *willingness-to-pay for a reduction in the risk of incurring those damages.*[57] The willingness-to-pay reflects the intuitive notion that damages are, afterall, disagreeable. Therefore, it usually exceeds the expected value of avoided damages. It is presumed that people are willing to pay something extra for a *margin of safety* depending upon the degree of damages involved, their assessment of the degree of risk (i.e., of the uncertainties affecting the estimate of the expected value of the damages), and their individual risk tolerance for the type of damage involved. It has been suggested that altruism provides another motive for additional willingness-to-pay. Studies have shown that the safety of water supplies is perceived to have a societal value to consumers, reflecting concerns for sensitive populations and civic pride.[58] Thus, an extra measure of insurance is part of the benefit being derived from SDWA regulations, supplemental to the expected value of the avoided health damages. This willingness-to-pay concept of benefits is quite consistent with the structure of the SDWA which stipulates that MCLs be established as close as feasible to the no adverse effect level (i.e., as close as feasible to the MCLG), *plus a margin of safety.*

In the Surface Water Treatment Rule Regulatory Impact Analysis,[59] for example, economic damages associated with contracting giardiasis were estimated to lie within a range of $1400 to $1800 per case (1986 dollars) based on valuation of medical costs and lost work.[60] Using this estimate of the cost of illness together with estimates of the costs of coping with waterborne disease outbreaks, the expected value of damages avoided was compared to the projected costs of installing filtration. The results indicated that net benefits might be negative in the small system size categories, depending upon the assumptions made regarding the risk of infection.[61] However, viewing the same results in light of the uncertainties not captured in the analysis, and in light of the presumed willingness to pay for an extra margin of safety, it is possible to make a subjective judgement that net benefits are in fact positive. For example, the above damage estimate does not take account of the fact that about 0.1 percent of cases of waterborne disease may result in a fatality.[62] In addition, there are significant economic impacts accompanying the epidemic occurrence of waterborne disease -- instances in which a substantial portion of the population is simultaneously infected. Quantitative valuation of "willingness-to-pay" is inherently more difficult than valuation of direct damages and is ultimately somewhat subjective. (NB: neither the SDWA, nor EO 12291 require EPA to demonstrate that net benefits are positive.)

Similarly, regulatory impact analyses (RIAs) developed for SDWA regulations governing carcinogens, have often shown negative net benefits in the small system size categories. Under the damages avoided approach, cancer incidence is valued at $400,000 per case, reflecting lost income and medical costs. Under the willingness-to-pay approach, cancer incidence is valued at $8,000,000 per case. The willingness-to-pay figure is taken from economic research on the value of life which draws its conclusions from data on wage rate differentials in high risk occupations and other evidence.[63] The $8,000,000 per case figure is not literally intended as an estimate of the value of life, but rather of the willingness-to-pay to reduce the risk of premature death. Typically, RIAs on SDWA regulations governing carcinogens have used the $8,000,000 figure. Using this figure, the net benefits of proposed MCLs for many

contaminants are negative in the small system size categories and are sometimes negative in the larger system size categories as well. In the final analysis, determining the margin of safety for carcinogens is a judgement call and the SDWA does not constrain that judgement to adhere to a cost-benefit criterion.

6.2.4.2 Benefits Concepts Relevant to Disinfection By-Products Regulation

The regulation of disinfection by-products presents a distinctly different type of benefits valuation problem, unlike that posed by any other drinking water contaminant or group of contaminants. The valuation of benefits is complicated because there are multiple health risks involved and measures to reduce one type of risk may increase another. The ideal solution would be one which minimizes the total incidence of adverse health effects. Since the incidences of the different health effects are inversely related to each other, a means of trading-off one benefit for another is needed.

Exhibit 35 illustrates a transformation of the conventional benefit/cost framework into a theoretically equivalent form that is more suited to the multiple trade-offs involved. It shows that maximizing health *damages avoided* per dollar of treatment expenditure is the same as minimizing health *damages incurred* per dollar of treatment expenditure. Mathematically, minimizing total social costs is the "dual" -- the mirror image of maximizing net benefits. As described in Technical Note 2, both formulations yield the same answer, but the dual is easier to work with since treatment costs and the costs stemming from both types of health damages can be simply added together to compute the total cost.

A means of capturing the extra willingness to pay for a margin of safety within such a "damages avoided" context has been suggested by envisioning a category of "anxiety damages" (i.e., without the insurance benefit inherent in a safety margin, there would be comparable anxiety damages).[64] Thus, total willingness-to-pay equals the total damages, where total damages are conceived as the sum of direct economic damages (lost work and medical expenses) plus anxiety damages. Within this framework, the health damages incurred are valued in this analysis on the basis of willingness-to-pay estimates: $3,000 per case of giardiasis and $8,000,000 per case of cancer.

The willingness-to-pay rationale implicit in this economic framework serves to clarify an important aspect of the nature of potential trade-offs; they may consist of conflicts between competing safety margins as much as trade-offs of actual health effects.

6.2.4.3 Analysis of Trade-offs In Terms of Total Social Costs

Viewed in the minimum total cost framework, the evaluation of disinfection by-product regulatory alternatives entails trade-offs between five different dimensions of costs. As by-product controls are applied, they impose treatment and monitoring costs (dimension 1) while reducing by-product cancer risks (dimension 2) and potentially increasing endemic and epidemic microbial risks from source water contaminants (dimension 3). As more stringent by-product controls are introduced, they may generate additional cancer risks (e.g., bromate) and microbial risks (e.g., Cryptosporidium, or pathogenic bacterial growth in the distribution system) as side effects (dimensions 4 and 5).

In order to clarify the nature of the trade-offs within this minimum total cost framework, it is necessary to model how the five different dimensions change simultaneously; one or more types of costs decreasing while others increase as a result of the opposing relationships. Currently, the DBP-RAM provides quantification covering only the first three dimensions (*the core problem*). Exhibits 36 through 39 present results for the four different scenarios defined to analyze the core problem, showing a family

of cost curves for each. Plotted as a function of THAA MCLs are: by-product treatment costs (dimension 1), costs of cancer cases incurred (dimension 2), costs of Giardia cases incurred (dimension 3), and the total cost. With respect to dimension 2, the current DBP-RAM does not include quantification of cancer risk associated with brominated haloacetic acids. With respect to dimension 3, the DBP-RAM quantifies increased Giardia outbreak risk, but the expected value of damages associated with outbreaks have not been included in the total cost results to simplify the comparison in this first iteration of the analysis. While the additional damages associated with increased outbreak risks would be significant, they would not change the shape of the resulting total cost curves, but would steepen the slope. Costs of *unknown* cancer risks (dimension 4) and *unknown* microbial risks (dimension 5) introduced by use of alternate disinfectants are unquantified in the current DBP-RAM.

Both the cancer and giardiasis incidence estimates are based on maximum likelihood risk assessment procedures, as described in Section 5.4 and Technical Note 1. As noted in Section 5.4, the dose-response relationships presently being utilized produce aggregate results for both cancer and waterborne disease incidence that are much lower than the levels potentially implied by recent epidemiological studies in both areas. Conceivably, both types of health risks could be much greater than indicated by the current dose-response functions.

6.2.4.3.1 MCL Alternatives

The total cost curves for the SWTR scenarios shown in Exhibits 36 and 38 have an assymetric shape which suggests that the lowest total cost will result from the least stringent THAA MCL (60 ug/l). This result implies that the side-effect of increased giardiasis risk outweighs the gains in cancer risk reduction. The trade-off is a reflection of the apparent flaw in the current SWTR with regard to the level of risk reduction assured at the first customer, discussed at length above. Moreover, if the potentially significant giardiasis outbreak risk were also reflected in the current set of total cost curves, the picture would be even more assymetric.

Exhibits 37 and 39 present total cost curves for the ESWTR scenarios. These are also assymetric, but have minimum points suggesting least cost THAA MCLs lie in a range of 40 to 50 ug/l. The reason there is a potential for by-product reduction in these two scenarios is that an enhanced SWTR would eliminate the trade-off with respect to Giardia risk while introducing very little additional treatment cost and contributing only a small offsetting increase in cancer risk, according to the DBP-RAM. Significantly, detailed results tabulated in Appendix A indicate that the increased outbreak risks induced by by-product controls would be eliminated in the ESWTR scenarios.

Comparing results of *with vs. without* alternate disinfectant scenarios (Exhibits 36 vs. 38, and 37 vs. 39), indicates that the nature of the trade-offs is not markedly different between the two scenarios. As discussed in section 6.2.3, above, the treatment costs are higher in the *without* alternate disinfectant scenarios, but the difference is less significant at the most stringent MCLs because similar proportions of plants would be driven to GAC in both scenarios. It is at the most stringent MCLs, however, where the trade-offs implied by the *with* alternate disinfectant scenarios would be different in ways that are not shown in the present results due to the inability to incorporate quantitative assessment of additional side effects introduced by alternate disinfectants: carcinogenic by-products of alternate disinfectants and inadvertent microbial risks introduced by alternate disinfectants.

The results summarized in Exhibits 36 through 39 point to a conclusion that the potential for trade-offs between cancer risk (dimension 2) and microbial risk (dimension 3) is significant without an

enhanced SWTR in place. The uncertainties associated with the risk assessment procedures assumed in DBP-RAM and the exposure assessment methodology of DBP-RAM are so great that there is no confident means of defining an error bound around these results. The individual microbial and cancer risk assessments are subject to a wide range of potential error. It is conceivable that either of the two could be in error in ways which would cause the total cost curves to exhibit very different shapes (e.g., significant underestimation of cancer risk). The exposure assessment produced by DBP-RAM, while producing roughly plausible results in terms of mean values, could be in much greater error at the extremes where trade-offs may be more acute. Consideration of the additional uncertainty presented by unquantified cancer and microbial risks introduced by use of alternate disinfectants (dimensions 4 and 5) further complicates the picture.

6.2.4.3.2 Technology-Based Alternatives

The current set of DBP-RAM results indicates there is a significant potential for trade-offs between microbial and cancer risks if by-product MCLs are established in the absence of an enhanced SWTR. In the alternative, there has been some mention of technology-based approaches in the hope that trade-offs may be more avoidable with such approaches. The alternative to establishment of MCLs under the SDWA is the specification of a treatment technique. Normally, treatment techniques can be used only when measurement problems prevent the establishment of MCLs. A rationalization might be made that, in this unique case, the difficulty of relating MCLs to resulting health risks could be considered a measurement problem.

One treatment technique approach would be to specify a membrane technology capable of reducing both microbial and cancer risks simultaneously. Because membrane filtration removes microbial contaminants, it might provide a means of progressing without an enhanced SWTR. The cost of installing nanofiltration in all the large surface water systems that filter but do not soften has been very roughly estimated to be on the order of $5 billion per year ($150/household/yr. x [103 million persons/3 persons per household]). By comparison, the results in Exhibit 36 indicate that the total social cost of a THAA MCL of 60 ug/l in the SWTR *With Alternate Disinfectants* Scenario -- a rough proxy for the status quo -- is about $1 billion per year, nearly all in the form of cancer damages ($358 million/yr) and Giardia damages ($639 million/yr). In addition to the unfavorable economics, it is incorrect to conceive of membrane technology as being free of trade-offs. Membrane technologies would not remove bromide and may result in a shift to brominated by-products (in some systems) which may be more potent carcinogens. In addition the solid waste and water wastage impacts of these technologies would pose significant cost and environmental issues.

Another technology-based alternative would be to adopt an approach similar to that used in the Lead and Copper Rule. The objective would be to require optimized application of the simplest and most inexpensive by-product control strategies by all plants above a specified action level. Under this approach, systems above the action level would be required to demonstrate that they have eliminated prechlorination and optimized coagulation processes, relative to their unique raw water and treatment conditions. DBP-RAM analysis of a similar option (81% not prechorinating and optimizing coagulation; see Exhibits 40 and 41) shows that at the most stringent MCL of 10 ug/l, about one-third of the known cancer risk (dimension 2) would be removed at a fairly low cost cost ($122 million per year). The apparent effectiveness of an option requiring elimination of prechlorination and optimization of coagulation as the only available treatments reflects an inherent feature of the influent simulation -- that most of the aggregate cancer risk is in the large number of plants that have average influent conditions, not in the small percentage of plants that have extreme influent conditions. In this way, the technology-based approach applies

the low cost treatments more extensively to more of the total known cancer risk, achieving significant reduction without introducing the higher costs and unknown risks associated with alternate disinfectants.

Such an approach would not be free of significant trade-offs, however. One downside is that it would provide uneven protection, leaving much cancer risk untouched in the small percentage of plants that have extreme influent conditions. Another major inescapable trade-off is that the elimination of prechlorination would generate offsetting increases in Giardia risks in about the same proportions in this scenario as in the other DBP-RAM scenarios. In fact, results in Exhibits 40 and 41 indicate that it is these two first steps in the least cost algorithm that are responsible for most of the increased risk of giardiasis. The development of an enhanced SWTR would therefore also be a requisite for implementation of this strategy.

An additional drawback is the fact that the optimization of coagulation could cause a shift to more brominated by-products that are potentially more potent carcinogens. Furthermore, there are some plants in which influent conditions (e.g., alkalinity) are particularly unsuited to optimization of coagulation, or in which site conditions are particularly unsuited to the addition of contact time to compensate for the loss of prechlorination. As with the membrane technologies, the cost and environmental consequences of the solid waste and water wastage impacts of such a strategy would have to be fully evaluated. All these factors would have to be weighed by states in making individual optimization decisions. A final obstacle, therefore, would be the capacity of state primacy agencies to make plant-by-plant determinations regarding the optimization of treatment.

7.0 Summary Observations

The DBP-RAM may be viewed as simply an explicit, systematic framework for testing the hypothesis that a specified regulatory strategy will result in a net decrease in residual health risk. In the current analysis, the uncertainties and unknowns dominate. The only clear conclusion seems to be that an enhanced SWTR could eliminate increased microbial risk; and that such enhancement might not contribute significant additional treatment cost or cancer risk (in systems already chlorinating).

The current DBP-RAM results are intended as starting points in this attempt to define and analyze a manageable and meaningful *core problem*. The broader utility of the DBP-RAM framework lies in the fact that modelling such a process requires explicit specification of the methodology and assumptions that underly the trade-off functions. Within this explicit framework, it is possible to investigate the many remaining *unknowns* and the sensitivity of the results to uncertainties in the current *place holder* assumptions.

The "what-if" phase of analysis that lies ahead has potential to reveal which *unknowns* and which *place holders* have the greatest influence on the results. The importance of missing information can be evaluated by examining various additional *place holder* hypotheses regarding *unknown* processes, or by simply accentuating the pure *unknowns* that lie outside the model, in the manner adopted in this paper.

The DBP-RAM provides a frame of reference for evaluating, or anticipating the implications of new scientific understanding or technology. For example, the technology to practically implement an enhanced SWTR may not yet exist, but the potential of such a development has been usefully evaluated. In this way, the DBP-RAM can serve as a framework for evaluating the value of research as well as the relative importance of different research objectives. Significantly, in the current DBP-RAM results, the

total social cost curve most closely approximating the status quo has an intercept that implies existing health damages are on the order of one billion dollars per year. This provides a benchmark against which the value of research and of technology development can be assessed.

A number of sensitivity tests of current *place holder* assumptions are presently underway in response to comments offerred by the EPA Science Advisory Board. The sensitivity of current results is being evaluated with respect to: influent TOC assumptions, influent bromide assumptions, seasonal variation, over-design assumptions, prechlorination assumptions, chlorine dose and contact basin sizing assumptions, chlorine decay assumptions, trihalomethane formation equations, influent Giardia assumptions, and Giardia infection modelling. In addition to sensitivity tests, the modelling framework is presently being expanded to encompass surface water plants which employ lime softening and to examine differences in the implied trade-offs when model assumptions are modified to reflect the circumstances faced by small water systems, serving fewer than 10,000 persons. In addition, a formation equation to predict bromate occurrence and exposure is being added.

Ultimately, the utility of "what-if" analysis will diminish. The number of conceivable variations of assumptions far exceeds the number of public water supplies. At some point, it would make more sense to apply the EPA Water Treatment Plant Model to each individual plant than it would to continue to guess about them in aggregate. Efficient selection of follow-up DBP-RAM analyses should still offer further improvements in the understanding of the problem before that point is reached. Beyond that point, however, there must be a recognition that no amount of analysis can overcome many of the uncertainties inherent in this problem. A modelling framework such as that of the DBP-RAM is useful in gaining understanding of the potential significance of uncertainties, unknowns, and variability, but it cannot supply the measure of judgement that will eventually be required to devise a solution in the presence of such factors.

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Technical Note 1

Cancer Risk Assessment Procedures

The cancer risk estimates for the trihalomethanes and haloacetic acids included in the DBP-RAM are based on dose-response relationships developed from animal bioassays for carcinogenicity using the linearized multistage model for low dose extrapolations. In the DBP-RAM, both upper limit and maximum likelihood estimate values for the dose-response relationships for these substances have been used, as discussed further below.

The EPA carcinogen risk assessment guidelines provide a discussion and rationale for computing and using an upper limit value to characterize the carcinogenicity dose-response relationship for use in risk assessments. While noting the need to examine and compare dose-response results from various extrapolation models, these guidelines recommend the use of the linearized multistage model as the model of choice, emphasizing that this model provides a plausible upper limit to the risk that is consistent with some proposed mechanisms of carcinogenicity.

It is noteworthy that the EPA guidelines also state that such an upper limit estimate "does not necessarily give a realistic prediction of the risk. The true value of the risk is unknown, and may be as low as zero. The range of risks, defined by the upper limit of the chosen model and the lower limit which may be as low as zero, should be explicitly stated. An established procedure does not yet exist for making "most likely" or "best" estimates."

The linearized multistage model produces values for the "slope" of a line relating the "extra" incidence of cancer over background rates (the y axis value) with the dose of a contaminant received (the x axis value). The dose is usually expressed in terms of mg/kg-day (milligrams of the substance received per kilogram of body weight per day), and the incidence is usually treated as a unitless value. Therefore, the units for this slope describing the risk are $(\text{mg/kg-day})^{-1}$. (Note that the "unitless" incidence could also be expressed in units of "cases per individual per lifetime.")

The mathematical form of the multistage model for determining the extra risk is:

$$A(d) = 1\text{-}\exp[-(q_1 d + q_2 d^2 + \ldots + q_k d^k)]$$

where $A(d)$ is the extra risk at dose d (see, e.g., Anderson et al., 1983). In this model, the "point estimates" of the coefficients q_i (and therefore the extra risk function $A(d)$ at any dose d) are calculated by maximizing the likelihood function of the data. The upper 95% confidence limits on the extra risk are then determined from the upper 95% confidence limit on the parameter q_1, which is denoted as "q_1^*". The q_1^* value is then used as the upper bound estimate of the risk at low doses. Based on this methodology, then, the q_1 value would be considered the maximum likelihood estimate of the risk.

As noted above, the risk value is presented in units of $(mg/kg\text{-}day)^{-1}$. It is often convenient to express the risk in terms of an exposure value that corresponds to specified risk levels, such as 10^{-4}, 10^{-5}, or 10^{-6} (that is, exposure corresponding to a 1 in 10,000, 1 in 100,000 or 1 in 1,000,000 chance of a carcinogenic response, respectively). For drinking water contaminants, these risk levels are usually expressed in terms of a drinking water concentration that an individual is assumed to experience for a lifetime. Most often for organics, the drinking water concentrations corresponding to these risk levels are expressed in units of ug/l. The arithmetic for converting the q_1^* and q_1 values to corresponding drinking water concentrations associated with various risk levels is detailed in the attached Exhibit. As noted there, these conversions involve the assumptions of a 70 kg individual consuming 2 liters of drinking water per day for a lifetime.

Notwithstanding the EPA guidelines recommending the use of the upper limit for risk assessments involving carcinogens, the DBP RAM uses, as previously noted, both the "maximum likelihood estimate" (q_1) and the upper 95% confidence limit (q_1^*) values of risk for the DBPs. The former "maximum likelihood estimate" value may provide a more similar basis for comparing DBP cancer incidence with waterborne disease incidence given that the Giardia risk estimates have been determined only in terms of a maximum likelihood estimate, as discussed further below. The latter, upper bound cancer risk estimate provides a more direct form of comparison of the risks estimated for the DBPs with cancer risks estimated for other drinking water contaminants.

A specific example of this "risk" arithmetic using chloroform is as follows. EPA has estimated that the unit lifetime risk values using the upper 95% confidence interval ($q1^*$) and Maximum Likelihood Estimate ($q1$) for chloroform are 6.1×10^{-3} and 3.5×10^{-4} $(mg/kg\text{-}day)^{-1}$, respectively. To express these unit risks in terms of drinking water concentrations — that is, the unit lifetime risk per $\mu g/L$ — these values are divided by 70 kg (the assumed body weight per individual), multiplied by 2 L/day (the assumed drinking water consumption), and divided by 1,000 (to convert mg into μg).

	MLE	Upper 95% CI	(Units)
Cancer Risk Factors	3.5×10^{-4}	6.1×10^{-3}	$(mg/kg\text{-}day)^{-1}$
Divide by 70 kg:	5.0×10^{-6}	8.7×10^{-5}	$(mg/day)^{-1}$
Multiply by 2 L/day:	1.0×10^{-5}	1.7×10^{-4}	$(mg/L)^{-1}$
Divide by 10^3 $\mu g/mg$:	1.0×10^{-8}	1.7×10^{-7}	$(\mu g/L)^{-1}$

To determine the drinking water concentration that corresponds to a specific lifetime risk level (e.g., 10^{-4}, 10^{-5}, or 10^{-6}) the lifetime risk level of interest is divided by the unit risk value expressed, as shown above, in terms of $(\mu g/L)^{-1}$. For example, the chloroform drinking water concentration that corresponds to a lifetime risk of 10^{-4} based on the upper 95% confidence interval is obtained by dividing 10^{-4} by 1.7×10^{-7} $(\mu g/L)^{-1}$, giving 573 $\mu g/L$, which is rounded

to 600 μg/L. That is, an individual exposed to drinking water with approximately 600 μg/L of chloroform present for his/her lifetime, and assuming the 70 kg body weight and 2 L/day consumption, is estimated to have a one in ten-thousand chance of cancer (above background cancer rates). The chloroform drinking water concentrations corresponding to the 10^{-4}, 10^{-5}, and 10^{-6} risk levels for both the MLE and upper 95% confidence interval unit risks obtained by similar calculations, including rounding, are shown below.

Risk Level	MLE	Upper 95% CI	(Units)
10^{-4}	10,000	600	μg/L
10^{-5}	1,000	60	μg/L
10^{-6}	100	6	μg/L

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DBP Cancer Risk Calculation Data and Analysis

- **Model requires calculation of "cases per year:"**

Population Exposed (persons) x DBP Concentration (µg/l) x Annual DW Risk Factor $\left(\frac{\text{cases/person/year}}{\mu\text{g/l}}\right)$ = cases/year

- **Derivation of Annual DW Risk Factor from MLE or Upper 95% CI Lifetime Risk Factor:**

MLE or Upper 95% CI Lifetime Risk Factor — **Conversion Factors:** — **Lifetime DW Risk Factor** — **Conversion Factor** — **Annual DW Risk Factor**

$$\left(\frac{\text{cases/person/lifetime}}{\text{mg/kg/day}}\right) \times \frac{1}{70\text{kg} \times \frac{1}{2\text{l/day}} \times 10^3\ \mu\text{g/mg}} = \left(\frac{\text{cases/person/lifetime}}{\mu\text{g/l}}\right) \times \frac{1}{70\ \text{years/lifetime}} = \left(\frac{\text{cases/person/year}}{\mu\text{g/l}}\right)$$

Divide Lifetime DW Risk Factor into 10^{-4}, 10^{-5}, 10^{-6} to obtain DW concentrations (µg/l) for these lifetime risk levels

MLE and Upper 95% CI Lifetime Risk Factors Used:			DW Concentrations (µg/l) for Lifetime Risks (for Upper 95% CI)			
DBP	MLE	Upper 95% Conf. Int.	10^{-4}	10^{-5}	10^{-6}	Comments
Chloroform	3.5×10^{-4}	6.1×10^{-3}	600	60	6	MLE from R. Bull, 95% CI from draft HA
Bromodichlormethane (BDCM)	8.2×10^{-4}	2.5×10^{-2}	140	14	1.4	MLE from R. Bull, 95% CI from draft HA
Dibromochloromethane (DBCM)	8.2×10^{-4}	2.5×10^{-2}	140	14	1.4	Assumed to be the same as BDCM
Bromoform	4.4×10^{-4}	7.9×10^{-3}	400	40	4	MLE from R. Bull, 95% CI from draft HA
Dichloroacetic acid	8.8×10^{-2}	2.8×10^{-1}	12.5	1.25	0.125	Provided by R. Cantilli (OST)
Tichloroacetic acid	2.1×10^{-2}	6.3×10^{-2}	55	5.5	0.55	Provided by R. Cantilli (OST)

Technical Note 2

Equivalence of "Maximum Net Benefit" and "Minimum Total Social Cost" Objectives

Introduction

The issue of trade-offs among alternative regulatory options may be approached by either minimizing total social cost or maximizing the net benefit. Total social cost includes 1) the cost of treatment and monitoring, and 2) the value of health damages incurred. The net benefit includes 1) value of direct health damages avoided, 2) "willingness-to-pay" for a reduction in the risk of incurring health damages, and minus 3) the cost of treatment and monitoring. The following discussion provides an intuitive method of showing the equivalence of two approaches without using a rigid mathematical proof. First, necessary and sufficient conditions for maximizing the net benefit are derived. Second, the optimal degree of treatment maximizing the net benefit is shown to be the same as the optimal degree of treatment minimizing total social cost. Therefore, the equivalence of maximizing the net benefit and minimizing total social cost objectives can be established.

Maximizing Net Benefit

The health effects associated with microbial contaminants and disinfection by-products in drinking water are waterborne diseases and cancer, respectively. Depending upon the degree of treatment applied, both types of health damages may be assessed by estimating the "willingness to pay" and direct damages.

1. Value of Health Damages Incurred

The total value of health damages *incurred* at any time can be defined as the sum of the value of waterborne diseases and cancer cases incurred at that time. This definition can also be expressed as

$$D_t(\delta) = G_t(\delta) + C_t(\delta) \tag{1}$$

where t = any time instant, and $t \geq 0$,
δ = degree of treatment, and $\delta \geq 0$,
$D_t(\delta)$ = value of health damages incurred at time t,
$G_t(\delta)$ = value of waterborne disease incurred at time t, and
$C_t(\delta)$ = value of cancer cases incurred at time t.

2. Value of Health Damages Avoided

Similarly, the value of health damages *avoided* at any time is expressed as

$$A_t(\delta) = D_{t=0}(\delta=0) - D_t(\delta) = [G_{t=0}(\delta=0) - G_t(\delta)] + [C_{t=0}(\delta=0) - C_t(\delta)] \tag{2}$$

where $A_t(\delta)$ = value of health damages avoided at time t,
$D_{t=0}(\delta=0)$ = value of health damages incurred at time 0 (baseline),
$G_{t=0}(\delta=0)$ = value of waterborne disease incurred at time 0 (baseline), and
$C_{t=0}(\delta=0)$ = value of cancer cases incurred at time 0 (baseline).

3. Cost of Treatment and Monitoring

The cost of treatment and monitoring under the regulation may be denoted by $R_t(\delta)$. Assuming that no treatment is installed before the regulation (i.e., a "clean slate"), the baseline cost of treatment and monitoring is zero, or

$$R_{t=0}(\delta=0) = 0 \tag{3}$$

4. Net Benefit

The net benefit from the regulation is the difference between value of health damages avoided and the cost of treatment and monitoring. It can be defined as

$$B_t(\delta) = A_t(\delta) - R_t(\delta) \tag{4}$$

where $B_t(\delta)$ = the net benefit at time t.

5. Maximization of Net Benefit

The objective of the trade-off analysis is to solve for the optimal degree of treatment that maximizes the net benefit. The optimal degree of treatment δ^* is found when

$$B_t(\delta^*) = \underset{\delta \geq 0}{\text{Max}}\ B_t(\delta) = A_t(\delta^*) - R_t(\delta^*) \tag{5}$$

Assuming that $B_t(\delta)$ has finite first order derivative and that second order derivative exists, δ^* may be found by applying the first order condition

$$\frac{\partial B_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^*} = \frac{\partial A_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^*} - \frac{\partial R_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^*} = 0 \tag{6}$$

and second order condition

$$\frac{\partial^2 B_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^*} = \frac{\partial^2 A_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^*} - \frac{\partial^2 R_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^*} \leq 0 \tag{7}$$

Equation (6) is the necessary condition for optimization. The set of solutions to this equation includes all the possible values of δ^* that maximize the net benefit $B_t(\delta)$, except when $B_t(\delta)$ is maximized at the boundary $\delta = 0$. Equation (7) is the sufficient condition for maximizing $B_t(\delta)$, meaning that if δ^* satisfies both equations (6) and (7) then δ^* is the optimal degree of treatment to maximize the net benefit, provided that $B_t(\delta)$ is not maximized at $\delta=0$.

Assuming that the degree of treatment $\delta = 0$ is not the optimal solution, equation (6) implies that the marginal value of health damages avoided is equal to the marginal treatment expenditure with respect to the degree of treatment when the net benefit is maximized.

Minimizing Total Social Cost

Total social cost is the sum of the value of health damages incurred and the cost of treatment and monitoring. Let $S_t(\delta)$ represent the total social cost, it is defined as

$$S_t(\delta) = D_t(\delta) + R_t(\delta) \tag{8}$$

Total social cost is minimized if the optimal degree of treatment δ^{**} can be found for

$$S_t(\delta^{**}) = \underset{\delta \geq 0}{\text{Min}}\ S_t(\delta) = D_t(\delta^{**}) + R_t(\delta^{**}) \tag{9}$$

By applying the first order condition, the value of δ^{*} may be solved from

$$\frac{\partial S_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} = \frac{\partial D_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} + \frac{\partial R_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} = 0 \tag{10}$$

To minimize $S_t(\delta)$, the optimal solution δ^{**} must also satisfy the second order condition

$$\frac{\partial^2 S_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} = \frac{\partial^2 D_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} + \frac{\partial^2 R_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} \geq 0 \tag{11}$$

From equation (2), it is known that

$$D_t(\delta) = D_{t=0}(\delta=0) - A_t(\delta) \tag{12}$$

Substituting $D_t(\delta)$ from equation (12), equations (10) and (11) become

$$\frac{\partial S_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} = \frac{\partial D_{t=0}(\delta=0)}{\partial \delta}\Big|_{\delta=\delta^{**}} - \frac{\partial A_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} + \frac{\partial R_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} = 0 \tag{13}$$

and

$$\frac{\partial^2 S_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} = \frac{\partial^2 D_{t=0}(\delta=0)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} - \frac{\partial^2 A_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} + \frac{\partial^2 R_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} \geq 0 \tag{14}$$

Recalling that $D_{t=0}(\delta=0)$ is a constant describing the baseline condition, it has zero derivative.

The equations (13) and (14) can be rearranged as

$$\frac{\partial S_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} = \frac{\partial A_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} - \frac{\partial R_t(\delta)}{\partial \delta}\Big|_{\delta=\delta^{**}} = 0 \tag{15}$$

and

$$\frac{\partial^2 S_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} = \frac{\partial^2 A_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} - \frac{\partial^2 R_t(\delta)}{\partial \delta^2}\Big|_{\delta=\delta^{**}} \leq 0 \tag{16}$$

Equivalence of the Two Optimization Processes

Note that the equations (15) and (16) are of the same form as equations (6) and (7), respectively. It follows that the sets of solutions to equations (5) and (9) are identical *for* $\delta > 0$. In other words, the two optimization processes are equivalent for any degree of treatment other than zero. To complete the argument, it must be proven that if $\delta = 0$ is the optimal degree of treatment for maximizing net benefit $B_t(\delta)$, it also minimizes total social cost $S_t(\delta)$, and vice versa.

If $\delta = 0$ is maximizing net benefit $B_t(\delta)$, then the net benefit associated with no treatment is greater than the net benefit associated with any positive degree of treatment, or

$$B_t(\delta=0) = \underset{\delta \geq 0}{\text{Max}}\ B_t(\delta) \geq B_t(\delta>0) \tag{17}$$

By substituting for $B_t(\delta)$ from equation (4), the above equation is transformed into

$$A_t(\delta=0) - R_t(\delta=0) \geq A_t(\delta>0) - R_t(\delta>0) \tag{18}$$

Replacing for $A_t(\delta)$ from equation (2), the inequality (18) becomes

$$[D_{t=0}(\delta=0) - D_t(\delta=0)] - R_t(\delta=0) \geq D_{t=0}(\delta=0) - D_t(\delta>0) - R_t(\delta>0) \tag{19}$$

It is true that $D_{t=0}(\delta=0)$ is equal to $D_t(\delta=0)$ because health damages remain constant over time if no treatment is installed. Thus the above expression can be rearranged as

$$D_t(\delta=0) + R_t(\delta=0) \leq D_t(\delta>0) + R_t(\delta>0) \tag{20}$$

Recalling equation (8), the above inequality is shown to be

$$S_t(\delta=0) \leq S_t(\delta>0) \tag{21}$$

This inequality implies that $\delta=0$ also minimizes total social cost $S_t(\delta)$. Similarly, we can show that if $\delta=0$ minimizes total social cost $S_t(\delta)$, it also maximizes net benefit $B_t(\delta)$. Therefore, maximizing the net benefit is equivalent to minimizing total social cost for any degree of treatment.

EXHIBITS AND APPENDIX MATERIAL

Analysis of Potential Trade-offs In Regulation of Disinfection By-Products

John E. Cromwell, III & Xin Zhang
Wade Miller Associates, Inc.

Frank Letkiewicz
Abt Associates, Inc.

