**POINT-OF-USE WATER TREATMENT DEVICE FOR
DISASTER RELIEF**

A Thesis

presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil and Environmental Engineering

by

Patricia Marie Compas

December 2009

© 2009
Patricia Marie Compas
ALL RIGHTS RESERVED

COMMITTEE MEMBERSHIP

TITLE: Point-of Use Water Treatment Device for Disaster Relief

AUTHOR: Patricia Marie Compas

DATE SUBMITTED: December 2009

COMMITTEE CHAIR: Dr. Tryg Lundquist, Civil & Environmental Engineering
Assistant Professor

COMMITTEE MEMBER: Dr. Yarrow Nelson, Civil & Environmental Engineering
Professor

COMMITTEE MEMBER: Dr. Sam Vigil, Civil & Environmental Engineering
Professor

ABSTRACT

Point-of-Use Water Treatment Device for Disaster Relief

Patricia M. Compas

After large-scale disasters, prevention of water-borne illness in the survivors is important to rescue and recovery. Thirst can quickly force survivors to drink contaminated water, and thus clean water must be provided almost immediately. However, in many cases, transport of clean water and/or water treatment devices into disaster zones requires days, and water transport is costly and potentially difficult. Alternatively, compact water treatment methods can be provided, but they can be expensive (hand-pumped filters) or only partially effective (chlorine tablets). More complete treatment, including removal of turbidity and parasite cysts, is provided by individual chlorine-flocculant doses, such as PÜR[®] Purifier of Water[™] (PÜR[®]) packets, but the standard PÜR[®] treatment procedure uses buckets and filter cloth, which may be difficult to procure in disaster zones. In the present research, a waterbag was developed to provide a treatment and storage container, and water quality testing was performed to determine if these waterbags could meet emergency drinking water guidelines for both quality and quantity.

The 10-liter volume waterbags were designed using low-density polyethylene (LDPE) and coupled with PÜR[®] packets to clarify and disinfect the water. The water outlet was also fitted with a filter apparatus containing a 1- μ m polypropylene filter pad for multi-barrier treatment. The PÜR[®] packets, manufactured by Proctor & Gamble, contain a mixture of ferric sulfate, calcium hypochlorite, and other chemicals to treat approximately 10 liters (2.5 gallons) of water. To optimize the PÜR[®] flocculation/disinfection process within the waterbag, mixing and settling variations were

examined through a set of experiments, and an optimal treatment protocol was selected which included 20 inversions, 5 minutes of vigorous mixing, 10 minutes of horizontal settling, and 15 minutes of vertical settling. Tests were primarily conducted with irrigation reservoir water altered with physical and chemical constituents based on the United States Environmental Protection Agency (U.S. EPA) Test #2 challenge water recipe. Results indicated that the waterbag treatment unit consistently met World Health Organization (WHO) emergency drinking water guidelines. The treatment reduced pathogen levels from 10^4 CFU/liter to non-detectable limits, reduced turbidity ranging from 50 NTU to 500 NTU to < 5 NTU, and chlorine residual was detected but not always within the WHO recommended range of 0.2 mg/L to 0.5 mg/L. Lastly, a U.S. EPA Challenge Water Experiment was conducted, treating U.S. EPA Test Water #2 in triplicate prototypes. Test results did meet the pH and turbidity requirements; however, the U.S. EPA Water Purifier Guidelines minimum microorganism log-removal reduction requirements for purifier devices were not met. Design modifications are being addressed for the treatment to meet these requirements.

The waterbag itself has advantages for both filling and carrying compared to commonly used jerry-cans. The cylindrical bag can facilitate collection, treatment, transport, and storage within a single point-of-use unit, demonstrating the potential to provide improved drinking water quality during disaster relief situations in developing countries.

ACKNOWLEDGMENTS

I would like to thank the following people for their encouragement, time, and support:

My Cal Poly Advisors: Dr. Tryg Lundquist, Dr. Yarrow Nelson, and Dr. Sam Vigil

Students: Steve Barr, Adam Wegener, Tomiko Oden, Casey Kelleher, Kylie Hensley, Maggie Herzog, Katie Spahr, Roman Couvrette, Morgan O'Hare, Imran Rahman, Dan Frost, Jorge Montezuma, Wilson Wong, Chris McCann, and Claire Miller

C3RP Program: Jim Dunning and Susan Opava

Aquaya Institute: Jeff Albert

Cal Poly Professors: Dr. Sema Alptekin, Dr. Pete Schwartz, and Dr. Patrice Engle

Advisors: Steve Rieve (American Red Cross), Greg Allgood (P&G), Thomas Handzel (CDC), Robert Cooper (BioVir Labs & UC Berkeley), Keith Vorst (Cal Poly plastics and packaging professor), Rich Boberg (Founding team of Network Appliance, Inc.)

Cascade Designs Inc.

Reliance Products, LP

U.S. Navy, especially Bill Varnava, Port Hueneme, Calif.

Engineers Without Borders-Cal Poly, especially the Nicaragua 2009 team

ATRAVES, USA and Nicaragua

SCORE – San Luis Obispo

Family & Friends

Mom & Dad

David Markman

My Editors: Mom Compas, David Markman, Grandpa Compas

I am extremely grateful for the following awards and the financial support provided by the prizes. This thesis research was entirely funded by prize monies.

Cal Poly Innovation Quest Competition, 2007 (1st place, Bob Barron Award)

<http://iq.innovationq.org/>

Cal Poly Ray Scherr Business Competition, 2008 (1st place)

<http://bplan.calpoly.edu/>

Clinton Global Initiative University (CGI U) Outstanding Commitment Award, 2008

<http://cgiu.clintonglobalinitiative.org/Page.aspx?pid=1853>

<http://www.clintonglobalinitiative.org/>

Cal Poly Honors Program: National Science Foundation Grant, 2009

<http://honors.calpoly.edu/>

Cal Poly Honors Program: Humanitarian Service Learning Competition (Two rounds), 2009

<http://honorsprojects.com/husel/projects.php>

TABLE OF CONTENTS

List of Tables	xii
List of Figures	xiv
Chapter 1 - Introduction.....	1
Chapter 2 - Background.....	6
2.1 - Drinking Water Contamination during Emergencies	6
2.1.1 - Microbiological Parameters & Environmental Diseases.....	7
2.1.2 - Non-Microbiological Parameters	11
2.2 - Drinking Water Guidelines and Objectives for Emergency Response	14
2.3 - Emergency Water Treatment Process Categories.....	17
2.3.1 - Modular and Mobile Treatment Units.....	19
2.4 - Microbiological Water Purifiers Protocol.....	22
2.4.1 - Performance Requirements.....	23
2.4.2 - Test Water Properties	25
2.5 - Current POU Emergency Water Treatment Methods.....	27
2.5.1 - Boiling	29
2.5.2 - Solar Disinfection	30
2.5.3 - Chlorine Disinfection	32
2.5.4 - Filtration	40
2.5.5 - Combined Flocculation/Disinfection.....	43
2.5.6 - Safe Storage.....	44
2.6 - PŪR® Purifier of Water	47
2.6.1 - How it Works.....	48
2.6.2 - Chemical Ingredients and Details of the Treatment Process	49
2.6.3 - Distribution Models & Partners.....	56
2.6.4 - PŪR® Treatment Intervention Studies.....	57
2.7 - Emergency Field Kits & Transportation.....	63

Chapter 3 - Prototype Design and Development	66
3.1 - Prototype Design.....	67
3.1.1 - Material Selection.....	68
3.1.2 - Design Capacity and Geometry.....	69
3.1.3 - Design Components.....	73
3.1.4 - Usability.....	84
3.1.5 - Transport.....	85
3.2 - Building the Prototype	86
Chapter 4 - Materials and Methods.....	90
4.1 - Experimental Design.....	90
4.2 - Filter Selection Experiments.....	91
4.2.1 - Prepared Water	92
4.2.2 - Filter Material	92
4.2.3 - Procedures	93
4.3 - Baseline Water Quality Experiments.....	94
4.3.1 - Experiment B-1: Water Collection and Preparation.....	95
4.3.2 - Experiment B-1: Procedures.....	96
4.3.3 - Experiments B-2 and B-3: Water Collection and Preparation	96
4.3.4 - Experiment B-2: Procedures.....	100
4.3.5 - Experiment B-3: Procedures.....	101
4.4 - Optimization Experiments	101
4.4.1 - Water Collection and Preparation.....	101
4.4.2 - Procedures	104
4.5 - Analytical Methods.....	112
4.6 - U.S. EPA Challenge Water Experiments.....	116
4.6.1 - Mock Run Experiment: Water Preparations & Procedures.....	117
4.6.2 - U.S. EPA Challenge Water Experiment: Water Preparations and Procedures.....	118

Chapter 5 - Results and Discussion	122
5.1 - Filter Selection Experiments.....	122
5.1.1 - Experiment A-1: Hemp Filters	123
5.1.2 - Experiments A-2 through A-6: 100% Cotton Cloth Filters.....	124
5.1.3 - Experiment A-7: Woven Bleach White Kona [®] Cotton Filters.....	125
5.1.4 - Experiment A-8 and A-9: 1- μ m Polypropylene Felt Cloth Filters.....	126
5.1.5 - Experiments A-7 through A-9: 10-L Prototypes Settled Turbidity	127
5.1.6 - Selected Filter Material	128
5.2 - Baseline Water Quality Experiments.....	130
5.2.1 - Experiment B-1: Treating SLO WWTP Primary Effluent	131
5.2.2 - Experiment B-2: First Drumm Reservoir + Swine Unit Pond Water Test..	134
5.2.3 - Experiment B-3: Standard P $\bar{U}$ R [®] Bucket Protocol vs. the Prototype	138
5.3 - Optimization Experiments	146
5.3.1 - Experiment C-1: Inversion Variations.....	147
5.3.2 - Experiment C-2: Horizontal Mixing Variations.....	151
5.3.3 - Experiment C-3: Horizontal and Vertical Settling Variations.....	154
5.3.4 - Experiment C-4: First Filtration Test	157
5.3.5 - Experiment C-5: Regulating Flow.....	161
5.3.6 - Experiment C-6: Introducing Vigorous Horizontal Mixing.....	163
5.3.7 - Experiment C-7: Evaluating Vigorous Mixing and Settling Methods	168
5.3.8 - Experiment C-8: Inversion Variations.....	175
5.3.9 - Experiment C-9: Various Initial Turbidities.....	181
5.4 - U.S. EPA Challenge Water Experiments.....	187
5.4.1 - Mock Run Experiment.....	187
5.4.2 - Test of Cascade Designs Inc. Prototype	191
5.4.3 - U.S. EPA Challenge Water Experiment.....	193
Chapter 6 - Conclusions.....	203
6.1 - Prototype Design Conclusions.....	203

6.2 - Experimental Conclusions	205
6.3 - Future Research	207
References.....	210
Appendix A.....	220
Appendix B	224
Appendix C	229
Appendix D.....	232
Appendix E	238
Appendix F.....	241

LIST OF TABLES

Table 2.1 - Major environmental diseases in emergency settings (Wisner & Adams, 2002).	9
Table 2.2 - Basic water survival needs required on a daily basis defined by the Sphere Project (The Sphere Project, 2006).	15
Table 2.3 - Water quality objectives for emergency response (The Sphere Project, 2006; World Health Organization, 2006; U.S. Environmental Protection Agency, 1987).	16
Table 2.4 - U.S. EPA and NSF guidelines for minimum microbiological reduction requirements (U.S. EPA, 1987; USACHPPM, 2008).	24
Table 2.5 - U.S. EPA challenge water test properties for Test Water #1 and Test Water #2 (U.S. Environmental Protection Agency, 1987).	26
Table 2.6 - CDC Safe Water System program recommended free chlorine concentrations after the addition of sodium hypochlorite (Centers for Disease Control and Prevention, 2005).	34
Table 2.7 - CDC Safe Water System summary on the effect of chlorine inactivation of selected pathogens including bacteria, viruses, and protozoa (Kasper, 2007).	35
Table 2.8 - THMs WHO guidelines and U.S. EPA maximum contaminant level (Lantagne, Blount, Cardinali, & Quick, 2008).	39
Table 2.9 - Criteria for safe water storage containers based on minimizing contamination and user acceptance, developed by the CDC and UNICEF (UNICEF, 2008; Mintz, Reiff & Tauxe, 1995).	45
Table 2.10 - PÜR [®] sachet ingredients including a chlorine disinfectant, iron salt coagulant, and coagulant and flocculating aids (Souter, Cruickshank, & Stoddart, 2007; Reller, et al., 2003).	50
Table 2.11 - Guatemalan water treatment intervention study results pre- and post-Treatment with PÜR [®] and SWS treatment systems (Rangel, Lopez, Mejia, & Mendoza, 2003).	58
Table 2.12 - UNICEF WASH program standard hygiene kit items that were handed out during Cyclone Nargis relief efforts in Myanmar (UNICEF WASH Program, 2008).	64
Table 4.1 - Test water recipes for Experiment B-2 and B-3	98
Table 4.2 - Test water recipe for Optimization Experiments.	102
Table 4.3 - Test variables examined during Optimization Experiments	109
Table 4.4 - Example sampling plan for a single prototype	111
Table 4.5 - Mock Run test water recipes for the bucket and prototype tests.	117
Table 5.1 - Summary table of filter material layers used to achieve <5 NTU turbidity after 500 mL filtered.	129
Table 5.2 - Pre- and post- treatment water quality characteristics of SLO wastewater treatment facility primary effluent for Experiment B-1.	132

Table 5.3 - Water quality characteristics of test water comprised of a mixture of Drumm Reservoir and Swine Pond waters, with turbidity additions prior to prototype treatment for Experiment B-2.	134
Table 5.4 - Experiment B-2 water quality characteristics for the Treated and Control Bag	135
Table 5.5 - Experiment B-3 pre-treatment water quality characteristics of blended Drumm Reservoir and Swine Pond water with the addition of A2 Fine Test Dust and Instant Ocean.	139
Table 5.6 - Experiment B-3 post-treated water quality characteristics for the bucket and prototypes.....	144
Table 5.7 - Mixing and settling procedures for Bags 1 through 5 in Experiment C-1. ..	148
Table 5.8 - Mixing and settling procedures for Bags 1 through 5 in Experiment C-2. ..	151
Table 5.9 - Mixing and settling procedures for Bags 1 through 5 in Experiment C-3. ..	155
Table 5.10 - Mixing and settling procedures for Bags 1 through 3 in Experiment C-4.	158
Table 5.11 - Mixing and settling procedures for Bags 1 through 4 in Experiment C-6.	164
Table 5.12 - Mixing and settling procedures for Bags 1 through 4 in Experiment C-7.	169
Table 5.13 - Mixing and settling procedures for Bags 1 through 4 in Experiment C-8.	175
Table 5.14 - Initial water quality characteristics of Experiment C-9 where initial turbidities differed in each prototype.....	181
Table 5.15 - Experiment C-9 post-treated water quality characteristics for all prototypes	184
Table 5.16 - Mock Run Experiment water recipe based on the U.S. EPA Challenge Test Water #2.....	188
Table 5.17 - Challenge Test Water #2 prepared by BioVir Staff for the July 13, 2009, Cal Poly prototype testing (BioVir Laboratories, Inc., 2009)	194
Table 5.18 - Physical and chemical water quality characteristics post filtration during the Challenge Test Water #2 test at BioVir Laboratories.....	196
Table 5.19 - <i>R. terrigena</i> results from the U.S. EPA Challenge Water Experiment at BioVir Laboratories (BioVir Laboratories, Inc., 2009)	198
Table 5.20 - Coliphage results from the U.S. EPA Challenge Water Experiment at BioVir Laboratories (BioVir Laboratories, Inc., 2009)	198
Table 5.21 - Microsphere results from the U.S. EPA Challenge Water Experiment at BioVir Laboratories (BioVir Laboratories, Inc., 2009)	198
Table 5.22 - U.S. EPA Challenge Water Experiment results compared to the emergency response objectives for turbidity, chlorine residual, and pH.	199
Table 6.1 - Prototype design storage and user criteria in comparison to the CDC and UNICEF safe water storage criteria (as found in Table 2.9).	203

LIST OF FIGURES

Figure 1.1 - World map of 2008 natural disasters (Munich Re Group, 2008).....	2
Figure 2.1 - The five "F" diagram of diarrheal disease transmission routes (UNICEF, undated).....	8
Figure 2.2 - General water treatment process train for surface water to remove turbidity using clarification, sedimentation, filtration, disinfection, and storage (adapted from MWH, 2005).	18
Figure 2.3 - Oxfam upflow clarifier modular unit (Evenproducts, 2005).	20
Figure 2.4 - IFRC ERU's installed in Aceh, Indonesia in 2004, to provide treatment in tanks and in large bladder systems (International Federation of the Red Cross and Red Crescent Societies, 2005).	21
Figure 2.5 - POU system treatment options for developing countries in daily use and in disaster relief settings.....	29
Figure 2.6 - The SODIS method using sunlight and thermal energy to inactivate pathogens within a 6-hour period (Eawag, 2009).	31
Figure 2.7 - Chlorine reaction flow chart for drinking water (Centers for Disease Control and Prevention, 2005).	33
Figure 2.8 - PSI's SWS chlorination product in Nigeria, Water Guard (Centers for Disease Control and Prevention, USAID, 2008).	37
Figure 2.9 - Standard "Oxfam Bucket" (Left) and CDC SWS Program storage container (Right) provided for daily POU storage and in disaster relief efforts (Centers for Disease Control and Prevention, USAID, 2009).	46
Figure 2.10 - Jerry cans provided by IFRC Societies during the 2008 Cyclone Nargis relief efforts in Myanmar (International Federation of Red Cross and Red Crescent Societies, 2008).	47
Figure 2.11 - PŪR [®] sachet used to treat 10 liters of water (P&G, 2003).	49
Figure 2.12 - PŪR [®] treatment instructions printed on the back of PŪR [®] sachets (The Aquaya Institute, 2006).	49
Figure 2.13 - Uncharged particles colliding and forming flocs (Zeta Meter, Inc., 1993).	52
Figure 2.14 - The Double Layer model for a single colloid (Zeta Meter, Inc., 1993).	53
Figure 2.15 - Colloids embedded in precipitate forming sweep flocs (Zeta Meter, Inc., 1993).	53
Figure 2.16 - Kenyan drinking water samples showing varying turbidities and the resulting PŪR [®] treatment system turbidity (P&G's Children's Safe Drinking Water Program, 2005).	60
Figure 2.17 - IFRC distributing disaster relief kits to Myanmar villages after the 2008 Cyclone Nargis (International Federation of Red Cross and Red Crescent Societies, 2008).	64
Figure 3.1 - Conceptual model of research and development based on set goal.	67

Figure 3.2 - Sealing LDPE film with the ULINE® tabletop impulse sealer at Cal Poly. .	69
Figure 3.3 - Side view of the Mark I prototype used in the research, with features indicated.....	71
Figure 3.4 - Side view of the Mark I prototype with dimensions shown.....	72
Figure 3.5 - PVC mat (Left) cut to 1” x 10” dimensions and hemmed to the top end of the prototype as reinforcement for dry-bag style closure (Right).....	73
Figure 3.6 - Spring-loaded valve with a 5/8” Outlet (Left), secured to LDPE film (Right).	74
Figure 3.7 - The valve and 100% cotton cloth from a dissected bag following a filter selection experiment to determine if the material effectively reduced turbidity levels to <5 NTU.	75
Figure 3.8 - Versa Laser™ cutting 1-μm polypropylene cloth.....	76
Figure 3.9 - Cut cloth at 3-in diameter disks	76
Figure 3.10 - 1-μm polypropylene cloth examined under microscope at 10x magnification to show needle punched fibers on an unused cloth purchased from Rosedale Products of California, Inc.	78
Figure 3.11- 1-μm polypropylene cloth examined under microscope at 10x magnification to show particle and floc capture by needle punched fibers on a cloth purchased from Rosedale Products of California, Inc., (Cloth shown after an Optimization Experiment.)	78
Figure 3.12 - 1-μm polypropylene cloth after filtration showing surface particle layer after an Optimization Experiment (Left) compared to an unused cloth (Right).....	79
Figure 3.13 - Millipore™ stainless steel filter holder used during the Filter Selection, Baseline, and a couple of the Optimization Experiments before it was replaced by a custom filter housing.....	80
Figure 3.14 - Conceptual 2-D drawing of filter apparatus in SolidWorks 2009 (design by A. Wegener).....	82
Figure 3.15 - 3-D filter apparatus model shown in SolidWorks 2009 with 1-μm polypropylene cloth secured in the apparatus (design by A. Wegener).	82
Figure 3.16 - Rapid Prototyping Machine, Object Eden 260 with the Build Tray at the Center (A. Wegener shown in the photo).	83
Figure 3.17 - Clear resin filter apparatus.	83
Figure 3.18 - The pictographic instructions were developed to guide the users through the treatment steps. The pictographs begin with collecting water from a surface water body (Left) follow through steps omitted here (see Appendix F), and end with the users drinking the water (Right). Each step in between was established during the optimization experiments.	85

Figure 3.19 - Prototype #1 shown filled with 6-L volume of water to test sealing strength (Left). The drop cloth plastic purchased had nicks in the material that sprung leaks (Right).	86
Figure 3.20 - Prototype #2 shown with Velcro™ closure and handles holding a 10 liter water volume.	87
Figure 3.21 - Prototype #3 containing 10 liters of water at a longer length and shorter width prototype.	87
Figure 3.22 - Prototype #4, the Mark I design, was the selected design for the Baseline and Optimization Experiment series (prototype shown during the Optimization Experiment with attached filter apparatus).	88
Figure 3.23 - Zip-Lock™ closure on the modified Mark I prototype fabricated by Cascade Designs Inc. for the Challenge Water Experiment at BioVir Laboratories, Benicia, CA.	89
Figure 3.24 - Welded outlet port on the modified Mark I prototype fabricated by Cascade Designs Inc. (Seattle, WA).	89
Figure 4.1 - Experiment naming convention.	91
Figure 4.2 - Filter Selection Experiment A-8 showing vertical settling with the prototype hanging on a gate (Left) and turbidity samples taken over the 30-minute settling time, pre-filter and post-filter (Right).	94
Figure 4.3 - Primary effluent tank at the San Luis Obispo Wastewater Treatment Facility where 10-gallons of primary effluent water was collected for Baseline Experiment B-1.	95
Figure 4.4 - Collecting Drumm Reservoir water in 5-gallon buckets at the outlet point northwest of the Cal Poly Farm Shop along Brizzolara Creek.	97
Figure 4.5 - Collecting Swine Unit pond water in 500-mL sampling bottles at the water's edge along the Sports Complex Road side of the pond (Steve Barr).	97
Figure 4.6 - Mixing test water recipe with blender (Left) and then adding the blender contents to the remaining volume in refuse container mixed by 1/3 HP sump pump (Right) prior to filling prototypes for treatment testing.	100
Figure 4.7 - Test water recipe preparations for Experiment C-9, in which the dispensing container was set on the mixer for five minutes.	103
Figure 4.8 - IDEXX Quanti-Trays®/2000 after 24-hour incubation at 35°C from Baseline Experiment B-3. The tray on the left shows the presence of total coliform bacteria in the pre-treatment water sample at 10x dilution while the tray on the right represents a non-diluted post-treated prototype sample free from total coliform bacteria.	114
Figure 4.9 - IDEXX Defined Substrate Technology® to detect total coliform bacteria and <i>E. coli</i> in water (IDEXX Laboratories, Inc., 2007).	115
Figure 4.10 - Hosecock clamp used to regulate flow discharged from the spring-loaded valve in order to not overload the filter cloth.	116

Figure 4.11 - Prepared water container set in ice to drop the temperature to 4°C for the Mock Trial Experiments based on the U.S. EPA Purifier Guidelines.	118
Figure 4.12 - BioVir staff member inoculating the Test Water #2 with the challenge microorganisms and microspheres.....	119
Figure 4.13 - Dr. Tryg Lundquist (left) and Dr. Robert Cooper (right) filling a prototype with the Challenge Test Water #2 prior to treatment testing at BioVir Laboratories in Benicia, CA.....	120
Figure 5.1 - Turbidity from three 6-L prototypes were measured prior to filtration and post-filtration. Filters were two- or three- ply hemp cloths. Three-ply hemp cloth provided turbidities lower than the 5 NTU standards.	124
Figure 5.2 - Five plies of 100% cotton Hanes® cloth were required to bring filtered turbidities below the 5 NTU standard. The tests were performed with the 6-L prototypes.	125
Figure 5.3 - During Experiment A-7, the clarity of the PÜR® treated water was higher for greater numbers of layers, with seven layers being required to achieve a turbidity of 1.88 NTU.	126
Figure 5.4 - For Experiments A-8 and A-9, pre-filtered turbidity measured 47.8 NTU and 32.6 NTU, respectively. Once filtered through the 1-µm polypropylene cloth, turbidities decreased to 2.16 NTU and 0.85 NTU.	127
Figure 5.5 - Turbidity removal rates decreased drastically after 10 minutes of settling, and final 30-minute turbidities were similar for all levels of initial turbidity.	128
Figure 5.6 - Experiment B-1, Bag 1, shown with clogged 1-µm polypropylene cloth after 500 mL of treated water was filtered. In the background, the prototype is shown with settled flocs at the conical bottom; however, the water did not improve sufficiently in clarity, having only reached a filtered turbidity of 227 NTU.	133
Figure 5.7 - Turbidity measurements over the 30 minute settling period for the Treated Bag in Experiment B-2. The turbidity initially rose to a peak of 859 NTU, then gradually the decreases before slightly increasing to a final, pre-filtered turbidity of 187 NTU. ...	136
Figure 5.8 - Settled flocs shown in the conical sediment trap of the Treated Bag in Experiment B-2. The treated water did not meet the minimum turbidity standard of 5 NTU.	138
Figure 5.9 - During the bucket tests fluffy flocs formed and settled after 5 minutes of vigorous mixing and 5 minutes of settling (Left, looking through the water). The water was then decanted through a 100% cotton filter cloth and stored for a minimum of 20 minutes (Right).	140
Figure 5.10 - During the prototype treatment, fluffy flocs clumped together and settled during the vertical settling process (Left). At the end of the test, the flocs were retained in the prototype's conical sediment trap with the supernatant water above (Right).....	141

Figure 5.11 - Turbidity over the 30 minute settling period for the Bag 1 and Bag 2 in Experiment B-3. The final pre-treatment turbidities reached for Bag 1 and Bag 2 were 21.7 NTU and 59.3 NTU, respectively.	142
Figure 5.12 - Pre- and post- filter turbidity measurements for the buckets and prototypes tested in Experiment B-3. Final filtered turbidity measurements, at the “yield” volume (where filtered clogged), range from 1 NTU to 3 NTU. Initial post-filter 15 mL were not taken for the buckets since the standard treatment procedure calls for the entire volume to be filtered after 10 minutes, not after the entire 30 minute treatment time.	143
Figure 5.13 - Experiment C-1 pre- and post- filter turbidity measurements for Bag 1 through Bag 5. Inverting the prototype more resulted in lower pre-filtered turbidities for Bag 1 through Bag 4. While prototypes with higher pre-filtered turbidities produced lower filtered turbidity measurements.	149
Figure 5.14 - Experiment C-2 pre- and post- filter turbidity measurements for Bag 1 through Bag 5. Mixing the prototype horizontally showed improvement in water clarity during the 30-minute treatment period.	152
Figure 5.15 - Transitional steps from horizontal settling to vertical settling. Settled flocs observed to slide down back side of prototype to the conical sediment trap (left, middle). The flocs re-suspend just above the valve but eventually settle back to the bottom (right).	154
Figure 5.16 - Pre- and post- filter turbidity measurements for Bag 1 through Bag 5 in Experiment C-3, in which horizontal and vertical settling steps were different for each prototype.	156
Figure 5.17 - Pre- and post- filter turbidity measurements for Bag 1 through Bag 3 in Experiment C-4, in which horizontal and vertical settling steps differed for each prototype, along with the horizontal mixing in Bag 3.	159
Figure 5.18 - Filtered turbidity samples for 8 L total volume filtered for Bag 1 through Bag 3 in Experiment C-4. Filtered samples decreased in turbidity from 0 L to 3 L, but eventual level off after 3 L filtered.	159
Figure 5.19 - Filtration Rates for Bag 1 through Bag 3 compared to the tap water control bag in Experiment C-4. Filtration rates followed a decreasing trend due to less head in the prototypes.	160
Figure 5.20 - Filtered turbidity varied with controlled flow rate during Experiment C-5. Restricted flow rates resulting in filtered turbidity measurements of <5 NTU.	163
Figure 5.21 - Average turbidity measurements prior to filtration produced by gentle and vigorous mixing intensities during Experiment C-6.	165
Figure 5.22 - Turbidity measurements over the volume output of each prototype. Bag 1 through Bag 3 turbidity measurements were sampled after filtration; whereas Bag 4 turbidity samples were not filtered.	166

Figure 5.23 - Filtration rates shown during the course of the filtration run for each prototype. Bag 1 and Bag 2 flows ranged between 1.3 L/min and 0.5 L/min. Bag 3 ranged between 1.4 L/min to 0.6 L/min.....	167
Figure 5.24 - Pre-filter and post-filter turbidity after 15 mL and 100 mL were filtered, as shown for the four prototypes that underwent 5 minutes of vigorous mixing. Bag 2 through Bag 4 showed an increase in turbidity at the 15 mL sample, but decreased along with Bag 1 after the first 100 mL filtered.	170
Figure 5.25 - Turbidity measurements during the filtration run for each prototype. Turbidities ranged from 1.31 NTU to 2.82 NTU (15 mL filtered turbidities excluded from this figure).....	171
Figure 5.26 - Filtration rates during the filtration run of the full yield volume of the prototypes. Filtration rates started at 1.5 L/min and decreased to 0.7 L/min.	171
Figure 5.27 - In Experiment C-7 and observed in the other Optimization Experiments, flocs were observed to stick to the inside wall of the bags. Tapping on the wall of the prototype encouraged the flocs to settle to the bottom. Some of the flocs do flow out with the effluent, but are filtered out by the 1- μ m polypropylene filter cloth.	173
Figure 5.28 - Pre-filter and post-filter turbidity after 15 mL and 100 mL shown for five prototypes at varying inversions. Turbidity increased at the 15 mL filtration point and then decreased at the 100 mL sampling point (this is also seen in Figure 5.24). Bag 2, C-7 had the most drastic turbidity change at the three sampling points.	176
Figure 5.29 - Turbidity measurements sampled over the volume output of each prototype. Generally, turbidities decreased in the prototypes, except for Bag 4, in which the turbidity measured approximately 5 NTU throughout the filtration run. The start of the filtered volume shown for each prototype corresponds to 100 mL.....	177
Figure 5.30 - Filtration rates measured during the 7.1 L filtration run. Bag 1 through Bag 3 filtered at a similar rate from 1.3 L/min decreasing to 0.5 L/min, while Bag 4 and Bag 2, C-7 maintained slightly higher filtration rates, from 1.5 L/min to 0.8 L/min.....	178
Figure 5.31 - Optimized laboratory procedures based on the Optimized Experiment results.	180
Figure 5.32 - Pre-filter and post-filter turbidities after 15 mL and 100 mL had been filtered for five prototypes at various initial turbidities. Turbidity increased at the 15-mL filtration point and then decreased at the 100-mL sampling point (as observed in Figure 5.24 and Figure 5.28).	182
Figure 5.33 - Turbidity measurements at 1-L increments during filtration. Generally, turbidity decreased over the course of filtration or remained consistent throughout the filtration run.	183
Figure 5.34 - Filtration rates recorded over the 6-L volume output. up to 7.1 L volume. The filtration rates were between 0.5 L/min to 1.0 L/min.	183

Figure 5.35 - Pre-filter and post-filter turbidities after 15 mL and 4 L were filtered for the prototype and bucket tests using a version of Challenge Water #2. The prototype treated water was filtered using the 1- μ m polypropylene filter cloth, and the bucket treated water was filtered with a 100% cotton cloth.....	189
Figure 5.36 - Filtration rates recorded during filtration of the full volume output. The filtration rate ranged between 0.4 L/min to 0.8 L/min for the treated prototype.	192
Figure 5.37 - Floc movement varied in each prototype. Bag 1 (left) had floating flocs and some suspended flocs, while Bag 3 (right) had lots of suspended flocs. Bag 3 shown to the right is after 5 minutes of vertical settling, so the water clarity continued to improve from what is shown here.	195
Figure 5.38 - Final pre-filtered turbidities ranged between 7.68 NTU to 9.44 NTU during the U.S. EPA Challenge Water Experiment.	196
Figure 5.39 - Pre-filter and post-filter turbidities after 4 L were filtered during the U.S. EPA Challenge Water Experiment.	197
Figure 5.40 - Log reduction comparisons of the three prototypes from the U.S. EPA Challenge Water Experiment to the 1987 U.S. EPA Purifier Guidelines minimum log reduction requirements.....	200

CHAPTER 1 - INTRODUCTION

The threat of natural disasters and emergencies to human health is a major issue facing the world today. Natural disasters often prevent people from sustaining their normal living conditions, causing risk to health and life. The World Health Organization (WHO) cites that the number of people affected by disasters is increasing, with “an average of 147 million people per year between 1981-1990,” increasing to “an average of 211 million people per year between 1991-2000” (Wisner & Adams, 2002). As the world population continues to grow, the number of vulnerable people increases, recorded at 255 million affected per year between the years of 1994 to 2003 (Guha-Sapir, Hargitt, & Hoyois, 2004). This number is exemplified by the many disasters within 2008 that displaced millions of people globally (**Figure 1.1**). In May 2008, Cyclone Nargis threatened the lives of millions in Myanmar. Their health was at risk as they were “forced to drink out of puddles and drinking reservoirs contaminated by dead bodies” (CNN.com, 2008). Soon after, in 2008, Sichuan, China, endured a 7.9 earthquake, displacing over 45.5 million people, leaving 5 million homeless, and damaging over 47,000 kilometers of drinking water pipelines (USGS, 2008), elevating the risk of waterborne diseases in the displaced population.

Figure 1.1 - World map of 2008 natural disasters (Munich Re Group, 2008).

International law entitles people affected by disasters to protection and assistance from domestic government (e.g., FEMA and National Guard in the U.S.) and/or international relief organizations (e.g., Red Cross/Crescent, UNICEF, USAID, and CARE) (Davis & Lambert, 2007). These humanitarian organizations respond by providing immediate needs of food and water, medical aid, and shelter to the displaced people. Water and sanitation expenditures by leading relief organizations have increased an average of 45% per year from 2001-2007 and by 87% since 1999 (UN Financial Tracking Service, 2008). For example, in 2006 the Office of U.S. Foreign Disaster Assistance (OFDA) of USAID, responded to 74 disasters affecting more than 173 million people in 55 countries, where flooding was the most common disaster. The OFDA's total budget during 2006 was \$569

million, in which \$403 million was devoted to the purchase and distribution of emergency supplies and \$86 million on the water and sanitation sector (USAID OFDA, 2006).

Relief organizations respond to water supply needs with the resources and funds available, with the goal of providing basic water needs to victims and meeting the water quality criteria needed for survival. According to Steve Rieve, Senior Director of Product Management & Business Planning for the American Red Cross, “Providing clean drinking water is the number one challenge in disaster zones” (Rieve, 2008). Current methods to provide clean water to disaster areas are slow and costly. After disasters, governments and aid organizations move tons of supplies ranging from tents and mobile hospitals to generators and earthmoving equipment. Jerry cans (5-gallon plastic jugs) for water are almost always part of the supplies delivered, but one 5-gallon jerry can occupies nearly one cubic foot and weighs 42 pounds, when full. When roads are damaged and trucks are desperately needed for supplies, this inefficient use of transport is unfortunate.

Alternatively, compact water treatment methods can be provided, but they are often expensive (hand-pumped filters) or only partially effective (chlorine tablets). More complete treatment, including removal of turbidity and parasite cysts, is provided by individual chlorine-flocculant doses, such as PÜR® Purifier of Water™ (PÜR®) sachets, but the standard PÜR® treatment procedure uses buckets and filter cloth, which may be difficult to procure or transport in disaster zones (The Aquaya Institute, 2006). To overcome the difficulties, the research described here was performed to develop and test

an individual point-of-use treatment device -- a plastic waterbag with a geometry that will facilitate effective coagulation, flocculation, sedimentation, and disinfection with PŪR[®] sachets. The innovative features of the patented design include mixing by bubble displacement and short particle settling distance (Lundquist, 2009).

The goal of the research is to contribute to the development and design of the unit based on the needs of the relief organizations and users. Design objectives, including material selection, geometry and capacity, treatment methods, usability (e.g., ease of use and pictographic instructions), and cost were evaluated to help create a device with the ultimate goal of facilitating safe water provision in four ways: (1) It is easy to fill under difficult conditions, even in shallow water; (2) It can be carried as a backpack or sling with little fatigue; (3) With the addition of a single 4-g PŪR[®] sachet, it removes turbidity, arsenic, cysts, viruses, and bacteria from 10 L; and (4) It provides hygienic storage and dispensing.

The inventor of the waterbag is Dr. Tryg Lundquist, Cal Poly Civil and Environmental Engineering professor. To-date, the waterbag development has won recognition and monetary prizes for the goal of providing an alternative water treatment device for governments and relief organizations to rapidly deploy in a disaster relief setting, providing safe, reliable drinking water for the end user. Former President Bill Clinton presented an Outstanding Commitment Award to Cal Poly student Patricia Compas at the Clinton Global Initiative annual meeting in New York in 2008. The waterbag won 1st place at the 2007 Cal Poly Innovation Quest Competition and at the 2008 Ray Scherr Business Plan Competition. Cal Poly was also invited to the prestigious statewide DFJ

Venture Challenge in Palo Alto in 2008. Less than a year after filing, in 2009 the US Patent Office issued a patent for the waterbag (#7,514,006). Additionally, award money was received for two-round winnings from the Cal Poly Honors Program's Humanitarian Service Learning competition.

The purpose of the research presented in this thesis is to complete the optimization of the waterbag design, method of use, and to test the efficacy of the final design. The specific objectives included:

1. Design a prototype based on relief organizations' and displaced people's needs.
2. Conduct water quality experiments to finalize treatment protocol based on the most effective combination of rapid mixing, slow mixing, and settling times.
3. Conduct water quality experiments to determine efficacy of the device in meeting the World Health Organization and the US Environmental Protection Agency emergency drinking water guidelines.

CHAPTER 2 - BACKGROUND

This chapter focuses on drinking water contamination faced in natural disasters and the emergency response standards for drinking water provisions. A review of water treatment process categories is presented with an emphasis on point-of-use treatment methods currently used by relief organizations, followed by a detailed examination of the single point-of-use treatment, Proctor & Gamble's PÜR[®] Purifier of Water[™] (PÜR[®]) sachets.

2.1 - Drinking Water Contamination during Emergencies

During large-scale disasters, like Cyclone Nargis and the earthquake in Sichuan, China, water supplies may be contaminated or destroyed. Thirst can quickly force victims to drink contaminated water, exposing them to infection leading to diseases such as diarrhea, cholera, typhoid, and infectious hepatitis. Assuming toxic chemicals are not present in the water, the two major concerns during an emergency situation are microbial pathogens and suspended matter (Handzel, 2007). The three major pathogens from microbial contamination that cause diarrheal diseases are: bacteria (e.g., *E. coli* and salmonella), protozoan parasites (e.g., *Giardia* and *Cryptosporidium*), and viruses (e.g., Norwalk and Rotavirus). Suspended matter is also a health concern as it can carry pathogens, interfere with water treatment, such as chlorine disinfection, and alter the taste and odor of the water (The Aquaya Institute, 2006). The threat of disease from lack of clean drinking water was apparent during the aftermath of the December 2004 Asian tsunami. World Health Organization relief workers feared that the number of disease-caused deaths would exceed the number of victims killed by the tsunami itself, stating, "Poor quality and quantity of water and insufficient sanitation, overcrowding and poor

hygiene in temporary camps will bring forward the risk of outbreaks of different diarrheal diseases. Thorough and sustained water purification is an absolute priority” (Freeman & Szymanski, 2005; Clasen & Smith, 2005).

