Low Flow Stacked Rapid Sand Filtration
Summer 2013 Report

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Abstract

In India, there are currently seven Low Flow Stacked Rapid Sand Filters under construction, with an anticipated completion date of September 15, 2013. AguaClara has developed several new design features for these new filters, so the goal of this summer's work was to conceptualize and create these devices. The first device is a backwash initiator that displaces the sand to give water a preferential flow path when the filter is clogged and backwashing is hindered. This is done by inserting a square rod at the top of the filter that can be rotated to push sand away radially. Second, a fluidization tester needs to be installed because the plants in India will be using opaque stainless steel for their filter walls. Thus, a ball rod connected to the filter via a Jaco fitting has been created. If the ball rod can move easily, the sand is fluidized; if it cannot, then the sand needs to be further backwashed, and the initiator should be used. Finally, sand drains will be implemented in all AguaClara sand filters in case any maintenance requiring the media to be removed is necessary. The Summer 2013 team has constructed a similar design to that being implemented in India using push-to-connect fittings on the pilot scale filter. All of these innovations seem to be viable options for use in the field, assuming they maintain the filter's water- and air-tight characteristics.

1 Introduction

Mankind depends on water to survive. While developed countries, like the United States, are able to utilize modern technology to provide clean water to their citizens, less wealthy countries do not have the same resources. AguaClara and Agua Para el Pueblo have built municipal scale water treatment plants in Honduras that use appropriate technologies developed by AguaClara. Recently, AguaClara has expanded its designs and operation plans to India, where the goal is to provide purified drinking water to several thousand rural villages. While the design philosophy and technologies will be the same in India, there are several design challenges that must be met in order to provide clean water in this context. As the primary source for the system will be well water, the influent water will have a lower turbidity than that present in Honduras – this reduces the AguaClara system components into simply a chemical doser and a stacked rapid sand filter. Additionally, the plants in Honduras are meant to supply water to cities of people, while each AguaClara plant built in India will only supply water to the immediate community of several hundred to a thousand villagers. This means that the design flow rate through the system should be low, hence the designation of the filter as the low flow stacked rapid sand filter (LFSRSF). While lower flow rates ensure that the water will spend a greater amount of time in the filter and thus be subject to a more thorough cleaning, it may pose issues for backwashing, especially if the filter is clogged or extremely dirty.

AguaClara LLC began building a plant in India in June 2013. The team has been communicating with Maysoon Sharif, the primary team there, and Professor Weber-Shirk to determine their immediate needs to build in India. Testing and modification of the current stacked rapid sand filter will need to be done before it can be properly implemented in India. Several LFSRSF units are slated to be constructed in India by September 15th of 2013.

2 Literature Review

2.1 Engineering Fluid Mechanics 9th edition by Crowe, Elger, Robinson, and Williams

The Engineering Fluid Mechanics textbook offers basic hydraulic knowledge on areas of interest for a LFSRSF. Some specific areas of interest include the energy equation describing friction (Darcy-Weisbach) and minor losses (due to contractions, bends, valves, etc.) along with their coefficients. The orifice equation could be useful in understanding and modifying the sand drain and the filter in general. This information was useful for understanding the conditions and challenges that implementing the filter in developing countries will face.

