Foam Filtration, Final Research Report

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Abstract

The primary goal of foam filtration is to design a low cost, locally sourced, easy to operate water filtration system. Throughout the semester, backwash cleaning efficiency experiments were performed on the small-scale filter, designed in Fall 2014 to hydraulically model the full scale filter implemented in El Carpintero. The objective of these experiments was to determine an empirical relationship between backwash pore velocity and the percent mass removal of the particles from the foam during the cleaning cycle. Experimentation with different pore sizes revealed a new mechanism for filtration: the foam acts as a sedimentation tank, providing a large surface area for the flocs to settle. This is contrary to the initial hypothesis that coagulant-covered flocs stuck to the inside of the pore walls, and that a large shear force would be required to remove the flocs during backwash. Evidently, there is still much to be understood with regards to the mechanisms behind filtration and backwash.

Apart from work in the laboratory, the team continues to analyze data collected from experiments performed on the full-scale filter in El Carpintero by AguaClara engineer, Walker Grimshaw, to understand the discrepancies between performance in the laboratory and in the field.

Much of the semester was spent preparing for the EPA P3 Conference held on April 10th and 11th in Washington, DC. The team fabricated a small scale model of the technology, prepared a technical report, and created a poster display for the competition, and received an Honorable Mention for its efforts in creating an “Off-Grid Solution to Drinking Water Treatment.”

Table of Contents

Introduction

AguaClara competed for an EPA P3 Phase II Award in 2012 and won an Honorable Mention for Phase II in 2015 for its foam filtration research. The foam filtration team works to produce a feasible design that can be replicated in the field. The following bullet points are characteristics of the population the filter is designed for, the features the filter will have, and the way the water flows through the filter.

Target Demographic

- **Medium-size villages** of up to 1,000 people
- When **municipal plants are impractical** in terms of cost
- **Emergency situations** when traditional municipal systems have failed
- **Temporary situations** such as refugee camps

Features

- **Flow** rate: 1 L/S or serves roughly 1000 people at 86 L/person/day
- Low **cost**: less than $1000 USD initial cost
- Locally sourced: all **materials** can be found locally except the foam
- Easy to **build**: requires a small number of readily available tools, and is simple and transparent in design
- Easy to **operate**: little operation time is needed and operation is relatively simple
- **Gravity-powered**: only gravity powers the filter; there are no electrical components

How The Water Flows

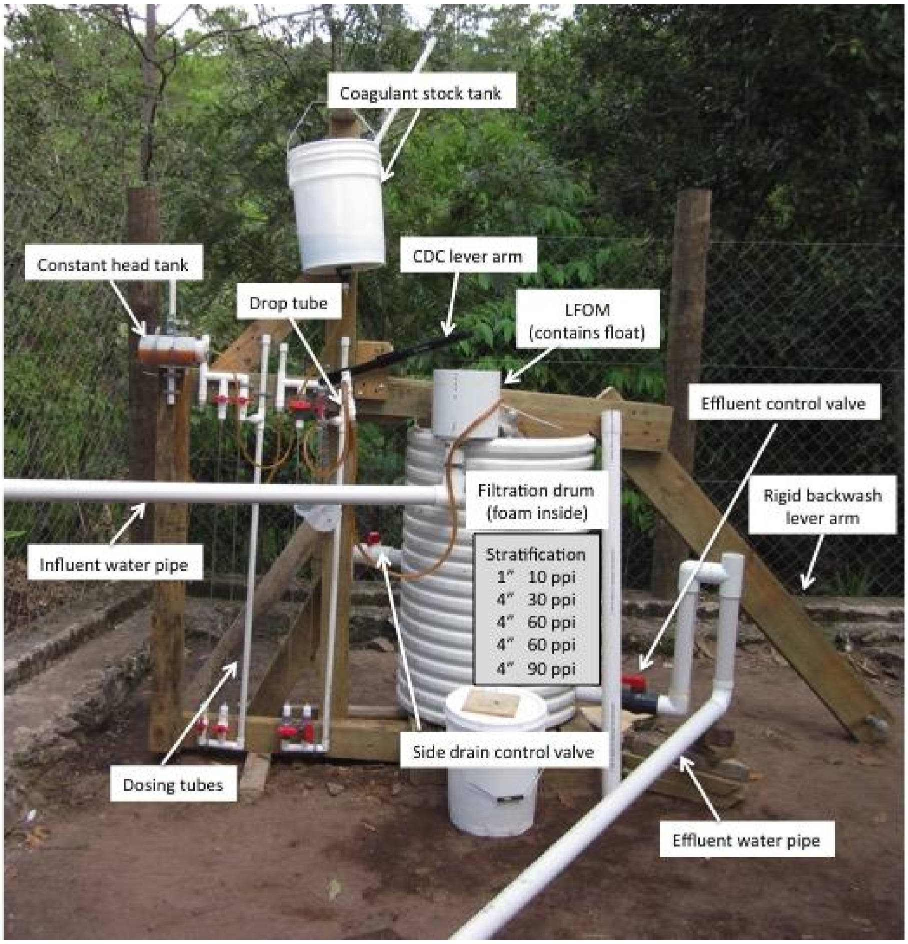

Figure 1: *An illustration of the full scale prototype in El Carpintero. The raw water is dosed by by the CDC system and enters the foam layers held in the 24 inch pipe. The water percolates through the foam and the flocs get stuck in the foam, leaving much lower turbidity effluent. Effluent is dosed with chlorine before delivery to communities.*

Entrance

The filter is gravity powered, so the entrance must be above the rest of the filter. The filter is designed to receive a flow rate of up to 1 L/s. Due to the filter's ability to handle extremely high turbidity water (+500 NTU), the filter can have an influent of surface water such as streams, ponds, and lakes. The water is carried from the source in a pipe that is brought to the entrance LFOM in the filter.

Linear Flow Orifice Meter (LFOM) and Chemical Dose Controller System (CDC)

The LFOM and CDC work in tandem to dose the water with coagulant before the water enters the foam and chlorine after at a user-specified rate. The LFOM maintains a linear relationship between water height in the entrance tank and flow in the plant. The dose controller automatically adjusts the chemical flow to account for varied influent flow rates to maintain a constant dose.

Figure 2a and 2b: *The inverse linear flow orifice meter, as installed in the El Carpintero prototype pilot. Figure 2a shows the float (attached to the lever arm) contained inside the LFOM. Figure 2b shows the orifice pattern designed to maintain the linear relationship between the water height (the float height) and the flow rate into the filter body.*

Foam

The water then enters the foam layers from the top and percolates through the foam, starting in the coarsest foam and working towards the finer foam at the bottom. It was theorized (according to the Adhesive Nanoglobs Coagulation hypothesis) that the main mechanism of filtration was the attraction of the precipitated coagulant to the cell walls of the foam. However, it was concluded during experimentation that instead of providing an immense area for the coagulant to “stick to,” the foam actually provides a large area for the flocs in the coagulated water to settle.

Figure 3: *One of the foam discs used in the prototype pilot in El Carpintero. A hole was drilled through the center of the disc to allow for the aluminum mast to pass through all the foam layers.*

Effluent

The effluent is then dosed with chlorine by the CDC to ensure disinfection both at the filter and through the distribution system.

Literature Review

Foam Filtration is an emerging technology that has not yet been well-documented by other investigators throughout the country. Previous Foam Filtration teams reports were reviewed, and their findings are documented in the Previous Work section of this report.

Previous Work

Summer 2014

A backwash system is being used to clean the foam rather than a compression disk system, as it was determined that the compression system could not be operated by only one person. Over the summer, research was done that showed the backwash system has a much higher cleaning efficiency than compression, and requires much less force (~300 lbs) so it is operable by one person. The filter was able to achieve nearly the same run times for similar experiments performed days apart, indicating that the foam was adequately cleaned via the backwashing method between experiments. The apparatus was able to filter 100 NTU water down to 1.35 NTU for about 75 minutes, with a resulting cleaning efficiency of 71 percent.

The wooden lever system uses a 4:1 force ratio, and was chosen as wood because PVC was determined to have deflected much of the force applied by the operator. A side valve system is being used to drain dirty backwash water from the system. The lever arm system allows for a side valve to be used, as varying water level is not a concern with this design. The side drain system is connected to the drum using spin welding.

Fall 2014

Testing concluded that foam does indeed leach a significant amount of chemicals into water. The exact composition of the leached chemicals has not yet been determined, but it can be assumed that esters and ethers, which the foam consists of, make up a large portion of the leachate. Refer to the Fall 2014 Research Report for detailed documentation of the testing, and a literature review of chemical leaching and its potential risks.

A small-scale model of the foam filter was developed consisting of:

- 4” clear PVC pipe
- Sump pump in a 55 gallon clearwell for supplying both influent and backwash water
- Coagulant dosing pump (100 rpm)
- Clay dosing pump (600 rpm) that maintains 800 NTU influent water reading in turbidimeter
- 200 kPa pressure sensors for measuring headloss through the filter and the flow rate through the filter (using the change in height of water in a 55 gallon drum)

This model has been used in an effort to determine empirical relationships between factors such as backwash pore velocity and filter cleaning efficiency. Rules and states for the pumps, sensors, and turbidimeters have been set up in Process Controller, the software used to control the pumps, and record turbidimeter and pressure sensor data. The steps for experimental set-up are saved in the Research folder in the Foam Filter Google Drive.

The Chemical Dose Controller (CDC) used in full-scale AguaClara plants was modified in the following ways, allowing it to be integrated with the foam filter:

- The constant head tank (CHT) is now constructed from a Nalgene bottle, improving chlorine resistance.
- A float was placed in the LFOM and attached to the lever arm with a stainless steel rod, eliminating the need for an entrance tank and reducing the chance of accidental chemical overdoses.
- Major Headloss Elements (MHE) are now oriented vertically, reducing the filter’s overall footprint.

