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Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter

Report 1: Intrinsic Effectiveness

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1 Project Background

1.1 Hurricane Mitch, USAID, and CACEDRF

In October 1998, Hurricane Mitch devastated Central America, causing over 3,000 deaths in Nicaragua alone (USAID 2001, 2001a). An estimated 18 percent of the population of Nicaragua was affected by Mitch, and water and wastewater systems serving 804,000 people suffered over US$560 million in damage. The Unites States provided US$22 million in immediate humanitarian and food aid, and an additional US$8 million to start reconstruction activities in health, agriculture, and micro-finance.

In May 1999, the United States Congress authorized US$621 million in aid under the Emergency Supplemental Appropriations Act (USAID, 2001). These funds were authorized to support reconstruction in countries affected by Hurricanes George and Mitch, and were later authorized to cover Hurricanes Floyd and Lenny, as well as the earthquake of January 1999. This appropriation created an account named the Central American and Caribbean Emergency Disaster Recovery Funds (CACEDRF).

USAID is responsible for administering US$586.8 million of the US$621 million allocated under CACEDRF (USAID, 2001a). Of the total funds, US$94.1 million was allocated for economic reactivation, public health, school rehabilitation, disaster mitigation, and municipal restoration in Nicaragua. As of June 30, 2001, a significant amount of progress on projects relating to water supply and sanitation had already occurred (Table 1-1).

Table 1-1: CACEDRF Successes Relating to Water Supply and Sanitation in Nicaragua

Category	Success
Economic Reactivation	57,000 households incorporated environmentally sustainable practices on their farms 8,000 hectares of watershed area protected
Public Health	2,440 wells rehabilitated or built 5,740 latrines constructed 600 seepage pits constructed 175 deep wells drilled in rural areas 10,000 training visits held to improve health behavior related to new water and sanitation infrastructure 6 health clinics constructed
School Rehabilitation	196 schools scheduled for rehabilitation of wells and latrines
Disaster Mitigation	Cleaning and stabilizing stream channels Construction of drainage channels
Municipal Restoration	Projects with local governments on storm drain systems, flood control, river deck construction

An additional goal of the rehabilitation program in Nicaragua is to investigate point-of-use household water filtration systems (USAID, 2001b). To this end, USAID worked to install 40,000 sand filtration units, supervised by Maria Alejandra Bosche. Ms. Bosche found that follow-up education was critical to the correct and continued use of the filter system (Bosche, personal conversation).

Secondly, USAID contracted with Jubilee House Community (JHC) to study the Potters for Peace (PFP) ceramic water filtration system. JHC, an intentional Christian community, is a 501(c)3 organization in North Carolina (JHC-CDCA, 2001). From 1979 – 1994, members of the community worked on shelters for homeless and battered women, as well as other social and justice issues, in North Carolina. In 1994, the community moved to Nicaragua, established the Center for Development in Central America (CDCA), and began working with communities in Nicaragua. After Hurricane Mitch, JHC-CDCA began to work on reconstruction projects in Nueva Vida, a nearby community swelled with displaced persons. USAID provided funding and supplies to build housing, a medical clinic, and latrines (USAID, 2001c). JHC and a group of volunteers worked with the community to build these facilities, in addition to a number of other projects. One of these other projects is the promotion of the Potters for Peace water filtration system to provide safe drinking water for families in Nueva Vida.

JHC worked with PFP to contract Daniele Lantagne, Principal of Alethia Environmental and Lecturer in Civil and Environmental Engineering at the Massachusetts Institute of Technology, to complete the project. The project was divided into two deliverables, one addressing the intrinsic effectiveness of the filter, and the other addressing the performance of the filters under field conditions. Specifically the reports are to address the following:

Report 1: Intrinsic Effectiveness of the Potters for Peace Ceramic Filter

- Best practices for colloidal silver application.
- Expected filter flow rates with and without colloidal silver.
- Expected lifetime per application of colloidal silver.
- Concentration of silver in filtered water.
- Effects of ingestion of the silver.
- Inactivation of microbes as a function of the concentration of silver.
- Effectiveness of silver in removing other pollutants commonly found in the area of interest.

Completion Deadline: December 21, 2001

Report 2: Field Testing of the Potters for Peace Ceramic Filter

- Discussion of the performance of the filters under field conditions.
- Comparison of filter performance with other commonly used methods of treatment.

Completion Deadline: November 16, 2001

This report, Report 1, addresses the intrinsic effectiveness of the Potters for Peace filter. The first four chapters of this report are the same as the first four chapters in Report 2: Field Investigations (Lantagne, 2001a). These chapters provide background on this project, the Potters for Peace filter, waterborne disease, and colloidal silver as a disinfectant.

Report 1 continues by detailing the results of the following studies: (1) filtration studies, including filtration rate, filter pore size, and filter longevity; (2) colloidal silver studies, including application methods and necessary concentration for microbiological inactivation and (3) challenge studies, include pesticide removal, VOC removal efficiency, and protozoa and virus removal efficiency. Reviews of previous studies conducted, as well as research conducted for this project, are included within each section. Report 1 concludes with a summary of results and recommendations.

1.2 Water Supply and Sanitation in Nicaragua

Nicaragua is located in the center of the Central American isthmus and is the largest country in the region, with a surface area of 130,682 km^2 (PAHO, 1999). Nicaragua has three distinct topographical regions – the Pacific, Atlantic, and Central regions. The greatest percentage of the population lives on the Pacific coast and the lowest percentage lives on the Atlantic coast. Recovery from the devastation of Hurricane Mitch is ongoing. Although many roads and water supply systems have been repaired or replaced, some rural areas of the country have still not recovered to pre-Mitch levels of infrastructure.

Although most people living in urban areas have access to safe water and sanitation, a significant percentage of people in rural areas do not (Table 1-2). In addition, and possibly as a result, infant and under-5 mortality is high. Over half of the population lives in poverty, and the illiteracy rate is around 40 percent.

Table 1-2: Water Supply and Sanitation Indicators in Nicaragua

	World Bank (1999)	PAHO (2000)	PAHO (1999)	UNICEF (2000)
Population (millions)	4.9	5.1	4.5	4.9
Urban population (%)	55.8		63.7	
GNI per capita	US$410			US$430
Access to safe water	79%		37%	79%
Access to safe water (urban)	95%		93%	95%
Access to safe water (rural)	59%		12%	59%
Access to sanitation				84%
Access to sanitation (urban)	96%			96%
Access to sanitation (rural)	68%			68%
Under-5 mortality rate (per 1,000 live births)	43	55.8	66	
Infant mortality (per 1,000 live births)		45.2	47	
Maternal mortality (per 100,000 live births)		102	124	150
Life Expectancy (years)			68.4	
Population in poverty		50.3%	63%	
Literacy Rate – Women		69%	66%	
Literacy Rate – Men		50.3%		

A number of different international and national development organizations have worked in Nicaragua to increase access to safe water and sanitation. Many of the wells installed for water supply are Nicaraguan rope pump wells. These are an appropriate technology design utilizing a rope pulley to lift groundwater up to 6 meters (Sandiford, 1993). The systems are easy to use, low cost, simple to maintain, and made of locally available parts. In addition, rope pump wells show a 62 percent reduction in fecal coliform as compared to bucket wells. Currently, Bombas de Mecate markets the wells commercially in Nicaragua, without the need for external subsidies.

Anna Gorter conducted a series of studies on childhood diarrhea in Villa Carlos Fonseca, and published them in her book Childhood Diarhhoea and its Prevention in Nicaragua (1995). She investigated a series of variables and their relationship to childhood diarrhea and found the following:

Variables Reducing Childhood Diarrhea	Variables Increasing Childhood Diarrhea	No Relationship to Childhood Diarrhea
Distance to water supply	Increased number of children under 5	Ownership of latrine
Increased schooling of mother		
Hand-washing		
Domestic cleanliness		
Use of diapers in children		

After years of study, Gorter (1995) concluded that

> There are interactions among interventions, and therefore the effect of a particular intervention will not only depend on its own merit, but also on those of the other interventions with which it interacts. Theoretical models suggest that such interactions exist between water supply, sanitation and hygiene interventions. The impact of improvements in water supply, sanitation and hygiene together are greater than the sum of the effects of the interventions alone. Furthermore, if the interactions are strong, the health impact from an improved water supply may depend critically on whether sanitation and hygiene conditions are good or poor. The Villa Carlos Fonseca studies have made it clear that supplying only hardware is not sufficient to reduce the incidence of diarrhoea. Personal, domestic and especially community hygiene plays a crucial role in the transmission of diarrhoeal pathogens.

The conclusion of Gorter's research highlights the need for coordinated water supply, water treatment, and education programs in order to achieve the greatest improvement in human health.

2 The PFP Filter

2.1 Initial Filter Design

In 1981 the InterAmerican Bank financed a comparative study designed to determine which of 10 appropriate technology filters could be best adapted to the objectives of the project, which were (ICAITI, 1994):

1. To produce a domestic filter of suitable capacity;
2. In a self-supporting manner;
3. Whose production would foster economic activity at low income levels; and
4. Foster artisan activity.

ICAITI, an industrial research institute in Guatemala supported by the Organization for American States, was contracted to complete the research and to choose a model. Ten models were evaluated based on filtration flow, bacteriological efficiency, ease of manufacture, availability of materials, final cost, contribution to artisan activity, and ease of distribution. All but two models were discarded after initial review because they did not meet basic criteria. The two models not discarded were:

1. Lathed clay filter with feldspar, sawdust, and colloidal silver impregnation; and
2. Lathed clay filter with sand, sawdust, and colloidal silver impregnation.

None of the ten models investigated utilized chlorine as a disinfectant.

Further research was then conducted on the two models that met the basic criteria. This research, led by Fernando Mazareigos, did extensive bacteriological testing over a 3 to 10 month period. Results of this research include:

1. Of 302 filtered samples analyzed, only 6.3 percent were above 1.0 coliforms per 100 mL of water. The method used for analysis was most probable number.
2. Application of silver was determined to be more uniform when applied by brush as opposed to filtering water containing colloidal silver through the filtering element.
3. Frequent contamination was found both in the first few runs of the filter (41 percent contaminated) and after handling the element during sampling. This was attributed to handling the filter and ICAITI recommended that users refrain from touching the element during its useful life. Due to the omnipresent bacteria in the environment "usage of the filter must be accompanied by sanitary and hygienic practices in order to maximize the potential benefits to health."
4. Flow in the filters gradually declined from 3.5 Liters per hour on Day 1 to 1.97 Liters per hour on Day 365. The report contained no information on turbidity of the raw water supply.
5. ICAITI recommended not using the filter with chlorinated water. No reason was given.

Based on these results, ICAITI concluded that a colloidal silver impregnated ceramic filter was the only design that met all established criteria of the study. The United Nations then included this filter in their

Appropriate Technology Resource Material Manual. ICAITI concluded its study by producing a "Manual Para La Fabricacion De Filtros Artesanales De Agua Potable."

2.2 Filter Implementation

After a visit from Fernando Mazariegos, MAP International in Quito, Ecuador applied for funding to develop a factory in indigenous lands that would produce and market the water filter (MAP International, 1985). In 1983, USAID granted the funding, and, using that initial and then a second grant, MAP International worked with the local community to establish a factory.

A number of technical difficulties were encountered and solved during the establishment of the factory. These included:

1. Adaptations to the sand, clay and sawdust mixture were necessary to obtain the correct porosity.
2. It was difficult to make the external finished water receptacle impermeable.
3. It was difficult to find a supplier of colloidal silver in Mexico.
4. Adaptation of the kiln was necessary so that it could be hot enough to fire the filters.

In addition, laboratory tests with the filter indicated that with lower turbidity, flow rates would be more rapid. Thus, control of the filter production was deemed crucial to ensuring enough colloidal silver contact time to effectively reduce bacteriological contamination (IEOS, 1985; 1985a). Due to these issues, Ron Rivera, a ceramics consultant, was brought in to provide technical assistance.

These problems were solved, and the factory was completed. However, the majority of the grant resources were expended solving the problems, and not enough money was spent on development of the market. In the final report, MAP International (1985) stated that "the end of the project status can best be described as a water filter production unit that is capable of producing a quality product buy lacks a marketing unit that is capable of generating sales that are sufficient to enable the operation to sustain itself at a breakeven point of 83 units per month."

Although the MAP International project ended less than ideally, Ron Rivera continued to consult on other projects and proceeded to introduce the filter to potters in Ecuador, Bolivia, and Nicaragua (Rivera, personal communication). In addition, ICAITI continued to support the one family of potters making filters in the small village of Rabinal, Guatemala.

The next major step in the history of the filter came when Dominique Wilson, of AFAGuatemala, became interested in the filter. She was researching water purification and found that people were not using chlorine correctly and also were not boiling water long enough to ensure disinfection. Wilson received funding to investigate the ICAITI filter, and determined that health education and the filter could reduce childhood diarrhea (see Section 5.1 for detailed results). Unfortunately, the project ended with that study, as the NGO did not have a marketing strategy and discontinued work with the filter.

The next step in the history of the filter came when Ron Rivera was hired by Potters for Peace as their in-country supervisor in Nicaragua.

2.3 Potters for Peace

Potters for Peace (PFP) "seeks to build an independent, non-profit, international network of potters concerned with peace and justice issues. We will maintain this concern principally through interchanges involving potters of the (overdeveloped) North and (underdeveloped) South. PFP aims to provide socially responsible assistance to pottery groups and individuals in their search for stability and improvement of ceramic production, and in the preservation of their cultural inheritance (PFP, 2001)."

The PFP in-country supervisor, Ron Rivera, works with individuals, communities, and North American volunteers to learn and teach pottery techniques, and to market indigenous Nicaraguan pottery in the United States. PFP is recognized by Global Exchange as a fair trade company, and PFP associated ceramics are sold in fair trade stores across North America and Europe. The description on the Global Exchange web site (2001) describes PFP as an "international crafts solidarity organization of North American potters working to provide product development and export assistance to ceramic cooperatives in Nicaragua."

In addition, Ron has used his previous experience with the filter to develop filter factories and filter sales both in Nicaragua and around the world. Even though the filter factory in Nicaragua is successful and the filtration system is in high demand across the globe there has been some questioning of the PFP board as to whether this focus matches with their original goal (Rivera, personal communication). At the last PFP board meeting, it was decided that the current intense focus on the filtration system is something they want to continue to support. However, the board has established a mechanism for donors to contribute to only non-filtration system projects, if donors desire to support only the fair trade aspect of the organization.

Thus, PFP and Ron Rivera work to introduce the filter for general use in developing countries by establishing micro-enterprises of artisans making the filters and receptacles, and by partnering with NGOs that distribute the filter and provide education. From here on in the report, the ICAITI / PFP filter will be referred to simply as the PFP filter.

2.4 The PFP Filter Factory

The PFP water filters are produced in a factory in Managua, Nicaragua that employs four male staff ceramicists and one female part-time administrative assistant. The factory is in the process of becoming a legally recognized cooperative, owned by the workers and other interested parties to make up the requisite number of 10 for a cooperative in Nicaragua. The factory workers maintain their own Quicken files, and operate fairly independently, with some technical oversight from Ron Rivera. There has been a woman employee at the factory, but she resigned because of the difficulty of the labor.

The filter itself is 31 cm in diameter, 24 cm high, holds 7.1 Liters of water, and is shaped "like a coned flower pot (PFP, 2001)." The filter sits inside the receptacle like a vegetable steamer sits inside the steaming pot. Receptacles for the filter are either 20-Liter plastic buckets or thrown ceramic pots. A plastic (or in the past bronze) spigot attaches at the bottom of the receptacle. A plastic or ceramic lid is placed on top.

The process for making the filter is as follows:

1. 60 percent dry pulverized clay (including brick scraps that are not acceptable to bricklayers) and 40 percent screened sawdust are mixed together in a mixer.
2. Water is added to the mix to obtain the correct consistency.
3. The filters are then formed by hand, turned on a potter's wheel, or press-molded. In the Managua factory, filters are press molded using a 10-ton hydraulic jack.
4. Filters are fired at 887 degrees centigrade in a brick kiln using wood scraps from industry as the fuel source.
5. Filters are allowed to cool.
6. Filters are soaked for 24 hours to saturate the filter before flow testing.
7. The flow rate of each filter is tested to ensure a rate of between one and two Liters per hour – filters outside this range are discarded.
8. Filters are allowed to dry again.
9. 2 mL of 3.2 percent colloidal silver in 250 mL of filtered water are applied with a brush to each filter.
10. Filters are dried and sold.

