

Verde Valley Water Treatment System

Final Design Report



CRKL Engineering

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LIST OF ABBREVIATIONS

ElectroChemical Arsenic Remediation (ECAR)
Environmental Protection Agency (EPA)
Maximum Contaminant Levels (MCL)
Metro State University Denver (MSUD)
Standard Method (SM)

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PROJECT OVERVIEW

CRKL Engineering was tasked with designing and creating a bench scale water treatment system for a hypothetical community of 10,000 members located in the Verde Valley. The groundwater in this community is contaminated with arsenic and nitrate in concentrations of 1-2 mg/L and 25-40 mg/L, respectively [1]. Arsenic and nitrate can be naturally occurring in groundwater and can also enter the water source through agricultural runoff, fertilizers, animal and human wastes, and industrial activities [1]. CRKL Engineering was tasked with these two contaminants due to their harmful nature and common occurrence.

The presence of arsenic and nitrate in water has multiple adverse health effects. Prolonged exposure to arsenic can directly affect the skin, bladder, and lungs, including skin and lung cancer [2]. Noncancerous effects of arsenic include pregnancy complications, joint pain, loss of hearing, and increased risk for developing type two diabetes [1]. When nitrate is ingested, the human body changes nitrate into nitrite, causing issues in all ages, but specifically babies aging from newborns to three month olds. The ingestion of nitrate in infants and toddlers causes Blue Baby Syndrome, which develops because their immune systems are still developing, causing them to convert all of the ingested nitrate to nitrite. While babies convert 100% of the nitrate, humans with developed immune systems only convert about 10% of the total ingested nitrate to nitrite [1]. Even though only some of the nitrate is converted, vascular collapse typically occurs in older humans [1]. The health effects above were found to occur when the nitrate concentration within the subject was 10 mg/L and above, where anything below that level had no observable effects. Due to the health effects associated with these contaminants, the EPA has set forth standards for arsenic and nitrate [1].

The EPA has set forth a maximum contaminant level (MCL) to regulate arsenic and nitrate within water sources. Arsenic has a MCL of 0.01 mg/L and nitrate has a MCL of 10 mg/L [2]. CRKL Engineering’s design goal was for the water treatment system to treat the water to EPA Drinking Water Standards.

TECHNICAL COMPONENTS

Water Treatment Design Alternatives

Each team member completed a literature review to determine feasible treatment methods for the removal of arsenic and nitrate. There were three categories of treatment method alternatives identified: nitrate removal, arsenic removal, and dual treatment. Both the arsenic and nitrate treatment options were broken into three different categories: conventional, innovative, and sustainable. The team was most interested in the sustainable treatment options, therefore two team members completed reviews for sustainable treatment methods.

One conventional nitrate removal method researched was an ion exchange process where water is passed through a chloride filled material, which would then retain the nitrate ions in exchange for a less harmful chloride ion. This was a viable option because the materials are readily available, cost efficient, and the research done on this method can be used to determine the correct doses for the team's needs. One sustainable option for nitrate removal was the use of autotrophic bacteria as a biofilm. This method grows bacteria that converts nitrate to nitrogen gas, which replaces the nitrogen within the nitrate with a hydrogen molecule. This was considered because of the low waste production and the opportunity to conduct further research on a new technology. Another sustainable method was running water through woodchips that serve as a permeable reactive barrier. The woodchips supply an organic carbon source, which is an adsorptive material. The water then flows through a sand filter bed to complete the filtration process. This option was considered for its relatively low cost design, which could be easily employed in developing areas.

A conventional method researched for arsenic removal was an oxidation process where water is saturated with oxygen. For this method, a pretreatment method to convert arsenic to arsenite is needed because the ability of arsenite to oxidize faster than arsenic. This method was researched as a low cost and well-known method with extensive research to reference when creating the design. The innovative treatment method for arsenic was called ElectroChemical Arsenic Remediation (ECRA) [1]. ECRA requires the use of an electrical current passing through the contaminated water with surface-modified iron nanoparticles, which then attract the charged arsenic particles, helping them to settle out. This option was considered because of its proven ability to remove high percentages of arsenic. A sustainable method of removing arsenic was phytoremediation, which is the use of plants up taking minerals from soils, or in this case water, and storing it within the plant. The plant suggested for this method was hyacinth roots [1]. This method was suggested because it could easily be used in developing areas where disposal of byproducts is nearly impossible. Another sustainable treatment method was passing the water through specifically designed ceramic fibers. The reasoning behind this method was to use newly researched materials to absorb contaminants. This material was a viable design option due to high availability in all communities and low operation and maintenance costs. The water would need to be passed through porous alumina tubes where the arsenic is deposited because of its affinity for bonding with alumina.

There were two treatment methods researched that act as dual treatment. These options were considered because the cost of a single process system is significantly less than a multi-step process and a single treatment method can be better used in rural areas. The first dual treatment

option was an ion exchange using titanium dioxide-based hybrid media to attract both the arsenic and nitrate ions. Since ion exchange is a common process, the research done on this method and other similar methods would help the team in determining how to apply such concepts to the given situation. The second dual treatment system was also an ion exchange process using activated alumina as the treatment media. Research conducted showed this media effectively removes arsenic and nitrate individually, however, activated alumina has not been used as a dual treatment media yet. This media is a viable treatment option because of the low cost compared to titanium oxide and the ability to easily regenerate the material.

Design Decision

The final design was determined based off the creation of a decision matrix. The previously described alternatives were put into a decision matrix, as seen in Appendix 1. Table 1 illustrates a condensed version of the decision matrix used, showing the top ranked options to treat for arsenic, nitrate, and both. The criteria used to determine the best options are seen in the left column of the table. The criteria for the system are to be low cost and low energy, feasibility, the lifetime of the system, and low by-product production.

The parameters were assigned percentages by the team to properly weigh the importance of the criteria. A 1, 3, 9 system was used for scoring each design alternative. In this system, a 1 represents the worst option, a 3 represents a viable option, and a 9 represents the best possible solution. The “Raw Score” was determined based on the number assigned to each design parameter and multiplied by the weighted percent and then summed for all the criteria for each design.

Table 1: Decision Matrix

				Nitrate	Arsenic	Dual Treatment	
		Criteria	Weights (%)	Ion Exchange: Chloride	Phytoremediation Hyacinth Roots	Ion Exchange: Titanium Oxide	Ion Exchange: Activated Alumina
Parameters	1	Low-Cost	30	9	9	9	9
	2	Low-Energy	30	3	9	9	9
	3	Feasibility	20	9	3	9	9
	4	System Life-Time	15	3	3	3	9
	5	Minimal by-product	5	1	1	3	3
	6						
			Raw score	5.9	6.5	7.8	8.7
			Relative Rank	3	3	2	1

Using the raw score, each design was given a relative rank. In the full matrix in Appendix 1, it is seen that there are duplicate ranks. This is because the alternatives for arsenic were ranked separately from the alternatives for nitrate to determine the best combination. The two highest ranked alternatives fall under the category of dual treatment. The dual treatment ranked highest for both arsenic and nitrate and was given the 1st and 2nd ranks for both contaminants. From there, the rankings continued for arsenic and nitrate independently.

The final design is the one highlighted in green since it was the highest-ranking alternative. The

team determined ion exchange using activated alumina was the best option based on the criteria defined by the team. With this decision, the team determined to create a gravity-fed system using a packed column filled with activated alumina.

Final Design

The CRKL Engineering team determined the best design alternative to be a gravity-fed packed column system using activated alumina as the treatment media. The base that holds the packed column is constructed of segments cut from an 8' long 2" x 4" beam and segments from a 2' x 2' medium density fiberboard. The column is constructed of a 3' long and 3" diameter clear plastic tube, a plastic pipe adapter, caulk, a 3" PVC cap, a PVC ball valve, PVC fittings, Teflon tape, PVC pipe cement and ASB to PVC cement. The materials used for construction are pictured below in Figure 1. Not pictured are the stain, pipe adapter, and ASB to PVC cement due to complications experienced during construction that are discussed later.

