

# Fluoride, Fall 2015

Katie Dao, Pooja Desai, Auggie Longo

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## Abstract

The goal of the Fall 2015 Fluoride team is to optimally reduce the fluoride content in groundwater by improving the system already developed in Spring 2015. Groundwater in developing countries contains high levels of fluoride, so its consumption as drinking water causes crippling fluorosis, calcification of the bones, and a number of other serious conditions. To reduce the amount of fluoride in water, a stacked sand filter was created. This, in conjunction with the coagulant polyaluminum chloride, absorbs and precipitates the fluoride present in the groundwater - ultimately yielding safer, more “drinkable” water.

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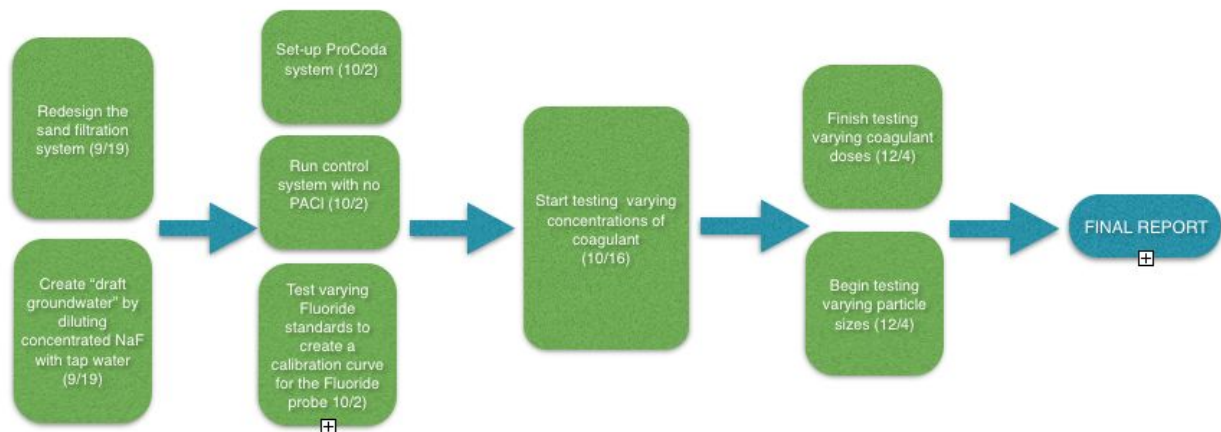
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# Task Timeline

## Task Map



## Task List

Friday, September 19 (Completed)

- Design and build a sand column apparatus (similar to the arsenic experiment) to analyze performance of PACI on fluoride removal
- Create "draft groundwater" by diluting concentrated NaF with tap water

Friday, September 25 (Completed)

- Finish conducting additional research on the relationship between PACI and Fluoride, and similar experiments that have been done in the past.

Friday, October 2 (Completed)

- Set-up ProCoDa system
- Test varying Fluoride standards to create a calibration curve for the Fluoride probe
  - Standards: 0 mg/L, 2.5 mg/L, 5 mg/L, 7.5 mg/L, 10 mg/L, 20 mg/L and 40 mg/L
- Run an experiment with no PACI added - establish a control condition

Friday, October 16 (Completed)

- Start testing various concentrations of coagulant to determine what concentration optimally removes Fluoride
  - Begin with 20 mg/L and move up or down in concentration based on results

Friday, December 4 (Completed)

- Finish testing various concentrations of coagulant to determine what concentration optimally removes Fluoride
  - Run two experiments per dose of coagulant
  - Test three different dosages of coagulant starting with 20 mg/L and changing the dosage based on the results received

## Introduction

In many developing countries, high levels of fluoride in groundwater have been found to have chronic effects on bone health. Though some countries intentionally add fluoride to water in order to strengthen teeth, overexposure to fluoride has grown as a problem worldwide. With 85% of its drinking water sourced from groundwater, India is the largest user of groundwater in the world and is at a high risk of overexposure to over-consumption of fluoride (EPA, 2013).

The team hopes to affordably, sustainably and reliably reduce fluoride levels in treated groundwater used for drinking water. Focusing on the groundwater used by the AguaClara plant in Jharkhand, India - we hope to develop a system that works efficiently with the AguaClara plant and affordable technology to monitor and reduce fluoride levels. Ultimately, our goal is to provide safe drinking water on tap to villages and communities worldwide that are dependent on fluoride-rich water sources. Currently we are focusing our efforts on drinking water systems in India. These systems only have filtration and then chlorination because the majority of the water they are distributing is ground water (EPA, 2013). Our system would have to work in this capacity.

# Literature Review

## ***Limitations and Hazards***

Over-absorption of fluoride can interfere with bone formation, cause the calcification of ligaments, arthritis, dental fluorosis and crippling fluorosis among other conditions (Lewis, 1997). Fluoride can cause irritation through inhalation, digestion, and touch and can cause damage to both eyes and exposed skin ("Hazardous Substance Fact Sheet, 2010).

Though there isn't an established "average" level of fluoride in India, the literature suggests that fluoride levels are seldom above 5 mg/L in groundwater. However, in the remote Karbi Anglong district of India, fluoride levels range from 5-23 mg/L causing severe anaemia, stiff joints, painful and restricted movement, mottled teeth and kidney failure (WHO, 2000).

According to the National Research Council (NRC), the maximum contaminant level (MCL) of fluoride in drinking water is 4 mg/L. However, a secondary limit of 2 mg/L has been established by the EPA to avoid potential cosmetic effects such as tooth and skin discoloration. The World Health Organization (WHO) established a safe upper limit of 1.5 mg/L to avoid all potential risks of fluoride consumption, with 0.8-1.2 mg/L providing a beneficial balance of fluoride and water by preventing tooth decay and strengthening the skeleton. The team will be striving towards the WHO guideline of 1.5 mg/L of fluoride for our research this semester.

## ***Fluoride Removal Methods***

A plethora of studies regarding methods for fluoride removal from groundwater have been previously conducted. Methods commonly cited include sorption media, co-precipitation chemicals, and contact precipitation chemicals. The sorption process, which uses either bone charcoal or activated alumina and clay, consists of the media being packed into columns that eventually reach saturation and must be renewed or regenerated (Bailey, 2006). Chemicals like polyaluminium chloride (PACl), aluminum sulfate and lime are used in the co-precipitation method. The chemicals are added in batches and used to precipitate out fluoride. These processes often produce egregious waste sludge that needs to be properly disposed of (Bailey, 2006).