Factory costs are calculated based on a daily output of 40 filters. The filters are sold for US$4.00 per filter to primarily NGOs interested in establishing their own water filtration program. Filters are sold without packaging or a finished water receptacle. The NGOs purchasing the filters bring cardboard boxes and trucks for delivery. Receptacles range from 20 Liter plastic buckets at US$3.00 each, to a basic ceramic model at US$8 each, to a very elaborate painted ceramic model at US$60.00 each. NGOs primarily purchase the basic plastic model because of ease of transport, lightweight, non-breakable material, and lower cost.

In total, approximately 12,000 filters have been sold to organizations that then distribute and support the filters in the communities. The largest purchasers buy 600 – 1,000 filters at a time. Organizations which have purchased large numbers of filters include: Red Cross Nicaragua, Plan International, Accíon Medíca Christiana, ADOVEC, PRONICA, and Médicos del Mundo. Most organizations receive funding from a donor or a grant to purchase the filters, and then distribute the filters in the communities. Because these are often one-time grant funded purchases, money is often not allocated for staff time in training and follow-up with families on filter system use.

Organizations that have purchased the filter from the factory in Managua include:

Federación Internacional de la Cruz Roja
ACSUR (Las Segovias – Cruz Roja Española)
Médicos del Mundo (Spain)
Médicos sin Fronteras (Belgium)
ENACAL – UNICEF (Matagalpa, Nicaragua)
SILAIS (Jinotega, Nicaragua)
Plan International
Project Concern International – USAID (CPI)
Fundación Rio
Alcaldía de Posoltega
Coorinadora San Juan de Limay
Centro e la Mujer Xochilt Acalt (Malpaisillo)
Centro de la Mujer San Francisco Libre
Comunidad Los Pasos
Voluntarios Cuerpo de Paz (Peace Corps)
Fundación Sol (Ocotal, Nicaragua)
Tecuilcan – Managua (Proyecto Nueva Vida)
Cantera
FUMDEC (Matagalpa, Nicaragua)
ADIC (Matagalpa, Nicaragua)
ADOVEC (Jinotego, Nicaragua) (With InterAmerican Foundation Funding)
Asociación de Madres La Paz Centro
Siempre Verde (Matagalpa, Nicaragua)
Hermanas del Buen Paston (Proyecto Nueva Vida)
PRONICA
AMLAE (San Juan de Limay)
Comité de Mujeres (Ocotal, Nicaragua)
Tienda Campesina (Achuapa)
Family Planning International (Guatamala)
CORDES (El Salvador)
Accíon Medíca Christiana (San Francisco Libre)

In addition to production in Nicaragua, Ron has worked with interested people and organizations in other countries to establish their own filter factories. People find PFP and the water filtration system via the Internet, and contact Ron. Ron will then visit and help set up a filter factory. In 2000, factories were established in Mexico, Bangladesh, and Cambodia. In 2001, factories were established in Haiti, Guatemala, El Salvador, and Nepal. These factories operate on a smaller scale than the Managua factory, but they follow the model of the development of the Managua site, and could all grow to meet demand.

In addition, factories are in the development stage for 2002 in Pakistan, Uzbekistan, and Ghana.

3 Waterborne Disease

3.1 Waterborne Disease

In the Report of the WHO Commission on Health and Environment (undated), the WHO described three mechanisms of transmittal for waterborne diseases. The three modes of transmission are:

1. Waterborne diseases

   > "These arise from the contamination of water by human or animal faeces or urine infected by pathogenic viruses or bacteria, which are directly transmitted when the water is drunk or used in the preparation of food."

2. Water-washed diseases

   > "Scarcity and inaccessibility of water make washing and personal cleanliness difficult and infrequent. Where this is so some diarrhoeal diseases and contagious skin and eye infections are prevalent. All waterborne diseases can also be water-washed diseases…. Water-washed diseases diminish whenever an adequate supply of water is available and used."

3. Water-based diseases

   > "Water provides the habitat for intermediate host organisms in which some parasites pass part of their life cycle."

In addition, the WHO detailed the public health impact worldwide of waterborne diseases (Table 3-1). A number of diseases have not yet had morbidity, mortality, and population at risk statistics developed, however, the statistics that have been enumerated show that a significant fraction of the world population is both at risk for, and contracts, waterborne diseases.

Table 3-1: Worldwide Public Health Impact of Waterborne Disease (WHO, undated)

Disease	Morbidity (per year)	Mortality (deaths / year)	Population at risk
Waterborne & water-washed			
Cholera			
Diarrheal disease	1,500 million episodes in children under 5	4 million in children under 5	Over 2,000 million
Enteric fevers	500,000 cases	25,000	
Poliomyelitis	204,000	25,000	
Ascariasis (roundworm)	1,000,000	20,000	
Leptospirosis			
Trichuriasis			
Water-washed			
Trachoma	6 – 9 million blind		500 million
Leishmaniasis	400,000 new infections / year		350 million
Relapsing fever			
Typhus fever			
Water-based			
Schistosomiasis	200 million	200,000	500 – 600 million
Dracunculiasis	Over 10 million		Over 100 million

The microorganisms that cause these waterborne diseases are classified as bacteria, protozoa, viruses, and helminthes (Levinson, 1996). These four organisms belong to different kingdoms and are eukaryotic (containing DNA with a nuclear membrane), prokaryotic (without a defined membrane), and noncellular (Table 3-2).

Table 3-2: Biologic Relationships of Pathogenic Microorganisms (Levinson, 1996)

Kingdom	Pathogenic Microorganism	Type of Cell
Animal	Helminthes	Eukaryotic
Protist	Protozoa	Eukaryotic
	Fungi	Eukaryotic
Prokaryote	Bacteria	Prokaryotic
	Viruses	Noncellular

Bacteria are single-celled prokaryotic (without nucleus) members of the eubacteria group (MEI, 1991). Although they are not eukaryotes (with a defined nucleus), they have similar cell chemistry to eukaryotes. Their size varies from 0.3 to 100 μm in length, depending on their shape (Table 3-3). *E. coli* is a rod shaped bacteria that is 0.5 μm in width and 2 μm in length. Most of the bacteria are larger than the 1μm pore size that Potters for Peace aims to maintain in their filter.

Table 3-3: Bacteria Types and Size (adapted from MEI, 1991)

Shape	Name	Size
Spherical	cocci, coccus	1 – 3 μm in diameter
Rod	bacilli, bacillus	0.3 – 1.5 μm in width 1.0 – 10 μm in length
Curved rod	vibrios	0.6 – 1.0 μm in width 2 – 6 μm in length
Spiral	spirilla	up to 50 μm
Filamentous		up to 100 μm and longer

Protozoa are single-celled eukaryotic (with a nucleus) organisms. They feed on bacteria and other microscopic organisms. *Giardia lamblia* and *cryptosporidium* are common disease-causing protozoa. Protozoa range in size from 8 – 100 μm.

Viruses are parasitic particles consisting of a strand of genetic material. They do not have the ability to synthesize new compounds, and instead invade the host cell and redirect the host genetic material to produce viral particles. Because they do not have the structure to reproduce themselves, viruses are the smallest of the disease-causing organisms, at 0.02 – 0.2 μm.

Helminthes are worms that are part of the animal kingdom. Platyhelminthes (flatworms) and Aschelminthes (flukes, tapeworms) are present in water bodies throughout the world, and enter the human body to cause diseases such as trichinosis, hookworm, and roundworm infestation.

Infectious agents commonly found in drinking water include members of the bacteria, virus, protozoa, and helminth groups and cause diseases ranging from diarrhea to jaundice to acute respiratory illnesses (Table 3-4).

Table 3-4: Waterborne Disease-Causing Organisms (MEI, 1991)

Organism	Disease	Remarks
Bacteria		
Escherichia coli	Gastroenteritis	Diarrhea
Legionella pneumophila	Legionellosis	Acute respiratory illness
Leptospira	Leptospriosis	Jaundice, fever
Salmonella typhi	Typhoid fever	Fever, diarrhea
Salmonella	Salmonellosis	Food poisoning
Shigella	Shigelloisis	Bacillary dysentery
Vibrio cholerae	Cholera	Heavy diarrhea, dehydration
Yersinia enterolitica	Yersinosis	Diarrhea
Viruses		
Adenovirus	Respiratory disease	
Enteroviruses (67 types, including polio, echo, etc.)	Gastroenteritis, heart anomalies, meningitis	
Hepatitis A	Infectious hepatitis	Jaundice, fever
Norwalk agent	Gastroenteritis	Vomiting
Reovirus	Gastroenteritis	
Rotavirus	Gastroenteritis	
Protozoa		
Balantidium coli	Balantidiasis	Diarrhea, dysentery
Cryptosporidium	Cryptosporidiosis	Diarrhea
Entamoeba histolytica	Amebiasis	Diarrhea, bleeding
Giardia lamblia	Giardiasis	Diarrhea, nausea, indigestion
Helminths		
Ascaris lumbricoides	Ascariasis	Roundworm infestation
Enterobius vericularis	Enterobiasis	Pinworm
Fasciola hepatica	Fascioliasis	Sheep liver fluke
Hymenolepis nana	Hymenolepiasis	Dwarf tapeworm
Taenia saginata	Taeniasis	Beef tapeworm
T. solium	Taeniasis	Pork tapeworm
Trichuris trichiura	Trichuriasis	Whipworm

Thus, a number of different organisms of varying size and pathology contribute to waterborne disease throughout the world. Two mechanisms in the PFP filter contribute to reduction of these organisms. The first mechanism is filtration. The PFP filter will trap any particle or organism that is larger than the pore size of the filter. PFP aims to have a pore size of 1 μm (1 micron). This would trap a significant portion of bacteria, and all protozoa and helminthes. However, viruses are smaller than 1 micron, and thus would not be trapped.

The second inactivation mechanism for organisms contributing to waterborne disease utilized in the PFP filter is colloidal silver.

4 Colloidal Silver as a Disinfectant

Silver is a soft, malleable metal, which is stable in water and oxygen but attacked by sulfur compounds in air to form a black sulfide layer (CRC, 1997). The atomic number of silver is 47, its atomic weight is 107.868, and it exists in its common valence states of Ag^{+}, Ag^{2+}, and the mineral form of argentite, $Ag^{2}S$. Typical ambient concentrations of silver are presented in Table 4-1. Silver is present throughout the environment in small concentration (milligram to nanogram), but is not essential for animal or plant life.

Table 4-1: Typical Ambient Concentrations of Silver (adapted from CRC, 1997)

Content	Concentration
Total Content in Soils	0.03 – 0.9 mg/kg
Soluble Content in Soils	0.01 – 0.05 mg/kg in 1 N NH_4AOC
Content in Sea Water	0.04 µg/kg
Content in Fresh Water	0.13 µg/kg
Content in Marine Animals	3 – 10 mg/kg
Content in Humans	Blood: < 2.7 µg/L Bone: 1.1 mg/kg Liver: <5 – 32 ng/g
Content in Animals	6 µg/kg
Content in Plants	0.01 – 0.5 mg/kg
Content in Common Foods	0.07 – 20 mg/kg
Essentiality	Plants: no Animals: no

The daily dietary intake by humans is estimated at 0.0014 to 0.08 mg (CRC, 1997). When the maximum CRC intake per day (0.08 mg) is calculated over a 70-year lifetime, a total of 2.0 grams of silver are ingested per person per lifetime.

$$0.08 \text{ mg / day} \bullet 365 \text{ days / year} \bullet 70 \text{ years} = 2.0 \text{ grams / lifetime}$$

Toxic intake for humans is 60 milligrams, while a lethal intake is 1.3 to 6.2 grams (CRC, 1997).

4.1 Silver Human Health Standards and Regulations

4.1.1 World Health Organization (WHO)

In their Guidelines for Drinking-Water Quality, 2nd Edition (1993), the WHO addressed human health effects of silver and guidelines values to prevent those effects.

WHO determined that:

1. The retention rate of silver in humans and animals is only 0 – 10 percent. The retained silver is mainly stored in the liver and skin. The half-life of silver in the liver is 50 days.
2. Silver is occasionally found naturally in ground and surface water at 5 μg/L.
3. Average human intake of silver is 7.1 μg/day.
4. The acute lethal dose of silver nitrate is a minimum of 10 grams.
5. Argyria is the only known human health effect of silver, and "is a condition in which silver is deposed on skin and hair."

Based on their research, the WHO recommended a guideline value for silver of 10 grams per lifetime. This is a NOAEL (no observed adverse exposure limit) standard. WHO concludes by stating "as the contribution of drinking-water to this NOAEL will normally be negligible, the establishment of a health-based guideline value is not deemed necessary." In 1996, the WHO reiterated this determination by designating silver as a "U" compound. "It is unnecessary to recommend a health-based guideline value for these compounds [U compounds] because they are not hazardous to human health at concentrations normally found in drinking-water."

However, the WHO addresses the fact that silver is often used as a disinfectant, and in such cases, "the daily intake of silver from drinking-water can constitute the major route of oral exposure." Thus, WHO has established an additional guideline value for when silver is "used to maintain the bacteriological quality of drinking-water." This guideline states "higher levels of silver, up to 0.1 mg/L (this concentration gives a total dose over 70 years of half the human NOAEL of 10 g) could be tolerated in such cases without risk to health."

Thus, the guideline value appropriate for use in analyzing the PFP filter is 0.1 mg/L (or 100 μg/L) in the finished, filtered water.

4.1.2 United States Environmental Protection Agency (USEPA)

The USEPA has also investigated silver to determine appropriate drinking water standards. The USEPA recommends a maximum intake of 5 μg/kg/day (1996). In the average 70-kilogram adult, this is equivalent to 350 μg/day. This recommendation was established to prevent argyria, "a medically benign but permanent bluish-gray discoloration of the skin. Argyria results from the deposition of silver in the dermis and also from silver-induced production of melanin." Argyria is "more pronounced in areas exposed to sunlight due to photoactivated reduction of the metal", and "although the deposition of silver is permanent, it is not associated with any adverse health effects."

In addition, "no evidence of cancer in humans has been reported despite frequent therapeutic use of the compound over the years." Silver was used for centuries to treat syphilis, and as an astringent in topical preparations.

The 2001 National Secondary Drinking Water Regulations recommends a maximum silver concentration of 0.10 mg/L (or 100 μg/L), but specifically states that "EPA recommends secondary standards to water systems but does not require systems to comply. However, states may choose to adopt them as enforceable standards." These secondary non-enforceable guidelines regulate "contaminants that may cause cosmetic effects or aesthetic effects in drinking water." The USEPA does not address separate standards for use of silver as a disinfectant. It is of note that the USEPA secondary standard is the same as the WHO guideline value for use of silver as a disinfectant: 0.1 mg/L or 100 μg/L.

4.1.3 Argyria

Argyria, "a medically benign but permanent bluish-gray discoloration of the skin," develops over time due to silver absorption into the skin (USEPA, 1996). Argyria begins in the eyes and the fingertips, and continues throughout the skin, especially in areas that are exposed to sunlight (Egli, personal conversation). The condition is irreversible, disfiguring, and non-cancer causing (Jacobs, 2001; USEPA, 1996). Current cases of argyria have resulted from: ingestion of silver coated candy to prevent smoking in Japan (Hanada, 1998), implanted acupuncture needles (Suzuki, 1997), an impacted earring (Sugden, 2001), treatment of venous leg ulcers using silver sulphadiazine (Russell, 1994), and ingestion of naturopathic colloidal silver (Egli, personal conversation).

Rosemary Jacobs, a woman who developed argyria as a child due to intranasal medication for allergies, is a speaker and advocate against the use of silver (Jacobs, 2001). She developed argyria over time as a young teenager, and her skin has been discolored throughout her life. Pictures of Ms. Jacobs convey the image of the effect of argyria on one's life, even though it is medically benign.

4.1.4 Colloidal Silver and USFDA/USEPA Regulation

A colloidal solution is "a true solution that consists of colloidal macromolecules and solvent and that is thermodynamically stable and readily reconstituted after separation of the macromolecules from the solvent (Stenesh, 1996)." Furthermore, a colloid is "a macromolecule or a particle in which at least one dimension has a length of 10^{-9} to 10^{-6} meters." Thus, colloidal silver is a stable solution of very small silver particles suspended in distilled water or proteins. Higher concentrations of colloidal silver (such as used by PFP) are suspended in proteins because they would not be stable in water (Quinto, personal conversation).

In 1999, the United States Food and Drug Administration (USFDA) issued a ruling that "all over-the-counter (OTC) drug products containing colloidal silver ingredients or silver salts for internal or external use are not generally recognized as safe and effective and are misbranded. FDA is issuing this final rule because many OTC drug products containing colloidal silver ingredients or silver salts are being marketed for numerous serious disease conditions and FDA is not aware of any substantial scientific

evidence that supports the use of OTC colloidal silver ingredients or silver salts for these disease conditions (Federal Register, August 17, 1999)."

