SUBLIME
engineering

Final Design Report: Water Filter for Uranium, Arsenic, and Bacteria Removal

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List of Acronyms/Symbols

As:	Arsenic
BAT:	Best Available Technology
BFA:	Bennett Freeze Area
CFUs:	Colony Forming Units
COC:	Contaminant of Concern
DI:	Deionized Water
DO:	Dissolved Oxygen
GAC:	Granular Activated Carbon
MDG:	Millennium Development Goal
MCL:	Maximum Contaminant Limit
NAU:	Northern Arizona University
NDWR:	Navajo Department of Water Resources
NNEPA:	Navajo Nation Environmental Protection Agency
NTU:	Nephelometric Turbidity Units (a measure of water turbidity)
NTUA:	Navajo Tribal Utility Authority
PWS:	Public Water Supply
TDS:	Total Dissolved Solids
TNTC:	Too Numerous to Count
USEPA:	United States Environmental Protection Agency
WHO:	World Health Organization
ZVI:	Zero Valent Iron
U:	Uranium

List of Tables and Figures

Acknowledgements

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1.0 Project Description

1.1 Project Purpose

The purpose of this project is to provide recommendations for the design of a low-cost, electricity-free water filtration unit capable of reducing uranium, arsenic, and coliforms to concentrations at or below their Maximum Contaminant Limits (MCLs), as established by the United States Environmental Protection Agency (USEPA), in order to provide safe drinking water to the residents of the former Bennett Freeze Area (BFA) of the Navajo Nation.

This project serves the residents of the former BFA and the project client, Forgotten People, a non-profit organization that advocates for the well-being of the residents of the former BFA by coordinating with other organizations interested in infrastructure development projects within the region.

1.2 Problem Statement

The 2 million acre area on the Navajo Nation known as the former BFA is occupied by approximately 20,000 individuals residing in an estimated 3,688 homes. Of the 3,688 homes, it is estimated that 2,685 (72.8%) do not have access to a regulated public water supply (Navajo Access Workgroup, 2010). Resident and client testimony support the assumption that most families residing in the former BFA obtain drinking water from unregulated water sources. Unregulated water sources include groundwater wells, surface water deposits, springs, and man-made livestock tanks (U.S. Army Corps of Engineers, 2000). This use of unregulated water supplies presents a problem for residents. Due to a combination of naturally occurring uranium deposits and abandoned uranium mines, many unregulated water sources have concentrations of uranium exceeding the MCL. Extensive uranium mining on the Navajo Nation occurred from the mid to late 1900s, and although these operations have since ceased, a legacy of uranium contamination exists in the area, including the BFA. Two remote wells, Tohatchi Springs and Badger Springs, present serious risks and they are the closest available water sources for residents in the Blackfalls region of the BFA (Ingram, 2011). Unregulated water sources have also shown elevated concentrations of arsenic above the MCL from natural sources and tested positive for coliforms (U.S. Army Corps of Engineers, 2000). Current USEPA MCLs for uranium, arsenic, and total coliform bacteria are 30 µg/L, 10 µg/L, and less than five percent of samples testing positive for coliforms per month, respectively (U.S. Environmental Protection Agency, 2013). Therefore, residents of the BFA are potentially drinking water containing three contaminants of concern (COCs): uranium, arsenic, and coliforms.

There are significant human health risks associated with drinking water with concentrations of uranium, arsenic, and coliforms above the MCLs. Health risks associated with consuming water with uranium concentrations above the MCL include an increased risk of cancer and kidney toxicity. Health risks associated with arsenic concentrations above the MCL include circulatory system damage, skin damage, and increased cancer risk. Health risks associated with consuming water containing coliforms can vary as the presence of coliforms is utilized as an indicator for the existence of a variety of pathogens. The effects of these pathogens may include acute and/or chronic gastric and respiratory illnesses (U.S. Environmental Protection Agency, 2013). In order to reduce the health risks associated with the drinking of contaminated unregulated water sources in the former BFA, it is necessary to assure the inhabitants of the area have access to water with concentrations of uranium, arsenic, and coliforms below USEPA MCL standards. More information about health risks related to uranium, arsenic and coliforms can be found in section 6.2, Contribution to Human Health.

1.3 Project Location

The former BFA consists of approximately 1.5 million acres (Navajo Access Workgroup, 2010). The area is named after past Commissioner of Indian Affairs, Robert Bennett. The Navajo and Hopi Settlement Act, Public Law 93-531, defines the borders of the area and the developmental restrictions imposed on its inhabitants. PL 93-531 defines the BFA as: "that portion of the Navajo Reservation lying west of the Executive Order Reservation of 1882 and bounded on the north and south by westerly extensions, to the reservation line, of the northern and southern boundaries of said Executive Order Reservation" (The 93rd Congress of the United States of America, 1966). There are few maps of the BFA in existence. The map in Figure 1.1(below) shows the BFA as determined by the U.S. General Accounting Office's Navajo-Hopi Resettlement Program in March 1991. A more detailed map is shown in Figure 1.2, where the BFA is outlined in red. A red arrow points to Flagstaff, Arizona.

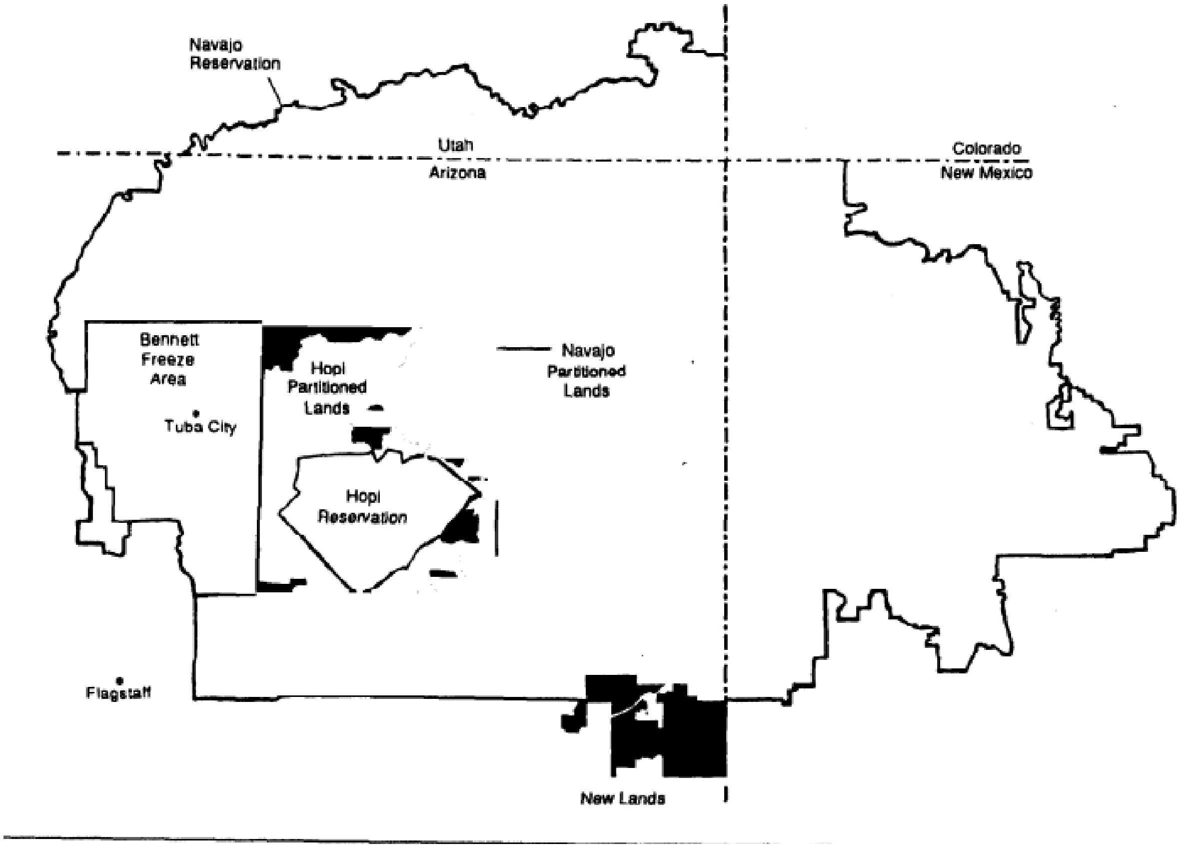


Figure 1.1: Map of the Bennett Freeze area, as determined by the U.S. General Accounting Office's Navajo-Hopi Resettlement Program *(United States General Accounting Office, 1991)*

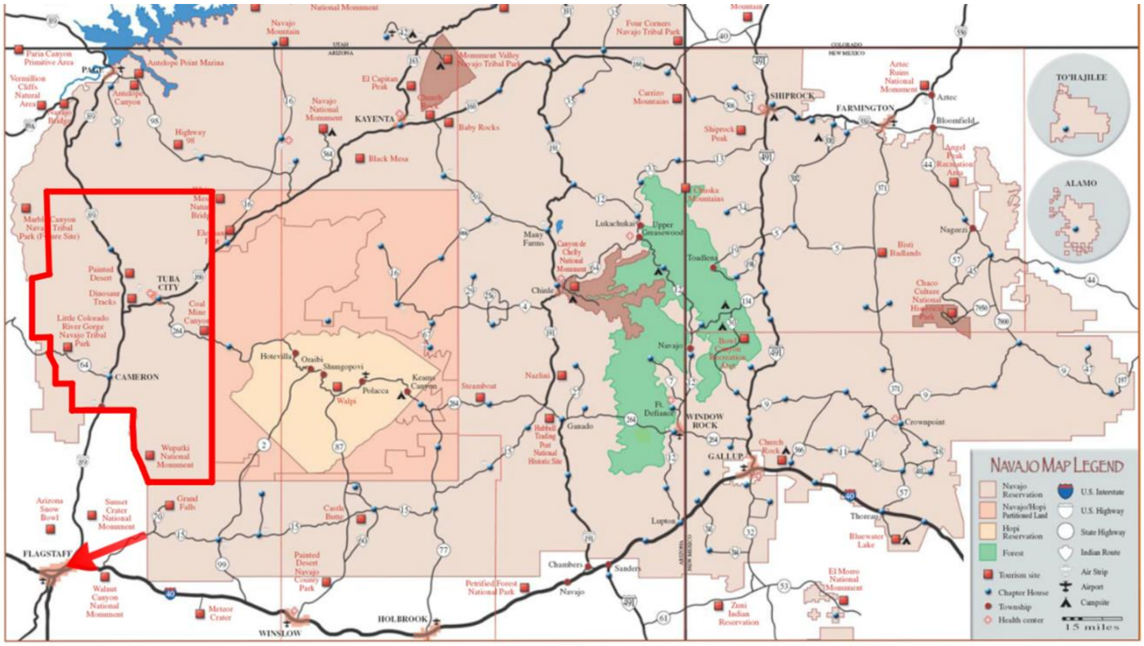


Figure 1.2: Map of the Bennett Freeze area, as shown by the area outlined in red *(Navajo Nation Map, 2008)*

The developmental restrictions placed on the residents of the BFA prohibited: "any new construction or improvement to the property and further includes public work projects, power and water lines, public agency improvements, and associated rights-of-way" (The 93rd Congress of the United States of America, 1966). The intention of PL 93-531 was to prevent development of the BFA until a land dispute between the Hopi and Navajo Nations could be settled. Unfortunately, the 43 year-long developmental freeze resulted in dire social and economic consequences for residents in the BFA; consequences exacerbated by an absence of infrastructure. Although the land dispute has not been resolved, PL 93-531 section 10(f), which prohibited development was repealed via PL 111-18 in 2009 (The 111th Congress of The United States of America, 2009). The repeal of PL 93-531 10(f) allows for the development of property and infrastructure to resume. Despite this, few improvements to the drinking water infrastructure have occurred.

1.4 Design Constraints and Design Requirements

Taking into consideration the lack of infrastructure and electricity in much of the former BFA as well as the requests of the Forgotten People organization, the following design constraints and requirements are developed for this project. The constraints impose restrictions on the design of the water filter. Requirements indicate what the design must accomplish.

1.4.1 Design Constraints

The device must:

- Function as a point-of-use device
- Operate without electricity
- Require minimal investment to construct and maintain
- Require minimal maintenance to continue operating effectively
- Incorporate features to maximize the ease of disposal for used filter materials

<u>Point-of-Use</u>

A point-of-use filter is the most viable water filtration option for the residents of the former BFA. This is for several reasons. Residents haul their water from community sources to their homes. According to the

Program Director of Forgotten People, Marsha Monestersky, installing any form of water treatment at the wellhead would require a lengthy and bureaucratic permitting process from the Navajo Nation. Therefore, a wellhead water treatment system is not advisable. Additionally, residents have been hauling water in large containers, and they are apt to continue using the same containers if a wellhead water treatment system is installed. These containers may contain uranium and arsenic residuals as well as bacteria. Therefore, it is best that a point-of-use water filter is developed for at home use to treat water after it has left the hauling containers.

No Electricity

Many residents in the former BFA do not have access to electricity. Those that do may utilize low-power solar panels or expensive generators. Therefore, the water filtration design should be able to operate without electricity.

Low-Cost

Most of the residents of the former BFA live in a state of poverty. Therefore, the final cost of materials, construction, and long-term maintenance of the proposed water filter must be kept to a minimum. In order to keep costs low, a low-tech solution will need to be developed. However, due to the project exclusions, noted in section 1.6, it is not possible to determine maintenance and replacement costs of the filter materials, nor is it possible to determine the cost of a full-scale device. Therefore, it is difficult to make a comparison of the design alternatives based on anything other than initial capital costs. While ensuring the cost is minimized is crucial for any water filter that will be implemented in the BFA, it is not feasible at this time to use this constraint as a criteria in design selection. It should be considered, however, in subsequent improvements to this project.

Ease of Maintenance

In order to ensure that the water filter functions as intended with minimal downtime, it must be well-maintained. Maintenance time and complexity should be minimized for the end user so that the filter is easy to service. The filter life should be maximized so that time between necessary maintenance is minimized. If maintenance is time consuming or difficult, residents may decide it is not worth using in their homes. For the same reason described under Low-Cost, and explained in section 1.6, Project Exclusions, required maintenance of the selected filter materials is currently unknown. While ensuring that the ease of maintenance is important, it is not feasible at this time to use this constraint as criteria in design selection. It should be considered, however, in subsequent improvements to this project.

Ease of Waste Disposal

The designed water filtration unit will require some form of waste disposal for the collected uranium and arsenic. The design should be able to facilitate easy and safe waste disposal. However, without current knowledge on the longevity of filter materials and the timeframe for waste disposal needs, it is also not feasible at this time to use this constraint as criteria in design selection.

1.4.2 Design Requirements

The device must:

- Be capable of reducing uranium and arsenic to concentrations below their MCLs
    - Less than 30 µg/L for uranium
    - Less than 10 µg/L for arsenic
- Be capable of producing coliform-free water
- Operate effectively in a pH range of 7.5-8.4
- Provide filtered water within a reasonable filtration time of 0-4 hours

Reduction of COCs and Coliform-Free Water

The main goal of this project is to design a water filter capable of reducing the uranium and arsenic concentration to levels below their MCLs and to provide coliform-free water in order to provide safe water for drinking.

Operational pH Range

The water filter must be able to operate in an initial water pH range of 7.5-8.4, which is the pH range of the water from the wells in the former BFA, as discussed in section 2.1.1, Water Chemistry of the BFA Wells.

Filtration Time

The water filter should be able to produce clean water in less than four hours, at the request of the client, so that residents do not have to wait for long-periods of time for water purification.

1.5 Changes to Project Scope

As the Sublime Engineering team conducted research into materials and methods for the removal of U and As to achieve concentrations below the MCLs, it became clear that low-cost, low-tech options are limited. Most of these options are still in the research and development phase, and are being considered by researchers around the world. Furthermore, due to time and costs associated with water analysis for U and As, difficulty in acquiring material resources in a timely manner, and the inability to create large volumes of water needed for testing, the scope of this project has been adjusted. The major change to the scope is the removal of the construction of a bench-scale model, the subsequent laboratory testing of the model, and the development of an Operations and Maintenance Manual. The updated scope only affects Task Four, and the changes/additions are presented in *italics* below. The deliverables, such as the 50% Design Report, Final Presentation, and Final Design Report are still included in Task Four, although not listed below. The original scope is included in Appendix A.

TASK FOUR: DESIGN AND DESIGN TESTING

Design and testing of the alternative materials are required. The following subsections detail the subtasks that must be addressed in order to complete the design and testing.

SUBTASK 4.1: DEVELOPMENT OF DESIGN CRITERIA AND CONSTRAINTS

In this subtask, the design criteria and constraints are fully developed. Adherence to the criteria and constraints must occur in subtasks 4.2, Identification of Alternative Methods and 4.9, Final Proposed Design.

SUBTASK 4.2: IDENTIFICATION OF ALTERNATIVE METHODS

This subtask involves the identification of multiple alternative methods to achieve *the reduction of arsenic, uranium, and coliforms to concentrations below their respective MCLs.* These alternative methods, *which may consist of various media or materials*, are based upon task three, Literature Review. Any *methods or* design ideas that would require special permitting from the Navajo Nation are excluded at the request of the client and include any designs that would be implemented at the water source.

SUBTASK 4.3: MATERIAL PURCHASING AND ACQUISITION

Any materials or equipment necessary for testing must be purchased.

SUBTASK 4.4: CONSTRUCTION OF TESTING APPARATUS

A laboratory testing apparatus needed for the testing of the selected alternative methods must be constructed.

SUBTASK 4.5: PREPARATION OF MATERIALS

The materials required for the alternative methods must be prepared for testing following suggested preparation procedures from the literature review. Depending on the material, this may involve cleaning and drying the material, preparing a sand matrix, or crushing the material to provide a greater surface area for removal.

SUBTASK 4.6: TESTING OF ALTERNATIVE METHODS

The selected methods must be tested for their ability to reduce uranium and arsenic. An experimental matrix for water sampling must be determined. Water quality analysis will include uranium and arsenic concentrations. However, testing of the selected method for coliform reduction will be excluded from this project due to known and confirmed procedures from the World Health Organization (WHO). However, the method and calculations for the coliform reduction must be prepared and documented.

SUBTASK 4.7: SAMPLE SHIPMENT FOR ALTERNATIVE METHODS

Samples taken during subtask 4.6, Testing of Alternative Methods, must be shipped to a laboratory facility for U and As analysis.

SUBTASK 4.8: CONSTRUCTION OF MODULAR DESIGN

A modular design capable of testing the alternative methods in series must be constructed. The selected alternative materials must be capable of being placed into their own individual modules. The modules must be able to be stacked in multiple configurations to determine the optimal order of materials in a water filtration unit for the reduction of uranium and arsenic.

SUBTASK 4.9: RECEIPT AND ANALYSIS OF ALTERNATIVE METHODS RESULTS

The receipt of the results from the shipment in Subtask 4.7, Sample Shipment for Alternative Methods, must be received and analyzed.

SUBTASK 4.10: TESTING OF MODULAR CONFIGURATIONS

Based upon the water quality results from subtask 4.6, Testing of Alternative Methods, modular configuration alternatives are determined. These methods will be tested in various configurations using the constructed modular system from subtask 4.7, Construction of Modular Design. An experimental matrix for water sampling must be determined. Water quality analysis will include uranium and arsenic concentrations. Coliform testing is excluded.

SUBTASK 4.11: SAMPLE SHIPMENT FOR MODULAR CONFIGURATIONS

Samples taken during subtask 4.10, Testing of Modular Configurations must be shipped to a laboratory facility for U and As analysis.

SUBTASK 4.12: RECEIPT AND ANALYSIS OF MODULAR CONFIGURATION RESULTS

The results from the shipment mentioned in Subtask 4.11, Sample Shipment for Modular Configurations, must be received and analyzed.

SUBTASK 4.13: FINAL RECOMMENDATIONS

After receiving results from subtask 4.8, Testing of Modular Configurations, recommendations for a design are made.

SUBTASK 4.10: PROJECT COST ANALYSIS

The project cost analysis shall incorporate the costs of project materials, specialty chemicals (U and As) and analytical laboratory tests. The project material costs shall consider the filter body materials, sand, gravel, and supplies used to construct the filter modules. Costs associated with maintaining the device, replacing filter materials, or building a bench-scale or full-scale device are excluded. The data needed to determine the maintenance and replacement of filter media is excluded from the project scope, as explained in section 1.6, Project Exclusions.

1.6 Project Exclusions

This project does excludes the construction of a bench-scale model and full-scale water filtration unit as well as implementation. Therefore, no laboratory or field testing will be conducted for a bench-scale model or full-scale water filtration device. Rather, a final design will be proposed based on laboratory testing of materials and various configurations of these materials. This exclusion is a result of time constraints for this project. Also as a result of time constraints, reaction kinetics for the materials chosen as alternatives cannot be established. The point of breakthrough for each material will also be unknown. Without this information, it is not possible to determine when the material will be exhausted, which makes it impossible to determine time intervals between maintenance. This limits the economic analysis for the project. An economic analysis which includes maintenance, replacement, and lifetime costs for filter materials is not possible in absence of this information.

2.0 Background

Prior to determining alternative water filtration designs, further research of the BFA is conducted. Extensive research of methods for removing arsenic, uranium, and bacteria from drinking water is also conducted. The results of this research are presented in the following sections.

2.1 Bennett Freeze Area Conditions

The development of public water supply (PWS) infrastructure in the former BFA falls under the jurisdiction of the Navajo Nation Environmental Protection Agency (NNEPA), The Navajo Nation Department of Water Resources (NDWR), and the Navajo Tribal Utility Authority (NTUA) (Navajo Access Workgroup, 2010). Development prohibition in the BFA resulted in the inability of these organizations to extend the delivery of PWS infrastructure development projects to the majority of residents in the area (Navajo Access Workgroup, 2010). Due to the lack of access to a regulated PWS and a combination of poor transportation infrastructure, lack of employment opportunities, and high cost of fuel, most residents in the BFA rely on local unregulated water sources for drinking water. Grab samples of unregulated water sources believed to have been utilized for drinking water on the Navajo Nation were analyzed by the U.S. Army Corps of Engineers and the USEPA between 1994 and 2000 (U.S. Army Corps of Engineers, 2000). Samples analyzed during this study exhibited concentrations of uranium and arsenic in excess of the USEPA MCLs.

The former BFA is occupied by approximately 20,000 individuals residing in an estimated 3,688 homes. Of the 3,688 homes, it is estimated that 2,685 (72%) do not have access to a regulated water supply (Navajo Access Workgroup, 2010). According to Thomas Rock, a Navajo PhD student studying bioaccumulation of uranium in sheep on the Navajo Nation under the supervision of Dr. Jani Ingram of the Chemistry Department at NAU, most residents haul their drinking water from unregulated water sources using trucks and a combination of truck-mounted large water tanks, 50 gallon drums, and 5 gallon containers. Some residents purchase drinking water from providers in Flagstaff or Tuba City; however, transportation costs do not favor this alternative.

2.1.1 Water Chemistry of the Bennett Freeze Area Wells

Grab sample water analysis data obtained by the U.S. Army Corps of Engineers and USEPA in 2000 details existing contamination levels of verified unregulated water sources located in the BFA. Total uranium concentrations, a summation of Uranium 234, Uranium 235, and Uranium 238 isotopes, range from 2.55 µg/L to 126 µg/L. Arsenic concentrations range from 0 µg/L to 145 µg/L (U.S. Army Corps of Engineers, 2000). The MCLs for U and As are 30 µg/L and 10 µg/L, respectively. There are three wells of interest in the BFA, as they contain elevated levels of U and As, according to a study conducted by Dr. Jani Ingram of the Chemistry Department at NAU in 2011. These wells include well number 5M-74 at Box Springs, an unnumbered well at Tohatchi Springs, and an unnumbered well at Badger Springs. Tohatchi Springs and Badger Springs are within 15 miles of one another, and are located in the remote Blackfalls region of the Navajo Nation (Ingram, 2011). The location of Badger Springs (A, coordinates 35,38,26.7611, -111,11,46.958), Tohatchi Springs (B, coordinates 35, 41,14.0106, -111,6,8.23381), and Box Springs (C, coordinates 35.50, -111.24) are indicated by green location markers in Figure 2.1.

Figure 2.1: Map of BFA Wells *(Google Maps, 2014)*

Table 2.1 includes a compilation of water chemistry data taken from Dr. Jani Ingram's water quality analysis completed in 2011 and the Navajo Nation Water Quality Project website maintained by Northwestern University that presents water quality data for the Navajo Nation from testing conducted by the U.S. Army Corps of Engineers (Ingram, 2011), (Northwestern University Chemistry Department, Unknown).