The quickest option for those facing these risks in a disaster situation is often surface water; though, this is generally the more polluted source (Dorea, Bertrand, & Clarke, 2006). The following subsections briefly describe the microbiological and non-microbiological parameters associated with surface water contamination during disaster situations and the environmental diseases associated with the polluted water.

2.1.1 - Microbiological Parameters & Environmental Diseases

The three major pathogens from microbial contamination: bacteria, protozoan parasite, and viruses, cause infectious diseases that can be transmitted from person to person or from water-related transmission routes. According to a study presented by the Disease Control in Humanitarian Emergencies, a program within the World Health Organization (WHO), “The risk for communicable disease transmission after disasters is associated primarily with the size and characteristics of the population displaced, specifically the proximity of safe water and functioning latrines...the level of immunity to vaccine-preventable diseases...and the access to healthcare services” (Watson, Gayer, & Connolly, 2007). The transmission routes of diseases, primarily diarrheal diseases, are shown in the five “F” diagram created by Kawata in 1978 (UNICEF, undated) (**Figure 2.1**). According to the five “F” diagram, barriers to fecal-oral transmission particular in emergency settings include a primary barrier (PB) and secondary barriers (SB). The primary barrier is sanitation practices; the secondary barriers encompass water quality

(including treatment and storage), water quantity, hygiene, and proper cooking methods (Clasen, 2007).

These transmission routes promote diseases, many of which are important in emergency situations. RedR Engineers for Disaster Relief have further defined these routes in their practical guide for relief workers, which is adapted in **Table 2.1**. Like **Figure 2.1**, it emphasizes that human excreta is the major cause of diseases.

Figure 2.1 - The five "F" diagram of diarrheal disease transmission routes (UNICEF, undated).

Table 2.1 - Major environmental diseases in emergency settings (Wisner & Adams, 2002).

Environmental Diseases	Causes	Critical during Emergencies?
Fecal-Oral Diseases (Diarrheas)	Drinking water contamination Poor personal hygiene Poor food hygiene	Yes (major causes of illness and death in epidemics)
Soil-Transmitted Diseases (Roundworm)	Soil contaminated by human excreta	Not critical in the short term
Water-Based Diseases (Schistosomiasis)	Disease vector is present in water contaminated by human excreta	Not critical in the short term
Vector-Diseases (Malaria)	Insect and rodent vectors	Yes (quickly causes illness and death)

The pathogenic microorganisms that cause these diseases include bacteria, viruses, and protozoan parasites. Each of these microorganisms is briefly described below. Helminthes are another category of disease-causing organism, but one not discussed in this research.

Bacteria - Bacteria are single-celled organisms that colonize in the human intestinal tract and are found in human excreta (Metcalf & Eddy, 2003). They range in size from approximately 0.1 to 10 μm and are present in contaminated water sources ranging from nonpathogenic to pathogenic bacteria. They have a negative surface charge, and they are environmentally resistant at the spore and cyst-like stage (MWH, 2005). Examples of pathogenic bacteria include the genus

Salmonella that contains a species of *Salmonella typhi* which causes typhoid fever in humans and *Vibrio cholera* a disease agent for cholera. An example of nonpathogenic bacteria that is associated with waterborne gastroenteritis and is used as an indicator organism is enteropathogenic *Escherichia coli* (Metcalf & Eddy, 2003).

Viruses – Viruses are pathogens structured with a nucleic acid core (DNA or RNA). They infect host cells by inserting genetic material to take control of the host system in order to reproduce themselves (Crites & Tchobanoglous, 1998). Humans excrete over 100 different types of enteric disease-causing viruses. From these 100 types, the viruses that affect health the most include enteroviruses (e.g., polio), Norwalk viruses, rotaviruses, reoviruses, and hepatitis A. The Norwalk virus and rotavirus are the major waterborne pathogens that cause diarrheal disease (Crites & Tchobanoglous, 1998). These viruses range in size from 0.02 to 0.08 μm (Metcalf & Eddy, 2003). They have a negative surface charge, and they are environmentally resistant (i.e., capable of surviving in the environment) at the virion (a single virus particle) stage (MWH, 2005).

Protozoan Parasites - Two of the major disease-causing protozoan parasites are *Cryptosporidium parvum* and *Giardia lamblia*. *Cryptosporidium parvum* exists in a protective hard-shelled cyst called an oocyst, which is the environmentally resistant stage. The oocysts have a negative surface charge and are approximately 3-5 μm in diameter (MWH, 2005; U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM), 2008). *Giardia lamblia* exist in the

environmentally resistant stage as cysts. They are also negatively charged and typically 8-10 μm in diameter (MWH, 2005). In comparison, *Cryptosporidium parvum* is found to be much more disinfectant-resistant than *Giardia* (U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM), 2008). Similarly, both parasites can significantly compromise the immune systems of the elderly, young children, people with cancer, and those with AIDS (Crites & Tchobanoglous, 1998). People in developing countries are particularly vulnerable as they may lack the resources, adequate healthcare, and water treatment provisions to overcome these disease-causing microorganisms.

Unfortunately, outbreaks of these microorganisms have caused disease in almost all post disaster situations. Outbreaks of diarrheal diseases were observed after the 2004 Bangladeshi floods, the December 2004 Southeast Asian tsunami, the 2005 Pakistan earthquake, and even post Hurricanes Allison and Katrina in the United States. These outbreaks were from a variety of infectious microorganisms, including *Vibrio cholera*, *Escherichia coli*, *Cryptosporidium parvum*, and *Salmonella* (Watson, Gayer, & Connolly, 2007).

2.1.2 - Non-Microbiological Parameters

Though the main concern with drinking water contamination is microbial pathogens, there are some non-microbiological parameters that alter the aesthetics of water and/or interfere with disinfection.

Turbidity - Turbidity measures the clarity of the water and can indicate the amount of suspended matter and microorganisms in a water sample. It is caused

by “suspended and colloidal matter such as clay, silt, finely divided organic and inorganic matter, and plankton and other microscopic organisms” (APHA et al., 1995). Surface waters are often found, especially after floods, with an increase in turbidity due to sediment loads. Turbidity is one of the most important physical characteristics of concern, as it degrades aesthetics, causes short filter runs, and reduces the effectiveness of chlorination as many pathogens may be “shielded” by the particles protecting the pathogens from disinfection. Turbidity acts as an indicator for bacteria, *Giardia* cysts, and *Cryptosporidium* oocysts (Davis & Lambert, 2007; USAID, 2005; Sawyer, McCarty, & Parkin, 2003; MWH, 2005). Turbidity is expressed in nephelometric turbidity units (NTU), and formazin suspensions are used as primary reference standards for measurement.

pH - pH expresses the hydrogen-ion activity, providing the intensity of the acid or base concentration in a solution (Sawyer, McCarty, & Parkin, 2003). Changes in pH affect chemical and biological treatment processes. For instance as noted by Wisner et al., in discussing environmental health in emergencies, “more alkaline [pH > 8] water requires a longer contact time or a higher free residual chlorine level at the end of the contact time for adequate disinfection” (Wisner & Adams, 2002).

Chlorine Residual - Though not a parameter found in non-treated surface waters, it is important to note the significance of chlorine residual. Chlorine residual is measured as free chlorine, and when it is present in the disinfected waters within a certain range, it indicates the chemical disinfectant was effective in killing the

microorganisms and the water is safe to drink. It is effective against bacteria and many viruses, but not protozoan parasites (refer to Section 2.5.3 for more details on free chlorine and inactivation of microorganisms). Chlorine residual is reported as a concentration, typically in mg/L.

Natural Organic Matter - Natural organic matter (NOM) is composed of particulate and dissolved organic matter, mainly originating from decomposing plants. NOM alters water color as well as reacting with chlorine to form disinfection byproducts (MWH, 2005). If not addressed appropriately, this can have an adverse effect on water treatment processes and public health. Typically, total organic carbon (TOC) is used to measure the concentration of NOM and reported in mg/L.

Chemical Parameters - Most chemical parameters are not of concern during the immediate time following a natural disaster since exposure to the chemicals begin to take effect after a long period of time, even if in the short-term it exceeds WHO chemical parameter guidelines (Wisner & Adams, 2002). By the time the long term recovery period is reached, another source will be used or a long term treatment option will be put in place by relief organizations or local governments. It is advisable to avoid sources significantly contaminated by chemical or even radiological pollution (Wisner & Adams, 2002). However, one parameter to measure is total dissolved solids (TDS). TDS consists of inorganic salts, organic matter, and dissolved gases (Sawyer, McCarty, & Parkin, 2003). Salinity in water can make it unfit for potable use and has shown to be a major issue as water was

deemed unfit to drink during emergency in South Iraq in 2004 following the Second Gulf War (Esposto, 2005).

2.2 - Drinking Water Guidelines and Objectives for Emergency Response

Relief organizations have set guidelines and objectives to meet target water quantity and water quality needs for the victims. Collectively, a joint effort by a group of humanitarian non-governmental organizations (NGOs) was established in 1997, The Sphere Humanitarian Charter and Minimum Standards in Disaster Response (hereafter, The Sphere Project), to improve the quality and accountability of emergency interventions. The Sphere Project is based on two core beliefs:

“First, that all possible steps should be taken to alleviate human suffering arising out of calamity and conflict and second that those affected by disaster have a right to life with dignity and therefore a right to assistance” (The Sphere Project, 2006).

The Sphere Project set minimum standards and guidance notes to meet in the provision of water and sanitation response. For instance, water consumption for survival purposes was identified and minimum standards were set for relief efforts (**Table 2.2**).

Table 2.2 - Basic water survival needs required on a daily basis defined by the Sphere Project (The Sphere Project, 2006).

Need	Volume (L / day)	Factors
Survival needs: water intake (drinking and food)	2.5 – 3	Depends on: the climate and individual physiology
Basic hygiene practices	2 – 6	Depends on: social and cultural norms
Basic cooking needs	3 – 6	Depends on: food type, social as well as cultural norms
Total basic water needs	7.5 – 15	

In addition to the Sphere Project, the WHO and the United States Environmental Protection Agency (U.S. EPA) have established protocols for drinking water quality in emergency response efforts. The WHO's *Guidelines for Drinking Water Quality*, 2006 edition, has a chapter devoted to applications of the guidelines in specific circumstances, such as emergency and natural disaster circumstances. The U.S. EPA *1987 Guide Standards and Protocol for Testing Microbiological Water Purifiers* ("U.S. EPA Purifier Guidelines," hereafter) is used as a guide to the acceptance of water treatment units for compliance with Safe Drinking Water Act requirements. It focuses on point-of-use devices that may be needed to temporarily treat contaminated public water supply or for emergency situations (see Section 2.4 for more detail). According to these organizations, the most critical parameters to test (**Table 2.3**) in an emergency/disaster situation are associated with the greatest waterborne risk to health, fecal pathogens, due to inadequate sanitation, hygiene, and protection of water sources (World Health Organization, 2006).

Table 2.3 - Water quality objectives for emergency response (The Sphere Project, 2006; World Health Organization, 2006; U.S. Environmental Protection Agency, 1987).

Parameter	To Demonstrate	Organization
Water Quality Objectives		
Turbidity	< 5 NTU	Sphere Project Handbook (2004), WHO (2006)
Chlorine residual	0.2-0.5 mg/L	Sphere Project Handbook (2004), WHO (2006)
<i>E. coli</i>	<1 CFU/100 mL	WHO (2006)
pH	6 to 8	WHO (2006)
Purifier Device Objectives		
Parasitic cysts	3-log removal (99.9%)	U.S. EPA Purifier Guidelines (1987)
Viruses	4-log removal (99.99%)	U.S. EPA Purifier Guidelines (1987)
Bacteria	6-log removal (99.9999%)	U.S. EPA Purifier Guidelines (1987)

Water treatment processes are needed in emergencies to prevent fecal pathogens from causing waterborne disease and this prevention is measured by meeting the guidelines set by the Sphere Project, the WHO, and the U.S. EPA.

2.3 - Emergency Water Treatment Process Categories

Conventional water treatment processes (**Figure 2.2**) are modified for smaller-scale units, implemented in disaster relief applications by relief organizations, NGOs, and local governments. The following treatment processes are defined below, followed by their roles in emergency drinking water treatment categories. Section 2.5 further describes these categories, but on a point-of-use scale. The general treatment processes phases include:

Clarification - This is a combination of physical and chemical processes that assist particle settling. After the water is screened, it is piped to the rapid mix tank where the addition of chemicals (for destabilization) and a pre-determined mixing energy coagulates the particles in the water that usually cannot settle on their own. After the mixing process, the water is gently agitated in the flocculation basin in which flocs, larger particle formations, are more readily removed through settling (MWH, 2005).

Sedimentation - a physical process in which larger particles, such as flocs, settle by gravity to the bottom of the tank over a given detention time.

Filtration - Filtration, also a physical process, assists in removing particles by granular, cloth, or membrane filtration, to obtain the desired turbidity. This process can stand alone as the clarification step or follow the clarification and sedimentation phases (MWH, 2005).

Disinfection - Disinfection, the final stage prior to storage, is a chemical process in which the water comes in contact with a chemical, such as chorine, for a predetermined time period to inactivate microorganisms from water, and maintain a disinfectant residual for the water distribution or storage phase (MWH, 2005).

Figure 2.2 - General water treatment process train for surface water to remove turbidity using clarification, sedimentation, filtration, disinfection, and storage (adapted from MWH, 2005).

These treatment processes are combined or implemented by relief organizations in water kits and larger prepackaged size units. There are three main water treatment classification categories defined for emergency use: modular treatment units (assembled on location), mobile treatment units (transported on trailers), and, point-of-use treatment units (Dorea, Bertrand, & Clarke, 2006). The first two, modular and mobile units, have been widely used throughout emergency relief efforts. However, point-of-use (POU) systems used at the household level have undergone many field tests for disaster relief applications, especially after the 2004 Indian Ocean tsunami (Clasen & Smith, 2005). The focus of this research is based on POU units, which are detailed in Sections 2.4 and 2.5. Modular and mobile units are briefly described below in Section 2.3.1.

2.3.1 - Modular and Mobile Treatment Units

Many organizations, such as Oxfam GB and Medicines Sans Frontieres (also known as Doctors without Borders) and the International Federation of Red Cross and Red Crescent Societies (IFRC), have developed modular and mobile systems for use in emergencies (Wisner & Adams, 2002). Oxfam GB is credited with developing a number of modular units including upflow clarifiers, vertical-flow roughing filters, and slow sand filtration package plants (Wisner & Adams, 2002). For instance, the upflow clarifier (**Figure 2.3**) has a doser that injects and mixes the coagulant prior to entering the main clarifier tank and polishes the water with a filter media above the floc blanket to remove any remaining alum flocs (Crompton & Clarke, 1997). Studies have shown that effluent turbidities have ranged from 0.82 to 1.54 NTU for these continuous flow systems (Dorea, Bertrand, & Clarke, 2006). The treated water can then be stored in “Oxfam tanks” in varying capacities of 11, 45, 70 and 90 m³ (Dorea, Bertrand, & Clarke, 2006).

Figure 2.3 - Oxfam upflow clarifier modular unit (Evenproducts, 2005).

There are two standard IFRC emergency response units (ERU) that provide both treatment and storage (**Figure 2.4**); one that holds 225,000 L of water per day for a population of 15,000, and a larger one that holds to 600,000 L of water per day for a population up to 40,000. This water is then disinfected and distributed by pipe or truck (International Federation of the Red Cross and Red Crescent Societies, 2005). These units can be transported by road or air and are installed on sight by a team of workers (Wisner & Adams, 2002).

Figure 2.4 - IFRC ERU's installed in Aceh, Indonesia in 2004, to provide treatment in tanks and in large bladder systems (International Federation of the Red Cross and Red Crescent Societies, 2005).

Mobile units on trailers and distributed in shipping containers have a variety of treatment processes available, such as coagulation, filtration, and disinfection, providing 4,000 to 50,000 L per hour. Though effective in treating water, they are costly to have on-hand for emergencies (Wisner & Adams, 2002). Additionally, tanker trucks are often deployed by relief organizations to deliver water to displaced people. Typically the trucks are filled with chlorinated water from an emergency water treatment plant prior to delivery. Unfortunately, the chlorinated water does not always make it to the displaced people. For instance, during the tsunami relief efforts, when the wait-time increased to five hours for trucks to fill at emergency water treatment plant stations, many left the lines early and filled at alternative sources deemed unsafe for drinking. The CDC conducted *E. coli* testing on 40 trucks, and based on the results, concluded that about one in six trucks delivered water contaminated with *E. coli*. The CDC attributed this to filling tankers at unsafe water sources, water from the emergency drinking water treatment plants seemed

inadequately chlorinated, and sediment remaining from previously unsafe water sources consumed residual chlorine from water obtained from the emergency drinking water station (Gupta & Quick, 2005).

POU treatment methods used for every-day household water treatment in developing communities were tested for their adaptability in emergency relief settings. POU treatment methods and storage capacities are much smaller in scale compared to the modular and mobile units. The POU methods are described below.

2.4 - Microbiological Water Purifiers Protocol

POU treatment systems, which include an array of physical and chemical treatment methods, either as a single barrier or multiple barrier systems, are also used in disaster relief efforts. The efficacy of each system is based on its ability to physically remove turbidity and microorganisms or by inactivating microorganisms present in the water, and the ease of use of the systems in developing country settings (Sobsey, 2002). As mentioned in Section 2.2, the U.S. EPA 1987 *Guide Standards and Protocol for Testing Microbiological Water Purifiers* maintains high standards for water purifiers, mainly POU systems, used by governmental agencies and NGOs, consumer groups, and manufacturers in disaster relief, foreign travel, backpacking and camping, and non-standard military situations. The protocol was established to lay a framework for experimental testing and evaluating microbiological water purifiers for U.S. EPA registration. It is focused on devices for temporary use or for emergency situations or to treat contaminated public water supply, but “not for use in extreme overseas situations, or for the conversion of wastewater for potable water use, or intended to significantly

remove chemical contamination” (U.S. Environmental Protection Agency, 1987). In addition to the U.S. EPA Purifier Guidelines, the U.S. Army Center for Health Promotion and Preventive Medicine (USCHPPM) in conjunction with NSF International, created a guide for purifiers in military application, the *NSF Protocol P248: Emergency Military Operations Microbiological Water Purifiers* (hereafter, NSF Protocol P248). The protocol is adapted from the U.S. EPA Purifier Guidelines and the NSF International Protocol P231. It does, however, vary in a number of ways from the U.S. EPA Purifier Guidelines (Cooper, 2009). The research presented here will focus on the U.S. EPA Purifier Guidelines, with some additional notes on microorganism requirements and indicator organisms based on the NSF Protocol P248.

2.4.1 - Performance Requirements

The U.S. EPA identifies a unit, “in order to be called a microbiological water purifier, must remove, kill, or inactivate all types of disease-causing microorganisms from the water, including bacteria, viruses, and protozoan cysts so as to render the processed water safe for drinking. Therefore, to qualify, a microbiological water purifier must treat or remove all types of challenge organisms to most specified standards” (U.S. EPA, 1987). The protocol is performance-based, thus, test conditions simulate realistic worst-case challenges and treated waters must meet minimum reductions for microorganism and physical water quality standards. The framework focuses on three basic types of microbiological water purifiers: ceramic filtration candle units, halogenated resins and units, and ultraviolet units; with filtration process included in all if necessary (U.S. EPA, 1987). The research presented will focus on the second treatment type only, halogenated disinfectants combined with filtration. The U.S. EPA and the NSF have identified

microbiological reduction requirements (**Table 2.4**) and other constituent reduction requirements for the given treatment; additionally, performance limitations are also required to provide an assurance or warning to the consumer that the treatment is beyond its effective lifetime capacity.

Table 2.4 - U.S. EPA and NSF guidelines for minimum microbiological reduction requirements (U.S. EPA, 1987; USACHPPM, 2008).

Challenge Organism ¹	Initial Concentration ²	Minimum Required Reduction	
		Log	%
Bacteria:			
<i>Klebsiella terrigena</i> (EPA, NSF)	10 ⁷ /100 mL	6	99.9999
<i>Escherichia coli</i> (NSF)			
<i>Bacillus atrophaeus</i> (spore form)			
Virus³:			
Poliovirus 1 and Rotavirus (EPA)	1 x 10 ⁷ /L	4	99.99
or,			
MS2 and fr coliphage (NSF)	1 x 10 ⁷ /L		
Cyst (Protozoan):			
a. <i>Giardia muris</i> or <i>Giardia lamblia</i> (EPA)	10 ⁶ /L	3	99.9
or,			
<i>Cryptosporidium parvum</i> oocysts (EPA, NSF)	5 x 10 ⁴ /L		

Challenge Organism ¹	Initial Concentration ²	Minimum Required Reduction	
		Log	%
b. As an option for units or components based on occlusion filtration: particles or spheres ⁴ , 4-6 microns	10 ⁷ /L	3	99.9

¹See Section 2.4.2 for reasons for selection of challenge organisms

²The influent challenge may constitute greater concentrations, but meeting at least the above concentrations is necessary to determine log reductions.

³Virus types are to be mixed in roughly equal 1 x 10⁷/L concentrations and a joint 4-log reduction will be acceptable (e.g., equally mix Poliovirus 1 and Rotavirus, or MS2 and fr coliphage).

Three identical microbiological purifier devices are to be tested simultaneously in order to show required removal. Each influent and effluent sample taken needs to be collected and analyzed in triplicate. The geometric mean calculated based on the triplicate samples can then be used to solve for the log reduction of each microbiological purifier device. In order for the device to meet the standards, each unit must continuously meet or exceed the log reduction requirements as described in **Table 2.4**; however, up to 10% of influent and effluent sample triplicates may vary from the reductions required by the following: 1 log for bacteria, 1 log for viruses, and ½ log for cyst removal (U.S. EPA, 1987; USACHPPM, 2008).

2.4.2 - Test Water Properties

In addition to the microbiological influent challenges, the U.S. EPA has established model test waters to represent non-stressed and stressed conditions, or non-challenge and challenged conditions. There are five total test waters, but the ones identified for this

research are Test Water #1 (General Test Water) and Test Water #2 (Challenge Test Water/Halogen Disinfection) (**Table 2.5**).

Table 2.5 - U.S. EPA challenge water test properties for Test Water #1 and Test Water #2 (U.S. Environmental Protection Agency, 1987).

Water	Required Properties	Recommendation
Test Water #1	Free of chlorine or other disinfectant residual pH range: 6.5-8.5 TOC: 0.1-5.0 mg/L Turbidity: 0.1-5 NTU Temperature: 20°C ± 5 °C TDS: 50-500 mg/L	Deionized water HCl or NaOH Humic Acid Test dust (0.3 µm) ¹ Sea salts
Test Water #2	Free of chlorine or other disinfectant residual pH 9.0 ± 0.2 TOC: no less than 10 mg/L Turbidity: no less than 30 NTU Temperature: 4°C ± 0.1 °C TDS: 1,500 mg/L ± 150 mg/L	Deionized water HCl or NaOH Humic Acid Test dust (0.3 µm) Deionized ice Sea salts

¹Recommendation for test dust is A2 Fine Test Dust ISO 12103-1

Each parameter, for Test Water #2, is altered to challenge the treatment method to the extreme. For instance, an increase in pH requires a longer chlorine contact time; thus, U.S. EPA recommends a challenge level of 9.0 ± 0.2, because it exceeds the recommended secondary level, but some source waters are still found at this pH level (U.S. EPA, 1987). NOM, which is measured as a TOC concentration, also interferes with halogen disinfection as it reacts with the disinfectant, requiring a higher dose to maintain the required chlorine residual, and can form disinfection byproducts. NOM can also impart a yellowish color to water and can interfere with other treatment methods such as coagulation and filtration by either consuming the chemical dose in the treatment or clogging the filters (MWH, 2005). Turbidity, as mentioned in section 2.1.2, at high levels

reduces the effectiveness of chlorination as many pathogens may be “shielded” by the particles protecting the pathogens from disinfection (Davis & Lambert, 2007; USAID, 2005; Sawyer, McCarty, & Parkin, 2003; MWH, 2005). The U.S. EPA recommends turbidity levels greater than 30 NTU, since this level has been observed in secondary wastewater effluent and in many surface water sources, especially after flood events. The U.S. EPA also cites that at lower temperatures, such as 4°C, halogen disinfection rates are slowed. Also, elevated levels of TDS have interfered with disinfection effectiveness as it may interfere with adsorptive processes. Lastly, the high concentrations of bacteria, viruses, and cysts represent concentrations of highly polluted stream waters. The microbial safety of water depends on the removal of these microorganisms, whether they may challenge the halogen disinfection (as with bacteria and viruses), or challenge the filtration process (as with *Cryptosporidium* oocyst) (U.S. EPA, 1987).

2.5 - Current POU Emergency Water Treatment Methods

“In recent years, the treatment of water at the household level has been shown to be more effective in preventing endemic diarrhea than traditional methods of improving or protecting the microbial quality of water at the source or to the point of distribution” (Clasen & Smith, 2005). This statement is supported by a study performed in 2005 by the World Bank and Fewtrell et al. who found in 15 household treatment interventions analyzed a 35% reduction in diarrheal disease, in comparison to only an 11% reduction of diarrheal disease from conventional source-based interventions. Furthermore, a Cochrane review of 38 randomized and controlled trials of household treatment interventions, showed a 47% reduction in diarrheal disease, compared to a 27% reduction from

improved sources (UNICEF, 2008). The successes of household water treatment systems (HWTS), also known as POU systems, as daily use systems for developing communities, has drawn attention to the systems adaptability in post-disaster situations. Field testing and documentation of the POU systems ramped up after the severe destruction caused by the Indian Ocean Tsunami at the end of 2004. There are many POU systems available; however, the ones that have rigorously been tested have the potential for widespread implementation, and “have shown to be effective in preventing waterborne disease in emergencies, including floods and other natural disasters, humanitarian disasters, and epidemics” (Clasen & Smith, 2005). The POU systems include: boiling and pasteurization, solar disinfection, chlorine disinfection, filtration, combined flocculation/disinfection, and improved household water storage vessels (WHO, 2009; Clasen & Smith, 2005; Sobsey, 2002). Besides boiling, each approach is comprised of different technologies and treatment options (**Figure 2.5**) developed and/or implemented by private industry and NGOs. The options are described in Sections 2.5.1 through 2.5.6, with the majority of focus on the flocculation/disinfection treatment, PÜR[®], described separately in Section 2.6.

Figure 2.5 - POU system treatment options for developing countries in daily use and in disaster relief settings.

2.5.1 - Boiling

Boiling is the most common method for treating water at the household level since it effectively kills bacteria, viruses, and protozoan parasites even in turbid waters. However, following a disaster, boiling may be impractical due to limited fuel and facilities available (WHO, 2006). It is estimated that one kilogram of wood is needed to boil one liter of water (Sobsey, 2002). Additionally, once the water is boiled, it becomes cooled and is vulnerable to recontamination from hands or storage in an open container, as there is no residual disinfectant present (Clasen, 2007). Following the Indian Ocean Tsunami, many displaced people were observed boiling their water for treatment. Jeff Albert, principal of Aquaya Institute and field responder during the 2004 tsunami, states that “many Indonesians boil their water as that is what generation after generation has

done, and it is promoted by the government as a safe drinking water solution” (Albert, 2009). Albert and his colleagues did find some evidence of contaminated water despite widespread reports of boiling (Clasen & Smith, 2005). In a sampling of 400 households, where boiling was encouraged, it was found that 47.5% of the samples tested positive for *E. coli* (Clasen, 2007). Boiling was still encouraged by NGOs as it was a familiar practice for the displaced people, and did not require educational programs for promotion (Clasen & Smith, 2005). In 2006, a cost analysis study was conducted in semi-urban Indian communities, estimating that the annual cost of boiling for households using liquid petroleum gas was US\$10.56, and households using wood as fuel source spent US\$8.28 (Clasen, et al., 2008).

2.5.2 - Solar Disinfection

Solar disinfection is a treatment method in which pathogens in water are inactivated by the ultraviolet rays from the sun. A common method used is the SODIS system developed by the Swiss Federal Institute for Aquatic Science and Technology (EAWAG) and EAWAG’s Department of Water and Sanitation in Developing Countries (SANDEC). The SODIS method is used to treat contaminated water in transparent plastic bottles exposed to sunlight for approximately 6 hours. The disinfection process occurs from sunlight radiation at wavelengths of 320-400 nm (the UV-A level) and by the increased water temperature (**Figure 2.6**) (EAWAG, 2009). To be effective, the method requires relatively clear water with turbidity <30 NTU, as suspended particles in water can reduce penetration from sunlight (EAWAG, 2009). The optimal treatment steps include: (1) filter or settle out solids from waters >30 NTU, (2) fill 1-2 liter plastic bottles

with water, (3) aerate the water by vigorously shaking, and (4) expose water to 6 hours of sunlight (Sobsey, 2002).

Figure 2.6 - The SODIS method using sunlight and thermal energy to inactivate pathogens within a 6-hour period (Eawag, 2009).

In a 1997 study conducted by Sommer et al., the most effective SODIS method was storing water in transparent plastic bags, resulting in a 3-log reduction (99.9%) of fecal coliform bacteria and *Vibrio cholerae* after a 140-min exposure time with water temperatures in excess of 50°C (Sommer, et al., 1997). Another study in 2005 focused on the survival of *Cryptosporidium parvum* oocysts in the SODIS batch-process. The study concluded that the infectivity of the parasite (inoculated at $17.6 \pm 6.7 \times 10^5$ oocysts) at 6 hours was reduced to $7.5\% \pm 2.5\%$ ($0.6 \pm 0.0 \times 10^5$ oocysts), and at the end of 12 hours was rendered completely noninfectious (Mendez-Hermida, Castro-Hermida, Ares, Kehoe, & McGuigan, 2005). The SODIS method, at a very minimal cost, has been used in over 20 developing countries by one million users (Lantagne, Quick, & Mintz, 2006). In disaster relief, bottles shipped with drinking water can be reused for the SODIS

treatment method. The WHO promoted this method, along with many others, during the Indian Ocean Tsunami in 2004 in its training courses to local NGOs (WHO, 2005).

2.5.3 - Chlorine Disinfection

Besides boiling, chlorinating water is one of the most widely-used practices for communities because of its ease of use, low cost, and its provision for a barrier to recontamination (WHO, 2005). When chlorine is added to water for treatment, it progresses through different reaction stages in which chlorine reacts with compounds in the water prior to disinfection (chlorine demand) and the remaining concentration is available for disinfection, known as free chlorine, or chlorine residual (Centers for Disease Control and Prevention, 2005). The chlorine reaction flow chart, adapted from the CDC, is shown in **Figure 2.7**. Chlorine sources include sodium hypochlorite (e.g., household bleach), chlorinated lime, or high test hypochlorite (e.g., chlorine tablets) and usually are added to water with a chlorine contact time of at least 30 minutes to kill pathogens (UNICEF, 2008; WHO, 2005).

Figure 2.7 - Chlorine reaction flow chart for drinking water (Centers for Disease Control and Prevention, 2005).

Free chlorine, also known as chlorine residual, is stable in water and can be maintained in the water for days if no organic materials demand the chlorine (Sobsey, 2002). Guidelines have been established for specific free chlorine concentrations to maintain effective disinfection. The goal differs between piped and household systems. For instance, the WHO established a guideline in 1993 for water consumed directly from a tap. It is defined as, “a residual concentration of free chlorine of greater than or equal to 0.5 mg/L after at least 30 minutes contact time at pH <8.0.” (Centers for Disease Control

and Prevention, 2005). Since household water treatment systems typically do not provide water directly from a distribution system, the CDC's Safe Water System program established guidelines for free chlorine when the water is stored in the home after a 30-minute contact time and after a 24-hour storage time (**Table 2.6**). Typically, water in developing countries is stored between 4 and 24 hours at the household level (Centers for Disease Control and Prevention, 2005).

Table 2.6 - CDC Safe Water System program recommended free chlorine concentrations after the addition of sodium hypochlorite (Centers for Disease Control and Prevention, 2005).

Contact Time	Free Chlorine Residual Concentration	Reasoning
At 30 minutes	≤ 2.0 mg/L	To minimize unpleasant taste and odor
At 24 hours	Minimum of 0.2 mg/L	To ensure microbiologically clean water

Chlorine is effective against most pathogens that cause diarrheal diseases in humans; however, some microorganisms are more resistant to inactivation. Ct factors can be used to characterize the effectiveness of chlorine against different pathogens. It is calculated by multiplying the concentration of chlorine residual (C) by the time the pathogen was exposed to the disinfectant (t). The higher the Ct factor, the more resistant the pathogen is to the chlorine concentration (Kasper, 2007). The CDC Safe Water System program's Kasper et al. compiled data from peer-reviewed research to determine Ct factors for the disease-causing bacteria, viruses, and protozoa. In addition to pathogens themselves,

temperature, pH, and the physical quality of the water influence the disinfectant's capacity to inactivate pathogens (Kasper, 2007; Sobsey, 2002). Generally, disinfection is more effective at higher temperatures and lower pH. Also, particulate and dissolved constituents in the water can increase the chlorine demand by consuming the chlorine disinfectant present in the water (Sobsey, 2002). Considering the above stated influences, chlorine is more effective against bacteria and viruses, while it is not effective against some protozoa, such as *Cryptosporidium parvum* (Table 2.7).

Table 2.7 - CDC Safe Water System summary on the effect of chlorine inactivation of selected pathogens including bacteria, viruses, and protozoa (Kasper, 2007).

Pathogen	C (mg/L)	t (min)	Ct factor	Variables Affecting Ct Factor		Source
				Temp (°C)	pH	
Bacteria						
<i>E. coli</i>	0.5	< 0.5	< 0.25	23.0	7.0	Zhoa, 2001
<i>Salmonella typhi</i>	0.05	20	1	20-25	7.0	Butterfield, 1943
<i>Vibro cholerae</i>	0.5	< 1	< 0.5	20.0	7.0	Morris, 1993
Viruses						
<i>Hepatitis A</i>	0.41	< 1	< 0.41	25.0	8.0	Grabow, 1983
<i>Poliovirus</i>	0.5	13	6.36	5.0	6.0	Thurston- Enriquez, 2003
<i>Rotavirus</i>	0.20	0.25	0.05	4.0	7.0	Vaughn, 1986

Pathogen	C (mg/L)	t (min)	Ct factor	Variables Affecting Ct Factor		Source
Protozoa						
<i>Giardia lamblia</i>	1.5	10	15	25.0	7.0	Jarroll, 1981
<i>Cryptosporidium parvum</i>	80	90	7,200	25.0	7.0	Korich, 1990

A common chlorine disinfection method used both for social marketing (a type of marketing with an aim for the social good) in developing countries and in emergency relief situations is the CDC Safe Water System (SWS) program. The program is based on POU water treatment with locally manufactured dilute sodium hypochlorite, safe storage for the treated water, and behavior change communications and sanitation practices. The SWS program exists in 25 countries and is shown to reduce diarrheal disease by 25-84% (Centers for Disease Control and Prevention, 2008). The social marketing of SWS was initiated through a partnership between the NGO, Population Services International (PSI), and the CDC in 1998, in which over 12 million sodium hypochlorite bottles, branded as “Clorin” in some countries and “Water Guard” in others (**Figure 2.8**), were sold per year. Costs can vary per country and by volume. The full cost of a single 250-mL Clorin bottle, for example, is US\$0.34, which includes production, marketing, distribution and overhead. The product is subsidized by USAID, so the retail price is US\$0.12 (Lantagne, Quick, & Mintz, 2006). A single bottle can treat approximately 1,000 L of water. In order to effectively use the product, a single cap-full of the solution is added to water in a container; it is then agitated, and allowed to sit for 30 minutes before drinking. The

dosage is set to meet the free chlorine concentration recommendations in **Table 2.6**, when water turbidities are <100 NTU (Lantagne D. S., 2008).

Figure 2.8 - PSI's SWS chlorination product in Nigeria, Water Guard (Centers for Disease Control and Prevention, USAID, 2008).

While the SWS program is principally focused on everyday use, it has also been used in emergency situations such as disease outbreaks (e.g., cholera), natural disasters, and complex emergencies (Lantagne D. S., 2008). The SWS emergency use program was developed in response to the Indian Ocean Tsunami in 2004. It is estimated that over 140,000 bottles of dilute sodium hypochlorite solution were shipped to the tsunami-hit region in Indonesia. Relief workers observed that the tsunami survivors were “willing to chlorinate their water during the initial phases of the disaster, perhaps accepting the unfamiliar taste when faced with dead bodies and other perceived sources of contamination; over time, some discontinued use of chlorine.” Testing of the product in

Indonesia, conducted by Widyastuti in 2005, indicated that the chlorine disinfectant resulted in an 81% lower risk of *E. coli* from contaminated stored water (Clasen & Smith, 2005). The sodium hypochlorite solution proved successful after Cyclone Nargis hit Myanmar in 2008. An NGO outfitted with the disinfectant was able to respond rapidly, and by July 2008, over 2,700 20-L jerry cans of sodium hypochlorite and 80,715 500-mL bottles were distributed during the emergency response; enough to treat 190 million liters of water (Lantagne D. S., 2008).

In addition to liquid sodium hypochlorite, tablets formed from the active ingredient dichloroisocyanurate (NaDCC), are also used in emergency water treatment (Global Hydration, 2009). The brand name of the tablets is Aquatabs[®], manufactured by Medentech[®] of Ireland. The tablets were tested on the household level by Clasen et al., in Dhaka, Bangladesh, where 50 households (intervention group) were given the NaDCC tablets, and the other 50 households (control group) received a placebo. Over the 4-month trial, the intervention group's water quality tests resulted in 2.80 MPN/100 mL of thermotolerant coliform bacteria, while the control group's count resulted in $>6.0 \times 10^3$ MPN of thermotolerant coliform bacteria. The use of NaDCC tablets for water treatment demonstrated an improved water quality for the intervention group; however, a concern arose from the high levels of chlorine residual in the water, greater than the WHO guideline of 5.0 mg/L (Clasen, Saeed, Biosson, Edmondson, & Shipin, 2007).

While chlorine is a common disinfectant, the health effects of disinfection by-products (DBP) raise questions regarding the use of chlorine. When chlorine is added to water, such as sodium hypochlorite, it reacts with water to form hypochlorous acid. This acid is

a strong oxidizing agent and reacts with natural organic matter to form DBPs (Centers for Disease Control and Prevention, 2005). There are four primary trihalomethanes (THM) that are categorized as DBPs, which include chloroform (CHCl_3), bromodichloromethane (CHCl_2Br), dibromochloromethane (CHClBr_2), and bromoform (CHBr_3). Each of the four THMs has a carbon atom at the center, surrounded by four atoms, including one hydrogen and three halogens. The WHO has established guidelines for each of the THMs and the U.S. EPA established a maximum contaminant level for total THMs (**Table 2.8**) (Lantagne, Blount, Cardinali, & Quick, 2008).

Table 2.8 - THMs WHO guidelines and U.S. EPA maximum contaminant level (Lantagne, Blount, Cardinali, & Quick, 2008).

THM	WHO ¹	U.S. EPA
	Guideline	MCL for total THMs
Chloroform	300 µg/L	80 µg/L
Bromodichloromethane	60 µg/L	
Dibromochloromethane	100 µg/L	
Bromoform	100 µg/L	

¹WHO also established an additive toxicity guideline value using fractions of each of the four THM concentrations observed. The resulting guideline value should be no greater than one.

