Final Design Report

AquaTech
Engineering Solutions

By Adam Avey, David Criswell, and Kelsey Criswell

Contents

List of Figures

List of Tables

Mission Statement

"AquaTech Engineering Solutions' mission is to use its technical expertise and resources to provide customers with more affordable, longer lasting product."

Statement of Work

Problem Statement

To design and fabricate a flow-through iron removal pretreatment module for a household reverse osmosis (RO) system. Our secondary objective involves optimizing the RO system for different levels of water hardness and contamination.

Figure 1: Pumps of Oklahoma Reverse Osmosis (RO) System

Preliminary Scope

The project to be undertaken is a design of an iron removal pretreatment system for a small reverse osmosis (RO) unit. The iron removal system will use naturally occurring air to oxidize and precipitate dissolved iron in well water incoming to the RO unit. The precipitate will be filtered out by an inexpensive filter. This is done in order to extend the life of the more expensive RO filter membranes. The iron removal system will feature a flow-through design and will be mounted on an auxiliary skid near the RO unit. Restrictions include refraining from using an air pump or other device that will require additional power to operate the pretreatment system.

Figure 2: Iron-fouled RO Membrane (Membranes should be white)

Location of Work

AquaTech tested hard well water from a Stillwater resident to establish the initial specifications listed below. The assembly and testing of the prototype was done in the Biosystems Demonstration Lab.

Description of Client

AquaTech conducted designs and testing for Pumps of Oklahoma, Incorporated. Pumps of Oklahoma is a wholesale supplier of industrial, municipal, agricultural, and environmental pumps. They supply submersible and above ground pump equipment all over the world. Pumps of Oklahoma is located in Oklahoma City, OK and has 18 employees. Adam Avey, the team leader of AquaTech, served as the summer intern for this company in the summer of 2012 and worked to design and fabricate the current Reverse Osmosis system.

Industry Analysis

Trends

Consumers in the United States pay scrupulous attention to the quality of the water they are drinking. This is evident with the increase of bottled water consumption in the U.S., which continues to climb throughout the years.

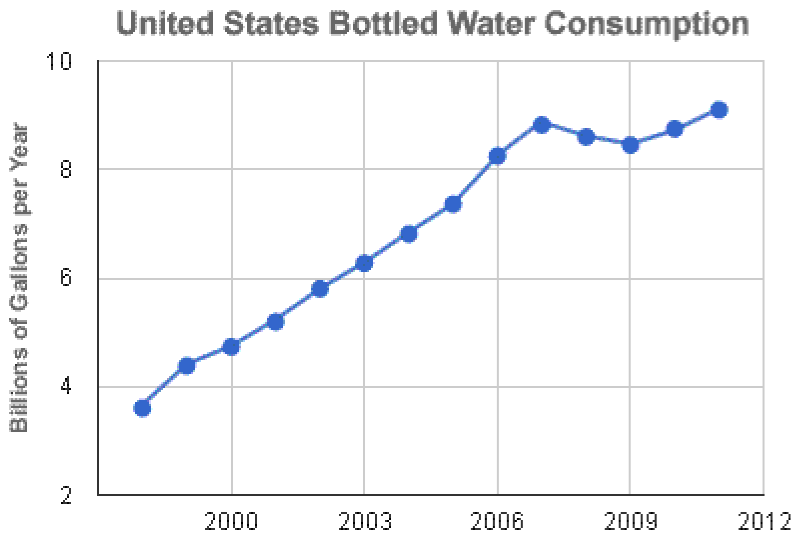


Figure 3: Bottled Water Consumption

Many people in the U.S. are concerned about drinking water because of contaminants such as bacteria, viruses, pesticides, petroleum products, metals and metalloids, and strong acids among others.

Technologies for water treatment are becoming more effective and less costly. Recently, there has been a lot of new developments in water treatment, some of them include: activated carbon, ozonation, ultraviolet germicidal irradiation, and bioceramic water amplification, among others.

Marketing Strategy

For this particular product a great marketing strategy would be selling the Reverse Osmosis System to construction companies that could put install it in houses, that way Pumps of Oklahoma could design a standard prototype for a particular type of houses and build a whole lot of them, instead of building customized products or products that couldn't probably fit in a particular house.

Requirements & Specifications

Customer Requirements

The details of AquaTech Engineering Solutions' project requirements were purposely left somewhat vague by our customer in order to prevent the limitation of creativity by previous suppositions. That being said, there were some baseline specifications that were met:

- The device must achieve the EPA standard of 0.3 parts per million (ppm) for iron content in drinking water.
- The device must treat the water in a continuously flowing stream.
- The device should be able to remove whatever substances (such as air) that have been added to the water stream before the stream continues on the reverse osmosis system.
- The device must stand alone on a skid separate from the RO system

After meeting with representatives from Pumps of Oklahoma after the fall design presentation, some design decisions were made on behalf on the client. Rather than use an eductor to oxidize the iron, hydrophobic modules will be used to complete the initial conversion of ferrous iron to ferric (insoluble) iron. Then, the insoluble ferric iron will be filtered by the inexpensive filter membranes before the water goes through the reverse osmosis filtration system in order to lengthen the life of the RO filter membranes.

Design Analysis

Design Changes

Following the fall design presentation, our client requested a change in design strategy. The new product development team at Pumps of Oklahoma requested that we incorporate hollow-fiber membranes and a contactor module as alternative to the spray or trickle aeration systems. The new system will serve as a “proof of concept” to demonstrate the effectiveness of using hollow-fiber hydrophobic membranes to aerate the inflowing water, oxidizing the dissolved iron and causing it precipitate.

Hydrophobic Membranes

The hydrophobic membranes and contactor membrane module was ordered from a supplier in the Czech Republic called Zena Membranes. Zena Membranes is a research and development company involved in supplying hollow fiber membranes.

The module that was ordered is the Macro040-P50 housed module. The data sheet supplied by Zena membranes may be seen in Appendix D.

Environmental and Societal Impacts

Environmental impacts of the proposed designs are considerably low considering that the proposed pretreatment systems do not require any chemical agents. These elements of design are used to promote the reduction of water pollution and carbon emissions. The iron pretreatment system will impact well water users by offering an alternative to common well water purification systems that requires less maintenance and less cost over time.

Financial Analysis

Because of the change in strategy enacted at the end of the fall semester our proposed prototype budget doesn't directly transfer to the current project design. The proposed prototype budget from the fall semester can be seen in Appendix A. The test setup and prototype expenditures from the spring semester can be seen in Table 1.

Table 1: List of Purchases

Date	Item	Supplier	Cost
11/15/2012	Iron Checker	Instrumart	67.00
12/12/2012	Testing Supplies	Instrumart	37.00
2/20/2013	100 Gallon Tank	Atwoods	75.98
2/20, 3/13, 4/01/2013	Plumbing Supplies	Lowe's	137.08
2/28/2013	Water Flow Meter	Dwyer Instruments	81.29
3/05/2013	1/8" 2 x 4 Tubular Steel	Stillwater Steel & Welding	304.80
4/23/2013	5 Micron Paper Filter	Winnelson - Stillwater	23.94
		Total:	$697.09

Experimentation

AquaTech identified several testing methods to properly determine important parameters that are needed to evaluate the iron pretreatment system that was designed for household reverse osmosis systems. The water used for each testing method will be first run through the Reverse Osmosis system to remove variability in the water source. Soluble iron will be added as needed for each test. Three tests will be run to determine the following:

1. Oxygenation Rate
2. Maximum Membrane Differential Pressure (Before Bubble Formation)
3. Iron Removal Rate

Methodology

For testing of the pretreatment system, a source of ferrous iron was needed. Ferrous Sulfate Heptahydrate ($FeSO_4*7H_2O$) was selected as the iron source because it is completely soluble in water. So, all the iron would be in the ferrous form and be converted by the presence of oxygen to insoluble ferric iron. The amount of ferrous sulfate needed can be seen in the calculations below. Each test was run with 25 gallons of water in a 100 gallon tank. The molecular weight of ferrous sulfate heptahydrate is 278.02g/mol.

Equation 1: Amount of iron available in each gram of FeSO4.

$$\frac{1\text{ mol Fe}}{1\text{ mol FeSO4}} * \frac{55.8\text{ g Fe}}{1\text{ mol Fe}} * \frac{1\text{ mol FeSO4}}{278.02\text{ g}} = 0.201 \frac{\text{g Fe}}{\text{g FeSO4}}$$

Equation 2: Conversion to find amount of FeSO4 needed for 50 gallon tank.

$$\frac{\text{Conc (mg Fe)}}{1\text{L}} * 50\text{ gallons} * \frac{3.79\text{ L}}{\text{gal}} * \frac{1\text{ mg FeSO4}}{0.201} = \text{mg FeSO4 needed per tank}$$

Equation 3: Conversion to find amount of FeSO4 needed for each 25 gallon test.

$$\frac{\text{Conc (mg Fe)}}{1\text{L}} * 25\text{ gallons} * \frac{3.79\text{ L}}{\text{gal}} * \frac{1\text{ mg FeSO4}}{0.201} = \text{mg FeSO4 needed per test}$$

Table 2: Required Iron Calculations from equations above.

Concentrations	**Per Tank (mg)**	**Per Tank (g)**	**Per Test (mg)**	**Per Test (g)**
0.1	94.42	0.09	47.21	0.05
0.5	472.09	0.47	236.04	0.24
1.0	944.17	0.94	472.09	0.47
2.0	1888.34	1.89	944.17	0.94
3.0	2832.52	2.83	1416.26	1.42
4.0	3776.69	3.78	1888.34	1.89
5.0	4720.86	4.72	2360.43	2.36
Sum	14729.08	14.73	7364.54	7.36

Equipment

In order for AquaTech to fulfill its experiments, the following equipment list was created.

Table 3: Equipment List.

	Equipment Required			
	Item	**Owner**	**Test No.**	**Obtained? (Y/N)**
1	Air Compressor	BAE Lab	1,2,3	Y
2	pH Probe	Dr. Brown	All	Y
3	pH Test Strips (back-up)	AquaTech	All	Y
4	Soluble Iron (Ferrous Sulfate Heptahydrate)	AquaTech	1,3	Y
5	Pressure Meter (Liquid)	AquaTech/Pumps	All	Y
6	Pressure Meter (Gas)	AquaTech/Pumps	All	Y
7	PVC and Fittings	AquaTech	All	Y
8	Dissolved Oxygen Meter	Dr. Storm	1	Y
9	Peristaltic Pump	Dr. Fox	All	Y
10	100 Gallon Tank	AquaTech/Pumps	All	Y
11	Inexpensive Filters	AquaTech/Pumps	All	Y

Polypropylene Hydrophobic Membrane

The membranes were obtained from Zena Membranes, a supplier in the Czech Republic. The Macro040-P50 housing module was purchased and shipped to Oklahoma State University by Pumps of Oklahoma. The membranes have a 0.1 µm pore size and a fiber burst pressure of >5.5 bar (79.77 psi). The data sheet can be seen in Appendix D.

Testing Procedures

All experimentation was carried out in the Demonstration Room of the BioSystems & Agricultural Engineering Laboratory. The water entering the iron pretreatment system was filtered using a reverse osmosis system provided by Dr. Storm. Soluble iron (ferrous sulfate) was added to the water as needed regarding each test. Three experiments were run and are listed below.

Test One: Oxygenation Rate

Run water at varied flow rates and measure dissolved oxygen (DO) levels at influent and effluent to determine oxygenation rate. Flow rates will be tested for different pressures (0 – 20 psi), increasing each experiment by 5 psi.

The oxygenation system was also tested to determine if an open or closed air valve system was more efficient. It was determined that leaving the valve open or closed did not make a significant difference in performance. Because closed valve was slightly more effective, it was used for the remainder of testing.

Test Two: Differential Pressure

Run water at constant flow and vary air and water pressures to determine the maximum membrane differential pressure for a given flow rate.

Test Three: Iron Removal Rate

Run water at constant flow and vary iron concentrations in influent to determine the iron removal rate. The following iron concentrations were tested: 0.3, 0.5, 1.3, 1.5, 2.3, and 5 parts per million. The Hanna iron checker was used to check the effluent from each run for each concentration.

Results

Test One: Oxygenation Rate

There was an overall 31% increase in oxygenation rate when the system pressure was increased to 20 psi. Figure 4 shows the rate of dissolved oxygen increase as the system pressure increases. The experimental data may be found in Appendix B.

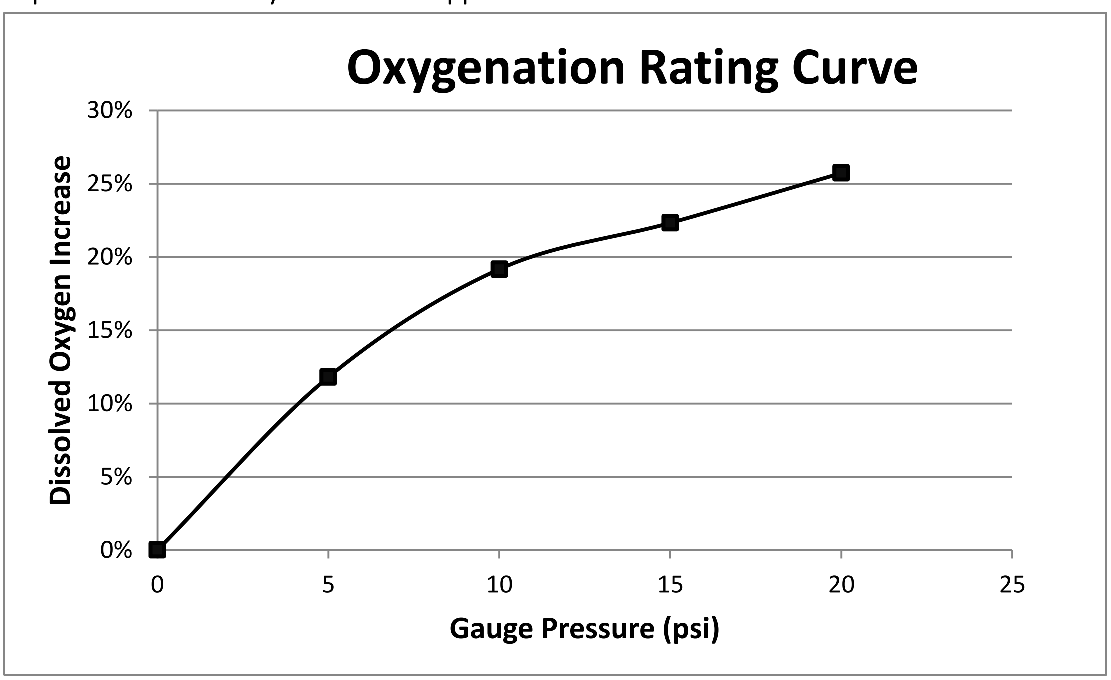


Figure 4: Oxygenation Rating Curve

The oxygenation rates were compared between open and closed air valve systems. Although the closed system originally appeared to maintain higher oxygenation efficiency, a statistical analysis proved that the systems are not significantly different. A paired-t test was used ($p = .05$). To remain consistent, AquaTech continued testing procedures using a closed air valve system.

Test Two: Differential Pressure

The differential pressure was determined by holding the system pressure constant (5, 10, 15, 20 psi) at a constant flow rate (1 gpm) and increasing the air pressure until bubbles formed. After bubble formation, the air pressure was backed off until the bubbles stopped. The differential pressure was about 2 psi above the system pressure.

Test Three: Iron Removal Rate

Iron removal was tested using RO water with solely the addition of ferrous sulfate ($FeSO_4$) initially. The raw data gathered from this test may be seen in Appendix C. The initial results were not the desired results for the system, so the pH was adjusted for the later tests. The tables below show the analyzed results of multiple tests that were run to optimize the pretreatment system. The raw data can be found in Appendix C.

Test 3.1: Open Tank

- Test #1: RO Water, 6.3pH
- Test #2 RO Water, 6.6pH adjusted with NaOH

Test 3.2: pH Increase

- Test #1: RO Water, 6.8pH adjusted with NaOH, no airflow
- Test #2: RO Water, 6.82pH adjusted with CaCO3, normal testing conditions

Test 3.3: Closed Tank

- Test #1: RO Water, 6.3pH adjusted with NaOH
- Test #2: RO water, 6.9pH, adjusted with NaOH
- Test #3 RO water, 7.2pH adjusted with NaOH

Table 7. Test 3.1 #1

	Initial (Fe)	**5 psi**	**10 psi**	**15 psi**	**20 psi**
Ferrous Fe Concentration (ppm)	**0.32**	**0.23**	**0.14**	**0.2**	**0.2**

Table 8. Test 3.1 #2

	Initial (Fe)	**Initial (Fe2+)**	**5 psi**	**10 psi**	**15 psi**	**20 psi**	**Final tank (Fe)**
Ferrous Fe Concentration (ppm)	**2.32**	**1.49**	**0.28**	**0**	**0**	**0**	**0**

Table 9. Test 3.2 #1

	Initial	**0 psi**	**5 psi**	**10 psi**	**15psi**	**20psi**
Concentration (Fe2+) ppm	**5**	**5**	**3.96**	**3.95**	**3.93**	**3.78**

Table 10. Test 3.2 #2

	Initial	5 psi	10 psi	15 psi	20 psi
Concentration (Fe2+) ppm	**2.19**	**1.72**	**1.57**	**1.33**	**1.19**

Table 11. Test 3.3 #1

	Initial	20 psi	Tank
(Fe 2+) Concentration (ppm)	**1.43**	**1.08**	**1.42**

Table 12. Test 3.3 #2

	Initial	20 psi	Tank
(Fe 2+) Concentration (ppm)	**1.3**	**0.16**	**0.5**

Table 13. Test 3.3 #3

	Initial	20 psi	Tank
(Fe 2+) Concentration (ppm)	**0.51**	**0.0**	**0.58**

Discussion

Test One: Oxygenation Rate

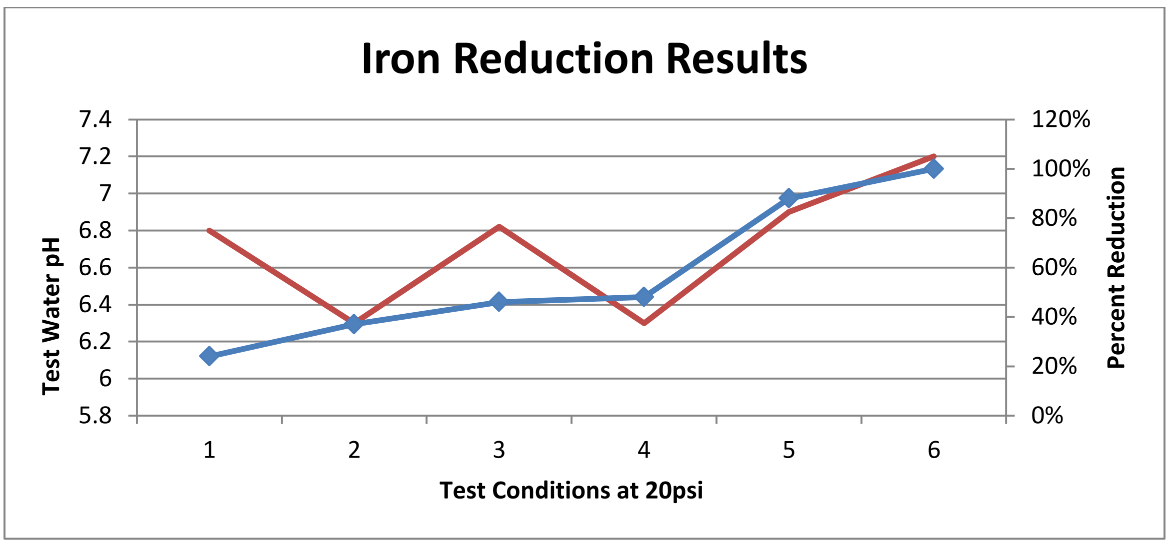
An increase of 31% dissolved oxygen was significant because it means our membranes are able to add dissolved oxygen that is available to the iron for use directly into the water stream. Dissolved oxygen availability is necessary for the iron to covert from its ferrous (soluble) form to its ferric form. More dissolved oxygen was obtained at higher pressures.

Test Two: Differential Pressure

The differential pressure is the pressure needed for the air to diffuse through the membranes into the moving water stream. The 2 psi pressure difference is valuable because at any given system pressure produced by a flow rate, the air pressure can easily be determined at 2 psi above the system pressure.

Test Three: Iron Removal Rate

After the initial tests, it was determined that the pH was too low for optimizing the iron conversion from ferrous iron to ferric iron. Sodium hydroxide (NaOH) was added to raise the pH and allow the iron to react with hydroxide (OH) and form solid Fe^{3+}. However, with the addition of NaOH, the reaction took place immediately. A yellowing of the test water was visible, as the dissolved iron began precipitating. Table 9 shows that the precipitated iron was easily removed by the 5 micron filter. We theorized that the iron precipitated almost immediately because of the high initial DO concentration of the test water. Table 10 displays the results of a test run through the skid without any airflow. The DO concentration increased slightly as pressure increased but this can be attributed to oxygen solubility's pressure sensitivity. Iron concentration was only slightly decreased. We believe this was caused by the slight increase in DO concentration. From these two tests we were able to gain that there is a complex interaction between pH and dissolved concentration. We also hypothesized that our desired oxidation reaction was happening in our open-air test tank before entering our system. To counter this and to prove the effectiveness of our system we conducted closed tank tests. These involved using a 5 gallon bucket with the lid on as our test tank, which reduced the test water's access to fresh air. By testing the un-oxidized iron left in the test bucket at the conclusion of the test, we were able to confirm that all oxygenation was occurring in our system and not in the tank. The results of significant tests are displayed graphically in Figure 5.



1	No Air Addtion [6.8pH]
2	Test #1 (No pH adjust)[6.3pH]
3	CaCO3 Adjust #1 [6.82pH]
4	Bucket Test 1 [6.3pH]
5	Bucket Test 2 [6.9pH]
6	Bucket Test 3 [7.2pH]

In all tests DO was increased from approximately 10ppm to 14ppm

Figure 5. Summarized Iron Reduction Results

Conclusion and Recommendations

In conclusion, our iron removal pretreatment system did exactly what it was designed to do. We found that it worked best when the test water pH was above 7.0, and if the water had a pH below 7.0 it was best to raise it via chemical addition. However, our sources in the plant and soil science department indicated that most naturally occurring ground water is somewhat basic, and therefore we anticipate excellent results when the system is integrated in the field. Because our work was simply “proof of concept”, Aquatech Engineering Solutions has some recommendations for a full-scale production model. First, a larger, more effective filter should be used. Even with lab-scale experiments our filter fouled to the point of ineffectiveness. Perhaps several filters could be used in parallel. Second, we recommend more research on membrane life. We simply did not run enough water through the module in order to make a quantitative statement on how the membrane module is affected by raw water. Last, we recommend more research regarding a full-scale model. Our system ran at 1/8th the flow rate of the RO system it was designed to precede, so capacity and pressure modifications will need to be made.

Project Schedule

A gantt chart was used to schedule the project.

Table 4: Spring semester schedule for AquaTech iron pretreatment system project.

Task Name	Duration	Start	Finish	Predecessors
Determine and locate materials for prototype	10 days	Mon 1/14/13	Fri 1/25/13	
Acquire materials	18 days	Mon 2/4/13	Wed 2/27/13	
Test Setup Research	5 days	Fri 1/11/13	Thu 1/17/13	
Module Selection	0 days	Mon 1/14/13	Mon 1/14/13	
Order Module	0 days	Fri 3/1/13	Fri 3/1/13	12
Design Test Setup	4 days	Mon 2/25/13	Thu 2/28/13	11
Research and Order Sensors	5 days	Wed 2/20/13	Tue 2/26/13	
Order Iron source	1 day	Mon 3/4/13	Mon 3/4/13	
Assemble prototype	6 days	Mon 3/25/13	Sat 3/30/13	10,15,13
Test prototype	10 days	Mon 4/1/13	Fri 4/12/13	17
Final product presentation and report	0 days	Tue 4/30/13	Tue 4/30/13	18

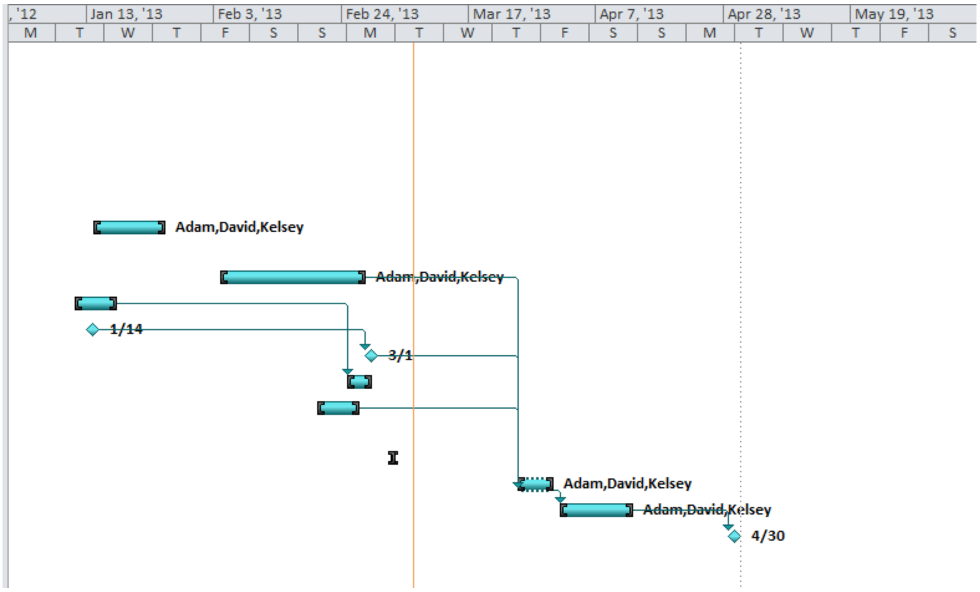


Figure 5: Gantt chart of 2013 AquaTech iron pretreatment system project.

