Spring 2014 Report

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Abstract

The Low Flow Stacked Rapid Sand Filter (LFSRSF) is a scaled-down version of the AguaClara Stacked Rapid Sand Filter (SRSF). Similar in theory of operation to the SRSF, the LFSRSF is optimized to treat smaller flow rates of 0.8 L/s. The current LFSRSF design in India uses multiple valves to switch from filtration to backwash; the LFSRSF research subteam at Cornell seeks to reduce the number of valves by designing a filter that uses hydraulic controls. In detailing the teams work this semester, this report seeks to accomplish three main goals: to document the design process for such a filter, to document the fabrication process to facilitate easy technology-transfer to India, and to document filter performance as tested to date.

This semester, the team calculated appropriate design specifications for slotted manifold, trunks, plumbing systems and sand for the filter, as well as created a unique flexible-tubing derived sand drain. The team completed all fabrication, and also set up a water-recycle and leak containment system to support testing, as well as a pressure sensor array to test flow-distribution between sand layers. The team then solved multiple water- and air-leak issues. Ultimately, the team was successful in ensuring that the LFSRSF backwashes easily, efficiently and whenever an operator may so desire.

Teams working on the project further must tackle three major issues: the current filter cannot handle backwash flow rates greater than around 0.6 L/s, its entrance and exit tanks need to be raised, and the filter also faces significant challenges of larger-than-expected head loss during backwash. Once these issues are solved, the hydraulically-controlled LFSRSF shall be truly ready to be deployed in the field.

1 Introduction

Clean water is a commodity that is often taken for granted by those living in developed countries. Yet for people of developing countries who are less fortunate, clean water is a hard to come by luxury. AguaClara, an engineering-based project team at Cornell University, seeks to bridge the gap by providing high-performing, low-costfiltration systems to developing countries. AguaClara began designing municipal water treatment plants for small towns in Honduras in 2005 and for villages in India 2013. Over the past few years, they have worked with Agua para el Pueblo in Honduras and AguaClara LLC to provide gravity powered filtration systems to several thousand rural community members. The Low Flow Stacked Rapid Sand Filter (LFSRSF) team is focused on designing a stacked rapid sand filter that is best suited for servicing flow rates of around 0.8 L/s. This is ideal for the implementation of filters in India, where the filtration system is servicing villages with fewer than 500 inhabitants. This semester, the team completed the filter design including simplified hydraulic controls and a sand drain and began testing the ability of the filter to switch between modes.

2 Literature Review

2.1 Low Flow Stacked Rapid Sand Filter Fall 2013 Report

The report from Fall 2013's 30 cm diameter filter subteam details the construction processes involved in fabricating the 30 cm filter, as well as key equations that govern flow and head loss through it. The calculated head loss through the main filter column will inform the design of plant components like the sand drain and slotted manifolds. Preliminary calculations related to the flow distribution through various filter layers detailed in this report are also notable.

2.2 "Novel Fluid Control System for Stacked Rapid Sand Filters" and "Stacked Filters: Novel Approach to Rapid Sand Filtration"

These papers, published in the Journal of Environmental Engineering in 2013 and 2012 respectively (corresponding author: Monroe Weber-Shirk) describe the operation of an AguaClara Stacked Rapid Sand Filter (SRSF) and the fluidic controls it employs 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. The LFSRSF is a closed column, unlike the SRSF that is open to the atmosphere, and does not use the siphon system in use in the SRSF. However, like the SRSF, 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 LFSRSFs being built in India, and assist in the development of a simplified way to initiate backwash.

2.3 Fluid Mechanics, 7th edition by Frank M. White

This textbook offers basic information on fluid mechanics theory and application. In reference to our project, chapters on pressure distribution in fluids, pipe flow, and flow through porous media are especially important.

2.4 Lecture Slides, CEE 4540, Sustainable Municipal Drinking Water Treatment, Monroe-Weber Shirk, Cornell University

A portion of these slides discuss AguaClara LFSRSF technology, and many of the mechanisms mentioned in the paper above. The Karman-Kozeny equation, the rationale for using 6 filter layers of a depth of 20 cm., and the relation of pipe stub heights in the inlet and exit tanks to filtration and backwash modes is well explained in these slides: all of these are critical elements to the LFSRSF as well.

3 Previous Work

The LFSRSF team is currently constructing a 30 cm filter that will eventually be used for research and testing. Its design is based off of LFSRSFs currently being constructed in India. A main purpose of the new design was to simplify hydraulic controls and reduce the design to only include one valve on the backwash pipe. This design also needed to have a separable filter column in order for the slotted manifold branches to be attached. An obstacle the team worked to overcome last semester was creating an alternative to buying 30 cm caps and gaskets for the main filter column as they are very expensive. Thus, the team decided to create a strong, watertight mechanism to connect the caps and for any other connection type needs. 1The caps were made of circular PVC plates that would connect to the main filter column using the gasket, shim stock, and hose clamp connection. For the entrance and exit tanks, the team used a 15.24 cm diameter PVC pipe and the same capping method described previously to create an entrance and exit tank that would meet the max height requirements they calculated they would need. Previous team members also designed a method for attaching the entrance and exit tanks to the filter column with flexible PVC tubing and barbed-to-male adapter fittings; they drilled holes for the barbed fittings with a hole saw and inserted them into the side of the filter, but did not finish attaching the PVC tubing.

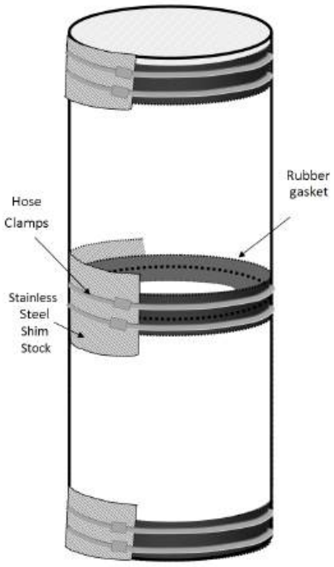

Figure 1: Filter Column in Two Parts. The team devised a method of creating a filter column that can be separated into two pieces so that slotted manifolds and other pipe fittings may be more easily added to the interior of the column. These two separable pipe pieces are joined with a combination of rubber, steel, and hose clamps. The top and bottom of the filter are held on with the same mechanism.

4 Filter Construction and Design

For the first part of the semester, the team focused on designing and building the filter, with the goal of beginning testing of filter components before the semester was through. Major design and construction challenges included the slotted manifolds, manifold trunks, and sand drain. The construction phase was completed several weeks before the end of the semester.

4.1 Manifold Trunks

The team machined seven PVC pipes, six 2.54 cm (1 in) in diameter and a seventh 5.08 cm (2 in) in diameter, to act as manifold trunks. Each pipe was cut to slightly less than the inner diameter of the 30 cm filter. Because the backwash manifold trunk attaches to a coupling that is glued into the side of the filter column, however, it required some special consideration, unlike the other manifold trunks, which are screwed in through the wall of the filter column and more easily inserted and removed. (It should be noted that the LFSRSF team does not recommend gluing these fittings in future filters: instead, all of the fittings should be screwed together through the filter column wall.) The backwash manifold trunk must be cut to a slightly shorter length than the other manifold trunks. Even when approximately 0.635 cm had been cut from the end of the trunk, the trunk was still too long to slide easily into the coupling in the filter column side (see left, 2). Thus, the team decided to angle the pipe on one side, cutting off an arc with width approximately 0.318 cm to create a slanted edge (see center, 2) that could then be easily slid into the coupling without requiring the further reduction of available area for the branches insertion.

Figure 2: Backwash Manifold Trunk The backwash manifold trunk was cut at a slight angle (center) so that it could be inserted into the coupling already glued in the side of the filter column. Before it was cut it did not fit into the filter (left), but after, (right), it fit with ease.

4.1.1 Manifold Trunk Caps

The team purchased six 2.54 cm caps for the six 2.54 cm trunks and one 5.08 cm cap for the backwash trunk. The 2.54 cm and 5.08 cm caps had approximately 2.159 cm of length cut from their ends to ensure enough space to attach the manifold branches. These measurements were determined with calipers, tested on pipes of appropriate diameter, and finally implemented after they had proved successful.

The cap for the backwash manifold trunk proved to be a special case, since even the cut cap extended too far along the length of the manifold trunk, blocking a portion of the pipe where manifold branches were meant to be inserted. To allow for a hole for this branch, small semicircles of slightly more than 1.27 cm in diameter were cut from the cap using a bandsaw. These semicircles are diametrically opposite each other, since the slotted manifold branches must extend from both sides (see 3).

Figure 3: Backwash Manifold Trunk Cap The backwash manifold trunk's cap had to be machined so that the pipe could have enough length to comfortably fit eight slotted branches. Small semicircles were cut in the sides of the cap to facilitate the insertion of the slotted pipes.

4.1.2 Attaching Trunks to Filter Column

The process of attaching the trunks to the filter column was vital to ensure that there where no leaks once the filter was run. To accomplish this the the team followed a systematic process in which rubber O-ring where alighned with the holes in the filter column. This alighnment was done within the filter column, thus the O-ring would make a seal betwen the coupling on one end of the trunk and the inner pipe wall. The manifold trunk would be lowered and alighned with the O-ring. Once this was done the barbed threaded coupling would be inserted from the other end of the hole and the O-ring would be between the trunk coupling and the pipe wall. The barbed coupling would then be tighten (whithout roating the trunk) to have a tight seal between the O-ring and the inner pipe wall. This method proved to prevent any leaks in this component of the system.