CDC's Lantagne et al. conducted a DBP formation study of POU chlorination of turbid and non-turbid waters in western Kenya. The team analyzed water from lakes, rivers, ponds, wells, and rainwater catchment systems, using chlorine based treatment methods such as the SWS sodium hypochlorite bleach and PÜR[®] sachets. Water turbidities ranged from 4.23 NTU to 305 NTU and after the addition of sodium hypochlorite, THM was analyzed after 1, 8, and 24 hours. The resulting THM concentrations were well below the

WHO guideline values. From this, the team concluded that POU chlorination treatment does not pose a significant health risk in regards to THM concentrations (Lantagne, Blount, Cardinali, & Quick, 2008). The PÜR[®] sachet treatment results are discussed in Section 2.6.2.

2.5.4 - Filtration

Filtration is a physical process that takes place prior to disinfection in standard water treatment facilities. However, for POU treatment, it often stands alone as a treatment process without introducing any chemicals to the water. The two main POU filtration methods are biosand filtration and ceramic filtration, with a third being cloth filtration. The effectiveness of these methods depends on the type of microorganisms being removed, the turbidity, and the type of filtration media.

A biosand filter is a slow sand filter adapted for household use. Similar to a slow sand filter, it consists of a supernatant that maintains the *schmutzdecke*, (bioactive layer on top of the sand media) which performs the majority of treatment, removing suspended solids and microbes (Lantagne, Quick, & Mintz, 2006). However, unlike a slow sand filter, the biosand filter is not a continuous flow system; it is set up for intermittent use. The user pours a bucket of water in the biosand filter bucket, allows it to filter through the sand and collects the treated water. The Center for Alternative Water and Sanitation Technologies (CAWST) has been a major player in testing the biosand filters in the laboratory and in the field. They have been working in Haiti since 2005, analyzing 107 long-term biosand filters and finding an average removal effectiveness of 98.5% for *E. coli* (CAWST, 2006). However, some drawbacks of the filters include a low rate of virus

removal and no chlorine residual protection of stored water (Woodrow Wilson International Center for Scholars, 2006). The NGO Samaritan's Purse has implemented many biosand filters, particularly in Cambodia. They also introduced them in Indonesia following the Indian Ocean Tsunami. It was reported that they were used more for the resettlement phase rather than the earlier phase of the emergency response due to transport challenges (Clasen & Smith, 2005). The hardware cost of the biosand filters range from US\$12-\$40 with unlimited use as long as proper operation and maintenance is conducted (Clasen, 2007).

Ceramic filters with small pores, sometimes enhanced with colloidal silver, are also a proven household technology. The NGO Potter's for Peace has developed a two-part system in which a ceramic pot rests in a plastic container. The water is added to the pot, passes through the pores in which contaminants are trapped, and the treated water is then stored in the plastic container (CAWST, 2006). The Potter's for Peace ceramic filter is coated with silver in order to help kill the pathogens. Studies have shown that the silver "disables the enzyme that pathogenic bacteria and fungi use for oxygen metabolism, thus suffocating them; destroys pathogens with an electric charge; renders pathogens unable to reproduce; and, kills parasites while in their egg stage" (CAWST, 2006). Field testing in Cambodia, Ghana, and Nicaragua resulted in undetectable total coliform levels in 93% of the 144 filtered water samples (Clasen, 2007). Education on filter use is important. For instance, UNICEF distributed 20,000 ceramic filters in Aceh after the Indian Ocean Tsunami, and they found that when the filters were distributed urgently after the disaster without training, most were seldom used. It was not until after the proper training did UNICEF see wider use and support of the system, particularly in the resettlement phase

(Clasen & Smith, 2005). UNICEF has continued to distribute filters post-disaster, to communities in Ghana after the 2007 floods and in Myanmar after 2008 Cyclone Nargis hit (Relief Web, 2007; Relief Web, 2009). Drawbacks of the ceramic filters include no chlorine residual protection for the stored water and low flow rates of 1-2 liters per hour (Woodrow Wilson International Center for Scholars, 2006).

The third filter method involves different compositions of natural fibers and polymer filter material that are used for POU water treatment. A very common practice is to decant water through a sari cloth (typically 100% cotton) placed over a container. For instance, a cholera study was performed in a Bangladeshi village in 2002 by the University of Maryland investigating the use of sari cloth and nylon in treating water. Frequent flood events in Bangladesh make boiling water not possible, and most villages drink untreated water for household use, especially after flooding. It was determined that folding a sari cloth four to eight times provided a pore size of approximately 20 μm . The University of Maryland determined that folding a sari cloth at least four times provided a 99% (2-log) removal of *Vibrio cholera*. However, as the sari cloth was used, it became loose, increasing the pore size. Additionally, nylon net with a mesh size of 150 μm was shown to remove the copepod Cyclops, which is a carrier of guinea worm (Colwell, 2003). In a previous Bangladeshi study, also performed by the University of Maryland, they found that folding a sari cloth more than four times increased the probability of clogging and decreased the filter efficiency (Huq, Chowdhury, Islam, Montilla, & Colwell, 1996). Sari clothes do, however, remain a very simple and inexpensive filtration method for POU treatment especially for households that otherwise do not have any method of treatment.

Most fabric cloths have pore sizes that will not prevent the passage of bacteria, viruses, and protozoa; but fiber cloth filters have pore sizes small enough (Sobsey, 2002). These filters require special fabrication methods and filter holders and may not be economical for in-country production. The WHO recommends water treatment devices for the removal of protozoa, such as *Giardia lamblia* and *Cryptosporidium parvum*, “that it has a filter media pore size of 1-micron or less” (WHO, 2005). There are many different filter styles and materials used, such as woven and nonwoven filter products. For instance, nonwoven needlefelt products are made of fibers such as polyester, polyamide, and polypropylene (Hutten, 2007).

2.5.5 - Combined Flocculation/Disinfection

Two POU treatment systems that combine flocculation and disinfection are Chlor-Floc[®] Water Purification Tablets and PÜR[®] sachets. Chlor-Floc[®] tablets were created as a replacement for iodine tablets, which often present treatment deficiencies such as slow kill of *Giardia lamblia* cysts and unpleasant taste and odor (Powers, Hernandez, Boutros, & Harper, 1994). Chlor-Floc[®] is manufactured by the Control Chemical Company in South Africa and distributed by Deatrick & Associates in the United States (Deatrick & Associates, undated). The primary flocculating agent is aluminum sulfate, and the active ingredient is NaDCC for disinfection (Powers, Hernandez, Boutros, & Harper, 1994). A Chlor-Floc[®] system includes 30 tablets, one plastic bag, and three filter pouches. Temperature dictates the number of tablets needed for proper treatment and settling times. In general, the directions for use are: (1) Fill bag with one liter of untreated water, (2) add one tablet, (3) close and shake the bag to dissolve the tablet, (4) swirl bag for 10 seconds, (5) let the bag sit for four minutes, (6) swirl the bag again for 10 seconds, (7)

followed by another sit period of 15 minutes, (8) pour the water through the filter pouches into a separate container like a canteen. This treatment method was tested using the U.S. EPA Purifier Guidelines and met the required minimum log-removal for bacteria, viruses, and *Giardia* cysts, at 6-, 4-, and 3-log removal, respectively. However, it did not meet the minimum removal requirement for *Cryptosporidium* oocysts at 3-log removal (Deatrick & Associates). Overall, a package of Chlor-Floc[®] (30 tablets) can treat approximately 15-30 liters, has a shelf-life of 3 years, and costs \$12.79 per package, according to the manufacturer, Deatrick & Associates. The PÜR[®] sachets are detailed in Section 2.6, as this treatment is the primary focus of the research presented hereafter.

2.5.6 - Safe Storage

During an emergency, water containers for transporting and storing water are as much a necessity as treatment. The design of storage and transport vessels is an important factor in reducing fecal coliform bacteria contamination. Containers used for water storage in developing countries include clay, plastic and metal buckets, jerry cans, collapsible containers, beverage bottles, and barrels (UNICEF, 2008). Though these are common, they do not always provide safe storage from fecal recontamination. The CDC and other organizations, such as UNICEF, have established design criteria for safe water storage vessels, such as durability and narrowness of openings (**Table 2.9**).

Table 2.9 - Criteria for safe water storage containers based on minimizing contamination and user acceptance, developed by the CDC and UNICEF (UNICEF, 2008; Mintz, Reiff & Tauxe, 1995).

X - somewhat important	Importance for water storage containers	Importance for water transport containers
XX - important		
XXX - very important		
Criteria for minimizing contamination		
Constructed of translucent, easily cleaned material (plastics, most metals, ceramics, polished concrete)	XXX	XXX
Tap to draw water or narrow spout (must not leak)	XXX	
Have a single opening, 8 cm ¹ in diameter, with a strong, tight fitting, to discourage the hands and ladles from contaminating storage vessel	XXX	XXX
Stable with a flat bottom	XXX	XXX
Criteria for usability / user acceptance		
Durable	XXX	XXX
Impact resistant (some plastics may not be)	X	XXX
Portable, hold less than 25-liter capacity, suitable for carrying water	X	XXX
Inexpensive	XXX	XXX
Available in local markets	XXX	XXX

¹Sometimes 8-cm diameters may be too small when containers are used to capture water from streams or other water sources

Improved storage methods proved a reliable option for safe storage after a 4-month trial in a Malawi refugee camp was conducted by Roberts et al. in 2001. The source water from wells had little to no contamination; however, it became contaminated from contact with villager's hands. An improved bucket system introduced into the refugee camp

improved the situation by reducing the mean fecal contamination by 69% (Nath, Bloomfield, & Jones, 2006). In many cases, safe storage containers are combined with treatment options for POU treatment, such as the SWS program and with PÜR[®] sachets. Commonly, jerry cans are provided by NGOs and relief organizations in disaster relief situations. For instance, the USAID Office of Foreign Disaster Assistance recorded in 2006 that they provided 5,000 to 10,000 containers per flood (USAID OFDA, 2006). Other containers available include the standard 14-L “Oxfam bucket” which costs approximate US\$4.00; the CDC has a 20-L SWS program container for approximately US\$5.00, excluding transport (**Figure 2.9**) (Centers for Disease Control and Prevention, USAID, 2009); and the IFRC Societies supplies 5 to 20 L containers post-disasters, as they did in Myanmar 2008 (**Figure 2.10**) (International Federation of Red Cross and Red Crescent Societies, 2008).

Figure 2.9 - Standard "Oxfam Bucket" (Left) and CDC SWS Program storage container (Right) provided for daily POU storage and in disaster relief efforts (Centers for Disease Control and Prevention, USAID, 2009).

Figure 2.10 - Jerry cans provided by IFRC Societies during the 2008 Cyclone Nargis relief efforts in Myanmar (International Federation of Red Cross and Red Crescent Societies, 2008).

2.6 - PŪR[®] Purifier of Water

In 1995, Proctor & Gamble (P&G) began working with the CDC on marketing bleach as a POU method. According to Dr. Greg Allgood, Director of Children's Safe Drinking Water at P&G and Senior Fellow in Sustainability, they were confronted with a dual challenge in providing bleach for the consumer who needs: (1) a visual indicator that the treatment is working, and, (2) a treatment that does more than just disinfect (Allgood, 2009). PŪR[®] Purifier of Water treatment technology, which combines coagulation, flocculation, and disinfection in one system, was developed through collaboration between P&G Health Sciences Institute and the CDC (World Business Council for Sustainable Development, 2006). The product is manufactured in P&G facilities in the Philippines and Pakistan and is sold in the North America region exclusively by Canadian plastics manufacturer, Reliance Products L.P.

2.6.1 - How it Works

PŪR[®] treatment sachets have many of the same ingredients as used in municipal water treatment plants but combined into a single sachet. According to Dr. Allgood, PŪR[®] treatment system works in three ways: (1) provides chlorine to disinfect the water and for a residual, (2) kills bacteria and viruses, and, (3) removes protozoan parasites, such as *Giardia lamblia* and *Cryptosporidium parvum* that are resistant to chlorine. The latter is accomplished, not by killing the parasites, but by removal through settling (Allgood, 2009). PŪR[®] has also been found to reduce concentrations of pesticides like DDT, undissolved heavy metals, and arsenic. However, the PŪR[®] treatment has not been shown to remove salinity, nitrate and fluoride, low molecular-weight organics like vinyl chloride, and dissolved heavy metals (The Aquaya Institute, 2006).

The process works by adding a single, 4 gram PŪR[®] sachet (**Figure 2.11**) to 10 liters of water contained in a bucket and then stirring the water for five minutes to mix in the coagulant and disinfectant, allowing the water to sit for five minutes until clear, and then decanting the water through a cotton cloth to capture flocs and filtering the water. Lastly, the water is left standing for 20 minutes to complete the total 30 minute disinfectant process. The water is ready for consumption or to be stored in a safe storage container (**Figure 2.12**) (P&G's Children's Safe Drinking Water Program, 2005). Supplies needed to conduct the treatment process include scissors or a knife to open the sachet, a spoon or rod for stirring, cloth fabric for the filter decanting process, and two containers that hold at least 10 liters (The Aquaya Institute, 2006).

Figure 2.11 - PÜR[®] sachet used to treat 10 liters of water (P&G, 2003).

Figure 2.12 - PÜR[®] treatment instructions printed on the back of PÜR[®] sachets (The Aquaya Institute, 2006).

2.6.2 - Chemical Ingredients and Details of the Treatment Process

The PÜR[®] sachet contains a powdered combination of a chlorine disinfectant (calcium hypochlorite), an iron salt coagulant (ferric sulfate), and additional coagulant and

flocculating agents to assist in the treatment process (The Aquaya Institute, 2006). The chemical concentration of the patented technology is proprietary information; however, the individual ingredients are discussed in the US Patent No. 7,201,856 B2 and in various journal articles (**Table 2.10**).

Table 2.10 - PÜR[®] sachet ingredients including a chlorine disinfectant, iron salt coagulant, and coagulant and flocculating aids (Souter, Cruickshank, & Stoddart, 2007; Reller, et al., 2003).

Ingredient	Molecular Formula	Purpose
Ferric sulfate	$\text{Fe}_2(\text{SO}_4)_3$	Coagulant
Calcium hypochlorite	$\text{Ca}(\text{ClO})_2$	Chlorine-based disinfectant
Sodium carbonate	Na_2CO_3	Alkaline agent
Potassium permanganate	KMnO_4	Oxidant, act as disinfectant
Bentonite		Swelling clay, excellent colloidal properties, Flocculant & flocculation aid
Polyacrylamide	polymer ($-\text{CH}_2\text{CHCONH}_2-$)	Flocculant & flocculation aid
Chitosan		Flocculant & flocculation aid

In order to understand the purpose of each ingredient, it is necessary to understand how the clarification and sedimentation treatment processes work and the role each ingredient has in these processes. The processes include coagulation, flocculation, and sedimentation. First, the water is screened, and then, it enters into rapid mix tank where chemicals are mixed in the water at a pre-determined mixing energy input to coagulate the particles which need assistance in settling. After the mixing process, the water is

gently agitated in a flocculation basin in which flocs, larger particle formations, are more readily removed by settling (MWH, 2005). Different coagulants and flocculants can be used in this process depending on dosage, cost, and pilot studies (e.g., metal salts such as ferric chloride, ferric sulfate, ferrous chloride, ferrous sulfate, etc.). Flocculant aids and polymers are sometimes added to enhance the flocculation process.

As with the PÜR[®] treatment process, ferric sulfate is the coagulant used, and assisted by bentonite clay, polyacrylamide, and chitosan as flocculation aids. The purpose of coagulation and flocculation is to remove particulates (e.g., pathogens), NOM, total organic carbon, and color (MWH, 2005). Coagulation is defined as “allowing particles to easily contact each other due to charge neutralization, also known as destabilization”, while flocculation “uses gentle stirring to promote formation of large visible flocs” (Lundquist, 2008). The key to effective coagulation and flocculation is understanding how colloids interact and the electrokinetic charge they carry. Each colloidal particle carries a like charge, usually a negative charge, and therefore repel one another, preventing floc formation. However, uncharged particles, which are charge neutral, collide with one another forming flocs (**Figure 2.13**), which are more readily able to settle (Zeta Meter, Inc., 1993).

Figure 2.13 - Uncharged particles colliding and forming flocs (Zeta Meter, Inc., 1993).

Looking deeper into the ionic nature of a colloid allows for an understanding of what is going on around the negative colloid and how the charge is then neutralized. The double layer model provides a visualization of a highly negative charged colloid, surrounded by a layer of positive counter-ions called a Stern Layer. Positive ions are still attracted to the individual negative charge colloid, but are repelled by the positive Stern Layer. This results in a Diffuse Layer, which forms an equilibrium of ions towards the outer boundary (**Figure 2.14**) (Zeta Meter, Inc., 1993). The thickness of the double layer depends on the number of ions in solution. For instance, the more positive ions present a greater potential to neutralize the colloid, which is demonstrated by a thinner Stern Layer. There is also theory known as the DLVO Theory that explains particle interactions based on the makeup of the double layer. Colloids will repulse each other as long as they remain negatively charged; however, when the double layer is compressed by the concentration of ions, flocculation will take place as the colloids attract one another (Zeta Meter, Inc., 1993).

Figure 2.14 - The Double Layer model for a single colloid (Zeta Meter, Inc., 1993).

Flocs begin to form as the destabilized particles collide with one another. As is the case with the PŪR[®] treatment system, colloid entrapment occurs by the addition of excessive amounts of coagulant dose which precipitate as hydrous metal oxides. The process is called sweep floc (**Figure 2.15**) because the colloids clump together, or are “swept from the bulk of the water”, and combine with the hydrous oxide floc (Zeta Meter, Inc., 1993).

Figure 2.15 - Colloids embedded in precipitate forming sweep flocs (Zeta Meter, Inc., 1993).

The flocculation aids within PŪR[®] sachets enhance the flocculation process. Bentonite clay is a swelling clay that can act as an adsorbent of metal ions. Bentonite contains SiO₂ and oxides of Mg, Ca, K, and Na (Srimurali, Pragathi, & Karthikeyan, 1997). It also increases the particulate content in the water, which aids in the formation of flocs if the water initially does not have many particulates. Polyacrylamide, and chitosan (naturally occurring polymer) are also flocculation aids.

The decomposition of polyacrylamide results in a residual acrylamide which brings up much concern as acrylamide is considered a genotoxic carcinogen. However, according to a study performed by the Holland Public Health Department, P&G has stated that the level of polyacrylamide used in treating water is 3 mg/L, within the safe drinking water standards (Laurent, Visser, & Fesselet, 1995).

For effective coagulation and flocculation to occur an appropriate amount of energy is needed to mechanically mix the chemicals in the water. In large systems a rotating agitator is used to mix the chemicals in the tank, and this energy creates eddy currents as a result of the velocity gradient in the fluid. The size of the eddy is important as particles smaller than the eddy will not be effectively mixed (Tchobanoglous & Schroeder, 1987). Mixing is a function of power, rotational speed, and the diameter of the mixing agitator. It varies based on the chemicals use, type of mixer, and the geometry of the tank. The main purposes of mixing are to promote: the hydrolysis of coagulants to desired form, the interaction of chemicals with particles and, the particle-to-particle collision at the required speed to build dense flocs. Coagulation depends on rapid mixing and the main design parameter is “Gt,” where G is the measure of mixing intensity and t is the

detention time in the tank, usually <10 sec. On the other hand, flocculation is associated with gentle (or slow) mixing. Slow mixing is necessary to optimize floc development with much lower velocity gradients compared to the rapid mixing stage, so as to prevent excessive shearing of flocs.

The PÜR[®] treatment system instructs the user to mix vigorously for five minutes and does not specify gentle mixing. Mixing is followed by decanting through a filter cloth and then allowing the unit process of sedimentation to occur. The larger flocs that have built up in the flocculation stage are now settable by gravity (Tchobanoglous & Schroeder, 1987).

The other PÜR[®] treatment ingredients include an alkaline agent, an oxidant, and a disinfectant. The alkaline agent, sodium carbonate, acts as a pH buffer to keep water at the accepted drinking water range and promotes pH that is optimal for coagulation. The oxidant, potassium permanganate, serves to destroy organic matter such as NOM and total organic carbon; it can also oxidize other metals susceptible to precipitation (MWH, 2005). Lastly, the calcium hypochlorite is a disinfectant that provides chlorine to inactivate pathogens as well as residual chlorine to prevent re-activation of pathogens and recontamination. As mentioned in Section 2.5.3, the CDC conducted a DBP formation study in POU chlorination of turbid and non-turbid waters in western Kenya. As with the SWS sodium hypochlorite method, the PÜR[®] treatment yielded results that met the WHO requirements. Initial water turbidities ranged from 4.23 NTU to 305 NTU; and after the PÜR[®] treatment, turbidities dropped to 0.93 to 2.1 NTU. THM concentration was analyzed after 1, 8, and 24 hours, and the resulting THM concentrations were below the

WHO guideline values. The team concluded from this that POU chlorination treatment does not pose a significant health risk in regards to THM concentrations (Lantagne, Blount, Cardinali, & Quick, 2008).

2.6.3 - Distribution Models & Partners

According to Dr. Allgood, P&G had a decision to make after they conducted field testing. They initially wanted to provide PŪR[®] commercially to make a profit, but they did not have the infrastructure in place to accomplish this goal. Therefore, they made it a not-for-profit effort, focusing on two different distribution models: (1) sustained markets, based on semi-commercial strategies, and, (2) emergency relief. P&G partnered with PSI, the same social market NGO that the CDC partnered with to implement the SWS project. Through this partnership, PŪR[®] entered the semi-commercial market, with PŪR[®] sachets being sold in nine countries, and then re-sold on the local level by store owners and women's groups. P&G also partnered with the NGO World Vision to provide PŪR[®] in schools and to more women's groups (Allgood, 2009). The PŪR[®] treatment has also played a role in improving the health of people living with AIDS and HIV. Self-help groups, in Kenya, for instance, were provided the infrastructure to sell PŪR[®] sachets and storage containers for income. In these sustained market settings, PŪR[®] is generally sold at product cost recovery for US\$0.10, at a cost of US\$0.01 per liter (Centers for Disease Control and Prevention, 2008). Individual sachets can treat 10-Liters of water and strips of 12 sachets are provided when ordered in bulk.

P&G recognized the potential of the PŪR[®] treatment for emergency relief, after NGOs requested 15 million sachets 24 hours after the Indian Ocean Tsunami in 2004. Since that

disaster, PŪR[®] has been used to respond to drinking water needs in emergencies such as cholera epidemics in Zimbabwe, floods in Bangladesh and Haiti, and in the 2008 Cyclone Nargis that hit Myanmar (Allgood, 2009). Individual PŪR[®] sachets are provided to relief organizations and NGOs at a cost of US\$0.035, not including shipping from the main distributor in Pakistan by ocean container (Centers for Disease Control and Prevention, 2008).

2.6.4 - PŪR[®] Treatment Intervention Studies

A number of studies have been performed on the efficacy of the PŪR[®] treatment system in the laboratory and in the field. This section will focus on the findings of six studies performed and published between the years 2000-2006, and then examines the recommendations and findings in a standard operating procedure guide for the use of PŪR[®] in emergency response settings.

Rangel et al., 2003:

The location of the first study reviewed was rural Guatemala in the year 2000. A joint assessment by the CDC and the Guatemalan Medical Entomology Research and Training Unit investigated different drinking water interventions. This field study was the second phase of a laboratory-based study in 2000 where Guatemalan village source water, with a median 120 *E. coli* CFU per 100 mL, was treated to WHO drinking water guidelines, of <1 *E. coli* CFU per 100 mL. In the field study, 100 randomly selected homes from four villages were selected to use the water treatment interventions. Three groups received the PŪR[®] treatment with either a CDC water storage vessel, a covered bucket with spigot, or no vessel; one group received the SWS bleach with a CDC storage vessel; and the final

group (the control) did not receive an intervention. Over four weeks, the water was tested for chlorine, turbidity, and *E. coli*, measured by the HACH DPD colorimetric method, HACH Portable Turbidimeter, and the IDEXX Laboratories' Colilert Quantitray 2000 kit, respectively. The results indicate that the PŪR[®] treatment method effectively chlorinated the water and reduced microbial contamination similarly to the SWS bleach (**Table 2.11**). The study was conducted during the dry season, thus, indicative of low water turbidities before treatment (Rangel, Lopez, Mejia, & Mendoza, 2003).

Table 2.11 - Guatemalan water treatment intervention study results pre- and post-Treatment with PŪR[®] and SWS treatment systems (Rangel, Lopez, Mejia, & Mendoza, 2003).

Group	Mean Turbidity (NTU)		Mean Free Chlorine (ppm)		Mean <i>E. coli</i> MPN/100mL	
	Pre	Post	Pre	Post	Pre	Post
No Intervention	8.2	7.6	0.0	0.0	510	938
SWS + CDC vessel	11.3	6.3	0.0	1.6	324	6
PŪR[®] + traditional vessel	6.2	4.6	0.0	1.5	753	418
PŪR[®] + CDC vessel	5.3	4.3	0.0	1.4	2,553	<1
PŪR[®]	7.3	4.4	0.0	2.3	1,435	<1

Reller et al., 2003:

In a related study, conducted by the same collaborators as the Rangel et al. study, 492 Guatemalan households were divided into five different water treatment groups, including, PŪR[®] sachets only, PŪR[®] plus a customized storage vessel, bleach, bleach plus vessel, and the control group (with no intervention). The study lasted for one year,

and the results were based on diarrheal episodes per 100 people per week. The control group had 4.31 diarrheal episodes per 100 people per week. This number was 24% lower for households using the PÜR[®] sachets, 29% lower for the PÜR[®] plus vessel group, 25% lower for the bleach group, and 12% lower for the bleach plus vessel group. It was also observed from a PÜR[®] treatment standpoint, that PÜR[®] sachets intervention group used approximately 6.0 sachets per week, which is equal to 8.6 liters of drinking water per day; while the PÜR[®] plus vessel group used 5.8 sachets per week, providing 8.3 liters of drinking water per day (Reller, et al., 2003).

Souter et al., 2003:

An in-depth study conducted by P&G's Health Sciences Institute investigated the efficacy of the PÜR[®] treatment system, both in the laboratory and in multiple field studies. The laboratory procedures and water preparations are based on the U.S. EPA Purifier Guidelines, as described in Section 2.4. Based on guidelines, the General Test Water and Test Water #2 (Challenge Test Water/Halogen Disinfection), as described in **Table 2.5**, were tested in the laboratory study. The water was inoculated with 14 different types of waterborne disease-causing bacteria, including *Salmonella typhi*, *Vibrio cholera*, and a mixture of fecal bacteria, along with the polio virus and rotavirus, and *Cryptosporidium parvum*. Additionally, arsenic was added to the challenge waters, either as arsenic (III) or arsenic (V). The results of the treated water met the reduction requirements as described in **Table 2.4**. The different bacteria, at initial concentrations of 1×10^7 to 9.2×10^9 bacteria/L, were reduced to <1 after treatment. The treatment system achieved a >4 -log removal of the poliovirus and rotavirus, and a >3 -log reduction of

Cryptosporidium oocysts, even at the low temperatures of 3-5 °C. Lastly, the initial level of arsenic was 500 to 1,000 µg/L, and after treatment resulted in a 99.7% removal. Field tests were performed on 320 samples from various sources in Guatemala, Kenya, Pakistan, the Philippines, and South Africa. Initial concentrations of *E. coli* ranging from 0 to 2.4×10^6 CFU/100 mL were reduced to non-detectable limits of <1 CFU/100 mL. Additionally, turbidities ranging from 0 to 1850 NTU and were reduced to 0.25 to 3.2 NTU (**Figure 2.16**) (Souter P. F., et al., 2003; P&G's Children's Safe Drinking Water Program, 2005).

Figure 2.16 - Kenyan drinking water samples showing varying turbidities and the resulting PUR® treatment system turbidity (P&G's Children's Safe Drinking Water Program, 2005).

Crump et al., 2005:

A collaborative effort between the CDC, P&G, and the Kenya Medical Research Institute, conducted a study on household drinking water treatment, primarily PÜR[®], in preventing diarrhea in rural western Kenya. The treatment interventions included PÜR[®], sodium hypochlorite (used in the SWS program), and standard practices in Kenya. The study tested for turbidity, the presence of *E. coli*, and the prevalence of diarrhea episodes. The study found that children less than 2-years old had significantly less diarrhea when their water was treated with PÜR[®] compared to the control group; this was also the case among people of all ages. Sodium hypochlorite yielded similar results. The team did find low free chlorine concentrations when measured during unannounced visits. They attribute this to prolonged storage or chlorine demand consumed by turbid waters. For instance, 44% of samples treated with PÜR[®] were found with free chlorine concentrations, while 61% of samples treated with sodium hypochlorite had concentrations of free chlorine (Crump, et al., 2005).

Luby et al., 2006:

Another study performed by the CDC, the Health Oriented Preventive Education in Pakistan, and the Aga Khan University in Pakistan, focused on the benefits of POU water treatment combined with hand washing with soap. The study concluded that there was no apparent benefit of combining PÜR[®] treatment with hand washing with soap. For example, the reduction in diarrhea among those receiving soap for hand washing promotion was 51%, while the reduction was 64% for those receiving the PÜR[®] treatment plus soap. They did observe that households used an average of 21.6 PÜR[®]

sachets per week, which is equivalent to 4.4 L of treated drinking water per person per day (Luby, et al., 2006).

Doocy & Burnham, 2006:

The final study described is the John Hopkins University's trial of PŪR[®] for 12 weeks in an emergency context, among 400 households in camps for displaced populations in Monrovia, Liberia. Doocy and Burnham observed that the camp residents had few water storage and transport vessels, and there was a persistent unmet need for affordable and effective POU water treatment. The trial investigated reduction in diarrhea incidences, chlorine residual levels, and the removal of coliform bacteria from treated water. The study concluded that the PŪR[®] treatment method significantly lowered diarrheal incidences, as diarrhea was reported 2.8% of weeks among PŪR[®] users, compared with 28.7% among the control groups. The study also found that chlorine residual levels met or exceeded the Sphere Guidelines standards in 85% of the observations. Lastly, the lead investigators concluded that "Point-of-use water treatment that incorporates flocculation and disinfection is ideal in the acute phases of emergencies when the only available water sources have high levels of turbidity and organic matter such that treatment with sodium hypochlorite is rendered ineffective" (Doocy & Burnham, 2006).

The Aquaya Institute, a non-profit institute that brings water solutions to developing communities, developed standard-operating-procedures for deployment of PŪR[®] in emergency response settings. It discusses application tips for the use of PŪR[®] and recommendations for overcoming potential challenges faced in the field for this POU treatment. A couple of the standout application tips include the importance of stirring the

water vigorously to form the flocs, which are a visual indicator that the treatment is working. The flocs should then be disposed away from people, either in the latrine or buried in the ground. The Institute did indicate that the chlorine will disappear from the water, and after 24 hours, the concentration will not be sufficient; therefore, it is important to safely store water until the user is ready to drink it. Overall, a single PÜR[®] sachet used by a household per day is appropriate for distribution; and two 12-strips of sachets will treat 240 liters of water, enough for three weeks. Major obstacles found in the field included unfamiliarity with the product and how to correctly use it, the dislike of the taste and odor, explaining why the color change occurs, and the availability of supplies needed to perform the treatment method. The Aquaya Institute reiterates the need for properly educating and training the relief workers and as well as the end users (The Aquaya Institute, 2006).

2.7 - Emergency Field Kits & Transportation

Many relief organizations look to provide family hygiene kits to supply tools and materials to families for sanitation and hygiene. UNICEF provides kits for an average family of five people for a month after a disaster. The items in a kit will depend on the situation and the availability of items locally (Oxfam, 2001). For instance, during the 2008 Cyclone Nargis response in Myanmar, the suggested standard hygiene kit provided by the UNICEF WASH program, and used by the IFRC, included items such as soap, buckets, jerry cans, cloths for filtering, and toothbrushes, as well as female sanitation products (**Table 2.12, Figure 2.17**) (UNICEF WASH Program, 2008).

Table 2.12 - UNICEF WASH program standard hygiene kit items that were handed out during Cyclone Nargis relief efforts in Myanmar (UNICEF WASH Program, 2008).

Soap	1250 g	(250 gm/person/month)
Soap bar for laundry	1000 g	(200 gm/person/month)
Bucket with lid,	50 litres	
Jerry can	10 litres	
Mug	1 unit	
Tooth-brush	5 unit	
Tooth-paste	150 g	
Nail clipper	1 unit	
Nappies for infants	3 unit	
Potties	1 unit	
Towels big (1.5' x 3')	2 unit	
Towel small (1.5' x 1')	3 unit	
muslin cloth 1 m x 1 m	1 unit	Water filtering HH level
<i>Sanitary Protection for Women (See guidance note 23rd May)</i>		
<i>Option 1 – Crowded Camp Settings</i>		
Lady Sanitary pads (disposable)	40 unit	2x20 pack
Lady knickers/panties	2 units	
<i>Option 2 – Rural Settings - Villages</i>		
“Win Thuzar” type material – 2 yards x 1 yard	2 Units	
Pieces elastic – 2 yards length	2 Units	
Safety pins	10 Units

Figure 2.17 - IFRC distributing disaster relief kits to Myanmar villages after the 2008 Cyclone Nargis (International Federation of Red Cross and Red Crescent Societies, 2008).

Transportation of the kits and other emergency relief items are a major expense for relief organizations. During the 2008 Cyclone Nargis relief efforts, the USAID had 40 Department of Defense C130 flights ship supplies from Thailand to Rangoon. The total

cost was US\$2.9 million. Per pallet of supplies, particularly jerry cans, this cost breaks down to US\$1.81/pound (resulting from US\$2.9 million per 40 flights per maximum of 40,000 pounds per flight).

General guidelines set by the USAID Field Operation Guide, state that a skid, like a pallet, (with dimensions of 48 by 40 by 50 in; displacing 56 ft³ and weighing 209 lbs) can hold up to a total of 600 collapsible 10-L water containers (USAID, 2005). Rigid jerry cans are also used in disaster relief. The same skid can hold approximately 32 rigid 5-gallon jerry cans (at dimensions of 10 by 10 by 15.125 in per jerry can). A skid filled with jerry cans has empty space because the rigid jerry cans do not pack completely inside the skids. Approximately 18 times more 10-L collapsible containers can fit within a skid compared to 5-gallon jerry cans.

CHAPTER 3 - PROTOTYPE DESIGN AND DEVELOPMENT

The standard method of use for PŪR[®] sachets requires two 5-gallon buckets, a stirring spoon, and a loose filter cloth (The Aquaya Institute, 2006), and its main intended use is routine water treatment during normal times. Delivering PŪR[®] kits into disaster zones and its subsequent use by the local population could be problematic for several reasons: (1) The bulkiness of the buckets makes transport inefficient unless other supplies are packed in the buckets; (2) The added cost of the rigid buckets diverts funds from other uses; (3) The method of use is somewhat cumbersome, and normally training is provided to new users; and (4) If the treated water is stored in the buckets, recontamination by hands and debris is a risk (The Aquaya Institute, 2006). This thesis project focused on developing and testing a product meant to overcome the disadvantages of the standard method of use for PŪR[®] in the disaster relief setting. The product developed was a plastic waterbag with a geometry that will facilitate effective coagulation/flocculation/disinfection with PŪR[®] sachets. The compactness and likely low cost of the bags make them well-suited to rapid, low-cost deployment by relief organizations. In addition, their ability to be sealed against recontamination is an advantage.

Prior to establishing the treatment protocol and conducting water quality experiments, the prototype design objectives and features were identified, and a series of prototype iterations was developed during preliminary water quality testing. Once a “proof-of-concept” prototype was selected, the optimization experiments were performed to determine a robust method for treating the water to emergency standards. Lastly, a prototype based on the “proof-of-concept” design was fabricated by Cascade Designs,

Inc. to be used by the Cal Poly team in field testing. This chapter details the prototype design and development, and it is followed by Chapter 4 in which the experiment material and methods are described (**Figure 3.1**).

Figure 3.1 - Conceptual model of research and development based on set goal.

3.1- Prototype Design

The four essential functions needed for the waterbag prototype are the following:

- 1) Easy water collection under difficult field conditions
- 2) Transport by an individual with limited fatigue
- 3) Effective treatment using PÜR[®] sachets
- 4) Hygienic storage and dispensing that prevents re-contamination

To achieve these design objectives, many decisions had to be made including (1) material selection, (2) bag capacity and geometry, (3) straps and handles, with the constraints of (a) durability, (b) final product cost, (c) simplicity of use, and, (d) water treatment effectiveness. During the development stages and experiments, new design features and

components were incorporated culminating in the “Mark I” prototype that was the subject of the “Challenge Test,” the final experiment covered by this thesis.

3.1.1 - Material Selection

Based on discussions with polymer expert and Cal Poly Industrial Technology Professor, Dr. Keith Vorst, low density polyethylene (LDPE) clear film plastic was chosen for the prototype, with impulse welding for fabrication, for reasons of convenience and low cost (Vorst, 2008). Readily available LDPE film is 6-mil thick, which is also the maximum thickness that can be welded by low-cost impulse sealers. Impulse sealing, also known as heated-tool welding or hot-plate welding, uses a pulse of intense thermal energy for a short period of time, followed by cooling, to seal the desired thermoplastic materials. Generally, the thermal energy is transmitted by a resistive, inductive, or high-frequency heated metal bar. Plastic film, generally thermoplastic, is sold in thicknesses from 0.5 to 10-mil; while anything greater than 10-mil is known as sheets. Plastic film electric strength (analogous to tensile strength) related to manufacturing and flexibility characteristics vary inversely to the film thickness. LDPE film is the most common film used in packaging as it combines high impact strength, toughness, and ductility. It is used as shrink film, thin film for automatic packaging, heavy sacking, and multilayer film (Harper & Petrie, 2003). LDPE is one of the less expensive films and has a shelf-life of greater than 10 years (Bartlett, 2009). A study conducted by the Navy in conjunction with Cascade Designs Inc., supports the choice of LDPE film in regards to inertness and chlorine decay. The study investigated the chlorine decay in water treatment bags. It found that the material composition of the bags affected the chlorine decay, with urethane

apparently reacting to consume chlorine and LDPE being inert with respect to chlorine residual decay (Gallagher & Varnava, 2009).

Initial prototype fabrication took place in the Cal Poly Industrial Technology plastics laboratory. Then a large-jaw impulse sealer was purchased. The Tabletop Poly Bag Sealer - Impulse, Model H-1029, with a seal length by width of 20-in x 1/16-in, and a max seal thickness of 12-mil (e.g., two sheets of 6-mil could be welded), was purchased from ULINE[®] Shipping Supply Specialists (**Figure 3.2**).

Figure 3.2 - Sealing LDPE film with the ULINE[®] tabletop impulse sealer at Cal Poly.

3.1.2 - Design Capacity and Geometry

The prototype geometry was designed to facilitate the four essential functions of the waterbag – collection, transport, treatment, and storage. The design features described hereafter (**Figure 3.3**), have been patented (US PTO No. 7,514,006). To be consistent

with the water volume treated by the standard PUR[®] method, a 10-L water volume was chosen for the prototype. In addition to the water volume, the internal volume of the prototype included headspace occupying at least 5% of the total volume. The headspace volume to be reserved was indicated to the user by a fill-line marked on the bag. The headspace of air forms an agitation air bubble for increased mixing intensity (Lundquist, 2009). Length to width ratios from 3:1 to 8:1 were recommended by the patent, and a 4:1 length to width ratio was selected for the Mark I prototype used in the testing and water quality experiments of this thesis (**Figure 3.4**). The prototype's high length-to-width ratio provided the following benefits: (1) rapid mixing by bubble displacement, (2) flocculation mixing by rolling or rocking the bag, (3) decrease particle settling distance when the bags are rested horizontally, (4) the ability to isolate sediment in the narrow bottom of the bag, and, (5) the ability to carry the bag as a neck pack, sling, purse, or backpack. The sealed end of the device included a conical cross section for collecting the sediment and preventing re-contamination of the water. Additionally, the open side of the device was a wide-mouth port functioning as the filling point for the 10-L. The wide-mouth port, in conjunction with the flexible elongated container and high length to width ratio, allowed for quick filling in shallow water such a stream (Lundquist, 2009). Lastly, the testing led to the addition of an attached filter to provide an additional barrier to pathogens and other particulates.