Each of these methods have benefits and pitfalls associated with them. Bone char used to be widely accessible, but in recent years has been limited in production. It can however, be generated within villages themselves for relatively low costs. Still, it is difficult to optimize bone char practice, and improper use leads to deteriorated water quality (Bailey, 2006). Water treated with poorly conditioned bone charcoal can have a smell similar to rotten meat and a displeasing appearance (Bailey, 2006). Another option similar to bone char is biochar, in which pine bark and different types of wood are used instead of bone char. Fluoride sorption by biochars has

been found to be comparable to that of activated carbons (Mohan, 1990), but has only been proved efficient in acidic conditions (Oh, 2012) .

The Nalgonda technique is a very popular way for developing countries to remove excess fluoride. A type of co-precipitation method, the overall process involves several steps, including rapid mixing, flocculation, sedimentation, filtration, and disinfection. In this method, alum and lime are used to create insoluble aluminium hydroxide that co-precipitates out the fluoride by settling towards the bottom of the tank. (Bhatnagar, 2011). The main advantage of this technique is that it uses materials that are easily accessible to developing regions (Bailey, 2006). The main disadvantage, however, is that the sludge containing the excess fluoride must be disposed of. Disposal is considered a serious environmental health problem, as the sludge contains highly concentrated fluoride. The sludge must be inaccessible to children and animals, and located nowhere near gardens or water sources (Bailey, 2006). Additionally, because the fluoride in the sludge is only loosely attached to the aluminium hydroxide flocs, water must be removed no later than a couple of hours after treatment (Bailey, 2006). In the Bailey article, experiments were able to get up to 84% removal (Bailey, 2006).

Contact precipitation with calcium and phosphate compounds is another plausible technique that requires a catalyst, namely bone char, in a contact bed that can act as a filter for the precipitate (Dahi, 2006). This leads to promising results, but still more research must be done to find the optimal time in which water contacts the catalyst. If more research is done, contact precipitation has the potential to be highly efficient and cost effective (Bailey, 2006). Research done by Eli Dahi reported removal of 75% from an initial fluoride concentration of 13 mg/L (Dahi, 2006).

This semester, the team decided to use the coagulant Polyaluminium Chloride to precipitate out fluoride in solution. Our group is exploring the possibility of pairing this process with a filter so less coagulant has to be added. Bailey et. al. (2006) note that if a coagulant is to be used, the coagulant must be mixed homogeneously into the solution to optimize filtration efficiency (Bailey, 2006). Thus, the team design plan utilizes this concept by incorporating a rapid mix for groundwater and coagulant.

### ***Varying pH to Increase Fluoride and Polyaluminium Chloride (PACl) removal***

The coagulant Polyaluminium Chloride will be the primary agent in removing fluoride from the water. However, after filtration, excess PACl can remain in drinking water and could lead to significant health issues. Ingallinella et. al. (2011) found that adding NaOH to filtered water increases the pH enough to precipitate PACl out of solution, so PACl concentrations in the drinking water are well below established toxicity levels. The EPA has set a secondary standard for aluminum and aluminum compounds at 0.05 to 0.2 mg/L, above which the

noticeable effect is salty water (EPA 2015). Additionally, there is little evidence that aluminum is acutely toxic for the average person (Carson, 2000).

The report described a set of tests that were carried out. These tests were done in two ways. The first was a jar test where the mixture of coagulant and fluoride was run through a Whatman 40 membrane and a pilot plant that ran the mixture first through gravel of around 12-20 mm and then through sand around 0.5 mm. There were three different tests of varying concentrations of coagulants and pH's including: (Ingallinella, 2011)

1. Testing different initial pHs of the influent raw water to determine if there was an effect on the percent removal of fluoride
2. Testing the effect of different pHs on the PACl removal, as tested with the output stream
3. Testing a combination of 1 and 2 to optimize fluoride and PACl removal. The report noted that to bring the concentration of fluoride below 2 mg/L and the concentration of PACl below 0.2mg/L in the output stream, using either a concentration of 125 mg/L or 100 mg/L of PACl must be used in the input streams for optimal fluoride removal.

The process that yielded optimal fluoride removal rates and sufficient levels of PACl followed the following steps:

1. Lowering the pH of the solution (5.5-6)
2. Filtering the solution
3. Increasing the pH of the solution (7.5-8)

Article (Year)	Author	Initial F-Concentration	Final F-Concentration	% Removal	Coagulant Used	PACl Dosage
Effectiveness of poly aluminum chloride (PAC) vis-a-vis alum in the removal of fluorides and heavy metals (2007)	<a href="#">Sonu Malhotra</a> , <a href="#">D.N. Kulkarni</a> & <a href="#">Sunil P. Pande</a>	7.6 mg/L	3.8 mg/L	50%	PACl	500 mg/L
Simultaneous removal of arsenic and fluoride from groundwater by coagulation-adsorption with polyaluminum chloride (2011)	<a href="#">Ana M. Ingallinella</a> , <a href="#">Virginia A. Pacini</a> , <a href="#">Rubén G. Fernández</a> , <a href="#">Romina M. Vidoni</a> & <a href="#">Graciela Sanguinetti</a>	2.4 mg/L	1.5 mg/L	62.5%	PACL	100 mg/L
Investigations on the column performance of fluoride adsorption by	Subhashini Ghorai & K.K. Pant	5 mg/L	0.7 mg/L	86%	Alum	200 g in adsorption bed

activated alumina in a fixed bed						
Removal of excess fluoride from water using residue from alum manufacturing process. Journal of Hazardous Materials	B. S. Chandravanshi & Feleke Zewge	40.0 mg/L	7.2 mg/L	82%	Alum	16 g/L
Fluoride Removal from Potable Water Supplies	F. W. SOLLO, JR., THURSTON E. LARSON and HENRY F. MUELLER *	4.75 mg/L	1.3 mg/L	72.6%	Alum	300 mg/L

Fig 1. Table of fluoride removal rates in other PACl and Alum removal experiments.

