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BIOLOGICALLY MEDIATED DETERIORATION OF WATER QUALITY IN DISTRIBUTION SYSTEMS

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RESEARCH PROGRAM

The current on-going research at the University of Missouri-Columbia is directed, both at determining the involvement of microorganisms in mediating chemical changes in water distribution systems and at evaluating the effectiveness of remedial measures for controlling water quality problems. This research has focused on five areas of study. Initially, an analysis of the extent of the problem has been made on the preliminary results of a utilities survey questionnaire. Secondly, laboratory manifold studies of organism growth and inhibition by a chemical disinfectant have been conducted, thirdly, field studies of several Missouri water systems have been made to develop sampling techniques and provide background data. Fourthly, the isolation and identification of microorganisms found in distribution system mains have been pursued. Finally, a simulated pipe loop system was constructed for studies of pipe materials and corrosion of pipes.

1. SURVEY QUESTIONNAIRE

To determine the extent and nature of water quality problems in distribution systems in the United States, a questionnaire was developed for water utility managers. This comprehensive questionnaire includes questions relating to raw and finished water quality in the distribution system, type of treatment, chemicals used for treatment, type and age of pipe used in the distribution system, frequency and nature of consumer complaints, remedial measures currently used, etc. With the support of the AWWA Research Foundation, this questionnaire has been mailed to some 2400 water utilities throughout the United States. As of September 1977, 354 questionnaires have been returned. The utilities responding encompass a broad spectrum of population size. (Table 1) The sources of the water supplies were categorized by EPA regions. (Table 2) The results indicate that 44.6% of responding utilities obtain water supply from ground water sources, 20.6% from lake water sources, and 14.4% from river sources. In addition, many utilities report using multiple water sources. About 20% of the utilities surveyed use at least two or more water supply sources. The type and numbers of water quality problems which have been reported by the utilities are listed in Table 3. The data indicated that taste and odor problems are the most frequently reported consumer complaints. Over 60% of the utilities reported these problems.

"Red" water ranked second with 47.7% of utilities reporting this problem. 46% reported problems with cloudiness of water. "Black water was reported by 16.7 % of the utilities. At least 80% of the utilities reported experiencing two or more types of water quality problems as reflected by their consumer complaints. These preliminary results indicated that, irregardless of the water supply sources, sizes of the utilities or the geographical regions, virtually every responding utility experiences some water quality problem in the distribution system. This survey also indicated that presently the most frequently practiced remedial treatment method is a main flushing program. Other remedial measures include increases in chlorine residuals at the plant, rechlorination in the system, adjustment of pH for calcium carbonate deposition and the addition of sequestering agents such as polyphosphates. From this national survey, several U.S. cities have been selected for a more detailed water quality monitoring program. The purpose of this monitoring program is to develop the base-line data concerning the water quality in the treatment plant and within a variety of distribution systems. Several important parameters which will be monitored are turbidity, pH, alkalinity, chlorine residuals, dissolved oxygen, ammonia-N, iron, sulfate, hydrogen sulfide, total organic carbon, phosphate, standard plate counts at 35°C and 20°C, and fecal coliform. Other microbiological analyses will include the isolation and enumeration of various types of microorganisms in the distribution system.

2. PIPE MANIFOLD STUDIES

To assess the potential for a treated water to support microbial growth and promote sediment deposition in a pipe system, laboratory studies were conducted by graduate students, David Huang and Nick Pinto. Only a summary of their findings will be presented here.

