QUESTIONS REGARDING DRINKING WATER DISINFECTION
Updated August, 2010

Q: Why are disinfectants added to the water?
A: Untreated surface water is vulnerable to contamination by bacteria, viruses and parasites that may cause human illness. These disease-causing microorganisms are also referred to as pathogens. Standards have been developed within the US and elsewhere in the world defining minimum standards of disinfection to protect against contamination by pathogens.
In the US, all drinking water suppliers using surface water are required by the U.S. Environmental Protection Agency (USEPA) to use disinfectants to inactivate pathogenic microorganisms in drinking water. Currently, chlorine, chloramine, ozone, chlorine dioxide and ultraviolet (UV) light are approved by the USEPA for disinfection during treatment (termed primary disinfection) (USEPA, 1989a; USEPA 2006b). Utilities must also maintain a smaller amount of disinfectant throughout the drinking water distribution system to limit bacterial growth (termed “residual” or secondary disinfection). Currently, chlorine, chloramine, and chlorine dioxide are approved by the USEPA for disinfection in the distribution systems. Chlorine dioxide is sometimes used for distribution system disinfection in smaller systems. Large systems typically do not use chlorine dioxide for distribution system disinfection because chlorine dioxide, like chlorine, is a strong oxidant and will not reach the most distant points in a large distribution system. Large water systems like the SFPUC must therefore choose between chlorine and chloramine for distribution system disinfection.
The USEPA’s Stage 1 Disinfectants/Disinfection Byproducts Rule (Stage 1 D/DBPR) limits concentrations of disinfectants by establishing a Maximum Residual Disinfectant Level (MRDL) of 4 mg/L Cl_2 for chlorine and chloramine (USEPA, 1998). Water provided by the SFPUC meets all Federal and State drinking water regulations. Pathogens are controlled by watershed protection, disinfection with chlorine or ozone plus chlorine during treatment, distribution system disinfection with chloramine, cross-connection control, and other water quality maintenance practices.

Q: What is the sequence of disinfectants applied at SFPUC for control of pathogenic microorganisms?
A: First, a strong disinfectant/oxidant is applied during water treatment for killing pathogens that might be present in the source water. SFPUC uses ozone and/or chlorine for this primary disinfection process. Beginning in 2011, UV light will be implemented for primary disinfection of Hetch Hetchy water source in addition to chlorine. Second, chloramine is formed to prevent microorganisms from growing in the pipes, which distribute water to the customers. Many large water systems with extensive service areas use chloramine instead of chlorine for distribution system disinfection because chloramine is less reactive and longer lasting in providing disinfection protection.

Q: What disinfection processes are available?
A: **Both chlorine and chloramine are proven disinfectants with considerable operating experience. Chlorine and chloramine are approved disinfectants, in addition to chlorine dioxide, ozone, and most recently ultraviolet light (UV) (USEPA 1989a, 2006b).**
Each of these approved disinfectants has advantages and disadvantages in terms of: (1) disinfecting effectiveness for specific microorganisms, (2) reactivity with natural organic matter and associated formation of disinfection by-products (DBPs), (3) formation of inorganic DBPs (e.g., bromate, chlorate, chlorite), and (4) disinfectant persistence to provide lasting protection in the pipes and water storage reservoirs of the distribution system. Chlorine dioxide, ozone and UV cannot be used for secondary disinfection because of limited or no residual disinfectant provided by these processes. Chlorine dioxide is used by some utilities for secondary disinfection in the distribution system but this disinfectant has several drawbacks: (1) formation of chlorite which is regulated by the USEPA (1998), (2) possibility of creating "cat-urine" odors in customer homes, (3) greater reactivity and, therefore, lower persistence in the distribution system, and (4) high cost

(USEPA, 1999).
The SFPUC continues to evaluate disinfection processes such as the planned use of UV light disinfection to augment chlorination and chloramination for the Hetch Hetchy source water to meet new drinking water regulations (i.e., the Long Term 2 Enhanced Surface Water Treatment Rule (USEPA, 2006b)). Potential disease-causing organisms (e.g., *Cryptosporidium)* have been found in the last 10 years to be resistant to chlorine disinfection but very sensitive to ultraviolet (UV) light. Consequently, the water industry is beginning to implement combinations of disinfectants (including UV light) to provide stronger defense against a variety of potential disease-causing microorganisms (Trussell, 2006). SFPUC has implemented a combination of disinfectants, chlorine followed by chloramine, to better disinfect the water. In the future, other disinfectants may be added to continually improve the disinfection process, meet future regulations and better serve SFPUC customers. For example, SFPUC plans on implementing UV disinfection for Hetch Hetchy water beginning in 2011, in addition to existing chlorination and chloramination. This project is estimated to cost approximately $121 million, including construction and project delivery costs, and will provide additional barrier against microbial contamination.