## Methods

The apparatus used for experimentation is shown in Figure 1 below. To begin, a source of coagulant and a source of raw water were created. The raw water was created by diluting 200 uM sodium fluoride (NaF). Varying dosages of PACl are used to treat the fluoridated water. Two pumps work to transport the two solutions from their respective containers, and a mixture is formed in the rapid mix piping. The diameter of the rapid mix tubing is small enough that the raw water and coagulant are sufficiently mixed. After the rapid mix, water is pumped up through a sand filter in order to remove the precipitate. Next, an Ion-Selective Electrode (ISE) probe in conjunction with ProCoDA measures and records the obtained voltages, which can be translated into fluoride concentrations through the use of a calibration curve.

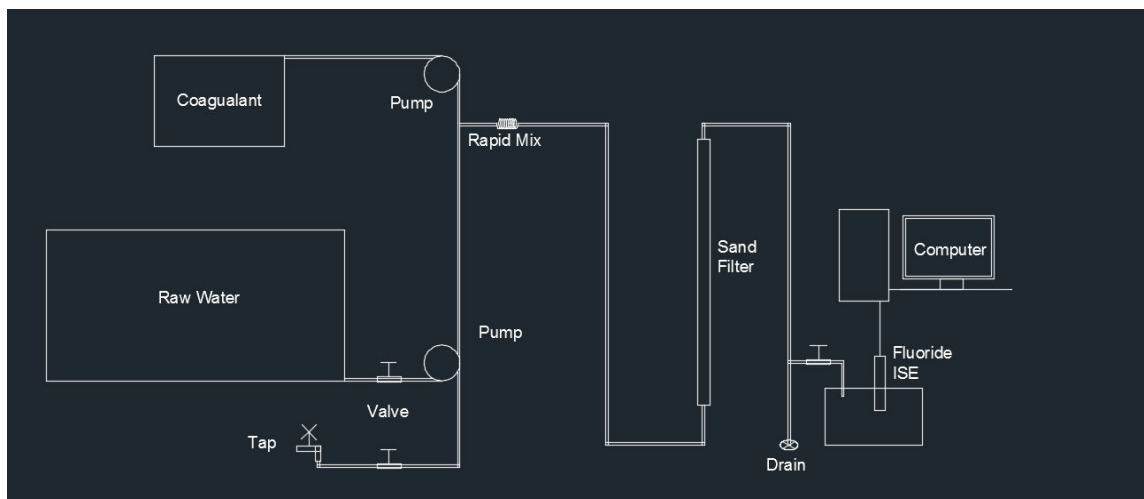


Fig 2. First draft diagram of the filtration system that will be used to both remove fluoride from raw water and record the obtained data values.

For the concentration of fluoride, WHO states that the safe upper limit of fluoride is 1.5 mg/L. Various concentrations of fluoride will be tested starting with 10 mg/L, a concentration known to cause serious health concerns. Though natural concentrations of fluoride in groundwater are seldom above 5 mg/L, there have been reports of concentrations up to 23 mg/L in India. The team decided to begin experiments with 10 mg/L as a middle ground, and intends to test concentrations both above and below 10 mg/L as testing progresses. To prepare the raw fluoride water, we used 37.5 mL of original NaF solution (0.2 M) with 15 L raw water to obtain a concentration of 10.0 mg/L.

$$C_{\text{standard}} * V_{\text{standard}} = C_{\text{rawwater}} * V_{\text{rawwater}}$$

### Eq 1. Calculation for raw water creation

$$0.2 \frac{\text{mol}}{\text{L}} * \frac{19 \text{ g NaF}}{\text{mol NaF}} * \frac{1 \text{ mol NaF}}{1 \text{ mol F}^-} * \frac{1000 \text{ mg}}{\text{g}} = 3800 \text{ mg/L}$$

$$(x) * (3800 \text{ mg/L}) = (15000 \text{ mL}) * (10.0 \text{ mg/L})$$

x = Amount of 0.2M fluoride solution to be put into 15 L of raw water = 39.5 mL

### **Preliminary Set-Up**

At the start of the set-up, raw water is held in a large five gallon bucket and PACl is held in a two liter jar with a lid. Each of these fluids is added to the system by peristaltic pumps, and then combined in a rapid mix before entering the filtration column. The rapid mix was created by wrapping a ¼ inch tube around a section of 1 in pipe. These were secured together by zip ties. From there the water flows up through the bottom of the sand filter and out through the top. Once the water has exited the filter, it is ready to be tested. In the set-up we used a combination of ¼ inch and ⅜ inch tubes to connect each of our components.

To create the sand filter, the team used a combination of couplings and copper mesh. For the filter itself we are using a 1 inch clear PVC pipe with one 1 inch coupling, a PVC compression pressure fitting and copper mesh. The mesh was cut to size so that it would fit into the compression pressure fitting, and the ledge on the fitting allowed the mesh to stay in place. The copper mesh was only attached to the bottom of the pipe so that sand can be taken out if necessary. Additionally, the column was only filled halfway with sand to ensure that sand would not escape the filtration system during backwash.

The blue water tube in the AguaClara lab and the raw water tube were both connected to a T-fitting that led to the the second “raw water” pump. Using the valve directly connected to the blue water tube, the water source can be adjusted based on the desire for filtration or



backwash. Initially, a T-fitting and a valve were added at the end of the system so that the effluent from the sand filter could directly flow into the overhead red waste tube. After discovering that the effluent composition and flow rate were affected by the waste products of a nearby team, a long ½ inch tube connecting the top of the sand filter to a bucket below the desk, was put in place. Samples are taken manually, in five minute intervals, right before water runs into the bucket. This batch method was put in place to keep the ion probe from having water continuously run over it, so that unnecessary deterioration would be prevented.