The burgeoning naturopathic market for colloidal silver in the United States prompted this ruling. In a cease-and-desist letter issued to Mr. Randy Winters, the USFDA quoted Mr. Winters' web site as stating, "colloidal silver has been proven to be useful against over 650 diseases, including cancer, without any known harmful side effects. It has been found to cause rapid regeneration of damaged cells and tissues, subdue inflammation and promote faster healing (FDA, 2000)." A simple web search for "colloidal silver" leads to numerous sites advertising unsubstantiated healing properties, and another set of sites selling home-based colloidal silver generation machines.

On August 8, 2001, I spoke with Ms. Roma Egli, the colloidal silver contact person at the USFDA, about the PFP filter and the use of colloidal silver for disinfection. Ms. Egli said that the USFDA does not deal with disinfection agents, and that the USEPA would regulate the use of colloidal silver in this manner. As long as PFP does not state that the filters are treating animals or humans for disease, and does not state that the colloidal silver is an antibiotic, the product is not regulated under the USFDA. She also mentioned that colloidal silver is used for water disinfection on transportation systems such as airplanes, trains, and boats. When asked, Ms. Egli did state that she has seen argyria cases in people only using naturopathic colloidal silver. No case she has seen is as severe as Rosemary Jacobs', but she has seen permanently blue fingertips. Overall, Ms. Egli expressed the viewpoint that the USFDA is concerned about labeling of colloidal silver as a medical drug when there is no research to support such claims. They are not concerned with colloidal silver as a disinfectant, and in fact Ms. Egli recommended that I talk with the Silver Institute (a promoter of colloidal silver as an antibiotic) about purchasing a generator to make colloidal silver in Nicaragua rather than importing it from Mexico. Because the generators are only capable of producing colloidal silver in the ppm range, as opposed to the 3.2 percent solution that PFP uses, this idea was determined to be not appropriate for PFP.

I then spoke with Wade Travathan, of the USEPA, about colloidal silver as a disinfectant. The EPA Office of the Pesticide Program regulates disinfectants because microorganisms in the United States are legally classified as pests. Thus, any product that kills microorganisms is classified under federal law as a pesticide. Mr. Travathan said that there are current, active products that are registered with EPA that use colloidal silver as a disinfectant. To become registered as a pesticide, you submit data that details toxicity and efficacy. You can refer to data that has already been submitted by another company, by offering that company appropriate compensation. The submission forms are available on the web site and submission is free of charge. However, there is a maintenance fee of US$1,000 dollars per year on your permit. The Office of the Pesticide Program can be reached at www.epa.gov/pesticides.

Thus, with the appropriate permitting from the USEPA Office of the Pesticide Program, and data supporting that the finished water concentration of silver is less than the USEPA secondary standard of 100 µg/L, a colloidal silver impregnated filter is a legal product to distribute and use in the United States and meets all USA regulations.

4.2 Silver in Ceramics

Potters for Peace is not the only organization to use silver as a disinfectant in ceramic filtration units. Basu (1982) in India soaked ceramic candle filters with a pore size of 6 – 31 microns, and a filtration

rate of 3 – 4 Liters per hour, in silver salts. Filtered water with this system was bacteria-free. Basu chose silver over gold as the bacteriocide, and also tested candle filters with finer pores that would capture the bacteria. The filtration rate was so slow with these finer pores, however, that the filters were "not of much practical value." Thus a larger pore size, combined with a disinfectant, is of more practical value because the flow rate is high enough to provide enough water for a family.

4.3 Mechanisms of Action of Silver

Russell (1994) details the historic uses of silver, beginning with Aristotle advising Alexander the Great to boil water and store it in silver or copper vessels to prevent waterborne disease on his campaigns. In 1869, Ravelin reported that silver exerted its antimicrobial effect at very low concentration; an effect with was later termed "oligodynamic" or "active with few" (Russell, 1994). In 1881, Crede advocated silver to prevent eye infections in newborns, and silver drops were used to prevent gonorrhea of the eye in newborns until very recently. In 1920, the microbiological action of silver was determined to be due to the Ag^+ ions formed by tarnishing, surface-oxidation, or electrical activation.

Today, silver is more commonly used as a drinking water and swimming pool disinfectant in Europe than in the United States (Russell, 1994). Studies have shown that silver can be used when chlorine is present for additional disinfection. Argyria, first reported in 1647, is less common today but is still reported.

Three main mechanisms are responsible for bacterial inactivation with silver (Russell, 1994):

1. Silver reacts with thiol (sulphydryl, SH) groups in the bacterial cell
    a. In structural groups
    b. In functional (enzymic) proteins
2. Silver produces structural changes in bacterial cell membranes
3. Silver interacts with nucleic acids

These three mechanisms are described in further detail in the following sections. Although it is unknown at this time which of these mechanisms is predominant in the PFP filter, laboratory data clearly shows that PFP filters impregnated with colloidal silver remove 99 – 100 percent of bacteria (CIRA-UNAN, various dates).

Heinig's research on silver deposited on an inert surface is of special note in relation to the PFP filter. Heinig (1993) showed silver on a large inert surface area exhibited a strong catalytic reaction with oxygen, which resulted in strong bactericidal activity. The factors controlling the rate of the catalytic reaction were: the size and dispersion of the silver on the surface area of the bed, and the volume of oxygen in solution. Heinig found that bacteria and viruses were killed on contact without the need for the release of metals into the water.

4.3.1 Silver as an Enzyme Inhibitor

"Living cells are characterized by a complex and beautifully organized pattern of chemical reactions mediated and directed by enzyme systems (Webb, 1963)." Webb continues by describing the theory of inhibiting enzymes as a means to understanding the "energetics of the cell."

> Directly distorting the pathways of enzymically directed reactions by the introduction of a chemical substance is one approach amongst others to alter metabolic activity. Other ways to alter metabolic activity including changing the temperature or the pH, by irradiation of high pressure, are nonspecific and seldom does one have any idea as to exactly what is occurring in the complex protoplasmic matrix. If one had to choose the most interesting and important characteristic of enzyme inhibitors, what it is that makes them one of the most powerful tools in so many fields of biological investigation, it would be their relative specificity. The more we know about the exact nature of the perturbation produced and the more selective this action can be made, the more likely it is that clear interrelationships will emerge and the goal of understanding the energetics of the cell be achieved.

A number of metals are known to inactivate the SH (sulfur-hydrogen, or sulfhydryl, or thiol) bond in enzymes. Silver is widely used in biochemistry applications to determine if an enzyme has a SH group as part of its functional structure.

Webb's summary of data collected on the action of silver on the SH bond shows extremely varied inactivation depending on specific enzyme and concentration (Table 4-2). These different reactivities could be attributed to an electric field surrounding the SH group, steric factors depending on where the SH group is in the protein structure, occurrence of disulfide linkages, complexes of the SH group with surrounding groups, and whether there is a single or double SH group. Other SH inhibitors studied include mercury, arsenite, cadmium, iodine, ferricyanide, and permanganate.

Although there exists a large variation, silver clearly inactivates certain enzymes in sources that are responsible for waterborne disease (Table 4-2). Waterborne disease sources are boldfaced in Table 4-2.

Table 4-2: Comparison of Enzyme Inhibition by Silver (adapted from Webb, 1966)

Enzyme	Source	Concentration of Ag^+, mM	Reference
Adenosinase	***Vibrio cholerae***	0.07	Agarwala, 1954
Alanine dehydrogenase	*Bacillus cereus*	0.1	O'Connor, 1960
Aldehyde dehydrogenase	*Acetobecer suboxydans*	0.015	King and Cheldelin, 1956
Aldolase	Rabbit muscle	0.02	Herbert et al, 1940
α-Amylase	*Bacillus subtilis*	0.1	Di Carlo and Redfern, 1947
β-Amylase	Sweet potato	0.01	Englard et al, 1951
Aspartase	*Propionibacterium peterssonii*	1	Ellfolk, 1953
Aspartase	***Escherichia coli***	1	Ichihara et al, 1955
ATP:P_i exchange enzyme	Rat liver	0.05	Chigo and Plaut, 1959
Carbonic anhydrase	Spinach leaves	0.1	Chiba et al, 1954a
Catechol oxygenase	Pseudomonas fluorescens	0.01	Hayaishi et al, 1957
Cholinesterase	Human erythrocytes	1	Mounter and Whittaker, 1953
Creatine kinase	Rabbit erythrocytes	0.1	Solvonuk et al, 1956
2'-Deoxyribosyl-4-aminopyrimidone-2,5-diP aminohydrolase	Monkey liver	0.01	Scarano et al, 1962
Dihydroxyacid dehydratase	Spinach leaves	0.2	Kanamori and Wixom, 1963
Elastase	Flavobacterium	1	Mandl and Cohen, 1960
FMN phosphatase	Rat liver	5	McCormick and Russell, 1962
β-Galactosidase	***Escherichia coli***	0.165	Knopfmacher and Salle, 1941
D-Glutamate oxidase	Aerobacter sp.	5	Mizushima and Izaki, 1958
Hydrogenase	***Escherichia coli***	1	Joklik, 1950 b
Leucine aminopeptidase	Rat kidney	10	Green et al, 1955
NADH:cytochrome c oxidoreductase	Pig liver	3	Garfinkel, 1957
NADH:H2O2 oxidoreductase	*Streptococcus faecalis*	0.001	Dolin, 1957
3-Phosphoglyceral-dehyde dehydrogenase	Rabbit muscle	0.01	Park et al, 1961
Proteinase	*Trifoium repens*	20	Brady, 1961
Protein disulfide reductase	Peas	0.009	Hatch and Turner, 1960
Pyrosphosphatase	Human erythrocytes	0.2	Nagnna and Menon, 1948
Pyruvate decarboxylase	Yeast	0.0025	Stoppani et al, 1952
Urocanase	*Pseudomonas aeruginosa*	1	Ota et al, 1956

Berger (1976) compared electrically generated silver (colloidal silver) with silver sulfadiazine and found that 16 organisms were inhibited at 1.25 µg/mL colloidal silver, and killed at 10.5 µg/mL colloidal silver (Table 4-3). With silver sulfadiazine, inhibition rates were much higher. Colloidal silver ions acted by

altering the mesosomal function of the cell. The mesosome is a part of the cell wall that is responsible for respiration. Mammalian cells showed no inhibition of function due to the silver.

Table 4-3: Concentration Needed for Inhibition and Inactivation of Bacteria

	Concentration needed for Inhibition (µg/mL)	Concentration needed for Inactivation (µg/mL)
E. coli	0.50	2.02
E. coli (dental)	1.03	8.25
Providencia stuartii	0.13	0.73
Proteus mirabilis	0.08	2.51
Pseudomonas aeruginosa	0.31	2.51
Serratia	0.08	0.51
Staphylococcus albus	0.12	0.85
Staphylococcus aureus	0.03	0.26
Staphylococcus aureus	0.25	8.25
Streptococcus group D	0.63	10.05
Streptococcus mitis	0.31	10.05
Streptococcus monila	1.25	10.05
Streptococcus mutans	0.63	10.05
Streptococcus pyogenes	0.24	0.48
Streptococcus pyogenes	0.24	0.48
Streptococcus salivarius	1.03	8.25

A number of other studies in the literature detail the effects of silver on different bacteria at varying concentrations.

4.3.2 Silver Interaction with Cell Walls

Russell (1994) details that silver binds to the cell membrane of bacteria. Sensitive cells then increase in size and cytoplasmic contents, and cell membrane and outer cell layers all present abnormalities. These abnormalities result in cell lysis and death. Hugo (1971) also discusses the role of silver in causing cell lysis, as the silver replaces compounds in the cell membrane that are required for cell membrane stability.

4.3.3 Silver Interaction with Nucleic Acids

Russell (1994) details the reaction between Ag^+ and the GC (guanine-cytosine) and AT (adenine-thymine) DNA base pairs). With UV-exposed DNA, the Ag^+ - DNA complex causes thymine dimerization and prevents DNA replication.

4.4 Silver in Medicine

Ever since Crede (1881) introduced the use of silver nitrate for the prevention of gonorrhea opthalmicum, silver has been a useful disinfectant in medicine. Although it fell out of favor in the 1930's due to the introduction of antibiotics and studies on argyria, silver is still studied, and used, in medicine today.

Becker (2000) tested silver for the regeneration of bone after trauma using a silver nylon anode consisting of silver crystals averaging 50 nM in diameter. Over 100 patients have been treated with no effects of argyria. The average rates of granulation tissue growth were noted as around 1 cm^2/day, a rate ten times higher than the non-silver-treated open bone graft granulation rate of 0.1 cm^2/day. With silver iontophoretic treatment all soft tissues as well as the vascular supply of the bone become contributors of granulation. Standard in vitro culture of these cells show characteristics of stem cells, indicating dedifferentiation of mature human cells or expansion of preexisting stem cells in the tissues. Becker (2000) states "the responsible agent for these cellular effects is believed to be the electrically generated silver ion."

In addition, silver sulfadiazine is used in acute burn wounds as an antibacterial agent on the skin (Tsipouras, 1997). Silver-coated iodine-colored bandages are specially made for burn patients. In addition, copper / silver ionization is used in the drinking water systems of more than 30 hospitals in the United States to control *Legionella* (Lin, 1997). *Legionella* is problematic for immuno-comprised patients, such as those with HIV.

Thus, although silver is not used as a wide-scale antibiotic anymore, the microbiological inactivation properties of silver are still used throughout medicine on a small-scale, but very present, level.

4.5 Silver in the PFP Filter – Summary (Not included in Report 2)

Professor Simon Silver, of the Department of Microbiology and Immunology at the University of Illinois in Chicago, studies bacterial inactivation, and resistance to, metals, including silver. He believes that the mechanisms of action of silver are very complicated due to the number of interaction sites, and the number of methods of inactivation (personal communication, 2001).

Thus, no matter the exact mechanism in each individual situation, silver and colloidal silver clearly exhibit an antimicrobial effect that has been used for centuries in medicine and to purify water. Although there currently exist regulatory enforcements curtailing the use of silver in the United States, these regulations do not apply to the use of colloidal silver in the PFP filter. Results reported in Report 2 showed that all water concentrations of silver after filtration in the PFP filter were well below both the USEPA and WHO standard (Lantagne, 2001a). The use of silver in the PFP filter therefore does not create a human health risk.

5 Filtration Investigations

A key variable in the PFP filter is the rate of filtration of water through the filter. The PFP factory ensures that all filters that are sold have a flow rate between one and two Liters per hour. Filters that test outside of this range are discarded. Ron Rivera determined this flow rate from the directions on the 0.32 percent silver Microdyn commonly sold in 25 mL bottles throughout Mexico that was originally applied to the PFP filter. The Microdyn directions for drinking water disinfection are to add one drop of the 0.32 percent solution into 2 Liters of water and wait 20 minutes. Then, the water is safe to drink. From this, Ron Rivera determined that 2 Liters of water should have at least a 20-minute contact time with the colloidal silver. A safety margin of three, to a time of 60 minutes for 2 Liters, was added because the water for disinfection is filtering through the filter and not remaining still in a container. Of note is that PFP is now using two mL of 3.2 percent industrial Microdyn silver solution on each filter instead of 10 mL of the 0.32 percent residential solution.

A number of questions exist on the mechanism of flow through the filter, and how filtration rate effects microbiological inactivation. In order to address these questions, three research avenues were investigated. First, the mechanisms of flow through the filter were reviewed. Secondly, changes in flow rate over time were investigated. Lastly, filters with different flow rates were analyzed for both colloidal silver concentration in the finished water and microbiological inactivation.

5.1 Mechanism of Flow through the PFP Filter

The pore size within the PFP filter is determined by the size and amount of sawdust that is added to the clay in the manufacturing process. This sawdust burns off during the firing process, and creates pores within the filter. Water then flows through these pores, with a higher filtration rate if the pores are larger and a lower filtration rate if the pores are smaller.

5.1.1 Pore Size

Industrial Analytical Service, Inc. (IAS) investigated the pore size of the PFP filter using a Scanning Electron Microscope (SEM) with x-ray elemental analysis capability. A piece from the lip of a new filter with colloidal silver was carefully removed and sent to IAS for analysis. The filter was evaluated at IAS for chemical composition, pore uniformity, and pore size.