4.1.3 Note on the Backwash Manifold Coupling

Even though the backwash manifold trunk was machined to better fit into the filter column (3), it was still a tight fit to insert it into the filter column, especially after the manifold branches were added. When trying to remove the manifold trunk from its coupling by pulling it up and out of the filter (after having successfully done so many times in the past) the team exerted too much torque on the coupling and a sizable piece of the coupling snapped off. The team was able to reglue the coupling with PVC primer and braced the reattached coupling piece by securing it with a hose clamp. The team is optimistic that this coupling will not leak (in any case, it is on the inside of the filter) nor be a future cause for concern, but it is nevertheless worth noting that the method of glueing a coupling through the filter wall carries the possibility of this mode of failure. This reinforces the team's recommendation that future filter designs screw threaded fittings together through the filter wall instead of gluing fittings into the filter wall. Using threaded fittings is more sustainable since they allow filter components to be more easily repaired, replaced, or removed , and slotted manifolds may be inserted more easily without the exertion of undue torque.

4.2 Manifold Branches: Design

The team worked on designing the slot length required for manifolds in the backwash branches and other filter branches. While the team was initially in the favor of using estimates for slot lengths as 30% of pipe circumference to quickly buy slotted manifolds without a careful examination of the code, they decided to invest the time and effort to rework the SRSF design code and build a clearer and more precise design for the LFSRSF. This exercise was complicated by the fact that the SRSF design algorithm did not include checks for the lower flow rates of the LFSRSF, and was consequently outputting negative values for slot lengt. The LFSRSF team thus re-coded the SRSF algorithm to include this check, and also provided the AguaClara Design Team this improved algorithm. A summary of the major design methods used is provided below:

4.2.1 Manifold lengths and placement on trunks

Manifold branch lengths in a square SRSF are all equal; thus the length on each manifold available for slots is relatively trivial to determine. In the LFSRSF however, the circular cross-section implies different manifold lengths. Minimum spacing between branches and branch diameters are user-defined inputs to the code, calculating the maximum number of branches that can fit on one side of a trunk is the first step:

$$N_{BranchMax} = floor\left[\frac{innerdiameter(ND_{FiBody}) - L_{FiTrunkA}}{outerdiameter(ND_{FiManBranch}) + S_{FiManBranch}}\right] \tag{1}$$

With a choice of nominal diameter of the manifold branches $(ND_{FiManBranch})$ =1.27 cm (0.5 in) , and a center to center spacing between these brances of $B_{FiManBranch} = 5cm$, (implying $S_{FiManBranch} = 3.73cm$), and $L_{FiTrunkA}$ =5.7 cm (the space required to join the trunk to the filter body), the maximum number of branch manifolds on side of a trunk is 4; thus 8 manifolds in total are on a trunk.

The correct spacing between branches is then recalculated by essentially rearranging equation 1 to give a between-branch spacing of $S_{FiManBranch}$ =

4.018 cm and center to center spacing of $B_{FiManBranch} = 6.152$ cm. Note that as the backwash and filtration trunks have the same diameter of branches (1.27 cm), the same values hold for the backwash trunk. The final arrangement of the branches on a trunk is shown in Figure 4)

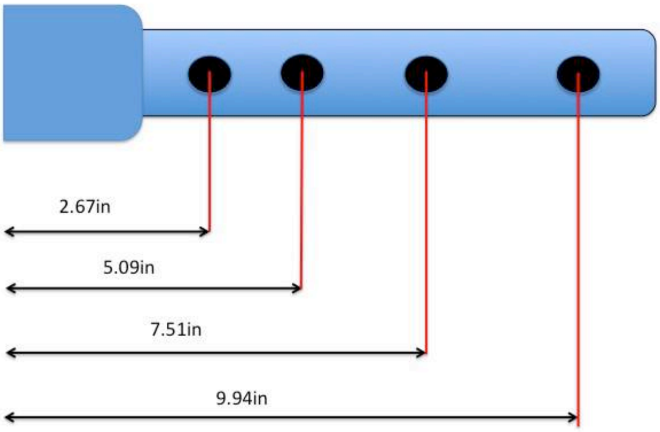

Figure 4: Trunk with Slotted Manifold Positions

Once the exact locations of the branches were found, the length of each branch was found using the intersecting chords formula (Figure 5), where one of the chords was the circle's diameter.

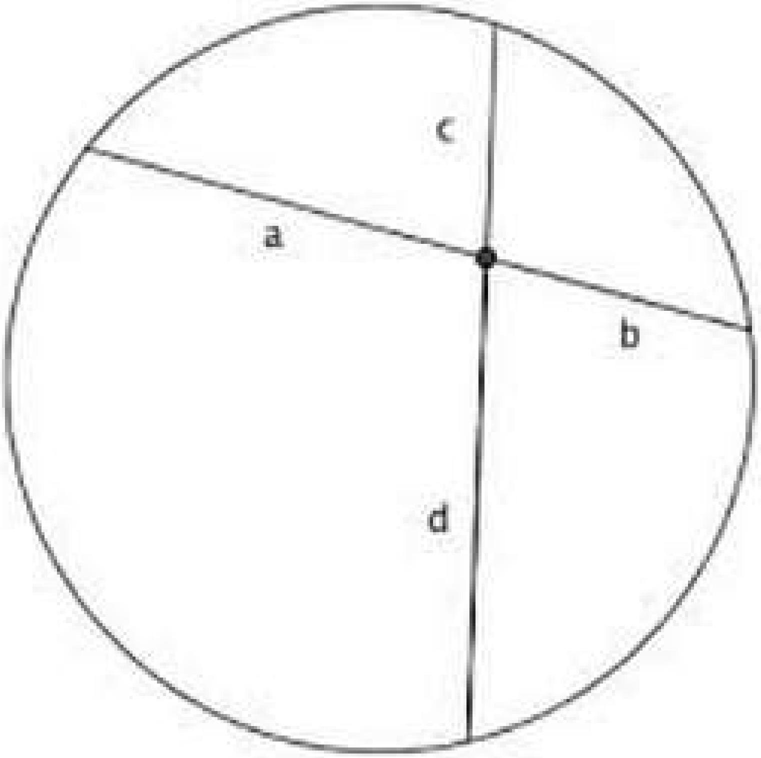

Figure 5: Intersecting Chords Theorem: $a \cdot b = c \cdot d$

For each manifold, the length of each branch (excluding the space taken up by the trunk itself is provided below. For the filter backwash branches, these lengths are:

$$L_{FiBwManBranch} = \begin{matrix} 3.481 \\ 4.639 \\ 4.449 \\ 2.860 \end{matrix} \; in$$

For the filter trunks, these are:

$$L_{FiManBranch} = \begin{matrix} 4.011 \\ 5.196 \\ 4.979 \\ 3.390 \end{matrix} \; in$$

The team decided to use a single manifold that extends through the trunk to serve as two branches, i.e, to eliminate the use of tee connector joints (Figure

6).For the exact length that each single manifold had to be cut to ($L_{Manifold}$), the lengths above were adjusted by the height of the caps dome ($L_{CapSpace} =$ 1.5875 cm (5/8in) and the outerdiameter of the trunk:

$$L_{ManifoldsToCut} = L_{FiManBranch} - 2 \cdot L_{CapSpace} + outerdiameter(ND_{FiTrunk}) \tag{2}$$

This gives a matrix of manifold lengths as follows:

$$L_{ManifoldsToCut} = \begin{matrix} 8.275 \\ 10.59 \\ 10.21 \\ 7.033 \end{matrix} \; in$$

Note that manifolds for the Backwash trunk are to be cut to the same length, they will simply have a larger fraction covered by the trunk.

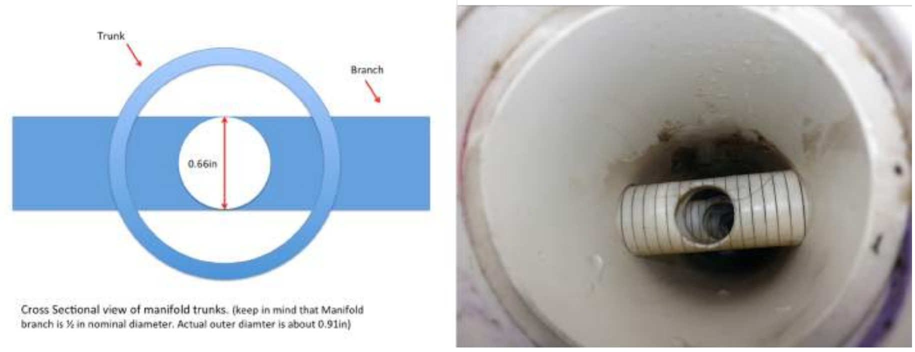

Figure 6: Cross Section of Manifold Trunk with Branch The manifold trunk branches were milled in order to allow water to pass through the trunks with less obstruction. The design for the manifolds and their branches is shown at left, while the actual manifolds as they have been implemented are shown at right.