Stig Regli & Bruce Macler
U.S. Environmental Protection Agency

Exhibits & Appendix Material

Exhibit 1

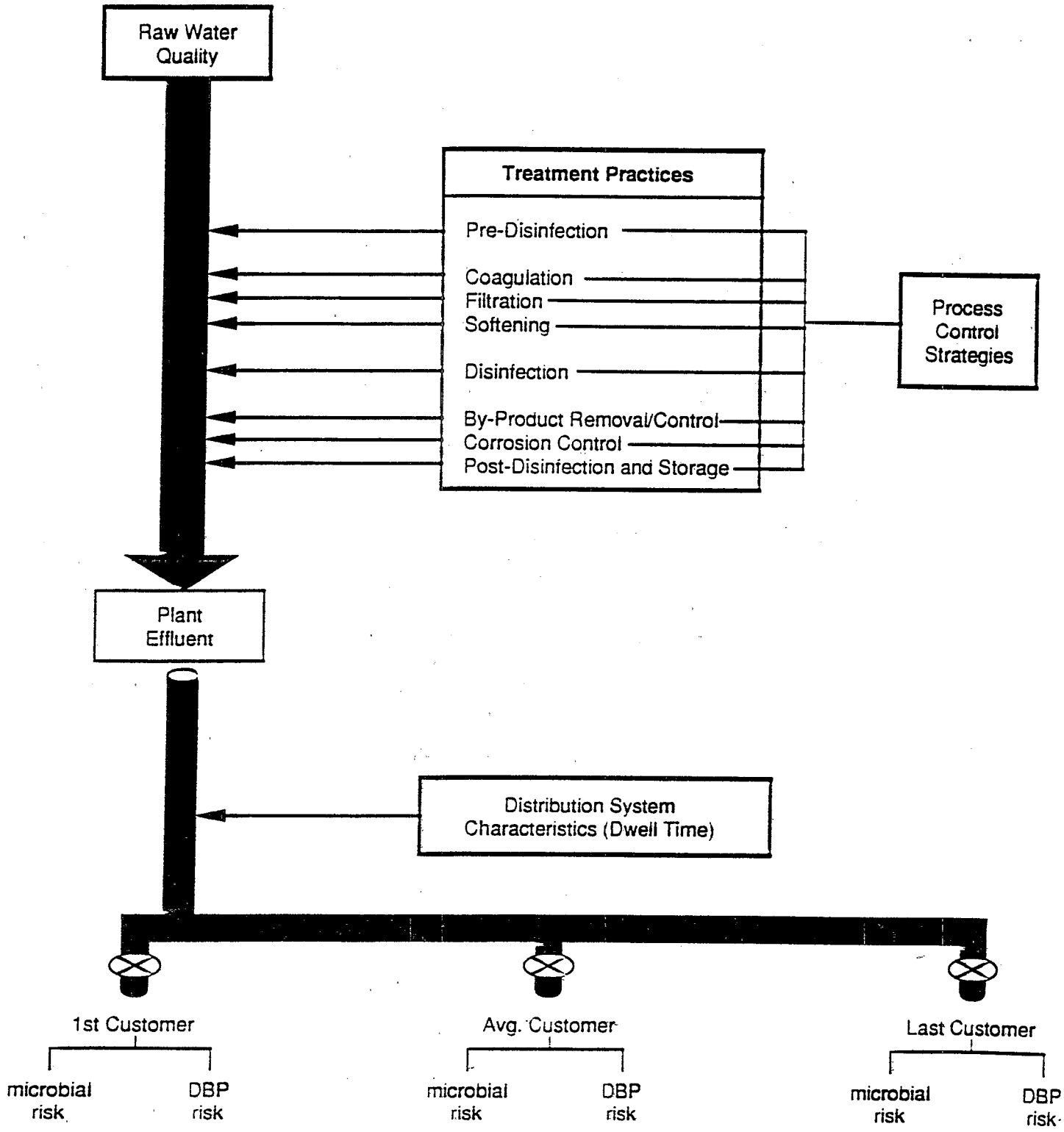

Raw Water Quality
Treatment Practices
Pre-Disinfection
Coagulation
Filtration
Softening
Disinfection
By-Product Removal/Control
Corrosion Control
Post-Disinfection and Storage
Process Control Strategies
Plant Effluent
Distribution System Characteristics (Dwell Time)
1st Customer
microbial risk
DBP risk
Avg. Customer
microbial risk
DBP risk
Last Customer
microbial risk
DBP risk

Exhibit 2

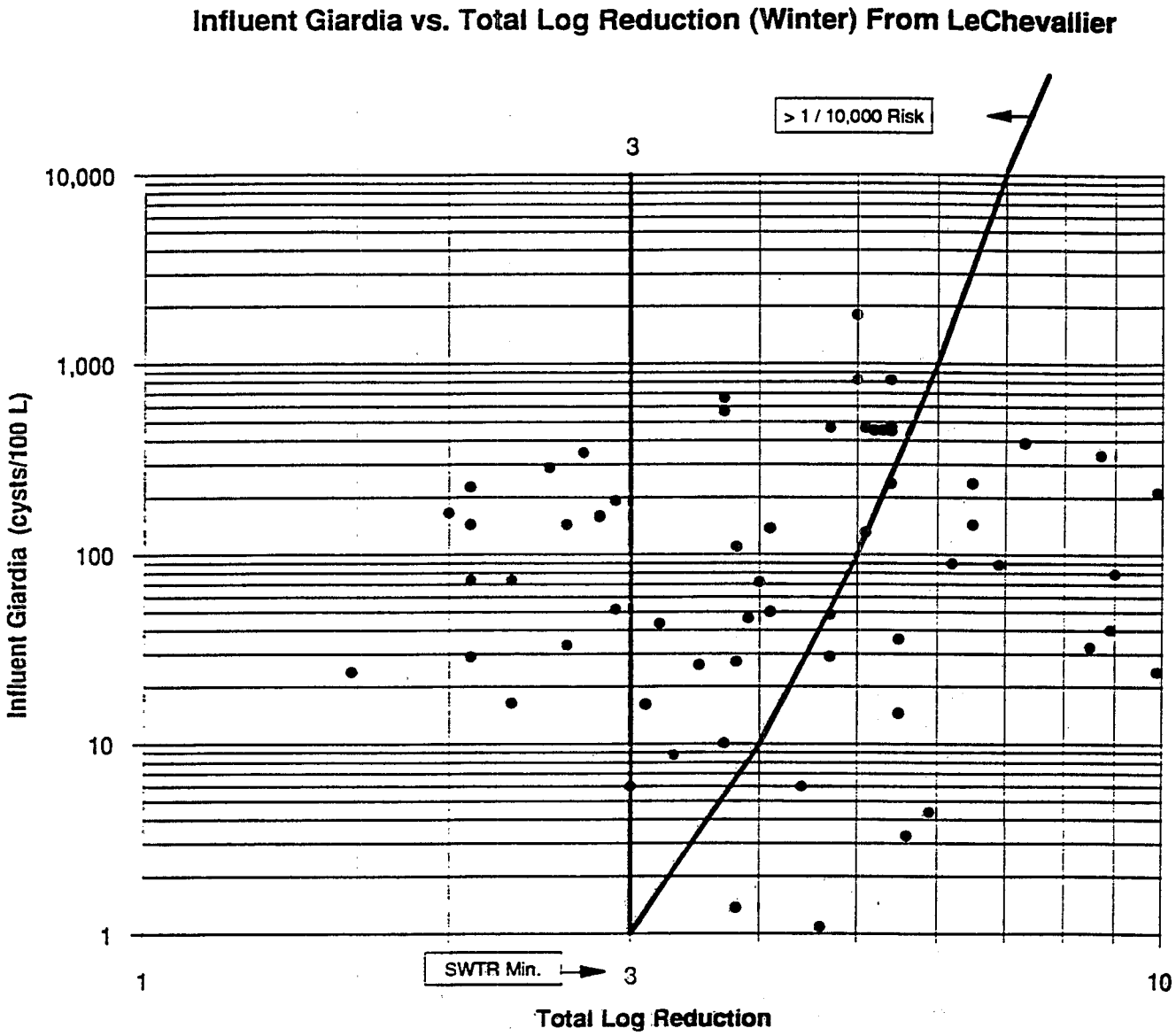

Influent Giardia vs. Total Log Reduction (Winter) From LeChevallier
> 1 / 10,000 Risk
3
10,000
1,000
100
10
1
Influent Giardia (cysts/100 L)
1
SWTR Min.
3
10
Total Log Reduction

Exhibit 3

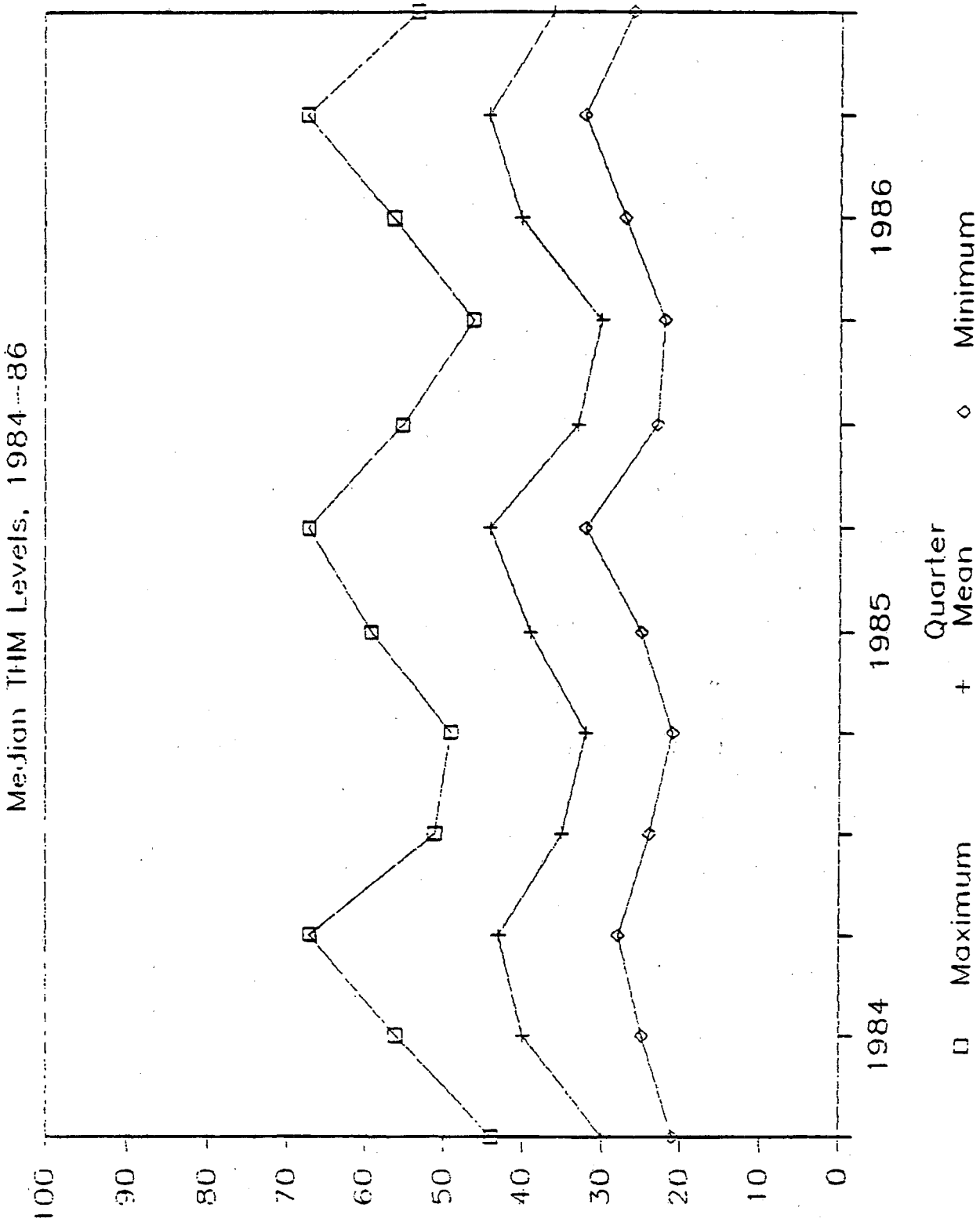

Median THM Levels, 1984--86
100
90
80
70
60
50
40
30
20
10
0
1984
1985
1986
Quarter
Maximum
Mean
Minimum

Exhibit 4

Disinfection By-Products Regulatory Analysis
Baseline Cancer Incidence -- Based on Occurrence Data
(Surface Water Systems)

Annual Cases = Population Exposed (persons) x DBP Concentration (µg/l) x Annual Risk Factor (cases/persons/year/µ

	High Case Estimate [1]		Low Case Estimate [2]	
	<10,000 people	≥10,000 people	<10,000 people	≥10,000 people
Total Population (million persons) [3]	17	145	17	1
Average Concentrations (µg/l)				
Chloroform	77.2	59.7		
Bromodichloromethane	24.8	17.4		6
Dibromochloromethane	10.4	6.3		3
Bromoform	1.4	0.8		0.
TTHMs	114	84		
Dichloroacetic Acid	27.7	22.1		6
Tichloroacetic Acid	16.6	17.00		5
THAAs	44	39		
MLE Annual DW Risk Factors [4]				
Chloroform	1.43E-10	1.43E-10		1.43E-
Bromodichloromethane	3.33E-10	3.33E-10		3.33E-
Dibromochloromethane	3.33E-10	3.33E-10		3.33E-
Bromoform	1.79E-10	1.79E-10		1.79E-
Dichloroacetic Acid	3.59E-08	3.59E-08		3.59E-
Tichloroacetic Acid	8.68E-09	8.68E-09		8.68E-
Cancer Incidence based on MLE (cases/yr.)				
Chloroform	0.19	1.24		0.
Bromodichloromethane	0.14	0.84		0.
Dibromochloromethane	0.06	0.30		0.
Bromoform	0.00	0.02		0.
TTHMs	0.4	2.4		0
Dichloroacetic Acid	17.3	115.0		3
Tichloroacetic Acid	2.5	21.4		6
THAAs	20	136		
Total				
Upper 95% CI Annual DW Risk Factors [5]				
Chloroform	2.49E-09	2.49E-09		2.49E-
Bromodichloromethane	1.02E-08	1.02E-08		1.02E-
Dibromochloromethane	1.02E-08	1.02E-08		1.02E-
Bromoform	3.22E-09	3.22E-09		3.22E-
Dichloroacetic Acid	1.13E-07	1.13E-07		1.13E-
Tichloroacetic Acid	2.57E-08	2.57E-08		2.57E-
Cancer Incidence Based on 95% CI (cases/yr.)				
Chloroform	3.3	21.6		5
Bromodichloromethane	4.4	25.7		9
Dibromochloromethane	1.8	9.3		5
Bromoform	0.1	0.4		0
TTHMs	10	57		
Dichloroacetic Acid	54.3	361.0		104
Tichloroacetic Acid	7.4	63.4		20
THAAs	62	424		1
Total				

[1] Based on occurrence data from: disinfection by-products field studies data (EPA,OGWDW,TSD)
[2] Based on occurrence data from Krasnes et.al., 1989
[3] Source: Federal Reporting Data System (FRDS)
[4] maximum likelihood estimate (MLE)
[5] upper 95% confidence interval

Population Served By Community Water Systems

(Total = 242 million)

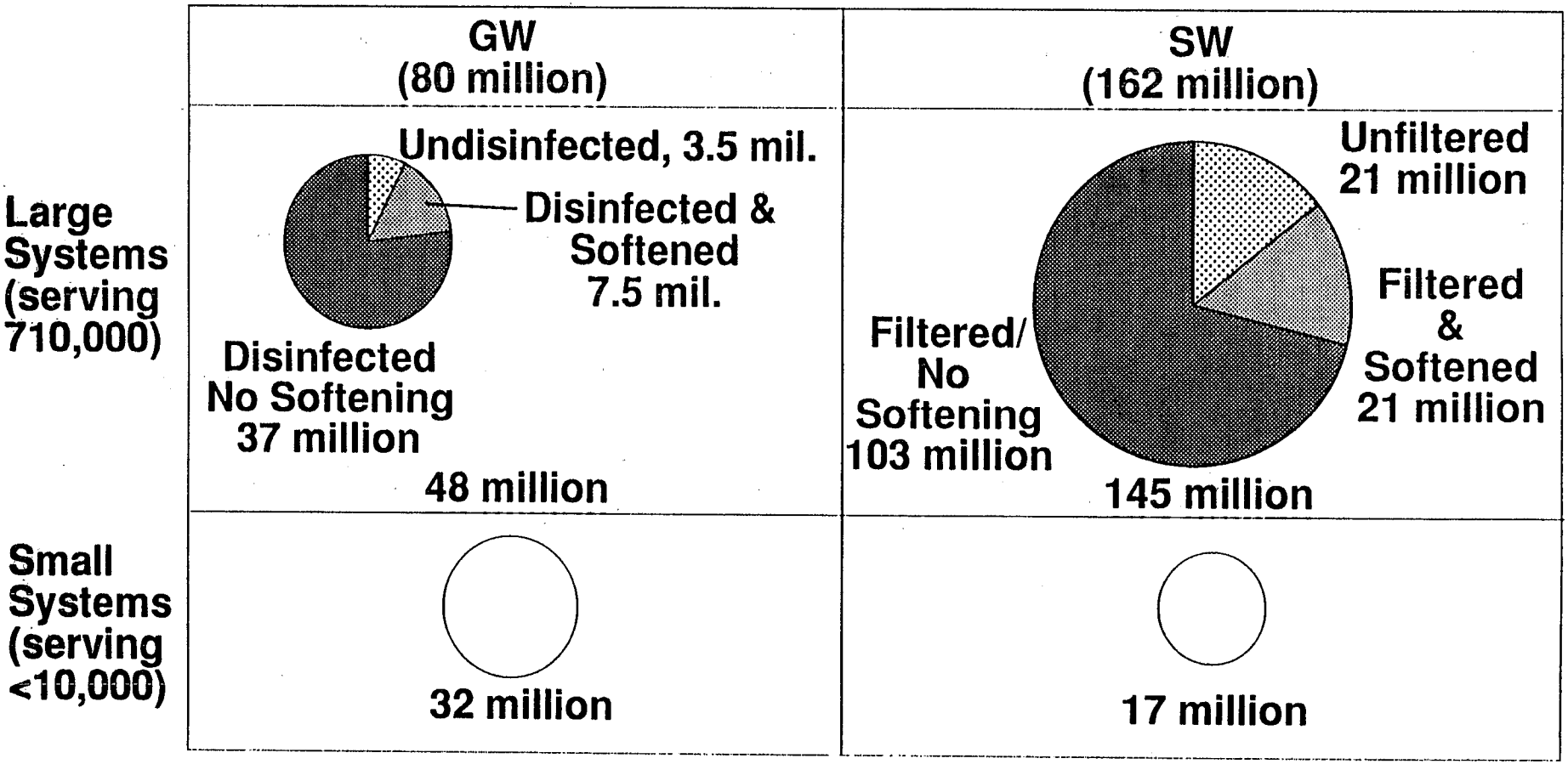
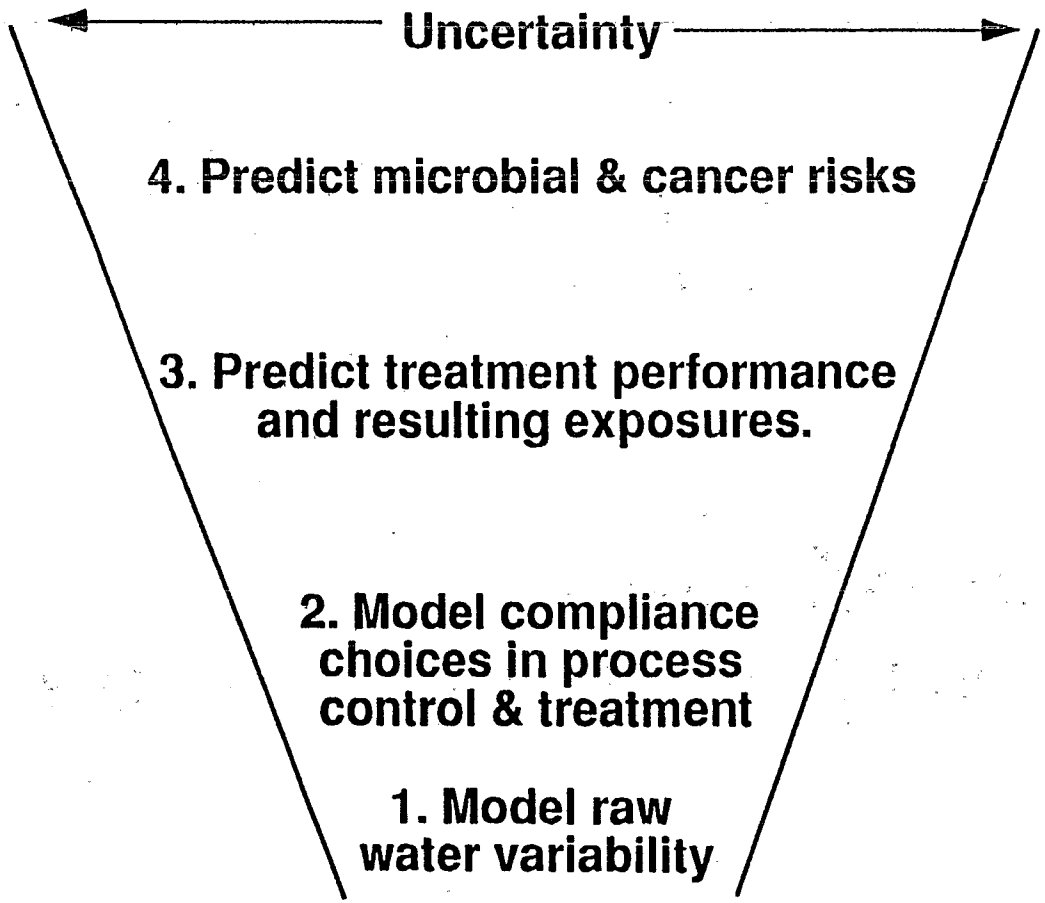


Exhibit 5

Major Steps in DBP Analysis



Analytical Tools:

Present cancer & giardia risk models

WTP model:
DBP equations &
CXT equations

WTP model assumptions

Monte Carlo simulation

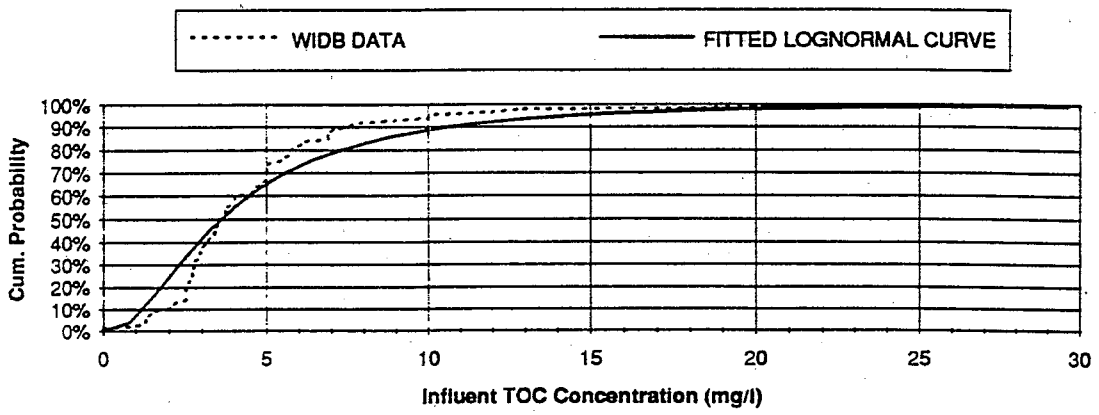
Exhibit 6

Exhibit 7

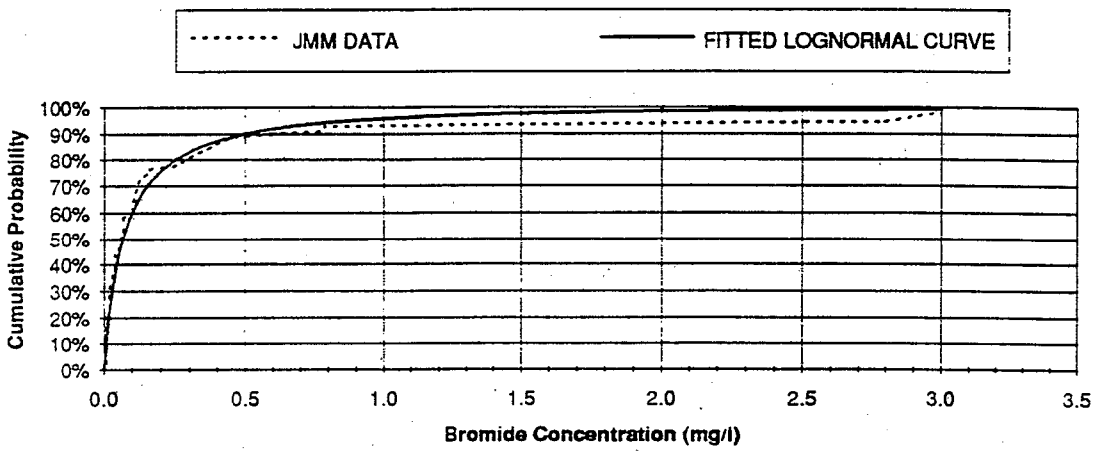
Draft: 5/13/92

SURFACE WATER WITHOUT FILTRATION/SOFTENING CUMULATIVE PROBABILITY DISTRIBUTIONS

Actual and Model-predicted Influent TOC Concentration



Actual and Model-predicted Bromide Concentration



Actual and Model-predicted Influent Giardia

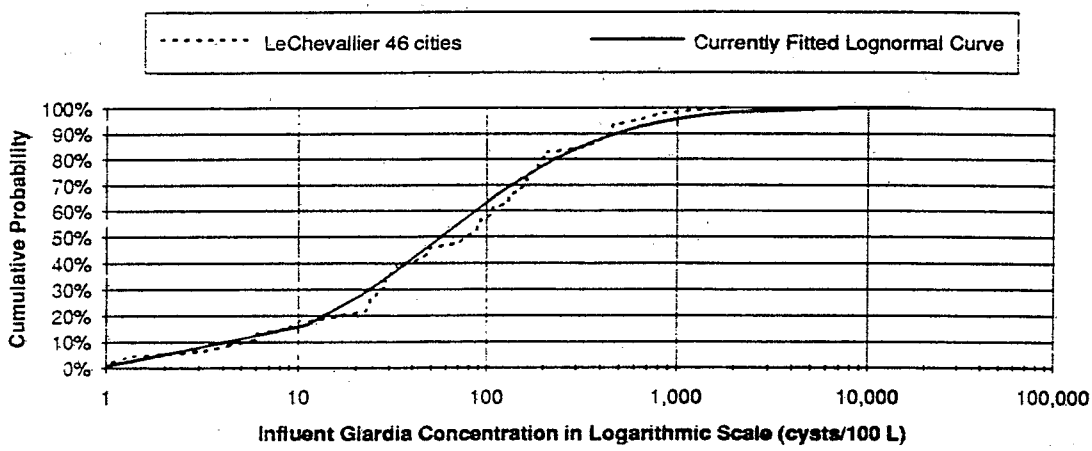
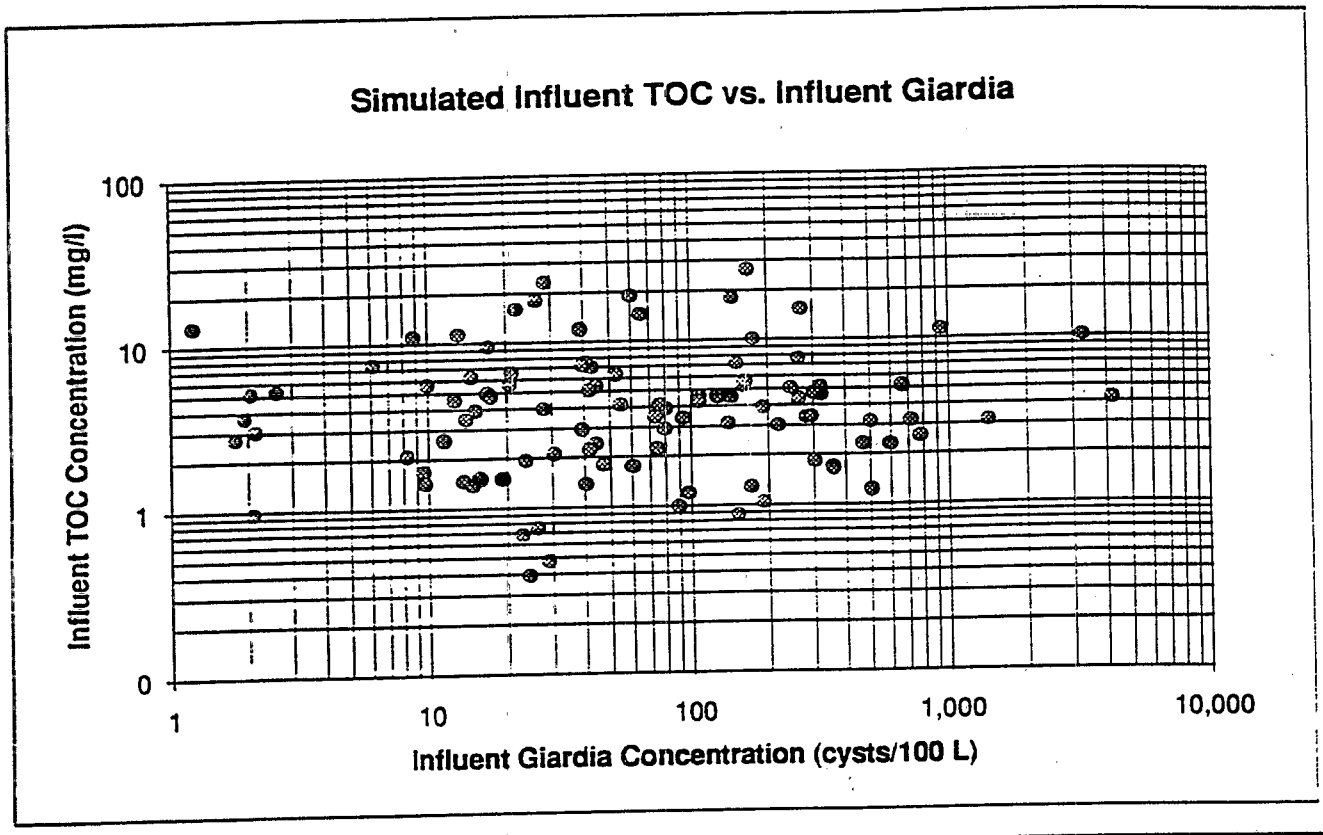
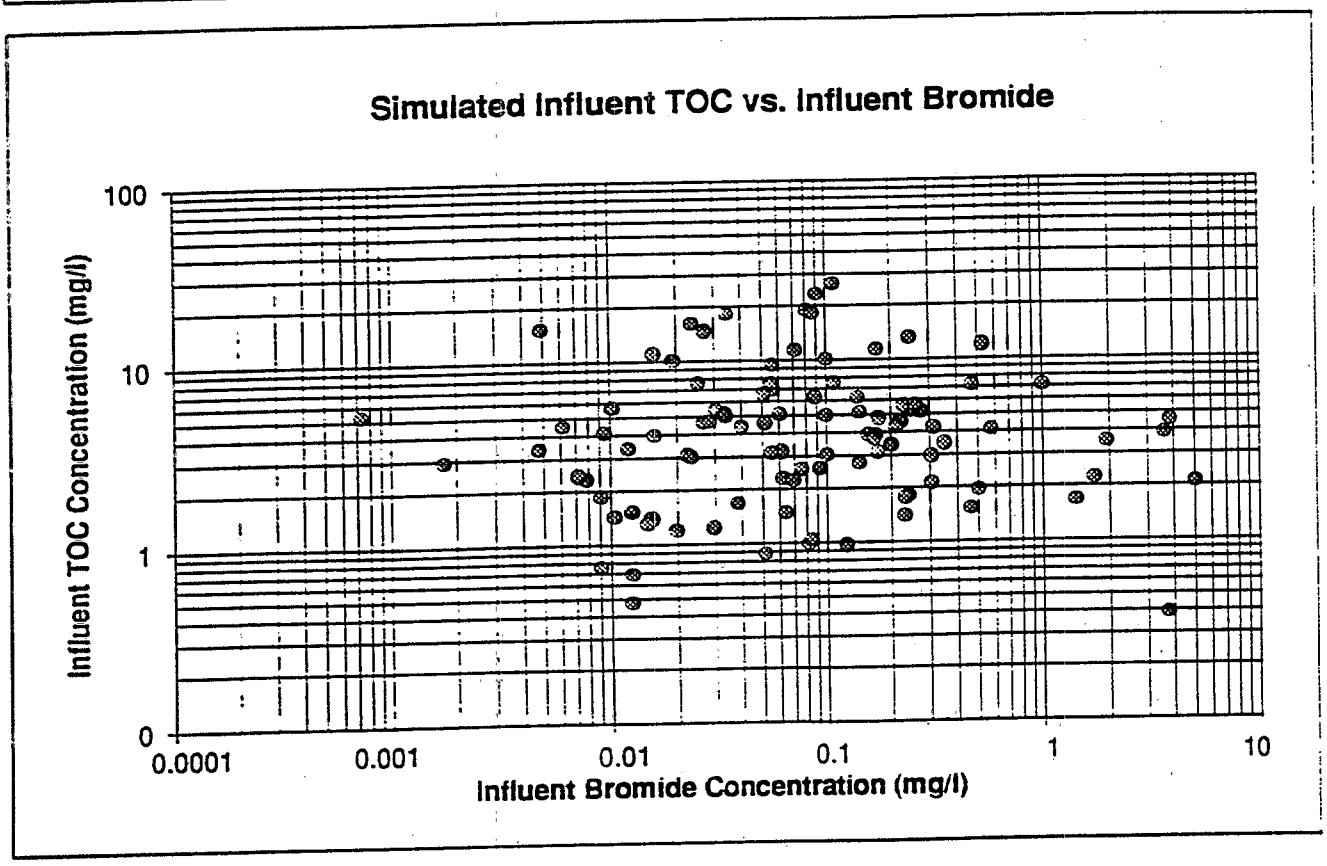