Q: Why is disinfection important?
A: Disinfection is proven to stop and prevent disease. Just a hundred years ago, waterborne typhoid fewer was a leading cause of death in the United States. Less than fifty years before that, the major cities in Europe and North America were ravaged by waterborne cholera (Morris, 2007). The importance of disinfection is exemplified by the dramatic reductions in typhoid in the early 20th century after widespread implementation of water treatment, including drinking water disinfection practices. In addition, when disinfection is discontinued due to operational failures, disease outbreaks have occurred. For example, an outbreak of E. Coli 0157:H7 occurred in Canada when chlorination of wells was interrupted (O'Connor, 2002).
Chemical disinfection became an integral part of municipal drinking water treatment over 100 years ago as a vital means for protection of public health. By the late 1880s it was clear that a number of important epidemic diseases were often waterborne, cholera, typhoid fever, and amoebic dysentery, among them. The twentieth century began with the development of continuous chlorination as a means for bacteriological control (Crittenden et al., 2005). McGuire (2006) listed "eight revolutions in the history of North American drinking water disinfection":

1) Application of chlorine for full-scale disinfection in Jersey City, NJ, in 1907. It took a court dispute and a legal deadline to clear away the objections and to apply what was until then only an experimental treatment method. Chemical treatment was involved and popular prejudice against its use was strong.
2) In 1914, the Secretary of Treasury established a standard for the coliform bacteria concentration in each sample.
3) In 1917 in Ottawa, Ontario, a combination of chlorine and ammonia was implemented to produce chloramine to solve taste and odor problems related to chlorine. The ammonia-chlorine process also produced stable chlorine residuals that persisted far into the distribution system. Denver Water has used the ammonia-chlorine process continuously since 1917. Chloramine disinfection was also applied in San Francisco prior to World War II (SFPUC, 1941). In Southern California in 1941, when the Colorado River water was first imported, chloramine was necessary to ensure that a residual could be maintained in the furthest reaches of the distribution system.
4) The discovery in 1974 of trihalomethanes (THMs) and the resulting regulation in 1979 limited THM levels to 100 ug/L (micrograms per liter, equivalent to ppb, or parts per billion). THMs are organic compounds produced from the chlorination of natural organic matter in drinking water, considered probable carcinogens. Subsequent to the identification of THMs, many other organic and inorganic "disinfection by-products" (DBP) have been discovered (Krasner et al., 2006).
5) Application of the product of C x T concept (disinfectant concentration C after the contact time T) in 1989 to be achieved during treatment of surface waters on a daily basis. The target

organisms of USEPA Surface Water Treatment Rule (SWTR) were viruses and the protozoan microorganism *Giardia lamblia* (USEPA, 1989a).

6) The change in focus from coliform bacteria concentration to presence-absence in no more than 5% positive coliform samples in any monthly set of distribution system samples, as mandated in 1989 by the USEPA Total Coliform Rule (TCR, USEPA, 1989b).
7) Regulations balancing the risk from microbial contamination and risks of disease from the disinfection by-products (DBPs): in 1998 Stage 1 Disinfectant/DBP Rule (USEPA, 1998) and in 2006 Stage 2 Disinfectant/DBP Rule (USEPA, 2006a). These two rules added new regulated DBPs and attempted to minimize peak concentrations of these compounds in the distribution system.
8) The cryptosporidiosis outbreak in Milwaukee, WI, in 1993 resulted in the promulgation in 2006 of the USEPA Long Term 2 Enhanced SWTR (USEPA, 2006b) specifying the degree of inactivation of protozoan microorganism *Cryptosporidium* or other protective measures to reduce the likelihood of an outbreak of cryptosporidiosis. The discovery in 1996 that ultraviolet light (UV) can economically disinfect *Cryptosporidium*, *Giardia*, and other pathogens will dramatically change how water is disinfected in the United States.

Within six years of implementing chlorination in Jersey City, half of the water treatment plants in the United States were using chlorine to disinfect water. By 1924 three thousand cities had turned to chlorine. The occurrence of serious waterborne diseases declined and diseases like cholera, typhoid and amoebic dysentery which had been common became rare. In 1900 an average American had a 5 percent chance of dying of a gastrointestinal infection before the age of seventy. By 1940 that likelihood had dropped to 0.03 percent and by 1990 it had fallen to about 0.00005 percent (Morris, 2007). Evidence clearly demonstrates that implementing disinfection has reduced waterborne disease and that failures in disinfection can result in increased levels of disease.

Q: What is chloramine?

A: Chloramine is a disinfectant added to water for public health protection. It is a combination of chlorine and ammonia that is currently considered best technology for controlling the formation of certain regulated organic disinfection byproducts. Chloramine is formed at the SFPUC treatment plants following treatment with ozone (at one SFPUC treatment plant) and with chlorine (at all SFPUC treatment plants). Chloramine is used as a distribution system disinfectant.