### **Calculating Flow Rate**

Because the system is primarily based on a system that was previously created to remove arsenic (Zhi, 2016), it was decided that similar flow velocities should be used for the filtration and backwash system. Because the arsenic system uses a ½ in diameter pipe and we are using 1 in diameter pipe, the team needed to calculate a flow rate that corresponded to the current system. The following are the calculations that were done to determine the system flow rate.

$$Flow\ Rate = Velocity * Surface\ Area = v * \pi * r^2$$

#### **Eq 2. Calculation of flow rate**

$$Flow\ Rate\ of\ Backwash = 14.1\ mm/sec * \pi * 12.7mm^2 = 7144\ mm^3/s = 7.14\ mL/s$$

$$Target\ Flow\ Rate = 1.009\ mm/sec * \pi * 12.7mm^2 = 511\ mm^3/s = 0.51\ mL/s$$

Flow Rate Comparison Table

<b>Calculation Corresponding to Filtration</b>	<b>US Units</b>	<b>SI Units</b>
Hui's Flow Rate	0.702 in <sup>3</sup> /min	191.7 mm <sup>3</sup> /sec
Hui's Radius of Pipe	0.301 in	7.645 mm
Target Velocity	2.47 in/min	1.009 mm/sec
Target Velocity of Backwash	33.32 in/min	14.1 mm/sec
Radius of Pipe	0.5 in	12.7 mm
Target Flow Rate	1.87 in <sup>3</sup> /min	0.51 mL/sec
Target Backwash Flow Rate	26.16 in <sup>3</sup> /min	7.14 mL/sec

Fig. 3 Table of calculations done to determine the overall system flow rate based on Hui's

*arsenic system*

Since it was not definite that the sand in the fluoride system is similar to the sand used in the arsenic system, trial and error should be used to find the correct flow rate. The sand needs to be fully fluidized when running the backwash, which means that the sand should increase to constant height around 1.33 times the settling size of the sand. Fluidization takes place as a result of the flow of sand through each of the individual sand particles. Using Hui's target velocity, the team was able to determine the backwash velocity of 14.1 mm/sec. Using the radius of the pipe, it was found that a flow rate of 7.14 mL/sec is appropriate to bring the sand to 1.33 times its initial size after fluidizing. This was further confirmed by manually measuring 1.33 percent of sand bed, and increasing the flow rate until fluidization reached the desired height. It was found that the calculated flow rate and experimentally determined flow rates were equivalent. As can be seen in Fig. 3, it was found that running the backwash for around 20 minutes brought the concentration of fluoride down to levels low enough that the system could be run again for a new experiment and thus the system was backwashed.

<b>Voltage Recorded</b>	<b>-log(concentration)</b>	<b>Concentration (mg/L)</b>	<b>Time/What Recorded</b>
-0.037	0.02289714523	0.9486431056	1:55 Backwash start
-0.0506	0.4560720305	0.3498871312	2:05 Backwash (10 minutes)
-0.0528	0.5261444384	0.2977525994	2:15 Backwash (20 minutes)
-0.0606	0.7745829756	0.1680416837	Tap water

*Fig. 4 Table of backwash concentrations*

**Creation of Standards**

Standard (mg/L)	Total volume of standard (L)	Volume of stock solution 1000 mg/L NaF needed (mL)	Volume of water needed (mL)
0	0.1	0	100
0.25	0.1	0.025	99.975
0.5	0.1	0.05	99.95
1	0.1	0.1	99.9
2	0.1	0.2	99.8
5	0.1	0.5	99.5
10	0.1	1	99
20	0.1	2	98
50	0.1	5	95

*Fig. 5 Table of calculations done to develop the standards necessary for the calibration curve.*

Starting with an initial concentration of 1000 ppm or 1000 mg/L, the team had to calculate the amount of water necessary to dilute the concentrated F- to the desired standards. The team created nine standards, as seen above, ranging from 0 to 50 mg/L. Calculations were made using the dilution equation  $M_1V_1 = M_2V_2$ , where  $M_1$  is the initial concentration,  $V_1$  is the initial volume,  $M_2$  is the final concentration after dilution and  $V_2$  is the the volume after the dilution. The above table calculates these values to create a volume of 100 mL for each standard.

### ***ProCoDA Set-Up and Initial Test Run***

The team set up the ProCoDA system and created rules and set points on ProCoDA that would allow the system to run properly. When the system was first run, there were multiple leaks around the system that were resolved by pushing the tubing further into the push-to-connects. Tap water was first run through the system to test if it worked properly. After fixing the leaks, the water smoothly flowed through the peristaltic pumps and sand filtration column, and then into the red waste tube for disposal. The next step was to run some of the imitation ground water through the system. In the initial running, the groundwater was not being pumped from the bucket into the sand filtration column. This was due to air being let out of the system at the valve, which is now fixed. Additionally, there was a minor setback when the filtration column head popped off the system, due to the team forgetting to open the valve to the waste pipe - creating a build up of both pressure and fluid in the system. This caused the mesh that holds up the sand to break and sand then flowed out of the bottom of the column. The team decided to take apart the sand filter to fix the mesh and also address and remove the large flocs on top of the sand column that were unable to be removed by the backwash. The broken mesh was replaced with a new mesh and the sand column was put back into place. Despite these complications, all issues are now resolved and the groundwater solution is now able to flow completely through the system and out into the waste container.

### ***Making a calibration curve***

To make the calibration curve, the nine standards mentioned in the previous section were tested using the probe and ProCoDA. The probe was put into one standard at a time, and the voltage was recorded every 10 seconds in the ProCoDa data log. The probe was left in each standard for as long as it took the voltage to equilibrate. The voltage average for each standard was then taken, and used to make a  $-\log(\text{concentration})$  vs. voltage plot. A trendline was established from the data points, and is to be used as the calibration curve.

In order to obtain accurate voltage readings, the probe is not touched during measurements to allow values to stabilize or “plateau” before recording them. Given these adjustments, on October 21, 2015 (Fig 5) , a linear calibration curve was established. To make sure that any day to day discrepancies in probe function were accounted for, it was determined that before each day of testing, a new curve would be created using the standards 1 mg/L, 10 mg/L and 20 mg/L. Any fluoride removal would be based on that calibration curve and based on the probe reading for concentration of the raw water for that day, as can be seen in Figure 6.