Table 2.1: Water Chemistry for BFA Wells

Water Quality Parameter	USEPA MCL Primary Standards	Well		
		Box Springs	Tohatchi Springs	Badger Springs
pH	6.5-8.5 (Secondary Standard)	7.8	8.2	8.4
Elemental U (µg/L)	30	Approx. 20-25	Approx. 70	Approx. 20-30
As (µg/L)	10	N/A	54.8	51.1
HCO_3^- (mg/L)	N/A	347	540	557
Cl^- (mg/L)	250 (Secondary Standard)	24	154	93
NO_3^- (mg/L)	10	2.5	1.28	1.04
SO_4^{2-} (mg/L)	250 (Secondary Standard)	195	151	136
PO_4^{3-} (mg/L)	N/A	0.01	0.07	0.01
Na^+ (mg/L)	N/A	156	349	280
K^+ (mg/L)	N/A	3.8	2.1	1.2
Mg^{2+} (mg/L)	N/A	13	2	4
Ca^{2+} (mg/L)	N/A	32	5	7

In Table 2.1, the U concentrations shown are determined by analysis performed by Dr. Ingram. The Tohatchi Springs U concentration is listed as approximately 70 µg/L. Large error may be present in this analysis because only two samples were analyzed. In February 2011, the U concentration was found to be 100 µg/L, but it was only 45 µg/L in October 2011. This may be due to seasonal weather changes. The well may have experienced dilution due to runoff from higher seasonal rates of precipitation. It's important to note that data on the U concentrations for the Navajo Nation wells from previous Ingram analyses and the U.S. Army Corps of Engineers provide a wide variation of results. No significant, robust study has been conducted to establish average U concentrations. What is presented here is the most recent and best data available. The Ingram report provides further hypotheses on the discrepancies. Regardless, the U concentration at Tohatchi Springs is above the 30 µg/L MCL established by the USEPA. The As concentrations are from the Navajo Nation Water Quality Project. While the As concentration was not available for Box Springs, it is above the 10 µg/L MCL for both Tohatchi and Badger Springs. The other water quality parameters that are presented have no established USEPA Primary MCLs, with the exception of nitrate. However, all three wells fall below the nitrate MCL of 10 mg/L. The three water quality parameters with Secondary Standards fall within the suggested USEPA range. Secondary standards are non-enforceable guidelines for substances which affect the aesthetic properties of drinking water.

The water chemistry of the three BFA wells is used to help determine the desired water chemistry for the synthetic water developed for this project, as described in section 4.2, Synthetic Water Development. Details and challenges of the synthetic water development are contained in that section. The key components of the synthetic water development are the U and As concentrations and the pH. Using the data presented in Table 2.1, the synthetic water goals are established. These goals are shown in Table 2.2.

Table 2.2: Desired Synthetic Water Goals Based on BFA Water Chemistry

pH Range	U (µg/L)	As (µg/L)
7.8-8.4	100	70

As shown in Table 2.2, the pH should be between 7.8 and 8.4. The U concentration should be 100 µg/L, which is the highest measured concentration of U for Tohatchi Springs from February 2011 and the highest U concentration in the BFA. The As concentration should be 70 µg/L, which was chosen to be slightly higher than the highest BFA As concentration of 54.8 µg/L. Because As is an increasing problem for water sources across the world, the team elected to increase the As concentration in the synthetic water to attempt to test materials and configurations capable of reducing higher concentrations of As than those found in the BFA.

2.1.2 Arsenic Speciation in Water in the Bennett Freeze Area

Arsenic removal from drinking water is complicated by the fact that As may be present in one of two forms: As(V), which is arsenate with a valence of five, as in $H_2AsO_4^-$ or $HAsO_4^{2-}$, or As(III), which is arsenite with a valence of three, as in $H_2AsO_3^-$ or H_3AsO_3. Most water treatment methods for As removal focus on removing As(V) anion and uncharged As(III) species since they are the most prevalent at a neutral pH as $H_2AsO_4^-$ and H_3AsO_3, respectively. In the Southwestern United States, As(III) is more common than As(V) (Farrell, Assessing Arsenic Removal Technologies, 2002). As(III) is more toxic and more difficult to remove than As(V). Many large-scale municipal operations utilize a preoxidation step to convert As from the trivalent to the pentavalent form for easier removal (Amin, et al., 2006). Preoxidation is difficult without aeration supplied from an electric device or through chemical means. Because one of the project constraints is to create an electricity-free water filter and the use of chemicals causes additional maintenance and complexity, preoxidation is not suitable for this project.

2.1.3 Uranium Speciation in Water in the Bennett Freeze Area

The potential health effects from drinking uranium contaminated water vary depending on the solubility of the uranium and its speciation in the water, which in turn are dependent upon the pH of the water, water hardness, and concentrations of ligands. Uranium is most commonly found in groundwater in its hexavalent oxidation state, U(VI), as the uranyl ion UO_2^{2+}. Carbonate and phosphate are usually the dominant ligands that affect U(VI) speciation in groundwater (Farrell, Bostick, Jarabek, & Fiedor, 1999). To determine the bioavailability and potential toxicity of uranium, the speciation of uranium in water is necessary. Unfortunately, Dr. Ingram's 2011 study was not able to determine the exact speciation of U in the water of the BFA wells. However, it was determined that the U was likely present as hexavalent U in the form of a uranyl-hydroxyl or uranyl-carbonate complex (Ingram, 2011).

2.2 Technology Review

Large-scale municipal water treatment systems in developing areas typically employ conventional methods of water treatment such as mechanical separation, coagulation and flocculation, chemical purification, disinfection processes, biological processes, aeration, and membrane technologies. These technologies are often used in combination to increase the effectiveness of water treatment (Mihelcic, Phillips, Barkdoll, Fry, & Myre, 2009).

The following technologies that are described for the removal of arsenic, uranium, or bacteria are evaluated for their efficacy in removing the contaminant of concern and their ability to be obtained and utilized at a low-cost without electricity as a point-of-use filter. Reasons for excluding or including a technology as an alternative are presented.

Arsenic has become an increasing global concern, especially in places such as Bangladesh and India. For this reason, there is more robust literature available on low-cost and low-tech solutions for arsenic removal from groundwater. Literature detailing low-tech methods for uranium removal is less prevalent. In many cases, uranium removal research focuses on environmental remediation of contaminated sites requiring the reduction of uranium concentrations in the mg/L range rather than the µg/L range. Most of this research does not note whether or not these emerging technologies are capable of reducing uranium to concentrations at or below the MCL. Additionally, much of the research lacks specifics such as detailed results of column tests or recommended contact times for effective removal.

2.2.1 Arsenic and Uranium

The following technologies are evaluated for their capability to remove U, As, or both U and As from water. Only a few of these methods are well documented, including activated alumina, coagulation/precipitation, ion exchange resins, lime softening, and membranes. Emerging technologies are also investigated. While less is known about these emerging technologies, many of them have been conceived for use in low-cost, low-tech, and/or rural applications. The emerging technologies include a composite iron matrix, granular ferric hydroxide, hydroxyapatite, orange peels, rice husks, zeolite, and zero valent iron. All of the technologies are presented alphabetically for ease of reference.

Activated Alumina: U and As

Activated alumina is listed as a Best Available Technology (BAT) for both uranium and arsenic, as determined by the US EPA. It is a granulated form of aluminum oxide (Al_2O_3) and is highly porous with a very large surface area over 200 m^2/g. It is best used in packed beds as an adsorbent. The activated alumina process is a physical/chemical process through which As or U ions are removed on the oxide surface. It can also be considered similar to ion exchange resins or adsorption through ligand exchange and chemisorption, although the kinetics of arsenic removal are slower than ion exchange resins. It is more effective for the removal of As(V) than As (III) because the competition for adsorption sites is greater for As(III). If used for the removal of As (III), pre-oxidation is recommended. Activated alumina is also best used at a pH between 5.5 and 6.0, since the efficiency of the activated alumina is decreases at higher pH values due to a net negative charge of the surface that electro-statically repels anions. Activated alumina also requires backwashing, regeneration of the media, or complete disposal as a hazardous waste every one to three years (U.S. Department of the Interior, Bureau of Reclamation, 2010) (Johnson, Heijnen, & Wurzel, 2001). Due to the low pH required and the low efficiency removal of As(III), activated alumina is not a viable option for use in the United States Southwest where As(III) is the dominant form of As. The liquid waste stream generated by activated alumina also may be too acidic, caustic, saline, or As-rich for conventional disposal (Johnson, Heijnen, & Wurzel, 2001).

Coagulation/Precipitation: U and As

The most common method to remove As(III) and As(V) is via chemical precipitation using iron and aluminum salts, and it is listed as a BAT for both U and As by the USEPA (Bang, Korfiatis, & Meng, 2005), (Farrell, Assessing Arsenic Removal Technologies, 2002), (Arizona Department of Environmental Quality, 2008). Ferric salts are typically more effective at removing As(III), and are therefore more commonly used. As removal occurs through chemical adsorption and co-precipitation during the formation of ferric hydroxides. Coagulation/precipitation can also reduce turbidity, iron, manganese, phosphate, and fluoride, while making improvements to odor and color. Although this is the most efficient method for the removal of As, it has several limitations. It is highly dependent upon the water chemistry, making it difficult to apply general principals to a wide-variety of water sources. Amounts of ferric or aluminum salts are dependent upon the speciation of the As, the pH and ionic composition of the water, and the scale of the treatment operation (Farrell, Assessing Arsenic Removal Technologies, 2002).

Additionally, chemical additions of this nature are difficult to control and operate point-of-use, especially because they require a large contact and/or settling basin and a filtration step. For these reasons, coagulation/precipitation is not an appropriate technology for this project.

Composite Iron Matrix (CIM): As

The National Academy of Engineering – Grainger Challenge Prize winner, the SONO filter, utilizes a specially manufactured composite iron matrix for arsenic removal, and was designed specifically for use in Bangladesh and Nepal (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010). The filter is capable of meeting both WHO and Bangladesh water quality standards for As, reducing As concentrations to less than 10 µg/L in studies of up to four years of use in households in Bangladesh. It can operate at a low-cost without chemical treatment or regeneration of media or the production of toxic waste. The residual material is a non-toxic solid self-contained iron-arsenate cement. The Composite Iron Matrix (CIM) was developed under a proprietary process utilizing food grade acid washes and is composed of 5-10 kg of cast iron turnings (92-94% Fe), 4-5% carbon, 1-2% SiO_2, 1-2% manganese, and 1-2% each of sulfur and phosphorous. The final CIM is porous and lighter than cast iron turnings alone. Additional details about other materials contained in the SONO filter can be found in the referenced article (Hussam & Munir, 2007). While the CIM seems to be an effective method, its application is specific to the SONO filter. Furthermore, the CIM is produced through a proprietary process. Developing a similar CIM could take years of research and development, and is therefore not appropriate for this project.

Granular Ferric Hydroxide (GFH): As

A granular ferric hydroxide filter is an emerging technology. Its simple operation makes it suitable for point-of-use. They are formed from poorly crystalized FeOOH. It is more effective than activated alumina, but suffers from competitive adsorption of phosphate and silicate. Iron oxides chemically adsorb As(III) and As(V). Once utilized, the GFH media is not intended for regeneration and should be disposed of and replaced (Farrell, Assessing Arsenic Removal Technologies, 2002). GFH is considered to be a proprietary iron-based adsorption material, and has been implemented in full-scale municipal systems in Germany. GFH materials have also been developed in Canada and the United States. Due to the proprietary nature of GFH, compositions and removal mechanisms are not fully known. This also makes GFH promising but expensive with little supporting data (Johnson, Heijnen, & Wurzel, 2001). Thus, GFH is excluded from this project.

Hydroxyapatite/ Synthetic Apatite/ Bone Char: U and As

Hydroxyapatite ($Ca_5(PO_4)_3(OH)$) is a crystal naturally occurring in the deposits of phosphate rock and in the bones and teeth of vertebrates. Synthetic apatite has a very high purity and well-characterized mineral structure. A study of various natural and synthetic apatites and bone char was conducted, with results provided as equilibrium distribution coefficients (K_d) values for a one-hour contact time. Higher K_d values indicate a greater ability of the material to remove U or As from the water. Through these studies, it was found that bone char and Bio-rad hydroxyapatite were best able to remove U at 15,737 mL/g and 48,001 mL/g, respectively. Bone char was not as good at removing As at approximately 18.4 mL/g (Thomson, Smith, Busch, Siegel, & Baldwin, 2009).

Bone from various animals, crushed and charred, has been found to remove heavy metals from water, including As and U. Bone char is both affordable, renewable, and available in most locations in the form of fish bone or from animal processing facilities (Goodier, 2011), (Thomson, Smith, Busch, Siegel, & Baldwin, 2009). However, bone char is eliminated as an option for this project due to opposition from the Navajo culture towards the use of bone remnants. Other forms of hydroxyapatite are eliminated due to limited research on their efficacy for the removal of U and As.

Ion Exchange: U and As

Ion exchange works by strongly attracting the contaminant to a site on the surface of a solid, allowing for a reversible displacement of the ion removed from the water (Johnson, Heijnen, & Wurzel, 2001). Researchers and engineers are increasingly capable of designing ion exchange resins that have more advanced properties that are particularly specific to arsenate, such as copper-doped materials. While ion exchange resins can be engineered to remove specific contaminants, their costs are typically high, often eliminating ion exchange as a potential alternative for a low-cost design (Johnson, Heijnen, & Wurzel, 2001). An alternative to the synthetic, highly-engineered ion exchange resin is natural zeolites. Zeolites are naturally occurring materials with crystalline structures with large internal pore spaces and very large surface areas with ion exchange capacities. Natural zeolite minerals such as clinoptilolite and chabazite have a strong affinity for arsenate and arsenite (Johnson, Heijnen, & Wurzel, 2001). While natural zeolites are less expensive, they are not as effective as the engineered ion exchange resins.

Ion exchange is listed as a BAT for both U and As by the USEPA (Bang, Korfiatis, & Meng, 2005), (Arizona Department of Environmental Quality, 2008). Ion exchange resins, although potentially expensive, are specially designed for the removal of specific contaminants. The resins are easy to regenerate, are applicable over a wide range of pH, and improve overall water quality by removing other potential contaminants such as nitrite and nitrate. They are also operable in a gravity-fed device. Therefore, ion exchange will be explored as an alternative for this project.

Lime Softening: U and As

This is one of the most common methods for the removal of As, and it is considered a BAT for both U and As removal by the USEPA, (Arizona Department of Environmental Quality, 2008). The process is similar to coagulation/precipitation. When lime ($Ca(OH)_2$) is applied, it hydrolyzes and combines with carbonic acid to form calcium carbonate, which acts as a sorbing agent for As or U removal. Lime softening is not feasible for this project because it requires a chemical application and the dose is based on water chemistry, which varies seasonally and by location. Lime softening also raises the pH of water to a range of 10-12 (Johnson, Heijnen, & Wurzel, 2001). Therefore, this method has been eliminated from further consideration.

Membranes (Microfiltration through Reverse Osmosis): U and As

Synthetic membranes are designed to be semipermeable so that some molecules are excluded while others are capable of passing through the membrane. Microfiltration and ultrafiltration are considered to be low-pressure membranes with larger pore sizes, requiring pressures of 10-30 psi, while nanofiltration and reverse osmosis are high-pressure membranes with smaller pore sizes requiring pressures of 75-250 psi. High-pressure membranes are advantageous in that they are capable of removing both microbial pathogens and various heavy metals from water, including As and U, as shown in Figure 2.2.

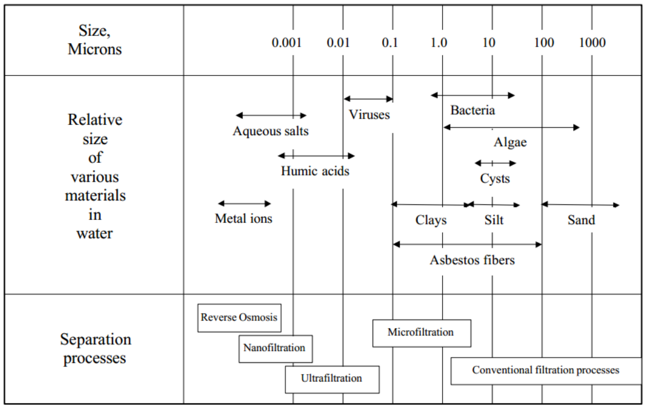


Figure 2.2: Filterable Materials through Membranes Based on Pore Size *(Johnson, Heijnen, & Wurzel, 2001)*

Membranes require pretreatment of the source water to prevent membrane fouling from organics, iron, particulates, manganese, and scale-forming compounds. Unfortunately, the low-pressure systems that are less expensive and less energy intensive are not capable of removing metals ions from water (Farrell, Assessing Arsenic Removal Technologies, 2002) (Johnson, Heijnen, & Wurzel, 2001).

Reverse osmosis (RO) is recommended by the USEPA as a BAT for both U and As (Bang, Korfiatis, & Meng, 2005), (Arizona Department of Environmental Quality, 2008). While RO is capable of reducing As and U to levels below their MCLs, it also removes other ions to very low levels, generating large quantities of concentrated brines that must be disposed of accordingly (Farrell, Assessing Arsenic Removal Technologies, 2002). Additionally, the electrical requirements, capital costs and operation and maintenance requirements for membrane filtration are high for RO and nanofiltration, making membranes inappropriate for this project (Thomson, Smith, Busch, Siegel, & Baldwin, 2009), (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010) (Raff & Wilken, 1999).

Orange Peels: U

The use of orange peel for the removal of uranium ions from aqueous solutions was recently studied in 2013 by a researcher in Egypt. This is a new uranium treatment technology with little research conducted, but is based on the premise that the orange peels will adsorb U. The orange peels in the study are cut into small pieces, washed multiple times with distilled water, and dried at 105°C. They are then milled and sieved by a 150-mesh size sieve. High removal efficiency and short contact time make orange peels an attractive option. The optimal contact time is found to be approximately sixty minutes. The disadvantage of orange peels is that the optimal pH for removal occurs at pH 4. At a pH greater than 4, the adsorption of U decreases. Adsorption is found to be constant over a range of temperatures. At an initial concentration of 25 mg/L of U, the orange peels were able to remove up to 98.16% of the U (Mahmoud, 2013). Although this study was conducted only once at high concentrations of U, and as a sorbent in a batch experiment rather than a column or filter, orange peels present a promising option for U uptake. They are a low-cost, natural, and renewable eco-friendly option. Due to their low-cost and the ease of acquisition, they are considered an alternative for this project.

Oxidation/Reduction: As

Oxidation is listed as a BAT for As by the USEPA (Bang, Korfiatis, & Meng, 2005). However it cannot be used alone for As treatment. Oxidation merely serves to convert arsenite, the more abundant trivalent form of As, to arsenate, the pentavalent form, in order to facilitate more efficient As removal. Additional treatment such as coagulation, adsorption, or ion exchange is necessary for actual As removal. Oxidation can be achieved through atmospheric oxidation, artificial oxidation, or chemical oxidation. Atmospheric oxidation is applied simply by allowing water to come into contact with the air. However, oxidation through air contact is a slow process, often taking weeks. Artificial oxidation can be achieved with electric-powered bubblers. Chemical oxidation is possible using chlorine, hypochlorite, ozone, permanganate, hydrogen peroxide, or Fenton's reagent (H_2O_2/Fe^{2+}) (Johnson, Heijnen, & Wurzel, 2001). Oxidation through chemical means requires knowledge of the source water's complete chemistry to determine the chemical dose, making oxidation a difficult to almost impossible step for this project.

Rice Husks: As

Rice husks, also known as rice hulls, have been studied and are considered to have tremendous potential for the removal of As from contaminated groundwater. Researchers found that both As(III) and As(V) were completely removed from a water with 100 µg/L of As, a flow rate of 1.7 mL/min and a pH of 6.5 via a single-step column experiment containing 6 g of rice husks with an average particle size of 510 µm. Rice husks are a by-product of the rice milling industry, making it a promising waste reuse product for the removal of As. Rice husks are composed of 49.3% by weight oxygen, 44.6% by weight carbon, and 5.6% by weight hydrogen. Additionally, it is 59.5% by weight volatile, 17.1% by weight ash, and 7.9% by weight moisture. The rice husks are washed and dried before use in the column. No chemicals are added. It is also found that the effectiveness of As removal increased with smaller rice husk grain size and slower flow rates (Amin, et al., 2006). Early research on rice husks found that it has an uptake capacity of 332 mg As per g of rice husks (Khalid, Ahmad, Toheed, & Ahmed, 1998). Similar to orange peels, rice husks are a low-cost, natural, renewable, and eco-friendly option. Due to their low-cost and the ease of acquisition, they can be considered an alternative for this project.

Zero Valent Iron (ZVI): U and As

Zero valent iron is an emerging technology that can often be found as iron filings, shavings, turnings, or pellets. ZVI has been in use for more than 20 years as an in situ treatment for contaminated groundwater, and has recently been employed as an As removal technology in Bangladesh. ZVI filters have been recommended as low-cost, energy efficient systems for the provision of safe drinking water (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010). ZVI has also been investigated by the U.S. Department of Energy (DOE) as a method to remove uranium from contaminated groundwater. Researchers suggest that ZVI is able to remove soluble U through the reductive precipitation of U(VI) to the less soluble U(IV) through the adsorption of uranyl to iron corrosion products (Farrell, Bostick, Jarabek, & Fiedor, 1999).

The majority of ZVI research has been conducted in a laboratory setting, with very few studies taking a field-based approach, and even fewer focusing on long-term use of ZVI filters. While there is much research to be done on ZVI for the removal of As. Several laboratory investigations have found that ZVI filings can remove both As(V) and As(III) to levels below 1 µg/L. However, the As removal is limited by the rate of iron corrosion. Fast rates of iron corrosion facilitate the removal of As, even in anaerobic water (Farrell, Assessing Arsenic Removal Technologies, 2002). It is important that the ZVI has the capability to form rust through oxidation, because the removal of As is attributed to adsorption by the iron hydroxides generated from the aerobic corrosion of ZVI. Using ZVI, 82.6% of As(III) and 99.8% of As(V) is removed under aerobic conditions, while less than 4% of As(III) and 9% of As(V) can be removed under anoxic conditions, proving the importance of oxygen and the formation of ferric hydroxide (Bang, Korfiatis, & Meng, 2005).

One negative aspect of ZVI is that the ferrous ion will be produced in the removal process and added to the effluent water, which may be a cause for concern (Johnson, Heijnen, & Wurzel, 2001). Additionally, filter clogging or caking may occur due to volumetric expansion during the iron corrosion process. As iron oxides form, they require more volume than ZVI. To address this issue, ZVI and sand matrices have been researched, and suggestions for incorporating the ZVI as a reactive iron zone within a layer of fine sand have been made. The most effective ZVI to sand ratio was determined to be 40% ZVI: 60% sand by volume, and the ZVI percent by volume should not exceed 52%. Researchers studying the use of ZVI and sand as a low-cost option note that more intensive research is necessary to fully investigate this technology (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010), (Noubactep, Temgoua, & Rahman, 2012).

The Kanchan Arsenic Filter (KAF) was developed by Tommy Ngai at the Massachusetts Institute of Technology for the purpose of water filtration to remove arsenic in Nepal. It makes use of a layer of iron composed of non-galvanized nails, which are placed on top of a sand filter (Ngai & Dangol, 2005). Other researchers have since proven the ineffectiveness of this system, attributing it to the design of iron nails which are not incorporated into a sand matrix. Without the sand matrix, water flowed through the nails too rapidly, therefore not facilitating enough contact time for arsenic removal (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010) (Chiew, Sampson, Huch, Ken, & Bostick, 2009).

The “Three Kolshi Filter” for Bangladesh also utilizes coarse sand and metal iron turnings, as well as other filtration media such as fine sand and wood charcoal. Laboratory tests of this low-tech, low-cost filter have shown that the filter is able to reduce the As concentration to 5 to 30 µg/L from variable initial concentrations of 80 to 1000 µg/L. The World Health Organization states that this filter shows great promise because it is highly effective, low-cost, easy to operate, and is culturally appropriate for its area of proposed use. It employs local materials and traditional, porous water containers (Kolshis). Success of the arsenic removal is partially attributed to the continuous diffusion of air and oxidation facilitated by the porous water containers. While the Three Kolshi Filter is not perfect, the sand and iron filing combination is considered for low-tech As removal applications (Johnson, Heijnen, & Wurzel, 2001) (Munir, et al., 2001).

A combination of ZVI in the form of mesh iron filings followed by a sand column reduces water samples containing 100 µg/L of As to less than 5 µg/L of As. Testing continued, and no breakthrough occurred after treating 34,000 bed volumes of water. After the water passed through the ZVI column, the iron concentration in the water was found to be between 3 and 6 mg/L, but this was reduced to less than 0.3 mg/L after passing through the sand column (Bang, Korfiatis, & Meng, 2005). These results are indicative of the possibility to create a low-cost filter using ZVI and sand for As removal. It is especially effective for water with higher dissolved oxygen (DO) concentrations and lower pH values (at or below neutral pH), as these conditions contribute to the iron corrosion necessary for As removal. For these reasons, ZVI is considered as an alternative method for As removal for this project.

2.2.2 Bacteria

The following technologies were evaluated for their capability to remove bacteria from water.

Boiling

Although boiling can effectively kill ova, cysts, bacteria, and viruses in water, it is generally not recommended for treatment for several reasons. Boiling requires a large amount of energy and may not be executed properly. If a person heats water without reaching boiling, the water may be falsely considered sterilized. Additionally, boiling in closed pots may serve to concentrate some volatile organic compounds and other contaminants of concern such as arsenic (Johnson, Heijnen, & Wurzel, 2001). Boiling is not considered as an alternative.

Chemical Disinfection

There are various ways to chemically disinfect water, including the use of ozone and numerous chlorine containing compounds. In addition to the chlorine compounds used in high-tech treatment plants or lower-tech, rural community-level water treatment plants, there are several chlorine containing compounds used in rural areas that are available for point-of-use. These can include liquid bleach that contains sodium hypochlorite with a range of 1-10% available chlorine, bleaching powder containing calcium hypochlorite that has up to 30% available chlorine, and high-test hypochlorite (often used as a chlorine shock treatment for swimming pools) containing 50-70% available chlorine. Appropriate dosages of chlorine depends on the chemical and physical properties of the water to be treated, and must be able to satisfy the chlorine demand as well as a chlorine residual of 0.5 mg/L. A minimum contact time of 30 minutes is recommended (Johnson, Heijnen, & Wurzel, 2001).