4.2.2 Manifold Slot Design

The length available for slots $L_{Manifold}$ was adjusted by the amount of pipe length covered by the cap ($Pi_{Cap} \cdot L_{CapHeight}$, where Pi_{Cap} is 0.7 - the percentage of cap left after sawing some of it off, and $L_{CapHeight}$ is the height of a cap = 1.024 in). This calculation has to take into account differences in backwash and other filter trunk diameters. The total available length for slots on both sides on a filter trunk (i.e, 8 branches) was calcualted to be 74.53 cm. For the backwash filter trunk, this value was 63.71 cm.

The design algorithm for calcualting slot length works as follows: it calculates minimum slot head loss based on pressure recovery in the backwash manifold during backwash. It then calculates the amount of slot area required that will provide this head loss. Based on this area and the available length of manifold branches, it calculates the length of slots required to achieve this head loss, under the constraint of a 0.2 mm wide slot and a 0.3175 cm (in) spacing between slots (the minimum allowed by the manufacturing company to ensure structural stability of the pipes). . If the returned curved length of slot is greater than 40% of the inner circumference of the branch (Pi_{Slot}), a while-loop increases the head loss by 0.05 cm, goes through the steps described above, and checks the length of the slot. The loop goes through this process until it arrives at an acceptable slot length. We chose a 40% threshold to ensure that at least 20% of a double-slotted pipe would remain for structural integrity purposes. As it turns out, we achieve a greater margin for Pi_{Slot} for the filter pipes, as we have a greater length of manifold branch pipe available due to the smaller trunk diameter (2.54 cm as compared to 5.08 cm for backwash)

For our system, the curved inner slot length for the backwash manifolds is 1.99 cm (0.783 in), with a total backwash design-head loss in the backwash slots of 14.38 cm. The design-head loss during forward filtration through these slots is 2.5 cm (this also the design head loss through all slots supplying a sand layer during forward filtration). The final geometry of the backwash branch manifold slots is shown in Figure 7

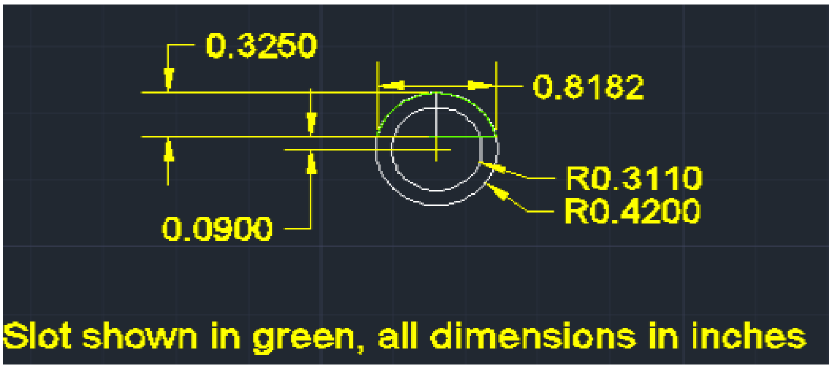

Figure 7: Final Specifications of Backwash Manifold Slots. Note that slot width is 0.2 mm, and spacing is 0.3175 cm (1/8 in)

To design the filter manifold branch slots, the algorithm calculates head loss through the filter slots, using the fact that the total area of these slots is twice that of the backwash slots (as the middle trunks of the filter serve two layers each). As flow is 1/6th of the plant flow in each layer, we do not face problems of head loss and slot length as we did for the backwash piping. Nevertheless, a manual check was included to ensure that the curved length of a slot was less than 40% of inner branch diameter. For the filter branches, an optimal curved inner length of a slot was calcualted as 1.699 cm (0.669 in, to cause a total design-head loss through all slots on a trunk (serving two filter layers) of 2.497 cm. The final geometry of the filter branch manifold slots is shown in Figure 8

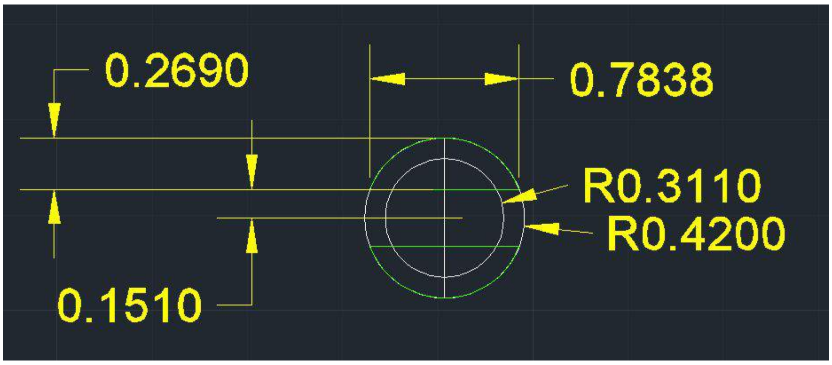

Figure 8: Final Specifications of Filter Manifold Slots. Note that slot width is 0.2 mm, and spacing is 0.3175 cm (1/8 in).

Based on the calculations described in this section, the team ordered manifolds as described in Table 1

Trunk	Length (ft)	ND (in)	Rows	Slot Chord Length (cm)
Backwash Trunk	8	0.5	1	4.618
Inner Filter Trunks	21	0.5	2	1.994
Top Filter Trunk	8	0.5	1	1.992

Table 1: Order of Slotted Manifolds with BigFoot Manufacturing Co. Spacing between slots is 0.3175 cm, and slot width is 0.203 mm

4.3 Manifold Branches: Assembly

Using calculations from the above section (Figure 4), the manifolds were marked to the required specifications. The procedure used was a simple two-man task of marking crosshairs onthe pipe with a measuring tape, ensuring that the tape was level to the pipe. This process was repeated for each of the 7 trunks (Figure 9).

Figure 9: Marked Manifolds The manifold trunks, marked to the specifications of the new slotted manifold design code.These trunks were milled to afford the insertion of the slotted branches.

The next step in successfully completing the trunks involved milling the pipe at the locations marked. The mill ensured that holes drilled at one end would be aligned with holes drilled on the opposite end.

For the trunks, the drilling came in three steps. The first was the aligning stage, the second the drilling stage, and the third the milling stage. First, the pipe was clamped to the mill between two plates. Once it was clamped, the pipe would be very carefully removed as to maintain the right distance between the clamps. Then a special positioning bit was attached to the mill and used, in combination with the electronic measuring tool on the mill, to determine the exact center of the pipe. The special bit works by a mechanism in which once a certain (very small torque) is applied to the bit, the bit jumps; thus, as one approaches the end of the clamp with the bit one can mark the exact edge of the clamp and therefore the exact edge of the pipe. One can mark this location as zero and then move the bit perpendicularly to the pipe to the other end of the clamp to mark the position of the other edge. Next this calculated distance was divided by two and the drill bit could be moved to the exact center of the pipe, where its position was fixed. Once the drill was aligned along the center of the pipe, we could proceed to drill the holes where the branches would be placed. The pipes had all been previously markedwith the locations of the centers of each of these holes (4). The first marking on the edge of each pipe was drilled first, and then the mill's electronic measuring tool was used to measure the exact distance to the next location, accurate to 4 places after the decimal (in inches). The drill was very precisely moved 6.152 cm to the next location of drilling. The same procedure would be repeated until four holes where drilled. The drill diameter was, however, smaller than the diameter necessary to insert the manifold branches through. This was because the manifold branches need to fit tightly in the trunks. Once the holes had been drilled for one trunk, the drill bit was changed to an end-mill bit that could shave off a small part of the walls of the hole, making it just wide enough for the branches to fit through but also be tight in place. The same positioning tool was used to make sure that the new drill bit was aligned with the drilled hole. Figures 10 and 11 show this process, and Figure12 shows the completed drilling process.

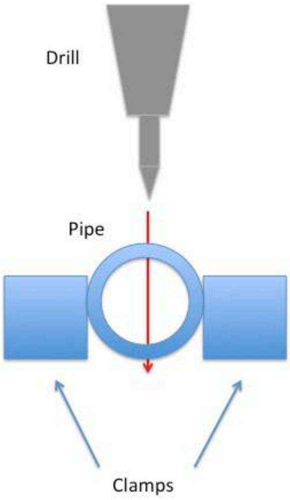

Figure 10: Schematic of the drilling process The manifold being milled is held in place by clamps, which do double duty in allowing the operator to locate the exact center of the pipe. Then the drill bit is lowered until the desired hole has been created.

Figure 11: Drilling the manifolds According to the process described in 10, the manifolds were milled to allow for the insertion of slotted branches. The slotted branches themselves were also milled in this way later in the construction process.

Figure 12: Drilling and Milling The manifold trunks were milled to allow for the insertion of the slotted manifold branches. These are the finished trunks before they have been filled with branches.

4.3.1 Manifold Branches

The LFSRSF received the final pieces for the construction of the manifolds from McMasterr.com, which included three types of manifold branches, the backwash manifolds, the top manifolds and the manifolds for the inlets in between. Each of the manifolds was measured and cut to the specifications dictated by the previos section. Once cut, each was marked at its halfway point where it would later be drilled (6). A drill bit of 0.66 in (21/32 in) was used to make the biggest hole possible without compromising the integrity of the branches. This was done for all the branches. The branches were inserted into the trunk and their holes aligned to minimize head loss.