Exhibit 8


Simulated Influent TOC vs. Influent Giardia
Influent TOC Concentration (mg/l)
100
10
1
0
1
10
100
1,000
10,000
Influent Giardia Concentration (cysts/100 L)


Simulated Influent TOC vs. Influent Bromide
Influent TOC Concentration (mg/l)
100
10
1
0
0.0001
0.001
0.01
0.1
1
10
Influent Bromide Concentration (mg/l)

Compliance Decision Tree

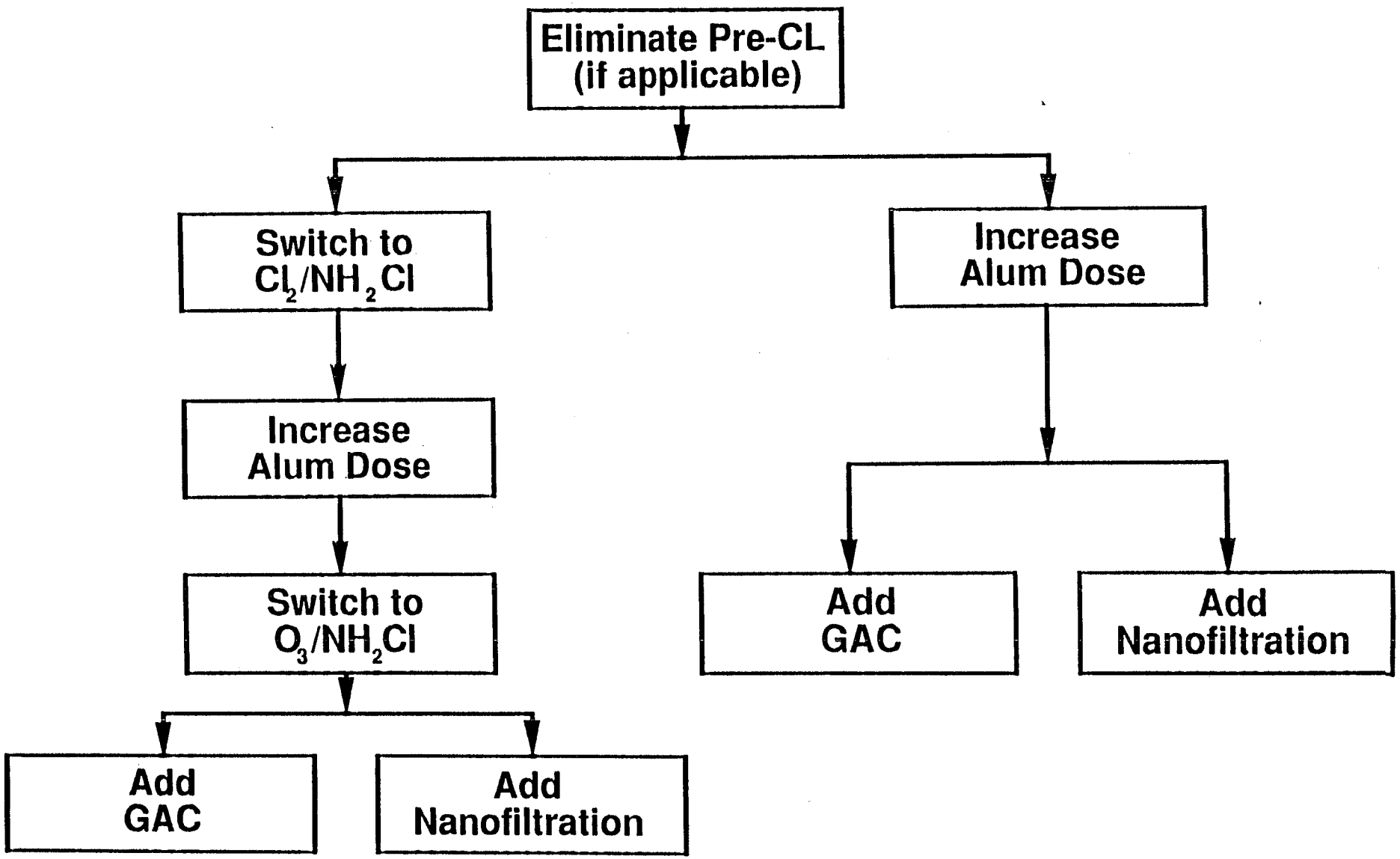


Exhibit 9

Exhibit 10

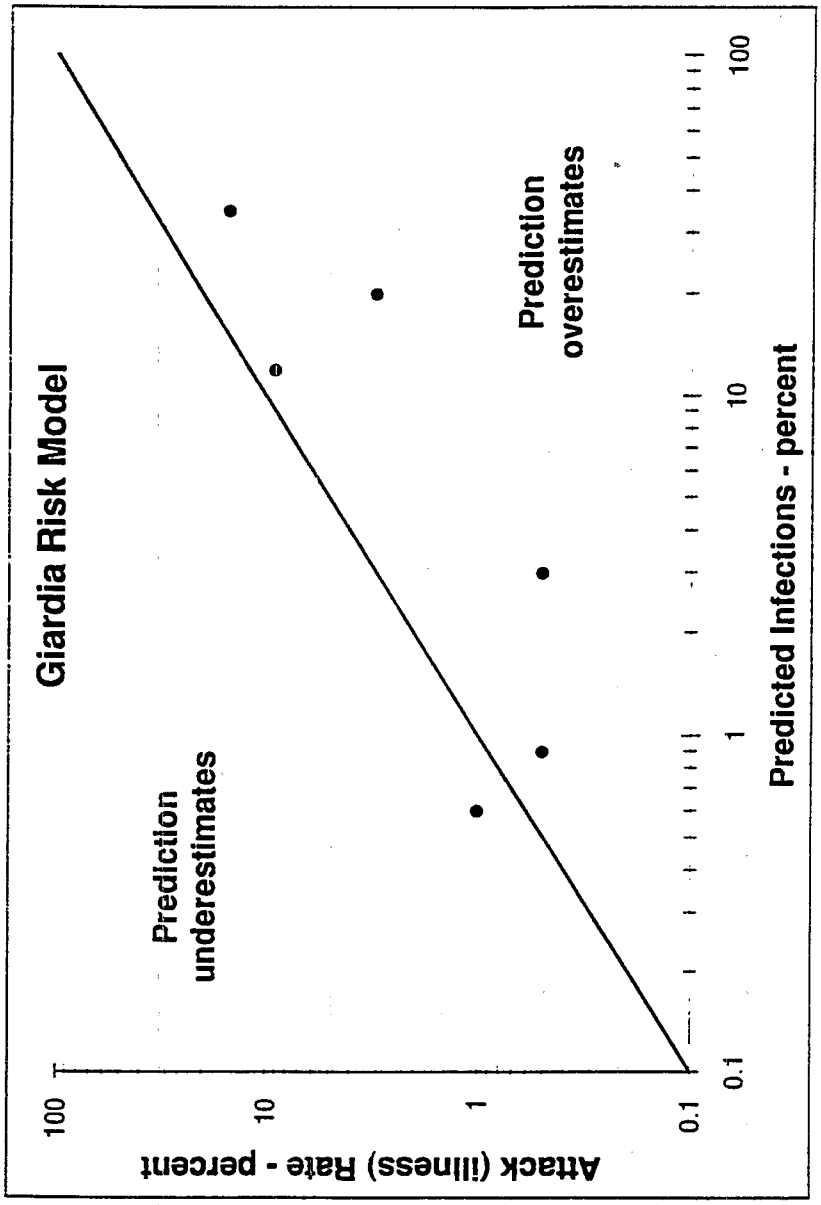

Giardia Risk Model
Prediction underestimates
Prediction overestimates
Attack (Illness) Rate - percent
100
10
1
0.1
0.1
1
10
100
Predicted Infections - percent

Exhibit 11

Overview of *Giardia* Modelling

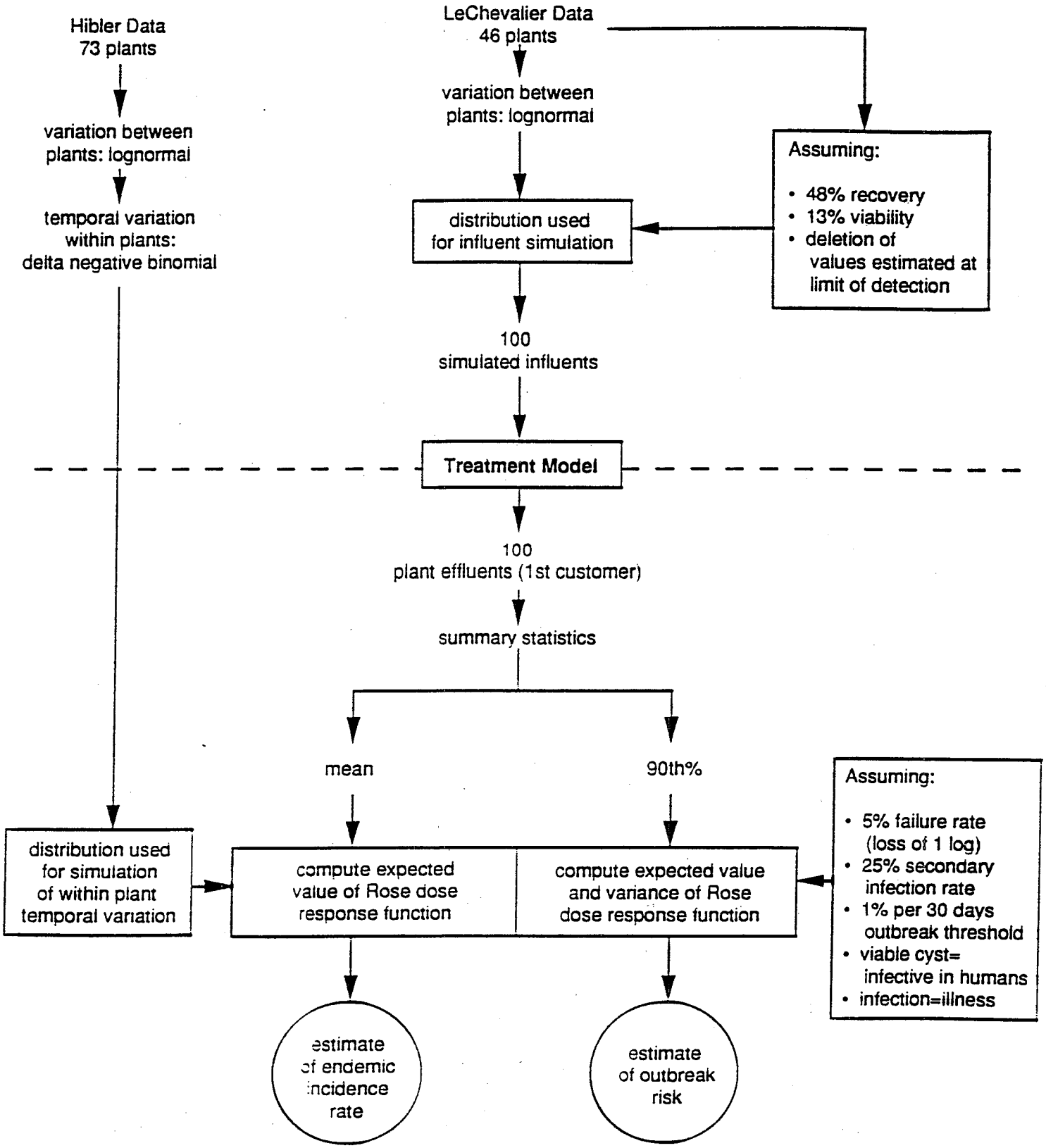


Exhibit 12

Overview of National-Level Model

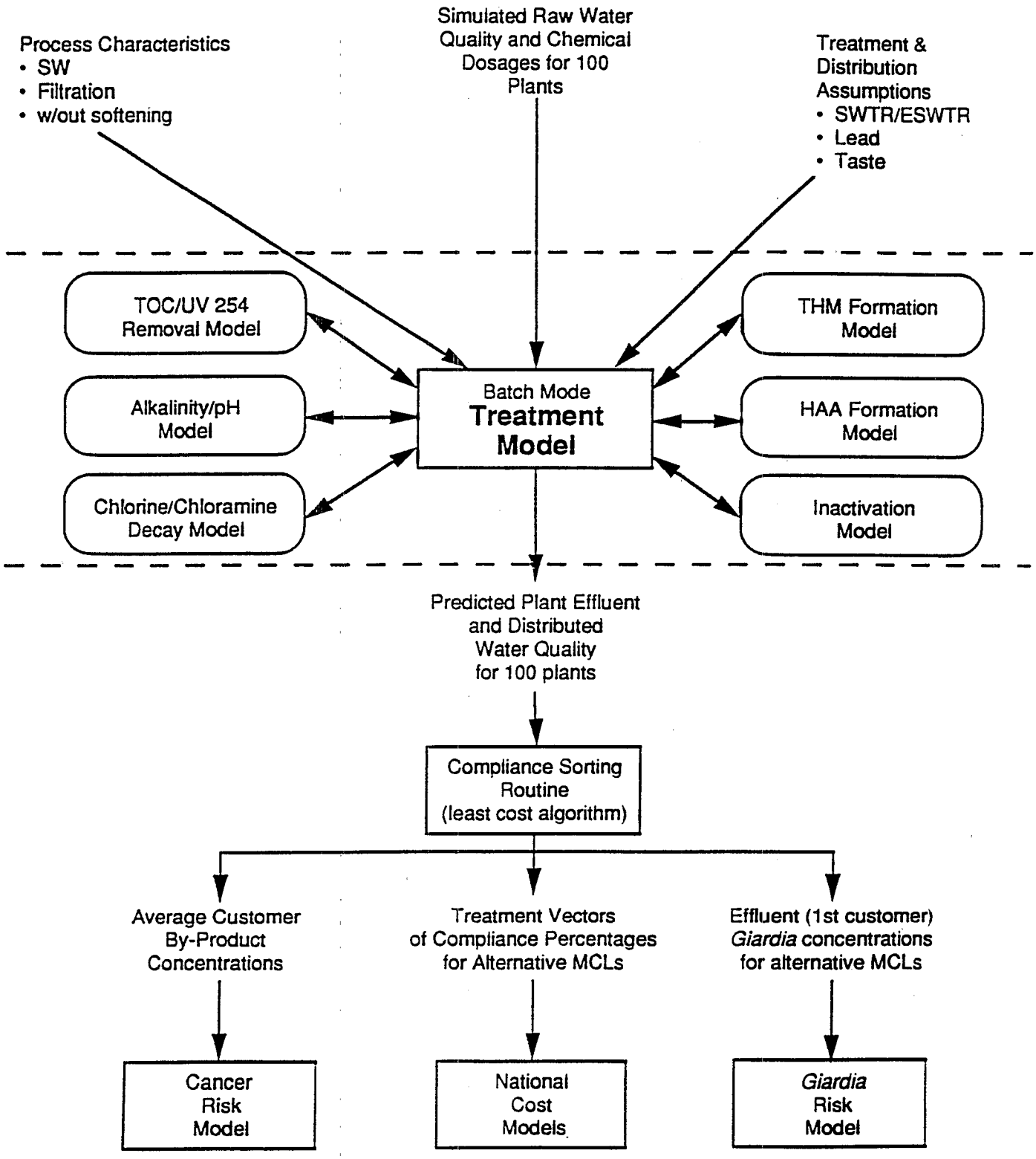
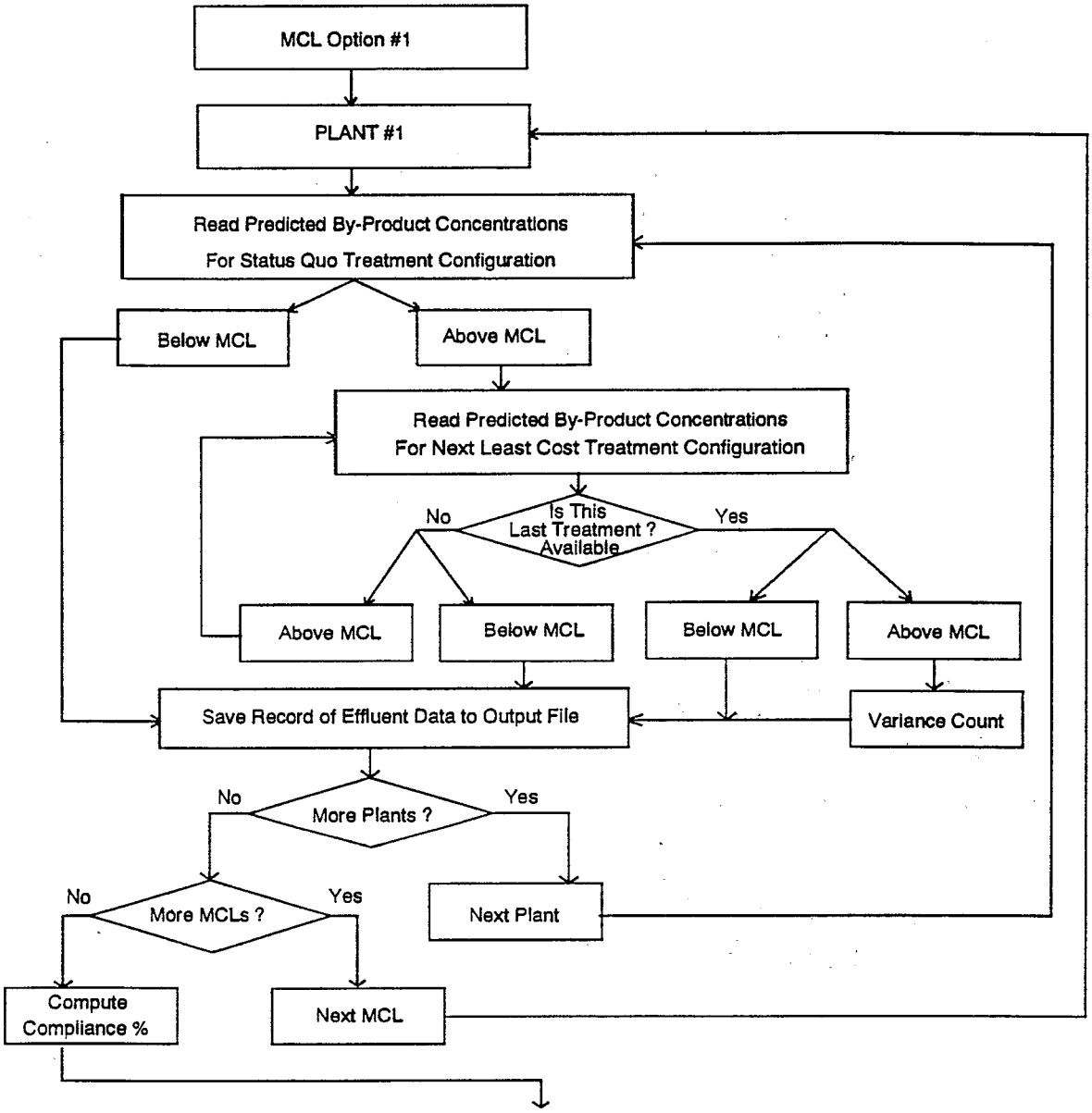


Exhibit 13

Compliance Sorting Routine



Compliance Percentages

SWTR Scenario W/ Alt. Disinf.	TTHM MCLs (ug/l) 100	75	50	25
No further treatment	61	49	33	17
Eliminate per-chlorination	21	25	23	10
Eliminate per-chlor & add ammonia	18	23	34	30
pre-chlor + ammonia + alum dose	0	3	9	27
pre-chlor + ammonia + alum + ozone	0	0	1	13
pre-chlor + ammonia + alum + ozone + GAC	0	0	0	3

Exhibit 14

The Core Problem

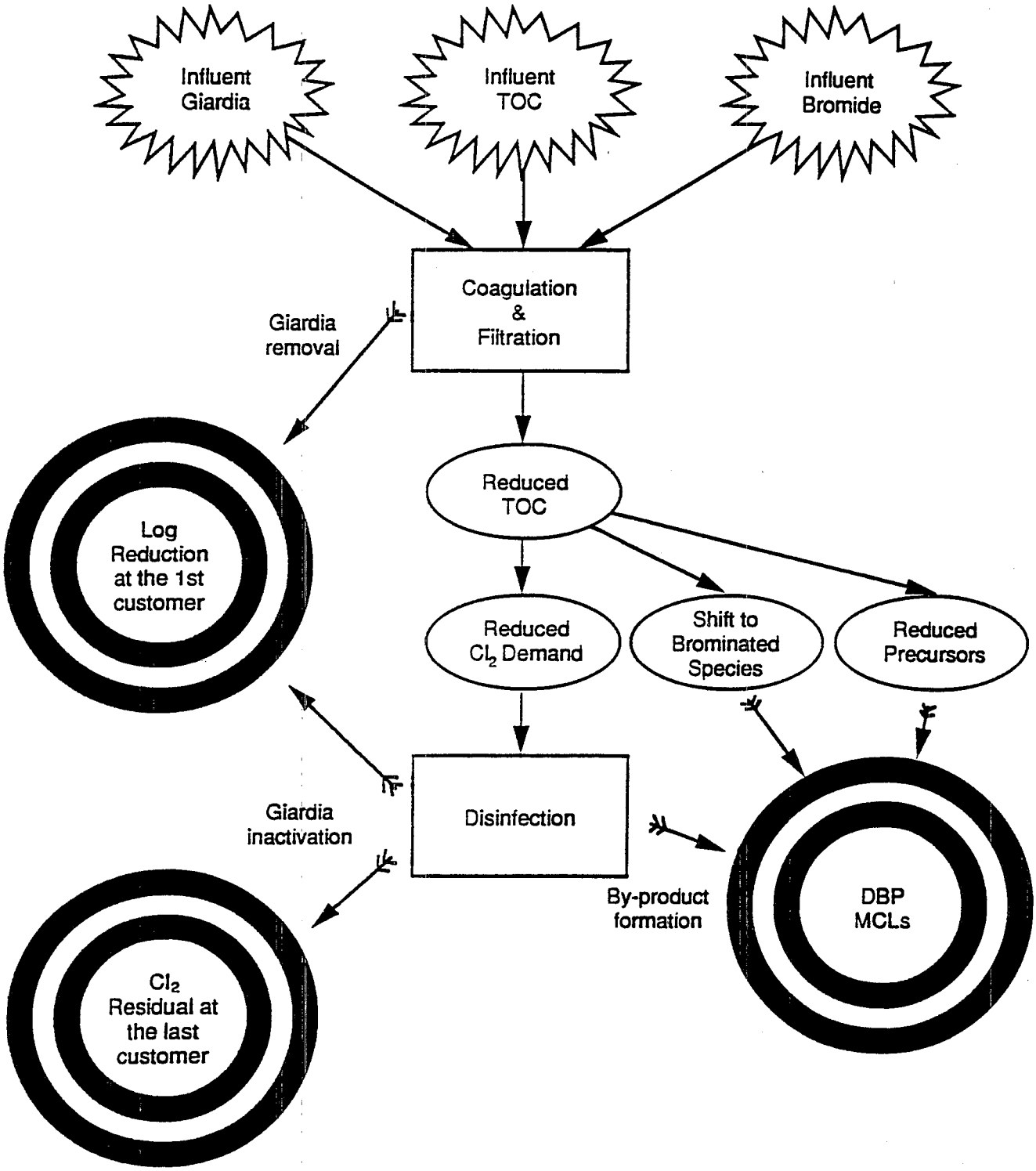


Exhibit 15

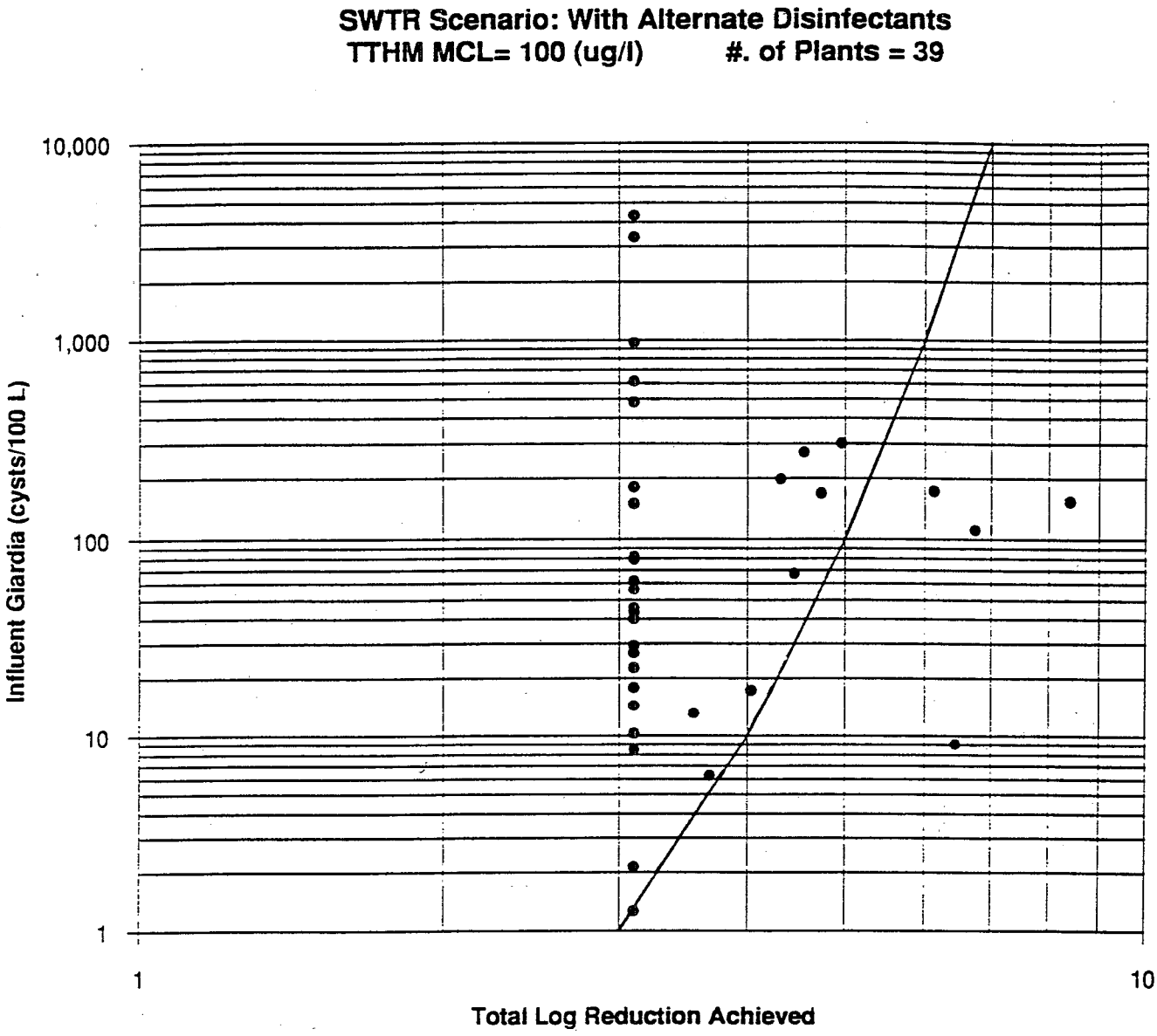

SWTR Scenario: With Alternate Disinfectants
TTHM MCL= 100 (ug/l)
#. of Plants = 39
10,000
1,000
100
10
1
Influent Giardia (cysts/100 L)
1
10
Total Log Reduction Achieved

Exhibit 16

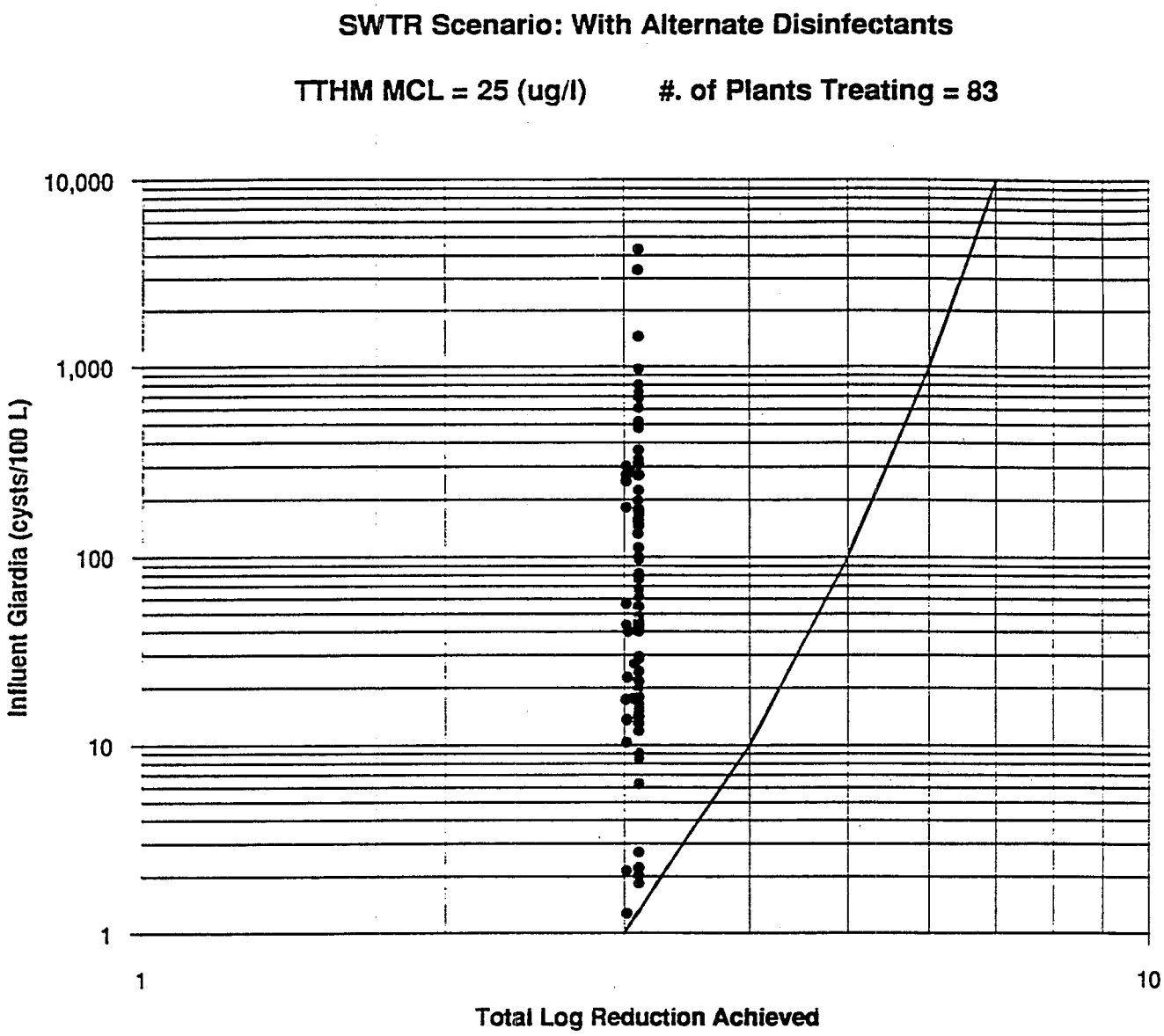

SWTR Scenario: With Alternate Disinfectants
TTHM MCL = 25 (ug/l)
#. of Plants Treating = 83
10,000
1,000
100
10
1
Influent Giardia (cysts/100 L)
1
10
Total Log Reduction Achieved

Exhibit 17

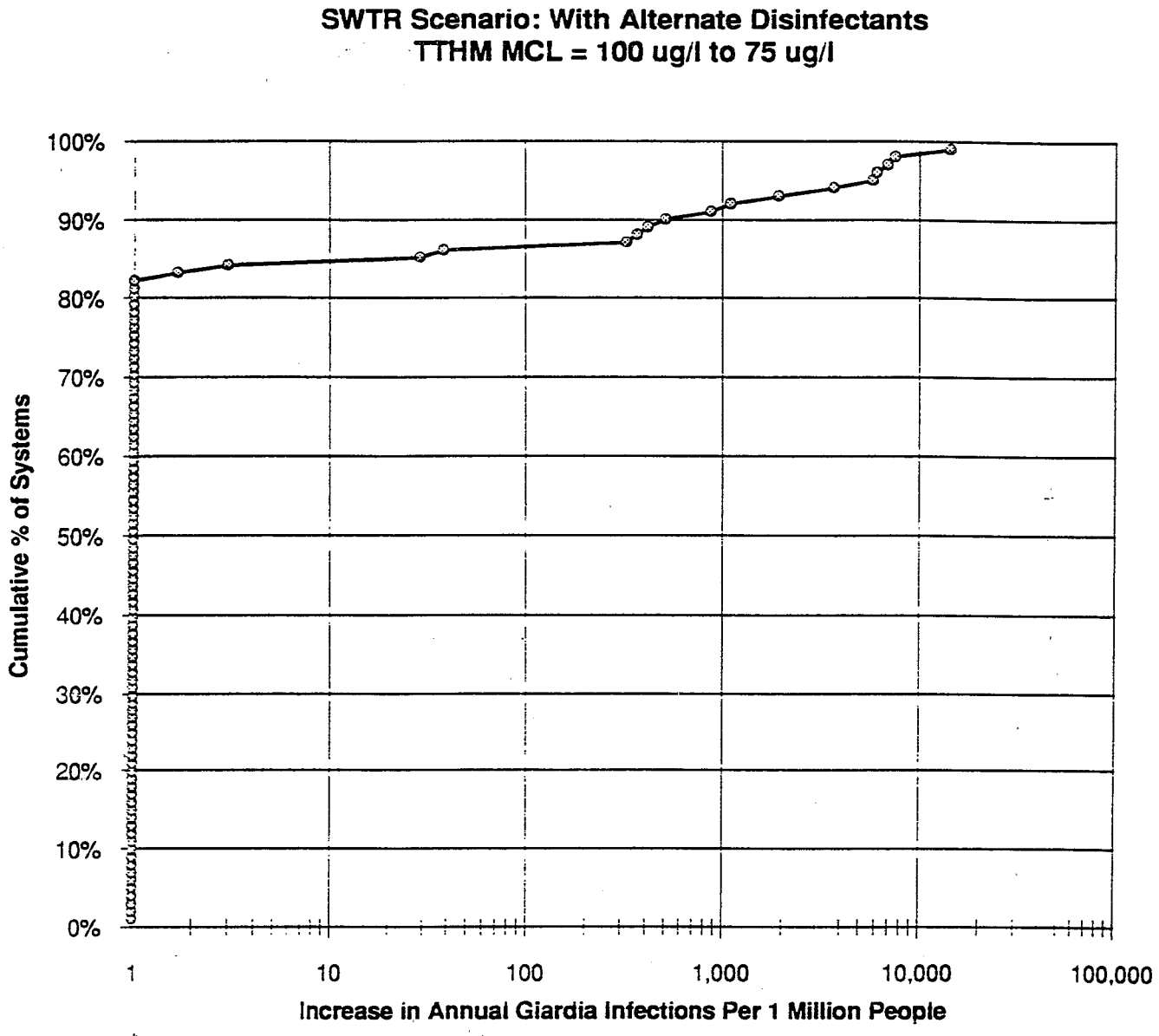

SWTR Scenario: With Alternate Disinfectants
TTHM MCL = 100 ug/l to 75 ug/l
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulative % of Systems
1
10
100
1,000
10,000
100,000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 18