Figure 3.3 - Side view of the Mark I prototype used in the research, with features indicated.

Polytech Waterbag
Mark I Design

Figure 3.4 - Side view of the Mark I prototype with dimensions shown.

3.1.3 - Design Components

Additional design features included a closure at the wide-mouth port to secure the volume, a dispensing unit to discharge the treated water, and a filter apparatus for final clarification to meet water quality standards. Possible closures for the wide-mouth opening could incorporate a rollable length secured with a clamp, various ties, hook and loop fasteners (e.g., VelcroTM), a Zip-lockTM closure, or some combination of these mechanisms (Lundquist, 2009). For the initial Mark I prototype, a rollable section with a 1-inch wide VelcroTM strips to seal the bag mouth and to strap the rolled section was used. Since the VelcroTM was attached with adhesive, it was not considered durable enough or leak-proof enough for commercial use. Clamps were rejected due to cost and the likelihood that they would be lost during field use. The second and final closure type used in the testing was a dry-bag style closure as often found on bags used for kayaking, white water rafting, and camping. To fabricate a dry-bag closure, a polyvinyl chloride (PVC) reinforcing mat material was needed to provide stiffness that minimized leaking. The cutting mat was cut to dimensions and then “hemmed” into the top of the bag (Figure 3.5). The closure was adapted to Prototype #4 discussed in Section 3.2.

Figure 3.5 - PVC mat (Left) cut to 1” x 10” dimensions and hemmed to the top end of the prototype as reinforcement for dry-bag style closure (Right).

However, the Zip-lock™ closure was chosen for the prototypes manufactured by Cascade Design, Inc (refer to **Figure 3.23** for Zip-lock™ closure).

After the water is treated, a dispensing port is needed for release of the water for drinking. In Prototype #4, a valve, coupled to a tube for delivery, was secured to the device on the conical cross section, 6.0-in above the bottom end of the prototype. The spring-loaded valve with two rubber gaskets to secure on either side of the LDPE film (**Figure 3.6**), was purchased for US\$0.49 from an Army Surplus store, Andy and Bax, in Portland, OR. The valve is 2 6/8” in length with an outer diameter (O.D.) of 5/8” at the discharge port, which is attached to 5/8” inner diameter (I.D.) tubing.

Figure 3.6 - Spring-loaded valve with a 5/8” Outlet (Left), secured to LDPE film (Right).

The final component is the filter apparatus attached to the tubing below the valve. The filtration member may be a filter cloth or a wire mesh having a pore size <0.5-mm to ensure certain pathogenic organisms which may be resistant to the biocide are removed from the treated water before consumption. The filtration member may contain an adsorbent, such as activated carbon grains for removing organics, metals and oxidants

and/or to assist in sediment filtration (Lundquist, 2009). During initial phases of prototype designing, Hanes[®] 100% cotton t-shirt cloth was used as a surface filter (**Figure 3.7**), similar to what is used in the PŪR[®] treatment system. However, it was soon replaced with a 1- μ m particle retention rating polypropylene filter bag, with a thickness of 0.125-in and cut into 3.0-in diameter disks, to also function as a surface filter. Multiple 1- μ m rating polypropylene cloth bags were purchased online from Aquatic Eco-Systems, Inc. (Florida), and later the cloth material was purchased from Rosedale Products of California, Inc (Rosedale Products: 1- μ m polypropylene felt cloth, order code: PO-1, non-glazed finish) .

Figure 3.7 - The valve and 100% cotton cloth from a dissected bag following a filter selection experiment to determine if the material effectively reduced turbidity levels to <5 NTU.

The 1- μ m polypropylene cloth was laser cut to desired diameter using AutoCAD 2009 and the Versa Laser[™] (**Figure 3.8**) in the Industrial and Manufacturing laboratories at Cal Poly. The process works by first drawing 2D circles of the filter cloths on a 12" by 24" plotting space in AutoCAD. The drawing is then plotted and sent the connected laser

interface, the ULS Ingraver, where the fabric and material thickness are defined. This information is then processed by the Versa LaserTM which cuts the fabric to the desired scale (**Figure 3.9**).

Figure 3.8 - Versa LaserTM cutting 1- μ m polypropylene cloth

Figure 3.9 - Cut cloth at 3-in diameter disks

The 1- μm rating polypropylene cloth is a needle-punched material used in filter bags for water treatment. Filter cloths are normally divided into two categories (woven and nonwoven) depending on structure. Polypropylene felt is characterized as a nonwoven cloth that is composed of needle punching fibers randomly placed (**Figure 3.10**) onto a woven backing called a scrim through a variety of chemical or heat bonding methods. Needle punching is a process in which the fibers “are entangled and mechanically interlocked by puncturing the web with a series of barbed needles” (Hutten, 2007). The felted filters can be two to three times thicker than woven filters and each fiber is a target to capture particles such as flocs by impaction and interception (**Figure 3.11**) (U.S. Environmental Protection Agency, 1995); while smaller particles collect on the surface of the filter forming a “schmutzdecke” film or ripening layer (**Figure 3.12**). According to the Rosedale Products of California, Inc., where the filter cloth was purchased, the nominal rating for the 1- μm polypropylene cloth is 50% efficiency. This 50% efficiency is the same for all nominal pore sizes ranging from 1- μm to 200- μm (Rosedale Filtration, 2008).

Figure 3.10 - 1-μm polypropylene cloth examined under microscope at 10x magnification to show needle punched fibers on an unused cloth purchased from Rosedale Products of California, Inc.

Figure 3.11- 1-μm polypropylene cloth examined under microscope at 10x magnification to show particle and floc capture by needle punched fibers on a cloth purchased from Rosedale Products of California, Inc., (Cloth shown after an Optimization Experiment.)

Figure 3.12 - 1- μ m polypropylene cloth after filtration showing surface particle layer after an Optimization Experiment (Left) compared to an unused cloth (Right).

For the research presented, each 1- μ m polypropylene cloth disk was used once to filter up to 10-L and then discarded. Multiple filter cloth uses (treating greater than 10-L) is not the subject of current research. Although, it is an important factor affecting the useful life and cost of the device that should be part of future investigations.

Lastly, a filter housing was needed to hold the 1- μ m polypropylene cloth during filtration. A MilliporeTM Stainless Steel Filter Holder 90-mm (**Figure 3.13**) was initially used, but due to bulkiness and restricted flow rates, a custom filter apparatus was designed and fabricated at Cal Poly.

Figure 3.13 - Millipore™ stainless steel filter holder used during the Filter Selection, Baseline, and a couple of the Optimization Experiments before it was replaced by a custom filter housing.

Taking the suggestion of a syringe filter concept, Industrial and Manufacturing Engineering student Adam Wegener designed a filter housing. Through a two-step process, he first conceptualized the design using computer software, SolidWorks 2009, and then built the model with a rapid prototyping machine, Object Eden 260, in Cal Poly's Mechanical Engineering laboratories (**Figure 3.14** through **Figure 3.15**) (Wegener, 2009).

The rapid prototyper took approximately six hours to build both halves of the filter apparatus. First, the print head deposited uncured resin onto the build tray (**Figure 3.16**); the resin was immediately cured with UV light. The layers were processed in the X and Y directions by the print head, and the build table moved downward 16 microns as each layer was deposited. The transparent resin was selected to reveal water flow within the

part. The two halves were held together by a pin hinge, which opened and closed like a clam shell (**Figure 3.17**). The 1- μ m polypropylene filter cloth was placed between the two halves with an O-ring surrounding the outer edge to prevent water leakage out of the housing. The inside surface of the halves had ribs running from the central hose barb to the outer boundary of the circle. This helped hold the filter cloth in place. Water flowed from the tubing through a 5/8" barb at the top half of the apparatus, through the filter cloth, and then was discharged at the outlet, another 5/8" barb. While the rapid prototyping technique was ideal for research, the materials and design would likely to be adjusted for mass production (Wegener, 2009).

Figure 3.14 - Conceptual 2-D drawing of filter apparatus in SolidWorks 2009 (design by A. Wegener).

Figure 3.15 - 3-D filter apparatus model shown in SolidWorks 2009 with 1- μ m polypropylene cloth secured in the apparatus (design by A. Wegener).

Figure 3.16 - Rapid Prototyping Machine, Object Eden 260 with the Build Tray at the Center (A. Wegener shown in the photo).

Figure 3.17 - Clear resin filter apparatus.

During the experimental testing of the waterbag and the filter apparatus, modifications to the filter device were conceived and improvements were made to the existing apparatus. To maintain consistency throughout the experiment, major changes to the apparatus were not made, other than increasing the thickness of the walls to improve the sealing for water tightness.

3.1.4 - Usability

Ease of use and user acceptance drive the design, experiments, and ultimately the success of the waterbag product. The goal of the design and treatment is to provide a family of four with enough water for a period of five to ten days, when packaged with a strip of 12 PŪR[®] sachets (sufficient for 120 liters). While the design objective is for multiple uses, the experiments performed in the current research were for a single use of the prototype with one PŪR[®] sachet and one filter cloth.

Proper execution of the treatment method would be crucial for users in a relief situation. Pictographic instructions were developed with graphics and symbols to demonstrate the treatment protocol (**Figure 3.18**). The goal was to have any culture, regardless of language, perform the treatment steps successfully. Iterations of the pictograph were designed by Dr. Lundquist and executed by Cal Poly Graphic Communication student, Tomiko Oden, assisted by Environmental Engineering student, Casey Kelleher. The final iteration for the Mark I design reflects the final procedural steps selected considering the Optimization Experiments (refer to Appendix F for Mark I pictographic instructions). One possibility is to have the pictographic instructions printed directly on the waterbag.

Figure 3.18 - The pictographic instructions were developed to guide the users through the treatment steps. The pictographs begin with collecting water from a surface water body (Left) follow through steps omitted here (see Appendix F), and end with the users drinking the water (Right). Each step in between was established during the optimization experiments.

3.1.5 - Transport

As introduced in Section 2.7, the USAID Field Operation Guide for transport to relief zones states that a single skid with dimensions of 48 by 40 by 50 in can hold approximately 600 collapsible 10-L water containers (USAID, 2005). The same skid can hold approximately 32 rigid 5-gallon jerry cans. Taking into account void space and a single 10-L waterbag prototype, with rolled dimensions of 12-in by 2.5-in, approximately 1280 waterbags could fit on a single skid. This corresponds to 40 times more 10-L waterbags per skid compared to rigid jerry cans and two times more compared to the collapsible containers.

3.2 - Building the Prototype

Building the prototype began with sealing two sheets of LDPE film to create a bag. Initial construction began with 6-mil drop-cloth plastic purchased from Home Depot in San Luis Obispo, CA, and sealed with the impulse sealer. The first prototype made this way could hold 6-L of water (Prototype #1) (**Figure 3.19**).

The next iteration, Prototype #2, held 10-L and incorporated a Velcro™ closure, a conical section at the bottom end, and handles cut into the excess plastic to assist the user in mixing (**Figure 3.20**). For Prototype #2 and all subsequent prototypes, the 6-mil LDPE plastic film was purchased from Plastic Sheeting Supply (aka IPS Packaging) in 6-ft by 100-ft rolls.

Figure 3.19 - Prototype #1 shown filled with 6-L volume of water to test sealing strength (Left). The drop cloth plastic purchased had nicks in the material that sprung leaks (Right).

Figure 3.20 - Prototype #2 shown with Velcro™ closure and handles holding a 10 liter water volume.

Prototype #3 was a longer prototype with a capacity of 10-L and carrying straps (Figure 3.21). After initial testing, this iteration was not selected for the Mark I design as the large length to width ratios was not easy to handle during mixing.

Figure 3.21 - Prototype #3 containing 10 liters of water at a longer length and shorter width prototype.

The final prototype that represents the Mark I design, Prototype #4, was comprised of the design components mentioned previously in Section 3.1.3: the dry-bag style closure, dispensing valve, and the filter apparatus (**Figure 3.22**). Prototype #4 had a length to width ratio of 4:1 and was the selected design for the water quality testing performed during the Baseline Water Quality and Optimization Experiments.

Figure 3.22 - Prototype #4, the Mark I design, was the selected design for the Baseline and Optimization Experiment series (prototype shown during the Optimization Experiment with attached filter apparatus).

In order to have a more durable bag for use in the Challenge Water Experiments, three Mark I dimension prototypes were produced by Cascade Designs Inc. in their facility in Seattle, WA. The prototypes were modified from Prototype #4, in that they had a Zip-

lock™ closure (**Figure 3.23**), and the conical end dispensed directly to ¼” tubing welded to the plastic (**Figure 3.24**), eliminating the dispensing valve. The flow was released by a clip on the tubing.

Figure 3.23 - Zip-Lock™ closure on the modified Mark I prototype fabricated by Cascade Designs Inc. for the Challenge Water Experiment at BioVir Laboratories, Benicia, CA.

Figure 3.24 - Welded outlet port on the modified Mark I prototype fabricated by Cascade Designs Inc. (Seattle, WA).

CHAPTER 4 - MATERIALS AND METHODS

PŪR[®] sachets were the chosen treatment chemical for the experiments conducted in the current research. A single 4-g PŪR[®] packet is designed to treat 10 L of water through coagulation/flocculation/disinfection (refer to **Table 2.10** for PŪR[®] packet ingredients). Based on the concepts of the two-bucket PŪR[®] 30-min treatment protocol, mixing and settling procedures were developed for the waterbag prototype. An optimal treatment protocol, meeting the < 5NTU WHO turbidity limit, was identified after nine experiments evaluated various mixing times and settling positions within the 30-minute treatment process. The additional treatment step of filtration was also investigated. The final treatment protocol was then translated into pictographic instructions.

4.1 - Experimental Design

Four main series of experiments were conducted throughout this research period: (1) Filter Selection Experiments – to determine what filter material meets the emergency drinking water turbidity limit of <5 NTU; (2) Baseline Water Quality Experiments – to test various source waters, (3) Optimization Experiments – to identify the most advantageous mixing and settling times and methods, and (4) U.S. EPA Challenge Water Experiments – to measure treatment performance using a standard Challenge Water recipe. The water collection, preparations, and experimental procedures for the first three-experiment series are described in the next three sections, 4.2 through 4.4. Water quality testing procedures for the three-experiment series are then described in Section 4.5. Separately, the EPA Challenge Water Experiments are detailed in Section 4.6.

For each individual experiment conducted, a new, unused prototype was constructed and then tested with the addition of a single 4-g PŪR[®] packet for treatment. After a single use, the LDPE film was disposed of and the valve dispensing ports were soaked for 1-hour in a 1:8 dilution of rubbing alcohol to tap water mixture to disinfectant the port. Additionally, standardized procedures were established during the Optimization Experiments and maintained thereafter. A naming convention for the experiments is detailed in **Figure 4.1**.

Figure 4.1 - Experiment naming convention.

4.2 - Filter Selection Experiments

The Filter Selection Experiments, consisting of nine total tests, were conducted with 6-L and 10-L volumes prototypes. Experiments A-1 through A-6 were conducted during prototype development, at which point only 6-L prototypes were designed. Each of the 6-L prototypes was treated with an entire PŪR[®] packet. From Experiment A-7 forward, each prototype contained 10-L of test water and was treated with a single PŪR[®] packet.

The overall objective of the experiments was to identify and select filter material needed to meet the emergency drinking water turbidity limit of <5 NTU.

4.2.1 - Prepared Water

For experiments A-1 through A-9 water was prepared by filling 5-gallon buckets with 14-L of San Luis Obispo City tap water and various concentrations of kaolin acid-washed powder/USP (Fisher Chemical, $\text{H}_2\text{Al}_2\text{Si}_2\text{O}_8 \cdot \text{H}_2\text{O}$, Catalog number K2-500) to increase turbidity. Kaolin amounts were not recorded since this was a screening experiment. The prototypes were filled with either 6-L or 10-L volumes of the prepared water. For experiment A-1 only, in addition to the above water, water from the fish pond southwest of the Cal Poly Orfalea College of Business building on California Boulevard was added.

4.2.2 - Filter Material

Different cloth materials were selected for filter materials and cut into 3-in diameter circles. Experiment A-1 used two- and three-ply cloth from Hemp Traders (Model: CT-TLT, CA-CL1, CA-K1). Hemp was used for this experiment since that was the cloth available at the time. Experiment A-2 through A-8 tested multi-ply Hanes[®] 100%-cotton t-shirts for the filter, and Experiment A-9 used a woven multi-ply Bleach White from Kona[®] Cotton (K001-1287 PFD). Lastly, a single-ply 1- μm polypropylene cloth (cut from an Aquatic Eco-Systems, Inc. bag vessel) was tested in Experiments A-10 and A-11. Each filter material was held in place using the Millipore[™] Stainless Steel Filter Holder apparatus (90-mm diameter), except for experiment A-1, in which the dispensing valve port was not yet adapted to the prototype. In this case, the samples were filtered through the cloth material which was placed securely over the top of a 500-mL beaker.

4.2.3 - Procedures

For each run, a single PŪR[®] packet was used to treat the water. Mixing and settling methods and times varied between experiments, but remained within the 30-minute contact time for disinfection, consistent with the standard PŪR[®] treatment method. After mixing, the prototype was hung on a gate (**Figure 4.2**) to allow for complete vertical settling during the 30-minute disinfection contact time. For Experiment A-1, samples were taken from the top opening of the prototype and then filtered through the hemp cloth into a beaker; an aliquot was then taken for turbidity measurement. For Experiments A-2 through A-7, all turbidity samples were taken after filtration and after the 30-minute settling to determine how many filter cloths were needed to meet the <5 NTU turbidity standard. The filtered turbidity measurements were taken within the first 500-mL of filtered water; the entire prototype volumes were not filtered during this experiment series. For Experiments A-8 and A-9, samples were taken in five-minute intervals to gain an understanding of improved clarity over the 30-minute settling period, and pre- and post- filter turbidity measurements were taken directly in 15-mL aliquots (**Figure 4.2**). Pre-filtered samples were taken directly from the valve outlet port, while post-filtered samples were taken from the Millipore[™] Stainless Steel Filter Holder outlet.

Figure 4.2 - Filter Selection Experiment A-8 showing vertical settling with the prototype hanging on a gate (Left) and turbidity samples taken over the 30-minute settling time, pre-filter and post-filter (Right)

4.3 - Baseline Water Quality Experiments

Once the filter material was selected, the next step was to test the prototype with different source waters to obtain some baseline water quality data to characterize the pre- and post-treated water. Three preliminary experiments were conducted: the first (B-1), was conducted with primary effluent from the San Luis Obispo water treatment facility, and the second and third (B-2 and B-3), were conducted with water from Drumm Reservoir and the Swine Unit Pond at Cal Poly. Each experimental design is detailed below.

The motivation for collecting pathogen-contaminated water, increasing its turbidity (and lowering the temperature in one case) was to evaluate pathogen removal as required in

the U.S. EPA Purifier Guidelines for microbiological and physical challenges (refer to Section 2.4). Instead of creating the water in the laboratory as the U.S. EPA Purifier Guideline established, the goal was to first test existing water sources, such as wastewater.

4.3.1 - Experiment B-1: Water Collection and Preparation

The test water was collected from the primary effluent tank at the San Luis Obispo Wastewater Treatment Facility (**Figure 4.3**) in two 5-gallon jerry cans on October 26, 2008, at 12:30pm. It was brought back to the laboratory at Cal Poly and half of the water volume was stored in a cooler filled with ice to drop the temperature to 4°C, and the remaining water volume was kept at room temperature, approximately 20°C. Two prototypes were then filled with 10 L of water, one with the 4°C water and the other with 20°C water. Kaolin acid-washed powder/USP was added to the waters once in the prototypes (the kaolin was not measured, just enough to increase turbidity).

Figure 4.3 - Primary effluent tank at the San Luis Obispo Wastewater Treatment Facility where 10-gallons of primary effluent water was collected for Baseline Experiment B-1.

4.3.2 - Experiment B-1: Procedures

Once the two prototypes and test waters were prepared, the PÜR[®] packets were added to the top end of the prototypes; they were closed, mixed by inverting the bag 180° repeatedly for 30 seconds, and then hung vertically on a 5½-ft tall coat rack to settle for 30 minutes. Turbidity measurements were taken pre-treatment, once every five minutes during the settling time, and post filter until it clogged. Temperature, pH, total suspended solids, total coliform, and *E. coli* tests were also performed on the pre- and post treated water.

4.3.3 - Experiments B-2 and B-3: Water Collection and Preparation

The test water for Experiments B-2 and B-3 was collected from the discharge outlet point of Drumm Reservoir in 5-gallon buckets (**Figure 4.4**) and at the Swine Unit Pond in 500-mL sampling bottles (**Figure 4.5**). The water was brought back to the laboratory and additional constituents were added to the water to increase the turbidity (kaolin acid-washed powder) and total dissolved solids (Instant Ocean), again in a partial mimicking of the U.S. EPA challenge water procedures (**Table 4.1**).

Figure 4.4 - Collecting Drumm Reservoir water in 5-gallon buckets at the outlet point northwest of the Cal Poly Farm Shop along Brizzolara Creek.

Figure 4.5 - Collecting Swine Unit pond water in 500-mL sampling bottles at the water's edge along the Sports Complex Road side of the pond (Steve Barr).

Table 4.1 - Test water recipes for Experiment B-2 and B-3

Experiment	Water Recipe	Amount
B-2	Drumm Reservoir water	10 L / prototype
	Swine Unit Pond	100 mL / 10 L
	Kaolin acid-washed powder	4.5 g / 10 L
B-3	Drumm Reservoir water	10 L / prototype
	Swine Unit Pond	100 mL / 10 L
	Kaolin acid-washed powder	4.5 g / 10 L
	Instant Ocean	10 g / 10 L

For Experiment B-2, two 10-L prototypes were filled with the test water recipe directly. For B-3, three prototypes and three standard PÜR[®] bucket tests were tested to provide a baseline comparison between the PÜR[®] bucket protocol and the prototype method. Prior to filling the prototypes and buckets, the test water recipe was homogenized using a Osterizer[®] glass blender on the liquefy setting, and a Flotec[®] submersible sump pump (Model FP0S2450A-08, 1/3 HP) contained within a 20-gallon RubberMaid[®] refuse container with a ball valve outlet. After the water was collected and the kaolin and Instant Ocean was weighed out, the test water recipe was homogenized according to these steps:

- 1) Fill RubberMaid[®] refuse container with all Drumm Reservoir water except for 1-L of the water, making sure the sump pump is off.

- 2) Fill blender with part Drumm Reservoir water, part Swine Unit pond water, part kaolin acid-washed powder, and part Instant Ocean. Blend for 1-minute on the liquefy setting.
- 3) Add the contents of the blender to the refuse container and repeat step 2 until all ingredients are homogenized (**Figure 4.6**).
- 4) Turn sump pump on in order to mix the entire test water volume (**Figure 4.6**).

During Experiment B-3 the sump pump was kept on the entire experiment. As each prototype was ready for use, 10-L volumes were filled from the ball-valve outlet on the refuse container into the prototype. This long mixing time from the sump pump caused the water temperature to increase. In order to minimize temperature fluctuations for future experiments, the sump pump remained on for 30 minutes to homogenize the water content and then all prototypes were immediately filled prior to the start of the experiment test.

Figure 4.6 - Mixing test water recipe with blender (Left) and then adding the blender contents to the remaining volume in refuse container mixed by $\frac{1}{3}$ HP sump pump (Right) prior to filling prototypes for treatment testing.

4.3.4 - Experiment B-2: Procedures

On November 22, 2008, two prototypes were tested using the water recipe described above. One prototype was treated using a single PÜR[®] packet, secured closed, mixed by repeatedly inverting the bag 180° for 30 seconds, and then hung vertically on the coat rack to settle for 30 minutes. The other prototype, the control, followed the same procedure of filling, mixing, and settling; but a PÜR[®] sachet was not added to the prototype. Turbidity measurements were taken pre-treatment, once every five minutes during the settling time, and post filter until clogged. Temperature, pH, total suspended solids, total coliform bacteria, and *E. coli* tests were also performed on the pre- and post-treated water.

4.3.5 - Experiment B-3: Procedures

On January 25, 2009, three prototypes (two treated with PÜR[®] sachets and one control unit not treated) and three standard PÜR[®] bucket tests (two treated PÜR[®] sachets and one control unit not treated) were tested. The treatment mixing and settling procedure for the prototypes was standardized at (1) add PÜR[®], (2) invert 20 times, at a 40 beats per minute pace, and, (3) settle vertically for 30 minutes. An inversion is defined as a 180° turn of the prototype in the air on its short axis. The inversion pace was maintained at 40 beats per minute with a metronome. The PÜR[®] bucket procedure was followed based on the standard PÜR[®] instructions (refer to **Figure 2.12** in Section 2.6.1). Additionally, each bucket was disinfected prior to the experiment. Turbidity was measured prior to treatment, once every five minutes during the settling time, and post filter until clogged. Temperature, pH, solids testing, chlorine residual, total coliform bacteria, and *E. coli* tests were also performed on the pre- and post treated water.

4.4 - Optimization Experiments

The Optimization Experiments included nine different tests with 10-L volume prototypes. The overall objective of the experiments was to identify the optimal mixing and settling protocol that yielded final post-treated turbidities of <5 NTU.

4.4.1 - Water Collection and Preparation

As with the Baseline Water Quality Experiments, the test water for all of the Optimization Experiments was collected from the discharge outlet point of Drumm Reservoir and the Swine Unit Pond at Cal Poly. The Drumm Reservoir water was stored in the laboratory out of the sunlight, and the Swine Unit Pond water was stored in the

refrigerator for a 24-hour period prior to experimentation. The day of the experiment (for C-1 through C-8), the water and constituents were prepared in the same way as B-2 and B-3 Experiments (refer to Section 4.3). However, to standardize each experiment, the sump pump was kept on for 30 minutes for mixing; and at the end of the 30 minute period, each prototype was filled immediately with 10 L. The water recipe created for these experiments used A2 Fine Test Dust (ISO 12103-1 from Powder Technology, Inc) in place of kaolin acid-washed powder (**Table 4.2**). The A2 Fine Test Dust is the recommended constituent for increasing water turbidity according to the U.S. EPA Purifier Guidelines (U.S. EPA, 1987).

Table 4.2 - Test water recipe for Optimization Experiments

Experiment	Water Recipe	Amount
Optimization Experiments	Drumm Reservoir water	10 L / prototype
	Swine Unit Pond	100 mL / 10 L
	A2 Fine Test Dust	5.0 g / 10 L ^{1,2}
	Instant Ocean	10 g / 10 L ²

¹5.0 g/10L was used for Experiments C-1 through C-8; however, the dust amount varied for each prototype tested in Experiment C-9.

²Appendix A describes the dust and Instant Ocean amounts in more detail.

Experiment C-9 tested waters at different initial turbidities; thus, water batches were prepared separately. A 15-L batch was prepared for each prototype for test water recipe mixing and dispensing purposes; however, each prototype was still filled with only 10-L of the test recipe water. The mixing preparation included homogenizing the swine unit water, the A2 Fine test dust, and Instant Ocean, using the liquefy setting, on the

Osterizer[®] glass blender for one minute, then adding it to the 15-L volume of Drumm Reservoir Water contained in a dispensing container set on a mixer with a magnetic stirrer bar (**Figure 4.7**). The mixer was set on stirring speed 6 for five minutes and then each prototype was filled with the 10-L volume and ready for treatment testing. The A2 Fine test dust was the only constituent that varied for each batch of water. Otherwise, each 15-L batch consisted of 15 L Drumm Reservoir water, 150 mL Swine Unit Pond water, and 15 g of Instant Ocean. The A2 Fine test dust per 15 L increased for each of the five prototypes tested, at 1.5 g, 3 g, 5.25 g, 8.25 g, to a max of 11.25 g of dust.

Figure 4.7 - Test water recipe preparations for Experiment C-9, in which the dispensing container was set on the mixer for five minutes.

4.4.2 - Procedures

Each optimization experiment tested different mixing and settling methods, and the time variable associated with each step. Rapid and gentle mixing are both steps in conventional water treatment facilities that promote coagulation and flocculation, followed by sedimentation. The standard PŪR[®] bucket method performs the rapid mix by stirring the powder steadily and rapidly in the water for five minutes. Once the particles in the water begin to flocculate, they settle; and the water is decanted into a clean bucket. The goal of the Optimization Experiments was to conduct these procedures in the prototype, in order to achieve low turbidity measurements prior to filtration. The first step was to estimate the mixing time and intensity needed to properly mix the PŪR[®] packet contents within the prototype. The estimation was performed based on conventional water treatment design and bubble column equations for power input in a bubble. The equations are introduced below, followed by method of analysis and assumptions made. The detailed calculations are shown in Appendix B.

For conventional water systems, mixing intensity is characterized by the root-mean-square (RMS) velocity gradient (G) of the system (MWH, 2005). The velocity gradient is a function of power dissipated per unit volume. The RMS velocity gradient is calculated with the following equation:

Equation 4.1

$$G = \sqrt{\frac{P}{\mu V}}$$

where G = RMS velocity gradient (energy input rate), s^{-1}

μ = dynamic viscosity of water, N·s/m²

P = power of mixing input to vessel, J/s

V = volume of mixing vessel, m³

For mixing vessels with rotating impellers, power is calculated by the following impeller design equation (Tchobanoglous & Schroeder, 1987). This equation was used to estimate the power input from mixing a bucket using a spoon per the PUR bucket method.

Equation 4.2

$$N_p = \frac{P}{\rho n^3 D^5}$$

where N_p = power number, dimensionless

ρ = density of water, kg/m³

n = rotational speed, rev/s

D = diameter of mixing impeller, (2/3 diameter of vessel)

Equation 4.1 and Equation 4.2 were used to estimate power input and RMS velocity gradient, G , corresponding to the bucket method, assuming similar properties to a conventional water mixing process. Assumptions include that the mixing spoon for the bucket method corresponds to a conventional mixing impeller and that the diameter of the mixing impeller is considered 2/3 the diameter of the bucket. The waterbag prototype was then analyzed using bubble column mixing equations (Blanch and Clark, 1997):

Equation 4.3

$$P = Q\gamma H$$

where: Q = volume/time

γ = unit weight of water

H = bubble travel distance

Considering the pressure equation $P_1 = P_2 + \gamma H$, Equation 4.3 can then be expressed as (Blanch and Clark, 1997):

Equation 4.4

$$P = Q_M \gamma H$$

where: Q_M = mean volumetric flow rate in the vessel; which is equivalent to:

$$Q_M = Q \frac{P_2}{P_{LM}}$$

where: P_{LM} = logarithmic mean pressure difference between the top and bottom of the vessel; which is equivalent to:

$$P_{LM} = \frac{P_1 - P_2}{\ln \frac{P_1}{P_2}}$$

where: P_2 = pressure at top of vessel (atmospheric pressure); P_1 = pressure at bottom of the vessel

Power (P) for the prototype is solved for in Equation 4.4 by using the P_{LM} and Q_M variables. Once power is solved for, the G value for the prototype can be obtained from Equation 4.1. Lastly, using the main design parameter of mixing, Gt, (where t is defined as the detention time in mixing vessel), detention time for the prototype was solved for using the known five minutes of detention time needed for the PÜR[®] bucket protocol. The mixing time estimated for the prototype was translated into “X” number of inversions for mixing of the prototype, based on a consistent beats per minute during mixing. The time estimated was 3.1-min of mixing which corresponds to 124 inversions

based on the 40 beats per minute (refer to Appendix B). This was used as a starting point for the Optimization Experiments.

The first Optimization Experiment, C-1, tested different inversion variations for mixing the prototype. Additionally, a single prototype in this experiment tested the upper detention time range at 5 minutes (based on the PÜR[®] bucket protocol) through horizontal mixing by rocking the prototype along its long axis. The results of this experiment dictated the mixing scenario of the subsequent Optimization Experiments. Settling orientation was also tested within the 30-minute limit. Reasons for changes in methods to optimize the procedure are presented in Chapter 5, Section 5.3. Each test variable examined became an integral part of optimizing the final treatment procedure in the laboratory. Mixing methods and intensities, along with settling methods (**Table 4.3**) affected the final turbidity prior to filtration. The treatment goal was to obtain the lowest turbidity prior to filtration to minimize clogging of the 1- μ m filter cloth. Lastly, the chosen protocol for the Mark I prototype was tested in Experiment C-9, with varying initial water turbidities to provide information on the protocol treatment efficacy. Each variable is defined below:

Inversion - An inversion was defined as a single 180° turn of the prototype in the air on the short axis, from vertical back to vertical. The inversions were performed at a rate of 40 beats per minute; this rate was maintained throughout the inversion mixing stage using a digital metronome.

Horizontal Mix - Horizontal mixing was performed with the prototype resting on the ground while rocking the prototype 180° (complete amplitude) along its long axis.

Horizontal Mixing Intensity - Two horizontal mixing intensities were tested. The first used a rate of 36 beats per minute. The second mixing intensity, introduced in Experiment C-6, was maintained at a rate of 100 beats per minute.

Horizontal Settling - Horizontal settling occurred after the horizontal mix by leaving the prototype on the ground for a defined time period. At the end of this period, the prototype was tilted to the vertical position. Fifteen seconds was the standardized time to move the prototype from the horizontal to vertical position.

Vertical Settling - Vertical settling was performed directly after the mixing stage or after the horizontal settling stage, depending on experiment. The prototype was hung on the 5½-ft coat rack to allow for vertical settling of the particles for a defined time period.

Table 4.3 - Test variables examined during Optimization Experiments

Experiment	Major Test Variables Examined
C-1	<p>4 prototypes: <u>Varied</u>: Number of inversions</p> <p><u>Constant</u>: Vertical settling</p> <p>1 prototype: Combination inversion and horizontal mix followed by 15 min horizontal settling and 15 min vertical settling</p>
C-2	<p>4 prototypes: <u>Varied</u>: Horizontal mix times</p> <p><u>Constant</u>: Number of inversions</p> <p>1 prototype: Combination inversion and horizontal mix followed by 15 min horizontal settling and 15 min vertical settling</p>
C-3	<p>5 prototypes: <u>Varied</u>: Horizontal and vertical settling</p> <p><u>Constant</u>: Number of inversions and horizontal mix</p>
C-4	<p>3 prototypes: <u>Varied</u>: Horizontal mix times, horizontal and vertical settling</p> <p><u>Constant</u>: Number of inversions</p>
C-5	<p>4 prototypes: <u>Varied</u>: Horizontal mix times, horizontal and vertical settling</p> <p><u>Constant</u>: Number of inversions</p>
C-6	<p>4 prototypes: <u>Varied</u>: Horizontal mix intensity, horizontal and vertical settling</p> <p><u>Constant</u>: Number of inversions</p>
C-7	<p>4 prototypes: <u>Varied</u>: Inversions, horizontal mix times, horizontal and vertical settling</p> <p><u>Constant</u>: No methods</p>
C-8	<p>4 prototypes: <u>Varied</u>: Number of inversions</p> <p><u>Constant</u>: Horizontal mix times, horizontal and vertical settling</p>
C-9	<p>5 prototypes: <u>Varied</u>: Initial turbidity</p> <p><u>Constant</u>: Number of inversions, horizontal mix times, horizontal and vertical settling</p>

For each experiment, turbidity was measured prior to treatment, once every five minutes during the settling time and post filtration. Furthermore, depending on the experiment, non-microbiological parameters (temperature, pH, suspended solids, and chlorine residual), and microbiological parameters (total coliform bacteria and *E. coli*) were also tested on the pre- and post-treated water. An example sampling plan is shown in **Table 4.4**. Sampling plans were adjusted depending on the test variables examined. For instance, turbidity measurements were taken once every 5 minutes only during the vertical settling prior to filtration but not during the mixing process or the horizontal settling stage. Additional parameters measured include flow parameters such as filtered volume discharged and the time period of the discharge in filter).

Table 4.4 - Example sampling plan for a single prototype

Sampling Point ¹	Test			
	Turbidity	Physical/ Chemical ²	Microbiological	Flow Parameters
Pre Treatment	X	X	X	
Pre Filter: 5 min	X			
Pre Filter: 10 min	X			
Pre Filter: 15 min	X			
Pre Filter: 20 min	X			
Pre Filter: 25 min	X			
Pre Filter: 30 min	X	X	X	
Post Filter Initial ³	X			
After 100 mL Filtered	X	X	X	
After 1.1 L	X			X
After 2.1 L	X			X
After 3.1 L	X			X
After 4.1 L	X			X
After 5.1 L	X			X
After 6.1 L	X			X
After 7.1 L	X	X	X	X
After 8.1 L	X			X
After 9.1 L	X			X

¹Samples taken from the tubing connected to the valve port.

²Physical/chemical parameters include: turbidity, temperature, pH, TSS, TDS, and chlorine residual.

³From this point on, all samples were filtered.

4.5 - Analytical Methods

The non-microbiological parameters measured in the aforementioned experiments include turbidity, temperature, pH, alkalinity, free chlorine (or free chlorine residual), and solids testing. Each water quality testing procedure is briefly described below.

Turbidity - Turbidity was measured with a HACH 2100P Turbidimeter (Catalog # 46500-00, Lot L7002). Prior to each experiment, the turbidimeter was calibrated with StablCal[®] cuvettes: 0.1 NTU, 20 NTU, 100 NTU, and 800 NTU). Samples were collected in the turbidimeter cuvettes, inverted several times, and measured. A single cuvette was read on the turbidimeter three times, and the average of these readings was the result recorded. Lastly, the cuvettes were washed with deionized water (DI) water after use, cleaned with silicone oil, and stored until the next experiment. For the U.S. EPA Challenge Water Experiments, the turbidimeter was calibrated using a new batch of HACH formazin standards.

pH and temperature - Samples were grabbed using 500-mL beakers and measured using a Mettler Toledo Seven Easy pH meter that has a pH range from 0 to 14 with a resolution of 0.01. It also has an automatic temperature compensation, which corrects for the effect of temperature between -5°C and 105°C. The pH meter was calibrated periodically according to instruction manual.

Alkalinity - Since the ferric sulfate in PÜR[®] sachets is acidic and pH affects coagulation (Sawyer, McCarty, & Parkin, 2003), the acid buffering capacity of the samples was occasionally measured by titration (APHA Method 2320 B).

Free Chlorine - The HACH DR/890 Colorimeter, using Program 9, was used to measure free chlorine with HACH “powder pillows” DPD Free Chlorine Reagent (Cat. #21055-69) for 10 mL samples immediately upon sample collection. The method reads free chlorine within the range of 0 to 2.00 mg/L and is accepted by the U.S. EPA for reporting wastewater and drinking water analysis (HACH Manual DR/890 Colorimeter, Method 8021, undated). According to HACH Manual (Method 8021), which is equivalent to U.S. EPA Standard Methods 4500-Cl G, the estimated non-detection limit is 0.02 mg/L.