2.2 Novel Fluid Control System for Stacked Rapid Sand Filters by Adelman, Weber-Shirk, Will, Cordero, Maher, and Lion

The two papers published under this name describe the hydraulic controls of the AguaClara Stacked Rapid Sand Filter (SRSF) when switching between filtration and backwash. The system uses a siphon pipe and air trap to initiate the two operational modes by opening an air valve in the siphon pipe for 5 seconds to initiate flow through the siphon for backwash and again to fill the siphon pipe with air to initiate filtration and to re-establish the air trap in preparation for the next backwash initiation. This is useful information in our efforts to find a simple solution to initiate backwash for the LFSRSF. The location of the siphon system is at the top of the filter chamber of the LFSRSF. This differs from the SRSF described in the paper, which has a siphon pipe that enters the side of the filter chamber and extends down to slightly above the sand bed. The lab scale LFSRSF also has 5 additional valves, 4 controlling inlet flow for each port, and one controlling outlet flow. These valves are currently necessary to initiate backwash. In the SRSF described in the paper, the flow in and out of the filter is controlled by the placement (height) of each inlet entrance and outlet box. These heights are governed by differential pressure and head losses. The calculations done for the SRSF configuration will aid in the modifications necessary to eliminate some of the excess valves of the LFSRSF and assist in the development of a simplified way to initiate backwash.

2.3 LFSRSF - AguaClara Final Report - Spring 2013

In this report, the project team (Mihir Gupta, Kris LaPan, Rachel Proske, Nadia Shebaro) outlined their work on the Low Flow Stacked Rapid Sand Filtration system over the course of the Spring 2013 semester. Their work focused on developing a small-scale filter unit for demonstration at the EPA P3 Competition in Washington, D.C. Two major innovations accomplished by the LFSRSF team's work over the semester were the design of new manifolds, as well as the design of a new sand drain. In the course of the work to be completed this summer, the new sand drain will be tested, and the team will look for ways to improve upon the design. Additionally, manifolds of the new type will need to be constructed.

In addition to improving upon the sand drain and constructing manifolds, a number of other future research goals were suggested at the end of the report. One important goal is to make the construction of the filter more practical for the needs of the communities in which it will be implemented. Of very high importance will be the improvement of the backwashing process. At present, the backwashing process is complicated (it requires turning multiple valves), and is inconsistent. Future work should be conducted to make the backwashing process easier for the operator to initiate and more reliable.

2.4 Professor Monroe Weber-Shirk's CEE 4540 notes: Filtration

The class slides developed by Professor Weber-Shirk in CEE 4540 – Sustainable Municipal Drinking Water Treatment cover a section on various types of depth filtration methods, specifically slow sand filtration, rapid sand filtration, and stacked rapid sand filtration (SRSF). 1 below (taken from Professor Weber-Shirk's notes) summarizes the primary differences.

System Comparison

Filter type	Velocity (mm/s)	Cleaning	Max Turbidity (NTU)	pC*	Area (m^2) for 1 L/s
Dynamic	0.4			0	2.5
Roughing[1]	0.17	5.5 mm/s downflow		0.5[2]	5.9
Slow	0.04	Scrape surface	10	0.8[2]	25
Multistage	0.03[3]		100[4]	1.3	33.4
Rapid	0.7 – 2.8	11 mm/s backwash	5[5]	1	0.55
Flocculation	2				0.5
Sedimentation	1			2.5	1
Stacked Rapid	1.8 x 6	11 mm/s backwash	3[5]	1[6]	0.093
AguaClara	0.63[3]		1000[5]	3.5	1.6

Figure 1: Summary of Water Treatment Methods

Additionally, these notes provided a thorough explanation of backwash, which needs to be initiated regularly in order the clean the sand bed of contaminants, normally when the filter effluent turbidity is greater than a treatment guideline or when the head loss across the filter exceeds a set value. Using an SRSF reduces the backwash water volume by a factor of the number of stacked layers used. As an application to the research conducted this summer, this information was important background information in designing a backwash initiation system that can be applied to a low flow rate scenario. Such conditions are similar to what will be available in India, where the system will be applied next.

3 Methods and Materials

3.1 Attempted Redesign

In an attempt to be able to control the flow rate and collect more thorough data, the sump pump that was providing flow through the filter was replaced with a peristaltic pump. A 600 RPM pump with 3 heads was used, but when calculating the flow rate this pump would provide, an error was made. The needed flow rate to achieve a velocity of 11 mm/s in the 4" diameter filter is approximately 5.3 L/min. The 600 RPM pump could supply 0.48 L/min in each head, giving a maximum of 1.44 L/min. Once the miscalculation was discovered, the original sump pump was reinstalled.