Ozone is not an appropriate technology because it requires an electrical source. Chlorine disinfection is considered as an alternative for this project. Chlorine disinfection has various advantages in that it’s very effective at reducing pathogens. The chlorine residual provides extra protection for water storage. The USEPA and WHO provide chlorination instructions for rural water sources. The disadvantage of this chemical application is the potential for human error. If too little chlorine is added, pathogens are not killed. If too much chlorine is used, the water may become unpalatable. Despite this concern, chemical application of chlorine is considered as an alternative for this project due to its low cost, energy-free application, and its demonstrated capability to remove bacteria.

Granular Activated Carbon (GAC)

Although found to be ineffective for the removal of As and U (Daus, Wennrich, & Weiss, 2004), GAC can be used for the removal of some organic compounds and microbial organisms including viruses and parasites. However, there are still coliform counts observed occasionally. Therefore, this is not the best method for the removal of bacteria (Stanfield, Lechevallier, & Snozzi, 2014).

Membranes (Microfiltration through Reverse Osmosis)

Membranes, as discussed in the technology review for U and As, can also be used for the removal of bacteria through the process of particle size exclusion. Cysts, bacteria, and viruses can be removed by ultrafiltration, nanofiltration, or RO (Johnson, Heijnen, & Wurzel, 2001). Once again, the electrical requirements, capital costs and operation and maintenance commitments for membrane filtration are high for RO and nanofiltration, making these membranes inappropriate selections for this project. Additionally, some degree of pre-filtration is necessary prior to any membrane filtration to prevent membrane fouling that causes inefficiencies, requiring an extra step and cost (Stanfield, Lechevallier, & Snozzi, 2014) (Thomson, Smith, Busch, Siegel, & Baldwin, 2009), (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010) (Raff & Wilken, 1999). Therefore, membranes are eliminated as an alternative method for bacteria removal.

Slow Sand Filtration

The first stage of slow sand filtration is coarse prefiltration through gravel or coconut husk to remove particulate matter. After the coarse prefiltration, water flows through a bed of sand. Slow sand filtration removes pathogens through a combination of physical, chemical, and biological processes. After a sand filter has been in operation for a period of time, a layer of microorganisms forms near the top of the sand bed. This microbial layer is known as the schmutzdecke. It is biologically active and consists of algae, bacteria, diatoms, and zooplankton. It requires two to eight weeks to fully form for effective use. This schmutzdecke ripening period is a major limiting factor for this project due to the time required for formation. Predatory microbes in the schmutzdecke attack and consume pathogens in the water, including *Giardia* and cryptosporidium. Pathogen removal may exceed 99%, but is typically followed by a chlorine disinfection step. Slow sand filters are also capable of reducing turbidity to less than 1 NTU, enterobacteria is reduced by 90-99.9%, enteroviruses and *Giardia* cysts are reduced by 99-99.9%, and *Cercaria* is reduced by 100%. Regardless, the WHO recommends that sand filters are always followed by some form of disinfection (Johnson, Heijnen, & Wurzel, 2001) (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010) (Noubactep, Temgoua, & Rahman, 2012), (Stanfield, Lechevallier, & Snozzi, 2014).

The downside of slow sand filters is that they can become clogged after one to three months of operation, requiring the top two to three centimeters of sand to be scraped off, including the schmutzdecke, decreasing effectiveness until the biolayer forms again. They work best with relatively clear source water, with an influent turbidity of less than 10 NTU recommended unless significant pre-filtration takes place. There can also be a combined multi-stage filtration process that uses a roughing filter of coarse gravel (Johnson, Heijnen, & Wurzel, 2001).

Slow sand filtration technology is not optimal for this project due to the time required for the schmutzdecke to form and the need for a constant flow of water to continually aerate the system allowing for microbial growth. Additionally, it is recommended by WHO that slow sand filters without constant head be followed by a disinfection stage. With this in mind, it is most appropriate to provide a bacterial disinfection shock treatment after filtration in lieu of slow sand filtration.

Ultraviolet Radiation

Ultraviolet radiation is an effective technology to kill pathogens. Effective treatment typically requires the use of electric ultraviolet lamps to irradiate water (Johnson, Heijnen, & Wurzel, 2001).

A Swiss research center, EAWAG, has proven that water stored in clear plastic bottles that have been exposed to a minimum of six hours of sunlight can remove over 99% of pathogens due to a synergistic effect of heat and irradiation of the water. It was found that this sunlight method requires water with low turbidity of less than 30 NTU. This method has been termed SODIS, Solar Disinfection, and due to minimal capital and operational costs, seems promising (Johnson, Heijnen, & Wurzel, 2001).

The use of ultraviolet radiation requiring an electric lamp does not meet this project's constraints. The SODIS method is also not feasible due to the long contact time and the need for sunlight. The time of day and weather conditions thus limit the time at which water can be treated.

3.0 Identification of Alternatives

The literature review yields a wide array of technologies available for the removal of arsenic and uranium. These technologies are evaluated for their ability to remove the contaminants of concern from aqueous solutions possessing similar characteristics to those of the contaminated sources in the BFA as described in Section 2.1.1, Water Chemistry of the BFA Wells. As the final design is essentially limited to the use of gravity and atmospheric pressure, ion exchange and adsorption are identified as the two most viable modes of removal. The efficacy of ion exchange and adsorption of the contaminants of concern are grounded in several parameters:

pH of Influent: The pH of the feed water largely effects the speciation of the arsenic and uranium contained therein. The efficacy of ion exchange and adsorption largely depends on the ionic reduction potential of the contaminants in the aqueous solution (Khandaker, Brady, & Krumhansl, 2009). For neutral compounds, ion exchange and adsorption are much less effective and rely on specific properties of the sorbent. Many ion exchange and adsorption materials are more effective at removing one species of the contaminants. Selection of the technologies discussed in this section is largely based on their demonstrated ability to remove the contaminants of concern in the pH range established in Section 2.1.1. Typical speciation of arsenic in aqueous solution in regard to pH is shown in Figure 3.1. Typical speciation of uranium in aqueous solution is shown in Figure 3.2.

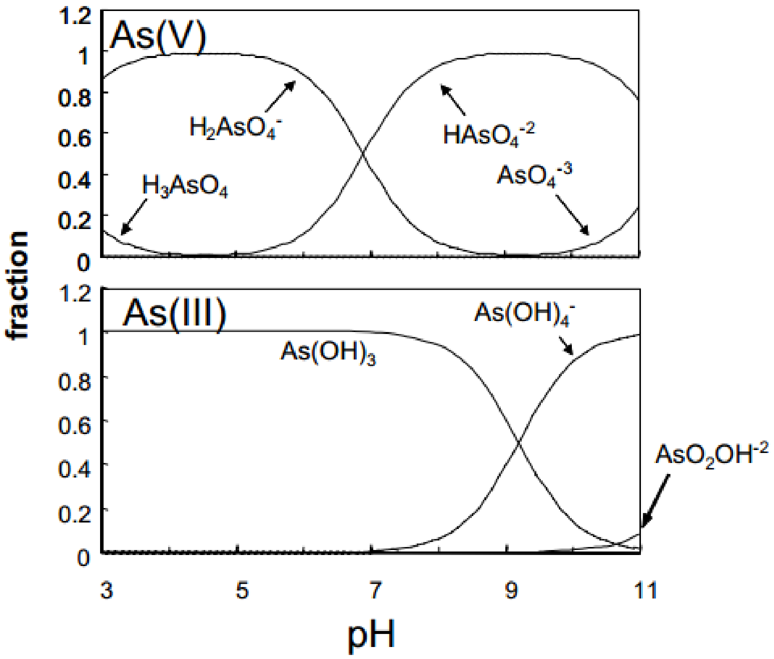


Figure 3.1: Arsenic Speciation in Aqueous Solutions (Khandaker, Brady, & Krumhansl, 2009)

pH Range	Predominant U-Species	Species Type
<5	UO_2^{2+}	Divalent Cation
5-6.5	UO_2CO_3	Neutral Molecule
6.5 - 7.6	$UO_2(CO_3)_2^{2-}$	Divalent Anion
> 7.6	$UO_2(CO_3)_3^{4-}$	Tetravalent Anion

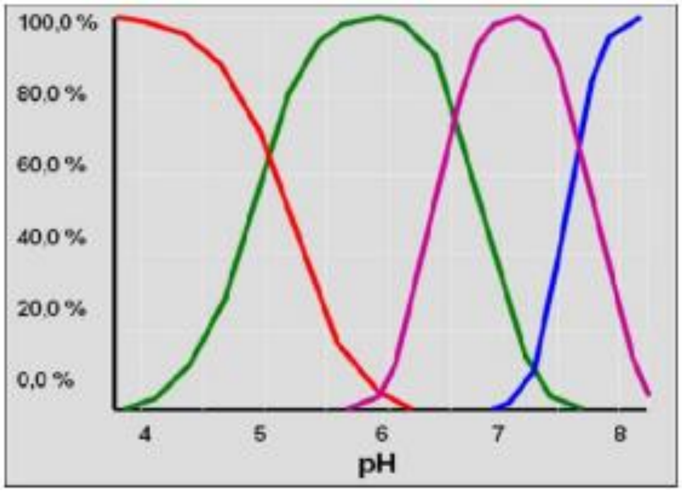


Figure 3.2: Uranium Speciation in Aqueous Solutions (Botha, Bester, & Hardwick, 2009)

Removal Efficiency: The literature review largely focuses on the ability of the investigated technologies to remove the contaminants of concern from the concentrations described in Section 2.1.1 to levels below the MCLs set by the USEPA. Most studies concerning ion exchange and adsorption technologies communicate the efficacy of the sorbent as a fraction of removal of the targeted contaminant. Only technologies demonstrating a removal efficiency great enough to reduce the concentrations of the contaminants of concern from those contained in the synthetic water to below the MCLs are considered.

Selected Materials: The literature review yields several alternatives for the removal of the contaminants of concern which satisfy each of the parameters. The selected materials are shown in Table 3.1.

Table 3.1: Proposed Removal of Contaminants by Filter Media

Filter Media	**Contaminant to be Removed by Filter Media**	
	Primary Removal	**Secondary Removal**
Ion Exchange Resin	Uranium	Arsenic
Orange Peels	Uranium	N/A
Zero Valent Iron	Arsenic	N/A
Rice Husks	Arsenic	N/A

The following subsections detail the contaminant removal mechanisms and justification for choosing each of these technologies for testing and possible use in the final design.

3.1 Ion Exchange Resin for U

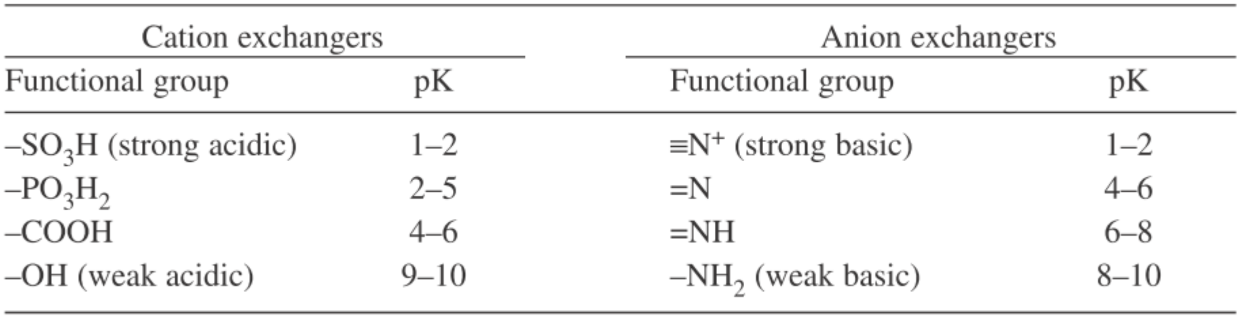
Ion exchange resins are highly specialized materials designed to remove specific contaminants from feed water. For this project, a general review of ion exchange alternatives focused on resin selectivity and affinity, ion exchange capacity, and ion exchange kinetics. Selectivity and affinity refer a hierarchy of substances a particular ion exchange resin can remove and maintain. Exchange capacity refers to the mass of contaminant which can be adsorbed per mass of resin, and is utilized to gauge maintenance and cost parameters. Exchange kinetics refers to the rate at which ion exchange occurs and relates directly to contact time.

The ion exchange process entails the exchange of ions electrostatically bound to the functional group of a solid matrix for the target contaminant. Ion exchange resins are generally selected for the removal of a particular contaminant. Several factors affect the resin's affinity to bond with ions in contaminated feed water. These factors include the charge and the ionic radii of the ion targeted for removal. The functional group is often an atom for which the resin has the least affinity. Ion affinity also affects sorption kinetics (International Atomic Energy Agency, 2002).

Mass transfer between solution and the active site of the resin takes place in five distinct steps. The order of these steps are: diffusion of the ion through the bulk solution, diffusion of the ion through the hydrated film which forms around the resin surface, diffusion of the ion through the resin, and finally the actual ion exchange chemical reaction like the one shown below. Reaction kinetics are limited by either diffusion through the thin film or diffusion through the particle. Reaction kinetics are also influenced by other characteristics of the feed water depending on which rate limiting step controls the specific ion exchange resin application (International Atomic Energy Agency, 2002).

Ion exchange resins are categorized by the type of ion they are designed to remove and the characteristic of their functional group. Resins are designated as cation or anion exchangers and the functional groups are categorized as strongly acidic, weakly acidic, strongly basic, and weakly basic. Table 3.2 shows some of the most common functional groups of cation and anion exchange resins and their respective negative log pK values.

Table 3.2: Common Functional Groups of Ion Exchange Resins *(International Atomic Energy Agency, 2002)*



Cation exchangers		Anion exchangers	
Functional group	pK	Functional group	pK
–SO_3H (strong acidic)	1–2	≡N^+ (strong basic)	1–2
–PO_3H_2	2–5	=N	4–6
–COOH	4–6	=NH	6–8
–OH (weak acidic)	9–10	–NH_2 (weak basic)	8–10

The following formula illustrates the basic ion exchange reaction between the divalent uranium dioxide ion and a strongly basic ion exchange resin.

$$2(R-N^{+})+UO_2\cancel{(CO_3)_2}+\cancel{6H_2O}\leftrightarrow R_2UO_2+2N+\cancel{2(CO_3)}+\cancel{6H_2O}$$

In this equation, R represents the solid matrix of the ion exchange resin, and nitrogen is the functional group. The carbonate and water are removed from the equation as they take no part in the ion exchange reaction. It is noted that during this particular ion exchange reaction, nitrogen is added to the treated water. The final selection of a particular ion exchange resin for either uranium or arsenic considers these reactions as mass transfers in order to assure harmful contaminants are not added to the treated water in concentrations greater than those suggested by regulations. It is also noted that the release of charged ions into the feed water may affect pH significantly. This effect is noted in the naming convention of the functional groups of the ion exchange resin. Basic functional groups tend to increase pH while acidic functional groups tend to decrease pH of the treated effluent (International Atomic Energy Agency, 2002).

An extensive review of laboratory studies focusing on the removal efficiencies of anion exchange resins for the treatment of uranium contaminated water yields percent removal in the range of 80-99% (Wilson) (Aieta, Singley, Trussell, Thorbjarnarson, & McGuire, 1987) (Lowry & Lowry, 1988) (Wisser, 2003). For the removal of uranium from solution an anion type exchange resin is required. Considering the possible affect the use of a strongly basic anion exchange resin may have on effluent pH, a weakly basic anion exchange resin is preferred. Rohm and Haas, a subsidiary of Dow Chemical Corporation, suggests the use of Amberlite™ PWA8 anion exchange resin for the treatment of uranium contaminated feed water for potable use. It is noted that this anion exchange resin may also remove arsenic from the feed water. No data is available for the removal efficiencies of this particular resin, though this resin is suggested by Rohm and Haas product specialists.

Adsorption capacity is well established for uranium removal using ion exchange resins due to their common use in uranium recovery in the uranium mining industry. In general, the capacities of ion exchange resins used in uranium removal are high when the target concentrations of the contaminants in the modeled water used in the testing phase of this project and the target amounts of water to be treated daily by the device are considered. This means that the final device would likely be able to operate for long periods of time between replacement or regeneration of the ion exchange resin.

Ion exchange resins are chosen for satisfaction of the design constraints and criteria. This technology has been shown effective in removal of uranium from aqueous solution in the target pH range. Although more costly than the organics considered for this design, ion exchange resins are relatively low-cost when considering the time interval between replacement or regeneration due to their high adsorption capacity. This technology is also selected as it can function in a gravity-fed system. Since ion exchange resins are highly engineered, the likelihood of design failure is minimal. Therefore, the testing of an ion exchange resin for this project is to ensure success of at least one filter material. However, other low-tech, low-cost, and innovative solutions are preferable.

3.2 Orange Peels for U

The use of organic materials for the removal of uranium from aqueous solution is well documented. The use of moss, biomass, and cherry stones have all shown surprising effectiveness in removing large fractions of influent uranium concentrations in concentrated feed streams. One study shows promising results for removing uranium from solution using orange peels (Mahmoud, 2013).

Orange peels have shown an adsorption of 75-85% of uranium concentration compared to initial concentrations and a capacity of 12-13 mg of uranium per gram of orange peel in laboratory testing in the pH range of 6-8. Contact time required to achieve this fraction of removal is one hour. The mechanism for removal is a combination of adsorption and ion exchange (Mahmoud, 2013).

Orange peels are chosen for their demonstrated ability to remove uranium from aqueous solution. The removal efficiency, pH range of effectiveness, and contact time is considered adequate for application in this design. The widespread availability and general low cost of oranges make this technology an attractive and cost-effective option for use in a low-tech point-of-use water filter.

3.3 Zero Valent Iron for As

As ZVI reacts with water with a high dissolved oxygen content, insoluble hydrous ferric oxide forms. These oxides have the capability to remove soluble arsenic through adsorption and precipitation processes. When utilizing a ZVI/sand matrix, the precipitate formed through this process can then be contained by the sand, thus removing the arsenic from the water (Chiew, Sampson, Huch, Ken, & Bostick, 2009).

Hydrous ferric oxide is formed under oxidizing conditions, as shown by the following three chemical reactions. Hydrous ferric oxide has a higher adsorptive capacity for As(V) than As(III) at a neutral pH, so more As(V) can be removed from the contaminated water (Bang, Korfiatis, & Meng, 2005).

$2Fe^0 + O_2 + 4H^+ \leftrightarrow 2Fe^{2+} + H_2O$

$4Fe^{2+} + 4H^+ + O_2 \leftrightarrow 4Fe^{3+} + 2H_2O$

$Fe^{3+} + 3H_2O \leftrightarrow Fe(OH)_3 + 3H^+$

The prevalence of hydrous ferric oxide is greatly affected by the dissolved oxygen content of the feed water. The ideal condition for application of ZVI for arsenic removal is between 4.3 and 5.5 mg DO/L. The pH of the feed water has also shown to greatly affect removal efficiency. The optimum pH is between 5 and 7, slightly below the pH of the water observed in the contaminated sources considered in this design. Regardless, the removal efficiency of greater than 85.7% is acceptable for use in this design. Reaction kinetics have not been adequately established for ZVI in arsenic removal.

Zero valent iron is chosen for satisfaction of the design constraints and requirements. ZVI has shown to be effective in completely removing As from aqueous solution in the target pH range. It is also a low-cost alternative that would work in a low-tech and gravity-fed point-of-use device.

3.4 Rice Husks for As

Rice husks have been shown effective in completely removing As from aqueous solution in column testing. This technology is shown to be effective in the pH range considered in this design (Amin, et al., 2006).

The mechanism of removal is either affinity adsorption or ion exchange between the As in the feed water and the carbon structure of the rice husk. Carbon contact with water reduces the oxygen to a hydroxyl, causing the carbon to lose electrons and become positively charged. This allows for uncharged As species prevalent in the target pH range to be removed via ion exchange or affinity adsorption (Amin, et al., 2006).

Rice husks are readily available through online retailers and are relatively inexpensive, as shown in section 8.0, Cost of Implementing the Design. Rice husks are a technology considered for the final design as it has been proven to be effective in removing As from aqueous solution in the desired pH range and satisfies the performance criteria. It is an excellent low-cost alternative which can be used in a low-tech point-of-use filtration device.

3.5 Additional Considerations

3.5.1 Granular Activated Carbon

Granular activated carbon (GAC) is considered as a post-treatment option to remove byproducts of the filtration processes. If it is observed during initial testing phases that organics like orange peels and rice husks, or inorganics such as ZVI and ion exchange resins affect the turbidity or mineral content of the treated water, then GAC can be used as a polishing media. GAC will be integrated into the design to clarify and remove byproducts of the filtration process. This technology is the only technology considered for the purpose of making the finished water more aesthetically appealing.

3.5.2 Chlorine Disinfection

Chlorine disinfection is the only technology considered for the removal of bacteria. Chlorine disinfection is the most common, low-cost, and low-tech disinfection treatment commonly employed for in-situ disinfection. The chlorine dose can be calculated based on the free available chlorine content of the specific chemical and the volume of water to be treated. This will be explained in detail in section 6.0, Final Design.

4.0 Testing and Analysis

The testing and analysis for this project includes developing a synthetic water for use in the laboratory to test materials for their removal efficiency, preparing and testing the alternative materials in column tests, analyzing the results of the column tests, preparing and testing various modular configurations, and analyzing the results of the modular configuration testing.

Although greatly desired, it was not possible to determine the point of breakthrough or failure for each material. Breakthrough refers to the point at which the material is no longer able to remove the contaminant to a level at or below its MCL because the material is saturated with the contaminant. Failure of the material includes breakthrough, but also refers to failure of the material itself, such as molding or rotting of organic materials like orange peels. Breakthrough and failure data was not achieved due to the amount of time required for vast quantities of water to filter through the material, the cost associated with the number of samples required for large volumes of water, and the cost associated with creating large quantities of synthetic water. Without the breakthrough or failure data, it is impossible to determine the longevity of each material, the maintenance required, and how the tested water quality parameters will change over time as the material filters additional volumes of water. Therefore, the results presented in this section should be considered to be preliminary and applicable only towards design recommendations rather than a final design.

4.1 Water Quality Analysis Methods

Throughout this project, various water quality parameters were measured in laboratory facilities at NAU and Metropolitan State College of Denver. These water quality parameters include pH, Solids, Turbidity, Coliforms, Hardness, Alkalinity, Dissolved Oxygen, Uranium Concentration, and Arsenic Concentration. The procedures for Coliforms, Hardness, and Alkalinity followed methods established by Standard Methods for the Examination of Water and Wastewater. The Uranium and Arsenic Concentration Testing followed EPA Method 6020. The Standard Methods can be found at http://www.standardmethods.org/Store/index.cfm (Standard Methods, 2014). The EPA Method can be found at: http://www.epa.gov/fem/methcollectns.htm (U.S. Environmental Protection Agency, 2014). Table 4.1 shows the water quality parameters that were tested and the method and instrument used.

Table 4.1: Water Quality Parameters and Associated Methods and Instruments

Water Quality Parameter	Testing Location	Test Method	Instrument Used
pH	NAU Water Quality Laboratory	N/A	Oakton pH/Conductivity/TDS meter, pH/CON 510 series
Total Dissolved Solids (TDS)	NAU Water Quality Laboratory	N/A	HANNA Instruments HI9828 pH/ORP/EC/DO meter
Turbidity	NAU Water Quality Laboratory	N/A	2100P Hach Turbidimeter
Coliforms	NAU Water Quality Laboratory	Standard Method 9222 B. Standard Total Coliform Membrane Filtration Procedure	N/A
Dissolved Oxygen (DO)	NAU Water Quality Laboratory	N/A	HANNA Instruments HI9828 pH/ORP/EC/DO meter
Hardness	NAU Water Quality Laboratory	Standard Method 2340 C. Titration Method	N/A
Alkalinity	NAU Water Quality Laboratory	Standard Method 2320 B. EDTA Titration Method	N/A
Uranium and Arsenic Concentrations	Metropolitan State College of Denver	EPA Method 6020	ICP-MS

4.2 Synthetic Water Development

Prior to testing any alternative methods of water treatment, a source of water needed to be identified. Actual well water could not be obtained from any of the BFA wells due to difficulty in securing permits and Navajo Nation Chapter House Resolutions for the sampling and removal of water from the Navajo Nation. For this reason, synthetic water was developed. As discussed in section 2.1.1, Water Chemistry for the BFA Wells, the water chemistry of the three BFA wells was used for the purposes of designing a synthetic water for this project. From the data presented in Table 2.2, the synthetic water goals are a pH of 7.8-8.4, a U concentration of 100 µg/L, an As concentration of 70 µg/L. Additionally, a coliform count of less than 100 CFU/100mL is desired. Since the BFA water is groundwater, the synthetic water should ideally be sourced from a groundwater well to best attempt to model the water chemistry.

Creating the synthetic water involved several steps. These steps include acquisition of a local water source containing coliforms, the acquisition of a local groundwater source with more characteristic water chemistry to better model the BFA groundwater, the determination of the ratio of groundwater to coliform-containing water, the creation of standard U and As solutions from purchased stock solutions, and spiking of the locally sourced water with the U and As standards.

4.2.1 Water Quality Analysis of Upper Lake Mary Water

In order to create a synthetic water with these parameters, a combination of groundwater and surface water is used. This is due to the necessity for the presence of coliforms and the desire to create a synthetic water most representative of the groundwater in the BFA. Groundwater is obtained from a private residential well in Flagstaff, AZ, but it could not be used alone as it does not contain coliforms.

A local water source in Flagstaff, Upper Lake Mary, contains coliforms, but this water is turbid and does not contain as much hardness or alkalinity as typical groundwater sources. The water used in the synthetic water creation is taken from a tap at the Lake Mary Water Treatment Plant prior to it receiving water treatment. This tap is easier to access than the actual lake, especially during the winter months.