In terms of chemical composition, the main chemical component of the filter in silicon, followed by oxygen and aluminum. Iron, sodium, magnesium, sulfur, and potassium are present in trace amounts. No silver is recorded by the x-ray element analysis because the amount of silver applied by PFP is not enough to create a recognizable peak in the x-ray analysis.

The composition of the filter is not uniform. There are both cracks and spaces within the filter. The cracks measure up to 150 microns (150 micrometers) in length, and the spaces measure up to approximately 500 microns in length (Figure 5-1). The pore size in areas not within a crack or space ranges from 0.6 microns to approximately 3 microns.

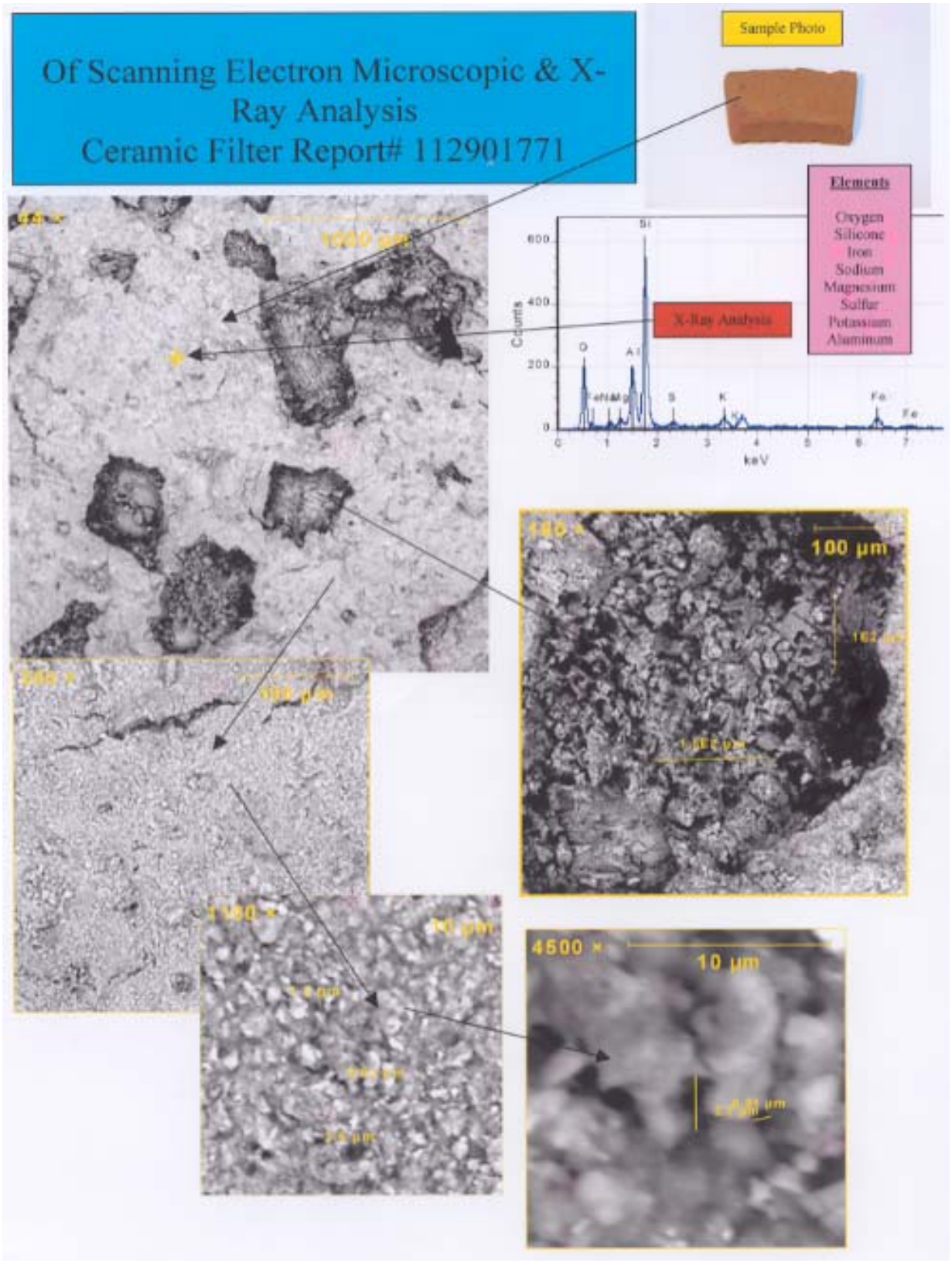

Figure 5-1: SEM Analysis of a Piece from the Lip of a PFP Filter

The filter, then, is composed of a number of large areas that, if they remain unconnected, serve only as reservoir space for water. If these large areas are connected, the filtration rate of the filter will be higher than the one to two Liters per hour, and will be discarded in the shop. The presence of these larger reservoir spaces explains why the flow rate increases in the first few uses of a new, dry filter. These reservoirs must fill with water before water flows through the filter into the receptacle.

The pore size in the filter ranges from 0.6 to 3.0 microns. The PFP pore size goal is 1.0 micron, in order to remove *E. coli* without the need for a disinfectant. These results show that PFP is well within range of their 1.0-micron goal. The variation in pore size is due to the location of the sawdust during firing.

Two further investigations are recommended if more information about pore size is desired.

1. The piece of the filter analyzed was from the lip (the top) of the filter. This is the area that has the least amount of force exerted on it during the manufacturing process. Therefore, it will probably have the largest cracks and spaces. Thus, the analysis completed is most likely the worst-case scenario. It would be interesting to break a filter, and complete SEM analysis on the lip and on the bottom of the filter, and compare the sizes of the cracks, spaces, and pores.
2. In the current manufacturing process, the clay and sawdust are mixed in a large industrial mixer. It would be interesting to make and complete SEM analysis on two filters: (1) Where the sawdust and clay have been mixed for a short amount of time (for example, 5 minutes) before shaping; and (2) Where the sawdust and clay have been mixed for a longer amount of time (for example, 20 minutes) before shaping. With additional mixing, perhaps the filters might be more uniform. Given the testing procedure to ensure filters with high flow rates are not sold, a more uniform filter might not be necessary, however.
3. It would be interested to test filtration rate and pore size in a filter made with sawdust screened to a finer consistency.

5.1.2 Mathematical Model of Flow Pattern in the PFP Filter

In 2001, Sten Eriksen completed a mathematical model of the flow patterns within the PFP filter for Red Cross International. Equations were developed to model flow through both the sides and the bottom of the filter, and then these equations were integrated with time to form an equation that was solved to determine the maximum allowable hydraulic conductivity of the filter.

Using Darcy's Law, the equation Eriksen (2001) determined for the sides of the filter is:

$$Q_s = \frac{k\Pi D}{2a} \times x^2 \qquad (1)$$

where:

Q_s	the flow through the sides of the filter
k	the hydraulic conductivity of the filter wall
D	the diameter of the filter
a	the width of the ceramic on the sides of the filter
x	the height of the water within the filter (zero is an empty filter)

Using Darcy's Law, the equation Eriksen (2001) determined for the bottom of the filter is:

$$Q_b = \frac{kx\Pi D^2}{4b} \tag{2}$$

where:

- Q_b the flow through the bottom of the filter
- k the hydraulic conductivity of the filter bottom
- D the diameter of the filter
- b the width of the ceramic on the bottom of the filter
- x the height of the water within the filter (zero is an empty filter)

Equations 1 and 2 were combined and integrated with time to form the equation:

$$T = \frac{b}{k}\ln\left(\frac{H(1+2\frac{x}{D})}{x(1+2\frac{H}{D})}\right) \tag{3}$$

where:

- it is assumed a is equal to b (the width of the ceramic on the bottom and sides of the filter is the same)
- T time
- b the width of the ceramic on the bottom and sides of the filter
- k the hydraulic conductivity of the ceramic
- H the maximum height of water within the filter
- D the diameter of the filter
- x the height of the water within the filter

Eriksen then solved Equation 3 to determine the maximum hydraulic conductivity that would allow for a 25-minute exposure time to the colloidal silver in the filter. Eriksen (2001) determined that the actual hydraulic conductivity was 1000 times greater than the allowable conductivity, and recommended "using the filter in connection with post clorination (sic) and without colloid silver".

Although Eriksen's derivations and mathematics are very solid, and a rederivation of the model yielded the same equations, two values that Erickson used in his equations to determine actual and maximum values of hydraulic conductivity were not ideal. The first is in the calculation of the maximum allowable hydraulic conductivity to allow 25 minutes of contact time with the colloidal silver.

Using Darcy's Law, Eriksen determined that the minimum time needed for bacterial inactivation would be the distance the water traveled through the colloidal silver layer divided by the velocity. This equation is:

$$T_{\min} = \frac{tb}{kH} \tag{4}$$

where:

T_{min}	is the minimum time needed for microbiological inactivation by the colloidal silver
t	is the thickness of the colloidal silver layer
Hk/b	is the maximum velocity through the bottom of the filter when the filter is full
H	the maximum height of water within the filter
k	hydraulic conductivity of the ceramic
b	width of the ceramic at the bottom of the filter

Rearranging this equation allows the solving of the equation for k:

$$k_{max} = \frac{tb}{T_{min}H} \tag{5}$$

Eriksen solved this equation using the following values for the variables:

t	0.1 mm (Eriksen); 4 mm (Updated)
b	10 mm
T_{min}	25 minutes
H	24 cm

Using these values, the maximum allowable hydraulic conductivity is 0.00001 meters/hour. However, the value assigned to the thickness of the colloidal silver level is suspect. Erickson cites "according to the paper by Earp" as his reference for this value. No date for the reference is given, and the Earp paper obtained for this report does not include that value.

The thickness of the colloidal silver layer appropriate for this equation would not be the theoretical thickness of a layer of colloidal silver. The appropriate thickness value here is the thickness of the colloidal silver layer coating the pores in the ceramic through which the bacteria comes into contact with the colloidal silver. For example, if the width of the ceramic on the bottom of the filter is 10 mm, and colloidal silver coated the pores within the ceramic throughout that 10 mm, it could be assumed that the width of the colloidal silver layer would be 10 mm. However, this would be incorrect, for very few of the bacteria would travel in a direct line across the filter wall. Most droplets of water and bacteria would travel a route that is not direct as it was diverted around solids and through pores and slowly made its way across the wall in a zigzag pattern. The term to account for this non-direct route through the microscopic pores within the filter is tortuosity. The more tortuous the path, the more actual distance a bacteria travels to get across those 10 mm, and the higher the tortuosity of the ceramic wall.

It is unknown at this time how deeply into the filter the colloidal silver seeps, although it is known that the colloidal silver is applied to both the inside and outside of the filter – so at the minimum there are two 0.1 mm layers on either side of the filter. However, visual inspection of the filter as silver is being painted on does show that the silver sorbs into the filter and 'disappears' to the eye. Thus, the assumption is made for the calculations here that the colloidal silver forms a layer coating the pores of the ceramic for at least one millimeter on both the inside and outside of the filter. This is an estimate at this point in time, and further analysis to refine this number is needed before more accurate calculations

can be determined. In addition, the tortuosity factor of the ceramic filter is estimated at a factor of 2. This also is an estimate, and further analysis is also needed to refine this factor.

Assuming a layer of silver one millimeter thick on either side of the filter gives a colloidal silver thickness value of 2 mm. Multiplying this value by a factor of 2 to account for the tortuosity gives a value of 4 mm for the thickness of the colloidal silver layer. This value accounts not for the theoretical thickness of a colloidal silver layer, but for the thickness of the colloidal silver layer that the bacteria is exposed to within the PFP ceramic filter.

Recalculating this equation using the new value of 4 mm for the thickness of the colloidal silver layer gives a maximum hydraulic conductivity value of:

$$k_{\max} = \frac{tb}{T_{\min} H} = 4 \cdot 10^{-4} \; meters / hour = 0.0004 \; meters / hour \tag{7}$$

The second value that was used in Eriksen (2001) and is updated here, is in the calculation of the actual hydraulic conductivity value based on the time needed for the filter to empty. Eriksen references Ron Rivera as stating that the filter takes one or two hours to empty completely. Actually, the flow rate of the filter is 1-2 Liters/hour, and in the laboratory testing completed by CIRA-UNAN the filter empties completely in approximately 7-9 hours. This longer time for the filter to completely empty was confirmed by the laboratory testing completed in the United States.

Eriksen used the combined equation integrated with time in order to calculate the actual hydraulic conductivity value (Equation 3).

$$T = \frac{b}{k} \ln \left(\frac{H(1 + 2\frac{x}{D})}{x(1 + 2\frac{H}{D})} \right) \tag{8}$$

This equation was rearranged to solve for *k*, hydraulic conductivity. Also, when x is close to zero (when the filter is almost empty), the numerator in the equation can be assumed to go to H because the value of (1 + 2x/D) goes to 1.

$$k_{actual} = \frac{b}{T} \ln \left(\frac{H(1 + 2\frac{x}{D})}{x(1 + 2\frac{H}{D})} \right) \approx \frac{b}{T} \ln \left(\frac{H}{x(1 + 2\frac{H}{D})} \right) \tag{9}$$

Ericksen solved the Equation 9 using the following values:

b	0.01 meters
T	1 hour (Eriksen), 8 hours (Updated)
H/x	100
H	0.24 meters
D	0.2 meters

Using these values, Eriksen obtained a value for actual hydraulic conductivity of 0.03 meters/hour. This is significantly larger than the allowable maximum hydraulic conductivity Eriksen calculated of 0.00001 meters/hour. His conclusion that the colloidal silver in the PFP is ineffective for microbial reduction is based on this calculation.

When the value of T is replaced with the updated amount of time needed to empty the filter, averaged at 8 hours, the value of the actual hydraulic conductivity decreases to 0.004 meters / hour. Thus, instead of a factor of 1000 between the maximum allowable and actual hydraulic conductivity, there is only a discrepancy of a factor of 10 (Table 5-1). Considering that the thickness of the colloidal silver layer that the bacteria is actually exposed to was a very rough estimate that needs additional laboratory analysis to verify its accuracy, this discrepancy may well be within the range of error of those estimates.

Table 5-1: Hydraulic Conductivity Values - Eriksen and Updated Values

	Maximum Allowable Hydraulic Conductivity (meters/hour)	Actual Hydraulic Conductivity (meters/hour)
Eriksen Calculation	0.00001	0.03
Updated Calculation	0.0004	0.004

The mathematical model that Eriksen developed to model flow through the PFP filter is both mathematically sound and very powerful. His model provides the framework to understand the interactions between hydraulic conductivity, time, pressure, and flow through the PFP filter at the macroscopic and microscopic level. Unfortunately, after completing the mathematically sound model, non-ideal values were placed within the equations to determine the maximum allowable, and the actual, hydraulic conductivities. The results obtained using these non-ideal values led to a conclusion that is not held up when updated values are used in the equations.

It is highly recommended that further research using the framework of Eriksens' model be completed. In addition, knowledge of the thickness of the colloidal silver layer that the bacteria are exposed to is critical to understanding the mechanism of bacterial inactivation and hydraulic conductivity. Research along these lines will provide a solid mathematical framework for the workings of the PFP filter.

5.1.3 Experimental Data

In order to provide some experimental counterpart to Eriksen, two filtering elements were obtained from the PFP factory with the same factory determined flow rate. These two filters had not yet had colloidal silver applied to them. These two filters were used to determine the flow pattern of water through the filter.

Initially, the factory filtration rate was confirmed with Managua city water (Table 5-2). Although the filtration rate determined in the laboratory was higher than that determined in the factory, the two filters had similar flow rates to one another in both cases. The higher filtration rate in the laboratory can be attributed to the fact that, before laboratory testing, both filters were soaked overnight using Managua city water. It is possible the increase in filtration rate was due to the fact that the cracks and spaces in the filter were full of water due to the soaking.

Table 5-2: Filtration Rate in Two Filters

	Filter 1	Filter 2
Factory Flow Rate (L / hour)	1.6	1.6
Laboratory Flow Rate (L / hour)	2.2	2.1

pH and conductivity were sampled during the initial filtration rate testing as well (Table 5-3). Of note is that pH increases, even in these filters, which do not have colloidal silver applied to them. This indicates that the pH increase seen in all sampling is due to the ceramic, and not the colloidal silver.

Table 5-3: Water Quality Results During Initial Filtration Testing of Two Filters

	Filter 1		Filter 2	
	Before Filtration	After Filtration	Before Filtration	After Filtration
pH	7.3	8.7	7.3	8.8
Conductivity	550	610	550	580

In order to test whether the majority of the water flows through the sides or the bottom of the filter, the bottom of Filter 1 was coated with 3 coats of impermeable paint mixed with 25 percent water, and then 3 additional coats of impermeable paint not mixed with water. This same procedure was completed on the sides of Filter 2. Managua city water was used to test the flow rate of these painted filters. The results show that the majority of the flow, 83 percent, flows through the sides of the filter (Table 5-4). Only 17 percent flows through the bottom of the filter. Eriksens' model predicts that the majority of the water will filter through the sides when the filter is full, and this experimental data confirms that result.