The SFPUC began using chloramine for distribution system disinfection for the second time in its history in February 2004. The SFPUC had used chloramine for disinfection from 1935 to 1944 (SFPUC Annual Reports; White, 1999) but stopped during WW II due to ammonia shortages. Chloramine is formed at the treatment plants by combining chlorine and ammonia at a weight ratio of 5:1 or slightly less – this maximizes formation of monochloramine, which is not volatile. Initially, for a few weeks early in 2004, chloramine target was as high as 3.5 mg/L Cl_2, and was subsequently decreased to 2.3 mg/L Cl_2. The current chloramine target concentration in the SFPUC system is 2.3 mg/L Cl_2 in plant effluent and slightly less in the distribution system. In the past, before chloramine was used in the SFPUC distribution system, the levels of chlorine in plant effluents ranged from 1.0 to 1.5 mg/L Cl_2. Thus chloramine levels are relatively higher than chlorine. Although chloramine is less reactive than chlorine and more stable from a practical water supply point of view, it is not a persistent chemical and eventually breaks down by itself (Valentine, 1998). Chloramine does not bioaccumulate or transfers up the food chain (Environment Canada, 2002).

Q: What is the history of chlorine and chloramine use for drinking water disinfection in the United States?
A: Both chlorine and chloramine have been used for disinfection for about the same length of time. The first regular use of chlorination in the United States was in 1908 (AWWA, 1998). It actually required a court dispute and a legal deadline to clear away the objections for applying chlorine (McGuire, 2006). By 1917, chlorine disinfection was adopted by hundreds of US water utilities and issues emerged with chlorine taste and odor. Chlorine readily combines with phenol to produce a wide variety of chlorophenols that at low concentrations impart a strong medicinal odor to water. In addition, chlorine itself has a significant, penetrating, and disagreeable odor (McGuire, 2006).
In 1917 in Ottawa, Ont., a combination of ammonia and chlorine was implemented to solve flavor and odor problems related to chlorine (McGuire, 2006). Chloramine has been used for disinfection in the United States since that time (USEPA, 1999; Kirmeyer et al, 2004). Chloramination enjoyed its greatest popularity between 1929 and 1939. In 1938, based upon replies to a questionnaire from 2,541 water suppliers in 36 states, 407 utilities reported using ammonia with chlorine. Denver, CO, has used a chloramination process continuously since 1917 (McGuire, 2006). The San Francisco Hetch Hetchy Aqueduct was chloraminated from 1935 until the ammonia supply became scarce during World War II in 1944 (SFPUC, 1941; White, 1999). The Metropolitan Water District of Southern California (MWDSC) implemented the use of chloramination in 1941 when Colorado River water was first delivered to Southern California. Chloramine disinfection was used so that a sufficient residual could be carried to the furthest reaches of the MWDSC distribution system (McGuire, 2006).
A survey in 1938 (AWWA, 1941) indicated that 33 of 36 surveyed states had a least one water supply that used chloramine. In California, 190 water supplies were reported to use chlorine and 35 chloramine, which was the second largest use of chloramine in any state after New York, where 69 water supplies were chloraminated. By 1936, 16% of all U.S. water treatment facilities were using chloramine. Due to the scarcity of ammonia during World War II use of chloramine declined until 1960s to a low of 2.6% facilities. After the enactment of the Federal Safe Drinking Water Act (SDWA) by the US Congress in 1974 and its subsequent Amendments, interest in using chloramine was renewed due to increasing focus on microbiological safety and reduction of DBPs. About 20% of treatment facilities used chloramine in 1990 (Kirmeyer et al., 2004). In 1996, approximately 6.9 million Canadians were supplied with chloraminated drinking water (Environment Canada, 2001). Many utilities in California serving a total population of over 20 million have been using chloramine for over 20 years. Chloramine is used worldwide on four continents.

Q: What is the history of chloramine application by SFPUC? A: Chloramine was successfully applied at SFPUC for control of biofilm in the tunnels and pipelines as well as in the distribution system to improve water quality for about 10 years after Hetch Hetchy supply was first introduced into the system, from 1935 through 1944.
Hetch Hetchy water was first delivered from the Sierra Nevada Mountains to Crystal Springs Reservoir in San Mateo County on October 28, 1934. The most serious issue for the Water Department when the Hetch Hetchy supply was first delivered was the appearance of *Crenothrix*, an iron bacteria. These non-pathogenic bacteria formed a “slimy growth” in the aqueduct impacting water flows and causing an objectionable taste. Testing was performed to control *Crenothrix* (SFPUC, 1935). From October 28, 1934 until June 6, 1935, the Hetch Hetchy water was chlorinated with a portable chlorinating unit. On June 6, 1935, a new permanent chlorinator started operation at the Irvington Portal. On June 15, 1935, an ammoniator was installed at Irvington to control the growth of *Crenothrix*.
Crenothrix in the Hetch Hetchy Aqueduct continued to be the most serious problem confronting the Water Department in 1935/1936 (SFPUC, 1937). Inspection revealed 1/8-inch slimy growth, which decreased the water flow, imparted taste and odor, and decreased dissolved oxygen in Hetch Hetchy water by 50%. Treatment with chlorine and ammonia (since June 17, 1935) at Irvington Portal had been most effective in removing the growth inside the entire Bay Crossing Pipeline, and did not generate taste or odor. A similar chlorine and ammonia facility was

designed for Tesla Portal (at the entrance to the Coast Range Tunnel). There were 19 chlorinators and 3 ammoniators installed that year at 11 different locations. An ammoniator was also installed at College Hill Reservoir to overcome algal taste due to algae growth in this open reservoir and to reduce stagnation in the dead ends of the distribution system, which was the cause of customer complaints (SFPUC, 1937).