A. Chlorine Inhibition Studies

The experimental apparatus, as shown in Figure 1, consists of six removable plexiglass tubes attached to a manifold system. The influent water was the University of Missouri laboratory tap water which has been supplemented with ammonium chloride, sodium phosphate, and TOC in the form of glucose. To each test manifold system, different concentrations of free available chlorine have been added continuously. The water quality was monitored weekly at the influent, effluent, and at an intermediate point. The accumulated sediments were recovered and analyzed. In spite of continual chlorination, analysis of the accumulated solids showed increases in biological growth with time. (Figure 2) With the addition of 0.5 mg/l chlorine, 80 - 100% of the available chlorine was in the form of a combined chlorine residual. Perhaps for this reason, 0.5 mg/l chlorination did not show any growth inhibition. However, the addition of 1.0 mg/l of chlorine resulted in a marked growth suppression. Decreases in the free available chlorine residuals and dissolved oxygen concentrations were consistently observed in the effluents from the manifolds. Moreover, the production of hydrogen sulfide was indicated in the test systems with 0 and 0.5 mg/l chlorine addition. Microbiological analysis confirmed the presence of sulfate-reducing organisms. Other heterotrophic organisms isolated were iron-precipitating organisms, pigmented Gram negative rods, and sulfur-oxidizing organisms. Due to the source of carbon (glucose) that was added to the system, slimy and cottony textured bioflocculation was noted in the manifold system.

B. Methane Stimulation Studies

Another experiment was conducted with the manifold system to determine if the addition of dissolved methane as a carbon source can enhance the biological growth in the pipe manifold system. No other substrate other than the methane was added to the system. The methane concentration added to the influent averaged 8.9 mg/l and 13.3 mg/l as measured by a Bendix 2500 gas chromatograph. Apparent growth enhancement by methane addition was observed. There was a 2 to 3 order of magnitude increase in the number of microorganisms found with methane addition as compared to the control system without methane. Further experiments are needed in order to determine the exact nature of methane as a possible primary substrate for microorganisms in distribution system.

3. FIELD STUDIES

The main thrust of our research is to determine the influence of microorganisms in mediating the chemical changes observed in distribution systems. A number of water sampling programs have been conducted with Missouri water utilities in order to determine whether observed water quality changes are due to the presence of microorganisms in the distribution system. Two of these utilities examined were the City of Boonville and Columbia, Missouri, water systems. Boonville, Mo. obtains its water from the Missouri River. Water treatment consists of softening, filtration and disinfection. Polyphosphates are added to stabilize the finished water. There are generally no significant water quality problems in the distribution system other than the seasonal taste and odor problems. Table 4 indicates the chemical water quality of the water distribution system. There were slight decreases in the chlorine residuals and in nitrate concentrations. Interestingly raw water contained 0.8 mg/l total dissolved sulfide. An apparent increase in total iron concentration at the distribution system was reflected in red water condition of the main flushing sample at the sampling location #3 of the distribution system. The results of other chemical parameters such as ammonia, TOC, total phosphate are difficult to evaluate.

Further monitoring of this distribution system is needed in order to evaluate the water quality changes observed here. When 5 mls of water samples were inoculated into various enrichment culture media, the following microbiological analyses were observed. (Table 5) Raw water contained sulfate-reducing, sulfur oxidizing, iron precipitating, nitrifying, denitrifying, nitrogen fixing and a variety of aerobic heterotrophs including spore forming rods. Above organisms other than the nitrifying organisms were detected in the treated water at the distribution system.

Columbia, MO obtains its water from wells in the Missouri River flood plain near McBaine, MO, which is about 9 miles south of Columbia.(Figure 3) The well aquifers are hydraulically connected to the Missouri River so that the water quality may be somewhat similar to that of the river. The water treatment process consists of lime softening, filtration and disinfection. In addition, there are few wells in the city of Columbia that augment the supply to the system in times of emergency or low pressure. Arriving in Columbia, the treated water is first transported to one large underground storage tank. After booster chlorination, water is pumped to the distribution system. Fourteen sampling sites were chosen throughout the distribution system to examine water quality changes. The results of the chemical analyses of a typical sampling day are given in Table 6. In some parts of the city, little or no free available chlorine was observed at times possibly due to the inflow of water from wells in the city. Because the pH of the water is in the range of 8.1-8.5, only about 10-20% of the free available chlorine is hypochlorous acid. The lack of disinfection efficiency by hypochlorite ion seems to be reflected in the increase in microorganisms in the distribution system. Unless the free available chlorine species is hypochlorous acid, a significant number of chlorine-resistant organisms can survive the disinfection process and be transmitted through the water distribution system. Occasionally, hydrogen sulfide was detected in a number of distribution water samples.