It should be noted that the lengths of the manifolds were changed for the backwash trunk, in order to compensate for the involved motion and dynamics of attaching it to the filter. The branch lengths were reduced to 17.9 cm, 26.8 cm, 25.9 cm and 20.34 cm. (This will not need to be the case for future filters that use the screw threaded fittings for the backwash manifold as well.)

4.3.2 Slotted Manifold Caps

Each branch and trunk of the slotted manifolds must be capped with a PVC cap to ensure that the only flow through the manifolds is through their slots. Since there are eight 1.27 cm branches (four on either side of the manifold trunk) per filter layer, the team purchased fifty-six 1.27 cm caps. To minimize the slot area on the branches covered when the caps are attached, the team then investigated the possibility of modifying the caps to reduce their length. Using a bandsaw, the team determined it is possible to cut the cap down to a more manageable size, leaving only smaller areas of cap available for gluing. Ultimately, the 1.27 cm diameter caps had 1.21 cm cut off from their ends (see Figure 13).

Figure 13: Slotted Manifold Caps Caps were cut down to size to better serve the needs of the LFSRSF, keeping slot area open and available for water flow instead of obstructed by a large PVC part. 1.27 cm diameter caps had 1.21 cm (0.475 in, shown) cut from their ends.

The final assembly of the trunks and manifolds in the filter is shown in Figure 14

Figure 14: Completed Slotted Manifolds The finished slotted manifolds, assembled in the filter column. The manifold branches and trunks were cut to size, the trunks milled to allow for the insertion of the branches, the branches milled to allow for less obstructed flow through the trunk, and caps attached to the ends of the branches. Note that the filter is upside down (i.e., the trunk seen on top is the backwash trunk)

4.4 Flexible Tubing

To join the inlet and exit tanks to the side of the filter column, 2.54 cm (1 in) inner and 3.18 cm (1.25 in) outer flexible tubing was cut to size and inserted over barbed-to-male adapter fittings for the filter trunks, and a 5.04 cm (2 in) tube was added for the backwash trunk. Initially, the length of each piece of tubing was constrained by the distance between each pair of adapter fittings and by the stipulation that the tubing should curve gradually instead of kinking sharply to avoid any unnecessary constrictions of flow. In measuring the tubing, the team increased the length of the tubing at their discretion from the minimum distance between adapters until the tubing presented no visible bend. On one occasion, a piece of tubing that had already been cut started to kink, but the team was able to remove the constriction by hose clamping that section of the pipe to remove the kink. Once all of the pieces of tubing were cut and attached to the barbed fittings, they were further secured to the barbed fittings with the addition of hose clamps (see 15).

Figure 15: Flexible tubing Flexible tubing and hose clamps, both of 2.54 cm diameter, were used to connect the inlet and exit tanks to the side of the main filter column.

Later in the design process, the team realized the need for longer lengths of flexible tubing, lengths that would effectively form large U-bends, reaching almost to the floor. This is discussed in more detail in the Backwash Testing section.

4.5 Inlet and Exit Tank Pipe Stubs

Pipe stubs help to maintain correct flow exit and entry to the filter column during backwash and normal filtration, and are designed based on filtration and backwash head losses. They were cut to the specifications from the previous semester's work (see Figure16). However, during operation testing, the team realized the need to increase the pipe stub heights during backwash. Presently, pipe stubs in the entrance tanks are 34.95 cm for the top inlet, 47.7 cm for the next inlet, and 48.5 cm for the third inlet. The backwash pipe remains without a stub, as originally designed. The effluent weir stub in the exit tank is now 35 cm in length, and the waste weir extends above the tank, effectively closing that exit, as the waste weir has not been employed through current testing endeavors. It should be noted that these are current experimental heights, and further work is necessary to optimize their heights.

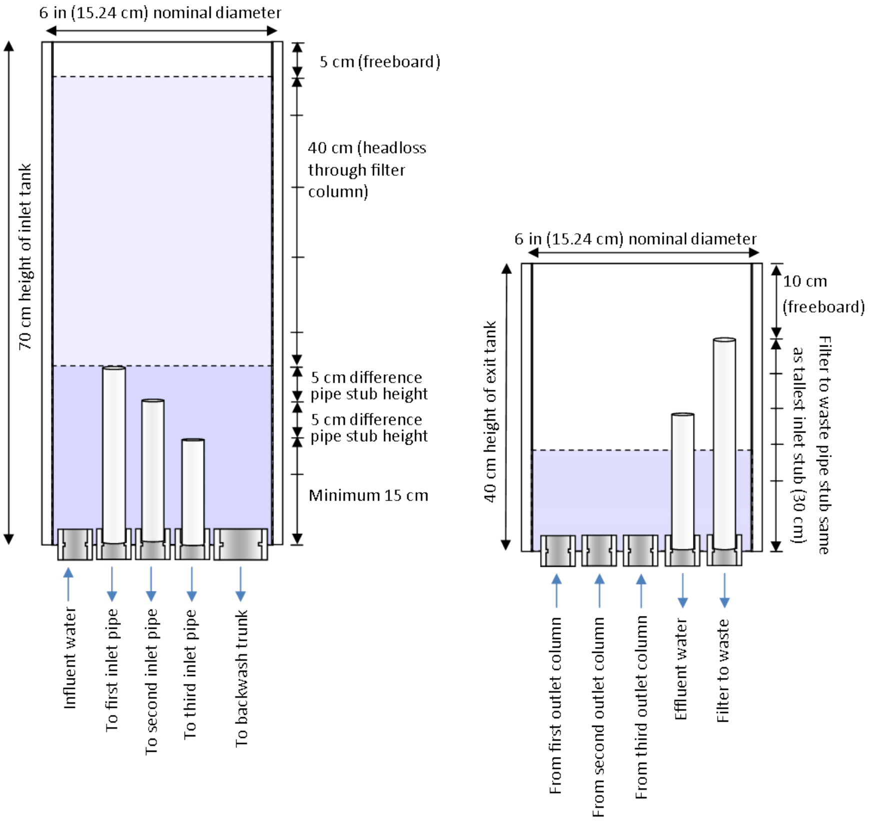

Figure 16: Original Pipe Stub Specifications

4.6 Backwash-to-Waste Pipe

The backwash-to-waste pipe was assembled from PVC pipe, a 90 degree elbow, a union, and a ball valve, all 3.81 cm in diameter. Pipe stubs of approximately 10 cm in length were cut from the PVC pipe and used to connect pipe components. The pieces were then joined using PVC primer and cement. The longest piece of the backwash pipe, a section of PVC which extends nearly the length of the filter column, was cut to a length of approximately 160 cm from a 3.81 cm diameter pipe. This length was determined by the height of the coupling on the side of the filter, with a length of approximately 10 cm removed from this total height to allow for the insertion of a bucket beneath the backwash pipe. This bucket is an important component of the water recycling system . The assembled backwash pipe was glued to the main filter column as described in 17.

Figure 17: Backwash Pipe The assembled 3.81 cm diameter backwash pipe. The backwash pipe (right) was attached to the main filter column (left), where it was glued using PVC primer and cement.

After backwash testing began, the backwash-to-waste pipe was slightly modified in its design to include a valve on the end of the longest piece of the backwash pipe. The motivation for this change is discussed in more detail in the Backwash Testing section. The team recommends that future filters incorporate a ball valve only at the bottom of this pipe, instead of having a valve above the union as well.

4.7 Filter Sand

A next step in the testing of the filter was to fill the main column with sand. Assuming that sand was filled to a height of 139.7 cm from the bottom of the filter, the team required ~100 L (152 kg) of sand to fill the column. The LFSRSF design uses sand with a d_{10} of 0.5 mm, and a Uniformity Coefficient of 1.6. However, the sand ordered from Ricci Sand was delivered as 0.45 mm with a UC of 1.4, which still suited team purposes.

In order to fill the filter column with sand, the team firstfilled the filter column with water up to the backwash pipe. This maintained the airtightness of the filter during sand addition, and moreover, prevented unwanted strain on the manifolds from the falling sand, allowing for a more even distribution of the sand. The sand was added in a circular motion along the cross section of the pipe to further ensure an even distribution, with consideration given to add the sand at a slow enough rate to prevent air from being trapped within the sand. The team introduced about 110 kg of sand into the filter column, approximately reaching the level of the top manifold.

4.8 Sand Drain

All filters require a sand drain so that they may be emptied of sand and water as necessary. However, this filter component has been associated with several challenges in the past. In previous semesters, teams working with smaller models of the LFSRSF experimented with different ways of closing the sand drain that allowed users to stop the flow when needed. Unfortunately, these various closing techniques, using everything from a ball valve to the palm of an operator's hand, did not provide an effective method of stopping the sand. In the case of the ball valve, sand infiltrated the seal and led to the malfunction of the valve. The use of the operator's hand, too, was exceedingly unreliable.