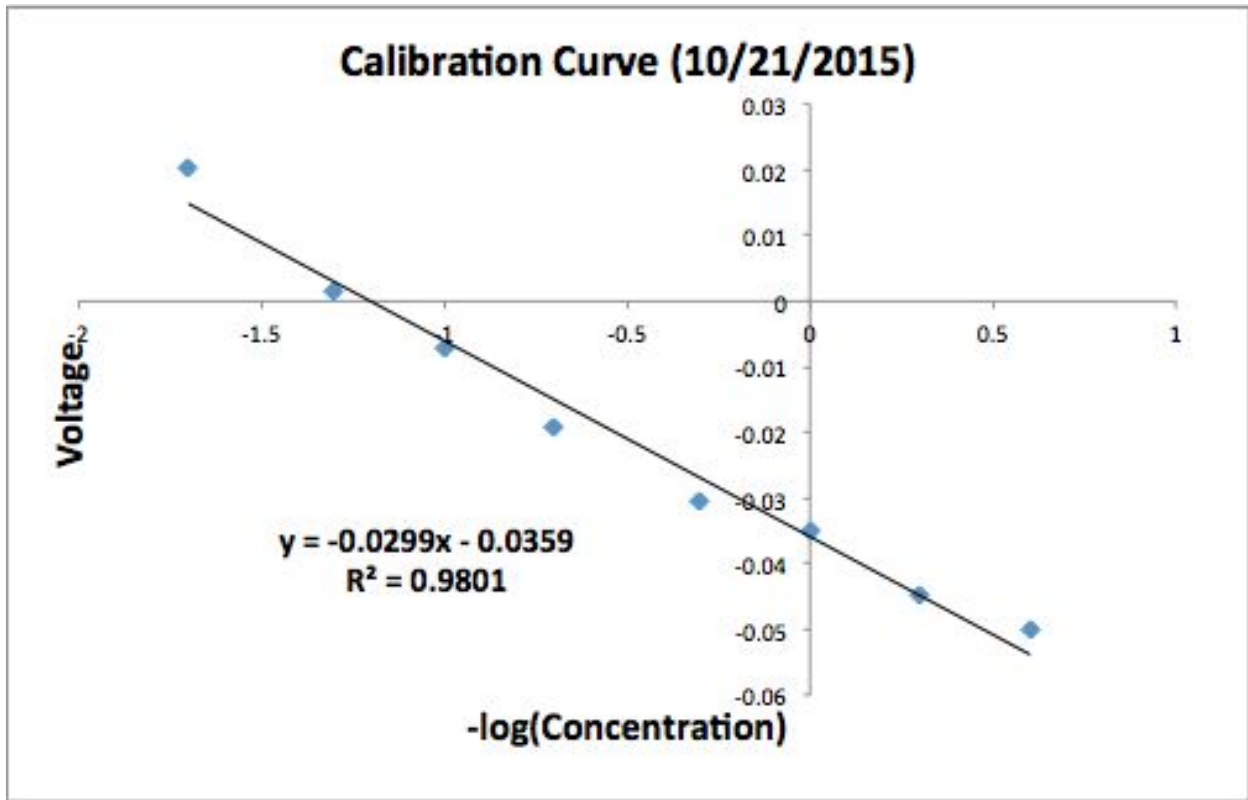


Fig. 6 Final Calibration Curve obtained on October 21, 2015.

Date:		
10/28/2015		
<b>Standard (mg/L)</b>	<b>-log(concentrations)</b>	<b>Voltage</b>
1	0	-0.032967934
10	-1	-0.004852059
20	-1.301029996	0.007112591

<b>Slope</b>	-0.03013100126	
<b>Y-intercept</b>	-0.0333465799	

Fig. 7: Example of daily calibration and slope creation log

From this graph and table, the team is then able to work backwards by using measured voltages to calculate the fluoride concentration of the raw water solution, the effluent with coagulant and raw water, and the effluent from backwash.

Raw water stock was created to allow for an influent concentration of 10 mg/L of fluoride. As seen in Figure 7, the flow rate and concentration of stock PACI was calculated by determining how dilute PACI becomes when incorporated into the stream of raw water.  $F \cdot C = F \cdot C$  was then used to calculate the necessary flow rate and concentrations needed and how to create them from the highly concentrated PACI stock in the AguaClara lab. It was found that using a flow rate of 0.093 mL/s supplies enough PACI for a run time of three hours. Using the table below, the team was able to determine the appropriate volume of coagulant necessary for run various trials.

<b>Process Specifications</b>			
Concentration of lab PACI	69400	mg/L	
Flow Rate of Water	0.53	mL/s	
Lifetime of Stock PACI	3	hours	
Volume of Stock PACI	1000	mL	
Concentrations of PACI going into sand column (mg/L)	Flow rate of PACI (mL/s)	Flow Rate going into sand column (mL/s)	Stock concentration of PACI (mg/L)
40	0.09259	0.62259	268.960
20	0.09259	0.62259	134.480
10	0.09259	0.62259	67.240
5	0.09259	0.62259	33.620

3	0.09259	0.62259	20.172
1	0.09259	0.62259	6.724
<b>Stock concentration of PACI (mg/L)</b>	<b>Volume of stock PACI (mL)</b>	<b>Volume of lab PACI needed (mL)</b>	<b>Amount of water needed (mL)</b>
268.960	1000	3.875504323	996.1244957
134.480	1000	1.937752161	998.0622478
67.240	1000	0.9688760807	999.0311239
33.620	1000	0.4844380403	999.515562
20.172	1000	0.2906628242	999.7093372
6.724	1000	0.09688760807	999.9031124

*Fig. 8 Process Specifications and Calculations*

### **Coagulant Dosing**

The team began trials with 20 mg/L of PACI and 10 mg/L of raw water. The system was first backwashed, and then run with just raw water to saturate the system with fluoride. The aim for these tests is to bring the fluoride concentration in the effluent of the system down to below 1.5 mg/L which is the limit for the WHO. The PACI concentrations will be increased until the fluoride concentration is below this limit and once that limit is reached, that will be the concentration to be used for 10 mg/L of fluoride in raw water.

After running the system for approximately an hour and a half with 20 mg/L of PACI, the concentration of fluoride went from 8.9 mg/L to a constant 3.7 mg/L, as can be seen in Figures 9 and 10. Percent removal of fluoride equaled 58%. Data values recorded from this trial are shown below, as a sample. First, voltage values were recorded and then converted to yield the  $-\log(\text{concentration})$  based on the calibration curve values of that day. The negative inverse log was then taken to obtain the final concentration measurement.

