Foam Filtration Research Final Report

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Introduction and Literature Review

A reticulated polyurethane foam filtration system combined with coagulant dosing has proven capable of providing clean, low-turbidity water; however the necessary addition of coagulant combined with a non-conventional cleaning method makes the foam filtration system inefficient and not ideal to be used on a municipal scale. For this reason, research on foam filtration methods have been geared towards engineering a portable and effective filtration unit to provide clean water to devastated areas in emergency situations. There is a great demand for such technology as proven by the 1994 Rwanda Crisis. In this case, 85-90% of deaths in refugee camps were caused by diarrhea [Toole and Waldman; Doocy and Burnham]. Providing a low-cost, sustainable clean water source in emergency situations is the best way to prevent waterborne diseases and dehydration. The foam filtration team has worked towards designing an apparatus that will provide at least 15 liters of water per day per person, based on the UNHCR's (United Nations High Commissioner for Refugees) recommendations for refugee situations [UNHCR]. The foam filter is small enough that it can be placed in the back of a pick up truck when needed and hooked up to the car's engine to harvest electricity needed to power the filtration process.

The current AguaClara foam filtration system utilizes a roughing and finishing filter to remove solid particles from influent water. Turbid water enters through the linear flow orifice meter (LFOM), which maintains a linear relationship between the water level and the flow rate of water through the system. Coagulant enters the LFOM in regulated doses to ensure consistent mixing of coagulant with influent water. The water flows through a 30 inch deep roughing filter, consisting of 30 ppi (pores per inch) foam, and then through a 15 inch deep finishing filter, consisting of 90 ppi foam. Before effluent water leaves the system, it is dosed with chlorine and exits the supercritical flow tube. Previous tests showed that head loss from the foam filters was negligible, but recent experimentation with an open system has proven otherwise.

Due to the head loss and effluent turbidity standards, the foam filters need to be cleaned. A "plunger" method of cleaning has proven to be an efficient and easy way to clean the foam filters. A long pole with a porous disc attached to one end is used to compress the foam and release solid particles trapped in the filters. This method is similar to squeezing out a dirty kitchen sponge. During the cleaning process, the foam must remain submerged in water to prevent the entrainment of air bubbles that would hinder filter performance. After plunging, the dirty water and released sediment flow out of exit valves located downstream of each filter.

At the 2012 National Sustainable Design Expo in Washington D.C. the AguaClara team showed that the foam filter system is effective in removing particles from water at relatively high turbidities; however, data from these tests does not give concrete evidence of the filter's performance in terms of realistic applications. At the expo, the turbidimeter was not properly calibrated, thus the data collected is not 100% accurate. Additionally, the filters were cleaned every 4 hours. Although this proved that the filters could return to their initial performance level after being cleaned via the plunger method, cleaning every 4 hours may be either too frequent or infrequent to maintain a high volume of treated water with acceptable effluent turbidity, in an emergency situation it is essential to maximize the volume of usable water while still maintaining quality standards. Effluent at the expo was dosed with clay and recycled so that the effluent became the influent. There is a possibility that coagulant built up in the filter columns, due to the recycle, improved performance beyond what it would have been in a more realistic experiment.

As a new and relatively unexplored technology, there is much research to be done in the realm of foam filtration. Our current and future research will focus on providing extensive data as to the performance of the foam filtration system at different turbidities as well as identifying more efficient cleaning cycles.

The World Health Organization included significantly reducing the number of "people without sustainable access to safe drinking-water and sanitation" in its list of 15 Millennium Development Goals [WHO]. Refining the foam filtration system has the potential to contribute to achieving this goal in addition to providing clean water to those who need it the most.

Materials and Methods

The foam filtration team has modified the original system prototype, which was demonstrated at the EPA National Sustainable Design Expo, in order to prepare it for extended testing and data analysis. As seen in Figure 1, the original apparatus consisted of two reticulated polyurethane foam filter columns mounted on an aluminum frame and connected by flexible tubing. However, due to high head loss, we could not run tests to breakthrough (effluent turbidity greater than 0.3 NTU) because the columns were too short. As such, we replaced the shorter columns with taller ones to allow longer tests. Additionally, ball valves were installed at the base of each column to facilitate cleaning. The modified apparatus is seen in Figure 2. The flow rate to be provided by the apparatus was calculated, as shown in Figure 3, to be just under 3 L/min.