A water quality analysis was conducted for Upper Lake Mary in November 2013 in order to determine basic water quality parameters of this source. These tests were limited to those that could be conducted in laboratory facilities at NAU, and therefore excluded testing for background concentrations of U and As. The collected water quality data includes pH, coliforms, turbidity, alkalinity, total hardness, and calcium hardness. The results of the initial water quality analysis for Upper Lake Mary from November 2013 can be seen in Table 4.2. The water used in this study was taken directly from surface water at Upper Lake Mary rather than the tap at the Treatment Plant. The full water quality report can be found in Appendix B.

Table 4.2: Water Quality Data for Upper Lake Mary

Water Quality Parameter	USEPA MCL Primary Standards	Average Values for Upper Lake Mary Water
pH	6.5-8.5 (Secondary Standard)	6.25
Total Coliforms (CFU/100mL)	No more than one sample can be total coliform-positive per month	TNTC
Turbidity (NTU)	5	53.6
Alkalinity (mg/L as $CaCO_3$)	N/A	37.2
Total Hardness (mg/L as $CaCO_3$)	N/A	35
Calcium Hardness (mg/L as $CaCO_3$)	N/A	28

Through this water quality analysis, several problems with the Upper Lake Mary Water are identified. First, the average pH of 6.25 is not within the desired range of 7.8-8.4. The water also contains a low level of hardness and alkalinity which is not characteristic of groundwater. Additionally, the turbidity is high, which could potential cause problems in any filtration unit. Most importantly the coliform count is too numerous to count (TNTC). Not only is this coliform count not representative of the bacterial contamination of the groundwater wells from the BFA, it was believed that the removal of such a high coliform level would not be possible through a low-cost, electricity-free water filter. Therefore, it is decided that the coliform-containing Upper Lake Mary water should be diluted with the water from the private groundwater well.

4.2.2 Dilution

In order to determine the correct ratio of groundwater to Upper Lake Mary water, a serial dilution test was performed in February 2014 and does not account for seasonal changes in coliform concentrations. The method and results of this test can be found in Appendix C. The water used during this dilution test was taken from the tap at the Lake Mary Water Treatment Plant. In this case, the tests indicate that undiluted, 100% Lake Mary water has an average of 37 CFUs/100mL, which is different from the Lake Mary Water tested in November 2013 that had a coliform count of TNTC. The difference in CFUs may be due to seasonal changes, location of sampling, and the length of time between taking the water samples and conducting the analysis. Despite a countable amount of CFUs in 100% Lake Mary water, use of groundwater is still desirable in order to better model the groundwater from the BFA. A ratio of 10%

Lake Mary water to 90% groundwater by volume is selected. The 10% Lake Mary water dilution test shows an average of 15 CFUs/100mL.

When creating the synthetic water, 60 gallons of water is produced in a clean, unused 90 gallon plastic trash receptacle secured from the City of Flagstaff Municipal Waste Department. Six gallons of Lake Mary water from the Lake Mary Water Treatment Plant is diluted with 54 gallons of residential groundwater. Due to the large volume of groundwater required, it is added to the container via an electric pump. The flow rate of the pump is established, and 60 gallons of water is transferred to the container based on time requirements and flow rate.

4.2.3 Uranium and Arsenic Spiking

In order to achieve the desired concentrations of 100 µg/L of U and 70 µg/L of As, as determined in section 2.1.1, Water Chemistry of the BFA Wells, the blended Lake Mary/groundwater is spiked with U and As. Stock solutions of U and As are purchased. The chemical information for these U and As stock solutions can be found in Appendices D and E, respectively.

Due to the highly concentrated nature of the purchased stock solutions (10,000,000 µg/L for both U and As) two standards are made, one for U and one for As. To create a standard, 100 mL of stock solution is added to a 1 L flask. The 100 mL of stock solution is then diluted to 1 L with deionized (DI) water. This results in two 1 L standards, one with a concentration of 1,000,000 µg/L of U and the other with a concentration of 1,000,000 µg/L of As. These standards are able to be stored in their 1 L containers and reduce the margin of error when spiking the synthetic water.

To spike the Lake Mary/Groundwater blend, 22.7 mL of 1,000,000 µg U/L standard and 15.9 mL of 1,000,000 µg As/L are added. Supporting calculations for the creation of the standards and the synthetic water spiking can be viewed in Appendix F.

4.2.4 Water Quality Analysis of Synthetic Water

A water quality analysis was conducted for the synthetic water in February 2014 in the NAU Water Quality Laboratory. The full water quality report can be viewed in Appendix G. Additional synthetic water analysis for U and As concentrations was conducted in late March, 2014 at the Metropolitan State College of Denver. The results of the water quality analysis for synthetic water can be seen in Table 4.3.

Table 4.3: Water Quality Data for Synthetic Water

Water Quality Parameter	USEPA MCL Standards	Desired Synthetic Water Goals	Average Values for Synthetic Water
pH	6.5-8.5 (Secondary Standard)	7.8-8.4	7.72
Total Coliforms (CFU/100mL)	No more than one sample can be total coliform-positive per month (Primary Standard)	Less than 100	2
Turbidity (NTU)	5 (Primary Standard)	N/A	7.85
Uranium (µg/L)	30 (Primary Standard)	100	84.71
Arsenic (µg/L)	10 (Primary Standard)	70	68.65
Total Dissolved Solids (mg/L)	500 (Secondary Standard)	N/A	139
Alkalinity (mg/L as $CaCO_3$)	N/A	N/A	101.97
Total Hardness (mg/L as $CaCO_3$)	N/A	N/A	102
Calcium Hardness (mg/L as $CaCO_3$)	N/A	N/A	97

The results in Table 4.3 show that the pH falls just short of the desired range of 7.8-8.4. As 7.72 is close to 7.8, with a percent difference of 1.03%, no chemical adjustments to alter the pH will be made. The dilution tests show that a blend of 10% Lake Mary water to 90% groundwater should yield, on average, 15 CFUs/100mL. However, the coliform count of the synthetic water is less than expected, at only 2 CFUs/100mL. This may be a result of changing water quality parameters due to the addition of U and As, or it may be a result of bacteria death as the water sits in the laboratory awaiting use in testing. The U concentration is approximately 15 µg/L less than desired. The reason for this is unknown. There may have been human error during the water spiking step. The As concentration of 68.65 µg/L is very close to the desired concentration of 70 µg/L. The turbidity, alkalinity, total hardness, and calcium hardness are more representative of groundwater sources than the 100% Lake Mary water that was tested in November 2013.

4.3 Materials

4.3.1 Ion Exchange for U

Although the Amberlite^{TM} PWA8 Ion exchange resin distributed by DOW Chemical would be an ideal ion exchange resin for U removal, due to cost and time constraints, it could not be acquired. The DOW Chemical Product Data Sheet for Amberlite^{TM} PWA8 can be seen in Appendix H. However, the Water Quality Laboratory at NAU already possesses Monoplus MP 500 Macroporous Strongly Basic Anion Resin, distributed by Sybron Chemicals, Inc, which is now Lewatit. The product information sheet for the Monoplus resign can be found at http://www.lenntech.com/Data-sheets/Lewatit-MonoPlus-MP-500-L.pdf. This resin, as seen in Figure 4.1, will be tested for the purposes of this project. To prepare this resin for use, it must be soaked for 24 hours in DI water.

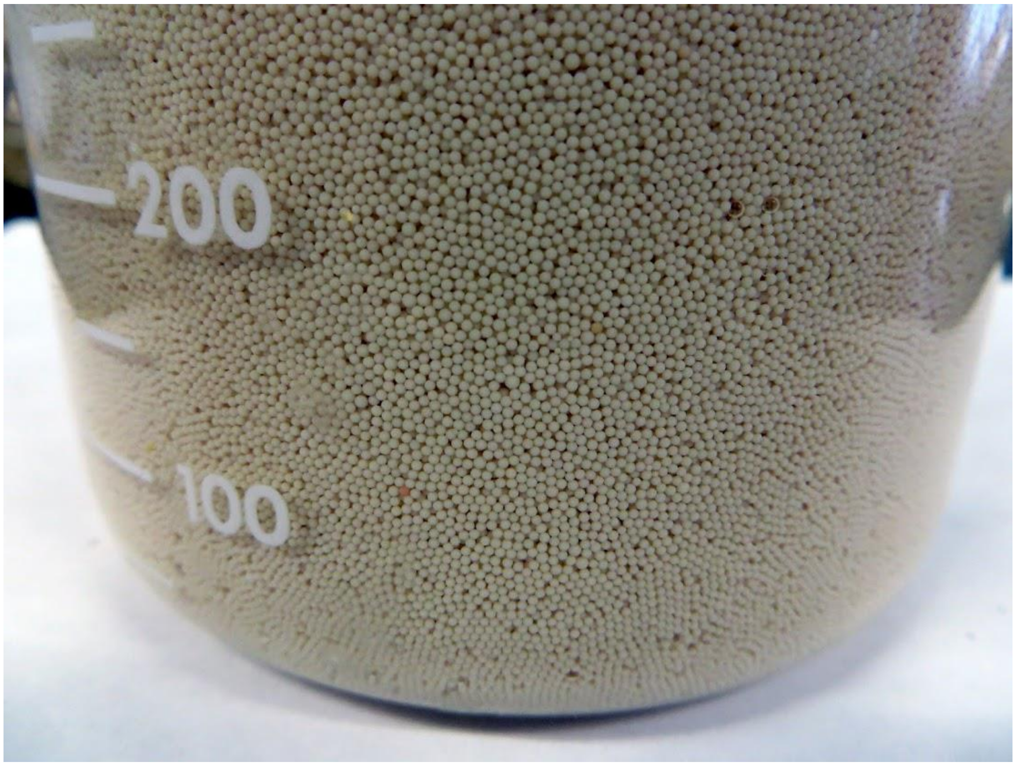


Figure 4.1: Ion Exchange Resin

The Monoplus MP 500 resin is not specifically designed for U removal, nor is it intended for potable water use. However, it is similar to the Amberlite resin in that it is also a basic anionic resin. If the Monoplus resin is able to remove U from the synthetic water, it can be assumed that the Amberlite resin that is specifically engineered for U removal for potable water use will be capable of greater removal efficiency.

4.3.2 Orange Peels for U

Oranges are purchased at a local grocery store in Flagstaff, AZ. They are peeled, and the dried in an over for a period of 24-36 hours. Initial drying occurs in a convection oven at 105°C for 12 hours. They are then dried overnight for 9-10 hours in open air. They are dried for an additional 3 hours in the water quality laboratory oven at 103°C in a crucible. The orange peels are prepared in a laboratory blender to achieve the diameter size seen in Figure 4.2. Wet orange peels are shown in Figure 4.3. This process for the preparation of orange peels is recommended by the research conducted by M.A. Mahmoud (2013).

Figure 4.2: Dried and Finely Chopped Orange Peels

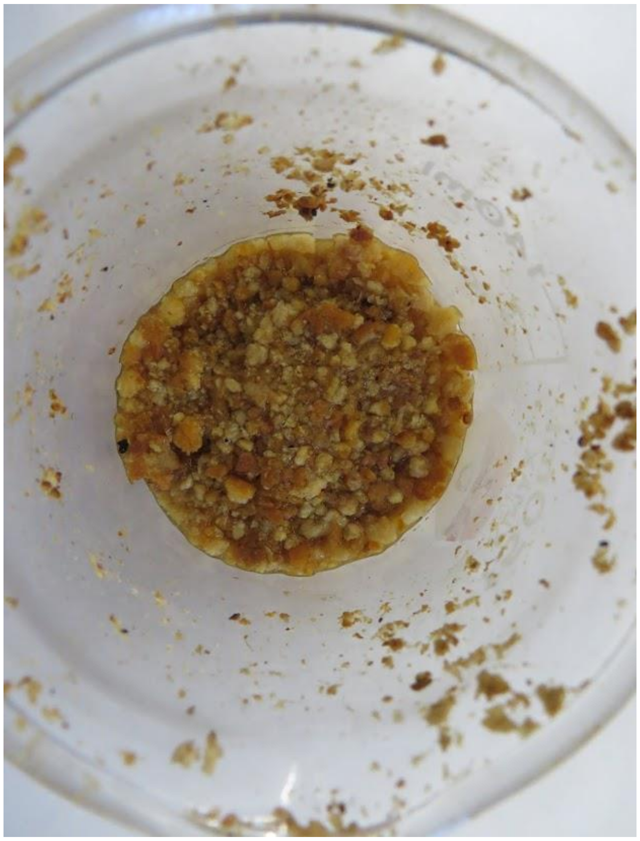


Figure 4.3: Orange Peels Saturated with Water

4.3.3 Zero Valent Iron for As

Two materials are selected for testing the ZVI alternative. First, steel turnings made from AISI 1020 Cold Rolled Steel, composed of 0.17-0.23% carbon, 99.08-99.53% iron, 0.30-0.60% manganese, less than 0.040% phosphorous, and less than 0.050% sulfur, are provided by the NAU Machine Shop (MatWeb, 2014), and can be seen in Figure 4.4.

Figure 4.4: ZVI Turnings in Original State

The ZVI is coated with APEX 9000 Water Soluble Cutting Oil. The MSDS for this oil can be found here: file:///C:/Users/cd393/AppData/Local/Downloads/A-411_%20APEX%209000%20SOL.pdf. The ZVI turnings are rinsed with tap water and cleaned with a soap solution to remove the cutting oil. This caused the ZVI to rust, and this iron oxide formation helps to facilitate the arsenic removal. The turnings are cut into smaller pieces to allow for greater surface area and easier distribution in the columns during testing. The ZVI turnings in their final state can be seen in Figure 4.5.

Figure 4.5: ZVI Turnings in Final State

Iron filings, which have a smaller particle size and greater potential surface area for water contact, were selected as the second ZVI material. “Science magnets,” used for school magnetic experiments were selected for their low cost. They can be seen in Figure 4.6.

Figure 4.6: ZVI Filings

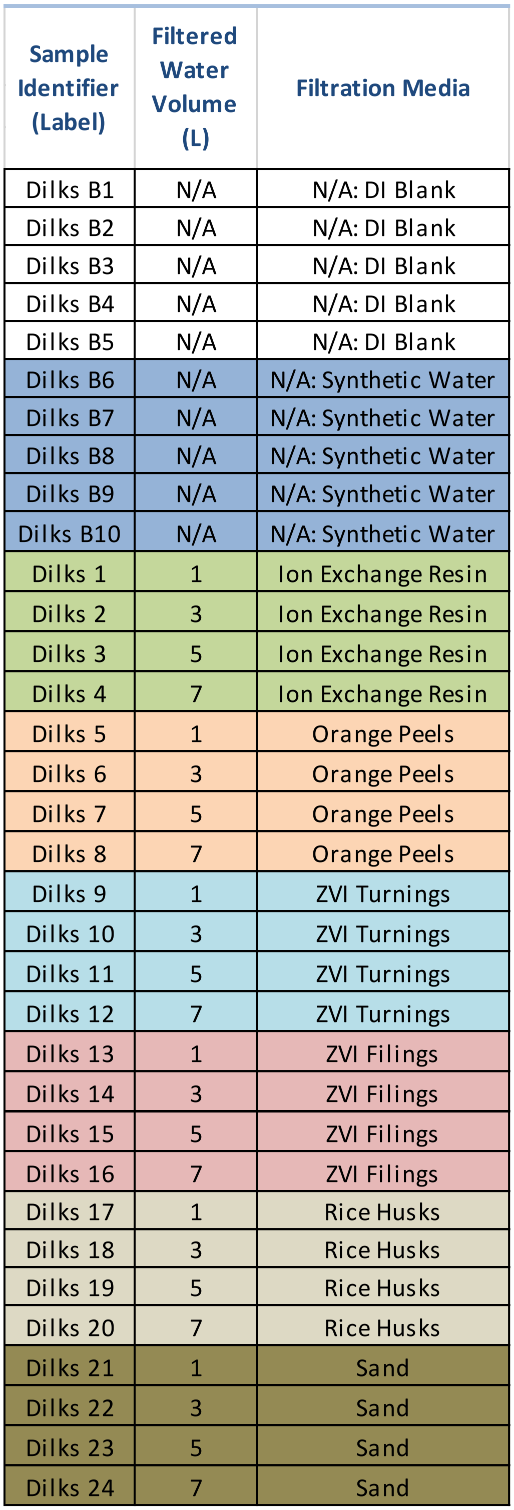
4.3.4 Rice Husk for As

Rice husks, distributed by the LD Carlson Company, are purchased from Amazon.com, and can be seen in Figure 4.6. According to the research of M.N. Amin, et al., to prepare the rice husks, the collected materials should be washed with DI water several times to remove dust and fines. The washing process should be repeated until the color of the wash water is transparent. However, it is decided that washing is not necessary since the obtained rice husks were pretreated and no dust or fine particles are noticed. The rice husks need to be sieved. According to Amin et al., 780 µm (0.031in)-sized rice husks are required. Thus, sieve No. 18 and No. 20 are used to obtain a size between 0.0331 in and 0.0394 in. Using the closest available sieve size in the Soils Laboratory at NAU, the No. 10 size sieve is selected. Thus, the final sieved size of the rice husks is between 0.0787 in and 0.0331 in.

Figure 4.6: Rice Husks from LD Carlson Company

4.4 Experimental Matrix

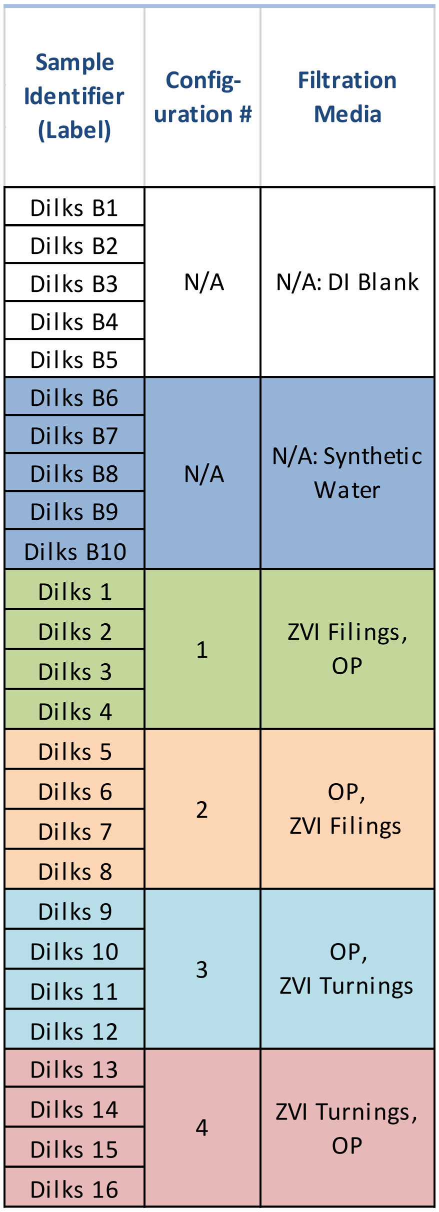
Experimental matrices are necessary for the testing of the alternative materials and the modular configurations. The experimental matrix for the alternative materials can be seen in Figure 4.7. It involves testing five DI water blanks, five synthetic water samples, four effluent samples each from the five materials of interest, and four effluent samples each from the sand control. This results in a total of 34 samples for the testing of the alternative materials. Each of the materials are tested with 7 liters of synthetic water. The four effluent samples were taken at 1 L, 3 L, 5 L, and 7 L. In addition to testing each of the 20 material water samples for U and As, they were analyzed for pH, turbidity, TDS, and DO. The results of this testing are described in section 4.6, Results of Alternative Methods Testing.



Sample Identifier (Label)	Filtered Water Volume (L)	Filtration Media
Dilks B1	N/A	N/A: DI Blank
Dilks B2	N/A	N/A: DI Blank
Dilks B3	N/A	N/A: DI Blank
Dilks B4	N/A	N/A: DI Blank
Dilks B5	N/A	N/A: DI Blank
Dilks B6	N/A	N/A: Synthetic Water
Dilks B7	N/A	N/A: Synthetic Water
Dilks B8	N/A	N/A: Synthetic Water
Dilks B9	N/A	N/A: Synthetic Water
Dilks B10	N/A	N/A: Synthetic Water
Dilks 1	1	Ion Exchange Resin
Dilks 2	3	Ion Exchange Resin
Dilks 3	5	Ion Exchange Resin
Dilks 4	7	Ion Exchange Resin
Dilks 5	1	Orange Peels
Dilks 6	3	Orange Peels
Dilks 7	5	Orange Peels
Dilks 8	7	Orange Peels
Dilks 9	1	ZVI Turnings
Dilks 10	3	ZVI Turnings
Dilks 11	5	ZVI Turnings
Dilks 12	7	ZVI Turnings
Dilks 13	1	ZVI Filings
Dilks 14	3	ZVI Filings
Dilks 15	5	ZVI Filings
Dilks 16	7	ZVI Filings
Dilks 17	1	Rice Husks
Dilks 18	3	Rice Husks
Dilks 19	5	Rice Husks
Dilks 20	7	Rice Husks
Dilks 21	1	Sand
Dilks 22	3	Sand
Dilks 23	5	Sand
Dilks 24	7	Sand

Figure 4.7: Experimental Matrix for Testing Alternative Methods

The experimental matrix for the modular configurations can be seen in Figure 4.8. It involves testing five DI water blanks, five synthetic water samples, and four effluent samples each from four modular configurations. The selection and details of the four modular configurations are discussed in section 4.8, Testing of Modular Configurations. This experimental matrix results in a total of 26 samples for the testing of the modular configurations. Each of the configurations is tested with 10 L of synthetic water. The four effluent samples are taken at 2.5 L, 5 L, 7.5 L, and 10 L. In addition to testing each of the 16 material water samples for U and As, they are analyzed for pH, turbidity, TDS, and DO. The results of this testing are described in section 4.8, Results of Modular Configurations Testing.



Sample Identifier (Label)	Config-uration #	Filtration Media
Dilks B1	N/A	N/A: DI Blank
Dilks B2		
Dilks B3		
Dilks B4		
Dilks B5		
Dilks B6	N/A	N/A: Synthetic Water
Dilks B7		
Dilks B8		
Dilks B9		
Dilks B10		
Dilks 1	1	ZVI Filings, OP
Dilks 2		
Dilks 3		
Dilks 4		
Dilks 5	2	OP, ZVI Filings
Dilks 6		
Dilks 7		
Dilks 8		
Dilks 9	3	OP, ZVI Turnings
Dilks 10		
Dilks 11		
Dilks 12		
Dilks 13	4	ZVI Turnings, OP
Dilks 14		
Dilks 15		
Dilks 16		

Figure 4.8: Experimental Matrix for Testing Modular Configurations

4.5 Testing of Alternative Materials

As described in section 4.3, Materials, five materials are selected for column tests. The five materials are all tested between layers of coarse sand. For this reason, sand is tested individually as a control to determine if it has a removal efficiency that may interfere with the removal efficiency of the materials.

The testing apparatus, depicted in Figure 4.9 consists of a 1.75 inch inner diameter acrylic column with the capacity to hold at least 20 inches of sand and material. The acrylic column connects to an elevated reservoir via plastic tubing. There is a diffuser at the top of the acrylic column in order to facilitate a uniform flow through the column. The flow rate is controlled by an in-line ball valve.

Figure 4.9: Column Testing Apparatus

The column is filled with to a total of 20 inches, composed of sand and material. The ratios of sand to material used for each test are described in sections 4.5.2 – 4.5.7. The experimental procedure consists of the following steps:

1. Fill column with approximately 2 inches of gravel. The gravel prevents the sand and materials from clogging the outlet at the bottom of the column.
2. Place the appropriate sand and material quantities on top of the gravel.
3. Connect the column to the tubing and reservoir system.
4. Place a 1 L or larger graduated cylinder under the apparatus to collect effluent.
5. Allow approximately 1 L of DI water to flow through the column to ensure the column is operating properly and to completely saturate the materials.
6. Use a pump to fill the reservoir with approximately 10 L of synthetic water.
7. Allow the synthetic water to flow through the column while maintaining a constant head of water on top of the material in the column.
8. Collect the effluent in the graduated cylinder as it exits the column. After 1 L has accumulated in the cylinder, pour the effluent into beakers.
9. Use the effluent in the beakers to fill one centrifuge tube to send for U and As analysis. Use the remaining effluent in the beakers to test for pH, turbidity, TDS, and DO.
10. Repeat steps 7 and 8 after 3 L, 5 L, and 7 L has flowed through the column.

4.5.1 Synthetic Water and DI Water Blanks

As described in section 4.4, Experimental Matrix, synthetic water samples are collected in five separate centrifuge tubes and DI water samples were collected in another five centrifuge tubes for U and As analysis.

4.5.2 Sand Control

To conduct the column test for the sand control, approximately 20 inches of sand are placed in the column. This equates to a volume of 788.3 mL of sand. Samples are placed in centrifuge tubes and analysis is conducted after the collection of 1 L, 3 L, 5 L, and 7 L of effluent from the column.

4.5.3 Ion Exchange Resin

To conduct the column test for the ion exchange resin, approximately 3 inches of sand are placed in the column, followed by 14 inches of resin, and then an additional 3 inches of sand. This equates to a volume of 55.18 mL of resin and 236.5 mL of sand. Samples are taken after the collection of 1 L, 3 L, 5 L, and 7 L of effluent from the column. The sand is primarily utilized with the resin to keep the resin in place. Without the sand, the resin begins to float in the column when water flowed through.

4.5.4 Orange Peels

To conduct the column test for the orange peels, a volume ratio of sand to orange peels is utilized. This ratio is determined experimentally in the lab based upon observations of clogging of the column and time for percolation of the water through the column. The ratio selected for column testing is 85% sand to 15% orange peels. This results in 670.1 mL of sand and 118.3 mL of orange peels. The quantity of sand is divided evenly and placed below and above the orange peels in the column. Samples are taken after the collection of 1 L, 3 L, 5 L, and 7 L of effluent from the column. Figure 4.10 depicts the packing of the orange peels in the column.