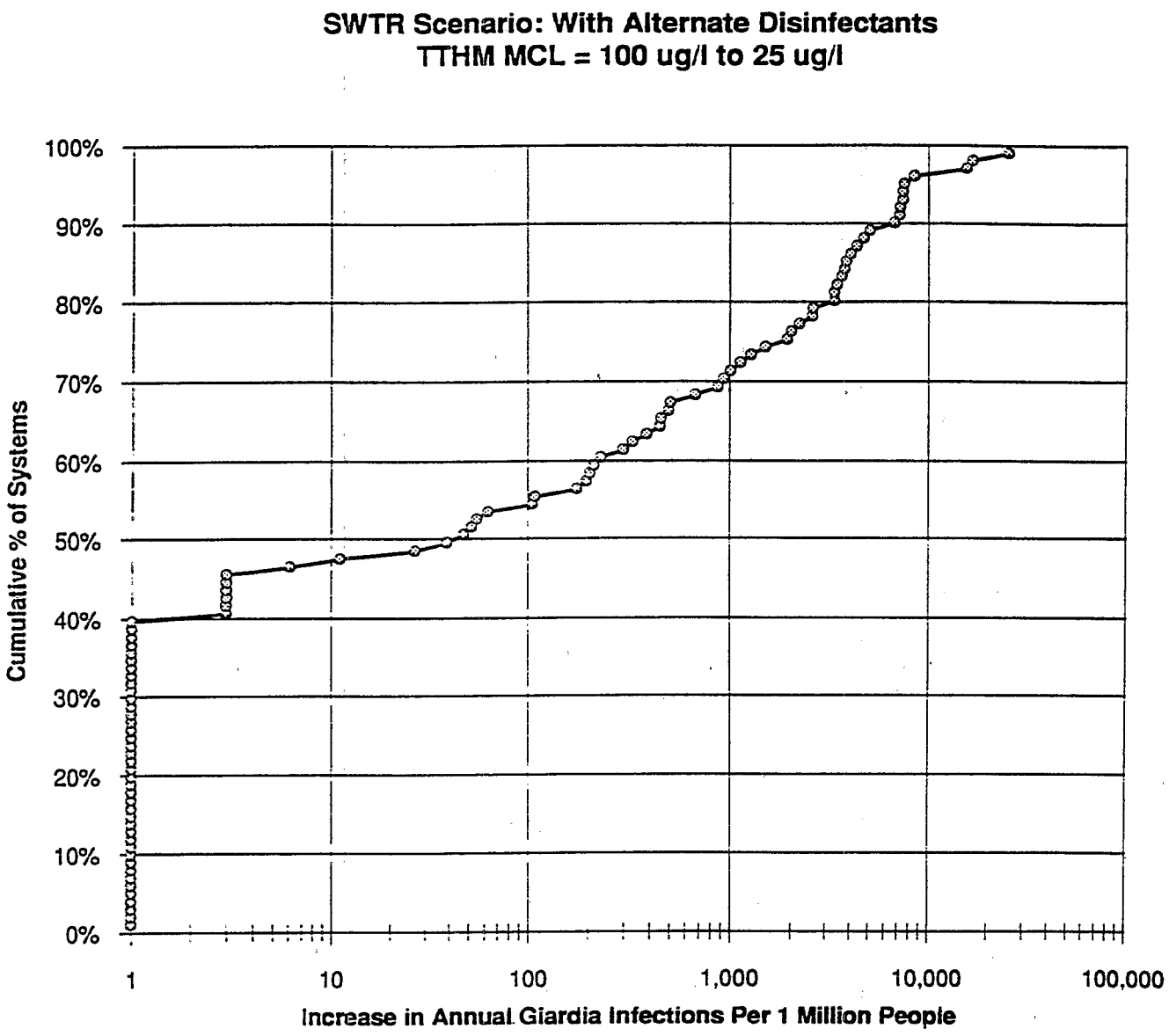

SWTR Scenario: With Alternate Disinfectants
TTHM MCL = 100 ug/l to 25 ug/l
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulative % of Systems
1
10
100
1,000
10,000
100,000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 19

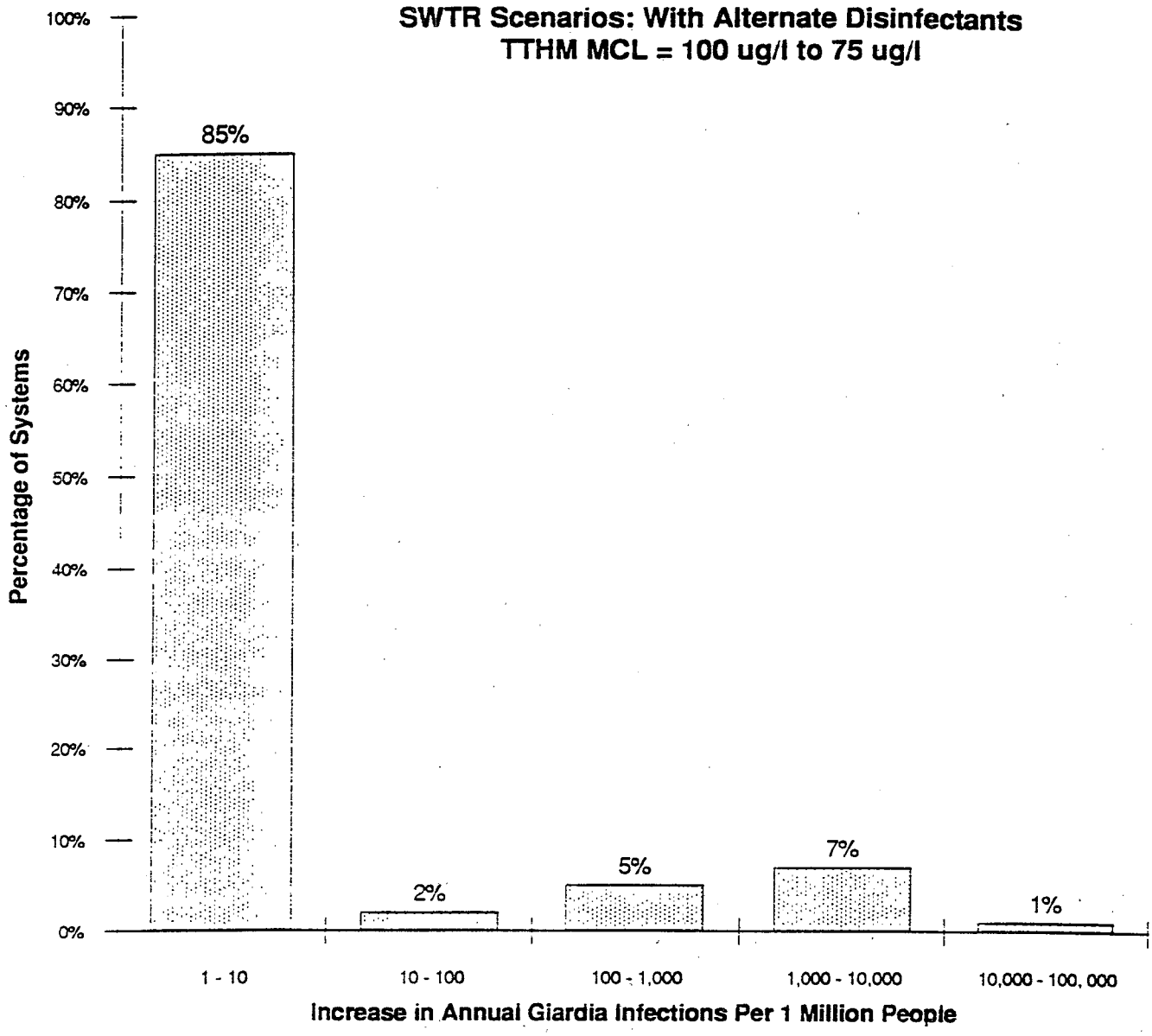

SWTR Scenarios: With Alternate Disinfectants
TTHM MCL = 100 ug/l to 75 ug/l
Percentage of Systems
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
85%
2%
5%
7%
1%
1 - 10
10 - 100
100 - 1,000
1,000 - 10,000
10,000 - 100, 000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 20

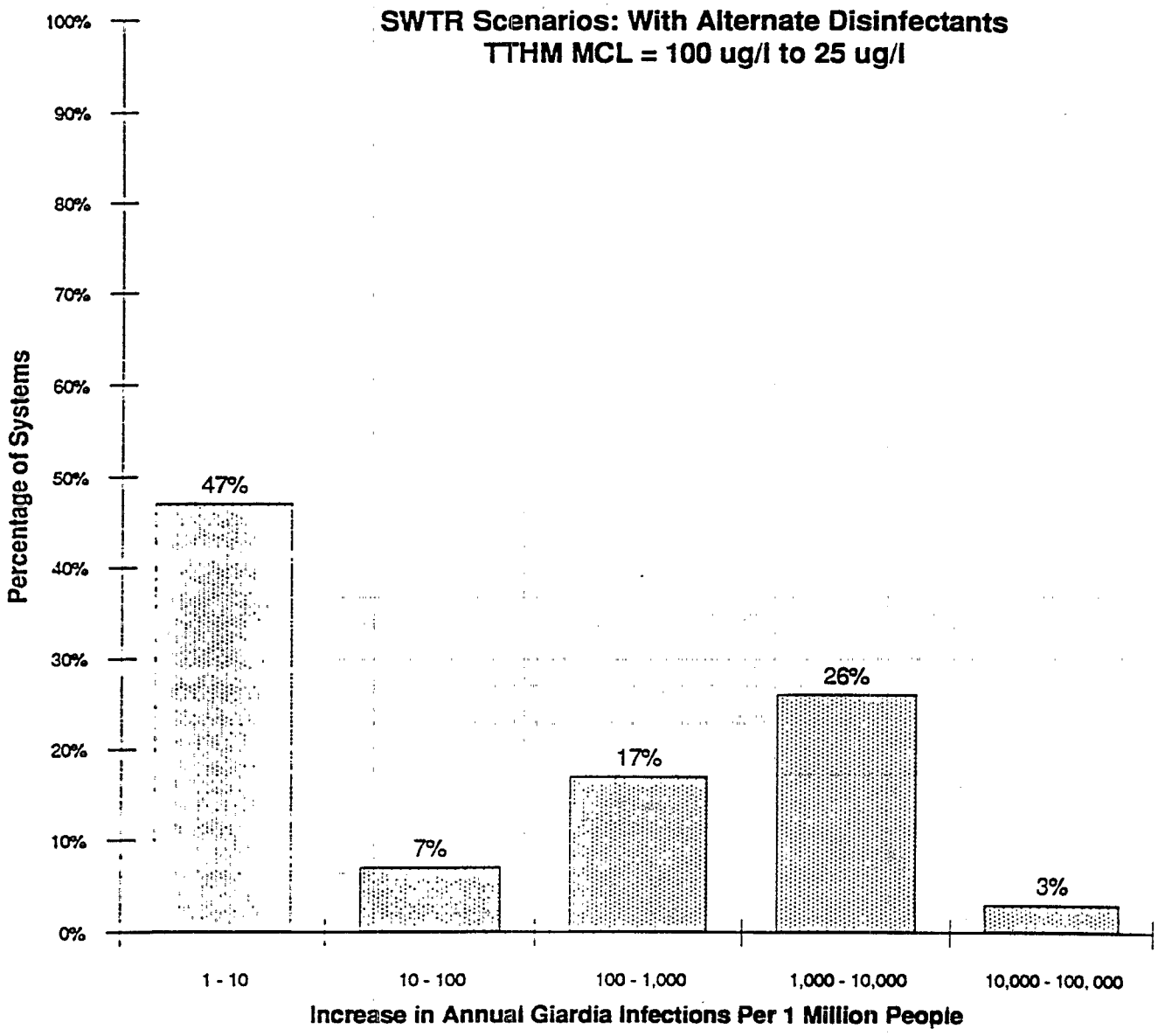

SWTR Scenarios: With Alternate Disinfectants
TTHM MCL = 100 ug/l to 25 ug/l
Percentage of Systems
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
47%
7%
17%
26%
3%
1 - 10
10 - 100
100 - 1,000
1,000 - 10,000
10,000 - 100,000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 21

SWTR Scenario: With Alternate Disinfectants

From TTHM MCL = 100 ug/l to 75 ug/l
Change in Risks Per 1 Million People

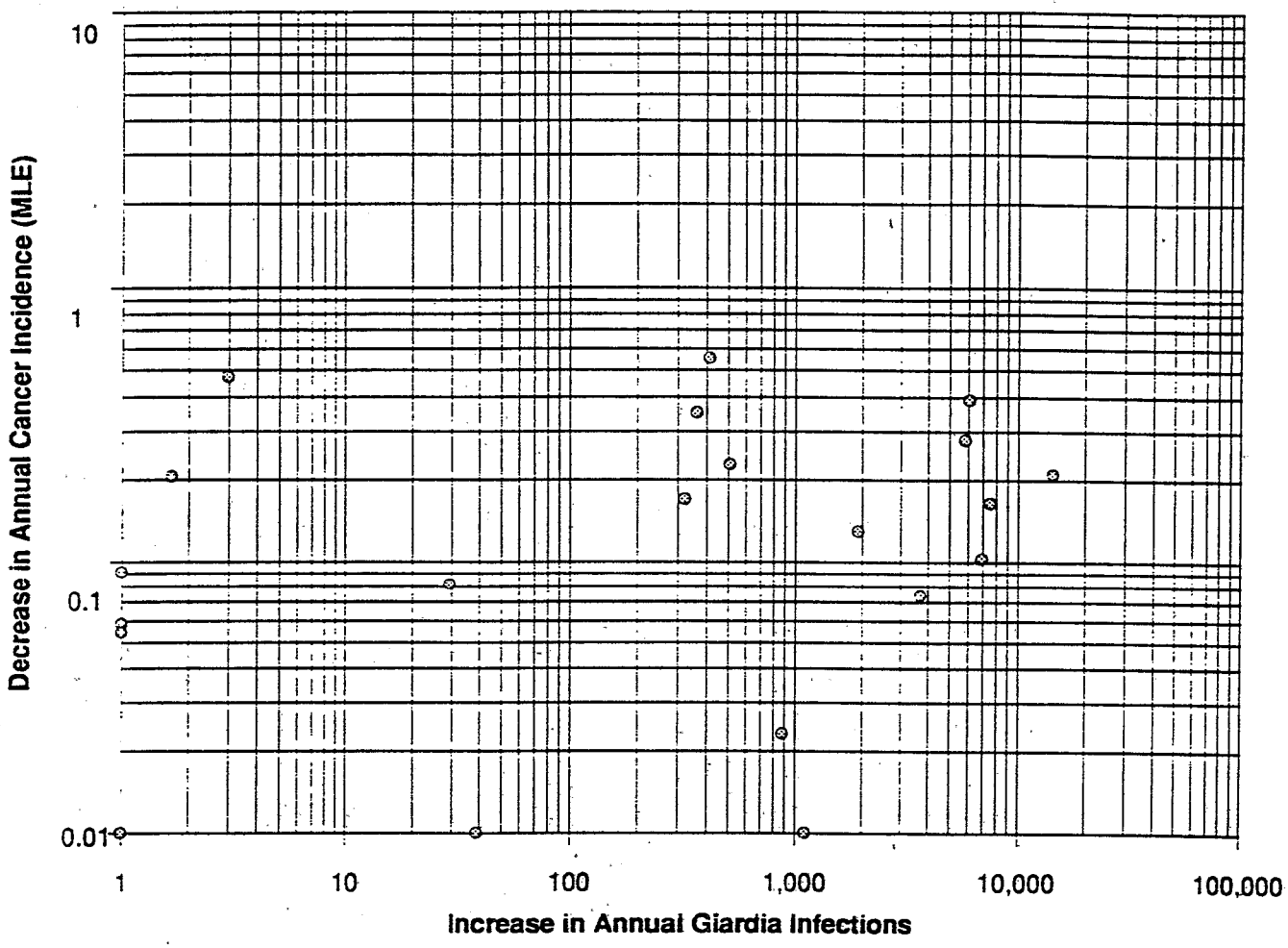


Exhibit 22

SWTR Scenario: With Alternate Disinfectants

From TTHM MCL = 100 ug/l to 25 ug/l
Change in Risks Per 1 Million People

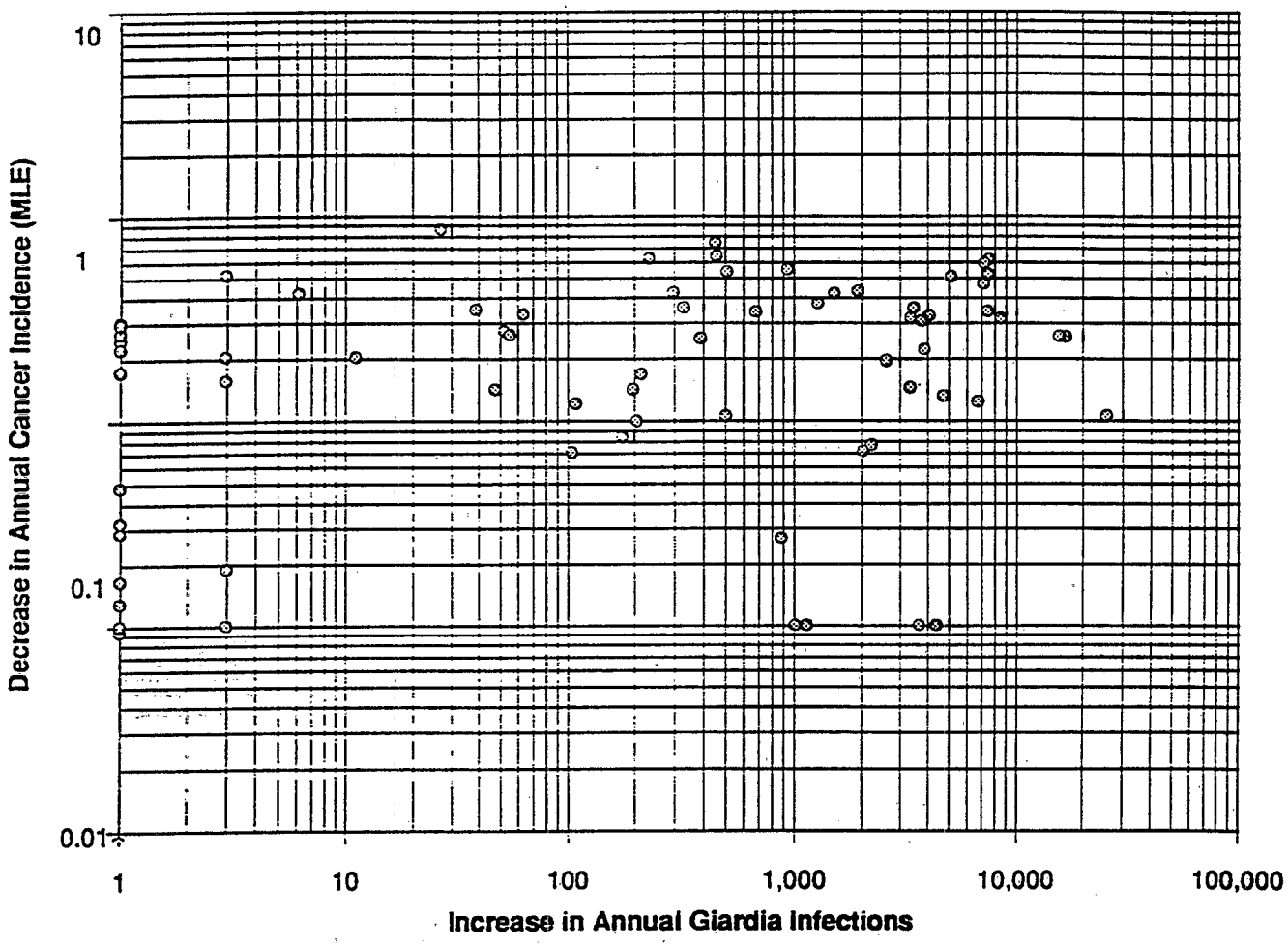


Exhibit 23

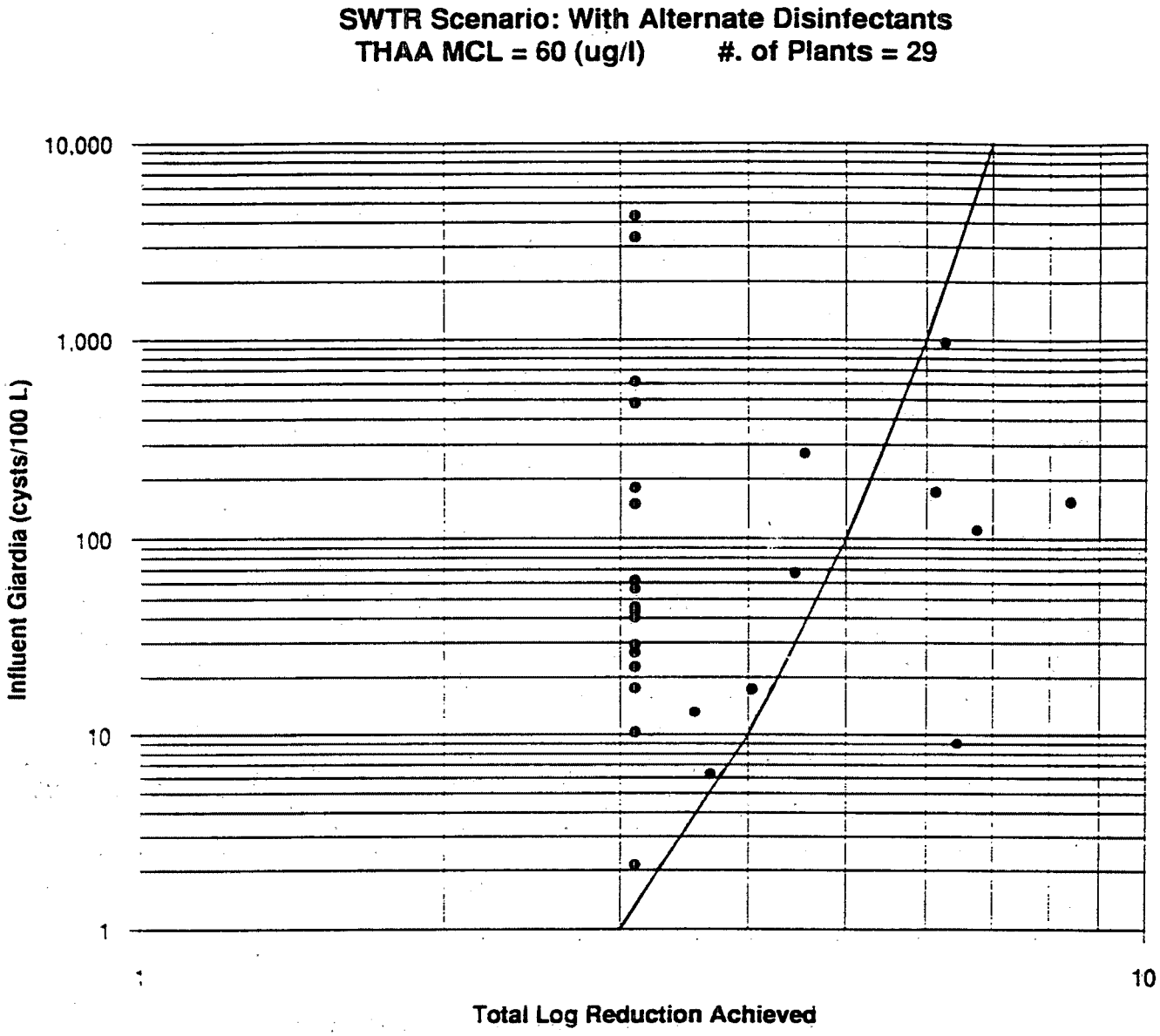

SWTR Scenario: With Alternate Disinfectants
THAA MCL = 60 (ug/l)
#. of Plants = 29
10,000
1,000
100
10
1
Influent Giardia (cysts/100 L)
1
10
Total Log Reduction Achieved

Exhibit 24

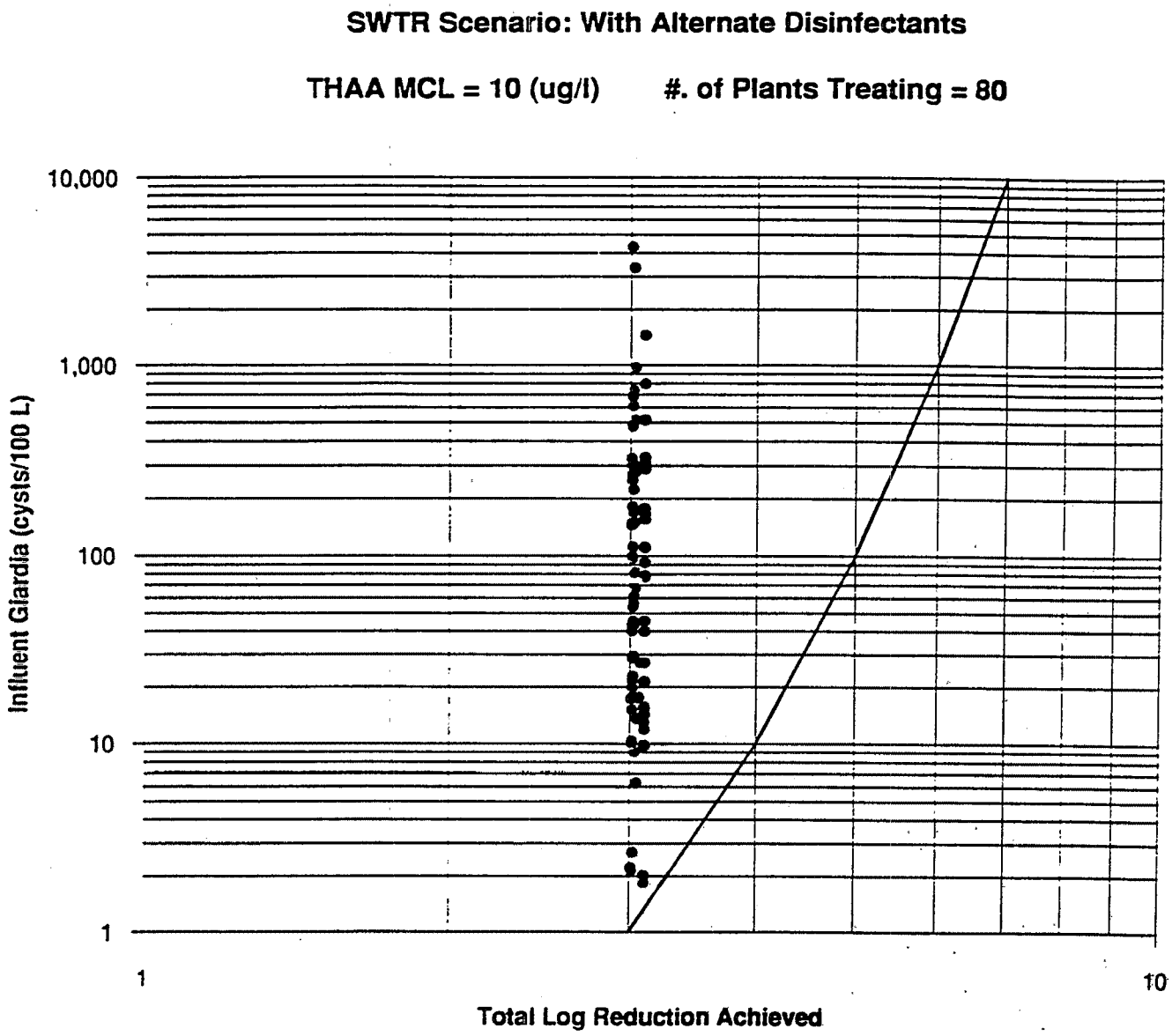

SWTR Scenario: With Alternate Disinfectants
THAA MCL = 10 (ug/l)
#. of Plants Treating = 80
10,000
1,000
100
10
1
Influent Giardia (cysts/100 L)
1
10
Total Log Reduction Achieved

Exhibit 25

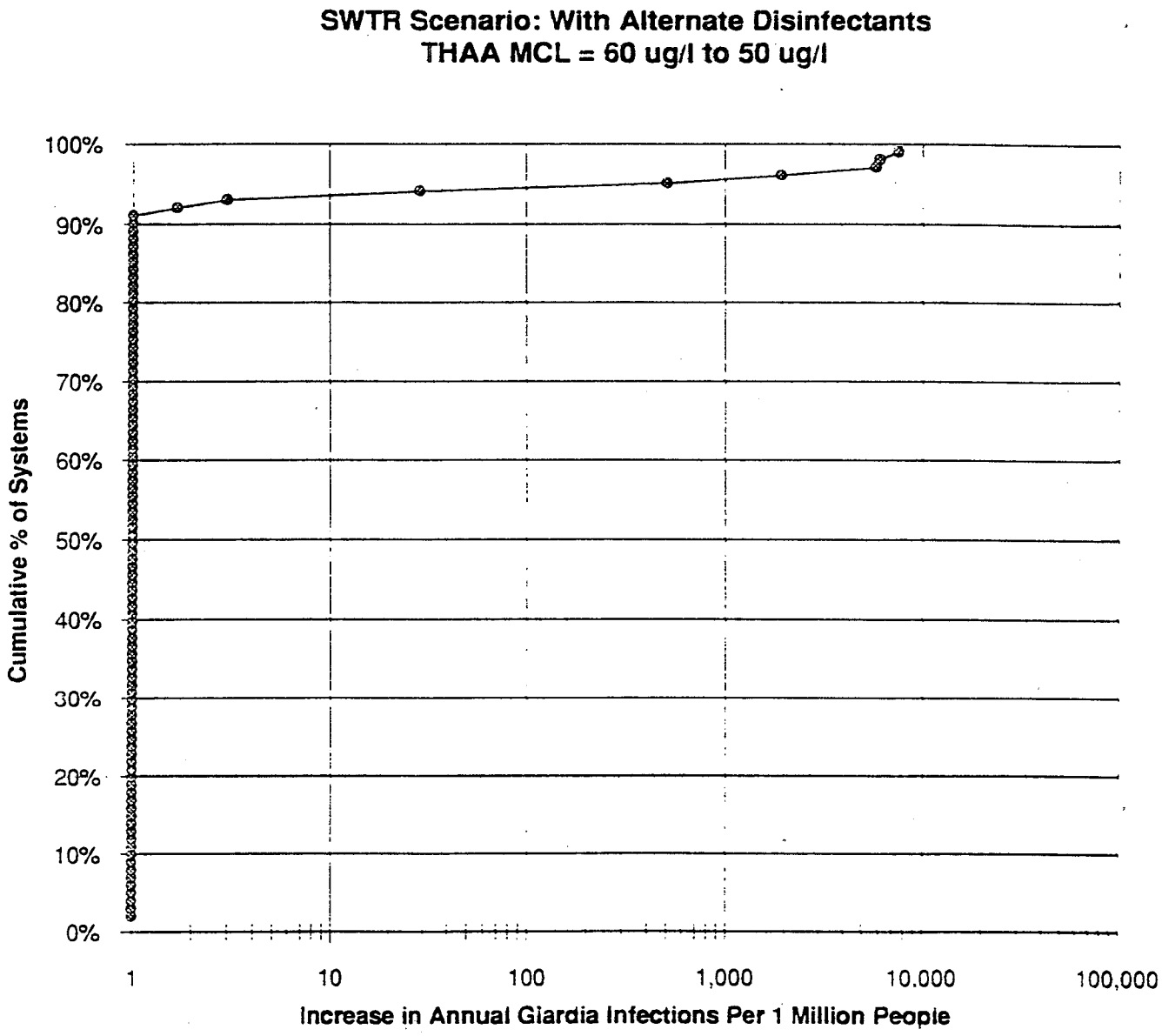

SWTR Scenario: With Alternate Disinfectants
THAA MCL = 60 ug/l to 50 ug/l
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulative % of Systems
1
10
100
1,000
10,000
100,000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 26