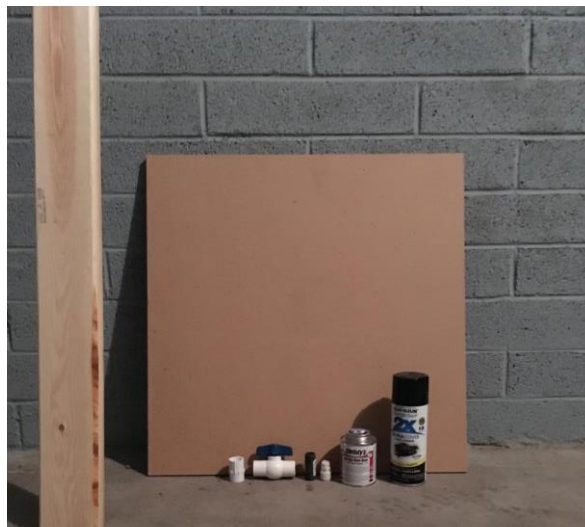


Figure 1: Construction Materials

Four 1' segments of the 2" x 4" compose the legs of the base. Nailed to the legs is a 1' x 1' piece of the medium density fiberboard with a hole cut in the middle. This hole was cut so that the valve on the end of the packed column could fit through, but the rest of the column could not. Two 8" segments of the 2" x 4" were nailed adjacent to the hole and a 6" x 12" piece of the medium density fiberboard was nailed to the top of those. Similarly to the other piece, the team cut a hole in the middle; however, this hole was cut slightly bigger so that the entire column could slide easily out of the base. Triangular edges were cut off of the top piece for aesthetic appeal. This piece was constructed to act as support for the column. The entire base was coated in a stained sealant to give the base a dark, glossy finish as well as prevent any water from seeping into the wood. Figures 2 and 3 show the base before and after the stain was applied.



Figure 2: Unstained Base

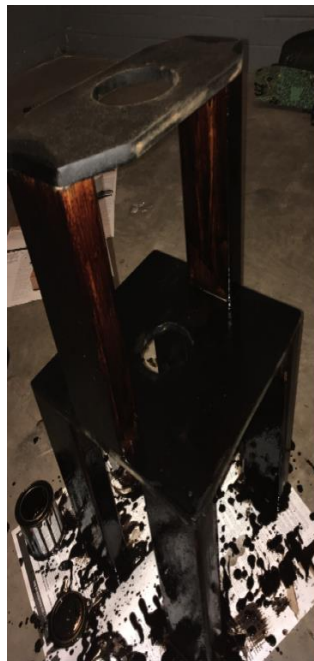


Figure 3: Base with one coat of stain

The first step to constructing the column was assembling the nozzle apparatus. The team decided to use a ball valve on the end of their column so they could take samples at desired times. The team purchased a threaded PVC ball valve and screwed a reducer into the end of that using Teflon tape and PVC pipe cement. The team did this to reduce the stream of effluent from the column to make collecting samples easier. On the other end of the valve the team attached a female-to-female adapter that was attached to a small (about 1" diameter) PVC fitting, completing the nozzle apparatus, which is pictured below in Figure 4.



Figure 4: Nozzle Apparatus

The team drilled a hole in the PVC cap as close to the same size as the fitting as possible to ensure a tight fit. The team sealed the nozzle apparatus to the cap using caulk. A half-inch layer of caulk was applied to the rim of the inside of the cap and then the end of the tube was placed into the cap within the layer of caulk to seal the tube to the cap. After 36 hours, the cap and cylinder did not create a strong bond and easily came apart, so the team purchased the pipe adapter and ASB to PVC cement. This adapter is slightly larger than the cap so the team had to drill a larger hole in the top support to allow the column to fit through. The cap fit extremely snug into one end of the adapter, and the other end of the adapter fit snug into the column. The team used ASB to PVC cement to seal these pieces together and caulk to seal the outer rim where the adapter fits into the column. The completed column is pictured below in Figure 5.



Figure 5: Nozzle apparatus connected to column

Testing/Analysis

The following sections highlight the testing and analysis processes that were used within the design.

Water Contamination

The first analysis method completed by the team was the creation of the water solution that would be used in testing. Three different solutions were created: a solution with arsenic and nitrate, one with only arsenic, and one with only nitrate. These solutions had to be created to ensure the starting conditions of 1-2 mg/L of arsenic and 25-40 mg/L of nitrate. The team targeted starting concentrations of 1.5 mg/L and 35 mg/L of arsenic and nitrate, respectively. The team chose to create the three solutions so that the activated alumina could be tested to treat each contaminate individually and together. Calculations were completed to determine the amount required of the three stock solutions. These numbers were based on needing at least 100 mL of solution for arsenic testing and 20 mL of sample for nitrate testing. The amount of chemicals necessary to contaminate the solution to appropriate levels was then calculated. The hand calculations done to complete this section can be seen in Figures 15 and 16 in Appendix 2. Table 2 presents the important information found through calculations to create all three water solutions. This table provides the amount of the solution that was created and the chemical amounts necessary to contaminate the water to reach the desired contaminant concentrations.

Table 2: Constituents needed for water contamination

Solution	Amount (L)	Arsenic pentoxide	Sodium Hydroxide	Sodium Nitrate
Arsenic and Nitrate	8.5	19.5585 mg	51 mg	407.83 mg
Arsenic	2.5	5.752 mg	15 mg	-
Nitrate	1.5	-	-	71.97 mg

A Standard Method (SM) was used to determine the combination of arsenic pentoxide and sodium hydroxide that was needed to contaminate the stock solutions with arsenic. The Standard Methods for the Examination of Water and Wastewater, 18th Edition 1992 was used to find this process. Stoichiometry was used, with the help of Dr. Terry Baxter and Gary Slim, to determine the amount of sodium nitrate that was needed to contaminate the stock solution with nitrate. The stock solutions were all created using distilled water, as instructed by the Standard Methods book. A picture of the procedure that was followed for arsenic contamination can be seen in Figure 17 of Appendix 3. Figure 6 below shows the constituents used to contaminate the water to the desired starting conditions.

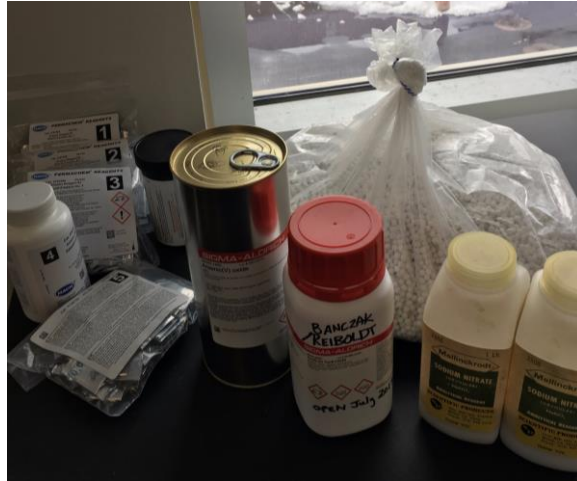


Figure 6: Water contamination chemicals

Water Testing using Constructed Design

The second task completed within the lab was water testing using the team's bench scale model. Activated alumina was placed inside the completed design. About 250 mL of the nitrate stock solution was poured onto the activated alumina within the column. There was enough activated alumina in the model to allow all of the liquid to be in contact with the beads. The team chose this testing method with assistance from technical advisor, Dr. Terry Baxter, who recommended all of the contaminated water stays at the same level, or below, the activated alumina.

The team collected 50 mL of water from the model using the valve on the bottom of the clear PVC tube at four different time increments for each trial. Based on previous research of activated alumina reducing arsenic levels, the team collected samples after the water had sat in the column for 1, 5, 20, and 60 minutes. For each time increment for nitrate testing, about 50 mL of sample was collected to have at least 20 mL of sample required for the nitrate test. With the solutions containing arsenic, an additional 15 mL of solution for the arsenic HACH test kit, and exactly 50 mL of sample to send Dr. Ketterer were collected. Four trials were completed for the nitrate solution, using new activated alumina each trial. Unfortunately, after the team completed all of the testing of the nitrate only solution the valve at the base of the column failed and the team determined the original design plan would not work to continue testing. The group then shifted to using a large graduated cylinder with the same proportions of activated alumina and water, and collect the needed samples at the designated times. This method was used for the combined solution and arsenic only solution. Ten trials were completed to have a total of 40 samples for the solution that contains arsenic and nitrate, and five trials were completed for the arsenic stock solution to give the team 20 samples.

