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FILTRATION OF GIARDIA CYSTS AND OTHER SUBSTANCES

VOLUME 3: RAPID RATE FILTRATION

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Giardiasis is an intestinal disease reported with increasing frequency, especially in the western and northeastern United States. The disease is caused by ingestion of cysts of the protozoan Giardia lamblia. The cysts are commonly found in the cold, clear streams of mountain environments, which are used as a source water supply by many communities. This report investigates the effectiveness of rapid-rate filtration in removal of Giardia cysts and other substances of concern; it delineates the role of selected design criteria and operating conditions. The problems associated with rapid-rate filtration are examined as a part of the EPA research program focused on the water treatment problems of small communities. Special reference is made to the difficulties with cold, low turbidity raw waters.

Francis T. Mayo
Director

ABSTRACT

FILTRATION OF *GIARDIA* CYSTS AND OTHER SUBSTANCES
VOLUME 3: RAPID RATE FILTRATION

The efficiency of rapid rate filtration for removal of *Giardia lamblia* cysts, standard plate count bacteria, total coliform bacteria, and turbidity was determined experimentally under a wide range of operating conditions. Percent removals were evaluated by means of a lab-scale pilot plant at temperatures of 4°C and 18°C, for low turbidity water, at hydraulic loading rates of 8 cm/min (2 gpm/ft^2), 24 cm/min (5 gpm/ft^2) and 33 cm/min (8 gpm/ft^2), for "in-line" filtration, for three filter media, and using three chemicals. Testing was performed also using a 1.3 L/s (20 gpm) field-scale rapid rate filtration pilot plant. The range of testing was narrower and focused on ascertaining the findings at the lab-scale.

The study has shown that rapid rate filtration is a highly efficient treatment process for low turbidity waters when proper chemical pretreatment is used. Certain polymers, such as Magnifloc 572C® or Magnifloc 573C® in conjunction with alum will effectively coagulate low turbidity, low temperature water, i.e. when raw water turbidity level is less than 1 NTU, and when temperature is 0-4°C. Lab-scale results, for example, showed that using 5 mg/L of alum as $Al_2(SO_4)_3.14H_2O$ followed by 1.5 mg/L Magnifloc 572C, *Giardia* cyst removals were 99 percent, and standard plate count bacteria and total coliform bacteria removals were greater than 99 percent. At the same time, corresponding turbidity removals of about 80 percent were obtained using raw water having less than 1 NTU turbidity. With no chemical pretreatment, removals of all substances, including *Giardia* cysts, ranged from only 10 percent to 70 percent.

The results showed that rapid rate filtration will effectively treat low turbidity water, and will removal *Giardia* cysts if proper chemical pretreatment is used. Proper chemical pretreatment is difficult to determine and to evaluate for low turbidity waters since the usual measures of effectiveness such as turbidity removals and coliform bacteria removals are based upon very low amounts in the raw water. Pilot plant testing is imperative to ascertain proper chemical pretreatment, when using low turbidity waters.

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CONTENTS

TABLES

FIGURES

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SECTION 1

INTRODUCTION

CONTEXT OF RESEARCH

In recent years giardiasis has been recognized as a water-borne disease of national importance. Most of the outbreaks have been traced to Giardia lamblia cysts in drinking water, which have been associated with ineffective water treatment. Colorado is one of the states in which the disease is endemic and where outbreaks of giardiasis have been frequent, particularly in small mountain communities. Outbreaks have been reported in other states with increasing frequency as awareness of the problem has increased.

Concern developed at Colorado State University (CSU) in 1979 following investigations were conducted by the Colorado Health Department, particularly those of Blair (1980). From this concern and an awareness of the growing extent of the problem nationally by the U.S. Environmental Protection Agency (EPA), an EPA-CSU Cooperative Agreement was developed entitled, "Removal of Giardia lamblia from Water Supplies - Appropriate Water Treatment for Small Systems." It should be noted also that the organism Giardia lamblia could be classified as a specific contaminant as defined by PL93-523, the Safe Drinking Water Act and is therefore of regulatory concern to EPA in its administration of the Act.

The overall project encompassed evaluation of three water treatment technologies--slow sand filtration, diatomaceous earth filtration, and rapid-rate filtration. Previous reports by Bellamy et al. (1984) and Lange et al. (1984) have given results of research on removal of Giardia cysts by slow sand filtration and diatomaceous earth filtration, respectively.

This volume evaluates the use of rapid-rate filtration with respect to ascertaining design and operating conditions for removal of Giardia lamblia cysts. Special emphasis was given to operation under low-turbidity, low-temperature water conditions such as that found in the ambient water supplies of the Rocky Mountain Region. At the same time, there was interest in determining whether a surrogate measure could be found for removing Giardia cysts.

INVESTIGATION

Purpose

The purpose of this research was to determine how to remove *Giardia lamblia* cysts from water supplies by rapid-rate filtration for conditions prevailing in the Rocky Mountain Region. Here raw water turbidity is less than 1 NTU during fall and winter seasons, and temperatures approach 0°C during winter. The problem reduces to one of determining how to make the process effective for conditions of low turbidity and temperature.

Objectives

The objectives of this research were as follows: (1) to determine how to chemically pretreat low-turbidity, low-temperature water for efficient rapid-rate filtration, (2) to evaluate percent removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and *Giardia* cysts under various conditions of chemical pretreatment for low-turbidity, low-temperature water, (3) to determine the respective roles of process variables on removal efficiencies of the above parameters, and (4) to ascertain whether a surrogate indicator could be found to assess the percent removal of *Giardia lamblia* cysts by rapid rate filtration. Surrogate indicators investigated in the fourth objective included percent removals of turbidity, standard plate count bacteria, total coliform bacteria, and particles.

Process variables investigated in the third objective included: chemical pretreatment conditions (coagulants used, dosages of coagulants, sequence of coagulant addition), mode of filtration ("in-line" versus "direct"), media (single versus dual), filtration rate, temperature, and run time.

Scope

In the rapid rate filtration process, there are numerous variables that determine effectiveness. They include: water characteristics such as temperature, turbidity, alkalinity; chemical pretreatment conditions such as primary coagulant used, secondary coagulant used, dosages of each, and mixing intensity and detention times in both rapid mix and flocculation, and whether settling is used; and filter conditions such as filtration rate, and media. There are no mathematical models existing to consolidate these variables. Thus to ascertain relationships, empirical testing must be done to find relationships of interest, using a physical model (a pilot plant). Thus the research was experimental and utilized two pilot plants: (1) a laboratory-scale rapid rate filtration pilot plant, and (2) a field-scale 1.3-l/s (20 gpm) rapid rate filtration pilot plant.

With so many variables, tens of thousands of tests could be conducted. Therefore the method of this research was to maintain constant many of the above variables and to vary the others over limited ranges. Thus raw water

conditions used were restricted to those found in the Rocky Mountain Region during fall and winter seasons, e.g. low turbidity. Some initial "familiarization testing" was conducted with both pilot plants, however, using Horsetooth Reservoir water which has turbidity levels of 5 to 10 NTU. Since this water is more easily treatable it was used to develop testing procedures. The investigation of temperature effect at the lab-scale used only two temperatures, 3°C and 18°C. Colder temperatures with the lab-scale pilot plant were not possible because of ice formation at lower temperatures. With the field-scale pilot plant temperature could not be controlled and so operation was at ambient temperatures, which reached 0°C. Hundreds of commercial polymers are available, but screening was conducted only until effective ones were found.

Even with such restrictions a total of 178 test runs were conducted using the lab-scale pilot plant over an 18 month period. Using the field-scale pilot plant 131 test runs were conducted, with 31 of these using raw water having turbidity level of less than 1 NTU. The approach was to use the lab-scale pilot plant to ascertain functional relationships and the field-scale pilot plant to confirm these findings for ambient conditions.

Significance

Outbreaks of giardiasis due to water borne transmission of *Giardia lamblia* cysts in drinking water are a national problem. The treatment technology associated with virtually all of the outbreaks has been rapid rate filtration.

While deficiencies in the operation or design of the rapid rate filtration process have not been ascribed definitively, many outbreaks have occurred under conditions of no chemical pretreatment. In this mode of operation, i.e. without chemical pretreatment, the filter media acts merely as a "strainer."

The practice of using no chemicals is common in the Rocky Mountain Region during fall and winter seasons when raw water turbidities of mountain streams are less than 1 NTU. In addition, coliform counts of these waters are low, e.g. 100 per 100 mL. Also during winter, temperatures will approach zero degrees Celsius.

There are three basic problems associated with such conditions. First, raw water turbidity levels already meet drinking water standards, and the low coliform counts can be handled easily by disinfection. Thus there is a general lack of perception that a problem exists. Second, effective coagulation and filtration under such conditions, e.g. low turbidity, low temperature, is simply beyond the state-of-the-art of knowledge about the rapid rate filtration process. This is not to say that low turbidity waters have not been filtered successfully. An example is at Duluth as described by Black and Veatch (1975) (Logsdon et al., 1983) and Schleppenback (1984), where water from Lake Superior, having less than 1 NTU turbidity, has been filtered to remove asbestos fibers. Also Kimmeyer (1979) described filtration of low turbidity waters from the Tolt River in Washington. Such

cases notwithstanding, it is true generally that knowing what to do is not clear, even if there is perception that a problem exists. And third, since the ambient turbidities and coliform counts are so low, there is question on how to evaluate the effectiveness of the filtration process.

To better ascertain how to treat this low turbidity, low temperature, water by the rapid rate filtration process would both advance the state-of-the-art of the process and at the same time provide the knowledge needed to remove Giardia cysts, a major national problem. In addition, with many communities using the rapid rate filtration process, advancement of the state-of-the-art of practice will permit these plants to improve the overall level of health protection. This will make cost-effective a large aggregate amount of capital investment in existing plants. The documented outbreaks of giardiasis associated with low turbidity waters demonstrate that filtration merely to meet the 1 NTU standard is not adequate to protect public health.

GIARDIASIS

The disease giardiasis has been recognized world wide over recent years. It is prevalent in Russia, particularly in Leningrad (Brodsky et al., 1974). In the United States, the first documented water borne outbreak was in Aspen, Colorado during the winter of 1965-66. A survey of 1094 skiers who had vacationed in Aspen showed that 123 (11 percent) had developed symptoms similar to giardiasis (Craun, 1979). Outbreaks have occurred most frequently in the Rocky Mountains, in the Northwest, and in the Northeast. Visvesvara and Healy (1978) estimate three to seven percent of the adult population harbor the parasite. Colorado is one of the states where the disease is endemic. Outbreaks have been reported in Aspen, Vail, Boulder, Estes Park, Hideway Park, etc. (Davies and Hibler, 1978), and recently in Purgatory (Colorado Disease Bulletin, March 31, 1984). Blair (1979, 1980) has investigated outbreaks at Estes Park and Vail, where rapid rate filtration was used, and recovered Giardia cysts from filtered water. An outbreak occurred at Empire, Colorado in 1981; the town used chlorination but no other treatment. The most recent Colorado outbreak was at Purgatory, in January 1984. Chlorine was the only treatment in this case, but it is notable that levels were maintained at about 2.5 mg/L (Colorado Disease Bulletin, March 31, 1984) with about 4 hours detention time (Blair, 1984, personal communication).

In the Northwest the first documented outbreak was in 1976 in Camas, Washington (Pluntze, 1983). Some 600 persons or about 10-15 percent of the population, were affected. The source of infection was found to be beavers. Leavenworth, Washington had a similar outbreak in 1980, also reported by Pluntze, which affected 27 percent of the population, or 578 persons. In these cases the water was treated by rapid rate filtration.

One of the largest outbreaks of giardiasis occurred in Rome, New York from November 1974 to June 1975 (Shaw et al., 1977). A total of 350 residents had laboratory confirmed cases and an estimated 5,300 others may have been symptomatic. Chlorine was the only treatment. This was the first

outbreak in which Giardia lamblia cysts were recovered from a municipal water supply.

The disease has been reported also in Banff National Park by DeWalle and Jansson (1983), where 121 confirmed cases occurred in the winter of 1981-82. It has become a major concern in Alberta and in British Columbia. In November 1983 the British Columbia Water and Wastes Association held a seminar on the topic to convene those having knowledge and interest about the problem (British Columbia Water and Wastes Association, 1983). Cleasby (1983) reported that at Bradford, Pennsylvania in 1979 an estimated 2900 persons were affected. During recent months, since the fall 1983, further outbreaks have been reported at Houtzdale, Pittston, and McKeesport in Pennsylvania (Logsdon, 1984, personal communications).

Giardiasis is an intestinal disease caused by ingestion of cysts from the protozoan, Giardia lamblia. Ingestion of one to ten cysts is sufficient to cause the disease (Rendtorff, 1977). The diseae symptoms will appear with two to thirty five days after ingestion, with one to two weeks being the most common incubation period.

Giardia lamblia is a pathogenic intestinal parasite found in humans and in other warm blooded animals. The beaver has been thought to be a common source of cysts, but Hibler (1979) has reported recovery of cysts from a wide variety of wild animals. Recently, Hibler (personal communication, 1984) has indicated the muskrat may be a major source cysts found in streams. In addition dogs are commonly infected (and have served as the source of cysts for this research).

The organism Giardia lamblia has two life stages, a reproductive trophozoite stage, and a dormant cyst stage. The cysts, which are the form found in the environment, are about 7 to 12 micrometers in their smallest dimension, and can survive about two months in cold water (Hibler, 1984, personal communication). Upon ingestion the cyst becomes a trophozoite and attaches to the lining of the small intestine. Figure 1 shows drawings of both cyst and trophozoite, with dimensions indicated.

There are at least two morphologically different species of Giardia, Giardia lamblia and Giardia muris. It is not certain among researchers how many actual species exist in addition to these. Therefore species names have been ascribed to Giardia depending upon the host. Jakubowski (1979) has listed those with claw like median bodies to include Giardia lamblia (man), Giardia canis (dog), Giardia cati (cat), Giardia bovis (ox), etc. Those with rounded median bodies are Giardia muris and are found in the house mouse, rat, and hamster. Hibler (1984, personal communication) believes that the species listed in the first group are the same and may be cross transmitted between hosts of different animal species. Hibler (Davies et al., 1983) has reported self infection using Giardia cysts obtained from dogs. Then Hewlett et al. (1982) established that Giardia cysts from humans can infect dogs.

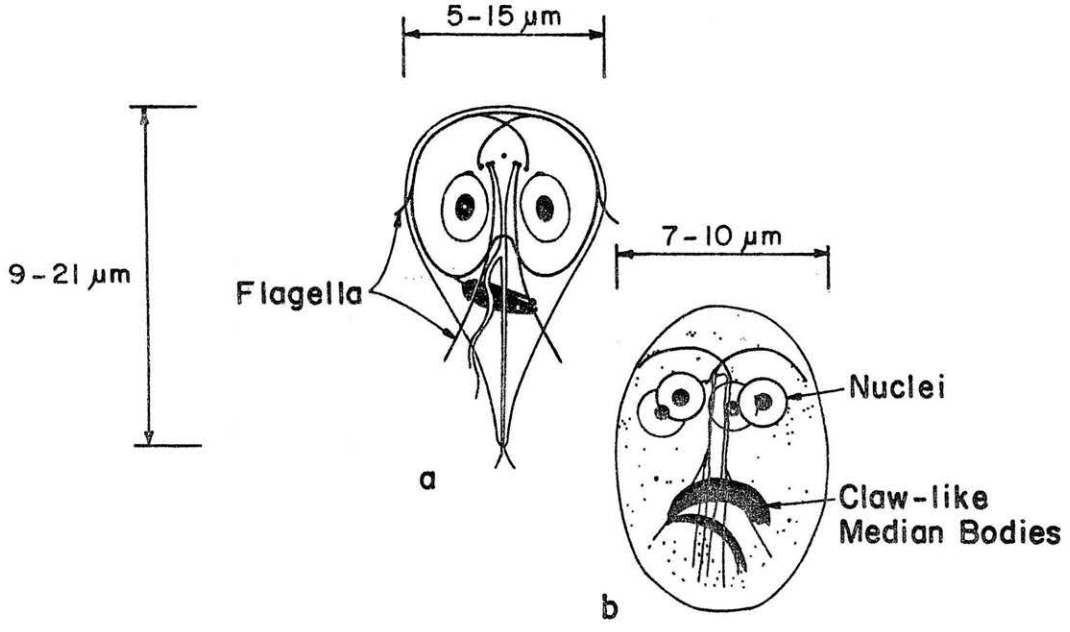

Figure 1. Sketches of a) trophozoite, and b) cyst stages of Giardia lamblia (Jackubowski and Hoff, 1979).

Thus the designation Giardia lamblia is believed proper for the Giardia cysts used in this research, which were obtained from dog fecal samples.

TREATMENT OF MOUNTAIN WATERS

Characteristics

The flows of mountain streams in the Rocky Mountain Region, and also the Sierra Nevadas in California and the Cascades in Washington have a typical "snowmelt hydrology." In other words, most of the flow volume occurs during spring runoff about mid April through June. During the summer and into the fall snowmelt continues from higher elevations at a slower rate and is complemented by base flow from aquifers. During the spring runoff period the turbidity level is nominally about 30 NTU and may even reach 200 NTU for example if a thunderstorm occurs. These waters are treatable by conventional rapid rate filtration, e.g. rapid mix, flocculation, sedimentation, and filtration, though operators may have difficulty adjusting coagulant dosages. A visible floc readily forms with proper coagulation. As the spring runoff recedes, however, the turbidity levels decline and may stabilize at 0.5 to 1 NTU from September until mid April. Temperatures will decline also, approaching zero degrees Celsius in December and January. Total dissolved solids may be very low throughout the year, e.g. nominally about 50 to 100 mg/L. Alkalinity also may be low, e.g. 40-50 mg/L as $CaCO_3$.

Table 1 illustrates showing monthly water quality for the Cache La Poudre River at the Fort Collins Water Treatment Plant No. 1, located in Poudre Canyon, about twelve miles from the city center. The table shows that average turbidity for 1980 is less than 1 NTU during six of the twelve

Table 1. Characteristics of Cache La Poudre River water for calendar year 1979 at Fort Collins Water Treatment Plant No. 1.

Cache La Poudre River, 1979			1981
Month	Temperature (°C) Average	Turbidity (NTU) Average	Total Coliform Bacteria (org/100 ml)
January	0.55	0.62	<1
February	0.55	0.63	<1
March	2.68	0.65	<1
April	8.29	3.0	100
May	9.10	9.3	8
June	10.20	6.45	--
July	15.23	2.30	198
August	14.5	4.17	96
September	14.8	1.20	77
October	9.7	0.65	82
November	0.89	0.49	10
December	0.61	0.47	4
Yearly Average	7.26	2.49	

* City of Fort Collins, Colorado, monthly data report for 1979.

months, and average temperature is less than 1°C during four months. The characteristics shown in Table 1 for the Cache La Poudre River, are typical of other mountain streams in the Rocky Mountains. But there are exceptions. Table 2 shows characteristics for water from Horsetooth

Table 2. Characteristics of water from Horsetooth Reservoir during 1979 at Fort Collins Water Treatment Plant No. 1 during months of operation.[1/]

Horsetooth Reservoir, 1979			1981
Month	Temperature (°C) Average	Turbidity (NTU) Average	Total Coliform Bacteria (org/100 ml)
April	6.5	4.3	<1
May	7.3	4.5	<1
June	-	5.1	--
July	8.0	6.1	2
August	8.0	6.73	3
September	8.2	7.3	4
October	8.5	7.75	19
Yearly Average	7.71	5.9	

1/ City of Fort Collins, Colorado, monthly data report for 1979.

Reservoir at Fort Collins Water Treatment Plant No. 2. It shows April to October because the plant operates only during those months. Total dissolved solids are about 50 mg/L and total alkalinity is about 40 mg/L as $CaCO_3$, whole turbidity ranges between 4.3 NTU and 7.8 NTU.

Treatment Practices

During spring runoff when turbidity levels are 10 to 50 NTU nominally, conventional water treatment (rapid mix, flocculation, sedimentation, filtration) is used for waters from mountain streams. The processes of coagulation and flocculation occur as expected under these conditions, with floc formation, and effective filtration.

Under conditions of low turbidity, prevailing from September or October until April, and low temperature, e.g. November through February, coagulation is difficult. If chemicals are used it is difficult to develop a floc. For such reasons, and because the 1 NTU turbidity standard can be met even with the raw water, chemical pretreatment is often terminated during the low turbidity period. The filtration process is simply 'straining' during this mode of operation. This is of course, contrary to the concept of rapid rate filtration; chemical coagulation is an intrinsic part of the process. Along with this discussion it should be noted that some plants have used high dosages of alum,, e.g. 15 to 50 mg/L, which forms a visible floc with low turbidity water and should provide effective filtration. Others use filter aids, some of which are doubtful in their effectiveness. Another approach with low turbidity waters is to add bentonite clay to develop artificial turbidity to facilitate coagulation.

The 'straining' mode of operation likely passes small particulates and microorganisms as may be found in these low turbidity waters. Blair (1979, 1980) has reported on C. Hibler's examinations of particulate concentrates obtained from fiber filters used to sample finished waters in which chemical pretreatment was not practiced. The filters contained cysts, strongyles eggs, and nematodes. Thus Giardia cysts, bacteria, and other substances may readily pass through the filter, even though the effluent water turbidity is meeting the 1 NTU drinking water standard. Also, total coliform bacteria levels typically are less than 100 org/100 mL in these mountain waters. Thus if the coliform concentration in the finished water is only 50 org/100 mL it does not mean that effective filtration has occurred; the percent removal may have been very little. Similarly, the percent removals of turbidity are typically only 20-50 percent, e.g. from 0.5 NTU in raw water to 0.3 NTU in finished water. From this argument, a low turbidity level and a low total coliform bacteria concentration in the finished water do not indicate the water is safe for drinking. Giardia cysts, and indeed other pathogens, could be present in the finished water as various outbreaks have indicated.

Problems in Treatment

How to treat low turbidity water, e.g. water having turbidity less than 1 NTU, is insufficiently addressed in the literature, and it is not a part of

the lore of practice. The basic premise of rapid rate filtration is that effective coagulation must occur, leading to a floc. If abundant, a portion of the floc must settle in a sedimentation basin so that filters are not overloaded. The residual floc is intended to penetrate the filter media where it is stored until backwash. Backwash occurs when headloss becomes excessive, or when turbidity breakthrough occurs. The floc forms more readily when charged colloidal particles are present which are neutralized by a metal ion, e.g. Al^{+++}.

In low turbidity Colorado waters, colloid particles may be less abundant, and the coagulation reaction may not occur as indicated above. The mechanisms involved are not known. Probably it is a 'sweep' coagulation that occurs, as defined by Amirtharajah and Mills (1982), if alum is used as the primary coagulant. Neither has practice evolved, since the raw waters meet the 1 NTU turbidity standard. The role of temperature is not understood either. Whether the problem of difficult coagulation is due to low turbidity or low turbidity combined with low temperature is not known.

LITERATURE REVIEW ON RAPID RATE FILTRATION

Development

The first filter to supply water to a whole town was at Paisley, Scotland, completed in 1804. This was what is termed today a 'slow sand filter.' It is a technology that spread through Europe in the nineteenth century. The first slow sand filter built in the United States was at Poughkeepsie, New York in 1872, under the supervision of James Kirkwood. By 1890 only a few had been built in the United States.

American practice evolved along a different line, which resulted in what is known today as 'rapid rate filtration.' The technology had its origins in England when in 1791 James Peacock patented the idea of a 'reverse flow wash.' This is, of course, one of the distinguishing features of rapid rate filtration as contrasted with slow sand. The method of sediment removal in the former is termed 'mechanical,' vis a vis 'manual' for latter. The technology was developed further by a succession of European patents, each providing a slight improvement, or modification. The idea of mechanical agitation by rakes and of surface wash, were among the patented ideas.

The American activity began in 1867 in St. Louis with a patent, on a filter similar to Peacock's, by Henry Flad. In 1880 Daniel Otis in New York patented a filter with backwash, surface wash, and mechanical rakes.

In 1885 another basic distinguishing feature, chemical coagulation, was added to the rapid rate filtration technology. Col. L. H. Gardner, Superintendent of the New Orleans Water Co. conducted small-scale experiments on coagulation to clarify the muddy waters of the Mississippi River. At the same time Isaiah Hyatt, working on an industrial water supply using raw water from the same source, acted upon Gardner's suggestion to try a coagulant, perchloride of iron. Hyatt made a revolutionary advance, however, by combining this with filtration, using filters sold by the Newark Filtering

Company. In 1885 this new technology was first applied to a municipal water supply in Somerville, New Jersey. Hyatt claimed that by 1888 the technology had been adopted by some 30 towns.

By 1890 many commercial filter manufacturing companies had entered the market, each with its own patented variation of the same theme. Most of these filters were pressurized, and were premanufactured.

In 1891 the National Water Purifying Co. contracted with the City of New Orleans to supply clear water from the Mississippi River, for one of the largest mechanical filtration plants ever built. The plant used coagulation and filtration with no provision to first settle the sediment-laden waters of the Mississippi. The plant was a spectacular failure and the company could not fulfill its contract. Later the City of New Orleans took over operation and built what is called today a pilot plant, under the direction of Robert S. Weston, to learn how to treat these waters. From this work a 40 mgd water treatment plant, comprised of sedimentation, coagulation and filtration, was designed and put in operation in 1909.

The first comprehensive studies of the rapid rate filtration process were conducted by George W. Fuller. In 1895-97 the city of Louisville, Kentucky engaged Fuller, and others, to examine several patented processes including three makes of filters. This was after some 20 years of searching by Louisville for an effective filtration technology to treat the waters of the Ohio River. The greatest lesson of the Louisville experiments was to underline the important role of presedimentation and precoagulation in the operation of mechanical filters treating highly turbid waters. Cleasby (1981) credits Fuller with establishing the hydraulic loading rate criterion of 2 gpm/ft^2 (8.3 cm/min), which was adopted by virtually all state health departments and has remained almost inviolate until recent years. Fuller also acknowledged that without adequate chemical pretreatment, there is no assurance of acceptable water.

A new era in design of the mechanical filters was launched in 1902 when a 34 mgd mechanical filtration plant, designed by George W. Fuller, was placed in operation at Little Falls, New Jersey. In shape the filters were rectangular rather than round, and in structure they were reinforced concrete rather than wood or iron. Also the coagulants were added not at the point of entry of the water into the filter, but at the point of entry into a detention basin, to permit coagulation and flocculation (evidently without mechanical mixing). Also air scour was used in this plant.

At this point, which began really after the work at Louisville, the modern era of rapid rate filtration began. The technology was firmly established in the United States, and slow sand filtration never gained a strong foothold.

Later, by 1920, both baffle basins for rapid mix, and paddle wheel flocculation basins were used. These are mentioned by Langlier (1921), which is notable also because the idea of the classic jar-test was introduced in the same article.

Rapid rate filtration technology was studied further in the 1930's by Baylis at Chicago, together with Hudson (Baylis et al, 1971, and Hudson, 1981). Baylis showed that floc penetrates into the sand media, but that the amount of penetration depends upon the character of the floc. He showed also that finished water quality did not deteriorate with hydraulic loading rates as high as 5 gpm/ft^2 (24 cm/min).

The next substantial innovation was the introduction of dual media filtration, e.g. coarse anthracite and sand (Conley, 1961). The idea was to permit the chemical floc to penetrate into the filter, in accordance with the concepts by Baylis, and thus to permit longer filter runs. At this time the idea of high hydraulic loading rates, e.g. 5 gpm/ft^2 (24 cm/min) and even 8 gpm/ft^2 (33 cm/min), was further confirmed and reinforced. Stimulated by this work, higher rates were introduced into practice and were an established concept by the 1970's.

Principles

The basic premises of rapid rate filtration are based upon removal of turbidity from raw water so that the water is both safe and palatable for drinking. Usually if turbidity removal occurs, such that drinking water standards are met, significant removals of bacteria, viruses, cysts, etc. will occur also.