Solids - Total suspended solids (TSS) and total dissolved solids (TDS) were measured according to Standard APHA Methods 2540 C and D. Following Standard APHA Methods, Fisher Scientific G4 glass fiber filter circles, with a nominal pore size of 1.2- μm , were prewashed and ashed. The detection limit for TSS reading is 2.5 mg of dried residue. Even with the necessary volume size filtered, detection limits were reached in some experiments, and reported as Non-Detect (ND). The filtrate from the filtration was used for TDS testing (APHA et al., 1995).

The microbiological parameters measured included total coliform bacteria and *E. coli*. These parameters were both tested using the IDEXX Colilert[®] method (EPA approved) as described below.

Total Coliform Bacteria and E. coli - Grab samples were taken pre- and post- treatment with I-Chem Security-Snap BacT 100-mL bottles. The bottles were sterile, nontoxic polypropylene containing one 10-mg sodium thiosulfate tablet per bottle. Serial dilutions were performed on pre-treatment samples at 100x and 1000x dilutions using DI water and autoclaved glassware, while post-treatment samples were not diluted. Duplicate

samples were taken. After experimenting, the samples were brought to the Cal Poly biology department for Colilert[®] tray sealing and incubating. The steps for the 24-hour Colilert[®] quantification include: (1) Add Colilert[®] reagent to 100-mL sample and mix well, (2) pour into Quanti-Tray[®]/2000 (counts from 1 to 2,419), (3) seal in the Quanti-Tray Sealer (IDEXX Cat. # WQTS2X-115), (4) place in incubator for 24 hours at 35°C, and, (5) read results (**Figure 4.8**), referring to the Colilert[®] Most Probable Number (MPN) table, where yellow wells equate to positives for total coliform bacteria, and yellow/fluorescent wells represent *E. coli* (IDEXX Laboratories, Inc., 2007).

Figure 4.8 - IDEXX Quanti-Trays[®]/2000 after 24-hour incubation at 35°C from Baseline Experiment B-3. The tray on the left shows the presence of total coliform bacteria in the pre-treatment water sample at 10x dilution while the tray on the right represents a non-diluted post-treated prototype sample free from total coliform bacteria.

The Colilert[®] method uses Defined Substrate Technology[®] to detect total coliform bacteria and *E. coli* in water (**Figure 4.9**) (IDEXX Laboratories, Inc., 2007). According to IDEXX, as coliform bacteria grow in Colilert[®] media, they use β -galactosidase to metabolize the nutrient indicator ONPG, and change it from colorless to yellow, while *E. coli* use β -glucuronidase to metabolize MUG and create fluorescence. Most non-coliform bacteria do not have these enzymes, and thus, do not grow. For the non-coliform bacteria with these enzymes, they are suppressed by Colilert[®] media, minimizing false positives and false negatives (IDEXX Laboratories, Inc., 2007).

Figure 4.9 - IDEXX Defined Substrate Technology[®] to detect total coliform bacteria and *E. coli* in water (IDEXX Laboratories, Inc., 2007).

The last parameter measured was flow through the filter. From Experiment C-6 forward, the flow was regulated using a hosecock clamp around the tubing (**Figure 4.10**). It was positioned after the valve port but prior to the water entering the filter apparatus to regulate the flow as to not hydraulically overload the filter. Filtration rates were taken by timing the discharge of water through the filter into a 1,000-mL beaker.

Figure 4.10 - Hosecock clamp used to regulate flow discharged from the spring-loaded valve in order to not overload the filter cloth.

4.6 - U.S. EPA Challenge Water Experiments

After optimizing the mixing and settling procedures, the next step was to test the prototype with the U.S. EPA Challenge Test Water #2 to evaluate the performance of the chlorine disinfection and filter unit. First, a Mock Run Experiment was conducted using the PÜR[®] bucket method and a prototype waterbag. During this test, only the physical and chemical components of the U.S. EPA Test Water #2 were used; no microorganisms were added to the test water recipe. Second, a quick experiment, similar to the Mock Run Experiment, tested the filtration rates using the mock challenge water. Finally, a U.S. EPA Test Water #2 experiment was conducted at BioVir Laboratories in Benicia, CA, with the collaboration of Dr. Robert Cooper and staff.

4.6.1 - Mock Run Experiment: Water Preparations & Procedures

The water recipe for the Mock Run Experiment was based on the U.S. EPA Test Water #2 recipe, except no microorganisms were added to this water. Temperature, pH, turbidity, organic matter, and total dissolved solids were altered according to the U.S. EPA Purifier Guidelines (Table 4.5).

Table 4.5 - Mock Run test water recipes for the bucket and prototype tests.

Test Water Recipe	Amount for Bucket	Amount for Prototype
Reverse Osmosis treated San Luis Obispo, CA water	10 L / bucket	15 L of which 10 L used for the prototype
pH adjustment using NaOH	To reach a pH of 9.0	To reach a pH of 9.0
Ice	To reach 4°C	To reach 4°C
A2 Fine Test Dust ¹	5 g / 10 L	7.5 g / 15 L
Instant Ocean ¹	10 g / 10 L	22 g / 15 L ²
Humic Acid ¹	400 mg / L	600 mg / 15 L

¹Appendix A describes the A2 Fine Test Dust, Instant Ocean, and Humic Acid in more detail.

²The Instant Ocean amount was increased for the prototype since the initial TDS measured for the bucket test was 1030 mg/L. This is less than the U.S. EPA Purifier Guideline challenge of 1500 mg/L. Increasing the Instant Ocean concentration increased the initial prototype initial TDS reading to 1570 mg/L.

The test water recipe was homogenized in the same way as in the Optimization Experiment C-9 with the addition of the humic acid. Once the water was prepared, sodium hydroxide (NaOH) was added to increase the pH of the water to 9.0, and then the water container was placed in a cooler filled with ice to drop the temperature to 4°C (Figure 4.11).

The PÜR[®] bucket protocol was performed based on the standard PÜR[®] instructions and the prototype treatment was based on the procedures selected from the Optimization Experiment results. Turbidity, temperature, pH, TSS, and TDS were analyzed for each experiment.

Figure 4.11 - Prepared water container set in ice to drop the temperature to 4°C for the Mock Trial Experiments based on the U.S. EPA Purifier Guidelines.

The quick waterbag prototype test followed the same water preparations and procedures as the Mock Run Experiment. However, temperature and pH were not adjusted (remaining at 20°C and a pH of 8.00). Turbidity and filtration rates were recorded over the total volume output.

4.6.2 - U.S. EPA Challenge Water Experiment: Water Preparations and Procedures

This experiment was conducted by the Cal Poly team at BioVir Laboratories in Benicia, CA, on July 13, 2009, under the supervision of Dr. Robert Cooper and his staff. The objective of the experiment was to conduct the Test Water #2 challenge experiment on three 10-L prototypes (fabricated by Cascade Designs Inc., June 2009) using the PÜR[®]

treatment and standard procedures identified in the Optimization Experiments. The three prototypes were challenged with the bacterium *Raoultella terrigena* (ATCC 33257), two coliphage types MS2 (ATCC 15597-B1) and fr (ATCC15767-B1), and with 3.1- μ m diameter fluorescent microspheres as a surrogate for *Cryptosporidium* oocysts (Duke Scientific Corp, Palo Alto, CA). The organisms and microsphere suspensions were prepared by BioVir staff along with the challenge water (40 L of Test Water #2) (refer to **Table 2.5** for the U.S. EPA Purifier Guideline's test water properties).

Just prior to the challenge, the test water was inoculated with the microorganisms and microspheres (**Figure 4.12**). The microorganisms were prepared per standard BioVir protocols. The test water was constantly mixed using a magnetic stirring device, and then each bag was filled with 10-L of the test water prior to treatment testing (**Figure 4.13**).

Figure 4.12 - BioVir staff member inoculating the Test Water #2 with the challenge microorganisms and microspheres

Figure 4.13 - Dr. Tryg Lundquist (left) and Dr. Robert Cooper (right) filling a prototype with the Challenge Test Water #2 prior to treatment testing at BioVir Laboratories in Benicia, CA.

After filling each of the prototypes, a PÜR[®] packet was added to the top end of the prototype; it was secured closed, and the coagulant-disinfectant process began as the contents were mixed and settled according to the Mark I prototype procedures identified from the Optimization Experiment results. The optimal mixing and settling method, is as follows: (1) add PÜR[®], (2) invert 20 times at a rate of 40 beats per minute, (3) mix horizontally at a rate of 100 beats per minute for 5 minutes, (4) settle horizontally for 10 minutes, (5) settle vertically for 15 minutes, and, 6) filter water. For each prototype, the Cal Poly team measured turbidity once every five minutes during the vertical settling time and at the post-filtration point when 4 L had been filtered. Temperature, pH, and chlorine residual were also taken at the end of the 4-L filtration.

The runs were ended after 4 L had been filtered so that the samples represented the middle-point of the treated water. Therefore, the 4th liter filtered was collected by BioVir staff into sterile 1-L bottles containing enough sterile sodium thiosulfate to neutralize any residual disinfectant that might be present in the sample. Additionally, a composited influent sample (sub-samples taken when the first bag was filled and when the last bag was filled) was collected from the 40-L Challenge Water reservoir. The three prototype tests were started at about 10-min intervals. The influent and product water samples were kept refrigerated until assayed, usually a period of no more than 3 hours. The *R. terrigena* assays were performed by BioVir using the membrane filter method with mFC agar incubated for 20 to 24 hours at 35°C; the results being reported as colony forming units (CFU) per 100 mL. The combined bacteriophage were assayed using the Adams double agar overlay method and reported as plaque-forming units (PFU) per mL (not 100 mL). The microspheres were enumerated by direct microscopic count using epi-fluorescent microscopy and reported as spheres per L (BioVir Laboratories, Inc., 2009) (refer to

Appendix C for BioVir Laboratories Microbial Seed Requirement Report for the challenge water experiment).

Flow rates of the filtered water were also recorded for each prototype. For the first prototype only, TOC samples were collected at the end of the 30-minute settling period pre- and post- filtration. The TOC samples were collected in volatile organic analysis (VOA) vials containing HCl preservative provided by Creek Environmental Laboratories in San Luis Obispo, CA. The samples were refrigerated until they were transported to Creek Environmental Laboratories which performed the TOC analysis according to Standard APHA Methods 5310 B.

CHAPTER 5 - RESULTS AND DISCUSSION

This chapter presents the results and discussion for the four main series of experiments conducted: (1) Filter Selection Experiments, (2) Baseline Water Quality Experiments, (3) Optimization Experiments, and, (4) U.S. EPA Challenge Water Experiments. Lastly, a summary is provided on the September 2009 preliminary field testing of the waterbag prototype in Nicaragua.

5.1 - Filter Selection Experiments

The main objective of the Filter Selection Experiments was to identify which cloth material filtered out sediment and particles from PUR[®] treated water to meet the WHO emergency guidelines for turbidity. The guidelines state that the final treated water turbidity should be <5 NTU. The four different fabrics were hemp, two cotton materials, and polypropylene cloth. Each material was cut to 3-in diameter circular pads and

secured within the Millipore™ Stainless Steel Filter Holder 90-mm apparatus. Additionally, during the 0-30 minute treatment time required by the PÜR® treatment, turbidity was examined to determine the relationship between settling time and turbidity. Kaolin amounts were not recorded during this experiment set since these tests were the initial screening experiments; thus, initial turbidities varied significantly. Experiments A-1 through A-6 were conducted during prototype development, at which point only 6-L prototypes were designed. Each of the 6-L prototypes was treated with an entire PÜR® packet. From Experiment A-7 forward, each prototype contained 10-L of test water and was treated with a single PÜR® packet. The following subsections provide the results obtained during the experiments, which led to a final cloth selected for the remaining experiments.

5.1.1 - Experiment A-1: Hemp Filters

Experiment A-1 tested two- and three-ply hemp cloth (Hemp Traders USA, Models CT-TLT, CA-CL1, and CA-K1). Three 6-L prototypes (Bag 1, Bag 2, and Bag 3) had different initial water turbidities: 376 NTU, 531 NTU, and 687 NTU. After the PÜR® packet was added to the water, the prototype was inverted 10 times, settled horizontally for 10 minutes, and settled vertically for 20 minutes. At the end of the 30 minute period, pre-filter turbidities improved to 13.2 NTU, 15.4 NTU, and 21.4 NTU. Then, water was sampled from the top opening of the prototypes and filtered through either two- or three-ply hemp cloths, achieving turbidities ranging from 5.97 (2-ply) and 2.43 (3-ply) (**Figure 5.1**).

Figure 5.1 - Turbidity from three 6-L prototypes were measured prior to filtration and post-filtration. Filters were two- or three- ply hemp cloths. Three-ply hemp cloth provided turbidities lower than the 5 NTU standards.

5.1.2 - Experiments A-2 through A-6: 100% Cotton Cloth Filters

Multi-ply Hanes[®] 100%-cotton t-shirt material was used to filter water from 6-L prototypes for Experiments A-2 through A-6. Single prototypes were tested at varying initial turbidities for each experiment and then filtered after the 30-minute chlorine contact time and settling to determine the number of filter cloth layers required to decrease turbidity to <5 NTU. Initial turbidities for Experiments A-2 through A-6 ranged from 347-887 NTU, and pre-filtered turbidities ranged from 29.8-65.4 NTU after treatment in the waterbags alone. Five layers of the Hanes[®] 100% cotton cloth were required to reach the turbidity goal of <5 NTU. Three of the experiments, A-3, A-5, and A-6, used 5-ply cotton cloth filters resulting in turbidity levels of 4.46 NTU, 1.89 NTU, and 4.29 NTU, respectively (**Figure 5.2**).

Figure 5.2 - Five plies of 100% cotton Hanes® cloth were required to bring filtered turbidities below the 5 NTU standard. The tests were performed with the 6-L prototypes.

5.1.3 - Experiment A-7: Woven Bleach White Kona® Cotton Filters

Experiment A-7 tested woven multi-ply Bleach White Kona® cotton (Product #K001-1287 PFD) as a filter medium for the first 10-L prototype, with an initial turbidity of 561 NTU. At the end of 30 minutes, turbidity decreased to 48.0 NTU due to treatment with PÜR® in the waterbags only. The PÜR® treated water was then filtered through multiple Kona® cotton layers. Filtration through 5 cloth layers corresponded to a turbidity of 9.83 NTU. A turbidity of 1.88 NTU was achieved after filtering through seven cloth layers (Figure 5.3).

Figure 5.3 - During Experiment A-7, the clarity of the PÜR® treated water was higher for greater numbers of layers, with seven layers being required to achieve a turbidity of 1.88 NTU.

5.1.4 - Experiment A-8 and A-9: 1- μ m Polypropylene Felt Cloth Filters

The next two experiments, A-8 and A-9, tested a single-ply polypropylene cloth (1- μ m retention rated) cut from a filter bag. Each experiment tested water treated in a single 10-L prototype with initial turbidities of 285 NTU and 520 NTU. The final pre-filter turbidities resulted in 47.8 NTU and 32.6 NTU, decreasing to 2.16 NTU and 0.85 NTU post filtration (**Figure 5.4**).

Figure 5.4 - For Experiments A-8 and A-9, pre-filtered turbidity measured 47.8 NTU and 32.6 NTU, respectively. Once filtered through the 1-µm polypropylene cloth, turbidities decreased to 2.16 NTU and 0.85 NTU.

5.1.5 - Experiments A-7 through A-9: 10-L Prototypes Settled Turbidity

During this experiment series, turbidity measurements were recorded during the 30-minute treatment time for the 10-L prototypes to determine the relationship between settling time and improved water clarity. Turbidity measurements were taken every five minutes during the 30 minute chlorine contact period. Experiment A-7 turbidity decreased from 261 NTU at five minutes to 48.0 NTU at the end of 30 minutes; Experiment A-8 turbidity decreased from 147 NTU to 47.8 NTU; and Experiment A-9 turbidity decreased from 198 NTU to 32.6 NTU (**Figure 5.5**). The data show steep NTU decreases from 0- to 10-minutes, with a decreasing rate of improvement during the last 15 minutes. The turbidity did not measure below 30 NTU prior to filtration. Subsequent

experiments investigated these trends in more detail with variations in mixing and settling procedures (refer to Section 5.3).

Figure 5.5 - Turbidity removal rates decreased drastically after 10 minutes of settling, and final 30-minute turbidities were similar for all levels of initial turbidity.

5.1.6 - Selected Filter Material

The WHO emergency drinking water guideline for turbidity requires that final treated water measure <5 NTU. The Filter Selection Experiments determined which materials, and how many layers, met this requirement. For the 6-L prototypes, 3-ply hemp cloth and 5-ply 100% cotton Hanes[®] met the standard; however, for a 10-L prototype, seven layers of the Kona[®] cotton were required to improve water clarity to <5 NTU (**Table 5.1**). These turbidity measurements were achieved during the first 500-mL of water filtered at approximately a 0.5 L/min flow rate. Since the volume, and therefore head on the filter and flow rate, was different for the 6-L and 10-L prototypes, it is unclear whether the

higher layer requirement of the Kona[®] cotton was a material issue or a hydraulic loading issue. In any case, the number of cotton cloths needed to achieve turbidities <5 NTU coincides with the University of Maryland study in Bangladesh. Even though they did not measure turbidity, they determined that sari cloth (typically 100% cotton) when folded four to eight times provided a 99% (2-log) removal of *Vibrio cholera* (Colwell, 2003). The standard PŪR[®] bucket method also calls for cloth fabric to filter water prior to consumption. The PŪR[®] treated water in one bucket is decanted into a clean bucket through a cloth fabric at a lower head compared to the waterbag prototype; however, according the Standard Operating Procedures of PŪR[®] in emergency settings, multiple cloths may be necessary to inhibit flocs from being decanted into the clean bucket (The Aquaya Institute, 2006).

Table 5.1 - Summary table of filter material layers used to achieve <5 NTU turbidity after 500 mL filtered.

Filter Material	Number of Layers used to Achieve <5NTU	Range of Filtered Turbidity (Post 500 mL)
Hemp	3-ply	2.43 NTU - 3.92 NTU
Hanes [®] 100% Cotton	5-ply	1.89 NTU - 4.46 NTU
Kona [®] 100% Cotton	7-ply	1.88 NTU
1-μm Polypropylene	1-ply	0.85 NTU - 2.16 NTU

Even though the turbidity standard was achievable with all fabrics used, the durability of the cloth materials is a concern. When a woven cloth material becomes worn and loose, the pore size is increased (Hutten, 2007). The nonwoven needle-punched 1-μm polypropylene cloth appeared to be more durable than the cotton and hemp fabrics.

Selection of the polypropylene material as the routine filter material was also supported by the WHO recommendation for water treatment devices for removal of protozoa, such as *Giardia lamblia* and *Cryptosporidium parvum*: which calls for “a filter media pore size of 1-micron or less” (WHO, 2005). After the PÜR[®] treated water was filtered through a single 1- μ m pad, the turbidity standard was achieved for initial water turbidities of 285 NTU and 520 NTU. Due to its durability and small pore size, the 1- μ m polypropylene cloth was selected as the filter material for the subsequent experiments.

Lastly, another point to consider is that only 500 mL of the total volume was filtered during this experiment set. Filter ripening can occur from greater filtered volumes creating a particle layer on the filter pad which aids in improved trapping of particles and improving water clarity. Filter ripening was investigated in future experiments with the 1- μ m polypropylene cloth filter pad.

5.2 - Baseline Water Quality Experiments

The next experiment series tested 10-L prototypes with different source waters to obtain baseline data that characterized the pre- and post- treated water. Three baseline experiments were conducted: Experiment B-1, with primary effluent from the San Luis Obispo water treatment facility, Experiment B-2 and B-3 with water from Drumm Reservoir and the Swine Unit pond at Cal Poly. The goal of these experiments was to evaluate how the prototype coupled with the PÜR[®] treatment performed with different source water conditions. The following subsections provide the results obtained during the experiments and each subsection is followed by a discussion of the results.

5.2.1 - Experiment B-1: Treating SLO WWTP Primary Effluent

Primary effluent from the San Luis Obispo, CA, wastewater treatment plant with the addition of kaolin acid-washed powder was prepared in two 10-L prototypes, one chilled to 4°C and the other kept at room temperature at approximately 20°C. The motivation for collecting primary effluent, changing the temperature, and increasing turbidity is based on the U.S. EPA Protocol Challenge Waters microbiological challenge and physical challenge (refer to Section 2.4). Instead of creating the challenge water in the laboratory as described in the U.S. EPA Purifier Guidelines, the goal was to first test existing water sources, such as wastewater. The water quality prior to treatment is characterized in **Table 5.2**.

After adding the PÜR[®] packets, the prototypes were inverted 10 times and hung vertically to allow the flocs to settle. Turbidity readings were taken every five minutes during the 30 minute settling period. Pre-filter turbidities were 227 NTU for Bag 1 and 150 NTU for Bag 2, and filtered turbidities were 111 NTU and 143 NTU, respectively (**Table 5.2**). The filtered water turbidities were taken after 500 mL of water was filtered through the 1-µm polypropylene filter cloth. No further water was sampled as the filter cloth clogged at 500 mL (**Figure 5.6**). Chlorine residual and TSS concentrations were also sampled from the filtered water. The TSS concentrations did not change in Bag 1 due to treatment. In Bag 2, they did decrease to 20 mg/L. Chlorine residual concentrations of 0.48 mg/L and 0.50 mg/L were measured after the 30 minute settling period, meeting the CDC SWS program recommended concentration of less than or equal to 2.0 mg/L. However, even with the residual chlorine concentrations found, the disinfectant did not remove total coliform bacteria or *E. coli* sufficiently

samples were processed for this experiment; but the bacteria concentrations, even at 10,000x dilutions, exceeded the Colilert Quanti-Tray[®]/2000 maximum concentration of 2,419 MPN/100 mL (IDEXX Laboratories, Inc., 2007).

Table 5.2 - Pre- and post- treatment water quality characteristics of SLO wastewater treatment facility primary effluent for Experiment B-1.

Water Quality Parameter	Bag 1 (Pre-Treatment)	Bag 1 (Post-Treatment)	Bag 2 (Pre-Treatment)	Bag 2 (Post-Treatment)
Temperature (°C)	4.0	10.0	22.8	23.0
Turbidity (NTU)	301	227 (Pre-Filter) 111 (Post-Filter)	268	150 (Pre-Filter) 143 (Post-Filter)
pH	7.7	NS ¹	7.7	NS ¹
Chlorine Residual (mg/L)	ND ¹	0.5	ND ¹	0.48
TSS (mg/L)	60	60	60	20
Total Coliform Bacteria (MPN/100 mL)	>2419	>2419	>2419	>2419
<i>E. coli</i> (MPN/100 mL)	>2419	>2419	>2419	>2419

¹NS = Not Sampled

¹ND = Non-Detect (HACH Method 8021, estimated detection limit is 0.02 mg/L)

Figure 5.6 - Experiment B-1, Bag 1, shown with clogged 1- μ m polypropylene cloth after 500 mL of treated water was filtered. In the background, the prototype is shown with settled flocs at the conical bottom; however, the water did not improve sufficiently in clarity, having only reached a filtered turbidity of 227 NTU.

5.2.1.1 - Discussion of Experiment B-1 Results

Bag 1 and Bag 2 from Experiment B-1 performed poorly and did not meet all of the WHO emergency water quality guidelines, as final filtered turbidities were greater than 100 NTU. Additionally, the filter cloth clogged after filtering only 500 mL of water, leaving 9.5 L unfiltered. This indicates, and was confirmed visually, that particles and organic matter remained suspended in the water and did not coagulate into settleable flocs.

Primary effluent obviously could not be treated sufficiently with the PUR and waterbag method. Therefore, no further primary effluent experiments were performed. The focus shifted to treating source water that represented flood-like conditions. Henceforth, the remaining Baseline Experiments and Optimization Experiments treated source waters collected from a stormwater reservoir and a swine waste pond (refer to Materials and

Methods Section 4.3 for the Baseline Experiment test waters and Section 4.4 for the Optimization Experiment test waters).

5.2.2 - Experiment B-2: First Drumm Reservoir + Swine Unit Pond Water Test

Experiment B-2 was the first of many experiments in which Drumm Reservoir and Swine Unit Pond water were the base water for the test water recipes. Two prototypes were tested in this experiment, one was treated with PÜR[®], and the other was a control. The control mimicked the mixing and settling procedures, but did not receive a PÜR[®] coagulant/disinfectant packet. The initial water quality characteristics for the prototypes are summarized in **Table 5.3**.

Table 5.3 - Water quality characteristics of test water comprised of a mixture of Drumm Reservoir and Swine Pond waters, with turbidity additions prior to prototype treatment for Experiment B-2.

Water Quality Parameter (Pre-Treatment)	Treated Bag	Control Bag
Temperature (°C)	18	18
Turbidity (NTU)	521 ¹	302 ¹
pH	7.99	8.00
Chlorine Residual	NS ²	NS ²
TSS (mg/L)	136	96.5
Total Coliform bacteria (MPN/100 mL)	2.04 x 10 ⁴	1.57 x 10 ⁴
<i>E. coli</i> (MPN/100 mL)	1.05 x 10 ⁴	1.03 x 10 ⁴

¹Despite equal amounts of kaolin powder added, initial turbidities varied substantially; this may be from not homogenizing the test water recipe prior to the experiment. This problem was overcome in later experiments.

²NS = Not Sampled

The treatment process consisted of PÜR[®] packet addition (excluded from the control), inversion of the prototypes 10 times, followed by hanging vertically to allow the flocs to settle. Turbidity readings were taken every five minutes during the 30-min settling period. The pre-filter turbidities (post 30-minutes) for the Treated Bag and Control Bag were 187 NTU and 283 NTU, respectively. Thus, treatment in the waterbag alone (with PÜR[®]) reduced turbidity by 64%, compared to the control waterbag without PÜR[®] that decreased turbidity only by 6%. Once filtered, the turbidities dropped to 11 NTU and 218 NTU, a 94% and 23% decrease, respectively. The Treated Bag also had a residual chlorine concentration of 0.15 mg/L and showed a decrease in TSS, total coliform bacteria, and *E. coli* concentrations. The final treated water quality characteristics are summarized in **Table 5.4**.

Table 5.4 - Experiment B-2 water quality characteristics for the Treated and Control Bag

Water Quality Parameter (Post-Treatment)	Treated Bag	Control Bag
Temperature (°C)	18	18
Turbidity (NTU) (Pre-Filter)	187	283
Turbidity (NTU) (Post-Filter)	11	218
pH	7.63	8.02
Chlorine Residual (mg/L) ¹	0.15	NS ²
TSS (mg/L)	11	86.5 mg / L
Total Coliform bacteria (MPN/100 mL)	8.31 x 10 ²	1.68 x 10 ⁴
<i>E. coli</i> (MPN/100 mL)	4.57 x 10 ²	1.12 x 10 ⁴

¹Chlorine residual estimated detection limit is 0.02 mg/L (HACH Method 8021)

²NS = Not Sampled

Additionally, turbidity gradually decreased during the settling period for the Treated Bag during five minutes to 25 minutes (**Figure 5.7**). From time zero to five minutes, the turbidity increased drastically from 521 NTU to 859 NTU, and between the time of 25 and 30 minutes, the turbidity increased slightly from 154 NTU to 187 NTU (**Figure 5.7**). The peaks in turbidity, particularly the initial peak of 859 NTU, is attributed to the PÜR[®] packet ingredients: ferric sulfate, which turns the water an orange tint, in combination with bentonite, a swelling clay that initially increases the particulate content in the water.

Figure 5.7 - Turbidity measurements over the 30 minute settling period for the Treated Bag in Experiment B-2. The turbidity initially rose to a peak of 859 NTU, then gradually decreases before slightly increasing to a final, pre-filtered turbidity of 187 NTU.

5.2.2.1 - Discussion of Experiment B-2 Results

The Treated Bag showed much better results when compared to the Control Bag throughout the course of Experiment B-2. However, the filtered water from the Treated Bag did not meet the WHO emergency guidelines. The filtered water turbidity of 11 NTU

is greater than the 5 NTU standard. The residual chlorine level of 0.15 mg/L was not sufficient for disinfection. The total coliform bacteria and *E. coli* results were greater than the WHO requirement of <1 *E. coli* MPN/100 mL. *E. coli* were present at 450 MPN/100 mL.

During the experiment, the Treated Bag did produce settable flocs; however, the clarity of the water did not improve to WHO turbidity guidelines (**Figure 5.8**), which was also the case in Experiment B-1. Additionally, the settling turbidities, as shown in **Figure 5.7**, demonstrate that particles are flocculating and settling, but not to the PÜR[®] treatment potential as observed in previous experiment series, A-7 through A-9. The flocs present showed that the coagulant in the PÜR[®] packet worked; however, the presence of suspended solids and the levels of *E. coli* found do not coincide with the typical standard PÜR[®] system results of <1 *E. coli* MPN/100 mL found in studies performed by Rangel et al., and Souter et al. in 2003. Rangel and Souter also reported filtered turbidity measurements, filtered through a cloth fabric, ranging from 4.4 to 4.6 NTU and 0.25 to 3.2 NTU, respectively. Although, the Rangel et al. study did find a mean *E. coli* presence of 418 *E. coli* MPN/100 mL in water treated by PÜR[®] and stored in a traditional Guatemalan vessel. The initial water had a concentration of 753 *E. coli* MPN/100 mL (Rangel, Lopez, Mejia, & Mendoza, 2003), resulting in less than 0.5-log removal. When comparing this data to Experiment B-2, the Treated Bag did achieve a > 1-log removal of *E. coli*, but still did not meet the WHO emergency guidelines of <1 *E. coli* MPN/100 mL.

The results from Experiment B-2 led to the question: Can the prototype coupled with the PÜR[®] packet achieve treatment levels demonstrated by the standard PÜR[®] bucket

protocol? The PŪR[®] packet is formulated with a coagulant, disinfectant, and flocculating aids, and has proven to yield results, both in the laboratory and field, that meet the WHO emergency guidelines. Therefore, the next step in the experimental process was to understand how the standard PŪR[®] treatment system in buckets performed in regards to mixing, settling, and filtration; and how this compares to the prototype of interest when treating the same source water.

Figure 5.8 - Settled flocs shown in the conical sediment trap of the Treated Bag in Experiment B-2. The treated water did not meet the minimum turbidity standard of 5 NTU.

5.2.3 - Experiment B-3: Standard PŪR[®] Bucket Protocol vs. the Prototype

In Experiment B-3, the standard operating procedures of three standard PŪR[®] bucket tests (two treated with PŪR[®] sachets and one control unit not treated) were compared to three prototypes (two treated with PŪR[®] sachets and one control unit not treated). A standard procedure was introduced for the prototype treatment in this experiment: (1) add PŪR[®], (2) invert 20 times, at a 40 beats per minute pace, and, (3) settle vertically for 30

minutes. The initial water quality characteristics for the buckets and prototypes are summarized in **Table 5.5**. A2 Fine Test Dust and Instant Ocean, for increasing turbidity and TDS concentrations, were added to the test water to simulate U.S. EPA Challenge Water #2 recipe (refer to **Table 2.5** in Section 2.4.2 for the test water properties established by the U.S. EPA). Initial water temperatures for the buckets and prototypes varied since the 1/3 HP sump pump was running in the refuse container for mixing during the entire course of the experiment. The water temperature for the prototype is higher since the prototypes were filled approximately 1.5-hours after the buckets were tested.

Table 5.5 - Experiment B-3 pre-treatment water quality characteristics of blended Drumm Reservoir and Swine Pond water with the addition of A2 Fine Test Dust and Instant Ocean.

Water Quality Parameter (Pre-Treatment)	Initial Water
Temperature (°C)	22.7 (bucket), 30 (prototype)
Turbidity (NTU)	569
pH	8.17
TSS (mg/L)	371.5
TDS (mg/L)	1300 mg / L
Total Coliform bacteria (MPN / 100 mL)	1.79×10^4
<i>E. Coli</i> (MPN / 100 mL)	5.14×10^3

The PÜR[®] coagulation, flocculation, and settling processes were observed in both the buckets and prototypes. As for the buckets, after 5 minutes of vigorous mixing, the flocs settled within a 5 minute period prior to filtration. Large fluffy flocs were observed. The supernatant water was then decanted through the 100% cotton filter cloth into a clean

bucket, to remain for 20 minutes to reach the 30 minute chlorine contact time period (**Figure 5.9**). As for the waterbag prototypes, fluffy flocs formed and clumped together once the prototype was hung vertically. From visual observation, the water clarity also improved during the 30 minute settling time for both of the prototypes (**Figure 5.10**).

Figure 5.9 - During the bucket tests fluffy flocs formed and settled after 5 minutes of vigorous mixing and 5 minutes of settling (Left, looking through the water). The water was then decanted through a 100% cotton filter cloth and stored for a minimum of 20 minutes (Right).

Figure 5.10 - During the prototype treatment, fluffy flocs clumped together and settled during the vertical settling process (Left). At the end of the test, the flocs were retained in the prototype's conical sediment trap with the supernatant water above (Right).

During the 30 minute settling period, turbidity decreased significantly for Bag1 and Bag 2 (**Figure 5.11**), for Bag 1 and Bag 2. The prototypes started with an initial pre-treatment turbidity of 569 NTU. Bag 1 quickly decreased to 220 NTU after 5 minutes, and then reached turbidity of 21.7 NTU after 30 minutes. While Bag 2 decreased to 494 NTU after 5 minutes, and reached a final 59.3 NTU after 30 minutes.

Figure 5.11 - Turbidity over the 30 minute settling period for the Bag 1 and Bag 2 in Experiment B-3. The final pre-treatment turbidities reached for Bag 1 and Bag 2 were 21.7 NTU and 59.3 NTU, respectively.

The post-filtered turbidity measurements were similar for the buckets and prototypes (Figure 5.12). However, turbidity measurements were taken at different volume filtered for the bucket and waterbag prototypes. The filtered turbidity for the buckets was taken after 9.8 L of water was filtered; which was the total volume yield of each bucket. The filter material used was a 100% cotton cloth provided by Reliance Products sold in PÜR® kits from Wal-Mart. On the other hand, the 1- μ m polypropylene filter cloth used for the prototypes clogged after filtering 2 L; thus the filtered turbidity was taken at two points: after an initial 15 mL aliquot sample and at the 2 L mark. The rest of the prototype water volume was then filtered through a new filter cloth, yielding a total water volume of 8 L filtered for both prototypes. The remaining water quality constituents sampled at the end

of the filter runs are summarized in **Table 5.6**, particularly, *E. coli* was reduced to <1 MPN/100 mL for all cases.

Figure 5.12 - Pre- and post- filter turbidity measurements for the buckets and prototypes tested in Experiment B-3. Final filtered turbidity measurements, at the “yield” volume (where filtered clogged), range from 1 NTU to 3 NTU. Initial post-filter 15 mL were not taken for the buckets since the standard treatment procedure calls for the entire volume to be filtered after 10 minutes, not after the entire 30 minute treatment time.

Table 5.6 - Experiment B-3 post-treated water quality characteristics for the bucket and prototypes.

Water Quality Parameter (Post-Treatment)	Units	Bucket 1	Bucket 2	Bag 1	Bag 2
Temperature	°C	22.9	22.2	27.2	27.8
Turbidity (Post Filter)	NTU	1	1	3	1
pH	--	7.72	8.08	NS	NS
TSS ¹	mg / L	2.75	2.50 (ND)	3.75	3.75
Chlorine Residual ²	mg / L	0.12	0.12	0.10	0.06
Total Coliform bacteria (Pre-filter, Post-filter yield)	MPN / 100 mL	NS, < 1	NS, < 1	< 1, < 1	6.85, 1.0
<i>E. Coli</i> (Pre-filter, Post-filter yield)	MPN / 100 mL	NS, < 1	NS, < 1	< 1, < 1	< 1, < 1

¹TSS detection limit is 2.50 mg of dried residue (APHA et al., 1995). Bucket 2 reached this detection (ND) limit even with the necessary volume filtered.

²Chlorine residual estimated detection limit is 0.02 mg/L (HACH Method 8021)

5.2.3.1 - Discussion of Experiment B-3 Results

The final filtered treatment results for the prototypes and buckets met the WHO emergency turbidity standard (<5 NTU) and *E. coli* (≤ 1 MPN/100 mL). The turbidity measurements and decrease in TSS concentrations confirmed that the PÜR[®] treatment effectively coagulated the particles (**Figure 5.9, Figure 5.10**). However, a couple of questions are raised regarding the differences between the bucket test and waterbag prototype test. First, why did the waterbag prototypes not reduce turbidity as much as the bucket test prior to filtration? This may be due to difference in contact time between the bucket and waterbag prototype. For instance, the bucket test water is decanted into a clean bucket after 10 minutes of chlorine-contact time; the remaining 20-minutes is

without solids (or flocs) in the bucket. Whereas the solids in the waterbag prototype settle to the bottom conical sediment trap; however, they are not isolated from the water, remaining in contact with the water and thus continuing to consume the chlorine demand (as seen in lower chlorine residual concentrations in **Table 5.6**). The second question raised is: why did the filter cloth clog? The filter cloth was observed to clog when using the MilliporeTM stainless steel housing. In future experiments this issue is mitigated with a new filter housing and by regulating flow rate.

Overall, even though *E. coli* was not present in the water, low chlorine residual concentrations were measured, raising the concern that too much of the chlorine disinfectant was consumed by dissolved organic matter. Mixed results are documented in the literature regarding chlorine residual concentrations in PŪR[®] treated water. The Rangel et al. study found high levels of free chlorine, ranging from 1.4 to 2.3 mg/L, when treating rural Guatemala waters (Rangel, Lopez, Mejia, & Mendoza, 2003). Additionally in the 2006 Doocy & Burnham study, 85% of the chlorine residual samples met or exceed the Sphere Guidelines of 0.5 mg/L, which coincide with the WHO emergency drinking water guidelines (Doocy & Burnham, 2006). However, in the 2005 Crump study in Kenya, the team found low free chlorine concentrations when measured during unannounced visits; only 44% of samples treated with PŪR[®] were found with free chlorine concentrations. They attribute this to prolonged storage or chlorine demand consumed by turbid waters (Crump, et al., 2005). Therefore, the varying results indicate that the PŪR[®] treatment may not meet chlorine residual concentration guidelines, but the PŪR[®] treatment intervention studies reviewed in Section 2.6.4 show that the minimal removal of pathogens is still reached; which was confirmed in this experiment.

The pre-filtered water turbidities differed between the buckets and prototypes (**Figure 5.12**). One of the buckets reached the turbidity standard of <5 NTU prior to filtration, and the other was just above at 7 NTU. In contrast, the pre-filtered turbidities from the waterbag prototypes were 22 NTU and 59 NTU. The prototypes thus relied on the 1- μ m polypropylene filter to reach turbidity levels of <5 NTU.

Achieving pre-filtered turbidities similar to the bucket test became an objective for future experiments. In the Optimization Experiments, the mixing intensity of the bucket was first calculated and then a set of experiments was conducted based on this intensity. Mixing and settling variables were also tested to establish an optimized procedure that reached low turbidity levels prior to treatment. Ultimately, low turbidity levels prior to filtration would enable complete filtration of the entire prototype volume before clogging the 1- μ m polypropylene cloth.

In subsequent experiments, a procedural change addressed keeping water temperatures at room temperature (approximately 20°C). During the water preparation and mixing, the sump pump was run for only 30 minutes to mix the test water recipe contents, at which time the water was dispensed into each prototype. The limited mixing time prevented overheating of the water by the submersible pump motor.

5.3 - Optimization Experiments

The goal of the Optimization Experiments was to achieve low turbidity prior to filtration. The first step was to estimate the mixing intensity needed to properly mix the PÜR[®] packet contents within the waterbag prototype. The estimation was performed based on

conventional water treatment design coagulation and flocculation equations, introduced in Section 4.4.2. The mixing intensity of the bucket, established using the mixing design parameter, Gt , at “ t ” equal to 5 minutes, was used to calculate the equivalent mixing time for the prototype. The calculated prototype mixing time was 2.9-min. Converting time to number of inversions, using a 40 beats per minute rate per inversion, corresponded to a 124 inversions (refer to Appendix B for calculations). From this, the Optimization Experiment series began with an experiment testing increasing the number of inversions for mixing, and progressed to further mixing and settling variations.