Acknowledgements

AquaTech Engineering Solutions would like to thank Micah Goodspeed of Pumps of Oklahoma, Dr. Chad Penn, Dr. Dan Storm, Dr. Garey Fox, Dr. Paul Weckler, Dr. Glenn Brown, and Stuart Wilson of Oklahoma State University for their help and time throughout this project.

Appendix A

Fall Design Report

AquaTech
Engineering Solutions

By Adam Avey, David Criswell, and Kelsey Criswell

Mission Statement

"AquaTech Engineering Solutions' mission is to use its technical expertise and resources to provide customers with more affordable, longer lasting product."

Statement of Work

Problem Statement

To design and fabricate a flow-through iron removal pretreatment module for a household reverse osmosis (RO) system. Our secondary objective involves optimizing the RO system for different levels of water hardness and contamination.

Figure 4: Pumps of Oklahoma Reverse Osmosis (RO) System

Preliminary Scope

The project to be undertaken is a design of an iron removal pretreatment system for a small reverse osmosis (RO) unit. The iron removal system will use naturally occurring air to oxidize and precipitate dissolved iron in well water incoming to the RO unit. The precipitate will be filtered out by an inexpensive filter. This is done in order to extend the life of the more expensive RO filter membranes. The iron removal system will feature a flow-through design and will be mounted on an auxiliary skid near the RO unit. Restrictions include refraining from using an air pump or other device that will require additional power to operate the pretreatment system.

Figure 6: Iron-fouled RO Membrane (Membranes should be white)

Location of Work

AquaTech will be testing hard well water from a Stillwater resident to establish the initial specifications listed below. The assembly and testing of the prototype will be done in the Biosystems Lab. Initial calculations used water conditions at Pumps of Oklahoma in Oklahoma City, OK due to equipment shipping difficulties.

Description of Client

AquaTech will conduct designs and testing for Pumps of Oklahoma, Incorporated. Pumps of Oklahoma is a wholesale supplier of industrial, municipal, agricultural, and environmental pumps. They supply submersible and above ground pump equipment all over the world. Pumps of Oklahoma is located in Oklahoma City, OK and has 18 employees. Adam Avey, the team leader of AquaTech, served as the summer intern for this company in the summer of 2012 and worked to design and fabricate the current Reverse Osmosis system.

Industry Analysis

Trends

Consumers in the United States pay scrupulous attention to the quality of the water they are drinking. This is evident with the increase of bottled water consumption in the U.S., which continues to climb throughout the years.

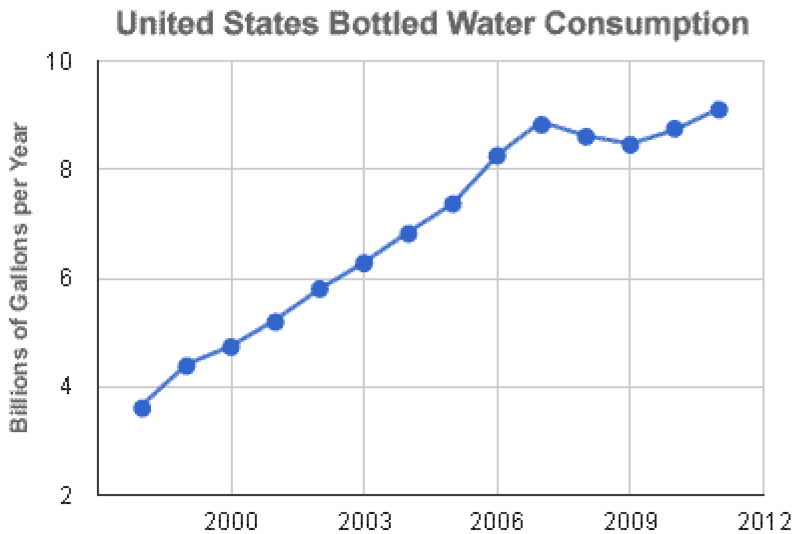


Figure 7: Bottled Water Consumption

Many people in the U.S. are concerned about drinking water because of contaminants such as bacteria, viruses, pesticides, petroleum products, metals and metalloids, and strong acids among others.

Technologies for water treatment are becoming more effective and less costly. Recently, there has been a lot of new developments in water treatment, some of them include: activated carbon, ozonation, ultraviolet germicidal irradiation, and bioceramic water amplification, among others.

Marketing Strategy

For this particular product a great marketing strategy would be selling the Reverse Osmosis System to construction companies that could put install it in houses, that way Pumps of Oklahoma could design a standard prototype for a particular type of houses and build a whole lot of them, instead of building customized products or products that couldn't probably fit in a particular house.

Competitive Products

The most common water treatment products that are used for well water are listed below in **Table 1**.

Table 5: Competitive Products

Product	Technique	Price Range	Website
Terminox ISM	Chlorine injector and mixing tank	$550 - $975	www.budgetwater.com
Pyrolox	Granular water filtration media	$670 -$ 885	www.qualitywaterforless.com
Greensand	Glauconite greensand filtration media	$625 - $885	www.qualitywaterforless.com
Birm	Filtration media	$435 - $710	www.qualitywaterforless.com
Eagle Redox Alloy	Iron Oxidization Catalyst	$25	www.qualitywaterforless.com

Technical Analysis

The U.S. Environmental Protection Agency (EPA) secondary drinking water standard for iron is 0.3 parts per million. Above this level, water may develop an orange color. AquaTech researched several different methods in order to create a pretreatment that will remove ferrous iron from drinking water. A chemical analysis was conducted in order to quantify the amount of oxygen needed to oxidize the iron and filter it mechanically. Methods were examined from common household water treatment systems, large-scale wastewater aeration systems, and existing patents used for iron oxidation and removal.

Chemical Analysis

The team used the following reaction equation found in **Appendix B**. The team used water conditions of the Pumps of Oklahoma water well, assuming 3.2 ppm Iron, Fe, in the water.

Using $Fe(II) + \frac{1}{4} O_2 + 2OH^- + \frac{1}{2} H_2O \longrightarrow Fe(OH)_{(s)}$

Given 3.2ppm Fe in tested water,

$3.2 mg/L\ Fe * mol/55.85g\ Fe * 1g/1000mg * \frac{1}{4}\ mol\ O_2/1\ mol\ Fe * 32g\ O_2/1\ mol\ O_2 = 0.000458\ g/L\ O_2$

$= 0.458\ mg/L\ O_2$

$= 0.459\ ppm\ O_2$

Air is composed of about 21% O_2. Since air has a molecular weight of about 28.96g/mol, there is about 251 mg/L of O_2 available in the air. This is assuming the ideal gas law holds and that the temperature of the air is about 25^oC and at standard pressure. Therefore, there should be adequate amounts of oxygen available in the incoming air to completely oxidize the Fe(II) to Fe(OH).

Common Methodology

Water Softeners

Water softeners, which charge water with resins such as potassium chloride and sodium chloride, are commonly used to remove low levels of ferrous iron around 1 – 3 ppm. However, it is not uncommon to remove up to 10 depending on the water conditions. The pH level highly affects the oxidization process of iron, which is unwanted with the use of a water softener. Therefore, softeners increase performance with a lower pH level. However, water softeners are often expensive units ranging from $500 to over $1000. Also, the resin must be replaced regularly, becoming an increasingly expensive task that is often done by qualified contractors. Since many water softeners work by replacing the hard metals with sodium, this can create a possible health issue. People with history of hypertension or heart risk are advised to abstain from using water softeners, since it will add a new level of salt into your daily diet.

Aeration Systems

Large-scale Treatment

Many wastewater treatment plants use different aeration systems in order to achieve an adequate level of oxygen transfer required for aerobic waste treatment. Two principal types of aeration systems are diffusion-air systems and mechanical aeration. While diffusion-air aeration requires an introduction of air or pure oxygen by a submerged diffuser, mechanical aeration devices agitate the water to promote a mixture with the air from the atmosphere. Thus, mechanical aeration requires a motor and power source, but not a pumping system.

Two common types of mechanical aeration used in postaeration systems are low-speed surface aerators and submerged turbine aerators. Low-speed surface aerators are typically the most economical choice, except when high oxygen transfer rates are required. Most plants maintain two or more aerators in rectangular basins.

One of the most economical aeration systems is called cascade aeration. Cascade aeration uses the available head and a thin film of water to create turbulence as it falls over a series of steps. The most common equation used for cascade aeration was developed by Barrett in 1960:

$$H = \frac{R-1}{0.11ab(1+0.046T)} \qquad \text{(English Units)}$$

where $R = \text{deficit ratio} = \frac{C_S - C_O}{C_S - C}$

C_S = dissolved oxygen saturation concentration of the wastewater at temperature T, mg/L

C_O = dissolved oxygen concentration of the postaeration influent, mg/L

C = required final dissolved oxygen level after postaeration, mg/L

a = water-quality parameter equal to 0.8 for a wastewater-treatment plant effluent

b = weir geometry parameter for a weir, b = 1.0; for steps, b = 1.1; for step weir, b = 1.3

T = water temperature, ^{o}C

H = height through which water falls, ft

However, this technique requires enough flow to raise DO levels and often takes up a large amount of space. For water conditions at the Pumps of Oklahoma well in Oklahoma City, OK, the team assumed that C_S is 9.08 mg/L at 20 ^{o}C (Appendix D), C_O is 0 mg/L (assume anaerobic groundwater), C is 3.6 mg/L (assuming there is a higher limit of iron, 25 mg/L), a is 0.9 due to water clarity, b is 1.0, and T is 20 ^{o}C. With these inputs, the height, H, is calculated to be 3.5 feet. However, this design would require wide lateral movement as well as its height requirement. While this may be a low-cost option, the space requirement and difficulty of installation makes this an inadequate option.

Household Water Treatment

In some household iron oxidation systems, a venturi apparatus, or eductor, aerates the water so that the ferrous iron is oxidized, resulting in a ferric form. Once converted to ferric iron, the water is able to be run through a mechanical filtration unit for iron removal. In order for the system to run smoothly, the oxygen must be then removed from the water so the fluid is in a single-phase form. In order for this to occur, a deaeration technique must be applied. Although eductors are relatively expensive, the maintenance requirements are very low, since there is no chemical or resin required to refill. However, many eductors are installed with an air compressor to ensure proper iron oxidation. Compared to water softeners, a high pH level is desired in order for an optimized oxidization rate. Little safety risk was found with the use of venturi apparatus.

Patent Searches

AquaTech found four patents that proved particularly relevant to the iron pretreatment system focusing in the aeration and deareation of water. Full patents can be found in **Appendix A**.

- *Reactor Apparatus for Treating Water in Iron Removal System* (US 5725759)
- *Water Aerator and Method* (US 4255360)
- *Method and Apparatus for Removing Iron from Well Water* (US 5080805)
- *Iron Removal System and Method* (US 5096580)

Reactor Apparatus for Treating Water in Iron Removal System, patent 5725759, was published in 1998 and provides a valuable method to deaerate the water before it continues past pretreatment. *Water Aerator and Method*, patent 4255360, was published in 1981 and gives an example of a submergible electrically powered water pump used for the aeration of water. *Method and Apparatus for Removing Iron from Well Water*, patent 5080805, was published in 1992 and focuses on water aeration by means of a bubbling device connected to a source of pressurized air. *Iron Removal System and Method*, patent 5096580, was published in 1992 and uses a venturi apparatus to mix the air and untreated water. In theory, patents 4255360 and 5725759 could be combined to convert the ferrous iron to a ferric state through aeration and then proceed to deaerate the water to form a single-phase fluid in the system.

Requirements & Specifications

Customer Requirements

The details of AquaTech Engineering Solutions' project requirements have purposely been left somewhat vague by our customer in order to prevent the limitation of creativity by previous suppositions. That being said, there are some baseline specifications that must be met:

- The device must achieve the EPA standard for acceptable iron content in drinking water.
- The device must treat the water in a continuously flowing stream.
- The device should avoid the use of additional mechanical hardware (such as a compressor).
- The device should be able to remove whatever substances (such as air) that have been added to the water stream before the stream continues on the reverse osmosis system.
- The device must stand alone on a skid separate from the RO system

Development of Quantitative Engineering Specifications

Essential quantitative data will be acquired via chemical calculations and controlled physical experimentation. The details are as follows:

AquaTech Engineering Solutions will conduct experiments to determine a well water sample's iron oxidation potential with a given ferrous iron concentration. Experiments to quantify the ideal air to water ratio and required residence time will be performed. Establishing these two parameters will allow flow rates to be defined and for the selection of a reaction vessel, venturi, aeration nozzle, and precipitate filter.

To determine the ideal air to water ratio, first, a theoretical chemical analysis will be performed. Bottle testing will follow to establish the physical limitations of the theoretical maximum given our particular circumstances. Bottles will be filled with certain air and water volumes and immediately mechanically agitated for a given amount of time, filtered through 5-micron paper filter and then tested for iron content. Initial physical testing values will be based upon the theoretical maximum found through chemical analysis.

Bottle testing will also be the means of determining the most appropriate residence time for maximum ferrous-to-ferric iron conversion. The most effective air to water ratio (determined previously) and mechanical agitation will preface increasing residence times. Following residence time, the sample water will be filtered through 5-micron filter paper and then tested for iron content. Results from this series of experiments and the previous will be recorded and analyzed via Microsoft Excel.

Experimentation

A lab test was researched and conducted to determine if the Hanna Instruments Iron Checker would be able to correctly calculate the amount of ferrous iron in the well sample in addition to the total amount of iron present in ppm. After the lab tests were finished, a field test was conducted on a well for real ferrous and total iron values.

Lab Test

To ensure field readings accuracy, a standard curve for ferrous iron was derived in the lab using the following reagents and procedure (Figure 2). The concentration of ferrous ammonium sulfate used was originated from *Standard Methods for the Examination of Water and Wastewater* (Standard, 1980). The remaining reagent concentrations were derived from a lab that was conducted at Truman State University (Truman, 2008).

Table 2: Reagents used in making Fe(II) standards

Reagent	Molecular Formula	Use
Ferrous Ammonium Sulfate 6- Hydrate	$Fe(NH_4)(SO_4)_2*6H_2O$	Known amount of ferrous iron in standard
(1,10) Phenanthroline	$C_{12}N_2H_8$	Coloring Agent
Sodium Acetate	$NaOCOCH_3$	Buffering agent to fix pH
Sulfuric Acid	H_2SO_4	Stabilizes Fe(II) and takes care of impurities

A mass spectrophotometer sends out a pre-set wavelength of light and reads the absorbance of that light through a sample. The absorbance can be used to calculate the concentration of a substance, like iron, by Beer's Law as seen below:

$$A = \varepsilon bc$$

Where A = Absorbance

ε = Molar Extinction Coefficient (L/mol*cm)

b = Path length (1cm)

c = Concentration (mol/L)

Beer's law is valid for absorbance, which is dimensionless, between 0.1 and 1.0 in which it has a linear relationship with concentration (Muller, 2000). This is used to check standard solutions. The wavelength used for iron by the Hanna Instruments Iron Checker is 525nm, so the mass spectrophotometer was also set at 525nm.

The standards were made according to the procedure below to achieve $[Fe(Phen)_3]^{2+}$. This molecule turns a bright reddish orange color and can be measured by the mass spectrophotometer (Muller, 2000).

$Fe^{2+} + 3\ Phen \rightarrow [Fe(Phen)_3]^{2+}$

1. Dissolve 0.7022g of $Fe(NH_4)(SO_4)_2*6H_2O$ and 2.5mL of sulfuric acid to 1L with deionized water.
2. In a separate 100mL volumetric flask, add 0.1g of (1,10) phenanthroline and fill to volume with deionized water (DI). Stir on stirrer until solution is clear.
3. In another 100mL volumetric flask, add 10g of sodium acetate and fill to volume with DI. Stir on stirrer until solution is clear.
4. Set out 7 100mL volumetric flasks for the 7 standards (0.1, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0ppm) and label them accordingly.
5. In the 5.0ppm flask, add 5mL of the ferrous ammonium sulfate solution, 10mL of (1,10) phenanthroline solution, and 8mL of the sodium acetate solution. Fill to volume with DI water and allow them to set for 10 minutes before measuring their absorbance with the mass spectrophotometer.
6. For the other six standards, repeat Step 5 except add the corresponding amount of ferrous ammonium sulfate solution as the flask reads. For example, for 4ppm add 4mL of $Fe(NH_4)(SO_4)_2*6H_2O$, etc.
7. Read each absorbance and record the absorbance vs. concentration at 525nm.
8. Plot absorbance vs. concentration in Excel and check linearity of the line. If R^2=0.99 or better, than Beer's Law was fulfilled.

The standards were measured and the linearity was conserved, as seen below.

Table 3: Standards and Absorption measured by mass spectrophotometer

Standard	Absorption
0	0
0.1	0.034
0.5	0.158
1.0	0.239
2.0	0.562
3.0	0.75
4.0	1.145
5.0	1.43

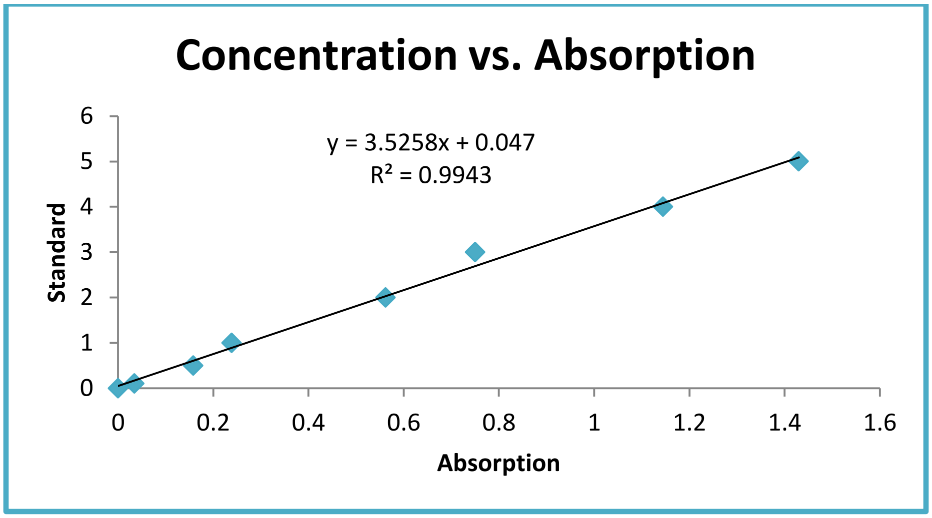


Figure 1: Plot of standard concentration of ferrous iron vs. absorption

Figure 2: Ferrous Iron Standards in the lab

Field Test

A field test was conducted at a local home in Stillwater, OK. The well tested has been tested for high concentrations of sulfate, another inorganic that makes water "hard". A new batch of (1,10) phenanthroline and sodium acetate was made in the lab that afternoon to take to the well site in addition to the Hanna Instruments Test Reagents for total iron content. Supplies needed for the field test were borrowed from Dr. Penn from the Plant and Soil Science department at OSU. Four well samples were tested for both total iron and ferrous iron and can be seen in Table 4. The field procedure was conducted as follows:

For ferrous iron concentration:

1. Draw 20mL of well sample and fill to the brim of the tube and seal to minimize oxidation.
2. Take 10mL of well sample and put into one cuvette (cuvette 1) to use as the zeroing agent for the Hanna Instruments Iron Checker.
3. Add 1.0mL of the pre-made (1,10) phenanthroline and 0.8mL of the pre-made sodium acetate solution to a separate 10mL cuvette (cuvette 2).
4. Fill cuvette 2 to volume with raw well sample.
5. Seal cuvettes and click the button on the Hanna Instruments Iron Checker to turn it on.
6. Place cuvette 1 in the checker and click the button again.
7. Open and place cuvette 2 in the checker and hold the button until the timer on the checker begins.
8. After two minutes, the concentration of ferrous iron will read digitally. Record the concentration and repeat.

For total iron concentration:

1. Draw 20mL of well sample and fill to the brim of the tube and seal to minimize oxidation.
2. Take 10mL of well sample and put into one cuvette to use as the zeroing agent for the Hanna Instruments Iron Checker.
3. Click the button on the checker and place the zeroing sample into the checker.
4. Click the button again.
5. Remove the cuvette and add one packet of the Hanna Instruments Test Reagents to the 10mL sample.
6. Gently swirl until the reagent is dissolved and place back into the checker.
7. Hold the button on the checker until the timer begins.
8. Record concentration reading after two minutes and repeat with a new sample.

Table 4: Field test results

Sample	Ferrous Iron (ppm)	Total Iron (ppm)
1	0.45	-
2	0.44	-
3	0.39	-
4	0.41	-
5	-	0.60
6	-	0.53
7	-	0.56
8	-	0.52
Average	0.43	0.55

Figure 8: Adam and David Prepare Well Sample

Figure 9: Deep Water Well Used for Testing

Development of Quantitative Engineering Specifications

Essential quantitative data will be acquired via chemical calculations and controlled physical experimentation. The details are as follows:

AquaTech Engineering Solutions will conduct experiments to determine a well water sample's iron oxidation potential with a given ferrous iron concentration. Experiments to quantify the ideal air to water ratio and required residence time will be performed. Establishing these two parameters will allow flow rates to be defined and for the selection of a reaction vessel, venturi, aeration nozzle, and precipitate filter.

To determine the ideal air to water ratio, first, a theoretical chemical analysis will be performed. Bottle testing will follow to establish the physical limitations of the theoretical maximum given our particular circumstances. Bottles will be filled with certain air and water volumes and immediately mechanically agitated for a given amount of time, filtered through 5-micron paper filter and then tested for iron content. Initial physical testing values will be based upon the theoretical maximum found through chemical analysis.

Bottle testing will also be the means of determining the most appropriate residence time for maximum ferrous-to-ferric iron conversion. The most effective air to water ratio (determined previously) and mechanical agitation will preface increasing residence times. Following residence time, the sample water will be filtered through 5-micron filter paper and then tested for iron content. Results from this series of experiments and the previous will be recorded and analyzed via Microsoft Excel.

Design Concepts

After the team's review of several iron removal systems listed in the Technical Analysis, the following two designs were developed. Both options were designed in order to minimize power and space requirements in order to prove suitable as a household unit.

Aeration via misting nozzles

This design option receives the influent directly from the well and passes it through an eductor. The eductor draws air into the stream, creating a turbulent, two-phase flow. AquaTech employee and teammate Adam Avey observed over the summer that the air introduced into the water formed in large bubbles. This was determined by attaching clear vinyl tubing onto the effluent side of the eductor. The stream then continues on to the reaction vessel where nozzles disperse the fluid into finer droplets. The fine dispersion maximizes the contact between oxygen and the iron-rich water and therefore increases the dissolved iron's exposure to oxygen, aiding in the reaction process. The liquid water collects below the nozzles where a burp valve maintains the water level by releasing spent air from the reaction vessel. The air in the reaction vessel is continually refreshed by the air drawn in by the eductor and released by the burp valve. The de-aerated water then continues on the RO skid so that the now precipitated iron can be filtered out before the stream enters the reverse osmosis membranes. Figure 1 displays the concept. The eductor is pictured at (A.), the misting nozzles at (B.) and the burp valve at (C.)

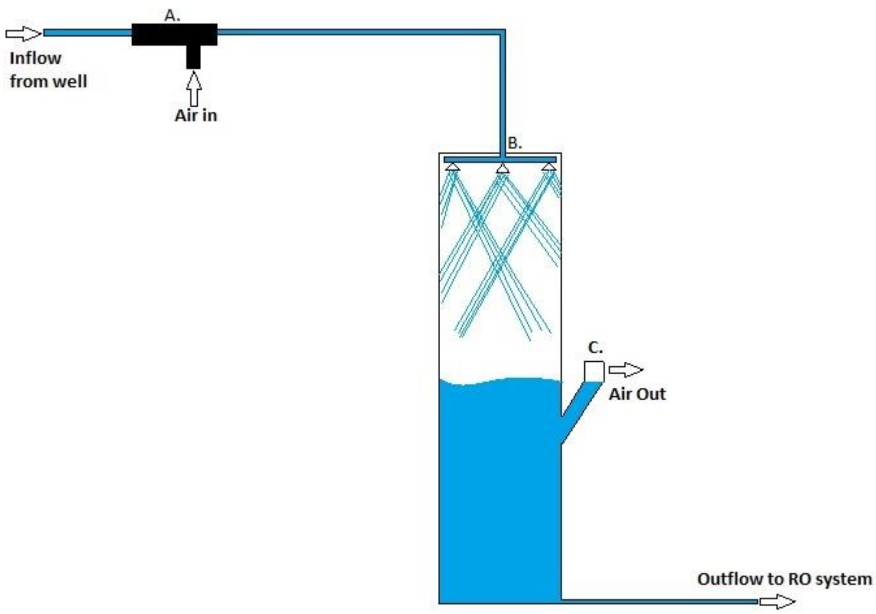


Figure 10: Design One – Nozzles

Vessel Sizing

The vessel was sized assuming a residence time of 30 seconds is necessary for the iron to be oxidized by the introduced air. However, it is important that the residence time necessary is directly dependent upon the pH level in the well water. With a peak flow rate of 8 gallons per minute and a residence time of .5 minutes, the vessel would be required to hold 4 gallons, equal to 924 in^3. A vessel with a diameter of 6 inches and a height of 33 inches would be able to 933 in^3 of water and therefore will be able to hold the incoming well water. However, initial calculations were made using an assumed vessel height of 48 inches.