For the experiments, clean influent tap water is pumped via submersible pump from a bucket to the Linear Flow Orifice Meter (LFOM). Water is con-

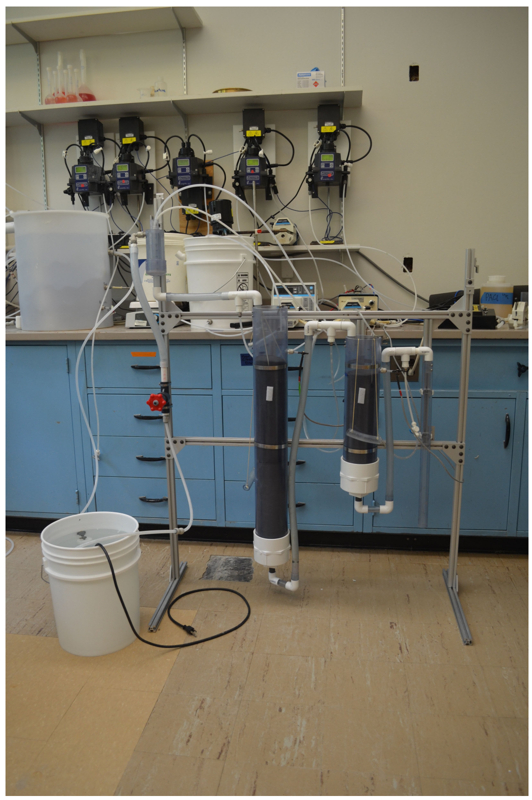

Figure 1: Original Foam Filter Apparatus

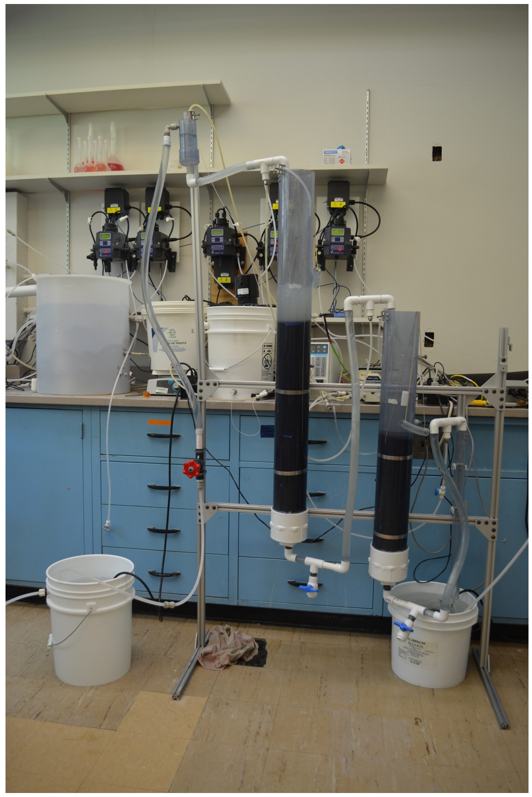

Figure 2: Modified Foam Filter Apparatus

System flow rate

$D_{Filter} := 4in$

Filter diameter and filtration velocity

$V_{Filter} := 6\,\frac{mm}{s}$

$A_{Filter} := \pi \cdot \left(\frac{D_{Filter}}{2}\right)^2 = 12.566\,in^2$

Filter surface area

$Q_{Filter} := V_{Filter} \cdot A_{Filter} = 2.919\,\frac{L}{min}$

Total flow rate to be delivered by the pump

Figure 3: Apparatus Flow Rate Calculation

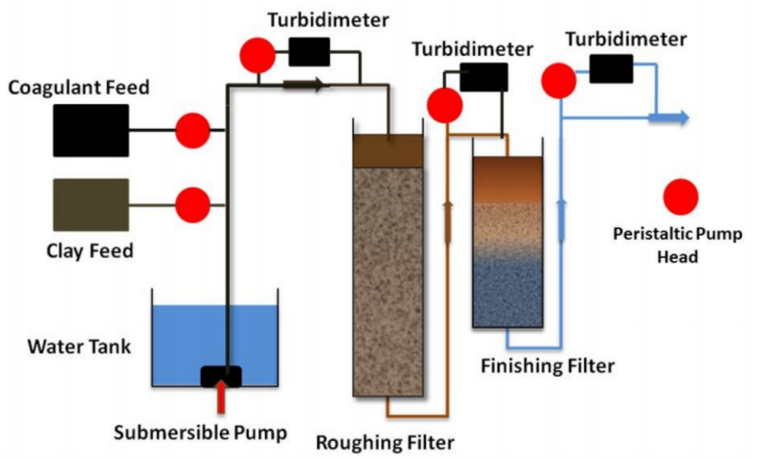

Figure 4: Schematic of Apparatus Connections

tinuously supplied to the bucket from the sink, and a float valve installed in the bucket prevents overflow. In the LFOM, the water combines with clay and coagulant, at stock concentrations of 20 g/L and 3.2 g/L respectively, each pumped into the LFOM from separate buckets with a peristaltic pump. The influent turbidities are controlled by increasing or decreasing the flow rate of the dosing pump. The dosing pump is set at a specific rate in order to control the amount of clay and coagulant that is added to influent water in order to reach a desired turbidity. The mixture will flow through the 30 ppi roughing filter, the 90 ppi finishing filter, and exit through the supercritical flow pipe to a drain. To properly test the effectiveness of the system and prevent buildup of coagulant in the filters, the effluent water is not recycled.

Three turbidimeters have been connected to the apparatus to monitor the turbidity of the water as it flows through the system. The first is attached to the tube connecting the LFOM to the roughing filter, and measures the turbidity of the influent water. The second draws from the tube connecting the roughing and finishing filters to measure the intermediate turbidity of the water. The third turbidimeter is attached to the tube above the supercritical flow pipe, and records the effluent turbidity. Water is pumped through these turbidimeters by a peristaltic sampling pump.