Figure 4.10: Column Test for Orange Peels

4.5.5 ZVI Turnings

To conduct the column test for the ZVI turnings, a volume ratio of 60% sand to 40% ZVI turnings is utilized. This ratio is determined during the literature review (Noubactep, Care, Togue-Kamga, Schoner, & Woafa, 2010), (Noubactep, Temgoua, & Rahman, 2012). The column is filled with approximately 473.0 mL of sand and 315.3 mL of ZVI turnings. The quantity of sand is divided evenly and placed below and above the ZVI turnings in the column. Samples are taken after the collection of 1 L, 3 L, 5 L, and 7 L of effluent from the column. Figure 4.11 depicts the packing of ZVI turnings in the column.

Figure 4.11: Column Test for ZVI Turnings

4.5.6 ZVI Filings

The column test for the ZVI filings uses the same volumetric ratio for sand to ZVI as the ZVI turnings. Therefore, the ZVI and sand volumes are the same as the turnings, and samples are collected in the same manner. Figure 4.12 depicts the packing of ZVI turnings in the column.

Figure 4.12: Column Test for ZVI Filings

4.5.7 Rice Husks

To conduct the column test for the rice husks, the quantity of rice husks required is calculated based upon experimental research (Amin, et al., 2006). These calculations are included in Appendix I. The column is packed with 65 g of rice husks, which is approximately 202.5 mL by volume. The remainder of the column was filled with 585.8 mL of sand. The quantity of sand is divided evenly and placed below and above the rice husks in the column. Samples are taken after the collection of 1 L, 3 L, 5 L, and 7 L of effluent from the column. Figure 4.13 depicts the packing of rice husks in the column.

Figure 4.13: Column Test for Rice Husks

4.5.8 Summary of Material Quantities

Table 4.4 provides a summary of the volumes of sand and material needed for each test.

Table 4.4: Summary of Sand and Material Quantities by Test

Test	Sand Volume (mL)	Material Volume (mL)
Sand Control	788.3	N/A
Ion Exchange Resin	236.5	551.8
Orange Peels	670.1	118.3
ZVI Turnings	473.0	315.3
ZVI Filings	473.0	315.3
Rice Husks	585.8	202.5

4.6 Results and Discussion of Alternative Methods Testing

Summary tables of the results are presented in sections 4.6.1 – 4.6.7 for the synthetic water and DI blanks and each of the column tests. The full data set of the results can be seen in Appendix J. The results for each column test present a comparison of water quality parameters of the effluent from each of the materials vs. the USEPA MCLs and synthetic water. The U and As concentrations are the most important water quality parameters. The ability of the material to reduce the U and As concentrations from the influent synthetic water is expressed as removal efficiency (%), which is calculated as:

$$Removal\ Efficiency\ (\%) = \left(1 - \frac{C}{C_0}\right) * 100\%$$

Where:
C = concentration of U or As in µg/L in the effluent
C_0 = concentration of U or As in µg/L in the synthetic water

The other water quality parameters tested are pH, turbidity, TDS and DO. While other water quality tests would be beneficial, such as iron concentration in the effluent, pH, turbidity, TDS, and DO were simple and quick tests to complete in the NAU Water Quality Laboratory. It's important to test for pH, as the ZVI and orange peels have optimal pH ranges for operation. ZVI is best able to remove arsenic at a pH between 5 and 7, while orange peels work optimally at a pH of 4, with decreasing removal efficiency for U as pH increases. Turbidity is also important since the USEPA has a primary standard for turbidity of 5 NTU. When filtering water through materials, there is a potential for turbidity to increase. This turbidity must be monitored for considerations of a final design. TDS is also a quick and simple test, and provides some insight into the changing composition of the effluent as the water filters through the column. DO is monitored because the ZVI operates at an optimal level of 4.3 to 5.5 mg DO/L.

4.6.1 DI Water Blanks and Synthetic Water

The results for the DI water blanks and the synthetic water from the column tests are presented in Tables 4.5 and 4.6, respectively.

Table 4.5: Results of DI Blanks, Column Test

Deionized Water Blanks			
Average Uranium Concentration (µg/L)	Uranium MCL (µg/L)	Average Arsenic Concentration (µg/L)	Arsenic MCL (µg/L)
0.02	30	0.00	10

As seen in Table 4.5, the average U concentration is 0.02 µg/L in the DI blanks, indicating the calibration is off slightly. This deviation is accounted for in all subsequent U concentrations that are presented. The average As concentration is 0.00 µg/L in the DI blanks.

Table 4.6: Synthetic Water Results, Column Test

Synthetic Water			
Average Uranium Concentration (µg/L)	Uranium MCL (µg/L)	Average Arsenic Concentration (µg/L)	Arsenic MCL (µg/L)
84.71	30	68.65	10

As seen in Table 4.6, the average U concentration in the synthetic water is 84.71 µg/L. This is less than the desired U concentration of 100 µg/L. There is a possibility that human error occurred during the creation of the synthetic water. The average As concentration in the synthetic water is 68.65 µg/L, which is close to the desired 70 µg/L. The slight deviation from 70 µg/L may be due to the large and imprecise quantity of well water that was used to create the synthetic water. The volume of well water was measured using a pump and an estimated flow rate, so the volume added was approximated, causing the As concentration to deviate from the desired 70 µg/L.

4.6.2 Sand Control

Sand is tested by itself during the column tests to determine if it is capable of removing any U or As from the synthetic water. Because all the materials tested are tested in combination with sand, it is important to determine if the material's apparent removal efficiency is affected by the sand. Table 4.7 presents the results of the sand control.

Table 4.7: Sand Control Results, Column Test

Sand						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**1**	**3**	**5**	**7**
Uranium Concentration (μg/L)	30 (Primary MCL Standard)	84.71	77.65	77.64	84.13	81.43
Uranium Removal Efficiency	N/A	N/A	8.33%	8.35%	0.68%	3.87%
Arsenic Concentration (μg/L)	10 (Primary MCL Standard)	68.65	38.28	47.12	53.12	55.48
Arsenic Removal Efficiency	N/A	N/A	44.24%	31.36%	22.62%	19.18%
pH	6.5-8.5 (Secondary Standard)	7.56	7.73	7.63	7.34	7.72
Turbidity (NTU)	5 (Primary Standard)	8.0	17.5	22.8	14.8	2.9
TDS (mg/L)	500 (Secondary Standard)	88	101	103	108	111
DO (mg/L)	N/A	7.46	8.25	8.22	8.50	8.82

After examining the results in Table 4.7, the following trends and analysis are presented.

Uranium Removal Efficiency: The sand proves ineffective at U removal, with removal efficiencies ranging from 0.68% to 8.35%. It is concluded that sand filtration is not effective for U removal and does not affect the removal efficiency of other materials when used in a material and sand matrix.

Arsenic Removal Efficiency: The sand is also ineffective for the removal of As, with removal efficiencies ranging from 19.18% to 44.24%. It is concluded that sand filtration is not effective for As removal and has minimal effect on the removal efficiency of other materials when used in a material and sand matrix. Additionally, the removal efficiency decreases as the volume of filtered water increases.

pH: All of the pH values of the effluent from the sand column are within the 6.5-8.5 range suggested by the secondary standard from the USEPA, showing it is safe to use in combination with other filter materials.

Turbidity: The turbidity decreases from 17.5 NTU to 2.9 NTU as the volume of filtered water increases. The turbidity of the last sample is the only value less than the USEPA primary standard for turbidity. From this data, it appears that it may be possible for the turbidity to further decrease as the volume of filtered water increases.

TDS: All of the TDS values of the effluent from the sand column are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in combination with other filter materials in terms of TDS.

DO: The DO values range from 8.22 to 8.82 mg/L. Because this range is so close to DO saturation of water, 9.07 mg/L at 20°C, it is potentially inaccurate, suggesting that the DO meter used may be defective (U.S. Environmental Protection Agency, 2012).

4.6.3 Ion Exchange Resin

The results of the ion exchange resin column test are presented in Table 4.8. It is expected that the ion exchange resin will be able to remove both U and As.

Table 4.8: Ion Exchange Resin Results, Column Test

Ion Exchange Resin						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**1**	**3**	**5**	**7**
Uranium Concentration (µg/L)	30 (Primary Standard)	84.71	0.13	0.09	0.09	0.09
Uranium Removal Efficiency	N/A	N/A	99.85%	99.89%	99.89%	99.89%
Arsenic Concentration (µg/L)	10 (Primary Standard)	68.65	2.27	1.90	1.84	1.86
Arsenic Removal Efficiency	N/A	N/A	96.69%	97.23%	97.32%	97.29%
pH	6.5-8.5 (Secondary Standard)	7.56	7.80	7.76	6.60	6.18
Turbidity (NTU)	5 (Primary Standard)	8.0	4.8	2.9	2.6	2.6
TDS (mg/L)	500 (Secondary Standard)	88	131	145	146	148
DO (mg/L)	N/A	7.46	8.90	8.90	8.61	8.47

After examining the results in Table 4.8, the following trends and analysis are presented.

Uranium Removal Efficiency: The ion exchange resin proves to be the most effective material for U removal. The U concentration is less than the MCL of 30 µg/L at each volume of filtered water, ranging from 0.09 to 0.13 µg/L.

Arsenic Removal Efficiency: The ion exchange resin also proves to be the most effective material for As removal. The As concentration is less than the MCL of 10 µg/L at each volume of filtered water, ranging from 1.84 to 2.27 µg/L.

pH: The pH decreases as the volume of filtered water increases. The pH values are within the 6.5-8.5 range suggested by the secondary standard from the USEPA, until the last sample, where the pH drops below 6.5. This is a potential cause for concern. If additional testing is conducted for larger volumes of water, it is important to monitor the value of the pH.

Turbidity: The turbidity decreases from 4.8 to 2.6 NTU as the volume of filtered water increases. The turbidity values are all less than the 5 NTU suggested by the primary standard from the USEPA. From this data, it appears that it may be possible for the turbidity to further decrease as the volume of filtered water increases.

TDS: All of the TDS values of the effluent from the ion exchange resin are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values range from 8.47 to 8.90 mg/L. Because this range is so close to DO saturation of water, 9.07 mg/L at 20°C, it is potentially inaccurate, suggesting that the DO meter used may be defective (U.S. Environmental Protection Agency, 2012).

Summary: It is concluded that an ion exchange resin is an effective filter media for the removal of both U and As. It is also capable of reducing the turbidity of the effluent to less than the primary standard USEPA. However, an effluent pH of less than the range of 6.5-8.5 may be problematic and should be tested further.

4.6.4 Orange Peels

The results of the column test for the orange peels are presented in Table 4.9. It is expected that the orange peels would be able to remove U only.

Table 4.9: Orange Peels Results, Column Test

Orange Peels						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**1**	**3**	**5**	**7**
Uranium Concentration (µg/L)	30 (Primary Standard)	84.71	0.82	0.52	0.57	0.52
Uranium Removal Efficiency	N/A	N/A	99.03%	99.39%	99.33%	99.39%
Arsenic Concentration (µg/L)	10 (Primary Standard)	68.65	26.07	48.31	46.35	49.82
Arsenic Removal Efficiency	N/A	N/A	62.02%	29.63%	32.48%	27.43%
pH	6.5-8.5 (Secondary Standard)	7.56	6.86	6.96	7.00	7.05
Turbidity (NTU)	5 (Primary Standard)	8.0	56.9	9.4	3.4	2.5
TDS (mg/L)	500 (Secondary Standard)	88	149	131	129	108
DO (mg/L)	N/A	7.46	8.49	8.91	7.45	7.45

After examining the results in Table 4.9, the following trends and analysis are presented.

Uranium Removal Efficiency: The orange peels prove to be extremely effective for U removal. The U concentration is less than the MCL of 30 µg/L at each volume of filtered water, ranging from 0.52 to 0.82 µg/L. It is unknown if the removal efficiency will increase over time. Additional testing and data would be required, as will be discussed in section 5.8, Project Improvements and Expansion.

Arsenic Removal Efficiency: The orange peels prove ineffective in removing As. The concentration of As in each of the samples is above the MCL of 10 µg/L.

pH: The pH increases slightly as the volume of filtered water increases. However, all the pH values are within the 6.5-8.5 range suggested by the secondary standard from the USEPA.

Turbidity: The turbidity decreases from 56.9 to 2.5 NTU as the volume of filtered water increases. The initial jump in turbidity is likely a result of the orange peels creating a type of orange juice. As more water filters through the peels, less juice is created and the turbidity decreases. The turbidity values of the final two samples are less than the 5 NTU suggested by the primary standard from the USEPA. From this data, it appears that it may be possible for the turbidity to further decrease as the volume of filtered water increases.

TDS: All of the TDS values of the effluent from the orange peels are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values range from 7.45 to 8.91 mg/L. Because this range is so close to DO saturation of water, 9.07 mg/L at 20°C, it is potentially inaccurate, suggesting that the DO meter used may be defective (U.S. Environmental Protection Agency, 2012).

Summary: It is concluded that orange peels may be an effective filter media for the removal of U but not As. They are also capable of reducing the turbidity of the effluent to less than the primary USEPA standard after 5 L of water has filtered through the column.

4.6.5 ZVI Turnings

The results of the column test for the ZVI turnings are presented in Table 4.10. It is expected that the ZVI turnings will be able to remove As only.

Table 4.10: ZVI Turnings Results, Column Test

Zero Valent Iron Turnings						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**1**	**3**	**5**	**7**
Uranium Concentration (µg/L)	30 (Primary Standard)	84.71	27.91	49.64	70.92	41.69
Uranium Removal Efficiency	N/A	N/A	67.05%	41.40%	16.28%	50.79%
Arsenic Concentration (µg/L)	10 (Primary Standard)	68.65	6.26	4.76	5.60	6.84
Arsenic Removal Efficiency	N/A	N/A	90.88%	93.07%	91.84%	90.04%
pH	6.5-8.5 (Secondary Standard)	7.56	7.41	7.58	7.69	7.29
Turbidity (NTU)	5 (Primary Standard)	8.0	36.9	0.7	0.9	3.2
TDS (mg/L)	500 (Secondary Standard)	88	118	126	126	126
DO (mg/L)	N/A	7.46	6.90	6.56	6.60	6.94

After examining the results in Table 4.10, the following trends and analysis are presented.

Uranium Removal Efficiency: The ZVI turnings prove to be ineffective for U removal. Although the U concentration is less than the MCL of 30 µg/L at the first sample, the concentration of U increases afterwards to values above the MCL.

Arsenic Removal Efficiency: The ZVI turnings prove to be an effective material for As removal. The As concentration is less than the MCL of 10 µg/L at each volume of filtered water, ranging from 4.76 to 6.84 µg/L.

pH: The pH fluctuates between 7.29 and 7.69 as the volume of filtered water increases. All the pH values are within the 6.5-8.5 range suggested by the secondary standard from the USEPA.

Turbidity: The turbidity decreases from 36.9 to 0.7 NTU, but then increases to 3.2 NTU at the final sample. The initial jump in turbidity is likely a result of any residue on the turnings that were obtained from the NAU Machine Shop. As more water filters through the turnings, any residue or dirt on the turnings is removed, and less turbidity results. The turbidity values of the final three samples are less than the 5 NTU suggested by the primary standard from the USEPA. More data would be needed to conclude a trend in turbidity.

TDS: All of the TDS values of the effluent from the ZVI turnings are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values range from 6.56 to 6.94 mg/L. This is higher than the optimal operable range for ZVI of 4.3 to 5.5 mg/L. If the DO level is reduced to the optimal range, it is possible that additional As removal could result.

Summary: It is concluded that ZVI turnings may be an effective filter media for the removal of As but not U. They are also capable of reducing the turbidity of the effluent to less than the primary USEPA standard after 3 L of water has filtered through the column.

4.6.6 ZVI Filings

The results of the column test for the ZVI filings are presented in Table 4.11. It is expected that the ZVI filings are able to remove As only.

Table 4.11: ZVI Filings Results, Column Test

Zero Valent Iron Filings						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**1**	**3**	**5**	**7**
Uranium Concentration (µg/L)	30 (Primary Standard)	84.71	0.11	0.15	0.14	0.12
Uranium Removal Efficiency	N/A	N/A	99.87%	99.82%	99.83%	99.86%
Arsenic Concentration (µg/L)	10 (Primary Standard)	68.65	7.92	2.29	1.29	0.79
Arsenic Removal Efficiency	N/A	N/A	88.46%	96.66%	98.12%	98.85%
pH	6.5-8.5 (Secondary Standard)	7.56	8.64	9.04	8.42	8.43
Turbidity (NTU)	5 (Primary Standard)	8.0	9.1	12.4	21.4	15.1
TDS (mg/L)	500 (Secondary Standard)	88	56	63	66	81
DO (mg/L)	N/A	7.46	8.69	7.35	7.63	7.82

After examining the results in Table 4.11, the following trends and analysis are presented.

Uranium Removal Efficiency: Although the ZVI filings are expected to remove As only, the filings prove to be effective for U removal. The U concentration is less than the MCL of 30 µg/L for all samples, ranging from 0.11 to 0.15 µg/L.

Arsenic Removal Efficiency: The ZVI filings also prove to be an effective material for As removal. The As concentration is less than the MCL of 10 µg/L at each volume of filtered water, ranging from 0.79 to 7.92 µg/L. The removal efficiency increases as the volume of filtered water increases. From this data, it appears that it may be possible for the removal efficiency to further increase as the volume of filtered water increases.

pH: The pH fluctuates between 8.42 and 9.04 as the volume of filtered water increases. The pH values of the last two samples are within the 6.5-8.5 range suggested by the secondary standard from the USEPA. Additional testing is needed to determine if pH will consistently remain within the USEPA range.

Turbidity: The turbidity fluctuates between 9.1 and 21.4 NTU. All of the turbidity values are greater than the 5 NTU suggested by the primary standard from the USEPA. This may be a cause for concern.

TDS: All of the TDS values of the effluent from the ZVI filings are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values range from 7.35 to 8.69 mg/L. This is higher than the optimal operable range for ZVI of 4.3 to 5.5 mg/L. If the DO level is reduced to the optimal range, it is possible that additional As removal could result.

Summary: It is concluded that ZVI filings may be an effective filter media for the removal of both U and As. The pH range is above the USEPA standard initially, but eventually decreases to the USEPA range. Further testing should be done to confirm the pH of the effluent is safe. Additionally, the turbidity is higher than the USEPA primary standard of 5 NTU. Therefore, an additional filter material would be required to reduce the turbidity.

4.6.7 Rice Husks

The results of the column test for the rice husks are presented in Table 4.12. It is expected that the rice husks are able to remove As only.

Table 4.12: Rice Husks Results, Column Test

Rice Husks						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**1**	**3**	**5**	**7**
Uranium Concentration (µg/L)	30 (Primary Standard)	84.71	0.77	1.38	7.89	67.41
Uranium Removal Efficiency	N/A	N/A	99.09%	98.37%	90.69%	20.42%
Arsenic Concentration (µg/L)	10 (Primary Standard)	68.65	29.63	51.48	56.36	61.02
Arsenic Removal Efficiency	N/A	N/A	56.84%	25.01%	17.90%	11.11%
pH	6.5-8.5 (Secondary Standard)	7.56	6.79	6.85	6.70	7.05
Turbidity (NTU)	5 (Primary Standard)	8.0	14.5	5.8	8.6	5.5
TDS (mg/L)	500 (Secondary Standard)	88	84	114	115	99
DO (mg/L)	N/A	7.46	7.28	7.68	7.96	8.11

After examining the results in Table 4.12, the following trends and analysis are presented.

Uranium Removal Efficiency: The rice husks prove to be an ineffective material for U removal. The U concentration is less than the MCL of 30 µg/L until the final sample. The U concentration of the first sample is 0.77 µg/L, but then increases to 67.41 µg/L after 7 L of filtered water.

Arsenic Removal Efficiency: The rice husks also prove ineffective in removing As. All of the samples are above the 10 µg/L MCL, ranging from 26.63 to 61.02 µg/L. These As concentrations increase as the volume of filtered water increases.

pH: All of the pH values of the effluent from the rice husks were within the 6.5-8.5 range suggested by the secondary standard from the USEPA.

Turbidity: The turbidity fluctuates between 5.5 and 14.5 NTU. All of the turbidity values are greater than the 5 NTU suggested by the primary standard from the USEPA.

TDS: All of the TDS values of the effluent from the rice husks are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in combination with other filter materials in terms of TDS.

DO: The DO values range from 7.28 to 8.11 mg/L. This data is not extremely significant for this test as DO is not known to have an effect on the operation of rice husks.

Summary: It is concluded that rice husks are not an effective filter media for the removal of As or U. They will not be considered further.

4.7 Selection of Materials for Modular Configurations

The materials to be tested in the modular configuration are determined by the results of the summaries presented in sections 4.6.3-4.6.7. Table 4.13 presents a summary and comparison of the U and As concentrations for each of the materials.

Table 4.13: Comparison of Materials for U and As Removal

Comparison of all Materials							
				Filtered Water Volume (L)			
Contaminant	**USEPA MCL Standard**	**Synthetic Water**	**Filter Media**	**1**	**3**	**5**	**7**
Uranium Concentration (µg/L)	30 (Primary Standard)	84.71	**Sand**	77.65	77.64	84.13	81.43
			Ion Exchange Resin	0.13	0.09	0.09	0.09
			Orange Peels	0.82	0.52	0.57	0.52
			ZVI Turnings	27.91	49.64	70.92	41.69
			ZVI Filings	0.11	0.15	0.14	0.12
			Rice Husks	0.77	1.38	7.89	67.41
Arsenic Concentration (µg/L)	10 (Primary Standard)	68.65	**Sand**	38.28	47.12	53.12	55.48
			Ion Exchange Resin	2.27	1.90	1.84	1.86
			Orange Peels	26.07	48.31	46.35	49.82
			ZVI Turnings	6.26	4.76	5.60	6.84
			ZVI Filings	7.92	2.29	1.29	0.79
			Rice Husks	29.63	51.48	56.36	61.02

As shown in Table 4.13, the ion exchange resin proves effective for both U and As removal. However, it is not included in the configuration testing for three reasons. First, because ion exchange resins are engineered to work, there is little question of their success. Second, if an ion exchange resin is placed in series with other materials, the results for the efficiency of the system may potentially be based primarily upon the removal efficiency of the ion exchange resin, as it will be able to remove the U and As that the other materials in the series may not. Third, this project seeks to use low-cost and innovative solutions. Ion exchange resins are known to work, but are not necessarily innovative or low-cost. Therefore, the modular configurations focus on the use of orange peels, ZVI filings, and ZVI turnings. Orange peels are selected for their ability to remove U, ZVI filings are selected for their ability to remove both U and As, and ZVI turnings are selected for their ability to remove As. Rice husks are eliminated because they are not able to remove U or As. The criteria for material selections is based only upon the effectiveness of the material to remove either U or As. Decision matrices are not used for this reason.

4.8 Testing of Modular Configurations

The purpose of the modular configuration testing is to determine the removal efficiency of a series of materials. The modular configuration device was designed with ease of maintenance in mind. Each material is placed in a separate module (or compartment), with the ability to detach from the system in order to perform maintenance on or replace one material at a time. Four different modular configurations are selected for testing. These configurations are discussed in sections 4.8.4 – 4.8.7.

The experimental filtration device, depicted in Figure 4.14, consists of two modules containing the filtration and support media (i.e. sand, orange peels, iron filings, gravel). The module housing consists of a 4.75 inch outer diameter clear acrylic tubing with an inner diameter of 4.20 inches. 120 mesh screening is fixed to the bottom of each module with epoxy. This prevents the washout of any materials and provides additional support for the module materials. The modules are held together by a 4 inch x 5.25 inch in-line rubber coupling secured using 0.5 inch wide and 1/16 inch thick steel adjustable pipe clamps. The rubber coupling has a thickness of 0.5 inch and allows for a tight seal between the acrylic tubing. The use of couplings in the design allows for easy access to the materials. This allows users to perform maintenance, material replacement and breakthrough monitoring. 5.25 inch x 2.5 inch rubber caps with a thickness of 0.5 inch are used at both the top and bottom of the device. Additionally, 1 inch nylon nozzles are attached to these caps to allow for the inflow and outflow of contaminated and treated water. To guarantee a tight seal at the nozzles, two 0.475 inch rubber washers are placed on each side of the rubber caps. The nozzles are held in place by a nylon retaining nut. The modular system is connected to an elevated reservoir via plastic tubing. The flow rate is controlled by a ball valve.

Figure 4.14: From Left to Right- One Empty Module, Two Modules Connected by Rubber Couplings, Configuration Connected to Reservoir and Ready for Testing

The experimental procedure for the modular configurations is as follows:

1. Fill each module with approximately 4 inches of gravel so the sand and material starts at the visible portion of the acrylic column. The gravel prevents the sand and materials from clogging or filtering through the screen at the bottom of the module.
2. Place the appropriate sand and material quantities on top of the gravel.
3. Connect the modules in the order desired with the rubber couplings.
4. Connect the modular system to the tubing and reservoir system.
5. Place a 1 L or larger graduated cylinder under the apparatus to collect effluent.
6. Allow approximately 1 L of DI water to flow through the system to ensure it is operating properly and to completely saturate the materials.
7. Use a pump to fill the reservoir with approximately 12 L of synthetic water.
8. Allow the synthetic water to flow through the modular system while maintaining a constant head of water on top of the material in the first module.
9. Collect the effluent in the graduated cylinder as it exits the system. After 2.5 L has accumulated in the cylinder, pour the effluent into a clean container.
10. Use the effluent in the container to fill one centrifuge tube to send for U and As analysis. Use the remaining effluent in the container to test for pH, turbidity, TDS, and DO.