While installing the peristaltic pump, the backwash drain was moved into a large bucket on the floor, instead of the sink, so as to provide a few extra feet of head difference. This is a more realistic representation of the filter assembly that will be built in the field. The bucket has a sump pump in it that then pumps the water into the sink for disposal. The sump pump is managed by Process Controller based on a pressure sensor in the bottom of the bucket that communicates the water level in the bucket. There were also adjustments made to the inlet tubing during the redesign. There was a soft rubber cuff and two metal hose clamps that held the intersection of the stiff pipe that leads to the inlet manifold and the soft tubing that feeds the water from the pump. This flexible cuff was inefficient and was prone to leaking (both water out of the system and air into the system), so it was replaced by gluing a threaded female adapter to the 1" clear PVC pipe and using the appropriate barbed/threaded male adapter in the clear tubing.

3.2 Pilot Scale LFSRSF System

The pilot scale LFSRSF under study was a 2.261 m tall vertical 4" clear PVC pipe filled to about 1.541 meters with sand media. Both the filter height and the sand height have been altered in the course of installing the three new devices. The LFSRSF has a manifold with four inlet pipes feeding it, and a manifold with three outlet pipes leaving the system. The unit has multiple ball valves to enable the operator to control the flow through the filter. In the current configuration, the team has returned to the original sump pump configuration to provide flow through the filter. Though this will require that the team measure flow manually, it will provide the head necessary to initiate fluidization of the entire sand bed for backwash.

3.3 Sand Drainpossible

The Spring 2013 LFSRSF team created a spreadsheet to design a sand drain model model that could be implemented on both the full scale and on the pilot scale LFSRSF. They used a design that is comprised of a vertical pipe connected to a downward-angled pipe which exits the filter, and has a valve at the outlet. This is the design that has been used until the present in the plants built in Honduras. In India, however, it will be necessary to use a different type of sand drain. Rather than having a downward-angled outlet pipe, as has been done in previous models, the design for India has a horizontal section through the pipe wall and inside the filter. The concern with using this design scheme is that this horizontal section might enable sand to settle within the drain, potentially clogging it. The water treatment facilities to be built in India by September 15th, 2013 will include this new sand drain. Thus, the goal of this summer's research was to implement an approximate replica of this design on the pilot scale model to determine if it will be a sustainable design in the field. The team has finalized a design that employs a vertical tube, which reaches into the lower sand layer. It is connected by a few push-to-connect joints and a length of tube to a ball valve outside the filter, where the flow of sand can be controlled. This setup can be seen in 2 below.

Figure 2: Sand Drain

3.4 Backwash Initiator Device

While the experiments examining the filter under severely clogged conditions showed backwashing to be possible, the team has designed a backwash initiator device that can be used in the scenario that the filter is unable to backwash. This would mean that if the sand bed is unable to fluidize, the operator can turn a shaft within the filter by rotating a handle on top of the filter, and creating a long channel up through the sand bed. This will form a preferential flow path for the influent water to travel up the bed, eroding the sand, and allowing the bed to fluidize. The implementation of the design involved replacing the filter's cap in order to accommodate the initiator's through-wall fitting. The device can be seen in 3 below.