The new chloramination station located at Tesla Portal was completed on the Hetch Hetchy Aqueduct in FY1936/1937 and reported to be the largest chloramine treatment plant in the world at the time. There were a total of 23 chlorinators and 6 ammoniators at 12 different stations throughout the system. Chlorine and ammonia treatment of Calaveras water was initiated at the reservoir outlet on October 29, 1936 and determined effective for *Crenothrix* control (SFPUC, 1938).

Nelson A. Eckart, General Manager and Chief Engineer of the San Francisco Water Department reported in 1940 (Eckart, 1940) that chlorination and ammoniation reduced raw water bacteria from 12-15% positive for coliform organisms to 0-1.4 %, well under the 10% allowable under federal requirements of the day. Dosages averaged 0.3 mg/L, with chlorine to ammonia ratio of 5:1 (Eckart, 1940).

Disinfection practice changed at SFPUC between 1942 and 1944 as a result of World War II: higher dose of chlorine was applied, primarily at Tesla and Calaveras and fewer disinfection stations were in operation. Biofilm control in the tunnels and pipelines was provided by either chlorination or chloramination (SFPUC, 1943a and 1943b). Chloramination was discontinued some time in 1944 due to ammonia shortages. High chlorine doses were needed for biofilm control (SFPUC 1947) and to maintain adequate chlorine residuals (SFPUC, 1949).

Q: What is the history of regulatory approval of chloramine?

A: Chloramine has been used as a municipal drinking water disinfectant for over 90 years. Chloramine is an approved treatment and distribution system disinfectant by the USEPA (USEPA, 1990). The World Health Organization (WHO, 1996) states that chloramine is useful for maintaining a disinfectant in distribution systems.

The Stage 1 Disinfectant and Disinfection By-Product Rule (USEPA, 1998) established maximum residual disinfectant levels for chlorine and chloramine of 4 mg/L Cl_2 in the distribution system. Residuals higher than 4 mg/L Cl_2 levels of chlorine or chloramine are allowed for short-term distribution system disinfection.

The use of chloramine as a disinfection agent, when compared to chlorine, reduces the formation of disinfection byproducts (DBPs). The reduction in DBPs is an improvement in public health protection. DBPs are currently regulated by the USEPA under Stage 1 and Stage 2 D/DBP Rules (USEPA, 1998 and 2006a). The Surface Water Treatment Rule (USEPA, 1989a), SWTR, established the C x T values (concentration, C, after given contact time, T, with the disinfectant) required for disinfection of *Giardia* and viruses during treatment with chlorine, chloramine, ozone, or chlorine dioxide. The SWTR also established that the minimum disinfectant residual should be detectable in the distribution system for either chlorine or chloramine.

Q: What is the current and future use of chloramine for drinking water disinfection?

A: Chloramine is a proven disinfectant used extensively in the Bay Area, California, across the US and worldwide. Most major utilities in California use chloramine as a final drinking water disinfectant. In the Bay Area, Santa Clara Valley Water District (since 1984), Contra Costa Water District (since 1981), Alameda County Water District (since 1985), Marin Municipal Water District (since 1995), Zone 7 Water Agency in Livermore, Pleasanton and Dublin (since 1990) and the East Bay Municipal Utility District (since 1998) have provided chloraminated water to their customers. The Metropolitan Water District of Southern California has provided chloraminated water in the 1940's and then again since the mid 1980s and the City of San Diego since 1982. More than one in five Americans use drinking water treated with chloramine. (USEPA, 2009)

USEPA's Information Collection Rule data (2002) indicated that of 353 treatment plants examined 34.7% of the systems used chloramine with some combination of chlorine pretreatment, while

11.5% of the systems used chloramine with chlorine dioxide or ozone pretreatment.
Seidel et al. (2005) conducted the most recent chloramine survey in 2004 (363 utilities from 50 states responded to the survey, including SFPUC) with the following results: 29% of community water systems used chloramine for secondary disinfection and another 3% were in the process of switching to chloramination, about 12% contemplated the switch in the near future. The proportion of utility respondents that intended to or considered switch to chloramine, increased with system size. More than 25% of utility respondents that served more than 100,000 customers indicated that they intended to or seriously considered switch to chloramine.
The reported median target chloramine concentrations were 2.7 mg/L at the plant effluent location, 2.0 mg/L at the distribution system average residence time location, and 1.0 mg/L at the distribution system maximum residence time location (Seidel et al., 2005).
In 2007, the AWWA Disinfection Systems Committee conducted its fourth survey of drinking water disinfection practices. Chlorine gas remained the predominant disinfectant; however its use decreased from 70% of all surveyed systems in 1998 to 63% of respondents in 2007 because many utilities changed from gas to bulk liquid chlorine and on-site generation. Use rates of chloramine (30%), chlorine dioxide (8%), ozone (9%), and ultraviolet light (2%) increased from the prior 1998 survey (AWWA, 2008a). The planned future changes to free chlorine alternatives were estimated as follows: 10% of respondents planned change to chloramine, 16% planned to add UV, 7% planned to add ozone, and 4% chlorine dioxide (AWWA, 2008b).