Table 5-4: Flow Rate in Filters Painted to Impede Flow

	Filter 1 Painted Bottom	Filter 2 Painted Sides
Flow Rate through sides (L / hour)	1.04	
Flow Rate through bottom (L / hour)		0.21

This result is interesting on a number of levels:

1. When looking at the filter as it is flowing, the majority of the filtered water drips into the receptacle from a circular ring around the bottom of the filter. This result shows that the water flows through the side walls of the filter, then down along the outside of the filter, and then drips into the receptacle from the bottom.
2. The total flow from the two filters tested does not sum to the total flow of one unpainted filter. In fact, there is 43 percent less total flow. This implies a synergistic effect between the sides and bottom that also accounts for some of the total flow.
3. These results indicate that special care should be taken to ensure colloidal silver application on the sides of the filters, for a large percentage of the water filters through the sides.

5.2 Changes in Filtration Rate over Time

In order to determine the lifetime of the PFP filter, it is necessary to research how the filtration rate changes over time, and if that filtration rate can be rejuvenated. For, when the filtration rate becomes low enough such that the filter no longer provides enough drinking water, the filter loses its effectiveness.

5.2.1 Previous Studies

The initial ICAITI study (1984) investigated the flow rate of seven filters of Models 9 and 10 over one year. Models 9 and 10 were the two clay models with colloidal silver application investigated as options. The percent reduction of filtration rate in these filters over one year ranged from 39 to 64 percent (Table 5-5). This result is similar to the results reported in Report 2, where in communities with filter projects, filtration rates decreased markedly over time, especially in turbid waters (Lantagne, 2001a).

Table 5-5: Filtration Rate in the ICAITI Filters Over a Period of One Year

	Model 9 - Flow Rate (Liters / day)			Model 10 – Flow Rate (Liters / day)			
Age (Days)	Filter 1	Filter 2	Filter 3	Filter 1	Filter 2	Filter 3	Filter 4
15	3.5	3.8	3.5	3.5	5.5	5.5	3.8
38	2.9	2.9	2.8	2.9	4.0	3.7	2.8
95	2.8	2.8	2.7	2.7	3.1	2.8	2.4
140	2.7	2.8	2.7	2.6	2.7	2.6	2.4
187	2.5	2.6	2.5	2.3	2.4	2.3	2.1
229	2.3	2.4	2.3	2.1	2.1	2.1	1.9
241	2.3	2.5	2.3	2.1	2.2	2.0	1.9
261	2.3	2.3	2.3	2.1	2.1	2.0	1.9
275	2.3	2.3	2.3	2.1	2.0	2.0	1.8
365	2.14	2.14	2.14	1.97	1.97	1.97	1.97
Percent reduction in one year	39	44	39	44	64	64	48

5.2.2 Field Investigations on Filtration Rate

In order to investigate this reduction of filtration rate over time, the filter from home Mancotal-6 was collected from the home, and replaced with a new filter. The collected filter was analyzed in the laboratory in Nicaragua during the October field month.

The flow rate of this filter in the home was fairly low, at 0.40 Liters per hour (Table 5-6). In the laboratory, with Managua city water, the flow rate was comparable at 0.52 Liters per hour. After scrubbing both the inside and outside of the filter with a toothbrush to remove all the particles attached to the filter walls, the flow rate increased to 2.1 Liters / hour. A further baking of the filter in a household kitchen oven to possibly bake out any remaining particles did not further increase the filtration rate.

Table 5-6: Effect of Scrubbing and Baking on Filtration Rate of Mancotal-6 Filter

Filter Mancotal-6	Flow (L / hour)
In field, with well water	0.40
In laboratory, with Managua water	0.52
After scrubbing with toothbrush	2.1
After baking in household cooking oven overnight	1.9

These results agree with the recommendations of the manufacturer Katadyn. Katadyn produces colloidal-silver impregnated ceramic filters for use in camping and other applications. They recommend a regular scrub of the ceramic filter in order to rejuvenate the filtration rate (undated). The reason the scrubbing is necessary is that any particles larger than 2 microns (the pore size in the Katadyn ceramic filter) remain on the outside of the filter. Katadyn specifically mentions that although this scrub removes a microlayer of ceramic, the filter is thick and can withstand many such scrubbings.

Therefore, the filtration rate of the PFP filter can be maintained indefinitely provided that users scrub the filter regularly to prevent build-up of particulate matter on the surface of the filter that impedes the flow of water through the filter. One potential problem with this recommendation relates to the colloidal silver application. When the colloidal silver is painted on a dry filter, the solution containing the silver sorbs into the ceramic to such depth that it is not possible to tell where you have painted after a small amount of time. This indicates that the colloidal silver is sorbing onto the ceramic at a depth greater than the layers that would be scrubbed off using a brush to rejuvenate flow. This indication has not been tested, however, and a recommendation for further research is to apply colloidal silver to a filter and complete microbiological testing of that filter. Then, that filter could be scrubbed to approximate 24 monthly scrubbings (assuming two years of use in a highly turbid area), and microbiological testing completed a second time. If there is no reduction in microbiological quality of the finished water, then this method does not remove significant amounts of the colloidal silver.

5.3 Finished Water Quality at Different Filtration Rates

The last filtration rate investigation researched microbiological inactivation using four filters with four different filtration rates. First, four filters with different filtration rates and without colloidal silver application were obtained from the PFP factory during the October field month. These filters were then tested to determine the relationship between filtration rate, finished water silver concentration, and microbiological inactivation.

First, the laboratory filtration rate was established. The factory filtration rates established for these four filters were: 1.0 Liters/hour, 1.5 Liters/hour, 2.1 Liters/hour, and 2.5 Liters/hour. The filtration rates established in the laboratory were different from those established in the factory (Table 5-7). Part of this variance is that the filters in the laboratory were soaked overnight in order to fill the spaces in the filter.

The filtration rates of these filters were tested in the laboratory using water from a known contaminated well in Tipitapa. Of note is that the laboratory filtration rate for the filters with the factory filtration rate of 2.1 and 2.5 was determined to be the same (3.0 Liters/hour). For this reason, the filter with the factory filtration rate of 2.5 was removed from this study to avoid sampling from two similar filters.

Table 5-7: Laboratory Filtration Rate in Four Filters without Colloidal Silver

	Filter 1	Filter 2	Filter 3	Filter 4
Factory Filtration Rate	1.0	1.5	2.1	2.5
Laboratory Filtration Rate (Liters/hour)	1.52	1.65	3.0	3.0
Conductivity (µmho/cm)	1060	1120	1130	1140
pH	8.4	8.3	8.3	8.3

Microbiological samples were collected before and after filtration in the laboratory to determine if the filter removed microbiological contaminants without the presence of colloidal silver. No filter removed total coliform or hydrogen-producing bacteria, but three of the four filters did remove *E. coli* without the colloidal silver present (Table 5-8). This corresponds well with the scanning electron microscope analysis that shows the pore size within the filters is within the range to remove *E. coli* without the need for a disinfectant.

Table 5-8: Microbiological Results without Colloidal Silver in Four Filters

			Factory Filtration Rate			
	Raw Water	Control	1.0	1.5	2.1	2.5
H_2S-producing	+	–	+	+	+	+
Total Coliform	+	–	+	+	+	+
E. coli	+	–	–	+	–	–

Next, 2.0 mL of 3.2 percent colloidal silver diluted in 300 mL of bottled water was painted on each of the three remaining filters. Following the procedure following in the PFP factory, two-thirds of the silver was applied on the inside of the filters, and one-third was applied on the outside. Filtration rates, conductivity, and finished water pH remained similar after the addition of colloidal silver. This shows that the colloidal silver does not affect the filtration rate in the filter, or the conductivity or the pH of the finished water. Filters were allowed to dry both before and after colloidal silver application.

Table 5-9: Filtration Rate after Colloidal Silver Application in Three Filters

	Filter 1	Filter 2	Filter 3
Factory Filtration Rate	1.0	1.5	2.1
Laboratory Filtration Rate (Liters/hour)	1.57	2.04	2.9
Conductivity (μmho/cm)	1020	1110	1020
pH	8.3	8.3	8.3

Next, water from the contaminated well in Tipitapa was run through each of the three filters. Filtered water from this first run with colloidal silver applied was collected, preserved, and transported back to the United States for analysis of silver concentration at Toxicon Laboratories in Bedford, Massachusetts. Second and third runs with water from the well in Tipitapa were completed, and water samples were also collected, preserved, transported, and analyzed for silver concentration.

Results from these first three runs with these three filters show that no filtered water sample exceeds the WHO guideline value or USEPA secondary drinking water standard value (Table 5-10). In addition, silver concentration in the filtered water decreased markedly after the first use of the filter (Figure 5-2). No correlation was seen between flow rate and silver concentration, indicating that flow rate does not affect the amount of silver that does not sorb to the ceramic, and thus run off in the first few uses of the filter.

Table 5-10: Silver Concentration in Filtered Water in Three Filters

	Silver Concentration in the Filtered Water (μg/L)		
	Filter 1.0	Filter 1.5	Filter 2.0
First Run	44	61	29
Second Run	11	19	18
Third Run	12	21	15

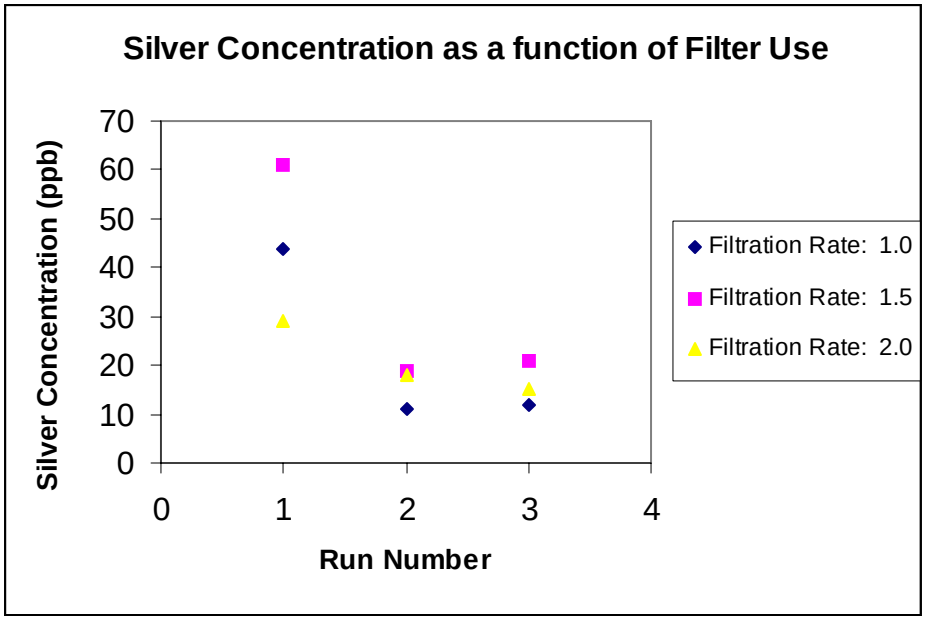

Figure 5-2: Silver Concentration as a Function of Filter Use and Filtration Rate

This data also supports the current PFP recommendation not to use the water from the first run of the filter. PFP recommends discarding water from the first run due to a metallic taste, but after the first run, the silver concentration decreases significantly. A recommendation for further research is to continue silver sampling past three runs to determine when and how the silver concentration in the filtered water decreases. In the field sampling, after six months of use there was only detectable silver concentration in the finished water of two of the 24 filters. Currently, no data exists between three uses and six months of use.

After completion of the flow studies on these three filters, the filters were brought to the Water Resources Laboratory at the Autonomous University of Nicaragua in Managua (CIRA-UNAN) for microbiological testing. CIRA-UNAN also used water from the contaminated well at Tipitapa to complete their microbiological tests.

Results from the laboratory microbiological sampling show that all three filters removed 100 percent of the total coliform and fecal coliform (Table 5-11). Unfortunately, the raw water contained no *E. coli,* so it was not possible to determine the percentage removal of *E. coli.* It is of interest that in the data presented within this section the filter with the factory filtration rate of 1.5 had the most variable laboratory filtration rate (Tables 5-7 and 5-9), the highest silver concentration in the finished water (Table 5-10), and the only bacteria in the finished water (Table 5-11). Although none of the values are above standards, this indicates something is occurring within this filter. This oddness is not resulting in a filtration rate above 2.0 Liters/hour that would indicate at the factory that the filter needs to not be sold.

Table 5-11: Microbiological Results in Three Filters with Different Filtration Rates

	Raw Water	Factory Filtration Rate		
		1.0	1.5	2.1
Total Coliform	3108	0	0	0
Fecal Coliform	1583	0	0	0
Fecal Streptococcus	33	0	2	0
E. coli	0	0	0	0

Given that all three of the filtration rates sampled removed the significant percentage of the bacteria, it would be of interest to collect samples from a filter with a significantly higher filtration rate (for example, 4 Liters/hour) to determine if microbiological removal also occurs at that rate.

5.4 Filtration Rate Conclusions and Recommendations for Further Research

Based on the results of the filtration rate investigations above, the following conclusions are presented:

1. The pore size within the filter ranges from 0.6-3.0 microns. Larger cracks and spaces within the ceramic exist. If these cracks and spaces are unconnected, the limiting size of the filter remains the 0.6-3.0 micron pore size.
2. Application of colloidal silver does not affect the filtration rate within the filter, or the conductivity or pH of the finished water.
3. The majority of the filtration occurs through the sides of the filter, and thus it is important to ensure application of colloidal silver within this area.
4. Scrubbing of the filter with a brush rejuvenates a diminished flow rate due to accumulation of solids on the surface of the ceramic, and should be undertaken periodically.
5. Three of four filters tested removed *E. coli* without colloidal silver application, indicating that the pore size is small enough in the majority of the filters to remove *E. coli.*
6. Even in the first use of the filter, the concentration of colloidal silver is not above the WHO and USEPA standards. The concentration is significantly higher in the first use than the second, however, and it is recommended that PFP maintain the policy of recommending the disposal of water from the first use of the filter.
7. Filters of factory flow rates between 1.0 and 2.0 Liters/hour, and laboratory flow rates up to 3.0 Liters/hour, removed 100 percent of total coliform and fecal coliform.

Although much research has been undertaken, a significant amount of questions were raised during this study that could be investigated further. Recommendations for further research include:

1. Determination of whether the bottom of the filter has a smaller pore size, and whether mixing the clay and sawdust longer creates a more uniform pore size within the filter.
2. Expansion of the mathematical framework begun by Eriksen (2001) in order to mathematically model and understand the filter.

3. Determination of the effect on the colloidal silver concentration and microbiological inactivation after repeated scrubbings of the filter.
4. Determination of the percentage microbiological reduction in filters with higher filtration rates.
5. Determination of another method besides flow rate to determine if a filter is ineffective.

6 Colloidal Silver Investigations

Two variables relating to colloidal silver were investigated for this study. The first was the relationship between the application method and microbiological inactivation. The second was the relationship between colloidal silver concentration and microbiological inactivation.

6.1 Application Method Investigation

During the October field month, three new filters with the same factory filtration rate were obtained from the PFP factory before application of colloidal silver. The factory filtration rate of these filters was 1.6 Liters/hour. These filters were painted with 2 mL of 3.2 percent colloidal silver diluted in 300 mL of bottled water using three different methods:

1. Painting half of the 300 mL solution on the inner part of the filter and half on the outer part;
2. Painting two-thirds of the 300 mL solution on the inner part of the filter and one-third on the outer part; and
3. Painting all of the 300 mL solution on the inner part of the filter.

Method 2 is the current practice in the PFP factory.

Three runs with water from the contaminated well in Tipitapa were conducted in each filter. Silver samples were collected, preserved in nitric acid, transported, and analyzed in the United States at Toxicon Laboratories after each of these runs. Silver concentration samples were not taken from Filter 2 because the application method in this filter was the same as the three filters studied in the filtration rate study (Table 5-10).