Figure 3: Square Rod Backwash Initiator

3.5 Fluidization Bed Tester

In the pilot scale model, the level of fluidization during backwash is determined by watching the sand bed height rise to a certain level in the clear PVC filter. Due to the difficulty of procuring clear PVC in both India and Honduras, this method needs to be changed. A couple of options have been considered, and one has been selected for testing. Among those considered were a series of push-to-connects and tubes that would be configured to allow a metal rod to be moved around in the bed. The connection through the filter would use a push-to-connect fitting. The metal rod would need to be smaller than the tubing and the fitting to allow movement for fluidization testing. The concept is that if the rod can move easily, the sand is fluidized. The system would also need to be capped off on one end to maintain the air- and water-tightness of the filter. A second option with a similar concept used a Fernco fitting and PVC pipes instead of push-to-connects and tubes. The third option would be to install one or two pieces of glass on the filter. There should be sufficient light to illuminate the media within the filter so that the operator can see the sand's movement. This option requires the local fabricator to be able to cut and seal holes for the glass on the stainless steel structure. One idea that was tested and was not successful was a 1/8" brass rod inserted through a push-to-connect bulkhead, and sealed with a 1/2" rubber rod. This design can be seen in 4. As it turned out, the brass rod was too flexible, and the rubber rod was too stiff to make this a tenable solution. The final option, which has been implemented successfully, is a ball rod attached to the sand filter using a Jaco connection, which can be seen in 5 below.

Figure 4: Brass Rod Fluidization Tester

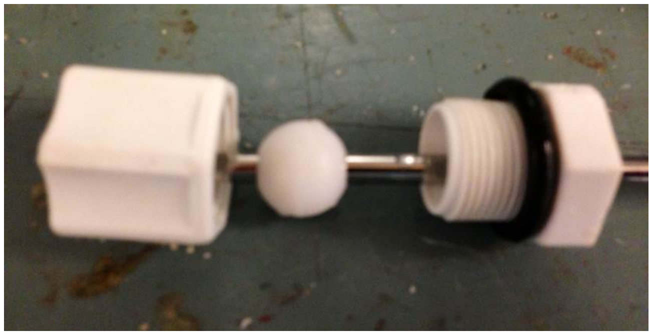

Figure 5: Ball Rod Fluidization Tester

4 Analysis

4.1 Backwash Under Clogged Conditions

The filtration system has consistently demonstrated an ability to backwash effectively while clogged. To test this, filtration was run with very high turbidity, coagulant-dosed water (approximately 500 NTU with 20 mg/L of PACl) until the filter accrued at least 40 cm of head loss. Head loss measurements were zeroed at the start of filtration. For these trials, clogging took between roughly 40 and 60 minutes to achieve. Upon reaching the 40 cm mark, the filter was considered clogged, and backwash was attempted. During backwash, excellent fluidization of the sand bed was achieved, and there was very good removal of clay accumulated in the media. Turbidity measurements of the backwash slurry were beyond the measurement capabilities (1100 NTU) of the MicroTOL turbidimeters used. Within 15 to 20 minutes of backwashing, the turbidity of the water visible within the filter and leaving as effluent had returned to that of the tap water.

The clogging time for the filter has had some significant variation. Initially, the filter took 65 minutes to clog with inlet turbidity of about 450 NTU and 10 mg/L of PACl. The second clogging time was about 48 minutes with an inlet turbidity of 500 NTU and 10 mg/L of PACl. The third time was even shorter with a clogging taking 42 minutes with inlet turbidity of 400 NTU and an undefined coagulant dosage. The coagulant dose is unknown, because the entire coagulant stock tank (over 2 liters of 1 mg/L coagulant solution) was poured into the filter while the filter was off. This happened when the team was replacing the tubing in the pump after realizing that, in order to achieve a coagulant dose of 20 mg/L, the tubing in the peristaltic pump needed to be changed. Previously, the pump had been equipped with size 16 tubing, which allows for a maximum flow rate of 79.8 mL/min with the peristaltic pump. This maximum flow rate equates to roughly 10 mg/L given a 1 mg/L solution, and an assumed flow rate of 8000 mL/min in the entire filter. Thus, a dose of 20 mg/L requires a flow rate of about 160 mL/min. In order to achieve this flow rate, the size 16 tube was replaced with size 18 tube. While the replacement operation was successful, overall, the team forgot to close the valve to the coagulant stock. Without the peristaltic pump holding the coagulant back, the entire tank dumped into the filter, and it took 42 minutes to achieve 40 cm of head loss. Finally, the most recent trial took only 39 minutes to clog the filter with similar turbidity of 500 NTU and 20 mg/L of PACl. This trial even exceeded the typical 40 cm of head loss to 45 cm. A summary of this data can be seen in 1 below, and graphed in 6.