Design Calculations

The theoretical pressures and velocities were calculated at various locations throughout the designed system. This was accomplished by using the equation of continuity, Bernoulli's equation, the head loss equation (Darcy-Weisbach), and a venture equation. The equations previously listed are expressed below respectively:

- $Q = V_1A_1 = V_2A_2$
- $\frac{p_1}{\gamma} + \frac{{V_1}^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{{V_2}^2}{2g} + z_1 + h_L$
- $h_L = h_{L_{major}} + h_{L_{minor}} = f\frac{l}{D}\frac{V^2}{2g} + K_L\frac{V^2}{2g}$
- $Q = C_v A_T \sqrt{\frac{2(p_1 - p_2)}{\rho(1-\beta^4)}}$

Table 6: Pressure and Velocity Table

	Velocity (ft/s)	Pressure (psi)	Head Loss (ft)
1	3.3	60	-
2	3.3	58.3	0.18
3	23.3	55.9	2.66
4	52.4	47.4	2.87
5	93.3	8.4	2.67
6	0.09	48.4	0
7	3.3	48.3	0.04

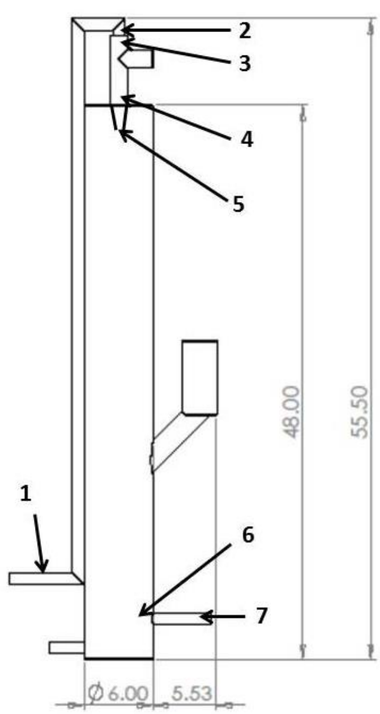


Figure 11: CAD Design with Pressures

The calculations were made with the assumption that only one nozzle would be necessary. The total head loss due to friction loss and fittings is 8.4 feet. The pressure drop across the eductor is 8.5 psi.

Nozzle Selection

For the selection of the nozzle, AquaTech inquired upon Bete, a leader in spray nozzle manufacturers. Bete TF nozzles are specialized to emit very fine droplets, which would increase contact between oxygen and the high-iron water.

With a peak flow rate of 8 gallons per minute and a pressure of around 50 psi, they recommended the BETE TF-12. The specification sheet located in **Appendix C** was consulted and it was found that a pressure of 4.13 Bar, equal to 47.4 psi (as seen in **Table 2** at point 4), would be within the operating capacity of the nozzle.

Figure 12: BETE TF-12 Nozzle

Aeration via porous media

This design option also uses an eductor to directly receive the raw well water. The eductor draws air into the stream, creating a turbulent, two phase flow. The stream then continues to the reaction vessel where it is distributed evenly over a bed of porous media. The porous media bed consists of small spheres with baffles to achieve a large surface area. An example of this media is pictured in Figure 2. The porous media bed is packed tightly, but air space is left between the spheres. The water flow over the spheres remains turbulent, promoting excellent air/water contact and thorough mixing. After passing through the porous media bed the aerated water collects at the bottom of the reactor vessel before continuing on to the RO skid. The precipitated iron is filtered out before entering the reverse osmosis membranes. Just as in the misting nozzle concept, the water level in the reactor vessel is maintained with a burp valve. Figure 3 displays the concept. The eductor is pictured at (A.), the porous media bed at (B.) and the burp valve at (C.)

Figure 13: Porous Media

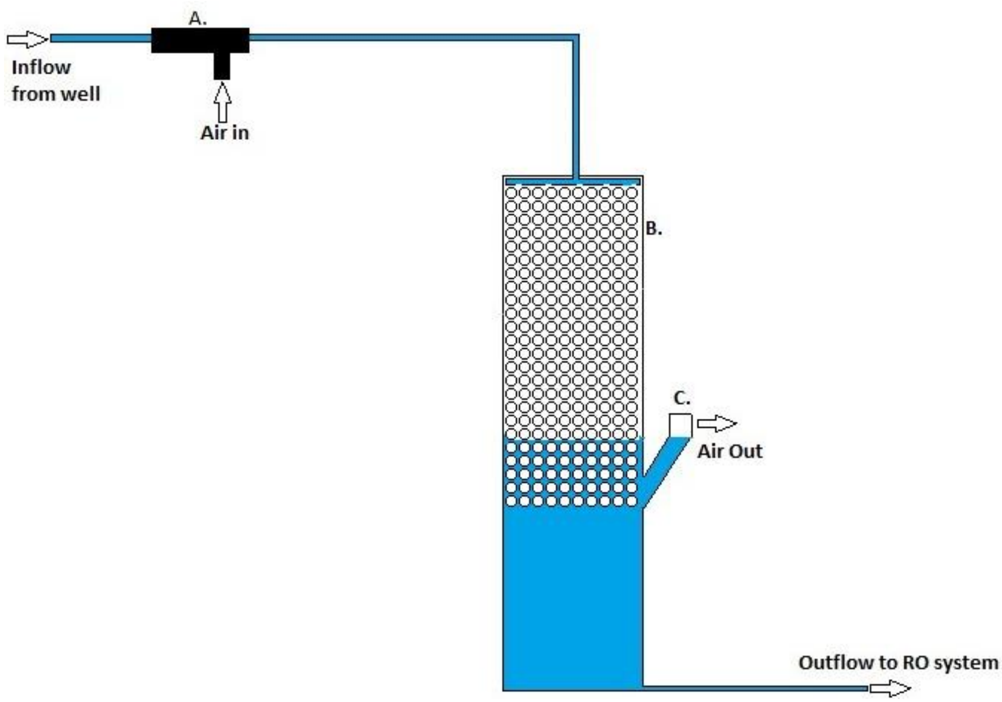


Figure 14: Design Two – Porous Media

AquaTech considers both of the above designs to be feasible options. At this point, performance differences are difficult to calculate, given the variability of both systems. Maintenance requirements are also difficult to estimate because of the varying quality of water that both systems might treat. However, it can be predicted that both systems will require more maintenance when exceptionally hard water is being treated. The misting nozzle option is a very affordable option. However, the spherical porous media is readily available and relatively inexpensive. Both options can be tailored to treat different levels of iron concentration. In most cases, the size of the reaction vessel would be increased with increasing dissolved iron concentration.

Design Calculations

The theoretical pressures and velocities were calculated at various locations throughout the designed system. However, due to the addition of the porous media in the vessel, pressures and velocities were not able to calculated. There is an equation by Darcy which is used to calculate velocities through a porous media, such as soils, but this equation cannot be applied because there are too many unknowns in the equation that cannot be assumed.

Table 7: Velocity and Pressure Table for Porous Media Design

	Velocity (ft/s)	Pressure (psi)	Head Loss (ft)
1	3.3	60	-
2	3.3	58.3	0.18
3	23.3	55.9	2.66
4	52.4	47.4	2.87

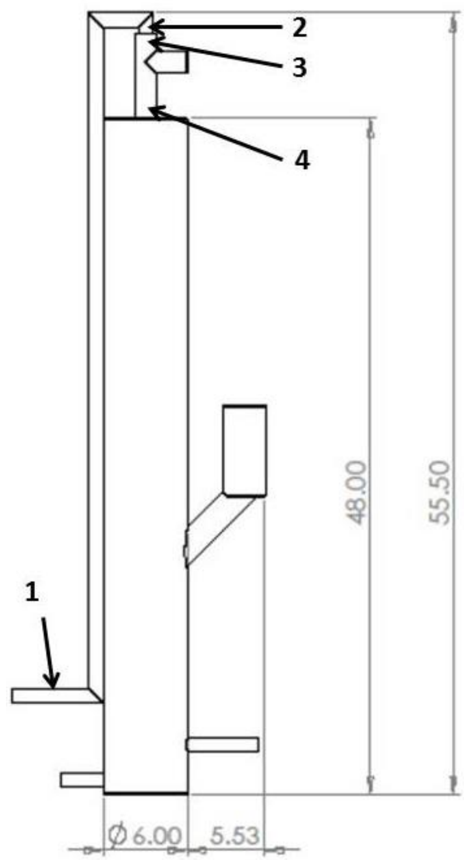


Figure 15: CAD Design II with Pressures

Team leader Adam Avey constructed the following drawing in SolidWorks to present the design in a three-dimensional form. The green piece at the bottom of the tank is valve that was added towards the end of the design process. The team decided that a valve would be needed in order to release the possible accumulation of inorganic particulates in the case that the pretreatment system and RO unit is used intermittently. If the flow is not continuous, particles, such as precipitated iron, will have the opportunity to settle to the bottom of the tank, which could possible disrupt the flow of the system or prove detrimental to the mechanical filter proceeding the pretreatment process. The purple piece is the eductor, the yellow the inflow pipe, and the brown the outflow pipe.

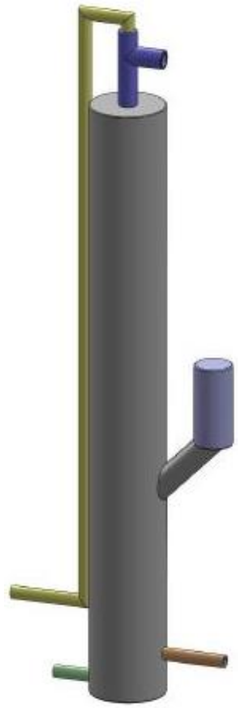


Figure 16: 3-D SolidWorks Drawing

Environmental and Societal Impacts

Environmental impacts of the proposed designs are considerably low considering that the proposed pretreatment systems do not require any chemical agents or power requirement. These elements of design are used to promote the reduction of water pollution and carbon emissions. The iron pretreatment system will impact well water users by offering an alternative to common well water purification systems that requires less maintenance and less cost over time.

Prototype Budget

The following budget was organized with the help of Pumps of Oklahoma employees Micah Goodspeed and Adam Avey:

Aeration via Misting Nozzles

Table 8: Design One Budget

Eductor	$160.00
Piping & Fittings	$20.00
Burp Valve	$65.00
Nozzles	$15.00

Total: $260.00

Aeration via Porous Media

Table 9: Design Two Budget

Eductor	$160.00
Piping & Fittings	$20.00
Burp Valve	$65.00
Filter Media	$100.00

Total: $345.00

Work Breakdown Structure

AquaTech organized a list of deliverables for the team to accomplish throughout the fall and spring semesters. The following task list was constructed and used to form the Gantt chart shown in the **Project Schedule** section.

1. Determine theoretical maximum oxidation values via chemical analysis
    - 1.1. Locate local well water source with high iron content
    - 1.2. Bottle tests to measure dissolved oxygen levels (DO)
    - 1.2.1. Acquire Iron Checker Colorimeter
2. Empirically test physical well water samples to determine maximum oxidation potential in a real-world process
    - 2.1 Bottle test local water source
3. Analyze test results in regard to potential product designs
    - 3.1. Compare with air compressor or pump analysis
    - 3.2. Determine most effective air introduction method
4. Sketch and evaluate potential product designs
    - 4.1. Hard sketches in notebooks
    - 4.2. CAD drawings for prototype
    - 4.3. Conduct flow rate/ mass balance analysis
5. Assemble fall design report
    - 5.1. Research background information
    - 5.1.1. Patent research analyses
    - 5.2. Compile design drawings
    - 5.3. Write out proposal for design and supporting statements
6. Give fall design presentation for client
    - 6.1. Make PowerPoint Presentation

6.2. Incorporate customer feedback

7. Determine and locate materials for prototype

    7.1. Research materials and their specifications to fit our product

    7.2. Internet search for price and shipping comparisons

    7.3. Order materials

    7.4. Request/Reserve lab space for building

8. Acquire materials

9. Assemble prototype

10. Test prototype

    10.1. Meet EPA standard of 3 ppm Iron

    10.2. Calculate/Measure flow rate

    10.3. Measure Iron removed

    10.4. Measure oxidation rate

    10.5. Measure oxygen removal

    10.6. Measure power input

    10.7. Test durability of product

    10.8. Develop Operation and Maintenance (O&M) specifications

11. Final product presentation and report

    11.1. Compile data into report

    11.1.1. Insert drawings and calculations

    11.1.2. Analysis and comparison to original design

    11.1.3. Does it meet requirements?

    11.2. Make PowerPoint presentation

Project Schedule

The following schedule and Gantt chart were composed to organize AquaTech's tasks:

Table 10: Project Schedule

Task Name	Duration	Start	Finish
Physically test local water samples to determine max real-world oxidation values	2 days	Mon 11/5/12	Tue 11/6/12
Analyze test results in regards to potential product designs	1 day	Wed 11/7/12	Wed 11/7/12
Sketch and evaluate potential product designs	1 day	Thu 11/8/12	Thu 11/8/12
Assemble Fall desing report	2 days	Wed 11/21/12	Thu 11/22/12
Give fall design presentation for client	0 days	Fri 11/23/12	Fri 11/23/12
Determine and locate materials for prototype	10 days	Mon 1/14/13	Fri 1/25/13
Acquire materials	10 days	Mon 1/28/13	Fri 2/8/13
Assemble prototype	14 days	Mon 2/11/13	Thu 2/28/13
Test prototype	7 days	Fri 3/1/13	Mon 3/11/13
Final product presentation and report	0 days	Tue 4/30/13	Tue 4/30/13

Appendix B

Location: BAE Demo Room   Date: 4/8/2013
Description: Oxygenation Test
Personell: Avey, Criswell & Criswell

Test Number: 01-01   pH: 6.0   Flow Rate: 1 gpm

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Air Flow (SCFH)	Fe Conc. (ppm)
1	10.50	11.10	5	76.5	0
2	10.30	12.41	10	75	0
3	10.48	13.17	15	75	0
4	10.55	13.87	20	74	0
5					
6					
7					
8					
9					
10					

Notes: Open/Flow-through (for the air); allowing some air to escape to open atmosphere

Test Number: 01-02   pH: 6.3   Flow Rate: 1 gpm

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Air Flow (SCFH)	Fe Conc. (ppm)
1	10.65	12.13	5	0	0
2	10.65	12.80	10	0	0
3	10.65	13.47	15	0	0
4	10.70	14.10	20	0	0
5					
6					
7					
8					
9					
10					

Notes: Air valve closed/dead end; forcing all air into water

Comments:

Appendix C

Location: BAE Demo Room Date: 4/10/2013
Description: Iron Removal Test
Personell: Avey, Criswell & Criswell

Test Number: 02-01 pH: 6.3 Flow Rate: 1 gpm Total Fe Influent: 0.32

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Air Flow (SCFH)	Ferrous Fe Conc. (ppm)	Total Fe Conc. (ppm)
1	10.65	-	5	0	0.23	
2	10.65	12.74	10	0	0.14	
3	10.65	13.21	15	0	0.2	
4	10.65	13.52	20	0	0.2	
5	10.65	13.79	25	0	0.19	
6						
7						
8						
9						
10						

Notes: Closed air; Let flow 5 min, then took sample

Test Number: 02-02 pH: 6.12 Flow Rate: 1 gpm Total Fe Influent: 0.73

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Air Flow (SCFH)	Ferrous Fe Conc. (ppm)	Total Fe Conc. (ppm)
1	11.07	12.50	5	0	0.73	
2	11.07	12.90	10	0	0.75	
3	11.19	12.87	15	0	0.73	
4	11.23	13.42	20	0	0.78	
5						
6						
7						
8						
9						
10						

Notes: Air valve closed/dead end; forcing all air into water

Location: BAE Demo Room **Date:** 4/10/2013
Description: Iron Removal Test
Personell: Avey, Criswell & Criswell

Test Number: 02-03 **pH:** 6.0 **Flow Rate:** 1 gpm **Total Fe Influent:** 3.14

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Air Flow (SCFH)	Ferrous Fe Conc. (ppm)	Total Fe Conc. (ppm)
1	11.11	12.74	5	0	5.00	2.09
2	11.11	13.22	10	0	0.09	2.75
3	11.32	13.63	15	0	5.00	1.55
4	11.55	13.73	20	0	5.00	1.11
5			Tank	0	5.00	1.89
6						
7						
8						
9						
10						

Notes: Iron input - 3.14 Total ppm ... took 4.8 g of iron sulfate

Location: BAE Demo Room **Date:** 4/17/2013
Description: Iron Removal Test, Adjusted pH with NaOH
Personell: Avey, Criswell & Criswell

Test Number: 03-01 **pH:** 6.6 **Flow Rate:** 1 gpm

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Fe Conc. (ppm)
1	-	-	5	0.28
2	-	-	10	0
3	-	-	15	0
4	-	-	20	0

Notes: There was no ferrous iron left in the tank either.
All iron was oxidized before the system.

Location: BAE Demo Room **Date:** 4/17/2013
Description: Iron Removal Test, Adjusted pH with NaOH and **no air flow**
Personell: Avey, Criswell & Criswell

Test Number: 03-02 **pH:** 6.4 **Flow Rate:** 1 gpm

Sample	Influent DO (mg/L)	Pressure (psi)	Air Flow (SCFH)	Fe Conc. (ppm)
1	10.04	Init.	0	5
2		5	0	3.96
3		10	0	3.95
4		15	0	3.93
5		20	0	3.78

Notes: 24% iron reduction
No air flow used in test with small reduction, so air is necessary for oxidation.

Location: BAE Demo Room **Date:** 4/17/2013

Description: Iron Removal Test, Adjusted pH with NaOH

Personell: Avey, Criswell & Criswell

Test Number: 03-03 **pH:** 7.48 **Flow Rate:** 1 gpm

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Fe Conc. (ppm)
1	-	-	Init.	0.19
2			5	0
3			10	0
4			15	0
5			20	0

Notes: Init. Total iron concentration was 2.53 ppm, ferrous iron was 0.19 ppm.
Oxidizing quickly in tank, especially if pH is above 7.0 threshold.

Location: BAE Demo Room **Date:** 4/22/2013
Description: Iron Removal Test, Adjusted pH with $CaCO_3$
Personell: Avey, Criswell & Criswell

Test Number: 03-04 **pH:** 6.82 **Flow Rate:** 1 gpm

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Fe2+ Conc. (ppm)
	10.38	10.38	Init. = 0	2.19
1	-	11.89	5	1.72
2	-	13.35	10	1.57
3	-	14.26	15	1.33
4	-	14.3	20	1.19

Notes: 45.6% reduction, pH not over 7.0 threshold.

Location: BAE Demo Room **Date:** 4/23/2013
Description: Iron Removal Test, NO pH adjustment, Bucket Tests
Personell: Avey, Criswell & Criswell

Test Number: 03-05 **pH:** 6.35 **Flow Rate:** 1 gpm

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	Pressure (psi)	Fe2+ Conc. (ppm)
	10.32	-	Init. = 0	1.43
1	-	-	20	1.08
2	-	-	15	0.86
3	-	-	10	0.75
4	-	-	tank	1.42

Notes: With closed bucket tests, oxidation was solely from membranes.
47.5% Reduction, so need pH adjustment.

Location: BAE Demo Room **Date:** 4/23/2013
Description: Iron Removal Test, NaOH pH adjustment, Bucket Tests
Personell: Avey, Criswell & Criswell

Test Number: **03-06** **pH:** **6.90** **Flow Rate:** **1 gpm**

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	After Fe^{2+} (min)	Fe2+ Conc. (ppm)
1	10.3	-	Init. = 0	1.3
2	-	-	2	0.44
3	-	-	3	0.18
4	-	-	4	0.14
5	-	-	5	0.16
6	-	-	Tank	0.5

Notes: With closed bucket test, all at 20 psi pressure.
87% reduction at pH=6.9.

Location: BAE Demo Room **Date:** 4/23/2013
Description: Iron Removal Test, NaOH pH adjustment, Bucket Tests
Personell: Avey, Criswell & Criswell

Test Number: **03-07** **pH:** **7.2** **Flow Rate:** **1 gpm**

Sample	Influent DO (mg/L)	Effluent DO (mg/L)	After Fe^{2+} (min)	Fe2+ Conc. (ppm)
1	10.3	-	Init. = 0	0.51
2	-	-	3	0
3	-	-	4	0
4	-	-	5	0
5	-	-	Tank	0

Notes: With closed bucket test, all at 20 psi pressure.
100% reduction at pH=7.2. Note that initial total iron = 1.78 but oxidized very quickly.

Appendix D

Macro040-P50

Membrane Characteristic

Membrane type	Hollow fiber – P5
Membrane material	Polypropylene
Pore size	0.1 μm
Typical flux	150 lm^2h@1bar 15°C *
OD/ID	240/310 μm
Surface treatment	None-hydrophobic**
Fiber burst pressure	>5.5 bar
Fiber collapse pressure	>3.5 bar
Strength	2 N/fiber

* Depend on feed quality

** None, single primered, permanent

Module Characteristic

Membrane surface area	0.4 m^2
Module flux	60 l/h@1bar 15°C *
Housing material	PVCu/clear PVCu
Potting material	Polyurethane **
pH resistance	2-11
Max working pressure	5 bar
Max working temperature	40°C
Connection	hose barb d16 ***
Dimensions	375x85x25 mm
Weight	170 g

* Depend on feed quality

** For special applications epoxy can be used

*** Connections can be easily customized, for larger quantities Luer Lock outlets can be used

Pretreatment System for Reverse Osmosis

Adam Avey, David Criswell, & Kelsey Criswell

AquaTech
Engineering Solutions

Mission Statement

"AquaTech Engineering Solutions' mission is to use its technical expertise and resources to provide customers with more affordable, longer lasting products."

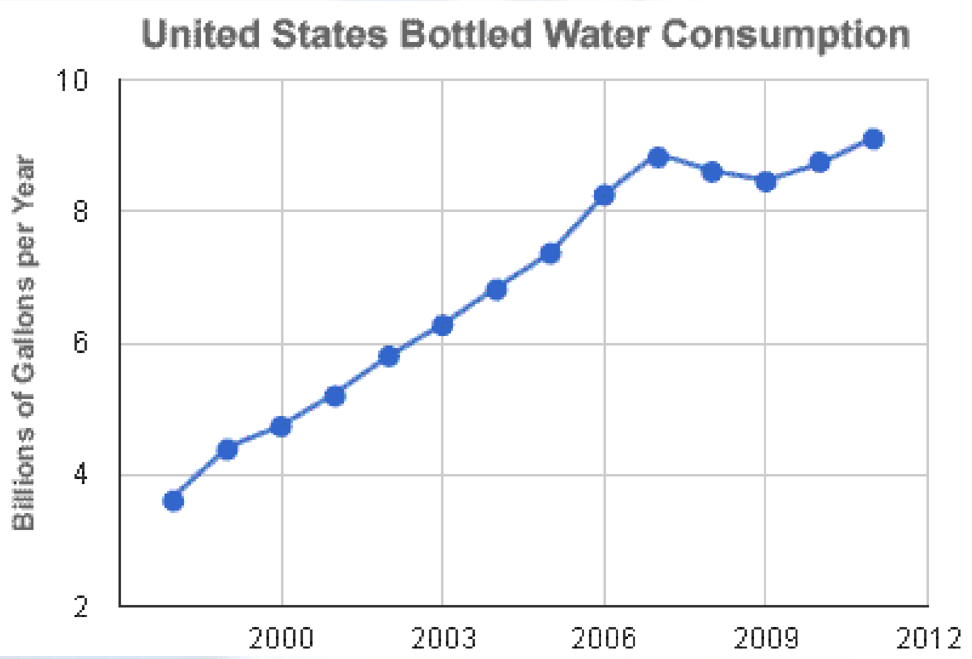
Problem Statement

"To design and fabricate a flow-through iron removal pretreatment module for a household reverse osmosis (RO) system."

Reverse Osmosis System

Target Group

- Rural Homeowners
- Small Businesses



http://geology.com/articles/bottled-water.shtm

Market Analysis

- Agriculture Business Teammate:
  Sergio Ruiz Esparza Herrera

- Strategy:
  - Design standard prototype
  - Sell RO system to construction firms

  - According to www.bccresearch.com the Reverse Osmosis industry is expected to have a compound annual growth rate of 7.3% over the next 5 years.