Q: What are the types of chloramines that can be formed under special circumstances?
A: There are three inorganic chloramines that can be theoretically formed under different conditions of water pH and/or chlorine to ammonia weight ratio: monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine (NCl_3). Under the conditions existing in full-scale drinking water distribution systems at pH values above 8 (pH in the SFPUC system varies between 8.6 and 9.4, depending on the water source) and chlorine to ammonia weight ratios of 5:1 or below, monochloramine is the only observed chloramine species (100%).
While not formed in the SFPUC system, dichloramine and trichloramine could be formed if the SFPUC were to significantly increase the chlorine to ammonia ratios and lower pH values. Above pH 7.5, trichloramine is not detectable at any chlorine to ammonia ratios (USEPA, 1994; White, 1999; Environment Canada, 2001).
While dichloramine and trichloramine likely have good disinfecting capabilities, they cause taste and odor. In addition, they are much less stable than monochloramine; therefore, their formation should be avoided. Trichloramine, which in its pure form is very volatile and pungent, cannot exist in chloraminated water systems without the presence of chlorine and it has been known to form in the chlorinated distribution systems long after leaving the treatment plant. This situation is corrected by converting the chlorine residual to monochloramine (White, 1999).
Trichloramine may occur during the practice of “breakpoint chlorination” (i.e., when excess amounts of chlorine are added to the water containing chloramine and/or ammonia to develop chlorine residual). Trichloramine may form in swimming pools if pH and chlorine dose are not properly maintained. It is also a nuisance chemical in wastewater treatment. It is so volatile and unstable that is it difficult to quantify by analytical methods (White, 1999).
Small amounts of organic chloramines may also form in chlorinated or chloraminated water if certain organic nitrogen compounds, including amino acids and nitrogen heterocyclic aromatics, are present (Environment Canada, 2001; White, 1999, Lee and Westerhoff, 2009). Chlorine forms organochloramines almost instantaneously, whereas monochloramine reacts slower. With very few exceptions, all organochloramines are nongermicidal and nontoxic to aquatic life (White, 1999, Amiri et al., 2010). Experience indicates that trace levels of organochloramines can be formed in all treated natural waters. Available data indicate that inorganic monochloramine is predominant chloramine in SFPUC system.

Throughout this document, the term chloramine refers to monochloramine. Where it is important to distinguish between monochloramine, dichloramine, and trichloramine, the specific terms are used. Due to concerns expressed by some customers about the potential presence of dichloramine and trichloramine in our chloraminated distribution system, SFPUC requested an independent opinion on chloramine speciation. The opinion by a recognized chemistry expert can be found on SFPUC website at http://sfwater.org/detail.cfm/MC_ID/13/MSC_ID/166/MTO_ID/399/C_ID/3408.

Q: What was the reason for changing distribution system disinfectant from chlorine to chloramine at SFPUC as well as at many other water utilities?
A: Two properties of chloramine enable the SFPUC to minimize potential for microbial contamination and comply with Federal regulations. First, because chloramine is longer lasting than chlorine, it helps achieve compliance with the Surface Water Treatment Rule. Second, chloramine forms much lower levels of regulated DBPs than chlorine, thus enabling compliance with Federal rules governing DBPs.
The SFPUC implemented chloramination in the distribution system in February 2004. The primary driver for changing the distribution system disinfectant from chlorine to chloramine was to reduce the formation of trihalomethanes (THMs) and haloacetic acids (HAAs). In the late 1970s and early 1980s it was discovered that chlorine reacts with naturally occurring organic matter to form THMs, HAAs and other disinfection by-products (DBPs). Subsequent research showed that exposure to THMs over a lifetime may statistically increase the rates of some cancers. To protect public health, the USEPA began regulating four THMs in 1979, with a maximum contaminant level (MCL) of 100 ug/L (or one hundred parts per billion). Chloramine reduces the formation of these potentially carcinogenic DBPs and therefore makes water safer for human consumption. In 1998 (USEPA, 1998), the MCL for four THMs was further reduced to 80 ug/L and new MCLs were promulgated by the USEPA for five haloacetic acids (60 ug/L HAA) and other inorganic DBPs bromate (resulting from ozonation) and chlorite (resulting from chlorine dioxide application).
The choice of disinfectant(s) depends on many factors. Utilities must balance many considerations to simultaneously fulfill the requirements of numerous drinking water quality regulations. The change of disinfectants or treatment process is always preceded by careful planning, testing, and review of similar practices at other water utilities. In California, the application of any proven or new drinking water treatment processes must be approved by the California Department of Public Health (CDPH), a primacy agency for the State of California, to assure the compliance of public water systems with the requirements of the Safe Drinking Water Act (SDWA) and its Amendments. Chloramination is not simply an add-on process at the end of the treatment plant but must be fully integrated into the design and the operation of the water treatment facilities and the distribution system (Kirmeyer et al., 2004).