5.3.1 - Experiment C-1: Inversion Variations

Varying inversions were tested to determine if more inversions during the mixing process helps coagulate particles to improve water clarity. The “ Gt ” calculation for a prototype called for 124 inversions; however, this was considered impractical given the weight of the waterbags. Therefore, a fifth prototype was tested based on the five minute mixing process of the standard PÜR[®] bucket treatment with a horizontal settling step. Five prototypes were tested according to the procedures presented in (Table 5.7).

Table 5.7 - Mixing and settling procedures for Bags 1 through 5 in Experiment C-1.

Step	Procedure	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5
(Number of inversions or time)						
Step 1	Add PÜR [®] to all waterbag prototypes					
Step 2	Invert ¹	20	40	80	100	20
Step 3	Mix Horizontally	0-min	0-min	0-min	0-min	4.5-min
Step 4	Settle Horizontally	0-min	0-min	0-min	0-min	5-min
Step 5	Settle Vertically	30-min	30-min	30-min	30-min	25-min

¹Inversions were conducted using a metronome pace of 40 beats per minute.

For all tests, the initial water quality characteristics of the water included an initial turbidity of 487 NTU, pH of 8.48, temperature of 24.1°C, and alkalinity of 283 mg CaCO₃/L. The turbidities for each waterbag prototype decreased significantly over the 30-minute settling period. The pre-filtered turbidity after settling in the waterbag prototypes decreased with increased mixing. The turbidity was three times lower for 100 inversions compared to 20 inversions (**Figure 5.13**). The results show that the higher the pre-filtered turbidities, as with Bag 1 through Bag 3, the lower the final filtered turbidities. The filtered turbidity samples were the first 15 mL of filtered water.

Other final water quality characteristics included temperature (21.2 to 23.3°C), pH (7.60 to 8.08), and alkalinity (283 to 330 mg CaCO₃/L). Chlorine residual, TSS, total coliform bacteria, and *E. coli* testing was not performed for the experiment.

Figure 5.13 - Experiment C-1 pre- and post- filter turbidity measurements for Bag 1 through Bag 5. Inverting the prototype more resulted in lower pre-filtered turbidities for Bag 1 through Bag 4. While prototypes with higher pre-filtered turbidities produced lower filtered turbidity measurements.

5.3.1.1 - Discussion of Experiment C-1 Results

The results from Experiment C-1 show that mixing is important to achieve a low pre-filter turbidity. More inversions correspond to a lower pre-filtered turbidity at the end of the 30 minute settling process. However, inverting a prototype more than 20 times is not realistic for a typical user; as inverting 22 pounds can become cumbersome. Bag 5, which incorporates a horizontal mixing method, solved this problem and actually produced the lowest pre-filtered turbidity measurement of 9.52 NTU. The importance of mixing is also reiterated when comparing Bag 1 and Bag 5, both having been inverted 20 times. The additional 4.5 minutes of horizontal mixing improved water clarity from 33.2 NTU (in Bag 1) to 9.52 NTU (in Bag 5). So the question became: how to perform the mixing and for how long does the mixing need to last to achieve low pre-filtered turbidities?

Experiment C-2 begins to determine these variations by looking at horizontal mixing at various times preceded by 20 inversions.

More inversions, however, did not correspond to lower filtered turbidities, as one may expect. Bag 1 through Bag 3 all resulted in filtered turbidities <5 NTU even though their pre-filtered turbidities were higher than Bag 4 and Bag 5. The likely reason for this is that the water with more particulates, and potentially larger particles, created a ripening layer on the 1- μ m polypropylene filter cloth, thus, creating a barrier to prevent particle breakthrough. Bag 4 and Bag 5 did not create a ripening layer on the cloth after 15 mL filtered. No further filtered turbidity measurements were taken to determine if turbidities in Bag 4 and Bag 5 would have decreased more. Experiments C-4 and C-5, in Sections 5.3.4 and 5.3.5, addressed this issue.

The filter flows (~4 L/min but dropped significantly till cloth clogged using MilliporeTM stainless steel filter holder) during this experiment were not consistent or regulated. Improved filtered turbidities and larger volumes filtered were achieved in later experiments with the filter flow rate controlled at a lower rate.

The other water quality constituents, such as temperature, pH, and alkalinity, were all within expected water quality effluent standards, and did not vary much from the initial water readings recorded. The range of 283 to 330 mg CaCO₃/L matches or exceeds the original concentration 283 mg CaCO₃/L, which is reflected in the pH range of 7.60 to 8.08, which meet drinking water guidelines.

5.3.2 - Experiment C-2: Horizontal Mixing Variations

Varying horizontal mixing times were tested to determine if a specific mixing time was optimal for the coagulation process. Keeping at total treatment time of 30 min, the various horizontal mixing times affected the time remaining for vertical settling. The prototypes were tested according to the procedures presented in **Table 5.8**. The initial water turbidity was 477 NTU, with a pH of 8.16, and a temperature of 23.7°C.

Table 5.8 - Mixing and settling procedures for Bags 1 through 5 in Experiment C-2.

Step	Procedure	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5
(Number of inversions or time)						
Step 1	Add PÜR [®] to all waterbag prototypes					
Step 2	Invert ¹	20	20	20	20	20
Step 3	Mix Horizontally	0-min	4.5-min	10-min	15-min	4.5-min
Step 4	Settle Horizontally	0-min	0-min	0-min	0-min	10-min
Step 5	Settle Vertically	30-min	25-min	20-min	15-min	15-min

¹Inversions were conducted using a metronome pace of 40 beats per minute.

The turbidities for each prototype decreased over the settling period and post-filtration (**Figure 5.14**). Horizontal mixing improved turbidity at the end of the 30-minute period; however, turbidity is not significantly improved by horizontally mixing it for longer than 4.5 minutes. Once the water was filtered, the turbidity measured <5 NTU. The filtered turbidity samples were the first 15 mL of filtered water, taken only once. Temperature and pH values did not vary much from the initial water readings recorded. Post-filtered temperature readings ranged from 21.1°C to 22.9°C, and pH ranged from 7.22 to 7.49.

Chlorine residual, alkalinity, TSS, total coliform bacteria, and *E. coli* testing was not performed for the experiment.

Figure 5.14 - Experiment C-2 pre- and post- filter turbidity measurements for Bag 1 through Bag 5. Mixing the prototype horizontally showed improvement in water clarity during the 30-minute treatment period.

5.3.2.1 - Discussion of Experiment C-2 Results

Just as in Experiment C-1, Experiment C-2 results showed the importance of mixing in waterbag treatment, especially in achieving low pre-filter turbidities. Horizontally mixing the prototype did produce lower pre-filtered turbidities compared with Bag 1, in which no horizontal mixing took place. This was also the case in Experiment C-1, Bag 5. Time, however, is not a factor. The results indicate that there is no significant decrease in water turbidity for a 4.5 min vs. 15 min horizontal mixing time. Turbidities remained between 19.5 NTU and 23.9 NTU. Therefore, there is no need to horizontally mix the water for

more than 4.5 minutes, or hereafter mixed for 5 minutes. Additionally, filtered turbidities for all five prototypes met the WHO turbidity guidelines.

The addition of horizontal settling achieved a pre-filter turbidity of 14.5 NTU, the lowest turbidity of the five prototypes. This is evident when comparing Bag 2 to Bag 5, in which the only procedural difference was additional horizontal mixing. Bag 5 resulted in a pre-filtered turbidity measurement 5 NTU less than that of Bag 2. Theoretically, the horizontal settling stage allows for a shorter settling distance of the flocs when compared to vertical settling only. After 10 minutes of horizontal settling, the prototype is lifted carefully, allowing the settled flocs to slide down the back end of the prototype into the conical sediment trap. During the transition to vertical settling, the flocs were observed to re-suspend just above the valve outlet due to a resulting eddy current as the prototype was shifted positions. However, the remaining vertical settling period allows the re-suspended flocs to re-settle (**Figure 5.15**). The next experiment, Experiment C-3, tested additional variations in horizontal settling.

Figure 5.15 - Transitional steps from horizontal settling to vertical settling. Settled flocs observed to slide down back side of prototype to the conical sediment trap (left, middle). The flocs re-suspend just above the valve but eventually settle back to the bottom (right).

5.3.3 - Experiment C-3: Horizontal and Vertical Settling Variations

Varying horizontal and vertical settling times were tested to determine if a specific combination of settling procedures made a difference in pre-filter turbidities. The five waterbag prototypes were tested according the procedures presented in **Table 5.9**. The initial water turbidity was 499 NTU, with a pH of 8.48, and a temperature of 22.4°C.

Table 5.9 - Mixing and settling procedures for Bags 1 through 5 in Experiment C-3.

Step	Procedure	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5
(Number of inversions or time)						
Step 1	Add PÜR [®] to all waterbag prototypes					
Step 2	Invert ¹	20	20	20	20	20
Step 3	Mix Horizontally	5-min	5-min	5-min	5-min	3-min
Step 4	Settle Horizontally	20-min	15-min	10-min	0-min	0-min
Step 5	Settle Vertically	5-min	10-min	15-min	25-min	27-min

¹Inversions were conducted using a metronome pace of 40 beats per minute.

After settling, Bag 1 resulted in final pre-filtered turbidity of 280 NTU, Bag 2 at 77.3 NTU, Bag 3 at 23.2 NTU, Bag 4 at 34.8 NTU, and Bag 5 at 27.6 NTU. The post filter turbidities of Bag 1 through Bag 5 were 2.26 NTU, 1.87 NTU, 2.45 NTU, 2.39 NTU, and 6.51 NTU, respectively (**Figure 5.16**). The filtered turbidity samples were the first 15 mL of filtered water.

Temperature and pH values remained consistent with the initial water characteristics. Post-filtered temperatures ranged from 21.1°C to 22.4°C, and pH ranged from 7.28 to 7.31. Chlorine residual, alkalinity, TSS, total coliform bacteria, and *E. coli* testing was not performed for the experiment.

Figure 5.16 - Pre- and post- filter turbidity measurements for Bag 1 through Bag 5 in Experiment C-3, in which horizontal and vertical settling steps were different for each prototype.

5.3.3.1 - Discussion of Experiment C-3 Results

Experiment C-3 data showed that the settling orientation and durations do play a role in decreasing the pre-filtered turbidities at the end of the 30 minute settling period. When the prototype was vertically settled for 10 minutes or less, it resulted in higher turbidities (77.3 NTU and 280 NTU), compared to prototypes that were settled vertically for 15 minutes or more (23.2 NTU to 34.8 NTU). This may be due to the re-suspension of flocs when transitioning the prototype from the horizontal to vertical position (**Figure 5.15**). Based on this experiment, more than 10 minutes of vertical settling is needed to re-settle the suspended flocs.

As shown by Bag 5, 3 minutes of horizontal mixing resulted in similar pre-filtered turbidities as Bag 3 and Bag 4 that were horizontally mixed for 5 minutes (**Figure 5.16**); however, no major conclusions can be made about Bag 5's procedures as the 27 minutes of vertical settling could have also decreased water turbidity.

5.3.4- Experiment C-4: First Filtration Test

While still obtaining pre-filtered turbidity measurements, the subsequent experiments began to focus on post-filtered turbidities and flow rates through the filter apparatus. The smaller-profile filter apparatus, designed and built at Cal Poly (Section 3.1.3, **Figure 3.17**), was integrated at this point in the process. The goal was still to achieve low turbidity measurements prior to filtration, but also to achieve the WHO emergency turbidity guideline of <5 NTU in all filtered samples of the entire prototype volume.

Turbidity and flow rates were investigated for three prototypes in Experiment C-4, to understand how filtration rates through the 1- μm polypropylene filter cloth affect turbidity. The first two prototypes were tested according to the procedures presented in **Table 5.10**. The initial water turbidity was 501 NTU, with a pH of 8.46, and a temperature of 23.4°C.

Table 5.10 - Mixing and settling procedures for Bags 1 through 3 in Experiment C-4.

Step	Procedure	Bag 1	Bag 2	Bag 3
		(Number of inversions or time)		
Step 1	Add PUR [®] to all waterbag prototypes			
Step 2	Invert ¹	20	20	20
Step 3	Mix Horizontally	5-min	5-min	3-min
Step 4	Settle Horizontally	10-min	0-min	0-min
Step 5	Settle Vertically	15-min	25-min	27-min

¹Inversions were conducted using a metronome pace of 40 beats per minute.

The pre-filtered turbidity measurements resulted in much higher pre-filtered turbidity, 86.1 NTU, for Bag 3 which underwent 20 inversions and 3-minutes of horizontal mixing and no horizontal settling. Bags 1 and 2 achieved lower pre-filter turbidity after undergoing 5-minutes of horizontal mixing (**Figure 5.17**). Post filter turbidities after the first 700 mL filtered for Bag 1 through Bag 3 were 11.1 NTU, 10.1 NTU, and 9.12 NTU, respectively. Four more filtered turbidity samples were measured for each of the prototypes, until approximately 8 L of water was filtered. From the 0-L to 3-L filtration range, each of the prototypes' turbidities decreased to 1.68 NTU to 5.58 NTU. From the 3-L to 8-L filtration range, the turbidities were consistent within a 1 NTU increment (**Figure 5.18**).

Figure 5.17 - Pre- and post- filter turbidity measurements for Bag 1 through Bag 3 in Experiment C-4, in which horizontal and vertical settling steps differed for each prototype, along with the horizontal mixing in Bag 3.

Figure 5.18 - Filtered turbidity samples for 8 L total volume filtered for Bag 1 through Bag 3 in Experiment C-4. Filtered samples decreased in turbidity from 0 L to 3 L, but eventual level off after 3 L filtered.

Filtration rates were also recorded during this experiment and compared to filter rates of tap-water in the waterbag prototype, defined as the control standard. The flow was not regulated during this experiment. Filtration rates decreased over time (**Figure 5.19**), due to headloss in the filter of the waterbag prototype as particulate matter built up on the filter cloth surface.

Figure 5.19 - Filtration Rates for Bag 1 through Bag 3 compared to the tap water control bag in Experiment C-4. Filtration rates followed a decreasing trend due to less head in the prototypes.

5.3.4.1 - Discussion of Experiment C-4 Results

In Experiment C-4, the filtered turbidities over the course of the run did not meet the WHO turbidity guideline of <5 NTU 100% of the time. Of the five samples taken, Bag 1 met the guidelines 80% of the time, and, Bag 2 and Bag 3 met it 60% of the time.

The potential reasons that the turbidity guideline was not satisfied were due to high flow rates through the filter apparatus causing breakthrough to occur through the 1- μ m filter. As seen in **Figure 5.17**, the turbidity measurements were high (between 9 to 11 NTU) after 700 mL filtered. This is the first time in the Experiment C tests that high post-filter turbidities were measured and also the first time the new low-profile filter apparatus was tested. In this test, breakthrough of particulate matter was observed after 3 L were filtered, as samples did not improve in clarity. After 3 L were filtered, the samples did not improve in clarity. The expectation is that the ripening layer would form on the filter cloth and produce consistent levels of turbidity <5 NTU. Prior to introducing the low-profile apparatus, the MilliporeTM stainless steel filter holder used maintained restricted flows providing a flux that generally gave good turbidity readings; however, the MilliporeTM filter holder clogged prior to filtering the entire prototype volume; thus the need for an improved filter housing.

The next experiment, C-5, tested the same apparatus with a regulated flow rate through the filter. The hypothesis was that a regulated flow rate between 0.5 L/min to 1.5 L/min (since this flow worked with the MilliporeTM filter holder) will result in turbidities <5 NTU.

5.3.5 - Experiment C-5: Regulating Flow

A single prototype was tested to begin to prove the hypothesis formed at the end of Experiment C-4: a regulated flow rate range from 0.5 L/min to 1.5 L/min will result in turbidity measurements <5 NTU. A hosecock clamp (Section 4.5, **Figure 4.10**) was used to regulate flow discharged from the spring-loaded valve of the waterbag prototype. The

clamp helped to regulate the flow as to not hydraulically overload the filter. Filtered turbidity measurements were the only parameter recorded in this experiment; flow rates were not yet recorded as adjustments were made to hosecock clamp.

The prototype was tested according to the following procedure: (1) add PÜR[®], (2) invert 20 times, at a 40 beats per minute pace, (3) mix horizontally for 5 minutes, (4) settle horizontally 10 minutes, and (5) settle vertically for 15 minutes. Pre-treatment turbidity measured 477 NTU and pre-filtered turbidity measured 15.2 NTU. Turbidity of filtered samples were taken in 15 mL or 100 mL increments during the first 500 mL of water filtered through the apparatus. The samples were either flowing freely or restricted by the hosecock clamp. As shown in **Figure 5.20**, restricted flow produced filtered turbidities in the range of 1.91 NTU to 3.27 NTU, while unrestricted flow resulted in filtered turbidities >5 NTU.

Figure 5.20 - Filtered turbidity varied with controlled flow rate during Experiment C-5. Restricted flow rates resulting in filtered turbidity measurements of <5 NTU.

5.3.5.1 - Discussion of Experiment C-5 Results

Restricting the flow with the hosecock clamp did produce turbidity measurements of <5 NTU confirming that restricted flow significantly improved the final water turbidity. The hosecock clamp, hereafter, was integrated into the filtration system to maintain these low turbidities to meet WHO emergency guidelines.

5.3.6- Experiment C-6: Introducing Vigorous Horizontal Mixing

In Experiment C-6, in addition to investigating regulated flow rates with the hosecock clamp, a more rapid horizontal mixing step was introduced to identify the effects of mixing intensity on water turbidities. Horizontal mixing was standardized into two types of intensities, gentle and vigorous, and tested to determine what mixing intensity achieved lower pre-filtered turbidities. Gentle mixing was standardized as rocking the

prototype, horizontally on the ground, from one side to the other (a single complete cycle of rocking motion) along its long axis at a frequency of 36 beats per minute. This same mixing intensity was used for the horizontal mixing steps in all previous experiments. Vigorous mixing was standardized as rocking the prototype through a complete cycle along its long axis at frequency of 100 beats per minute.

Four prototypes were tested according to the following procedures presented in **Table 5.11**. The initial water turbidity, temperature, and pH were 535 NTU, 23.3°C and 8.44, respectively.

Table 5.11 - Mixing and settling procedures for Bags 1 through 4 in Experiment C-6.

Step	Procedure	Bag 1	Bag 2	Bag 3	Bag 4
(Number of inversions or time)					
Step 1	Add PÜR® to all waterbag prototypes				
Step 2	Invert ¹	20	20	20	20
Step 3	Mix Horizontally	5-min (Gentle) ²	5-min (Gentle) ²	5-min (Vigorous) ³	5-min (Vigorous) ³
Step 4	Settle Horizontally	0-min	10-min	0-min	10-min
Step 5	Settle Vertically	25-min	15-min	25-min	15-min

¹Inversions were conducted using a metronome pace of 40 beats per minute.

²Gentle horizontal mixing performed at 36 beats per minute.

³Vigorous horizontal mixing performed at 100 beats per minute.

The pre-filtered turbidities are graphed in **Figure 5.21**, to compare the effects of turbidity due to gentle and vigorous. Vigorous mixing resulted in lower turbidity values, 3.68 NTU and 10.4 NTU, compared to gentle mixing, which gave 18.9 NTU and 21.3 NTU. Additionally, Bag 4 resulted in lower pre-filtered turbidity compared to Bag 3; this is most likely due to the horizontal settling step in which the flocs had a shorter distance to settle.

Figure 5.21 - Average turbidity measurements prior to filtration produced by gentle and vigorous mixing intensities during Experiment C-6.

Post filtered turbidities were also recorded at approximate sampling points of 15 mL and 100 mL (100 mL takes only about 3 seconds of total filtration time), 1.2 L, 4.2 L, and 8.2 L, for Bag 1 through Bag 3. Bag 4 samples were not filtered; thus, not included in **Figure 5.22** nor in **Figure 5.23**. Turbidity measured <5 NTU for all prototypes after 100 mL filtered, except for Bag 1 (**Figure 5.22**). Bag 1, Bag 3, and Bag 4 total yield output was

between 8 L and 8.2 L, while Bag 2 total yield output was 7.6 L. This variation in filtration end point was due to the water level falling below the valve port outlet. These outputs ranged from 1.3 L/min decreasing to 0.5 L/min for Bag 1 and Bag 2, and 1.4 L/min decreasing to 0.6 L/min for Bag 3 (**Figure 5.23**).

Figure 5.22 - Turbidity measurements over the volume output of each prototype. Bag 1 through Bag 3 turbidity measurements were sampled after filtration; whereas Bag 4 turbidity samples were not filtered.

Figure 5.23 - Filtration rates shown during the course of the filtration run for each prototype. Bag 1 and Bag 2 flows ranged between 1.3 L/min and 0.5 L/min. Bag 3 ranged between 1.4 L/min to 0.6 L/min.

5.3.6.1 - Discussion of Experiment C-6 Results

In Experiment C-6, vigorous mixing was shown to produce lower pre-filtered turbidities compared to gentle mixing (**Figure 5.21**). This reiterates how mixing intensities directly affect coagulation. The vigorous mixing, at 100 beats per minute, provided enough energy to mix the coagulant and create flocs that were easily settlable during flocculation and sedimentation. Gentle mixing, at 36 beats per minute, still provided energy to mix the coagulant and form flocs, but the turbidity measurements showed that a higher mixing energy was necessary to reach lower turbidity levels. This held true even with different settling methods. Bag 4 even reached the WHO turbidity guideline of <5 NTU without filtration. This was the first prototype in all experiments to this point in time that had reached turbidities <5 NTU without filtration. Bag 1 through Bag 3 turbidity

measurements satisfied the hypothesis that a regulated flow rate range from 0.5 L/min to 1.5 L/min will result in turbidities <5 NTU.

Up to this point in the process, the conclusions reached for the optimized treatment procedures for the Mark I design include: (1) inversions shall not exceed 20 inversions, and (2) horizontal mixing shall be performed at 100 beats per minute. Questions still remained: What settling methods are optimal, and can low pre-filtered turbidity measurements be maintained if less than 20 inversions are performed? The next experiments, C-7 and C-8, addressed these questions.

5.3.7 - Experiment C-7: Evaluating Vigorous Mixing and Settling Methods

In Experiment C-7, vigorous mixing was paired with different settling methods to identify which procedure resulted in lower pre-filter turbidity measurements. Post filtration and filter rates were also recorded.

Four prototypes were tested according to the following procedures presented in **Table 5.12**. The initial water turbidity, temperature, and pH were 507 NTU, 20.2°C and 8.36, respectively.

Table 5.12 - Mixing and settling procedures for Bags 1 through 4 in Experiment C-7.

Step	Procedure	Bag 1	Bag 2	Bag 3	Bag 4
(Number of inversions or time)					
Step 1	Add PÜR [®] to all waterbag prototypes				
Step 2	Invert ¹	20	20	20	0
Step 3	Mix Horizontally ²	5-min	5-min	3-min	5-min
Step 4	Settle Horizontally	0-min	10-min	10-min	10-min
Step 5	Settle Vertically	25-min	15-min	17-min	15-min

¹Inversions were conducted using a metronome pace of 40 beats per minute.

²All prototypes underwent vigorous horizontal mixing, performed at 100 beats per minute.

Pre-filtered turbidities and the turbidity after the first two filtered sampling points are graphed in **Figure 5.24**, to show the turbidities reached prior to filtration and post-filtration. Pre-filtered turbidity measurements range from 4.21 NTU to 10.5 NTU. The initial turbidity taken after 15 mL was filtered, showed that Bag 2 through Bag 3 increased to 20.9 NTU to 23.9 NTU, while Bag 1 measured the only decrease, to 3.65 NTU. After 100 mL was filtered, all turbidities decreased between 1.94 NTU to 2.82 NTU.

Figure 5.24 - Pre-filter and post-filter turbidity after 15 mL and 100 mL were filtered, as shown for the four prototypes that underwent 5 minutes of vigorous mixing. Bag 2 through Bag 4 showed an increase in turbidity at the 15 mL sample, but decreased along with Bag 1 after the first 100 mL filtered.

After the 100 mL sampling point, turbidity was taken in 1 L increments during filtration up to the total yield output of the prototypes. Considering only samples at the 1-L point and beyond, turbidity measured <5 NTU for all prototypes through the filter run, ranging between 1.31 NTU to 2.82 NTU (**Figure 5.25**). For Bag 1, total yield output was 8.1 L, and, for Bag 2 through Bag 4, total yield output was 7.1 L (this was due to additional non-filter samples taken in between, thus, total yield would have been 8.1 L). The filter flow rate was 1.5 L/min initially, decreasing to 0.7 L/min for all prototypes (**Figure 5.26**).

Figure 5.25 - Turbidity measurements during the filtration run for each prototype. Turbidities ranged from 1.31 NTU to 2.82 NTU (15 mL filtered turbidities excluded from this figure).

Figure 5.26 - Filtration rates during the filtration run of the full yield volume of the prototypes. Filtration rates started at 1.5 L/min and decreased to 0.7 L/min.

5.3.7.1 - Discussion on Experiment C-7 Results

Vigorous mixing paired with either vertical settling or a combination of horizontal and vertical settling resulted in low pre-filtered turbidities. Pre-filtered turbidity measurements did differ in the prototypes that underwent the same treatment process but had varied settling methods. Bag 1, which was settled vertically, resulted in a pre-filtered turbidity of 10.5 NTU; while, Bag 2, which was settled both horizontally and vertically, measured a pre-filtered turbidity of 4.21 NTU (**Figure 5.24**). This pre-filtered turbidity difference was also observed in Experiment C-6. Following the same 20 inversions and 5 minutes of vigorous mixing, Bag 3, just vertically settled, measured 10.4 NTU; whereas, Bag 4, with horizontal and vertical settling, measured 3.68 NTU (**Figure 5.21**). Based on these experimental results, it was decided to pair vigorous mixing with 10 minutes of horizontal settling and 15 minutes of vertical settling in future testing.

Additionally, during the vertical settling phase, flocs were observed to stick to the inside wall of the prototype, particularly in the waterbag prototypes that were only settled vertically (**Figure 5.27**). Tapping the side of the waterbag helped in settling the flocs sticking to the side of the prototype. These remaining flocs have the potential to flow out with the effluent; thus, the filter material is a necessary barrier in filtering out any remaining particles, even in waters that result in pre-filtered turbidity measurements <5 NTU.

Figure 5.27 - In Experiment C-7 and observed in the other Optimization Experiments, flocs were observed to stick to the inside wall of the bags. Tapping on the wall of the prototype encouraged the flocs to settle to the bottom. Some of the flocs do flow out with the effluent, but are filtered out by the 1- μ m polypropylene filter cloth.

The initial filtered turbidities (at the 15 mL sample point for Bag 2 through Bag 4) unexpectedly increased rather than decreased as seen in previous experiments. The turbidity increase was observed in the prototypes that had relatively low pre-filtered turbidities (< 10 NTU) at the end of the 30 minute period. The turbidity did reach the expected < 5 NTU measurement after filtering 100 mL through the cloth. It is hypothesized that the discrepancy is based on the ripening layer forming on the filter cloth. According to the results in this experiment, between 0 mL and 100 mL filtered, the ripening layer is forming on the cloth, particulates are still breaking through, and it is not

until after 100 mL of water is filtered does the cloth begin to produce turbidity measurements of <5 NTU. Experiments C-8 and C-9 examined this hypothesis.

Bag 3 in this experiment, with only a 3 minute vigorous mixing time, resulted in a pre-filtered turbidity of 8.17 NTU. While this is a low measurement, and the filtered turbidity was <5 NTU for this prototype, it was determined to maintain the vigorous mixing at the robust 5 minute length. Maintaining the longer mixing time provides a safety factor. For instance, in disaster zones, displaced user's may not have access to a clock/watch, and by instructing them to mix for the robust 5 minutes will hopefully mitigate the issue of not mixing long enough.

The next question to address now becomes: Are 20 inversions needed to precede 5 minutes of vigorous mixing? The filtered turbidity for Bag 2 (at 20 inversions) and Bag 4 (no inversions) took an almost identical path through the filtration run (**Figure 5.25**). Demonstrating that inverting the prototype does not make an immediate difference when followed by 5 minutes of vigorous mixing. However, Experiment C-8 investigated this in more detail by comparing various inversion intervals followed by vigorous mixing, and horizontal and vertical settling.

Most importantly, filtered turbidity measurements met the WHO turbidity guideline of <5 NTU (**Figure 5.25**), and similar to Experiment C-6, each prototype satisfied the hypothesis that a regulated flow rate range from 0.5 L/min to 1.5 L/min will result in turbidities <5 NTU.

5.3.8 - Experiment C-8: Inversion Variations

In Experiment C-8, inversion variations were paired with vigorous mixing, and horizontal and vertical mixing to identify if inverting the prototype less than 20 times produces low pre-filter turbidity measurements. Post filtration and filter rates were also recorded.

The treatment procedures for the four prototypes are summarized in **Table 5.13**. The initial water quality characteristics include an initial turbidity of 509 NTU, pH of 8.40, and a temperature of 20.9°C. For the purpose of comparison to a 20 inversion prototype, Bag 2 from Experiment C-7 is shown in the following graphs. It is graphed as Bag 2, C-7: 20 inv., and represented by the light blue color.

Table 5.13 - Mixing and settling procedures for Bags 1 through 4 in Experiment C-8.

Step	Procedure	Bag 1	Bag 2	Bag 3	Bag 4
(Number of inversions or time)					
Step 1	Add PÜR [®] to all waterbag prototypes				
Step 2	Invert ¹	10	6	4	2
Step 3	Mix Horizontally ²	5-min	5-min	5-min	5-min
Step 4	Settle Horizontally	10-min	10-min	10-min	10-min
Step 5	Settle Vertically	15-min	15-min	15-min	15-min

¹Inversions were conducted using a metronome pace of 40 beats per minute.

²All prototypes underwent vigorous horizontal mixing, performed at 100 beats per minute.

Pre-filtered turbidities and the first two filtered sampling points are graphed in **Figure 5.28**, to show the turbidity prior to filtration and post-filtration. Pre-filtered turbidity measurements range from 4.21 NTU to 6.77 NTU. The initial filtered turbidity taken at

15 mL, show that all prototypes, except for Bag 1, increased in turbidity. Bag 2, C-7 measured the highest increase at 23.9 NTU. After 100 mL filtered, all turbidities decreased between 1.95 NTU to 5.11 NTU (**Figure 5.28**).

Figure 5.28 - Pre-filter and post-filter turbidity after 15 mL and 100 mL shown for five prototypes at varying inversions. Turbidity increased at the 15 mL filtration point and then decreased at the 100 mL sampling point (this is also seen in Figure 5.24). Bag 2, C-7 had the most drastic turbidity change at the three sampling points.

Just as in Experiment C-7, turbidity was taken in 1-L increments during filtration up to the total yield output of the prototypes. Considering only samples at the 1-L point and beyond, turbidity measured <5 NTU for Bag 1 through Bag 3 and Bag 2, C-7, ranging between 1.16 NTU to 3.03 NTU (**Figure 5.29**). Bag 4, however, produced water turbidities close to 5 NTU, ranging from 4.67 NTU to 5.58 NTU.

Figure 5.29 - Turbidity measurements sampled over the volume output of each prototype. Generally, turbidities decreased in the prototypes, except for Bag 4, in which the turbidity measured approximately 5 NTU throughout the filtration run. The start of the filtered volume shown for each prototype corresponds to 100 mL.

Filtration rates were measured up to 7.1 L of output. The filtration rates for Bag 1 through Bag 3 were similar, starting at 1.3 L/min and ending at 0.5 L/min. While Bag 4 and Bag 2, C-7 maintained slightly higher rates throughout, flowing at 1.5 L/min and ending at 0.8 L/min (**Figure 5.30**).

Figure 5.30 - Filtration rates measured during the 7.1 L filtration run. Bag 1 through Bag 3 filtered at a similar rate from 1.3 L/min decreasing to 0.5 L/min, while Bag 4 and Bag 2, C-7 maintained slightly higher filtration rates, from 1.5 L/min to 0.8 L/min.

5.3.8.1 - Discussion of Experiment C-8 Results

Experiment C-8 results indicate that inverting a prototype less than 20 times when followed by 5 minutes of vigorous mixing, 10 minutes of horizontal settling, and 15 minutes of vertical settling, does produce low (<10 NTU) pre-filtered turbidity measurements. Based on **Figure 5.28**, Bag 1 through Bag 4 pre-filtered turbidity measured between 5.55 NTU and 6.77 NTU. Bag 2, C-7, did result in the lowest pre-filter turbidity at 4.21 NTU, and this is reconfirmed in Bag 4, Experiment C-6, in which pre-filtered turbidity measured 3.68 NTU. The treatment method performed on these two prototypes met the WHO emergency turbidity guideline, even prior to filtration. Therefore, 20 inversions was the chosen number of inversions for the first mixing process step in the laboratory. This decision was made on the grounds that 20 inversions is at the

top end of the range; therefore, in the field, if a user inverts the bag less than 20 times, the water could be assumed to reach low turbidity measurements based on the data shown in **Figure 5.29**. Additionally, even though the latter two prototypes met the emergency turbidity requirement prior to filtration, the 1- μ m filter cloth is still necessary as it helps maintain water clarity to <5 NTU. The majority of the time filtered turbidity measured <3 NTU (**Figure 5.29**).

The filtered turbidity measurements, prior to 100 mL, shown in **Figure 5.29**, also validates the hypothesis formed at the conclusion of Experiment C-7: the ripening layer forms during the 0 mL to 100 mL filtration point, thus the water clarity improves to <5 NTU at the start of 100 mL filtered. Lastly, <5 NTU turbidity was maintained by filtration rates between 0.5 L/min and 1.5 L/min.

All of the Optimization Experiments thus far have tested the variations in mixing time, mixing intensities, and settling methods and times. The optimal procedures chosen from the experiments are based on the higher end mixing intensities and time. The optimized laboratory protocol for the Mark I design was as follows: (1) add PÜR[®], (2) invert 20 times at a rate of 40 beats per minute, (3) mix horizontally at a rate of 100 beats per minute for 5 minutes, (4) settle horizontally for 15 minutes, (5) settle vertically for 15 minutes, and, (6) filter water (**Figure 5.31**). These Mark I procedures were also translated to pictograph instructions (see Appendix F). This procedure was tested at different initial turbidity levels in the final Optimization Experiment, C-9.

1. Add PÜR®

2. Invert for rapid mixing

3. Roll for 5 min, 4. Settle horizontally for 10 min

5. Hang vertically to settle for 15 min

6. Filter prior to drinking

Figure 5.31 - Optimized laboratory procedures based on the Optimized Experiment results.

5.3.9 - Experiment C-9: Various Initial Turbidities

In Experiment C-9, five different prototypes with various initial turbidities were tested based on the optimized protocol to determine if the method produced consistent water quality results over a range of turbidities. The initial water quality characteristics for the prototypes are summarized in **Table 5.14**. Initial turbidities ranged from 54.0 NTU to 839 NTU.

Table 5.14 - Initial water quality characteristics of Experiment C-9 where initial turbidities differed in each prototype

Water Quality Parameter (Pre-Treatment)	Units	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5
Temperature	°C	21.1	20.5	21.0	20.2	20.3
Turbidity	NTU	54.0	130	233	400	839
pH	--	7.85	8.14	8.05	8.13	8.42
TSS	mg / L	NS ¹	133	229	364	454
Total Coliform bacteria	MPN / 100 mL	3.10×10^2	8.05×10^2	3.60×10^2	3.05×10^2	1.13×10^3
<i>E. Coli</i>	MPN / 100 mL	< 1	1.50×10^2	1.00×10^2	1.00×10^2	1.00×10^2

¹ NS = Not Sampled

After treatment the pre-filtered turbidity measured between 4.04 NTU to 14.3 NTU. The highest pre-filtered turbidity was observed for the waterbag prototype which received the lowest turbidity initial water (Bag 1). The initial post-filtered turbidity taken after 15 mL had been filtered showed that all prototypes increased to between 15.4 NTU to 24.3 NTU. Once 100 mL was filtered through the 1-µm cloth, turbidities decreased to between 2.01 NTU and 3.74 NTU (**Figure 5.32**).

Figure 5.32 - Pre-filter and post-filter turbidities after 15 mL and 100 mL had been filtered for five prototypes at various initial turbidities. Turbidity increased at the 15-mL filtration point and then decreased at the 100-mL sampling point (as observed in Figure 5.24 and Figure 5.28).

Just as in the previous Experiments C-7 and C-8, turbidity measurements were taken in 1-L increments during filtration up to the total yield output of the prototypes, and filtration rates were recorded during this period. Considering only samples at the 1-L point and beyond, turbidity measured <5 NTU for all prototypes through the filter run, ranging between 1.68 NTU and 3.54 NTU (**Figure 5.33**). Readings were taken up to the 6-L point for Bag 1 through Bag 4 and up to the 5-L point for Bag 5. The total yield of 9 L was not reached as additional water samples were taken for TSS and bacteria measurements. The filtration rates started at 1.0 L/min and decreased to 0.5 L/min for all prototypes (**Figure**

5.34). The filtration rate remained somewhat below the tap water test control prototype although even the tap water control showed a 2-3 fold reduction in flow rate.

Figure 5.33 - Turbidity measurements at 1-L increments during filtration. Generally, turbidity decreased over the course of filtration or remained consistent throughout the filtration run.

Figure 5.34 - Filtration rates recorded over the 6-L volume output. up to 7.1 L volume. The filtration rates were between 0.5 L/min to 1.0 L/min.

The prototypes were also analyzed for final chlorine residual, TSS concentrations, and for the presence of total coliform and *E. coli* bacteria. The final treated water quality characteristics are summarized in **Table 5.15**. Each water quality parameter improved after treatment compared with the initial test water. Bags 2, 3, and 5 reduced total coliform bacteria and *E. coli* to <1 MPN/100 mL; however, Bag 1 and Bag 4 did not fully remove total coliform and *E. coli* bacteria.

Table 5.15 - Experiment C-9 post-treated water quality characteristics for all prototypes

Water Quality Parameter (Post-Treatment)	Units	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5
Chlorine Residual ¹	mg / L	0.02 (ND)	0.07	0.08	0.10	0.15
TSS (Pre-filter)	mg / L	4.00	5.40	5.20	6.40	4.40
TSS (Post-filter) ²	mg / L	1.93 (ND)	1.53 (ND)	2.20 (ND)	2.70	3.00
Total Coliform bacteria (Pre-filter)	MPN / 100 mL	4.41 x 10 ¹	< 1	< 1	2.15 x 10 ²	< 1
Total Coliform bacteria (Post-filter)	MPN / 100 mL	2.95 x 10 ¹	< 1	< 1	1.44 x 10 ¹	< 1
<i>E. Coli</i> (Pre-filter)	MPN / 100 mL	1.52 x 10 ¹	< 1	< 1	6.28 x 10 ¹	< 1
<i>E. Coli</i> (Post-filter)	MPN / 100 mL	5.20	< 1	< 1	5.08 x 10 ¹	< 1

¹Chlorine residual estimated non-detection limit is 0.02 mg/L (HACH Method 8021). Bag 1 measured 0.02 mg/L and is less than or equal to detection limit (ND=Non-detect).

²TSS detection limit is 2.50 mg of dried residue (APHA et al., 1995). Bags 1, 2 and 3 reached this non-detection (ND) limit even with the necessary volume filtered.