The silver concentrations in the finished water during the first three runs of Filter 1 are similar to the results seen in the filtration rate studies (Table 6-1, Table 5-10). However, the results from Filter 3 are very different. When no colloidal silver was applied to the outside of the filter, no silver was seen in the finished water in the first two runs. This indicates that only silver applied to the outside of the filter flows into the finished water. A possible explanation is that any silver not sorbed to the ceramic on the inside of the filter could be picked up by water and sorbed to the ceramic further in the filter. Any silver not sorbed to the ceramic on the outside of the filter can only flow into the filtered water.

Table 6-1: Silver Concentration Results – Different Silver Applications

	Colloidal Silver Concentration in Finished Water (µg/L)		
	Filter 1: ½ inside, ½ outside	Filter 2: ⅔ inside, ⅓ outside	Filter 3: all inside
Run 1	35		ND[1]
Run 2	13		ND
Run 3	15		No sample taken.

1. Non detect. Detection limit: 5 µg/L

After completion of the first three runs, filters were delivered to CIRA-UNAN for completion of microbiological analysis using water from the contaminated well in Tipitapa.

The results of the microbiological analysis show that the filters with colloidal silver applied inside and outside remove 100 percent of the total coliform, fecal coliform, and fecal streptococcus (Table 6-2). Unfortunately, no *E. coli* was present in the raw water in order to test removal efficiencies of *E. coli.* In Filter 3, however, only 87 percent of total coliform, 80 percent of fecal coliform, and 91 percent of fecal streptococcus were removed. Thus, the silver applied to the outside of the filter is critical to maintaining 100 percent reduction of bacterial indicators.

Table 6-2: Microbiological Results – Different Silver Applications

	Raw Water	Silver Application		
		Filter 1: ½ inside, ½ outside	Filter 2: ⅔ inside, ⅓ outside	Filter 3: all inside
Total Coliform	3108	0	0	390
Fecal Coliform	1583	0	0	315
Fecal Streptococcus	33	0	0	3
E. coli	0	0	0	0

The silver applied to the outside of the filter could be critical to inactivation by two methods: (1) The silver sorbs into the filter from two sides and thus creates a larger depth with colloidal silver and a longer contact time; or (2) The silver on the outside of the filter provides final disinfection as the water leaves the filter. Based on these results, as well as the mathematical model of the filter and the effect of scrubbing of the filter, it is important to determine the depth to which the silver penetrates into the ceramic. This depth is probably dependent on a number of factors, including amount of water the silver is diluted in, pore size of the filter, tortuosity of the path of the water, and dryness of the filter when the colloidal silver is applied.

6.2 Finished Water Quality at Different Concentrations of Colloidal Silver

In order to investigate the effects of colloidal silver concentration on finished water microbiological data, five filters with the same factory filtration rate of 1.5 Liters/hour were obtained from the PFP factory before application of colloidal silver. These filters were coated with five different amounts of colloidal silver:

1. No silver;
2. Two mL of 94 ppm colloidal silver from Natural Immunogenics in Florida;
3. One mL of 3.2 percent (32,000 ppm) solution of Microdyn;
4. Two mL of 3.2 percent (32,000 ppm) solution of Microdyn; and
5. Five mL of 3.2 percent (32,000 ppm) solution of Microdyn.

All colloidal silver was diluted in 300 mL of bottled water before application. The application method was by brush with $2/3^{rd}$ of the solution on the inner part of the filter and $1/3^{rd}$ of the solution on the outer part of the filter.

The 94-ppm concentration colloidal silver was obtained from Natural Immunogenics in Miami, Florida, USA. Natural Immunogenics produces and distributes 'Sovereign Silver' colloidal silver for the naturopathic market in the United States (Quinto, personal communication and visit, 19-10-01). Their laboratory is equipped with highly technical equipment, including a scanning electron microscope. They produce their silver within the laboratory, and test each of their batches of colloidal silver to ensure quality. They also maintain sample volumes of each of their batches, and test them over time.

Natural Immunogenics markets a 10-ppm concentration colloidal silver. They developed for PFP a special high concentration of 94 and 150 ppm. These were clearly labeled by Natural Immunogenics as "not for consumption". Their colloidal silver is suspended in water, as opposed to the protein suspension of Microdyn, because it is such a low concentration. At higher concentrations, the silver is not stable in water. The 94-ppm sample was used in this study to determine if this high concentration for Natural Immunogenics, but low concentration for PFP, would inactivate bacteria in the PFP filter.

In order to test these different concentrations of colloidal silver, first three runs with water from the contaminated well in Tipitapa were conducted in each filter. Silver samples were collected, preserved in nitric acid, transported, and analyzed in the United States at Toxicon Laboratories after each of these runs. Silver concentration samples were not taken from Filter 1 because no silver was applied, or from Filter 3 and 4 because the concentrations in these filters were similar to the filters studied in the filtration rate study (Table 5-10).

No silver was seen in the finished water using the Natural Immunogenics 94-ppm concentration colloidal silver (Table 6-3). In addition, the amount of silver seen in the finished water using 5 mL of 3.2 percent Microdyn was similar to the values seen when using on 2 mL of colloidal silver (Table 5-10). This indicates that the application method and not the concentration is more important in determining the concentration of silver in the finished water.

Table 6-3: Silver Concentration Results – Different Silver Concentrations

	Colloidal Silver Concentration in Finished Water (µg/L)				
	Filter 1: no silver	Filter 2: 2 mL of 94 ppm	Filter 3: 1 mL of 3.2%	Filter 4: 2 mL of 3.2%	Filter 5: 5 mL of 3.2%
Run 1		ND[1]			37
Run 2					17
Run 3					14

1. Non-detect. Detection limit: 5 µg/L

After completion of the first three runs, filters were delivered to CIRA-UNAN for microbiological analysis using water from the contaminated well in Tipitapa.

Results from the microbiological analysis show 100 percent reduction in total coliform, fecal coliform, and fecal streptococcus in the three filters with different concentrations of the Microdyn colloidal silver (Table 6-4). The filter without colloidal silver removed 98 percent of the total coliform, 97 percent of the fecal coliform, and 82 percent of the fecal streptococcus. The filter with the Natural Immunogenics silver removed only 76 percent of the total coliform, 63 percent of the fecal coliform, and 75 percent of the fecal streptococcus. Unfortunately, there was no *E. coli* in the raw water to determine *E. coli* removal efficiencies.

Although the filter without silver performed very well, the filter with the Natural Immunogenics silver performed significantly less well, indicating that there is significant variation in the ability of filters without Microdyn colloidal silver to remove bacteria. Thus, it is not recommended that filters be used without colloidal silver. In addition, the Natural Immunogenics 94-ppm silver is not effective for microbiological inactivation in the PFP filter. Although the Natural Immunogenics silver is well made and produced, the concentration is simply not high enough to ensure disinfection in the PFP filter. The concentration of the Microdyn colloidal silver is 340 times greater than the Natural Immunogenics silver, and this is important for microbiological inactivation.

Table 6-4: Microbiological Results – Different Silver Concentrations

	Raw Water	Silver Concentration				
		No silver	2 mL 94 ppm	1 mL 3.2%	2 mL 3.2%	5 mL 3.2%
Total Coliform	3108	55	745	0	0	0
Fecal Coliform	1583	47	590	0	0	0
Fecal Streptococcus	33	6	8	0	0	0
E. coli	0	0	0	0	0	0

6.3 Colloidal Silver Conclusions and Recommendations for Further Research

Based on the results of the colloidal silver investigations above, the following conclusions are presented:

1. No method of silver application (up to half the silver on the outside of the filter) or concentration of silver applied to the filter (up to 5 mL of 3.2 percent Microdyn) resulted in filtered water from the first three runs of the filter being above the WHO and USEPA standards for silver concentration.
2. Microbiological reduction was not complete when colloidal silver was not applied to the outside of the filter.
3. Although the filtration process alone removes a significant amount of the bacteria, this amount is variable, and the colloidal silver is necessary for complete removal of bacteria.
4. The high concentration of colloidal silver in Microdyn is necessary for complete removal of bacteria.

Although much research has been undertaken, a significant amount of questions were raised during this study that could be investigated further. Recommendations for further research include:

1. There is a question of how far the colloidal silver penetrates into the filter when painted on. This is important not only for application, but also for mathematical modeling of the filter, and to determine any negative effects of scrubbing of the filter.

7 Microbiological Challenge Investigations

A number of studies investigating the capacity of the filter to remove microbiological contaminants have been completed on the PFP filter and are reviewed in the following section.

7.1 Investigation of Non-Indicator Bacteria Found on Plates

In conversation, laboratory technicians at the Center for the Investigation of Water Resources at the Autonomous University of Nicaragua (CIRA-UNAN) noted that while sampling for the four bacterial indicators in water filtered with the PFP filter, often other small bacteria grew on the plates used to grow the indicator bacteria (personal conversation, 10-2001). They were interested in identifying these bacteria to determine what they were and whether they pose a risk to human health. Using biochemical techniques, these non-indicator growths were identified from the growths seen on the plates during the analysis of microbiological reduction of the filters with different flows rates and different concentrations of colloidal silver.

Two species of bacteria were identified using these techniques: *Aeromonas* and *Pleisomonas*. *Aeromonas* are gram-negative rods found in water, soil, food, and animal and human feces (Levinson, 1996). One species of the genus causes wound infections, diarrhea, and sepsis, especially in immunocompromised patients. Thus, *Aeromonas* can be found naturally, and can also be an indicator of human waste. *Pleisomonas shigelloides,* one species of *Pleisomonas,* is a gram-negative rod associated with water sources. It causes self-limited gastroenteritis, primarily in tropical areas, and can cause invasive disease in immunocompromised individuals.

Both genii are classified as 'minor bacterial pathogens' in Levinson (1996), and because both are associated with water sources it makes sense that these would be found in the water used in the filter. The fact they were not filtered out in this study shows that there is potentially a minor health risk to immunocompromised individuals who drink water from the PFP filter if the disease-causing species are the species that are not captured by the filter.

7.2 Studies Outside Nicaragua

7.2.1 Honduras

In November 1999, Ron Rivera conducted a feasibility study in Honduras. Water from the chlorinated, piped water supply system and well water were tested with filters manufactured in Nicaragua. The reduction in microbiological indicators showed that the Nicaraguan filter is feasible in Honduras (CESCCO, 1999). The filter removed 100 percent of the total coliform and fecal coliform from both the city chlorinated supply, and the well water. The filter also removed slightly more total coliform than boiling (Table 7-1).

Table 7-1: Microbiological Results in Honduras, 1999

Sample	Total Coliform (col / 100 mL)	Fecal Coliform (col / 100 mL)
Well water	150	100
Filtered well water	0	0
Boiled well water	2	0
City chlorinated, piped system	1,700	700
Filtered city water	0	0

7.2.2 Bolivia

A feasibility study in Bolivia was funded to determine if the filters would be applicable in Bolivia. Although the microbiological results were good, the project failed because of a lack of marketing of the filter. River water and filtered river water was tested on July 10, 1986 for Meals for Millions (Laboratorio de Microbiologia de Alimentos). The filter in Bolivia removed total coliform, fecal coliform, and 99.99 percent of the aerobic bacteria count (Table 7-2).

Table 7-2: Microbiological Results in Bolivia, 1986

Test	River Water	Filtered Water
Substances in suspension	Scant	Very scant
Aerobic Bacteria Count	300,000	10
Total Coliform (MPN)	460	Negative
Fecal Coliform	Positive	Negative
Salmonella	Negative	Negative

7.3 Studies Within Nicaragua: CIRA-UNAN

PFP has extensively worked with the Center for the Investigation of Water Resources at the Autonomous University of Nicaragua (CIRA-UNAN) to test different Nicaraguan filters for microbiological removal. CIRA-UNAN's standard laboratory practice is to clean receptacles first with detergent and then sterile distilled water (personal conversation, 10-01). This ensures that the receptacles do not recontaminate the filtered water.

7.3.1 July 2001

Two filters that had been used continuously at a restaurant for two years with unchlorinated well water were tested to see if they still removed microbes. Both filters removed 100 percent of both fecal and total coliform (Table 7-3).

Table 7-3: Microbiological Challenge – 2-year-old Restaurant Filters

	Fecal Coliform		Total Coliform	
	Before	After	Before	After
Filter 1	90	0	110	0
Filter 2	40	0	140	0

7.3.2 June 2000

A comparison study of filters made by hand and filters made in the PFP factory was completed. Four new handmade filters (BO-1 through BO-4) were compared with two new factory filters (5662, 5670). In addition, this study compared filters with and without colloidal silver application. All filters (both handmade and factory made) with colloidal silver removed 100 percent of all four microbiological indicators (Table 7-4). All three filters without colloidal silver removed 100 percent of the fecal streptococcus. The handmade filters without colloidal silver performed significantly less well than the factory made filter without colloidal silver. This indicates that either the pore size is larger, or the uniformity is less, in the handmade filters, and the colloidal silver is necessary to remove the bacteria the ceramic does not remove.

The results obtained here comparing filters with and without silver are similar to the results presented in Tables 5-8 and 6-3.

Table 7-4: Microbiological Challenge – Handmade and Factory Filters with and without Silver

Filter Number	Silver	Total Coliform	Fecal Coliform	Fecal Streptococcus	*E. coli*
Raw Water		3,000	250	245	250
BO-1	yes	0	0	0	0
BO-2	yes	0	0	0	0
BO-3	no	170	45	0	0
BO-4	no	300	45	0	45
5662	yes	0	0	0	0
5670	no	15	0	0	0

7.3.3 June 2000

An NGO working in Malpaisillo, Nicaragua purchased filters and trained local women to produce the receptacles. After three months, the NGO collected water samples and brought them to CIRA-UNAN for analysis. Although it is unknown how the samples were collected and preserved, the filter tested removed the majority of the four microbiological indicators.

Table 7-5: Microbiological Challenge – Malpaisillo Filters

	Total Coliform	Fecal Coliform	*E. coli*	Fecal Streptococcus
Before Filtration – Well Water	170	20	10	20
After Filtration	2	0	0	3

7.3.4 December 1999

In December 1999, CIRA-UNAN conducted challenge tests looking at one filter that was seven years old, and at three filters with different receptacle cleaning methods. The seven-year-old filter removed 100 percent of the total and fecal coliform, but actually increased slightly the fecal streptococcus contamination (Table 7-6). Of note is the before the year 2000, only 1 mL of 3.2 percent Microdyn colloidal silver was applied to the filters for disinfection. In 2000, the amount was doubled to provide an additional safety margin.

Filters with receptacles cleaned with chlorine or the solid detergent Extran removed 100 percent of all three microbiological indicators. The filter with the receptacle cleaned with liquid detergent had very slight contamination with total and fecal coliform. This data underscores the need for good receptacle cleaning practices in the field with the families.

Table 7-6: Microbiological Challenge – 7-year-old Filter and Receptacle Cleaning Methods

	Total Coliform	Fecal Coliform	Fecal Streptococcos
Control	87,000	13,000	7
7 years old filter	0	0	11
R-213 with receptacle washed with chlorine	0	0	0
R-83 with receptacle washed with detergent (liquid)	1	1	0
R-215 with receptacle washed with Extran (solid)	0	0	0

7.3.5 August / September 1999

In August 1999, the new press to mold the filters was used in the manufacturing process at the factory for the first time. Prior to this time, all filters were made by hand. Eight filters from the first batch made with the press were tested to determine if the press produced filters that met microbiological standards. Each of the eight filters was tested twice. All filters removed at least 98 percent of the microbiological indicators, and more than half removed 100 percent of all four indicators (Table 7-7).

In addition, the rise in pH due to the ceramic was seen in these samples, which correlates with the results obtained elsewhere in this study.

Table 7-7: Microbiological Challenge – Eight Pressed Filters

Filter	Total Coliform	Fecal Coliform	Fecal Streptococcus	*E. coli*	pH	Conductivity
Control	79,000	68,000	2,800	550	7.75	1090
R-83	0	0	0	0	8.22	1146
R-128	100	0	0	0	8.34	1122
R-168	0	0	0	0	8.39	1084
R-213	0	0	0	0	8.33	1154
R-214	0	0	0	0	8.34	1072
R-215	0	0	0	0	8.32	1165
R-223	0	0	0	0	8.34	1176
R-308	0	0	0	0	8.09	1149
Control	47,000	46,500	2,230	46,500	8.15	1132
R-83	0	0	1	0	8.39	1085
R-128	50	0	8	0	8.42	1061
R-168	0	0	4	0	8.43	1075
R-213	0	0	1	0	8.4	1052
R-214	0	0	0	0	8.49	1076
R-215	0	0	1	0	8.41	1043
R-223	100	50	3	50	8.19	1125
R-308	700	0	11	0	8.3	1143

The velocity of the above tested filters was 5-8 Liters in 7-9 hours. In addition, lab technicians noted growths of fungus on the outside of the filter, and bacteria on the culture plates that were not any of the above four groups. The growth on the outside of the filters was attributed to the fact that colloidal silver was not applied to the outside of these filters. The colloidal silver application process was changed after this investigation so that colloidal silver was also applied on the outside of the filter. Further investigation of bacteria on the culture plates was conducted for this study and results are presented in Section 7-1.