Turbidity is a measure of the light scattering intensity of colloidal suspended particles. According to Black (1948), to remove these colloids, their negative charges must be neutralized. This is possible by addition of a metal salt to the water such as $Al_2(SO_4)_3$ or $FeCl_3$, to provide a charge neutralizing cation, such as Al^{+++} or Fe^{+++}. This action 'destabilizes' the colloidal suspension and permits aggolmeration. Stumm and O'Melia (1968) have added further basic concepts to coagulation theory, pointing out that adsorption of coagulants plays a key role in the process. Coagulation of low turbidity waters is addressed in terms of 'sweep' coagulation. This has been described further by Amirtharajah and Mills (1982). In the process of 'sweep' coagulation, a metal precipitate forms as a crystal, which may, according to Edzwald (1981), enmesh the destabilized colloid, as for example $Al(OH)_3$. All of this is termed 'coagulation.' The terms are defined further by Hudson and Wolfner (1967) as 'the process of chemical reaction of the coagulant in water.' The rapid mix basin then has the purpose of bringing the reactants in contact. The rate of the reaction is proportional to the number of contacts per unit time, which is proportional to the mixing intensity, G (sec^{-1}), and the detention time, T, in the basin.

The crystals must grow in size to permit formation of a 'floc.' This occurs by slow agitation in a flocculation basin. The agitation is turbulence, which has the function of promoting contacts between particles. The objective of flocculation is to cause the floc to grow sufficient in size so that the floc suspension may be settled or filtered.

Usually, in most waters, the floc is abundant so that if all of it is permitted to reach the filters, the rate of headloss would be very high, thus

reducing the run length. For this reason, sediment basins are used before filtration to reduce the solids loading on the filter.

The filtration step is intended to remove the floc by permitting penetration of it into the filter bed. Here the characteristics of the floc are important. It is often described as being 'tough,' 'strong,' 'pin point,' 'fragile,' etc. According to Hudson (1981) if a large 'strong' floc reaches the filter bed there may be little floc penetration, and very short filter runs. The floc will merely accumulate on the surface of the filter bed.

The above treatment train, i.e., rapid mix, flocculation, sdimentation, filtration, is termed 'conventional' filtration. The beginning of this idea was described by Fuller in 1897 (as reported by M. N. Baker, 1949), who states, 'The evidence is very decisive that so far as practicable the suspended matter should be removed before reaching the sand layer, and that, at that point, the water should be thoroughly coagulated. Further it is clear that subsidence should be employed with waters of this character to a degree where the amount of coagulant to be applied just before the entrance to the filter should not frequently exceed 2 grains per gallon.'

Modern Theory

While modern practice began after the work of Fuller and his co-workers in 1897, modern theory began in the 1960's. Black (1948) provided the beginning, incorporating concepts of colloid chemistry as a basis for explaining coagulation. Langlier and Ludwig (1952) showed empirically, by jar tests, the role of pH and alum dosage on settled water turbidity, and the role of cation exchange capacity of the colloids.

In an effort to develop a more scientific basis for determining coagulant dosage, Black (1958, 1961, 1962), and Riddick (1961) introduced the idea of zeta potential. Instrumentation has been developed to measure zeta potential but the technique is not used widely.

The use of polymers as 'coagulant aids' and as 'filter aids' began about 1960 (Pugh and Heller, 1960). O'Melia (1969) has described the mechanisms concerning how the polymers interact with metal-ion flocs.

Coagulation theory began to develop a true scientific sophistication with the work of Stumm and Morgan (1962). This has been developed further by Stumm and O'Melia (1968) and by Stumm (1977). Also Ives (1977) conducted a NATO Advanced Study Institute, in which various persons developing coagulation theory were convened. Ives (1975) also conducted such an institute on the subject of filtration.

Ives' work on filtration (1961) was the beginning of modern filtration theory. Here he has introduced the idea of surface forces between the sand media and the particles to be removed. Camp (1964) has demonstrated also that floc will attach to sand grains and indeed coat them. This deviates from (or adds to) the concept that discrete floc particles enter the filter

and remain intact. At the same time, Cleasby and Baumann (1962) have worked continuously on the topic of filtration. They state that, 'the surface cake only develops where filtering a suspension that has a strong tendency to be removed at the surface, a suspension in which the particles have adequate internal strength to resisting the hydraulic shear force tending to wash them down into the filter.' From this the idea is further reinforced that the nature of the filtration process is dependent upon the kind of coagulation that has occurred.

Recent work has been directed toward 'direct filtration,' as described by Logsdon (1978, 1983) and Tate et al. (1977). This mode of filtration, defined as coagulation, flocculation, filtration, has been advocated in recent years for water having turbidity levels of less than about 30 NTU nominally.

The role of process variables has been investigated by Cleasby (1962) and Roebeck (1964). These investigations have been experimental.

Filtration of Low Turbidity Waters

The treatment of low turbidity waters has seldom been a specific concern in either theory or practice. Since the raw water may already have turbidity levels of less than 1 NTU, which meets the standard, there has been little impetus to understand treatment. Even with the preoccupation with removal of Giardia cysts, the concern has been to control the symptom rather than the cause. Indeed water treatment plants are designed usually toward the more severe turbidity problems occurring during spring runoff.

Some have reported handling of treatment problems involving low turbidity waters. These include the work at Lake Superior, related to removal of asbestos fibers, where raw water having less than 1 NTU turbidity was treated to produce a finished water of about 0.05 NTU and at Seattle where low turbidity Tolt River water was treated (Logsdon et al., 1983). DeWalle et al. (1984) have reported on treating waters having raw water turbidities of 1 to 5 NTU. They have shown that at the Hoquiam Water Treatment Plant, turbidity reductions of 90 percent are possible using alum treatment with 4 NTU raw water, but only 20 to 50 percent is possible using alum treatment when raw water turbidity is only 1 NTU. Without chemical pretreatment turbidity reduction is only 10 to 50 percent with 1 NTU raw water.

Effect of Temperature

Brief and scant information appears in the literature about the effect of temperature on coagulation and filtration. Most of the literature relates the temperature effect on pH, and the density and viscosity of water, as factors in floc formation. Conflicting conclusions concerning the effect of temperature on floc formation using alum or iron salts is drawn by past reseachers. Leipold (1934) found that temperaure change has no effect on floc formation or flocculation. Velz (1934) concluded that an increase in temperature required an increase of coagulant, and that a decrease in

temperature permitted a decrease in the amount of coagulant to produce the same result. Both of these findings are in conflict with the results by Mohtadi and Rao (1973) who studied the temperature effect on flocculation for synthetically prepared water. They found the decreasing water temperature required an increase in alum dosage to achieve the same degree of flocculation. Mohtadi and Rao found that a given degree of flocculation can be achieved with the same quantity of flocculant at different temperatures provided the flocculation is carried out at the optimum pH value. This confirms a similar finding by Camp et al. (1940).

In winter, mountain region surface waters are low in both temperature and turbidity. Operators often complain of difficulty in treating such waters. It is not known if this difficulty is due to the temperature effect or because of low turbidity influent water, or both. Because of such difficulty in treating this water and because the raw waters have turbidity levels less than 1 NTU, it is common practice to omit chemical pretreatment. The filter media acts as a strainer only and most likely passes microorganisms such as Giardia cysts (Logsdon, 1981).

To sum up, very little has been done to explore the effect of temperature on coagulation and filtration. Whether winter treatment difficulties are due to low temperature, or low turbidity, or both, is not addressed in the literature.

Filtration of Giardia Cysts

Logsdon (1981) reports that after reviewing the literature he found '...no research on water filtration for Giardia cyst removal.' Logsdon (1981) states also, that filtration studies of the 1930's and 1940's were, however, conducted for removing Entamoeba histolytica cysts.

SECTION 2

SUMMARY AND CONCLUSIONS

Removal of Giardia cysts by rapid rate filtration is associated with effective operation of the process itself, and not with any particular technique of operation. The fact that Giardia cysts have passed through water treatment plants employing rapid rate filtration is indicative of the fact that effective operation may not be occurring. Usually these cases have occurred in plants using raw water having low temperature and low turbidity. Difficulty in attaining effective operation under such conditions is believed, in this work, to be an industry generic problem. Thus to understand the factors influencing removal of Giardia cysts by rapid rate filtration requires a more comprehensive understanding of how to make the process more effective for low temperature, low turbidity raw waters, in general. Results are summarized in terms of percent removals of various parameters, e.g. Giardia cysts, total coliform bacteria, standard plate count bacteria, and turbidity. Then the effects of process variables on removals are reviewed. These include coagulants, dosages, mode of filtration, media, filtration rate, temperature, etc.

The experimental work was conducted using a laboratory-scale rapid rate filtration pilot plant, and involved 178 experimental test runs. To confirm the findings from the lab-scale pilot plant, the field-scale pilot plant was operated under a more limited range of conditions, e.g. coagulants and dosages were preselected, hydraulic loading rate was fixed, etc. Some 131 test runs were conducted using the field-scale pilot plant, with 31 using low turbidity water. Work with this pilot plant also examined Giardia removal efficiencies using water from Horsetooth Reservoir, which had turbidity levels of 5 to 10 NTU.

The sections following summarize the findings and conclusions of the research. First the findings relative to polymer selection for treatment of low-turbidity, low-temperature water are reviewed. Removal efficiencies are discussed second, and then the influences of process variables on removals are described. Finally the explorations concerning the use of surrogate indicators for Giardia cyst removal are reviewed.

CHEMICAL PRETREATMENT

The search for chemical coagulants focused on the use of polymers, to be used in conjunction with alum. Two polymers, Magnifloc 572C R and Magnifloc 573C®, were found to be highly effective in treating low

turbidity, low temperature water. Ten were tested and the others were found to be not effective for the low turbidity, low temperature conditions. Effectiveness was judged initially using turbidity removal as the measure. Based upon these results further testing was done to determine removals of bacteria and Giardia cysts.

The results show that it is feasible to treat effectively low turbidity, low temperature water by means of rapid rate filtration. To attain effective treatment polymer selection is critical and must be based upon screening, using turbidity removal as a measure of effectiveness. Determination of the range of effective dosages of alum and polymer requires additional testing.

REMOVALS

Removals of the five parameters tested were affected most by chemical pretreatment. With no chemical pretreatment percent removals varied from nearly zero to about 70 percent. With "nonoptimum" chemical pretreatment percent removals were more variable, but in general, improved only slightly. Using "optimum" chemical pretreatment, however, removals of turbidity consistently exceeded 80 percent, and removals of bacteria and Giardia cysts always exceeded 95 percent, with many removals more than 99 percent. These findings were corroborated by the field-scale testing.

These results again underline the importance of chemical pretreatment in rapid rate filtration. With no chemical pretreatment the process cannot be expected to provide an effective barrier to the passage of pathogens when they occur in the raw water supply. With proper chemical pretreatment, however, removals of bacteria and Giardia cysts can be expected to exceed 95 percent.

PROCESS VARIABLES

Process variables investigated included chemical pretreatment variables such as coagulant selection, dosages of coagulants, and sequence of coagulant additions, and mode of process train, i.e. "in-line" or "direct." Also, investigated were the use of both single media and dual media, filtration rate, temperature, and run time. All of this was done using the lab-scale pilot plant.

Coagulant Selection

Ten polymers were tested with respect to effectiveness in turbidity removals for low turbidity waters. They were tested as primary coagulants, as coagulant aids with alum, and two were tested as filter aids. The filter aid polymers were found to be not effective with results about the same as when no chemicals were used. Two coagulant aids, Magnifloc 572C R and Magnifloc 573C R , were found to produce turbidity removals generally over 80 percent when used with alum. Removals of bacteria and Giardia cysts exceeded 95 percent when using these polymers as coagulant aids. Results with the other polymers were more variable.

Dosages of Coagulants

The "surface" of percent turbidity removal was "mapped" as a function of alum dosage and polymer dosage, using Magnifloc 572C R . The "mapping" showed that the polymer alone is not effective, nor was alum alone (except at dosages of about 40 mg/L). With only a small alum dosage, however, e.g. about 2 to 5 mg/L, 1 to 2 mg/L of polymer was effective in reducing turbidity levels from <1 NTU to as low as 0.05 NTU. This surface remained relatively flat at 0.05 NTU or at 0.1 NTU, for alum-polymer dosages in any combination up to 20 mg/L alum and 8 mg/L polymer. Removals of bacteria and Giardia cysts exceeded about 95 percent, and more frequently than not exceeded 99 percent, for dosage combinations which gave the highest percent removal of turbidity. The "optimum" dose was deemed to be the lowest certain to give the highest turbidity removal efficiency. This was the approximate dose range used for the field-scale testing.

Field-Scale Testing of Coagulants

Filtration Without Coagulation--

The results of the field-scale testing also confirmed the necessary role of chemical pretreatment in effective filtration of low-turbidity water. Tests with the WATER BOY showed that without chemical pretreatment, i.e. a coagulant dosage of "none", large numbers of Giardia cysts and coliform bacteria passed through the filter, while turbidity removals were only about 10 percent. This was shown for two waters, Horsetooth Reservoir water having turbidity levels of 5 to 10 NTU, and Cache La Poudre River water having turbidity levels of <1 NTU.

Coagulation of Horsetooth Reservoir Water--

The field results showed that when using Horsetooth Reservoir water all polymers tested, either alone or with alum, were highly effective, e.g. >90 percent removals occurred for Giardia cysts and coliform bacteria, and removals were often >99 percent. Removals were equally high for both "nonoptimum" coagulant dosages and for "optimum" coagulant dosages. Thus removals were not highly sensitive to differences in polymers or to dosages of a given polymer for this water.

Coagulation of Cache La Poudre River Water--

Results for testing using water from the Cache La Poudre River showed that only one chemical combination tested, Magnifloc 572-C used with alum, was effective in coagulation for filtration of low-turbidity water. For this combination at "optimum" dose removals were >94 percent for both Giardia cysts and coliform bacteria. Removals for the "nonoptimum" dosages, or removals with other coagulants, were about the same as for the "none" coagulant dosage condition, e.g. removals were only 30 percent nominally. These findings underline the importance of coagulant selection and dose determination when filtering low-turbidity waters, i.e. those having turbidity levels less than 1 NTU.

Sequence of Coagulant Additions

Generally in practice, if a two stage rapid mix is used, alum is added in the first stage and polymer is added in the second stage. Alternatively, both may be added simultaneously in one basin.

The results showed that effluent turbidity levels from the filters were the same whether alum and polymer added in sequence or simultaneously. Filtered water turbidity levels were noticeably higher, however, for the polymer-alum sequence.

These results show that a single basin, with both alum and polymer added simultaneously, is as effective as the use of two basins in sequence. Pilot testing should be conducted, however, as each water is unique.

Mode of Filtration

Two modes of filtration were investigated, "in-line" and "direct." Removals of turbidity were the same for both modes when using raw water having turbidity levels of less than 1 NTU. In-line filtration was tested also for waters having turbidity as much as 14 NTU. While turbidity removal efficiency was high, headloss increased rapidly, which would indicate short filter runs.

Water treatment plants could be designed to permit use of "in-line" filtration over the period when turbidity levels are about 1 NTU, which may extend from about August to April in the Rocky Mountain Region. Again, pilot testing should be conducted. Such plant should be designed for flexible operation, to permit "in-line" filtration when raw water turbidities are low, with "direct" filtration as another option, and conventional filtration for the high turbidity spring runoff conditions.

Comparison of Media

The use of both single media and dual media was compared with respect to turbidity removal. Turbidity removals were the same for both media for several conditions of chemical pretreatment, including no chemicals. The initial headloss for single media was appreciably higher, however, than for dual media, e.g. 11 cm Hg versus 6 cm Hg. This difference can be accounted for by the differences in sand depth. The rate of headloss increase was higher also for the single media.

These results showed that both sand and dual media have the same effectiveness in removal of turbidity. The appreciably higher headloss and higher rate of increase of headloss seen in the sand filter confirm that a single media filter is not attractive as an alternative for practice.

Filtration Rate

Removals of turbidity, bacteria, and *Giardia* cysts were measured for filtration rates of 8, 20, 32, and 41 cm/min (e.g. 2, 5, 8, and 10 gpm/ft^2).

All removals were high ranging from 90 percent for turbidity to 99 percent for total coliform bacteria, and showed no appreciable change in percent removals for filtration rates of 8, 20, and 32 cm/min. A noticeable decline was seen, however, for the filtration rate of 41 cm/min.

Thus, for filtration of low turbidity waters, the rate of filtration up to 32 cm/min has little effect on pecent removals. If higher rates are contemplated, pilot testing should be conducted.

Temperature

Pairs of tests were conducted at 5°C and at 18°C for identical conditions. Four such pairs of tests were conducted for four different coagulant dosages. Percent removals were measured for turbidity, standard plate count bacteria, and total coliform bacteria. The data are not conclusive. Some pairs show almost identical removals between the two temperatures, while others show an appreciable difference. Further experimental work is warranted.

Run Time

Removals of turbidity, standard plate count bacteria, total coliform bacteria and Giardia cysts were measured at "run times" of 30 min and at 90 min. There were not appreciable differences in percent removals for the two "run times." Percent removal of turbidity was seen to increase sharply from zero minutes to 30 minutes and to remain about the same thereafter. The noticeable change in the 0-30 min period was due to the time required for coagulated water to travel from the rapid mix basin to the filter effluent. Filter to waste would be warranted only to insure that the coagulated water is in contact with the filter, vis-a-vis in treated water used in backwash. Mixing of coagulated water with backwash water would cause a nonoptimum dosage to be applied to the filter.

SURROGATE INDICATORS OF GIARDIA REMOVAL

Exploration of relationships between the dependent variables, e.g. turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts, was done by means of plots and statistical analyses. All of the above dependent variables (except Giardia cysts) were examined to determine if a relation existed between percent removal of the given parameter and percent removal of Giardia cysts. Histogram plots showed definite relationships, e.g. high percent removals of turbidity were associated with high percent removals of Giardia cysts. Statistical tests, e.g. the student t-distribution, showed 99.5 percent confidence levels, indicating that functional relationships exist between removals of the above parameters and removals of Giardia cysts.

All parameters examined were found to be suitable as indicators of percent removal of Giardia cysts by rapid rate filtration. Turbidity is recommended because it is easy to use. In general, if 70 percent turbidity removal is achieved, then there is 0.85 probability that removals of Giardia

cysts exceed 95 percent. Similar relationships exist for the other parameters investigated. There was a lower confidence level, however, using particle counting as a surrogate indicator.

Turbidity was found to be a good indicator of percent removals of other parameters as well, e.g. standard plate count bacteria, and total coliform bacteria. High removals of turbidity, e.g. from 0.5 NTU to 0.1 NTU, are evidence that filtration has occurred with effective coagulation. If effective coagulation-filtration occurs, then very high removals can be expected for all substances, e.g. bacteria, cysts, etc.

Field-scale results showed that percent removals of turbidity were associated with percent removals of Giardia cysts and coliform bacteria. These associations were established in testing using waters from both Horsetooth Reservoir and the Cache La Poudre River. Also associations were established between percent removals of coliform bacteria and percent removals of Giardia cysts. These associations indicate that coagulants effective in reducing turbidity by more than 80 percent will remove coliform bacteria and Giardia cysts at the 90 to 98 percent level, corroborating findings at the lab-scale.

Percent removal of total coliform bacteria would be an excellent indicator of filtration efficiency. In low turbidity water situations, however, the ambient water concentrations of total coliform bacteria are very low, e.g. 0-100 org/100 mL. Because suitable measures of filtration effectiveness may be lacking when dealing with low turbidity waters, the use of a lab-scale pilot plant, operated adjacent to the full scale plant, is strongly recommended. The raw water for the pilot plant could be spiked with a source of coliform bacteria as a means to evaluate existing or contemplated treatment.

SECTION 3

METHODS

RESEARCH PLAN

The research plan was based upon utilization of two physical models of the rapid rate filtration process. One was a 1.32 L/min flow capacity laboratory-scale rapid rate filtration pilot plant, constructed for this research. The other was a 76 L/min flow capacity trailer mounted WATER BOY® field-scale rapid rate filtration pilot plant. The pilot plants were used to ascertain the effect of selected independent variables on a group of dependent variables. The dependent variable of major interest was the removal of Giardia lamblia cysts. Others included removals of turbidity, standard plate count bacteria, total coliform bacteria, and particles. The independent variables, which are "process" variables, are the coagulants used, dosages of coagulants, coagulant sequence, mode of filtration, filter media, filtration rate, temperature, and run time. Thus the research plan was to conduct experiments varying the magnitude or a characteristic of each independent variable systematically while holding the others constant, and at the same time, measuring the responses of the dependent variables. The laboratory-scale pilot plant was used to test the effects of many process variables over a wide range. The field-scale pilot plant was used to confirm findings obtained using the laboratory-scale pilot plant. The range of testing was more limited and was done under ambient conditions.

In this section the overall research plan is described. It includes: a description of the testing space, an outline of the experimental design, and a review of the work plan.

Testing Space

Figure 2 illustrates the concept of the experimental "testing space." The dependent variables, Giardia cysts, turbidity, particles, total coliform bacteria, and standard plate count bacteria, are indicated by the heavy vertical arrow. They "respond" to the independent variables categorized as water characteristics, chemical basin conditions, and filter condition. Within the categories the independent variables, i.e. process variables are identified. Twelve such variables are shown in this conceptual depiction. Conceptually each arrow represents a possible range of testing for the respective variable depicted. The temperature arrow for example indicates the range of the testing space for these experiments, e.g. 0°C to 20°C. It shows "tic marks" at temperatures where tests might be performed. The

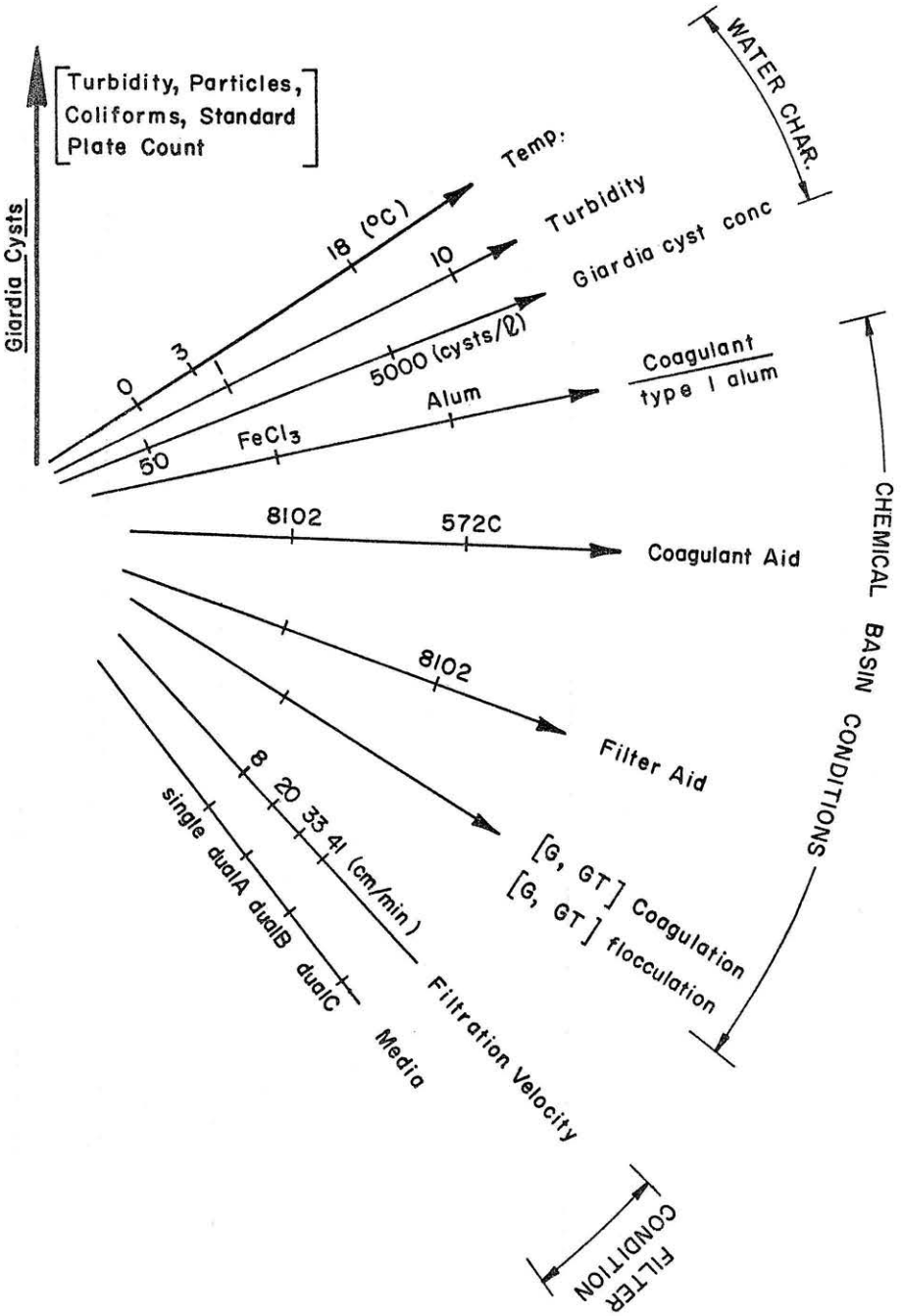

Figure 2. Experimental testing space illustrating the range of experimental work.

turbidity arrow shows tic marks at 1 NTU and at 10 NTU. This was the turbidity domain where all testing was conducted. But the focus of the experimentation was on waters having raw water turbidities of less than 1 NTU.

Figure 2 is an approximation of the actual testing space in which experiments were conducted for the laboratory-scale pilot plant. For the field-scale pilot plant the range of testing was more limited. The knowledge gained during the laboratory-scale experiments was used as the starting point in conducting the field-scale verifications. The main point is that within the range possible for each variable, tests were conducted only at selected points; otherwise the amount of testing would be prohibitive.

Experimental Design

Figure 3 is a three-dimensional matrix showing a portion of the experimental testing space for the laboratory-scale work. It illustrates a design for systematically conducting a sequence of experiments to evaluate the effect of process variables on removal of Giardia cysts by rapid rate filtration. The matrix shows the sequence of testing by starting the experiments at the easiest condition for removal of Giardia cysts, deemed to occur at point 1, where coagulation should be easiest. If substantial Giardia cyst breakthrough occurs under such conditions, then one would conclude that rapid rate filtration is not effective under any conditions. Then we terminate experiment, "TE". If no substantial breakthrough occurs, "NB", then more severe conditions will be imposed in the sequence indicated. Finally, if we end up at point 8 (i.e. 5°C, <1 NTU, 33 cm/min), and no breakthrough occurs, we can conclude the rapid rate filtration is highly effective under the most severe conditions. If any of the tests are terminated, indicated as "TE," then different coagulants will be tried and the sequence will be repeated. While this diagram is for illustrative purposes only, it shows conceptually the approach toward the research.

Plan of Experimentation - Laboratory-Scale Pilot Plant

The first task in the experimental program was to screen polymers for use as coagulant aids. Several hundred polymers are on the market. This was done using a "jar-filter" test technique, reported by Choi (1983) and by Brink (1984). Nine polymers were obtained as samples from manufacturers and were tested in conjunction with alum as the primary coagulant. Turbidity removal was the measure of effectiveness used. Two polymers, Magnifloc 572C® and Magnifloc 573C® were selected for conducting most of the experimental work using low turbidity water.

The next step involved comparing single media of sand with dual media of anthracite and sand. Since the rate of headloss increase was higher with single media, further testing was done exclusivey with dual media.