5.3.9.1 - Discussion of Experiment C-9 Results

The optimized method performed in Experiment C-9 produced consistent turbidity, TSS, and chlorine residual results, and, for the majority of the test bags, did treat total coliform and *E. coli* bacteria to <1 MPN/100 mL. However, total coliform and *E. coli* bacteria were present in the treated water produced by two of the prototypes.

As shown in **Figure 5.32**, for the pre-filter, post-filter after 15 mL were filtered, and post-filter after 100 mL were filtered, turbidity measurements remained consistent with the trends observed in Experiments C-7 and C-8. All pre-filtered turbidity, except for Bag 1 in Experiment C-9, measured <10 NTU. Bag 1, with an initial turbidity of 54.0 NTU, had the lowest initial turbidity of the prototypes tested to that point in time and reached a pre-filtered turbidity of 14.3 NTU. The reason for not reaching <10 NTU may be due to the low concentration of particles, which decreases flocculation efficiency (MWH, 2005). However, just as in Experiments C-7 and C-8, the initial 15 mL filtered exhibited water turbidities to increase to between 15.4 and 24.3 NTU, which may be due to the lack of a developed ripening layer on the filter pad since this is only the beginning of the filtration run. Once 100 mL was filtered (requiring only about 3 seconds of total filtration), the water quality improved to <5 NTU for the remainder of the filtrations. Therefore, even though the pre-filtered turbidity of Bag 1 was higher than the other prototypes, the final filtered turbidities met the WHO emergency turbidity requirement. Again, this reiterates the importance of the 1- μ m filter cloth in meeting the requirement.

Over the 6 L filtered, none of the prototypes clogged to the point where the filtration rate was impractically low. The filtration rates remained between 0.5 L/min and 1.5 L/min.

The total prototype volume was not filtered due to TSS and bacteria sampling needs. However, when comparing to the Tap Waterbag control, as shown in **Figure 5.34**, to the other prototypes, the decreasing filtration rate is observed, but if the data were extrapolated to 8 L, the filtration rate would drop below 0.5 L/min for all prototypes.

The final pre- and post- filtered treatment results for Bag 2, Bag 3, and Bag 5 met the WHO emergency guidelines for turbidity (< 5 NTU) and *E. coli* (≤ 1 MPN/100 mL). As discussed for Experiment, B-3, these are two of the major constituents of concern during emergency situations (Handzel, 2007). The turbidity measurements and decrease in TSS concentrations in all prototypes confirm the PÜR[®] coagulant was effectively mixed in the water and flocs settled based on the optimized protocol. Low chlorine residual concentrations were observed, and similar to the discussion of Experiment B-3 results, the PÜR[®] treatment may not meet chlorine residual concentration guidelines depending on the source water concentrations of reduced substances (e.g., organic matter and hydrogen sulfide) (Crump, et al., 2005).

Bag 1 and Bag 4 achieved only a 1-log removal of total coliform and *E. coli* bacteria. This may be due to experimental error in Colilert[®] testing for total and *E. coli* bacteria for these prototypes. For instance, in Bag 1, the initial *E. coli* bacteria reading was < 1 MPN/100 mL. However, *E. coli* bacteria were measured in pre- and post- filtered samples. The PÜR[®] studies, for the most part, result in < 1 *E. coli* MPN/100 mL; however, *E. coli* bacteria has been found in field samples after treatment, only obtaining a 0.5-log removal of microorganisms (Rangel, Lopez, Mejia, & Mendoza, 2003). Overall, the majority of the prototypes met the emergency water quality guidelines.

The next step in prototype testing was to challenge the prototype and method using the U.S. EPA Purifier Guidelines (1987). The question posed in the next experiments was: To what extent will the prototype and method meet the WHO emergency guidelines when physically and microbial challenged by the U.S. EPA Challenge Water, Test Water #2.

5.4 - U.S. EPA Challenge Water Experiments

The final experiments focused on treating the U.S. EPA Challenge Water, Test Water #2, to determine to what extent the prototypes could meet the U.S. EPA reduction requirements. Three experiments were conducted: (1) a mock run of the Test Water #2 at the Cal Poly laboratories, not including the microorganisms; (2) a test of the Cascade Design, Inc. prototype and, (3) the full U.S. EPA Challenge Test conducted at BioVir Laboratories in Benicia, CA.

5.4.1 - Mock Run Experiment

The Mock Run Experiment was performed to verify whether turbidity measurements met the WHO guideline of <5 NTU when treating the U.S. EPA Challenge Test Water #2, for both the standard PÜR[®] bucket test and a waterbag prototype. During this test, the water was only physically challenged; no microorganisms were added to the test water recipe. The water recipe was created according to the U.S. EPA Purifier Guidelines, and is summarized in Section 4.6, **Table 4.5**. The initial water quality characteristics for the bucket and prototype are summarized in **Table 5.16**. TOC was not measured in this experiment, but humic acid was added to increase TOC concentrations to greater than 10 mg/L.

The standard bucket method was used according to the PÜR® instructions (**Figure 2.12**), and the optimal waterbag protocol was used for the prototypes (refer to **Figure 5.31**).

Pre-filtered turbidities measured at the end of the 30-min settling time were 20.4 NTU for the waterbag prototype and 1.48 NTU for the bucket, while filtered turbidities taken at the 4-L mark resulted in 1.72 NTU and 1.29 NTU, respectively (**Figure 5.35**).

Table 5.16 - Mock Run Experiment water recipe based on the U.S. EPA Challenge Test Water #2

Water Quality Parameter (Pre-Treatment)	Units	Prototype	Bucket
Temperature	°C	4.0	4.1
Turbidity	NTU	439	443
pH	--	9.05	9.08
TSS	mg / L	422	324
TDS	mg / L	1460	1030

Figure 5.35 - Pre-filter and post-filter turbidities after 15 mL and 4 L were filtered for the prototype and bucket tests using a version of Challenge Water #2. The prototype treated water was filtered using the 1- μ m polypropylene filter cloth, and the bucket treated water was filtered with a 100% cotton cloth.

Prototype turbidity measurements were also taken in 1-L increments and ranged from 1.14 NTU to 1.72 NTU. Additionally, filtration rates were incrementally recorded over the 4-L output, and the total filtration time was 6 minutes and 24 seconds. The water initially filtered at a rate of 0.8 L/min and dropped to 0.4 L/min. It took 30 minutes to filter the entire 10 L through the 100% cotton cloth during the bucket test compared to less than 10 minutes for the waterbag prototype. Lastly, final TSS concentrations resulted in 1.80 mg/L for the prototype and 1.60 mg/L for the bucket.

5.4.1.1 - Discussion on Mock Run Experiment Results

The Mock Run Experiment did verify that the waterbag prototype met the WHO guideline of <5 NTU turbidity when treating the U.S. EPA Challenge Test Water #2, under the physical/chemical challenge. The standard PÜR® bucket test also met this turbidity guideline. The literature shows the standard PÜR® bucket test has passed the full U.S. EPA Challenge Test Water #2 minimum requirements when tested by P&G's Health Sciences Institute (Souter P. F., et al., 2003; P&G's Children's Safe Drinking Water Program, 2005).

The pre-filtered turbidities were very different for the prototype and bucket. The prototype was 20.4 NTU while the bucket turbidity measured 1.48 NTU. This discrepancy may be due to the different methods of discharging the water. The water in the bucket is decanted into another bucket in which the system is not pressurized and most flocs remain at the bottom of the bucket; whereas the prototype discharges water from the near the bottom of the bag (~6 in) and is pressurized under its own head, possibly forcing flocs into the outlet. When comparing this prototype test to Experiment C-9 results, it may be more likely that the challenge water parameters of cold temperatures and increase in humic acid caused a higher pre-filtered turbidity than expected, which was not observed for the bucket test. Experiment C-9 pre-filter turbidity measurements ranged from 4.04 NTU to 14.3 NTU. Therefore, the filter apparatus and 1- μ m cloth is important to the prototype system under these challenged water conditions. The turbidity levels after four liters filtered were comparable for the waterbag prototype and bucket, at 1.72 NTU and 1.29 NTU.

This experiment proved that the PÜR[®] treatment when coupled with the prototype did meet turbidity standards, but further information was needed to understand to what extent the #2 water humic acid consumes the PÜR[®] chlorine and coagulants, affecting the disinfection, coagulation, and filtration processes. The elevated pH, high TOC concentration, high turbidity levels, and low temperature, often interfere with the halogen disinfection and the coagulant (U.S. Environmental Protection Agency, 1987).

5.4.2 - Test of Cascade Designs Inc. Prototype

Prior to performing the full U.S. EPA Challenge Water Experiment, a quick test was conducted to confirm the efficacy of the treatment protocol and filtration rates using the Cascade Designs, Inc. prototypes. The prototypes were produced by Cascade Designs Inc., from their facility in Seattle, WA, at the end of June 2009. The prototypes were modified from Prototype #4, in that the prototype had a Zip-lock[™] style closure and the outlet hose barb was welded to the plastic film, replacing the bulkhead fitting and dispensing valve. The flow was released by a hose clamp clip on the tubing upstream of the filter apparatus.

The Cascade Design Inc. fabricated prototype was tested with the same water as the Mock Run Experiment, but the temperature remained at 20°C as opposed to 4°C in the Mock Run Experiment, and the initial turbidity was lower at 51.3 NTU. Once treated, the pre-filter turbidity measured 2.86 NTU; filtered turbidity at 15 mL measured 5.10 NTU, and after 250 mL was filtered it measured 1.25 NTU. Filtered turbidity also was measured in 1-L increments over the total volume output of 8.25 L, with results between 0.81 NTU and 1.29 NTU. Additionally, the filtration rate of the 8.25 L was recorded and

compared to the tap water Cascade Designs Inc. prototype (**Figure 5.36**). The prototype filtration rate ranged between 0.4 L/min and 0.8 L/min, while the tap waterbag filtration rate ranged between 0.5 L/min and 1.7 L/min.

Figure 5.36 - Filtration rates recorded during filtration of the full volume output. The filtration rate ranged between 0.4 L/min to 0.8 L/min for the treated prototype.

5.4.2.1 - Discussion on Test of Cascade Designs Inc. Prototype Results

The experimental results showed little difference between the Cascade Designs Inc. prototypes and the Cal Poly-made prototypes. Turbidity, post 15 mL filtered, was less than the emergency drinking water guideline of <5 NTU, and the filter cloth was able to filter the entire volume output. The filtration rate did drop below the minimum target flow of 0.5 L/min but only while filtering the final liter. Based on this test, the Cascade

Designs Inc. prototypes were used in the following experiment, the U.S. EPA Challenge Water Experiment.

5.4.3 - U.S. EPA Challenge Water Experiment

The U.S. EPA Challenge Water Experiment was conducted by the Cal Poly team at BioVir Laboratories in Benicia, CA, on July 13, 2009, under the supervision of Dr. Robert Cooper and staff. The objective of the experiment was to conduct the Test Water #2 challenge experiment on three 10-L prototypes using the PÜR[®] treatment and standard procedures identified in the Optimization Experiments (**Figure 5.31**). Three identical prototypes (Bag 1, Bag 2, and Bag 3), fabricated by Cascade Designs, Inc., were challenged with the bacterium *Raoultella terrigena* (ATCC 33257), two coliphage types MS2 (ATCC 15597-B1) and fr (ATCC15767-B1), and with 3.1-µm diameter fluorescent microspheres as a surrogate for *Cryptosporidium* oocysts (Duke Scientific Corp, Palo Alto, CA). The organisms were prepared by BioVir staff along with the challenge water (40 L of Test Water #2). Additionally, physical and chemical parameters were altered according to the Challenge Test Water #2 water recipe (**Table 5.17**). The Cal Poly team conducted the treatment tests and sampled for turbidity, final temperature, pH, chlorine residual, TOC, and filtration rates. The BioVir staff analyzed the influent composite sample and the final filtration sample, at 4 L produced, for *R. terrigena*, coliphages, and microspheres. The test water quality for the three prototypes is summarized in **Table 5.17**, and was prepared based on the U.S. EPA Purifier Guidelines for Challenge Test Water #2. The results for each sample are detailed below, first focusing on turbidity and filtration and then followed by a full summary of constituents sampled.

Table 5.17 - Challenge Test Water #2 prepared by BioVir Staff for the July 13, 2009, Cal Poly prototype testing (BioVir Laboratories, Inc., 2009)

Parameter	Value
Volume	40 L (de-chlorinated Benicia, CA, tap water)
pH	9.0
Chlorine	Non Detect
TDS	1447 mg / L
Turbidity	39 NTU ¹
TOC	11.5 mg / L
Temperature	4°C

¹Before humic acid added

Another item recorded were the lots of the three PÜR[®] packets. The three PÜR[®] packets used in this test were manufactured in August 2007 by P&G, with an expiration date of July 2010. The PÜR[®] packets for Bag 1 and Bag 2 originated from Lot #7214032203 and Bag 3 from Lot #7214032201.

During the settling time, floc formation and settling observations were recorded (as with previous experiments). Bag 1 water was observed to contain some suspended flocs and floating flocs; whereas Bag 2 did not have any floating flocs, but the water color remained a light-orange tint meaning dissolved constituent was not taken up in the flocs. Lastly, Bag 3 had suspended flocs throughout, but did not contain any floating flocs (**Figure 5.37**). The final physical water quality characteristics are summarized in **Table 5.18**.

Figure 5.37 - Floc movement varied in each prototype. Bag 1 (left) had floating flocs and some suspended flocs, while Bag 3 (right) had lots of suspended flocs. Bag 3 shown to the right is after 5 minutes of vertical settling, so the water clarity continued to improve from what is shown here.

Table 5.18 - Physical and chemical water quality characteristics post filtration during the Challenge Test Water #2 test at BioVir Laboratories.

Water Quality Parameter (After 4 L Filtered)	Bag 1	Bag 2	Bag 3
Temperature	15.1 °C	14.2 °C	16.0°C
Turbidity	1.50 NTU	4.76 NTU	1.51 NTU
pH	7.07	6.92	7.30
Chlorine Residual ¹	0.06 mg / L	NS ²	0.21 mg / L

¹Chlorine residual estimated non-detection limit is 0.02 mg/L (HACH Method 8021).

²NS = Not Sampled

Pre-filter turbidity measurements were taken during the 15-min vertical settling period and final pre-filtered turbidities ranged between 7.86 NTU and 9.44 NTU (**Figure 5.38**). After filtering 4 L, turbidities measured 1.50 NTU for Bag 1, 4.76 NTU for Bag 2, and 1.51 NTU for Bag 3 (**Figure 5.39**).

Figure 5.38 - Final pre-filtered turbidities ranged between 7.68 NTU to 9.44 NTU during the U.S. EPA Challenge Water Experiment.

Figure 5.39 - Pre-filter and post-filter turbidities after 4 L were filtered during the U.S. EPA Challenge Water Experiment.

The initial challenge water and Bag 1 filtered water were sampled for total organic carbon analysis by Creek Environmental Laboratories, in San Luis Obispo. The initial TOC concentration, prior to treatment, was 11.5 mg/L. This concentration was reduced to an average of 0.7 mg/L pre-filtration, and then increased slightly to an average of 1.14 mg/L at the end of the 4-L filtration run (refer to Appendix D for the Creek Environmental Laboratories TOC Analysis Report).

Filtration rates were also recorded during the 4-L filter run. For Bag 1, the filtration rate was from 0.5 L/min to 0.4 L/min; Bag 2 was from 1.4 L/min to 1.0 L/min; and Bag 3 was from 1.1 L/min to 1.0 L/min.

Lastly, the results of the microorganism challenge, analyzed by BioVir Laboratories staff, are summarized in **Table 5.19** through **Table 5.21**. *R. terrigena* was reported in colony forming units (CFU) per 100 mL, the combined bacteriophage was reported as plaque forming units (PFU) per mL (not 100 mL), and the microspheres were reported as

spheres per L (not per mL) (BioVir Laboratories, Inc., 2009). Refer to Appendix E for the final July 20, 2009 BioVir Laboratories Test Report on the Polytech Waterbag Challenge Experiment.

Table 5.19 - *R. terrigena* results from the U.S. EPA Challenge Water Experiment at BioVir Laboratories (BioVir Laboratories, Inc., 2009)

Influent	Bag 1		Bag 2		Bag 3	
CFU / mL	CFU / mL	Log Red.	CFU / mL	Log Red.	CFU / mL	Log Red.
1.6×10^6	1.4×10^2	4.0	$>1 \times 10^2$	<4.2	<1	>6.2

Table 5.20 - Coliphage results from the U.S. EPA Challenge Water Experiment at BioVir Laboratories (BioVir Laboratories, Inc., 2009)

Influent	Bag 1		Bag 2		Bag 3	
PFU / mL	PFU / mL	Log Red.	PFU / mL	Log Red.	PFU / mL	Log Red.
4.8×10^5	1.8×10^5	0.4	2.3×10^5	0.3	<1	>5.7

Table 5.21 - Microsphere results from the U.S. EPA Challenge Water Experiment at BioVir Laboratories (BioVir Laboratories, Inc., 2009)

Influent	Bag 1		Bag 2		Bag 3	
Spheres/L	Spheres/L	Log Red.	Spheres/L	Log Red.	Spheres/L	Log Red.
4.9×10^5	5.7×10^2	2.9	4.2×10^3	2.1	9.1×10^2	2.7

5.4.3.1 - Discussion on U.S. EPA Challenge Water Experiment Results

The U.S. EPA Challenge Water Experiment results showed that each prototype met the WHO emergency turbidity guideline; however, the other U.S. EPA Purifier Guidelines

minimum reduction requirements were not entirely met by any of the three prototypes. Most striking was the difference in the results between each identical bag, as discussed below.

First, the results are compared to the minimum water quality objectives for emergency response related to turbidity, chlorine residual, and pH (**Table 5.22**). These objectives were set by the Sphere Project, WHO, and U.S. EPA (**Table 2.3**). The results confirm that the turbidity and pH emergency objectives were met by all three prototypes, while the Bag 3 chlorine residual concentration was the only result that fell within the chlorine residual concentration range. Low chlorine residual concentrations can prevent complete pathogen kill, and when comparing the required reduction removal set by the U.S. EPA, only the prototype with the sufficient chlorine residual met the microbiological requirements (**Figure 5.40**). The U.S. EPA calls for three identical microbiological purifier devices to be tested, and each unit must continuously meet or exceed the log reduction requirements (U.S. Environmental Protection Agency, 1987).

Table 5.22 - U.S. EPA Challenge Water Experiment results compared to the emergency response objectives for turbidity, chlorine residual, and pH.

Parameter	To Demonstrate	Bag 1	Bag 2	Bag 3
Turbidity	< 5 NTU	1.50 NTU	4.76 NTU	1.51 NTU
Chlorine Residual ¹	0.2-0.5 mg/L	0.06 mg / L	NS ²	0.21 mg / L
pH	6 to 8	7.07	6.92	7.30

¹Chlorine residual estimated non-detection limit is 0.02 mg/L (HACH Method 8021).

²NS = Not Sampled

Figure 5.40 - Log reduction comparisons of the three prototypes from the U.S. EPA Challenge Water Experiment to the 1987 U.S. EPA Purifier Guidelines minimum log reduction requirements.

Bag 3 surpassed the minimum log reduction for both the *R. terrigena* and viruses, but did not meet the minimum 3-log reduction for *Cryptosporidium*/microspheres, although the result was borderline. Bag 1 and Bag 2 did not meet or exceed any of the minimum log reduction requirements but produced similar *Cryptosporidium*/microspheres log-reductions as Bag 3. These results differed from the Souter et al. 2003 study which demonstrated that the standard PUR[®] treatment method exceeded all minimum U.S. EPA Purifier Guidelines log-reduction requirements using the bucket method.

Focusing on just the present experiment, the question raised is: Why was there such a great difference in treatment results between the prototypes despite undergoing identical mixing and settling procedures? A theory for this variability is insufficient mixing of the recipe water, as described next.

Forty-liters of Test Water #2 was prepared by BioVir Laboratories and mixed on a magnetic mixer. The first waterbag prototype was filled, underwent the treatment testing and sampling, and then the process was repeated for the second and third prototypes. If the contents of the challenge water source reservoir were not well-mixed, Bag 1 and Bag 2 may have received humic acid particles that settled to the bottom of the reservoir, which had an outlet near its bottom. By the time Bag 3 was filled, these particles could have been dissolved or flushed out during the filling of the previous bags. Bag 3, then, would have received water with a lower humic acid concentration, possibly explaining the better disinfection achieved by Bag 3.

Assuming that the PÜR[®] packets in the different lots had equal compositions, the vastly different results among the prototype bags must be due to experimental variability, which could include inconsistent filter operation. The filter apparatus may not have fully-sealed, allowing the passage of water around the filter cloth; thus microspheres had the potential to escape physical removal and end up in the effluent sample. During the experiment, binder clips were used to help mitigate sealing issues; however, the apparatus did not maintain a leak-proof seal. Improving the seal will decrease this error in the future.

Physical removal of *Cryptosporidium* oocysts (approximately 3-5 μm in diameter), is necessary through coagulation, sedimentation, and 1- μm filtration. However, in this

experiment, the 3.1- μm diameter microspheres were not removed to the minimum 3.0-log reduction guideline (log reductions ranged from 2.1 to 2.9). The 1- μm filter cloth is rated to remove 50% of particles larger than its 1- μm nominal retention size (Rosedale Filtration, 2008). Thus, 3.1- μm microspheres had some potential to escape physical removal and reach the effluent.

CHAPTER 6 - CONCLUSIONS

The results reported here led to the development of a Mark I prototype waterbag and an optimized method of use. Three main goals of the project were to (1) design a prototype, (2) conduct water quality experiments to optimize the mixing and settling procedures, and, (3) conduct water quality experiments to determine efficacy of the device in meeting the WHO emergency drinking water guidelines and the U.S. EPA Purifier Guidelines. Concluding remarks on each goal are presented below.

6.1 - Prototype Design Conclusions

The development stages of the prototype led to the Mark I design in which a 10-L volume is contained with an air headspace volume necessary for mixing the water. The Mark I design meets the majority of the CDC and UNICEF safe water storage criteria for minimizing contamination and user acceptance (**Table 6.1**; refer to **Table 2.9** for the importance of the criteria). This comparison is just focused on the prototype design as a container, not on the water quality results, which are discussed in the following section.

Table 6.1 - Prototype design storage and user criteria in comparison to the CDC and UNICEF safe water storage criteria (as found in Table 2.9).

Criteria	Met by prototype?	Explanation
Criteria for minimizing contamination:		
Constructed of translucent, easily cleaned material (plastics, most metals, ceramics, polished concrete)	Yes/Maybe	Translucent LDPE is used. While LDPE is easily cleaned, cleaning the waterbag between uses was not investigated in the current research.
Tap to draw water or narrow spout (must not leak)	Yes	The waterbag has a tap with valve or hose clamp.

Criteria	Met by prototype?	Explanation
Have a single opening, 8 cm in diameter (or greater), with a strong, tight fitting cap, to discourage hands and ladles from contaminating storage vessel	Yes	Single wide-mouth opening larger than 8 cm for water collection purposes. Roll-down closure prevents recontamination.
Stable with a flat bottom	Partially	Waterbag prototype must be hung by straps or rested horizontally.
Criteria for usability / user acceptance:		
Durable	Yes	During storage: LDPE plastic has a >10 year lifespan when stored properly in a warehouse. However, PUR packets currently have a 2-year shelf life rating. During use: The waterbags are designed for about 10 uses.
Impact resistant (some plastics may not be)	No	While the waterbag is impact resistant, it is not puncture resistant.
Portable, hold less than 25-liter capacity, suitable for carrying water	Yes	Current capacity is 10 L when coupled with a PUR [®] packet.
Inexpensive	Yes	Although cost estimates have not been finalized, the materials used in the waterbag+filter are likely to make the price comparable to simple plastic buckets or containers such as the “Oxfam bucket” or the CDC SWS container.
Available in local markets	No	The possibilities for local manufacturing or distribution not been investigated at this point.

The prototype shows promise in satisfying safe storage and user needs according to the criteria.

6.2 - Experimental Conclusions

The prototype, when coupled with the PÜR[®] treatment, was tested as an alternative to the standard PÜR[®] bucket protocol and to determine the efficacy of the device in meeting the WHO emergency drinking water guidelines and U.S. EPA Purifier Guidelines.

Based on the Filter Selection Experiments (A-1 through A-9), the 1-µm polypropylene filter cloth fulfilled the physical filtration needed to meet the WHO emergency turbidity guideline. The hemp and 100% cotton cloth did filter to the standard level but only with multiple layers, which can be cumbersome and not as durable as the 1-µm cloth.

The Baseline Water Quality Experiments provided initial treatment results for the prototype for comparison to the PÜR[®] standard bucket method. The source water experiment, B-3, testing the reservoir and pond water mixture, resulted in comparable prototype and bucket values for turbidity, <5 NTU after filtration, and *E. coli* removed to <1 MPN/100 mL. These results met the WHO emergency guidelines.

The Optimization Experiments identified the set of treatment steps that achieved the lowest pre-filtered turbidity measurements. An optimal procedure was identified for the Mark I design, and eight experiments tested different mixing variations and intensities, settling variations and times, and flow regulation. The utmost important result from these experiments was that an energetic and prolonged mixing period is needed to achieve effective coagulation and flocculation with PUR reagents. Experiment C-6 introduced the "vigorous" mixing intensity in which the prototype was rocked horizontally at 100 beats per minute, compared to the gentle mixing rate of 36 beats per minute used previously. Once vigorous mixing became part of the protocol, pre-filtered turbidities dropped, some

even reaching <5 NTU prior to filtration. The final Optimization Experiment compared the Mark I optimized procedures for different initial turbidity waters, and all final filtered turbidities measured <5 NTU, meeting the WHO emergency turbidity guideline. *E. coli* were also measured, and three of the five prototypes in this experiment met the emergency guideline of <1 MPN/100 mL. The final optimized laboratory protocol for the Mark I design was as follows: (1) add PÜR[®], (2) invert 20 times at a rate of 40 beats per minute, (3) mix horizontally at a rate of 100 beats per minute for 5 minutes, (4) settle horizontally for 15 minutes, (5) settle vertically for 15 minutes, and, 6) filter water (Figure 5.31).

Lastly, the U.S. EPA Challenge Water Experiments provided more insight into the treatment method. Challenge Test Water #2 was treated in triplicate waterbag prototypes. Test results did meet the pH and turbidity requirements; however, the U.S. EPA Water Purifier Guidelines minimum microorganism reduction requirements were not met. While this is a disappointing result, the U.S. EPA Purifier Guidelines are highly conservative and not necessarily entirely relevant to the waterbag for emergency relief situations. The U.S. EPA Purifier Guidelines is specific for device objectives while the WHO guidelines for emergency, are specific to disaster relief situations, were repeatedly met by the final Mark I waterbag prototype with optimized method of use. Most importantly, the Challenge Water test provided valuable information that is motivating further improvements in the waterbag design and method of use.

6.3 - Future Research

Several important issues need to be resolved before the concept of a waterbag with chemical treatment packet for disaster relief can be ready for relief organization use. One is its current inability to treat U.S. EPA Challenge Water #2 with its high humic acid content, which consumes chlorine disinfectants and coagulants. Although the U.S. EPA Purifier Guidelines testing protocols likely represent extreme worst-case water quality compared to typical floodwaters, it is of course still a worthwhile goal to develop a waterbag process that can consistently treat Challenge Water #2 successfully. Achieving this goal with a low-cost device is the main challenge. Considering the millions of people each year whose water supplies are contaminated during disasters, a balance may have to be struck between the cost of devices and their ability to treat Challenge Water #2.

Already some of the drawbacks of the Mark I design brought to light by the present research led to a substantially different Mark II design that is the subject of ongoing studies. The Mark II design introduces improvements in design manufacturability, mixing method and timing, and filter media. However, the progress made on mixing, sedimentation, and filtration with the Mark I design are fundamental to the Mark II work.

Future research is necessary in the areas of laboratory testing, field testing, and manufacturability. The laboratory research includes testing and optimization of the mixing procedure of the Mark II design, which may decrease mixing time from the current 5 minutes and/or provide better flocculation of Challenge Water #2. The filter support housing and filter media needs to be evaluated for improvements. Simple improvements such as using thicker filter cloth or filter pads or finer pored filter cloth

would likely improve water quality results but with the potential disadvantages of flow rates and quicker clogging.

Robustness testing should be conducted on mixing methods and duration to judge the importance of natural variations in how the users interpret and execute the pictographic instructions. Similarly, the duration of the pause between PÜR[®] packet addition and the start of mixing may affect performance. Additionally, other coagulant/disinfectant combinations could be developed. Finally, a challenge water representing more typical flood water quality might be developed for the evaluation of the waterbag and other devices for this market. Potential research in this area involves categorizing and summarizing past disaster events, particularly floods, in order to get a well-represented water in regards to pH, temperature, background natural organic matter, total dissolved solids, turbidity, and microbial contamination. An alternative, more realistic challenge water recipe, which would challenge the purifier device yet simulate realistic conditions, could have drastic impacts on providing a low-cost device for water treatment during emergencies and humanitarian efforts.

Field testing is recommended with the potential to establish opportunities through partnerships with the network of relief organizations and corporations. Continued testing of the pictograph instructions, waterbag closure, mixing times and energy input, and water quality results will help create a product that meets user's and relief organization's needs.

The fundamental concern and groundwork for the present research is based on the essential human need for clean drinking water, especially in the critical time following a

natural disaster. As Steve Rieve of the American Red Cross has stressed, “Providing clean drinking water is the #1 challenge in disaster zones” (Rieve, 2008). The statistics show that during emergency situations, “diarrheal diseases have accounted for more than 40% of deaths in the acute phase¹ of the emergency. Over 80% of deaths are among children under 2 years of age” (Connolly, 2005). Clean water must be provided rapidly to prevent widespread illness. The prototype has been designed and tested to overcome this burden, with the goal of providing an alternative point-of-use water treatment device that is simple, compact, and inexpensive for widespread distribution.

¹ Acute phase of an emergency is defined as “when the crude mortality rate goes above 1 per 10,000 per day in a displaced population” (Connolly, 2005).

REFERENCES

- Albert, J. (2009, April 16). Experiences in Disaster Relief Settings. (P. Compas, Interviewer)
- Allgood, G. (2009, March 31). Safe Drinking Water: How One Company Makes a Difference in the Developing World. Baltimore: John Hopkins University, School of Advanced International Studies.
http://fora.tv/2009/03/31/Greg_Allgood_Making_Water_PUR#.
- APHA et al. (1995). *Standard Methods for the Examination of Water and Wastewater* (19th Edition ed.). (A. D. Eaton, L. S. Clesceri, & A. E. Greenberg, Eds.) Washington, DC: APHA, AWWA, WEF.
- Bartlett, G. (2009, April 24). Manufacturing Discussions. (T. Lundquist, P. Compas, M. Herzog, & J. Dunning, Interviewers)
- BioVir Laboratories, Inc. (2009). *Test Report: Polytech Waterbag Challenge, Project No. 091924*. Benecia: BioVir Laboratories.
- Blanch, H., & Douglas C. (1997). *Biochemical Engineering*. New York: Marcel Dekker, Inc.
- CAWST. (2006). *Filtration Technology*. Retrieved June 2009, from CAWST: <http://www.cawst.org/index.php?id=128>
- Centers for Disease Control and Prevention. (2005). *Chlorine Residual Testing Fact Sheet, CDC SWS Project*. Retrieved September 16, 2008, from CDC Safe Water System Publication: http://www.cdc.gov/safewater/publications_pages/chlorineresidual.pdf
- Centers for Disease Control and Prevention. (2005, August 25). *Disinfection By-Products and the Safe Water System*. Retrieved June 16, 2009, from CDC Safe Water Systems Publications - Chlorine Information: http://www.cdc.gov/safewater/publications_pages/thm.pdf
- Centers for Disease Control and Prevention. (2008). *Household Water Treatment Options in Developing Countries, Flocculant/Disinfectant Powder*. Cincinnati: CDC.
- Centers for Disease Control and Prevention. (2008, January). *Safe Water System, A Low-Cost Technology for Safe Drinking Water*. Retrieved June 2009, from Centers for Disease Control and Prevention, U.S. Department of Health and Human Services: <http://www.cdc.gov/safewater>

- Centers for Disease Control and Prevention, USAID. (2008). *Preventing Diarrheal Disease in Developing Countries: Proven Household Water Treatment Options*. Atlanta: CDC.
- Centers for Disease Control and Prevention, USAID. (2009). *Preventing Diarrheal Disease in Developing Countries: Safe Storage of Drinking Water*. Atlanta: CDC.
- Clasen, T. (2007). *Point-of-Use Water Treatment in Emergencies and Development Settings*. London: London School of Hygiene & Tropical Medicine, Department Infectious & Tropical Diseases.
- Clasen, T., & Smith, L. (2005). *The Drinking Water Response to the Indian Ocean Tsunami Including the Role of Household Water Treatment*. London School of Hygiene & Tropical Medicine. Geneva: World Health Organization.
- Clasen, T., McLaughlin, C., Nayaar, N., Boisson, S., Gupta, R., Desai, D., et al. (2008). Microbiological Effectiveness and Cost of Disinfecting Water by Boiling in Semi-Urban India. *The American Journal of Tropical Medicine & Hygiene* , 79 (3), 407-413.
- Clasen, T., Saeed, T. F., Boisson, S., Edmondson, P., & Shipin, O. (2007). Household Water Treatment using Sodium Dichloroisocyanurate (NaDCC) Tablets: A Randomized, Controlled Trial to Assess Microbiological Effectiveness in Bangladesh. *The American Society of Tropical Medicine and Hygiene* , 76 (1), 187-192.
- CNN.com. (2008). *Bloated Corpses Pile Up; First U.S. Aid Flight Arrives in Myanmar*. Retrieved May 13, 2008, from CNN.com:
http://www.cnn.com/2008/WORLD/asiapcf/05/12/myanmar.aid/index.html?eref=rss_topstories
- Colwell, R. (2003). Reduction of Cholera in Bangladeshi Villages by Simple Filtration. *Proceedings of the National Academy of Sciences of the United States of America*, 100 (3), 1051-1055.
- Connolly, M. A. (2005). *Communicable Disease Control in Emergencies: A Field Manual*. Geneva: World Health Organization.
- Cooper, R. (2009, May 5). BioVir Laboratories, Inc., Benicia, Calif. (T. Lundquist, Interviewer).
- Cooper, R. (2008, August 19). BioVir Laboratories, Inc., Benicia, Calif (T. Lundquist, Interviewer).

- Crites, R., & Tchobanoglous, G. (1998). *Small and Decentralized Wastewater Managment Systems*. Boston: McGraw-Hill.
- Crompton, J., & Clarke, B. (1997). *Well*. Retrieved June 1, 2009, from Developments in surface water treatment for Emergency/Refugee Situations: <http://www.lboro.ac.uk/well/resources/consultancyreports/task0065/pdf/r6572.pdf>
- Crump, J. A., Otieno, P. O., Slutsker, L., Keswick, B. H., Rosen, D. H., Hoekstra, R. M., et al. (2005). Household Based Treatment of Drinking Water with Flocculant-Disinfectant for Preventing Diarrhoea in Areas with Turbid Source Water in Rural Western Kenya: Cluster Randomised Controlled Trial. *BMJ.com* , *Doi: 10.1136/bmj.38512.618681.EO*, 1-6.
- Davis, J., & Lambert, R. (2007). *Engineering in Emergencies, 2nd Edition*. Warwickshire: Intermediate Technology Publications Ltd.
- Deatrick & Associates. (undated). *Chlor-Floc(R) Water Purification Tablets*. USACHPPM Water Supply Management.
- Doocy, S., & Burnham, G. (2006). Point-of-use Water Treatment and Diarrhoea Reduction in the Emergency Context: an Effectivenss Trial in Liberia. *Tropical Medicine adn International Health* , 11 (10), 1542-1552.
- Dorea, C. C., Bertrand, S., & Clarke, B. A. (2006). Particle Separation Optoins for Emergency Water Treatment. *Water Science adn Technology: A Journal of the International Association on Water Pollution Research* , 53 (7), 253-260.
- Eawag. (2009). *SODIS, Solar Water Disinfection*. Retrieved June 5, 2009, from A Water Treatment Process used at Household Level: <http://www.sodis.ch/>
- Esposto, S. (2005). *Sustainable Water Treatment in Emergency*. Rome: Universita Degli Studi Di Roma "la Sapienza".
- Evenproducts. (2005). *Evenproducts Water for Life*. Retrieved June 1, 2009, from Justice Roche News Media Specialists: http://www.justice-roche.com/evenproducts/uploads/water_aid_brochure_2005.pdf
- Freeman, D., & Szymanski, C. (2005). *PSI Sends Critical Water Purification Tools to Tsunami Survivors*. Geneva: World health Organization: Household Water Treatment & Safe Storage Network Bulletin.
- Gallagher, K., & Varnava, B. (2009, May 18). Meeting with Cascade Designs Inc., NFESC, and Cal Poly Waterbag Team. (T. Lundquist, P. Compas, J. Dunning, & M. Herzog, Interviewers)

- Global Hydration. (2009, May). *Global Hydration*. Retrieved June 2009, from Product and Services - Aquatabs(R): <http://www.globalhydration.com/aquatabs-water-purification-tablets.htm>
- Guha-Sapir, D., Hargitt, D., & Hoyois, P. (2004). *Thirty Years of Natural Disasters 1974-2003: The Numbers*. Centre for Research on the Epidemiology of Disasters. Belgium: Presses Universitaires de Louvain.
- Gupta, S., & Quick, R. (2005). *Inadequate Drinking Water Quality from Tanker Trucks following a Tsunami Disaster, Aceh, Indonesia, June 2005*. Retrieved May 13, 2009, from Emerald Insight: <http://emeraldinsight.com/Insight/ViewContentServlet;jsessionid=541B464517A9DF5D3BE4F544AD5898C2?contentType=NonArticle&Filename=Published/NonArticle/Articles/07315aaa.001.html>
- Handzel, T. (2007, December 3). (T. Lundquist, & P. Compas, Interviewers)
- Harper, C. A., & Petrie, E. M. (2003). *Plastic Materials and Processes, a Concise Encyclopedia*. Hoboken: Wiley-Interscience.
- Huq, A., Chowdhury, M., Islam, M. S., Montilla, R., & Colwell, R. R. (1996). A Simple Filtration Method To Remove Plankton-Associated *Vibrio Cholerae* in Raw Water Supplies in Developing Countries. *Applied and Environmental Microbiology*, 62 (7), 2508-2512.
- Hutten, I. M. (2007). *Handbook of Nonwoven Filter Media*. Burlington: Elsevier Ltd.
- IDEXX Laboratories, Inc. (2007). *Colilert: IDEXX Water Microbiology*. Retrieved 2008, from www.idexx.com/water
- International Federation of Red Cross and Red Crescent Societies. (2008). *Myanmar, Cyclone Nargis, September 2008*. Retrieved June 29, 2009, from International Federation of Red Cross and Red Crescent Societies: <http://www.ifrc.org/photo/Myanmarcyclone0908/image6.asp>
- International Federation of the Red Cross and Red Crescent Societies. (2005). *Emergency Response Units (ERU)*. Retrieved June 1, 2009, from IFRC Disaster Management: <http://www.ifrc.org/what/disasters/responding/drs/tools/erus/erutypes.asp#ws>
- Kasper, A. (2007). *Safe Water System -- Effect of Chlorination on Inactivating Selected Pathogens*. Centers for Disease Control and Prevention, Atlanta, Georgia.
- Kols, A. (2008). *PATH Safe Water Project -- Project Brief, January 2008*. PATH, Seattle, Wash.