Chemistry

- $Fe(II)SO_4 + 2\ OH^- \rightarrow Fe(OH)_2 + SO_4^{2-}$
  - Need a slightly alkaline environment

- $Fe(II) + O_2 \longleftrightarrow Fe(III) + HO^-_2$

  $O_2^- + H_2O \longleftrightarrow HO_2 + OH^-$

Design Concept

- Add oxygen to a flowing stream of water to oxidize a concentration of dissolved iron, turning it from a soluble state to an insoluble state, and then proceed to mechanically filter out the precipitate to reduce the total amount of iron in the water stream.

Original Design Concept

- Eductor
- Minimize power input requirement
- Avoid using a holding tank
- Avoid sending bubbles in RO system

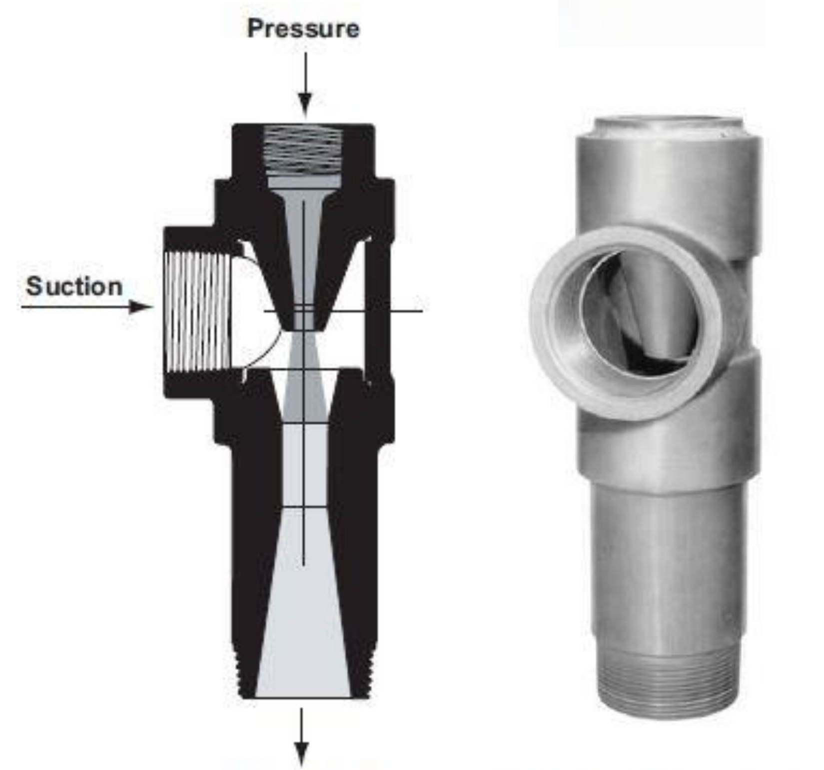
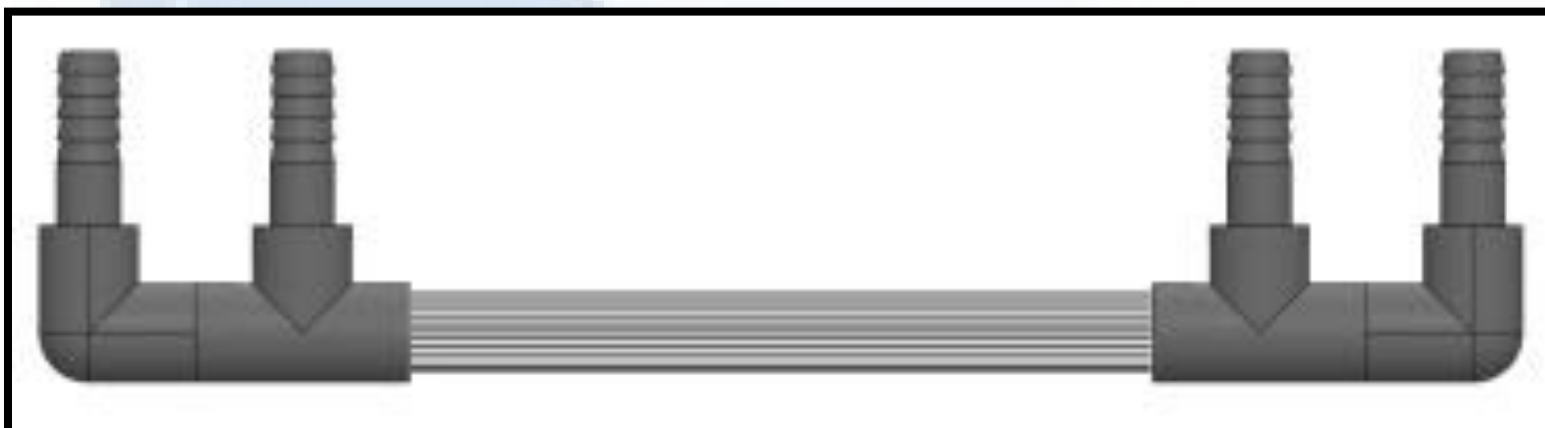


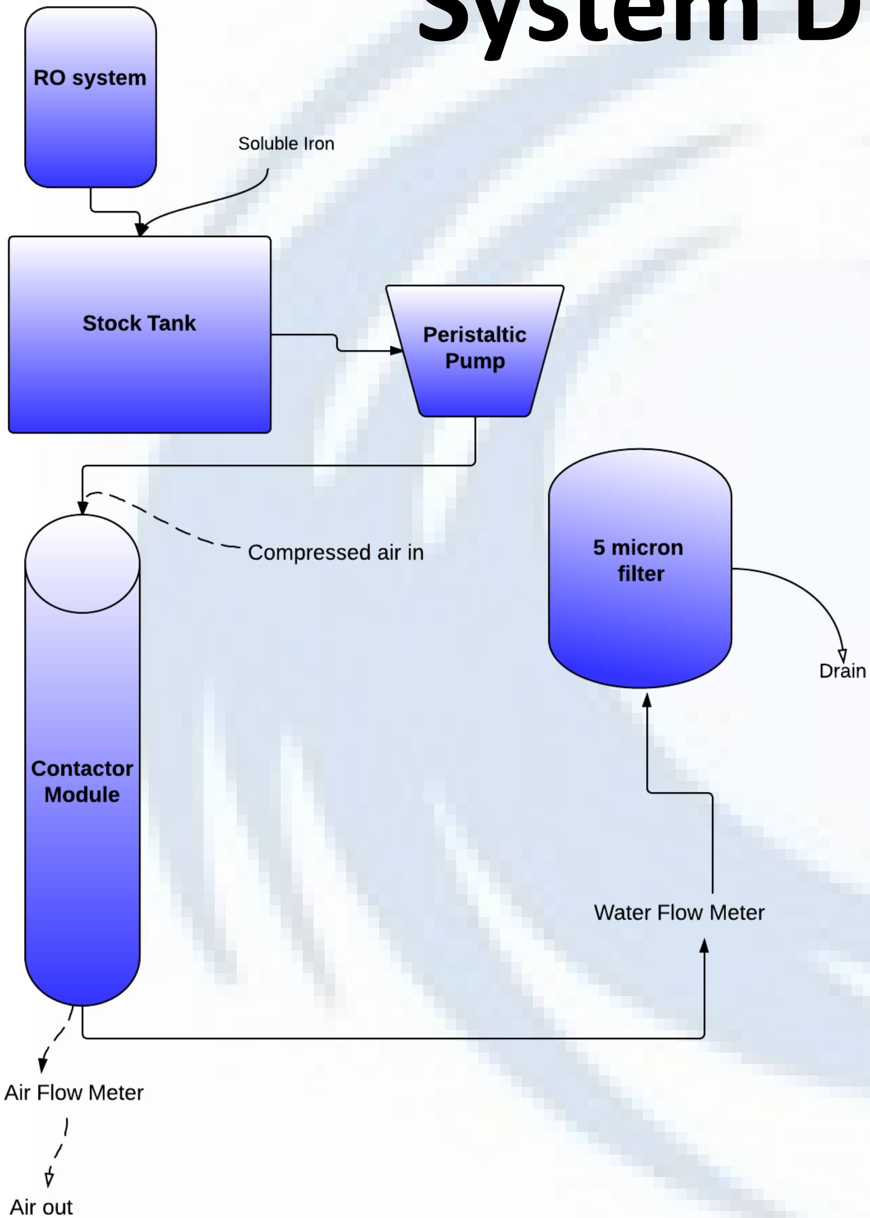
Fig. 5. FIG. 264 PVC EDUCTOR.

Revised Design Concept

- Polypropylene hydrophobic membrane
- Pore size: .1 µm



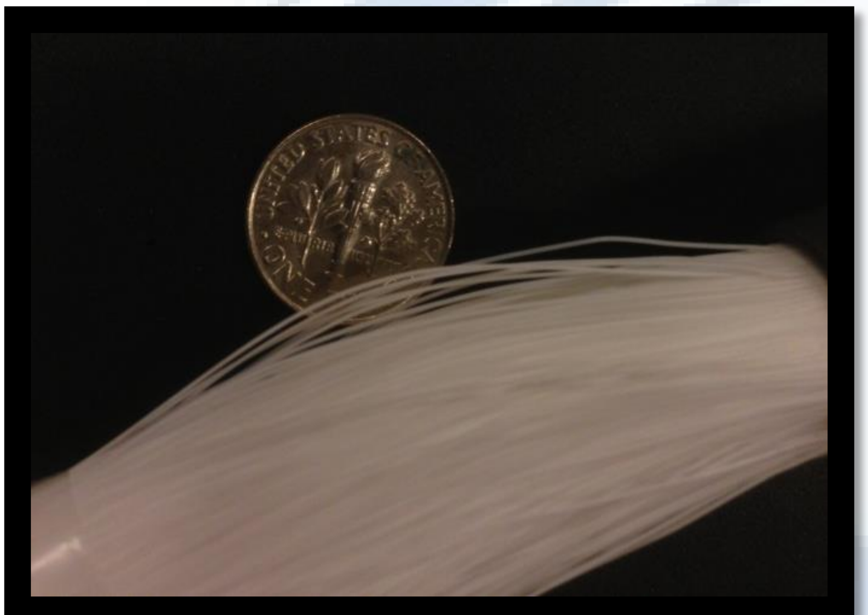
System Diagram



Equipment

Equipment

- Membranes and Contactors



ZENA membranes

Experimentation

1. Maximum Membrane Differential Pressure
2. Oxygenation Rate
3. Iron Removal Rate

Methodology: Test One

- Maximum Membrane Differential Pressure
  - Independent Variables:
    - Flow Rate (1 gpm)
    - Solution (Pure RO water)
    - Water Pressure (5 – 20 psi)
  - Dependent Variables:
    - Presence or absence of bubbles in membrane module

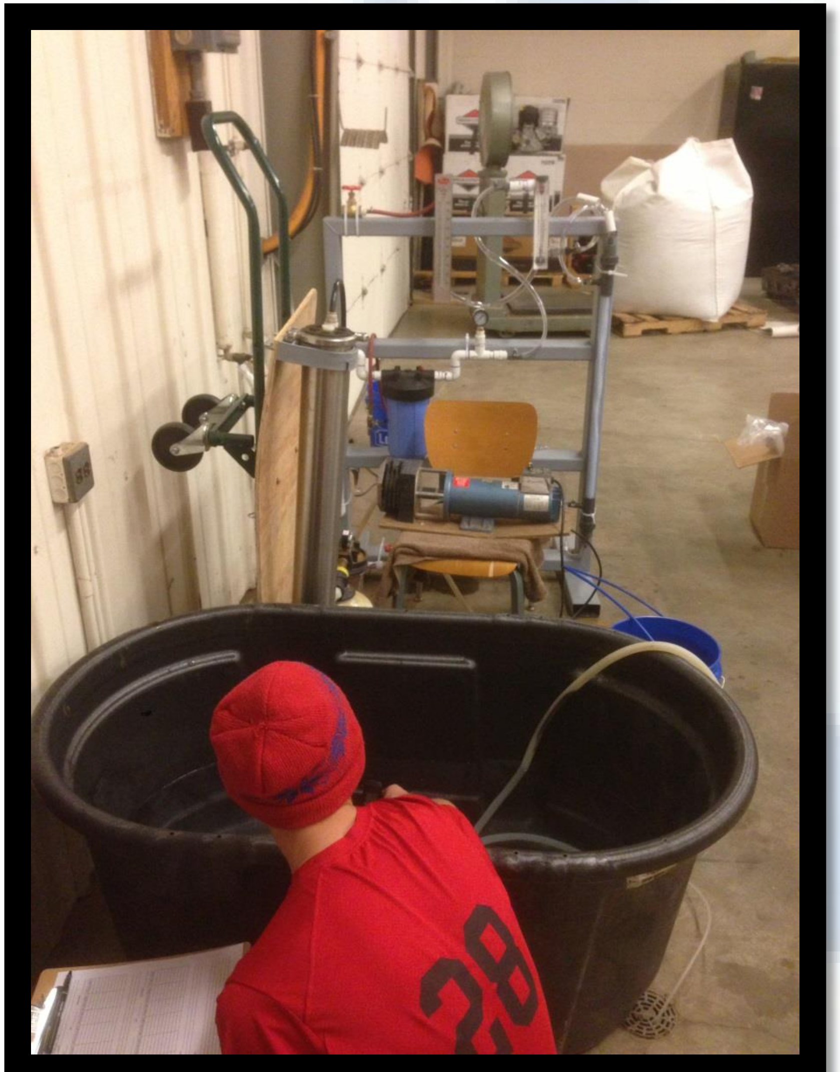
Results: Test One

- Max differential pressure before bubble formation is approximately 2 psi above system water pressure.

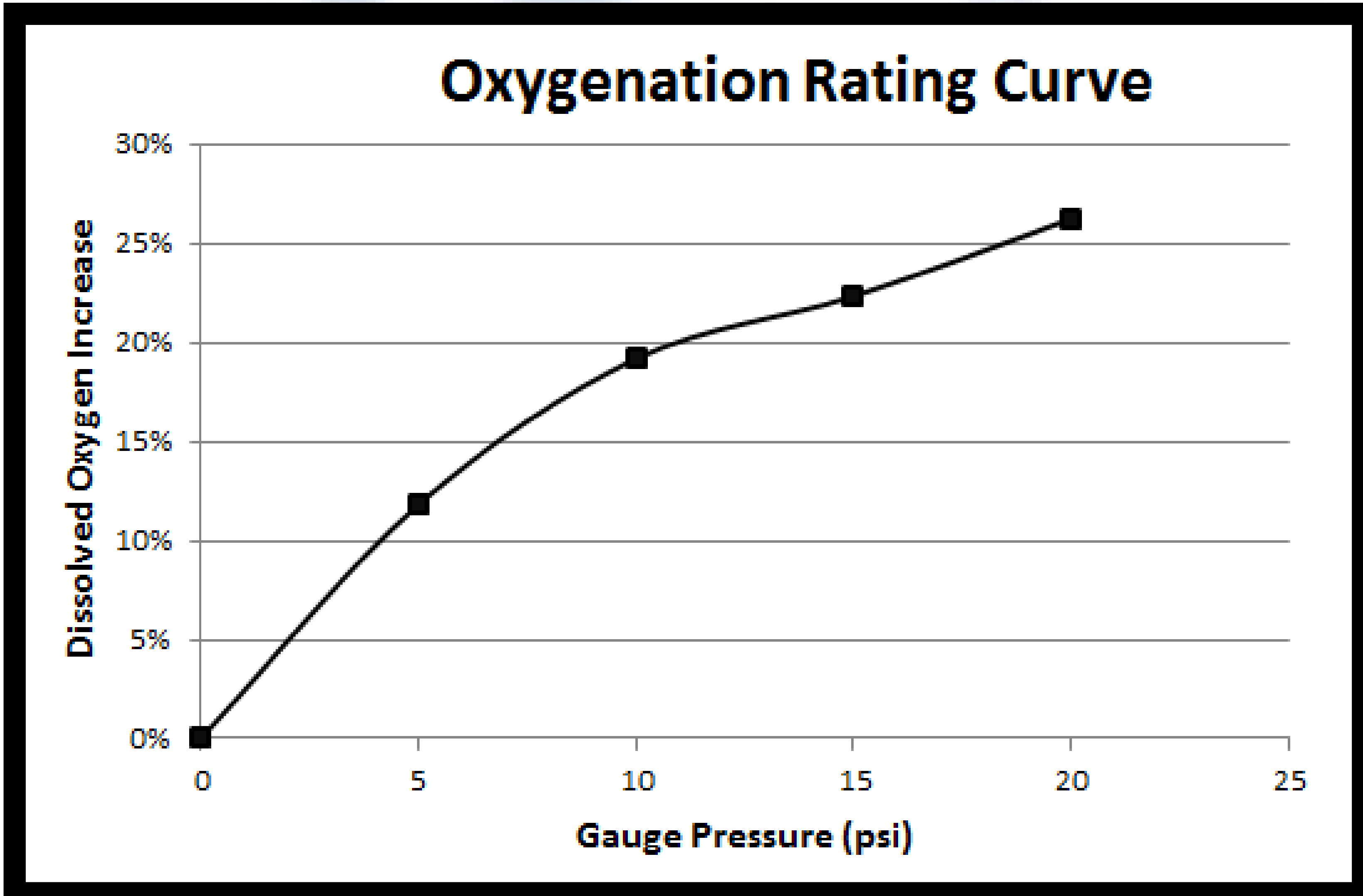
Methodology: Test Two

- Oxygenation Rate
  - Independent Variables:
    - Flow Rate (1 gpm)
    - Solution (Pure RO water)
    - Pressures (5 – 20 psi)
  - Dependent Variable:
    - Dissolved Oxygen levels

Testing Procedures



1. Measure DO in influent
2. Run system at given pressure
3. Measure DO in effluent


Oxygenation Rating Curve
Dissolved Oxygen Increase
30%
25%
20%
15%
10%
5%
0%
0
5
10
15
20
25
Gauge Pressure (psi)

Test 2: Oxygenation Rate

- Air valve open vs. air valve closed
- t = .2569; not significantly different

Methodology: Test Three

- Iron Oxidation and Removal
  - Independent Variables:
    - Iron concentrations (0.3, 0.7, 1, 3, 5 ppm)
    - Flow Rate (1 gpm)
    - Pressure (5 – 20 psi)
  - Dependent Variable:
    - Effluent Iron concentration

Testing Procedures

1. Create known soluble Iron concentration
2. Test pH level
3. Run system at given pressures
4. Measure Iron in effluent

Test 3.1: Open Tank

- Test #1:
  - RO water, 6.3 pH
- Test #2:
  - RO water, 6.6 pH adjusted with NaOH

Test 3.1 Results

- Test #1

	Initial (Fe)	5 psi	10 psi	15 psi	20 psi
Ferrous Fe Concentration (ppm)	0.32	0.23	0.14	0.2	0.2

  – 38% reduction

- Test #2

	Initial (Fe)	Initial (Fe2+)	5 psi	10 psi	15 psi	20 psi	Final tank (Fe)
Ferrous Fe Concentration (ppm)	2.32	1.49	0.28	0	0	0	0

  – 100% reduction but…

Test 3.2: pH Increase

- Artificial Increase using:
  - NaOH
  - $CaCO_3$
- Simulate basic groundwater conditions

Test 3.2 pH Increase

- Test #1
  - Raise pH to 6.8 with NaOH addition
  - No air flow
- Test #2
  - Raise pH to 6.82 with $CaCO_3$ addition
  - Normal testing conditions

Test 3.2 Results

- Test #1
  - 24% Fe reduction

	Initial	0 psi	5 psi	10 psi	15psi	20psi
Concentration (Fe2+) ppm	5	5	3.96	3.95	3.93	3.78

- Test #2
  - 46% Fe reduction

	Initial	5 psi	10 psi	15 psi	20 psi
Concentration (Fe2+) ppm	2.19	1.72	1.57	1.33	1.19

Test 3.3: Closed Tank

- Used closed system to minimize contact with atmosphere
- Simulate groundwater conditions

Test 3.3 Closed Tank

- Test #1
  - pH adjusted to 6.3 with NaOH
- Test #2
  - pH adjusted to 6.9 with NaOH
- Test #3
  - pH adjusted to 7.2 with NaOH

Test 3.3 Results

- Test #1: 24% Fe reduction

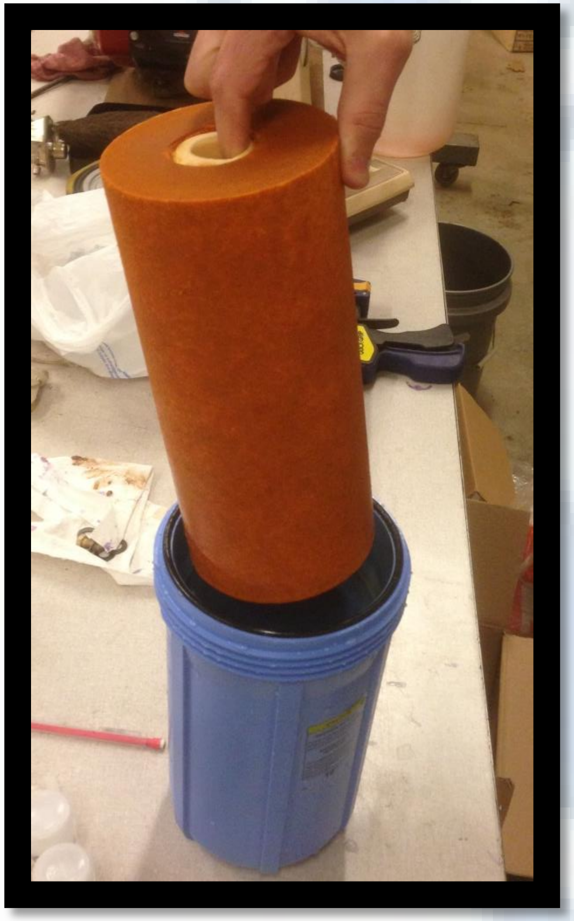
	Initial	20 psi	Tank
(Fe 2+) Concentration (ppm)	1.43	1.08	1.42

- Test #2: 88% Fe reduction

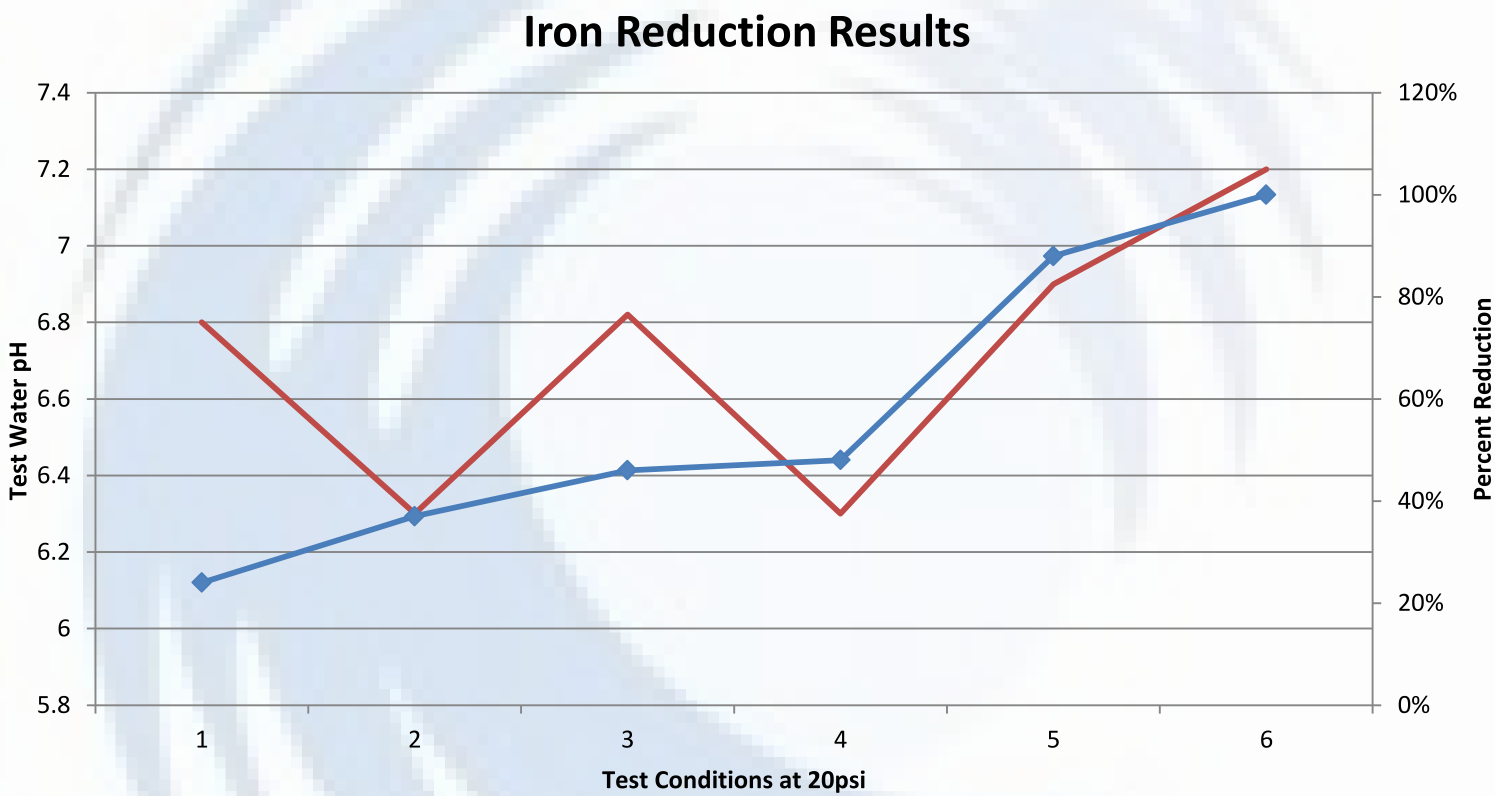
	Initial	20 psi	Tank
(Fe 2+) Concentration (ppm)	1.3	0.16	0.5

- Test #3: 100% Fe reduction

	Initial	20 psi	Tank
(Fe 2+) Concentration (ppm)	0.51	0.0	0.58



Summary



1	No Air Addtion [6.8pH]
2	Test #1 (No pH adjust)[6.3pH]
3	CaCO3 Adjust #1 [6.82pH]
4	Bucket Test 1 [6.3pH]
5	Bucket Test 2 [6.9pH]
6	Bucket Test 3 [7.2pH]

In all tests DO was increased from approximately 10ppm to 14ppm

Conclusion

- System effectively removes iron
- System works best with water with pH > 7.0
- Requires chemical addition for acidic water sources

Recommendations

- Larger/More efficient filter
- Further research on life of membranes
- Further research on high flow rate systems with multiple modules

Questions?