Also in the initial period two modes of rapid rate filtration were compared, e.g. "in-line," which is rapid mix followed by filtration, and "direct," which is rapid mix, flocculation, and filtration. Since results

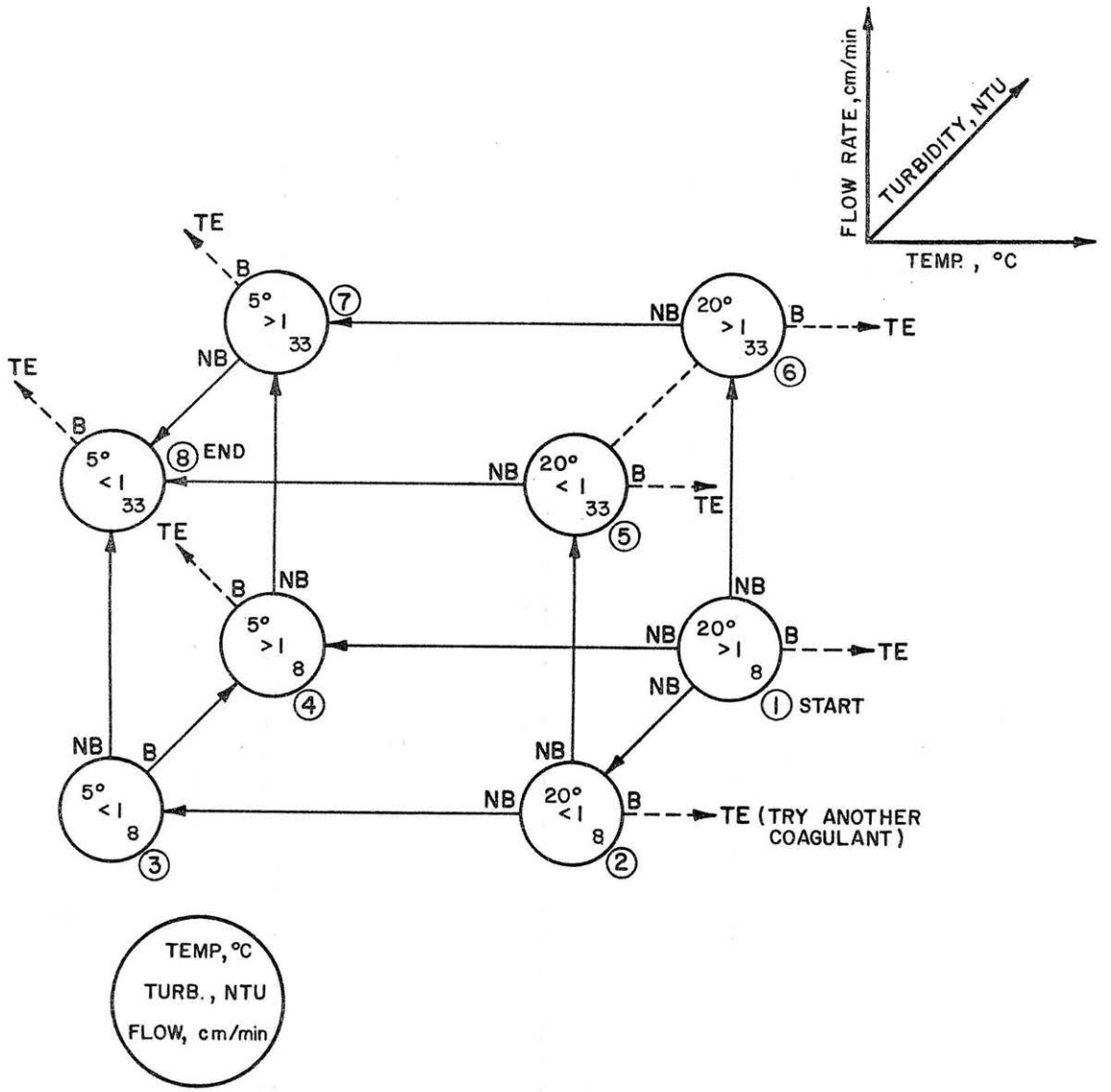

Figure 3. Matrix of testing space illustrating conceptually a possible sequence of experiments using the laboratory-scale rapid rate filtration pilot plant.

were the same all further work was done using "in-line" filtration.

In addition, for the purpose of learning the behavior of the system and to develop experience, raw water from Horsetooth Reservoir was used in initial exploratory testing. This water is more easily treatable as compared with low turbidity water. The data obtained are indicated in Table A-1, but they were not a main focus of this research.

After these preliminary results were obtained, the research could focus on fewer variables, such as filtration velocity, temperature, etc. Table 3

Table 3. Process variables and their operating conditions during rapid rate filtration experiments for *Giardia* cyst removal.

Process Variable	Operating Conditions
Raw water	(1) Horsetooth Reservoir water treated with diatomaceous earth to reduce turbidity to less than 1 NTU. (2) Cache La Poudre River water, winter condition at <1 NTU.
Temperature	$3^{o}C$ and $18^{o}C$
Coagulants	Alum Polymers Magnifloc 572C Magnifloc 573C Nalco 8102
Coagulant sequence	Alum added first then polymer Polymer added first then alum Alum and polymer in same mixing basin
Filter media	Single media: 76 cm bed sand D_{10} = 0.43, UC = 1.5 Dual Media: 30 cm sand bed D_{10} = 0.43, UC = 1.5; 45 cm anthracite D_{10} = 0.9, UC = 1.5 Dual Media: 30 cm sand bed D_{10} = 0.5, UC = 1.4; 45 cm anthracite D_{10} = 0.9, UC = 1.5
Hydraulic loading rate	2,5,8 gpm/ft^2 (8.24, 22.5, 32 cm/min)
Pretreatment process	"In-line" mode, one or two stage of rapid mix with 180-290 sec detention time, and G = 40-300 sec^{-1} each stage

describes the process variables used in the experimental program and describes the operating range for each.

The dependent variables measured are listed in Table 4. They were chosen in order to provide a full complement of variables which possibly could serve as indicators of filtration performance. The same set of dependent variables were measured during both laboratory-scale and field-scale testing, except particles were not counted for the latter work.

Table 4. Dependent variables measured in testing rapid rate filtration performance.

1. Turbidity
2. Giardia lamblia cysts
3. Total coliform bacteria
4. Standard plate count bacteria
5. Particle counts

Plan of Experimentation - Field-Scale Pilot Plant

The overall research plan used for the field-scale experimentation is enumerated below.

i) Select coagulants based upon bench-scale and laboratory-scale pilot plant results.

ii) Establish fixed conditions for conducting the field-scale testing (e.g. filtration mode, hydraulic loading rate, etc.), based upon results of laboratory-scale pilot plant testing.

iii) Develop effluent turbidity vs coagulant dose curves for each coagulant selected in step i).

iv) Determine removals of Giardia cysts and coliform bacteria for each coagulant at "optimum" and "nonoptimum" dosages with respect to turbidity removal, and also for "zero" dosage of coagulants.

v) Establish the headloss and effluent turbidity vs time relations for the effective coagulants at "optimum" dosage.

vi) Execute steps i) to v) for Horsetooth Reservoir water and for low-turbidity Cache La Poudre River water.

The above plan encompassed two categories of testing: i) effluent turbidity vs coagulant dose; and ii) Giardia cyst and coliform bacteria

removals vs coagulant dose. The effluent turbidity vs coagulant dose tests were to establish relationships between finished water turbidity and coagulant dosage, for specified conditions (e.g. type of water, hydraulic loading rate, etc.). The purpose was to determine the "optimum" coagulant dosage range for the field-scale pilot plant, as defined by turbidity removal. The effluent turbidity after one-hour of operation was taken as the "stabilized" turbidity. No Giardia cysts or coliform bacteria were injected during these tests.

Once the relationship between effluent turbidity and coagulant dosage was established, tests were performed to determine removals of Giardia cysts and coliform bacteria at "optimum" and "nonoptimum" chemical dosages, and at "zero" dosages. The "zero" dosage tests were to establish a "baseline" to compare Giardia cyst and coliform bacteria removals with the same tests using coagulant chemicals.

The Giardia cyst and coliform bacteria removals vs coagulant dose testing protocol consisted of: i) backwashing; ii) starting the raw water pump, the chemical feed pumps, and the contaminant injection pump; iii) waiting for one-hour for the system to stabilize; iv) sample influent and effluent for Giardia cysts and coliform bacteria concentrations.

PILOT PLANT - LABORATORY-SCALE

The laboratory-scale rapid rate filtration pilot plant was the physical model used to conduct the experimental work over a broad range of process variables. Figure 4 is a schematic drawing of the pilot plant showing each of the components comprising it, e.g. chemical feed, rapid mix, flocculation, sedimentation, and filtration. Figure 5 is a photograph showing the overall layout. After the rapid mix, the pilot plant is dual train. It was set up to operate in "in-line," "direct," or "conventional" filtration modes. It was designed to permit maximum flexibility in chemical pretreatment, and in controlling process variables such as temperature and filtration velocity. Descriptions follow of the pilot plant components and their respective operations.

Description of Laboratory-Scale Pilot Plant

The pilot plant, shown in Figures 4 and 5, was designed for dual train operation to permit concurrent testing with two different independent variables. All components were designed for pressure operation because of limited height available for the filters. It has four filter columns, e.g. two of 5 cm diameter and two of 10 cm diameter. The maximum pumping capacity was 1.32 L/min. At this flow the pilot plant, with one of the 5 cm filters, could be operated for 16 hours duration with one filling of the 1400 liter milk cooler used to store the raw water supply. The maximum filtration velocity possible is 65 cm/min (16 gpm/ft^2) if one of the 5 cm filters is operated alone with the maximum flow of 1.32 liters/min. Appendix C shows the design computations and shop drawings for each unit process.

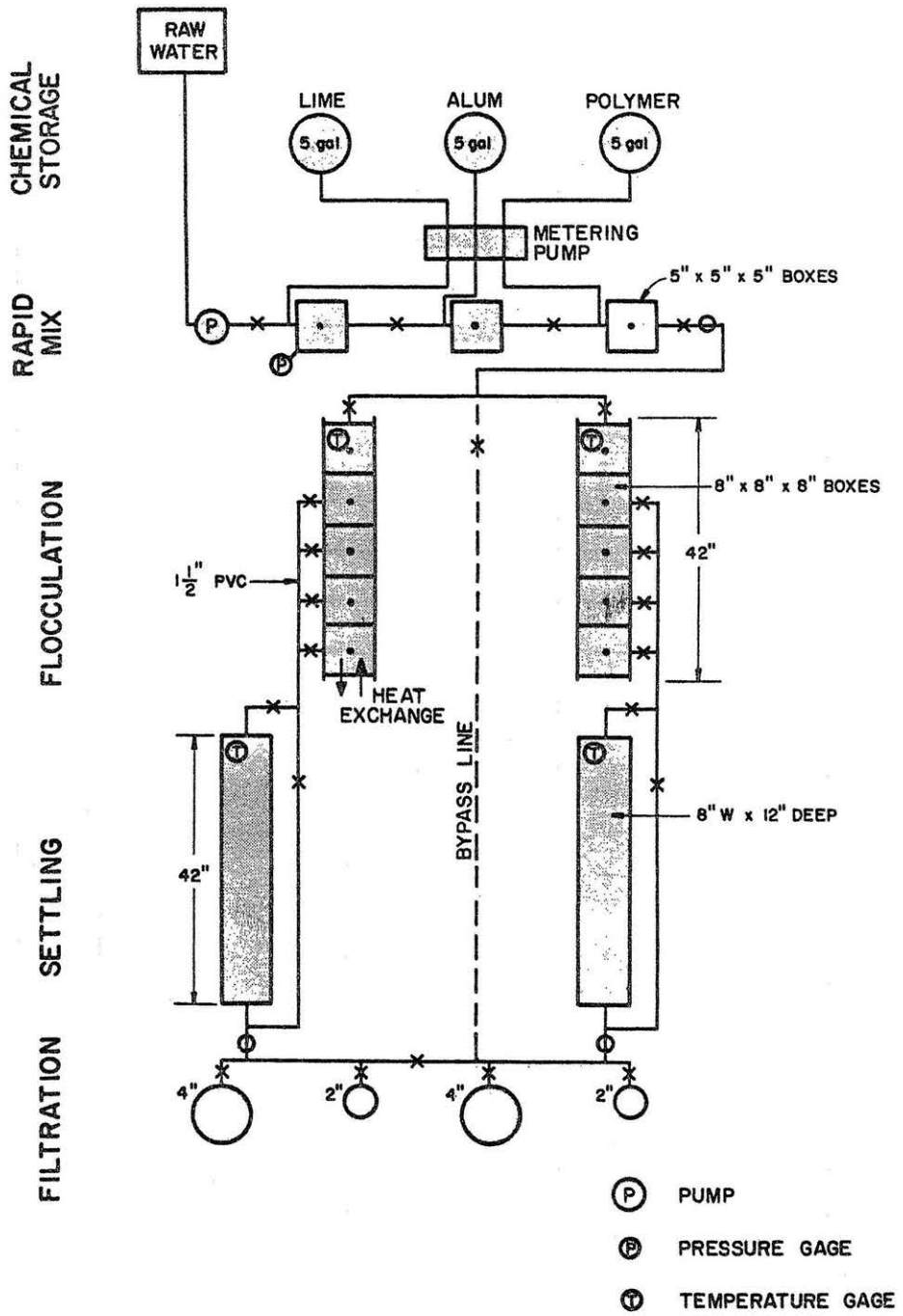

Figure 4. Schematic drawing of laboratory-scale rapid rate filtration pilot plant.

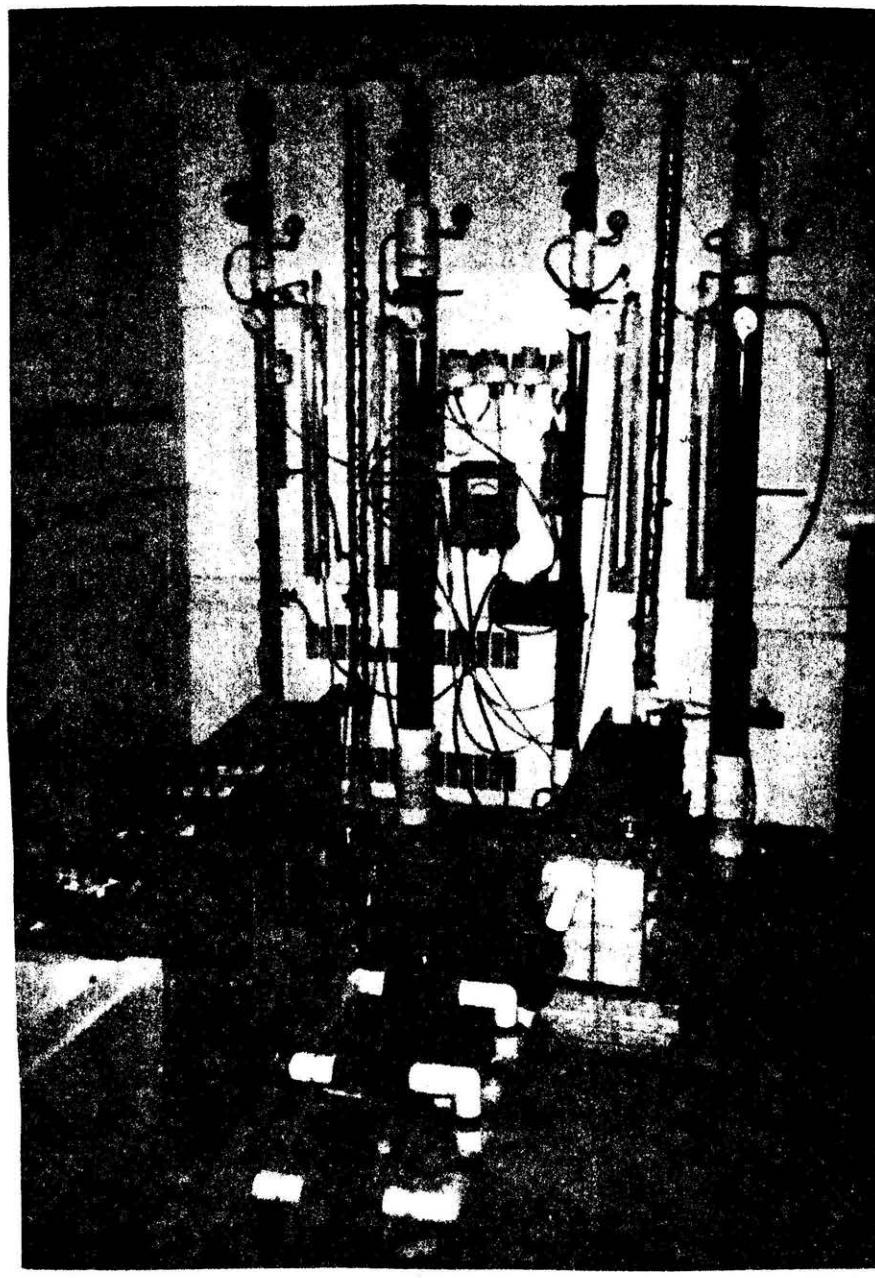

Figure 5. Photograph of laboratory-scale rate filtration pilot plant.

Water Storage—

A 1400 liter milk cooler was used for storage and temperature control of the raw water. Figure 6 is a photograph. For a filtration run, Giardia cysts and total coliform bacteria were added to the milk cooler in known concentrations.

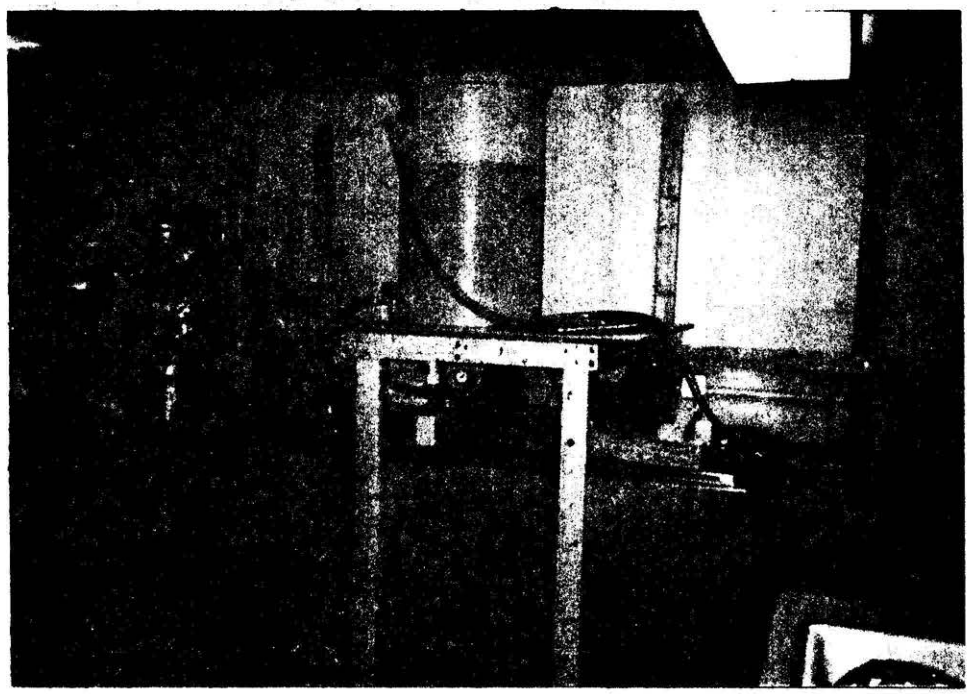

Figure 6. Milk cooler for storage and temperature control of raw water supply for laboratory-scale rapid rate filtration pilot plant.

Pump—

The pilot plant was operated under pressure using a Fluid Metering Model FMI piston pump, having flow capacity of 1.32 L/min. To control pressure fluctuations, a pressure damper was located after the pump. A pressure gauge was located at the top of the damper. Pressure fluctuations were not detectable.

Rapid Mix—

Three rapid mix boxes were located in series after the pump-damper unit. Figure 7 shows the units. These boxes are each 12.7 cm x 12.7 cm x 12.7 cm inside dimensions. Each stirring paddle has four rectangular blades 1.25 cm x 1.25 cm each, mounted on the stirring shaft. Appendix C gives complete design detail. The paddle speeds are controlled by variable speed motors. Chemicals may be added in sequence, one to each box from three storage tanks.

The piping from the pump to the rapid mix basins was modified from that shown in Figure 4 to permit flow directly to the second basin or to the third basin, as well as to the first basin. Also the flow from the third basin

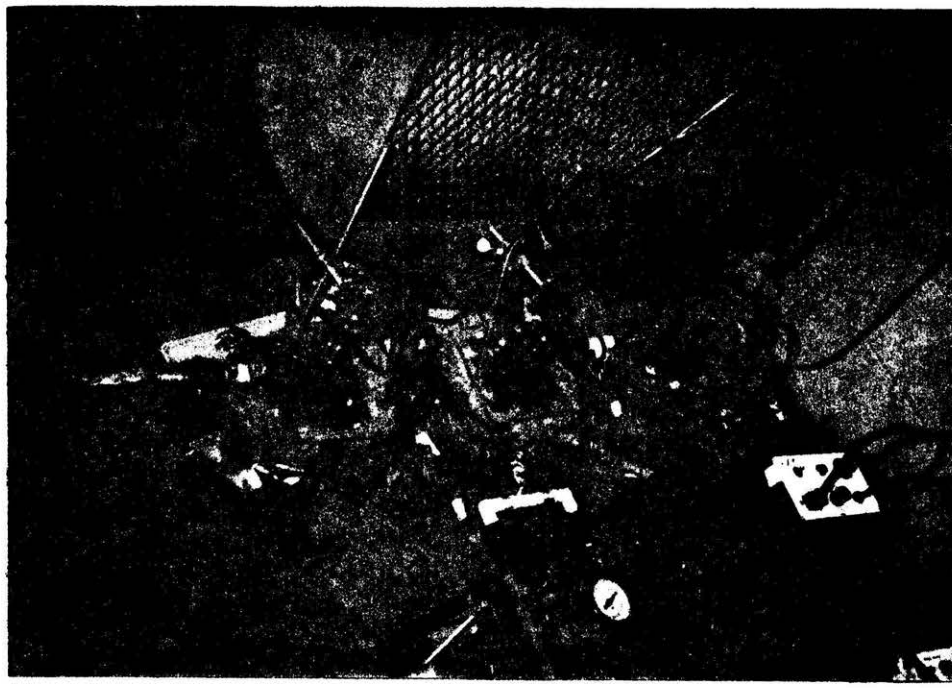

Figure 7. Rapid mix units, laboratory-scale rapid rate filtration pilot plant.

could enter either or both of the flocculation basins, or bypass these, using 2.54 cm inside diameter flexible tubing, to enter the filters.

Chemical Storage--

Figure 8 shows three 20 liter plastic tanks used for chemical storage. The chemicals were mixed and flows were controlled by a multichannel metering pump. The chemicals set-up was for lime, alum, and polymer, which was the designed feed sequence to the rapid mix basins. The concentrations of the chemicals in storage were matched to the low limit capacity of the metering pump, which was 0.2 mL/min, and the chemical dosage required. The maximum flow of a metering pump channel was 20 mL/min.

Flocculation Basins--

Figure 9 shows one of the two floccuation basins. The flow from the rapid mix may be split into the two basins. Each basin has five compartments, 20.3 cm x 20.3 cm x 20.3 cm dimensions. The basin can be operated using two, three, four or five compartments by means of valves on the pipe manifold.

Each compartment contains a flocculation paddle having four verticle blades 0.95 cm wide and 14.6 cm long, spaced 3.17 cm and 5.71 cm from the shaft. The paddles are driven by individual variable speed motors, controlled by rheostats, also shown in Figure 9.

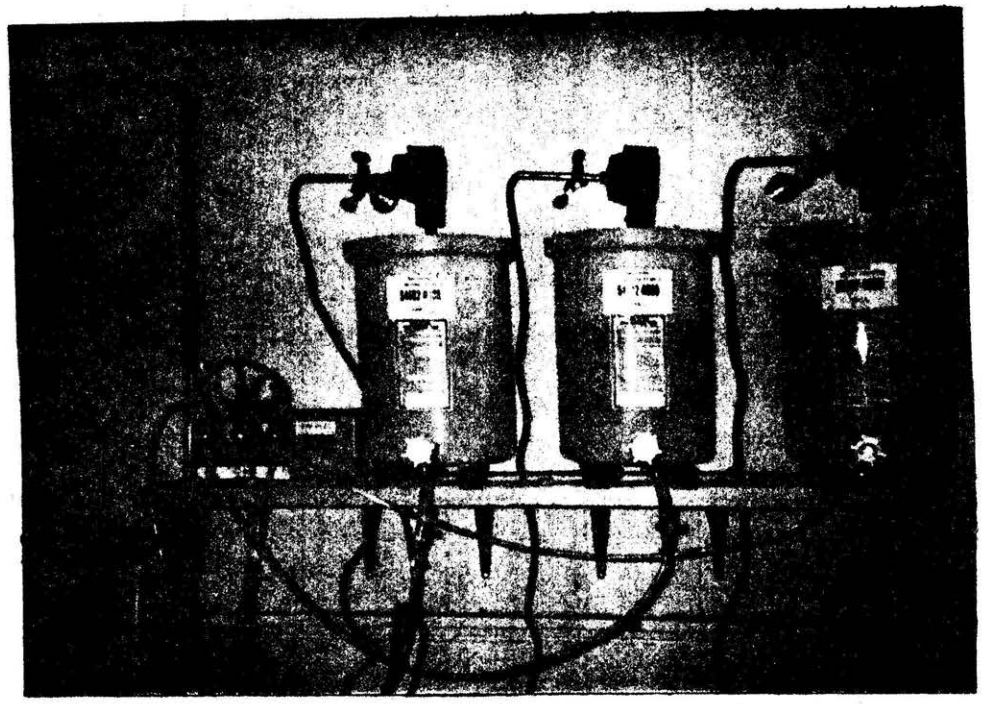

Figure 8. Chemical feed tanks and metering pumps, laboratory-scale rapid rate filtration pilot plant.

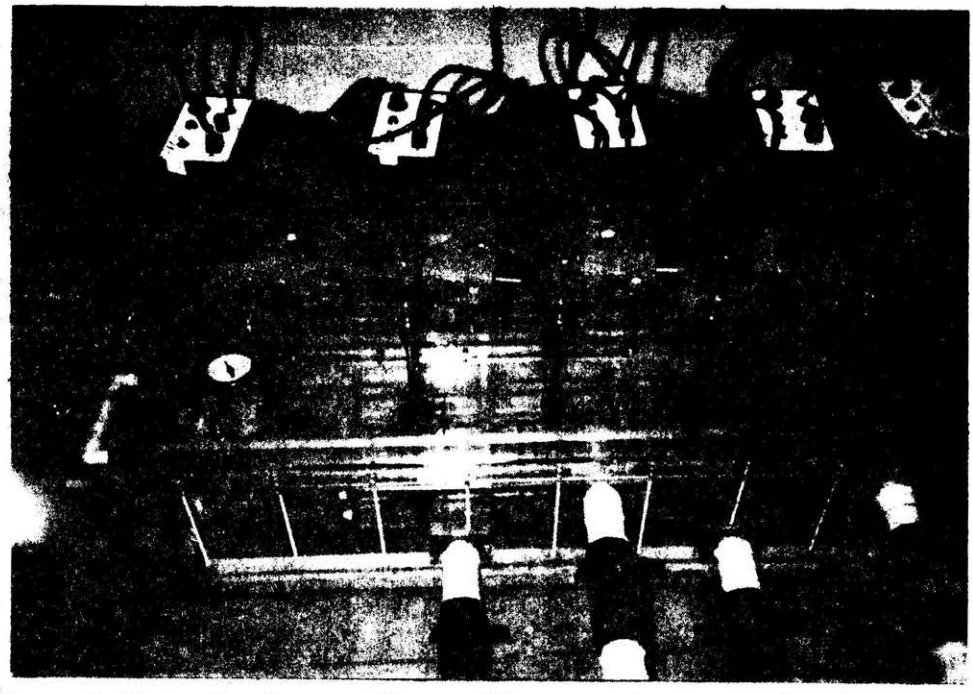

Figure 9. Flocculation basins with paddles, motors, and rheostats for laboratory-scale rapid rate filtration pilot plant.