4. ISOLATION AND IDENTIFICATION OF MICROORGANISMS IN WATER DISTRIBUTION SYSTEMS

In Columbia, most of the water mains are lined either with bituminous materials or with cement. From the experience of the Columbia water superintendent, corrosion of underlying cast iron pipe is not indicated generally. However, deposits of calcite and iron precipitates are observed in the distribution mains. Analysis of total iron indicated increase in iron concentration in the distribution system.

In Columbia, the TOC concentration in treated water is about 5 mg/l. Predominant organic substances have been found to be phthallate and humic substances. Even though the organic content of treated water is low, heterotrophic organisms are found in significant concentrations. (Figure 4)

The following pictures are photomicrographs of some of the heterotrophs found in various water distribution systems, including the Boonville and Columbia, Missouri, water systems. Only a cursory identification of these organisms has been made. (Figure 5): Gram negative irregular shaped rods, yellow pigmented on standard method agar, Arthrobacter sp. (Figure 6): Gram negative straight rods, orange pigmented, Flavobacterium sp. (Figure 7): Gram negative short rods, light yellow pigmented, Enterobacter sp. (Figure 8): Gram negative straight rods, non-pigmented, Pseudomonas sp. (Figure 9): Filamentous organism with slimy layer, Iron bacteria. (Figure 10): Branched rods, Actinomycete sp. (Figure 11): Aggregating rods. (Figure 12): Non-specific iron-precipitating organisms. In general, many of these aerobic heterotrophs did not grow well in the standard method agar. Spore-forming organisms were found to be more prevalent in these areas where red water problems have been persistent. It is known that many heterotrophic organisms such as Pseudomonas, Enterobacter, and Mycobactium form precipitates with iron. Their activity could result in increase in high iron concentrations at specific locations in the distribution system due to precipitation and bioflocculation.

Other groups of microorganisms observed in water distribution systems are nitrogen-fixing heterotrophs, such as those shown in Figures 13 and 14. Cursory identification of these cultures indicate Azotobacter and Beijerinchia species. Occasionally, yeasts, acid-fast bacilli, and spirillum bacteria have been detected.

It was noted that where "red water" problems are known to be persistent, both sulfate-reducing and sulfur-oxidizing organisms were consistently found. Figure 15 is a photomicrograph of one of the anaerobic sulfate-reducing organisms found in distribution systems.

Figure 16 illustrates what happens to a mixed culture of microorganisms when the culture has been influenced by a toxic substance, such as hydrogen sulfide. A degree of bioflocculation occurs between the cell debris and inorganic flocs.

In studies with Missouri water utilities, dissolved hydrogen sulfide has been detected in distribution water samples. When raw water samples of a number of utilities were examined, occasionally nitrifying autotrophic organisms have been observed. Usually, other autotrophic organisms, such as the sulfur-oxidizing organism, Thiobacillus sp., have been detected more frequently in water distribution systems. Fig. 21. The significance of these autotrophic organisms is that they can use carbon dioxide as their carbon source, while their metabolic products may be utilized by other heterotrophic organisms.

Stalk-producing organisms, such as Caulobacter and Hyphomicrobium species, have been observed in many distribution water samples. (Figures 17 and 18) These organisms require very little organic substrate. The importance of these stalk-producing organisms may be their ability to form a biological network for aggregation with other organisms. This bioflocculation phenomena is well-illustrated in the photomicrograph, Figure 19.