Q: What are the benefits of using chloramine instead of chlorine in the distribution system?
A: The benefits of chloramine compared with chlorine for distribution system disinfection are: (1) longer lasting disinfectant and ability to reach remote areas, (2) effectiveness as a disinfectant for biofilms, (3) tendency to form lower levels of regulated DBPs (e.g., THMs and HAAs), which are probable carcinogens (USEPA, 1998), and (4) ability to minimize chlorinous or other objectionable taste and odors.
Chloramine is more stable and lasts longer in the water in the distribution system because it is less reactive than chlorine. The water agencies that have converted to chloramine report that customers note an improvement to flavor of the water. Research on the taste-and-odor quality of drinking water has demonstrated the benefits of monochloramine over chlorine. The San Francisco Public Utilities Commission's (SFPUC's) change to chloramine helps ensure compliance with more stringent federal and state drinking water quality regulations. In San Francisco, chloramination has virtually eliminated the presence of *Legionella* species in large building hot water heaters (Flannery et al., 2006).

Q: What are the drawbacks of using chloramine instead of chlorine in the distribution system?
A: The drawbacks of using chloramine compared with chlorine for distribution system disinfection are: (1) potential temporary deleterious effects on older elastomeric materials sometimes used in some home appurtenances and plumbing fixtures, (2) vulnerability to the microbiological process known as nitrification, (3) potential formation of chloramine related DBPs if precursor material is present in the source water (Kirmeyer et al., 2004).
The treatment precautions for hemodialysis clinics and fish cultures must be taken both with chlorine and with chloramine (Amato, 2005). Certain natural rubber products and their derivatives used in household appliances (e.g., toilet tank valves, hot water heater dip tubes) will deteriorate faster with chloramine than with chlorine (Reiber, 1993). If such effects are experienced, replacing these items with alternative materials available in the plumbing and hardware stores will eliminate this temporary nuisance rubber deterioration. Chlorine tablets for toilet water tanks may significantly increase the corrosion of submerged rubber parts in these appliances and plumbers typically do not recommend their use.
Vulnerability of chloramine to nitrification can be remedied by several practices, including: a) reducing the detention time of water in the drinking water storage reservoirs and low-use pipelines, b) keeping the system clean of deposits, which may harbor bacteria, c) flushing when necessary, and d) monitoring the system. All these actions have an additional benefit for customers by providing fresher, shorter "shelf age" water. Typically, a change to chloramine has been preceded and followed by distribution system capital improvements aimed at decreasing water age such as: seasonal or permanent outages of water tanks, improving mixing within the tanks, redesign of pressure zones for better interconnectivity, changing pumping schedules to improve stored water turnover, or installation of new water quality monitoring stations (Wilczak et al., 1996, Odell et al., 1996; AWWA 2006a).

Q: What is nitrification and how does it impact water quality?
A: Nitrification is a microbial process by which ammonia is sequentially oxidized to nitrite and nitrate ions. In extreme cases, nitrification may cause a depletion of chloramine disinfectant thus allowing bacterial regrowth.
Every utility using chloramine needs to assess nitrification potential and implement proper control measures. Nitrite and nitrate ions produced due to nitrification are of no water quality significance in SFPUC system. Other impacts of nitrification may include some decrease in alkalinity, pH, and dissolved oxygen (Wilczak et al., 1996; Kirmeyer et al. 2004).
Nitrification is a utility operational issue and does not pose any health concerns. Nitrification results from metabolism and growth of harmless non-pathogenic nitrifying bacteria that are ubiquitous in soils and water. Utilities implement operational control measures, including decreased water age and enhanced monitoring to limit the extent of nitrification (AWWA, 2006a). After this optimization period the customers benefit from fresher water that was stored for a shorter period of time in the distribution system. Nitrification can sometimes increase soluble lead contamination of potable water by reducing pH (Zhang et al. 2009). SFPUC has implemented a vigorous nitrification monitoring and control program and has been successful in controlling the nitrifying bacteria and maintain stable pH in our system.
For example, nitrification occurred in two small fire storage tanks in San Francisco due to a long water detention time in these facilities. SFPUC has already redesigned piping in these storage tanks thereby completely eliminating nitrification at these sites. No nitrification was observed in any of the large water storage reservoirs in San Francisco in six years after chloramine conversion, likely due to a combination of low water temperature and large solar-powered water mixers installed in these facilities, which eliminated any stagnation. In the fall of 2009 SFPUC started addition of a small amount of chlorine to a pipeline serving water to Treasure Island to control nitrification.