<b>Voltage Recorded</b>	<b><math>-\log(\text{concentration})</math></b>	<b>Concentration (mg/L)</b>	<b>Time/What Recorded</b>
-0.05	0.6008537032	0.2506953605	After Backwash
-0.0055	-0.9493144138	8.89845101	Raw water

-0.06	0.9492060891	0.1124071433	3:43 Start
-0.0565	0.827282754	0.1488391722	3:50
-0.0098	-0.7995228879	6.302645609	4:10
-0.006	-0.9318967945	8.548635395	4:30
-0.0065	-0.9144791752	8.21257172	Using coagulant 4:49
-0.0146	-0.6323137427	4.28858224	Using coagulant 4:56
-0.0158	-0.5905114564	3.895035824	Using coagulant 5:06
-0.0166	-0.5626432655	3.652946112	Using coagulant 5:18
-0.0164	-0.5696103132	3.712020049	Using Coagulant 5:30

Fig. 9 Concentration of fluoride at various time intervals (20 mg/L PACl with 10 mg/L raw water Trial 1)

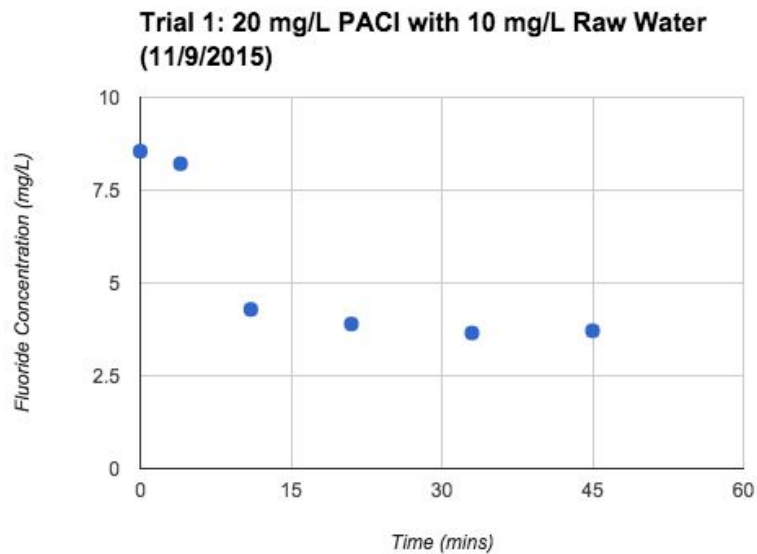


Fig. 10 Graph of the change in concentration of fluoride using 20 mg/L of PACl

When the experiment was replicated, fluoride levels went from 10.3 mg/L in the influent raw water to 5.7 mg/L in the effluent (Fig. 11). Results from this trial yielded 56% fluoride removal. In this trial, and all trials that will follow - the system is simply backwashed before beginning, as prior saturation with raw water was deemed unnecessary after the first trial. In these graphs, the initial fluoride concentrations begin at the state of the water after backwash. Then as the fluoride and coagulant are pumped through the system, the fluoride concentration will rise and after the course of around 45-60 minutes, the fluoride concentration plateaus to a

certain value and this is the final concentration after the addition of the coagulant. From this number we can then calculate the percent removal.

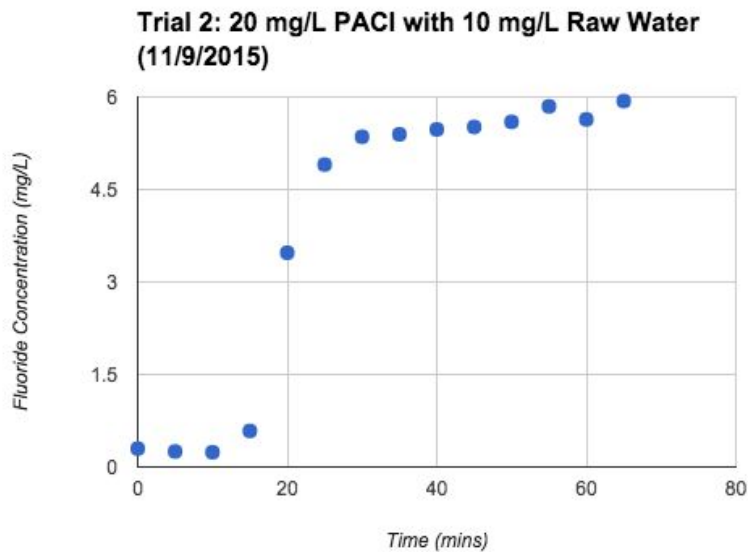


Fig. 11: Graph of the change in concentration of fluoride using 20 mg/L of PACI

The next step was to increase the concentration of PACI to 40 mg/L, in an effort to bring the final concentration of fluoride under 1.5 mg/L - in accordance with WHO fluoride regulations. When 40 mg/L of PACI was used with 10 mg/L of raw water, concentrations of fluoride went from 10.8 mg/L down to 1.75 mg/L (Fig. 12). Percent removal of fluoride from this trial was 84%.