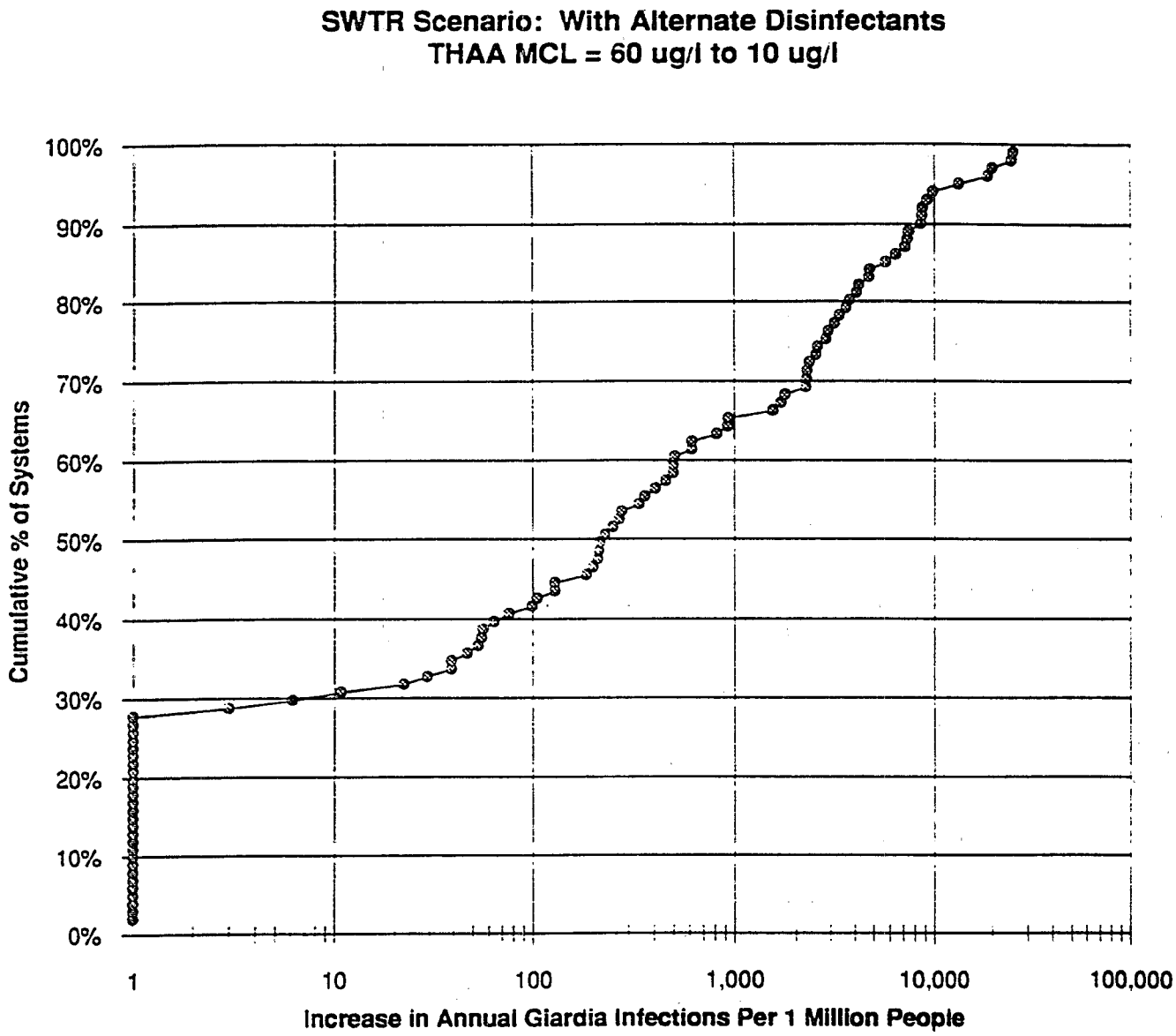

SWTR Scenario: With Alternate Disinfectants
THAA MCL = 60 ug/l to 10 ug/l
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulative % of Systems
1
10
100
1,000
10,000
100,000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 27

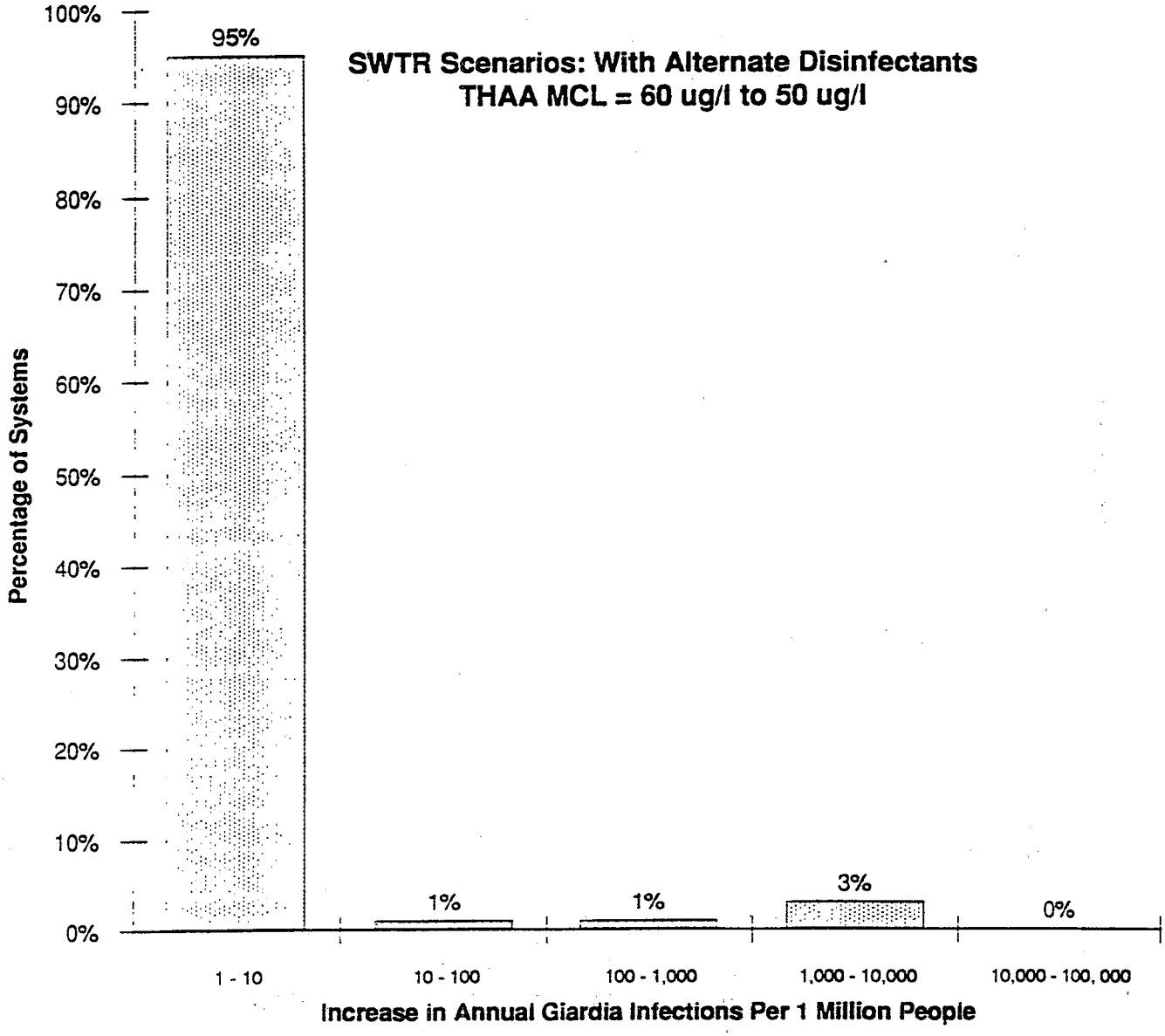

SWTR Scenarios: With Alternate Disinfectants
THAA MCL = 60 ug/l to 50 ug/l
Percentage of Systems
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
95%
1%
1%
3%
0%
1 - 10
10 - 100
100 - 1,000
1,000 - 10,000
10,000 - 100, 000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 28

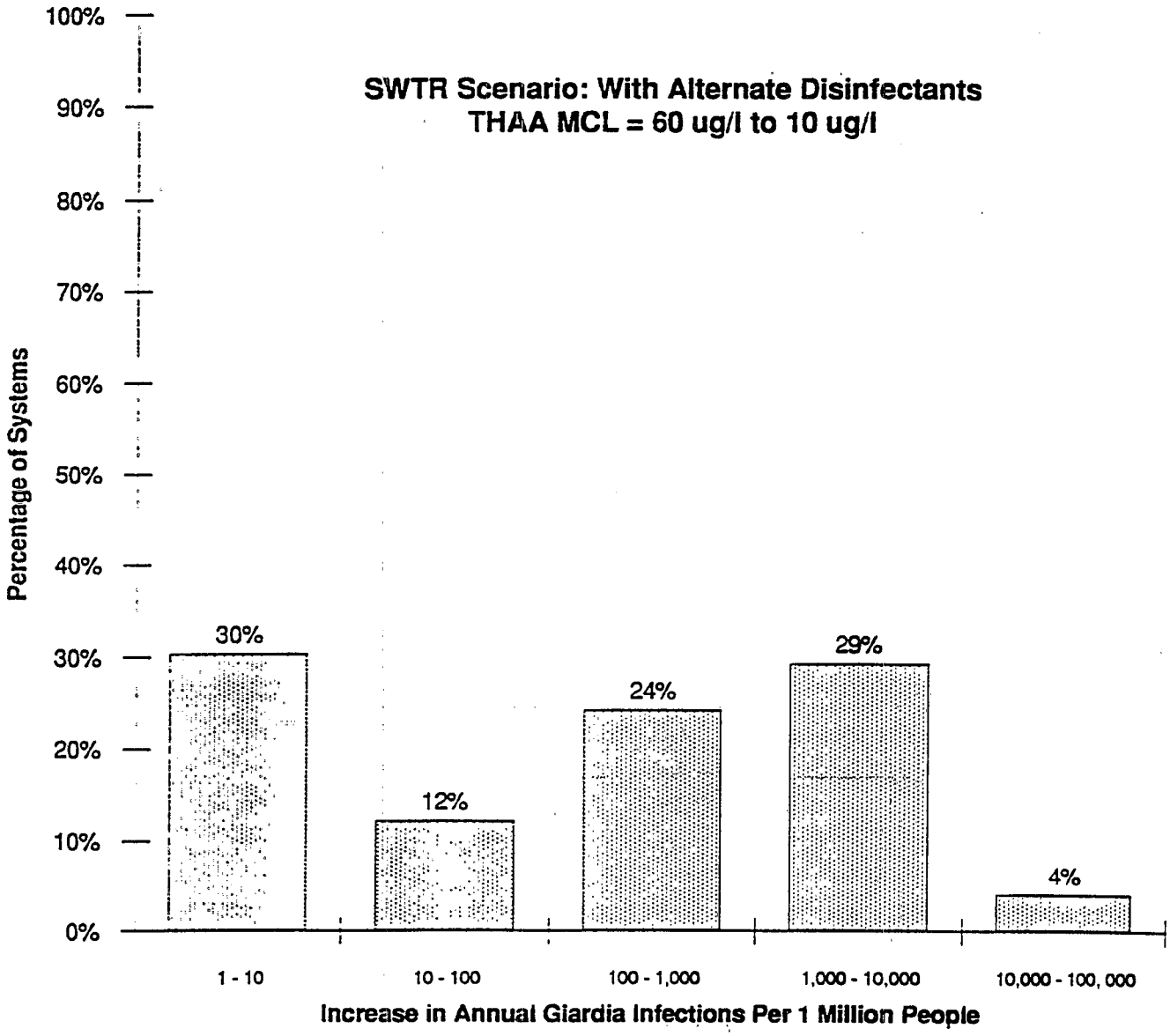

SWTR Scenario: With Alternate Disinfectants
THAA MCL = 60 ug/l to 10 ug/l
Percentage of Systems
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
30%
12%
24%
29%
4%
1 - 10
10 - 100
100 - 1,000
1,000 - 10,000
10,000 - 100, 000
Increase in Annual Giardia Infections Per 1 Million People

Exhibit 29

SWTR Scenario: With Alternate Disinfectants

From THAA MCL = 60 ug/l to 50 ug/l
Change in Risks Per 1 Million People

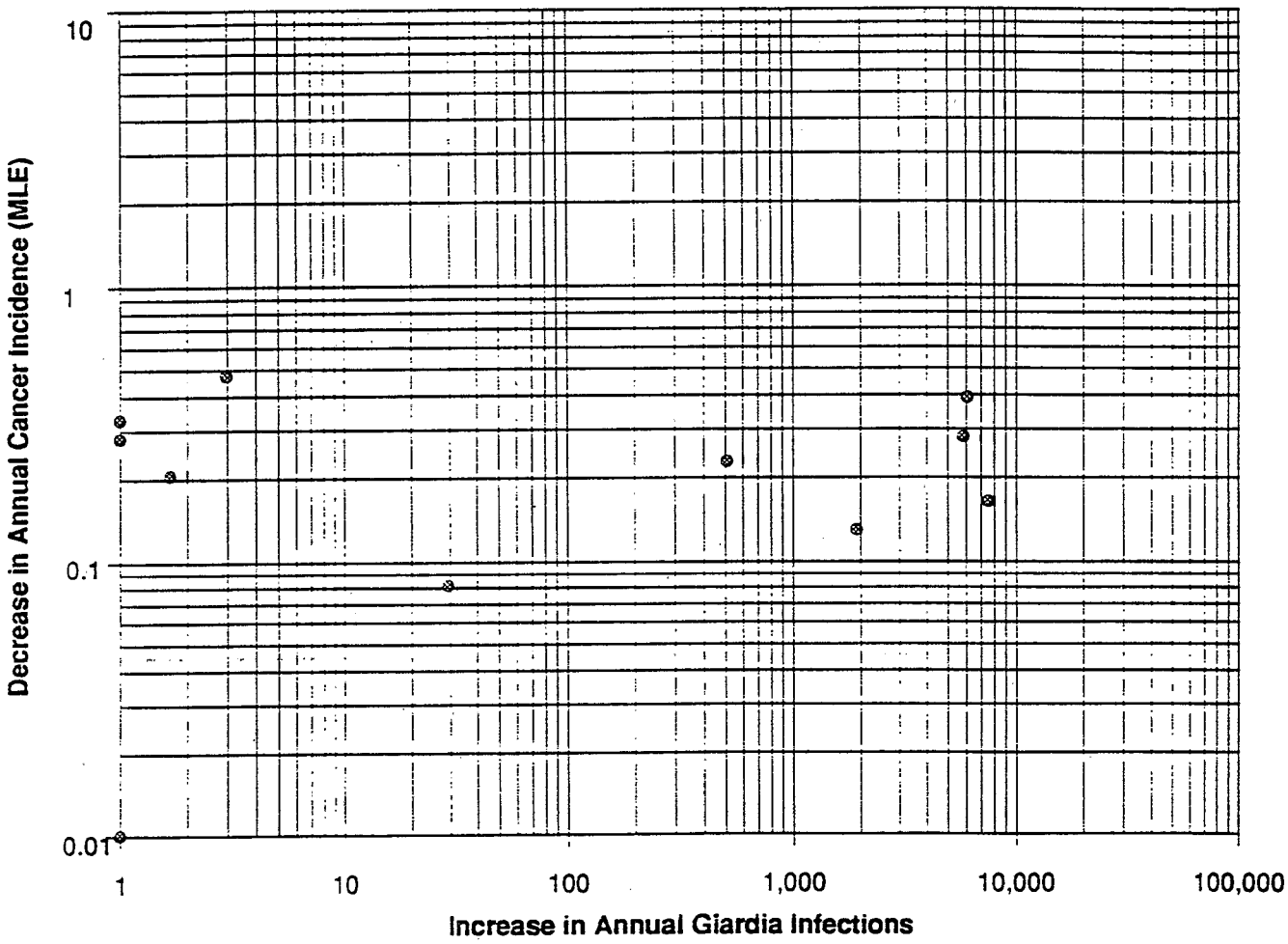
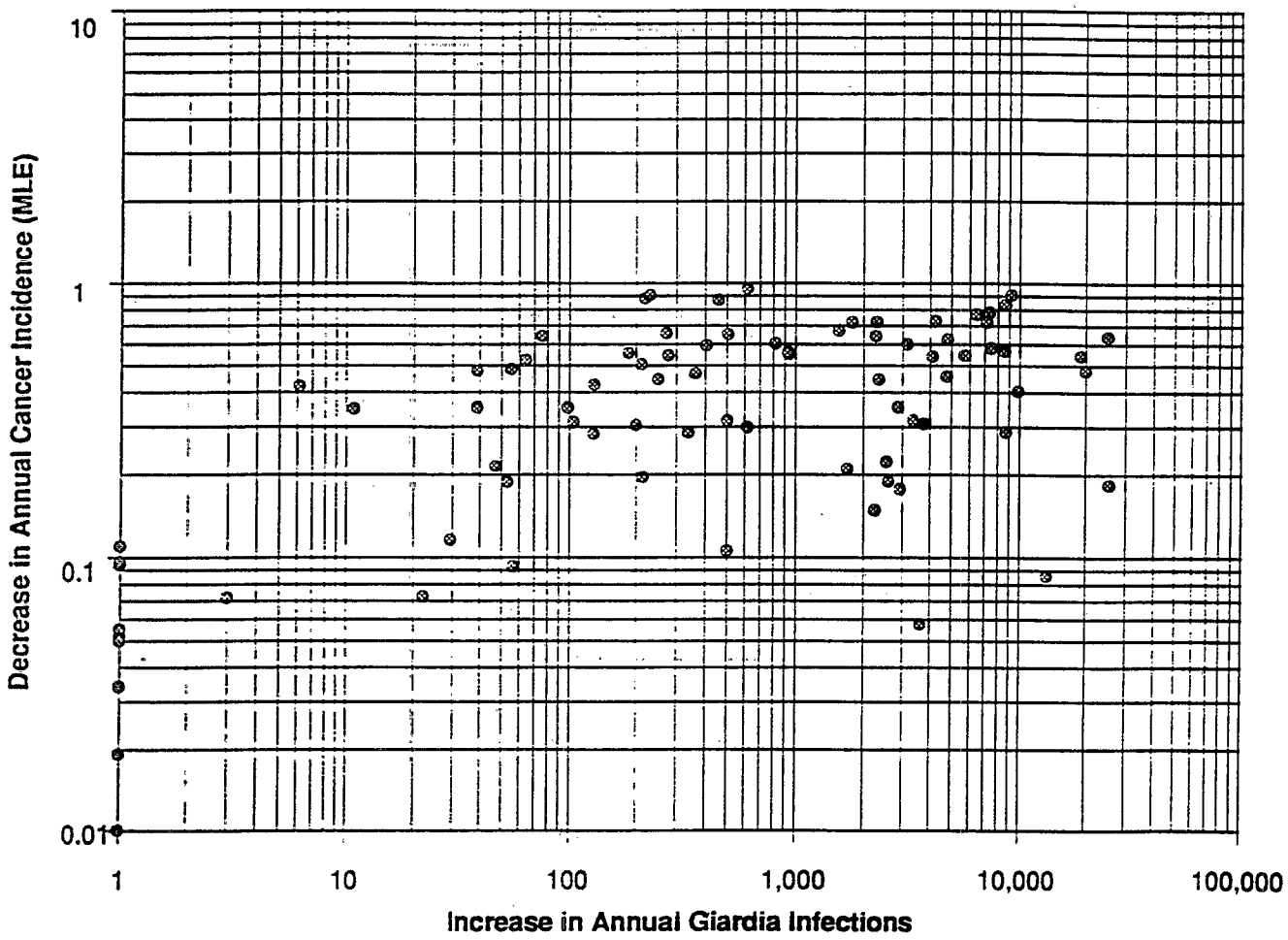


Exhibit 30

SWTR Scenario: With Alternate Disinfectants

THAA MCL = 60 ug/l to 10 ug/l
Change in Risks Per 1 Million People



W/ Alternate Disinfectants

SWTR Scenario	Total Annual Treatment Cost ($M/Yr.) *	Total Capital Cost ($M)	Number of Cancer Cases Remaining/Yr.		Incremental Annual Treatment Cost ($M/Yr.)	Incremental Cost Per Case of Cancer Avoided ($M/case)		Incremental Number of Cancer Cases Avoided/Year	
			95%	*MLE*		*95%*	*MLE*	*95%*	*MLE*
THAA MCLs									
60	2	17	139	45	–	–	–	–	–
50	12	20	131	42	10	1	4	8	3
40	21	61	118	38	9	1	2	13	4
30	71	266	101	32	50	3	9	17	6
20	383	2,433	69	22	312	10	30	32	10
10	922	6,547	35	11	539	16	50	34	11

ESWTR Scenario	Total Annual Treatment Cost ($M/Yr.) *	Total Capital Cost ($M)	Number of Cancer Cases Remaining/Yr.		Incremental Annual Treatment Cost ($M/Yr.)	Incremental Cost Per Case of Cancer Avoided ($M/case)		Incremental Number of Cancer Cases Avoided/Year	
			95%	*MLE*		*95%*	*MLE*	*95%*	*MLE*
THAA MCLs									
60	7	18	143	46	–	–	–	–	–
50	16	55	135	43	8	1	3	8	3
40	38	94	122	39	22	2	5	14	4
30	120	504	101	32	82	4	12	21	7
20	422	2,737	69	22	302	10	30	31	10
10	963	6,887	35	11	541	16	50	34	11

*** Costs are annualized at 10% interest rate over 20 years.**

Exhibit 31

W/out Alternate Disinfectants

SWTR Scenario	Total Annual Treatment Cost ($M/Yr.) *	Total Capital Cost ($M)	Number of Cancer Cases Remaining/Yr.		Incremental Annual Treatment Cost ($M/Yr.)	Incremental Cost Per Case of Cancer Avoided ($M/case)		Incremental Number of Cancer Cases Avoided/Year	
			95%	*MLE*		*95%*	*MLE*	*95%*	*MLE*
THAA MCLs									
60	104	788	130	42	–	–	–	–	–
50	118	889	124	40	13	3	8	5	2
40	202	1,524	105	34	84	4	13	19	6
30	353	2,668	80	26	151	6	19	25	8
20	588	4,446	55	18	235	9	28	26	8
10	957	7,240	31	10	369	15	48	24	8

ESWTR Scenario	Total Annual Treatment Cost ($M/Yr.) *	Total Capital Cost ($M)	Number of Cancer Cases Remaining/Yr.		Incremental Annual Treatment Cost ($M/Yr.)	Incremental Cost Per Case of Cancer Avoided ($M/case)		Incremental Number of Cancer Cases Avoided/Year	
			95%	*MLE*		*95%*	*MLE*	*95%*	*MLE*
THAA MCLs									
60	118	889	131	42	–	–	–	–	–
50	118	889	124	40	0	0	0	7	2
40	218	1,651	105	34	101	5	16	19	6
30	336	2,541	82	26	118	5	16	23	8
20	588	4,446	55	18	252	9	29	27	9
10	974	7,368	30	10	386	15	47	25	8

*** Costs are annualized at 10% interest rate over 20 years.**

Exhibit 32

Exhibit 33

Compliance Percentages

SWTR Scenario W/ Alt. Disin.	THAA MCLs (ug/l) 60	50	40	30	20	10
No further treatment	70	64	56	48	37	19
Eliminate pre-chlor	12	15	16	12	8	3
Eliminate pre-chlor & add NH3	18	17	22	22	8	1
pre-chlor + NH3 + alum dose	0	4	5	14	23	22
pre-chlor + NH3 + alum + Oz	0	0	1	3	7	5
pre-chlor + NH3 + alum + Oz + GAC	0	0	0	1	17	50

Compliance Percentages

Enhanced SWTR Scenario W/ Alt. Disin.	THAA MCLs (ug/l) 60	50	40	30	20	10
No further treatment	70	62	56	47	35	17
Eliminate pre-chlor	11	16	16	12	10	3
Eliminate pre-chlor & add NH3	17	18	16	12	4	0
pre-chlor + NH3 + alum dose	2	3	10	18	18	15
pre-chlor + NH3 + alum + Oz	0	1	2	10	16	15
pre-chlor + NH3 + alum + Oz + GAC	0	0	0	1	17	50

Exhibit 34

Compliance Percentages

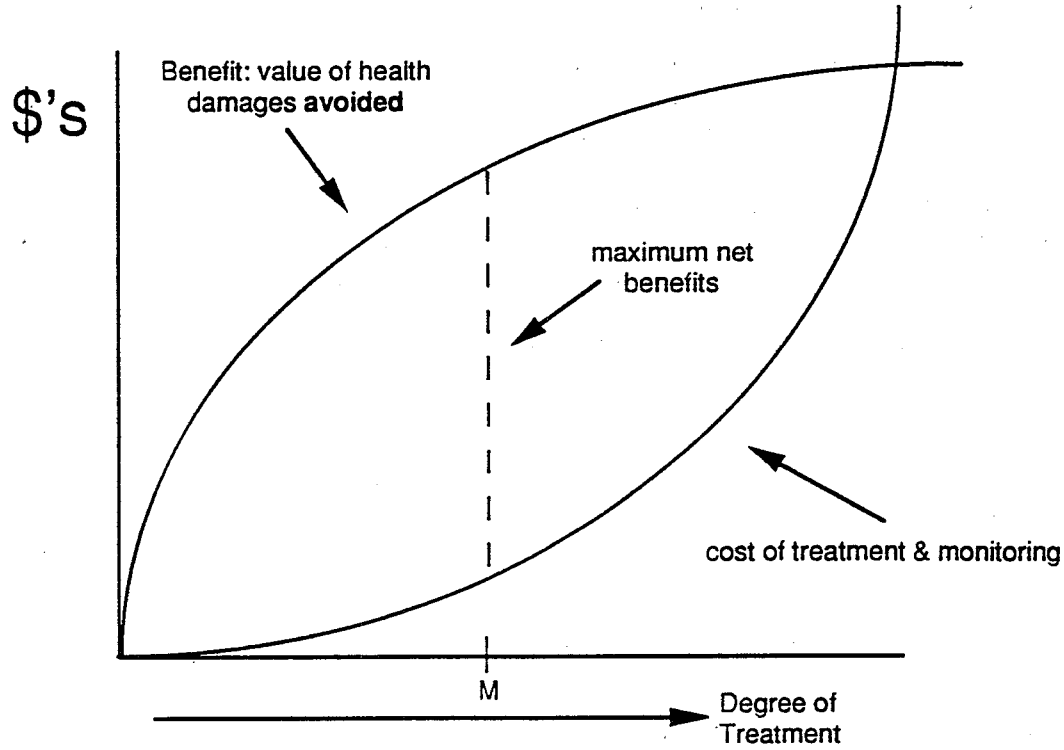
SWTR Scenario W/out Alt. Disin.	THAA MCLs (ug/l) 60	50	40	30	20	10
No further treatment	70	64	56	48	37	19
Eliminate pre-chlor	12	15	16	12	8	3
Eliminate pre-chlor & modify alum	11	14	16	19	20	21
Eliminate pre-chlor + alum + GAC	7	7	12	21	35	57

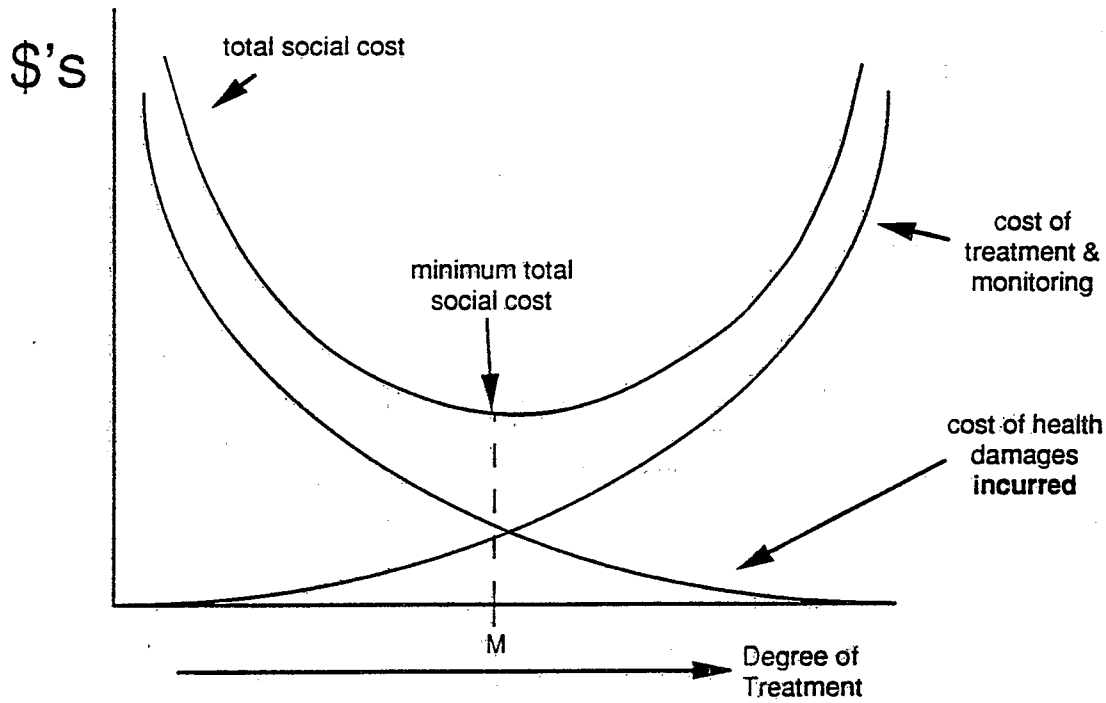
Compliance Percentages

Enhanced SWTR Scenario W/out Alt. Disin.	THAA MCLs (ug/l) 60	50	40	30	20	10
No further treatment	70	62	56	47	35	17
Eliminate pre-chlor	11	16	16	12	10	3
Eliminate pre-chlor & modify alum	12	15	15	21	20	22
Eliminate pre-chlor + alum + GAC	7	7	13	20	35	58

Exhibit 35

Equivalence of "Maximum Net Benefit" and "Minimum Total Social Cost" Objectives





Maximizing Health Damages Avoided Per Dollar of Treatment Expenditure	=	Minimizing Health Damages Incurred Per Dollar of Treatment Expenditure

Exhibit 36

MODEL OUTPUT (surface w/o softening): SWTR W/ ALTERNATIVE DISINFECTION

Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre–chlorination
3 – eliminate pre–chlor + add ammonia
4 – pre–chlor + ammonia + alum dose
5 – pre–chlor + ammonia + alum + ozone
6 – pre–chlor + ammonia + alum + ozone + GAC

Population = ***103,000,000*** ***(persons)***

THAA MCL (µg/l)	Annual Treatment Cost * ($M)	Cost of Cancer** @ $8m/case ($M)	Cost of Giardia @ $3,000/case ($M)	Total Costs ($M)
60	2	358	639	1,000
50	12	338	714	1,064
40	21	304	849	1,174
30	71	259	974	1,304
20	383	177	1,239	1,798
10	922	91	1,729	2,742

*** Capital costs are annualized at 10% interest rate over 20 years.**
**** MLE of cancer incidence from HAAs.**

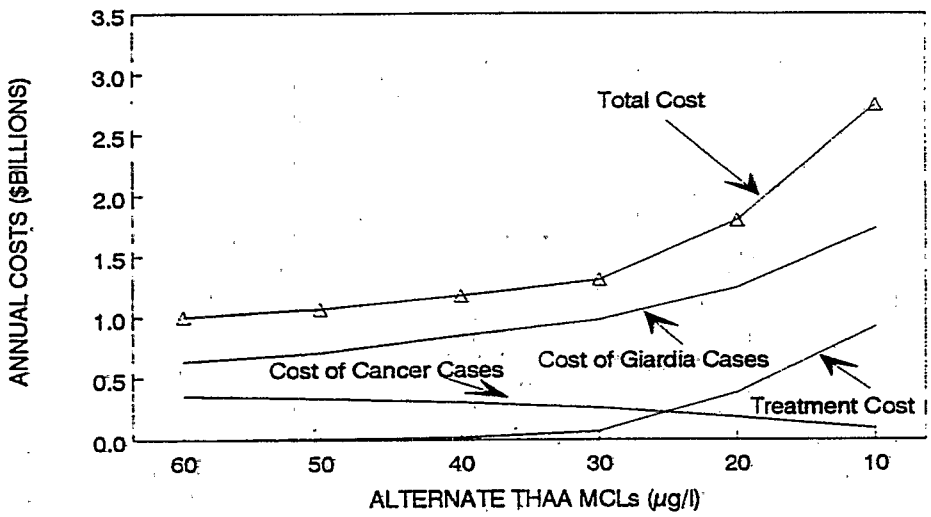


Exhibit 37

MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/ ALTERNATIVE DISINFECTION

Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre–chlorination
3 – eliminate pre–chlor + add ammonia
4 – pre–chlor + ammonia + alum dose
5 – pre–chlor + ammonia + alum + ozone
6 – pre–chlor + ammonia + alum + ozone + GAC

Population = ***103,000,000*** ***(persons)***

THAA MCL (μg/l)	Annual Treatment Cost * ($M)	Cost of Cancer** @ $8m/case ($M)	Cost of Giardia @ $3,000/case ($M)	Total Costs ($M)
60	7	369	0.8	377
50	16	348	0.8	364
40	38	313	0.9	351
30	120	258	1.0	379
20	422	178	1.0	601
10	963	91	1.0	1,055

*** Capital costs are annualized at 10% interest rate over 20 years.**
**** MLE of cancer incidence from HAAs.**

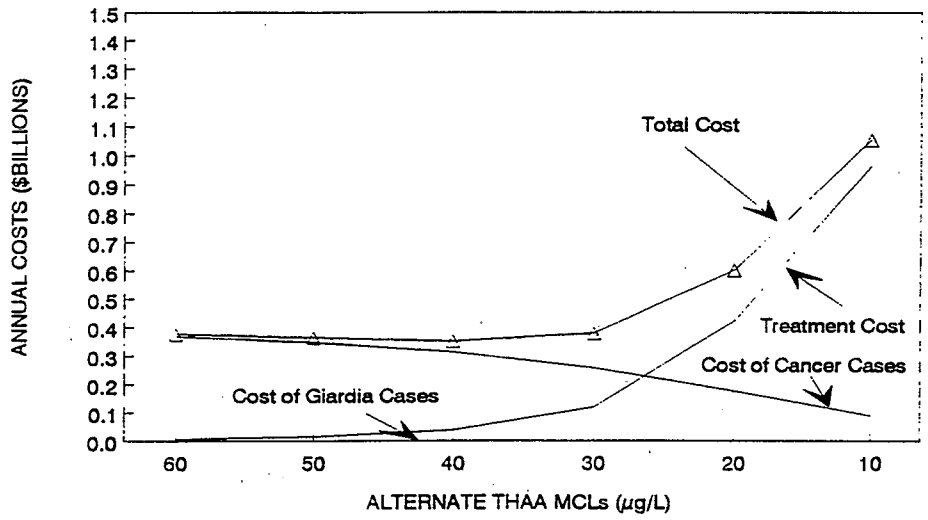


Exhibit 38

MODEL OUTPUT (surface w/o softening): SWTR W/O ALTERNATIVE DISINFECTION

Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre–chlorination
3 – eliminate pre–chlor + modify alum dose
4 – pre–chlor + alum dose + GAC

Population = *103,000,000* *(persons)*

THAA MCL (µg/l)	Annual Treatment Cost * ($M)	Cost of Cancer** @ $8m/case ($M)	Cost of Giardia @ $3,000/case ($M)	Total Costs ($M)
60	104	334	740	1,17
50	118	320	772	1,21
40	202	270	831	1,30
30	353	206	972	1,53
20	588	140	1,212	1,94
10	957	79	1,519	2,55

* Capital costs are annualized at 10% interest rate over 20 years.
** MLE of cancer incidence from HAAs.