Acknowledgements

- Dr. Paul Weckler, Biosystems & Ag. Eng.
- Micah Goodspeed, Pumps of Oklahoma
- Dr. Glenn Brown, Biosystems & Ag. Eng.
- Dr. Dan Storm, Biosystems & Ag. Eng.
- Dr. Garey Fox, Biosystems & Ag. Eng.
- Dr. Chad Penn, Plant & Soil Sciences
- Stuart Wilson, Plant & Soil Sciences

Fall Design Report

AquaTech
Engineering Solutions

By Adam Avey, David Criswell, and Kelsey Criswell

Table of Contents

List of Figures

List of Tables

Mission Statement

"AquaTech Engineering Solutions' mission is to use its technical expertise and resources to provide customers with more affordable, longer lasting product."

Statement of Work

Problem Statement

To design and fabricate a flow-through iron removal pretreatment module for a household reverse osmosis (RO) system. Our secondary objective involves optimizing the RO system for different levels of water hardness and contamination.

Figure 1: Pumps of Oklahoma Reverse Osmosis (RO) System

Preliminary Scope

The project to be undertaken is a design of an iron removal pretreatment system for a small reverse osmosis (RO) unit. The iron removal system will use naturally occurring air to oxidize and precipitate dissolved iron in well water incoming to the RO unit. The precipitate will be filtered out by an inexpensive filter. This is done in order to extend the life of the more expensive RO filter membranes. The iron removal system will feature a flow-through design and will be mounted on an auxiliary skid near the RO unit. Restrictions include refraining from using an air pump or other device that will require additional power to operate the pretreatment system.

Figure 2: Iron-fouled RO Membrane (Membranes should be white)

Location of Work

AquaTech will be testing hard well water from a Stillwater resident to establish the initial specifications listed below. The assembly and testing of the prototype will be done in the Biosystems Lab. Initial calculations used water conditions at Pumps of Oklahoma in Oklahoma City, OK due to equipment shipping difficulties.

Description of Client

AquaTech will conduct designs and testing for Pumps of Oklahoma, Incorporated. Pumps of Oklahoma is a wholesale supplier of industrial, municipal, agricultural, and environmental pumps. They supply submersible and above ground pump equipment all over the world. Pumps of Oklahoma is located in Oklahoma City, OK and has 18 employees. Adam Avey, the team leader of AquaTech, served as the summer intern for this company in the summer of 2012 and worked to design and fabricate the current Reverse Osmosis system.

Industry Analysis

Trends

Consumers in the United States pay scrupulous attention to the quality of the water they are drinking. This is evident with the increase of bottled water consumption in the U.S., which continues to climb throughout the years.

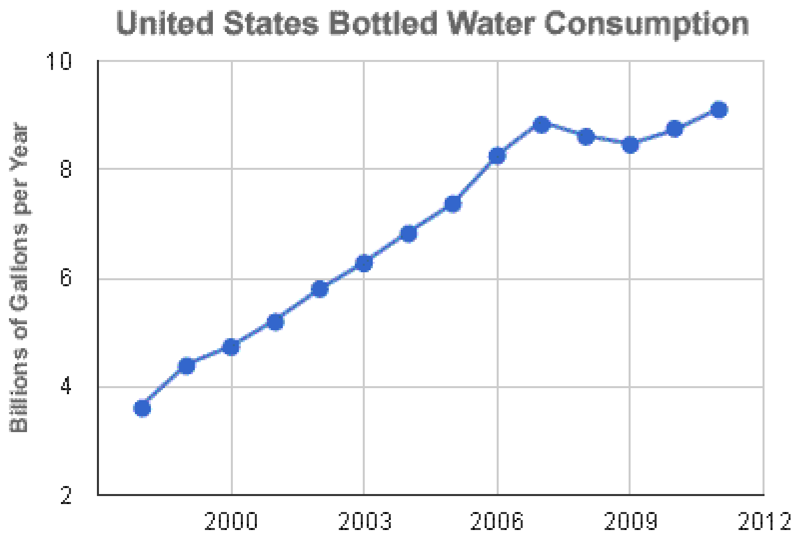


Figure 3: Bottled Water Consumption

Many people in the U.S. are concerned about drinking water because of contaminants such as bacteria, viruses, pesticides, petroleum products, metals and metalloids, and strong acids among others.

Technologies for water treatment are becoming more effective and less costly. Recently, there has been a lot of new developments in water treatment, some of them include: activated carbon, ozonation, ultraviolet germicidal irradiation, and bioceramic water amplification, among others.

Marketing Strategy

For this particular product a great marketing strategy would be selling the Reverse Osmosis System to construction companies that could put install it in houses, that way Pumps of Oklahoma could design a standard prototype for a particular type of houses and build a whole lot of them, instead of building customized products or products that couldn't probably fit in a particular house.

Competitive Products

The most common water treatment products that are used for well water are listed below in **Table 1**.

Table 1: Competitive Products

Product	Technique	Price Range	Website
Terminox ISM	Chlorine injector and mixing tank	\$550 - \$975	www.budgetwater.com
Pyrolox	Granular water filtration media	\$670 -\$ 885	www.qualitywaterforless.com
Greensand	Glauconite greensand filtration media	\$625 - \$885	www.qualitywaterforless.com
Birm	Filtration media	\$435 - \$710	www.qualitywaterforless.com
Eagle Redox Alloy	Iron Oxidization Catalyst	\$25	www.qualitywaterforless.com

Technical Analysis

The U.S. Environmental Protection Agency (EPA) secondary drinking water standard for iron is 0.3 parts per million. Above this level, water may develop an orange color. AquaTech researched several different methods in order to create a pretreatment that will remove ferrous iron from drinking water. A chemical analysis was conducted in order to quantify the amount of oxygen needed to oxidize the iron and filter it mechanically. Methods were examined from common household water treatment systems, large-scale wastewater aeration systems, and existing patents used for iron oxidation and removal.

Chemical Analysis

The team used the following reaction equation found in **Appendix B**. The team used water conditions of the Pumps of Oklahoma water well, assuming 3.2 ppm Iron, Fe, in the water.

Using $Fe(II) + \frac{1}{4} O_2 + 2OH^- + \frac{1}{2} H_2O \longrightarrow Fe(OH)_{(s)}$

Given 3.2ppm Fe in tested water,

$3.2mg/L\ Fe * mol/55.85g\ Fe * 1g/1000mg * \frac{1}{4}\ mol\ O_2/1\ mol\ Fe * 32g\ O_2/1\ mol\ O_2 = 0.000458\ g/L\ O_2$

$= 0.458\ mg/L\ O_2$

$= 0.459\ ppm\ O_2$

Air is composed of about 21% O_2. Since air has a molecular weight of about 28.96g/mol, there is about 251 mg/L of O_2 available in the air. This is assuming the ideal gas law holds and that the temperature of the air is about 25^oC and at standard pressure. Therefore, there should be adequate amounts of oxygen available in the incoming air to completely oxidize the Fe(II) to Fe(OH).

Common Methodology

Water Softeners

Water softeners, which charge water with resins such as potassium chloride and sodium chloride, are commonly used to remove low levels of ferrous iron around 1 – 3 ppm. However, it is not uncommon to remove up to 10 depending on the water conditions. The pH level highly affects the oxidization process of iron, which is unwanted with the use of a water softener. Therefore, softeners increase performance with a lower pH level. However, water softeners are often expensive units ranging from $500 to over $1000. Also, the resin must be replaced regularly, becoming an increasingly expensive task that is often done by qualified contractors. Since many water softeners work by replacing the hard metals with sodium, this can create a possible health issue. People with history of hypertension or heart risk are advised to abstain from using water softeners, since it will add a new level of salt into your daily diet.

Aeration Systems

Large-scale Treatment

Many wastewater treatment plants use different aeration systems in order to achieve an adequate level of oxygen transfer required for aerobic waste treatment. Two principal types of aeration systems are diffusion-air systems and mechanical aeration. While diffusion-air aeration requires an introduction of air or pure oxygen by a submerged diffuser, mechanical aeration devices agitate the water to promote a mixture with the air from the atmosphere. Thus, mechanical aeration requires a motor and power source, but not a pumping system.

Two common types of mechanical aeration used in postaeration systems are low-speed surface aerators and submerged turbine aerators. Low-speed surface aerators are typically the most economical choice, except when high oxygen transfer rates are required. Most plants maintain two or more aerators in rectangular basins.

One of the most economical aeration systems is called cascade aeration. Cascade aeration uses the available head and a thin film of water to create turbulence as it falls over a series of steps. The most common equation used for cascade aeration was developed by Barrett in 1960:

$$H = \frac{R-1}{0.11ab(1+0.046T)} \qquad \text{(English Units)}$$

where $R = \text{deficit ratio} = \frac{C_S - C_O}{C_S - C}$

C_S = dissolved oxygen saturation concentration of the wastewater at temperature T, mg/L

C_O = dissolved oxygen concentration of the postaeration influent, mg/L

C = required final dissolved oxygen level after postaeration, mg/L

a = water-quality parameter equal to 0.8 for a wastewater-treatment plant effluent

b = weir geometry parameter for a weir, b = 1.0; for steps, b = 1.1; for step weir, b = 1.3

T = water temperature, °C

H = height through which water falls, ft

However, this technique requires enough flow to raise DO levels and often takes up a large amount of space. For water conditions at the Pumps of Oklahoma well in Oklahoma City, OK, the team assumed that C_S is 9.08 mg/L at 20 °C (Appendix D), C_O is 0 mg/L (assume anaerobic groundwater), C is 3.6 mg/L (assuming there is a higher limit of iron, 25 mg/L), a is 0.9 due to water clarity, b is 1.0, and T is 20 °C. With these inputs, the height, H, is calculated to be 3.5 feet. However, this design would require wide lateral movement as well as its height requirement. While this may be a low-cost option, the space requirement and difficulty of installation makes this an inadequate option.

Household Water Treatment

In some household iron oxidation systems, a venturi apparatus, or eductor, aerates the water so that the ferrous iron is oxidized, resulting in a ferric form. Once converted to ferric iron, the water is able to be run through a mechanical filtration unit for iron removal. In order for the system to run smoothly, the oxygen must be then removed from the water so the fluid is in a single-phase form. In order for this to occur, a deaeration technique must be applied. Although eductors are relatively expensive, the maintenance requirements are very low, since there is no chemical or resin required to refill. However, many eductors are installed with an air compressor to ensure proper iron oxidation. Compared to water softeners, a high pH level is desired in order for an optimized oxidization rate. Little safety risk was found with the use of venturi apparatus.

Patent Searches

AquaTech found four patents that proved particularly relevant to the iron pretreatment system focusing in the aeration and deareation of water. Full patents can be found in **Appendix A**.

- *Reactor Apparatus for Treating Water in Iron Removal System* (US 5725759)
- *Water Aerator and Method* (US 4255360)
- *Method and Apparatus for Removing Iron from Well Water* (US 5080805)
- *Iron Removal System and Method* (US 5096580)

Reactor Apparatus for Treating Water in Iron Removal System, patent 5725759, was published in 1998 and provides a valuable method to deaerate the water before it continues past pretreatment. *Water Aerator and Method*, patent 4255360, was published in 1981 and gives an example of a submergible electrically powered water pump used for the aeration of water. *Method and Apparatus for Removing Iron from Well Water*, patent 5080805, was published in 1992 and focuses on water aeration by means of a bubbling device connected to a source of pressurized air. *Iron Removal System and Method*, patent 5096580, was published in 1992 and uses a venturi apparatus to mix the air and untreated water. In theory, patents 4255360 and 5725759 could be combined to convert the ferrous iron to a ferric state through aeration and then proceed to deaerate the water to form a single-phase fluid in the system.

Requirements & Specifications

Customer Requirements

The details of AquaTech Engineering Solutions' project requirements have purposely been left somewhat vague by our customer in order to prevent the limitation of creativity by previous suppositions. That being said, there are some baseline specifications that must be met:

- The device must achieve the EPA standard for acceptable iron content in drinking water.
- The device must treat the water in a continuously flowing stream.
- The device should avoid the use of additional mechanical hardware (such as a compressor).
- The device should be able to remove whatever substances (such as air) that have been added to the water stream before the stream continues on the reverse osmosis system.
- The device must stand alone on a skid separate from the RO system

Development of Quantitative Engineering Specifications

Essential quantitative data will be acquired via chemical calculations and controlled physical experimentation. The details are as follows:

AquaTech Engineering Solutions will conduct experiments to determine a well water sample's iron oxidation potential with a given ferrous iron concentration. Experiments to quantify the ideal air to water ratio and required residence time will be performed. Establishing these two parameters will allow flow rates to be defined and for the selection of a reaction vessel, venturi, aeration nozzle, and precipitate filter.

To determine the ideal air to water ratio, first, a theoretical chemical analysis will be performed. Bottle testing will follow to establish the physical limitations of the theoretical maximum given our particular circumstances. Bottles will be filled with certain air and water volumes and immediately mechanically agitated for a given amount of time, filtered through 5-micron paper filter and then tested for iron content. Initial physical testing values will be based upon the theoretical maximum found through chemical analysis.

Bottle testing will also be the means of determining the most appropriate residence time for maximum ferrous-to-ferric iron conversion. The most effective air to water ratio (determined previously) and mechanical agitation will preface increasing residence times. Following residence time, the sample water will be filtered through 5-micron filter paper and then tested for iron content. Results from this series of experiments and the previous will be recorded and analyzed via Microsoft Excel.

Experimentation

A lab test was researched and conducted to determine if the Hanna Instruments Iron Checker would be able to correctly calculate the amount of ferrous iron in the well sample in addition to the total amount of iron present in ppm. After the lab tests were finished, a field test was conducted on a well for real ferrous and total iron values.

Lab Test

To ensure field readings accuracy, a standard curve for ferrous iron was derived in the lab using the following reagents and procedure (Figure 2). The concentration of ferrous ammonium sulfate used was originated from *Standard Methods for the Examination of Water and Wastewater* (Standard, 1980). The remaining reagent concentrations were derived from a lab that was conducted at Truman State University (Truman, 2008).

Table 2: Reagents used in making Fe(II) standards

Reagent	Molecular Formula	Use
Ferrous Ammonium Sulfate 6- Hydrate	$Fe(NH_4)(SO_4)_2*6H_2O$	Known amount of ferrous iron in standard
(1,10) Phenanthroline	$C_{12}N_2H_8$	Coloring Agent
Sodium Acetate	$NaOCOCH_3$	Buffering agent to fix pH
Sulfuric Acid	H_2SO_4	Stabilizes Fe(II) and takes care of impurities

A mass spectrophotometer sends out a pre-set wavelength of light and reads the absorbance of that light through a sample. The absorbance can be used to calculate the concentration of a substance, like iron, by Beer's Law as seen below:

$$A = \varepsilon bc$$

Where A = Absorbance

ε = Molar Extinction Coefficient (L/mol*cm)

b = Path length (1cm)

c = Concentration (mol/L)

Beer's law is valid for absorbance, which is dimensionless, between 0.1 and 1.0 in which it has a linear relationship with concentration (Muller, 2000). This is used to check standard solutions. The wavelength used for iron by the Hanna Instruments Iron Checker is 525nm, so the mass spectrophotometer was also set at 525nm.

The standards were made according to the procedure below to achieve $[Fe(Phen)_3]^{2+}$. This molecule turns a bright reddish orange color and can be measured by the mass spectrophotometer (Muller, 2000).

$Fe^{2+} + 3\ Phen \rightarrow [Fe(Phen)_3]^{2+}$

1. Dissolve 0.7022g of $Fe(NH_4)(SO_4)_2*6H_2O$ and 2.5mL of sulfuric acid to 1L with deionized water.
2. In a separate 100mL volumetric flask, add 0.1g of (1,10) phenanthroline and fill to volume with deionized water (DI). Stir on stirrer until solution is clear.
3. In another 100mL volumetric flask, add 10g of sodium acetate and fill to volume with DI. Stir on stirrer until solution is clear.
4. Set out 7 100mL volumetric flasks for the 7 standards (0.1, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0ppm) and label them accordingly.
5. In the 5.0ppm flask, add 5mL of the ferrous ammonium sulfate solution, 10mL of (1,10) phenanthroline solution, and 8mL of the sodium acetate solution. Fill to volume with DI water and allow them to set for 10 minutes before measuring their absorbance with the mass spectrophotometer.
6. For the other six standards, repeat Step 5 except add the corresponding amount of ferrous ammonium sulfate solution as the flask reads. For example, for 4ppm add 4mL of $Fe(NH_4)(SO_4)_2*6H_2O$, etc.
7. Read each absorbance and record the absorbance vs. concentration at 525nm.
8. Plot absorbance vs. concentration in Excel and check linearity of the line. If R^2=0.99 or better, than Beer's Law was fulfilled.

The standards were measured and the linearity was conserved, as seen below.

Table 3: Standards and Absorption measured by mass spectrophotometer

Standard	Absorption
0	0
0.1	0.034
0.5	0.158
1.0	0.239
2.0	0.562
3.0	0.75
4.0	1.145
5.0	1.43

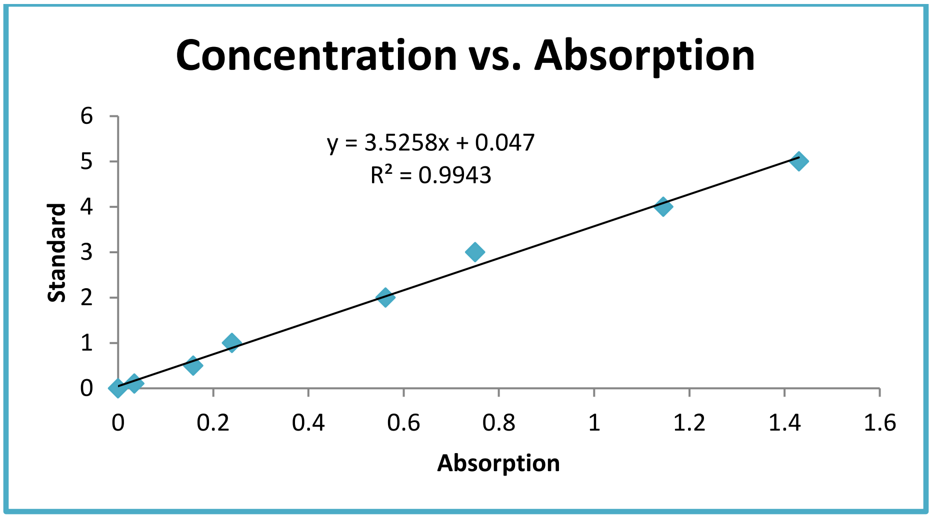


Figure 1: Plot of standard concentration of ferrous iron vs. absorption

Figure 2: Ferrous Iron Standards in the lab

Field Test

A field test was conducted at a local home in Stillwater, OK. The well tested has been tested for high concentrations of sulfate, another inorganic that makes water "hard". A new batch of (1,10) phenanthroline and sodium acetate was made in the lab that afternoon to take to the well site in addition to the Hanna Instruments Test Reagents for total iron content. Supplies needed for the field test were borrowed from Dr. Penn from the Plant and Soil Science department at OSU. Four well samples were tested for both total iron and ferrous iron and can be seen in Table 4. The field procedure was conducted as follows:

For ferrous iron concentration:

1. Draw 20mL of well sample and fill to the brim of the tube and seal to minimize oxidation.
2. Take 10mL of well sample and put into one cuvette (cuvette 1) to use as the zeroing agent for the Hanna Instruments Iron Checker.
3. Add 1.0mL of the pre-made (1,10) phenanthroline and 0.8mL of the pre-made sodium acetate solution to a separate 10mL cuvette (cuvette 2).
4. Fill cuvette 2 to volume with raw well sample.
5. Seal cuvettes and click the button on the Hanna Instruments Iron Checker to turn it on.
6. Place cuvette 1 in the checker and click the button again.
7. Open and place cuvette 2 in the checker and hold the button until the timer on the checker begins.
8. After two minutes, the concentration of ferrous iron will read digitally. Record the concentration and repeat.

For total iron concentration:

1. Draw 20mL of well sample and fill to the brim of the tube and seal to minimize oxidation.
2. Take 10mL of well sample and put into one cuvette to use as the zeroing agent for the Hanna Instruments Iron Checker.
3. Click the button on the checker and place the zeroing sample into the checker.
4. Click the button again.
5. Remove the cuvette and add one packet of the Hanna Instruments Test Reagents to the 10mL sample.
6. Gently swirl until the reagent is dissolved and place back into the checker.
7. Hold the button on the checker until the timer begins.
8. Record concentration reading after two minutes and repeat with a new sample.

Table 4: Field test results

Sample	Ferrous Iron (ppm)	Total Iron (ppm)
1	0.45	-
2	0.44	-
3	0.39	-
4	0.41	-
5	-	0.60
6	-	0.53
7	-	0.56
8	-	0.52
Average	0.43	0.55

Figure 4: Adam and David Prepare Well Sample

Figure 5: Deep Water Well Used for Testing

Development of Quantitative Engineering Specifications

Essential quantitative data will be acquired via chemical calculations and controlled physical experimentation. The details are as follows:

AquaTech Engineering Solutions will conduct experiments to determine a well water sample's iron oxidation potential with a given ferrous iron concentration. Experiments to quantify the ideal air to water ratio and required residence time will be performed. Establishing these two parameters will allow flow rates to be defined and for the selection of a reaction vessel, venturi, aeration nozzle, and precipitate filter.

To determine the ideal air to water ratio, first, a theoretical chemical analysis will be performed. Bottle testing will follow to establish the physical limitations of the theoretical maximum given our particular circumstances. Bottles will be filled with certain air and water volumes and immediately mechanically agitated for a given amount of time, filtered through 5-micron paper filter and then tested for iron content. Initial physical testing values will be based upon the theoretical maximum found through chemical analysis.

Bottle testing will also be the means of determining the most appropriate residence time for maximum ferrous-to-ferric iron conversion. The most effective air to water ratio (determined previously) and mechanical agitation will preface increasing residence times. Following residence time, the sample water will be filtered through 5-micron filter paper and then tested for iron content. Results from this series of experiments and the previous will be recorded and analyzed via Microsoft Excel.

Design Concepts

After the team's review of several iron removal systems listed in the Technical Analysis, the following two designs were developed. Both options were designed in order to minimize power and space requirements in order to prove suitable as a household unit.

Aeration via misting nozzles

This design option receives the influent directly from the well and passes it through an eductor. The eductor draws air into the stream, creating a turbulent, two-phase flow. AquaTech employee and teammate Adam Avey observed over the summer that the air introduced into the water formed in large bubbles. This was determined by attaching clear vinyl tubing onto the effluent side of the eductor. The stream then continues on to the reaction vessel where nozzles disperse the fluid into finer droplets. The fine dispersion maximizes the contact between oxygen and the iron-rich water and therefore increases the dissolved iron's exposure to oxygen, aiding in the reaction process. The liquid water collects below the nozzles where a burp valve maintains the water level by releasing spent air from the reaction vessel. The air in the reaction vessel is continually refreshed by the air drawn in by the eductor and released by the burp valve. The de-aerated water then continues on the RO skid so that the now precipitated iron can be filtered out before the stream enters the reverse osmosis membranes. Figure 1 displays the concept. The eductor is pictured at (A.), the misting nozzles at (B.) and the burp valve at (C.)