Testing for each solution was completed over several days. After nitrate testing, the team realized the supply of activated alumina was too low to use new activated alumina each trial and thus used the same activated alumina for five trials at a time for the remaining tests. Two batches of activated alumina were used throughout the ten combined solution trials. This resulted in two duplicate trials of five tests for the combined solution. The arsenic solution testing consisted of five trials where the same batch of activated alumina was used.

Nitrate Testing

The team completed all nitrate testing in the lab using HACH method #8171 - Cadmium Reduction Method to determine remaining concentrations of nitrate in the samples. This method used a DR 3900 spectrophotometer, NitraVer5 powder pillow indicator, sample bottles, deionized water and 20 mL of sample [4]. The fully detailed procedure can be seen in Figure 18 in Appendix 4.

This method involved adding a powder pillow into 10 mL of sample and shaking for one minute before allowing the sample to rest for the reaction time of five minutes. During the reaction time, the blank was created with another 10 mL of sample in a separate bottle, then cleaned, and placed in the spectrophotometer to zero the machine. Once the reaction time was completed the sample with the powder pillow was placed in the DR 3900 to obtain a reading of the nitrate concentration. The DR 3900 spectrophotometer reads the nitrate concentration by using light passing through the sample and determining the concentration down to a minimum nitrate level of 0.3 mg/L. There were several instances when the readings were shown as a negative, which indicates a concentration below the minimum detection level. In these instances, the team decided that these samples would use the value of 0.3 mg/L because they cannot guarantee a value lower than the minimum detection level.

This method was used to complete testing for all the samples involving nitrate. The team also completed nitrate tests for the stock solutions to ensure the beginning concentration in the solutions fell within the range of 25-40 mg/L. Nitrate testing occurred during the sampling processes and continued when sampling was complete using the stored samples. In Figure 7, team members Camille and Robert are seen using the DR 3900 spectrophotometer. The results of these tests are illustrated in later sections and further discussed.



Figure 7: Nitrate Testing

Arsenic Testing

The arsenic testing for the collected samples includes several processes. The team completed on-site arsenic testing to determine preliminary arsenic levels in some, but not all samples, to ensure removal of arsenic was occurring. A sample from each trial and from each stock solution was tested using the HACH Arsenic Low-Level Test Kit. This test kit included test strips, a reaction bottle with lid, five reagents labeled Reagent #1 through #5 and a color chart for the indicator test strip to determine the arsenic concentration [5]. A dilution was completed first to conduct the arsenic tests at the proper concentration. The dilution consisted of 12.5 mL of sample and 37.5 mL of distilled water to meet the required 50 mL at the specific concentration. Due to the dilution, all results were multiplied by a factor of three to get an estimate of the remaining arsenic concentration.

The full detailed procedure can be seen in Figure 19 in Appendix 4. A test strip was inserted into the cap, which was then set aside for later use during testing. The 50 mL diluted sample was added to the reaction vessel, followed by the addition of Reagent #1 and stirred to allow the powder to dissolve. Then Reagent #2 was added and the sample was left to rest for a three-minute reaction period after being swirled to dissolve Reagent #2. Reagent #3 was added next, mixed, and left to rest for two minutes before stirring again and adding a level scoop of Reagent #4. Reagent #5 was added and the cap was immediately secured onto the bottle. With the addition of Reagent #5, no shaking could occur but lightly swirling the bottle was required to prevent the sample from contacting the test strip pad. The sample was set aside for a minimum of 30 minutes, but no more than 35 minutes, swirling twice during this period of time. After this final waiting period, the test strip was removed and compared to the color chart seen in Figure 8 to determine the approximate remaining arsenic concentration.



Figure 8: HACH Arsenic Test Kit in use

Once all samples were collected, those containing arsenic were packaged and sent to Dr. Michael Ketterer at MSUD in Denver, CO for a further analysis of arsenic concentrations remaining. Dr. Ketterer received 64 samples from the team: 4 with initial stock solutions containing arsenic and 60 contained treated water samples. Figure 9 illustrates the packaging of the samples.



Figure 9: Packaged Samples

Dr. Ketterer analyzed the samples using inductively coupled plasma mass spectrometry for an accurate arsenic concentration reading. The data determined by Dr. Ketterer was used for the analysis portion of this project.

Results

CRKL Engineering received the arsenic testing results from Dr. Ketterer by email on April 6th. The team analyzed the results separately for each solution that was created. The following sections highlight the results for each of the solutions and present graphs regarding the percent removal of each contaminant.

Arsenic Stock Solution Results

The initial concentration of arsenic in the solution was 1.732 mg/L. The team's goal was to reduce this concentration to the EPA Drinking Water Standard of 0.01 mg/L, which would require 99.423 percent reduction. The same batch of activated alumina was used for each of the five trials conducted with this solution. Table 3 below shows the final arsenic solution concentrations found by Dr. Ketterer.

Table 3: Arsenic Solution Results

Arsenic Solution				
	1 minute	5 minutes	20 minutes	60 minutes
Trial	Arsenic (mg/L)	Arsenic (mg/L)	Arsenic (mg/L)	Arsenic (mg/L)
1	0.768	0.24	0.061	0.026
2	0.741	0.278	0.09	0.048
3	0.89	0.388	0.15	0.073
4	0.992	0.461	0.166	0.096
5	1.127	0.461	0.181	0.107
Averages	0.904	0.366	0.130	0.070
Standard Dev.	0.143	0.092	0.046	0.030

The team was disappointed with the results obtained from this test as none of the final concentrations reached the EPA Drinking Water Standard. Although these tests failed, the team noticed two trends in regard to arsenic removal via activated alumina. The first trend was one that the team expected: more arsenic was removed the longer the solution remained in contact with the activated alumina. In each trial, more and more arsenic was removed with each successive time interval. The second trend that the team noticed was the decrease in efficiency of the activated alumina. With each successive trial, less arsenic was removed at each time interval. Figure 10 on the following page shows a plot of the percent removal for each trial.