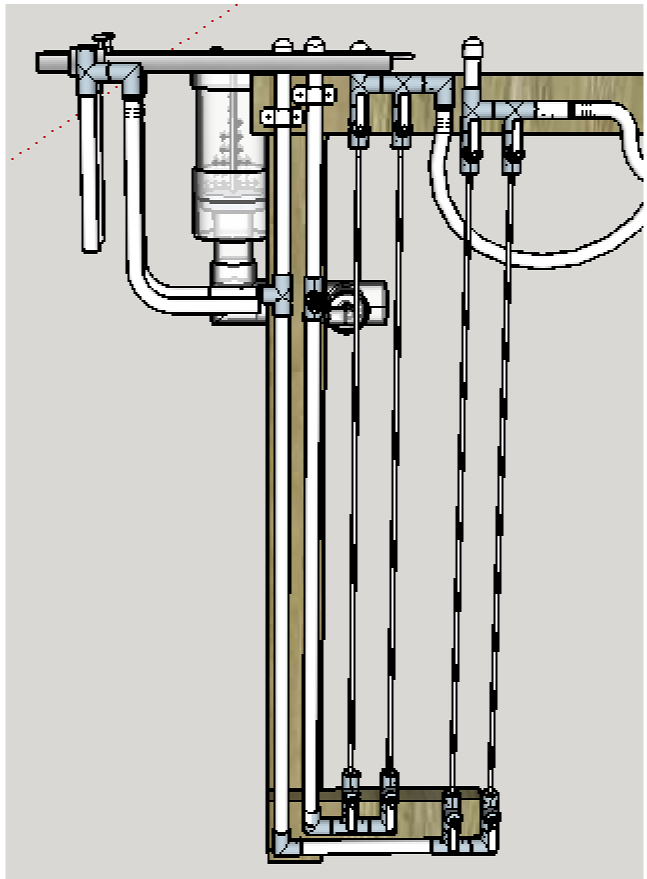

Figure 4: *This is a side view of the newly designed CDC system. The MHE is vertically oriented, the LFOM is also the influent pipe, and the float is located inside the LFOM. The tubing running from the MHE to the drop tubes is flexible over all the positions the slide on the drop tube can go to. The two cut-off tubes come from the CHTs that are outside of the frame.*

The lid that had previously covered the foam filter had to be permanently removed to accommodate the new LFOM design. To compensate for the support lost by the lid's removal, a vertical lever arm rigidly connecting to the base of the filter was constructed.

These modifications to the foam filter design were implemented in the El Carpintero pilot filter in the winter of 2015 by Walker Grimshaw and members of the Fall 2014 Foam Filtration team. See the El Carpintero section for further detail.

Additional Notes

Additional information about previous work can be found in the Summer and Fall 2014 Final Research Reports (see references section).

EPA P3 Competition

Overview

The team travelled to the EPA P3 competition in mid April and completed many different projects to prepare for the event. A small subsection of the foam filter team (Kristin Chu and Valerie Piestch) wrote the report describing the foam filter progress thus far. Ali constructed a poster for the presentation and Ethan built a small-scale foam filter as a demonstration unit.

Small Filter Demo

Purpose

The goal of the small filter demo is to be a teaching aid that gives a broad audience insight into the key operations of the foam filter while potentially serving as a research apparatus. The following design uses a plunger to backwash the foam rather than the lever arm system used in the large system, so that the demo may be easily constructed while preserving the key backwashing process. The filter is in a piece of closed, clear PVC, enabling the user to see the filtration and backwashing process directly. Additionally, the Fernco caps on the end that make the filter a closed system enable one to build arbitrarily high head during forward filtration. To backwash the filter, the operator will remove the top fernco, slowly pull up on the plunger handle, then plunge rapidly to induce backwash. The backwash water on the top will then be dumped by the operator into the reservoir to "re-dirty" the water that will be used for additional filter runs. Figure 5 below shows the filter operating in forward filtration, when dirty water from the reservoir is pushed through the filter until it begins to clog. The second figure, Figure 6 shows the backwash water being dumped back into the reservoir to be filtered again.

Design

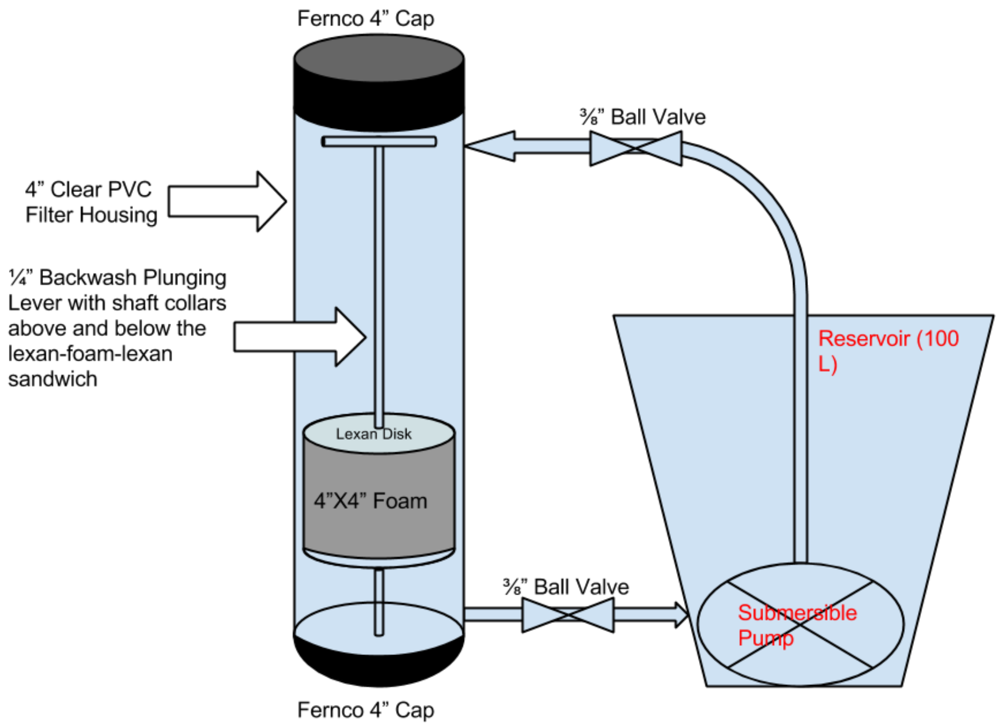

Figure 5: *The design of the small filter demo that was constructed for the EPA P3 convention in April. Note that the filter body can be sealed, enabling high head accumulation.*

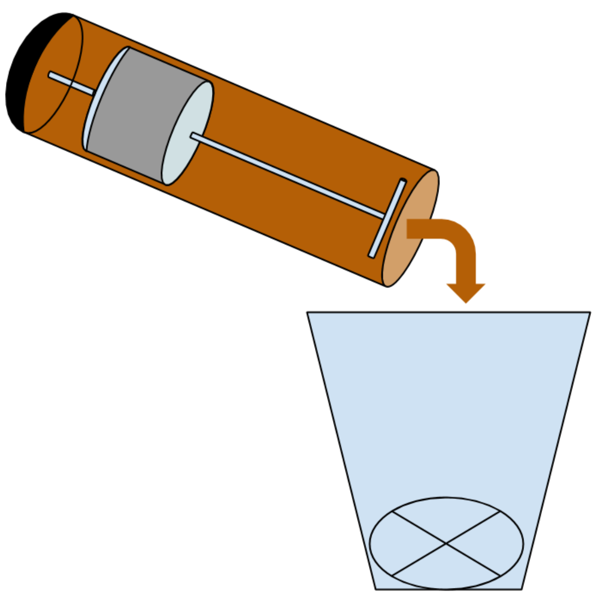

Figure 6: *The method for draining the backwash water from the demo filter. The same water will then be used to filter again, enabling simple recycle without additional flocculation.*

Parameters

The only parameters that remain the same between the large and small scale filters are the filtration velocity and the foam pore size, both of which play a critical role in defining the filter performance. The following table describes the parameters of the small demo filter :

Table 1: *Parameters for the small-scale demo filter used in the 2015 EPA 3 Competition.*

Filtration Velocity (mm/s)	Required Forward Flow Rate (L/s)	Influent Turbidity (made turbid with kaolin clay, NTU)	Clogging Volume For 4" 90 PPI (L)	Clay (g) (1.7 mg clay/NTU/L)	PACl (L of 1 g/L sol. to make 10 mg/L)
6	.05	400 NTU	50	50	.5

Critical General Information

In the months leading up to the Expo, the team attended EPA P3 training sessions held by James Rea, a specialist in technical communication. The following is a list of information compiled during those talks that proved critical to know when discussing foam filtration with the judges (serving as a "cheat sheet" for the presentation). See the script document for answers to tough questions proposed by Walker and Monroe.