One hole has been drilled into the side of each filter, just above the fully extended height of the foam, where pressure sensors are attached. This will allow the increase in head loss to be tracked over the course of filtration cycles. This data will help determine if head loss is an acceptable indicator of when the filters should be cleaned. The turbidity and head loss data will be recorded in Process Controller for each experiment. Figure 4 shows a more detailed schematic of how the system is set up.

After about four weeks of testing influent turbidities ranging from 100NTU

Figure 5: Foam Filters Before & After Cutting

to 450 NTU, the performance level of the 90 ppi foam dropped drastically and failed to treat the effluent to below 0.3 NTU. For consistency, all three foam parts were replaced. Three rectangular foam blocks (two 30 ppi and one 90 ppi) were cut with a band saw and smoothed with a razor blade until they were circular. Holes for the plastic handles were drilled about an inch from the top of each block, then they were reinserted into the filter columns. Figure 5 shows the foam before and after cutting.

Upon the conclusion of three 450 NTU performance tests, about a week was spent studying the cleaning process and evaluating its effectiveness. The roughing and finishing filters are cleaned with a "plunger," or a long pole with a flat, circular head. Holes evenly spaced around the outside of the head enable water flow during plunging, allowing the foam to remain completely submerged and thus preventing air pockets from forming during the cleaning cycle. The plunger is used to compress the filter, forcing clay particles out of the foam and through the valves at the bottom of the apparatus. Figure 6 shows a head-on view of the plunger.

To evaluate the cleaning process, a single test was conducted for three days with an influent turbidity of 450 NTU. Instead of running the filter to breakthrough, the roughing filter was cleaned as soon as the roughing filter effluent reached 5% of the influent turbidity, about 22.5 NTU. The finishing filter was not cleaned until the conclusion of the test. Using this method, the length of a 450 NTU test was extended by essentially combining multiple 2 hour 450NTU

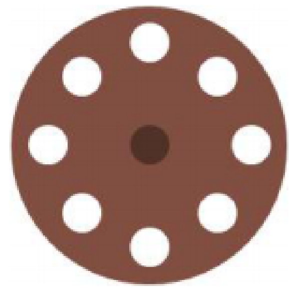

Figure 6: Topside View of the Plunger Head

tests in succession.

Results and Analysis

Filtration Performance

Thus far, we have completed a series of tests at 100 NTU, 200 NTU, and 450 NTU, in addition to an extended test at 450 NTU to assess the effectiveness of an alternate method of cleaning. We recorded data for the influent and effluent turbidities for both the roughing filter and finishing filter, pC* values to compare efficiencies, and the length of each test. The unit pC* serves as an effective measurement of filter performance and is calculated by taking the negative log of the effluent turbidity over the influent turbidity. This information is presented in Table 1. Time and head loss values in the table are recorded at breakthrough of the finish filter, when effluent turbidity exceeds 0.3 NTU. After each filter cleaning cycle, the effluent turbidity and head loss in both columns appear to return to pre-test levels.

Head Loss and Cycle Timing

To a large extent, the tests performed this summer have determined how often the components will require cleaning independent of a turbidity test, but further testing will be required to refine these boundaries. With unreliable electricity and less precise handheld turbidity meters in the field, it would be useful for an operator to be able to rely on visual cues like color of the filter columns or head loss as flocs build up in the filter bed to know when the filter media needs cleaning. As more particles accumulate in the reticulated polyurethane foam, the effluent will eventually have a higher turbidity. The columns will appear muddier and there will be additional head loss as pores in the foam become clogged. The goal was for one of these cues to be obvious and predictable enough that an operator would not need a turbidity meter to know when a

Table 1: Comparison of Experiments to Date

Experiment	Influent Turbidity	Time to Breakthrough	Terminal Roughing Head Loss (cm)	Terminal Finishing Head Loss (cm)	Average Overall pC*
1	100NTU	7h 5m	44.03	20.64	3.71
2	100NTU	8h 9m	49.03	11.96	3.75
3	100NTU	8h 4m	44.58	13.87	3.32
4	200NTU	2h 3m	20.05	22.027	2.83
5	200NTU	3h 31m	30.68	29.49	3.62
6	450NTU	2h 6m	33.96	23.37	4.01
7	450NTU	1h 23m	25.60	11.13	4.02
8	450NTU	1h 25m	27.15	10.46	4.02
9	1000NTU	50m	20.74	10.90	4.05

column needs cleaning. However, based on the difference in head loss between the 450 NTU, 200 NTU, and the 100 NTU tests that have been performed so far, head loss may not be a viable indicator.