Table 1: Clogging times with various turbidity and coagulant doses

Date	Time to Clog	Influent Turbidity	Coagulant Dose	Head Loss
7/12/13	65 min	450 NTU	10 mg/L	41 cm
7/15/13	48 min	500 NTU	10 mg/L	40 cm
7/15/13	42 min	400 NTU	N/A	40 cm
7/16/13	39 min	500 NTU	20 mg/L	45 cm

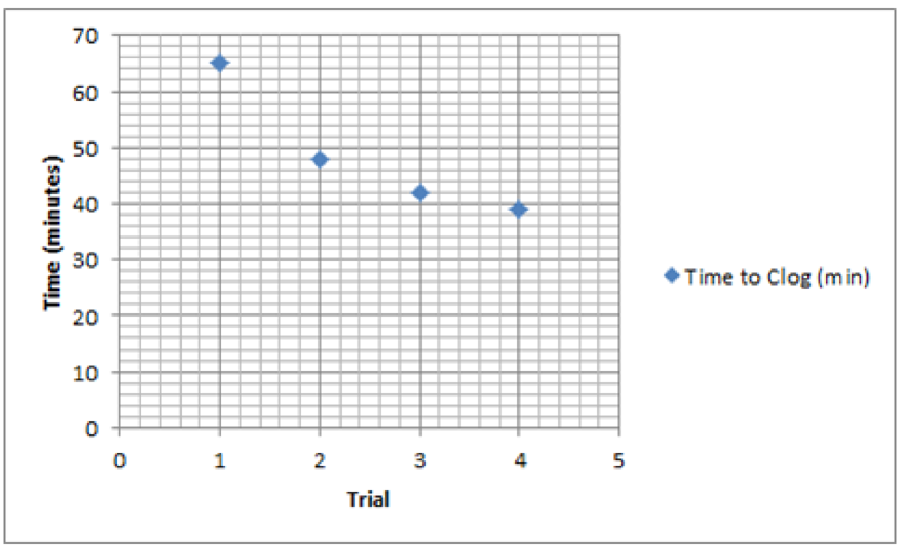

Figure 6: Clogging Time in Sand Filter

There are a few potential explanations for why the filter is clogging slightly faster with each new trial. First, it may be that the overall head loss in the filter has increased after each filtration and backwash cycle, resulting in a higher initial head loss for each trial. This could be due to clay and coagulant left behind in the system after backwash, which seems like the most likely cause. If this is the case, it would change the flow rate provided by the sump pump over time. A look into the change in flow rate due to this change in initial head loss may be necessary. With every reduction in system flow rate, the constant flow rate of coagulant would become higher in proportion to the system flow rate, resulting in an overall greater concentration of coagulant in the system. A higher coagulant concentration corresponds with larger floc sizes, which would be more likely to clog the filter. The other possibility is that the filter does not have significant residual effects from previous trials, and the increase in both coagulant and turbidity are the main contributors to faster clogging time. If this is the case, then it appears that the coagulant dose has a greater affect on the clogging time than the inlet turbidity (clay dose).

4.2 Sand Drain

The sand drain installation on the pilot scale LFSRSF initially posed some difficulty, as it was a challenge to get the through-wall coupling to seal correctly. A 1/2" fitting is slightly large for a 4" diameter pipe, so the seal was not easy to make. In order to get a proper seal, a through-wall coupling with better threads, and a thicker (3/16") O-ring were purchased. The seal worked well after this point.

Once the filter passed water-tightness tests, it was filled with sand. After a filtration run, the filter was run in backwash mode. When fluidization was achieved, and the backwash initiator and fluidization tester had been tested, the sand drain was tested. The sand drain demonstrated very good results. Once the valve was opened, the fluidized sand flowed readily out of the sand drain. Sand did not clog the horizontal section, and the flow was very constant. Additionally, the sand drain caused all of the sand to exit the filter so that only water was left in the filter.