1. ***Set us apart***: What can you accomplish with this grant money in two years that other teams can't? (Question provided by Walker)
2. Economics
    a. Payback time (v. bottled water, v. dirty water)
    b. Cost
        i. Capital: $2,000 for current pilot filter in El Carpintero, $4,000 for the structure to house the two filters
        ii. Maintenance: $60 per million liters of water produced (covers operator, PACl and chlorine)
    c. Treat X number of people
        i. El Carpintero is a community of 160 households (a population of about 700).
        ii. Will implement two 1.5 L/s foam filters, which will provide ~370 L/day per person in El Carpintero.
    d. X cheaper than bottled water
        i. Reticulated polyurethane foam costs approximately $1700 USD per cubic meter. Assuming a foam lifetime of 1 year and an average filtration

velocity of 4 mm/s, the cost translates to $6.70 USD per million liters of water produced. The alternative, bottled water, costs $1.50 USD for 20 liters in Honduras. This translates to about 1/10,000th the cost of bottled water.

   e. X times more effective than investing in healthcare

3. Sustainability
   a. Carbon Footprint of the filter is small compared to any of the alternatives:
      i. Prices reflect energy requirements and the price of foam is insignificant compared with the price of plastic associated with bottled water or the price of fuel for trucking in water from Tegucigalpa. (1/10,000th of the cost)
   b. From Walker: How do these small communities operate the filter? Is that socially and economically sustainable?
4. Filter Parameters
   a. Achieved pC* of 2.5
   b. Treats the equivalent to 150 times the amount of flow for same size biosand filter
   c. Made from all local materials (even foam most likely can be found locally)
   d. What happens to the foam after it wears down?
   e. How long does the foam last?
   f. From Walker: How difficult is it to operate the cleaning mechanism? Can anyone lift up this lever arm?
5. Foam Questions from Walker
   a. Is the foam sustainably produced?
   b. Is the foam sustainably sourced? How can you ensure it is always available to developing countries and how do you make sure they can afford it?
   c. What do all these small communities do with the foam once it is no longer useful as a filtration medium?
   d. If similar foam has been used for so long in aquariums, why has it not been used until now for drinking water?
   e. Are there other kinds of foam (less specific than the ones you use) that could also serve as a filter?
6. Questions from Monroe
   a. What will you do with 75k?
   b. Where will the project have accomplished by the summer of 2017?
   c. Why not use membrane filters for villages?
   d. Why not use slow sand filters for villages?
   e. Why not use the StaRS filter for villages?
   f. How much will it cost for a village of 500 people?
   g. Why are you considering adding flocculation? How will that improve the filter?
   h. What will you do with all of the foam waste?
   i. How big are the pores in the foam filter?
   j. Oh.. so then you only remove particles bigger than the pore size and hence you don't remove pathogens. That must mean the water isn't really safe to drink.

k. Does the filter remove anything else beside particles?
l. Why are you going to research Dissolved Organic matter if the filter is designed to remove particles?
m. Would you recommend this filter be used in Haiti where they have had problems with cholera?
n. Will the foam filter work on groundwater? (answer... Many groundwater sources are under the influence of surface water and do have particle and pathogen contamination. Know what foam DOESN'T do too!)
o. Will foam filtration remove arsenic (careful here... Answer is likely yes!).

Poster

The EPA P3 conference required a 36” by 90” poster (which currently hangs on the wall of the Foam Lab). The poster meets the following requirements.

Poster Instructions (taken from the Team Info Package)

Title

The P3 poster should contain the catchy, attention-grabbing title that you already submitted and a more scientific subtitle.

Contents

The P3 poster should contain summaries of all of the following six major elements of the P3 project report. P3 teams must provide a comprehensive overview of their research objectives and results, as well as publications and presentations, in language that would be understood by the general public. P3 teams should describe conclusions and implications for further research, development or implementation. P3 teams are strongly encouraged to present the information with photographs, tables, graphs and charts where appropriate and to provide website links to their publications or related research efforts.

1. Background and Problem Definition
    • Relationship to people, prosperity and the planet
    • Relevancy and significance to developing or developed world
    • Implementation of the P3 team project as an educational tool
2. Purpose, Objectives, Scope
3. Data, Findings, Outputs/Outcomes
4. Discussion, Conclusions, Recommendations
    • Streamlined life cycle costing and analysis, if appropriate
    • Quantifiable and/or qualitative benefits to people, prosperity and the planet
5. Proposed P3 Phase II Project Description
6. References

Format

A PowerPoint template will be provided and its use is required for all P3 team posters on display at the Expo. The poster must be displayed and is the only item permitted to be displayed on the provided poster board (4’ x 8’ of useable space).

As will be noted on the template, we recommend that the following fonts be used:

1. Public-Friendly Title: Arial Black 60 point (white)
2. Official Abstract Title: Arial Bold 44 point (white)
3. Headings: Arial Black 46 point (black)
4. Body Text: Arial 18 to 36 point depending on amount (black)
5. Photo captions, text in charts and graphs: Arial no smaller than 18 point (black unless different colors are necessary for the graphic)

You may use smaller font sizes on your poster, but keep in mind that the font sizes were recommended to ensure that visitors can read the text from a distance. The poster will be at least 6’ away from the readers.The poster should be printed in color at 200% to achieve a final output size of 36” x 90”.

Video

Val and Annie made a video of the foam filtration technology to be displayed at The Expo. The video was shown on a laptop throughout the extent of the P3 Conference.

Results

In conclusion of this year’s EPA P3 exposition, the team received an honorable mention for the progress of the foam filtration technology. Throughout the competition, the team received thought-provoking questions and motivational support from the community. Below is feedback to be shared with the EPA conference chairs and advice for future teams competing for P3 awards:

Feedback for EPA

- It is suggested that the EPA provide a scoring rubric for the participating teams, with point values for each aspect of the project (report, presentation, multi-disciplinary team, etc.)
- On the poster, perhaps it should be mandated that competing teams include the project’s “inventions” - what is the novel design piece that makes each team deserve $75,000?

Advice for future teams

Overall, preparing for tough questions in the weeks leading up to the Expo proved to be very beneficial to the team’s performance. Prior to travelling to D.C., information sheets were prepared from questions to be expected from the judging panel. This, coupled with a mock panel involving Monroe, was helpful in improving the team's ability to answer the wide range of questions asked by the judges.

In addition, it is recommended that teams have the demo apparatus and poster ready one full week before leaving for the Expo. If the poster is to be printed in the CEE office, Carl Cornell prefers to have at least two days for the printing process.

The team did not receive the anticipated feedback summary from the judges, however, future teams should inquire about this feedback, as it may prove useful if foam filtration competes for the P3 Award again.

Methods

Research Approach

The foam research approach is a two-pronged style that addresses both the implementation using a full scale model as well as the governing equations and design parameters for foam filtration using a smaller and easier to operate model. The small scale model provides information on cleaning efficiency, filtration efficiency, clean out force required, pore size effects, etc…, which can be scaled up for any design. The large prototype filter provides information on the ease of use of the filter, the design challenges due to scale, and a much closer representation of the filter constructed in El Carpintero. The larger filter also enables the team to test the filter-sized LFOM and CDC system.

Large Filter and Recycle System

The following figures provide a more in-depth view to the overall experimental setup outlined in Figure 1. Figure 7 is a rendering of the large filter design completed in SketchUp over the summer. This provides a more clear understanding of the components of the backwash system inside the drum. The two crosses are to be connected with a mast that runs through the middle of the foam. The list of methods used to operate the large filter can be found in the Summer 2014 Research Report.

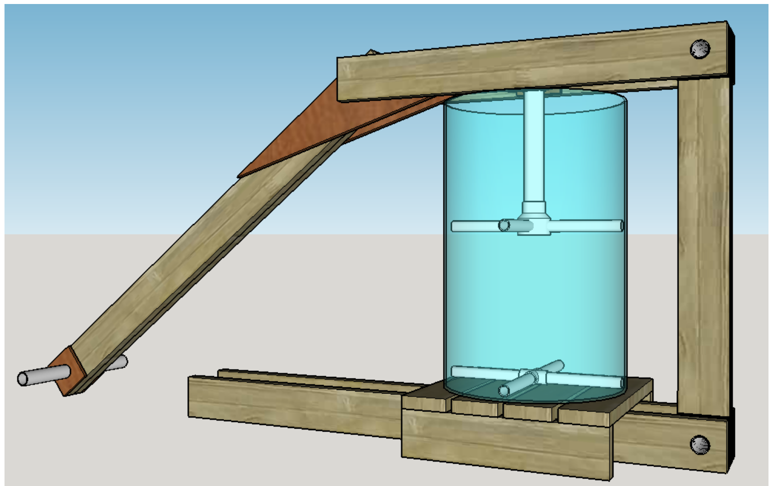

***Figure 7**: Large filter design*

Small Filter Test Unit

The basis of this design is a simple approach to backwash. Manually pushing the foam through the water for backwash yields many variables, especially with regard to an inconsistent force used to plunge the foam. In the case of a large 55 gallon drum, this manual force is necessary to achieve the velocity needed for cleaning. However, for the 4” small pipe filter, such a force is not needed. The backwash method for this design, pumping the water through the foam layers rather than plunging the foam itself, will allow for the isolation of important variables. The first variable to be isolated and analyzed will be the pore velocity through the pores of the foam and its effect on performance. Figure 8 below is a schematic of the design.

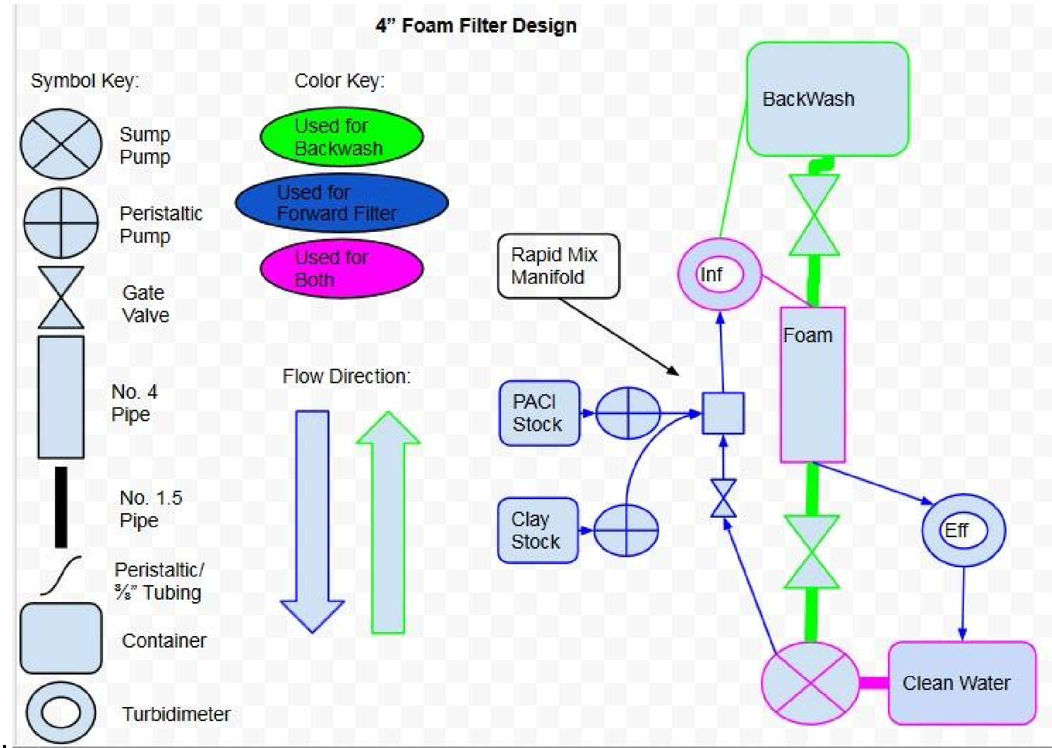

***Figure 8**: Schematic of Small 4" Pipe Filter*

Design Characteristics

The filter was designed keeping the following characteristics in mind:

- **Easy to operate:** setting up an experiment takes little time and the filter is not prone to flooding. The small filter will be connected to a sump pump located in a drum, and use the same experimental set-up previously used for the full-scale filter.
- **Accurate results:** the filter was designed in such a way that it will produce useful results for the large filter. The two filters are hydrologically very similar.
- **Transparent:** the filter body that houses the foam is clear to enable easy viewing of the foam both in backwash and in normal operation.
- **Highly measured and controlled:** all aspects of the filter's operation will be carefully measured, including the pressures between each foam layer, the influent and effluent turbidity, the backwash waste turbidity, the backwash force required, the filter flow rate, the coagulant dose and more. Creating an air-tight system allows for easily manipulation of the system and the ability to track changes during testing. A pressure sensor will be attached to a tube running the length of the filter and used to determine the headloss through the foam.