Figure 7 shows the influent, roughing filter, and finishing filter turbidities throughout one test, including during the cleaning process at the end. For an influent of 200 NTU, the roughing filter functioned for about 45 minutes, until it became too clogged with clay. After the roughing filter effectively stopped working, the finishing filter continued to provide an effluent below the US EPA potable water standard of 0.3 NTU for another 45 minutes, for a total of roughly 1.5 hours of effective filtering. Figure 10 shows the head loss data captured by our pressure sensors for the same test. Head loss in the roughing filter was about 15 cm and increased linearly during the entire test. Head loss in the finishing filter was minimal until the roughing filter was no longer functioning, then built up quickly and at the end of the test was approximately 20 cm. After cleaning the filters, which occurred at just under 2 hours into the test, the water heights in both filter columns returned to the level consistent with clean bed head loss. This means that the plunger cleaning method is effective and is capable of returning the foam to its original filtration capacity after each test.

The tests with an influent turbidity of 100 NTU lasted about 7-8 hours, which is 4 times the length of a 200 NTU test. Breakthrough in the roughing filter did not occur for between 4 and 8.5 hours. Additionally, some tests had to be stopped before breakthrough because the roughing filter column was not tall enough to accommodate terminal head loss. Head loss in the finishing filter ranged from 11 to 20 cm at the end of the tests. Figure 11 shows the influent and effluent turbidities for the 100 NTU tests and Figure 10 shows the head loss traces. These results differ significantly from the results of the 200 NTU tests, although the effluent turbidity from the roughing filter is similar and the head loss is linear, which is consistent with depth filtration theory and the 200 NTU test results. Additionally, particles had visibly penetrated the roughing and finishing filters more deeply (causing the foam to appear muddier to a greater

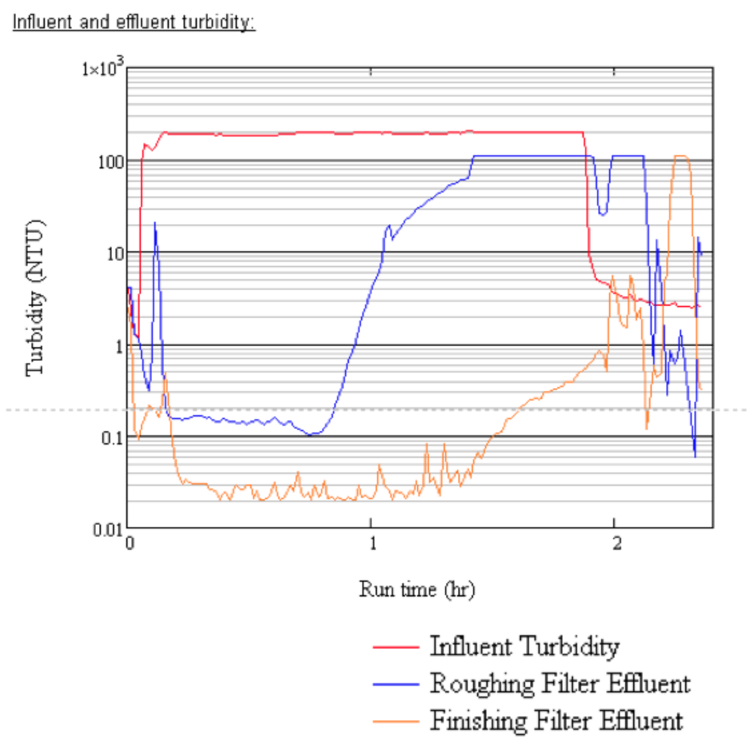

Figure 7: Influent, Roughing, and Finishing Turbidities for a 200 NTU Test

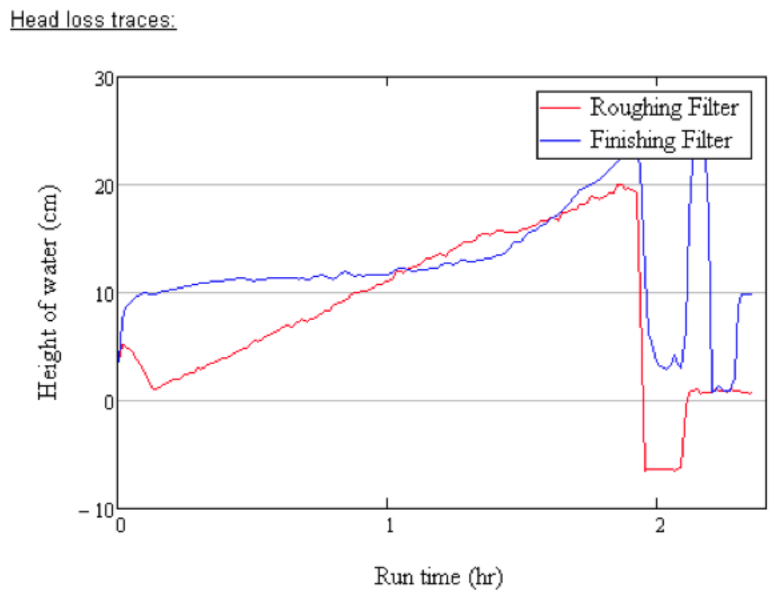

Figure 8: Roughing and Finishing Head Loss for a 200 NTU Test

depth) during the 100 NTU test than during the 200 NTU test.