Q: What are the disinfecting properties of chloramine as compared with chlorine?
A: Chlorine is a stronger oxidant/disinfectant than chloramine and acts more rapidly as a primary disinfectant (e.g. to inactivate pathogenic microorganisms). Chloramine lasts

longer than chlorine as a residual disinfectant. These differences account for how the SFPUC uses each in combination.

Disinfection of pathogens is achieved by holding a target microorganism in contact with a minimum level of chemical disinfectant concentration (C) for a minimum length of time (T) to obtain a certain level of kill (or inactivation). This is referred to as the CT concept. Promulgation of the Surface Water Treatment Rule (SWTR) in 1989 specified for the first time CT values for treatment of surface waters. The SWTR's main target organisms were viruses and the protozoan microorganism *Giardia lamblia* (McGuire, 2006). Additionally, the SWTR mandates maintaining disinfectant residual in the distribution system.

SFPUC relies on chlorine for disinfection of pathogenic cysts, bacteria, and viruses at three of its treatment facilities. One SFPUC treatment facility uses a combination of ozone followed by chlorine for disinfection. Chlorine is also used by SFPUC for pipeline disinfection and water tank disinfections after outages or construction. Chloramine is formed at the end of the treatment process to maintain disinfection throughout the distribution system. Chloramine is an approved treatment and distribution system disinfectant by the USEPA (USEPA, 1990). The World Health Organization (WHO, 1996) states that chloramine is useful for maintaining a disinfectant in distribution systems.

Chloramine is a less reactive (weaker) oxidant and disinfectant than chlorine, which is actually an advantage in the distribution system because chloramine lasts and disinfects longer. The disinfection effectiveness of chloramine should not be discounted. Studies have shown that chloramine matches the effectiveness of chlorine when contact times are sufficiently long. Additionally, chloramine has shown superior performance for the disinfection of biofilms. These results have led to the wide use of chloramine as disinfectant in distribution systems (AWWA, 2006b).

In the slightly alkaline pH range typical for drinking water distribution systems, the disinfecting effectiveness of chlorine is diminished for inactivation of bacteria, cysts and viruses, whereas the effectiveness of chloramine is not impacted (USEPA, 1990; White, 1999). This is because chlorine (hypochlorous acid) dissociates to hypochlorite ion at higher pH while chloramine remains as monochloramine as long as pH is above neutral. Disinfection with chloramine in the distribution system is superior to chlorine, which is also evident from SFPUC water quality monitoring. It must be recognized that, regardless of the disinfectant chosen, the water distribution system can never be regarded as biologically sterile.

The use of multiple disinfectants in sequence improves disinfection effectiveness, because synergistic effects may occur. For example, the exposure of *E. coli* bacteria to mixtures of chlorine and chloramine resulted in a greater inactivation than would be predicted by their individual effectiveness. Similarly, the combinations of disinfectants (chlorine followed by chloramine, ozone followed by chlorine or chloramine, chlorine dioxide followed by chlorine or chloramine) may offer a greater level of inactivation of the *Cryptosporidium* protozoan oocysts (AWWA, 1999; West et al. 1998; Li et al, 2001).

Q: What is the mechanism of chlorine and chloramine disinfection and is there a benefit of applying two different disinfectants instead of one?

A: Rates of microbial inactivation depend upon several factors including: the type and concentration of the disinfectant, contact time with the disinfectant, temperature, type and number of microorganisms, pH, and disinfectant demand (Jacangelo et al., 1987). It has been suggested that chlorine and chloramine act by two different mechanisms. Chlorine is a very reactive molecule and rapidly reacts with nucleic acids, most nucleotides, purine and pyrimidine bases, proteins and amino acids. Carbohydrates and lipids are generally unreactive to chlorine. Chloramine reacts rapidly only with the sulfur-containing amino acids, and the heterocyclic aromatic amino acid, tryptophan. Slow reactions of chloramine were observed with nucleic acids, purine and pyrimidine bases and the alpha amino group of amino acids. These slow reactions may become important when the rapidly reacting materials are masked or buried (Jacangelo et al., 1987). Most studies on the mode of action of chlorine in bacteria have implicated the disruption of the cell membrane. Chloramine does not severely damage the cell envelope. Chloramine inactivation has been suggested to occur through the blockage or destruction of

several enzymes and cofactors. The mode of action of chloramine appears to involve multiple hits by the disinfectant on the bacterial cell and reactions at several sensitive sites in the bacteria, which precede inactivation (Jacangelo, et al., 1987).

Some studies have shown that chlorination followed by chloramination is more effective for disinfection of the protozoan *Cryptosporidium parvum* oocysts than chlorine alone (West et al., 1998). The future of drinking water disinfection will rely on multiple disinfectants applied in sequence (Trussell, 2006).