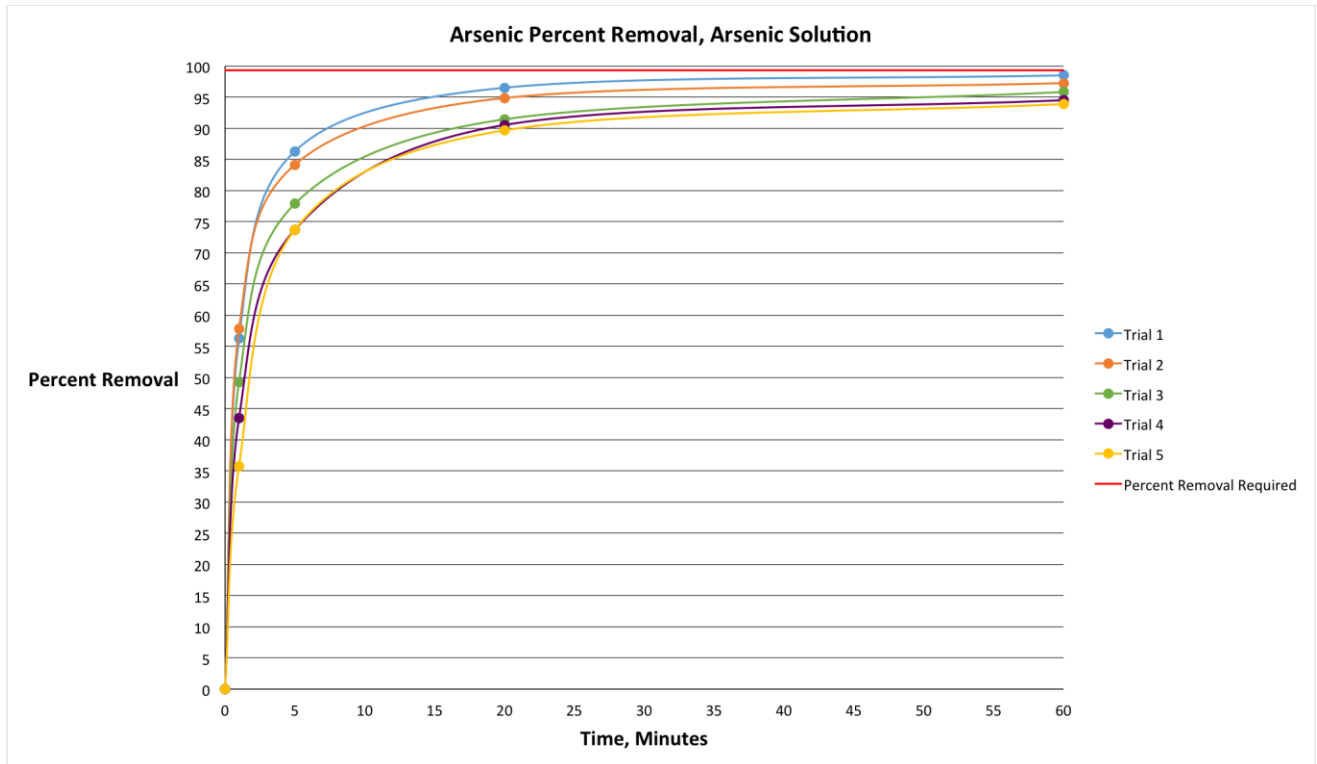


Figure 10: Percent Removal, Arsenic Solution

This plot clearly displays the aforementioned trend with each trial appearing below the previous trial. The red, horizontal line at 99.423% indicates the required removal to reach the EPA Drinking Water Standard. None of the trials reach, or are above, that line.

Nitrate Stock Solution Results

The starting nitrate stock solution concentration was 35 mg/L. The team was trying to reduce the concentration to the EPA Drinking Water Standard of 10 mg/L. As a reminder, each of the four trials completed for this solution used new activated alumina media. Table 4 below provides the results found for the nitrate solution.

Table 4: Nitrate Solution Results

Nitrate Solution				
	1 minute	5 minutes	20 minutes	60 minutes
Trial	Nitrate (mg/L)	Nitrate (mg/L)	Nitrate (mg/L)	Nitrate (mg/L)
1	24.750	0.3	0.3	0.3
2	24.752	0.3	0.3	0.3
3	31.824	1.5	0.3	0.3
4	26.078	0.3	0.3	0.3
Averages	26.851	0.6	0.3	0.3
Standard Dev.	2.922	0.5	0	0

The team was very pleased with the nitrate stock solution results. By the 5-minute test for each trial, the solution was already well below the EPA allowable concentration. Each value that reached EPA Drinking Water Standard is highlighted within the table. The results yielding through these four trials prove that activated alumina is a desired media for the fast, precise removal of nitrate. Figure 11 below presents the results as a percent removal for each trial.

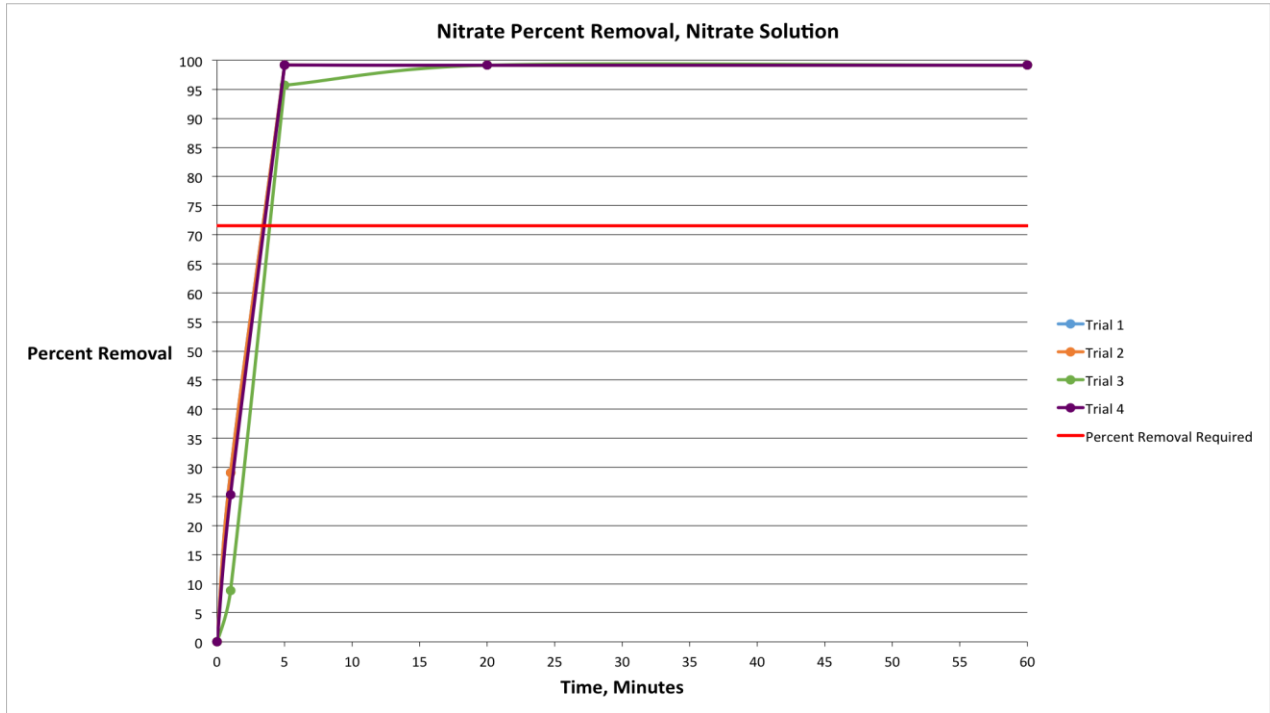


Figure 11: Percent Removal, Nitrate Solution

The red line at 71.429% represents the desired percent removal to reach the EPA Drinking Water Standard. The graph clearly shows that by 5 minutes within each trial, the percent removal of nitrate far surpasses the desired removal. It may seem that there are only two trials presented on the graph, but this is because the results are so consistent that the trials are overlapping on areas of the graph.

Combined Stock Solution Results

The initial concentration of arsenic in the combined solution was 1.487 mg/L, requiring 99.328 percent reduction. The initial concentration of nitrate in the combined solution was 35 mg/L, requiring 71.429 percent reduction. 10 trials were run with this solution and new activated alumina was added before the first trial and before the sixth trial. Table 5 below shows the final arsenic solution concentrations found by Dr. Ketterer.

Table 5: Arsenic Concentrations, Combined Solution Results

Arsenic and Nitrate Solution				
	1 minute	5 minutes	20 minutes	60 minutes
Trial	Arsenic (mg/L)	Arsenic (mg/L)	Arsenic (mg/L)	Arsenic (mg/L)
1	0.584	0.124	0.038	0.011
2	0.625	0.153	0.057	0.024
3	0.472	0.158	0.071	0.043
4	0.693	0.296	0.116	0.063
5	0.846	0.307	0.132	0.082
6	0.584	0.164	0.045	0.012
7	0.462	0.18	0.062	0.037
8	0.649	0.226	0.086	0.052
9	0.634	0.234	0.111	0.069
10	0.339	0.105	0.056	0.047
Averages	0.589	0.195	0.077	0.044
Standard Dev.	0.133	0.065	0.031	0.023

The team achieved more favorable results for arsenic removal using the combined solution than the arsenic solution. The team had two trials (highlighted in yellow) that nearly reached the EPA Drinking Water Standard, surpassing it by 1 and 2 micrograms. This data followed the same trends as the arsenic solution, with more arsenic being removed as more time passed, and less arsenic being removed with each successive trial. Figure 12 below shows a plot of the percent removal for each trial.