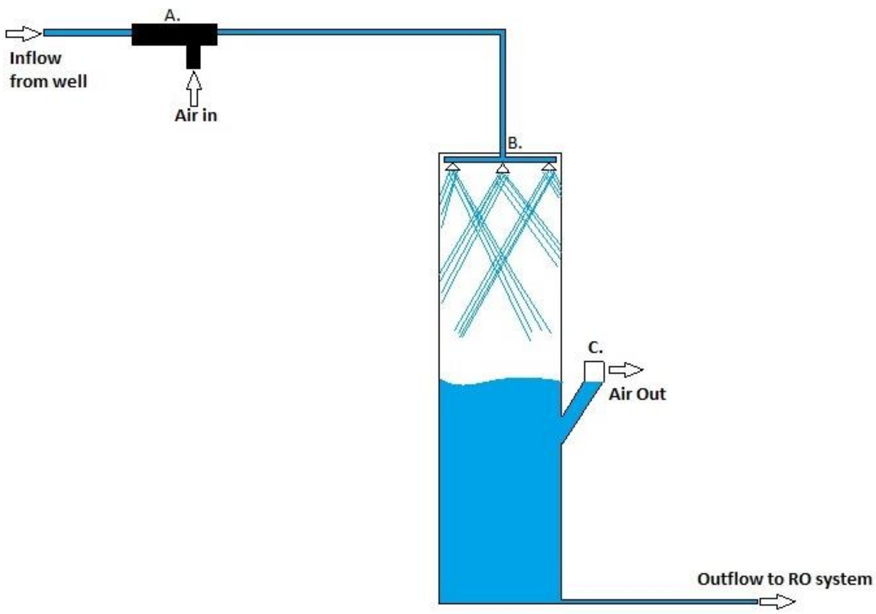


Figure 6: Design One – Nozzles

Vessel Sizing

The vessel was sized assuming a residence time of 30 seconds is necessary for the iron to be oxidized by the introduced air. However, it is important that the residence time necessary is directly dependent upon the pH level in the well water. With a peak flow rate of 8 gallons per minute and a residence time of .5 minutes, the vessel would be required to hold 4 gallons, equal to 924 in^3. A vessel with a diameter of 6 inches and a height of 33 inches would be able to 933 in^3 of water and therefore will be able to hold the incoming well water. However, initial calculations were made using an assumed vessel height of 48 inches.

Design Calculations

The theoretical pressures and velocities were calculated at various locations throughout the designed system. This was accomplished by using the equation of continuity, Bernoulli's equation, the head loss equation (Darcy-Weisbach), and a venture equation. The equations previously listed are expressed below respectively:

- $Q = V_1 A_1 = V_2 A_2$
- $\frac{p_1}{\gamma} + \frac{{V_1}^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{{V_2}^2}{2g} + z_1 + h_L$
- $h_L = h_{L_{major}} + h_{L_{minor}} = f\frac{l}{D}\frac{V^2}{2g} + K_L\frac{V^2}{2g}$
- $Q = C_v A_T \sqrt{\frac{2(p_1 - p_2)}{\rho(1-\beta^4)}}$

Table 2: Pressure and Velocity Table

	Velocity (ft/s)	Pressure (psi)	Head Loss (ft)
1	3.3	60	-
2	3.3	58.3	0.18
3	23.3	55.9	2.66
4	52.4	47.4	2.87
5	93.3	8.4	2.67
6	0.09	48.4	0
7	3.3	48.3	0.04

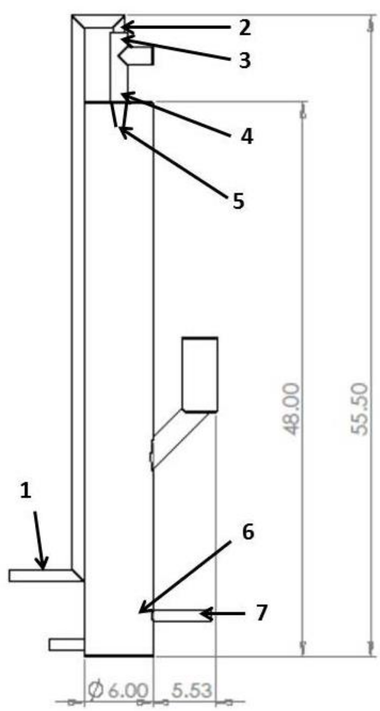


Figure 7: CAD Design with Pressures

The calculations were made with the assumption that only one nozzle would be necessary. The total head loss due to friction loss and fittings is 8.4 feet. The pressure drop across the eductor is 8.5 psi.

Nozzle Selection

For the selection of the nozzle, AquaTech inquired upon Bete, a leader in spray nozzle manufacturers. Bete TF nozzles are specialized to emit very fine droplets, which would increase contact between oxygen and the high-iron water.

With a peak flow rate of 8 gallons per minute and a pressure of around 50 psi, they recommended the BETE TF-12. The specification sheet located in **Appendix C** was consulted and it was found that a pressure of 4.13 Bar, equal to 47.4 psi (as seen in **Table 2** at point 4), would be within the operating capacity of the nozzle.

Figure 8: BETE TF-12 Nozzle

Aeration via porous media

This design option also uses an eductor to directly receive the raw well water. The eductor draws air into the stream, creating a turbulent, two phase flow. The stream then continues to the reaction vessel where it is distributed evenly over a bed of porous media. The porous media bed consists of small spheres with baffles to achieve a large surface area. An example of this media is pictured in Figure 2. The porous media bed is packed tightly, but air space is left between the spheres. The water flow over the spheres remains turbulent, promoting excellent air/water contact and thorough mixing. After passing through the porous media bed the aerated water collects at the bottom of the reactor vessel before continuing on to the RO skid. The precipitated iron is filtered out before entering the reverse osmosis membranes. Just as in the misting nozzle concept, the water level in the reactor vessel is maintained with a burp valve. Figure 3 displays the concept. The eductor is pictured at (A.), the porous media bed at (B.) and the burp valve at (C.)

Figure 9: Porous Media

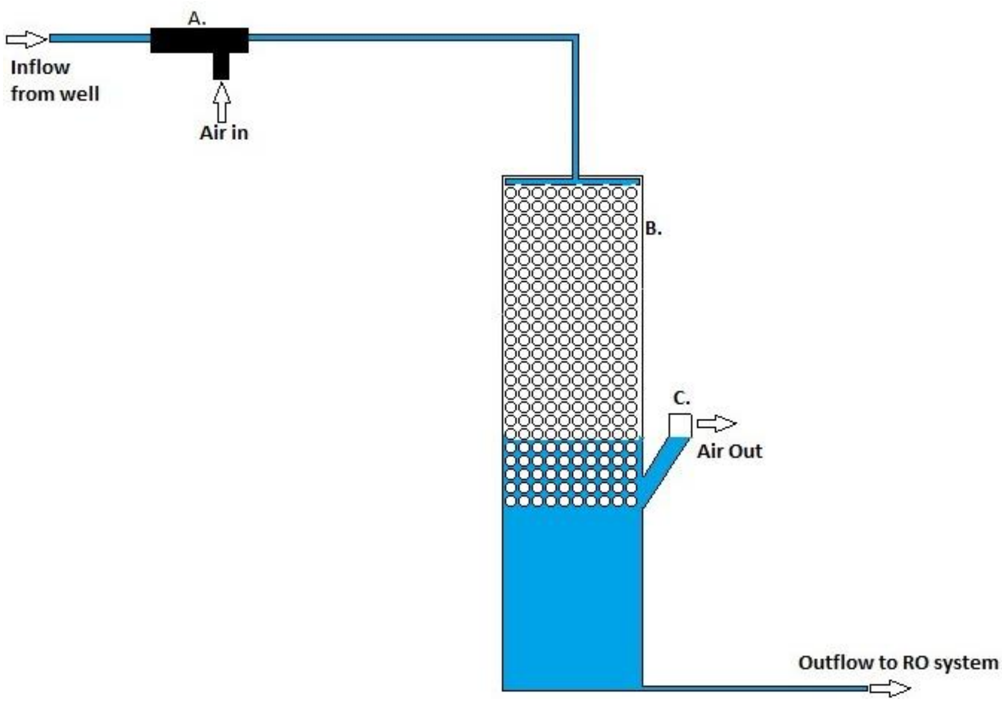


Figure 10: Design Two – Porous Media

AquaTech considers both of the above designs to be feasible options. At this point, performance differences are difficult to calculate, given the variability of both systems. Maintenance requirements are also difficult to estimate because of the varying quality of water that both systems might treat. However, it can be predicted that both systems will require more maintenance when exceptionally hard water is being treated. The misting nozzle option is a very affordable option. However, the spherical porous media is readily available and relatively inexpensive. Both options can be tailored to treat different levels of iron concentration. In most cases, the size of the reaction vessel would be increased with increasing dissolved iron concentration.

Design Calculations

The theoretical pressures and velocities were calculated at various locations throughout the designed system. However, due to the addition of the porous media in the vessel, pressures and velocities were not able to calculated. There is an equation by Darcy which is used to calculate velocities through a porous media, such as soils, but this equation cannot be applied because there are too many unknowns in the equation that cannot be assumed.

Table 3: Velocity and Pressure Table for Porous Media Design

	Velocity (ft/s)	Pressure (psi)	Head Loss (ft)
1	3.3	60	-
2	3.3	58.3	0.18
3	23.3	55.9	2.66
4	52.4	47.4	2.87

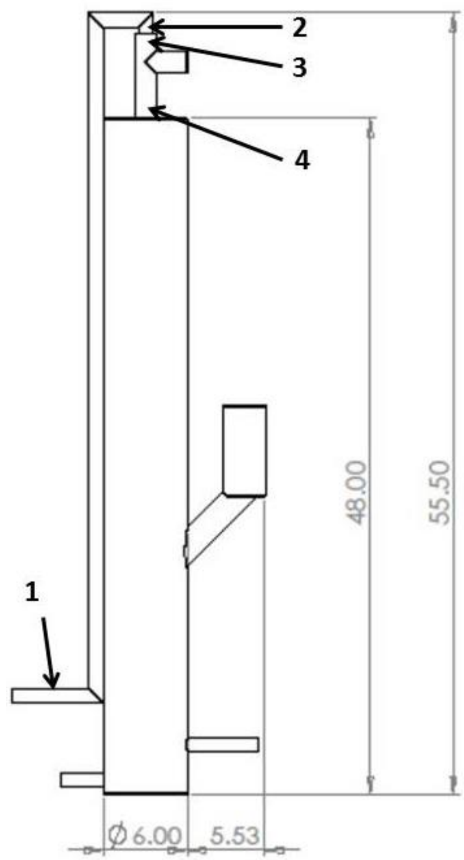


Figure 11: CAD Design II with Pressures

Team leader Adam Avey constructed the following drawing in SolidWorks to present the design in a three-dimensional form. The green piece at the bottom of the tank is valve that was added towards the end of the design process. The team decided that a valve would be needed in order to release the possible accumulation of inorganic particulates in the case that the pretreatment system and RO unit is used intermittently. If the flow is not continuous, particles, such as precipitated iron, will have the opportunity to settle to the bottom of the tank, which could possible disrupt the flow of the system or prove detrimental to the mechanical filter proceeding the pretreatment process. The purple piece is the eductor, the yellow the inflow pipe, and the brown the outflow pipe.

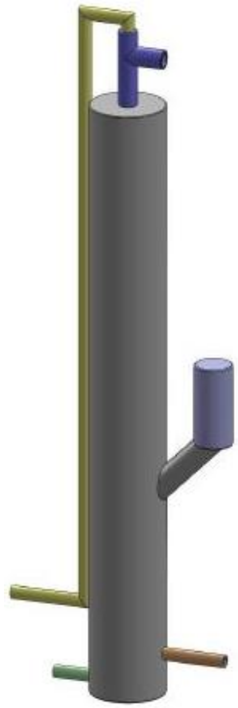


Figure 12: 3-D SolidWorks Drawing

Environmental and Societal Impacts

Environmental impacts of the proposed designs are considerably low considering that the proposed pretreatment systems do not require any chemical agents or power requirement. These elements of design are used to promote the reduction of water pollution and carbon emissions. The iron pretreatment system will impact well water users by offering an alternative to common well water purification systems that requires less maintenance and less cost over time.

Prototype Budget

The following budget was organized with the help of Pumps of Oklahoma employees Micah Goodspeed and Adam Avey:

Aeration via Misting Nozzles

Table 4: Design One Budget

Eductor	$160.00
Piping & Fittings	$20.00
Burp Valve	$65.00
Nozzles	$15.00
Total:	$260.00

Aeration via Porous Media

Table 5: Design Two Budget

Eductor	$160.00
Piping & Fittings	$20.00
Burp Valve	$65.00
Filter Media	$100.00

Total: $345.00

Work Breakdown Structure

AquaTech organized a list of deliverables for the team to accomplish throughout the fall and spring semesters. The following task list was constructed and used to form the Gantt chart shown in the **Project Schedule** section.

1. Determine theoretical maximum oxidation values via chemical analysis
    1.1. Locate local well water source with high iron content
    1.2. Bottle tests to measure dissolved oxygen levels (DO)
    1.2.1. Acquire Iron Checker Colorimeter

2. Empirically test physical well water samples to determine maximum oxidation potential in a real-world process
    2.1 Bottle test local water source
3. Analyze test results in regard to potential product designs
    3.1. Compare with air compressor or pump analysis
    3.2. Determine most effective air introduction method
4. Sketch and evaluate potential product designs
    4.1. Hard sketches in notebooks
    4.2. CAD drawings for prototype
    4.3. Conduct flow rate/ mass balance analysis
5. Assemble fall design report
    5.1. Research background information
    5.1.1. Patent research analyses
    5.2. Compile design drawings
    5.3. Write out proposal for design and supporting statements
6. Give fall design presentation for client
    6.1. Make PowerPoint Presentation

6.2. Incorporate customer feedback

7. Determine and locate materials for prototype

    7.1. Research materials and their specifications to fit our product

    7.2. Internet search for price and shipping comparisons

    7.3. Order materials

    7.4. Request/Reserve lab space for building

8. Acquire materials

9. Assemble prototype

10. Test prototype

    10.1. Meet EPA standard of 3 ppm Iron

    10.2. Calculate/Measure flow rate

    10.3. Measure Iron removed

    10.4. Measure oxidation rate

    10.5. Measure oxygen removal

    10.6. Measure power input

    10.7. Test durability of product

    10.8. Develop Operation and Maintenance (O&M) specifications

11. Final product presentation and report

    11.1. Compile data into report

    11.1.1. Insert drawings and calculations

    11.1.2. Analysis and comparison to original design

    11.1.3. Does it meet requirements?

    11.2. Make PowerPoint presentation

Project Schedule

The following schedule and Gantt chart were composed to organize AquaTech's tasks:

Table 6: Project Schedule

Task Name	Duration	Start	Finish
Physically test local water samples to determine max real-world oxidation values	2 days	Mon 11/5/12	Tue 11/6/12
Analyze test results in regards to potential product designs	1 day	Wed 11/7/12	Wed 11/7/12
Sketch and evaluate potential product designs	1 day	Thu 11/8/12	Thu 11/8/12
Assemble Fall desing report	2 days	Wed 11/21/12	Thu 11/22/12
Give fall design presentation for client	0 days	Fri 11/23/12	Fri 11/23/12
Determine and locate materials for prototype	10 days	Mon 1/14/13	Fri 1/25/13
Acquire materials	10 days	Mon 1/28/13	Fri 2/8/13
Assemble prototype	14 days	Mon 2/11/13	Thu 2/28/13
Test prototype	7 days	Fri 3/1/13	Mon 3/11/13
Final product presentation and report	0 days	Tue 4/30/13	Tue 4/30/13

Appendix A

Appendix B

Appendix C

References

APHA, AWWA, WPCF. 1980. *Standard Methods for the Examination of Water and Wastewater*. 15th ed. American Public Health Association.

Metcalf & Eddy. 2003. Incorporated. *Wastewater Engineering: Treatment and Reuse.* 4th ed. New York. McGraw-Hill

Laura Muller. 2000. "Spectrophotometric Determination of Iron in a Vitamin Tablet," General Chemistry Lab, Wheaton College. Available at: http://www.wellesley.edu/Chemistry/Chem105manual/Lab04/lab04.html. Accessed: Nov. 27, 2012.

Munson, Bruce R., Donald F. Young, and Theodore H. Okiishi. 2006. *Fundamentals of Fluid Mechanics.* 5th ed. Massachusetts. John Wiley & Sons, Inc.

Truman State University CHEM 222 Lab Manual. 2008. Available at: http://chemlab.truman.edu/chem222manual/pdf/ironspec.pdf. Accessed: Nov. 27, 2012.

Acknowledgements:

A special thanks goes out to all those who assisted the team members of AquaTech with their project. Especially the following persons:

Dr. Paul Weckler, BioSystems & Agricultural Engineering

Micah Goodspeed, Pumps of Oklahoma

Dr. Greg Wilber, OSU Civil & Environmental Engineering

Dr. Chad Penn, OSU Plant & Soil Sciences

Stuart Wilson, OSU Plant & Soil Sciences,

John Rodgers, Stillwater Resident and Water Well Owner

Sergio Ruiz Esparza Herrera, OSU Agriculture Business Student

Pretreatment System for Reverse Osmosis

Adam Avey, David Criswell, & Kelsey Criswell

AquaTech
Engineering Solutions

Mission Statement

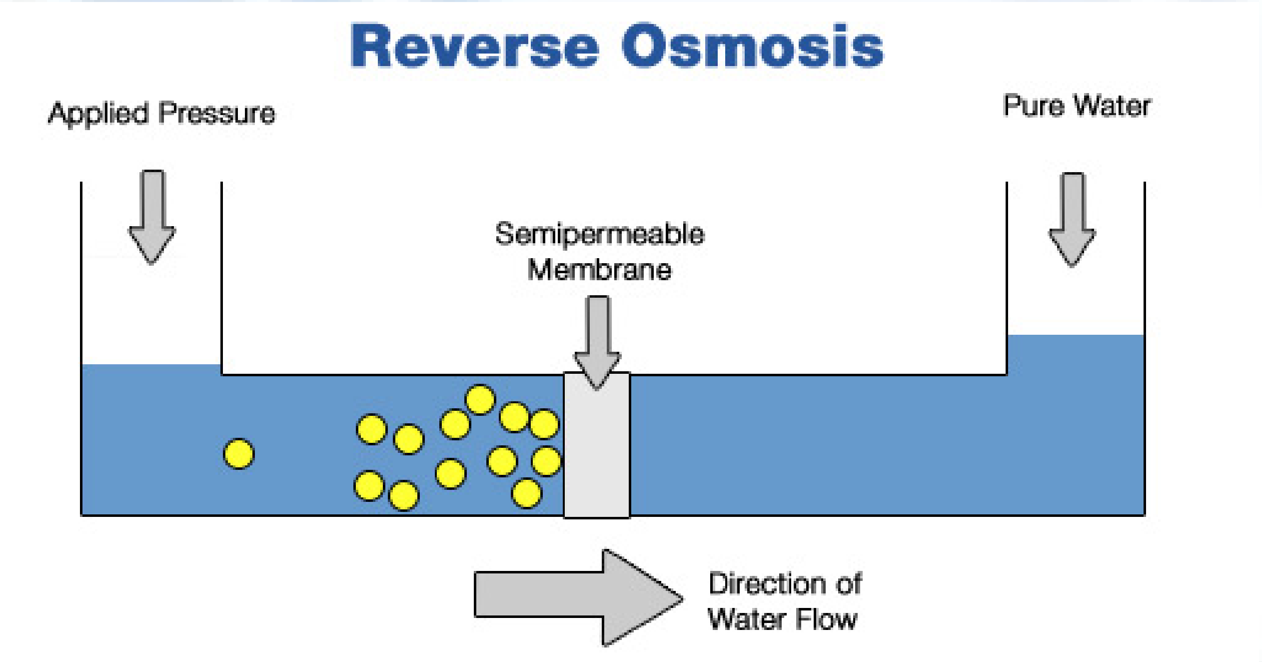
"AquaTech Engineering Solutions' mission is to use its technical expertise and resources to provide customers with more affordable, longer lasting products."

Client: Pumps of Oklahoma

- Wholesale Supplier of Pumps
  - Water Well, Environmental, Solar, Petroleum
- 18 employees
- Located in Oklahoma City

Reverse Osmosis System

Reverse Osmosis



Thewaterq.com

Problem Statement

"To design and fabricate a flow-through iron removal pretreatment module for a household reverse osmosis (RO) system."

Iron Fouls Membranes

- EPA Standard: .3 pmm
- Requires extra maintenance and cost

Scope of Work

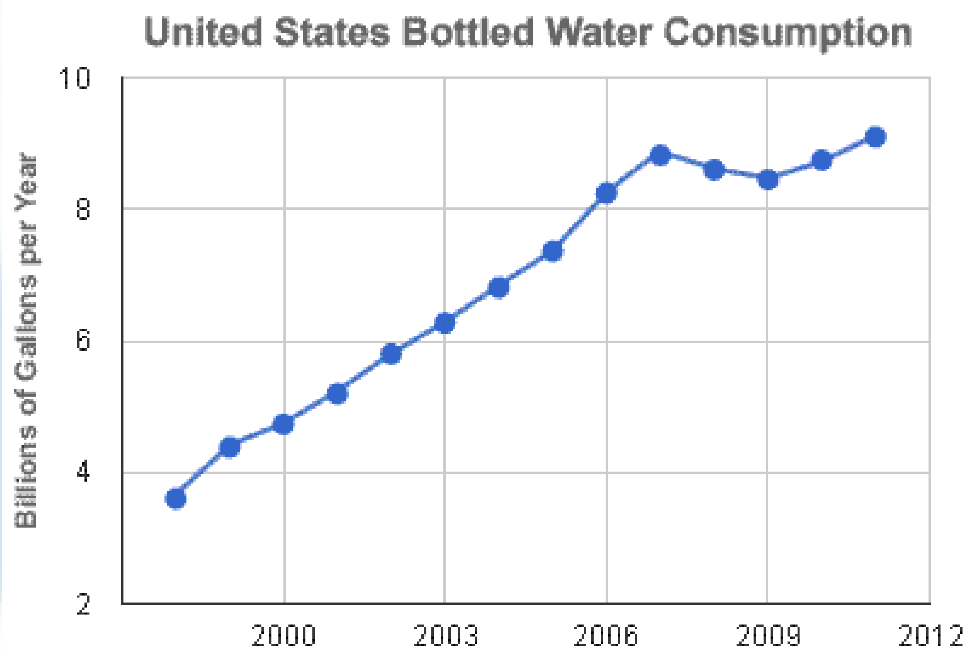
- Precedes a household RO unit
- Refrain from using:
  - Air pump
  - Power source

Standards

- NSF drinking water standards
- EPA drinking water standards

Target Group

- Rural Homeowners
- Small Businesses



http://geology.com/articles/bottled-water.shtm

Customer Requirements

- Treat a continuously flowing stream.
- Avoid additional mechanical hardware (such as a compressor).
- The device should be able to remove whatever substances (such as air) that have been added to the water stream.

Market Analysis

- Agriculture Business Teammate:
  Sergio Ruiz Esparza Herrera

- Strategy:
  - Design standard prototype
  - Sell RO system to construction firms

  - According to www.bccresearch.com the Reverse Osmosis industry is expected to have a compound annual growth rate of 7.3% over the next 5 years.