7.3.6 February 1999 / April 1999

After Hurricane Mitch, emergency filters were distributed in Communidad El Paso in Granada because the community well and sand filter was contaminated. The community used ceramic filters to reduce the turbidity of the water from the sand filter, and stopped using the filters when the water from the sand filter became clear again.

Results show that the sand filter was contaminated in both February and April, and that the PFP ceramic filter reduced microbiological contaminants (Tables 7-8 and 7-9).

Table 7-8: Microbiological Challenge – Sand Filter and Ceramic Filter, February

	Total Coliform	Fecal Coliform	Fecal Streptococcus	*E. coli*
Sand filter	130	2	4	2
Sand filter, then ceramic filter in lab at CIRA-UNAN	<2	<2	<2	
Sand filter, then ceramic filter in lab at CIRA-UNAN	0	0	2	

Table 7-9: Microbiological Challenge – Sand Filter and Ceramic Filter, April

	Total Coliform	Fecal Coliform	Fecal Streptococcus	*E. coli*
Sand filter	210	50	2	15
Sand filter and ceramic filter 1 at CIRA-UNAN	<2	<2	<2	
Sand filter and ceramic filter 2 at CIRA-UNAN	13	<2	<2	
Sand Filter and ceramic filter 3 at CIRA-UNAN	80	6	2	2

7.3.7 May 1992

Six new filters that were thrown on a potter's wheel were tested. These filters had 10 mL of 0.32 percent Microdyn colloidal silver solution applied in 250 mL of water. All filters removed 100 percent of the fecal coliform.

Table 7-10: Microbiological Challenge - Hand-thrown Filters

Filter Number	Fecal Coliform / 100 mL
1	0
1a	0
1b	0
2a	0
2b	0
5	0
Raw Water	>300

7.4 Microbiological Challenge Conclusions and Recommendations

Based on the results of the microbiological challenges detailed above, the following conclusions are presented:

1. Some small bacteria, which are potentially a human health concern, pass through the filter when tested in the laboratory at CIRA-UNAN.
2. This summary of the historical data clearly shows that many different filter designs over the years remove 98-100 percent of the indicator bacteria present in the source water.
3. Studies of filters that are two and seven years old indicate that the filters still effectively remove microbiological contaminants. This indicates that the colloidal silver does not 'wear out', and that with proper maintenance, there seems to be no need to reapply silver to the filter. Currently, the PFP recommendation is to reapply the colloidal silver once per year to the filter. This does not seem to be necessary based on the laboratory data. However, reapplication of colloidal silver provides a safety factor in the field that should not be removed without more extensive testing.

Although much research has been undertaken, a significant amount of questions were raised during this study that could be investigated further. Recommendations for further work include:

1. Although the recommendation from ICAITI is to replace the filter every year (Yetter, 1999) the colloidal silver seems not to 'wear out'. More microbiological investigations with filters that have been used in the field for extended periods of time could be conducted to determine if there is an upper time limit for colloidal silver replacement.

8 Arsenic Challenge

In response to a question from Bangladesh, PFP conducted an arsenic challenge on the filter in June of 2000 at CIRA-UNAN. Water spiked with arsenic was run through two filters, and finished water samples were taken every five Liters. Percentage retention of arsenic decreased significantly with sample volume, and the test was discontinued after 20 Liters in the filter with colloidal silver, and after 10 Liters in the filter without colloidal silver. More arsenic was retained in the filter with the colloidal silver (Table 8-1). One hypothesis is that the small amount of activated carbon that is present on the bottom of the filter due to the firing process retains the arsenic. However, this amount of carbon is small, and thus only a small amount of arsenic can be retained before the carbon is saturated.

It is clear from these results that the filter did not remove arsenic, and as such would not be appropriate for use in Bangladesh without modification.

Table 8-1: Arsenic Challenge Results

With Silver		Without Silver	
Volume	Retention of Arsenic	Volume	Retention of Arsenic
5 Liters	88.75 percent	5 Liters	81.79
10 Liters	82.05 percent	10 Liters	63.06
15 Liters	65.23 percent		
20 Liters	58.78 percent		

9 Pesticide and VOC Challenge Studies

Pesticides are widely-used within Nicaragua, and pesticide poisoning of agricultural workers is widespread (McConnell, 1993). In addition, Keifer (1996) determined that only one-third of people with a pesticide poisoning in Nicaragua reported it to the Regional Pesticide Poisoning Registry. Keifer (1996) states that "underreporting of pesticide poisonings disguises the enormity of the problem in developing countries."

Because of the extensive use of pesticides for agriculture, studies investigating ambient residual levels of pesticides have been completed. Castilho (2000) found higher concentrations of pesticides in the dry season as opposed to the rainy season. DDT, DDD, DDE, and toxaphene with the most common organochlorine residues found in the water and sediment, while endrin, aldrin, dieldrin, and lindane (gamma-BHC) were more frequently found in the waters of rivers and wells. Calero (1993) also found high concentrations of DDT, and its metabolites DDD and DDE, in fish. In terms of human health, Dorea (2001) found levels of DDE, DDT, dieldrin, and heptachlor in umbilical cord blood of mothers and their babies.

The research cited above details both the pesticide problem and the most common pesticides seen within Nicaragua. Due to the contamination of potential drinking water sources, it is important to determine whether the PFP filter can remove pesticides.

Volatile organic compounds (VOCs) are compounds primarily made up of carbon, hydrogen, and halogen (chlorine, bromine) atoms. They are used extensively in industry for purposes ranging from additives to solvents to dry cleaning to manufacturing processes. Although no research was found in the literature on ambient levels of VOCs in Nicaragua, PFP has been approached by various agencies asking whether the PFP filter removes certain VOCs.

9.1 Pesticide Challenge Study

The 'TCL Pesticides Mix' standard that contains 2000 µg/L of seventeen common pesticides and pesticide degradation products was obtained from the supplier Supelco (Table 9-1). Twenty liters of 100 µg/L concentration pesticide challenge solution was mixed in the laboratory at MIT with this standard using dilution water treated with reverse osmosis, distillation, ion-exchange, and finally total organic carbon removal. Molecular formulas, molecular weight, and half-lives of these pesticides were researched to provide a framework for potential correlation with removal efficiencies (Table 9-1). Of note is that endrin, heptachlor, methoxychlor, DDT, and gamma-BHC can all be removed by filtration through granulated activation carbon (Verschueren, 1996).

Table 9-1: Pesticides Used in the Challenge Study (Data from Verschueren, 1996)

Pesticide	Molecular Formula	Molecular Weight	Half-life	Use
aldrin	$C_{12}H_8Cl_6$	364.93	185 hours	insecticide, fumigant
alpha-BHC	$C_6H_6Cl_6$	290.85		insecticide
beta-BHC	$C_6H_6Cl_6$	290.85		insecticide
gamma-BHC	$C_6H_6Cl_6$	290.85	4,590 hours	insecticide
delta-BHC	$C_6H_6Cl_6$	290.85		insecticide
4,4'-DDE	$C_{14}H_8Cl_4$	319.05	in sealed jar: 0% removal after 8 weeks	military product, DDT impurity
4,4'-DDT	$C_{14}H_9Cl_5$	354.5	74 hours	insecticide
dieldrin	$C_{12}H_8Cl_6O$	381	12,940 hours	insecticide, stereoisomer of endrin
endosulfan I	$C_9H_6Cl_6O_3S$	406.9	in sealed jar: 100% removal in 4 weeks	insecticide
endosulfan II	$C_9H_6Cl_6O_3S$	406.9	in sealed jar: 100% removal in 4 weeks	isomer of endosulfan I
endosulfan sulfate	$C_9H_6Cl_6O_4S$	422.9		degradation product on endosulfan
endrin	$C_{12}H_8Cl_6O$	380.90		insecticide, stereoisomer of dieldrin
endrin aldehyde				
endrin ketone				
heptachlor	$C_{10}H_5Cl_7$	373.34	in sealed jar: 100% removal in 2 weeks	insecticide
heptachlor epoxide	$C_{10}H_5Cl_7O$	389.30	in sealed jar: 0% removal in 8 weeks	degradation product of heptachlor
methoxychlor	$C_{16}H_{15}Cl_3O$	345.65		insecticide

Two filters were challenged with this concentration of pesticides: (1) A new filter with colloidal silver; and (2) A filter that was used in a home in Jingüina, Nicaragua (Home 5 from Report 2) for 18 months and transported to the United States. Samples were collected from the new filter after filtration of three liters of spiked water, and from both filters after filtration of 8.5 liters of spiked water. A sample with a known concentration of 100 µg/L was also collected. Samples were put on ice and delivered to Toxikon Laboratories in Massachusetts, where they were analyzed for pesticides using USEPA Method 608.

The results from this sampling (Table 9-2) are inconclusive. First, the standard value input into the filter was intended to be 100 µg/L. As seen from the lab analysis of the standard, the input value ranged 6-49 µg/L. This indicates a problem with the pesticide mix itself, with the mixing of the mix into the dilution water, with lose of the pesticides in the process, or with the laboratory analysis.

Table 9-2: Pesticide Challenge Results in Two Filters

Pesticide	New Filter 3 Liters (µg/L)	New Filter 8.5 Liters (µg/L)	Used Filter 8.5 Liters (µg/L)	Influent Standard (µg/L)
aldrin	ND[1]	ND	ND	6.9
alpha-BHC	22	31	15	34
beta-BHC	20	30	19	32
gamma-BHC	20	31	16	32
delta-BHC	21	45	28	49
4,4'-DDE	ND	ND	ND	9.0
4,4'-DDT	ND	ND	ND	6.4
dieldrin	ND	ND	0.06	12
endosulfan I	0.07	2.9	0.41	11
endosulfan II	ND	4.3	0.31	14
endosulfan sulfate	0.52	17	3.8	17
endrin	ND	ND	0.23	15
endrin aldehyde	0.28	3.0	1.0	29
endrin ketone	2.7	17	6.4	14
heptachlor	ND	ND	0.072	6.2
heptachlor epoxide	0.070	3.8	0.43	11
methoxychlor	ND	ND	ND	6.3

1. Non-detect. Detection limit 0.04 or 0.10 µg/L.

In addition, pesticides that were not detected in the filtered water in the new and used filters were correlated not with size or half-life, but instead were correlated with a low influent concentration. Thus, no correlations between removal rate and molecular weight or half-life can be determined.

The one result that is of interest is that all of the pesticides that were detected had a lower removal rate in the new filter after 8.5 Liters than at 3 Liters. This indicates that breakthrough of pesticides occurs in the filter, although this indication is very weak considering the quality of the results. Further testing of pesticides to determine retention rates and possible breakthrough is recommended.

9.2 Volatile Organic Compound Challenge Study

A VOC standard mix that contains 2000 µg/L of 54 common VOCs was obtained from the supplier Supelco (Table 9-3). Twenty liters of 100 µg/L concentration VOC challenge solution was mixed in the laboratory at MIT with this standard using dilution water treated with reverse osmosis, distillation, ion-exchange, and finally total organic carbon removal. Molecular weight, molecular formula, and vapor pressure values were researched for each of the VOCs in the mix to provide a framework for potential correlation with removal efficiencies of individual compounds.

Table 9-3: VOCs Used in the Challenge Study (Data from Verschueren, 1996)

Volatile Organic Compound	Molecular Formula	Molecular Weight	Vapor Pressure (mm Hg, 20 C)	Use
Benzene	C_6H_6	78.11	76	industrial
Bromobenzene	C_6H_5Br	157.02	3.3	solvent, additive
Bromochloromethane	CH_2BrCl	129.38		
Bromodichloromethane	$CHBrCl_2$	163.8		fire extinguishers, solvent, heavy liquid
Bromoform	$CHBr_3$	252.77	5.6 (25 C)	fire-resistant chemicals, solvent, heavy liquid
Carbon tetrachloride	CCl_4	153.82	90	dry-cleaning, industrial
Chlorobenzene	C_6H_6Cl	112.56	8.8	solvent, manufacturing
Chloroform	$CHCl_3$	119.38	160	industrial
Cis 1,3-dichloropropene	$C_3H_4Cl_2$	110.97	43 (25 C)	soil fumigant, nematocide
Cis-1,2-dichloroethylene	$C_2H_2Cl_2$	96.95	200 (25 C)	solvent, refrigerant, additive
Dibromochloromethane	$CHBr_2Cl$	208.3		manufacturing
Dibromomethane	CH_2Br_2	173.83		
Ethylbenzene	C_8H_{10}	106.17	7	manufacturing, solvent, asphalt constituent
Hexachlorobutadiene	C_4Cl_6	261	22 (100 C)	solvent, industrial liquid
Isopropylbenzene	C_9H_{12}		3.2	manufacturing, catalyst, gasoline
m-xylene	C_8H_{10}	106.16	6	in gasoline
Methylene Chloride	CH_2Cl_2	84.93	349	paint stripping, manufacturing
m-butylbenzene	$C_{10}H_{14}$	134.21	1 (23 C)	petroleum refining
n-propylbenzene	C_9H_{12}	120.19	2.5	manufacturing, solvent, asphalt constituent
Napthalene	$C_{10}H_8$	128.16	1 (53 C)	petroleum refining
o-xylene	C_8H_{10}	106.17	5	petroleum distillation
p-isopropyltoluene				
p-xylene	C_8H_{10}	106.17	6.5	in gasoline
Sec-butylbenzene	$C_{10}H_{14}$	134.21	1.1	
Styrene	C_8H_{10}	104.14	5	manufacturing, plastics
Tert-butylbenzene	$C_{10}H_{14}$	134.21	1.5	
Tetrachloroethene				
Trans 1,3-dichloropropene	$C_3H_4Cl_2$	110.97	34	soil fumigant
Trans 1,2-dichloroethylene	$C_2H_2Cl_2$	96.95	200 (14 C)	solvent
Trichloroethylene (TCE)	C_2HCl_3	131.5	60	dry-cleaning, solvents, refrigerant
1,1-dichloroethane	$C_2H_4Cl_2$	98.96	180	vinyl chloride, solvent, degreasing
1,1-dichloroethylene	$C_2H_2Cl_2$	96.95	500	adhesives, synthetic fibers
1,1-dichloropropene	$C_3H_4Cl_2$	110.97		
1,1,1-trichloroethane	$C_2H_3Cl_3$	133.41	100	degreaser, solvent, adhesive
1,1,1,2-tetrachloroethane				
1,1,2-trichloroethane	$C_2H_3Cl_3$	133.41	19	solvent
1,1,2,2-tetrachloroethane	$C_2H_2Cl_4$	167.86	5	manufacturing, solvent
1,2-dibromo-3-	$C_3H_5Br_2Cl$	236.35	0.8	soil fumigant, nematocide

chloropropane				
1,2-dibromoethane	CH_2Br_2	173.83		
1,2-dichlorobenzene	$C_6H_4Cl_2$	147.01	1	manufacturing, solvent, fumigant
1,2-dichloroethane	$C_2H_4Cl_2$	99	61	manufacturing, tobacco flavoring
1,2-dichloropropane	$C_3H_6Cl_2$	112.99	42	intermediate, lead scavenger
1,2,3-trichlorobenzene	$C_6H_3Cl_3$	181.46	0.3	solvent, coolant
1,2,3-trichloropropane	$C_{12}H_6Cl_3NO_3$	318.5		herbicide
1,2,4-trichlorobenzene	$C_6H_3Cl_3$	181.46	0.3	solvent, dielectric fluid
1,2,4-trimethylbenzene	C_9H_{12}	120.19		manufacturing, gasoline
1,3-dichlorobenzene	$C_6H_4Cl_2$	147.01	2.3	
1,3-dichloropropane	$C_3H_6Cl_2$	112.99		
1,3,5-trimethylbenzene	$C_6H_3(CH_3)_3$	120.19		intermediate
1,4-dichlorobenzene	$C_6H_4Cl_2$	147.01	0.6	moth repellant, deodorizers
2-chlorotoluene	C_7H_7Cl	126.58	2.7	solvent, intermediate
2,2-dichloropropane	$C_3H_6Cl_2$	112.99		
4-chlorotoluene	C_7H_7Cl	126.59		

Two filters were challenged with this concentration of VOCs: (1) A new filter with colloidal silver; and (2) A filter that was used in a home in Jingüina, Nicaragua (Home 5 from Report 2) for 18 months and transported to the United States. Samples were collected from the new filter after filtration of three liters of spiked water, and from both filters after filtration of 7 liters of spiked water. A sample with a known concentration of 100 µg/L was also collected. Samples were put on ice and delivered to Toxikon Laboratories in Massachusetts, where they were analyzed for VOCs using USEPA Method 524.