Flow through the filter:

Forward-Filter Mode

In forward-filter mode, water is pumped from the large drum (the purple Clean Water box in Figure 8) using a sump pump, where it is dosed with clay to simulate turbid raw water. Coagulant is added before a portion of that water is sent through the influent turbidimeter, then rejoined with the rest of the raw water to be filtered. The water is pumped up into the top of the filter. Pressure sensors are installed before and after the filter body in order to empirically measure the head loss through the filter. After passing through the air-tight filter, the filtered effluent is sent through the effluent turbidimeter and into the backwash drum, where the height of water measurements are used to determine the flow rate through the filter body.

Backwash Mode

Water is pumped using a sump pump in the Clean Water tank into the bottom of the filter and up through the foam layers. The flow rate at which the water is pumped through the layers is controlled by a gate valve after the filter body. A portion of the dirty water that results from the backwash is sent through the turbidimeter, while the remaining portion is collected in the backwash drum (green in the schematic) and wasted. Again, the height of water measurements in this tank are used to determine the backwash flow rate.

Clogging the Filter

In order to test backwash efficiency, the filter is first clogged with “dirty” water, a mixture consisting of clay and PACl. This mixture is pumped through the filter until the filter until the influent and effluent turbidimeters show the same reading, indicating that the filter is no longer removing any flocs from the water.

Backwashing

Before beginning the backwash cycle, constant pressure is created in the system by closing the gate valve at the top of the filter, and running the sump pump at the filter’s base. The gate valve is then opened very slightly, allowing water to flow through the filter at a constant velocity and removing flocs trapped in the foam. A portion of the water exiting the filter is sent through the turbidimeter before being directed into the backwash drum with the rest of the water pumped through the pipe.

Upon opening the gate valve, a spike can be seen in the effluent turbidity vs time graph recorded in Process Controller (see Figure 10). Water is allowed to pass through the filter at this initial velocity until the effluent turbidity decreases and eventually reaches a constant value, indicating that no further flocs are being removed at the current water velocity. The gate valve is then opened further, creating a higher backwash velocity, and the process is repeated. As backwash velocity increases, spikes in effluent turbidity become less dramatic, due to the large volume of water that the removed flocs were dispersed in. The lower spikes may be attributed to the fact that by the time these higher velocities have been reached, a large portion of the clay mass has already been removed from the foam with lower velocities. It is important to note that an absence in dramatic turbidity spikes does not necessarily indicate that these higher backwash velocities are less efficient than lower velocities, but rather, that this method of data collection may not properly indicate their performance.

Eventually, as the process of incrementally increasing backwash velocity is repeated, the flow rate becomes higher than the backwash drum can support, and data collection must be frozen in order to empty the backwash clearwell and fill the influent clearwell. This can be done by closing the valves leading to and from the filter body, creating an isolated system

At lower backwash velocities, the effluent water has higher turbidities than the turbidimeters can read. To compensate for this, the effluent is diluted prior to entering the turbidimeters, so that an accurate reading can be obtained and used for the purpose of analysis.

Data Analysis Procedure

Goals

- Determine a relationship between pore water velocity and backwash cleaning efficiency
- Understand how headloss through the filter is affected by pore size
- Test the cleaning performance of various pore sizes

Data Given

The following data was given, and formed the "raw" data for the analysis.

- Height of Water (HW) was given using a 7 kPa pressure sensor attached to the bottom of the backwash well (where the backwash water went to.)
- Filter Headloss (HL) was given using a 7 kPa pressure sensor with ones side attached below the foam in the filter and one above.
- Influent Turbidity was measured using an HF Scientific turbidimeter. Note that this measured influent turbidity during the Forward Filtration step and measured Backwash Turbidity during the Backwash step.
- Effluent Turbidity was measured using an HF Scientific turbidimeter. Note that this measured effluent turbidity during the Forward Filtration step and measured nothing during the Backwash step (not the influent!)
- Flow rates for: PACl, Forward Filtration plant flow, and dilution measurements were recorded manually and assumed to be constant throughout the operation. They were added to each spreadsheet in the "constants" section.

Inferred Data

- Backwash and Forward Filtration flow rates were inferred by using the derivative of the height of water. In the following equation, A_{Drum}, the cross-sectional area of the drum, and H_W, the height of water, were given and Q was solved for: $Q = (dH_W/dt) * A_{Drum}$
- The turbidity of the clearwell where backwash water was being drawn from was assumed to have the turbidity of the lowest value on the backwash (influent) turbidimeter during backwash.

Calculating Mass Added During Forward Filtration

The NTU*liters was calculated using a simple mass balance coupled with the flow rate integrated over the running time of forward filtration. The mass was then determined using the

NTU-Liters to mass of kaolin clay conversion constant to determine the actual mass in the filter[1], $C_{K/(NTU*L)}$, assumed to equal 1.7 mg kaolin clay/(NTU*Liter). The following equation calculates the mass directly from the given data to determine the total mass trapped within the filter:

$$M_{FF@t_f} = C_{K/(NTU*L)} \int_0^{t_f} Q_{FF} * \Delta NTU dt = C_{K/(NTU*L)} \int_0^{t_f} (dH_W/dt) * A_{Drum} * (NTU_{eff} - NTU_{inf})dt$$

Calculating Mass Removed During Backwash

The mass removed during backwash was calculated in a similar way (NTU*flow rate) but with a couple modifications to account for the dilution factor, K_D, of the backwash turbidity measurement, and the turbidity of the clearwell water that used to backwash and to dilute the backwash water once it had been flushed through the filter. The turbidity of the clearwell water, $NTU_{Clearwell}$, was assumed to be the minimum constant that the backwash turbidity “sank to” after a turbidity spike. The following derivation shows how to calculate the turbidity of the backwash water, NTU_{BW}, given the dilution factor, K_D=(dilution flow/backwash flow), the measured turbidity, NTU_M, and the turbidity of the water used to dilute the backwash water, NTU_D:

$$NTU_M = M_T/Q_T = (NTU_D Q_D + NTU_{BW}\, Q_{BW})/(Q_D + Q_{BW}) \Rightarrow$$

$$NTU_{BW} = K_D\, (NTU_M - NTU_D) + NTU_M$$

To calculate the mass of clay removed from the filter, $M_{BW@t}$, the backwash turbidity calculated above, NTU_{BW}, is then substituted into the same equation used to calculate the mass removed from the filter at a given time, t, as shown in the equation below:

$$M_{BW@t} = C_{K/(NTU*L)} \int_0^{t} Q_{BW}(t) NTU_{BW} dt$$

$$= C_{K/(NTU*L)} \int_0^{t} (dH_W\, /dt) A_{Drum} (K_D (NTU_M - NTU_D) + NTU_M)) dt$$

Spreadsheet Method: Height of Water to Backwash Pore Velocity

1. The height of water over the course of the filter backwash runtime was graphed. The data collected while discharging the backwash basin (when it became too full) was deleted. In addition, the values obtained for the headloss through the filter AND the backwash turbidity during that backwash basin discharge were deleted. (Note: all the raw data was saved in the RAW tabs of each pore size spreadsheet.)
2. A new column was created for the accumulated height of water by adding the previous maximum of a given run to the next, so that the graph was always increasing.

[1] NEED THE CLAY TO NTU LITER CONVERSION PAPER REFERENCE HERE!!

3. The derivative of the height of water data was taken by subtracting the n-1 cell from the nth cell, and converted to backwash pore velocity by multiplying by (A_{Drum}/A_{Filter}) both found in the constants worksheet.
4. This data was then graphed to identify the distinct flow rates (which were found to be horizontal lines at various locations). The data was color-coded so that each new flow rate is represented by a different color. All transitions (if they exist) were coded with red to signify they won't be used in the averaging step.
5. For each of the color codings, the velocities were averaged. This was made into a new column that has the same averaged value for each of the averaged sections and the next red transition section.
6. The velocities were re-graphed with the average velocities column to confirm that the average represented the center of the noisy velocity data.

See **Figures 9a, 9b and 9c** depicting the pore velocity, average pore velocity, and turbidity data for each of the three different pore sizes: 30, 60, 90 PPI.