The water temperature in the flocculation compartments could be controlled by 0.64 cm diameter copper tubes used as heat exchange elements. The coolant can be circulated from an external heat exchanger, capable of refrigeration or heating. Testing established that the heat exchange system can maintain freezing temperature in the flocculation basin in the refrigeration mode.

The manifold pipes from the basins are 3.8 cm dia. This large size was selected both to have sufficient velocity to maintain the floc in suspension, and to avoid floc breakup by turbulence. The pipes used were clear PVC plastic to permit observation of floc movement. This pipe system leads to the sedimentation tank but permits bypass to the filters.

Sedimentation Basin—

The sedimentation basin was designed to handle a wide range of detention times and overflow velocities. The former can range from 1 to 1.7 hr for the highest flows. Figure 10 is a photograph of the tank. The tank is 20.3 cm wide and 33.0 cm in depth at the head and 30.5 cm in depth at the end. The length is variable from 52 cm to 100 cm, through the use of partitions. If a short tank length is used the distance between the partitions can be connected by short pipe lengths. An air drain valve is located on the top surface of the basin. A copper tube heat exchange element is located inside for temperature control, which can be seen in Figure 10. The tank also has an inclined floor toward the head with a floor drain to remove settled floc and drain the basin.

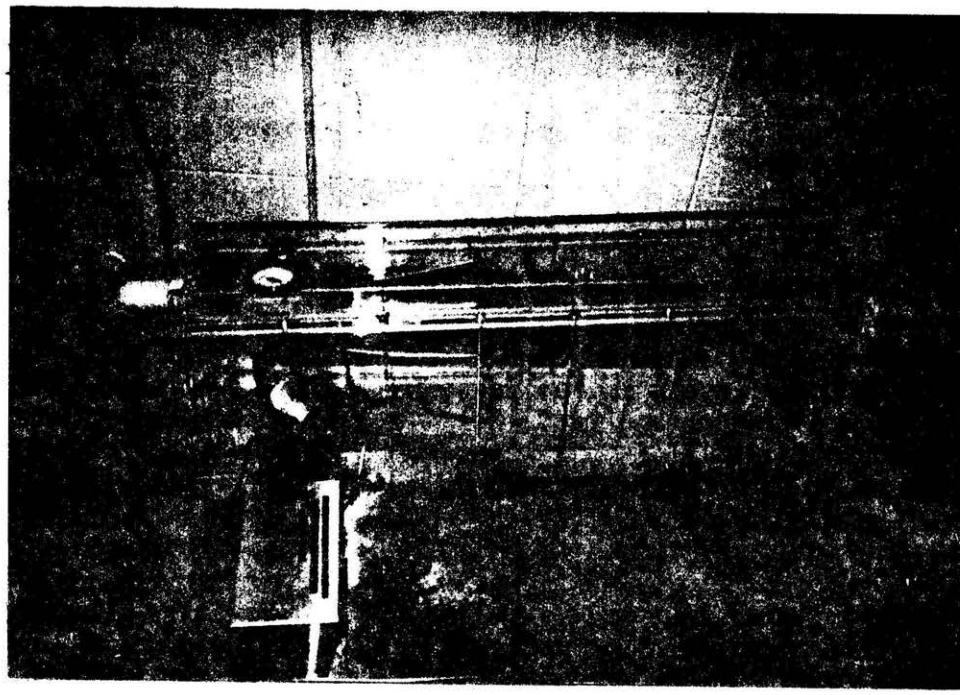

Figure 10. Sedimentation tank, for laboratory-scale rapid rate filtration pilot plant.

Filters--

Figure 4 shows the general layout of the four filters in relation to the other components. The photograph Figure 5 also shows the four filters in relation to the other components of the pilot plant. The filters, in sequence from left to right designated by inside diameters and media used in initial experiments, are: 5.0 cm sand, 10 cm dual media, 5.0 cm dual media, and 10 cm sand. Additional information on media was given in Table 3.

The manifold system to the filters permits operation of any combination of filters with either of the two flocculation-sedimentation trains. The system can be operated also from rapid-mix coagulation to filtration, i.e. "in-line" filtration.

The sieve analysis for the sand used is shown in Figure 11. The effective diameter was 0.43 mm, and uniformity coefficient was 1.50, which are common specifications in practice. The seive analysis for the anthracite is shown in Figure 12. The effective diameter was 0.9 mm and the uniformity coefficient was 1.5, which also conforms with practice.

Figure 13 shows a close-up for one of the 10 cm filter columns. The system was set up for air scrubbing conducted prior to or during to backwash. This also alleviates the problem of the entire media lifting at once during backwash. Headloss across the media in each column was measured by a mercury manometer. Tap connections were located at different distances along the length of the column. These permitted both sampling and pressure measurements between any two points. Temperature and pressure gauges were located at the top of the column.

The flow from any column could be directed through a 1.2 cm diameter pipe for Giardia cyst sampling as shown in Figure 14. Constant head overflow weir devices were located for tail water control, maintained above the media, which insured that negative pressures within the filters were avoided.

Operation

Sources of Water--

When turbidity levels in the Cache La Poudre River were 1 NTU or less then water was transported from the river by two trailer mounted 1000 liter tanks, shown in Figure 15. This water was then pumped to the milk cooler for use. The water was obtaind from the river at the site of Fort Collins Water Treatment Plant No. 1.

Flow--

The pilot plant flows were regulated by a positive displacement pump (FLUID Metering Model FMI®) having flow range between 0 and 1.3 liters/min. The flow was controlled by changing stroke length of the piston, which was calibrated on a dial. This was used to set the flow; measurement was made volumetrically.

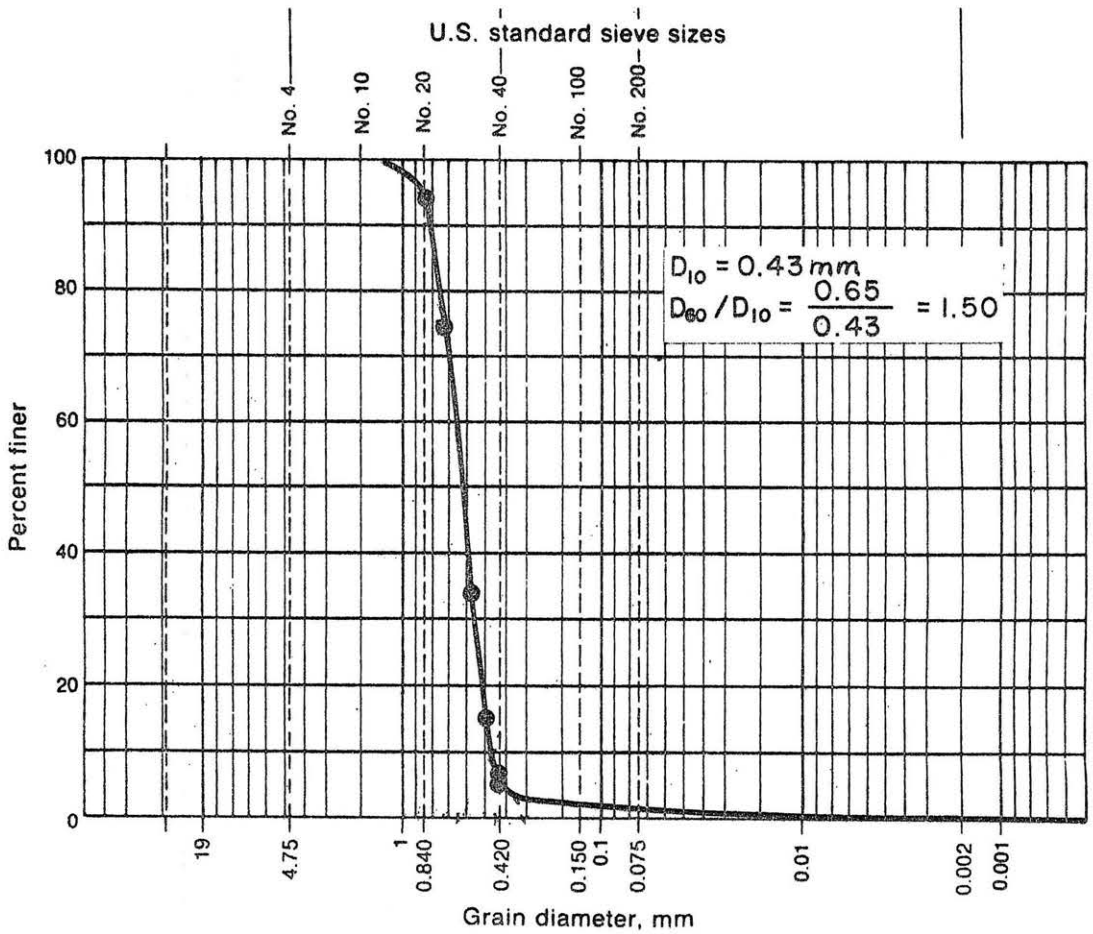

Figure 11. Sieve analysis for filter sand, used in sand filter and sand portion of dual media filter, laboratory-scale rapid rate filtration pilot plant. Source of sand was Loveland treatment plant at Big Thompson Canyon.

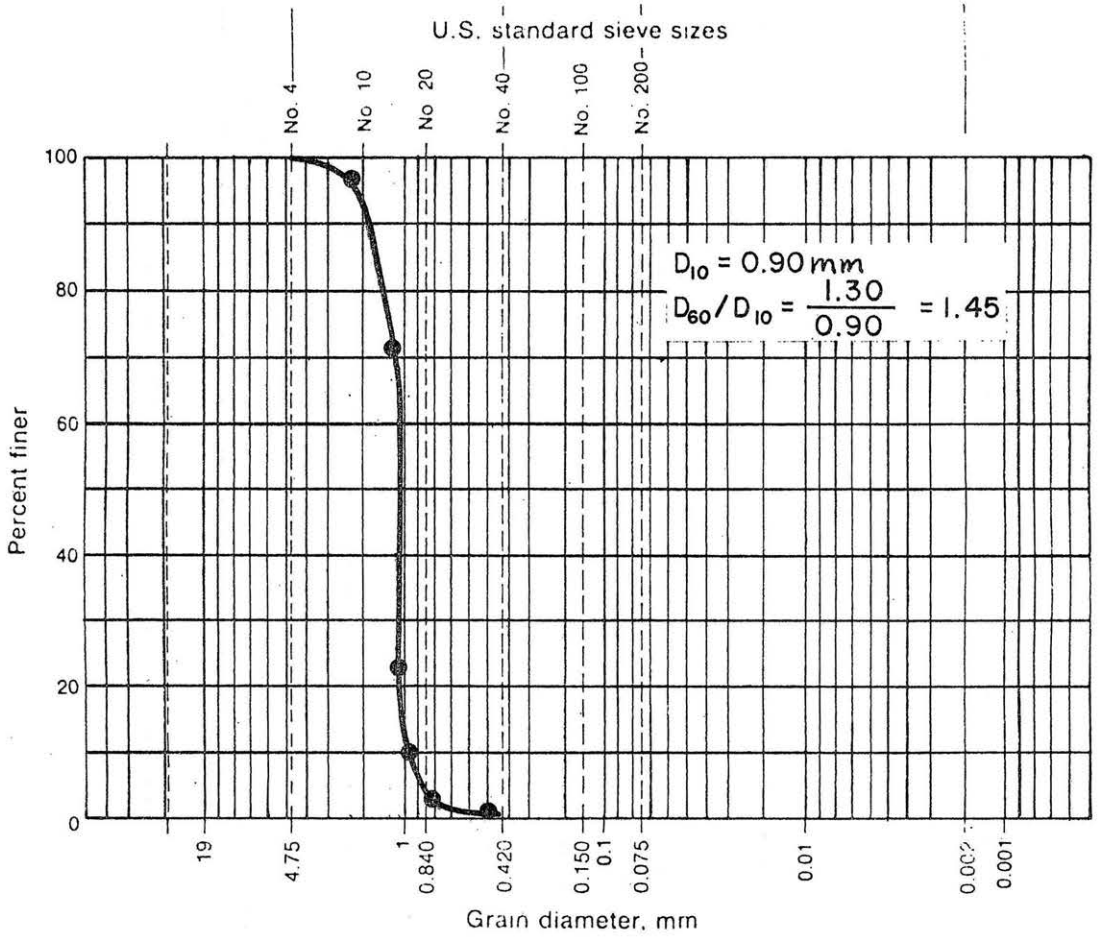

Figure 12. Sieve analysis for anthracite used in dual media filter, laboratory-scale rapid rate filtration pilot plant. Anthracite has brand name Philterkol Special No. 1.

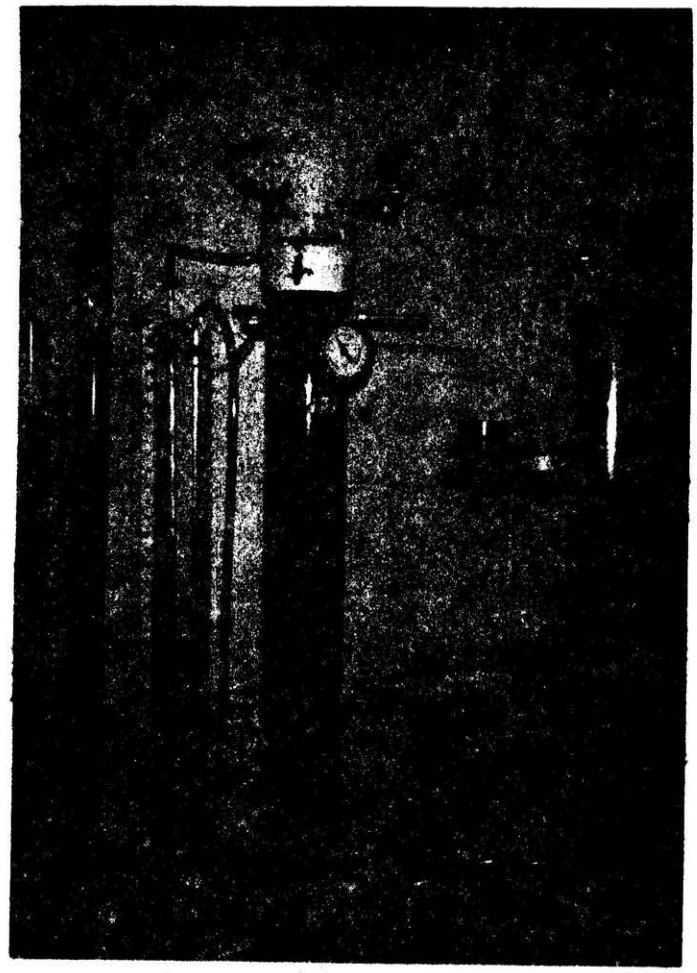

Figure 13. Close-up of 10 cm diameter filter column, laboratory-scale rapid rate filtration pilot plant.

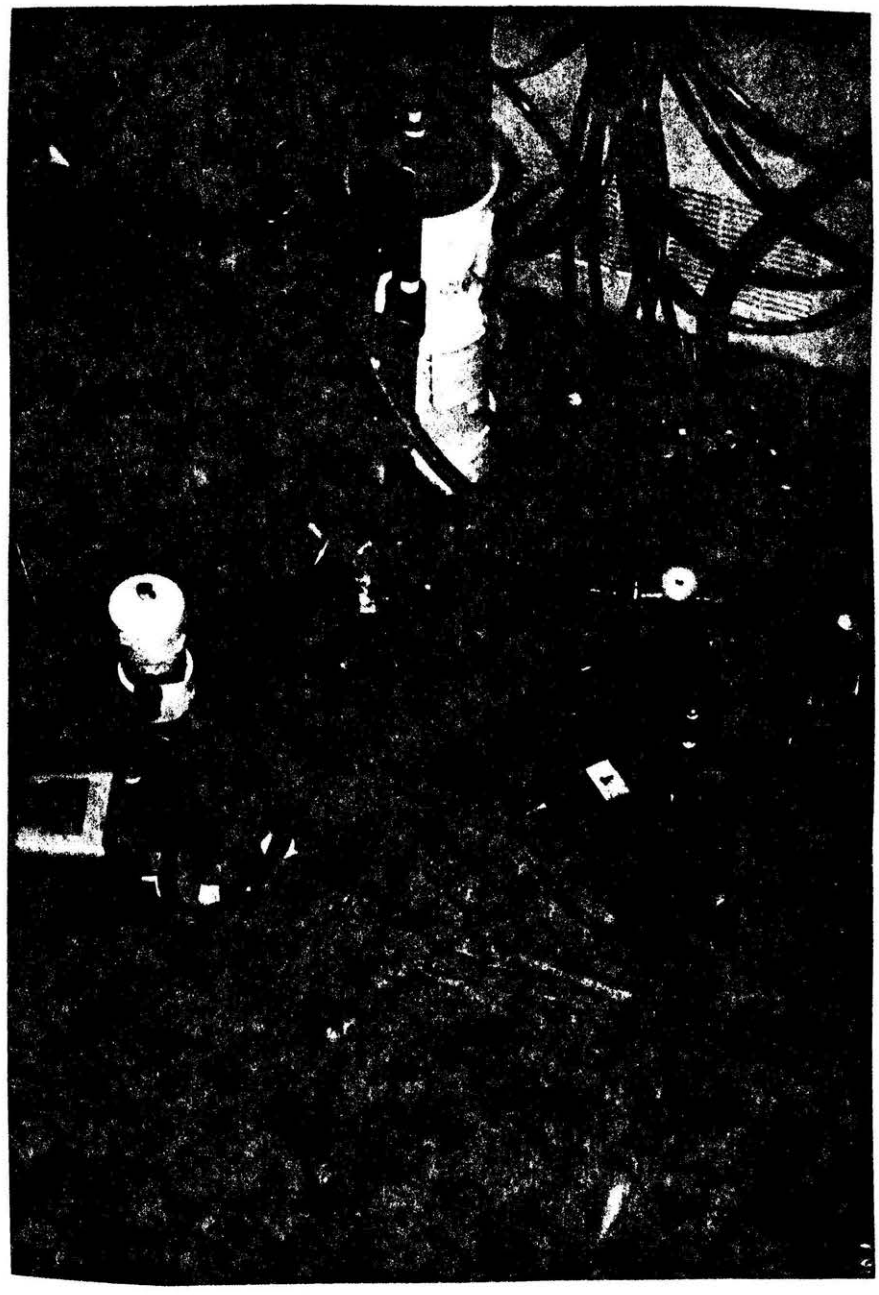

Figure 14. Membrane filter, 142 mm diameter, set up for *Giardia* cyst sampling of filter effluent, laboratory-scale rapid rate filtration pilot plant.

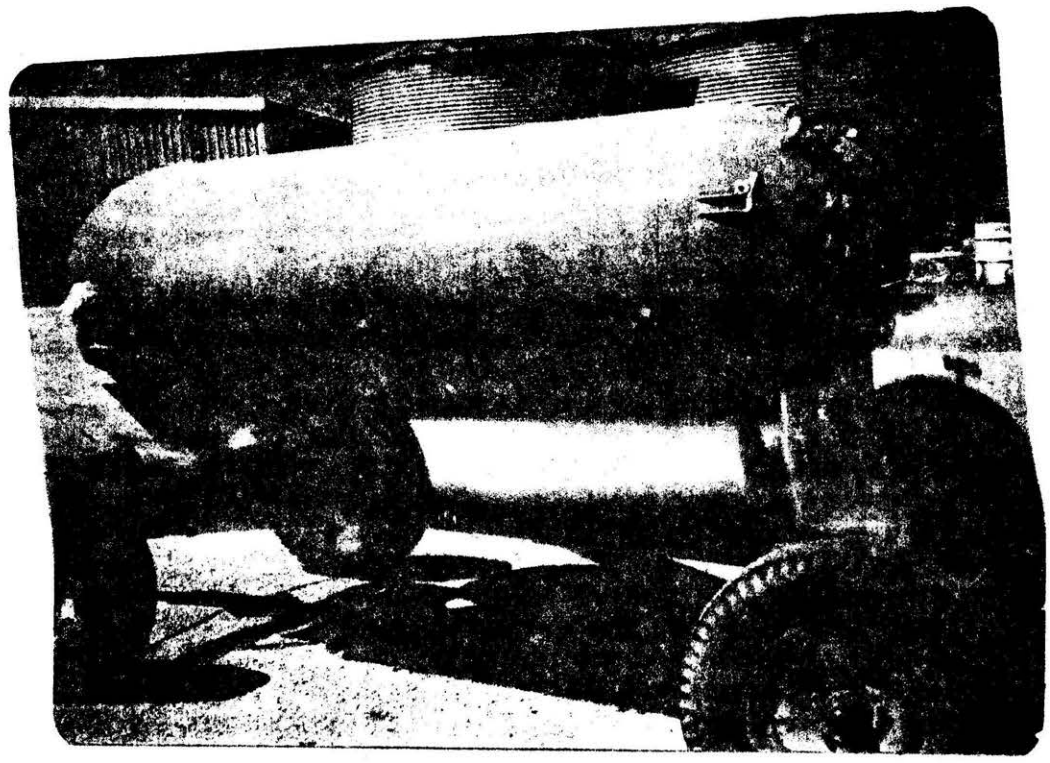

Figure 15. Tanks mounted on trailer for hauling water from Cache La Poudre River for laboratory-scale rapid rate filtration pilot plant. Tank capacity is 1000 liters each cylinder. Lining is stainless steel.

Rapid Mix—

As noted, the three rapid mix basins could be operated three or two in sequence, or using only one basin. The mixing intensity, as measured by velocity gradient G, could be controlled by varying the motor speed for the mixer, using a rheostat SCR Cole Parmer Model 4555-30 ®. The motor was a COLE-PARMER Model C-4555 ®, and had two shafts for different speed ranges. The higher speed shaft had an upper limit of rotational speed, in the coagulation box filled with water, of 720 rpm. Early in the experimentation rotational speeds used were only 150 rpm, with corresponding G of about 37 sec^{-1}. Later a speed of 600 rpm was used to give a G value of about 300 sec^{-1}. Appendix C shows the calculations of G for the paddle mixer design used. Figure C-7 shows the G vs paddle shaft rpm for 4°C and 20°C. Subsequent to Run 70, G values were maintained in the range 200 sec^{-1} to 300 sec^{-1}.

Chemical Feed—

Chemical feed rates were set and maintained by a Cole-Parmer Model C-7091 R multichannel positive displacement "bellows" pump. Flows were set by

using graduations for each channels used, and were measured volumetrically for 10 minutes duration. The range of flows possible was 0 to 20 mL/min for each channel. The flows used depended upon the concentration of the stock solution and the dosage required. Flows of stock solution were calculated by materials balance, e.g.

$$\text{Flow in pilot plant} \times \text{chem. conc. desired} = \text{Flow from stock sol.} \times \text{chem. conc. in stock sol.}$$

To illustrate, if the pilot plant flow is 450 mL/min, the polymer concentration desired is 3.0 mg/L, and the polymer concentration in the stock solution is 1 gm/L, then the stock solution flow must be 1.35 mL/min. These flows were checked volumetrically about once each hour.

The stock solutions were made up daily. The polymer stock solution, using liquid polymer, was made up by pipetting 1.0 mL of polymer, presumed to have density of 1.0 gm/mL, to 1000 mL of distilled water. The liquid polymer was presumed for measuring purposes to be pure polymer, albeit the polymer solutions as provided by the manufacturers have unspecified concentrations of both salt and water. The alum stock solution was made up using liquid alum, in which 10 mL of liquid alum, containing 6430 mg $Al_2(SO_4)_3.14H_2O$, was added to 990 mL of distilled water. Appendix I shows the calculations involving liquid alum, based upon manufacturers data.

Flocculation—

The flocculation basin was operated only for the first two test runs. Later, comparisons were made between "in-line" and "direct" filtration which documented that the effluent turidities were the same when using low turbidity waters. In preliminary testing it was established that the flocculation basin temperature could be maintained at about 3°c.

Sedimentation—

The sedimentation basins were not used. Settleable floc was not observed in any of the tests with low turbidity water.

Filtration—

In preliminary testing two filters were run simultaneously. With such operation, however, it was not possible to obtain all of the necessary readings due to the labor requirement. Therefore, only one filter was operated during subsequent test runs. The major concern was to maintain a selected filtration rate. This was done by volumetric measurements, every two hours. Temperature was maintained constant by copper coils in the head of the filter, using a Neslab Model RTE-4 ® circulating heat exchanger. The lowest temperature used was 3°C, since ice formation was a problem with lower temperatures. Pressure measurements were obtained in the head of the filter using a pressure gage. Headloss was measured by a mercury manometer.

Backwash was done at the termination of a test run. It was preceded by about 5 minutes of air scour, followed by 10 to 15 minutes of backwash in which the air scour was continued.

Three media were used during the testing program: single media of Loveland sand (from the Loveland, Colorado treatment plant), dual media (with Philterkol No. 1 ® anthracite and Loveland sand), and dual media (with Philterkol No. 1 ® anthracite and Fort Collins sand). The latter was used to be compatible with field-scale testing using the WATER BOY ® field-scale pilot plant.

Screening Chemicals--

Because of the large number of polymers available, and the thousands of dosage combinations, a bench-scale screening procedure was developed. This procedure was called the "jar-filtration" test, and is reported by Choi (1983) and by Brink (1984). The traditional jar test has no utility with low turbidity water, since flocs do not form. Therefore, it was decided to use the jar test as a simulated chemical pretreatment in conjunction with six small dual media filters, 5 cm diameter x 50 cm media depth. After rapid mix, the two liters of chemically pretreated water were poured through the filters, according to a procedure established. Effluent turbidities were measured and plotted as functions of chemical dosages. Typical U-shaped or L-shaped curves were always produced. Comparisons with the pilot plant results for the same conditions showed similar turbidity responses. Therefore, this procedure was used to screen polymers and to establish approximate dosages for the pilot plant testing. This procedure will be described in a forthcoming paper based upon the thesis works of Choi and Brink.

PILOT PLANT - FIELD-SCALE

A field-scale pilot plant was used to conduct further experiments under ambient raw water conditions. It was used to verify findings from the experimental work using the laboratory-scale pilot plant operated under controlled raw water conditions, such as using a uniform batch of water from a tank and with temperature control.

Description of Field-Scale Pilot Plant

Appendix D describes the field-scale pilot plant and its operation. Figure 16, which is the same as Figure D-6, is a schematic diagram of the WATER BOY rapid rate water filtration plant as modified for use in this research. Figure 16 shows the chemical feed system, the contaminant injection system, the sampling system, and the "in-line" filtration mode, which was used in this research. Figure 17 is a photograph of the WATER BOY. The WATER BOY is a Neptune Microfloc model WB-27 package water treatment plant. It was purchased by the U.S. Environmental Protection Agency Drinking Water Research Division in Cincinnati and mounted on a 22 foot trailer in order to have a mobile water treatment plant as a research tool. The plant was loaned to Colorado State University for this project.