11. Repeat steps 9 and 10 after 5 L, 7.5 L, and 10 L has flowed through the system.

4.8.1 Scale-up Procedure

Because the modular configurations are constructed from acrylic tubes with an inner diameter of 4.2 inches rather than the 1.75 inch inner diameter of the column test, calculations are performed to determine how to scale-up the volume of each material. This is done in three steps.

The first step is to determine the average hydraulic conductivity of the sand and material matrices from the alternative methods testing. This is completed using Darcy's Law, shown below.

$$\frac{Q}{A} = K_{avg}\left(\frac{h + b_T}{b_T}\right)$$

Where:
Q = Flow rate (cm^3/s)
A = Cross sectional area of column (cm^2)
K_{avg} = Average hydraulic conductivity (cm/s)
h = Head on top of column (cm)
b_T = Total column thickness (cm)

The second step is to find the theoretical hydraulic conductivity for each material. This is based on the following equations:

$$K_{avg} = \frac{b_T}{\frac{b_1}{K_1} + \frac{b_2}{K_2} + \frac{b_3}{K_1}}$$

$$\Downarrow$$

$$K_2 = \frac{b_2}{\frac{b_T}{K_{avg}} - \frac{b_1}{K_1} - \frac{b_3}{K_1}}$$

Where:
b_1 = Thickness of top layer, sand (cm)
b_2 = Thickness of middle layer, material (cm)
b_3 = Thickness of bottom layer, sand (cm)
K_1 = Hydraulic conductivity of top layer, sand (cm/s)
K_2 = Hydraulic conductivity of middle layer, material (cm/s)
K_1 ($=K_3$) = Hydraulic conductivity of bottom layer, sand (cm/s)

The third step is to determine the thickness of each layer for each module. This is based on Darcy's Law from step one and an Excel model. The goal is to prevent a negative head on top of the material in the module. The values for the thicknesses are selected while attempting to keep the total thickness of all materials in a module less than 22.5 cm. All scale-up calculations can be viewed in Appendix K.

4.8.2 Scale-up Values

Table 4.14 shows the material, thickness and volume for each layer of a module. The module containing orange peels and sand is shown first. The ZVI turnings and ZVI filings module are constructed in the same manner.

Table 4.14: Scale-up Values for Modules

Scale-up Values for Modules										
Composite	**Top Layer Material**	**Top Layer Thickness (in)**	**Top Layer Volume (mL)**	**Middle Layer Material**	**Middle Layer Thickness (in)**	**Middle Layer Volume (mL)**	**Bottom Layer Material**	**Bottom Layer Thickness (in)**	**Bottom Layer Volume (mL)**	**Total Module Thickness (in)**
Orange Peels and Sand Module	Sand	1.7	379.9	Orange	0.6	134.1	Sand	1.7	379.9	3.9
ZVI and Sand Module	Sand	0.8	187.7	ZVI	1.1	250.3	Sand	0.8	187.7	2.8

4.8.3 Synthetic Water and DI Water Blanks

As described in section 4.4, Experimental Matrix, synthetic water samples are collected in five separate centrifuge tubes and DI water samples are collected in another five centrifuge tubes for U and As analysis.

4.8.4 Configuration #1: ZVI Filings Followed by Orange Peels

The first configuration tested consists of the ZVI filings module on top with the orange peels module on the bottom. Samples are taken after the collection of 2.5 L, 5 L, 7.5 L, and 10 L of effluent from the modular configuration.

4.8.5 Configuration #2: Orange Peels Followed by ZVI Filings

The second configuration tested consists of the orange peels module on the top and the ZVI filings module on the bottom. The same ZVI and orange peels are used in this test as the first. Therefore, while the samples are taken after the collection of 2.5 L, 5 L, 7.5 L, and 10 L of effluent from the modular configuration, these volume points equate to 12.5 L, 15 L, 17.5 L, and 20 L.

4.8.6 Configuration #3: Orange Peels Followed by ZVI Turnings

The third configuration tested consists of the orange peels module on top with the ZVI turnings module on the bottom. Both the ZVI turnings and orange peels are fresh materials. Samples are taken after the collection of 2.5 L, 5 L, 7.5 L, and 10 L of effluent from the modular configuration.

4.8.7 Configuration #4: ZVI Turnings Followed by Orange Peels

The fourth configuration tested consists of the ZVI turnings module on the top and the orange peels module on the bottom. The same ZVI and orange peels are used in this test as the third. Therefore, while the samples were taken after the collection of 2.5 L, 5 L, 7.5 L, and 10 L of effluent from the modular configuration, these volume points equate to 12.5 L, 15 L, 17.5 L, and 20L.

4.9 Results and Discussion of Modular Configurations Testing

Summary tables of the results are presented in sections 4.9.1 – 4.9.5 for the synthetic water and DI blanks and each of the modular configurations. The full data set of the results can be seen in Appendix L. The results for each modular configuration present a comparison of water quality parameters of the effluent from each of the modular configuration vs. the USEPA MCLs and synthetic water. As in the column tests, the U and As concentrations are the most important water quality parameters and the ability of the modular configuration to reduce the U and As concentrations from the influent synthetic water is expressed as removal efficiency. The other water quality parameters tested are pH, turbidity, TDS and DO for the same reasons expressed in section 4.6, Results and Discussion of Alternative Methods Testing.

It is noted that pressurization of the air void between the bottom of the top module and the airspace at the top module may form as water drains from the first module into the second module. The water entering the second module needs to displace the air. Unfortunately, this air can only displace through either the saturated media in the first module or the saturated media in the second. It is believed that the air was not able to escape and affected the flow rate through, and flow characteristics within, the filter media. This is supported by lower than anticipated flow rates and less than satisfactory performance of the filter media in removing the contaminants. After analyzing the results, which are presented in sections 4.9.2 – 4.9.5, this hypothesis was tested by drilling a hole in the air void above the filter media in the second module. A hose was fixed in this hole and extended to above the top of the module. Higher flow rates and better distribution of flow were observed. This indicates that the flow characteristics in the filter media may have been restricted during the modular tests, with only a small cross-sectional area being utilized by the flow. This may have led to premature saturation of the filter media, poor flow rates, and uncharacteristic uranium and arsenic removal. Future expansions to this project should take this into consideration.

4.9.1 DI Water Blanks and Synthetic Water

The results for the DI water blanks and the synthetic water from the configuration tests are presented in Tables 4.15 and 4.16, respectively.

Table 4.15 Results of DI Blanks, Configuration Testing

Deionized Water Blanks			
Average Uranium Concentration (µg/L)	Uranium MCL (µg/L)	Average Arsenic Concentration (µg/L)	Arsenic MCL (µg/L)
0.01	30	0.05	10

As seen in Table 4.15, the average U concentration is 0.01 µg/L in the DI blanks, indicating the calibration is off slightly. This deviation is accounted for in all subsequent U concentrations that are presented. The average As concentration is 0.05 µg/L in the DI blanks. This deviation is also accounted for in all subsequent As concentrations that are presented.

Table 4.16 Synthetic Water Results, Configuration Testing

Synthetic Water			
Average Uranium Concentration (µg/L)	Uranium MCL (µg/L)	Average Arsenic Concentration (µg/L)	Arsenic MCL (µg/L)
91.56	30	69.81	10

As seen in Table 4.16, the average U concentration in the synthetic water is 91.56 µg/L. This is less than the desired U concentration of 100 µg/L, and greater than the 84.71 µg/L measured during the column tests. While human error may have occurred during the column tests, it is possible that the U analysis with the ICP-MS method, as described in section 4.1, Water Quality Analysis Methods, may contain an error. The average As concentration in the synthetic water is 69.81 µg/L, which is close to the desired 70 µg/L.

4.9.2 Configuration #1: ZVI Filings Followed by Orange Peels

The results for Configuration #1 are presented in Table 4.17. It is expected that the orange peels may not remove U because the pH of the water flowing through the ZVI filings increases to 8.5-9, based on the results from the column tests. Orange peels operate best at a pH of 4, and their efficiency decreases as pH increases.

Table 4.17 Configuration #1 Results, Configuration Testing

Configuration #1: ZVI Filings, OP						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**2.5**	**5**	**7.5**	**10**
Uranium Concentration (µg/L)	30 (Primary Standard)	91.56	0.32	6.12	27.32	41.23
Uranium Removal Efficiency	N/A	N/A	99.65%	93.32%	70.16%	54.97%
Arsenic Concentration (µg/L)	10 (Primary Standard)	69.81	8.13	8.69	19.81	21.51
Arsenic Removal Efficiency	N/A	N/A	88.35%	87.55%	71.62%	69.19%
pH	6.5-8.5 (Secondary Standard)	7.89	7.32	7.31	7.43	7.63
Turbidity (NTU)	5 (Primary Standard)	4.8	38.1	4.9	7.8	2.3
TDS (mg/L)	500 (Secondary Standard)	88	182	112	115	115
DO (mg/L)	N/A	7.4	6.79	6.20	5.84	5.43

After examining the results in Table 4.17, the following trends and analysis are presented.

Uranium Removal Efficiency: Configuration #1 is effective for U removal for the first 7.5 L, however, the last sample at 10 L increases to 41.23 µg/L. Overall, the configuration is not effective for U removal, especially since the U concentration increases as the volume of filtered water increases.

Arsenic Removal Efficiency: A similar trend occurs for the As removal as the U removal. The As concentration increases as the volume of filtered water increases, and the configuration is not effective for As removal.

pH: The pH increases slightly as the volume of filtered water increases. However, all the pH values are within the 6.5-8.5 range suggested by the secondary standard from the USEPA.

Turbidity: The turbidity shows an overall decreasing trend from 38.1 NTU to 2.3 NTU. While the second and last sample are less than the 5 NTU suggested by the primary standard from the USEPA, it is not possible to conclude if the turbidity would remain under the limit as greater volumes of water are filtered. Therefore, additional testing is necessary.

TDS: All of the TDS values of the effluent from Configuration #1 are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values decrease as the volume of filtered water increases from 6.79 to 5.43 mg/L. This is close to the optimal operable range for ZVI of 4.3 to 5.5 mg/L. Therefore, it's not likely that the DO negatively affects the operation of the configuration.

Summary: It is concluded that Configuration #1 it not an effective configuration for the removal of U and As because it is not able to reduce the contaminants to levels below their MCLs after 7.5 L of water is filtered through the configuration.

4.9.3 Configuration #2: Orange Peels Followed by ZVI Filings

The results for Configuration #2 are presented in Table 4.18. It is expected that the orange peels are be better able to remove U than in Configuration #1 because they receive the water first, and their full surface area is utilized. ZVI filings operate best at a pH between 5 and 7. Since the orange peels are known to reduce the effluent of the pH to about 6.9-7, the ZVI will receive water just at the extreme of its optimal range but lower than that of the synthetic water's pH of 7.89. Therefore, the ZVI filings are expected to be better able to remove As than in Configuration #1.

Table 4.18 Configuration #2 Results, Configuration Testing

Configuration #2: OP, ZVI Filings						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**2.5**	**5**	**7.5**	**10**
Uranium Concentration (µg/L)	30 (Primary Standard)	91.56	7.83	4.16	3.14	2.80
Uranium Removal Efficiency	N/A	N/A	91.45%	95.46%	96.57%	96.94%
Arsenic Concentration (µg/L)	10 (Primary Standard)	69.81	6.53	2.93	2.14	2.27
Arsenic Removal Efficiency	N/A	N/A	90.64%	95.80%	96.93%	96.75%
pH	6.5-8.5 (Secondary Standard)	7.89	8.43	8.37	8.32	8.33
Turbidity (NTU)	5 (Primary Standard)	4.8	61.8	8.3	7.6	23.3
TDS (mg/L)	500 (Secondary Standard)	88	82	97	109	108
DO (mg/L)	N/A	7.4	5.82	5.89	5.55	5.63

After examining the results in Table 4.18, the following trends and analysis are presented.

Uranium Removal Efficiency: Configuration #2 proves to be very effective for U removal. The U concentration is less than the MCL of 30 µg/L at each volume of filtered water, ranging from 7.83 to 2.80 µg/L. The removal efficiency increases as the volume of filtered water increases. From this data, it appears that it may be possible for the removal efficiency to further increase as the volume of filtered water increases.

Arsenic Removal Efficiency: Configuration #2 also proves to be very effective for As removal. The As concentration is less than the MCL of 10 µg/L at each volume of filtered water, ranging from 6.53 to 2.27

µg/L. The removal efficiency increases as the volume of filtered water increases. From this data, it appears that it may be possible for the removal efficiency to further increase as the volume of filtered water increases.

pH: The pH decreases slightly as the volume of filtered water increases. However, all the pH values are within the 6.5-8.5 range suggested by the secondary standard from the USEPA.

Turbidity: The turbidity fluctuates between 7.6 and 61.8 NTU. All of the turbidity values are greater than the 5 NTU suggested by the primary standard from the USEPA. This may be a cause for concern.

TDS: All of the TDS values of the effluent from the ZVI filings are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values fluctuate as the volume of filtered water increases from 5.55 to 5.89 mg/L. This is close to the optimal operable range for ZVI of 4.3 to 5.5 mg/L. Therefore, it’s not likely that the DO is negatively affecting the operation of the configuration.

Summary: It is concluded that Configuration #2 is an effective configuration for the removal of both U and As. The pH of the effluent falls within the USEPA range, but the turbidity does not. Therefore, an additional filter material would be required to reduce turbidity.

4.9.4 Configuration #3: Orange Peels Followed by ZVI Turnings

The results for Configuration #3 are presented in Table 4.19. It is expected that Configuration #3 will have similar results to that of Configuration #2 because the orange peels are on top followed by ZVI.

Table 4.19 Configuration #3 Results, Configuration Testing

Configuration #3: OP, ZVI Turnings						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**2.5**	**5**	**7.5**	**10**
Uranium Concentration (µg/L)	30 (Primary Standard)	91.56	20.17	47.42	50.85	67.13
Uranium Removal Efficiency	N/A	N/A	77.97%	48.21%	44.46%	26.68%
Arsenic Concentration (µg/L)	10 (Primary Standard)	69.81	7.36	10.84	12.08	14.98
Arsenic Removal Efficiency	N/A	N/A	89.46%	84.48%	82.69%	78.54%
pH	6.5-8.5 (Secondary Standard)	7.89	7.78	7.54	7.56	7.56
Turbidity (NTU)	5 (Primary Standard)	4.8	9.0	3.7	3.1	2.9
TDS (mg/L)	500 (Secondary Standard)	88	96	91	97	107
DO (mg/L)	N/A	7.4	5.41	5.26	5.41	5.48

After examining the results in Table 4.19, the following trends and analysis are presented.

Uranium Removal Efficiency: Surprisingly, Configuration #3 does not perform in the same manner as Configuration #2 for U removal. Unlike Configuration #2, Configuration #3 was is not able to remove U to less than the MCL of 30 µg/L at each volume of filtered water. After 2.5 L, the configuration fails.

Arsenic Removal Efficiency: Configuration #3 also doesn't perform in the same manner as Configuration #2 for As removal. Configuration #3 is not able to remove As to less than the MCL of 10 µg/L at each volume of filtered water. After 2.5 L, the configuration fails.

pH: The pH decreases slightly as the volume of filtered water increases. However, all the pH values are within the 6.5-8.5 range suggested by the secondary standard from the USEPA.

Turbidity: The turbidity decreases from 9.0 to 2.9 NTU. The turbidity values of the final three samples are less than the 5 NTU suggested by the primary standard from the USEPA. From this data, it appears that it may be possible for the turbidity to further decrease as the volume of filtered water increases.

TDS: All of the TDS values of the effluent from the ZVI filings are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values fluctuate as the volume of filtered water increases from 5.26 to 5.48 mg/L. This is within the optimal operable range for ZVI of 4.3 to 5.5 mg/L. Therefore, it's not likely that the DO is negatively affecting the operation of the configuration.

Summary: It is concluded that Configuration #3 it not an effective configuration for the removal of U and As because it is not able to reduce the contaminants to levels below their MCLs after 5 L of water has filtered through the configuration.

4.9.5 Configuration #4: ZVI Turnings Followed by Orange Peels

The results for Configuration #4 are presented in Table 4.20. It is expected that Configuration #4 will have similar results to that of Configuration #1 because the ZVI is on top followed by orange peels.

Table 4.20 Configuration #4 Results, Configuration Testing

Configuration #4: ZVI Turnings, OP						
			Filtered Water Volume (L)			
	USEPA Standards	**Synthetic Water**	**2.5**	**5**	**7.5**	**10**
Uranium Concentration (µg/L)	30 (Primary Standard)	91.56	57.11	59.34	72.35	73.63
Uranium Removal Efficiency	N/A	N/A	37.62%	35.19%	20.97%	19.58%
Arsenic Concentration (µg/L)	10 (Primary Standard)	69.81	21.83	17.69	15.58	17.88
Arsenic Removal Efficiency	N/A	N/A	68.73%	74.66%	77.68%	74.38%
pH	6.5-8.5 (Secondary Standard)	7.89	7.38	7.54	7.50	7.78
Turbidity (NTU)	5 (Primary Standard)	4.8	6.6	1.9	1.9	1.8
TDS (mg/L)	500 (Secondary Standard)	88	111	104	106	106
DO (mg/L)	N/A	7.4	6.08	5.86	5.75	5.61

After examining the results in Table 4.20, the following trends and analysis are presented.

Uranium Removal Efficiency: Configuration #4 performs much worse than Configuration #1. Configuration #4 is not able to remove U to less than the MCL of 30 µg/L at any volume of filtered water.

Arsenic Removal Efficiency: Configuration #4 is not able to remove As to less than the MCL of 10 µg/L at any volume of filtered water.

pH: The pH increases as the volume of filtered water increases. However, all the pH values are within the 6.5-8.5 range suggested by the secondary standard from the USEPA.

Turbidity: The turbidity decreases from 6.6 to 1.8 NTU. The turbidity values of the final three samples are less than the 5 NTU suggested by the primary standard from the USEPA. From this data, it appears that it may be possible for the turbidity to further decrease as the volume of filtered water increases.

TDS: All of the TDS values of the effluent from the ZVI filings are lower than the 500 mg/L secondary standard from the USEPA, showing it is safe to use in this respect.

DO: The DO values decrease as the volume of filtered water increases from 6.08 to 5.61 mg/L. This is close to the optimal operable range for ZVI of 4.3 to 5.5 mg/L. Therefore, it's not likely that the DO is negatively affecting the operation of the configuration.

Summary: It is concluded that Configuration #4 it not an effective configuration for the removal of U and As because it is not able to reduce the contaminants to levels below their MCLs at any volume of water.

5.0 Final Recommendations

Based upon the results discussed and analyzed in section 4.9, Results and Discussion of Modular Configurations Testing, several final recommendations are given. The recommendations suggest the materials that could be used for U and As removal, the most likely configuration of these materials, the need for additional adsorptive layer, and a method for disinfection. Considerations for ion exchange resins are also included. Finally, a discussion of the sustainability of this project and the potential for improvements and expansion of the project are presented.

As noted in section 4.0, Testing and Analysis, the point of breakthrough or failure for each material could not be obtained during testing. Without the breakthrough or failure data, it is impossible to determine the longevity of each material, the maintenance required, and how the tested water quality parameters will change over time as the material filters additional volumes of water. As this data guides the device dimensions and material quantities, these values cannot be determined at this time. Recommendations for achieving such data are explained in section 5.8, Project Improvements and Expansion.

5.1 Uranium Removal

The results of column tests and the modular configurations show that orange peels are likely to be an effective material for the removal of uranium from contaminated water. With an initial concentration of 84.71 µg/L of U in the synthetic water, the final concentration of U in the effluent after passing through the orange peels was 0.82 µg/L after 1 L, 0.52 µg/L after 3 L, 0.57 µg/L after 5 L, and 0.52 µg/L after 7 L of filtered water, which is significantly lower than the USEPA MCL of 30 µg/L. Additionally, when coupled with ZVI filings in Configuration #2, the U concentration is significantly reduced. With an initial concentration of 91.56 µg/L of U in the synthetic water, the final concentration of U in the effluent after passing through both modules was 7.83 µg/L after 2.5 L, 4.16 µg/L after 5 L, 3.14 µg/L after 7.5 L, and 2.80 µg/L after 10 L of filtered water. Once again, this is much lower than the MCL of 30 µg/L.

Optimization of the volume of orange peels is necessary prior to finalizing a water filtration device, and is dependent upon the determination of the reaction kinetics of the orange peels and their longevity. This will be discussed further in section 5.8, Project Improvements and Expansion.

5.2 Arsenic Removal

The results of column tests and the modular configurations shows that ZVI filings are most effective material for the removal of arsenic from contaminated water. With an initial concentration of 68.65 µg/L of As in the synthetic water, the final concentration of As in the effluent after passing through the ZVI filings was 7.92 µg/L after 1 L, 2.29 µg/L after 3 L, 1.29 µg/L after 5 L, and 0.79 µg/L after 7 L of filtered water, which is significantly lower than the USEPA MCL of 10 µg/L. Additionally, when coupled with orange peels in Configuration #2, the As concentration is significantly reduced. With an initial concentration of 69.81 µg/L of As in the synthetic water, the final concentration of As in the effluent after passing through both modules was 6.53 µg/L after 2.5 L, 2.93 µg/L after 5 L, 2.14 µg/L after 7.5 L, and 2.27 µg/L after 10 L of filtered water. Once again, this is much lower than the MCL of 10 µg/L.

ZVI filings also appear to be effective for U removal, as shown by the column test. With an initial concentration of 84.71 µg/L of U in the synthetic water, the final concentration of U in the effluent after passing through the ZVI filings was 0.11 µg/L after 1 L, 0.15 µg/L after 3 L, 0.14 µg/L after 5 L, and 0.12 µg/L after 7 L of filtered water, which is significantly lower than the USEPA MCL of 30 µg/L. This removal efficiency is not expected.

As is the case for the orange peels, optimization of the volume of ZVI filings is necessary prior to finalizing a water filtration device, and is dependent upon the determination of the reaction kinetics of the ZVI filings and their longevity. This will be discussed further in section 5.8, Project Improvements and Expansion. The potential of ZVI filings to exchange iron for the As or U it removes may be a cause for concern. Further testing of the effluent for iron concentration should be completed to ensure it is below the secondary USEPA MCL of 0.3 mg/L (U.S. Environmental Protection Agency, 2013).

5.3 Modular System

A version of the modular system presented in section 4.8, Testing of Modular Configurations is recommended for its ability to maintenance one module without disrupting the other. Design improvements to the modular system include providing easier maintenance for the orange peels, which is discussed further in section 5.7, Project Sustainability, and installing a ventilation system for all modules except the first in order to facilitate uninhibited flow. For example, a 0.5 inch diameter vent can be installed in the top of the module to allow for the pressure in the module to equalize with atmospheric pressure. This prevents the occurrence of a vacuum effect in modules that causes the water to filter through only a small portion of the material at a reduced flow rate. The recommended modular system is depicted in Figure 5.1. Once again, the exact dimensions of the modular system have not yet been determined due to the lack of data regarding reaction kinetics and material longevity.

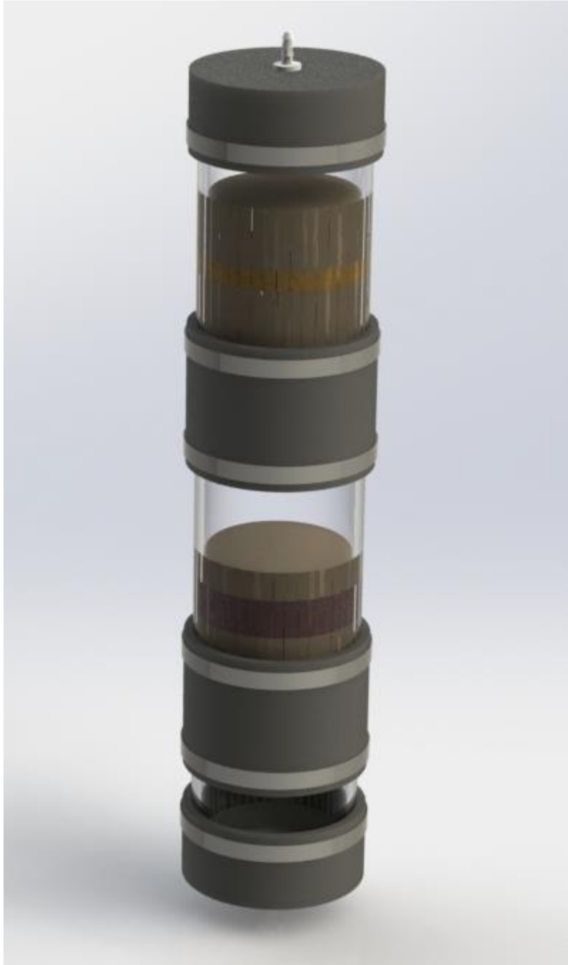


Figure 5.1: Recommended Modular System – Orange Peels on Top, ZVI Filings on Bottom

Based on the results from the Modular Configurations Tests, the only configuration proving effective is the combination of orange peels as the first module followed by ZVI filings. However, it is recommended that additional tests be conducted for confirmation. If flow patterns are corrected in the modular system, it is possible that the other configurations may also be effective.

5.4 Additional Polishing Step/Adsorption Layer

Although not tested, a layer of adsorbing material should follow the arsenic and uranium removal layers. This adsorptive layer could consist of granular activated carbon, and would be utilized to trap any particulates or iron that have possibly exchanged from the ZVI layer. This would improve quality and turbidity of the final effluent (Noubactep, Temgoua, & Rahman, 2012).