Competitors

- Advanced Water Solutions
- Culligan
  - Under counter drinking water systems
- Haynes Equipment Company
  - Industrial RO systems

Competitors

Product	Technique	Price Range	Website
Terminox ISM	Chlorine injector and mixing tank	\$550 - \$975	www.budgetwater.com
Pyrolox	Granular water filtration media	\$670 -\$ 885	www.qualitywaterforless.com
Greensand	Glauconite greensand filtration media	\$625 - \$885	www.qualitywaterforless.com
Birm	Filtration media	\$435 - \$710	www.qualitywaterforless.com
Eagle Redox Alloy	Iron Oxidization Catalyst	\$25	www.qualitywaterforless.com

Technical Analysis

- Wastewater Treatment Systems
- Household Treatment Systems
- Patents
- Chemical Analysis

Wastewater Treatment Systems

1. Diffusion-Air Systems
2. Mechanical Aeration

Cascading Aerator

- Economical
- Low Tech

Cascading Aerator

$$H = \frac{R-1}{0.11ab(1+0.046T)}$$ (English Units)

- where $R = \text{deficit ratio} = \frac{C_S - C_O}{C_S - C}$
- C_S = DO saturation concentration, mg/L
- C_O = DO concentration of influent, mg/L
- C = required DO level, mg/L
- a = water-quality parameter
- b = weir geometry parameter for a weir
- T = water temperature, ^{o}C
- H = height through which water falls, ft

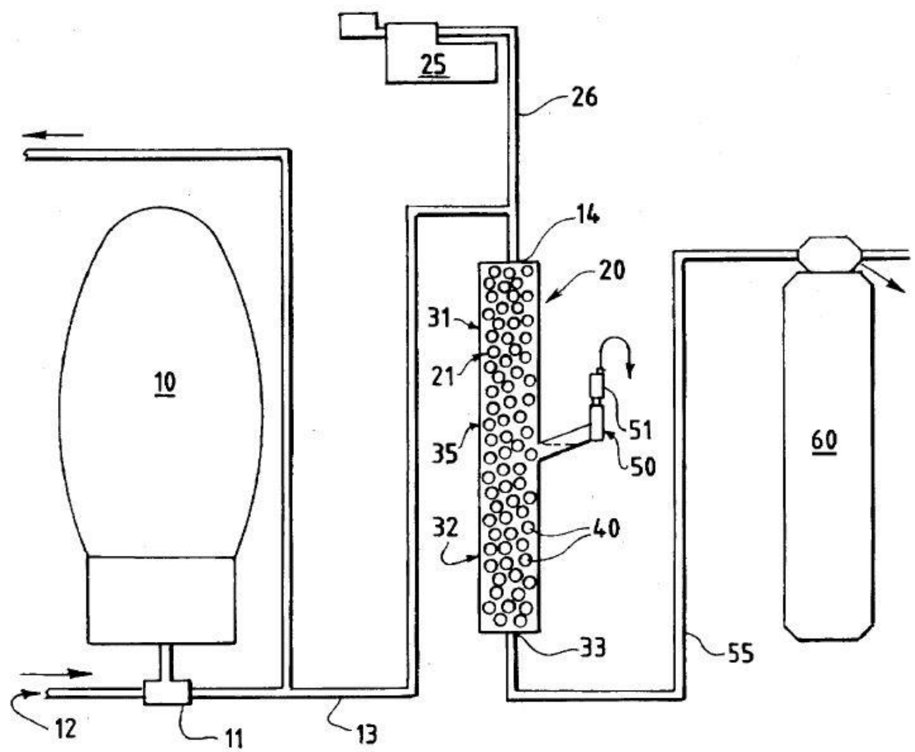
Household Treatment Systems

- Aeration via air pump
- Water softeners

Patents

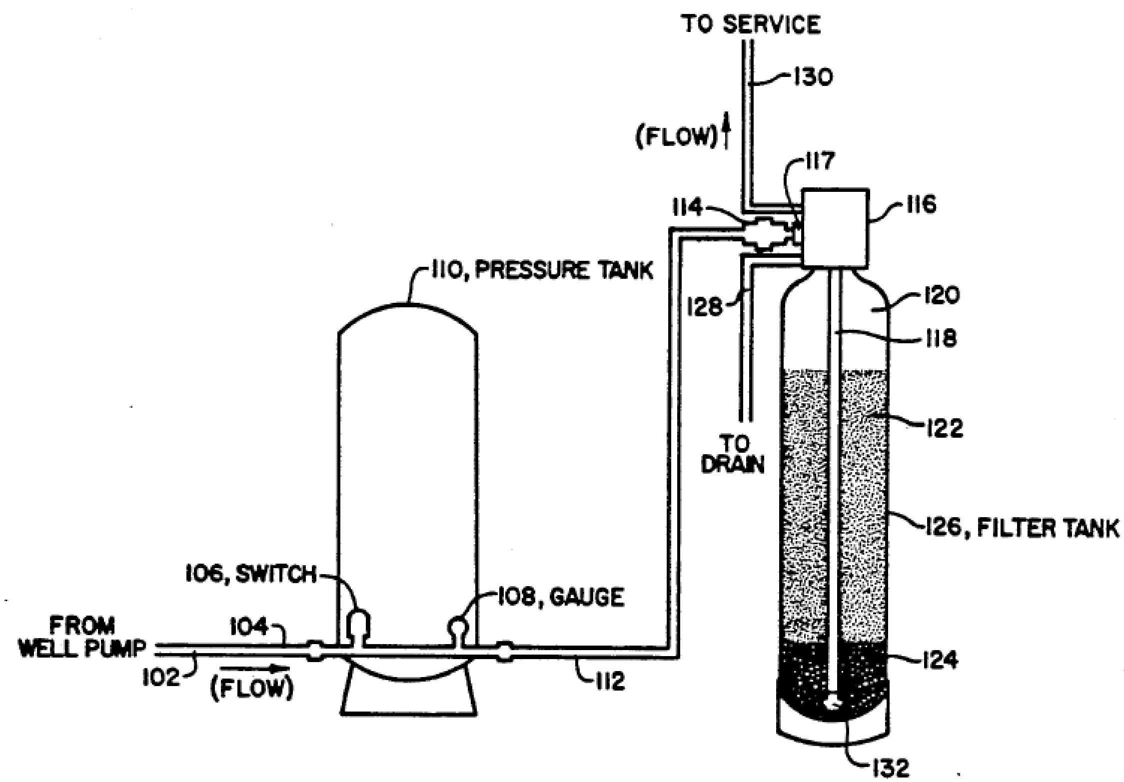
United States Patent [19] [11] **Patent Number:** **5,725,759**

Schlafer et al. [45] **Date of Patent:** **Mar. 10, 1998**



Patents

United States Patent [19] | [11] **Patent Number:** 5,096,580
Auchincloss | [45] **Date of Patent:** Mar. 17, 1992



Patents

(12) **United States Patent**
Kohlenberg

(10) **Patent No.: US 6,325,943 B1**
(45) **Date of Patent: Dec. 4, 2001**

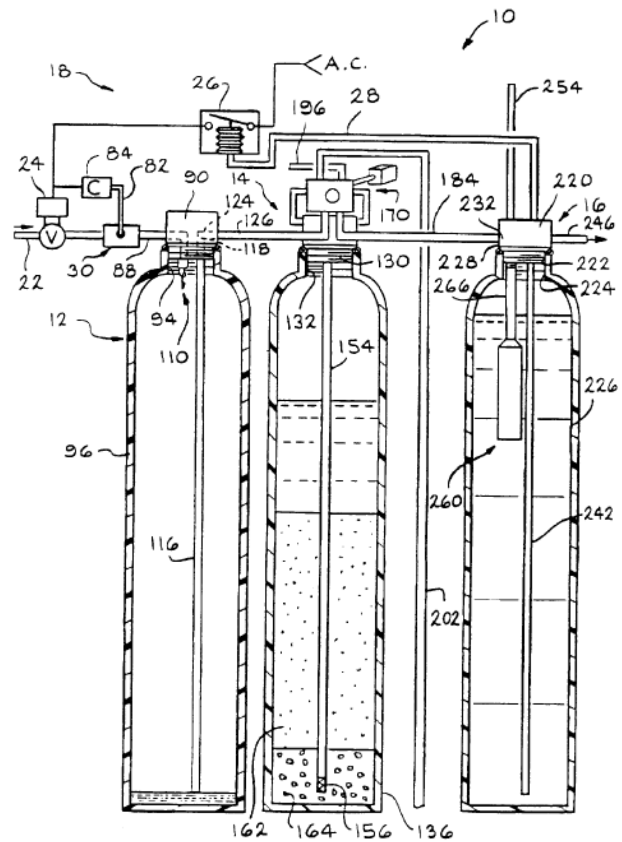


FIG. 1

Chemical Analysis

$Fe(II) + \frac{1}{4}\, O_2 + 2OH^- + \frac{1}{2}\, H_2O \longrightarrow Fe(OH)_{(s)}$

(Stumm, 1961)

- From Pumps of Oklahoma, 3.2 ppm Iron
  - Assumption: 3.2 ppm Fe(II)

3.2mg/L Fe * mol/55.85g Fe * 1g/1000mg * ¼ mol O_2/1 mol Fe * 32g O_2/1 mol O_2 = 0.000458 g/L O_2

= 0.458 mg/L O_2 needed to oxidize 3.2 mg/L Fe(II)

Chemical Analysis

Chemical Analysis for 5 ppm Fe(II)

$Fe(II) + \frac{1}{4} O_2 + 2OH^- + \frac{1}{2} H_2O \quad Fe(OH)_{(s)}$ (Stumm, 1961)

Concentrations needed to oxidize 5 ppm Fe(II):

For O_2 : 0.716 ppm

For H_2O: 0.8 ppm

For Air: 3.41 ppm

Note: Air is about 21% O_2

Chemical Analysis

Design Flow Rates

Known: 8 gpm water through eductor

$$Q_{air} = 8gpm\ H_2O * \frac{3.758L}{gal} * \frac{0.8\text{mg}\ H_2O}{\text{L}} * \frac{1\ \text{mol}}{18\ \text{g}H_2O} * \frac{0.25\text{mol}\ O_2}{0.5\text{mol}\ H_2O}$$

$$* \frac{32\text{g}O_2}{molO_2} * \frac{28.97g\ air}{6.704g\ O_2} * \frac{1L}{3.41mg\ air} * \frac{1\ gal}{3.785\text{L}}$$

= 7.2 gpm air needed

Lab Preparation

Standard curve for ferrous iron

Reagents List:

Reagent	Molecular Formula	Use	Concentration
Ferrous Ammonium Sulfate 6- Hydrate	$Fe(NH_4)(SO_4)_2*6\ H_2O$	Known amount of ferrous iron in standard	0.7022 g in 1 L
(1,10) Phenanthroline	$C_{12}N_2H_8$	Coloring Agent	0.1 g in 100 mL
Sodium Acetate	$NaOCOCH_3$	Buffering agent to fix pH	10 g in 100 mL
Sulfuric Acid	H_2SO_4	Stabilizes Fe(II) and takes care of impurities	2.5 mL in 1 L

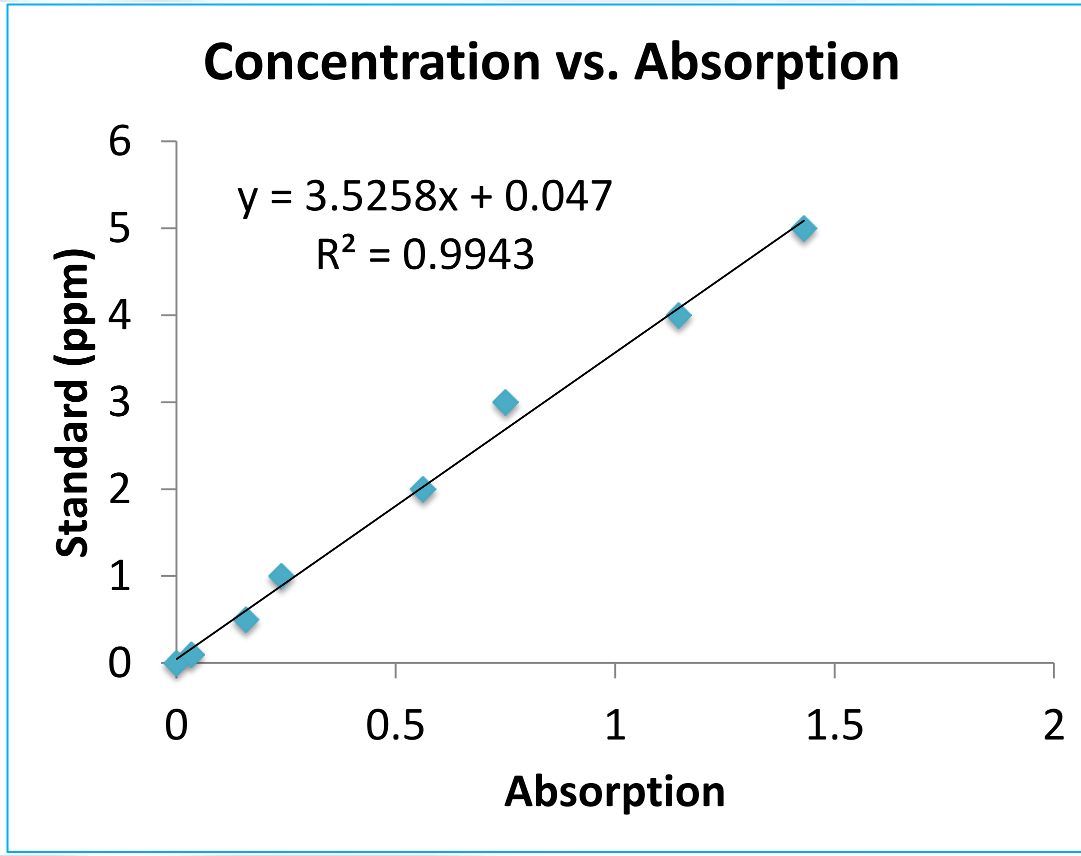
Lab Preparation

$Fe^{2+} + 3\ Phen \rightarrow [Fe(Phen)_3]^{2+}$ (Muller, 2010)

- Used Mass Spectrophotometry to test Hanna Checker readings of Fe(II)
- Absorption vs. Concentration is linear (Beer's Law)

Lab Preparation

Standard	Absorption
0	0
0.1	0.034
0.5	0.158
1.0	0.239
2.0	0.562
3.0	0.75
4.0	1.145
5.0	1.43



Lab Preparation

Ferrous Iron standards starting from 0.1 ppm on left to 5 ppm on far right

Testing Local Well

- Hanna Instruments HI 721

Testing Local Well

2 Tests Conducted

- Total Iron
- Ferrous Iron

Testing Local Well

Ferrous Iron Content

- Field Test Procedure
  - Fill 10 mL cuvette with well sample to zero Checker
  - 1.0 mL of (1,10) Phenanthroline solution
  - 0.8 mL of sodium acetate solution
  - Fill to volume (10 mL) with raw well water
  - Place in Checker and read concentration in ppm

Testing Local Well

Total Iron Content

- Field Test Procedure
  - Fill 10 mL cuvette with well sample to zero Checker
  - Add one packet of HI721-25 Iron HR Reagent
  - Gently swirl until dissolved
  - Place in Checker and read concentration in ppm

Testing Local Well

Results from Well Test

Sample	Ferrous Iron (ppm)	Total Iron (ppm)
1	0.45	-
2	0.44	-
3	0.39	-
4	0.41	-
5	-	0.60
6	-	0.53
7	-	0.56
8	-	0.52
Mean	0.42	0.55

Design Analysis

- Minimize:
  - Power Requirement
  - Space Requirement
  - Maintenance

Eductor

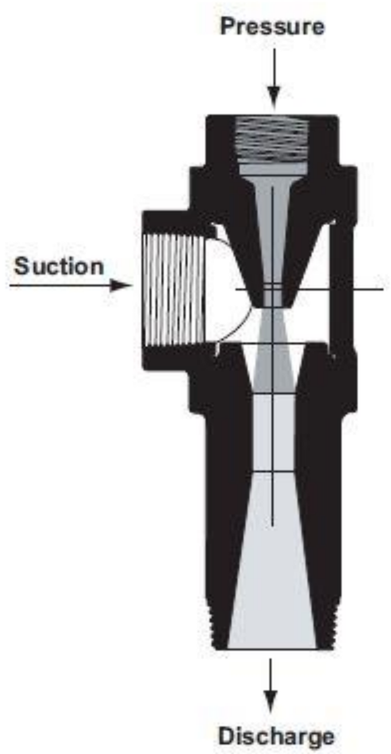
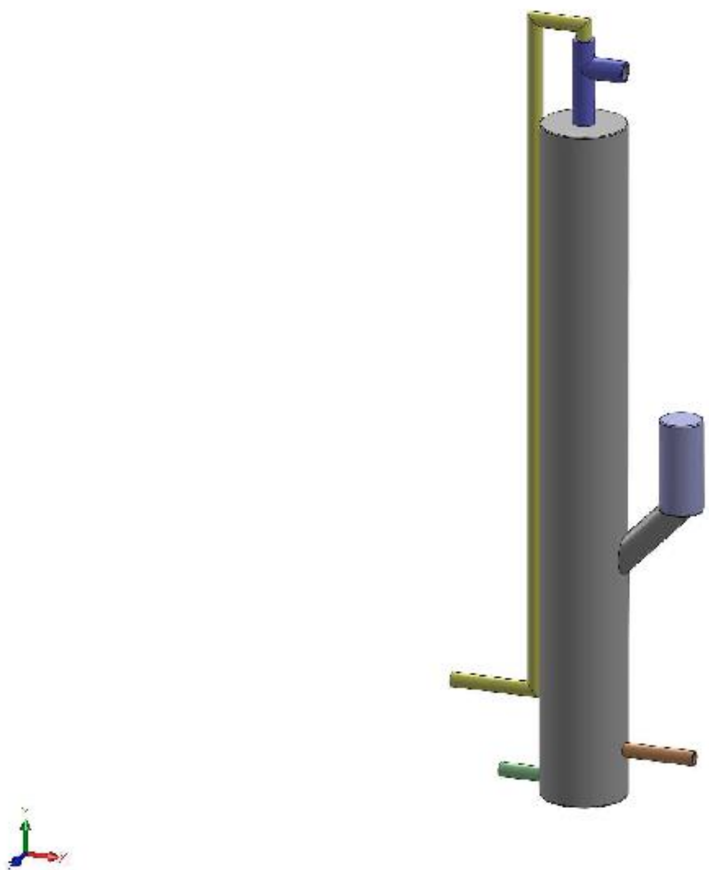


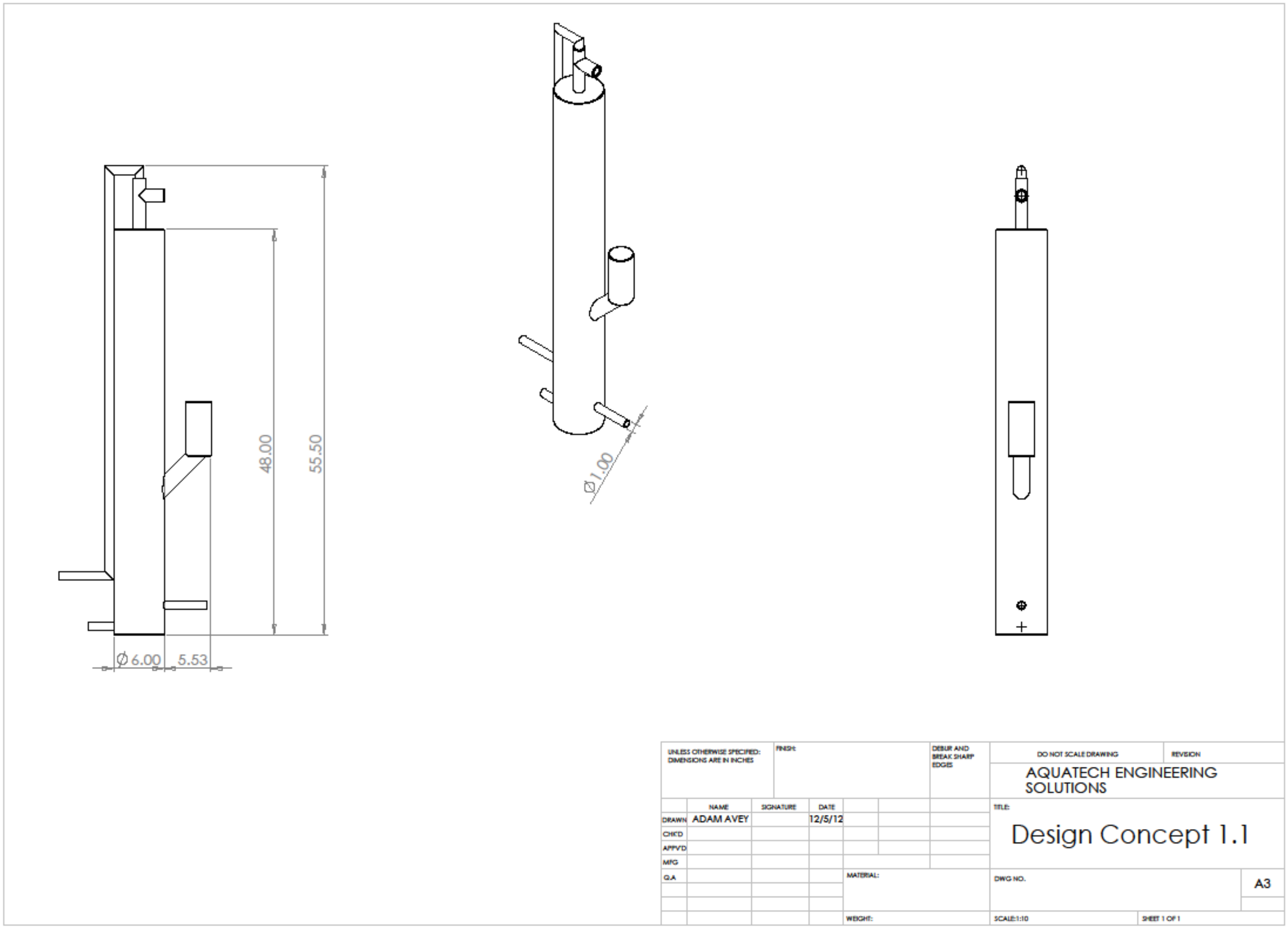
Fig. 5. FIG. 264 PVC EDUCTOR.

Design Concept



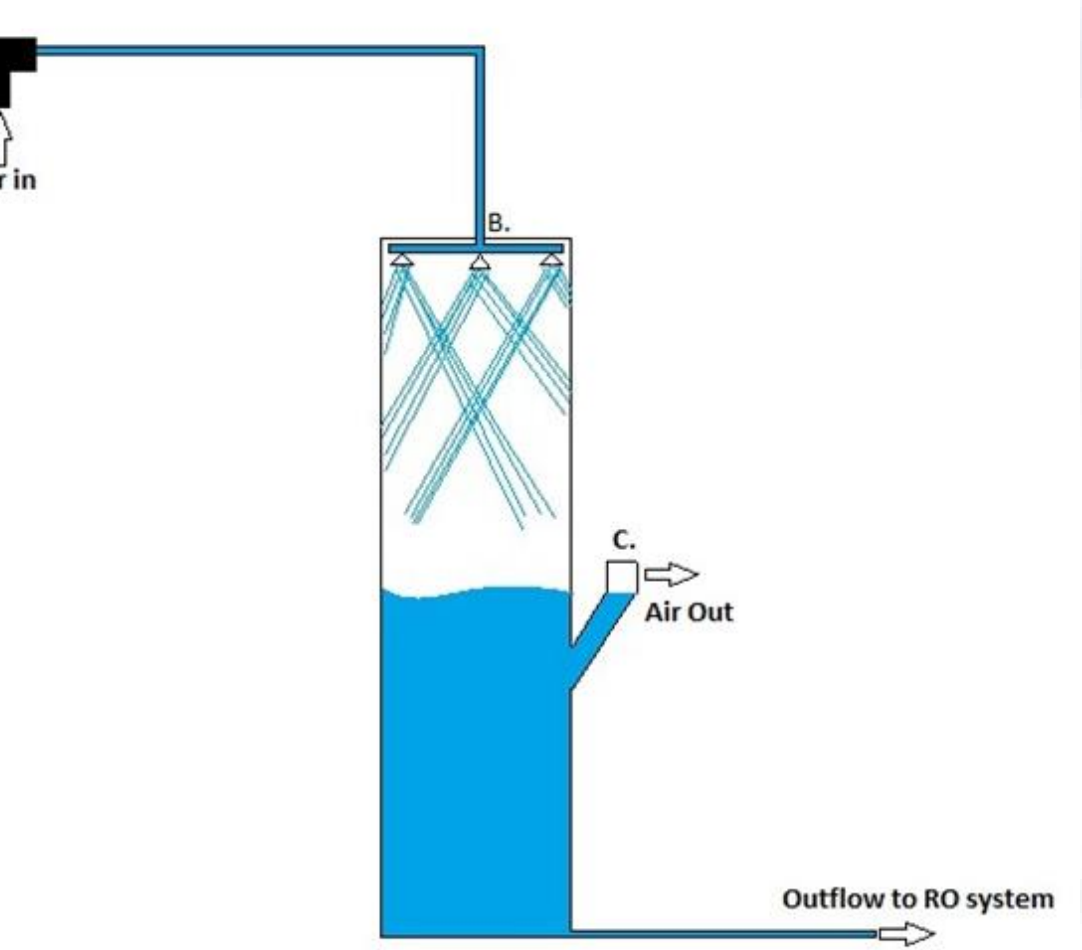
Air Relief Valve

Design Concept



Design Concept 1

Aeration via misting nozzles



Calculations

- Continuity:

$$\mathrm{Q} = V_1 A_1 = V_2 A_2$$

- Bernoulli's Equation:

$$\frac{p_1}{\gamma} + \frac{{V_1}^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{{V_2}^2}{2g} + z_1 + h_L$$

- Head Loss Equation:

$$h_L = h_{L_{major}} + h_{L_{minor}} = f\,\frac{l}{D}\frac{V^2}{2g} + K_L\,\frac{V^2}{2g}$$