Although nominally rated at 76 L/min (20 gpm), the WATER BOY has an upper limit water production capacity of 102 L/min (27 gpm), which is 16.6 m/hr (6.75 gpm/ft^2) hydraulic loading rate. At the production rate of 76 L/min (20 gpm), the plant can furnish water for 192 people based upon a per

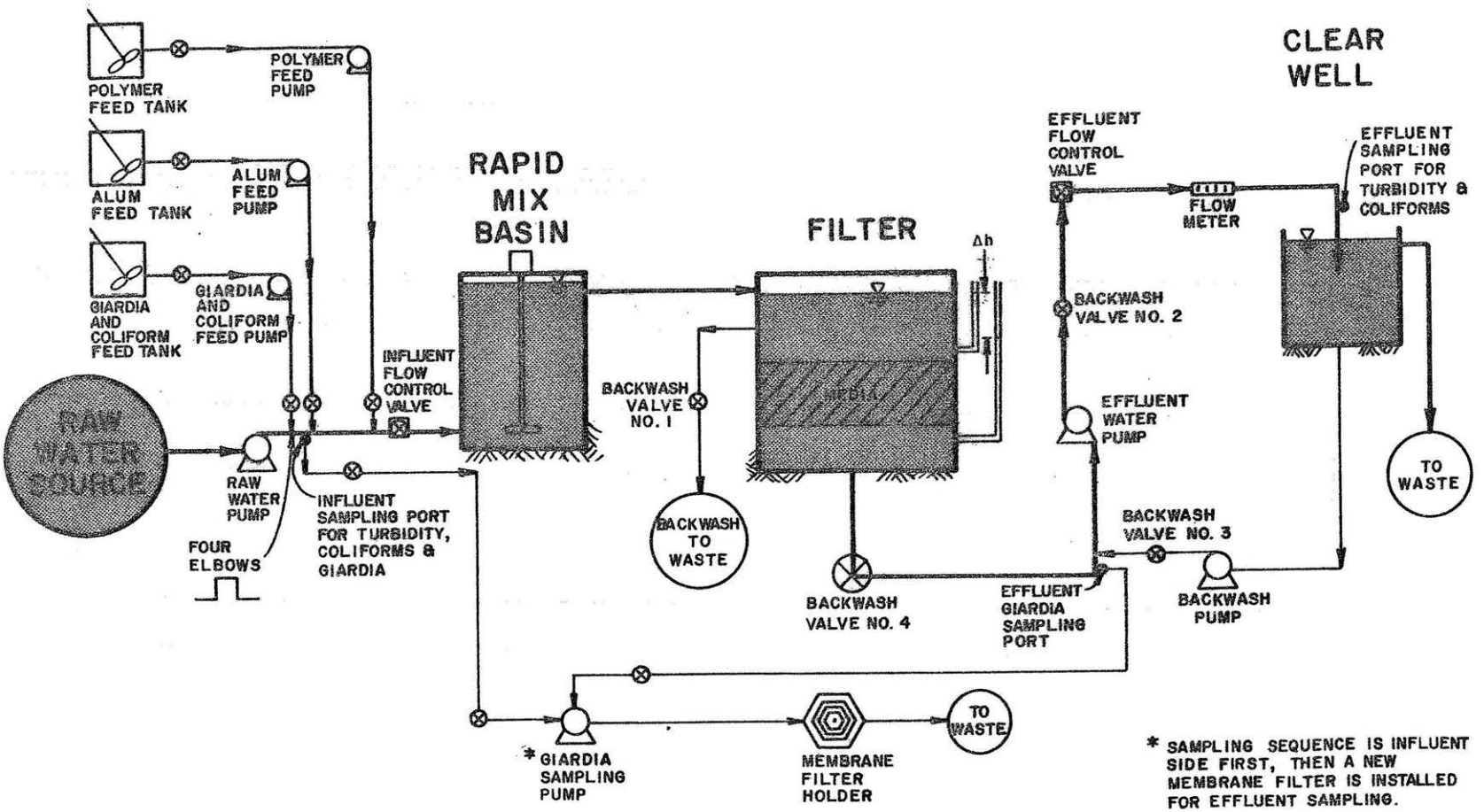

Figure 16. Schematic diagram of the WATER BOY pilot plant showing chemical feed, contaminant feed, and sampling system.

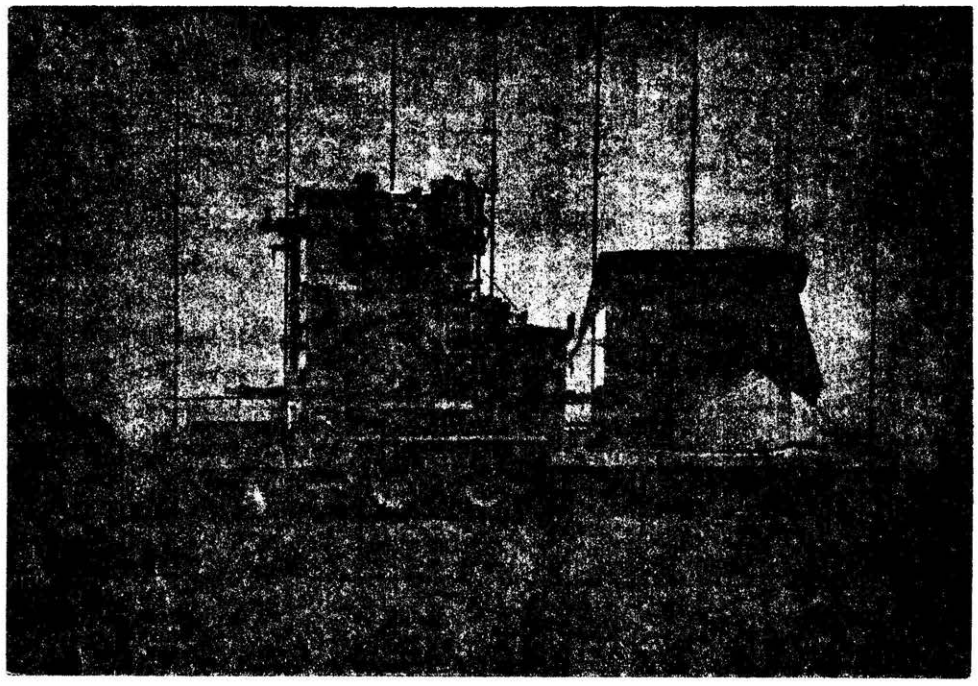

Figure 17. WATER BOY pilot plant on 22 foot trailer. The large cylindrical tank is the 4000 L clear well.

capita water consumption of 568 L/day/person (150 gpd/person). The plant is flexible in operation, permitting easy conversions between the three modes of filtration, i.e. "conventional" (rapid mix, flocculation, sedimentation, filtration), "direct" (rapid mix, flocculation, filtration), and "in-line" (rapid mix, filtration).

Appurtenances Utilized with Pilot Plant

Additional appurtenances were added to the pilot plant to provide for chemical feed, contaminant injection, and sampling. Figure 16 shows these appurtenances schematically, and Table 5 lists them. Special attention was given to in-pipe mixing of chemicals and contaminant injection. For example, the contaminants were injected into the middle of the pipe and four elbows were added to insure proper mixing prior to influent sampling at another point in the pipe. Similar precautions were taken to insure representative effluent samples. Appendix D describes the modifications for these purposes.

Test Conditions for Field-Scale Pilot Plant

Raw Water—

Three types of water were used in the field-scale pilot plant experimentation: i) Horsetooth Reservoir water, ii) Cache La Poudre River water during spring runoff, and iii) Cache La Poudre River water during late

Table 5. Appurtenances for Field-Scale Rapid Rate Filtration Pilot Plant[1/]

Item	Purpose & Specifications	Manufacturer	Model Designation
Raw Water Pump	Pumps Raw Water into Rapid Mix	Goulds Pumps, Inc.	XSH 15
Contaminant Feed Pump	Meters the contaminant batch into the main flow (0 to 1120 mL/min)	Fluid Metering, Inc	RP-D
Alum Feed Pump	Meters alum solution into main flow (0 to 75 mL/min)	Precision Control	111311-361
Polymer Feed Pump	Meters polymer solution into main flow (0 to 75 mL/min)	Precision Control	111311-361
Sodium Thiosulfate Feed Pump	Feeds $Na_2S_2O_3$ solution into effluent stream for dechlorination (50 to 1000 cc/min)	Cole Parmer	212
Giardia Sampling Pump	Diverts sampling stream from main flow through membrane filter (0 to 8.5 L/min)	Grainger	Rotary Beam Pump 1P771
Giardia Sampling Pump Motor	Drives *Giardia* sampling pump (3/4 hp)	Grainger	27846
Contaminant Batch Mixer	Agitates contaminant batch	Lightnin Mixers	Series 20
Alum Batch Mixer	Mixes alum solution	Wilkens-Anderson Co.	Power Stirrer
Polymer Batch Mixer	Mixes polymer solution	Cole Parmer	4555 H
Rapid Mix Basin Mixer	Disperses chemicals in rapid mix basin (1/4 hp) 1725 rpm	Lightnin Mixers	Mark II
Membrane Filter Holder	Holds 5 μm pore size 293 mm diameter membrane filters made by Nucleopore Corporation	Gelman Sciences	11873
Ratio Turbidimeter	Measures grab samples for turbidity	Hach Chemical Co.	18900-10
Flow-through Turbidimeter	Monitor influent and effluent turbidity	Hach Chemical Co.	1720-A

[1/] Neptune Microfloc Model WB-27 package water treatment plant rated at 76 L/min called WATER BOY®.

fall and winter when the raw water turbidity was less than 1 NTU. Table 6 shows the raw water characteristics of these waters. These characteristics are about the same from year to year.

Filtration Conditions--

All testing was conducted using "in-line" filtration with hydraulic loading rates between 9.7 and 12.6 m/hr (4 and 5.2 gpm/ft^2). Table 6 shows the ranges of filtration conditions which were tested.

Table 6.[1/] Raw Water Characteristics for Field-Scale Testing (average yearly ranges)

Characteristic	Horsetooth Water	Cache La Poudre During Spring Runoff	Cache La Poudre During Low Turbidity
Turbidity (NTU)	3 to 12	10 to 11	0.5 to 1.5
Temperature (C)	2 to 15	6 to 12	<1 to 7
pH	7.0 to 8.0	7.0 to 8.0	7.5 to 8.0
Alkalinity[2/]	10 to 50	30 to 40	35 to 45

[1/] Source: Summary of Chemical Analysis, 12 month averages, City of Fort Collins, 1981.

[2/] mg/L as $CaCO_3$.

Table 7. Filtration Conditions for Field-Scale Pilot Plant Testing

Condition	Range of Value Tested
Flow Rate, L/min (gpm)	60.1 to 83.3 (16 to 22)
Hydraulic Loading Rate, m/hr (gpm/ft^2)	9.7 to 12.6 (4 to 5.2)
Rapid Mix Detention Time, T sec (minutes)	145 to 250 (2.4 to 4.2)
Rapid Mix Velocity Gradient, G per sec	660 to 780
Rapid Mix GT	95000 to 200000
Turbidity of Water NTU	0.4 to 44
Temperature of Water ^{o}C	<1 to 13

Coagulants--

The selection of coagulants was based upon the results of the laboratory-scale pilot plant work. The chemicals selected, including the use of no chemicals i.e. "none", were used for a range of conditions to simulate what was anticipated would be both "good" and "poor" treatment. The chemicals used are enumerated as follows:

i) No Chemicals, i.e. filter used as strainer.

ii) Magnifloc 572-C as sole coagulant,

iii) Magnifloc 573-C as sole coagulant,

iv) Nalco 8102 as sole coagulant,

v) Alum as sole coagulant,

vi) Alum followed by Nalco 8102,

vii) Alum followed by Magnifloc 572-C.

Based upon the laboratory-scale pilot plant work, all but the last was anticipated to result in "poor" filtration results. This provided for an anticipated range of results to verify the laboratory-scale work.

MEASUREMENTS AND QUALITY CONTROL

The sampling and measurements taken routinely during test runs are described here with respect to methods, frequency, instruments used, and quality control. A quality control program was designed to assure that valid measurements were obtained and that equipment performed as intended. The paragraphs following describe these for both the laboratory-scale and field-scale pilot plant work. Procurement of cysts is discussed first.

Procurement of Giardia Cysts

Giardia cysts were obtained from dog feces at the Larimer County Humane Society, Fort Collins, Colorado. The fecal samples were taken to Dr. Hibler's laboratory at Colorado State University and checked for the presence of cysts. If cysts were present, then the sample was weighed and then added to an equal weight of cool, distilled water in a mason jar and stored at between 2 and 8°C until used. The cysts obtained were not used if over 10 days old. When used with the laboratory-scale pilot plant, this suspension of dog feces and distilled water, containing nominally about 5 million cysts, was placed into the milk cooler feed tank where it was mixed with raw water. When used with the field-scale pilot plant the suspension was mixed with water and raw primary sewage in 50 liter vessel from which the suspension was metered into the raw water stream.

Laboratory-Scale Measurements and Quality Control

Table 8 summarizes all measurements obtained using the laboratory scale rapid rae filtration pilot plant along with sampling methods, sampling points, sampling frequency, and quality control methods. All parameters used to measure filtration efficiency are listed. Table 9 summarizes routine measurements obtained to ascertain conditions of operation.

Cyst Sampling—

The only special comments required concerning Tables 8 and 9 relate to sampling and analysis of Giardia cyst samples. Sampling of the cyst suspension in the milk cooler was done by pumping a flow from the milk cooler tank through a 5 micrometer, 142 mm membrane filter and counting the

Table 8. Sampling and measurement of filtration efficiency parameters obtained in operation of laboratory-scale rapid rate filtration pilot plant.

Parameter Measured	Sampling Method	Sampling Points	Frequency of Sampling	Measurement Technique	Quality Control[3]
Turbidity	Grab, in cuvette	Milk cooler Filter effluent	Two hours Hourly	Turbidity meter Hach Model 1400	Standardized daily using 1.8 NTU standard
Particles	Grab, 300 mL bottle	Milk cooler Filter effluent	Daily Daily	Coulter counter Model TA II	Bottle washed with soap and rinsed with distilled water passed through 2 μ membrane filter. Coulter counter was standarized by use of standards having known particle numbers and sizes.
Standard plate count bacteria	Grab, using 250 mL sterile bottle	Milk cooler Filter effluent	Daily Daily	Plate count using tryptone glucose extract agar (DF0002-01-7)[1]	Duplicate plates and blank plate
Total coliform bacteria	Grab, using 250 mL sterile bottle	Milk cooler Filter effluent	Daily Daily	Plate count using Mendno MF agar[1]	Duplicate plates and blank plate
Giardia cysts	142 mm, 5 μm polycarbonate membrane filer sampling entire effluent[2]	Milk cooler Filter effluent	Daily Daily	Sample was washed from membrane filter, and analyzed by micropipette technique in lab of C. P. Hibler	1. Sampling. Filter holders were washed with hot, soapy water and rinsed. Collected samples were refrigerated. 2. Analysis. Standard lab protocol followed. 3. Cyst condition. A refrigerated cyst sample from the batch used in experiments was observed after test runs to ascertain cyst morphology.

[1] Microbiological Methods for Monitoring the Environment, EPA Publication 600/8-78-017, Cincinnati, 1978.

[2] Sampling was continued until pressure at top of filter column reached 5 psi; usually the sample volume was 20 to 40 liters.

[3] See Appendix H.

Table 9. Monitoring measurements and quality control in operation of laboratory scale rapid rate filtration pilot plant.

Parameter Measured	Measurement Method	Points of Measurement	Frequency	Instruments Used	Quality Control
Temperature	Perm. immersion	Milk cooler	Twice daily	Mercury therm.	NBS[2] thermometer
	Perm. mount in basin	Rapid mix basin	Hourly	Dial therm.	NBS therm.
	Perm. mount in col.	Filter column top	Hourly	Dial therm.	NBS therm.
	Temporary immersion	Filter tailwater cup	Hourly	Mercury therm.	NBS therm.
Flow	Volumetric	Filer effluent	Two hours	1000 mL grad. cyl. and stopwatch	Volumetric meas.
Chemical stocks					
1. Alum	no analysis	N.A.[1]	N.A.	N.A.	Liquid alum stock solution replaced after 2-3 months from F.C. W.T.P. No. 2
2. Polymers	no analysis	N.A.	N.A.	N.A.	Liquid polymers replaced after 2 to 3 months from manufacturer
Chemical feed res. concentrations					
1. Alum	Addition of stock solution	Alum feed res.	Solution made daily	Pipette and 1000 mL grad. cylinder	Daily change of solution
2. Polymer	Addition of stock solution	Polymer fed res.	Solution made daily	Pipette and 1000 mL grad. cylinder	Daily change of solution
Chemical feed rates	Volumetric feed from burrette	Alum	Hourly	Burrette and stopwatch	Volumetric meas.
		Polymer	Hourly		
Speed of mixing	Instrument	Shafts of mixers	Daily	Tachometer	Calibration with another instrument

[1] N.A. Not applicable.

[2] NBS National Bureau of Standards.

Perm - permanent

cysts retained. Sampling of the filter effluent was accomplished by passing the entire flow from the laboratory-scale rapid rate filter through the 5 micrometer pore size, 142 mm Nucleopore® polycarbonate membrane filter. About 20-40 liters were passed through the filter for each Giardia sampling; as much as 80 liters were passed through a filter during some test runs. This sampling technique was patterned after that described by Luchtel (1980). Of special interest is whether Giardia cysts remain on the membrane filter after washing. This was investigated by C. P. Hibler early in the investigation. Microscopic scans of the membrane filter after washing revealed no Giardia cysts. Complete review of the sampling procedure is given by Lange et al. (1984). Appendix J contains additional details on procurement of cysts, analysis techniques, detection limits, and results of related experiments.

Counting--

The Giardia cysts from the concentrated effluent samples were processed for microscopic counting by the micropipette technique. The cyst counting protocol was developed by Dr. C. P. Hibler, Professor of Pathology, Colorado State University. The results of the micropipette technique are reported by Dr. Hibler as the number of cysts found in the concentrated effluent sample. To obtain a cyst/liter concentration, this number is corrected for a sampling recovery efficiency and then divided by the volume of filter effluent passed through the membrane filter. When zero cysts are recovered, the Giardia cyst reported is in terms of detection limits. This is explained in Appendix J, after Bellamy et al. (1984).

Field-Scale Measurements and Quality Control

Measurements during operation of the field-scale pilot plant were similar to those obtained with the laboratory-scale pilot plant, with some deviations because of the differences in instruments or scale. The methods are described, but special attention is given to the problem of sampling flows. The quality control methods are incorporated in narrative format.

Flow Measurements--

Flows measurements were made volumetrically, and documented on the individual test data sheets. In this way, there were no discrepancies as to flow rates being obtained from pump settings.

Temperature--

Thermometers were standardized against a National Bureau of Standards Thermometer. Discrepancies were marked and the correction was applied when used.

Turbidity--

The measurement of turbidity was done by grab samples so that the samples could be measured using a Hach Ratio Turbidimeter Model 18900-10® This was the same as in the laboratory-scale testing. A photograph of the instrument is shown in Figure 18. Figure 16 shows that the influent samples were obtained after sufficient mixing of the suspension of Giardia

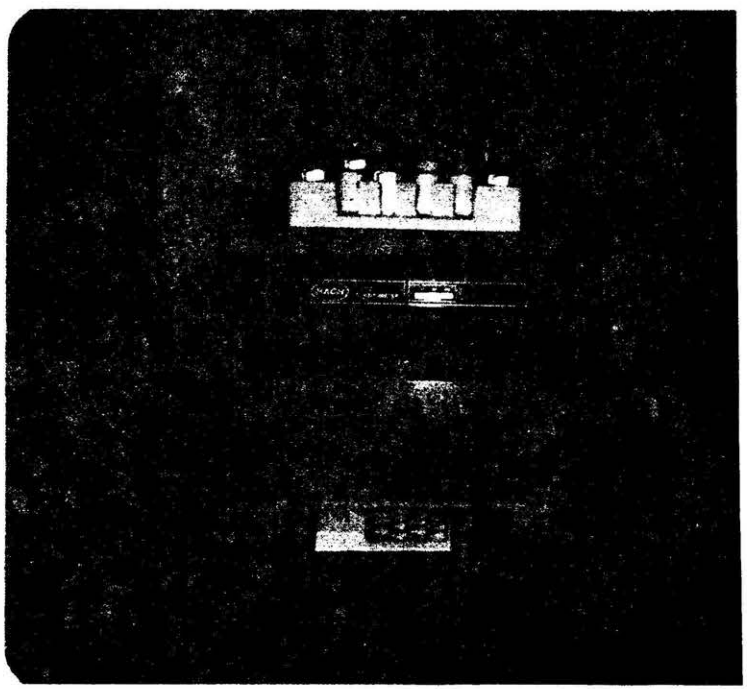

Figure 18. Hach ratio turbidimeter model 18900-10 used to measure turbidity.

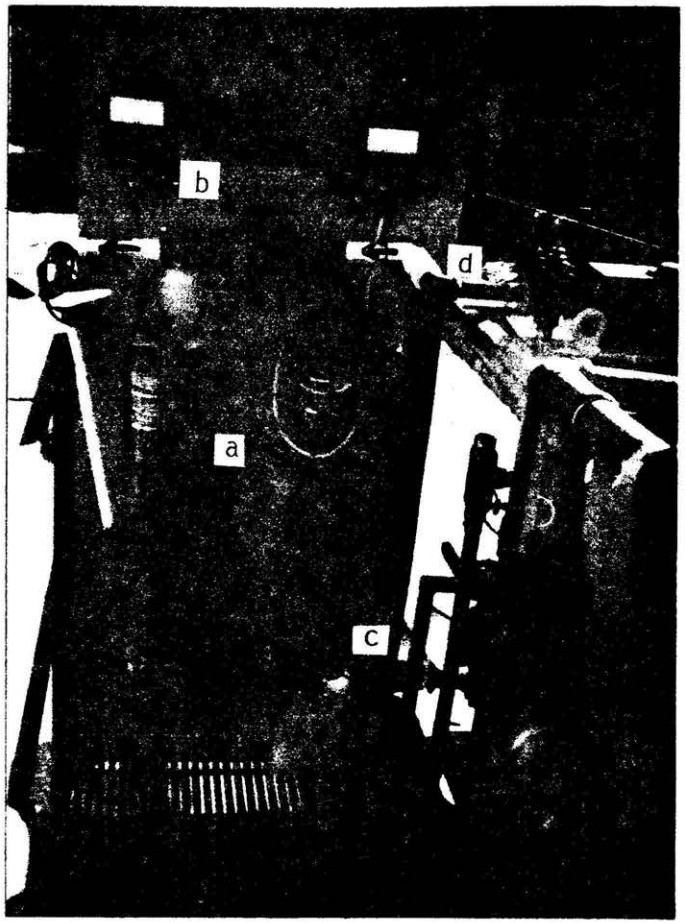

Figure 19. a) Hach flow-through turbidimeters, b) flow meter used to measure main flow, c) backwash valve #1, d) effluent flow control valve.

cyst and sewage with the influent stream. The effluent grab samples were obtained from the pipe discharging into the clear well. Figure 19 shows two Hach Flow-Through Turbidimeters, Model 1720-A®, used for monitoring purposes.

The Hach Ratio Turbidimeters, one at the Engineering Research Center and one at the Fort Collins Water Treatment Plant No. 1, were calibrated with formazin standards. They were checked daily with manufacturer-supplied reference solutions, and adjusted if needed. The flow-through meters were calibrated against the ratio turbidimeters.

Bacteria—

Influent and effluent coliform samples were obtained from the same ports as turbidity samples as shown in Figure 16. Coliform samples were obtained in autoclaved bottles and taken to the ERC microbiology laboratory, where culturing was in accordance with total coliform membrane filter procedures (Standard Methods, 1980). Standard plate counts were cultured at the same time.

The coliform source was wastewater primary effluent. The primary effluent was mixed with raw water and placed into the Giardia and coliform feed tank, 50 liter capacity, and then metered into the main flow stream along with the Giardia cysts.

For quality control, the autoclave operation was checked by the manufacturer, and all instruments and gauges were certified as operating correctly. In addition, the autoclave was checked each time with heat-sensitive tape.

The temperatures of the incubator and water bath were checked every other day when in use. The incubator was allowed to stabilize for two hours when temperature adjustments were made.

Bacterial Analyses—

Filter sterility was monitored by randomly choosing one of the 0.45 micrometer filters and placing it on a Petri dish of the standard coliform agar. This plate was then put through the same incubatiion as one of the other plates, but no water was filtered through it. The plate was then checked for growth after 24-hours, as were the other plates. Whenever possible, duplicate plates of each sample dilution were simultaneously prepared and counted. The average number between corresponding plates was the number reported. Once prepared, plates were refrigerated and kept for no longer than ten days.

Headloss Measurement—

Figure 20 shows the headloss board used to measure headloss across the filter. Water piezometers were used to measure head, with taps located above and below the filter media.

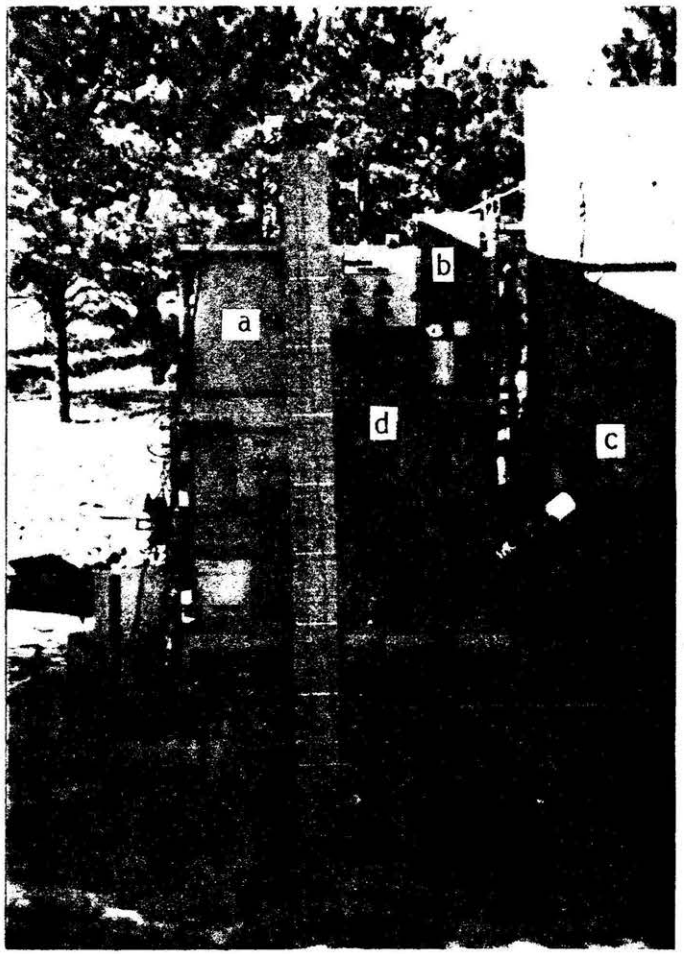

Figure 20. Side view of WATER BOY: a) headloss board with piezometers, b) main control panel, c) backwash hose, d) minor control panel.

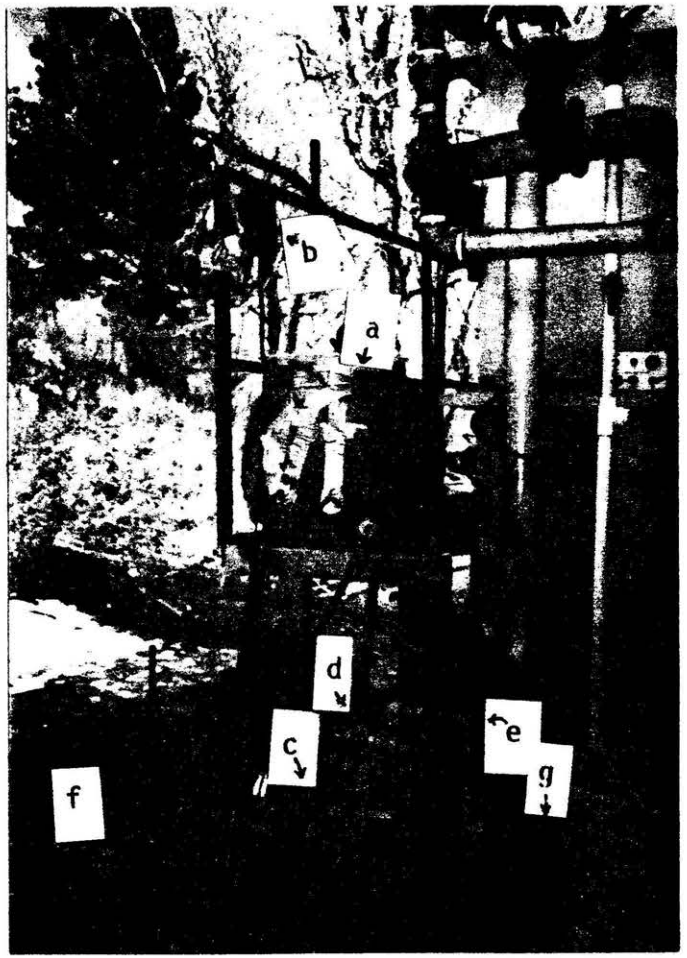

Figure 21. Contaminant feed system: a) batch tank, b) mixer, c) injection port, d) metering pump, e) four elbows for mixing contaminants with raw water, f) raw water line, g) influent sampling port for Giardia, coliforms, and turbidity.