5. PIPE LOOP SYSTEM

Studies of a number of water distribution systems in Missouri, including the Columbia water system, seem to indicate that water quality changes in the distribution system can be attributed at least partly, to microorganisms. The significance of the growth of chlorine-resistant organisms in the distribution system needs to be evaluated in terms of their potential interaction with the various chemicals in water as well as sediments that have already formed in the distribution mains. To accomplish this, a simulated pipe loop system is being constructed (Figure 20) This pipe loop system will permit the examination of the potential role of microorganisms in influencing the corrosion rate of iron and water quality changes in pipe systems made of PVC and steel pipe materials. The apparatus will consist of two influent basins and four holding basins. The test water will be filtered through a 0.45 uM cartridge filter to remove any microorganisms and sediments. This filtered water will be transported to the holding basins connected to the PVC pipe loop system and to the steel pipe loop system. Another parallel system will be tested with unfiltered water with microorganisms Six cast iron coupons will be inserted into the test PVC pipe to examine the corrosion rate of the metal, while six removable steel pipe sections will be incorporated into the steel pipe system to evaluate the microbial growth and sediment formations. Corresponding water quality changes will be monitored at both influent and holding basins.

REMEDIAL MEASURES

The ultimate purpose of the overall research effort is to determine the best remedial measure for controlling sediment deposition including biological growths. This enormous task can only be achieved if the concerned people of the waterworks industry make a coordinated effort to study the problem on a national basis, systematically, and search for effective, long-term solutions to the problem.

ACKNOWLEDGEMENT

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TABLE 1

Classification of the Responding Utilities to the Population Size

Population Range	Number of Utilities	Percentage
Less than 1000	28	8%
1000 - 5000	85	24%
5000 - 10,000	39	11%
10,000 - 50,000	104	29%
50,000 - 100,000	35	10%
Greater than 100,000	54	15%
Not Listed	9	3%

TABLE 2

Water Supply Sources of Utilities

EPA Region	Total Nos. Responding Utilities	Ground	Lake	River	Ground and River	Ground and Lake	River and Lake	Ground River, & Lake	Not Listed
I	12	4	6	0	0	2	0	0	
II	25	11	7	3	3	1	0	0	
III	24	3	7	9	1	0	3	1	
IV	44	25	7	6	2	2	1	1	
V	97	57	25	5	5	3	1	0	1
VI	21	5	10	2	1	3	0	0	
VII	39	18	2	8	7	3	0	0	1
VIII	18	5	2	4	2	1	3	1	
IX	47	21	7	6	8	1	2	1	1
X	27	9	0	8	7	0	3	0	
Total	354	158	73	51	36	16	13	4	3
Percent		44.6%	20.6%	14.4%	10.2%	4.5%	3.7%	1.1%	0.8%

TABLE 3

Water Quality Problems Cited by Utilities

EPA Region	Taste	Odor	Cloudi-ness	Red	Black	Others*
I	6	6	5	6	1	2
II	10	9	5	12	5	3
III	16	16	14	10	6	2
IV	35	28	22	24	9	7
V	59	60	39	62	19	9
VI	14	15	12	7	1	3
VII	27	20	21	17	10	4
VIII	11	9	10	5	2	3
IX	32	30	23	16	5	13
X	20	16	14	10	1	6
Total	230	209	105	169	59	52
Percent	65.0%	59.0%	46.6%	47.7%	10.7%	14.7%

*Others: Pressure, Chlorine, Sands, Color

TABLE 4

Chemical Analysis of Boonville Water Distribution System
(Sampling Date: June 22, 1977)

Sample	pH	Chlorine Residual Free	Chlorine Residual Combined	Dissolved Sulfide	Nitrate
Raw Water	6.8	0	0	0.8	0.8
Finished Water	8.2	0	1.4	0	0.4
F.H. @ Water St.	8.1	0	1.05	0	0.1
F.H. @ Kohn St.	8.14	0.8	0.4	0	0.05

Sample	Ammonia	Total Iron	TOC	Total Phosphate
Raw Water	NM	0.3	7.6	0.09
Finished Water	0.75	0	5.0	0.15
F.H. @ Water St.	0.85	0.18	5.4	0.23
F.H. @ Kohn St.	0.7	0.05	5.0	0.05

Concentration Units: mg/l

TABLE 5 Microbiological Analysis of Boonville Water Distribution System (Sampling Date: June 22, 1977)