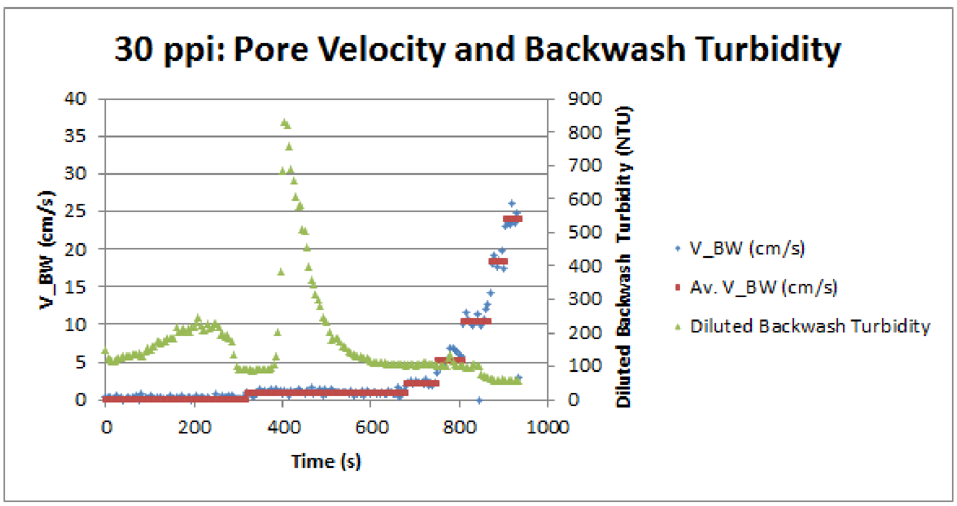

Figure 9a. Graphical depiction of Backwash Velocity (in blue), Average Backwash Velocity (in red), and the Diluted Backwash Turbidity (in green) for the 30 PPI pore size. Values are shown on the same graph to show the correlation between changes in velocity and spikes in turbidity. As shown, spikes in turbidity become less dramatic as pore velocity is increased. This indicates that most of the mass was removed in the second pore velocity step (indicated by the large spike in turbidity ~400 seconds into the experiment).

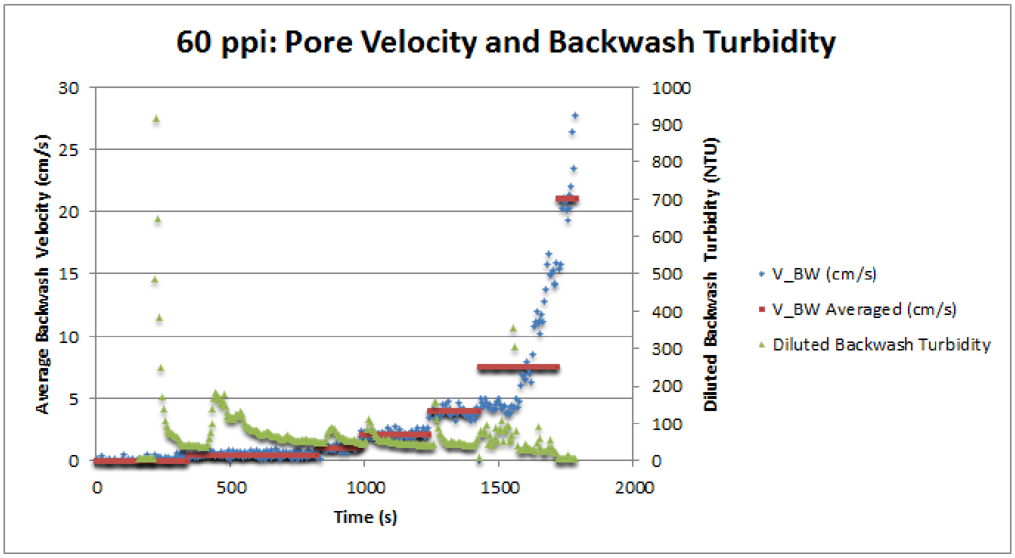

Figure 9b. Graphical representation of Backwash Velocity (in blue), Average Backwash Velocity (in red), and Diluted Backwash Turbidity (in green) for the 60 PPI pore size. It is hypothesized that the initial spike shown on the graph is due to the settled flocs on top of the 60 PPI foam layer. That is, the initial turbidity does not reflect flocs dislodged from the foam layer, rather flocs that settled on top of the foam after a period of 72 hours in which the foam was left idle before the backwash cycle was performed.

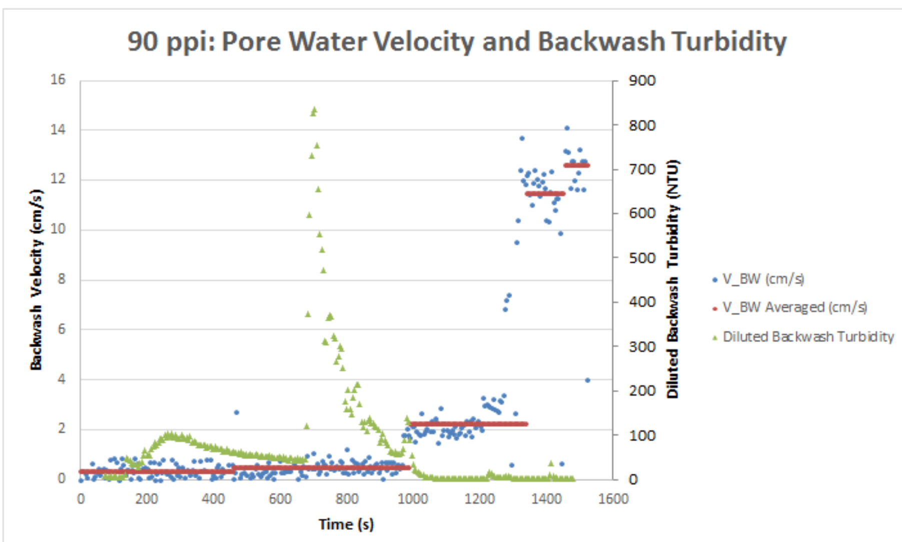

Figure 9c. Graphical representation of Backwash Velocity (in blue), Average Backwash Velocity (in red), and Diluted Backwash Turbidity (in green) for the 90 PPI pore size. As shown, much of the mass was removed with a pore velocity of about 0.5 cm/s. This spike in turbidity, reaching ~850 NTU follows a slight change in velocity from 0.3 to 0.5 cm/s.

Results and Discussion

NOTE: Data collected during the 2/27 and 3/13 backwash efficiency experiments (Figures 9 & 10) do not reflect the methods for raw data adjustments described above. These equations were developed and employed on the 4/20 data analysis and all following experiments. In addition, the method for data collection and analysis has been standardized and can be found here.

Backwash Efficiency Testing: 2/27 Experiment

Data collected during this experiment was too "noisy", and cannot be used for analysis. This is most likely due to the 200kPa pressure sensor that was used for collection, which was exchanged for a 7kPa pressure sensor to be used in later experiments.

In addition, turbidimeter data collection methods will also need to be altered, as initial turbidity spikes were too high for the meters to read. A peristaltic pump with two drive heads will be used to continuously dilute the effluent water with clean water to levels that the turbidimeters are capable of reading, so that accurate measurements can be collected and used for analysis.

Overall, this initial experiment did not result in data that could provide insight into the relationship between backwash velocity and cleaning efficiency. However, it did highlight key shortcomings of our experimental design that must be altered to move forward with successful data collection.

Backwash Efficiency Testing: 3/13 Experiment

The backwash experiment was repeated using a 7kPa sensor, which resolved the previous issue of "noisy" data. However, turbidity readings were still higher than the turbidimeters could support at certain points throughout the experiment.

The data in Figure 9 indicates that the backwash velocities were still acting linearly rather than exponentially decaying to full mass removal. That suggests that either the original hypothesis of exponential decay of the remaining mass in the filter with respect to pore velocity is wrong, or that the experiment never achieved high enough backwash velocities to exhibit exponential behavior.

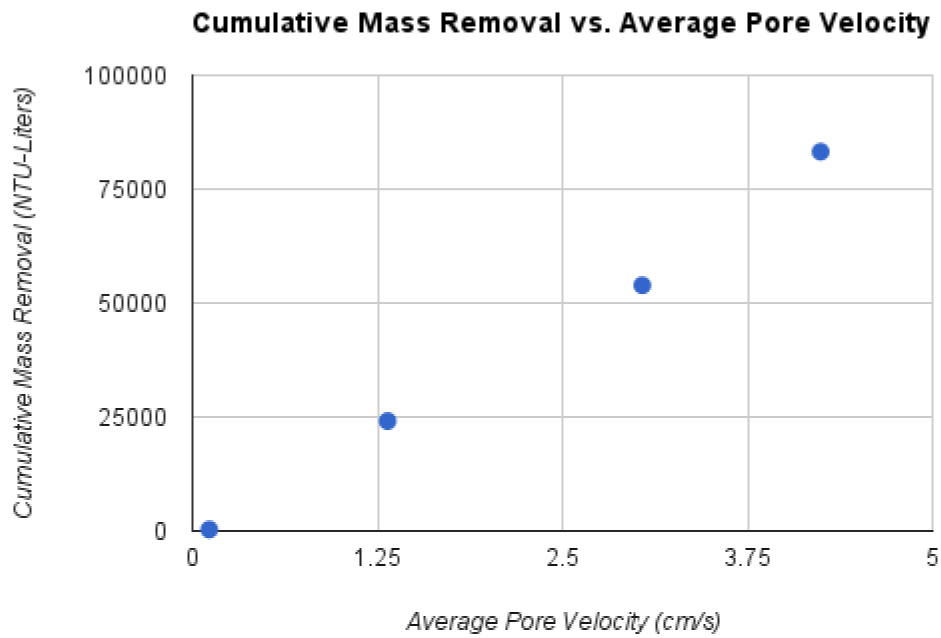

Figure 9: *Cumulative mass removed (NTU-Liters) vs average pore velocity (cm/s) data from 3/13/15 experiment. Spikes in turbidity were higher than the turbidimeters could support, and the maximum turbidity reading of 1100 NTUs was used, rather than extrapolation, when making mass removal calculations.*