Q: How has chloramine performed in SFPUC distribution system so far in terms of control of microorganisms?
A: Monitoring results indicated that the incidence of positive coliform bacteria samples decreased by 75 percent and that the heterotrophic plate count bacteria levels decreased by as much as a factor of ten comparing with free chlorine. A significant decrease in *Legionella* levels in San Francisco hot water heaters is an additional important benefit of chloramination. At the same time, growth of nitrifying bacteria in the distribution system has been controlled.
SFPUC monitors its distribution system for coliform bacteria as mandated by the Total Coliform Rule (TCR, USEPA, 1989b). Additionally, although not required, SFPUC monitors its distribution system for heterotrophic plate count (HPC) bacteria using the sensitive R2A method. Chloramination has improved TCR compliance and lowered the levels of HPC bacteria in the distribution system by a factor of 10, as compared with chlorine. This is likely due to higher and longer-lasting disinfectant residuals provided by chloramine. Similarly, chloramination has virtually eliminated the presence of *Legionella* species in San Francisco in hot water heaters (Flannery et al., 2006). *Legionella* bacteria were found to be much more resistant to chlorine than *E. coli* and other coliforms that have been used as indicator organisms to monitor potable water quality (Kim et al., 2002). *Legionella* bacteria have been known to cause pneumonic legionellosis and severe influenza-like illness. Hospitals supplied with drinking water disinfected with chloramine are less likely to have Legionnaires' disease outbreaks than those that use water containing chlorine (Kim et al., 2002). In an independent opinion by a leading medical university professor posted on SFPUC website indicates that control of *Legionella* is a significant public health benefit. Immuno-compromised individuals may consider boiling drinking water regardless of the disinfectant applied, depending on recommendations from their physician. It is technologically impossible to provide sterile drinking water by any utility.

Q: Why doesn't the SFPUC use ozone or ultraviolet light instead of chloramine?
A: SFPUC applies ozone and chlorine for primary disinfection at one of its treatment plants. Chlorine alone is used for primary disinfection at the remaining treatment facilities. Ultraviolet light will be used for treatment of Hetch Hetchy water to augment current chlorine disinfection beginning in 2011. However, ozone and ultraviolet light do not provide lasting disinfectant in the water and cannot be used as disinfectants in the distribution system.

Q: Why doesn't SFPUC remove organic matter before disinfection and use chlorine for disinfection?
A: Chemical pretreatment and filtration are already used at two SFPUC treatment plants. This treatment lowers but does not prevent THMs or other chlorinated DBPs from forming during chlorination. The removal of a portion of natural organic matter (NOM) from the Hetch Hetchy water would require chemical pretreatment by adding aluminum or iron coagulant salts and filtration of 300 million gallons of water per day. A facility capable of this type of treatment would cost billions of dollars to build and have operating costs on the order of millions of dollars per year, based on recent general cost estimates from AWWA for membrane filtration plants (AWWA, 2005a) and other estimates from the California Resource Agency (Environmental Defense, 2006). There would be significant operational impacts of filtration, including loss of gravity system and the need for pumping of all water delivered to the Bay Area.
There is no guarantee that even such costly treatment would allow SFPUC and its retail

customers to remain in compliance with DBP regulations with chlorine disinfection in the distribution system. Disinfection by-product (DBP) precursor removal efficiencies are site-specific and vary with different source waters and treatment techniques. Many utilities use coagulation and filtration to remove a portion of natural organic matter (NOM) present in the source water and still need to use chloramine for DBP minimization; this has been true for all large utilities in California. Large systems with large emergency water storage volume are unlikely to be able to control DBPs unless they use chloramine in the distribution system. SFPUC continues to apply chlorine at the treatment plants for disinfection of protozoan cysts, bacteria, and viruses. Chlorine is also used by SFPUC for pipeline disinfection and water tank disinfections after outages or construction. Chloramine is used for residual disinfection in the distribution system.

DBP precursor removal may also carry unintended effects. Because coagulation and filtration remove total organic carbon (TOC) but not bromide, in some waters containing high levels of bromide there may be an increase in the bromide-to-TOC ratio and a shift to more brominated species during chlorination (although this would not be expected in SFPUC waters). Brominated DBPs may be of higher health concern than the chlorinated species within the same class (Bull et al. 2001). The addition of salts could increase the corrosivity of Hetch Hetchy water.

SFPUC thoroughly evaluated all alternative methods to comply with DBP regulations. Water utilities do not conduct basic health research to test water disinfectants. Decisions are based on USEPA and CDPH approved technologies and cost considerations. Chloramine has performed very well in the SFPUC distribution system, significantly reducing the formation of regulated disinfection by-products and allowing SFPUC to meet current and future USEPA regulations. At the same time, chloramine has improved control of biofilm in the SFPUC distribution system, lowering the incidence of coliform positive samples, reducing heterotrophic plate count (HPC) bacteria by up to an order of magnitude, and virtually eliminating *Legionella* from the hot water heaters in large buildings.