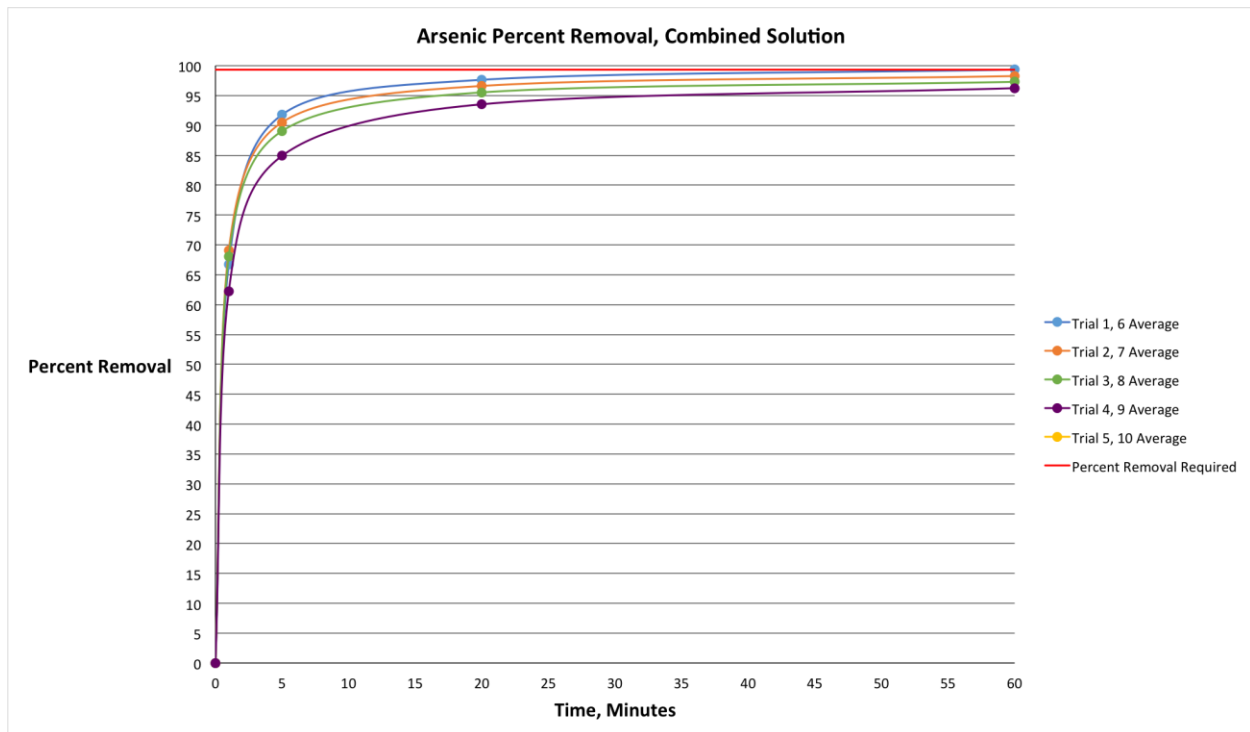


Figure 12: Arsenic Percent Removal, Combined Solution

Trials 1 and 6, 2 and 7, and so on, were averaged to reflect the two batches of activated alumina used. This plot shows the same trends as the previous Arsenic Percent Removal plot, with each successive trial achieving less removal.

Table 6 below shows the final nitrate concentrations in the combined stock solution.

Table 6: Nitrate Concentrations, Combined Solution Results

Arsenic and Nitrate Solution				
	1 minute	5 minutes	20 minutes	60 minutes
Trial	Nitrate (mg/L)	Nitrate (mg/L)	Nitrate (mg/L)	Nitrate (mg/L)
1	8.84	0.30	0.30	0.30
2	15.47	0.30	0.30	0.30
3	0.30	7.07	33.60	0.30
4	4.86	0.30	0.30	0.30
5	10.17	0.30	0.30	0.30
6	19.01	15.03	35.80	-
7	11.05	0.30	0.30	0.30
8	26.08	0.30	0.30	13.70
9	23.87	22.10	0.30	11.50
10	11.93	0.30	0.30	5.75
Averages	13.16	4.63	7.18	3.64
Standard Dev.	7.67	7.42	13.77	5.10

As was demonstrated by the nitrate solution, activated alumina is a desirable media for the treatment of nitrate in water. The values highlighted in green are the concentrations below the EPA Drinking Water Standard of 10 mg/L. That level was reached three times before the 5-minute mark, unlike the nitrate solution. There were also instances of competitive removal during these trials. Whereas the nitrate solution saw no spikes in nitrate concentration after the 5-minute mark, the nitrate concentration rose to above the EPA Drinking Water Standard six times in the combined solution. This was because of the higher likelihood of activated alumina targeting the arsenic and replacing the nitrate with it. This may have been due to the pH of the solution, which was raised by the activated alumina. Arsenic is more easily removed at a higher pH at around 10, while nitrate is most easily removed at a pH of 6.5. Figure 13 on the following page shows a plot of the percent removal of nitrate for each trial.

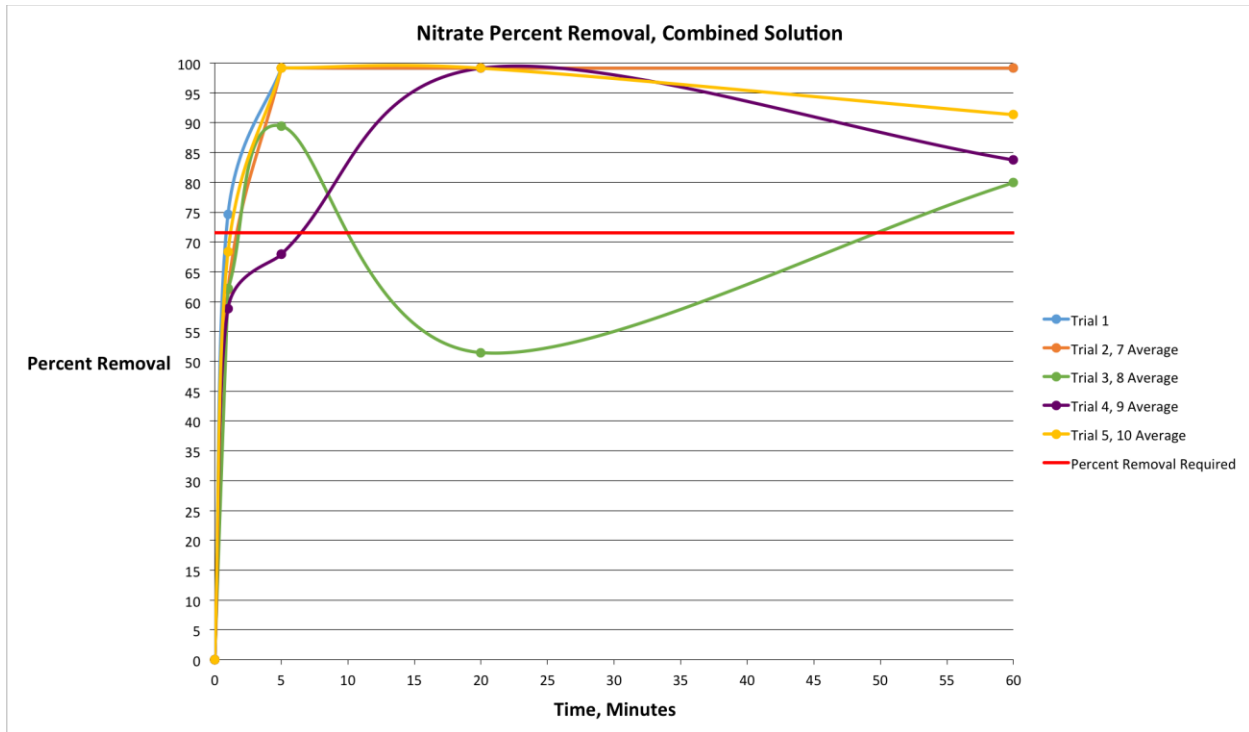


Figure 13: Nitrate Percent Removal, Combined Solution

This plot clearly displays the competitive adsorption that was occurring during these trials. Trial 6 was omitted because the 20-minute test was an outlier and the 60-minute trial did not have enough solution remaining to complete a nitrate test. Although there was competitive adsorption, there was enough nitrate removed to meet the EPA Drinking Water Standard. This data displayed a very similar trend to the previous nitrate results and further solidifies that activated alumina is a desirable media for the removal of nitrate from water.