During draining, the team tested a method proposed by Dr. Weber-Shirk: enable the valve to be opened and closed during draining by plugging the drain, and allowing the sand to settle away from the valve. Upon first inspection, this idea did not appear to work. Even though the water in the drain pipe was clarified temporarily, sand rushed in after a few seconds, and the valve was ruined when the team tried to close it.

Originally, the team suspected that this effect was due to gravity causing the dense sand to displace the less dense water out of the tube. A discussion with Dr. Weber-Shirk caused the team to question this assumption, and further testing was performed. During this testing, special care was given to ensure that the tube was totally plugged so that no water exited the tube. When this seal was carefully made, sand settled in the drain, filling most of the vertical section, and occupying roughly half of the horizontal tube's cross-section. When even a little leak was allowed in the plug, the velocity in the drain was sufficient to transport sand and cause the drain to fill with sand. It is likely, then, that the first tests did not have a complete seal on the drain. A perfect seal is somewhat difficult to achieve, as sand particles easily get between the plug and the tube, preventing an adequate seal.

Based on these findings, it appears that this sand drain design is a viable option, as it transports sand effectively and reliably. Additionally, a ball valve appears to be feasible, provided that an adequate seal can be provided to interrupt draining when needed. Because the drain will be scaled up in terms of flow rate and diameter, it may be good to consider a more suitable drain than the palm of a hand. Due to the interference of sand, a sufficient seal proved hard to obtain with only a 1/2" diameter sand drain. In designing the sand drain, it would be good to ensure that there is a sufficiently long length of tube after the valve. When drainage is first initiated, there is a high content of sand in the effluent. When the drain is plugged, a column of sand settles in the tube, and fills more than three-quarters of the height of the tube. Thus, it is important that the tube be long enough so that the remaining fraction of the height of the drain (including the valve) be free of sand when sealed. When less sand remains in the filter, there is a corresponding decrease in the proportion of sand in the effluent flow. When the drain is plugged at a later stage in drainage, the settled sand column may only reach half or less than half of the vertical drain height.

4.3 Backwash Initiator

Two tests have been conducted using the backwash initiator thus far. The first trial was simply a backwash with no prior filtration. This test provided an interesting component to the trial as the sand in the filter had just been replaced and was not completely settled. With this unsettled sand there were gaps in various portions that allowed a clear sight of the dirty water within the filter. As the backwash initiator was turned and the square rod displaced sand, it was observed that the water within the pores of the unsettled sand began to move upward and toward the rod with a conic motion. Although the rod did not make the sand fluidize immediately, the conic motion of the water toward the rod is seen as evidence that the initiator was successful in creating a preferential flow path to assist backwashing.

The second trial was conducted after running filter mode until there was 70 cm of head loss. While backwashing, the initiator was turned and inlet manifold valves were closed one by one from top to bottom. It was observed that the sand near the rod fluidized before the sand on the opposite side of the rod at each layer as each manifold was closed. This may indicate that the initiator has a direct influence on which side the sand fluidizes first. However, the rod is also on the half of the filter where the inlet mainfolds enter the filter, so this could be another explanation as to why that side of the filter tends to fluidize first. The backwash initiator can be placed on the opposite side of the filter to test whether this difference in fluidization times for the two halves of the filter is due to the rod or the inlet manifolds.

While backwashing, there tends to be a plug of sand that begins to move upward. This usually occurs when some of the upper valves are closed. When this phenomenon happened, the initiator was turned, and the plug was instantly broken up and settled. This could be a result of change in radial pressure as the rod is turned. It could also be that the preferential flow path created by the initiator causes the plug to erode rapidly.

Theses observations give evidence that the square rod backwash initiator is a practical solution for assisting backwash.