Injection of Giardia cysts--

Figure 21 shows the contaminant injection system used to inject the suspension of raw water, dog feces suspension, and wastewater primary effluent. The suspension was agitated by a mixer while it was metered into the main flow stream by a positive displacement pump.

Giardia Sampling--

Sampling of Giardia cysts was done by passing a sampling stream, tapped from the influent and effluent pipes, respectively, through a membrane filter. Figure 16 shows the points in the flow scheme where the influent and effluent were sampled for Giardia. Figure 22 shows the membrane filter apparatus used to hold the 293 mm diameter, 5-micrometer pore size, polycarbonate filters made by Nucleopore Corporation.

The following steps enumerate the procedure to obtain either an influent, or effluent, Giardia sample. The only difference between an influent and an effluent sampling procedure was the point where the sampling stream was withdrawn from the main stream. Again, Figure 16 shows the Giardia cyst sampling ports.

i) Place membrane filter on stainless steel support plate, and securely screw on top of filter holder.

ii) Attach the Giardia sampling pump to the sampling port. The sampling pump is shown in Figure 23 as setup for sampling.

iii) Attach sampling pump to membrane filter.

iv) Open sampling port and turn on sampling pump.

v) Open air vent on membrane filter holder until water comes out, then close air vent. This bleeds air from filter holder.

vi) Collect the effluent from the filter holder in a calibrated tank. The flow rate used was about 2 gpm; this represents about 10 percent of the main flow stream.

vii) Pass the sampling stream through the filter holder until the headloss across membrane filter reaches about 20 psi, then turn-off pump and close port.

viii) Wait a few minutes until the water goes through the filter holder and into the calibrated tank.

ix) Record amount of water collected in calibrated tank.

x) Disconnect sampling pump from filter holder.

xi) Tilt membrane filter holder over a glass pyrex tray and open the holder slowly allowing excess water to flow into tray. This is shown in Figure 24.

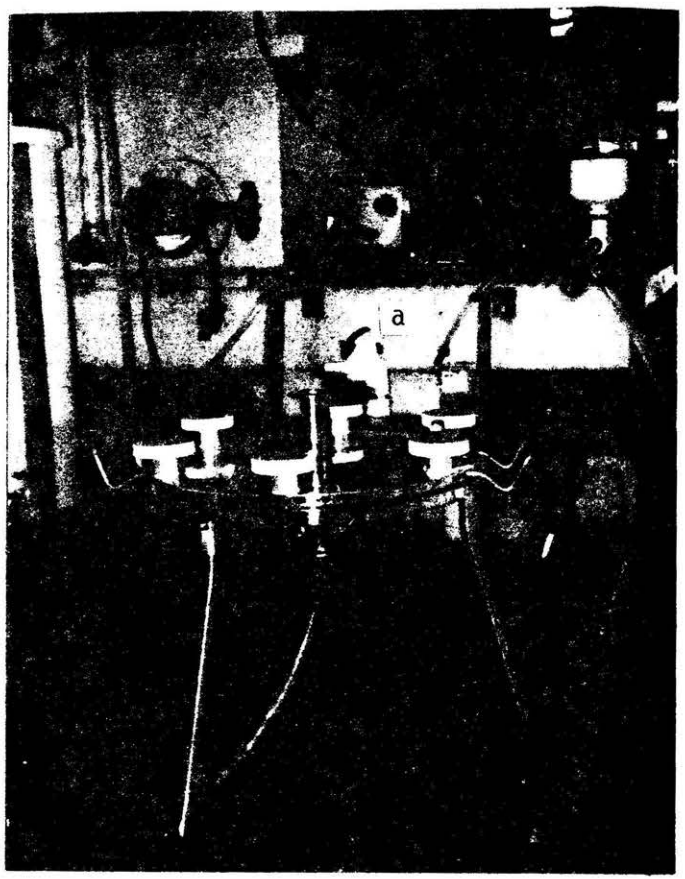

Figure 22. a) Membrane filter holder used to hold 5μm pore size, 293 mm diameter membrane filters.

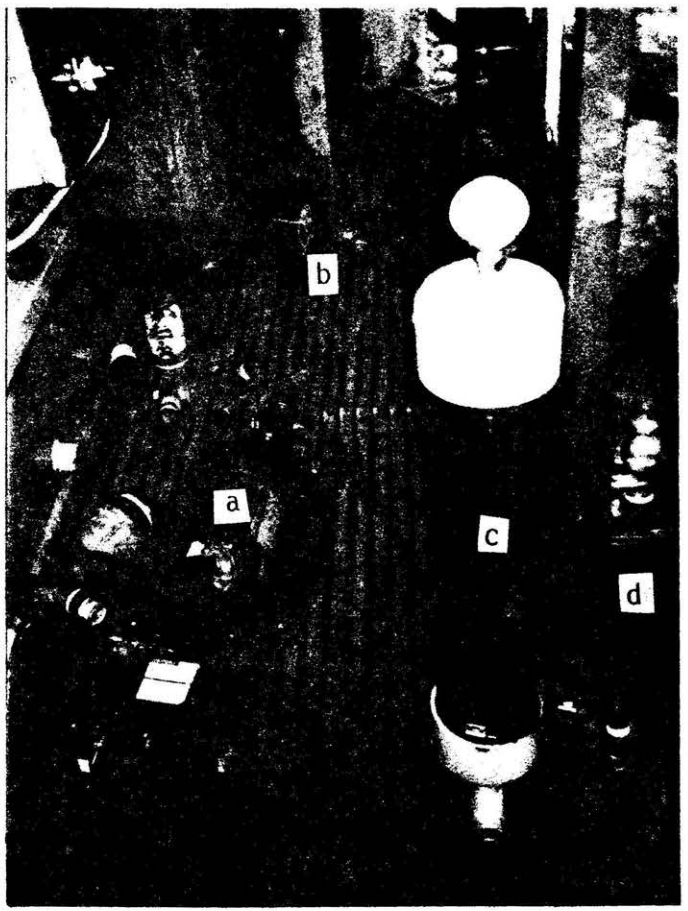

Figure 23. a) Giardia sampling pump, b) effluent sampling port for Giardia, c) dampener to stabilize the sampling stream, d) flow meter used to measure sampling flow rate

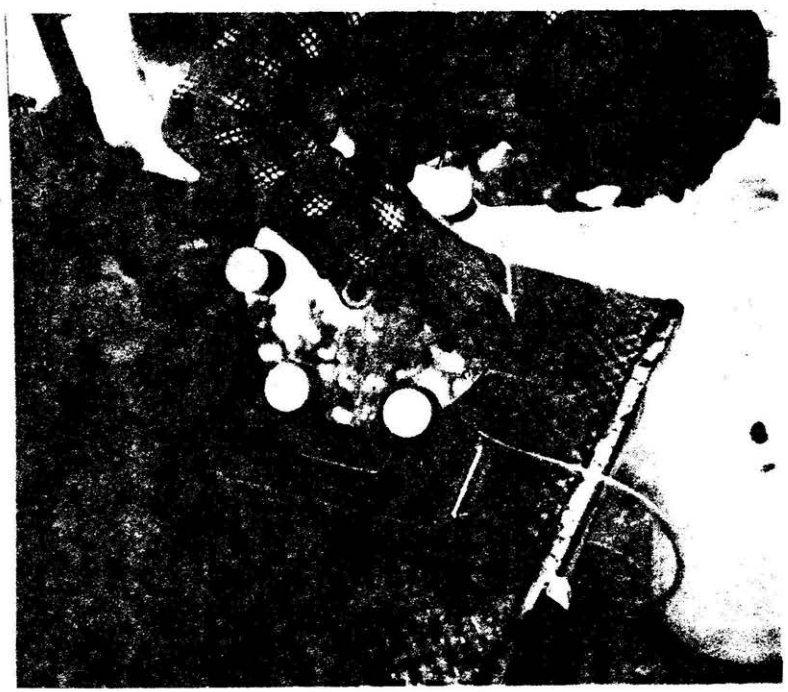

Figure 24. Membrane filter holder being opened allowing excess water to flow into pyrex tray.

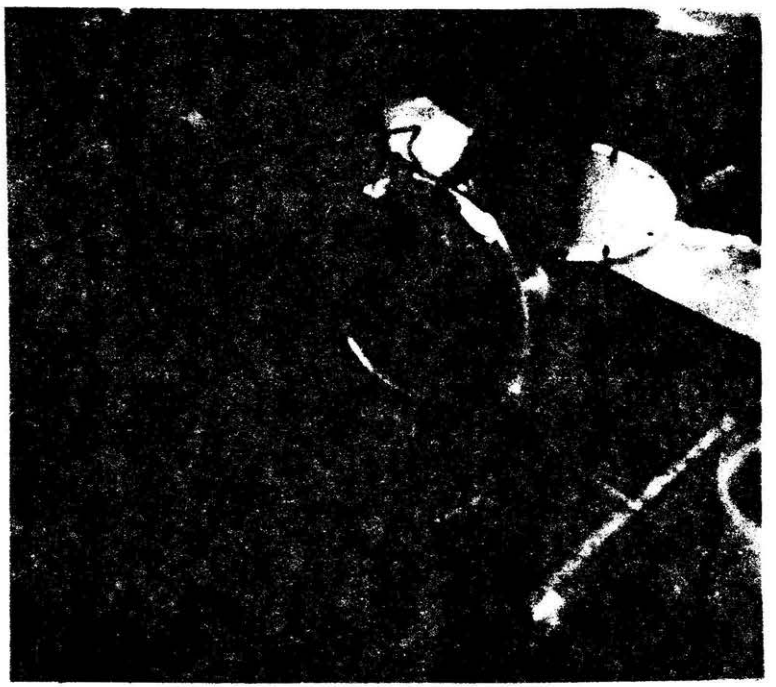

Figure 25. Top of membrane filter holder being rinsed, allowing wash water to flow into pyrex tray.

xii) Take top of filter holder off and rinse it, allowing the wash water to flow into the pyrex tray. Figure 25 shows this.

xiii) Tilt filter holder over tray and rinse cysts from membrane filter into tray. Shown in Figure 26.

xiv) Pour contents of tray into a mason jar labeled with sample number, as shown in Figure 27. Spray off tray to assure complete transfer of sample.

xv) Refrigerate sample immediately, and transport to Pathology Laboratory for counting of cysts recovered.

Giardia Measurement Quality Control--

The measurement of Giardia cysts was controlled by: i) insuring that the concentrations of cysts in the sampling streams were representative of the concentrations in the main flow stream; ii) sampling the influent water, after the cysts were injected, exactly as the effluent was sampled; and iii) performing "no chemical" Giardia cyst runs.

Representative samples were insured by following standard sampling procedures. For example, the sampling streams were taken from the center of the pipe, and the velocities of the sampling streams were made equal to the velocity of the main flow stream. Also, the influent sampling port was directed upstream to allow the "stream lines" direct access to the port.

The influent sample was obtained exactly as the effluent sample, i.e., both streams were run through the same pump, and then through the membrane filter holder. The sampling sequence was to sample the influent side first, then insert a new membrane filter and sample the effluent.

The "no chemical" Giardia cyst removal tests established references to compare removals when chemicals were used. In this way the effect of coagulant dosage could be evaluated.

DATA HANDLING

Aquisition of Data

During test runs all operating data were recorded on forms developed for this research. Data from analysis of samples were recorded on individual data sheets for the respective parameter being measured. Appendix E contains one sample of each data sheet used, with data from one test run shown for illustration.

Data Processing

Tables E-1 and E-2 contain all data for a given test run using the laboratory-scale pilot plant. These data were converted as necessary by

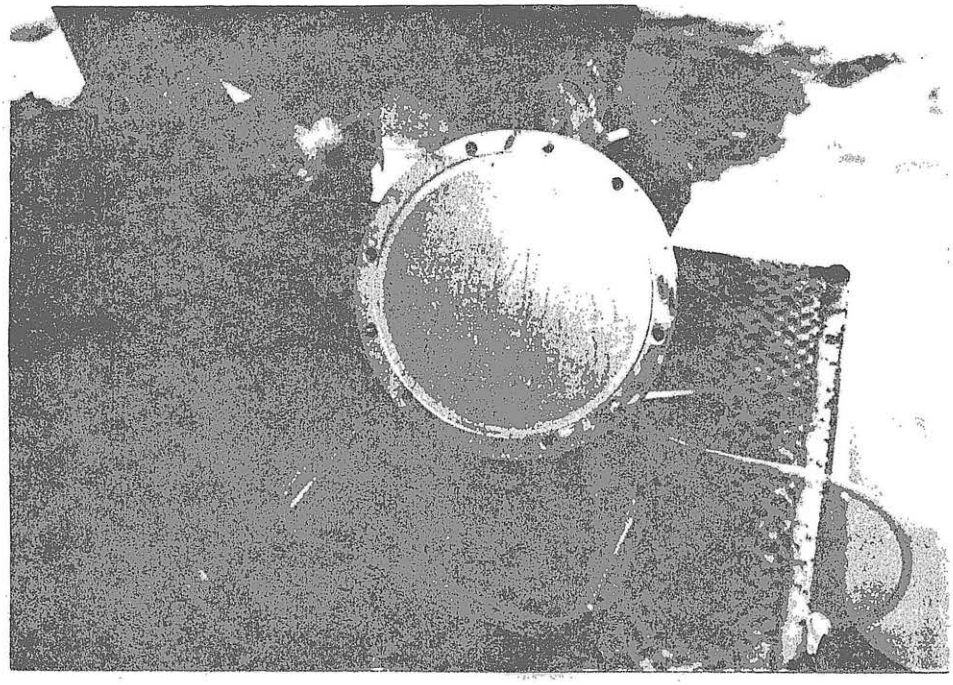

Figure 26. Membrane filter being rinsed. The cysts which were strained from the sampling stream are transferred to the pyrex tray.

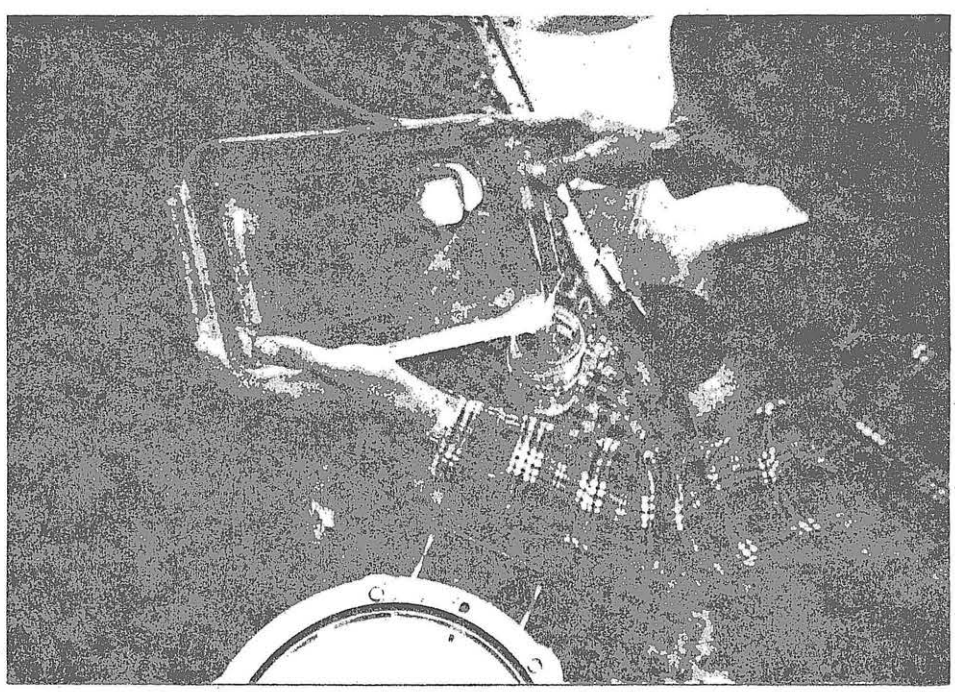

Figure 27. Transferring the contents of the pyrex tray to the mason jar.

hand calculation to the form needed. For example, the alum concentration in the raw water was obtained by multiplying the (flow of alum in milliliters liquid alum per minute) times (0.643 grams liquid alum as $Al_2(SO_4)_3.14H_2O$ per milliliter liquid alum) divided by (flow of raw water in milliliters per minute). The rpm of the paddle in the rapid mix basin and the temperature measurement were used to enter Figure C-7, which gave the corresponding G value. In this manner all data were converted to the form needed for developing relationships between variables of interest. These data were recorded in accordance with the format of a "master" data table, as one line of the table. Upon accumulation of several lines, e.g. several test runs, the data were transferred to a word processor file, where the table was allowed to grow.

Master Data Tables

All data were accumulated in a "master data table", which is Table A-1, in Appendix A for the lab-scale pilot plant results and Table B-1 in Appendix B for the field-scale pilot plant results. Table A-1 has 36 columns, grouped according to the following categories: test identification, influent water characteristics, chemical basin description, filter conditions, filter effluent data. Table A-1 in Appendix A is comprised of 12 sheets, which can be cut and taped together using the match lines indicated. The aggregated table is 4 sheets wide in accordance with the data categories. It is 3 sheets high to accomodate data from 178 test runs. Table B-1 can be taped together also, in the same manner.

For work using the field-scale pilot plant, data were recorded on forms shown in Table E-7. All the data for a given run was recorded on one of these sheets, including reduced data such as detected influent Giardia and coliform concentrations. In this way, any information on a run could be obtained by referring to the respective data sheet.

From these individual data sheets, the "master" table, Table B-1, was constructed. From this master table, all figures and tables illustrating the experimental testing were constructed.

Plots, Tables, and Statistical Analyses

Portions of the master tables, stored in a word processing file, was transferred to files in the CSU CYBER 720 computer, as needed for a particular analysis. For example, to ascertain the relation between turbidity and total coliform bacteria these data were transferred as "vectors" to a file in the CYBER. Once in the file, statistical analyses were performed as desired using package programs. Plots were also generated from the statistical analyses. Other parameters were transferred to the CYBER files in the same manner, and plots were generated to ascertain relationships. These plots were used as tools of analysis from which hand drawn graphs were developed, e.g. three-dimensional histogram plots.

SECTION 4

RESULTS AND DISCUSSION

This chapter first summarizes experimental results for removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts by rapid rate filtration using low turbidity water. Second it describes relationship found between the above dependent variables and process variables. The process variables examined included: coagulants selection, dosages of coagulant, coagulant sequence, filtration treatment train, filtration media, filtration rate, temperature, and run time. And third, it examines relationships between removals of Giardia cysts and removals of turbidity, total coliform bacteria, etc., in an effort to find a surrogate indicator for the former. All results for these first three activities were obtained using the laboratory-scale rapid rate filtration pilot plant. Finally, results obtained using the field-scale pilot plant are summarized in the last section.

Some 178 test runs were performed over an 18 month period using the laboratory-scale pilot plant, and some 144 test runs were performed using the field-scale pilot plant. Table A-1 in Appendix A is a "master" table summarizing all results obtained using the laboratory-scale pilot plant. Table B-1 in Appendix B is a similar "master" table summarizing all resuls from the field-scale pilot plant testing. Table A-2 shows Giardia cyst removal efficiencies corrected for detection limits. All tables and graphs used in this chapter were constructed from data contained in Tables A-1, A-2, and B-1, respectively.

REMOVALS - LABORATORY-SCALE PILOT PLANT

Table 10 summarizes percent removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts for low turbidity water at low temperatures, e.g. 2°C to 4°C. Results of 21 test runs are shown for three categories of chemical pretreatment: (1) "none," e.g. no chemicals were used, (2) "nonoptimum," e.g. a nonoptimum chemical dose was used as measured by turbidity removal, (3) "optimum," e.g. an optimum chemical dose was used as measured by turbidity removal. Samples were taken after one hour of a test run for "none," and 2 to 4 hours for "nonoptimum" and "optimum" chemical dose. Two sources of low turbidity water were used in the testing: (1) natural low turbidity water from the Cache La Poudre River, and (2) artificial low turbidity water produced by filtration of Horsetooth Reservoir water by diatomaceous earth filtration. Filtration rates ranged from 8.2 cm/min to 41.4 cm/min (10 gpm/ft^2). Both dual media

Table 10. Effect of chemical pretreatment on removal of turbidity, standard plate count bacteria, total coliform bacteria, particles and Giardia cysts for low turbidity artificial water, and low turbidity Cache La Poudre River water, by "in-line" rapid sand filtration[1/,2/,3/].

Run No.	Conditions: Filter V (cm/min) 4/	Conditions: Filter Media 5/	Conditions: Water Source 6/	Conditions: Water Temp. (°C)	Pretreatment: Chemicals used: Dosage Category 7/	Pretreatment: Chemicals used: Species	Pretreatment: Chemicals used: Dosage (mg/l)	Filter Effectiveness: Percent Removal: Turbidity	Standard Plate Count	Total Coliform	Particle Count	Giardia Cysts
46	8.46	Sand(L)	HDE	3.0	None	None	0.0	27.3	-51.3	13.8	85.8	7.6
47	22.59	Dual(L)	HDE	3.0	None	None	0.0	-72.4	-66.6	25.0	98.7	96.3
49	22.20	Sand(L)	HDE	2.0	None	None	0.0	-13.8	20.6	60.0	98.6	>99.9
48	8.26	Dual(L)	HDE	3.0	None	None	0.0	-18.2	-108.2	38.4	94.2	99.9
119	41.40	Dual(F)	CLP	3.0	None	None	0.0	18.8	9.7	5.3	89.7	41.9
120	32.00	Dual(F)	CLP	3.0	None	None	0.0	18.8	16.1	-7.5	85.8	36.4
121	20.70	Dual(F)	CLP	3.0	None	None	0.0	18.1	16.1	1.1	82.2	36.3
122	9.60	Dual(F)	CLP	3.0	None	None	0.0	15.6	99.6	99.9	81.2	68.3
69	22.69	Dual(L)	HDE	3.0	Nonoptimum	alum/573c	15.0/1.1	73.6	78.8	99.9	-142.4	99.2
82	22.45	Dual(L)	HDE	3.0	Nonoptimum	alum/572c	8.8/0.6	61.0	38.0	- 8/	99.6	- 8/
114	7.8	Dual(F)	CLP	3.0	Nonoptimum	alum/572c	23.7/1.2	69.0	96.8	99.0	58.9	95.3
50	8.20	Sand(L)	HDE	4.0	Optimum	alum/572c	2.1/0.9	88.9	82.3	>99.9	98.6	97.8
51	23.48	Dual(L)	HDE	3.0	Optimum	alum/572c	4.1/1.7	86.1	85.4	83.0	98.9	99.1
52	8.45	Dual(L)	HDE	4.0	Optimum	alum/572c	2.1/1.2	91.7	95.6	>99.9	99.2	99.7
53	23.19	Sand(L)	HDE	4.0	Optimum	alum/572c	3.4/2.1	82.6	- 8/	>99.9	93.8	99.5
70	22.20	Dual(L)	HDE	3.0	Optimum	alum/573c	7.6/1.3	88.7	98.4	99.5	81.9	99.4
81	8.35	Dual(L)	HDE	3.0	Optimum	alum/572c	6.8/0.9	85.4	97.8	99.9	98.3	- 8/
104b	8.26	Dual(F)	CLP	3.5	Optimum	alum/572c	13.4/0.6	82.4	99.5	79.8	98.6	98.7
106	8.47	Dual(F)	CLP	3.5	Optimum	8102N	0.5	-43.1	99.9	>99.9	87.0	39.5
107b	8.38	Dual(F)	CLP	3.0	Optimum	alum/572c	11.3/0.5	92.7	96.7	90.0	95.4	>99.9
118	9.37	Dual(F)	CLP	3.0	Optimum	alum/572c	23.7/1.4	85.5	98.4	99.4	- 8/	97.6

1/ Abstracted from Table A-1 and Table A-2, Appendix A.
2/ Artificial water was obtained by Diatomaceous Earth filtration of Horsetooth Reservoir water, filtered water turbidity ranged from 0.2 to 0.6 NTU. See also footnote 6.
3/ The term "In-Line" filtration is the designation for treatment train comprised of rapid mix and filtration, e.g. no flocculation or sedimentation.
4/ The term V is used as hydraulic loading rate which equals flow divided by area of filter.
5/ Sand (L) was obtained from Loveland Treatment Plant at Big Thompson Canyon. Bed depth was 76cm. Dual (L) means the bed was comprised of 30 cm sand from Loveland and 45 cm anthracite having trad name Philterkal Special No.1(produced by Reading Anthracite Coal Company. Pottsville, PA. 17901). Dual(F) Fort Collins means that the bed was comprised of 30 cm sand was obtained from Fort Collins Treatment Plant No.2 and 45 cm Philterkal Special No.1(R) anthracite.
6/ HDE is water obtained from Horsetooth Reservoir, filtered by Diatomaceous Earth to give low turbidity, e.g. 0.2 to 0.6 NTU
CLP is low turbidity raw water obtained from the Cache La Poudre River during the period September to April when raw water turbidity was generally 0.4 to 0.7 NTU.
7/ "Optimum" and "none optimum", are designated of coagulant dosages producing turbidities of filterd water which are minimum and greater than minimum, respectively.
8/ No sample taken.

and sand was used. Results are described for each of the dependent variables in the paragraphs following.

Turbidity

Table 10 shows the effect of chemical pretreatment on turbidity removal. For the eight "none" coagulant dosage tests, i.e. coagulant chemicals were not added, turbidity removals were -72 to 19 percent. With a "nonoptimum" dosage of chemicals removals increased to the 61 to 74 percent range. But if "optimum" dosage was used percent removals were 83 to 93. Finished water turbidity was about 0.05 NTU, generally.

Standard Plate Count Bacteria

Table 10 shows that the standard plate count bacteria removal percentages range from -108 to 20 for seven of the eight test performed without chemical addition, with the eighth test showing 99 percent removal. For three "nonoptimum" test runs, removal percentages ranged from 38 to 97 percent. For the nine test runs, using optimum coagulant dosages, removal pecentages ranged from 82 to 99.9 percent. These results also illustrate that high removals can be expected for chemical dosages that are "optimum."

Total Coliform Bacteria

Table 10 shows that for those tests performed with no chemical pretreatment the total coliform bacteria removal percentages ranged from -7 to 99.9 percent. For the "nonoptimum" chemical dosages removals were greater than 99 percent. For the nine test runs using "optimum" chemical dosages removal percentages ranged from 80 to greater than 99.9 percent. Most were greater than 99 percent.

Particles

Table 10 shows percent removals of particles in the 2.52 to 50.8 micrometer (μm) size range. For the no chemical pretreatment condition the removal percentages ranged from 81 to 99 percent. For the "nonoptimum" chemical dosages, particle removals ranged from -142 to 99.6. Table 10 also shows that for the nine "optimum" coagulant dosages, removal percentages ranged from 82 to 99 percent. The use of 8102N used as a filter aid gave a removal of 87.0 percent. These results, show high removals of particles when no chemicals were used, which are inconsistent with turbidity and bacteria removal results. These results indicate that particle counting was not useful as an indicator of filtration performance.

Giardia Cysts

Table 10 shows percent removals of Giardia cysts, based on the detected cysts concentrations (Table A-2), for twenty test runs. The table shows that with no chemical pretreatment the removal percentages for five test runs ranged from 8 to 68. But for three test runs removals were greater than 96 percent. It should be noted that cyst characteristics are different from one

batch to another, e.g. some are hardy and retain their shape for several weeks while others deteriorate within days. Dr. Hibler indicated that the cysts used in Runs 47, 48, 49 were a batch that deteriorated quickly, as determined by the sample maintained under refrigeration as a control. This would account for the high "removals" noted. For other runs the control cysts showed no such deterioration. At "nonoptimum" chemical dosages removal percentages ranged from 95 to 99 percent. For eight test performed with "optimum" chemical dosages, the Giardia cysts removals were greater than 98 percent, with five exceeding 99 pecent. Using the filter aid 8102N removal was 39.5 percent.