Project Implementation Cost

Since the team ended up completing a feasibility study for activated alumina, the cost of implementation decided for the team is an estimate of how much activated alumina would be needed to treat the water for the Verde Valley community. The cost estimate will not involve the packed column implementation, or the energy necessary to run the system, due to lack of necessary information.

Table 7 below summarizes the total cost for activated alumina determined by the team.

Table 7: Cost of activated alumina

	Nitrate	Arsenic	Annual Totals
Activated Alumina Required (lbs)	11,455	455	11,910
Cost	\$16,955.00	\$675.00	\$35,260.00

To estimate an amount of activated alumina needed to complete the treatment necessary, a 60 gallons per day per person (gpd) was estimated. This volume comes from the Arizona average of 100 gpd per person [6]. However, 70% of this water is used for watering landscape and since the Verde Valley region is known to have less landscaping, there was assumed to be less water needed from this and thus 60 gpd per person was assumed. Using this assumption, the 10,000-person community would use 600,000 gpd. Based on this rate, and a cost of \$1.48 per pound of activated alumina [7] the required activated alumina to treat nitrate would be 11,455lbs at a cost of \$16,955.00 and to treat arsenic would be 455lbs at a cost of \$675.00. Additionally, the team decided to have four sets of activated aluminum, two for arsenic and two for nitrate, to allow one set to be regenerated while the other is in use. The calculations for the amount of pounds required can be found in Appendix 5. This brings the total cost to \$35,260.00. Additionally, no hazardous waste costs are associated with this because EPA guidelines allow for arsenic to be spread at a concentration of 41 kg/hectare, which is a much higher concentration than the team's plant will produce [8]. This eliminates any hazardous waste cost.

SUMMARY OF PROJECT RECOMMENDATIONS

Based off the feasibility study completed by CRKL Engineering, there are many recommendations for the client using the analysis that was completed. When completing preliminary literature reviews, it was learned that activated alumina may treat nitrate-contaminated solutions. Through the test analysis completed using just the nitrate stock solution, the team is confident with the treatment of nitrate using activated alumina. Based on the consistent and accurate nitrate test results, CRKL Engineering would highly recommend a packed column with activated alumina for nitrate removal.

In terms of treating arsenic and nitrate together using activated alumina, the team would recommend a multi-unit treatment system. By adjusting the pH of the solution, one column could be used to treat arsenic and the other could treat nitrate. Our results yielded high percent removal efficiencies regarding both of the contaminants, which is why the team believes this is a viable media to treat both arsenic and nitrate.

The last recommendation that the team has is for the client to obtain activated alumina isotherm data before moving forward with any of these findings. An isotherm will tell the capacity of a material and the amount of this material needed to treat specific concentrations. This can be easily completed through lab work by testing a variety of concentrations of the arsenic and nitrate solutions in beakers filled with activated alumina. With the capacity of the media known, an optimum packed column design can be created for both contaminants. With this isotherm data, lowering the amount of activated alumina that is needed for the treatment system would reduce the cost of implementation.

SUMMARY OF PROJECT COSTS

Within the design process that began in August 2016, CRKL Engineering created a basic schedule for the spring 2017 semester to ensure the project would be carried out in a timely manner. CRKL Engineering planned for work to begin over winter break 2017 and continue

through May 2017, when the final deliverables were due. Table 8 shows the original schedule that was made by CRKL Engineering.

Table 8: Proposed Project Schedule

Task Name	Duration	Start	End
4.0 Design Preparations	27 days		
4.1 Acquire Lab Space	5 days	1/9/17	1/13/17
4.2 Lab Certifications	5 days	1/9/17	1/13/17
4.3 Acquire Lab Materials	11 days	1/19/17	2/2/17
4.4 Water Contamination	6 days	2/2/17	2/9/17
5.0 Design Development	67 days		
5.1 Design Construction	16 days	2/2/17	2/23/17
5.2 Water Testing	5 days	2/23/17	2/28/17
5.2.1 Send Samples for Testing	4 days	2/28/17	3/3/17
5.3 Analyze Test Results	9 days	3/20/17	3/30/17
5.4 Final Presentation	9 days	4/17/17	4/27/17
5.5 Final Design Report & Website	75 days	1/23/17	5/5/17
6.0 Project Management			
6.1 Team Meetings		ongoing	
6.2 Client Meetings		ongoing	
6.3 Technical Advisor Meetings		ongoing	

With the guidance and assistance of those involved, CRKL Engineering did not account for the amount of communication that was needed to complete this project. Throughout components of the design, more meetings were necessary than were planned. This set the team back slightly in the beginning of the design phase. The design preparations task took longer than expected due to ongoing communication with the lab manager, Gary Slim, and the need for an experimental plan to begin work. Since the “acquiring lab space” task was slightly postponed, this created a delay in receiving all the chemicals and tests that were ordered through the lab facilities.

The team was able to collect design construction materials on their own and therefore moved the design construction task ahead of the water contamination task. This change created a one-week shift in the water-testing task. It was decided that our samples would be sent to Dr. Ketterer at MSUD for arsenic testing. After a phone call with him, it was decided that the team’s samples would be sent to him to on March 10th. Dr. Ketterer estimated a two-week turnaround period for the samples. The team had estimated a three-week turnaround period and had added an additional week to the analysis of the test results just in case any adjustments needed to be made throughout the semester. In the end, the arsenic analysis did take a full three weeks, which allowed just enough time for the team to analyze the test results before the final presentation. Table 9 shows the schedule that CRKL Engineering followed throughout the semester, which allowed for completion of the project in a timely manner.

Table 9: Actual Project Schedule

Task Name	Actual Start	Actual End
4.0 Design Preparations		
4.1 Acquire Lab Space	1/16/17	2/7/17
4.2 Lab Certifications	1/19/17	1/21/17
4.3 Acquire Lab Materials	1/16/17	2/13/17
4.4 Water Contamination	2/28/17	2/28/17
5.0 Design Development		
5.1 Design Construction	2/23/17	3/5/17
5.2 Water Testing	2/28/17	3/21/17
5.2.1 Send Samples for Testing	3/10/17	3/10/17
5.3 Analyze Test Results	4/6/17	4/23/17
5.4 Final Presentation	4/23/17	4/27/17
5.5 Final Design Report & Website	1/23/17	5/9/17
6.0 Project Management		
6.1 Team Meetings	ongoing	ongoing
6.2 Client Meetings	ongoing	ongoing
6.3 Technical Advisor Meetings	ongoing	ongoing

At the end of the fall 2016 semester, the team proposed a personnel hours estimation, along with a total project cost estimate. The original cost proposal hours of each team member can be seen in Table 10.

Table 10: Proposed Personnel Hours

Task	SENG Hours	ENG Hours	LAB Hours	INT Hours	AA Hours
Research	0	40	0	20	0
Water Contamination Preparation	24	0	80	80	0
Model Construction	40	56	40	24	0
Modeling	16	24	24	16	0
Result Analysis	32	32	0	0	160
Total	112	152	144	140	160
Total Project Hours	708				

Throughout the spring 2017 semester, each team member tracked their hours in the table provided above, depending on the task they were working on. Along with the original five categories for tracking personnel hours, the team added an additional category: lab preparations. Lab preparation was added due to the extensive hours that this task took for the team. The team had not projected so many hours would fall into this category when creating their original time

proposal. Table 11 below shows the actual personnel hours completed by the team, separated by task. The last row in the table provides the originally projected hours to allow for an easy comparison.

Table 11: Actual Personnel Hours

Task	SENG	ENG	LAB	INT	AA
Research	20	15	18	20	10
Lab Preparation	8	9	10	3	20
Water Contamination	10	9	7	10	4
Model Construction	10	26	0	8	7
Modeling	20	32	110	40	20
Results Analysis	40	26	0	0	18
Total	108	117	145	81	79
Projected	112	152	144	140	160

Based on Tables 10 and 11, the team came up with total expected hours and total achieved hours. Table 12 below shows the comparison of these two numbers.