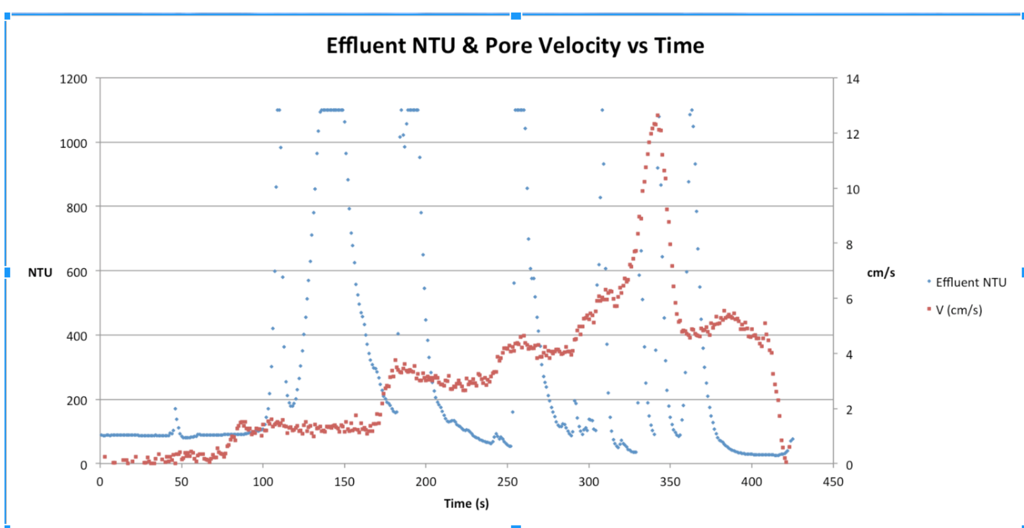

Figure 10: *Effluent NTU & pore velocity (cm/s) vs time data from 3/13/15 experiment. Increased pore velocity upon opening gate valve is followed by dramatic spike in effluent NTUs.*

Backwash Efficiency Testing (30, 60 & 90 ppi):

The results of the pore water velocity experiment for 30, 60, and 90 ppi foam pore sizes shown in **Figure 11** indicate that foam pore size has a small effect on the cleaning efficiency to average pore water velocity relationship. This suggests that clogged foam between sizes 30 PPI (0.846 mm) to 90 PPI (0.282 mm) need similar velocities to get adequately cleaned. In **Figure 9**, the cleaning efficiency for all the pore sizes was plotted against the average pore water velocity to determine the velocity needed to achieve adequate cleaning.

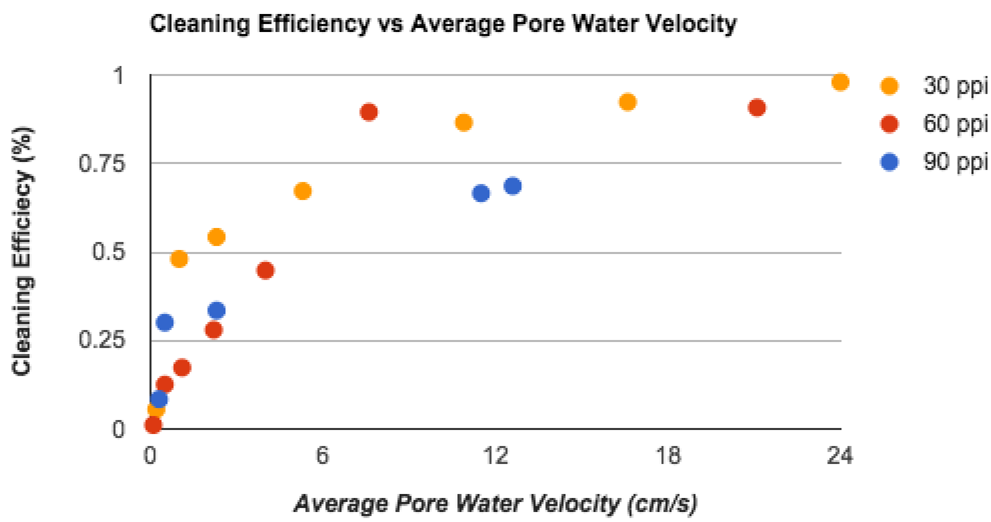

Figure 11. Graph depicting the results of the Cleaning Efficiency versus Pore Water Velocity experiment. As shown, the cleaning efficiencies increase with increasing pore water velocities for 30, 60, and 90 PPI foam.

Since the above relationship did not seem to be related to the filter pore size as was proposed, the filter headloss versus cleaning efficiency was analyzed.

Filter Headloss

Another limitation on achieving high cleaning efficiencies is the force the filter operator is able to apply to plunge the filter. That force is directly related to the headloss through the filter at the specific velocity of the plunging stroke. A high head loss would prevent the operator from achieving high enough velocities for adequate cleaning. **Figure 12** indicates the headloss determined at various flow rates for each of the foam pore sizes (30, 60 and 90 PPI). Once a flow rate was manually set, the headloss exhibited negligent change despite the departure of mass from the filter. This is most likely because the flow rates were incrementally increased, and therefore relatively little mass was ejected from the filter for a given flow increase. If the increments between the flow rates were increased, the headloss would be expected to descend as mass was being removed, as shown in a few of the headloss vs. time graphs (90 PPI, for instance). The linear trend suggests that the foams are dominated by major losses (shear on the foam walls) rather than minor losses, which would instead exhibit a quadratic increase in headloss. As shown in the graph below (**Figure 12**), smaller pore size foams require higher headloss to achieve the same pore water velocities, suggesting that adding high PPI foam layers is energy expensive.

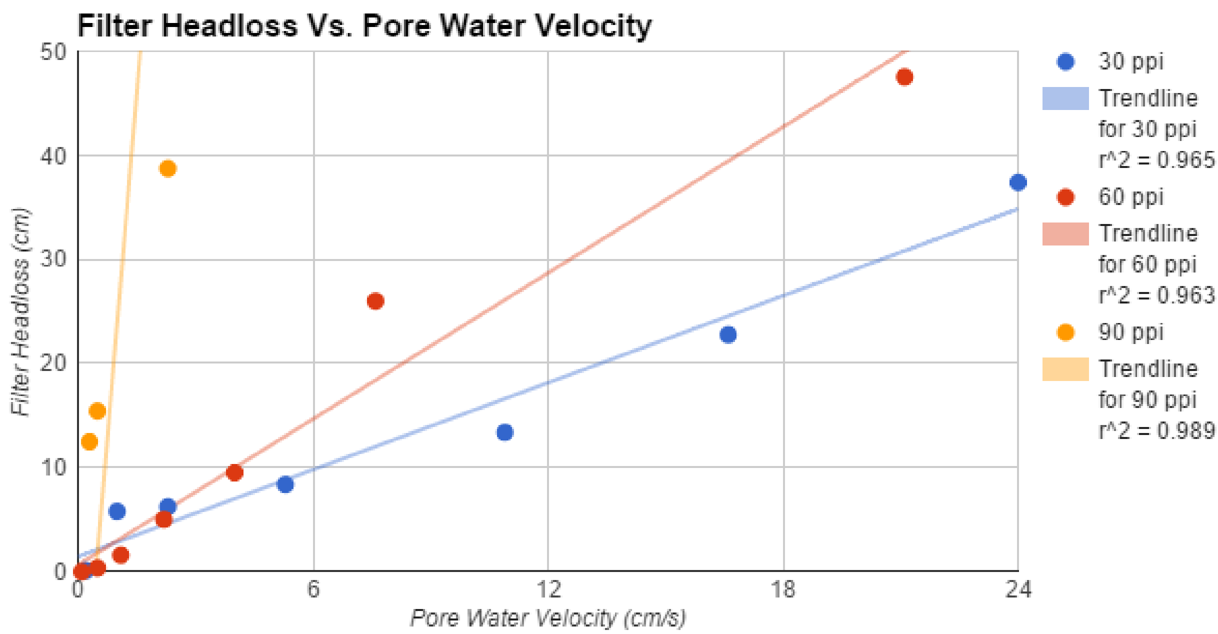

Figure 12. The headloss through the filter increases linearly with pore water velocity, suggesting that major losses (shear on the foam walls) are dominating throughout the foam. The depth of the foam used for these experiments was 10 cm (or 4”).

Filter and Backwash Mechanisms

In order to more fully understand how to design an effective filter, several mechanisms were proposed to be important in the trapping and removal of flocs from forward filtration and backwash, respectively. **Figure 11** includes summaries of four possible theories as to the mechanism for forward filtration in the foam filter. It is important to understand the mechanisms behind forward filtration, as they govern the understanding of the backwash mechanism, and how to achieve the highest cleaning efficiencies.

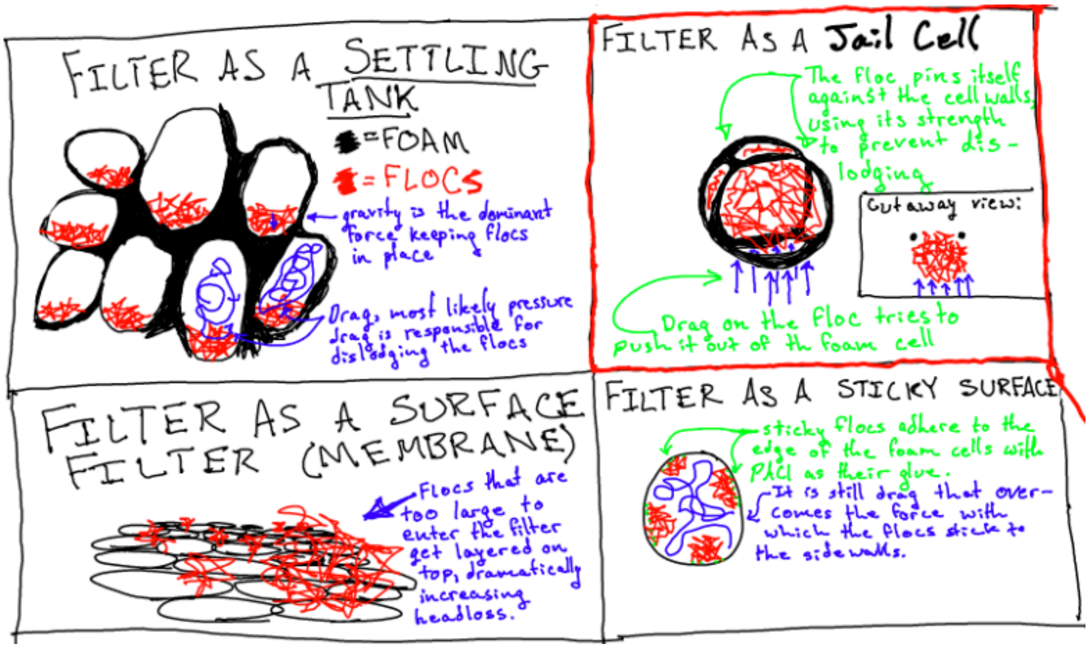

Figure 13. Depiction of the possible mechanisms for forward filtration.