Of special interest, these results show that with proper chemical pretreatment, rapid rate filtration will remove greater than 99.9 percent of Giardia cysts. Removals of Giardia cysts exceeded 97 percent for all filtration conditions imposed when optimum chemical dosages were used.

The data show that for optimum chemical pretreatment dosages, removals of turbidity, standard plate count bacteria, total coliform bacteria, particles, and Giardia cysts are uniformly high, e.g. greater than 80 percent for turbidity and 98 percent for all other parameters. For "nonoptimum" chemical dosages results are more variable with both high and low removals. For the "none," or no chemical pretreatment condition, removals are markedly lower for all parameters except particles, which ranged from 81 to 99 percent.

The results in Table 10 show that rapid rate filtration will work as a simple strainer when no chemicals are used, and will pass appreciable percentages of turbidity, bacteria, and Giardia cysts. They illustrate also the critical importance of proper chemical coagulation. It is imperative to select effective chemicals and to use proper dosages.

The removals of particles were high even when no chemicals were used, which was at variance with the results for the other parameters. Therefore, particles are felt to be not useful as a measure of filtration effectiveness, for the conditions examined.

Table 10 shows also that for "optimum" chemical dosages, it makes little difference whether single media or dual media is used. Neither is there any noticeable effect of hydraulic loading rate. The over-riding concern in treating low turbidity waters should be with determining which chemicals are effective and their dosages.

EFFECT OF PROCESS VARIABLES

The effect of process variables was ascertained by changing the magnitudes of each through a range of values while all other variables were maintained constant, using the laboratory-scale pilot plant. The process variables investigated were: coagulants, dosages of coagulants, sequence of coagulant addition, mode of filtration, comparison of single and dual media, filtration rate, temperature, run time.

Removal of turbidity was the principle focus because it was found to be indicative of removals of both bacteria and Giardia cysts. Removals of the latter were measured also during this phase of the investigation, but not for every test. The labor involved for measurements of bacteria and Giardia cysts was a concern, but the addition of Giardia cysts also caused changes in turbidity of the raw water, which was not acceptable for many of the tests involving low turbidity water. This section reviews the results of the effect of process variables on turbidity removal, and on removals of bacteria and Giardia cysts.

Coagulant Selection

Figure 28 compares five polymers with respect to effluent turbidity produced by means of jar-filter testing (see Choi, 1983). Clearly 572C shows the lowest effluent turbidity, e.g. 0.05 NTU. The other polymers shown could be as effective at other combinations of alum-polymer dosages. Such testing

Test Conditions
Run number(s) : 17,33
Raw water turbidity : 0.49 NTU
Temperature : 18C
Primary coagulant : Run 17 and Run 33 1.5 mg/l alum.
Secondary coagulant : Run 17 and Run 33 0.5 mg/l polymer.

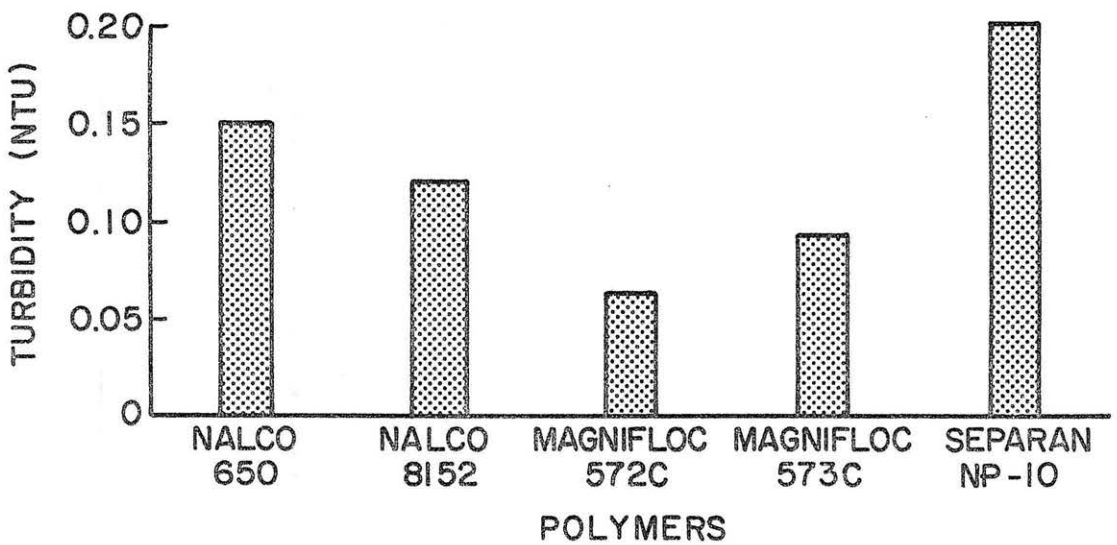

Figure 28. Comparison of turbidity reduction in jar-filtration testing by five polymers (Choi, 1983).

was not done, however, as the effort was limited in scope toward finding only one or two polymers which might be effective in filtration of low turbidity waters. Nine polymers were tested in this manner. They are listed in Table I-1, Appendix I.

Further testing of polymers was done using the laboratory scale rapid rate filtration pilot plant. The results, all of which are given in Table A-1, confirmed that Magnifloc 572C® and Magnifloc 573C® were effective in filtration of low turbidity waters.

Table 11, abstracted from Table A-1 and Table A-2, shows the percent removals, as data are available, for chemical pretreatment conditions indicated. Seven such conditions are indicated for four polymers used alone and used with alum. Also results are shown using alum alone, and the condition of "no chemicals". The data shown are for all conditions of hydraulic loading rate, media, temperature, and source of water. The data show very clearly that without chemical pretreatment, removals are quite low for all parameters, e.g. nominally about 30 to 60 percent removals. The polymers 572C and 573C used alone are not highly effective either, but results are variable. Neither is alum alone effective. The two polymers 572C or 573C with alum, however, are highly effective with removals generally greater than 80 percent for turbidity, more than 90 percent for standard plate count bacteria, 99 percent for total coliform bacteria, and 95 percent for Giardia cysts.

Figure 11 is a histogram showing percent removal of turbidity for nine coagulant conditions. This figure is a visual way to show the data in Table 11. It shows clearly the percent removal of turbidity is low when no chemical pretreatment is used, compared with using alum and Magnifloc 572C® or alum and Magnifloc 573C® for pretreatment. Figure 12 is a histogram showing percent removal of Giardia cysts for the same nine coagulation conditions. This figure is another plot for the data shown in Table 11. It illustrates further that with no chemical pretreatment the percent removal of Giardia cysts ranged from 40 to 80 percent, except for five test runs. Using alum and either Magnifloc 572C® or Magnifloc 573C® gave more than 95 percent of Giardia cyst removal in most of the test runs. These data show the importance of polymer selection in filtration of low turbidity water, and that a combination of the polymer and alum is necessary.

Dosages of Coagulants

Based upon the screening of polymers, described earlier , two, Magnifloc 572C and Magnifloc 573C, were selected for further testing to determine their effectiveness in removal of turbidity, for the turbidity range of <1 NTU, when used in combination with alum. The premise was that if substantial turbidity removal occurred then high removal efficiencies would also occur for bacteria and Giardia cysts. Thus the initial search was to ascertain the ranges of chemical dosages, for alum and polymer, to remove high percentages of turbidity.

Table 11. Removals of turbidity,, standard plate count bacteria, total coliform bacteria, and *Giardia* cysts, for different conditions of chemical pretreatment. Data shown are for low turbidity raw water, e.g. less than 1.5 NTU and for all conditions of hydraulic loading rate, media temperature, and source of water.

Chemical Species	Percent Removal			
	Turbidity	Standard Plate Count Bateria	Total Coliform Bacteria	*Giardia* Cyst
No chemical	27,-73,-18,-14,23 15,-2,-2,19,19 18,16,26,23,3 13,-5,27,28,1	-51,-67,-1.8,20,x x,x,x,10,16 16,96,-23,31,-10 24,-77,-25,-15,14	14,-25,38,60,x x,x,x,5,-7 1,99.9,0,0,92 75,-25,48,40,90	74,96,100,100,94 x,x,x42,36 36,68,49,72,98 x,x,x,x,x
Alum	-62,-144,-62	48,-600,-1.5	3,x,87	x,x,x
8102 N	-43,89,92,84,89 93,90,93,98,99 81	99.9,91,99,94,96 94,97,95,97,97 x	99.9,x,x,88,83 85,86,90,99,99 x	40,x,x,x,x x,x,x,x,x x
8100N	17,27	x,x	66,65	x,x
8170 N	14,43	92,84	x,x	x,x
8181 N	63,34,20,27,87 93,93	x,x,70,87,87 87,34	x,x,45,28,84 >99,97	x,x,x,x,x x,x
650	3	95	3	x
572C	58,53,-32,-5,-56 -27,18,35	97,x,91,62,56 -233,-77,90	100,x,99,99,92 x,-87,98	x,x,x,x,99.9 x,x,x
573C	74,53	46,85	99,71	x,x
Alum and 8102N	39,-3,-17,74	43,96,95,80	30,99,99,>99	95,100,91,100
NP10, Alum	80	x	x	x
Alum and 572C	90,96,96,97,77 59,86,82,77,87 81,87,84,84,79 86,91,89,91,89 86,92,83,94,79 83,85,61,86,60 93,92,90,89,85 95,56,62,38,61 79,82,15,83,-85 -177,-48,78,-118,-41 89,89,91,85,52 78,-30,30,70,86 83,85	99,98,99,99,x 63,99.9,94,86,x 96,x,95,42,86 x,x,x,x,82 85,96,x,90,x 94,98,38,x,93 97,98,63,98,94 96,96,99,0,97 99.3,99.8,78,98,83 76,92,83,79,75 -542,98,98,78,83 93,95,92,93,96 92,99.7	98,99,99,99,x 99,99,99,96,x x,x,99.9,99.9,96 x,x,x,x,99.9 80,99.9,99.9,99.9,x 99.9,99.9,99.9,x,90 90,x,98,97,99 99,99,99,99.9,99.9 99.9,99.9,99.6,99,99.9 99,99,x,x,x 96,97,99.5,99,93 99.8,98,99.6,99.7,99.5 99.9,99.9	x,x,x,x,x x,x,x,x,x x,x,x,x,x 100,100,100,92,98 100,100,100,87,x x,x,x,x,99.7 99.9,x,99.8,x,x x,91,97,95,95 85,97,97,98,x x,x,x,x,x 84,94,x,x,x x,x,x,x,x x,x
Alum and 573C	77,81,62,53,88 89,90,-0.7,73,89 96,95,-15,94,61 74,17,82,42,85 93,80,97,96,85 89,54,65,74,79	99.9,75,84,-8,89 91,87,17,79,98 99,99,18,98,x 99.9,50,99,98,84 41,x,32,95,x x,23,x,96,-98	99,98,98,99,x x,99.9,99.9,99.9,99 99.9,99.9,x,99.9,x 99.9,-24,80,45,91 99,x,x,x,x 100,99,99,99,98	x,x,x,x,x 99,99.9,94,99,99 99.9,99.9,x,99.5,96 99.5,97,99,x,x x,x,x,x,x x,x,x,x,x

x = No data.

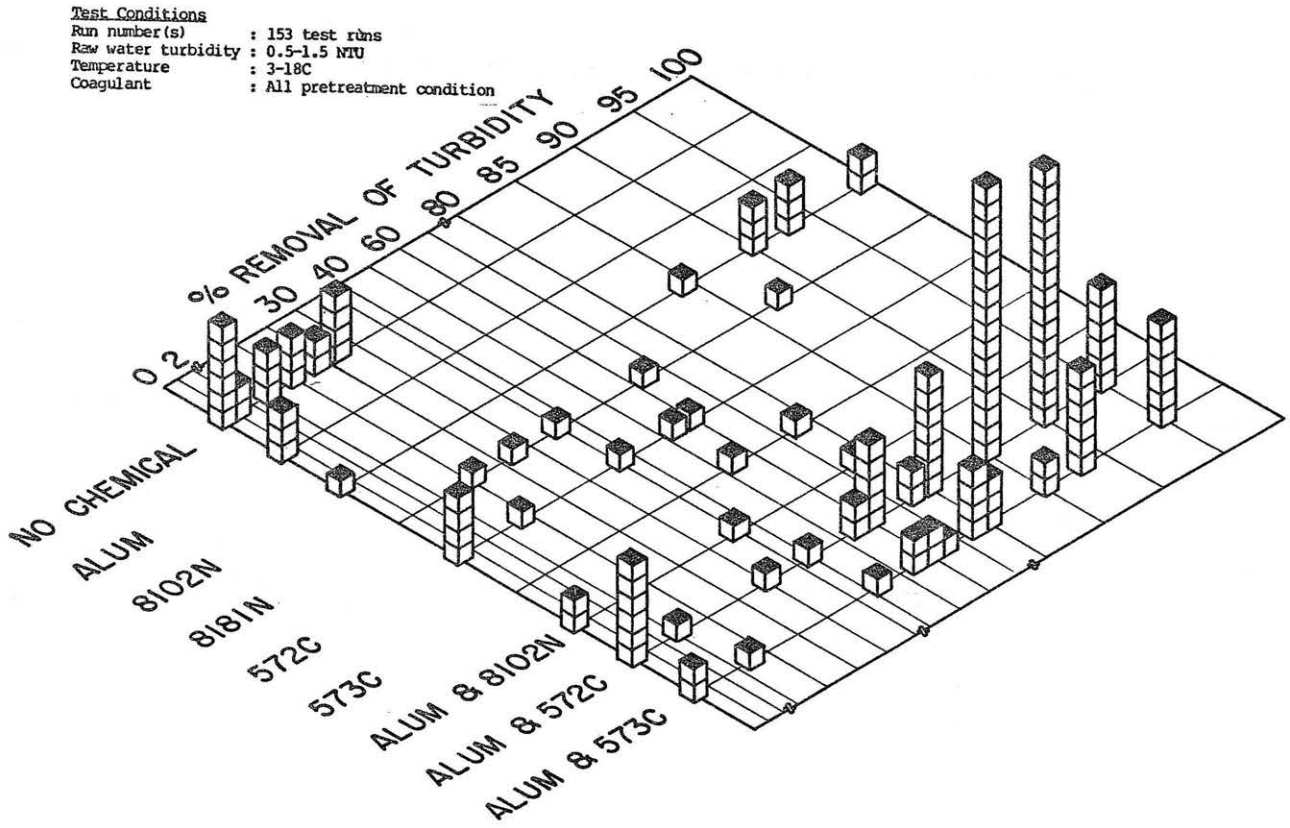

Figure 29. Histogram of turbidity percent removal and coagulant tested, using laboratory-scale rapid rate pilot plant. Each block represents one measurement set.

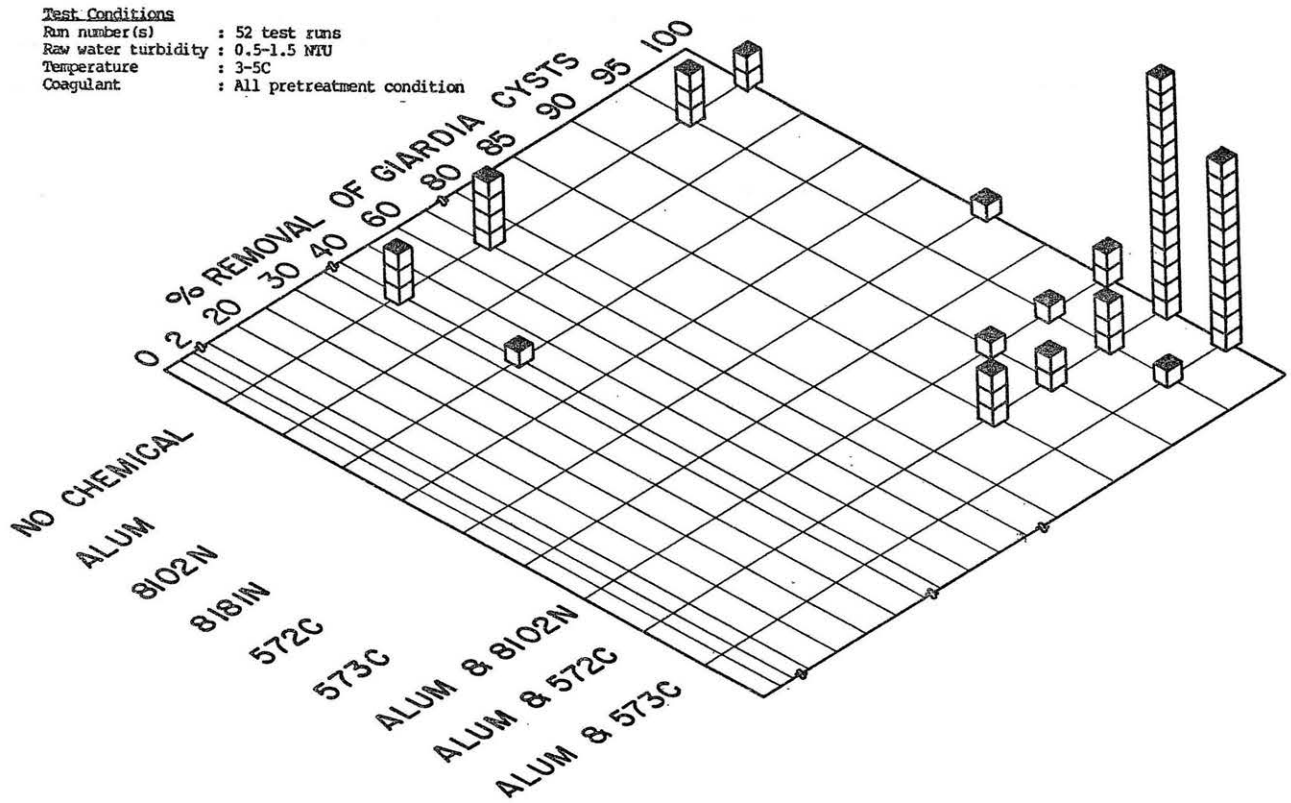

Figure 30. Histogram of Giardia cysts percent removal and coagulant tested, for laboratory-scale rapid rate pilot plant. Each block represents one measurement set.

The search was initiated using jar-filter testing for guidance. Dosages of alum and Magnifloc 572C® were found which resulted in turbidity reductions from about 0.5 NTU to 0.05 NTU. These dosages were then tested further, using the laboratory-scale pilot plant. The same dosage ranges also resulted in effluent turbidity levels of about 0.05 NTU.

At the same time, testing was continued using total coliform bacteria and Giardia cysts. Reductions in both were found to be greater than 95 percent when turbidity reductions were greater than 80 percent.

As test runs continued, data were accumulated for a wider range of alum-polymer dosages. While a turbidity response surface was not "mapped" systematically by this accumulation of points, nevertheless it became feasible to do so. Figure 31 indicates a response surface for filtration effluent turbidity versus dosages of alum and Magnifloc 572C. The shaded bars were obtained using the lab-scale pilot plant. The open bars were obtained by jar-filter testing. Table 12 gives the coordinates for the data points in Figure 31.

Figure 31 shows that coagulation and filtration using alum alone or polymer alone is not efficient. Turbidities of filtered water are in the same range as raw turbidities, or they may be higher. Raw water turbidities generally were less than 1 NTU. But jar-filtration testing (Run 39, 6/7/83) showed that continuation of alum addition caused increasing turbidity with a peak of about 4.8 NTU, followed by rapid decline to 0.3 NTU at 40 mg/L alum (with no polymer). These test run results are not shown in Figure 31 because they are off-scale. The results are similar to practice at the Dillon water treatment plant where 50 mg/L alum and 25 mg/L sodium carbonate are used to produce filtered water turbidity of about 0.1 NTU. When alum was used in combination with Magnifloc 572C, however, turbidities were reduced to 0.05 to 0.10 NTU. The alum dosage needed was only 3-7 mg/L. Regardless of the alum-polymer dosage combination, the filtered water turbidity remained in the 0.05 to 0.10 NTU range as seen in Figure 31. Thus virtually any dosage combination of alum and 572C will reduce the filtered water turbidity about 80 to 90 percent when compared with raw water. This means that one does not have to be too careful with dosages from the standpoint of efficiency, e.g. ratio of filtered water turbidity to raw water turbidity. From the standpoint of economics, however, the lowest dosages should be used.

Figure 31 shows also that the results obtained using the lab scale rapid rate filtration pilot plant were comparable with results using the bench scale jar-filtration testing. The use of the jar-filter testing is discussed elsewhere.

The effect of polymer dosage, for a range of alum dosages from 0.2 to 15.0 mg/L, on removal of Giardia cysts is shown in Figure 32, which is a histogram showing the numbers of observations for given percent removals of Giardia cysts and polymer dosages. It shows that removals exceeded 99 percent, with only three exceptions. The polymer dosages used most often in this work were 1 to 2 mg/L. This dosage is recommended because the data in

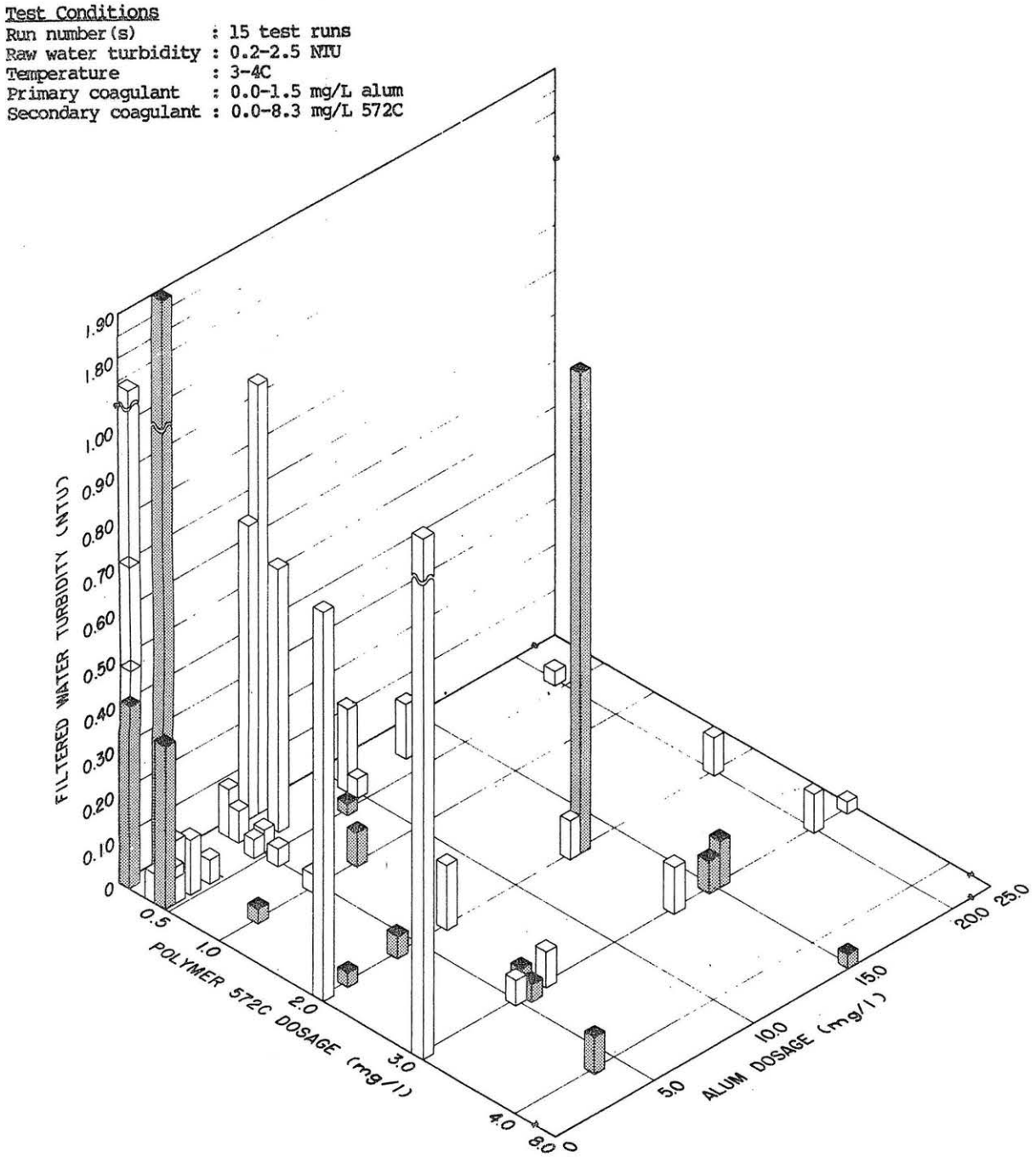

Figure 31. Turbidity of filtered water for various combinations of alum and polymer (Magnifloc 572C). Shaded bars were obtained using laboratory-scale rapid rate pilot plant. Open bars were obtained using jar-filtration apparatus. All tests were conducted at 3-5°C. Raw water turbidities were less than 1 NTU with exceptions as noted in Table 12.

Table 12. Filter effluent turbidities for low turbidity low temperature water with pretreatment using alum and Magnifloc 572C polymer. Data were obtained using sources indicated.

Run No.	Source of Data	Apparatus	Raw Water Turbidity (NTU)	Alum as $Al_2(SO_4)_3\ 14H_2O$ (mg/L)	Polymer Magnifloc 572C (mg/L)	Filter Effluent Turbidity (NTU)
13	EPA Report June 1983[1/]	Jar test	2.20	0.00	0.0	1.74
13	"	Jar test	2.20	2.00	3.0	1.79
13	"	Jar test	2.20	6.43	3.0	0.08
13	"	Jar test	2.20	12.9	3.0	0.10
13	"	Jar test	2.20	19.3	3.0	0.08
13	"	Jar test	2.20	25.7	3.0	0.23
19	"	Jar test	0.83	0.00	0.0	0.48
19	"	Jar test	0.83	0.00	2.0	0.86
19	"	Jar test	0.83	6.43	0.0	0.65
19	"	Jar test	0.83	6.43	2.0	0.14
19	"	Jar test	0.83	12.90	2.0	0.08
19	"	Jar test	0.83	19.30	2.0	0.08
21	"	Jar test	0.66	0.00	0.0	0.71
21	"	Jar test	0.66	0.00	0.3	0.66
21	"	Jar test	0.66	6.43	0.0	0.94
21	"	Jar test	0.66	6.43	0.3	0.58
21	"	Jar test	0.66	9.65	0.3	0.18
21	"	Jar test	0.66	12.90	0.3	0.12
68	Choi Thesis[2/] 1983	Jar test	0.40	0.5	0.4	0.14
68	"	Jar test	0.40	1.5	0.4	0.2
68	"	Jar test	0.40	2.5	0.4	0.05
68	"	Jar test	0.40	5.0	0.4	0.05
68	"	Jar test	0.40	10.0	0.4	0.04
68	"	Jar test	0.40	20.0	0.4	0.03
75	Choi Thesis 1983	Jar test	0.40	5.0	0.1	0.11
75	"	Jar test	0.40	5.0	0.2	0.07
75	"	Jar test	0.40	5.0	0.4	0.04
75	"	Jar test	0.40	5.0	0.6	0.04
75	"	Jar test	0.40	5.0	1.0	0.04
75	"	Jar test	0.40	5.0	3.0	0.53
79	"	Jar test	0.40	1.5	0.2	0.25
37	Master Table[3/]	Pilot Plant	0.19	15.30	8.33	0.03
38	"	"	0.19	1.47	1.97	0.03
40	"	"	0.19	5.57	2.59	0.04
43	"	"	0.64	5.48	2.81	0.06
44	"	"	0.76	3.55	3.85	0.08
51	"	"	0.36	4.08	1.68	0.05
52	"	"	0.36	2.07	1.17	0.03
81	"	"	0.48	6.70	0.80	0.07
82	"	"	0.59	8.82	0.55	0.23
84	"	"	2.20	12.60	1.97	1.05
87A	"	"	2.50	14.70	2.40	0.10
87B	"	"	2.50	14.70	2.90	0.07
77	"	"	0.47	0.00	0.00	0.40
136	"	"	1.19	2.08	0.00	1.9
159	"	"	0.45	0.00	0.4	0.26

[1/] Al-Ani, et al., EPA Report, June 1983.