Recognizing the flaws of previous methods, the team developed a new approach to the sand drain design. The basic mechanism of this design involves stopping sand flow by raising a long piece of flexible tubing above the water level in the entrance tank. The sand can exit from the bottom of the filter though a 2.54 cm barbed fitting that is attached to 2.54 cm nominal diameter flexible tubing.This barbed fitting was inserted into the filter column wall in the space between the backwash trunk's coupling and the first branch of slotted manifolds. In the interest of time, the team picked this diameter based on hole-in-the-bucket calculations for a water column; however, the actual physics of the draining sand would involve considering the pressure gradient within the filter, the changing density of sand as it drains, and the falling head available in spite of the filter column's being full. The 2.54 cm diameter replicates the sand drains used in filters in India (though with flexible tubing set up in favor of a siphon arrangement). The team will perform detailed calculations regarding the sand drain as time permits during testing.

4.8.1 Sand Drain Attachment

A crucial aspect to the success of the newly designed sand drain is the mechanism that would be used to attach the tubing to the filter such that the end of the drain pipe is high enough for the water not to overflow during filtration. The team wanted to design an attaching method that would be affordable and easy to construct, yet strong enough to hold the piping when it is filled with water.

A large obstacle is attaching a clamp with a flat attaching surface to a rounded exit tank made of PVC piping. The team wanted to avoid screwing parts or gluing anything to the side of the filter at the risk of leakage or in case changes in placement are needed.

Somewhat inspired by vacuum attachments, the team joined a length of flexible tubing to rigid plastic tubing to form the sand drain. This join was accomplished with a slip-coupling-to-barbed-male adapter. The rigid portion of the drain was included to allow it to be more easily supported on the side of the filter column, since clamps might deform a flexible pipe. The flexible end of the tubing was attached to the filter by tapping a barbed fitting into the filter column (see 18). This fitting was inserted in the space between the manifold trunk and its first branch at the front of the filter, in an attempt to place the drain somewhere where it would not too directly impact the flow through nearby slotted manifolds.

With the sand drain thus assembled from rigid and flexible tubing, the team attached it to the exit tank using hose clamps and two spring clamps held closed by screws. The spring clamps were threaded near the base to allow for the insertion of the hose clamp band, which was tightened to keep the clamp in place against the side of the filter (see 19). The screws in the spring clamps can be unscrewed to loosen the sand drain from its supported position.

Figure 18: Sand Drain Barbed-to-Male Adapter The filter column was drilled and tapped to allow for the insertion of the sand drain's threaded barbed-to-male adapter fitting. This fitting attaches to the length of flexible tubing that comprises the remainder of the sand drain.

Figure 19: Sand Drain The completed sand drain is comprised of a length of flexible and rigid tubing supported by clamps.

As an added benefit, the team quickly discovered that this clear plastic sand drain simultaneously fulfills the role of a manometer. This has been invaluable in monitoring filter hydraulics during preliminary testing stages.

4.8.2 Using the Sand Drain

Emptying the filter (when it doesn't contain sand) via the sand drain is simple. The spring clamps supporting the sand drain against the exit tank are unscrewed and the rigid length of piping removed from its place against the filter. The flexible nature of the rest of the sand drain allow it to be easily directed into any of various drain locations, including into the sink, into the water recycling bucket, or even into the kiddie pool if necessary. From each of these locations, the water may either be drained directly (see 20) or pumped into the sink.

Figure 20: Emptying the filter through the sand drain The sand drain, with its flexible tubing, may easily be directed into the sink for draining. Once insufficient head remains in the filter to drain into the sink, the water can be directed into the recycling bucket and pumped into the sink.

4.9 Sensor Array

A pressure sensor array to measure flow distribution between the filter layers was added to the main filter column, with sensors placed perpendicularly to and halfway between the top inflow and outflow pipes. To do this, the team had to first bisect the distance between the inflow and outflow pipes using a compass (see 21). Valves to accommodate the pressure sensors were specially machined, then tapped into the main filter column. Pressure sensors were connected to successive filter layers through the brass valves, then connected to an input box so that their measurements could be logged.

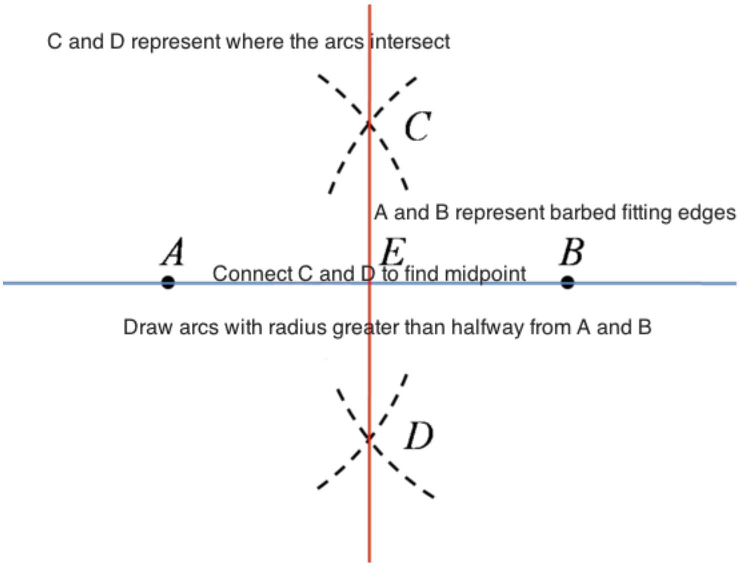

Figure 21: CompassBisection This method was used to determine the placement of the pressure sensors.

4.9.1 Placement of the Sensor Array

To draw a point level and perpendicular to the point of bisection, the team wrapped a hose clamp and used a level to make sure all the sides were level. Then, the outer diameter was used to calculate the circumference and a fourth of the circumference was the measurement used to designate a perpendicular mark, which is where the first sensor would be installed. After, a line was extended straight down from the first sensors placement using a level and the eleven other sensors were measured 10 cm apart under the first sensor.

The filter column contains 12 ports from which to gather data (see 22). As explained, the 12 ports are located on the lower section of the filter, a quarter circle away from the inlet and outlet pipes, and each port is placed 10 cm vertically away from each other (perpendicular to the cross-section of the pipe). This leaves an overall configuration where each port is 5 cm displaced from the center of the nearest inlet/outlet pipes. At each of these locations a 1/8 in threaded hole was tapped. A brass ball valve with a fine brass wire mesh soldered on to one side was screwed into each tapped hole. The wire mesh has separation of about 0.2 mm (0.007 in) preventing sand from leaking out of the filter through the sensor tubing. Thus, the brass valve will allow the removal of sensors without loosing water or sand. The other end of the brass valve will have a push-to-connect fitting where flexible tubes will then finish the interface between the pressure sensors and the filter column.

Figure 22: Sensor Array The filter column with all brass valves inserted. The filter column was tapped and these twelve valves inserted at regular intervals of 10 cm. The valves will soon be attached to pressure sensors and used to monitor flow distribution via differences in pressure.

4.9.2 Machining the Sensor Valves

As detailed in the previous section, the insertion of pressure sensors into the side of the filter requires specially machined valves. These valves must be soldered to mesh whose pore size is smaller than the diameter of sand. The team ran into unforeseen difficulty in the soldering process in that they did not realize that the brass valves contain plastic parts intended to maintain a watertight seal. Attempts to dismantle the valve to find an alternative site to solder, away from the meltable plastic, failed. Consequently, the team resolved to try to solder the mesh to the brass valve, despite the real risk of failure of the plastic seal, since all of the necessary materials were on hand. In the future, the team believes it would be easier to solder the mesh directly to threaded coupling which fit into the brass valves to avoid this complication. However, the trial run of soldering the brass valves was successful: when connected to a water source, the soldered valve successfully allowed and stopped water flow in appropriate succession. Thus, the team decided to proceed with soldering the valves, despite their plastic components (see 23).

After solderingexcess brass mesh was trimmed from the edges of the valve, and the threads deformed by the soldering process were cleaned by retapping . Teflon tape was wrapped around the rethreaded valves to create a more watertight seal between the valves and the filter column wall.

The team plans on testing the flow distribution of the filter column by measuring the pressure of the water through valves that were installed along the side of the filter column. These valves are spaced at a right angle from the inlet and outlet pipes and at a distance of 10 cm apart. Brass valves that were previously soldered with mesh along the inside opening were attached by tapping a 0.9525 cm threaded hole into the filter column. To drill these threaded holes, the team first drilled a non-threaded hole using a hand held drill. After, the holes were tapped using a tapping tool so they would have threads that the valves could screw into. The valves were wrapped with Teflon tape to prevent leakage before they were screwed into the filter and into the push-to-connect fittings.

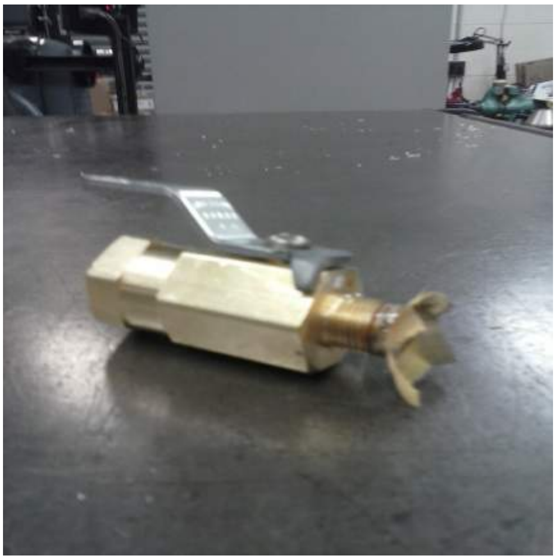

Figure 23: Soldered Brass Valve The team performed a trial run, soldering a brass valve to a small piece of brass mesh. Despite concerns that the heat of soldering would render the valve useless, when tested in the sink, the valve was able to control the flow with no visible leakage.