Sample	Aerobic Heterotrophs (Counts/ml)	Sulfate Reducers	Sulfur Oxidizers	Iron Precipitators	Nitrifiers	Denitrifiers	Nitrogen Fixers
Raw Water	TNTC	Yes	Yes	Yes	Yes	Yes	Yes
Finished Water	30.1	No	No	Yes	No	Yes	No
F.H. @ Water St.	313.2	Yes	Yes	Yes	No	No	No
F.H. @ Kohn St.	110.5	Yes	Yes	Yes	No	Yes	Yes

TABLE 6 Chemical Analysis of Columbia, MO Water Distribution System

Sample	pH	Chlorine Free (HOCl+ OCl)	Residuals (mg/l)	Combined (HOCl)	Dissolved Sulfide (mg/l)	Total Iron (mg/l)	TOC (mg/l)
1.	7.4	0	0	0	0.4	-	5.0
2.	8.5	1.8	0.14	0.2	0	0.02	4.9
3.	8.1	1.15	0.23	0.15	0	0.14	4.9
4.	8.1	0.55	0.11	0.15	0	0.10	4.4
7.	8.2	1.30	0.23	0.2	0	0.02	4.5
9.	8.15	1.05	0.20	0.15	0	0.12	4.9
11.	7.45	0	0	0.05	0.4	0.22	4.6
14.	8.0	0.1	0.2	0.10	0.3	0.22	4.3