Sticky Foam Walls Mechanism (Original Hypothesis)

It was originally hypothesized that the process by which foam filtration trapped in-coming flocs was via the attraction between the foam pore walls and the flocs (as depicted in the bottom right corner of **Figure 13**). Assuming this mechanism, it was further reasoned that the pore water velocity created during backwash would need to generate a large enough shear force to "un-stick" the flocs from the walls of the pores. As such, larger pore sizes (in this experiment, 30 PPI) would require much higher velocities than smaller pore sizes (i.e. 60 and 90 PPI) to create the shear force necessary to break the flocs free from the cell walls and achieve the same cleaning efficiency. As shown in **Figure 11**, this is not the case. Therefore, other mechanisms were theorized to dominate.

Surface Filtration

During certain stages of filtration, especially when the foam starts to reach its maximum mass-carrying capacity, the dominating mechanism becomes surface filtration, in which the flocs that are too large to enter the filter begin to layer on top of the foam surface. This layer greatly impedes flow through the foam, increasing the headloss through the filter. This floc layer is easily removed with small flow rates during backwash. **Figure 9b** shows a large turbidity spike with an average pore water velocity of only 0.08 cm/s, suggesting that the floc layer settled at the surface was easily removed from the filter, even at a small velocity.

“Settling Tank” Filtration

Another proposed mechanism for filtration is the “Filter as a Settling Tank,” as shown in the top left corner of **Figure 13.** In this proposed mechanism, the flocs settle on the surface area of the foam, and gravity is the principle force keeping the flocs in place. Assuming this method, the process by which the flocs are dislodged from the pores is a function of the upward component of drag (most likely pressure drag) exerted on the flocs by the pore water velocity induced during backwash. However; the projected surface area of the foam does not provide enough settling area that the achieved mass removal suggests. Therefore another mechanism must exist to explain the ability of the foam to capture a mass of particles that is directly proportional to the volume of the foam observed in the data.

“Jail Cell” Filtration

In order to account for the additional surface area needed, the mechanism outlined in the upper-right corner of **Figure 13** is proposed in which trapped flocs provide additional surface area. Specifically, as the flocs continue to collide with one another in the foam pores, they generate larger flocs that become lodged in the pores. If gravity were the dominant force in the system, the flocs would break through the pore cells. Instead, however, the force provided by the PACl holds the flocs in position, trapping them in the pore as if it were a jail cell. Not only does this theory account for the ability of foam to hold such a great amount of solids, but it also explains the increased headloss requirement to achieve cleaning efficiency data as it relates to pore sizes. In the “Jail Cell” filter, a floc must be broken to remove it from the cell. It is well-known in floc theory that smaller flocs are more dense and consequently stronger than larger flocs, and therefore smaller flocs require a higher drag force and consequently a higher pore water velocity to break. And since small foam cells (90 PPI) trap smaller flocs, one needs higher pore velocities to achieve higher cleaning efficiencies in finer foams. The maximum backwash velocity achieved in the 90 PPI foam only allowed for 68% cleaning efficiency, whereas the coarser foams achieved cleaning efficiencies above 90%. “Jail Cell” Filtration also explains many observed phenomenon of forward filtration, including: performance, effluent turbidity over time, and headloss curves, further emphasizing that “Jail Cell” Filtration seems to be a dominant mechanism.

Forward Filtration Results & Discussion

The following graph (**Figure 14**) depicts the performance of each of the pore sizes over the cumulated mass in the filter. As shown, the pC* for the 90 ppi remains around 1.75 until approximately 6 grams of clay have accumulated in the filter. This suggests that the 90 ppi foam is able to filter out clay particles until it reaches its mass carrying capacity of approximately 6 g.

The performance of the 60 ppi depicted in the graph below shows that performance actually increases with increased mass accumulated in the filter (up until about 3 g) before exponentially decreasing. This may suggest…

The pC* curve for the 30 ppi foam pore size shows an initial decrease in pC* down to about 0.3 with ~2 g of clay accumulated in the filter. After this point, pC* increases slightly, to about 0.6, before decreasing again as the cumulated mass in the filter approaches 4 g.

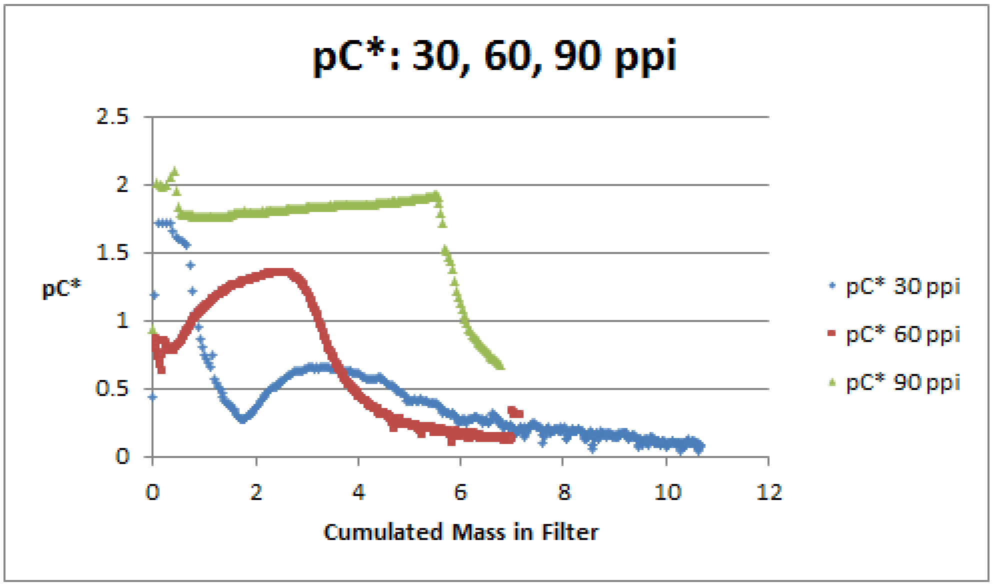

Figure 14: *pC* vs cumulated mass in filter (g) data for 30, 60, 90 ppi foam from 4/30/15, 5/6/15, and 4/20/15 experiments, respectively.*

The following graph depicts headloss through the filter for the 30, 60 and 90 ppi foam. For the 90 ppi, there is a clear transition from what is hypothesized to be depth filtration to surface filtration when the cumulated mass in the filter reaches ~4g. This transition is shown with a large increase in headloss.

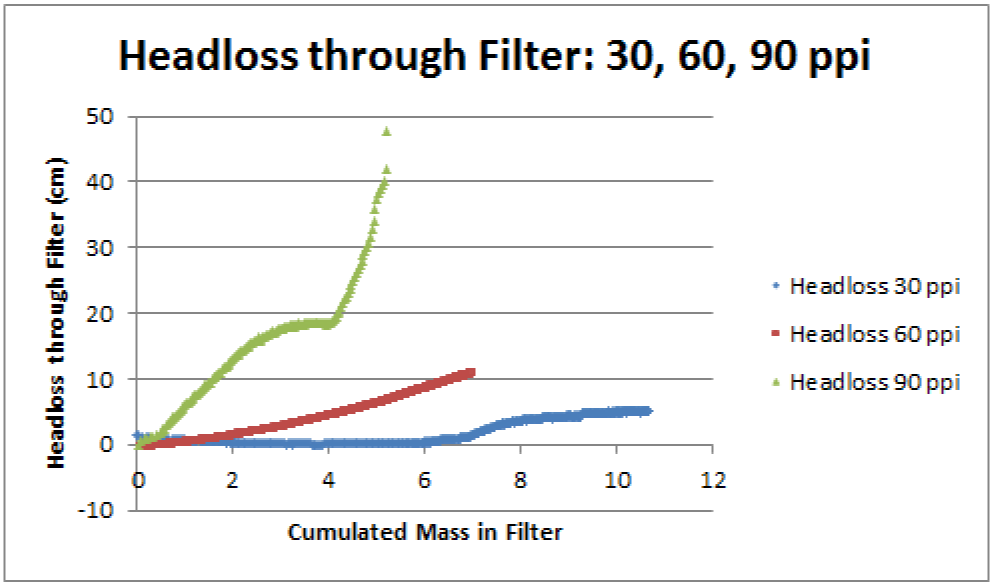

Figure 15: *Filter headloss vs cumulated mass in filter (g) data for 30, 60, 90 ppi foam from 4/30/15, 5/6/15, and 4/20/15 and experiments, respectively.*

Improvements/Ideas for Future Experimentation

- Backwash at even higher velocities to determine the expected exponential decay rate more accurately.
- Backwash using clean water so as to remove the 'DC' component from the turbidimeter data.
- Employ longer backwash times at given velocities in order to ensure more complete mass removal at particular velocities.
- Construct cumulative mass removal v. distance of water used (akin to the length of the backwash stroke of the foam) using a single flow rate for each cleaning cycle.
- Ensure the backwash data is replicable and resilient to varying PACl doses, and organic matter concentrations.
- Repeat experiments on various pore sizes.
- If a similar experiment were to be run again, using a smaller apparatus would be strongly suggested (order 1"). Such a choice would dramatically reduce required flow rates and thus make the expense and challenge of finding adequate pumps far less daunting.
- The next logical step this research could take would be to develop and test the mathematical implications behind the proposed "Jail Cell" Filtration theory. Those findings would give critical insight into effective filter designs, such as optimum stratification layering, required backwash velocities, and filter run times between clogging.