4.9.3 Attaching the Pressure Sensors

The team attached pressure sensors to this array of valves using 0.635 cm diameter flexible PVC tubing. This tubing was cut in short lengths that could be attached to the pressure sensor and to the push-to-connect fittings on the brass valves. Two small lengths of tubing left each sensor and were plugged into successive brass valves along the filter column's length. Once the fittings were attached the sensors will be connected to the data acquisition system and monitored to calculate flow distribution between various layers of the filter.

4.9.4 Sensor Data

In order to gain insight on the flow distribution between the six filter layers, twelve sensor ports were installed, as previously mentioned. We now utilized six different 7 kPa pressure sensors, where each will be connected across one layer. Each of the sensors is connected to EasyData software which will monitor the pressure through each pair of ports during the time of operation. The sensors will all be zeroed once the tank is filled with sand and water. When this happens any deviations from zero will indicate a difference in pressure arising from the flow through the sand in the filter column. Thus differences in sensor values will correspond to differences in flow between layers.

5 Filter Column Stability

Originally, the team had concerns with the strength and stability of the middle connection using a rubber gasket, shim stock, and hose clamps. They were afraid the filter would begin to list in one direction under the weight of the water in the inlet and outlet tanks. After consulting Professor Weber-Shirk, the team members came to the conclusion that the hose clamps were not tightened far enough to provide the kind of stability the filter connection needed to bear the pressure of all the water that will go inside it. Thus, the team decided to test the strength of a hose clamp to the limit with a torque wrench (Figure 24). The manufacturer rated the hose clamps to fail at 4.52 Nm (40 inch-pounds), so that was the first setting tested. The team found the hose clamps to fail at around 50 inch-pounds due to stripping of the hex head on the screw. After the hose clamps were tightened to 40 in-pounds, the connection of the filter column sections no longer twisted when it was laid horizontally, not even when each team member stood on it. So if the screws are tightened to 40 inch-pounds, the filter will be stable enough to withstand the weight of the water without listing. The connection provided by the gasket and hose clamps is robust enough to handle the forces present when the filter is carried by two people.

Figure 24: Torque Wrench Test A torque wrench was used to test the strength of the adjustable length hose clamps. It was confirmed that the hose clamps could withstand in excess of 40 inch-pounds of force without failing, which reaffirmed the team's plan to tighten all gasket joins part of the filter using a torque wrench.

5.1 Weight of Tanks and Neutralized Moment

The LFSRSF filter column is a large object with sufficient weight to cause injury to people and or damage to objects within its vicinity. With this notion in mind, the analysis of the stability of the column was performed to determine any critical circumstances that could cause the column to tip over. The analysis reveals that the filter column will not tip over under the right conditions. The method of analysis used was the Center of Mass method. It is based on the following formula:

$$X_{cm} = \frac{1}{M} \sum (m_i x_i) \tag{3}$$

where $X_{cm} = 5cm$, is the x or y coordinate of the center of mass, M is the total mass of the object, and m is the mass at a particular point x.

In this method, the center of mass of the filter column, along with the entry and exit tanks, was determined to be within the cross section of the filter column meaning that no net moment would be developed causing the filter column to tip over. The analysis also involved certain assumptions.The first assumption was to treat all three components as perfect cylinders. This would imply a center of mass along the center of the circular cross section. Secondly, the filter column would be empty. Only the weight of the pipe itself would be taken into account. On the other hand, both exit and entry tanks would be filled with water to represent a critical point of failure of the system. Finally, additional attachments to the filter were not considered and where assumed to have negligible effect. This includes the flexible pvc pipes, the manifolds, the gasket, the shimstock and the pvc sheet.

To calculate the mass of the entry/exit tanks and the filter column values for the weight per unit length of the Schedule 40 pvc pipe were researched and found online [1]. Given the dimensions of the each of the components, the total weight of the pipe was calculated and converted to a mass in kilograms. Then for the exit and entry tanks, the volume of each was calculated and multiplied by the density of water (1000 kg/m^3) to get the mass of water and then summed to the mass of the pipe. For the entry and exit tanks, an additional 10% of its calculated mass was added to account for any error and to give a margin of safety. It is also worth pointing out that the entry and exit tanks are never supposed to be completely filled with water. This simply adds a (large) additional margin of safety. With the origin located at the center of primary filter column, the distance from the origin to the centers of the entry and exit tanks was measured. Each center was a assigned a cartesian coordinate and the formula for center of mass was used to find the center of mass of the arrangement. Each center was a assigned a cartesian coordinate and the formula for center of mass was used to find the center of mass of the arrangement (Table 2)

	Length	Mass/Length	Adj. Mass	CoM
	(m)	(kg/m)	(kg)	(cm, cm)
Filter Column	2.1	14.9	31.52	(0, 0)
Entrance Tank	0.7	5.25	17.98	(27.5, 0)
Exit Tank	0.4	5.25	10.33	(19.88, 19)
Arrangement	NA	NA	59.83	(12, 3.3)

Table 2: Values and Results for Center of Mass (CoM) Calculation Calculations were performed to confirm that even the worse case scenario for the distribution of water weight within the filter would not fail.

We found that the center of mass coordinate was located within the cross section of the main filter column (inner radius of 15cm); hence no net moment would be developed, even at this extreme scenario, and the column would remain stable (See 25.)

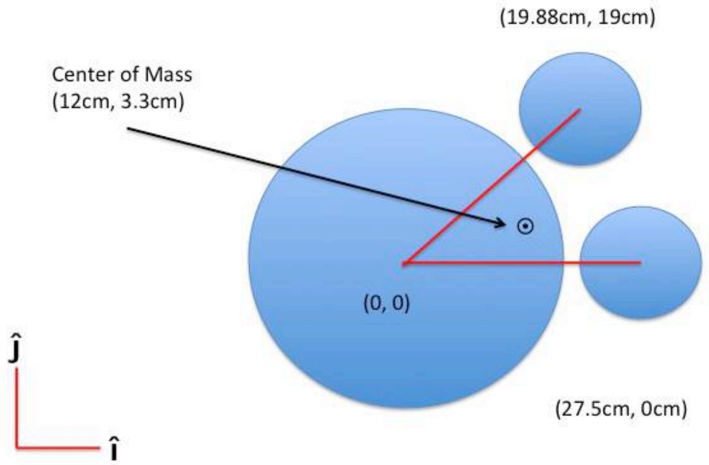

Figure 25: Worst Case Center of Mass. Even for the worst case, in which the filter column is empty and the entrance and exit tanks are filled with water, the center of mass for the filter column system lies above a point inside of the main column. This confirms the steadiness of the filter, showing that it is highly unlikely that the column will snap in two.

6 Water Recycling System

6.0.1 Recycling System

In order to continuously test the LFSRSF, a water recycling system was developed to work alongside the filter. This system (see 26) was designed to act as the source of water for the entrance tank and as the drain for the exit tank. The system will be sufficient to provide the filter with its necessary flow rate of 0.8 L/s with considerable allowance onon either side of this value. The team designed a system that is composed of a sump pump with the capacity to handle solids, a bucket, a delivery pipe to the influent pipe in the entrance tank with a gate valve to fine-tune flow rate, and a drain for the effluent water in the exit tank which will lead directly to the bucket. The bucket used has a capacity of 10 gallons and a height of 14 inches. The backwash drain pipe is also submerged in the bucket. The pump used is a Little Giant Pump (see 27) with the capacity to pump 2.59 L/s to a height of 3.05 m, which, given that the pump has to work against a maximum head of 2.34 m and deliver 0.8 L/s, ensures that even with major and minor head loss, the pump will be sufficient to satisfy the filter's requirements.

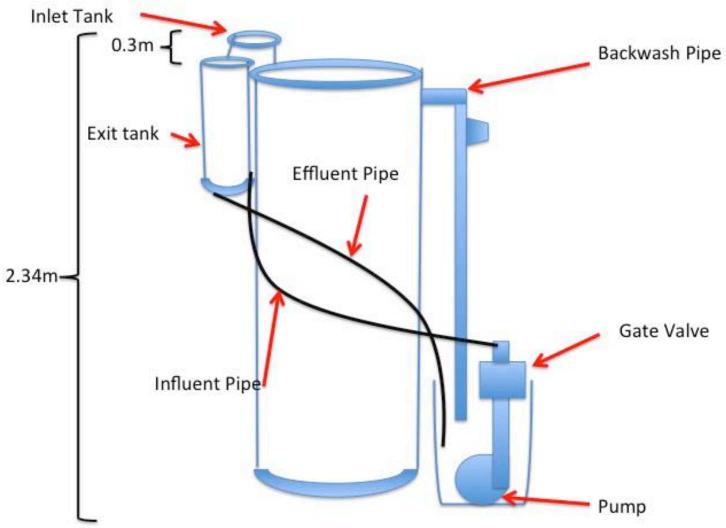

Figure 26: Recycling System The recycling system makes filter testing more efficient by allowing water to be reused..