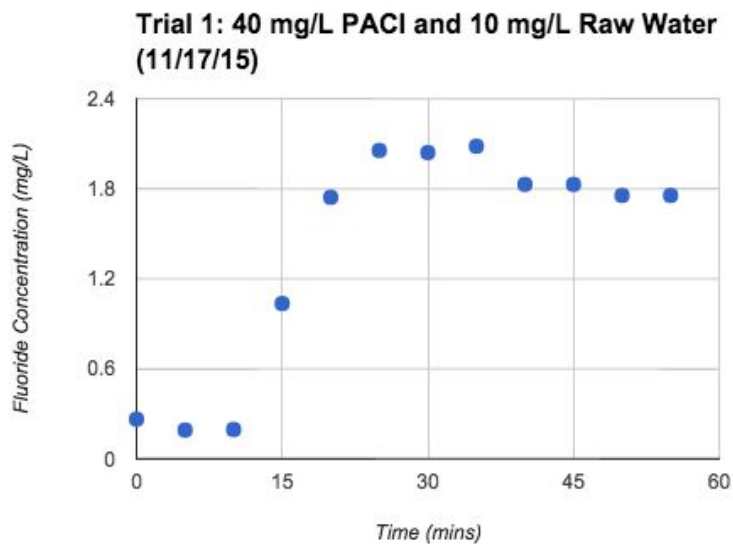
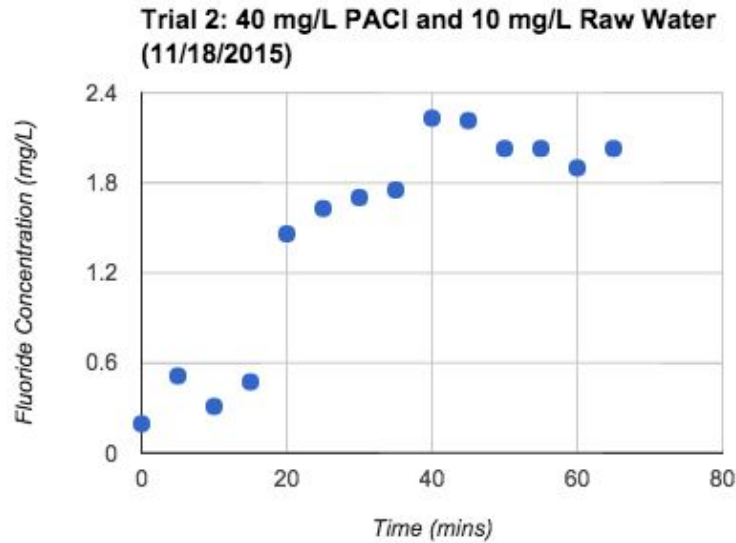


Fig. 12: Graph of the change in concentration of fluoride using 40 mg/L of PACI



When the experiment was replicated, fluoride levels went from 10.7 mg/L down to 2 mg/L (Fig. 13). Results from this trial yielded 81% removal.



*Fig. 13: Graph of the change in concentration of fluoride using 40 mg/L of PACl*

Finally, using a concentration of 50 mg/L of coagulant, both trials yielded a fluoride concentration of 1.40 mg/L and 0.64 mg/L respectively from around 10.3 mg/L of fluoride in the influent raw water yielded removal of percentages of 86% and 94%, which are both below the limit of 1.5 mg/L set by the WHO (Fig. 14 and 15). Therefore 50 mg/L gives the most cost efficient dosage of coagulant for 10 mg/L of fluoride in water that makes it safe to drink.

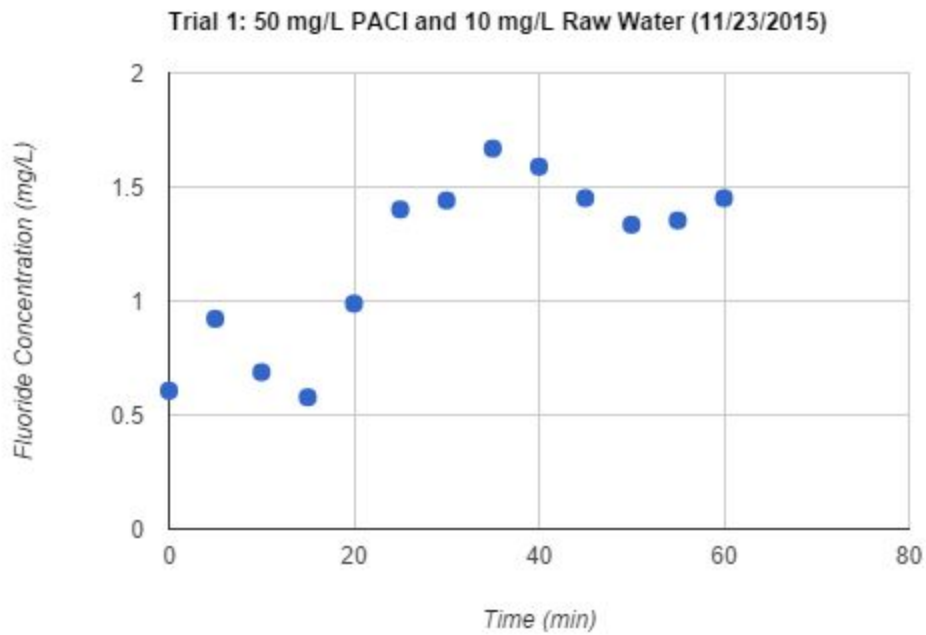


Fig. 14: Graph of the change in concentration of fluoride using 50 mg/L of PACl

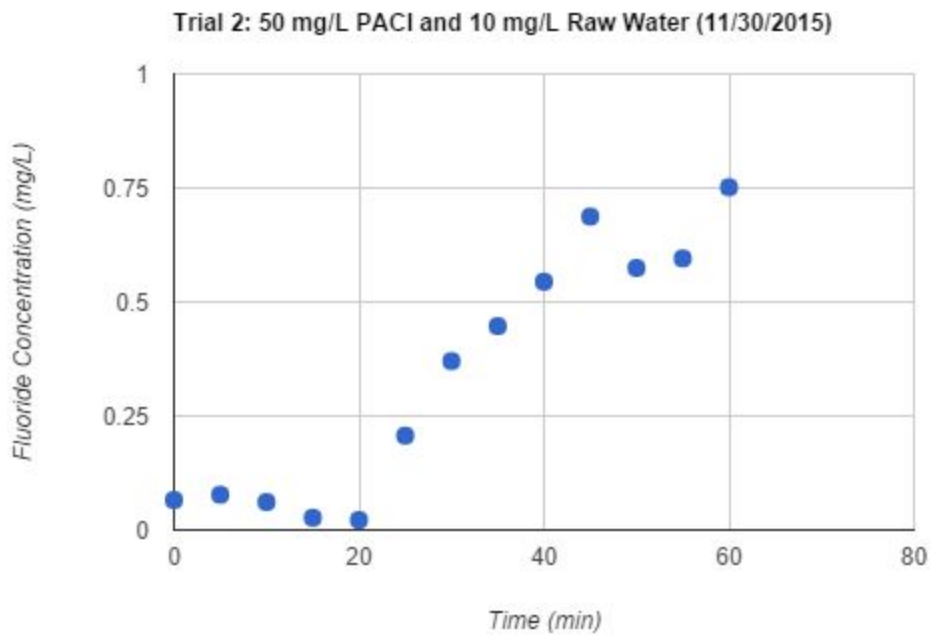


Fig. 15: Graph of the change in concentration of fluoride using 50 mg/L of PACl

## Summary of Results:

Trial Number/Coagulant Dosage	Initial fluoride concentration (mg/L)	Final fluoride concentration (mg/L)	Percent Removal
Trial 1, 20 mg/L	8.9	3.7	58%
Trial 2, 20 mg/L	10.3	5.7	56%
Trial 1, 40 mg/L	10.8	1.75	84%
Trial 2, 40 mg/L	10.7	2	81%
Trial 1, 50 mg/L	10.3	1.40	86%
Trial 2, 50 mg/L	10.4	0.64	94%