It is interesting to note that the 450 NTU tests each lasted a little less than two hours, longer than the 200 NTU tests although it was predicted that because of the heavier particle loading the tests would be much shorter. Breakthrough in the roughing filter occurred around 45 minutes into the test again, while the finishing filter continued to maintain 0.3 NTU effluent for about an hour after that. With each test, finishing filter head loss was an average of 15 cm and returned to clean bed head loss after plunging. Roughing filter head loss also returned to clean bed head loss after each cleaning cycle, but increased from 15 cm in the first test to 25 cm in the last test, potentially indicating a buildup of particles in the foam that increased the collision potential of particles in later tests. As expected, penetration of particles was more concentrated towards the top of each column of foam than in the 100 NTU and 200 NTU tests. Figure 11 shows the influent and effluent turbidities for the roughing and finishing filters and Figure 12 shows the head loss for the 450 NTU test.

In order to assess the lifecycle of the foam in the context of continuous use and to take advantage of the two-step filtration process, a test was run with an influent turbidity of 450 NTU in which the roughing filter was cleaned when effluent turbidity reached 5% of influent turbidity (22 NTU). Instead of requiring clean water to flush the system after cleaning, the influent turbidity was maintained at 450 NTU. As such, no clean water was necessary for flushing the foam, which increases the volume of water the filter can produce. Additionally,

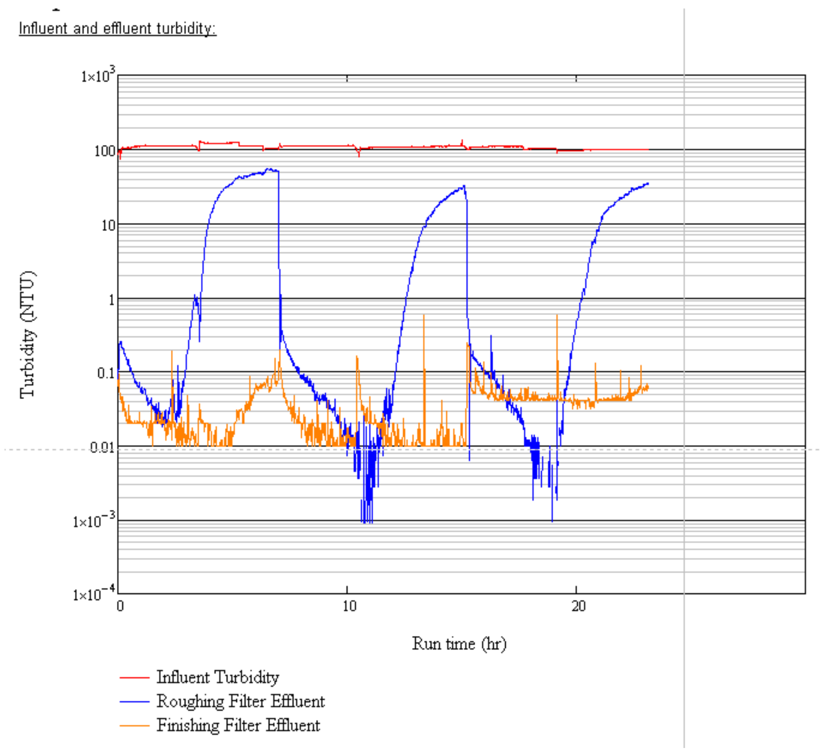

Figure 9: Influent, Roughing Filter, and Finishing Filter Turbidities for Three 100 NTU Tests