Conclusions

The results surprisingly indicate that finer foams are not easier to clean, and, in fact, may even be harder to clean than coarser foams. The originally hypothesized mechanism for how the flocs become attached to the foam does not explain the behavior observed in this experiment. To describe the observed dominant filtration mechanism in the foam, the "Jail Cell" filtration model was developed. Additionally, it was found that finer foams require greater headloss to achieve higher pore velocities than coarser foams due primarily to major losses. This suggests that finer foams should be used sparingly to reduce the backwashing force required to clean the foam. Furthermore, it may be possible that a reduction in finer foam use would require an increase in collision potential upstream of the foam, since less flocculation is observed in the larger pore sizes. This additional collision potential could be achieved with the addition of a flocculator upstream.

El Carpintero

Prototype Overview

During the January trip to Honduras in 2015, the foam filter prototype Walker began constructing in El Carpintero was equipped with a double-lever-arm CDC, a rigid vertical backwash lever arm, and a rigid central mast. The following figures show the improvements:

Figure 16a, 16b, 16c: *From left to right: (a) the double-lever-arm CDC doser, (b) the rigid vertical arm made rigid by a diagonal brace, and (c) the rigid aluminum mast and cross.*

The filter did not perform reliably well, and rarely produced turbidities under 5 NTU despite increased coagulant dosing. The following table (Table 2) shows average statistics regarding the filter:

Table 2: *Table summarizing the average filter performances during the 6 days of filter trials.*

Date	NTU In Ave	NTU Out Ave	PACl Dose Ave (mg/L)	Filter Duration (hours)	Total Filter HL (cm)	Mass Fraction Cleaned	pC* Ave	V Water Treated (L)
28/1	24.1	4.7	31.5	3.3	14.0	0.7	0.7	11094
29/1	27.7	13.1	55.1	1.8	15.3	1.1	0.3	6420
3/2	38.4	12.9	20.0	3.0	26.1	0.6	0.5	10680
4/2	30.8	5.6	35.8	2.0	29.5	0.9	0.8	7020
17/2	17.0	3.3	25.2	3.4	20.0	0.6	0.7	12000

18/2	16.9	5.1	27.5	3.3	35.5	0.6	0.5	11250

Forward Filter Efficiency Data

AguaClara Engineer, Walker Grimshaw, has been providing the foam filter team with data reflecting the efficiency of the filter in the field. It is hypothesized that the main discrepancies between filter performance in the field and in the lab is the presence of organic matter, as well as the use of different coagulant based on what is available in Honduras. The presence of organic matter requires higher doses of coagulant, since much of the coagulant is used up on the organic matter instead of coating the colloids to facilitate their aggregation into flocs.

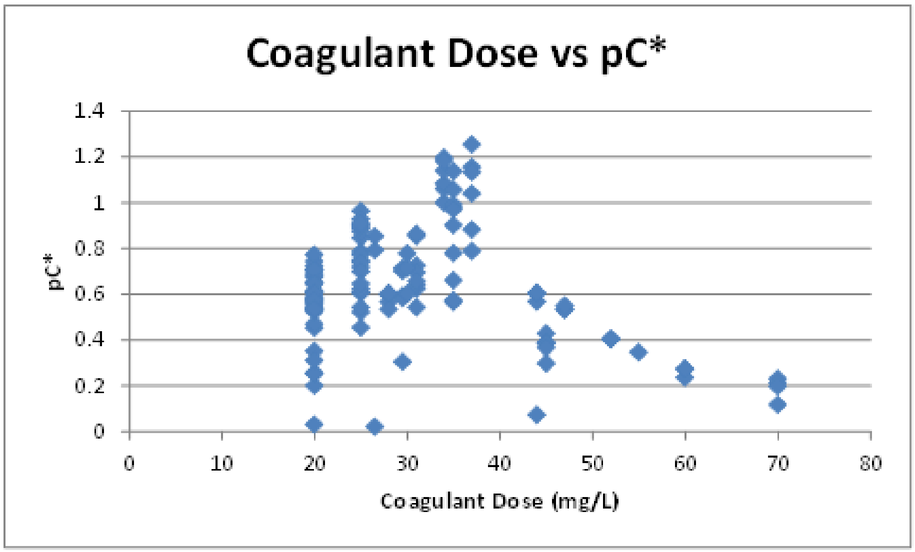

***Figure 17**: Coagulant Dose vs pC**

The plot above is a visual representation of the data collected on six different days in El Carpintero from January 28th to February 18th. As shown, pC increases with coagulant dose up to about 40 mg/L, after which it drops abruptly (from as far as 1.1 to 0.4) and continues to negatively affect performance as the dose is increased.*

Backwash Efficiency Data

Data from experiments performed by Walker on the filter prototype in El Carpintero during January and February 2015 have raised questions as to the efficacy of the backwash system.

Effect of coagulant on turbidity

The turbidity data collected on February 3, 2015 reflects that the turbidimeter used in the field measures a higher turbidity for coagulated water than for raw water, even though the two samples contain the same mass of flocs. See Table 3 below for a summary of the turbidity data.

Table 3: *Table comparing influent water turbidities before and after the addition of coagulant in El Carpintero during an experiment in February 2015*

Site	Date	Raw Water Turbidity (NTU)	Coagulant Dose (mg/L)	Coagulated Water Turbidity (NTU)
El Carpintero	02/03/2015	37.48	30	51.83
		37.59	30	44.48
		38.84	30	49.39
		37.79	30	42.08
Averages		**37.925**	**30**	**46.945**

It is hypothesized that this phenomena is due to the high coagulant dose (anywhere from 30-60 mg/L) used in foam filtration. A high coagulant dose affects the color of the water - changing it to a pale orange-yellow color - that is picked up by the turbidimeter. This causes an error in the measurements for backwash efficiency, sometimes yielding over 100% backwash efficiency, which does not follow the principle of conservation of mass.

Multiple backwashes

The filter requires several plunges to achieve a backwash efficiency of ~70%. This is contrary to what was shown in the lab during the Summer of 2014, where the team was able to achieve a 70% backwash efficiency with a single plunge. Data from El Carpintero collected on five days from the end of January through the first two weeks of February shows an average cleaning efficiency of 31.5% per plunge (with the exception of data from January 29th which shows an efficiency of over 100%. The data inconsistencies were confirmed as a result of improper cleaning of the filter from prior use, which is why it appeared as though more mass was removed than what had entered the filter during the experiment). See Table 4 below for a summary of backwash efficiency data.

***Table 4**: Table summarizing the cleaning efficiency per plunge and the total backwash cleaning efficiency for six trials performed in January and February 2015. Additional data regarding backwash cleaning efficiency can be found in the Honduras folder.*

Date	**# of Backwash Plunges**	**Average Efficiency per Plunge**	**Total Cleaning Efficiency**
28-Jan	4	25.50%	69.95%
29-Jan	3	293.43%	113.33%
3-Feb	3	28.63%	63.60%
4-Feb	4	40.03%	87.18%
17-Feb	3	25.13%	58.50%
18-Feb	2	40.25%	64.30%

Backwash Frame Design

The backwash frame used to lift the foam and plunge it through the water was not sufficient to prevent the top layer from deforming significantly and leaving large gaps between the pipe walls and the edge of the foam. During backwash, the water moves through these gaps in the foam instead of being forced through the pores, lowering the cleaning efficiency.

Figure 18: *The backwash frame design was altered in mid-February 2015 to include supports on the cross. It is hypothesized that these supports will help with the deformations in the top layer of foam and lead to more efficient backwash.*

In addition, the exit flow rate through the backwash drain was not high enough to prevent settling of flocs on the top layer of foam during backwash. Walker has increased the diameter of the backwash drain from 2” to 4” to allow for a higher exit flow rate and decrease the settling of flocs on to the top layer to further increase cleaning efficiency.

Lever Alterations

The filter arm fulcrum was raised slightly to reduce the horizontal movement of the lever arm that was proposed to allow short-circuiting of water during backwash. The ideal position for the fulcrum is to have the line bisecting the angle between the down and up position of the lever arm to be horizontal. However, this supposed improvement inexplicably inhibited the movement of the lever. After full deconstruction it was found that several screws bent under the strain exerted by the operator, and it was theorized that some part of the lever arm was jamming with the rest of the filter. Below are images of the filter. In the second, the old fulcrum (the empty hole) can be compared to where the new fulcrum is, roughly half the distance of backwash-mast throw up on the rigid, vertical post.

Figures 19a, 19b, and 19c: *(a) A close-up of the improvements to the lever-arm, (b) the new, higher position of the lever arm fulcrum, and (c) the current side-view of the filter.*

Additional Information

Photographs of the progress in El Carpintero can be found at on the AguaClara Picasa album.

Future Work

Long-term Goals

The largest challenges that remain to be dealt with are:

- Determining the toxicity of the foam leaching
- Developing a set of governing equations to guide the foam filter design
    - For forward filter:
        - Determining effect of stratification and various foam pore sizes on cleaning efficiency
        - Determining constraints for filter approach velocities
        - Develop an equation that may predict filter clogging time/ pressure in filter after time T given water influent NTU, PACl dose, filter geometry, flow rate, etc.
    - For backwash:
        - Find relationship between force and pore water velocity for various foam pore sizes
        - Develop relationship between pore water velocity and percent of foam cleaned: pC*=f(turb.in,C.PACL,U.filter, L.foam, PPI.foam, water.constituents)
        - Find out how many backwash cycles various foams can take before tearing/breaking/failing

References

Chu, K., Hinkley, M., Keller, E., & Pietsch, Valerie (2014, 12). *Foam Filtration Fall 2014.*

Brown, A., Erickson, S., Keller, E., & Kim, Ji Young (2014, 08). *Foam Filtration Summer 2014.*