Figure 27: Recycling Pump The Little Giant Pump that recycles water through the filter. This pump is set to provide a flow rate of 0.8 L/s and pumps directly into the filter's entrance tank.

7 Wet Testing

7.1 Testing Apparatus

The team realized the necessity of a secondary containment device that could collect water from any leaks, splashes or spills associated with the filter's operation. The team ordered the "General Foam 45 in Wading Pool Wonderous Ocean" from Sear's online catalogue, whose 114 cm diameter made it a great fit for the LFSRSF lab space. This diameter of pool allowed the filter column and the bucket from the water recycling system to fit comfortably within the pool's center (see 28), and its 9 cm depth ensured that the pool could collect any necessary quantity of water. The team set up a peristaltic pump, leading from the pool into the sink, to help drain it once water has accumulated. The team has been very satisfied with the kiddie pool as a secondary containment device: the plastic of the pool is sturdy, and it supports the weight of the filter, unlike inflatable pool options. It has so far been successful in preventing leaks from the filter or overflowing filter components from spilling on the floor.

Next, the team needed to address the challenge of accessing the filter from above, since the filter column and its tanks are very tall. The team obtained a portable step ladder, which was wheeled into position at the side of the filter column. This allowed the team members to easily reach the pipe stub within the inlet and exit tanks, as well as to monitor the water level in the filter column and the flow rate of water being pumped into the entrance tank. Since the ladder is portable, it can easily be wheeled away from the testing site at any time should increased access be necessitated.

Figure 28: Filter Testing Layout The filter column was placed in a kiddie pool that serves as a secondary containment device in the event of leaks. Both the filter column and the recycling system were positioned within this pool with plenty of room to spare. The pool was positioned close to the sink so that water could be easily pumped from or emptied into the sink. Because the filter is so tall, a step ladder became a second necessary addition to the testing setup, so that pipe stubs could be inserted and removed and flows within the filter monitored from above. The setup is also located alongside an input box that can monitor the pressure sensors and communicate with the server.

7.2 Preliminary Watertightness Testing of the Lower Column

To check the filter column for leaks, the team filled the sealed-off bottom half of the filter with water, filling the filter up to the top of the highest layer of slotted manifolds. The first few attempts to fill the filter were unsuccessful due to problematic seals between the barbed-to-male adapter fittings and the side of the filter column. The backwash manifold trunk's coupling, which is glued into the side of the filter, did not leak, but none of the other fittings attached to the other layers of the filter initially appeared watertight. The team determined that this was because the O-rings, which were placed on the outside of the filter, were getting squashed out of shape due to the outer curvature of the filter column and the lack of a sufficient ledge on the barbed fitting to hold the O-ring in place. They suspected that the problem could be ameliorated if the O-rings were instead pressed agaist the inner curvature of the filter. The column was emptied, the O-rings switched to the inside of the filter, and the filter's watertightness tested again. This time, there were no apparent leaks out of any of the barbed-to-male adapter fittings, nor from any of the brass valves of the sensor array. These tests left the team optimistic about the structural integrity of the filter and eager to continue further filter tests. However, this set-up was imperfect and yielded other problems in subsequent, more rigorous watertightness tests.

7.3 Testing the Entire Filter: Leakage Points and Solutions

The team continued testing the filter with water to test the filter for weak connections and possible leaks. A major concern during this stage of testing was that the gasket connection joining the filter column halves might begin to leak. After the filter was filled with water, leakage points were marked on the filter to be fixed after the filter was taken apart. Just as the team expected, the gasket connection was not entirely watertight. Though the water leakage through the gasket was far from torrential, the small amounts of water seeping through the gasket-to-pipe connection would bead into droplets and drip down the filter column. The team concluded that the leak path was due to the poor connection between the overstretched gasket and filter column. After testing out many different solution strategies, the team decided to wrap Teflon tape around the pipe where the two segments joined. The challenge here was moving the gasket into position over the Teflon tape without pushing it away from the connection point. This tape provided an extra layer that would provide contact between the gasket and filter column at all points, to ensure a water-tight seal.

Another point of leakage was found in the inlet and outlet piping's connection to the filter column. Previously, O-rings were inserted between the inside filter wall and manifold couplings to prevent water from escaping through this connection. The problem with this design, however, was that the threaded fitting connection would tighten against the wall of the filter before it tightened around the threads. This meant that water would be able to find a path out of the filter through the space between the threads. These fittings were removed and the threads were wrapped with three layers of Teflon tape. The Teflon tape cause the threads to tighten and create a water-tight seal at the same time that the O-ring tightened.

More leaks came from the pipe-to-tank connections of the entrance and exit tanks. The connections used to connect the flexible tubing to the inlet and outlet tanks were made by gluing couplings in the bottom of each tank. A concern was that the PVC glue would not provide a water-tight seal that would keep the water inside the tank. However, the gluing strategy turned out to be rather successful. There was only one connection that was slightly leaking, and after putting more PVC glue between the gap, the tank became watertight. Additionally, the team realized it would be best to screw in the barbed fittings into the couplings tightly before connecting the flexible pipes. The barbed fittings became difficult to screw in after the pipes were connected due to the torque in the pipes after they were twisted. This was most apparent in the backwash piping. After realizing the backwash fitting needed to be screwed in much more tightly, the team's new challenge became trying to get the fittings to screw in more tightly without having to remove the 5.08 cm tubing from the barbed fitting. In the end, they had to saw part of the pipe that was stuck to the barbed fitting off and tighten the fittings before heating the pipe and reattaching it to the barbed fitting.

8 Filter Operation Testing

Upon the conclusion of leak testing, the team began efforts to initiate both forward filter operation and backwash, the latter of which posed more of a challenge:

8.1 Testing: Forward Filter Operation

Forward operation of the filter was easily initiated. Once the sand and water were added to the filter, with the water recycling pump operating at a full 0.8 L/s, operation proceeeded without any problems. The team ascertained that about 44 cm of head loss were achieved between the filter's entrance and exit during this phase of normal operation, measured at a flow rate (maximum achievable during that run) of 0.75 L/s. Plumbing headloss, using the sand drain as a manometer, was ascertained to be 17cm. The predicted design head loss was 5.56 cm from a clean sand bed, 2.5 cm from the slots, and the remainder from inlet and outlet piping. Thus, the filter is showing much greater headloss than design during forward filtration, mostly due to plumbing or slots.

8.2 Backwash Testing

One of the most important functions of the redesigned LFSRSF is its ability to be easily backwashed: in the field, backwash might occur as frequently as daily. The team faced significant challenges of maintaining the filter bodys integrity as an air-tight unit during the initiation and through the duration of backwash. This is important as, in the current design, the backwash-to-waste pipe acts a siphon that draws water out of the filter during backwash. For the siphon to function, there must be a complete water connection from the exit of the backwash-to-waste pipe and the filter body. The following represent team efforts to prevent air from entering the filter body.

8.2.1 Air Removal During Backwash Initiation

The team faced challenges in the fact that the exit tank (and consequently, the exit weir) was not high enough to ensure that the top of the filter body was filled with water, as the exit weir was several centimeters below the top of the filter and below the top of the backwash-to-waste pipe. This meant that the top of the filter would always have some air when switching from forward filtration to backwash. Furthermore, the backwash-to-waste valve was placed towards the top of that pipe, which meant that it was hard to ensure that the entire pipe was filled with water when exiting into the waste tank: when the valve is shut, water below the valve tends to empty into the waste tank, leaving a section of the backwash-to-waste pipe filled with air. The team solved these problems by adding some (temporary) valves to the system. First, a 3.81 cm (1.5 inch) valve was added to the bottom of the backwash-to-waste pipe, so that the water column inside the pipe would extend to the waste tank at all times. A 3.81 cm (1 inch) valve was also added to the very top of the filter, i.e, on the top PVC plate (see 29). Finally, the team added a six-inch pipe to the top of the exit tank to extend its height (using duct tape) and an arbitrary pipe stub to the exit weir, both as stop-gap solutions to ensure that the exit weir was now placed taller than the top of the filter.

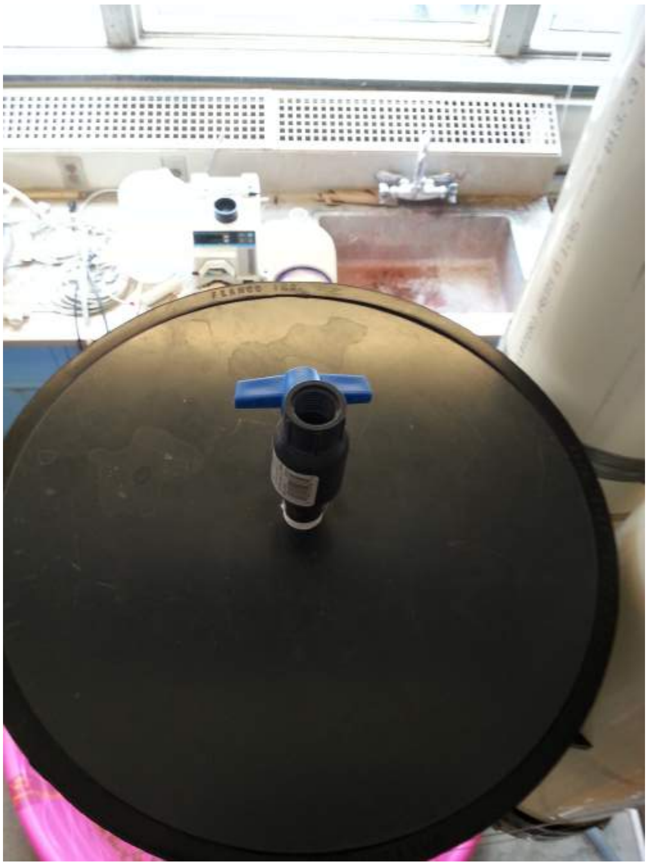

Figure 29: Air Release Valve A valve was added to the top cap of the LFSRSF so that the filter could be completely filled with water and all air trapped in the filter released before backwash. A hole was drilled and the valve was tapped into the PVC plate that makes up the filter's top cap.