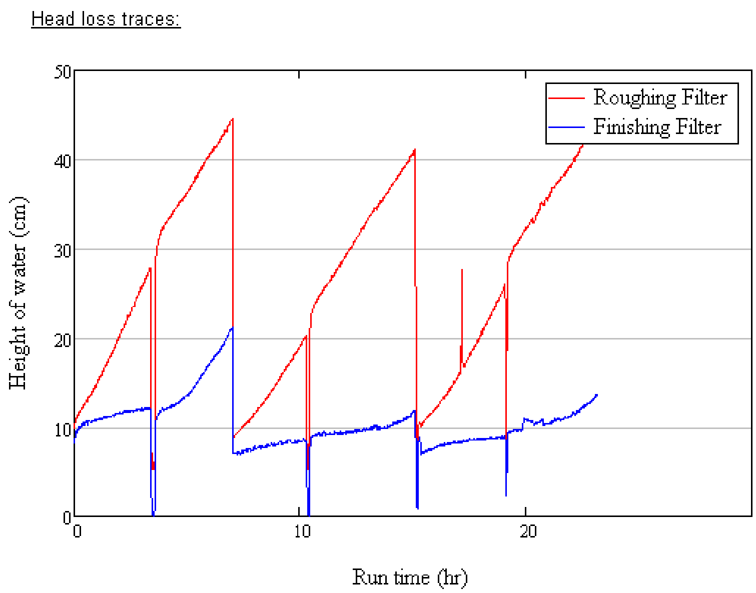

Figure 10: Roughing and Finishing Filter Head Loss for Three 100 NTU Tests

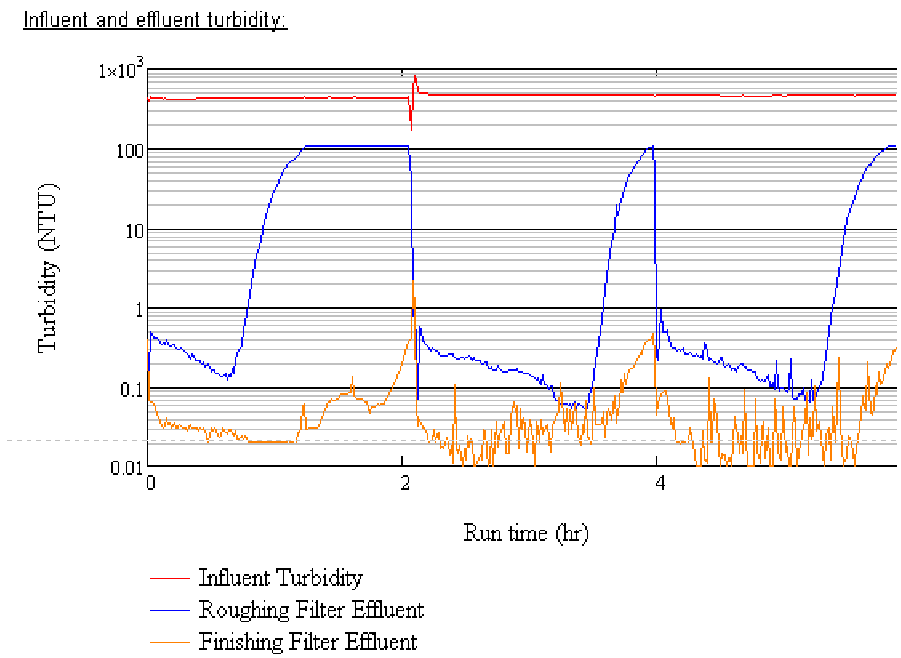

Figure 11: Influent, Roughing Filter, and Finishing Filter Turbidities for Three 450 NTU Tests

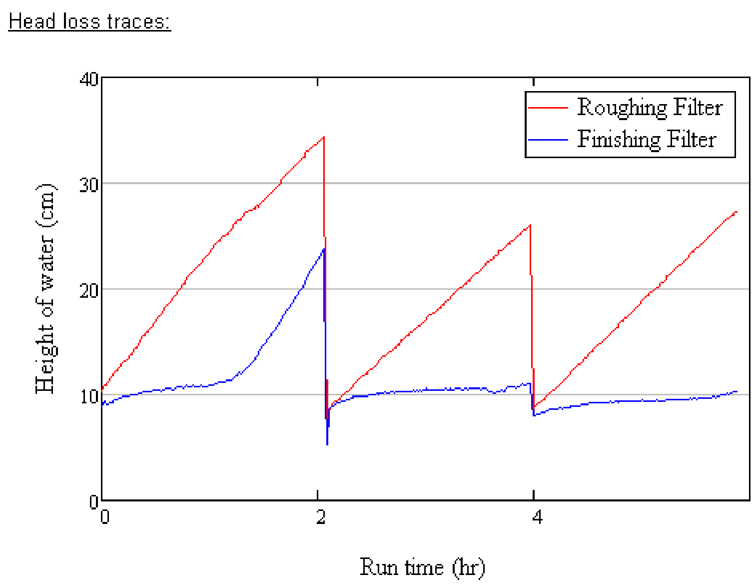

Figure 12: Roughing and Finishing Filter Head Loss for Three 450 NTU Tests

the filter was only offline for the time it took the finishing effluent turbidity to descend below 0.3 NTU, which may be a consistent enough time that turbidity measurements in the field will not be required. Figure 13 shows the influent and effluent turbidity for both the roughing and finishing filter during this test. It was not necessary to clean the finishing filter at all during the time the test was conducted. After each cleaning cycle, clean bed head loss was nearly achieved as shown in Figure 14. pC* remained consistent and consistently high for the entirety of the test. While these results are not conclusive, they provide a basis for further and longer testing of cleaning the columns one at a time before breakthrough is achieved. Doing so will provide insight into the actual life of the foam in continuous use and the feasibility of using head loss as an indicator of breakthrough before it occurs. It will also provide an environment conducive to testing the effectiveness of an external cleaning cycle to dislodge particles that build up in the foam that cannot be removed simply by plunging in the event that the foam could be reused.