- Lantagne, D. S. (2008). *CDC Safe Water System Experience in Developing Countries During Emergency Situations*. Centers for Disease Control and Prevention, Atlanta, Georgia.
- Lantagne, D. S., Blount, B. C., Cardinali, F., & Quick, R. (2008). Disinfection By-Product Formation and Mitigation Strategies in Point-of-Use Chlorination of Turbid and Non-Turbid Waters in Western Kenya. *Journal of Water and Health* , 6 (1), 67-82.
- Lantagne, D., Quick, R., & Mintz, E. (2006). *Household Water Treatment and Safe Storage Options in Developing*. Washington DC: Woodrow Wilson International Center for Scholars' Environmental Change and Security Program.
- Laurent, P., Visser, M., & Fesselet, J. F. (1995). *Household Drinking Water Systems and their Impact on People with Weakened Immunity*. Holland: Holland Public Health Department.
- Luby, S. P., Agboatwaia, M., Painter, J., Altaf, A., Billhimer, W., Keswick, B., et al. (2006). Combining Drinking Water Treatment and Hand Washing for Diarrhoea Prevention, a Cluster Randomised Controlled Trial. *Tropical Medicine and International Health* , 11 (4), 479-489.
- Lundquist, T. (2009). *Patent No. 7,514,006*. United States of America.
- Lundquist, T. (2008, November). Lecture on Coagulation and Flocculation for Cal Poly ENVE 535 Graduate Class.
- Lundquist, T. (2008, October). Mixing Lecture for Cal Poly ENVE 535 Graduate Class.
- Mendez-Hermida, F., Castro-Hermida, J. A., Ares, M., Kehoe, S. C., & McGuigan, K. G. (2005). Effect of Batch-Process Solar Disinfection on Survival of *Cryptosporidium parvum* Oocysts in Drinking Water. *Applied and Environmental Microbiology* , 71 (3), 1653-1654.
- Metcalf & Eddy. (2003). *Wastewater Engineering Treatment and Reuse* (4th ed.). New York: McGraw-Hill Inc.
- Mintz, E., Reiff, F., & Tauxe, R. (1995). Safe Water Treatment and Storage in the Home: A Practical new Strategy to Prevent Waterborne Disease. *JAMA* , 273, 948-953.
- Munich Re Group. (2008). *Munchener Ruck NatCatSERVICE, The Ten Largest Natural Catastrophes in 2008*. Retrieved February 24, 2009, from http://www.munichre.com/app_resources/pdf/press/press_releases/2008/2008_12_29_app1_en.pdf

- Munich Re Group. (2008). *Natural Disasters 2008, World Map*. Retrieved February 24, 2009, from http://www.munichre.com/app_resources/pdf/press/press_releases/2008/2008_12_29_app2_en.pdf
- MWH. (2005). *Water Treatment Principles and Design*. New Jersey: John Wiley & Sons, Inc.
- Nath, K., Bloomfield, S., & Jones, M. (2006). *Household Water Storage, Handling, and Point-of-Use Treatment*. Kolkata, India: International Scientific Forum on Home Hygiene.
- Oxfam. (2001). *Guidelines for Public Health Promotion in Emergencies*. Oxford: Oxfam Humanitarian Department.
- P&G. (2003). *PUR Purifier of Water (4g)*. Cincinnati: P&G Health Sciences Institute.
- P&G's Children's Safe Drinking Water Program. (2005). *PUR Purifier of Water*. Cincinnati: P&G Health Sciences Institute.
- Powers, E. M., Hernandez, C., Boutros, S. N., & Harper, B. G. (1994). Biocidal Efficacy of a Flocculating Emergency Water Purification Tablet. *Applied and Environmental Microbiology*, 60 (7), 2316-2323.
- Rangel, J. M., Lopez, B., Mejia, M. A., & Mendoza, C. (2003). A Novel Technology to Improve Drinking Water Quality: a Microbiological Evaluation of In-Home Flocculation and Chlorination in Rural Guatemala. *Journal of Water and Health*, 1 (1), 15-22.
- Reliance. (2008, May). (T. Lundquist, Interviewer)
- Relief Web. (2007, November 30). *Ghana: Situation report on floods, Nov 2007*. Retrieved June 25, 2009, from Relief Web: <http://reliefweb.int/rw/rwb.nsf/db900SID/EGUA-79RSAK?OpenDocument>
- Relief Web. (2009, January 27). *Myanmar Cyclone Nargis Labutta Hub Update No. 6*. Retrieved June 25, 2009, from Relief Web: <http://www.reliefweb.int/rw/rwb.nsf/db900SID/LSGZ-7NVE9D?OpenDocument>
- Reller, M. E., Mendoza, C. E., Lopez, M. B., Alvarez, M., Hoekstra, R. M., Olson, C. A., et al. (2003). A Randomized Controlled Trial of Household-Based Flocculant-Disinfectant Drinking Water Treatment for Diarrhea Prevention in Rural Guatemala. *American Journal of Tropical Medicine & Hygiene*, 69 (4), 411-419.

- Rieve, S. (2008, April). (T. Lundquist, Interviewer)
- Rosedale Filtration. (2008). Rosedale Filtration Master Catalog. Rosedale, CA.
- Sawyer, C. N., McCarty, P. L., & Parkin, G. F. (2003). *Chemistry for Environmental Engineering and Science* (5th ed.). New York: McGraw-Hill.
- Sharma, H. D., & Lewis, S. P. (1994). *Waste Containment Systems, Waste Stabilization, and Landfills: Design & Evaluation*. New York: John Wiley & Sons, Inc.
- Sobsey, M. D. (2002). *Managing Water in the Home: Accelerated Health Gains from Improved Water Supply*. Geneva: WHO.
- Sommer, B., Marino, A., Solarte, Y., Salas, M. L., Dierolf, C., Valiente, C., et al. (1997). SODIS -- An Emerging Water Treatment Process. *Journal of Water Supply: Research & Technology - Aqua* , 46 (3), 127-137.
- Souter, P. F., Cruickshank, G. D., & Stoddart, B. (2007). *Patent No. 7,201,856 B2*. US.
- Souter, P. F., Cruickshank, G. D., Tankerville, M. Z., Keswick, B. H., Ellis, B. D., Langworthy, D. E., et al. (2003). Evaluation of a New Water Treatment for Point-of-Use Household Applications to Remove Microorganisms and Arsenic from Drinking Water. *Journal of Water and Health* , 1 (2), 73-84.
- Srimurali, M., Pragathi, A., & Karthikeyan, J. (1997). A Study on Removal of Fluorides from Drinking Water by Adsorption onto Low-Cost Materials. *Environmental Pollution* , 99 (1998), 285-289.
- Tchobanoglous, G., & Schroeder, E. D. (1987). *Water Quality* . Readin: Addison-Wesley Longman.
- The Aquaya Institute. (2006). *Standard Operating Procedure for the Deployment of Proctor & Gamble's PUR Purifier of Water in Emergency Response Settings*. Retrieved April 28, 2008, from Aquaya Institute:
http://www.aquaya.org/files/Aquaya_PUR_SOP.pdf
- The Sphere Project. (2004). *The Sphere Handbook: Humanitarian Charter and Minimum Standards in Disaster Response*. Geneva: The Sphere Project.
- The Sphere Project. (2006). *Welcome to Sphere Project*. Retrieved December 3, 2007, from: http://www.sphereproject.org/component/option,com_frontpage/Itemid,200/lang,English

- U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM). (2008). *NSF Protocol P248 Emergency Military Operations Microbiological Water Purifiers*. Ann Arbor: NSF International.
- U.S. Environmental Protection Agency. (1995). *Fabric Filter Material*. Retrieved April 2, 2009, from EPA.gov:
[http://yosemite.epa.gov/oaqps/EOGtrain.nsf/fabbfcfe2fc93dac85256afe00483cc4/c4aba387f9325dca85256b6d004f7d96/\\$FILE/si412a_lesson4.pdf](http://yosemite.epa.gov/oaqps/EOGtrain.nsf/fabbfcfe2fc93dac85256afe00483cc4/c4aba387f9325dca85256b6d004f7d96/$FILE/si412a_lesson4.pdf)
- U.S. Environmental Protection Agency. (1987). *Guide Standards and Protocol for Testing Microbiological Water Purifiers. Report of Task Force*. U.S. Environmental Protection Agency.
- UN Financial Tracking Service. (2008). *2000-2008 Natural Disaster Global Humanitarian Contributions , Water and Sanitation Sector*. Retrieved May 12, 2008, from <http://www.reliefweb.int/fts>
- UNICEF. (undated). *Behavior Change Communication in Emergencies: a Toolkit*. Retrieved May 27, 2009, from Hygiene Promotion:
http://www.unicef.org/eapro/Hygiene_promotion.pdf
- UNICEF. (2008, January). *Promotion of Household Water Treatment and Safe Storage in UNICEF WASH Programmes*. Retrieved June 1, 2009, from UNICEF:
http://portal.worldwaterforum5.org/wwf5/en-us/Lists/Learning%20Centre%20application%20form/Attachments/6/6%20-%20LC%20-%20Promotion%20of%20HWTS_%20UNICEF_%20Jan%202008%20.pdf
- UNICEF. (2008). *UNICEF Handbook on Water Quality*. New York: UNICEF, Water Environment and Sanitation Section.
- UNICEF WASH Program. (2008). *WASH Cluster – Suggested standard Hygiene Kit Cyclone Nargis response*. UNICEF Emergency WASH Specialist.
- USAID. (2005). *Field Operations Guide for Disaster Assessment and Response*. Washington, DC: USDA Forest Service, International Program, and Disaster Assistance Support Program.
- USAID OFDA. (2006). *Annual Report for Fiscal Year 2006*. Retrieved May 2008, from USAID Office of U.S. Foreign Disaster Assistance:
http://www.usaid.gov/our_work/humanitarian_assistance/disaster_assistance/publications/annual_reports/pdf/AR2006.pdf

- USAID OFDA. (2005). *USAID Field Operations Guide 4.0*. Washington D.C.: USAID OFDA.
- USAID. (2008). *USAID OFDA*. Retrieved May 27, 2008, from USAID: http://www.usaid.gov/our_work/humanitarian_assistance/disaster_assistance/
- USGS. (2008). *Magnitude 7.9 - Eastern Sichuan, China: Earthquake Summary*. Retrieved August 27, 2008, from <http://earthquake.usgs.gov/eqcenter/recenteqswww/Quakes/us2008ryan.php>
- Varnava, B., & Gallagher, K. (2009, May 18). Navy Facilities Engineering Service Center and Cascade Designs, Inc. (T. Lundquist, P. Compas, M. Herzog, & J. Dunning, Interviewers)
- Vorst, K. (2008, January 31). (P. Compas, Interviewer)
- Watson, J. T., Gayer, M., & Connolly, M. A. (2007). Epidemics after Natural Disasters. *Emerging Infectious Diseases*, 13 (1), 1-5.
- Wegener, A. (2009, April 30). (P. Compas, Interviewer)
- WHO. (2005). *Emergency Treatment of Drinking Water at Point-of-Use, Technical Note No. 5*. Geneva: WHO.
- WHO. (2005). *Environmental Health Relief Efforts after the Tsunami in South East Asia*. New Delhi: WHO.
- WHO. (2006). *Household Water Treatment and Safe Storage Following Emergencies and Disasters: South Asia Earthquake and Tsunami*. Retrieved December 3, 2008, from World Health Organization: http://www.who.int/household_water/resources/emergencies.pdf
- WHO. (2009). *Household Water Treatment and Safe Storage: Treatment Technologies*. Retrieved June 4, 2009, from World Health Organization: http://www.who.int/household_water/research/technologies_intro/en/index.html
- WHO. (2005). *Preventing Traveller's Diarrhoea: How to Make Drinking Water Safe*. Sustainable Development and Healthy Environments Water, Sanitation and Health. Geneva: WHO.
- Wisner, B., & Adams, J. (2002). *Environmental Health in Emergencies and Disasters: A Practical Guide*. Geneva: World Health Organization.

Woodrow Wilson International Center for Scholars. (2006). *Water Stories: Expanding Opportunities in Small-Scale Water and Sanitation Projects*. Washington D.C.: Woodrow Wilson International Center for Scholars.

World Business Council for Sustainable Development. (2006). *Proctor & Gamble: Treating Water at its Point of Use, A Case Study*. Switzerland: World Business Council for Sustainable Development.

World Health Organization. (2006). *Guidelines for Drinking Water Quality: Incorporating First Addendum Volume 1, Recommendations. 3rd Edition*. Geneva: World Health Organization.

Zeta Meter, Inc. (1993). *Everything You Want to Know about Coagulation and Flocculation*. Staunton: Zeta Meter, Inc.

APPENDIX A

Constituent Amounts for Water Recipes based on U.S. EPA Protocol for Testing Water Purifiers (1987)

According to the U.S. EPA Protocol for Testing Water Purifiers, the recommended materials (non-microbiological) for adjusting test water characteristics include:

- pH; inorganic acids or bases (i.e., HCl, NaOH)
- Turbidity: A2 Fine Test Dust (ISO 12103-1)
- Total Dissolved Solids (TDS): sea salts or another equivalent source of TDS.
- Total Organic Carbon (TOC): humic acids

In order for the Test Water #2 (Challenge Test Water/Halogen Disinfection) to be at the challenge level, specified concentrations of each constituent is called for; this is detailed in Chapter 2, Table 2.5. These challenge amounts were also used in the Optimal Protocol and Mock Run U.S. EPA Challenge Water Experiments, and information on the materials used at the Cal Poly laboratories for turbidity, TDS, and TOC is detailed below.

Increasing Turbidity using A2 Fine Test Dust (ISO 12103-1)

The objective of this parameter test was to identify an approximate correlation of the dust to the corresponding turbidity. The correlation was then used as a guide when a desired turbidity level was needed for treatment experiments.

For this test, increasing increments of dust were added to individual, 1-L deionized water, blended for 30 seconds on the liquefy setting, using an Osterizer[®] glass blender, a turbidity measurement was then taken of the blended water, using a HACH Turbidimeter 2100P.

Fine Test Dust vs. Turbidity Correlation				
Dust (mg)	Turbidity Readings (NTU)			
	1	2	3	Average
100	64	63.9	65.7	64.5
200	152	154	152	153
250	184	184	181	183
350	306	309	303	306
450	412	422	414	416
550	531	530	522	528
650	673	673	663	670
750	575	771	766	704
1000	>>too high for turbidimeter to read			

Dust vs. Turbidity (for 1 Liter DI Water)

Total Dissolved Solids Concentrations with the Addition of Instant Ocean

The objective of this parameter test was to identify the total dissolved solids (TDS) concentration of Instant Ocean. Prior to analysis, the water compositions were blended for 30 seconds on the liquefy setting, using an Osterizer® glass blender. The TDS test was performed according to Standard APHA Methods 2540 D. Fisher Scientific G4 glass fiber filter circles, with a nominal pore size of 1.2 μm , were prewashed and ashed; and the filtrate from the filtration was used for TDS testing (APHA et al., 1995). TDS tests were performed on (1) 0.5 g/L of Instant Ocean added to 1 L of Drumm Reservoir Water; (2) 1.0 g/L of Instant Ocean added to 1 L of Drumm Reservoir Water; (3) 1.5 g/L Instant Ocean added to 1 L of Drumm Reservoir Water; (4) Drumm Reservoir Water; and, (5)

1.5 mg/L of Instant Ocean added to 1 L of deionized water. Based on the results, the combination of 1.0 g/L added to Drumm Reservoir Water was selected for the Optimal Protocol Experiment. Additionally, when deionized water was used, as for the EPA Challenge waters, the combination of 1.5 g/L added to deionized water was selected.

Resulting TDS Concentrations for Various Instant Ocean and Water Compositions

Water Composition	Average TDS Concentration (mg/L)
0.5 g/L Instant Ocean + Drumm Reservoir Water	1110
1.0 g/L Instant Ocean + Drumm Reservoir Water	1350
1.5 g/L Instant Ocean + Drumm Reservoir Water	1900
0.0 g/L Instant Ocean + Drumm Reservoir Water	650
1.5 g/L Instant Ocean + deionized water	1400

Total Organic Carbon Concentrations with the Addition of Humic Acid

The objective of this parameter test was to identify total organic carbon (TOC) content of the humic acid used in the Initial EPA Challenge Water Experiments. The humic acid selected was Alfa Aesar® 25 g bottle (Stock #41747, Lot #D25S004, CAS #1415-93-6). Prior to sampling, the water compositions were blended for 30 seconds on the liquefy settling, using an Osterizer® glass blender. Three samples, run in duplicate, were analyzed by Creek Environmental Laboratories, Inc., in San Luis Obispo, CA. VOA vials with HCl preservative were used to store the samples, were kept preserved until brought to the lab in order to not decrease to TOC due to biodegradation. Creek Environmental Laboratories performed the analysis according to Standard APHA Methods 5310 B.

TOC tests were performed on (1) 1 L Drumm Reservoir Water, 10 mL Swine Pond Water, with no addition of humic acid; (2) 1 L Drumm Reservoir Water, 10 mL Swine Pond Water, with the addition of 20 mg/L humic acid; (3) 1 L of deionized water with the addition of 20 mg/L of humic acid. According to the EPA Challenge Water, TOC concentrations need to be greater than 10 mg/L. Thus, it was estimated, based on the 6.6

mg/L TOC concentration from adding 20 mg/L humic acid, that by adding 40 mg/L of humic acid to deionized water, greater than 10 mg/L of TOC will be achieved.

TOC Concentrations for Various Water Compositions

APPENDIX B

Mixing Calculations: Calculating Power, G, and Mixing Time for PÜR® Bucket Protocol and for the Waterbag Prototype

The objective of the following calculations was to estimate the needed mixing time required for the prototype based on the mixing intensity of the PÜR® bucket protocol method. The estimation was based on equations for turbine mixing for the bucket and bubble column power input for the bag. Mixing intensity contributes to the rate of particle coagulation and flocculation (MWH, 2005). The following calculations are used to estimate the needed mixing time for the prototype. Velocity gradient is represented by the following:

$$G = \sqrt{\frac{P}{\mu V}}$$

where G = RMS velocity gradient (energy input rate), s^{-1}

μ = dynamic viscosity of water, $N \cdot s/m^2$

P = power of mixing input to vessel, J/s

V = volume of mixing vessel, m^3

(1) Calculate the power input to the PÜR® bucket protocol based on an impeller design equation (MWH, 2005).

$$N_p = \frac{P}{\rho n^3 D^5}$$

where N_p = power number, dimensionless (assumed to be 3.6, the value used for flat-bladed turbines, MWH, 2005)

ρ = density of water at 20°C, kg/m^3

n = rotational speed, r/s

D = diameter of mixing impeller, (2/3 diameter of vessel)

Solve for P assuming spoon mixing is conducted at 1 revolution/sec, rearranging the equation:

$$P = N_p \rho n^3 D^5$$

$$P = (3.6) \left(998 \frac{\text{kg}}{\text{m}^3} \right) \left(1 \frac{\text{rev}}{\text{sec}} \right)^3 (0.20 \text{ m})^5$$

$$P = 1.15 \text{ J/s}$$

(2) Solve for G for the P $\bar{U}R^{\circ}$ bucket protocol

$$G_{\text{bucket}} = \sqrt{\frac{1.15 \frac{\text{J}}{\text{s}}}{\left(1.00 \times 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}} \right) (0.010 \text{ m}^3)}}$$

$$G_{\text{bucket}} = 339 \text{ s}^{-1}$$

(3) Calculate power input for the prototype using the following bubble displacement equation (Blanch and Clark, 1997):

$$P = Q\gamma H$$

where Q = Bubble flow, m^3/s

γ = Specific weight of water, kg/m^3

H = Distance of bubble travel, m

With Point 2 being the water surface in the prototype, power input per liquid volume, when considering $P_1 = P_2 + \gamma H$, can be expressed as (Blanch and Clark, 1997):

$$P = Q_M \gamma H$$

where Q_M = mean volumetric flow rate in the vessel, which is equivalent to:

$$Q_M = Q \frac{P_2}{P_{LM}}$$

where P_{LM} = logarithmic mean pressure difference between the top and bottom of the vessel

$$P_{LM} = \frac{P_1 - P_2}{\ln \frac{P_1}{P_2}}$$

where P_2 = pressure at top of vessel (atmospheric pressure); P_1 = pressure at the bottom of the vessel

(4) Solve for P (power) of the waterbag by first solving for P_{LM} and then solving for Q_M

(4.1) Solve for P_{LM}

$$P_{LM} = \frac{P_1 - P_2}{\ln \frac{P_1}{P_2}}$$

Assumptions made regarding pressure in the waterbag vessel:

1. Bubble acts as an ideal gas.
2. Initial pressure, P_1 , occurs right at the beginning of a single inversion, so P_1 is located at the bottom of the water column in the prototype.
3. Water is incompressible.
4. P_2 is the absolute pressure at surface = $101,325 \text{ kg/m} \cdot \text{s}^{-2}$

Therefore, first solve for P_1 :

$$P_1 = \rho g H + P_2$$

where H = depth of water in the waterbag
 $= 28 \text{ in} = 0.71 \text{ m}$ (refer to **Figure 3.4**)
 $\rho = 998 \text{ kg/m}^3$
 $g = 9.81 \text{ m/s}^2$

$$P_1 = \left(998 \frac{\text{kg}}{\text{m}^3}\right) \left(9.81 \frac{\text{m}}{\text{s}^2}\right) (0.71 \text{ m}) + \left(101,325 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}\right)$$

$$P_1 = 108,276 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}$$

Solving for P_{LM} :

$$P_{LM} = \frac{108,276 \frac{\text{kg}}{\text{m} \cdot \text{s}^2} - 101,325 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}}{\ln \frac{108,276 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}}{101,325 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}}}$$

$$P_{LM} = 104,762 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}$$

(4.2) Solve for Q_M using the P_{LM} found in part (4.1)

$$Q_M = Q \frac{P_2}{P_{LM}}$$

where $Q = \text{Vol}_{\text{bubble}}/\text{time}$

Bubble = 10-cm in diameter

$$\text{Vol}_{\text{bubble}} = (4/3) (\pi) (5 \text{ cm})^3 = 523.6 \text{ cm}^3 = 0.000524 \text{ m}^3$$

$t = 1.2 \text{ s}$ bubble transit time

$$Q_M = \left(\frac{0.000524 \text{ m}^3}{1.2 \text{ s}} \right) \left(\frac{101,325 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}}{104,762 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}} \right)$$

$$Q_M = 0.000422 \frac{\text{m}^3}{\text{s}}$$

(4.3) Now solve for P , power

$$P = Q_M \gamma H$$

where $H = 0.71 \text{ m}$, headloss

$\gamma = 9790 \text{ N/m}^3$, unit weight of water

$$P = \left(0.000422 \frac{\text{m}^3}{\text{s}} \right) (9790 \text{ N/m}^3) (0.71 \text{ m})$$

$$P = 2.93 \text{ J/s}$$

(5) Solve for G for the waterbag

$$G_{\text{prototype}} = \sqrt{\frac{2.93 \frac{\text{J}}{\text{s}}}{\left(1.00 \times 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}}\right) (0.01 \text{ m}^3)}}$$

where $V = 10 \text{ Liters} = 0.01 \text{ m}^3$

$$G_{\text{prototype}} = 542 \text{ s}^{-1}$$

(6) Solve for Gt_{bucket} and $Gt_{\text{prototype}}$. This is a mixing design parameter, Gt , (where t is defined as the detention time in mixing vessel). Detention time for the prototype can be based on the estimated Gt for the PÜR[®] bucket protocol with its 5-min mixing time.

For Bucket:

$$\begin{aligned} Gt_{\text{bucket}} &= (339 \text{ s}^{-1})(5\text{min})\left(\frac{60 \text{ sec}}{1 \text{ min}}\right) \\ &= 101,700 \end{aligned}$$

For the prototype, what time is needed for $Gt_{\text{prototype}} = Gt_{\text{bucket}}$

$$Gt_{\text{prototype}} = 101,700$$

$$542 \text{ s}^{-1}(t_{\text{prototype}}) = 101,700$$

$$t_{\text{prototype}} = 188 \text{ sec} = 3.1 \text{ min}$$

(7) Translate time to number of inversions for mixing.

A single inversion occurs at a rate of 40 bpm (pace kept with a metronome).

So for 20 inversions, it takes approximately 30 seconds.

At this rate, for $t_{\text{prototype}} = 3.1 \text{ minutes}$, corresponds to 124 inversions.

APPENDIX C

BioVir Laboratories Microbiological Seed Requirements for Cal Poly Waterbag
Challenge Experiment (07/02/2009 BioVir Laboratories Report)

Cal Poly Bag Micro. Seed Requirements 07/02/09

1. Three Bags will be teted @ **10L per Bag**
2. Seed water will be made up in a 40L batch of test water #2. Use 50L carboy with bottom spigot on cart
3. Micro Seed:
 - a. *R. terrigena* :(6 log reduction)
 - i. Want **influent** concentration of **10^7 Cfu/100 mL**
 - ii. The concentration **in 40L reservoir is 4×10^8 Cfu**
 - iii. Stock = 1×10^{10}
 - b. Coliphage: MS2 and fr (4 log reduction)
 - i. Want influent concentration of **10^5 Pfu/mL**
 - ii. The concentration **in 40L reservoir is 4×10^9 Pfu**
 - iii. Stock MS2 $\times 10^{11}$; fr $\times 10^{10}$ pfu/mL
 - c. Fluorescent Beads: (3 log reduction)
 - i. Want $> 5 \times 10^4$ spheres / L
 - ii. The concentration **in 40L reservoir is 2×10^6 Spheres**
 - iii. Stock = 7×10^8 beads/mL

Media Needs;

1. *R. terrigena*
 - a. Assay by membrane filter
 - b. mFC medium (agar) incubated at 35C
 - c. There will be 4 samples (one influent and 3 product waters)
 - d. Each sample will have 3 dilutions
 - i. Inf: -3, -4 and -5 mLs
 - ii. Product:: 100, 10 and 1 mLs
 - e. A minimum requirement of 12 plates + 2 controls
2. Coliphage (the assay is for both phage at the same time)
 - a. Host Bacteria *E. coli* ATCC 15597
 - b. TSB bottom and top agar
 - c. Dilutions:
 - i. Influent: -3 and -4
 - ii. Product: 1 and -1
 - d. A minimum requirement of:
 - i. 16 Bottom agars + 2 controls
 - ii. 16 Top agars + 2 controls
3. Beads
 - a. Assay by direct microscopic count (no media needed)
 - b. Collect;
 - i. Influent: 500 mL min
 - ii. Product: collect one liter min,

Test water Makeup

1.

Test Water #2 and #3	
Constituent	Measure
pH	9.0
TOC mg/L	≥ 10
NTU mg/L	≥ 30
TDS mg/L	1500 ± 150
Temp °C	4 ± 1

2. Additives calc estimates:

a. TOC (Humic acid = 39% TOC)

i. Add 25.6 mg/L

ii. **$25.6 \times 40 = 1.03\text{g}/40\text{L}$**

b. NTU (Isofine)

i. Add 150 mg/L (NTU of 35)

ii. **$120 \times 40 = 4.8\text{g} / 40\text{L}$**

c. TDS: Add enough sea salts to Benicia tap to meet the TDS requirement.
Benicia Tap TDS runs about 200 mg/L

3. Thiosulfate sample neutralizer:

a. Sterile 5% $\text{Na}_2\text{S}_2\text{O}_4$ (anhydrous)

b. Add 2 mL /L of sample (will neutralize 22 mg/L Chlorine)

APPENDIX D

Creek Environmental Laboratories Total Organic Carbon Results for July 13, 2009 Experiment

CREEK ENVIRONMENTAL LABORATORIES, INC.

A Minority-owned Business Enterprise

141 SUBURBAN ROAD, SUITE C • SAN LUIS OBISPO, CA 93401 • (805) 545-9838 • FAX (805) 545-0107

Project : Cal Poly Waterbag, CE/ENVE
Invoice Number: Q3907
Invoice Date: 8/10/09

Page 1

BILL TO: Tryg Lundquist
Cal Poly CE/ENVE
Cal Poly 1 Grand Ave. 13-263
San Luis Obispo, CA 93407-0353

REPORT TO: Patricia Compas
Patricia Compas
916 West St.
San Luis Obispo, CA 93405

INVOICE

Log Number Sample ID

09-C10709 B1 Pre 30, A
09-C10710 B1 Pre 30, B
09-C10711 B1 Post, A
09-C10712 B1 Post, B

Analysis	Quantity	Net Price	Amount
-----	-----	-----	-----
TOC (Sub to Weck)	4	\$55.00	220.00
-----	-----	-----	-----
Invoice Total			\$220.00

Creek Environmental Laboratories, Inc.

Chain-of-Custody

141 Suburban Road, Suite C-5, San Luis Obispo, CA 93401 phone (805) 545-9838 fax (805) 545-0107 www.creeklabs.com sales@creeklabs.com

Order # Q3907

Please Print in Pen

☐ DW EDT

☐ LUFT EDF

☐ Custom EDD

Client Name <u>PATRICIA COMPAS</u>		Contact	Phone <u>(805) 215-2551</u>	Due Date: 24Hr 48Hr Other Normal TAT
Address <u>916 West St.</u> City <u>San Luis Obispo</u> State <u>CA</u> Zip <u>93405</u>		Fax	Cell <u>(805) 215-2551</u>	
Project Name/Number <u>Cal Poly Waterbury, CE/ENVE</u>		PO#	Copies To:	
Bill to: (if different from above) <u>Attn: Tryg Lundquist</u> Address <u>Cal Poly, 1 Grand Ave, 13-263</u> City <u>San Luis Obispo</u> State <u>CA</u> Zip <u>93407-0353</u>		Matrix Key: DW = Drinking Water AQ = Aqueous SL = Soil/Solid		
Sampler Name (Print) <u>PATRICIA COMPAS</u>	Comments: <u>Gift to Attn: Tryg Lundquist</u>			

Sample Description	Date/Time Sampled	Analysis	Matrix	Bottles	Preservative / Type Bottles	Creek Lab Sample #
B1 Pre 30, A	7/13/09 12 pm	TOC Analysis	AQ	1	WV/HCL/HO/M	10709
B1 Pre 30, B	"	"	"	1	"	10710
B1 Post, A	"	"	"	1	"	10711
B1 Post, B	12:15p	"	"	1	"	10712
B2 Pre 30, A	12:45p	"	"			
B2 Pre 30, B	"	"	"			
B2 Post, A	12:50p	"	"			
B2 Post, B	"	"	"			

RELINQUISHED BY (Sign) <u>Patricia Compas</u> (Print) <u>PATRICIA COMPAS</u> (Organization) <u></u>	DATE/TIME <u>7-23-09 10:40</u>	RECEIVED BY (Sign) <u>[Signature]</u> (Print) <u>Sarah Schuch</u> (Organization) <u>Creek Environmental Laboratories, Inc.</u>
---	--------------------------------	--

FOR LAB USE ONLY: Shipping Method: Client/ Lab/ Courier:

Sample Conditions: Temp: 13.0 Intact: Y/N Custody Sealed: Y/N

REMARKS Send email to: Pcompas@calpoly.edu, tryg.lundquist@calpoly.edu

Certificate of Analysis

Report Date: Thursday, July 30, 2009
Received Date: Friday, July 24, 2009
Received Time: 8:20 am
Turnaround Time: Normal

Client: Creek Environmental Laboratory
141 Suburban Road
San Luis Obispo, CA 93401

Phones: (805) 545-9838
Fax: (805) 545-0107

Attn: Orval Osborne
Project: Q3907

P.O. #:

Lab Sample ID: 9G24013-01 Sample ID: B1 Pre 30, A (10709) Matrix: Water
Sampled by: Patricia Compas Sampled: 07/13/09 12:00

Analyte	Result	DL	RL	Units	Dil	Method	Prepared	Analyzed	Batch	Qualifier
Total Organic Carbon (TOC)	0.69	0.032	0.30	mg/l	1	SM5310C	7/29/09	7/29/09 15:13	jlp W9G1099	

Lab Sample ID: 9G24013-02 Sample ID: B1 Pre 30, B (10710) Matrix: Water
Sampled by: Patricia Compas Sampled: 07/13/09 12:00

Analyte	Result	DL	RL	Units	Dil	Method	Prepared	Analyzed	Batch	Qualifier
Total Organic Carbon (TOC)	0.70	0.032	0.30	mg/l	1	SM5310C	7/29/09	7/29/09 15:13	jlp W9G1099	

Lab Sample ID: 9G24013-03 Sample ID: B1 Post, A (10711) Matrix: Water
Sampled by: Patricia Compas Sampled: 07/13/09 12:15

Analyte	Result	DL	RL	Units	Dil	Method	Prepared	Analyzed	Batch	Qualifier
Total Organic Carbon (TOC)	0.98	0.032	0.30	mg/l	1	SM5310C	7/29/09	7/29/09 15:13	jlp W9G1099	

Lab Sample ID: 9G24013-04 Sample ID: B1 Post, B (10712) Matrix: Water
Sampled by: Patricia Compas Sampled: 07/13/09 12:15

Analyte	Result	DL	RL	Units	Dil	Method	Prepared	Analyzed	Batch	Qualifier
Total Organic Carbon (TOC)	1.3	0.032	0.30	mg/l	1	SM5310C	7/29/09	7/29/09 15:13	jlp W9G1099

Certificate of Analysis

Quality Control Section

Conventional Chemistry/Physical Parameters by APHA/EPA/ASTM Methods - Quality Control

Batch W9G1099 - SM5310C

Blank (W9G1099-BLK1)

Prepared: 07/29/09 Analyzed: 07/29/09 15:13

Analyte	Sample Result	QC Result	Qualifier	Units	Spike Level	%REC	%REC Limits	RPD	RPD Limit
Total Organic Carbon (TOC)		ND		mg/l					

LCS (W9G1099-BS1)

Prepared: 07/29/09 Analyzed: 07/29/09 15:13

Analyte	Sample Result	QC Result	Qualifier	Units	Spike Level	%REC	%REC Limits	RPD	RPD Limit
Total Organic Carbon (TOC)		4.93		mg/l	5.00	99	90-110		

Matrix Spike (W9G1099-MS1)

Source: 9G23049-07

Prepared: 07/29/09 Analyzed: 07/29/09 15:13

Analyte	Sample Result	QC Result	Qualifier	Units	Spike Level	%REC	%REC Limits	RPD	RPD Limit
Total Organic Carbon (TOC)	0.161	5.00		mg/l	5.00	97	84-107		

Matrix Spike Dup (W9G1099-MSD1)

Source: 9G23049-07

Prepared: 07/29/09 Analyzed: 07/29/09 15:13

Analyte	Sample Result	QC Result	Qualifier	Units	Spike Level	%REC	%REC Limits	RPD	RPD Limit
Total Organic Carbon (TOC)	0.161	4.93		mg/l	5.00	95	84-107	2	20

Certificate of Analysis

Notes:

The Chain of Custody document is part of the analytical report.

Any remaining sample(s) for testing will be disposed of one month from the final report date unless other arrangements are made in advance.

All results are expressed on wet weight basis unless otherwise specified.

An Absence of Total Coliform meets the drinking water standards as established by the State of California Department of Health Services.

The Reporting Limit (RL) is referenced as laboratory's Practical Quantitation Limit (PQL).

For Potable water analysis, the Reporting Limit (RL) is referenced as Detection Limit for reporting purposes (DLRs) defined by EPA.

If sample collected by Weck Laboratories, sampled in accordance to lab SOP MIS002

Authorized Signature

Contact: Kim G Tu (Project Manager)

ELAP # 1132
LACSD # 10143
NELAC # 04229CA

The results in this report apply to the samples analyzed in accordance with the chain of custody document. Weck Laboratories certifies that the test results meet all requirements of NELAC unless noted in the Case Narrative. This analytical report must be reproduced in its entirety.

Flags for Data Qualifiers:

ND	NOT DETECTED at or above the Reporting Limit. If J-value reported, then NOT DETECTED at or above the Method Detection Limit (MDL).
Sub	Subcontracted analysis, original report enclosed.
Dil	Dilution Factor
DL	Method Detection Limit
RL	Method Reporting Limit
MDA	Minimum Detectable Activity

APPENDIX E

BioVir Laboratories, Test Report, Polytech Waterbag Challenge (Project No. 091924)

TEST REPORT

Project Title	Polytech Waterbag Challenge
Project No.	091924
Sponsor:	Cal Poly Corporation
C/O:	Prof. Tryg Lundquist California Polytechnic State University Civil & Environmental Engineering Department San Luis Obispo, CA 93407
Date:	July 20, 2009
From:	Robert C. Cooper, VP

Introduction: The Cal Poly Corp contracted with BioVir Laboratories to perform microbiological challenges of the *Polytech Waterbag* device being developed by Professor Lundquist and his students. Three bags were challenged with the bacterium *Raoultella terrigena* (ATCC 33257), two coliphage types (MS2 ATCC 15597-B1) and fr (ATCC15767-B1) and with 3.1µm diameter fluorescent microspheres as a surrogate for *Cryptosporidium* oocysts (Duke Scientific Corp, Palo Alto, CA.) On July 13, 2009 Professor Lundquist and two graduate students arrived at BioVir Labs with three test bags and the necessary ancillary equipment needed to operate the treatment units.

The challenge water (40L of Test water #2) was prepared by BioVir staff and had the quality shown in Table 1 below:

Table 1. Challenge Water #2	
Parameter	Value
Volume	1L
pH	9.0
Chlorine	ND Non Detect
TDS	1447 mg/L
NTU	39*
TOC	11.5 mg/L
Temperature	4° C
*Before Humic acid added	

Just prior to the challenge the test water was inoculated with the challenge microorganisms and microspheres. The seed microorganisms were prepared as per standard BioVir protocols. The test water was constantly mixed using a magnetic stirring device. Each bag was filled with 10L of the seeded test water at which point the Cal Poly group performed the treatment operation (adding the coagulant-disinfectant, mixing the contents and allowing the flocculated material to settle.) At the end of the required settling time samples of the product water were collected into sterile one liter bottles containing enough sterile sodium thiosulfate to neutralize any residual disinfectant that might be present in the sample. A composited influent sample (samples taken at the beginning and end of the challenge period) was collected from the 40 L seed reservoir.

The influent and product water samples were kept refrigerated until assayed, usually a period of no more than 3 hours. The *R. terrigena* assays were performed using the membrane filter method and employing mFC agar incubated for 20 to 24 hours at 35°C; the results being reported a colony forming units (Cfu) per mL. The combined bacteriophage were assayed using the Adams double agar overlay method and reported as plaque forming units (Pfu) per mL. The microspheres were enumerated by direct microscopic count using epi-fluorescent microscopy and reported as spheres per L.

Results: The results of the challenged are shown in the following Tables.

Table 2. <i>R. terrigena</i> Results Cal Poly Water Treatment Study						
Influent	Bag #1		Bag #2		Bag #3	
Cfu/mL	Cfu/mL	Log Red.	Cfu/mL	Log Red.	Cfu/mL	Log Red.
1.6×10^6	1.4×10^2	4.0	$>1 \times 10^2$	< 4.2	<1	> 6.2

Table 3. Coliphage Results Cal Poly Water Treatment Study						
Influent	Bag #1		Bag #2		Bag #3	
Pfu/mL	Pfu/mL	Log Red.	Pfu/mL	Log Red.	Pfu/mL	Log Red.
4.8×10^5	1.8×10^5	0.4	2.3×10^5	0.3	<1	>5.7

Table 4. Microsphere results Cal Poly Water Treatment Study						
Influent	Bag #1		Bag #2		Bag #3	
Spheres/L	Spheres/L	Log Red.	Spheres/L	Log Red.	Spheres/L	Log Red.
4.9×10^5	5.7×10^2	2.9	4.2×10^3	2.1	9.1×10^2	2.7

APPENDIX F

Mark I Pictographic Instructions Based on Optimal Protocol