The present system works as follows: during normal operation, the small valve at the very top of the filter body must be shut, the valve at the top of the backwash-to-waste must be open, and the valve at its exit must be shut. To switch to backwash, the valve on top of the filter column is opened, so that all the air inside the filter column exits through it. When water begins to get out of this valve, it is shut, and immediately after, the valve at the bottom of the backwash-to-waste is opened slowly. Under this method of operation, the filter successfully switches to backwash mode: the sand bed is fluidized and the filter backwashes.

Note these are stop-gap solutions that the team used to test the filter's ability to backwash. A final design solution for new LFSRSFs must be implemented as follows: the exit weir must be raised so that it is at least higher than the top of the backwash pipe, and preferably to as high as the filter body (and as a consequence, the heights of the entrance and exit tanks must also be raised), and the backwash-to-waste valve must be placed at the bottom of the backwash-to-waste pipe such that it is always under the water level in the waste tank. Alternately a water seal trap can be added to the backwash pipe to prevent air from entering the pipe. These solutions will ensure that the backwash siphon is easily set up during every backwash run.

8.2.2 Airtightness During Backwash

Once the backwash-siphon is set up, it is imperative to ensure that no air leaks into the system and breaks the siphon. Air can enter from three main areas: the entrance piping and entrance tank, the outlet piping and exit tank, or via the backwash pipe itself.

During initial tests when backwash-initiation was achieved, the team noticed that the filter cycled between backwash and backwash failure (overflowing of the entrance tanks) as large air pockets were being sucked into the filter through the entrance pipe stubs. This was especially a problem when the water level was rising or falling past the entrance weirs, when air pockets would get sucked in due to the fact that water was entering the pipe stubs at great speed. The team also noticed that air was being pulled in from the exit tanks through the top two outlet pipes, as the pressure in this part of the filter was low enough to be able to suck air in from the exit tanks (which are empty during backwash). The backwash-to-waste pipe was not found to be a problem in terms of air leaks - as long as its exit was always under water.

The team solved the issue in a similar method to the SRSF solution in Honduras: by looping the entrance and exit tubing so that the bottom of the loops are at floor-level, a water-seal is created in the form of a U-tube (see 30). This implies that the even though the pressure inside the filter column is negative (less than atmospheric), air does not enter the filter body once backwash is initiated. Backwash trials found this solution to work well.

Figure 30: U-Tube and Flexible Tubing In order to keep air from entering the filter column, the lengths of flexible tubing connecting the filter to its inlet and exit tanks were extended, creating large U-bends that allowed pressures to stabilize. The resulting water seal prevents air from passing through the tubing into the side of the filter column. Two such loops have been added to the entrance tank, and two further loops have been added to the exit tank.

8.2.3 Head loss Problems During Backwash

During the backwash operation of the filter, it became apparent that the head loss through the filter wasmore substantial than anticipated. The manifestation of this excessive head loss came in the form of water overflowing the entrance tank when the filter was run at its regular flow rate, thus the team was forced to run the backwash under the intended flow rate of 0.8 L/s. At the beginning of backwash at a flow rate of 0.55 L/s, there was 13 cm of headloss per 20 cm of sand in the fluidized sand bed, approximating the total head loss through the sand bed at 102.7 cm, lesser than a design headloss of 120 cm - mainly due to the smaller sand size delivered. A huge cause for concern was that there was 40 cm of initial head loss in plumbing and slots, which gre to a steady state of 90 cm as flow rates and the filter stabilized, apart from sand bed head loss (found using the sand drain as a manometer). This is much greater than the 14.4 cm expected through the slots during backwash and much greater than expected (negligabe) plumbing head losses It might also be the case that during backwash, the manometer provides an estimate of headloss through the bottom fluidized sand as well as plumbing.

The task was now to identify where this excessive head loss was developing within the apparatus. Several suspects came to mind, including the possibility that there was sand inside the manifolds, that the sand bed was not fluidizing, that the slot area was less than required by the specifications, or that the cross-sectional configuration of the trunk/branch assembly (6) had introduced more head loss that had not been properly accounted. Two of the suspects were confidently discarded by a series of tests. The first was discarded by removing the flexible tube to the bottom manifold. The filter was operated in reverse with the water entering through the exit tank. The water exited through the backwash manifold and out the backwash trunk through the side of the filter column (the backwash flexible pipe was detached) where we could probe for presence of sand. No sand was observed and thus there is no evidence of a sand leak in the backwash slotted pipe manifold. Regarding the fluidization of the sand layer, the team was able to conclude that the sand was fluidized by allowing a little bit of sand to be injected into the sand drain pipe but without actually leaving the sand drain. This is only possible if the sand is fluidized. The team narrowed down the sources responsible for this head loss to either the slot area (possibly faulty manufacturing) or the cross-sectional arrangement of trunks, . The head loss through the slots should be measured as soon as possible to determine if our estimates of slot head loss are incorrect, and slot dimensions of delivered pipes should be measured to as great an accuracy as possible to check against design specifications. Further exact calculations of headloss in the trunk-manifold arrangement are also necessary.

In order to keep testing, the team managed to temporarily circumvent backwash initiation difficulties due to excessive head loss by adding pipe stubs (via pipe couplings) to the originally designed ones. The final setup had a pipe stub of 34.95 cm for the top inlet layer, 48.5 cm for the next inlet layer (third one from top to bottom), and 47.5 cm for the fifth inlet layer.

8.2.4 Final Water Levels and Flow Rates During Backwash

Once the filter is in backwash mode, water levels in the inlet piping fall to below the entrance tank for all inlet piping, and water levels in the exit tank are also below the bottom of the tank in the outlet tubing. The water level in the entrance tank is just below the lowest new pipe stub that was added. However, to maintain this level, backwash could only be maintained in current trials to a maximum flow rate of around 0.65 L/s. Flow rates higher than this caused the entrance tank to overflow due to head loss problems described above: faster velocities at greater flows imply greater head losses, which causes the entrance tank to back up.

9 Conclusion

Theis semester, the team successfully completed the construction of a working LFSRSF. Filter trunks and slotted manifolds were designed and inserted into the filter, a finished sand drain was constructed with PVC tubing, and brass valves were used to attach pressure sensors to the filter, the integrity of the filter column was improved and sand was added into it.. The team also set up a water recycling system and secondary containment. The team has tested various parts of the filter for water- and air-tightness and was able to eliminate all leaks. Finally, the LFSRSF was succesfully operated in normal filtration and backwash modes..

10 Future Work

Future teams will need to identify the source of higher than expected backwash head loss and change the slotted manifolds if necessary. The inlet and outlet systems will need to have their elevations adjusted to enable full operation of the filter using the backwash valve to completely control the mode transitions. Testing the filter over a range of turbidities and to failure are also imporant next steps. The current team is optimistic of the potential of the hydraulically-controlled LFSRSF! Thought will be required to properly design the pipe stubs (optmizing Figure 16) that will be used in the entrance and exit tanks. The pipe stubs help to maintain correct flow exit and entry to the filter column during backwash and normal filtration, and must also be optimized for flow distribution, possibly by the addition of caps and orifices to introduce necessary head loss. The entrance and exit tanks must also be raised to combat higher-than-expected degrees of head loss through the filter column. To do this, the 40 cm tall, 15.42 cm (6 in) diameter exit tank should be replaced with a taller version of the same diameter pipe, so as to hold a taller effluent weir. The plate at the bottom of the exit tank and its trappings can easily be fitted to a new 15.42 cm pipe, since the tanks are capped according to the gasket, stainless steel shimstock, and hose clamp method. Once inlet and exit tank placement is more carefully figured and the exit tank is lengthened as needed to ensure easy backwash, the team may further refine the dimensions of these stubs to ensure that they are acting properly in their distribution of water throughout the filter.

Spin welding should be explored as a potentially superior method to create fittings on the filter body, inlet, and outlet tank.

11 Team Reflection

As a team, we functioned well together. We bring different strengths to the table, with a good mix of fabrication experience, previous LFSRSF work, knowledge of fluids (and AguaClara) theory,and MathCAD experience. This helped us to divide our work, though some fabrication tasks required the full team effort, as did design decisions on the pump, sand drain and piping. The LFSRSF corner of B60 Hollister is always an animated one, we plan on continuing to put all that energy wholeheartedly into a well functioning filter!

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