Calculations

- Venturi Equation:

$$Q = C_v A_T \sqrt{\frac{2(p_1 - p_2)}{\rho(1 - \beta^4)}}$$

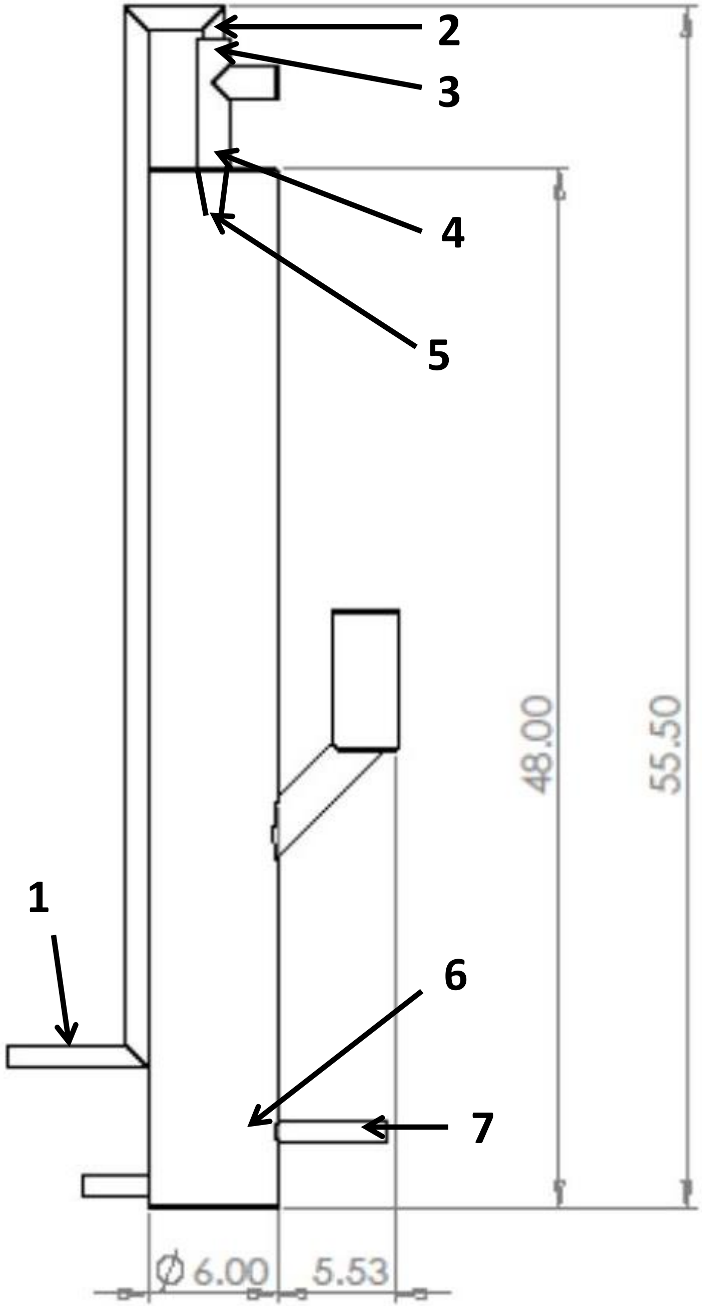
- $\Delta p = 8.5$ psi

Calculations

- Reaction Vessel Sizing
  - 30 second residence time, +- depending on pH, etc.

$$(8\ gal/min)(.5\text{min}) = (4gal)$$

$$D = 6.065in$$
$$A = 28.89in^2$$
$$4gal = 924in^3$$
$$H = 32in$$



	Velocity (ft/s)	Pressure (psi)	Head Loss (ft)
1	3.3	60	-
2	3.3	58.3	0.18
3	23.3	55.9	2.66
4	52.4	47.4	2.87
5	93.3	8.4	2.67
6	0.09	48.4	0
7	3.3	48.3	0.04

Total Head Loss = 8.4 ft

Dimensions are approximate. Check with BETE for critical dimension applications

TF Full Cone Flow Rates and Dimensions

Full Cone, 60° (NN), 90° (FCN or FFCN), 120° (FC or FFC), 150° and 170° Spray Angles, 1/8" to 4" Pipe Sizes, BSP or NPT

Male Pipe Size	Nozzle Number	Available Spray Angles 60° 90° 120° 150° 170°	K Factor	LITERS PER MINUTE @ BAR 0.5 bar	0.7 bar	1 bar	2 bar	3 bar	5 bar (Above 5 bar not recom. for PTFE)	10 bar (High Pressure Operation recom. for Metal Only)	20 bar	Approx. (mm) Orif. Dia.	Free Pass Dia.	Dim. (mm) for Metal Only* A	B	C	Wt. (g) 60° 90° 120° Metal	Plas.
1/8	TF6	60° 90° 120° 150° 170°	3.19	2.26	2.67	3.19	4.5	5.5	7.1	10.1	14.3	2.38	2.38	42.9	14.3	42.9	28	6
	TF8	60° 90° 120° 150° 170°	5.93	4.19	4.96	5.93	8.4	10.3	13.2	18.7	26.5	3.18	3.18	42.9	14.3	55.6		
1/4	TF6	60° 90° 120° 150° 170°	3.19	2.26	2.67	3.19	4.5	5.5	7.1	10.1	14.3	2.38	2.38	47.6	14.3	47.6	35	6
	TF8	60° 90° 120° 150° 170°	5.93	4.19	4.96	5.93	8.4	10.3	13.2	18.7	26.5	3.18	3.18	47.6	14.3	60.3		
	TF10	60° 90° 120° 150° 170°	9.12	6.45	7.63	9.12	12.9	15.8	20.4	28.8	40.8	3.97	3.18	47.6	14.3	60.3		
3/8	TF6	60° 90° 120°	3.19	2.26	2.67	3.19	4.5	5.5	7.1	10.1	14.3	2.38	2.38	47.6	17.5	60.5	46	7
	TF8	60° 90° 120°	5.93	4.19	4.96	5.93	8.4	10.3	13.2	18.7	26.5	3.18	3.18					
	TF10	60° 90° 120°	9.12	6.45	7.63	9.12	12.9	15.8	20.4	28.8	40.8	3.97	3.18					
	TF12	60° 90° 120° 150° 170°	13.7	9.67	11.4	13.7	19.3	23.7	30.6	43.2	61.1	4.76	3.18					
	TF14	60° 90° 120° 150° 170°	18.5	13.1	15.4	18.5	26.1	32.0	41.3	58.4	82.6	5.56	3.18					
	TF16	60° 90° 120° 150° 170°	24.2	17.1	20.2	24.2	34.2	41.8	54.0	76.4	108	6.35	3.18					
	TF20	60° 90° 120° 150° 170°	37.6	26.6	31.5	37.6	53.2	65.1	84.1	119	168	7.94	3.18					
1/2	TF24	60° 90° 120° 150° 170°	54.9	38.8	46.0	54.9	77.7	95.1	123	174	246	9.53	4.76	63.5	22.2	77.7	85	14
	TF28	60° 90° 120° 150° 170°	75.2	53.2	62.9	75.2	106	130	168	238	336	11.1	4.76					
3/4	TF32	60° 90° 120° 150° 170°	95.7	67.7	80.1	95.7	135	166	214									
1	TF40	60° 90° 120° 150° 170°	153	108	128	153	216	264	341									
	TF48	60° 90° 120° 150° 170°	217	153	181	216	306	375	484									
1 1/2	TF56	60° 90° 120° 150° 170°	294	208	246	294	416	509	657									
	TF64	60° 90° 120° 150° 170°	385	272	322	385	545	667	861									
	TF72	60° 90° 120° 150° 170°	438	309	366	438	619	758	978									
2	TF88	60° 90° 120° 150° 170°	638	451	534	638	902	1110	1430	2020	2850	34.9	11.1	143	63.5	175	1300	227
	TF96[1]	60° 90° 120° 150° 170°	806	570	674	806	1140	1400	1800	2550	3600	38.1	11.1	176	63.5	178	1530	255
3	TF112[1]	60° 90° 120° 150° 170°	1170	825	976	1170	1650	2020	2610	3690	5220	44.5	14.3	219	88.9	235	3230	567
	TF128[1]	60° 90° 120° 150° 170°	1550	1090	1290	1550	2190	2680	3460	4891	6920	50.8	14.3					
4	TF160[1]	60° 90° 120°	2390	1690	2000	2390	3380	4140	5350	7570	10700	63.5	15.9	257	114		4790	765

For p = 47.4 psi = 4.13 Bar,
Nozzle is rated to 19.0 gpm

Flow Rate (l/min) = $K\sqrt{bar}$ *Dimensions are for bar stock, cast sizes may vary. **60° nozzles slightly longer; call BETE for details [1]Three turn nozzles

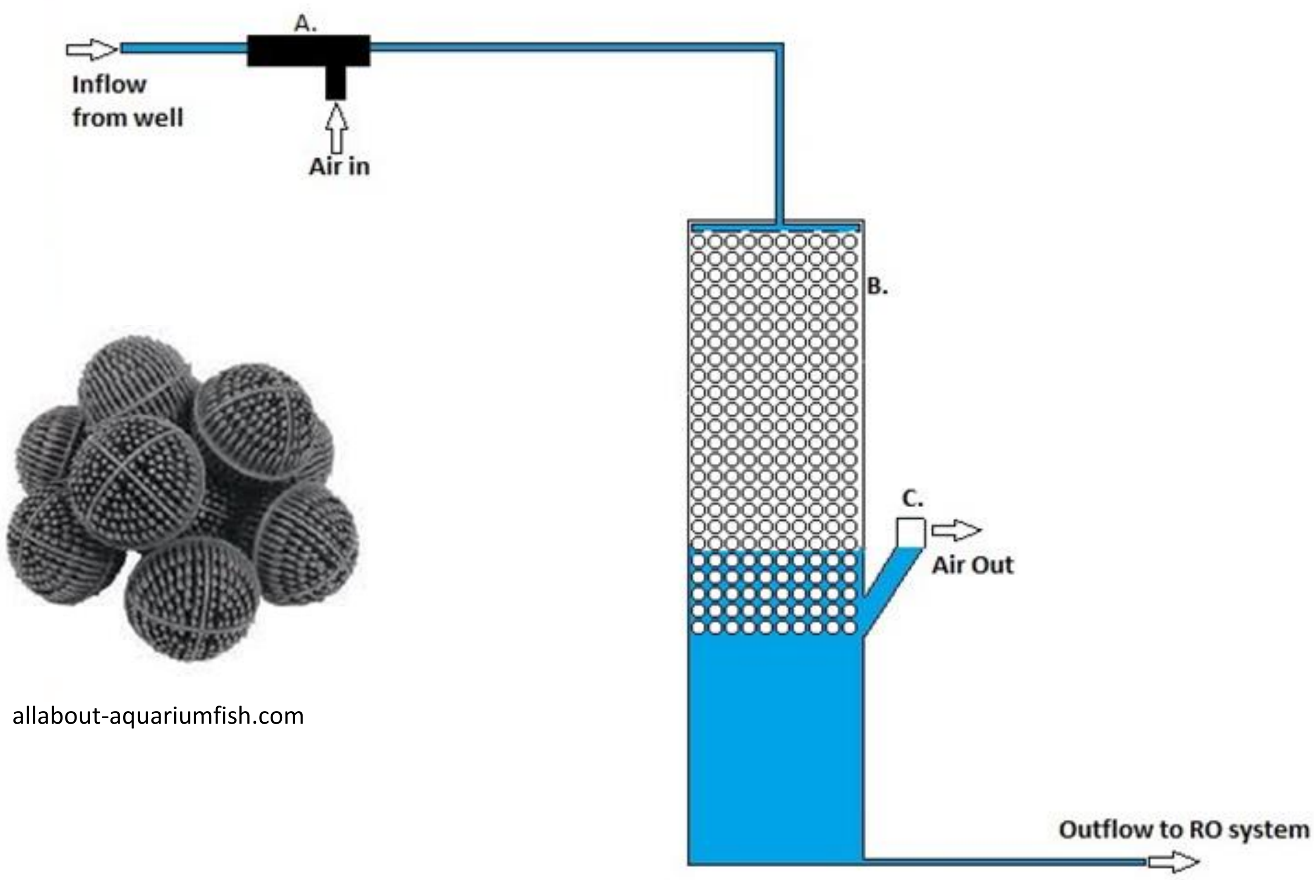
Standard Materials: Brass, 316 Stainless Steel, PVC, Polypropylene and PTFE (Poly. not available for TF6 thru TF10).

Spray angle performance varies with pressure. Contact BETE for specific data on critical applications.

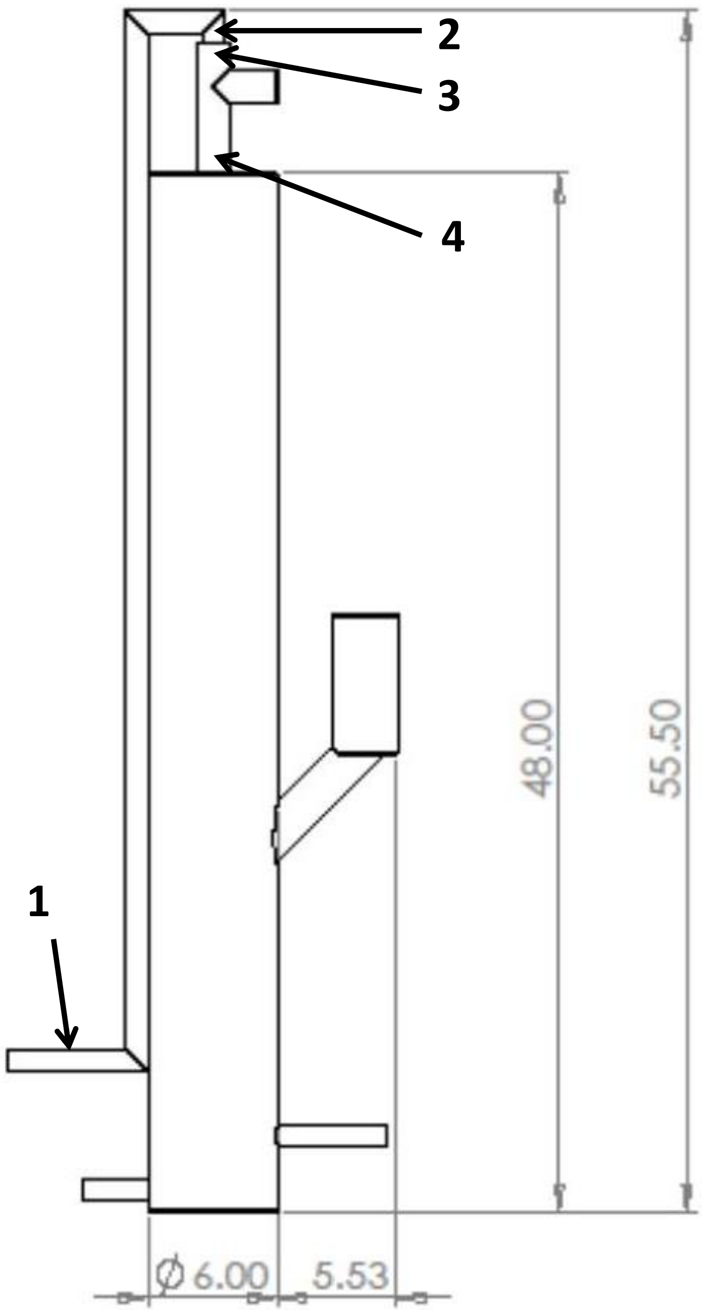
TO ORDER: *specify pipe size, connection type, nozzle number, spray angle, and material.*

Design Concept 2

Aeration via porous media

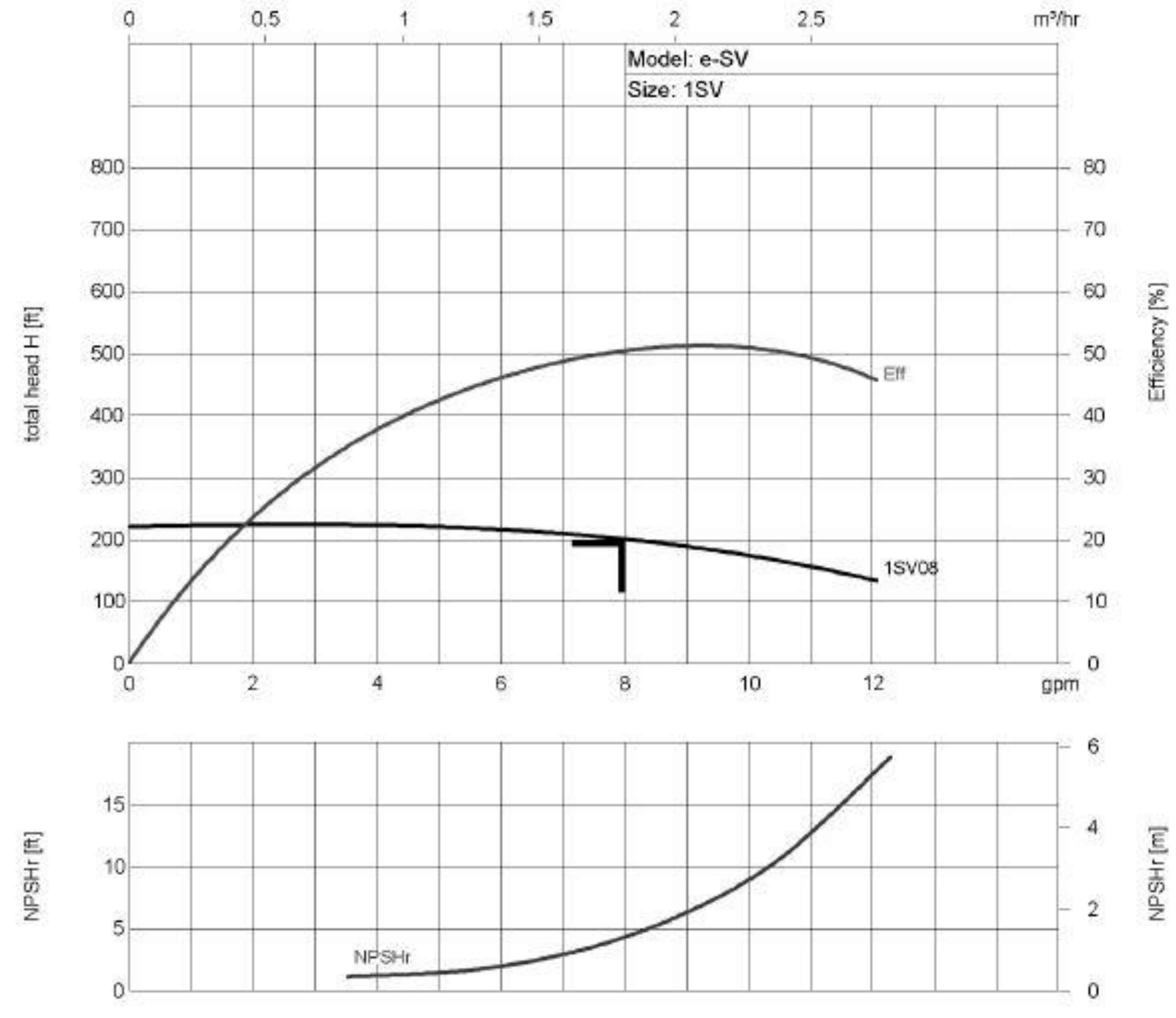


allabout-aquariumfish.com



	Velocity (ft/s)	Pressure (psi)	Head Loss (ft)
1	3.3	60	-
2	3.3	58.3	0.18
3	23.3	55.9	2.66
4	52.4	47.4	2.87

Pump Curve



0 0.5 1 1.5 2 2.5 m³/hr
Model: e-SV
Size: 1SV
total head H [ft]
Efficiency [%]
Eff
1SV08
0 2 4 6 8 10 12 gpm
NPSHr [ft]
NPSHr [m]
NPSHr

Proposed Budget

Aeration via Misting Nozzles

Part	Price
Eductor	$160.00
Piping & Fittings	$20.00
Air Release Valve	$100.00
Nozzles	$15.00
Total:	$295.00

Proposed Budget

Aeration via Porous Media

Part	Price
Eductor	$160.00
Piping & Fittings	$20.00
Air Release Valve	$100.00
Filter Media	$100.00
Total:	$380.00

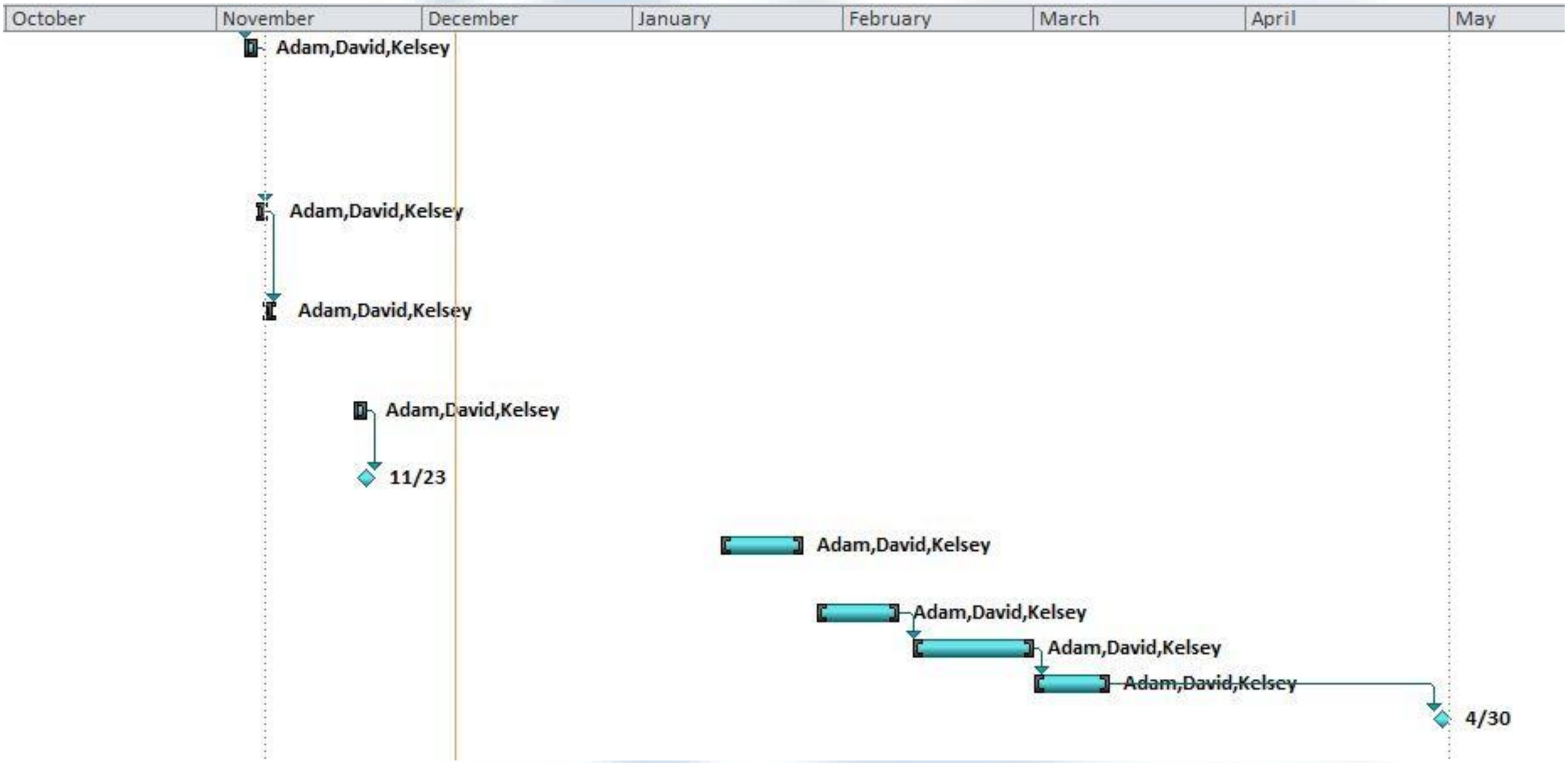
Next Step

- Order Components
- Assembly
- Testing

Schedule

Task Name	Duration	Start	Finish
Physically test local water samples to determine max real-world oxidation values	2 days	Mon 11/5/12	Tue 11/6/12
Analyze test results in regards to potential product designs	1 day	Wed 11/7/12	Wed 11/7/12
Sketch and evaluate potential product designs	1 day	Thu 11/8/12	Thu 11/8/12
Assemble Fall desing report	2 days	Wed 11/21/12	Thu 11/22/12
Give fall design presentation for client	0 days	Fri 11/23/12	Fri 11/23/12
Determine and locate materials for prototype	10 days	Mon 1/14/13	Fri 1/25/13
Acquire materials	10 days	Mon 1/28/13	Fri 2/8/13
Assemble prototype	14 days	Mon 2/11/13	Thu 2/28/13
Test prototype	7 days	Fri 3/1/13	Mon 3/11/13
Final product presentation and report	0 days	Tue 4/30/13	Tue 4/30/13

Gantt Chart



October
November
December
January
February
March
April
May
Adam,David,Kelsey
Adam,David,Kelsey
Adam,David,Kelsey
Adam,David,Kelsey
11/23
Adam,David,Kelsey
Adam,David,Kelsey
Adam,David,Kelsey
Adam,David,Kelsey
4/30

References

- APHA, AWWA, WPCF. 1980. *Standard Methods for the Examination of Water and Wastewater*. 15th ed. American Public Health Association.
- Metcalf & Eddy. 2003. Incorporated. *Wastewater Engineering: Treatment and Reuse.* 4th ed. New York. McGraw-Hill
- Laura Muller. 2000. “Spectrophotometric Determination of Iron in a Vitamin Tablet,” General Chemistry Lab, Wheaton College. Available at: http://www.wellesley.edu/Chemistry/Chem105manual/Lab04/lab04.html. Accessed: Nov. 27, 2012.
- Munson, Bruce R., Donald F. Young, and Theodore H. Okiishi. 2006. *Fundamentals of Fluid Mechanics.* 5th ed. Massachusetts. John Wiley & Sons, Inc.
- *Truman State University CHEM 222 Lab Manual.* 2008. Available at: http://chemlab.truman.edu/chem222manual/pdf/ironspec.pdf.Accessed: Nov. 27, 2012.

Appreciation

- Dr. Paul Weckler, Biosystems & Ag. Eng.
- Micah Goodspeed, Pumps of Oklahoma
- Dr. Greg Wilber, Civil & Environmental Eng.
- Dr. Chad Penn, Plant & Soil Sciences
- Stuart Wilson, Plant & Soil Sciences
- John Rodgers, Water Well Owner
- Sergio Ruiz Esparza Herrera, Ag. Business Teammate

Questions or Comments?

AquaTech
Engineering Solutions