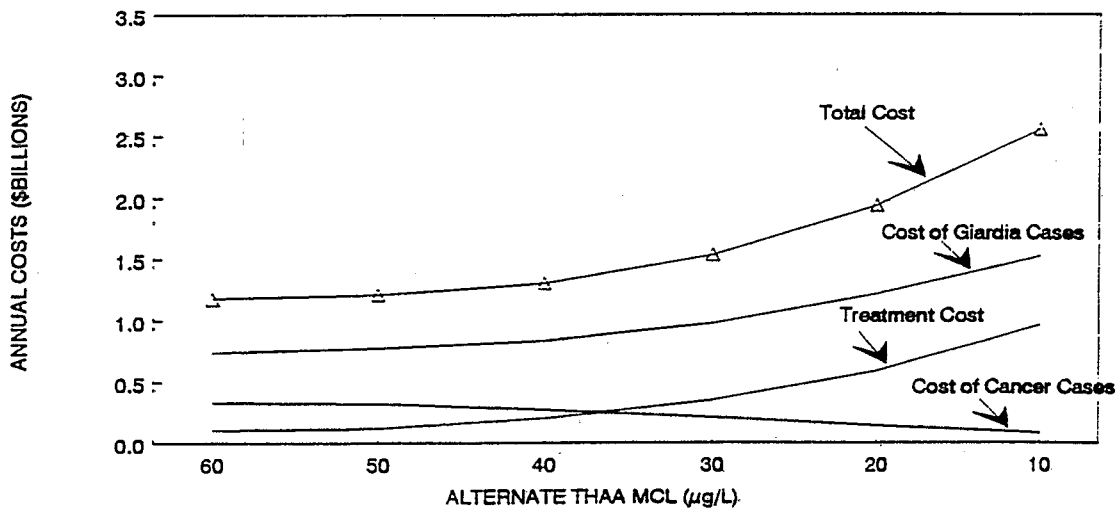


Exhibit 39

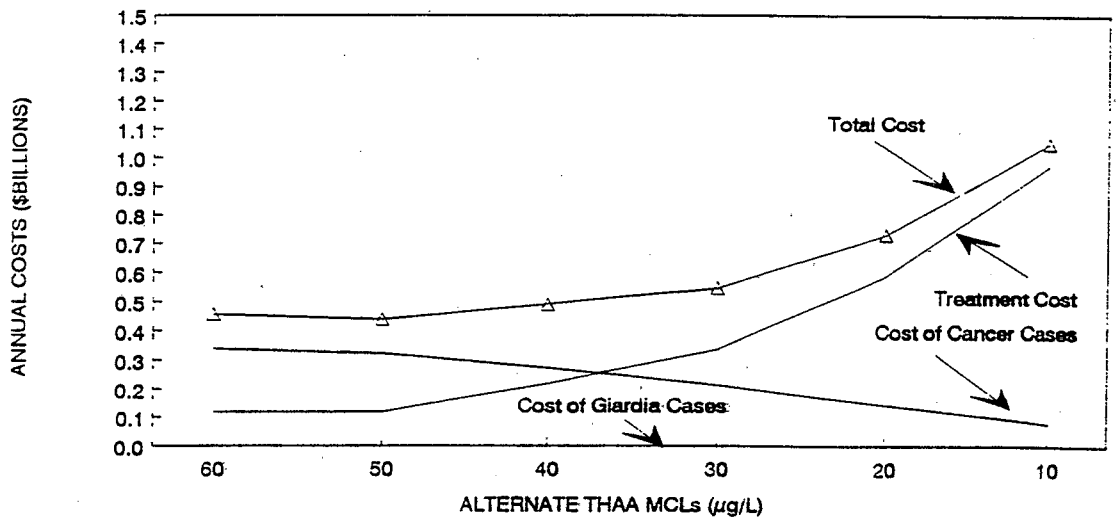
MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/O ALTERNATIVE DISINFECTIOI

Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre–chlorination
3 – eliminate pre–chlor + modify alum dose
4 – pre–chlor + alum dose + GAC

Population = ***103,000,000*** ***(persons)***

THAA MCL (μg/l)	Ann.Trt.* Cost ($M)	Cost of Cancer** @ $8m/case ($M)	Cost of Giardia @ $3,000/case ($M)	Total Costs ($M)
60	118	337	0.8	455
50	118	320	0.8	438
40	218	271	0.8	490
30	336	211	1.0	548
20	588	142	1.0	731
10	974	77	1.0	1,052

*** Capital costs are annualized at 10% interest rate over 20 years.**
**** MLE of cancer incidence from HAAs.**



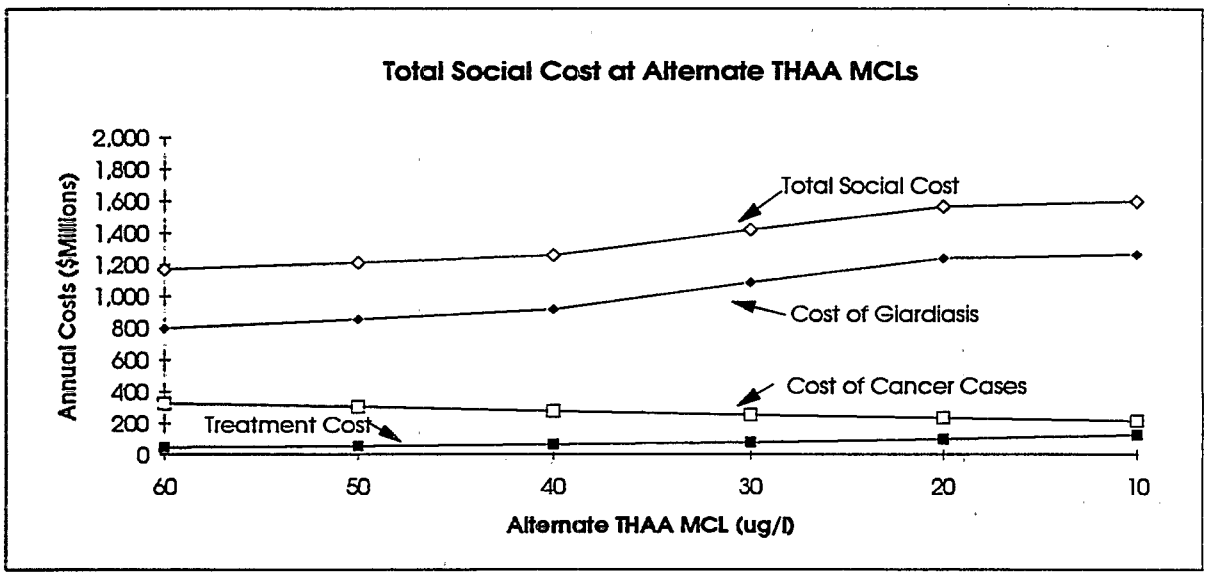
Model Output (surface water systems w/o softening) : SWTR w/ MODIFYING ALUM DOSE

Treatment Tier Code:
1 - not requiring further treatment modification
2 - eliminating prechlorination + modifying alum dose

Population = *103,000,000* *(persons)* *Number of Systems =* *977*

THAA MCL (ug/l)	Treatment Code	% of Systems Modifying Alum Dose*	Cumulative % of Systems <= MCL*	Annual Treatment Cost ($M) **	Cost ($M) of Cancer *** @$8M/Case	Cost ($M) of Giardiasis @$3K/Case	Total Social Cost ($M)
				(1)	(2)	(3)	(1)+(2)+(3)
60	2	30	93	45	326	796	1,167
50	2	36	93	54	303	853	1,210
40	2	44	88	66	275	917	1,258
30	2	52	79	78	254	1,086	1,418
20	2	63	65	95	234	1,237	1,565
10	2	81	43	122	215	1,261	1,597

* Includes 20% over-design factor.
** Maximum Likelihood Estimates (MLE) of cancer incidence associated with HAAs.
*** Capital costs are annualized at 10% interest rate over 20 years.



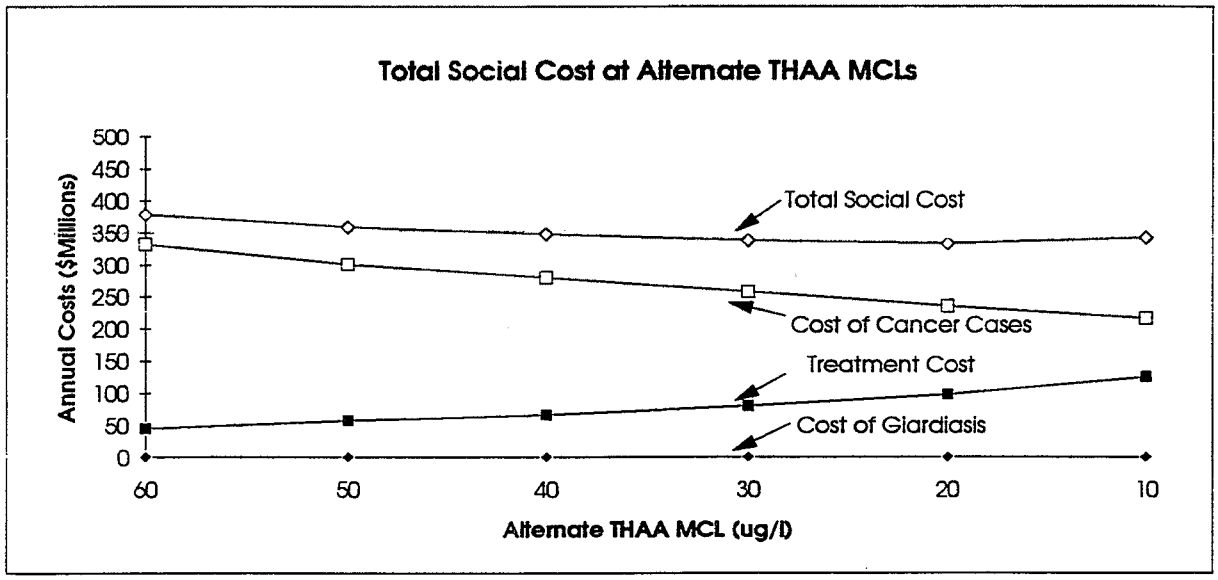
Model Output (surface water systems w/o softening) : Enhanced SWTR w/ MODIFYING ALUM DOSE

Treatment Tier Code:
1 - not requiring further treatment modification
2 - eliminating prechlorination + modifying alum dose

Population = ***103,000,000*** ***(persons)*** ***Number of Systems =*** ***977***

THAA MCL (ug/l)	Treatment Code	% of Systems Modifying Alum Dose*	Cumulative % of Systems <= MCL*	Annual Treatment Cost ($M) **	Cost ($M) of Cancer *** @$8M/Case	Cost ($M) of Giardiasis @$3K/Case	Total Social Cost ($M)
				(1)	(2)	(3)	(1)+(2)+(3)
60	2	30	93	45	332	0.8	378
50	2	38	93	57	300	0.8	358
40	2	44	87	66	280	0.9	348
30	2	53	80	80	258	1.0	339
20	2	65	65	98	235	1.0	333
10	2	83	42	125	216	1.0	342

* Includes 20% over-design factor.
** Maximum Likelihood Estimates (MLE) of cancer incidence associated with HAAs.
*** Capital costs are annualized at 10% interest rate over 20 years.



Appendix A

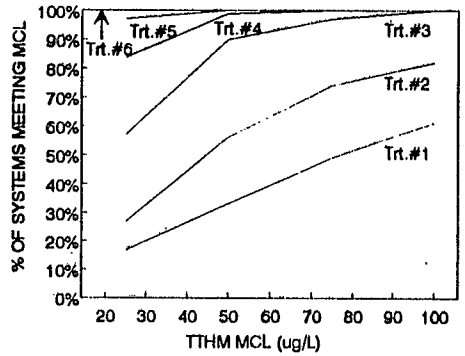
Exhibit A-1

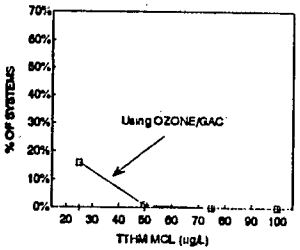
MODEL OUTPUT (surface w/o softening): SWTR W/ ALTERNATIVE DISINFECTION

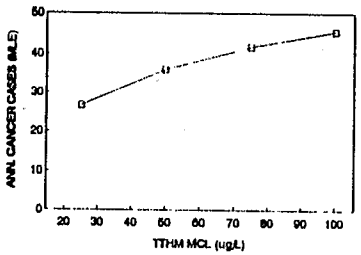
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

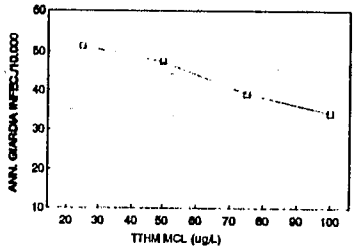
Population = 103,000,000 *(persons)*

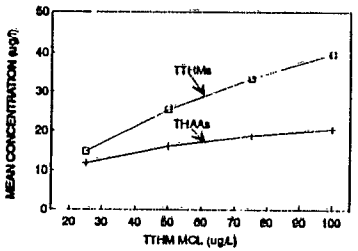
MCL (TTHMs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg.Cus.)[3]		Cancer Incidence				Giardia Infections	
						THMs		HAAs		Endemic[4]	Epidemic[5]
				TTHMs	THAAs	95%	MLE	95%	MLE	Infections	(90%) #.Yrs. to Outbreak
100	1	61	61	55	24	33.8	1.3	153.3	49.4		
100	2	21	82	42	20	27.0	1.0	136.1	43.7		
100	3	18	100	40	20	24.6	0.9	138.7	44.6		
100	4	0	100	40	20	24.6	0.9	138.7	44.6		
100	5	0	100	40	20	24.6	0.9	138.7	44.6		
100	6	0	100	40	20	24.6	0.9	138.7	44.6	340,992	2.99
75	1	49	49	55	24	33.8	1.3	153.3	49.4		
75	2	25	74	39	19	25.0	1.0	132.1	42.5		
75	3	23	97	34	19	21.0	0.8	129.8	41.7		
75	4	3	100	33	19	20.7	0.8	127.5	41.0		
75	5	0	100	33	19	20.7	0.8	127.5	41.0		
75	6	0	100	33	19	20.7	0.8	127.5	41.0	390,216	0.18
50	1	33	33	55	24	33.8	1.3	153.3	49.4		
50	2	23	56	37	18	23.9	0.9	126.6	40.7		
50	3	34	90	28	17	17.4	0.7	116.8	37.5		
50	4	9	99	26	16	16.0	0.6	110.4	35.4		
50	5	1	100	25	16	15.9	0.6	109.9	35.3		
50	6	0	100	25	16	15.9	0.6	109.9	35.3	474,985	0.04
25	1	17	17	55	24	33.8	1.3	153.3	49.4		
25	2	10	27	36	16	23.2	0.9	124.9	40.1		
25	3	30	57	23	16	14.1	0.5	107.7	34.6		
25	4	27	84	17	13	10.6	0.4	88.5	28.4		
25	5	13	97	15	12	9.9	0.4	84.6	27.2		
25	6	3	100	15	12	9.6	0.4	81.7	26.2	513,146	0.008











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

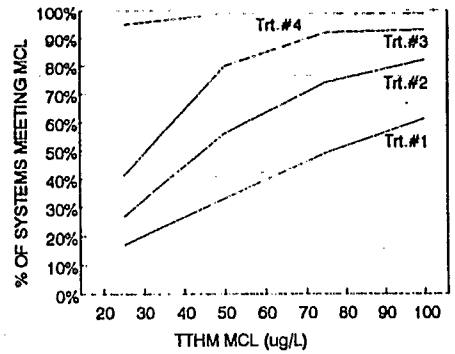
Exhibit A-2

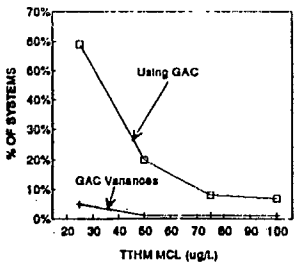
MODEL OUTPUT (surface w/o softening): SWTR W/O ALTERNATIVE DISINFECTION

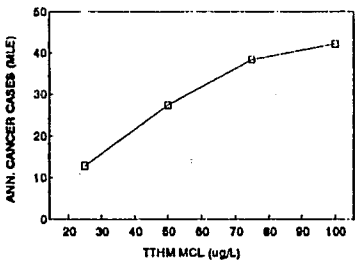
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

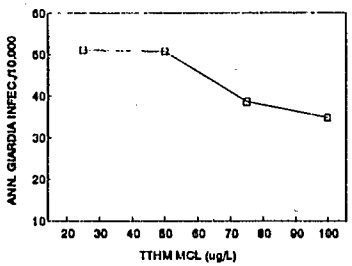
Population = *103,000,000* *(persons)*

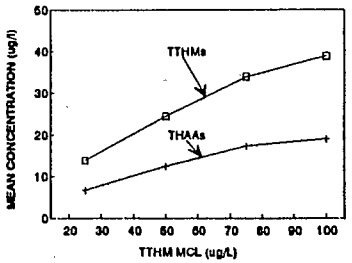
MCL (TTHMs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg.Cus.)[3]		Cancer Incidence				Giardia Infections	
						THMs		HAAs		Endemic[4]	Epidemic[5]
				TTHMs	THAAs	95%	MLE	95%	MLE	Infections	(90%) #.Yrs. to Outbreak
100	1	61	61	55	24	33.8	1.3	153.3	49.4		
100	2	21	82	42	20	27.0	1.0	136.1	43.7		
100	3	11	93	40	20	25.4	1.0	132.6	42.6		
100	4	7	99	39	19	24.7	0.9	128.4	41.3	347,110	1.091
75	1	49	49	55	24	33.8	1.3	153.3	49.4		
75	2	25	74	39	19	25.0	1.0	132.1	42.5		
75	3	18	92	35	18	22.5	0.9	122.1	39.2		
75	4	8	99	34	17	21.6	0.8	117.3	37.7	385,220	0.162
50	1	33	33	55	24	33.8	1.3	153.3	49.4		
50	2	23	56	37	18	23.9	0.9	126.6	40.7		
50	3	24	80	29	15	19.1	0.7	102.6	33.0		
50	4	20	99	24	13	16.4	0.6	83.3	26.8	507,790	0.035
25	1	17	17	55	24	33.8	1.3	153.3	49.4		
25	2	10	27	36	18	23.2	0.9	124.9	40.1		
25	3	14	41	26	13	17.3	0.6	88.5	28.4		
25	4	59	95	14	7	10.1	0.4	39.0	12.5	510,880	0.008











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

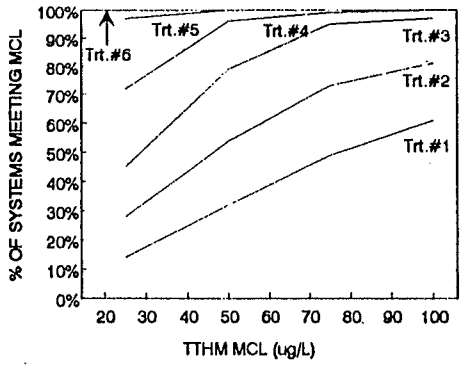
Exhibit A-3

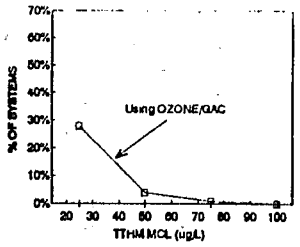
MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/ ALTERNATIVE DISINFECTION

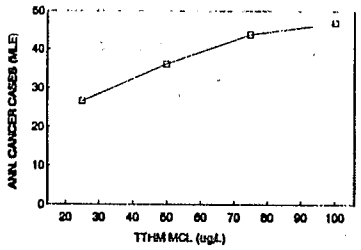
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

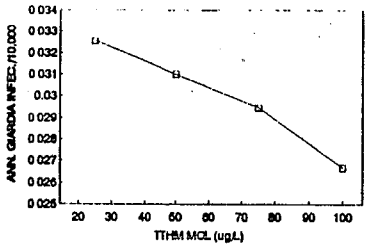
Population = *103,000,000* *(persons)*

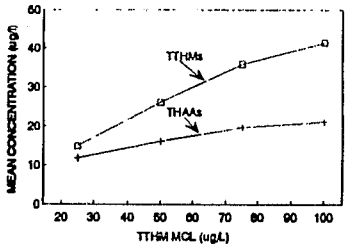
MCL (TTHMs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg.Cus.)[3]		Cancer Incidence				Giardia Infections	
						THMs		HAAs		Endemic[4]	Epidemic[5]
				TTHMs	THAAs	95%	MLE	95%	MLE	Infections	(90%) #.Yrs. to Outbreak
100	1	61	61	57	25	34.8	1.3	156.3	50.3		
100	2	20	81	44	21	26.0	1.1	139.6	44.9		
100	3	16	97	43	22	26.2	1.0	145.3	46.7		
100	4	3	100	41	21	25.8	1.0	142.6	45.8		
100	5	0	100	41	21	25.8	1.0	142.6	45.8		
100	**6**	**0**	**100**	**41**	**21**	**25.8**	**1.0**	**142.6**	**45.8**	**267**	**Infinity**
75	1	49	49	57	25	34.8	1.3	156.3	50.3		
75	2	24	73	41	20	26.0	1.0	135.9	43.7		
75	3	22	95	38	20	23.2	0.9	137.6	44.2		
75	4	4	99	36	20	22.2	0.9	134.3	43.2		
75	5	1	100	36	20	22.1	0.9	133.5	42.9		
75	**6**	**0**	**100**	**36**	**20**	**22.1**	**0.9**	**133.5**	**42.9**	**295**	**Infinity**
50	1	32	32	57	25	34.8	1.3	156.3	50.3		
50	2	22	54	39	19	24.9	0.9	130.4	41.9		
50	3	25	79	33	19	20.0	0.8	126.1	40.5		
50	4	17	96	27	17	16.9	0.6	112.6	36.2		
50	5	4	100	26	16	16.4	0.6	110.4	35.5		
50	**6**	**0**	**100**	**26**	**16**	**16.4**	**0.6**	**110.4**	**35.5**	**310**	**Infinity**
25	1	14	14	57	25	34.8	1.3	156.3	50.3		
25	2	14	28	37	19	24.0	0.9	128.0	41.1		
25	3	17	45	29	18	17.4	0.7	119.9	38.5		
25	4	27	72	19	14	12.4	0.5	93.9	30.2		
25	5	25	97	15	12	10.0	0.4	84.4	27.1		
25	**6**	**3**	**100**	**15**	**12**	**9.8**	**0.4**	**81.5**	**26.2**	**325**	**Infinity**











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

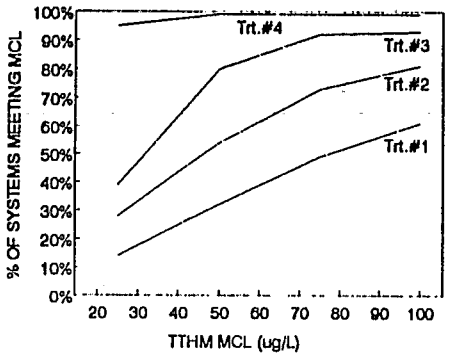
Exhibit A-4

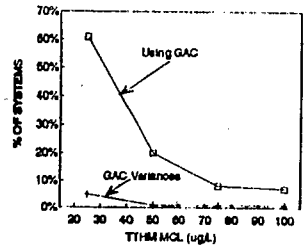
MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/O ALTERNATIVE DISINFECTION

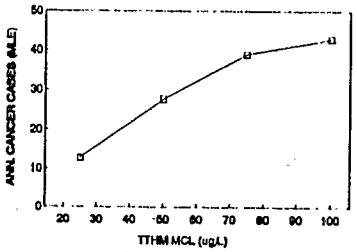
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

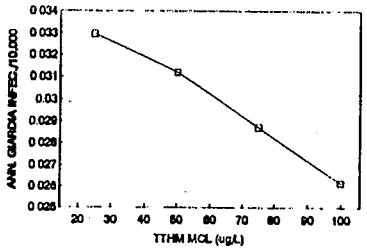
Population = 103,000,000 *(persons)*

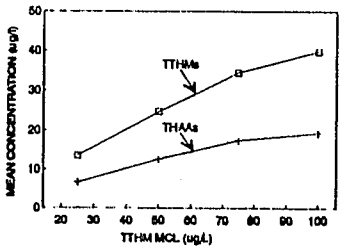
MCL (TTHMs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg.Cus.)[3]		Cancer Incidence				Giardia Infections	
						THMs		HAAs		Endemic[4]	Epidemic[5]
				TTHMs	THAAs	95%	MLE	95%	MLE	Infections	(90%) #.Yrs. to Outbreak
100	1	61	61	57	25	34.8	1.3	156.3	50.3		
100	2	20	81	44	21	28.0	1.1	139.6	44.9		
100	3	12	93	41	20	26.0	1.0	134.8	43.3		
100	4	7	99	40	19	25.2	1.0	130.5	41.9	262	Infinity
75	1	49	49	57	25	34.8	1.3	156.3	50.3		
75	2	24	73	41	20	26.0	1.0	135.9	43.7		
75	3	19	92	36	18	22.8	0.9	123.6	39.7		
75	4	8	99	34	18	21.6	0.8	118.6	38.1	287	Infinity
50	1	32	32	57	25	34.8	1.3	156.3	50.3		
50	2	22	54	39	19	24.9	0.9	130.4	41.9		
50	3	26	80	30	15	19.3	0.7	104.2	33.5		
50	4	20	99	25	13	16.5	0.6	84.5	27.1	312	Infinity
25	1	14	14	57	25	34.8	1.3	156.3	50.3		
25	2	14	28	37	19	24.0	0.9	128.0	41.1		
25	3	11	39	26	13	17.5	0.7	89.6	28.8		
25	4	61	95	14	7	9.9	0.4	38.8	12.5	330	Infinity











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

Exhibit A-5

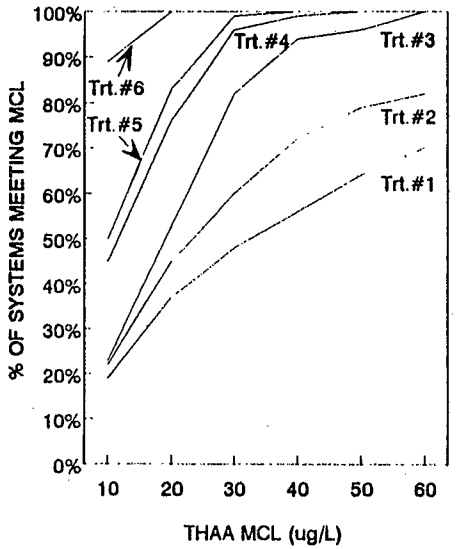
MODEL OUTPUT (surface w/o softening): SWTR W/ ALTERNATIVE DISINFECTION

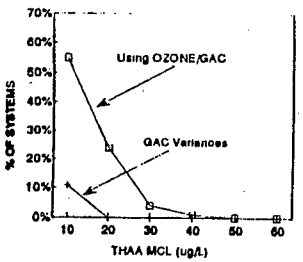
Treatment Code:

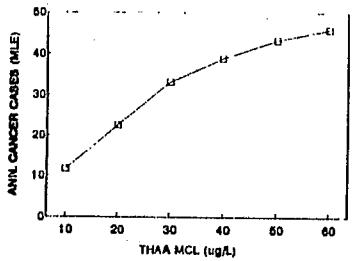
1 – not requiring further treatment modification	4 – pre-chlor + ammonia + alum dose
2 – eliminate pre-chlorination	5 – pre-chlor + ammonia + alum + ozone
3 – eliminate pre-chlor + add ammonia	6 – pre-chlor + ammonia + alum + ozone + GAC

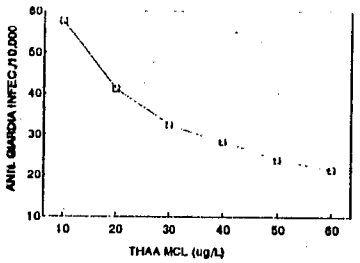
Population = 103,000,000 *(persons)*

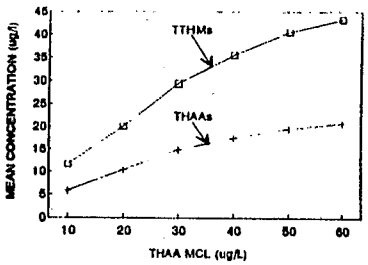
MCL (THAAs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg Cus.)[3]		Cancer Incidence				Giardia Infections	
						THMs		HAAs		Endemic[4]	Epidemic[5]
				TTHMs	THAAs	95%	MLE	95%	MLE	Infections	(90%) #.Yrs. to Outbreak
60	1	70	70	55	24	33.8	1.3	153.3	49.4		
60	2	12	82	46	21	30.2	1.1	139.9	45.0		
60	3	18	100	43	21	27.9	1.1	139.3	44.8		
60	4	0	100	43	21	27.9	1.1	139.3	44.8		
60	5	0	100	43	21	27.9	1.1	139.3	44.8		
60	**6**	**0**	**100**	**43**	**21**	**27.9**	**1.1**	**139.3**	**44.8**	**213,045**	**3,089.000**
50	1	64	64	55	24	33.8	1.3	153.3	49.4		
50	2	15	79	45	20	29.9	1.1	137.3	44.1		
50	3	17	96	42	20	27.3	1.0	134.8	43.3		
50	4	4	100	41	20	26.9	1.0	131.4	42.3		
50	5	0	100	41	20	26.9	1.0	131.4	42.3		
50	**6**	**0**	**100**	**41**	**20**	**26.9**	**1.0**	**131.4**	**42.3**	**237,889**	**2.496**
40	1	56	56	55	24	33.8	1.3	153.3	49.4		
40	2	16	72	42	19	28.0	1.1	131.5	42.3		
40	3	22	94	38	18	25.1	0.9	123.9	39.8		
40	4	5	99	36	18	24.5	0.9	118.7	38.1		
40	5	1	100	36	17	24.4	0.9	118.2	38.0		
40	**6**	**0**	**100**	**36**	**17**	**24.4**	**0.9**	**118.2**	**38.0**	**283,003**	**0.658**
30	1	48	48	55	24	33.8	1.3	153.3	49.4		
30	2	12	60	40	19	27.0	1.0	128.9	41.4		
30	3	22	82	34	17	22.7	0.8	115.2	37.0		
30	4	14	96	30	15	21.6	0.8	103.4	33.2		
30	5	3	99	30	15	21.5	0.8	101.8	32.7		
30	**6**	**1**	**100**	**29**	**15**	**21.4**	**0.8**	**100.8**	**32.4**	**324,821**	**0.174**
20	1	37	37	55	24	33.8	1.3	153.3	49.4		
20	2	8	45	39	18	25.9	1.0	126.1	40.5		
20	3	8	53	29	16	19.5	0.7	108.9	35.0		
20	4	23	76	23	13	17.4	0.6	88.0	28.2		
20	5	7	83	22	12	16.8	0.6	82.5	26.5		
20	**6**	**17**	**100**	**20**	**10**	**16.1**	**0.6**	**68.9**	**22.1**	**412,989**	**0.018**
10	1	19	19	55	24	33.8	1.3	153.3	49.4		
10	2	3	22	38	18	25.2	0.9	124.2	39.9		
10	3	1	23	26	16	17.1	0.6	108.6	34.9		
10	4	22	45	18	12	13.6	0.5	78.4	25.1		
10	5	5	50	15	10	12.1	0.4	67.6	21.7		
10	**6**	**50**	**89**	**12**	**6**	**10.4**	**0.4**	**35.3**	**11.3**	**576,460**	**0.006**











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

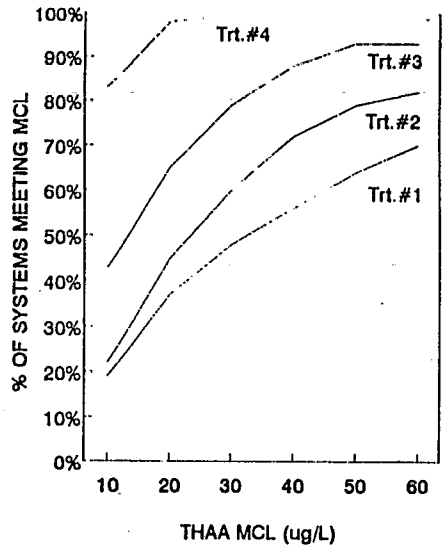
Exhibit A-6

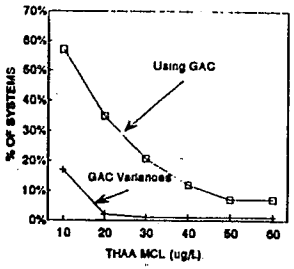
MODEL OUTPUT (surface w/o softening): SWTR W/O ALTERNATIVE DISINFECTION