Table 12: Personnel Hour Totals

Total Expected	Total Achieved
708	530

With the personnel hours being lowered, this also reduced the overall project costs that were estimated by the team. Table 13 on the following page provides the project cost broken down into personnel cost, lab work cost, analytical subcontract costs, and total project cost. The far right column provides the estimated project cost that the team completed in the fall 2016 semester.

Table 13: Project Costs

Cost	Classification	Hours	Rate \$/hr	Cost	Projected Cost
Personnel	SENG	108	\$132	\$14,256	\$14,780
	ENG	117	\$69	\$8,073	\$10,490
	LAB	145	\$52	\$7,540	\$7,490
	INT	81	\$19	\$1,539	\$2,660
	AA	79	\$41	\$3,239	\$6,560
	Total personnel			\$32,647	\$41,980
Lab Work	Materials		\$967	\$967	\$2,500
	Lab Rental	40 days	\$100/day	\$4,000	\$4,000
	Total Lab Work			\$4,967	\$6,500
Subcontract	Analytical			\$500	\$2,500
TOTAL				\$38,114	\$50,980

The team originally overestimated the cost in every category. This led to an overall cost reduction for the entire project. With the reduction in personnel cost, lab work cost, and analytical subcontracting cost, the total project savings ended up being about \$13,000.

REFERENCES

- [1] CRKL Engineering. (2016). *Verde Valley Water Treatment System; Proposal to Provide Professional Engineering Services*.
- [2] Environmental Protection Agency. *Drinking Water Arsenic Rule History*. [Online]. Available: <https://www.epa.gov/dwreginfo/drinking-water-arsenic-rule-history>.
- [3] American Public Health Association. (1992). *Standard Methods for the Examination of Water and Wastewater*.
- [4] HACH. (2014). Nitrate, MR, Cadmium Reduction Method. [Online]. Available: <https://canvas.jmu.edu/courses/1484140/files/73787038>.
- [5] HACH. Arsenic Low Range Test Kit. [Online]. Available: <https://www.hach.com/arsenic-low-range-test-kit/product-details?id=7640217303>.
- [6] “Residential Water Use,” AZ Water. [Online]. Available: http://www.azwater.gov/AzDWR/StatewidePlanning/Conservation2/Residential/Residential_Home2.htm.
- [7] “Activated Alumina F-200 3/16,” *Delta Adsorbents*, [Online]. Available: <https://www.deltaadsorbents.com/activated-alumina-f-200-316>.
- [8] Environmental Protection Agency, "Technologies and Costs for Removal of Arsenic from Drinking Water", The EPA, Washington DC, 2000.

APPENDICES

Appendix 1: Full Decision Matrix

Criteria	Weights (%)	Nitrate			Arsenic				Dual Treatment	
		Ion Exchange: Chloride	Bio Film Reactor	Permeable Reactive Barrier	Oxidation	Electro Chemical	Phytoremediation Hyacinth Roots	Ceramic membrane filters	Ion Exchange: Titanium Oxide	Ion Exchange: Activated Alumina
1 Low-Cost	30	9	3	1	9	3	9	9	9	9
2 Low-Energy	30	3	9	3	1	1	9	9	9	9
3 Feasibility	20	9	1	1	3	1	3	1	9	9
4 System Life-Time	15	3	3	9	9	9	3	3	3	9
5 Minimal by-product	5	1	9	3	1	3	1	1	3	3
6										
7										
	Raw score	69	47	29	5	29	65	61	78	87
	Relative Rank	3	4	5	5	6	3	4	2	1

Figure 14: Full Decision Matrix [1]

Appendix 2: Hand Calculations

Water solution calculations (arsenic)

Mixed solution (As and NO_3^-)

10 trials \rightarrow 4 sample times of 150 mL

800 mL per trial (200 mL extra)

Solution must be 8 L ; make 8.5 L in case.

SM 18th Edition 1992 page 3-30

Stock As(V) solution:

• Dissolve 1.534g arsenic pentoxide, As_2O_5 , in distilled water containing 4g NaOH. Dilute to 1 L;
1.00 mL = 1.00 mg As(V)

1.534g of As_2O_5 in 1 L = 1.534 mg/L As(V)
to create solution with 1.5 mg/L As(V):

1.534 mg of As_2O_5 in 1 L = 1 mg/L As(V)
then:

2.301 mg of As_2O_5 in 1 L = 1.5 mg/L As(V)

for 8.5 L \rightarrow (2.301 mg)(8.5)

$$= \boxed{19.5585 \text{ mg } \text{As}_2\text{O}_5}$$

for every 1.534 mg $\text{As}_2\text{O}_5 \rightarrow$ need 4 mg of NaOH

$$\left(\frac{19.5585 \text{ mg } \text{As}_2\text{O}_5}{1.534 \text{ mg } \text{As}_2\text{O}_5} \right) \left(4 \text{ mg NaOH} \right) = \boxed{51 \text{ mg NaOH}}$$

Arsenic solution

(5 trials)(4 times)(110 mL) = 2100 mL solution
 \approx 2.5 L solution

for 2 L \rightarrow (2.301 mg As_2O_5)(2.5) = $\boxed{5.7525 \text{ mg } \text{As}_2\text{O}_5}$

$$\left(\frac{5.7525 \text{ mg } \text{As}_2\text{O}_5}{1.534 \text{ mg } \text{As}_2\text{O}_5} \right) \left(4 \text{ mg NaOH} \right) = \boxed{15 \text{ mg NaOH}}$$

Figure 15: Stock Solution Calculations Page 1

water solution calculations (nitrate)

mixed solution

using NaNO_3^- : MW = 85 g/mol

NO_3^- : MW = 62 g/mol

$$\frac{62 \text{ g/mol NO}_3^-}{85 \text{ g/mol NaNO}_3} = 0.7294$$

Target concentration: 35 mg/L NO_3^-

$$\text{NaNO}_3 = \frac{35 \text{ mg/L NO}_3^-}{0.7294} = 47.98 \text{ mg/L NO}_3^-$$

Using NaNO_3 to make a 35 mg/L NO_3^- solution:

47.98 mg needed per L of solution

for 8.5 L of solution = 407.83 mg NaNO_3

Nitrate Solution

(5 trials)(4 samples)(50 mL) = 1000 mL solution needed

make 1.5 L of solution for some excess

$$47.98 \text{ mg} = 1 \text{ L}$$

then:

$$1.5 \text{ L} = \boxed{71.97 \text{ mg NaNO}_3}$$

Figure 16: Stock Solution Calculations Page 2

Appendix 3: Standard Methods

l. Arsenic(V) solutions:

1) *Stock As(V) solution:* Dissolve 1.534 g arsenic pentoxide, As_2O_5 , in distilled water containing 4 g NaOH. Dilute to 1 L; 1.00 mL = 1.00 mg As(V).

2) *Intermediate As(V) solution:* Prepare as for As(III) above; 1.00 mL = 10.0 μg As(V).

3) *Standard As(V) solution:* Prepare as for As(III) above; 1.00 mL = 0.100 μg As(V).