4.4 Fluidization Tester

The ball rod fluidization tester was placed into the sand drain, and a single test

was conducted on it. The Jaco c[illegible]onnection to the ball rod needed to be tightened to the point where it became water tight, making a seal with the ball itself. While making a strong connection and maintaining its water-tightness, the ball was unable to move as freely as desired, requiring a lot of force to wiggle the rod. This was not able to give the operator sufficient range of motion to determine whether or not the bed was fluidized. However, a design where a weight would be placed on the outside of the rod may still be applicable if the right balance is found. This size of the weight needs to be small enough to not influence the rod while the sand bed is intact, but great enough to move the ball by gravity during fluidization.

Although the connection did not enable an operator to have complete range of motion and feel inside the filter, there are still two differences that an operator could observe with the rod. While the sand bed is intact, the rod can be slightly moved. An operator would both be able to feel the rod overcoming the weight of sand, while also hearing the grinding. During fluidization, the rod will not grind through the sand, but will rather move more effortlessly, therefore eliminating both the feel and sound that one may experience with an intact sand bed. These circumstances can also be observed with the backwash initiator, but with the initiator it is less clear if the bottom of the filter has been fluidized, as the operator is feeling the resistance of entire depth of the sand bed.

These observations could be used in the field as a temporary test, but a more precise and smooth device should be conceptualized.

5 Conclusions

The majority of the team's work has been devoted to testing, maintaining, and troubleshooting the filtration system under suboptimal conditions, specifically very high turbidity and the resultant clogging. This work was to help ensure that the filter can operate effectively in the field under a range of difficult conditions that may be encountered. While the filter was able to backwash itself successfully, there is reason to suspect that, over time, backwashing may become more difficult over clogging cycles. A solution for this problem might be found in the backwash initiator. The initiator, in case of difficulty initiating backwash, is capable of creating a preferential flow path. The sand drain, also, appears to hold significant promise for application in the field, though more work is needed to control the flow of sand during drainage. Further work must also be conducted to improve upon the fluidization tester, which is only partially functional at this stage. Ongoing work will emphasize simple, reliable solutions to challenges encountered with the filtration system.

6 Future Work

6.1 Testing the Summer 2013's Design Add-ins

While initial testing has been conducted on the three new add-ins, further investigative work is necessary to confirm the efficiency, reliability, and ease-of-operation of the new additions. For the backwash initiator, alternating the side of the filter it is on, with respect to the inlet manifolds, might prove useful in determining whether it influences where fluidization first occurs. Also, it would be helpful to try, if possible, to clog the filter to a point where it cannot be backwashed by conventional means. This would provide an opportunity for the backwash initiator to prove its merits. As for the fluidization tester, the design will need to be improved to increase the range of motion possible, as well as the ease of motion. An entirely new design may be necessary. For the sand drain, investigations should be conducted to determine the optimal length of tube that should extend past the bottom of the valve so as to make plugging the drain an effective way to close the valve. Also, it would be useful to examine whether it might be possible to clog the sand drain.

6.2 Sand Filter Prototype Replacement

The current clear PVC pipe is beholden to several leaks because of the numerous holes that have been drilled into it throughout the course of its use. In the future, it would be helpful to replace the 4" PVC trunk of the sand filter. When replacing the trunk, it would be particularly useful to cut the trunk in half, and connect it by flanges, as suggested by Paul Charles. This would make it easier to disassemble the filter and to make changes to the inside of it. Under the current configuration, the installation of the sand drain was very challenging because of the limited access to the filter's interior.

6.3 Additional Tasks

At the beginning of the term, the Summer 2013 LFSRSF team had been charged with a large number of tasks, including but not limited to: designing and testing a sand bed height tester to be used for opaque filters in the field, making slotted pipe manifold design, and testing the clogging of the slotted pipes at high coagulant dosages and low turbidity. While the summer team was unable to complete these other challenges due to time constraints, they could be important future ventures for the LFSRSF team.