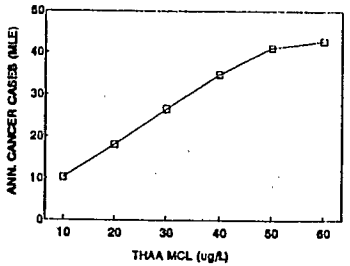
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

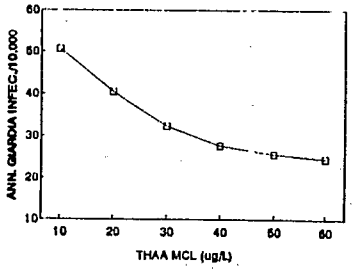
Population = 103,000,000 *(persons)*

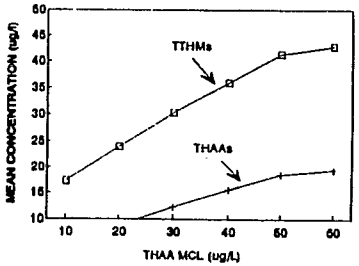
MCL (THAAs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg.Cus.)[3]		Cancer Incidence				Giardia Infections	
						THMs		HAAs		Endemic[4]	Epidemic[5]
				TTHMs	THAAs	95%	MLE	95%	MLE	Infections	(90%) #.Yrs. to Outbreak
60	1	70	70	55	24	33.8	1.3	153.3	49.4		
60	2	12	82	46	21	30.2	1.1	139.9	45.0		
60	3	11	93	44	20	29.2	1.1	134.0	43.1		
60	4	7	99	43	19	28.2	1.1	129.7	41.7	246,531	212.089
50	1	64	64	55	24	33.8	1.3	153.3	49.4		
50	2	15	79	45	20	29.9	1.1	137.3	44.1		
50	3	14	93	43	19	28.6	1.1	128.4	41.3		
50	4	7	99	41	19	27.7	1.0	124.5	40.0	257,263	1.091
40	1	56	56	55	24	33.8	1.3	153.3	49.4		
40	2	16	72	42	19	28.0	1.1	131.5	42.3		
40	3	16	88	39	17	26.6	1.0	116.8	37.5		
40	4	12	99	36	16	25.3	0.9	105.0	33.7	277,142	0.658
30	1	48	48	55	24	33.8	1.3	153.3	49.4		
30	2	12	60	40	19	27.0	1.0	128.9	41.4		
30	3	19	79	35	16	24.6	0.9	105.1	33.8		
30	4	21	99	30	12	22.7	0.8	80.3	25.8	324,038	0.174
20	1	37	37	55	24	33.8	1.3	153.3	49.4		
20	2	8	45	39	18	25.9	1.0	126.1	40.5		
20	3	20	65	31	14	22.2	0.8	93.9	30.1		
20	4	35	98	24	9	19.1	0.7	54.6	17.5	403,945	0.034
10	1	19	19	55	24	33.8	1.3	153.3	49.4		
10	2	3	22	38	18	25.2	0.9	124.2	39.9		
10	3	21	43	28	13	20.3	0.7	84.2	27.1		
10	4	57	83	17	6	14.6	0.5	30.6	9.8	506,430	0.006











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

Exhibit A-7

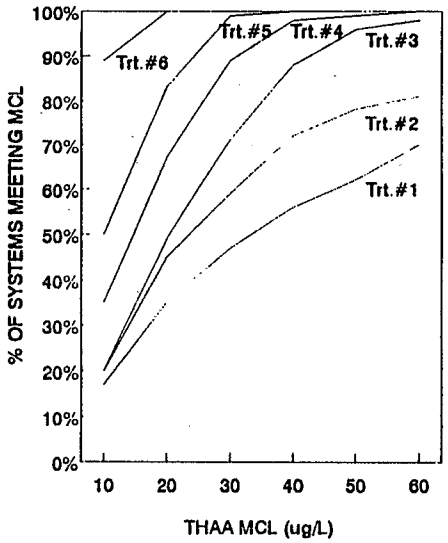
MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/ ALTERNATIVE DISINFECTION

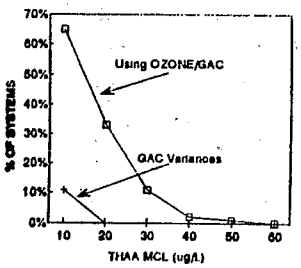
Treatment Code:

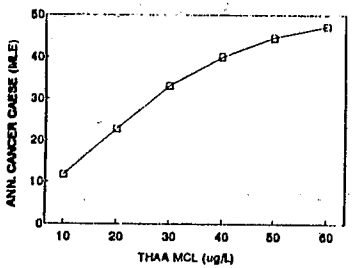
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

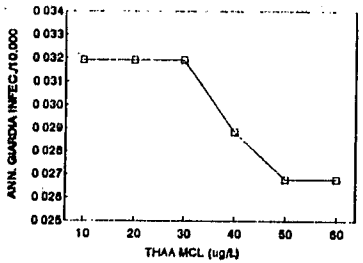
Population = *103,000,000* *(persons)*

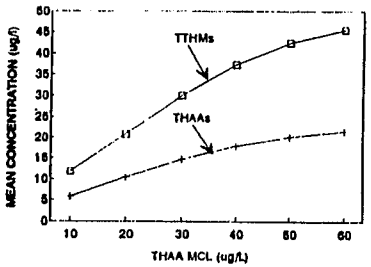
MCL (THAAs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg.Qus.)[3] TTHMs	THAAs	Cancer Incidence THMs 95%	THMs MLE	HAAs 95%	HAAs MLE	Giardia Infections Endemic[4] Infections	Epidemic[5] (90%) #.Yrs. to Outbreak
60	1	70	70	57	25	34.8	1.3	156.3	50.3		
60	2	11	81	48	21	31.2	1.2	143.2	46.1		
60	3	17	98	46	22	29.4	1.1	144.9	46.6		
60	4	2	100	45	22	29.1	1.1	143.4	46.1		
60	5	0	100	45	22	29.1	1.1	143.4	46.1		
60	**6**	**0**	**100**	**45**	**22**	**29.1**	**1.1**	**143.4**	**46.1**	**288**	**infinity**
50	1	62	62	57	25	34.8	1.3	156.3	50.3		
50	2	16	78	46	21	30.7	1.2	139.5	44.8		
50	3	18	96	44	21	28.7	1.1	139.3	44.8		
50	4	3	99	43	20	28.2	1.1	136.1	43.8		
50	5	1	100	42	20	28.1	1.1	135.3	43.5		
50	**6**	**0**	**100**	**42**	**20**	**28.1**	**1.1**	**135.3**	**43.5**	**288**	**infinity**
40	1	56	56	57	25	34.8	1.3	156.3	50.3		
40	2	16	72	44	20	29.0	1.1	135.1	43.4		
40	3	16	88	41	20	26.8	1.0	131.8	42.4		
40	4	10	98	38	18	25.9	1.0	123.2	39.6		
40	5	2	100	37	18	25.7	1.0	121.7	39.1		
40	**6**	**0**	**100**	**37**	**18**	**25.7**	**1.0**	**121.7**	**39.1**	**288**	**infinity**
30	1	47	47	57	25	34.8	1.3	156.3	50.3		
30	2	12	59	42	19	28.0	1.0	132.5	42.6		
30	3	12	71	37	19	24.8	0.9	124.9	40.2		
30	4	18	89	32	16	22.9	0.8	107.2	34.4		
30	5	10	99	30	15	22.2	0.8	101.6	32.6		
30	**6**	**1**	**100**	**30**	**15**	**22.2**	**0.8**	**100.6**	**32.3**	**319**	**infinity**
20	1	35	35	57	25	34.8	1.3	156.3	50.3		
20	2	10	45	40	19	26.8	1.0	129.0	41.4		
20	3	4	49	33	18	22.1	0.8	120.0	38.6		
20	4	18	67	26	14	19.2	0.7	95.9	30.8		
20	5	16	83	23	12	17.5	0.6	82.9	26.6		
20	**6**	**17**	**100**	**21**	**10**	**16.9**	**0.6**	**69.3**	**22.2**	**319**	**infinity**
10	1	17	17	57	25	34.8	1.3	156.3	50.3		
10	2	3	20	39	19	26.1	1.0	127.6	41.0		
10	3	0	20	31	18	20.0	0.8	122.9	39.5		
10	4	15	35	21	13	15.5	0.6	88.5	28.4		
10	5	15	50	16	10	12.4	0.4	67.6	21.7		
10	**6**	**50**	**89**	**12**	**6**	**10.6**	**0.4**	**35.4**	**11.3**	**319**	**infinity**











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

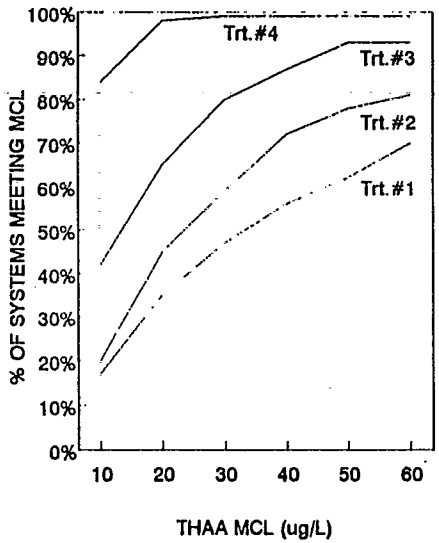
Exhibit A-8

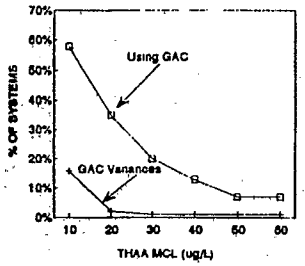
MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/O ALTERNATIVE DISINFECTION

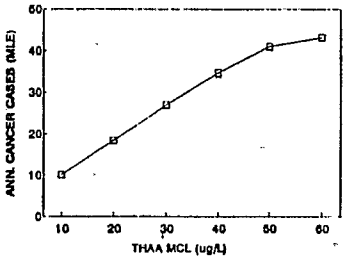
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

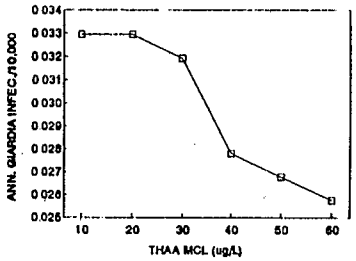
Population = 103,000,000 *(persons)*

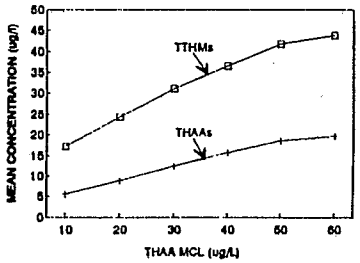
MCL (THAAs)	Trt. Code	% of Sys. Ending[1]	Cumulative % of Sys. < MCL[2]	Mean Concentrations of By-Products (Avg.Qus.)[3]		Cancer Incidence				Giardia Infections	
						THMs		HAAs		Endemic[4]	Epidemic[5]
				TTHMs	THAAs	95%	MLE	95%	MLE	Infections	(90%) #.Yrs. to Outbreak
60	1	70	70	57	25	34.8	1.3	156.3	50.3		
60	2	11	81	48	21	31.2	1.2	143.2	46.1		
60	3	12	93	45	20	29.9	1.1	135.3	43.5		
60	4	7	99	44	20	28.8	1.1	131.0	42.1	258	infinity
50	1	62	62	57	25	34.8	1.3	156.3	50.3		
50	2	16	78	46	21	30.7	1.2	139.5	44.8		
50	3	15	93	43	19	29.2	1.1	128.4	41.3		
50	4	7	99	42	19	28.2	1.1	124.5	40.0	268	infinity
40	1	56	56	57	25	34.8	1.3	156.3	50.3		
40	2	16	72	44	20	29.0	1.1	135.1	43.4		
40	3	15	87	40	18	27.3	1.0	119.2	38.3		
40	4	13	99	37	16	25.6	0.9	105.4	33.9	278	infinity
30	1	47	47	57	25	34.8	1.3	156.3	50.3		
30	2	12	59	42	19	28.0	1.0	132.5	42.6		
30	3	21	80	36	16	25.3	0.9	106.2	34.1		
30	4	20	99	31	13	23.3	0.8	82.0	26.4	319	infinity
20	1	35	35	57	25	34.8	1.3	156.3	50.3		
20	2	10	45	40	19	26.8	1.0	129.0	41.4		
20	3	20	65	32	14	22.7	0.8	95.1	30.5		
20	4	35	98	24	9	19.5	0.7	55.4	17.8	330	infinity
10	1	17	17	57	25	34.8	1.3	156.3	50.3		
10	2	3	20	39	19	26.1	1.0	127.6	41.0		
10	3	22	42	28	13	20.6	0.8	84.8	27.2		
10	4	58	84	17	6	14.6	0.5	30.0	9.6	330	infinity











[1] percent of systems installing each treatment tier (includes 20% over-design factor)
[2] cumulative percent of systems able to meet MCL at each treatment tier (includes 20% over-design factor)
[3] mean concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL
[4] assumes 10% of population exposed at first customer
[5] estimate for 90th percentile

Appendix B

Exhibit B-1

MODEL OUTPUT (surface w/o softening): SWTR W/O ALTERNATIVE DISINFECTION

Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

Population = 103,000,000 (persons)

MCL (TTHMs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)							
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA
100	99	39	20	9	9	0.61	19	9	7	0.9	0.3	0.3	0.3	0.01	41	35	6
75	99	34	17	8	8	0.58	17	9	6	0.8	0.3	0.3	0.3	0.01	38	32	6
60	99	29	14	7	7	0.55	15	8	5	0.7	0.2	0.3	0.2	0.01	33	28	5
50	99	24	11	6	6	0.57	13	6	4	0.6	0.2	0.2	0.2	0.01	27	23	4
35	98	19	8	5	5	0.63	9	4	3	0.5	0.1	0.2	0.2	0.01	19	16	3
25	95	14	5	4	4	0.63	7	3	2	0.4	0.1	0.2	0.1	0.01	13	11	2

MCL (THAAs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)							
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA
60	99	43	21	10	12	0.71	19	9	7	1.1	0.3	0.3	0.4	0.01	42	35	7
50	99	41	19	10	12	0.71	19	9	7	1.0	0.3	0.3	0.4	0.01	40	34	6
40	99	36	15	9	11	0.70	16	8	5	0.9	0.2	0.3	0.4	0.01	34	29	5
30	99	30	11	8	11	0.69	12	6	4	0.8	0.2	0.3	0.4	0.01	26	22	4
20	98	24	7	6	10	0.68	9	4	3	0.7	0.1	0.2	0.3	0.01	18	15	2
10	83	17	4	4	8	0.71	6	2	1	0.5	0.1	0.2	0.3	0.01	10	9	1

MCL (THAAs)	MCL (TTHMs)	Cancer Incidence THAAs
60	100	40
50	100	39
40	100	33
30	100	26
20	100	17
10	100	10
60	75	37
50	75	37
40	75	32
30	75	25
20	75	17
10	75	10
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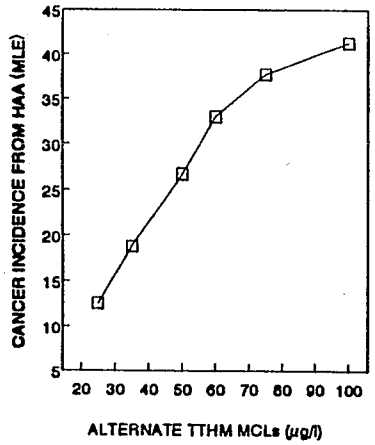
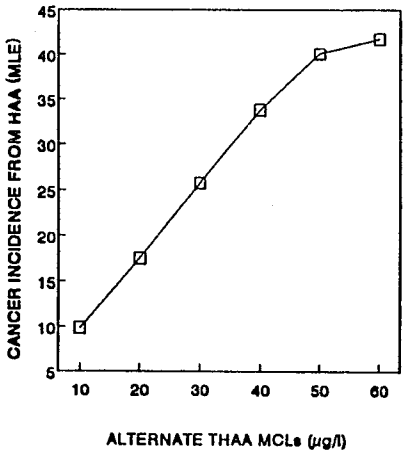
60	60	33
50	60	33
40	60	30
30	60	24
20	60	17
10	60	10
60	50	27
50	50	27
40	50	26
30	50	22
20	50	16
10	50	10
60	35	19
50	35	19
40	35	19
30	35	18
20	35	15
10	35	10
60	25	13
50	25	13
40	25	13
30	25	13
20	25	12
10	25	9

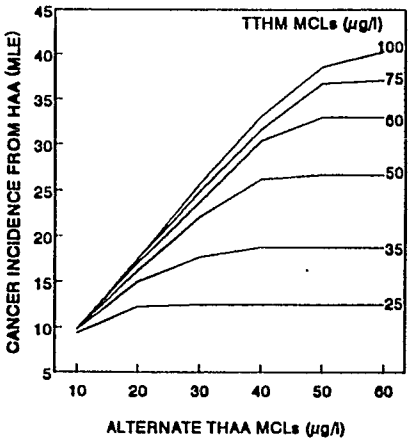
Cancer Incidence at Alternate TTHM MCLs



Cancer Incidence at Alternate THAA MCLs



Cancer Incidence at Alternate THAA / TTHM MCLs



[1] cummulative percent of systems able to meet MCL at the last treatment tier (includes 20% over-design factor)
[2] mean concentration at the last treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit B-2

MODEL OUTPUT (surface w/o softening): SWTR W/ ALTERNATIVE DISINFECTION

Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

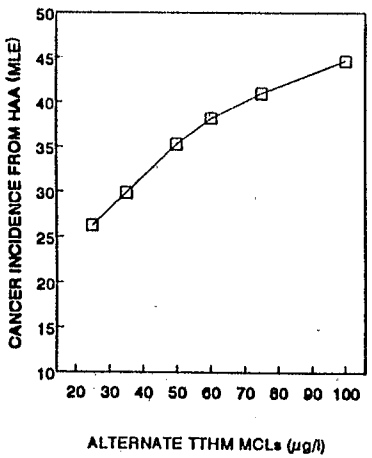
Population = 103,000,000 (persons)

MCL (TTHMs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)							
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA
100	100	40	21	9	9	0.60	20	10	8	0.9	0.3	0.3	0.3	0.01	45	38	7
75	100	33	18	8	8	0.55	19	9	7	0.8	0.3	0.3	0.3	0.01	41	35	6
60	100	29	15	7	6	0.50	17	9	6	0.7	0.2	0.2	0.2	0.01	38	33	5
50	100	25	13	6	6	0.46	16	8	5	0.6	0.2	0.2	0.2	0.01	35	30	5
35	100	19	9	5	5	0.42	14	7	4	0.5	0.1	0.2	0.2	0.01	30	26	4
25	100	15	7	4	4	0.34	12	6	4	0.4	0.1	0.1	0.1	0.01	26	23	3

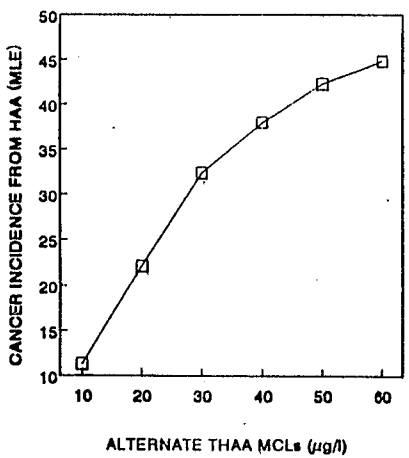
MCL (THAAs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)							
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA
60	100	43	22	10	11	0.69	21	10	8	1.1	0.3	0.3	0.4	0.01	45	38	6
50	100	41	19	9	11	0.68	20	10	7	1.0	0.3	0.3	0.4	0.01	42	36	9
40	100	36	16	9	11	0.66	17	9	6	0.9	0.2	0.3	0.4	0.01	38	33	4
30	100	29	11	7	10	0.63	15	8	5	0.8	0.2	0.3	0.4	0.01	32	28	4
20	100	20	6	5	9	0.57	10	5	3	0.6	0.1	0.2	0.3	0.01	22	20	6
10	89	12	2	2	7	0.49	6	3	1	0.4	0.0	0.1	0.2	0.01	11	10	0

MCL (THAAs)	MCL (TTHMs)	Cancer Incidence THAAs
60	100	44
50	100	41
40	100	37
30	100	32
20	100	22
10	100	11
60	75	40
50	75	40
40	75	37
30	75	32
20	75	22
10	75	11
60	60	38
50	60	38
40	60	36
30	60	31
20	60	22
10	60	11
60	50	35
50	50	35
40	50	35
30	50	31
20	50	22
10	50	11
60	35	30
50	35	30
40	35	30
30	35	29
20	35	21
10	35	11
60	25	26
50	25	26
40	25	26
30	25	26
20	25	21
10	25	11

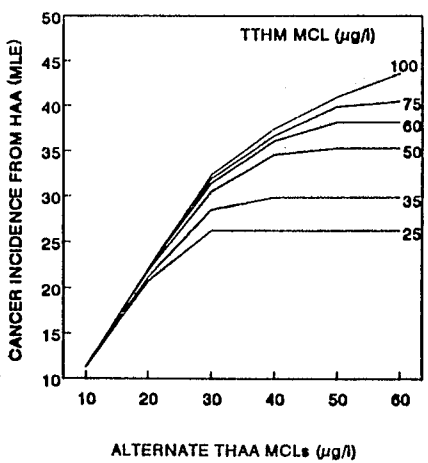
Cancer Incidence at Alternate TTHM MCLs



Cancer Incidence at Alternate THAA MCLs



Cancer Incidence at Alternate THAA / TTHM MCLs



[1] cummulative percent of systems able to meet MCL at the last treatment tier (includes 20% over-design factor)
[2] mean concentration at the last treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit B-3

MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/O ALTERNATIVE DISINFECTION

Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

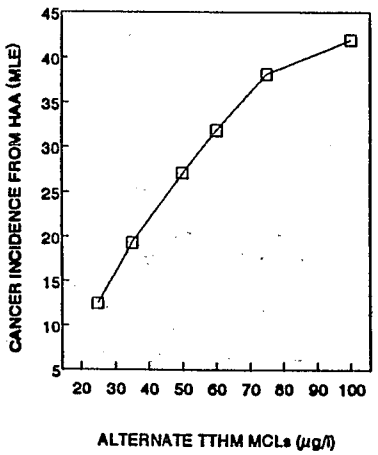
Population = 103,000,000 (persons)

MCL (TTHMs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)							
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA
100	99	40	20	9	10	0.58	19	10	7	1.0	0.3	0.3	0.3	0.01	42	35	7
75	99	34	18	8	8	0.54	18	9	6	0.8	0.3	0.3	0.3	0.01	38	32	6
60	99	29	14	7	7	0.51	15	7	5	0.7	0.2	0.3	0.2	0.01	32	27	5
50	99	25	11	7	6	0.53	13	6	4	0.6	0.2	0.2	0.2	0.01	27	23	4
35	98	19	8	5	5	0.58	9	5	3	0.5	0.1	0.2	0.2	0.01	19	17	3
25	95	14	5	4	4	0.59	7	3	2	0.4	0.1	0.2	0.1	0.01	12	11	2

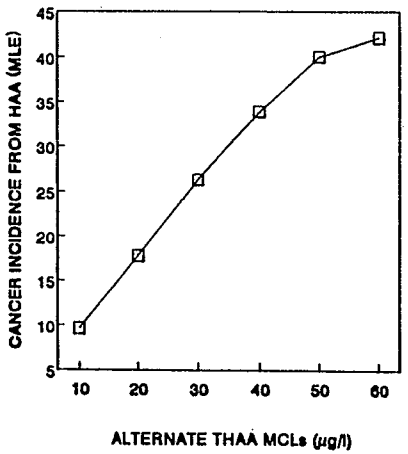
MCL (THAAs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)							
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA
60	99	44	21	10	12	0.69	20	10	8	1.1	0.3	0.4	0.4	0.01	42	35	7
50	99	42	19	10	12	0.68	19	9	7	1.1	0.3	0.4	0.4	0.01	40	34	6
40	99	37	15	9	11	0.67	16	8	6	0.9	0.2	0.3	0.4	0.01	34	29	5
30	99	31	11	8	11	0.66	13	6	4	0.8	0.2	0.3	0.4	0.01	26	23	4
20	98	24	7	7	10	0.64	9	4	3	0.7	0.1	0.2	0.3	0.01	18	15	2
10	84	17	4	4	8	0.66	6	2	1	0.5	0.1	0.2	0.3	0.01	10	8	1

MCL (THAAs)	MCL (TTHMs)	Cancer Incidence THAAs
60	100	40
50	100	38
40	100	33
30	100	26
20	100	18
10	100	10
60	75	37
50	75	37
40	75	31
30	75	25
20	75	18
10	75	10
60	60	32
50	60	32
40	60	30
30	60	24
20	60	17
10	60	10
60	50	27
50	50	27
40	50	27
30	50	22
20	50	16
10	50	10
60	35	19
50	35	19
40	35	19
30	35	18
20	35	15
10	35	9
60	25	12
50	25	12
40	25	12
30	25	12
20	25	12
10	25	9

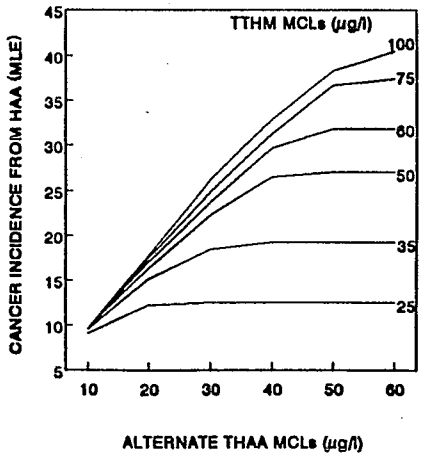
Cancer Incidence at Alternate TTHM MCLs



Cancer Incidence at Alternate THAA MCLs



Cancer Incidence at Alternate THAA / TTHM MCLs



[1] cummulative percent of systems able to meet MCL at the last treatment tier (includes 20% over-design factor)
[2] mean concentration at the last treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit B-4

MODEL OUTPUT (surface w/o softening): ENHANCED SWTR W/ ALTERNATIVE DISINFECTION

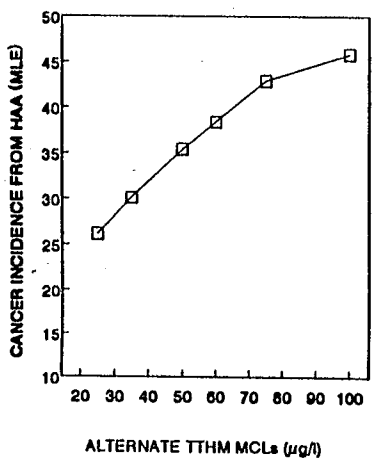
Treatment Code:
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC
5 – pre-chlor + ammonia + alum + ozone
6 – pre-chlor + ammonia + alum + ozone + GAC

Population = 103,000,000 (persons)

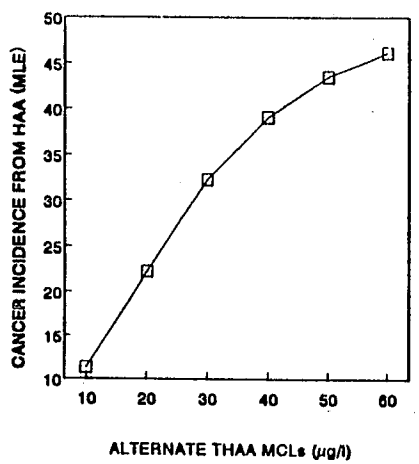
MCL (TTHMs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)								MCL (THAAs)	MCL (TTHMs)	Cancer Incidence THAAs
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA			
100	100	41	22	9	10	0.59	21	10	8	1.0	0.3	0.3	0.3	0.01	46	39	7	60	100	45
75	100	36	19	8	8	0.52	20	10	7	0.9	0.3	0.3	0.3	0.01	43	36	6	50	100	42
60	100	30	16	7	6	0.46	18	9	6	0.7	0.2	0.3	0.2	0.01	38	33	6	40	100	39
50	100	26	13	6	6	0.44	16	8	6	0.6	0.2	0.2	0.2	0.01	35	30	5	30	100	32
35	100	20	10	5	5	0.40	14	7	4	0.5	0.1	0.2	0.2	0.01	30	26	4	20	100	22
25	100	15	7	4	3	0.33	12	6	4	0.4	0.1	0.1	0.1	0.01	26	23	3	10	100	11
																		60	75	42
																		50	75	42
																		40	75	38
																		30	75	32
																		20	75	22
																		10	75	11
																		60	60	38
																		50	60	38
																		40	60	36
																		30	60	31
																		20	60	22
																		10	60	11
																		60	50	35
																		50	50	35
																		40	50	34
																		30	50	30
																		20	50	21
																		10	50	11
																		60	35	30
																		50	35	30
																		40	35	30
																		30	35	28
																		20	35	21
																		10	35	11
																		60	25	26
																		50	25	26
																		40	25	26
																		30	25	26
																		20	25	20
																		10	25	11

MCL (THAAs)	Cumulative % of Sys. < MCL[1]	Mean Concentrations of By-Products (Average Customer)[2]								Cancer Incidence (Maximum Likelihood Estimate)							
		TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA	TTHMs	CF	C2B	B2C	BF	THAAs	DCAA	TCAA
60	100	45	23	10	12	0.67	22	10	8	1.1	0.3	0.4	0.4	0.01	46	39	7
50	100	42	20	10	12	0.67	20	10	8	1.1	0.3	0.3	0.4	0.01	43	37	7
40	100	37	16	9	11	0.65	18	9	6	1.0	0.2	0.3	0.4	0.01	39	33	6
30	100	30	11	8	11	0.61	15	8	5	0.8	0.2	0.3	0.4	0.01	32	28	4
20	100	21	6	5	9	0.55	10	5	3	0.6	0.1	0.2	0.3	0.01	22	20	3
10	89	12	2	2	7	0.46	6	3	1	0.4	0.0	0.1	0.3	0.01	11	10	1

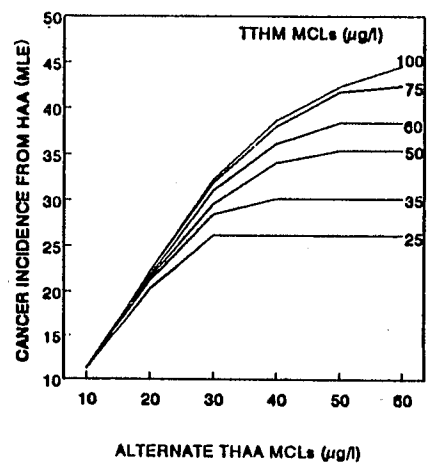
Cancer Incidence at Alternate TTHM MCLs



Cancer Incidence at Alternate THAA MCLs



Cancer Incidence at Alternate THAA / TTHM MCLs



[1] cummulative percent of systems able to meet MCL at the last treatment tier (includes 20% over-design factor)
[2] mean concentration at the last treatment tier of all systems; those meeting MCL and those not meeting MCL

Appendix C

Exhibit C-1

Concentrations of Individual THMs and HAAs at Alternate TTHM MCLs

Treatment Group Code:
1 – SWTR w/o Alternative Disinfection
2 – SWTR w/ Alternative Disinfection
3 – ENHANCED SWTR w/o Alternative Disinfection
4 – ENHANCED SWTR w/ Alternative Disinfection

Group	MCL	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
Code	(TTHMs)	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
1	100	39	39	78	20	14	55	9	8	22	9	3	44	0.6	0.3	2	19	17	44	9	8	24	7	5	20
1	75	34	36	56	17	13	44	8	7	18	8	3	35	0.6	0.3	2	17	14	39	9	7	20	6	5	17
1	60	29	30	46	14	11	38	7	7	16	7	3	31	0.6	0.3	2	15	12	35	8	6	19	5	4	14
1	50	24	24	39	11	9	28	6	6	13	6	3	26	0.6	0.4	2	13	11	28	6	5	16	4	3	11
1	35	19	18	27	8	7	21	5	5	10	5	3	18	0.6	0.4	2	9	9	20	4	4	11	3	3	7
1	25	14	14	20	5	4	14	4	4	8	4	2	12	0.6	0.4	2	7	6	15	3	3	8	2	1	5
2	100	40	39	78	21	16	57	9	7	22	9	3	48	0.6	0.3	2	20	18	45	10	10	24	8	6	20
2	75	33	34	56	18	15	46	8	7	16	8	3	36	0.6	0.3	2	19	17	39	9	9	20	7	6	17
2	60	29	29	46	15	13	35	7	7	16	6	2	25	0.5	0.3	2	17	17	35	9	9	18	6	5	14
2	50	25	25	39	13	12	31	6	5	13	6	2	21	0.5	0.2	2	16	17	31	8	9	16	5	5	12
2	35	19	20	27	9	9	22	5	4	9	5	2	19	0.4	0.2	2	14	14	26	7	7	14	4	5	10
2	25	15	15	20	7	7	15	4	4	7	4	1	13	0.3	0.2	1	12	12	21	6	6	12	4	3	7
3	100	40	39	76	20	16	59	9	9	22	10	3	47	0.6	0.3	2	19	17	45	10	8	24	7	5	21
3	75	34	36	57	18	13	46	8	8	18	8	3	33	0.5	0.3	2	18	14	40	9	7	20	6	5	17
3	60	29	27	45	14	11	37	7	7	15	7	3	23	0.5	0.3	2	15	12	33	7	6	17	5	4	14
3	50	25	24	39	11	10	29	7	6	14	6	3	23	0.5	0.3	2	13	11	30	6	5	17	4	4	11
3	35	19	18	28	8	7	20	5	5	10	5	2	15	0.6	0.4	2	9	9	21	5	4	11	3	3	7
3	25	14	13	20	5	4	14	4	4	8	4	2	12	0.6	0.4	2	7	6	15	3	3	8	2	1	5
4	100	41	41	75	22	17	59	9	8	21	10	2	51	0.6	0.3	2	21	19	45	10	10	24	8	7	21
4	75	36	37	57	19	17	46	8	8	19	8	2	31	0.5	0.3	2	20	19	39	10	10	20	7	7	16
4	60	30	30	45	16	14	36	7	7	16	6	2	23	0.5	0.3	2	18	18	34	9	10	17	6	6	14
4	50	26	26	39	13	12	32	6	6	13	6	2	22	0.4	0.2	2	16	15	32	8	7	17	6	5	13
4	35	20	20	27	10	9	22	5	5	10	5	2	19	0.4	0.2	2	14	13	26	7	7	14	4	4	10
4	25	15	15	19	7	7	15	4	4	8	3	1	13	0.3	0.2	1	12	12	21	6	6	12	4	3	7