The results of the VOC study are similar to that of the pesticide study. The laboratory values for the standard were closer to the intended value of 100 µg/L, with values ranging from roughly 50-100 µg/L. Some chemicals were not detected, however, which could be a result of the fact that with this many compounds it is difficult to separate out the peaks in the GC.

Removal rates varied depending on the compound, but in general less VOCs were removed after seven liters in the new filter than at three liters in the new filter (Table 9-4). This indicates that some breakthrough is occurring, although even at seven liters a good percentage of the VOCs are removed. Like in the pesticide study, the used filter at seven liters does slightly better than the new filter at seven liters.

Table 9-4: VOC Challenge Study Results in Two Filters

	Percent Removal			
Volatile Organic Compound	**Used Filter (7 Liters)**	**New Filter (3 Liters)**	**New Filter (7 Liters)**	**Standard**
Benzene	6.5	7.4	14	56
Bromobenzene	3.6	7.3	9.9	87
Bromochloromethane	26	ND[1]	43	82
Bromodichloromethane	16	30	30	65
Bromoform	16	29	30	100
Carbon tetrachloride	0.7	1.5	2.4	38

Chlorobenzene	3.4	5.8	7.9	70
Chloroform	10	ND	18	58
Cis 1,3-dichloropropene	17	30	33	80
Cis 1,2-dichloroethylene	10	ND	19	66
Dibromochloromethane	12	17	18	34
Dibromomethane	27	58	49	79
Ethylbenzene	1.4	2.2	3.7	60
Hexachlorobutadiene	ND	ND	0.51	73
Isopropylbenzene	0.73	1.3	2.3	54
m-xylene	2.6	4.8	6.7	110
Methylene Chloride	190	13	25	58
m-butylbenzene				
n-propylbenzene	0.59	1	1.7	61
Napthalene	7.4	13	9.7	100
o-xylene	2.1	3.8	5.3	61
p-isopropyltoluene				
p-xylene (included with m-xylene)				
Sec-butylbenzene	ND	0.57	1.3	47
Styrene	2.5	5.0	7.9	83
Tert-butylbenzene	0.53	0.97	2.2	62
Tetrachloroethene	0.66	1.3	1.9	48
Trans 1,3-dichloropropene	20	40	39	ND
Trans-1,2-dichloroethylene	3.6	ND	7.5	49
Trichloroethylene (TCE)	4.4	10	9.6	51
1,1-dichloroethane	7.5	1.2	14	56
1,1-dichloroethylene	0.88	ND	2.6	32
1,1-dichloropropene	1.0	1.6	3.1	39
1,1,1-trichloroethane	1.9	2.4	4.8	45
1,1,1,2-tetrachloroethane	7.6	11	14	88
1,1,2-trichloroethane	28	58	53	ND
1,1,2,2-tetrachloroethane	15	25	24	70
1,2-dibromo-3-chloropropane	13	32	25	90
1,2-dibromoethane	14	26	24	70
1,2-dichlorobenzene	2.4	5.8	7.5	81
1,2-dichloroethane	2	26	40	76
1,2-dichloropropane	15	22	27	62
1,2,3-trichlorobenzene	2.5	4.4	5	85
1,2,3-trichloropropane	17	33	27	87
1,2,4-trichlorobenzene	2	3.5	3.9	90
1,2,4-trimethylbenzene	1.4	2.4	2.9	69
1,3-dichlorobenzene	1.6	3.5	5.2	70
1,3-dichloropropane	ND	ND	ND	ND
1,3,5-trimethylbenzene	0.87	1.7	2.6	63
1,4-dichlorobenzene	1.7	3.6	5.1	72
2-chlorotoluene	1.4	2.5	4.0	54
2,2-dichloropropane	1.5	ND	3.0	33
4-chlorotoluene	1.8	3.2	4.5	63

1. Non-detect. Detection limit 0.50 µg/L.

Although this data is not conclusive, it does indicate that a percentage of the VOC concentration is removed at least in the first few Liters flowing through the PFP filter. More analysis is needed to determine removal rates over a longer period of flow.

9.3 Pesticide/VOC Conclusions and Recommendations for Further Research

Based on the results of the pesticide/VOC challenge investigations above, the following conclusions are presented:

1. The data is inconclusive, but the general trend can be seen that less pesticides and VOCs are removed as more spiked water is filtered through the PFP filter. This provides an indication that both pesticides and VOCs breakthrough the filter.

Although much research has been undertaken, a significant amount of questions were raised during this study that could be investigated further. Recommendations for further research include:

1. The data for both the pesticide and VOC sampling was not ideal. The values of the standards were not the expected level, and based on that it is difficult to determine removal rate. More studies are needed, with specific compounds of interest over a longer flow time, before conclusive data can be presented.

10 Protozoa and Virus Challenge Studies

Although the majority of the microbiological indicator studies focus on bacteria and bacterial indicators, protozoa and viruses in the water supply also cause human health effects. Challenge studies using protozoa and viruses were conducted at Analytical Services, Inc., a microbiological testing, research, and consulting laboratory in Williston, Vermont, USA.

10.1 Protozoa: *Giardia lamblia* and *Cryptosporidium parvum*

The three most prevalent gastrointestinal protozoans are *Giardia lamblia, Cryptosporidium parvum,* and *Entamoeba histolytica* (Girdwood, 1995). Together these three disease-causing agents cause more than one billion infections and more than one million deaths annually. Up to 20 percent of children in developing countries carry *Giardia lamblia*. This problem, however, is not limited to developing countries. In the United States *Giardia lamblia* is the most common cause of outbreaks of waterborne disease, although *Cryptosporidium parvum* infects a greater number of people in larger outbreaks (Casemore, 1995). Both *Giardia lamblia* and *Cryptosporidium parvum* are not inactivated by chlorine, so filtration is the method of choice for drinking water treatment (Hall, 1995). Pressdee (1995) determined that to achieve a 90 percent reduction in viability of *Cryptosporidium parvum*, a concentration of 3 g/L of chlorine must be exposed to the water for 1440 minutes. In addition, in order to reduce *Giardia lamblia* by 99 percent, 30-630 mg/min/L of chlorine is needed. These long chlorine exposure times increase the cost of water supply treatment by a factor of 4-5.

The largest protozoa outbreak in the United States occurred recently. In 1993, 403,000 people in Milwaukee, Wisconsin, drinking water that met all state and federal requirements, contracted cryptosporidosis (Addiss, 1995). The concentration of *Cryptosporidium parvum* in the contaminated Milwaukee drinking water was 6.7-13.2 oocysts/100 Liters of water. This concentration is extremely low, and raises the question of how to effectively sample for protozoa when in 100 Liters of water there are only 6-13 oocysts.

The life cycles of these two protozoa are similar. Protozoa of the genus Giardia are flagellates with an adhesive disk on the flattened ventral surface of their body (Kulda, 1978). They are approximately 7 microns in size, and exist in two forms: cysts and trophozoites. Trophozoites live in the duodenal and jejunal region of the human small intestine and are attached to the epithelium. They multiply by binary fission. Some individual trophozoites pass to the posterior of the small intestine, and encyst (form into a cyst) before being discharged in the feces. When ingested by a new host, the cyst excysts (form back into a tropozoite) after passing through the stomach and reaching the small intestine.

Depending on hygienic standards in a community, the incidence of giardiasis varies from 1-30 percent (Kulda, 1978). It is more frequent among children, and is acquired either by ingestion of cysts in contaminated food and drink or by fecal contact between one person and another. A total of 10-100 cysts are necessary to initiate infection. However, one milliliter of stool from some symptomatic patients contains more than 300 million cysts. Cysts do not survive desiccation, but remain viable in a wet environment or in water for over three months. Temperatures above 50 degrees Celsius kill the cysts, but they can survive short term freezing. *Giardia* are very resistant to chlorine-based

disinfectants, as less that 10 percent of cysts are killed after 24 hours of exposure to 1-3 percent chloramine. Flagyl is the preferred antibiotic to treat giardiasis in humans.

Cryptosporidium parvum is a coccidian parasite with worldwide distribution that is transmitted in the oocyst stage via the fecal-oral route (Girdwood, 1995). It is resistant to many potable water treatment processes, and the zoonotic component has been recognized by human infection from cattle. The oocysts are five microns in diameter, and release sporozoites in the small intestine when ingested by a suitable host. After invasion of the small intestine, the sporozoites undergo successive asexual and sexual multiplication to produce immature oocysts, which are then excreted. Asymptomatic infection in humans is uncommon. There is no specific treatment for cryptosporidosis.

Due to expense of the testing, protozoa and virus challenge testing was only conducted on one PFP filter. This was a new filter, with standard application of 2 mL of 3.2 percent Microdyn colloidal silver on both the inside and outside of the filter. Because this study "did not address variability in performance between units, the effects of compromised water quality on protozoa or viral reduction, the effective volume of water that can be treated, replicate sampling, etc." this data is preliminary, and is not "of publication quality (ASI, 2001)."

In order to challenge the filter with protozoa, ASI added live, infectious Cryptosporidium parvum and *Giardia lamblia* to dechlorinated, prefiltered, UV-disinfected carrier water. The challenge dose was 340,000 *Cryptosporidium* oocysts and 260,000 *Giardia* cysts. For efficiency, the two organisms were presented as a cocktailed challenge dose. The entire effluent from the filter was collected, filtered, and analyzed in general accordance with EPA Method 1623, modified for challenge study application.

Results from this protozoa challenge study are encouraging, as the PFP filter achieved greater than a 4-log reduction of both *Giardia lamblia* and *Cryptosporidium parvum* (Table 10-1). This is equivalent to greater than a 99.99 percent reduction of both protozoa.

Table 10-1: *Giardia lamblia* and *Cryptosporidium parvum* Removal Efficiencies

Protozoa	Influent – Total Applied (oo)cysts	Effluent – Total (oo)cyst detected in 7.0 Liters	Log Removal (% Removal)
Giardia lamblia	340,000	18	4.3 (99.994%)
Cryptosporidium parvum	260,000	6	4.6 (99.997%)

It is cautioned that only one PFP filter was subjected to this challenge for one single test. No replicate or variability or quality assurance sampling was completed. However, this result was expected based on the pore size determined using the scanning electron microscope analysis. The pore size within the PFP filter varies between 0.6-3.0 microns. Three microns is the upper limit to ensure filtration of *Cryptosporidium* oocysts, which can be smaller than the 5-micron average size (Paul Warden, ASI, personal communication, 20-12-01). *Giardia* cysts are slightly larger and are oval in shape, ranging from 5-7 microns in size. Thus, if the pore size is maintained at a maximum of three microns, it is expected that the PFP filter will remove a significant percentage of these protozoa. To ensure this

expectation, a full study with a variety of filters that incorporates quality assurance and replicate sampling is necessary.

10.2 Viruses

Viruses, on the other hand, are quite small, because they do not contain their own replication material. Due to their small size (0.02-0.2 microns), it was expected that the pore size of the PFP filter would not be small enough to trap viruses. The removal rate of viruses then depends on inactivation due to interaction with the colloidal silver, or other effects such as electrostatic attraction to the ceramic.

The MS2 coliphage is a bacteriophage (a virus that infects bacterial cells as opposed to animal cells). MS2 coliphage is approximately 0.025-0.027 microns in size, and is commonly used in challenge studies because it is relatively simple to propagate, rapid to assay, and not a human pathogen (Warden, personal communication, 12-2001). ASI challenged the PFP filter with an influent concentration of 4900 PFU/mL of water. An effluent sample was taken after 30 minutes of filtration, and a second effluent sample was taken after six hours of filtration. After six hours, the filter failed to achieve more than a 0.09 log reduction (more than 18.7 percent reduction) in MS2 concentration (Table 10-2).

Table 10-2: MS2 Coliphage Removal Efficiency

Sample Timepoint	Influent (PFU/mL)	Effluent (PFU/mL)	Log Removal (% removal)
T-30 minutes	4900	1500	0.5 (68.4%)
T-6 hours	No sample	4,000	0.09 (18.7%)

This lack of reduction capability can be attributed to the fact that MS2 Coliphage is significantly smaller than the average pore size of the PFP filter. Further research into the filters capacity to remove/inactivate viruses, using actual waterborne viruses and investigating the role of colloidal silver in inactivating viruses, is necessary.

10.3 Protozoa/Virus Challenge Conclusions and Recommendations for Further Research

Based on the results of the protozoa/virus challenge investigations above, the following conclusions are presented:

1. The results for the one new filter challenge tested for *Giardia lamblia* and *Cryptosporidium parvum* shows that the PFP filter achieves greater than a 4-log reduction in both protozoa. Thus, this PFP filter was significantly more effective on these two protozoa than chlorine.

2. The results for the one new filter challenge tested for MS2 Coliphage shows that the PFP filter achieves less than a 1-log reduction of this virus. Thus, this PFP filter was not effective at removing MS2 Coliphage.

Although much research has been undertaken, a significant amount of questions were raised during this study that could be investigated further. Recommendations for further research include:

1. Completion of a full study with quality assurance sampling to determine more precisely the log-reduction of protozoa.
2. Investigation of the role of colloidal silver in virus inactivation.
3. Completion of viral challenges of the PFP filter with actual waterborne viral pathogens.

11 Conclusions and Recommendations

The following summarizes the conclusions and recommendations presented within this report.

1. Filtration Rate Investigations

- The pore size within the PFP filter is 0.6-3.0 microns.
- Scrubbing of the filter rejuvenates the filtration rate, and should be undertaken periodically to increase the filter lifetime.
- *E. coli* is removed in a number of filters without colloidal silver application because the pore size is small enough to capture the *E. coli.* In addition, a significant fraction of total coliform and fecal coliform are removed without the colloidal silver, although it is not 100 percent removal. Thus, the colloidal silver is necessary for compete removal/inactivation of bacteria.

2. Colloidal Silver Investigations

- Application of colloidal silver to the filter does not affect the filtration rate or the pH and conductivity of the filtered water.
- Colloidal silver needs to be applied to both the inside and outside of the filter to achieve 100% bacterial inactivation.
- No sample from the first three runs of a number of filters, with filtration rates up to 2 Liters/hour and concentrations of Microdyn colloidal silver as high as 5 mL, exceeded USEPA or WHO standards for silver in drinking water.
- Colloidal silver manufactured for the naturopathic industry in the United States did not inactivate bacteria in the PFP filter, and it is recommended that PFP continue to use 2 mL of the industrial concentration (3.2 percent) of Microdyn.
- Filters as old as 7 years were tested and found to still remove 100% of total and fecal coliform, indicating that the lifespan of the colloidal silver is indefinite. However, the policy of reapplication every year that is recommended by PFP should not be abandoned without further testing, because it provides a important margin of safety.

3. Challenge Testing

- Microbiological challenges consistently show that many different variations of the filter all have effectively reduced bacterial indicators by 98-100 percent in the laboratory.
- Data from the arsenic challenge conducted by PFP showed a steep decrease in removal rate of arsenic with increasing amount of challenge water. Data from the pesticide and VOC challenge conducted for this study was inconclusive, but the general trend was the same as with the arsenic: a decreasing removal rate with increasing amount of challenge water.
- The one PFP filter tested achieved greater than a 4-log reduction of both *Cryptosporidium* and *Giardia.*
- The one PFP filter tested did not achieve a 1-log reduction of MS2 bacteriophage virus.

Based on these results, it is concluded that the PFP filter effectively removes and inactivates bacteria and bacterial indicators of disease-causing organisms. With the modifications recommended in Report 2, it is expected that the PFP filter could also reliably remove these organisms in the field. Preliminary results indicate that the PFP filter also removes protozoa, but not viruses. Further research is necessary to detail exact removal rates of protozoa, viruses, and contaminants. In addition, research is needed to determine the thickness of the colloidal silver layer within the ceramic. This will allow application of the mathematical model developed by Eriksen (2001), and a determination of the filter life based on removal of ceramic during the scrubbing process. Results to date indicate the filter life is indefinite, and currently decreasing flow rate and breakage are the limiting factors on filter life. Based on the results of Report 1 and Report 2, it is concluded that, with an education component for the users, the PFP filter is an effective and appropriate technology that improves both water quality and human health.

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Note: Dates in this section are listed in day-month-year format.

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