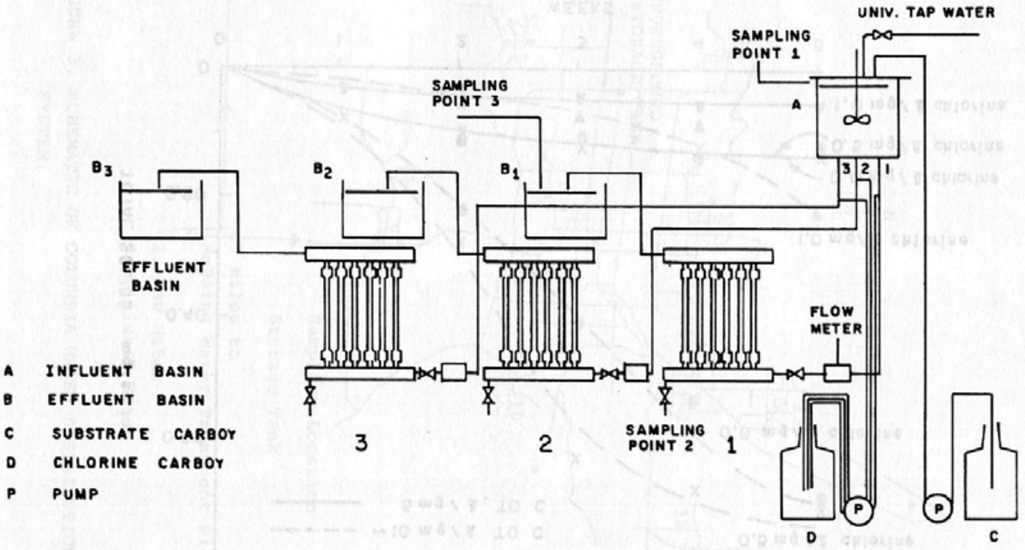

FIGURE 1 MANIFOLD EXPERIMENTAL SETUP

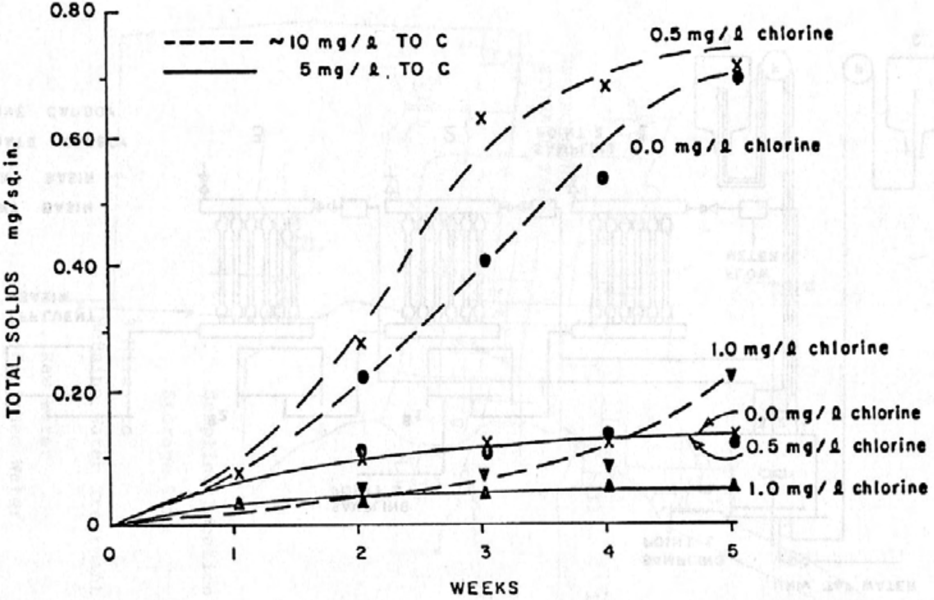

FIGURE 2 CHANGES IN TOTAL SOLIDS CONCENTRATION IN MANIFOLD TUBES AT DIFFERENT CHLORINE DOSES

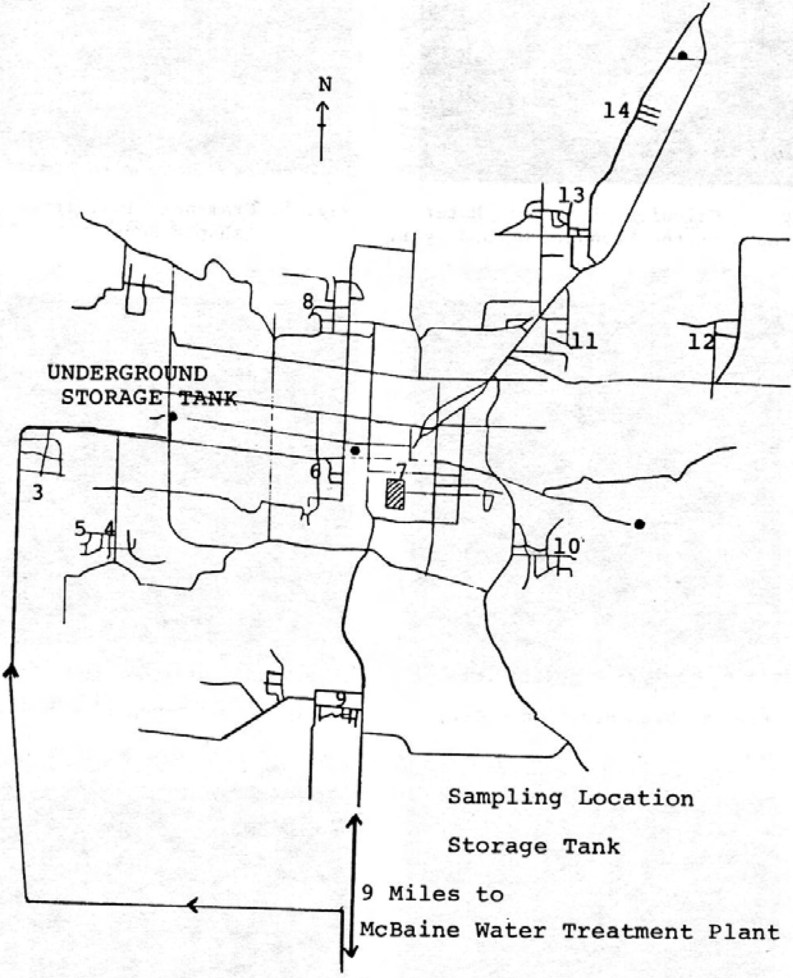

FIGURE 3. SCHEMATIC OF COLUMBIA WATER DISTRIBUTION SYSTEM.