* concentration at the last treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-2

Concentrations of Individual THMs and HAAs at Alternate TTHM MCLs
— SWTR w/o Alternate Disinfection —

Treatment Code: w/o Alternate Disinfection
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

MCL	Trt.	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
(TTHMs)	Code	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
100	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
100	2	42	41	78	21	15	58	9	9	23	11	3	53	0.7	0.4	2	20	17	46	10	9	24	8	6	21
100	3	40	41	78	20	15	55	9	9	22	10	3	44	0.6	0.3	2	20	17	44	10	9	24	7	6	20
100	4	39	39	78	20	14	55	9	8	22	9	3	44	0.6	0.3	2	19	17	44	9	8	24	7	5	20
75	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
75	2	39	39	78	20	14	51	9	8	22	10	3	39	0.6	0.3	2	19	17	44	10	8	24	7	5	19
75	3	35	37	58	18	14	44	8	8	19	8	3	35	0.6	0.3	2	18	17	39	9	8	20	7	5	17
75	4	34	36	56	17	13	44	8	7	18	8	3	35	0.6	0.3	2	17	14	39	9	7	20	6	5	17
60	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
60	2	38	37	78	19	13	51	9	8	22	9	3	39	0.6	0.3	2	19	17	44	10	8	24	7	5	19
60	3	32	33	48	16	12	44	8	7	16	8	3	32	0.5	0.3	2	17	14	36	8	7	19	6	4	16
60	4	29	30	46	14	11	38	7	7	16	7	3	31	0.6	0.3	2	15	12	35	8	6	19	5	4	14
50	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
50	2	37	34	78	18	13	51	9	8	22	9	3	39	0.6	0.3	2	18	15	44	9	8	24	6	5	19
50	3	29	27	48	14	11	35	7	7	16	7	3	31	0.5	0.3	2	15	12	34	8	6	19	5	4	14
50	4	24	24	39	11	9	28	6	6	13	6	3	26	0.6	0.4	2	13	11	28	6	5	16	4	3	11
35	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
35	2	37	32	78	18	13	51	9	8	22	9	3	39	0.6	0.3	2	18	15	44	9	8	24	6	5	19
35	3	27	25	48	13	11	35	7	6	15	7	3	31	0.5	0.3	2	14	12	33	7	6	17	5	4	14
35	4	19	18	27	8	7	21	5	5	10	5	3	18	0.6	0.4	2	9	9	20	4	4	11	3	3	7
25	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
25	2	36	32	78	18	13	51	9	7	22	9	3	39	0.5	0.3	2	18	14	44	9	8	24	6	5	19
25	3	26	23	48	12	10	35	7	6	15	7	3	31	0.5	0.2	2	13	12	33	7	6	17	4	3	14
25	4	14	14	20	5	4	14	4	4	8	4	2	12	0.6	0.4	2	7	6	15	3	3	8	2	1	5

* concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-3

Concentrations of Individual THMs and HAAs at Alternate TTHM MCLs
– SWTR w/ Alternate Disinfection –

Treatment Code: w/ Alternate Disinfection

1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum dose + ozone
6 – pre-chlor + ammonia + alum dose + ozone + GAC

MCL	Trt.	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
(TTHMs)	Code	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
100	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
100	2	42	41	78	21	15	58	9	9	23	11	3	53	0.7	0.4	2	20	17	46	10	9	24	8	6	21
100	3	40	39	78	21	16	57	9	7	22	9	3	48	0.6	0.3	2	20	18	45	10	10	24	8	6	20
100	4	40	39	78	21	16	57	9	7	22	9	3	48	0.6	0.3	2	20	18	45	10	10	24	8	6	20
100	5	40	39	78	21	16	57	9	7	22	9	3	48	0.6	0.3	2	20	18	45	10	10	24	8	6	20
100	6	40	39	78	21	16	57	9	7	22	9	3	48	0.6	0.3	2	20	18	45	10	10	24	8	6	20
75	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
75	2	39	39	78	20	14	51	9	8	22	10	3	39	0.6	0.3	2	19	17	44	10	8	24	7	5	19
75	3	34	35	59	18	15	48	8	7	16	8	3	36	0.6	0.3	2	19	17	41	10	9	20	7	6	18
75	4	33	34	56	18	15	46	8	7	16	8	3	36	0.6	0.3	2	19	17	39	9	9	20	7	6	17
75	5	33	34	56	18	15	46	8	7	16	8	3	36	0.6	0.3	2	19	17	39	9	9	20	7	6	17
75	6	33	34	56	18	15	46	8	7	16	8	3	36	0.6	0.3	2	19	17	39	9	9	20	7	6	17
60	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
60	2	38	37	78	19	13	51	9	8	22	9	3	39	0.6	0.3	2	19	17	44	10	8	24	7	5	19
60	3	31	30	52	17	13	46	7	7	16	7	2	26	0.5	0.3	2	18	17	38	9	9	20	6	5	17
60	4	29	29	46	15	13	37	7	7	16	6	2	25	0.5	0.3	2	18	17	35	9	9	18	6	5	14
60	5	29	29	46	15	13	35	7	7	16	6	2	25	0.5	0.3	2	17	17	35	9	9	18	6	5	14
60	6	29	29	46	15	13	35	7	7	16	6	2	25	0.5	0.3	2	17	17	35	9	9	18	6	5	14
50	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
50	2	37	34	78	18	13	51	9	8	22	9	3	39	0.6	0.3	2	18	15	44	9	8	24	6	5	19
50	3	28	26	50	15	13	34	7	6	14	6	2	25	0.5	0.2	2	17	17	35	9	9	19	6	5	14
50	4	26	25	39	13	12	31	6	5	13	6	2	21	0.5	0.2	2	16	17	31	8	9	16	5	5	12
50	5	25	25	39	13	12	31	6	5	13	6	2	21	0.5	0.2	2	16	17	31	8	9	16	5	5	12
50	6	25	25	39	13	12	31	6	5	13	6	2	21	0.5	0.2	2	16	17	31	8	9	16	5	5	12
35	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
35	2	37	32	78	18	13	51	9	8	22	9	3	39	0.6	0.3	2	18	15	44	9	8	24	6	5	19
35	3	25	23	50	13	11	34	6	5	12	6	2	23	0.5	0.2	2	16	16	35	8	8	17	6	5	14
35	4	20	20	28	10	9	23	5	4	10	5	2	19	0.4	0.2	2	14	14	27	7	7	14	5	5	11
35	5	19	20	27	10	9	23	5	4	9	5	2	19	0.4	0.2	2	14	14	27	7	7	14	4	5	10
35	6	19	20	27	9	9	22	5	4	9	5	2	19	0.4	0.2	2	14	14	26	7	7	14	4	5	10
25	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
25	2	36	32	78	18	13	51	9	7	22	9	3	39	0.5	0.3	2	18	14	44	9	8	24	6	5	19
25	3	23	19	50	12	10	34	5	4	12	5	1	23	0.4	0.2	2	16	15	35	8	8	17	5	5	14
25	4	17	16	24	8	7	19	4	4	8	4	1	13	0.3	0.2	1	13	12	24	7	7	13	4	4	9
25	5	15	15	20	8	7	15	4	4	8	4	1	13	0.3	0.2	1	12	12	22	6	7	12	4	4	8
25	6	15	15	20	7	7	15	4	4	7	4	1	13	0.3	0.2	1	12	12	21	6	6	12	4	3	7

* concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-4

Concentrations of Individual THMs and HAAs at Alternate TTHM MCLs
– Enhanced SWTR w/o Alternate Disinfection –

Treatment Code: w/o Alternate Disinfection

1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

MCL (TTHMs)	Trt. Code	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
		mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
100	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
100	2	44	42	79	22	17	60	10	9	26	11	3	55	0.6	0.4	2	21	18	47	10	9	25	8	6	21
100	3	41	42	76	21	17	59	10	9	22	10	3	47	0.6	0.3	2	20	18	45	10	9	24	8	6	21
100	4	40	39	76	20	16	59	9	9	22	10	3	47	0.6	0.3	2	19	17	45	10	8	24	7	5	21
75	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
75	2	41	39	79	21	16	51	10	9	23	10	3	41	0.6	0.3	2	20	18	45	10	9	25	7	6	19
75	3	36	37	57	18	15	46	9	8	19	8	3	33	0.5	0.3	2	18	17	40	9	8	20	7	5	17
75	4	34	36	57	18	13	46	8	8	18	8	3	33	0.5	0.3	2	18	14	40	9	7	20	6	5	17
60	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
60	2	39	37	79	20	14	51	9	8	23	10	3	41	0.6	0.3	2	19	17	45	10	9	25	7	5	19
60	3	32	31	49	16	12	41	8	7	16	7	3	30	0.5	0.3	2	16	13	35	8	7	18	6	4	16
60	4	29	27	45	14	11	37	7	7	15	7	3	23	0.5	0.3	2	15	12	33	7	6	17	5	4	14
50	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
50	2	39	36	79	19	14	51	9	8	23	10	3	41	0.6	0.3	2	19	17	45	10	9	25	7	5	19
50	3	30	28	49	15	12	40	8	7	16	7	3	30	0.5	0.3	2	15	13	34	8	6	18	5	4	15
50	4	25	24	39	11	10	29	7	6	14	6	3	23	0.5	0.3	2	13	11	30	6	5	17	4	4	11
35	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
35	2	38	35	79	19	13	51	9	8	23	10	3	41	0.6	0.3	2	19	16	45	10	8	25	7	5	19
35	3	28	25	49	13	11	40	7	7	15	7	3	30	0.5	0.3	2	14	12	34	7	6	17	5	4	15
35	4	19	18	28	8	7	20	5	5	10	5	2	15	0.6	0.4	2	9	9	21	5	4	11	3	3	7
25	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
25	2	37	35	79	19	13	51	9	7	23	9	3	41	0.5	0.3	2	19	15	45	10	8	25	7	5	19
25	3	26	23	49	12	10	40	7	6	15	7	3	30	0.4	0.2	1	13	11	34	7	6	17	4	4	15
25	4	14	13	20	5	4	14	4	4	5	4	2	12	0.6	0.4	2	7	6	15	3	3	8	2	1	5

* concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-5

Concentrations of Individual THMs and HAAs at Alternate TTHM MCLs
– Enhanced SWTR w/ Alternate Disinfection –

Treatment Code: w/ Alternate Disinfection

1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum dose + ozone
6 – pre-chlor + ammonia + alum dose + ozone + GAC

MCL	Trt.	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
(TTHMs)	Code	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
100	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
100	2	44	42	79	22	17	60	10	9	26	11	3	55	0.6	0.4	2	21	18	47	10	9	25	8	6	21
100	3	43	42	78	23	17	62	9	8	21	10	2	51	0.6	0.3	2	22	19	49	11	10	24	8	7	23
100	4	41	41	75	22	17	59	9	8	21	10	2	51	0.6	0.3	2	21	19	45	10	10	24	8	7	21
100	5	41	41	75	22	17	59	9	8	21	10	2	51	0.6	0.3	2	21	19	45	10	10	24	8	7	21
100	6	41	41	75	22	17	59	9	8	21	10	2	51	0.6	0.3	2	21	19	45	10	10	24	8	7	21
75	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
75	2	41	39	79	21	16	51	10	9	23	10	3	41	0.6	0.3	2	20	18	45	10	9	25	7	6	19
75	3	38	39	60	21	17	48	9	8	19	8	2	37	0.5	0.3	2	20	19	43	10	10	22	8	7	19
75	4	36	37	57	19	17	46	9	8	19	8	2	31	0.5	0.3	2	20	19	40	10	10	20	7	7	17
75	5	36	37	57	19	17	46	8	8	19	8	2	31	0.5	0.3	2	20	19	39	10	10	20	7	7	16
75	6	36	37	57	19	17	46	8	8	19	8	2	31	0.5	0.3	2	20	19	39	10	10	20	7	7	16
60	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
60	2	39	37	79	20	14	51	9	8	23	10	3	41	0.6	0.3	2	19	17	45	10	9	25	7	5	19
60	3	34	33	58	19	15	46	8	7	17	7	2	30	0.5	0.3	2	19	18	36	10	10	20	7	6	16
60	4	30	30	45	16	14	37	7	7	16	6	2	23	0.5	0.3	2	18	18	35	9	10	18	6	6	15
60	5	30	30	45	16	14	36	7	7	16	6	2	23	0.5	0.3	2	18	18	34	9	10	17	6	6	14
60	6	30	30	45	16	14	36	7	7	16	6	2	23	0.5	0.3	2	18	18	34	9	10	17	6	6	14
50	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
50	2	39	36	79	19	14	51	9	8	23	10	3	41	0.6	0.3	2	19	17	45	10	9	25	7	5	19
50	3	33	31	58	18	15	45	8	7	17	7	2	30	0.5	0.2	2	19	18	36	9	9	20	7	6	15
50	4	27	26	39	14	13	32	7	6	14	6	2	22	0.4	0.2	2	17	16	33	8	8	17	6	5	14
50	5	26	26	39	13	12	32	6	6	13	6	2	22	0.4	0.2	2	16	15	32	8	7	17	6	5	13
50	6	26	26	39	13	12	32	6	6	13	6	2	22	0.4	0.2	2	16	15	32	8	7	17	6	5	13
35	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
35	2	38	35	79	19	13	51	9	8	23	10	3	41	0.6	0.3	2	19	16	45	10	8	25	7	5	19
35	3	30	25	58	16	13	45	7	6	17	7	2	30	0.5	0.2	2	18	18	36	9	9	18	7	6	15
35	4	22	22	34	11	10	24	6	5	10	5	2	19	0.4	0.2	2	15	14	27	7	7	14	5	4	11
35	5	20	20	28	10	9	23	5	5	10	5	2	19	0.4	0.2	2	14	13	26	7	7	14	5	4	11
35	6	20	20	27	10	9	22	5	5	10	5	2	19	0.4	0.2	2	14	13	26	7	7	14	4	4	10
25	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
25	2	37	35	79	19	13	51	9	7	23	9	3	41	0.5	0.3	2	19	15	45	10	8	25	7	5	19
25	3	29	22	58	16	12	45	7	5	17	6	1	30	0.4	0.2	2	18	17	36	9	9	18	6	6	15
25	4	19	18	34	9	8	23	5	5	10	4	1	15	0.4	0.2	1	14	13	27	7	7	14	5	4	11
25	5	15	15	20	7	7	16	4	4	8	4	1	13	0.3	0.2	1	12	12	21	6	6	12	4	4	7
25	6	15	15	19	7	7	15	4	4	8	3	1	13	0.3	0.2	1	12	12	21	6	6	12	4	3	7

* concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-6

Concentrations of Individual THMs and HAAs at Alternate THAA MCLs

Treatment Group Code:
1 – SWTR w/o Alternative Disinfection
2 – SWTR w/ Alternative Disinfection
3 – ENHANCED SWTR w/o Alternative Disinfection
4 – ENHANCED SWTR w/ Alternative Disinfection

Group Code	MCL (THAAs)	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
		mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
1	60	43	39	90	21	16	51	10	8	30	12	3	69	0.7	0.3	3	19	17	43	9	8	22	7	6	20
1	50	41	37	90	19	16	45	10	7	30	12	3	69	0.7	0.3	3	19	17	38	9	8	19	7	6	17
1	40	36	28	89	15	13	35	9	7	27	11	3	63	0.7	0.4	3	16	15	30	8	7	16	5	5	12
1	30	30	23	78	11	10	28	8	6	21	11	3	63	0.7	0.4	3	12	12	23	6	6	12	4	4	9
1	20	24	19	78	7	7	17	6	5	16	10	3	63	0.7	0.4	3	9	9	15	4	4	8	3	3	6
1	10	17	13	65	4	3	11	4	4	9	8	2	63	0.7	0.4	2	6	5	11	2	2	5	1	1	4
2	60	43	38	90	22	16	56	10	7	29	11	3	66	0.7	0.3	3	21	18	43	10	10	22	8	6	20
2	50	41	36	90	19	16	46	9	7	29	11	3	66	0.7	0.3	3	20	18	38	10	10	19	7	6	17
2	40	36	27	86	16	15	35	9	6	25	11	2	60	0.7	0.3	3	17	18	31	9	9	16	6	6	12
2	30	29	21	78	11	12	25	7	5	20	10	2	60	0.6	0.3	3	15	17	24	8	9	13	5	5	9
2	20	20	15	71	6	6	14	5	4	12	9	1	60	0.6	0.3	2	10	11	16	5	6	9	3	3	5
2	10	12	5	55	2	2	4	2	2	7	7	1	54	0.5	0.2	2	6	6	9	3	3	6	1	1	3
3	60	44	40	91	21	17	51	10	8	30	12	3	71	0.7	0.3	3	20	18	42	10	9	22	8	6	19
3	50	42	37	91	19	17	46	10	8	30	12	3	71	0.7	0.3	3	19	18	37	9	9	19	7	6	17
3	40	37	29	89	15	14	36	9	7	27	11	3	69	0.7	0.4	3	16	15	31	8	7	17	6	5	12
3	30	31	24	78	11	11	28	8	6	22	11	2	69	0.7	0.4	3	13	12	23	6	6	12	4	4	9
3	20	24	20	78	7	7	17	7	6	16	10	2	69	0.6	0.4	3	9	9	15	4	4	8	3	3	6
3	10	17	12	73	4	3	11	4	4	9	8	2	69	0.7	0.4	2	6	5	11	2	2	5	1	1	4
4	60	45	41	90	23	18	58	10	8	29	12	2	70	0.7	0.3	3	22	20	44	10	10	22	8	7	21
4	50	42	37	90	20	18	46	10	8	29	12	2	70	0.7	0.3	3	20	20	36	10	10	18	8	7	16
4	40	37	29	89	16	16	36	9	6	27	11	2	63	0.6	0.3	3	18	19	31	9	10	16	6	7	13
4	30	30	23	78	11	12	24	8	5	21	11	2	63	0.6	0.3	3	15	17	22	8	9	12	5	6	8
4	20	21	15	75	6	6	13	5	4	14	9	1	63	0.6	0.3	2	10	11	16	5	6	9	3	3	5
4	10	12	5	61	2	2	4	2	2	7	7	1	58	0.5	0.2	2	6	6	9	3	3	6	1	1	3

* concentration at the last treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-7

Concentrations of Individual THMs and HAAs at Alternate THAA MCLs
– SWTR w/o Alternate Disinfection –

reatment Code: w/o Alternate Disinfection
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

MCL (THAAs)	Trt. Code	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
		mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
60	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
60	2	46	41	105	22	17	58	10	9	30	13	3	69	0.7	0.4	3	21	17	46	10	9	24	8	6	21
60	3	44	41	90	21	17	51	10	8	30	12	3	69	0.7	0.3	3	20	17	43	10	10	22	8	6	20
60	4	43	39	90	21	16	51	10	8	30	12	3	69	0.7	0.3	3	19	17	43	9	8	22	7	6	20
50	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
50	2	45	41	105	21	17	51	10	8	30	13	3	69	0.7	0.4	3	20	17	44	10	9	24	8	6	19
50	3	43	39	90	20	17	45	10	8	30	12	3	69	0.7	0.3	3	19	17	38	9	10	19	7	6	17
50	4	41	37	90	19	16	45	10	7	30	12	3	69	0.7	0.3	3	19	17	38	9	8	19	7	6	17
40	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
40	2	42	37	90	20	15	51	10	8	27	12	3	63	0.7	0.4	3	19	17	44	10	8	24	7	6	19
40	3	39	35	89	17	15	40	9	7	27	12	3	63	0.7	0.3	3	17	17	33	9	9	18	6	6	14
40	4	36	28	89	15	13	35	9	7	27	11	3	63	0.7	0.4	3	16	15	30	8	7	16	5	5	12
30	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
30	2	40	36	89	19	14	51	9	8	23	12	3	63	0.7	0.3	3	19	17	44	10	8	24	7	5	19
30	3	35	30	78	15	13	35	8	7	21	11	3	63	0.7	0.3	3	16	15	33	8	8	17	5	5	14
30	4	30	23	78	11	10	28	8	6	21	11	3	63	0.7	0.4	3	12	12	23	6	6	12	4	4	9
20	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
20	2	39	34	84	18	13	51	9	8	22	11	3	63	0.7	0.3	3	18	15	44	9	8	24	6	5	19
20	3	31	26	78	13	11	35	7	7	16	10	3	63	0.6	0.3	3	14	12	33	7	6	17	5	4	14
20	4	24	19	78	7	7	17	6	5	16	10	3	63	0.7	0.4	3	9	9	15	4	4	8	3	3	6
10	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
10	2	38	34	79	18	12	51	9	7	22	11	3	63	0.6	0.3	2	18	14	44	9	8	24	6	4	19
10	3	28	25	70	11	7	35	7	6	15	10	3	63	0.6	0.2	2	13	9	33	6	5	17	4	3	14
10	4	17	13	65	4	3	11	4	4	9	8	2	63	0.7	0.4	2	6	5	11	2	2	5	1	1	4

concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-8

Concentrations of Individual THMs and HAAs at Alternate THAA MCLs
– SWTR w/ Alternate Disinfection –

reatment Code: w/ Alternate Disinfection

1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum dose + ozone
6 – pre-chlor + ammonia + alum dose + ozone + GAC

MCL	Trt.	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
(THAAs)	Code	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
60	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
60	2	46	41	105	22	17	58	10	9	30	13	3	69	0.7	0.4	3	21	17	46	10	9	24	8	6	21
60	3	43	38	90	22	16	56	10	7	29	11	3	66	0.7	0.3	3	21	18	43	10	10	22	6	6	20
60	4	43	38	90	22	16	56	10	7	29	11	3	66	0.7	0.3	3	21	18	43	10	10	22	6	6	20
60	5	43	38	90	22	16	56	10	7	29	11	3	66	0.7	0.3	3	21	18	43	10	10	22	6	6	20
60	6	43	38	90	22	16	56	10	7	29	11	3	66	0.7	0.3	3	21	18	43	10	10	22	6	6	20
50	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
50	2	45	41	105	21	17	51	10	8	30	13	3	69	0.7	0.4	3	20	17	44	10	9	24	8	6	19
50	3	42	37	90	20	16	50	9	7	29	11	3	66	0.7	0.3	3	20	18	40	10	10	20	8	6	18
50	4	41	36	90	19	16	46	9	7	29	11	3	66	0.7	0.3	3	20	18	38	10	10	19	7	6	17
50	5	41	36	90	19	16	46	9	7	29	11	3	66	0.7	0.3	3	20	18	38	10	10	19	7	6	17
50	6	41	36	90	19	16	46	9	7	29	11	3	66	0.7	0.3	3	20	18	38	10	10	19	7	6	17
40	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
40	2	42	37	90	20	15	51	10	8	27	12	3	63	0.7	0.4	3	19	17	44	10	8	24	7	6	19
40	3	38	30	86	17	15	40	9	7	25	11	2	60	0.7	0.3	3	18	18	35	9	10	18	7	6	14
40	4	36	27	86	16	15	35	9	6	25	11	2	60	0.7	0.3	3	18	18	31	9	9	16	6	6	12
40	5	36	27	86	16	15	35	9	6	25	11	2	60	0.7	0.3	3	17	18	31	9	9	16	6	6	12
40	6	36	27	86	16	15	35	9	6	25	11	2	60	0.7	0.3	3	17	18	31	9	9	16	6	6	12
30	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
30	2	40	36	89	19	14	51	9	8	23	12	3	63	0.7	0.3	3	19	17	44	10	8	24	7	5	19
30	3	34	26	78	15	13	35	8	6	20	10	2	60	0.6	0.3	3	17	17	35	9	9	17	6	6	14
30	4	30	22	78	12	12	28	7	5	20	10	2	60	0.6	0.3	3	15	17	24	8	9	13	5	5	10
30	5	30	22	78	12	12	28	7	5	20	10	2	60	0.6	0.3	3	15	17	24	8	9	13	5	5	9
30	6	29	21	78	11	12	25	7	5	20	10	2	60	0.6	0.3	3	15	17	24	8	9	13	5	5	9
20	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
20	2	39	34	84	18	13	51	9	8	22	11	3	63	0.7	0.3	3	18	15	44	9	8	24	6	5	19
20	3	29	23	78	13	11	34	6	5	15	9	1	60	0.6	0.2	3	16	15	35	8	8	17	6	5	14
20	4	23	19	71	8	7	19	5	4	12	9	1	60	0.6	0.2	2	13	13	24	7	7	13	4	4	9
20	5	22	18	71	7	7	15	5	4	12	9	1	60	0.6	0.2	2	12	13	20	6	7	11	4	4	7
20	6	20	15	71	6	6	14	5	4	12	9	1	60	0.6	0.3	2	10	11	16	5	6	9	3	3	5
10	1	55	46	173	30	16	113	11	9	31	13	4	72	0.8	0.4	3	24	17	80	11	8	31	11	6	38
10	2	38	34	79	18	12	51	9	7	22	11	3	63	0.6	0.3	2	18	14	44	9	8	24	6	4	19
10	3	26	20	71	12	8	34	5	4	12	8	1	54	0.5	0.2	2	16	15	35	8	8	17	5	5	14
10	4	18	14	58	6	5	19	4	3	8	7	1	54	0.4	0.1	2	12	10	24	6	5	13	3	3	9
10	5	15	11	55	5	3	13	3	3	7	7	1	54	0.4	0.1	2	10	8	20	5	4	11	3	2	7
10	6	12	5	55	2	2	4	2	2	7	7	1	54	0.5	0.2	2	6	6	9	3	3	6	1	1	3

concentration at each treatment tier of all systems: those meeting MCL and those not meeting MCL.

Exhibit C-9

Concentrations of Individual THMs and HAAs at Alternate THAA MCLs
– Enhanced SWTR w/o Alternate Disinfection –

eatment Code: w/o Alternate Disinfection
1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + modify alum dose
4 – pre-chlor + alum dose + GAC

MCL	Trt.	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
THAAs)	Code	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
60	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
60	2	48	42	109	23	17	60	11	9	30	13	3	71	0.7	0.4	3	21	18	47	10	10	25	8	7	21
60	3	45	42	91	22	17	51	11	9	30	12	3	71	0.7	0.3	3	20	18	42	10	10	22	8	7	19
60	4	44	40	91	21	17	51	10	8	30	12	3	71	0.7	0.3	3	20	18	42	10	9	22	8	6	19
50	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
50	2	46	39	109	22	17	51	11	8	30	13	3	71	0.7	0.4	3	21	18	45	10	10	25	8	7	19
50	3	43	38	91	20	17	46	10	8	30	12	3	71	0.7	0.3	3	19	18	37	9	10	19	7	7	17
50	4	42	37	91	19	17	46	10	8	30	12	3	71	0.7	0.3	3	19	18	37	9	9	19	7	6	17
40	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
40	2	44	37	90	21	17	51	10	8	27	12	3	69	0.7	0.4	3	20	18	45	10	9	25	7	6	19
40	3	40	35	89	18	17	41	10	7	27	12	3	69	0.7	0.3	3	18	18	34	9	9	18	6	6	15
40	4	37	29	89	15	14	36	9	7	27	11	3	69	0.7	0.4	3	16	15	31	8	7	17	6	5	12
30	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
30	2	42	37	89	20	16	51	10	8	26	12	3	69	0.7	0.3	3	19	18	45	10	9	25	7	6	19
30	3	36	30	78	15	13	40	9	7	22	11	3	69	0.6	0.3	3	16	16	34	8	8	17	5	5	15
30	4	31	24	78	11	11	28	8	6	22	11	2	69	0.7	0.4	3	13	12	23	6	6	12	4	4	9
20	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
20	2	40	36	89	19	13	51	9	8	23	12	3	69	0.6	0.3	3	19	15	45	10	8	25	7	5	19
20	3	32	25	78	13	11	40	8	7	18	11	3	69	0.6	0.3	3	14	13	34	7	6	17	5	4	15
20	4	24	20	78	7	7	17	7	6	16	10	2	69	0.6	0.4	3	9	9	15	4	4	8	3	3	6
10	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
10	2	39	36	82	18	13	51	9	8	23	11	3	69	0.6	0.3	2	19	15	45	9	8	25	7	5	19
10	3	28	24	73	11	6	40	7	6	15	10	2	69	0.5	0.2	2	13	9	34	6	5	17	4	2	15
10	4	17	12	73	4	3	11	4	4	9	8	2	69	0.7	0.4	2	6	5	11	2	2	5	1	1	4

concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL

Exhibit C-10

Concentrations of Individual THMs and HAAs at Alternate THAA MCLs
– Enhanced SWTR w/ Alternate Disinfection –

Treatment Code: w/ Alternate Disinfection

1 – not requiring further treatment modification
2 – eliminate pre-chlorination
3 – eliminate pre-chlor + add ammonia
4 – pre-chlor + ammonia + alum dose
5 – pre-chlor + ammonia + alum dose + ozone
6 – pre-chlor + ammonia + alum dose + ozone + GAC

MCL (THAAs)	Trt. Code	Concentrations of By-Products (µg/L) (Average Customer)*																							
		TTHMs			Chloroform			Bromodichloromethane			Dibromochloromethane			Bromoform			THAAs			DCAA			TCAA		
		mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th	mean	median	95th
60	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
60	2	48	42	109	23	17	60	11	9	30	13	3	71	0.7	0.4	3	21	18	47	10	10	25	8	7	21
60	3	46	42	93	24	18	60	10	8	29	12	2	70	0.7	0.3	3	22	20	45	11	10	23	9	7	21
60	4	45	41	90	23	18	58	10	8	29	12	2	70	0.7	0.3	3	22	20	44	10	10	22	8	7	21
60	5	45	41	90	23	18	58	10	8	29	12	2	70	0.7	0.3	3	22	20	44	10	10	22	8	7	21
60	6	45	41	90	23	18	58	10	8	29	12	2	70	0.7	0.3	3	22	20	44	10	10	22	8	7	21
50	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
50	2	46	39	109	22	17	51	11	8	30	13	3	71	0.7	0.4	3	21	18	45	10	10	25	8	7	19
50	3	44	39	93	22	18	50	10	8	29	12	2	70	0.7	0.3	3	21	20	39	10	10	20	8	7	19
50	4	43	38	90	21	18	46	10	8	29	12	2	70	0.7	0.3	3	20	20	37	10	10	18	8	7	16
50	5	42	37	90	20	18	46	10	8	29	12	2	70	0.7	0.3	3	20	20	36	10	10	18	8	7	16
50	6	42	37	90	20	18	46	10	8	29	12	2	70	0.7	0.3	3	20	20	36	10	10	18	8	7	16
40	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
40	2	44	37	90	21	17	51	10	8	27	12	3	69	0.7	0.4	3	20	18	45	10	9	25	7	6	19
40	3	41	36	90	20	17	45	9	7	27	11	2	63	0.6	0.3	3	20	19	36	10	10	18	7	7	15
40	4	38	29	89	17	16	37	9	6	27	11	2	63	0.6	0.3	3	18	19	32	9	10	17	7	7	13
40	5	37	29	89	16	16	36	9	6	27	11	2	63	0.6	0.3	3	18	19	31	9	10	16	6	7	13
40	6	37	29	89	16	16	36	9	6	27	11	2	63	0.6	0.3	3	18	19	31	9	10	16	6	7	13
30	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
30	2	42	37	89	20	16	51	10	8	26	12	3	69	0.7	0.3	3	19	18	45	10	9	25	7	6	19
30	3	37	30	86	18	16	45	8	7	21	11	2	63	0.6	0.3	3	19	19	36	9	10	18	7	6	15
30	4	32	25	78	13	12	28	8	6	21	11	2	63	0.6	0.3	3	16	17	27	8	9	14	5	6	11
30	5	30	23	78	11	12	25	8	5	21	11	2	63	0.6	0.3	3	15	17	23	8	9	12	5	6	9
30	6	30	23	78	11	12	24	8	5	21	11	2	63	0.6	0.3	3	15	17	22	8	9	12	5	6	8
20	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
20	2	40	36	89	19	13	51	9	8	23	12	3	69	0.6	0.3	3	19	15	45	10	8	25	7	5	19
20	3	33	25	82	16	13	45	7	6	18	10	2	63	0.6	0.2	3	18	17	36	9	9	18	6	6	15
20	4	26	20	75	10	9	23	6	5	15	9	2	63	0.5	0.2	2	14	14	27	7	7	14	5	4	11
20	5	23	17	75	7	7	15	6	4	14	9	1	63	0.5	0.2	2	12	13	20	6	7	11	4	4	7
20	6	21	15	75	6	6	13	5	4	14	9	1	63	0.6	0.3	2	10	11	16	5	6	9	3	3	5
10	1	57	49	173	31	17	114	12	9	31	14	4	72	0.7	0.4	3	25	18	80	11	8	31	11	7	38
10	2	39	36	82	18	13	51	9	8	23	11	3	69	0.6	0.3	2	19	15	45	9	8	25	7	5	19
10	3	31	24	79	15	10	45	6	5	17	9	1	58	0.5	0.2	2	18	17	36	9	9	18	6	6	15
10	4	21	16	71	8	5	23	5	4	10	8	1	58	0.4	0.2	2	13	11	27	7	6	14	4	3	11
10	5	16	10	61	5	3	13	3	3	8	7	1	58	0.4	0.1	2	10	8	20	5	4	11	3	2	7
10	6	12	5	61	2	2	4	2	2	7	7	1	58	0.5	0.2	2	6	6	9	3	3	6	1	1	3

* concentration at each treatment tier of all systems; those meeting MCL and those not meeting MCL