As water following filtration may contain high concentrations of both natural organic matter (NOM) and iron (both soluble and insoluble), which may cause turbidity levels above the USEPA Primary Standard of 5 NTU, a down-flow fixed bed of granular activated carbon (GAC) can be utilized as a polishing step prior to disinfection. GAC treatment is a physiochemical process shown to be an effective technology for the removal of a wide array of dissolved organic contaminants as well as secondary contaminants such as iron (U.S. Environmental Protection Agency, 2000).

GAC is comprised of tiny clusters of carbon atoms stacked upon one another, and is produced by heating a carbon source (coal, lignite, wood, nutshells or peat) in the absence of air, thereby creating a high carbon content material (U.S. Bureau of Reclamation, 2010). This process also creates an extremely large amount of adsorption surface area, generally around 73 acre/lb (650 m^2/gram) to 112 acre/lb (1000 m^2/gram) (U.S. Bureau of Reclamation, 2010).

GAC adsorption treatment is a non-steady-state process that involves time- and resource-intensive bench-scale testing if the filter design is to be optimized for removal efficiency vs. treatment cost (capital, operational, and maintenance costs). For the proper sizing of bed depth needed for contaminant removal, adsorption isotherms need to be performed on outflow water from the primary filtration modules. From these isotherms, necessary empty bed contact times (EBCT) can be determined. The overall performance of GAC adsorption treatment depends on a number of factors such as the physical properties of the GAC (source of raw carbon, pore size distribution, surface area), the chemical and electrical properties of the carbon source as well as its hydrogen and oxygen content, the chemical composition and contaminant loading (primarily organic matter and iron), the temperature and pH of the water, and the GAC column kinetics (flow rate and contact time) (U.S. Bureau of Reclamation, 2010). Typical contact times range from 6 to 30 minutes for the tertiary treatment of drinking water depending on the contaminants. To avoid channeling, the minimum column diameter is recommended to be at least 50 times the particle effective size (Calgon Carbon Corporation, 2014).

Ingesting iron from drinking water is not directly associated with any adverse health effects. The only potential health concern lies within any trace impurities and microorganisms that are absorbed by iron solids. Therefore, the reasoning for removing any iron particulate released into the water through the filtration modules is based on aesthetics. Iron in concentrations greater than 0.3 mg/L in drinking water can cause undesirable odors and give the water a metallic taste (U.S. Environmental Protection Agency, 2013). Another consideration for the removal of iron from the water is that when soluble iron is exposed to oxygen or to a disinfectant such as chlorine during water treatment, it oxidizes to insoluble iron (U.S. Environmental Protection Agency, 2013). This can give the water a rusty and unpleasant appearance.

NOM removal likewise shares the aesthetic reasoning of preventing undesirable odors and taste. However, the presence of NOM prior to disinfection can lead to the potential for disinfectant by-products such as Trihalomethanes (THMs) (Calgon Carbon Corporation, 2014). Higher concentrations of organic matter in effluent can also dictate higher usage of HTH for disinfection as NOM encourages bacterial growth with a system (Calgon Carbon Corporation, 2014).

The benefits of using GAC are its simplicity and accessibility for home use. The limitations however for GAC treatment following filtration are that on a home-scale, regeneration (i.e. steam, thermal and chemical) is not possible due to high O&M costs and additional disposal would be necessary as spent carbon may contain high-levels of hazardous materials (U.S. Bureau of Reclamation, 2010). Additionally, as with the other filtration modules, careful observational monitoring for replacement would be needed as the GAC neared it breakthrough times.

5.5 Disinfection

Following the final GAC filtration step, the treated water should be disinfected. Disinfection is necessary to kill or inactivate bacteria, viruses and any other potentially harmful organisms in drinking water. The WHO suggests the use of high-test granular calcium hypochlorite (HTH) as a readily available chemical form of disinfection (World Health Organization, 2002).To remove any objectionable chlorine odor, it is also recommended that the disinfected water be aerated by pouring it back and forth from one clean container to another.

To determine the chlorine dosage needed to treat the drinking water, calculations are performed and included in Appendix M using methodology outlined in Box 18-3. The HTH product used for the calculations is Dry-Tec 68% Calcium Hypochlorite Powdered Chlorine Shock for swimming pools which is available in 48 lb quantities from Amazon. Step #1 in the calculations is the creation of a 1% stock solution of 1 L of water to be used for disinfection. In Step #2, the mass of HTH needed for this 1% stock solution is determined assuming that the strength or % chlorine available in the HTH is 65%. The mass needed for the 1% stock solution is 15.38g (approximately 1 tablespoon). Step #3 assumes a family's daily volumetric water usage is 37.5L (5 people, 7.5L/capita). This daily requirement is then utilized to determine the amount of HTH needed to disinfect water on both a daily (0.288g) and yearly (105.288g) basis. Step #4 in Appendix M evaluates the total cost per year to disinfect the filtered water. With the assumed family size, water usage and HTH product, it is determined that it would cost $0.70/year to disinfect water from the filtration device.

5.6 Ion Exchange Resin

The use of ion exchange resins to remove uranium from contaminated feed water is suggested. The specific resin suggested for the removal of uranium is Amberlite™ PWA8, manufactured by Dow Chemical Corporation. The Monoplus 500 resin manufactured by Lewatit, which is utilized during testing, is not suggested for use as it is not specifically designed for the removal of uranium nor is it suggested for use in the treatment of potable water; Amberlite™ PWA8 is.

Testing of the Monoplus 500 macroporous chloride ion type ion exchange resin yields a removal efficiency of 99%, and reduces the concentration of both uranium and arsenic to below the MCL. However, using the ion exchange resin as a means to remove both contaminants is not suggested. Even though the resin is capable of removing both of the contaminants of concern, the selectivity of ion exchange resins prohibits their use in removing multiple contaminants. The resin may be capable of removing more than one contaminant from a feed stream but the contaminant for which the resin has the highest selectivity will eventually replace the second contaminant at the bonding sites of the resin as it becomes saturated. This causes de-sorption of the second contaminant and can result in a sudden spike in the concentration of the second contaminant in the effluent water. This poses a health risk to end users by increasing the concentration of the second contaminant if the resin becomes saturated. This problem could be addressed by establishing a complete chemical profile of the feed water, reaction kinetics, and adsorption data to help anticipate saturation and establish a time interval at which the resin should be regenerated or replaced. This data is also necessary to determine the amount of resin to use in the device. As this data is unavailable for use in this design, and the feasibility of determining the complete chemical profile of the feed water is impractical, the use of ion exchange resin to remove multiple contaminants cannot be suggested.

It is suggested that if an ion exchange resin be used in a device designed to remove arsenic and uranium that it be used in a modular configuration in series with a separate technology which is used first to remove arsenic. The resin is used only to remove uranium from the resulting arsenic-free effluent. Reaction kinetics and total exchange capacity data should be determined. This data should be utilized to determine the amount and depth of the resin in the filter column as well as replacement and/or regeneration intervals.

Operation and maintenance is also a concern if an ion exchange resin is utilized. The ion exchange resin should not be disposed of, but regenerated using a 5% sodium hydroxide solution and the resulting brine be discarded. The end-user should not be required to regenerate the resin themselves, or dispose of the brine on site. The regeneration of the material should be performed by a trained professional in a laboratory setting. This reduces attractiveness of an ion exchange resin for use in a filter in a remote location with limited access to the required materials and facilities.

5.7 Project Sustainability

Maintenance, material availability, and operator education must be considered to determine the sustainability of using this water filtration device. This section briefly discusses the challenges associated with these subjects. Explanations detailing how the challenges can be addressed are included. After addressing these issues, a discussion of the feasibility of long term use is also included.

The device must require a minimal amount of maintenance. Maintenance is defined as the amount of time and frequency at which it is necessary to replace components or filter materials. In order to minimize maintenance, the device must be easy to disassemble and reassemble. Organic materials are suggested for the final design, and it is noted that these materials may decompose after being wetted. This increases the frequency at which the filter materials will be replaced while decreasing the useful life of the filter materials. To accommodate for the use of degradable organic materials, a mechanism which allows for the device to be disassembled and reassembled quickly and easily is necessary.

Material availability is also an issue. It is important that the filter body components and filter materials be readily available or easy to procure to minimize the amount of time spent acquiring materials. Unfortunately, access to materials used in the device is extremely limited in the BFA or other rural areas. The materials which are utilized in the filter body assembly, and the filter materials themselves, will require trips to hardware and grocery stores. Efforts have been made to only use commonly available hardware and filter materials, and focus is given to minimizing the frequency at which these components require replacement. Utilizing materials with a long useful life, such as the ion exchange resin, can decrease the frequency at which trips to obtain filter materials are made. A balance between the availability of filter materials and their useful life must be achieved. The ion exchange resin suggested for this application is only available by ordering directly from the manufacturer. The zero valent iron filings are not commonly available at local retailers, and would need to be ordered via the internet. Items which are commonly available for purchase at most supermarkets, such as oranges, may require more frequent replacement. It is assumed that orange peels can be obtained at the same time the end-user travels to get groceries, and special trips solely to acquire fresh filter materials is not necessary. To achieve balance, it is suggested that ion exchange resin be purchased in bulk. Oranges can also be purchased in bulk and prepared immediately. Iron filings, could be purchased in bulk as well. The ion exchange resin, prepared orange peels, and iron filings have a long shelf-life, and this solution minimizes the frequency at which they will need to be procured, at a greater up-front cost to the end-user.

Operators must be educated on the use of the device and preparation of filter materials to assure the device functions as intended. An operations manual detailing the assembly, maintenance, and troubleshooting of the device is necessary. The operations manual should be detailed and simultaneously easy to understand and use. Extensive testing of the device should be conducted to anticipate issues an operator may have.

This filtration device is only intended to provide potable water to the population affected by the BFA for a short period of time. It is strongly suggested that the NTUA provide access to potable water to residents in this area as soon as possible. This device is not intended to serve as a permanent substitute for a regulated municipal water supply. Difficulties in procuring materials, inconveniences of performing maintenance, and the education of the end-user on proper use pose challenges to the end user that can only be addressed by access to a regulated water supply.

5.8 Project Improvements and Expansion

This research and development project establishes several technologies which are useful in a water filtration device. However, for a fully engineered design, further testing of the reaction kinetics and capacity are necessary. This data was unavailable at the time of design for this project. The time required to establish these data is also unavailable. Therefore, reaction kinetics and adsorption capacity are excluded from this design. Due to the absence of this data, the construction of a bench scale device is also excluded. The use of an incomplete design poses a human health and subsequent liability risk. Establishing reaction kinetics allows for a more exact design of the amount of time necessary to achieve removal of the contaminants of concern. The total mass of contaminant which can be removed from solution through either adsorption or ion exchange on a mass per mass basis is the capacity of the material. By combining these data, it is possible to accurately design a device with an appropriate amount and depth of filter material. This section details the procedures and analysis of these data and serves as a supplemental guide for future research and development work to better address the problem statement and design a full-scale and mass-producible device.

Reaction kinetics is the term used to describe the rate at which a reaction takes place. This is important when designing a filtration device which relies on adsorption or ion exchange. Knowing the amount of time required to achieve a desired fraction of removal of the contaminants allows for a more accurate and precise design. If the conductivity of the filter materials is known, the amount of time the fluid is in contact with the filter media is known. By altering the depth of the filter material, the amount of time the fluid remains in contact with the material, is varied. The deeper the section of filter material, the longer the fluid is in contact with it.

Reaction kinetics can be established by performing “batch tests.” During these tests, contaminated water is placed in flasks which are secured to a shaker table. A variable amount of the adsorbent material is placed in each flask and samples are collected at regular intervals. The fraction removed can then be expressed as a function of time or as a mass transfer coefficient (Roy, Krapac, Chou, & Griffin, 1991). The mass transfer coefficient can be calculated using the following equation (Weber, 1972):

$$m = \frac{\rho_p \rho_l Q}{k\alpha} \int_{C_1}^{C_2} \frac{dC}{(C - C_e)}$$

Where:
m = mass of resin in the column (g)
ρ_p= resin density (g/mL)
ρ_l= fluid density (g/mL)
Q= feed flow rate (gal/hr)
k= mass transfer coefficient (meq/hr-ft^2)
α= resin surface per unit volume (ft^{-1})
C= ion concentration in solution (meq/L)
C_e= ion concentration in equilibrium with adsorbent (meq/L)

Variations of initial concentrations of the ion exchange resin and contaminant with sample collection conducted at specific times during the experiment and results can be analyzed using the following equation:

$$F_m ln\left|\frac{C_t - C_{et}}{C_0 - C_e}\right| = (ka)t$$

Where:
F_m= mass flux of solution (M/L^{2}T)
t = time of exposure (T)
k= mass transfer coefficient (L/T)
a= external area of adsorbent/volume (L^{-1})

C_e= equivalent concentration for amount adsorbed (M/L^3)
C_{et}= Equilibrium concentration at time t
C_t= Concentration at time t
C_0= Initial concentration of influent at t=0

The capacity of the resin can be calculated by noting the mass of adsorbent in the flask, the concentration of the contaminant in the original fluid, and the volume of the contaminated liquid. The capacity is reached when the concentration in the fluid no longer changes, or equilibrium occurs and the material is saturated.

Once reaction kinetics and capacity data are established, the depth of material in the column can be calculated based on the conductivity of the filter material and the desired contact time derived from the kinetics and capacity data. This can result in a more efficient design, and allows for the determination of an exact amount of material necessary to operate the device efficiently for a desired period of time, or a more exact estimate of replacement or regeneration of the filter materials.

Further improvements to the modular design are suggested. The use of a stronger adhesive or alternative method for securing the wire mesh to the base of the modules is necessary. As time was limited in the construction of the first modules, experimenting with various methods of securing the wire mesh was not possible. Further improvements should be made to assure the device can function for a long period of time without the risk of breakage. The mesh should be secured enough to allow for the module to be dropped from a reasonable height while fully loaded with material without breaking free from the cylinder.

A quick release mechanism for the module couplings is also suggested. A latch-and-lever pipe clamp assembly is likely the best option. Some modification to a pipe clamp, or metal banding may be necessary to integrate this technology into the device. Latch-and-lever mechanisms are widely used and procuring this component would not be difficult. Other methods which allow for easy separation of the filter modules are possible, and this is only one suggestion. It is necessary to make disassembly and reassembly of the device as quick and easy as possible to encourage more frequent inspection and replacement of spoiled or exhausted filter material to assure the device continues to work as intended.

If reaction kinetics, filter material capacity, and design flaws are addressed, the development of a bench-scale or full-scale device is very possible. If future researchers and developers decide to pursue this design, an operations and maintenance manual detailing the proper procedures to build, disassemble, and maintain the device is necessary. It is imperative to understand that there are serious risks to human health associated with miscalculating the parameters of the device, operating the filter materials beyond saturation, and allowing organics to rot and spoil while continuing to use the device. All of these risks must be addressed prior to certifying the device for consumer use.

6.0 Project Impacts

The impacts of this project are incredibly significant. The design of a water filter capable of removing coliforms and reducing U and As makes positive contributions to human health. The implications of this project for political systems, economic systems, and culture must be strongly considered prior to implementation of a final water filtration unit. Finally, there are potentially adverse effects for the natural environment.

6.1 Project Importance

In both the developing world and infrastructure-poor regions of developed countries, such as the Navajo Nation in the United States, the application of low-cost water treatment technology is imperative for the removal of contaminants that have various adverse health effects. In locales where community level water treatment facilities are not economically, politically, or logistically feasible, point-of-use water filtration units are the most practical alternative. Without access to potable water, human health is inevitably impacted, which has far reaching consequences that must be considered.

Conditions of poverty and poor infrastructure affect access to clean water and the prevention of water-borne diseases and illnesses resulting from long-term exposure to contaminated drinking water. More importantly, this scenario is often cyclical. Without access to clean water and the prevention of water-borne diseases, poverty is exacerbated and continuous. The cyclical process makes it difficult for those born in economically depressed regions, especially in the least developed nations, to move out of a state of poverty. In areas of high poverty, especially those that are in developing countries or slums, there is limited economic capacity or might to put forth the financing and effort to prepare and design for access to clean water. Without the access to clean water, a population will inevitably suffer from what are considered to be preventable water-borne diseases or water-related illnesses in wealthy, industrialized countries.

According to the Director-General of WHO, most water-borne illnesses have been eradicated from wealthy countries as living standards improved. Yet, this is not the case for the developing world, which is plagued by water scarcity, poor water quality, and inadequate sanitation. This, in turn, affects food security, health, livelihoods, and education. In many locations where people must travel long distances to haul water back to their homes, time for other activities such as productive businesses, farming, or schooling becomes limited. When poor water quality causes human health effects, the full capacity of an individual cannot be used for such activities. According to the Director General of the WHO, the state of sanitation in the world should be regarded as one of the greatest crises facing socioeconomic development (Chan, 2013).

In response to this water and sanitation crisis, the United Nations established the Millennium Development Goals (MDGs), of which there are eight. These eight MDGs were agreed upon by all countries that take part in the United Nations and all of the leading development organizations in the world. The purpose of the eight goals is to meet the needs of the world's poorest citizens by the year 2015, with the overarching goal of eradicating poverty. MDG Seven, to Ensure Environmental Sustainability, has a sub-goal to halve, by 2015, the proportion of the global population without sustainable access to safe drinking water and basic sanitation. However, there is no specific goal that aims to protect fresh water or groundwater sources from contamination that could cause them to be non-potable and without possibility for remediation. Part of this sub-goal of MDG 7 was met by 2010 when the proportion of people without access to improved sources of water was halved. From the initiation of the MDGs in 1990 until 2010, over two billion people gained access to improved drinking water sources; those using an improved water source increased from 76% to 89% over this ten year period. However, as of 2011, 768 million people were still without access to improved drinking water sources (United Nations, 2014).

Although the written, established goal for water has technically been met, half of the world population has a piped water supply in their homes, and deaths from diarrheal diseases are falling, the target set for sanitation is the most off-track of all the MDGs. Unfortunately, sanitation and access to clean water are inextricably linked. Additionally, the MDGs aren't designed to track the equitable distribution of benefits, as the Director-General of the WHO explains. Rather, progress is based on population averages and not on whether the improvements reach those with the most need. So, while the world met the MDG target overall for access to water, only 61% of the population in sub-Saharan Africa has access. There are gaps in access to clean water in and between countries, and those who are most vulnerable may not actually be experiencing improvements. Of most concern is the fact that the MDGs do not address water quality, which is the most important factor in reducing water-borne illnesses (Chan, 2013). Therefore, while the

MDGs focus on access to water, there is no focus on the quality of such water. This should be of the utmost concern, and is the major focus and contribution of this project.

6.2 Contribution to Human Health

6.2.1 Arsenic

As of 2006, the Arsenic Contamination in the World Report determined that 105 countries in the world suffer from elevated levels of arsenic in their drinking water sources, where approximately 151 million people worldwide are exposed to arsenic contamination with 147 million of these people living in Asia. The countries of most concern are Bangladesh, India, Pakistan, Vietnam, China, Myanmar, Argentina, Cambodia, Chile, Hungary, Taiwan, Vietnam, Japan, New Zealand, Germany, the United States, and Mexico (Murcott, 2013), (Bang, Korfiatis, & Meng, 2005). Elevated levels of arsenic may be present in water as a natural occurrence or due to human influence. Examples of anthropogenic arsenic causing activities include mining, pesticide and herbicide use, industrial effluent, and chemical waste disposal (Bang, Korfiatis, & Meng, 2005).

Groundwater is often favored over surface water as the main source of drinking water as it does not contain bacterial contamination in most cases. However, in many parts of the world, including Bangladesh, West Bengal, India, and the Navajo Reservation, arsenic naturally occurs in the water in concentrations several times the MCL, which is set at 50 µg/L in Bangladesh and 10 µg/L by the World Health Organization and the USEPA. In Bangladesh, for example, over 10 million tube wells have been installed since the 1970s, exponentially increasing the amount of groundwater consumed by the Bangladeshi population. A nationwide survey in Bangladesh found that one-third of the tubewells are contaminated with arsenic at concentrations about 50 µg/L, while two-thirds have concentrations above 10 µg/L. Avoiding the use of groundwater in arsenic contaminated areas is not feasible due to water scarcity, increasing pollution of surface water, and the inability to provide large-scale removal of microbial pathogens. Other options such as rain water catchment, storage, and use may be promising but inconclusively feasible in arid regions or during the dry season in countries that have wet and dry seasons. Therefore, there is an urgent need for the provision of water filtration units that are capable of removing arsenic to safe drinking levels in developing and rural areas such as Bangladesh and other South Asian countries (Cheng, et al., 2004).

Long-term exposure to arsenic through the ingestion of contaminated water may cause arsenic to become concentrated in liver, kidney, lung, and skin tissues (Bang, Korfiatis, & Meng, 2005). Effects to health include neurological, dermatological, gastrointestinal, cardiovascular, and renal diseases. Dermatological effects include skin lesions, hyperpigmentation changes (Figure 6.1) on the upper chest, arms, and legs, and keratosis (Figure 6.2) of the palms of the hands and soles of the feet. Arsenic is also a suspected carcinogen, causing skin cancer, bladder cancer, or lung cancer. At very high concentrations of arsenic, acute symptoms such as gastrointestinal disturbances including diarrhea and abdominal pain may occur. Recent research suggests that As may act as an endocrine disruptor even at extremely low concentrations (Smith, Lingas, & Rahman, 2000) (Amin, et al., 2006).

Figure 6.1: Hyperpigmentation on Hands due to Arsenic Ingestion *(Le, 2009)*

Figure 6.2: Keratosis of Hands and Feet due to Arsenic Ingestion *(Clinical effects of groundwater arsenic contamination in the GMB plain, 2014)*

6.2.2 Uranium

In recent years, global uranium contamination has been receiving more attention. People are likely to be exposed to uranium if they live in an area with naturally elevated amounts of uranium in rocks, soil, or water, or in areas near a uranium-contaminated site. People may also be exposed to uranium if their work involves mining and processing uranium ore. In most countries, especially developing countries, mining industries are actively players in the development of the countries; therefore, leaching and leaking of uranium from mining activities into water sources may occur. As a consequence, drinking water sources, such as surface and groundwater sources are potentially contaminated (Zavodsk, Kosorinova, Scerbakova, & Lesny, 2008).

There are insufficient data regarding the carcinogenicity of uranium in humans and experimental animals; however, certain health effects due to uranium contamination in water have been investigated. Nephritis, an inflammation of the kidneys, has been demonstrated to be one of the primary chemically induced effects of high levels of uranium in humans. An increasing number of epidemiological studies of populations exposed to uranium in drinking-water have shown a correlation with alkaline phosphatase and β-microglobulin in urine along with modest alterations in proximal tubular function (World Health Organization, 2011). Both inhalation and ingestion of uranium compounds have been shown to produce renal injury in laboratory animals characterized by damage to the glomerulus and proximal epithelium (Zavodsk, Kosorinova, Scerbakova, & Lesny, 2008). Lung cancer, bone cancer and impaired kidney function are other health effects caused by exposure to uranium-contaminated drinking water sources (U.S. Environmental Protection Agency, 2013). Additionally, because of the genotoxicity of uranium to people, exposure to uranium causes genetic and genomic changes and therefore impacts most organs in mammals, particularly the kidney, the brain and the reproductive system. Unexpectedly high levels of chromosome aberrations in uranium miners in Namibia have already been reported (Busby, 2010).

Due to the fact that people are highly dependent on valuable water resources, a water filtration unit that is capable of reducing uranium concentration to safe drinking water levels is an indispensable device to be implemented in the areas where high levels of uranium contamination exist.

6.2.3 Bacteria

Bacterial contamination in drinking water is always of concern for human health. In vulnerable populations, disease outcomes from illnesses resulting from waterborne bacteria may be more severe. Coliform bacteria serve as an indicator of the presence of waterborne pathogens, which cause more diseases than any other drinking water contaminant. Typhoid and paratyphoid fevers are typical infections caused by bacteria which are transmitted from feces to ingestion of water. Clean water prevents the spread of typhoid and paratyphoid, while bacteria-contaminated water is one of the pathways of transmission of the diseases. Most bacterial pathogens potentially transmitted by water infect the gastrointestinal tract and are excreted in the feces of infected humans. It was also reported that the 560,000 people in the United States of America may suffer from a moderate to severe waterborne infection and 1.7 million suffer from a mild to moderate waterborne infection each year. Diarrheal disease alone causes 2.2 million of 3.4 million water-related deaths each year (World Health Organization and the Organization for Economic Cooperation and Development, 2003). Additionally, there are some waterborne bacterial pathogens, such as Legionella, Burkholderia pseudomallei and atypical mycobacteria that can grow in water, which can possibly cause more severe diseases in humans (World Health Organization, 2011).

Bacteria removal technologies for drinking water are widely applied in water treatment plants. However, in most of the rural areas in developing countries, bacteria removal from drinking water sources is still not feasible due to financial issues, low energy supply, and a limited number of experts. Therefore, the implementation of water filtration devices that are able to reduce bacteria concentrations to safe drinking water levels in the rural areas where the water sources are highly contaminated by bacteria is an urgent task to accomplish.

6.3 Contribution to the Natural Environment

While the intention of the filtration device is to remove harmful concentrations of As and U from a contaminated groundwater source, negative impacts could arise from the accumulated waste the filter will generate over time. These wastes could be hazardous given their high concentrations of U and As and their ability to desorb or leach out of the filter materials if disposed of indiscriminately. While not addressed within the scope of this report, Toxic Characteristic Leaching Procedure (TCLP) analysis would need to be performed on the waste generated from the filtration device. Through the Resource Conservation and Recovery Act (RCRA), federal protocol dictates the USEPA approved testing method be used to determine if a waste should be characterized as hazardous (D-List) (U.S. Environmental

Protection Agency, 2014). If TCLP analytical results show As concentrations to be below the TCLP D-list maximum contamination levels (MCLs) the waste could be landfilled along with local municipal solid waste. For As, the designation is anything greater than 5.0 mg/L (U.S. Environmental Protection Agency, 2014). Currently, there are no legally binding TCLP numbers for U. Instead treatment residuals (<15 lbs) containing U are considered “mixed wastes” (D-List) subject to U.S. Nuclear Regulatory Commission (NRC) licensing requirements given its weight exceeds 0.05% of the spent filtration material weight (U.S. Environmental Protection Agency, 2014).