Figure 17: Arsenic Contamination Method

Appendix 4: Testing Method Procedures

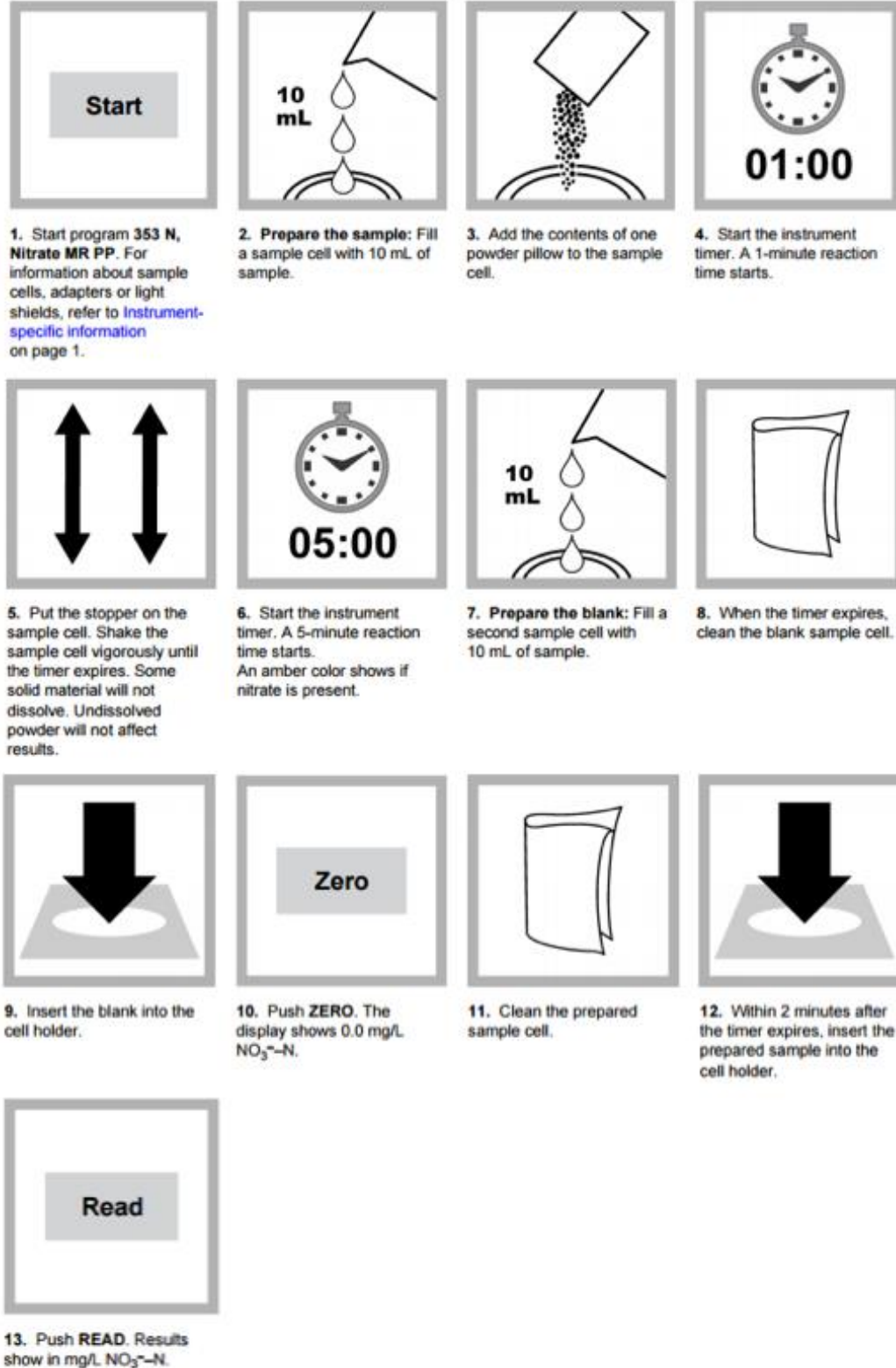
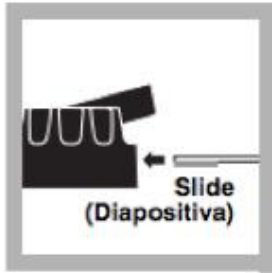
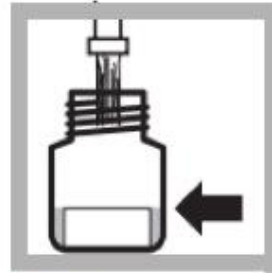


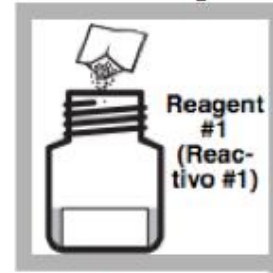
Figure 18: HACH Method for Nitrate [4]



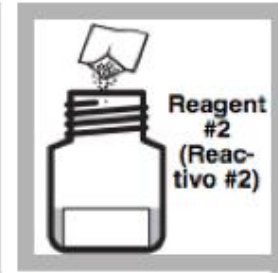
1. Lift the flap on the black cap and **slide** a test strip into the groove so that the reactive pad faces the small opening and completely covers it; secure by pressing the flap back in place.



2. Fill the reaction vessel with sample water to the fill line (50 mL).



3. Add the contents of 1 Reagent #1 powder pillow to the sample and swirl to dissolve.

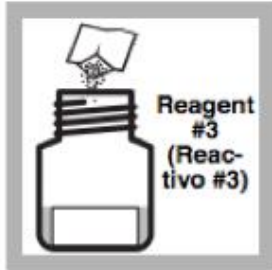


4. Add the contents of 1 Reagent #2 powder pillow to the sample and swirl to dissolve.

Note: Solution may be cloudy at this point.



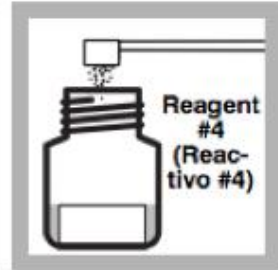
5. Wait at least 3 minutes.



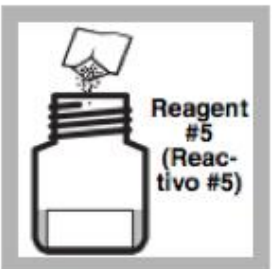
6. Add the contents of 1 Reagent #3 powder pillow to the sample and swirl to mix.



7. Wait at least 2 minutes and swirl again to mix.



8. Using the plastic scoop, add 1 level scoop of Reagent #4 to the sample and swirl to mix.



9. Add the contents of 1 Reagent #5 powder pillow to the sample.

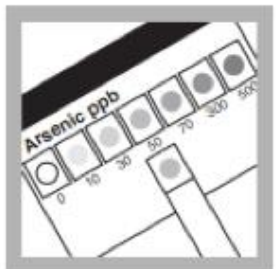


10. Immediately attach the black cap, with the test strip inserted, to the reaction vessel. **Do not shake or invert!**

Swirl to mix. Do not allow sample to contact the test strip pad.



11. Allow vessel to react for 30 minutes, but no more than 35 minutes; swirl twice during the reaction period.



12. Remove the test strip and immediately compare the developed color to the chart on the test strip bottle.

Note: For best results, read the strip outdoors in a shady place. Direct sunlight will change the color of the strip.

Figure 19: HACH Method for Arsenic

Appendix 5: Cost Calculations

Activated Alumina Required	
Nitrate:	Arsenic:
$X/M = K_d C_i^{1/n} - C_f = q$	"
$C_i = 35 \text{ mg/L}$	$C_i = 1.5 \text{ mg/L}$
$C_f = .1 \text{ mg/L}$	$C_f = .01 \text{ mg/L}$
$V = 1 \text{ L contaminated H}_2\text{O}$	$V = 1 \text{ L contaminated H}_2\text{O}$
$M = ?$	$M = ?$
$X = (35 \text{ mg/L} - .1 \text{ mg/L})(1 \text{ L}) = 34.9 \text{ mg}$	$X = (1.5 \text{ mg/L} - .01 \text{ mg/L})(1 \text{ L}) = 1.49 \text{ mg}$
$K = .0426 \text{ (}^{1/n} \text{g)} \text{ (}^{1/n} \text{mg)}$	$K = .10325 \text{ (}^{1/n} \text{g)} \text{ (}^{1/n} \text{mg)}$
$n = .446$	$n = .4$ (unitless)
$q = .0426 \text{ (}^{1/n} \text{g)} \text{ (}^{1/n} \text{mg)} \text{ (}^{1/n} \text{mg/L)}$	$q = .10325 \text{ (}^{1/n} \text{g)} \text{ (}^{1/n} \text{mg)} \text{ (}^{1/n} \text{mg/L)}$
$= .015255 \text{ mg/g}$	$= .016364 \text{ mg/g}$
$X/M = q$	$X/M = q$
$M = X/q = 34.9 \text{ mg} / .015255 \text{ mg/g}$	$M = X/q = 1.49 \text{ mg} / .016364 \text{ mg/g}$
$M = 2.28779 \text{ g}$	$M = .091053 \text{ g}$

Figure 20: Activated alumina needed