[2/] Choi, 1983.

[3/] Table 1, Appendix A, from this document.

Figures 31 and 32 show high removals can be expected with it and it is less expensive than if a higher dosage is used.

Examination of data in Table A-1 for removals of total coliform bacteria as affected by polymer dosage, indicates similar results as obtained for percent removals of turbidity and Giardia cysts. Dosage removal data were obtained also using the polymer Magnifloc 573C. These results are not reviewed because they were almost identical to the results obtained using the polymer Magnifloc 572C.

Sequence of Coagulant Addition

In coagulation practice, when two stage rapid mix is used, it is common to add alum and then polymer. Addition of polymer first is not practiced. When only one rapid mix basin is used both alum and polymer must be added simultaneously. Whether the sequence of coagulant addition results in different turbidity removal efficiencies was investigated briefly. Experiments were conducted at two temperatures, 7°C and 18°C, using water having turbidity <1 NTU.

Appendix G shows results of the experiments, plotted as filter effluent turbidity monitored against elapsed run time. Figure G-1, for results of tests at 7°C shows that there is little difference whether both alum and cationic polymer are added simultaneously in one rapid mix basin, or if alum is added to a first basin, followed by cationic polymer in the second basin; effluent turbidity is about 0.1 to 0.15 for both. If cationic polymer is added first, however, the effluent turbidity is appreciably higher, e.g. about 0.25 NTU.

Figure G-2, for results of tests at 18°C, shows effluent turbidity is about the same for all three sequences of coagulant addition, but that this time turbidities are slightly higher if alum is followed by cationic polymer. But simultaneous addition of both gives turbidity levels of about 0.05 NTU.

Mode of Filtration

Table 13 shows results of test runs comparing "in-line" filtration with "direct" filtration. The chemical dosages were "optimum" with respect to turbidity removal for the "in-line" filtration mode. The results show that both modes of filtration gave about the same effluent turbidities and about the same headlosses in the filter columns. Figure 33 illustrates these results in graphical format for Test Runs 148 and 149. Figure G-3, Appendix G, shows the plots for Runs 146 and 147. Logsdon (1983) reported on the use of "direct" filtration to treat low turbidity raw of Lake Superior. The turbidity was reduced to 0.05 NTU with influent turbidity <1 NTU.

These data show that the same filter effluent turbidity was produced whether "in-line" or "direct" filtration was used. Therefore the "in-line" filtration mode was used for this research.

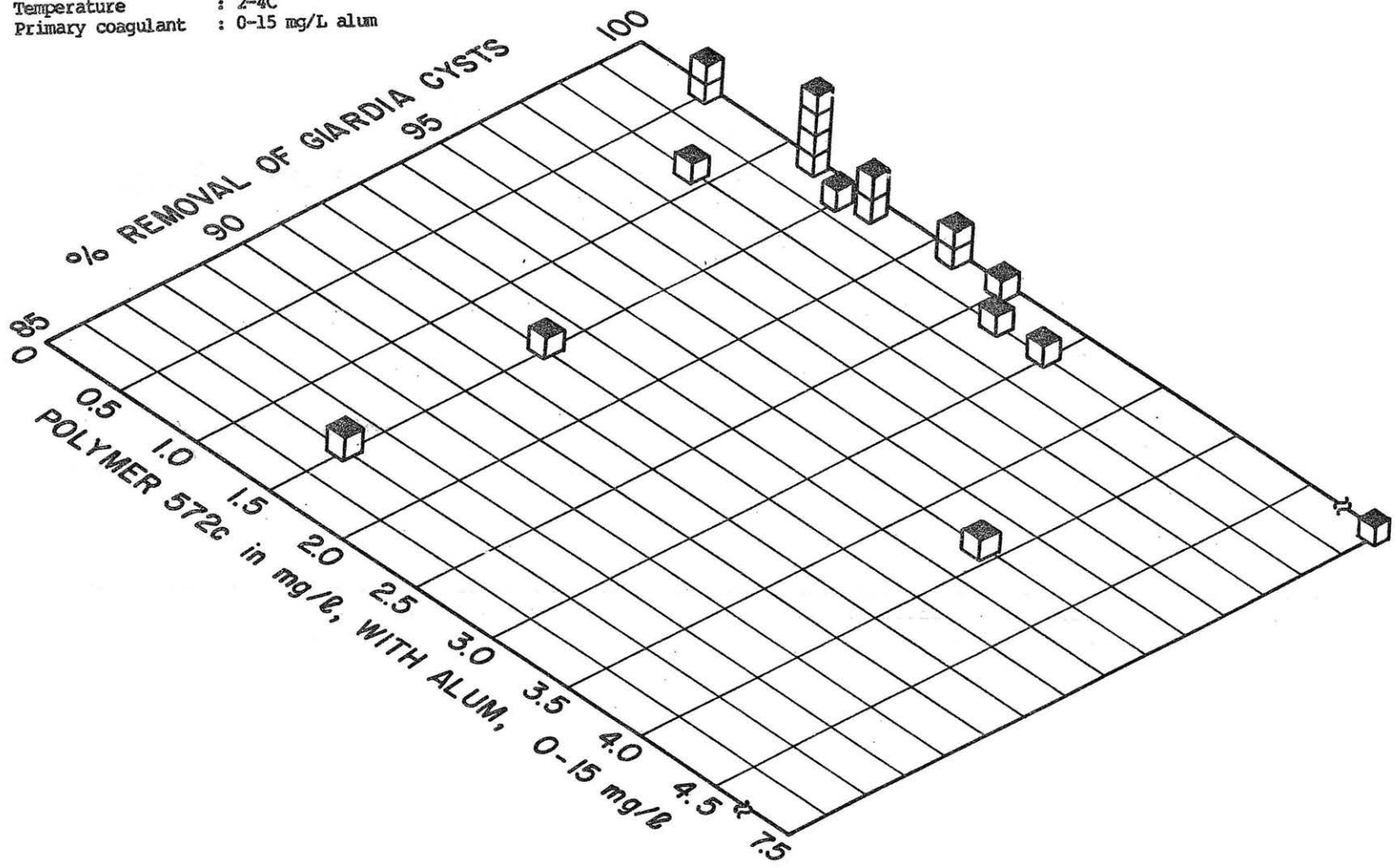

Figure 32. Histogram of Giardia cysts percent removal and dosage of Magnifloc 572C as coagulant aid using laboratory-scale rapid rate pilot plant. Each block represents on measurement set.

Table 13. "In-line" filtration versus direct filtration data.

Run No.	Influent Turbidity (NIU)	Filtration Mode	Alum[1] (mg/L)	Alum[1] GT	Polymer[2] (mg/L)	Polymer[2] GT	Floccultion Basin[3] G	Floccultion Basin[3] T	Floccultion Basin[3] G	Floccultion Basin[3] T	Time[4] (hour)	Head Loss (cm Hg)	Effluent Turbidity (NIU)
146	0.89	In-line	9.32	64824	0.351	64824	0	0	0	0	2.33	10.6	0.09
147	0.89	Direct	9.32	64824	0.351	64824	37.0	1106	36.8	1106	3.00	11.5	0.10
148	1.06	In-line	4.12	66984	0.62	66984	0	0	0	0	4.00	11.5	0.09
149	1.06	Direct	4.12	68542	0.65	68592	37.0	1171	36.8	1171	4.00	12.7	0.10

[1] Alum as $Al_2(SO_4)_3 \cdot 14H_2O$

[2] Polymer Magnifloc 572C

[3] $G = (P/uV)^{1/2}$

P = the power dissipated (lb ft/sec)

u = absoulte viscosity (lb-sec/ft^2)

V = the volume to which P is applied (ft^3)

G = velocity gradient (sec^{-1})

T = detention time (sec)=V/Q

Q = the flow rate (ft^3/sec)

[4] Time when reading taken.

Test Conditions
Run number(s) : 148 "in-line", 149 "direct"
Raw water turbidity : 1.06 NTU
Temperature : 4C
Primary coagulant : Run 148 and Run 149, 4.1 mg/L alum

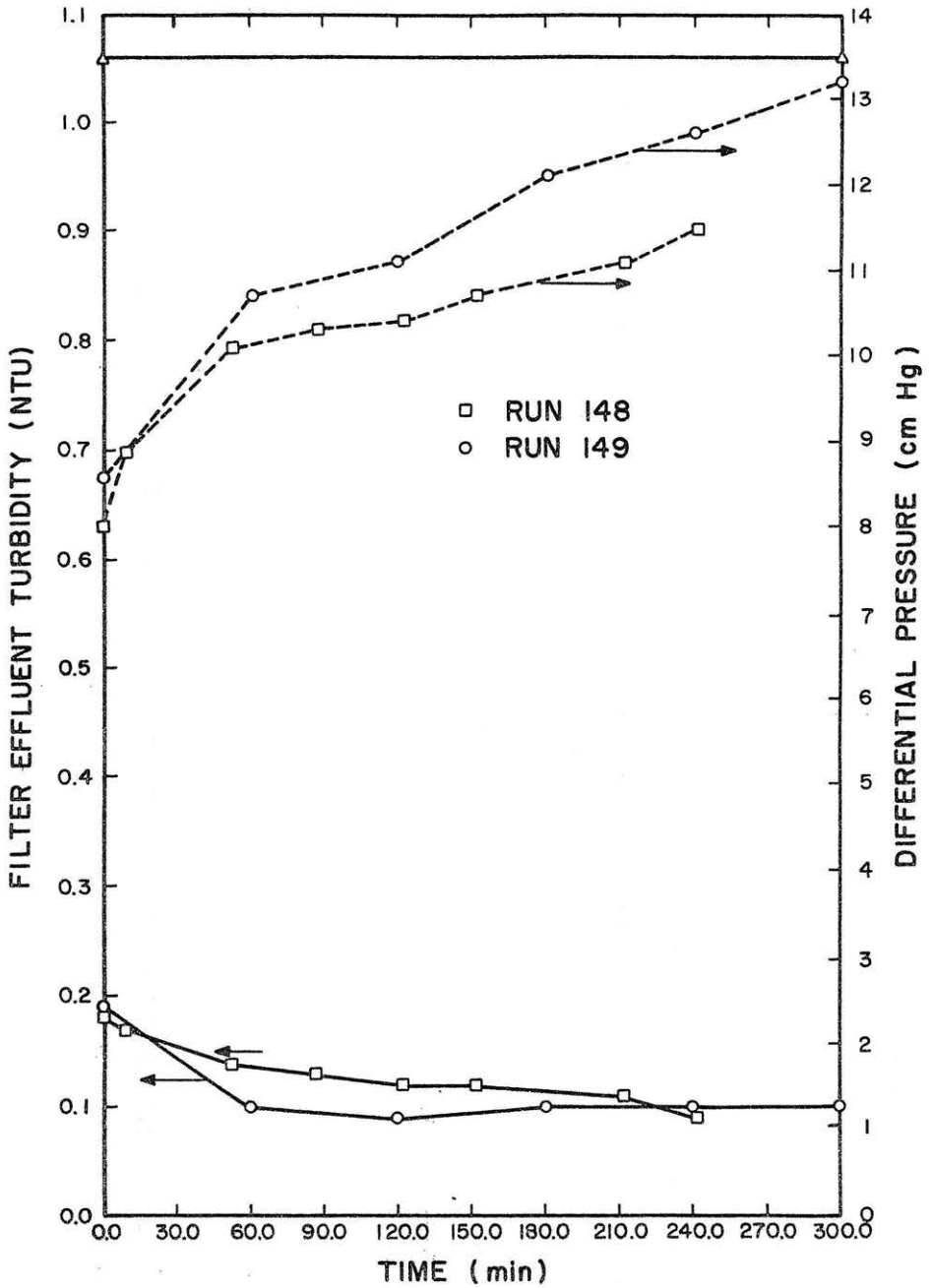

Figure 33. Comparison of turbidity and headless, for "in-line" and "direct" filtration. Laboratory-scale pilot plant using artificial low turbidity water from Horsetooth Reservoir, and dual media Fort Collins sand.

Comparison of Single and Dual Media

Table 14 summarizes results of test runs which compared the effluent turbidities and headloss for single media filter of 76 cm sand with a dual media filter of 30 cm sand, 45 cm anthracite. Three comparisons were made using the same tank of water for each pair. Figures G-4, G-5, G-6 are plots of the results showing turbidity and headloss vs time for each comparison pair.

The first comparison, seen in Figure G-4, was for the no chemical pretreatment condition. Results show comparable effluent turbidities but higher headloss for the single media, e.g. 6.8 cm Hg for single media vs 4.0 cm Hg for dual after 50 minutes of operation. The second comparison, seen in Figure G-5, was conducted using alum and polymer at optimum dosage with respect to turbidity removal. Effluent turbidities were 0.04 NTU for both, and again headloss was higher for the single media. The third comparison used only one coagulant, the polymer 573C. Effluent turbidity was 1.7 NTU for sand and 2.4 NTU for dual media. Headloss as 8.0 cm Hg for sand after 210 minutes of operation, versus 3.7 cm Hg for dual media as shown in Figure G-6.

Based upon these results, and due to the wide spread use of dual media, the latter was used in this research. Although the effectiveness for each was the same with respect to turbidity removal, the appreciably higher headloss experienced using sand as a single media confirms the use of dual media in practice.

Filtration Rate

Table 15 shows the effect of using different filtration rates, for two dual media filters, on removals of turbidity, standard plate count bacteria, total coliform bacteria, and Giardia cysts. Figures 34 and 35 are plots of these data for Fort Collins sand and for Loveland sand, respectively. Both figures show, for the four parameters plotted, that filtration rate has virtually no effect on percent removals in the range 8.1 cm/min (2 gpm/ft^2) to 24 cm/min (5 gpm/ft^2). As noted removals of total coliform bacteria were greater than 99 percent for all hydraulic loading rates while removals of standard plate count bacteria were greater than 96 percent and removals of Giardia cysts exceeded 95 percent except at the highest filration rate used. Further there is little effect up to 32.6 cm/min (8 gpm/ft^2) except a noticeable decline occurs in percent turbidity removal for filtration velocity for 40.8 cm/min, as shown in Figure 35. At the filtration rate of 40.8 cm/min (10 gpm/ft^2) the declines in percent removals are noticeable for total coliform bacteria and standard plate count bacteria, and markedly noticeable for Giardia cysts and turbidity.

Temperature

Table 16 shows effluent turbidity and percent removals of standard plate count bacteria and total coliform bacteria for temperatures of 5^{o}C and 18^{o}C, with all other conditions the same for each paired comparison. Comparison of

Table 14. Comparison of effluent and headloss for single and dual media using laboratory scale rapid rate filtration pilot plant.

Run No.	Influent[1/] Turbidity (NTU)	Media[2/]	Alum Dosage (mg/L)	Polymer Dosage[3/] (mg/L)	Time[4/] (min)	Headloss (cm Hg)	Effluent Turbidity (NTU)
76	0.5HDE	sand	0	0	50	6.8	0.4
77	0.5HDE	dual	0	0	50	4.0	0.4
71	1.0HDE	sand	15.5	1.3	210	10.9	0.04
72	1.0HDE	dual	15.5	1.3	210	5.7	0.04
98	2.4HDE	sand	0	8.8	210	8.0	1.7
99	2.4HDE	dual	0	7.5	210	3.7	2.4

1/ HDE is water obtained from Horsetooth Reservoir, filtered by Diatomaceous Earth to give low turbidity, e.g. 0.2 to 0.6 NTU.

2/ Sand was obtained from Loveland Treatment Plant at Big Thompson Canyon. Bed depth was 76cm. Dual means the bed was comprised of 30 cm sand from Loveland and 45 cm anthracite having trade name Philterkol Special (R) No.1(produced by Reading Anthracite Coal Company. Pottsville, PA. 17901).

3/ Polymer used was Magnifloc 573C (R)

4/ Time is elapsed time for corresponding headloss and effluent turbidity obtained from plots of data.

Table 15. Effect of filtration rate on removal of turbidity, standard plate count bacteria, total coliform bacteria, and Giardia cysts for dual media using two sources of sand[1/]. All other conditions were approximately the same. Laboratory-scale rapid rate filtration pilot plant was used. Coagulant dosages were those in which minimum effluent turbidity was attained.

Run No.	Filtration rate (cm/min)	Media	Chemical used[2/]	Turbidity			Total Coliform Bacteria			Standard Plate count Bacteria		
				Raw[3/] water (NTU)	Filter Effluent (NTU)	Percent removal	Influent (No./100mL)	Effluent (No./100mL)	Percent removal	Influent (No./mL)	Effluent (No./mL)	Percent removal
114	7.8	Anth/	23.2/1.2	1.13	0.10	91	695	<1	>99.9	27,500	880	96.8
113	20.6	F.C.	18.5/1.0	1.13	0.12	89	695	1	99.9	27,500	30,000	0.0
112	32.6	sand	18.5/1.0	1.13	0.3	73	1,500	8	99.5	30,000	410	98.6
111	41.0		18.6/1.0	1.13	0.5	57	1,500	15	99.0	30,000	1,300	95.7
118	9.4	Anth/	23.6/1.4	1.24	0.18	81	790	5	99.4	9,000	140	98.4
116	21.0	Lov.	23.3/3.0	1.28	0.23	82	1,400	<1	99.9	12,500	20	99.8
117	32.3	sand	37.3/1.6	1.24	1.05	15	790	3	99.6	9,000	2,000	77.8
115	40.4		34.3/1.6	1.28	0.27	79	1,400	<1	99.9	12,500	40	99.7

[1/] Anthracite used for both media was Philterkal (R), d_{10} = 0.9 mm, UC = 1.45. Fort Collins sand, d_{10} = 0.5 mm, UC = 1.4, Fort Collins sand was the term used to designate sand obtained from Fort Collins Treatment Plant No. 2. Loveland sand, d_{10} = 0.43 mm, UC = 1.5. Loveland sand is the term used to designate sand obtained from Loveland Big Thompson Canyon Water Treatment Plant.

[2/] Expressed as mg/L alum as $Al_2(SO_4)_3\ 14H_2O$ and mg/L Magnifloc 572 Polymer. Cache La Poudre River water with temperature of 3°C and turbidity 0.6 NTU.

[3/] Turbidity changed from 0.6 NTU to 1.13 NTU after contaminate of raw sewage and dog feces were added to milk cooler. Water was obtained from Cache La Poudre River in April 1983.

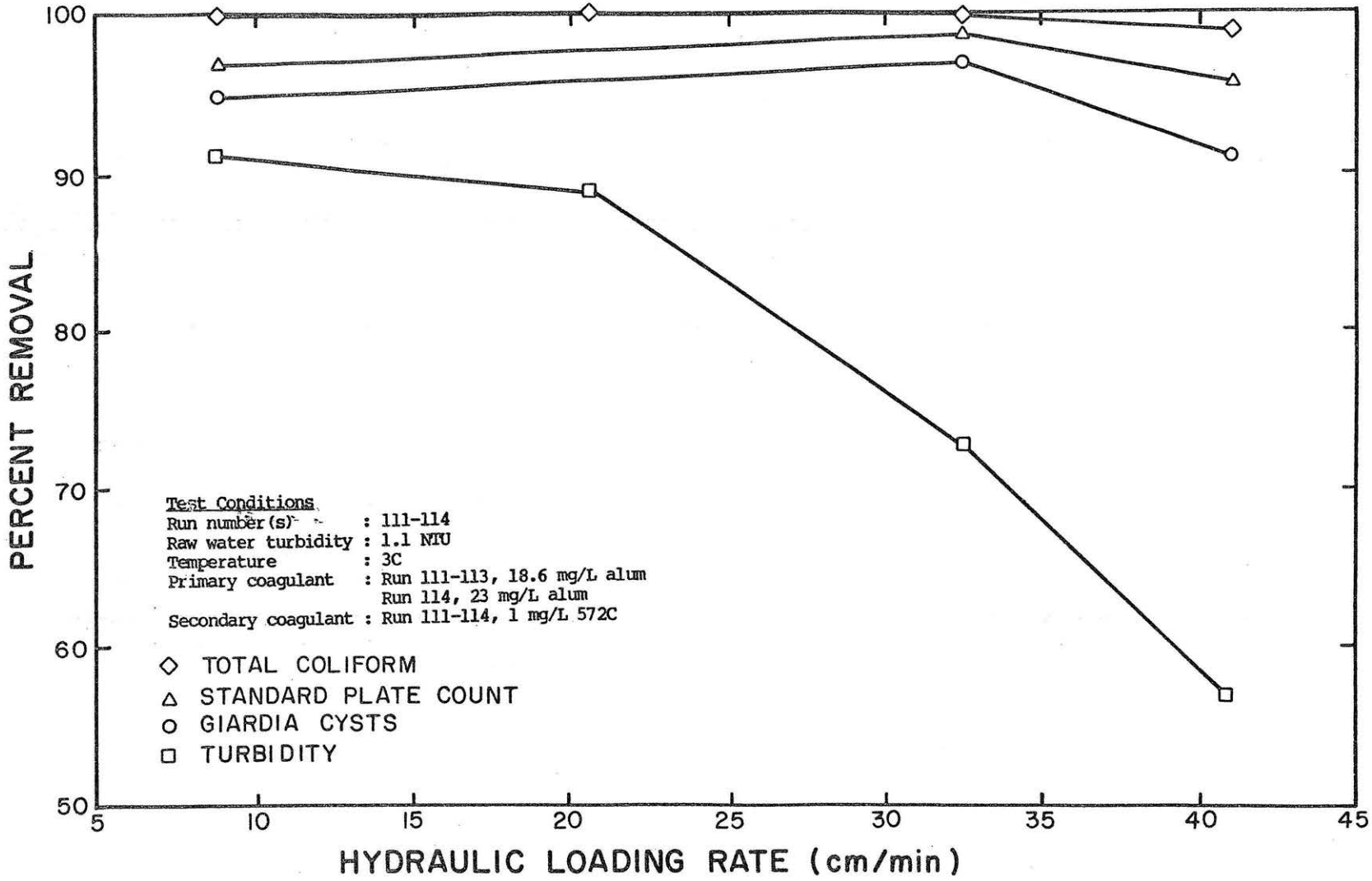

Figure 34. Effect of hydraulic loading rate on percent removal of turbidity, standard plate count bacteria, total coliform bacteria, and Giardia cysts, using laboratory-scale rapid rate filtration pilot plant packed with dual media with Fort Collins sand.

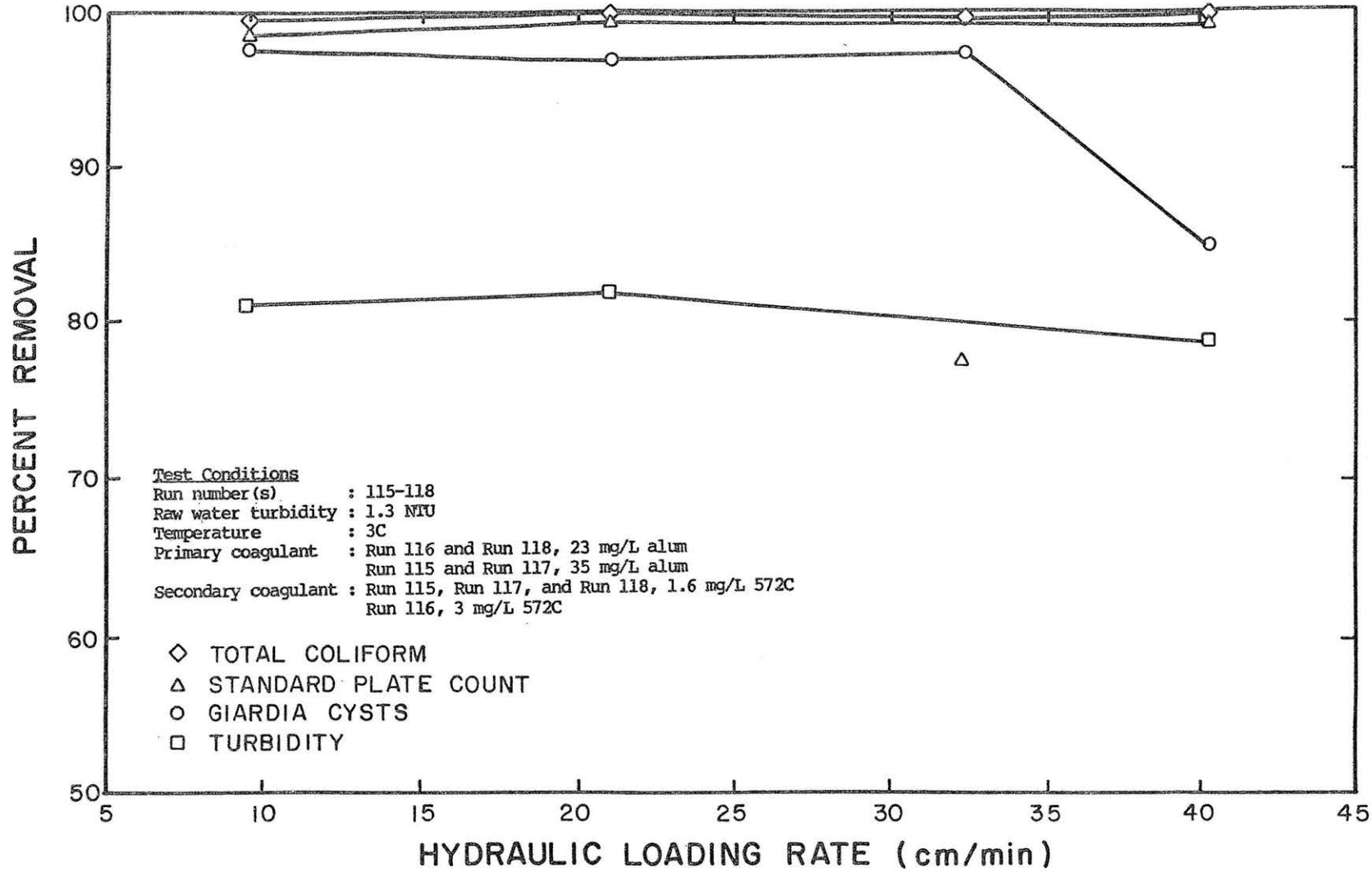

Figure 35. Effect of hydraulic loading rate on percent removals of turbidity, standard plate count bacteria, total coliform bacteria, and Giardia cysts using laboratory-scale rapid rate filtration pilot plant packed with dual media with Loveland sand.

Table 16. Effect of temperature on removal of turbidity, standard plate count bacteria, total coliform bacteria, for different chemical dosages.

Run No.	Influent Turbidity (NTU)	Chemical Species	Dosages (mg/l)	Temp. (°C)	Effluent Turbidity (NTU) 1/	% Removal Standard Plate count	% Removal Total Coliform
159	0.45	572C	0.42	5	0.3	90.0	97.0
151	0.45	572C	0.42	18	0.2	-77	86.6
160	0.45	Alum/572C 2/	4.31/1.85	5	0.10	95.89	99.5
152	0.45	Alum/572C 2/	4.31/1.85	18	0.08	77.6	>99
158	0.45	Alum/572C	5.47/0.48	5	0.2	93.7	99.7
154	0.45	Alum/572C	5.47/0.48	18	0.15	82.6	93.1
157	0.45	572C/Alum	1.00/9.0	5	0.32	91.5	99.6
155	0.45	572C/Alum	1.00/9.0	18	0.08	93.2	99.8

1/ Turbidity values was obtained from Figures E-7 to E-10, Appendix E at 90 minutes of filtration run time.

2/ Alum and polymer were added simultaneously using one rapid mix basin