Durability of Filter Media

While previous semesters' research and the few weeks of tests performed this summer have shown that filter performance returns to the high initial levels of performance after cleaning, wear on the reticulated polyurethane foam in long-term performance must be accounted for. Not all particles will necessarily be washed out during cleaning, and removal of particles may decline over the filter's life as cleaning and particle bombardment compromise the foam structure. Additionally, cleaning may fail to remove enough particles to return the filter to initial performance as an increasing number of particles remain trapped in the foam cells. Mechanical breakdown will determine how often the components need to be replaced, which is important for maintaining filters in working order. This occurred after the 200 NTU, one 450 NTU, and three 100 NTU tests. A 450 NTU test was run followed by a 100 NTU test, after which the effluent turbidity was unacceptably high even after extensive cleaning. This may have been caused by the high particle loading from the 450 NTU test in addition to the deep particle penetration of the 100 NTU test. Effluent turbidity of the beginning and end of the third 100 NTU test is visibly higher than previous tests (see Figure 9). The foam was replaced and another 100 NTU test was run, which lasted much longer and exhibited slightly better performance. Afterwards, we ran two more 450 NTU tests and a 1000 NTU test followed by another 100 NTU test. Performance appeared consistent, with a return to clean bed head loss and no noticeable impact on cycle time.

In addition to the mechanical considerations, it must be determined if reticulated polyurethane foam is a safe filter medium - i.e. whether it resists chemical breakdown that will lead to unsafe compounds in the clean effluent. However, reticulated polyurethane foam (like PVC pipe) is known to be a stable and durable material. Thus, the performance of the filter is not expected to mechanically or chemically decline noticeably over the course of these tests or during the type of short-term, intense use the filter would be subjected to in

Influent and effluent turbidity:

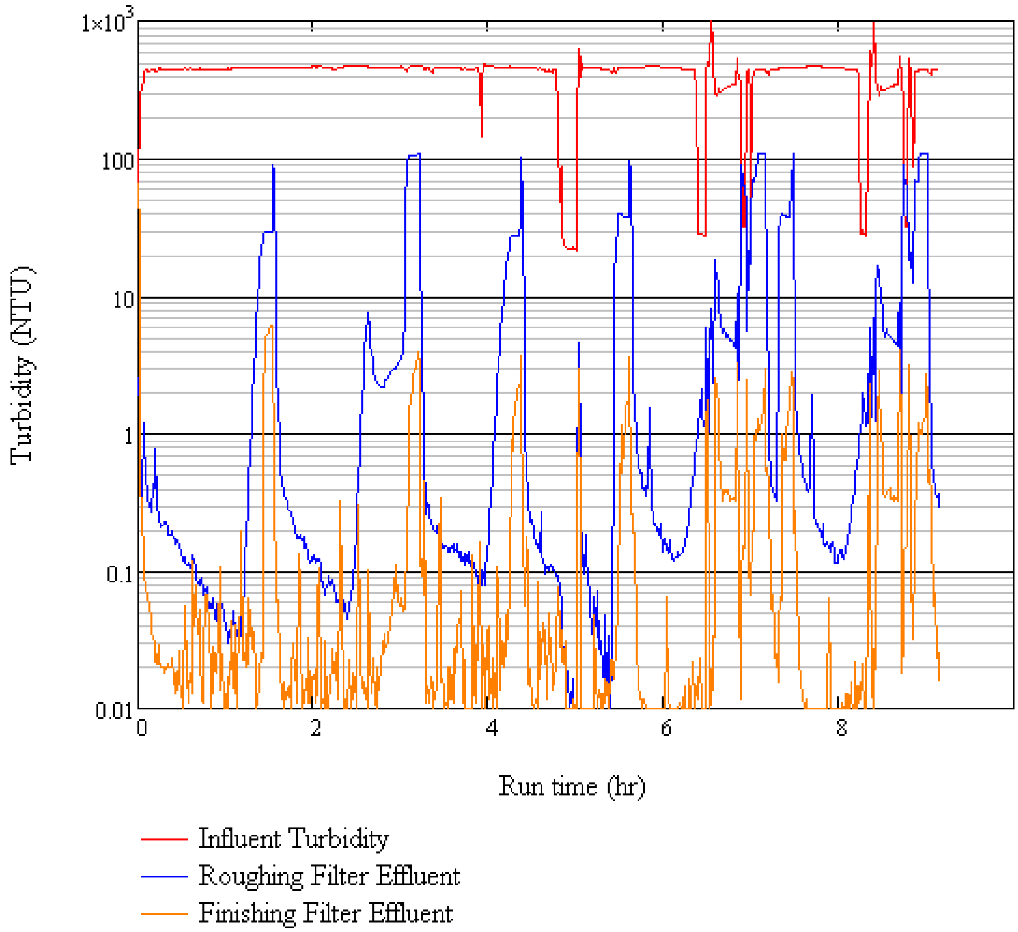

Figure 13: Influent, Roughing Filter, and Finishing Filter Turbidities for the Alternative Cleaning Cycle Test

Head loss traces:

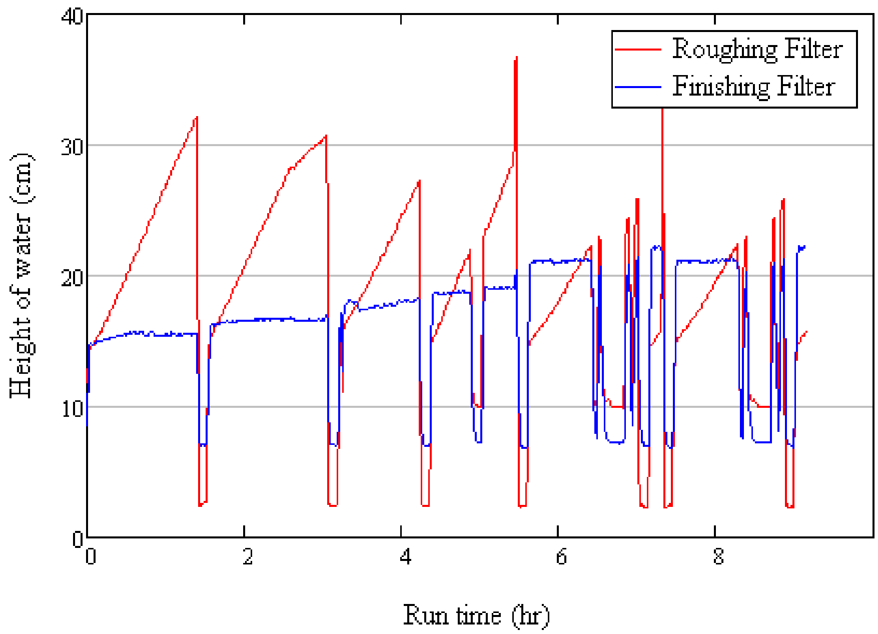

Figure 14: Roughing and Finishing Filter Head Loss for the Alternative Cleaning Cycle Test

the field. It may be of note that in previous tests the effluent water has had clay added to it and has been recycled as the influent so that coagulant may have built up in the filter columns and improved performance by facilitating the formation of flocs. But longer tests with multiple cleanings that avoid recycle of water have have shown that with respect to pC* the mechanical durability of the foam filtration unit is not affected after ripening by a lower dose of influent coagulant on this scale.

Conclusions

Reticulated polyurethane foam has shown to be an effective filter medium for the range of turbidities that have been tested this summer. We expect that any future tests will support this conclusion. The lifespan of the filter appears to be about 1 month at a range of turbidities with regular use, and the plunger method appears to be effective at cleaning the foam for the entirety of this lifecycle.

Filter runtimes can be extended if the roughing filter is cleaned whenever the roughing filter turbidity reaches 1-5% of the influent turbidity instead of when it breaks through into the finishing filter. Water cannot be filtered by the finishing filter while the roughing filter is cleaned, since all water passing through the roughing filter is drained; however this method is still beneficial as it reduces how frequently the finishing filter requires cleaning.

We do not believe at this time that head loss is a viable indicator of when the filter should be cleaned. As seen above in Table 1, the terminal head loss depends on both the influent turbidity and the condition of the foam over the course of its lifecycle.

Future Work

Although substantial data has been acquired pertaining to the foam filter's performance and the effectiveness of the plunger cleaning method, there are still many unanswered questions. Future foam filtration teams should run additional experiments using the alternative cleaning method in which the roughing filter is plunged as soon as it reaches 5% of the influent turbidity, rather than plunging both filters when the finishing filter reaches breakthrough (0.3 NTU). Comparing data regarding the alternative cleaning method to that regarding the original cleaning method may reveal which method is most effective and efficient, and whether the alternative cleaning cycle extends the foam's lifespan.

Future generations of foam filtration teams should make observations that may shed light on the long-term durability of the foam filters. The Summer 2012 team replaced the foam after approximately four weeks of testing influent water at varying turbidities. Future teams should continue to monitor the long-term life span of the foam to assess how long a foam column would last in the field. Further work will also be required to determine how many hours of continual use our life cycle tests are equivalent to and whether this number will be consistent for use in the field, which will be possible with the new type of cleaning test that began at the end of the summer. In addition to knowing how long the foam will last in the column, future teams should look into the usefulness of an external cleaning cycle for the foam in the event that it can be more thoroughly washed than with the plunger in the column in order to dislodge more particles so that foam can be reused.

Another focus of future teams should be identifying a physical indicator of the end of a filter cycle so operators will know when the columns need to be plunged. We originally thought that head loss depth or color might serve as indicators of breakthrough in a filter column; however, we found that color is too subjective and head loss appears to vary significantly with each influent turbidity tested. Without adequate turbidimeters in the field, we do not believe that head loss or color serve as viable indicators if the filters are to be operated in the way we have run our tests.

To ensure that the foam filter provides clean, safe drinking water, future work should be done to assess whether the mechanical and chemical breakdown of the foam releases harmful chemicals into effluent water. Although reticulated polyurethane foam is know to be stable and safe (like PVC), the blowing agent used in manufacturing the foam may be retained in the cells of the foam and wash out during a certain time at the beginning of the foam's life cycle. Work should be done to determine which compounds and at what concentration are coming out of the filter columns. This can be done by assessing water samples from the foam columns we replaced and the foam currently in the apparatus with a gas chromatograph. The company that manufactures the foam, New England Foam Inc. will have to be contacted to determine what blowing agent is used and whether it will present concerns.

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