*Fig. 16: Table of results using different concentrations of coagulant*

## Future Work

Though promising results were obtained this semester, the team will continue experimentation in preparation for the P3 competition. Varying concentrations of fluoride will also be tested, as 10 mg/L fluoride is not typically found in rural villages in India. The team also hopes to determine the time it takes for the PACl to saturate the sand by analyzing data from the pressure sensor. This data would be used to establish the max amount of time that the system could be run before it required backwashing. Additionally, various sand sizes will be tested in an effort to observe if particle size has any effect on fluoride removal, headloss and run time. Our current hypothesis for this is that if the particle size of the sand in the column is increased, say to small pebbles around 3-5 mm, the rate at which the headloss builds up in the system due to coagulant, will be reduced. This means that we can run experiments with longer run times since the sand filter isn't being clogged as quickly from the coagulant. However, with this larger sand, it could also lead to decreased fluoride removal percentages which means we would need to increase our concentration of PACl which will cost more money. To see the effects of changing the sand particle size, 50 mg/L of coagulant will be run through the system again to test what the percent removal is, and this will give an idea about whether or not a higher dosage is necessary for larger sand.

## References

- Bailey, K.; Chilton, J.; Dahi, E.; Lennon, M.; Jackson, P.; Fawell, J. "Fluoride in Drinking-water." World Health Organization (2006). Retrieved via [http://www.who.int/water\\_sanitation\\_health/publications/fluoride\\_drinking\\_water\\_full.pdf](http://www.who.int/water_sanitation_health/publications/fluoride_drinking_water_full.pdf).
- Bhatnagar, Amit, Eva Kumar, and Mika Sillanpää. "Fluoride Removal from Water by Adsorption—A Review." *Chemical Engineering Journal* 171.3 (2011), 811-40. Retrieved via [http://ac.els-cdn.com/S1385894711005845/1-s2.0-S1385894711005845-main.pdf?\\_tid=5d8fcf76-c445-11e4-b2bf-0000aab0f6c&acdnat=1425676473\\_1f8e45dd1c6d0875ba654f136a7f035f](http://ac.els-cdn.com/S1385894711005845/1-s2.0-S1385894711005845-main.pdf?_tid=5d8fcf76-c445-11e4-b2bf-0000aab0f6c&acdnat=1425676473_1f8e45dd1c6d0875ba654f136a7f035f).
- Dahi, E. "Development of the Contact Precipitation Method for Appropriate Defluoridation of Water." *Proceedings of the 2nd International Workshop on Fluorosis and Defluoridation of Water*, Nazareth, Ethiopia. (1997).
- EPA. "Basic Information about Fluoride in Drinking Water." (2013). Retrieved via <http://water.epa.gov/drink/contaminants/basicinformation/fluoride.cfm>
- EPA. "Secondary Drinking Water Regulations: Guidance for Nuisance Chemicals." Environmental Protection Agency, 23 Nov. 2015. Web. 11 Dec. 2015.
- Ghorai, Subhashini, and K. K. Pant. "Investigations on the Column Performance of Fluoride Adsorption by Activated Alumina in a Fixed-bed." *Chemical Engineering Journal* 98.1 (n.d.): 165-73. *Chemical Engineering Journal*, 15 Mar. 2004. Web. 11 Dec. 2015.
- Ingallinella, A., Pacini, V., Fernández, R., Vidoni, R., & Sanguinetti, G. "Simultaneous removal of arsenic and fluoride from groundwater by coagulation-adsorption with polyaluminum chloride." *Journal of Environmental Science and Health* (2011), Part A 46:11, 1288-1296, DOI: 10.1080/10934529.2011.598835. Retrieved via <http://www.tandfonline.com/doi/pdf/10.1080/10934529.2011.598835>
- Lewis, H.K. "Fluoride Intoxication: A Clinical-Hygienic Study." London (1937), 213-253. Retrieved via <http://www.fluoridation.com/skeletal.htm>.
- Mohan, D., Sharma, R., Singh, V., Steele, P., & Pittman, C. "Fluoride Removal from Water using Bio-Char, a Green Waste, Low-Cost Adsorbent: Equilibrium Uptake and Sorption Dynamics Modeling." *Industrial & Engineering Chemistry Research* 51.2 (2012), 900-914. DOI: 10.1021/ie202189v Retrieved via <http://pubs.acs.org/doi/ipdf/10.1021/ie202189v>
- New Jersey Department of Health. "Hazardous Substance Fact Sheet: Sodium Fluoride." (2010). Retrieved via <http://nj.gov/health/eoh/rtkweb/documents/fs/1699.pdf>.
- Oh, T., Choi, B., Shinogi, Y., & Chikushi, J. "Effect of PH Conditions on Actual and Apparent Fluoride Adsorption by Biochar in Aqueous Phase." Springer Science+Business (2012). Retrieved via [http://download.springer.com/static/pdf/0/art%253A10.1007%252Fs11270-012-1144-2.pdf?auth66=1425676548\\_4836fafcadd544bc5acac6fafc99229&ext=.pdf](http://download.springer.com/static/pdf/0/art%253A10.1007%252Fs11270-012-1144-2.pdf?auth66=1425676548_4836fafcadd544bc5acac6fafc99229&ext=.pdf)
- Zhi, Hui. "Arsenic(V) removal from drinking water by concurrent introduction of As contaminated water and Polyaluminum chloride in a sand filter medium: A thesis." Cornell University (2016).