The generated waste also has the potential of making a point source of contamination, such as a groundwater well that can be easily controlled (treated, sealed etc.) into a mobile source of environmental contamination. A mobile source is more likely to plume or become airborne, contaminating wider areas of surface water or soil. Education can be seen as one of the main limiting factors in the operation, proper disposal and handling of spent filtration material. While the filtration device may be seen as a treatment solution which is commercially viable and can be quickly implemented, education of rural users and local government oversight of disposal could be difficult to implement and lead to rather large hidden operational costs. For this reason, alternative point source removal or treatment methods should be evaluated. While considerably more costly, these solutions guarantee permanent removal of contaminates from the groundwater and potentially lessen the risks to uranium and arsenic exposure.

6.4 Contribution to Political Systems, Economies and Society

The development of a point-of-use water filter that can remove U and As may affect the political systems, economies, and societies the end users belong to. It is important to consider and anticipate these impacts prior to implementing any technology. Knowledge of the local political, economic, and societal procedures will aid in the development of an implementation plan. An implementation plan determines the best way to distribute a final device. This section discusses the impacts of the implementation of a point-of-use water filtration device in the former BFA. Special consideration is given to local policies, procedures, and economic climate. Development of an implementation plan is excluded.

The political impacts of implementation of a water filtration device must consider the agencies which currently regulate and manage public water supply in the Navajo Nation. The development of the public water supply (PWS) infrastructure falls under the jurisdiction of the Navajo Nation Environmental Protection Agency (NNEPA), The Navajo Nation Department of Water Resources (NNDWS), and the Navajo Tribal Utility Authority (NTUA) (Navajo Access Workgroup, 2010). Public awareness campaigns by the NTUA and NNEPA have been launched to discourage the use of water obtained at several contaminated sites by posting signs at these locations to discourage this practice. Providing a water filtration unit to residents in this area would be synonymous with suggesting these signs and awareness campaigns be ignored. This could be viewed as a violation of the authority of the bodies which govern water procurement and delivery on the Navajo Nation. To address this issue, it is strongly suggested that these governing bodies be consulted prior to distribution of any and all information, designs, materials, or devices to residents in this area.

It is also noted that Northern Arizona University, and the students involved in this and subsequent projects, have no authority or rights to intervene in resident and government affairs of the Navajo Nation. In order for any permissions or allowances to be made, all implementation plans must be supported and sponsored by official residents and citizens of the Navajo Nation. This means adhering to and respecting local political proceedings and policies. It is strongly suggested that the client be knowledgeable in these proceedings and willing to participate in these proceedings on behalf of the project participants to assure compliance. If such a client is unavailable, a willing representative with the appropriate qualifications should be sought to accommodate this need.

Economic impacts are also possible. The health effects of exposure to elevated concentrations of uranium and arsenic are discussed in section 6.2, Contribution to Human Health. Eliminating the consumption of contaminated water provides immediate decline in associated health risks. A reduction in health risks can lead to an improvement in quality of life and decreased costs of associated healthcare costs. However, the source of funding for implementation of this project remains unknown. If residents are required to pay for the materials and maintenance of the final device, these costs could have a negative economic impact on end users. It can be assumed that the costs of implementing the device are worth the overall improvement in consumer health.

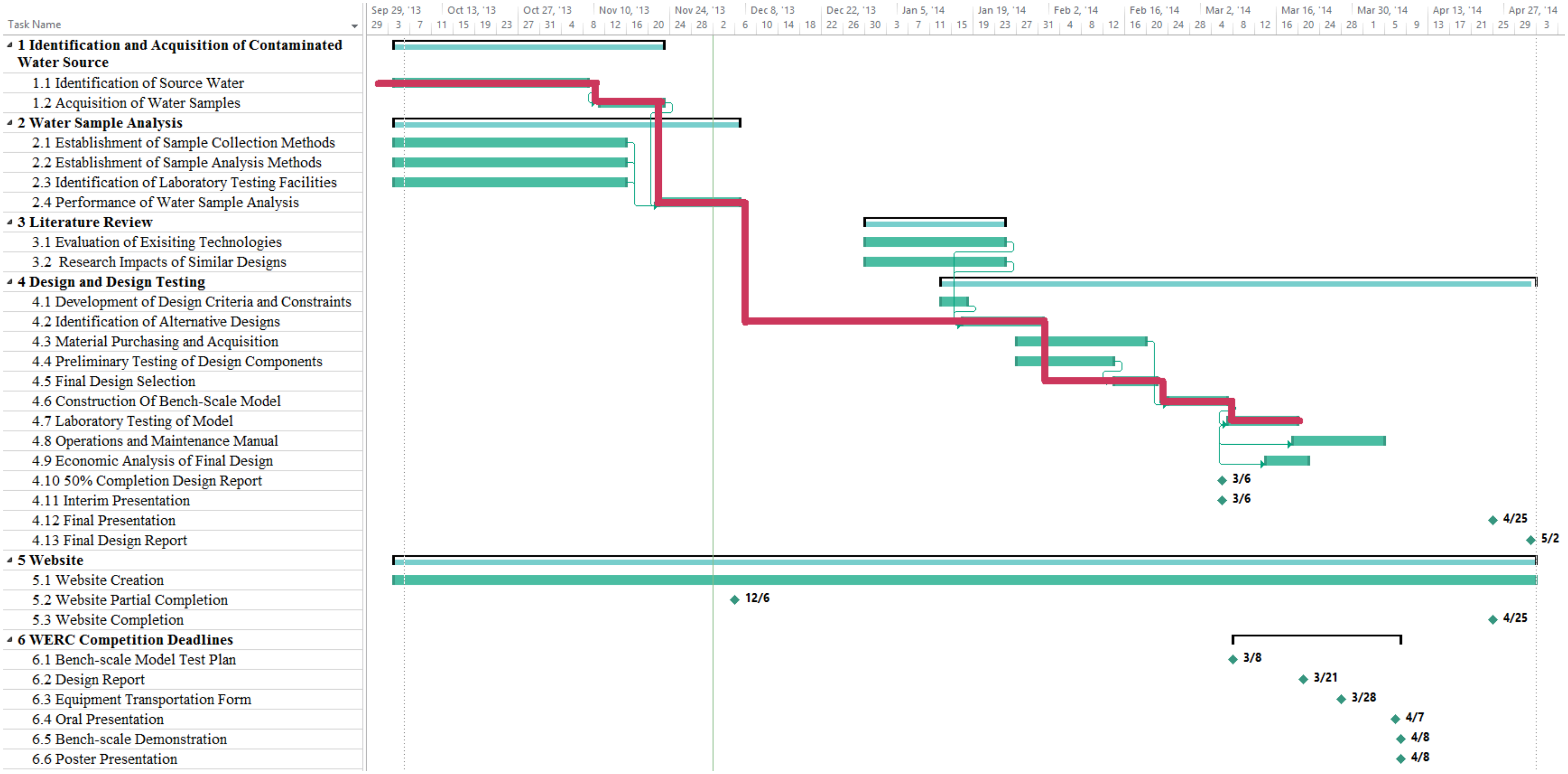
Impacts on society are also possible. The development of a water filtration device which is developed for at-home use in rural areas could be manipulated for use in other cases with different contaminants of concern. According to the World Health Organization's Water Quality and Health Strategy Goals from 2013-2020, more than half of the world's population will live in water-stressed areas (World Health Organization, 2013). As seen in the BFA scenario, as untreated potable water resources become more scarce or unavailable, residents of developed and developing countries alike are forced to consider contaminated water sources for potable use. Inexpensive and effective water treatment technologies may become more important to many societies. The society of the BFA may benefit greatly from this technology and may be able to utilize it until water infrastructure development projects replace the need for such technology with a well-regulated public water supply. Access to clean potable water could lead to an increase in general health, well-being, and productivity. The possibility of far reaching societal benefits including increased productivity in a post-BFA is supported by providing access to a clean and reliable water source.

7.0 Summary of Project Costs

In this section, differences between the original Gantt Chart from the Project Proposal and the final Gantt Chart are presented. A comparison of the proposed Cost Estimate for Engineering Services and the Final Project Costs is discussed.

7.1 Gantt Chart Comparison

As noted in section 1.5, Changes to Project Scope, the scope of the project was altered to reflect unforeseen project challenges. As a result, the Gantt Chart was updated to reflect these changes. The original Gantt Chart from the Project Proposal can be seen in Figure 7.1. This is followed by the final Gantt Chart in Figure 7.2.



Task Name

1 Identification and Acquisition of Contaminated Water Source
  1.1 Identification of Source Water
  1.2 Acquisition of Water Samples
2 Water Sample Analysis
  2.1 Establishment of Sample Collection Methods
  2.2 Establishment of Sample Analysis Methods
  2.3 Identification of Laboratory Testing Facilities
  2.4 Performance of Water Sample Analysis
3 Literature Review
  3.1 Evaluation of Exisiting Technologies
  3.2 Research Impacts of Similar Designs
4 Design and Design Testing
  4.1 Development of Design Criteria and Constraints
  4.2 Identification of Alternative Designs
  4.3 Material Purchasing and Acquisition
  4.4 Preliminary Testing of Design Components
  4.5 Final Design Selection
  4.6 Construction Of Bench-Scale Model
  4.7 Laboratory Testing of Model
  4.8 Operations and Maintenance Manual
  4.9 Economic Analysis of Final Design
  4.10 50% Completion Design Report
  4.11 Interim Presentation
  4.12 Final Presentation
  4.13 Final Design Report
5 Website
  5.1 Website Creation
  5.2 Website Partial Completion
  5.3 Website Completion
6 WERC Competition Deadlines
  6.1 Bench-scale Model Test Plan
  6.2 Design Report
  6.3 Equipment Transportation Form
  6.4 Oral Presentation
  6.5 Bench-scale Demonstration
  6.6 Poster Presentation

Figure 7.1: Original Gantt Chart *(Cummings, Dilks, Sun, & Weir, 2013)*

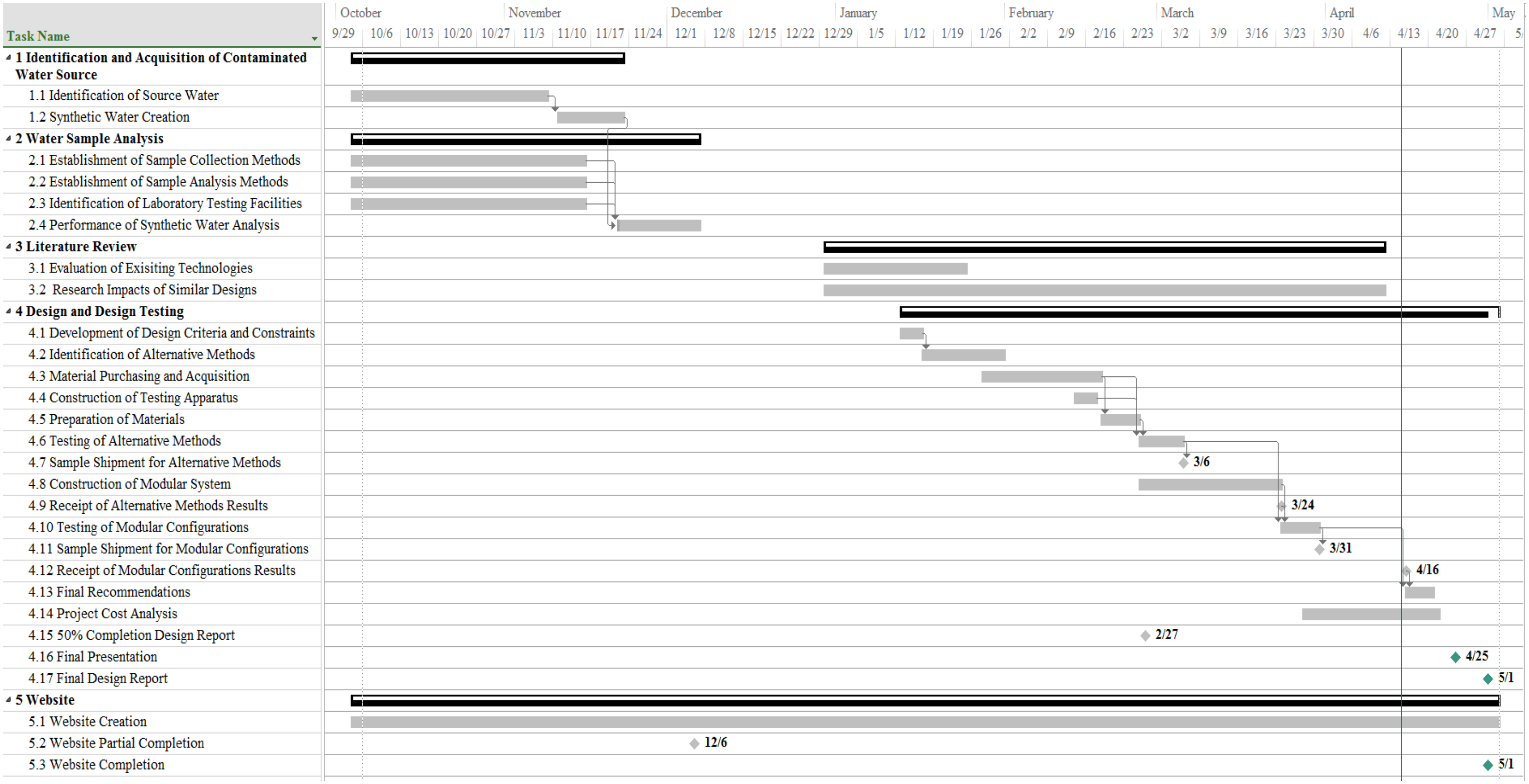


Figure 7.2: Final Gantt Chart

The following alterations were made to the original Gantt Chart:

1. Task 1.2 Acquisition of Water Samples became Synthetic Water Creation. This was renamed as a result of the team's inability to acquire samples from a contaminated drinking water source. Synthetic water using purchased U and As standards was created in the laboratory instead.
2. Task 2.4 Performance of Water Sample Analysis became Performance of Synthetic Water Analysis. This was a result of the need to test the synthetic water rather than an authentic contaminated water source.
3. Tasks 4.4 – 4.9 were revised to reflect the major changes to the project scope, as explained in section 1.5, Changes to Project Scope. Their revision resulted in the following new or reordered tasks:
    a. 4.4 Construction of Testing Apparatus
    b. 4.5 Preparation of Materials
    c. 4.6 Testing of Alternative Methods
    d. 4.7 Sample Shipment of Alternative Methods
    e. 4.8 Construction of Modular System
    f. 4.9 Receipt of Alternative Methods Results
    g. 4.10 Testing of Modular Configurations
    h. 4.11 Sample Shipment for Modular Configurations
    i. 4.12 Receipt of Modular Configuration Results
    j. 4.13 Final Recommendations
    k. 4.14 Project Cost Analysis
4. Task 4.10 50% Completion Design Report kept the same name but became Task 4.15.
5. Task 4.11 Interim Presentation was removed because it was no longer a required project deliverable.
6. Task 4.12 Final Presentation kept the same name but became Task 4.16.
7. Task 4.13 Final Design Report kept the same name but became Task 4.17.
8. The WERC Competition Deadlines were removed because the team decided not to enter the competition due to time constraints.

Deadlines for the 50% Completion Report and Website are altered in accordance with new deadlines established throughout the course of the project. Due to the major changes to the scope of the project and the turn-around time for water sample analysis for U and As, major adjustments are made to the time schedule. The sample shipment dates and receipt of sample analysis were included as diamonds on the Gantt Chart in Figure 7.2. These dates are critical for the schedule of this project, as other tasks relied on them. For example, Task 4.10, Testing of Modular Configurations could not begin until the receipt of the results from the alternative methods testing. Task 4.13, Final Recommendations could not be made until the receipt of the results from the modular configurations testing.

7.2 Comparison of Project Costs

The original Cost Estimate for Engineering Services from the Project Proposal can be seen in Table 7.1. This is followed by the Total Project Costs in Table 7.2. The following abbreviations were used:

SENG: Senior Engineer
ENG: Engineer
LAB: Lab Technician
INT: Intern
AA: Administrative Assistant

Table 7.1: Cost Estimate of Engineering Services *(Cummings, Dilks, Sun, & Weir, 2013)*

Cost Estimate for Engineering Services				
Personnel	Role	Hours	Rate ($/hr)	Cost ($)
	SENG	73	114	8,294
	ENG	223	58	12,952
	LAB	219	44	9,518
	INT	318	21	6,706
	AA	55	38	2,050
	Total Personnel	886		**39,520**
Travel				
	Local Meetings			
	4 meetings x 120mi/meeting	$0.40/mi		**192**
	Water Hauling			
	10 times x 10mi/haul	$0.40/mi		**40**
Subcontractor				
	Analytical Laboratory Tests			
	200 samples x $49/sample			**9,800**
Overhead				
				14,673
Total Cost Estimate				
				64,225

Table 7.2: Total Project Costs

Total Project Costs				
Personnel	Role	Hours	Rate ($/hr)	Cost ($)
	SENG	62	114	7,064
	ENG	237	58	13,755
	LAB	168	44	7,329
	INT	326	21	6,875
	AA	97	38	3,646
	Total Personnel	889		**38,670**
Travel				
	Water Hauling			
	4 times x 10mi/haul	$0.40/mi		**16**
Subcontractors				
	Analytical Laboratory Tests			
	120 samples x $19/sample + shipping			**2,290**
Overhead				
				14,727
Project Materials and Chemicals				
				984
Total Project Costs				
				56,687

Cost of Personnel

The total personnel costs of $38,670 for the project are very close to the projected costs of $39,520 from the proposal despite the changes to the scope. This is because the total project personnel hours of 889 is only slightly greater than the total projected personnel hours of 886, and the distribution of work for the project followed very closely to the projected distribution.

Cost of Travel

It was projected in the proposal that there would be four local meetings with the client at 120 miles per meeting. These meetings did not occur, and were thus removed from the Total Project Costs. It was also estimated that water hauling would occur 10 times at 10 miles per meeting. However, water was transported only four times during the course of the project. Therefore, the estimated cost of $232 for travel is much greater than the total travel cost of $16.

Cost of Subcontractor

The proposal estimated the cost of analytical laboratory tests at $9,800 based upon a quote from the analytical laboratory Test America for 100 U samples at $49 per sample and 100 As samples at $49 per sample. While NAU was able to receive a reduced price for analytical testing from the Metropolitan State College of Denver at $250 for up to 125 samples, if this project were to be repeated without the discount, the total cost of analytical laboratory tests would be $2280. This is based upon an updated quote from Test America for 60 U samples at $19 per sample and 60 As samples at $19 per sample. An additional cost of approximately $10 was added for sample shipment.

Cost of Overhead

The projected cost of overhead was $14,673. The final total project overhead is $14,727. Because overhead is a function of total personnel hours, the projected and actual overhead costs are similar due to similarity in projected and actual personnel hours.

Cost of Project Materials and Chemicals

The proposal overlooked the cost of project materials and chemicals. The total cost of project materials and chemicals amounted to $984. A more detailed breakdown of these costs can be viewed in Appendix N.

Total Project Costs

The proposal estimated the total project costs at $64,225. The actual total projects costs are $56,687. The major difference in cost was a result of differences in the cost associated with the analytical laboratory subcontractor.

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Appendices

Appendix A: Original Scope of Services

SCOPE OF SERVICES
The scope of services encompasses all tasks necessary to complete the project objective. The scope consists of five primary tasks. The tasks include: identification and acquisition of a contaminated water source, water sample analysis, a literature review, design and design testing, and the creation of a website. Primary tasks may be divided into several subtasks. Details describing each subtask are included.

TASK ONE: IDENTIFICATION AND ACQUISITION OF CONTAMINATED WATER SOURCE
The first task is to identify one or more contaminated water sources in the Bennett Freeze area. The selection of the water source is based on several pre-defined criteria. The criteria include: ease of access, confirmation of use as a drinking water source, and confirmation of contamination by contaminants of concern. The contaminants of concern include uranium, arsenic, and coliform bacteria at levels higher than the MCLs established by the U.S. EPA. The purpose of this task is to assure the water source contains the contaminants of concern as communicated by the client.

SUBTASK 1.1: IDENTIFICATION OF SOURCE WATER
This subtask addresses the establishment of a suitable water source for testing in the designed water treatment device. To complete this subtask, water quality data from research on the Navajo Nation conducted by Dr. Jani Ingram, Associate Professor of Chemistry at Northern Arizona University, may be used to identify a water source in the Bennett Freeze area which satisfies the aforementioned criteria. Due to political boundaries, the location of the source is very important. The location of the source is utilized in subtask 1.2, Acquisition of Water Samples. If water cannot be retrieved from the Navajo Nation, a suitable water source in northern Arizona that contains bacteria must be identified. This water can then be spiked with uranium and arsenic, as described in subtask 1.2.

SUBTASK 1.2: ACQUISITION OF WATER SAMPLES
Permission from political bodies of the Navajo Nation may be necessary to legally procure samples from the source identified in subtask 1.1, Identification of Source Water, for use in analysis, task one, Water Sample Analysis. Water samples may be acquired or created in a variety of ways:

<u>Acquisition of Navajo Nation Water:</u>
Samples are retrieved from the source water identified in subtask 1.1. Sample collection requires permission from one of the Navajo Nation's Chapter houses in the form of a Resolution. The particular Chapter House is dependent on the location of the selected water source. In order to acquire a Resolution to take water samples, the client must attend a Chapter House meeting to request the support of Sublime Engineering in sampling the water and transporting it off of the Navajo Nation.

<u>Acquisition of Non-Navajo Nation Water and Synthetic Water Development:</u>
If a resolution cannot be secured, then water from another source in northern Arizona, such as Upper Lake Mary, can be acquired to create synthetic water containing bacteria, uranium, and arsenic. The creation of synthetic water allows for various concentrations of uranium and arsenic to be tested by creating several different synthetic waters at various concentrations. The alkalinity, hardness, pH, turbidity, and solids of the synthetic water must be analyzed, as will be discussed in task two.

TASK TWO: WATER SAMPLE ANALYSIS
Task two involves a detailed analysis of the acquired water mentioned in subtask 1.2. Testing protocols established in the performance of this task are also necessary for the testing of the treated water from the

bench-scale device. These protocols are also utilized in task four, Design and Design Testing. The following subsections detail the subtasks that must be addressed in order to complete the water analysis.

SUBTASK 2.1: ESTABLISHMENT OF SAMPLE COLLECTION METHODS

This task requires research to determine standard of practice sample collection methods. The methods should identify proper water sampling techniques and chain of custody standards for sample collection. The purpose of this task is to establish quality control and quality assurance of experimental results, as well as to ensure the safety of the samplers.

SUBTASK 2.2: ESTABLISHMENT OF SAMPLE ANALYSIS METHODS

This task requires research of procedures that can be utilized to establish the background characteristics of the acquired or synthetic water and background concentrations of the contaminants of concern. The contaminants of concern include uranium, arsenic, and bacteria. Analysis of common water characteristics is also necessary to assure that any physical or chemical processes utilized in the final design consider their effects on performance. The intent is to assure that the final design considers the effects of variations in characteristics of the acquired or synthetic water. Common water characteristics that may be considered include, but are not limited to, solids, turbidity, hardness, alkalinity, and pH. A list of equipment necessary to complete the water analysis is generated and utilized in subtask 2.3, Identification of Laboratory Testing Facilities.

SUBTASK 2.3: IDENTIFICATION OF LABORATORY TESTING FACILITIES

The identification of laboratory testing facilities is required to complete the analysis of water samples. Utilizing the information from subtask 2.2, the equipment required to complete the detailed water analysis should be compared with the capabilities of Northern Arizona University (NAU) facilities. The purpose of this comparison is to identify which NAU facilities are viable for the completion of the water analysis and to determine any necessary radioactive or hazardous waste disposal requirements. Requests for access to the facilities identified during this process are made. If it is determined that a necessary procedure cannot be completed at NAU, it will be outsourced to a capable facility at a minimal cost.

SUBTASK 2.4: PERFORMANCE OF WATER SAMPLE ANALYSIS

This task requires the analysis of acquired or synthetic water samples in accordance with testing methods and guidelines outlined in subtask 2.2. Test results shall be analyzed and interpreted. Water quality reports will be generated.

TASK THREE: LITERATURE REVIEW

Task three involves conducting a literature review to establish existing technologies capable of removing the contaminants of concern. The purpose of the literature review is to assist in the process of generating ideas for the design alternatives of subtask 4.2, Identification of Alternative Designs. Research into potential impacts is also a subtask of the literature review.

SUBTASK 3.1: EVALUATION OF EXISTING TECHNOLOGIES

An investigation of potential physical, biological, and chemical separation processes to remove the contaminants of concern from the untreated water is necessary. An extensive literature review should ensure that a thorough evaluation of technologies is completed. The literature review also includes an examination of the best available technologies (BATs) for each of the contaminants, as suggested by the U.S. EPA or Arizona Department of Environmental Quality (AZDEQ). Any potentially useful technologies from the literature review should be categorized by their level of technological complexity, from low-tech to high-tech. The literature review will help to determine which technologies can be excluded as potential design alternatives. Investigating water treatment technologies utilized by the mining industry may also prove useful.

SUBTASK 3.2: RESEARCH OF IMPACTS OF SIMILAR DESIGNS

Cultural, social, economic and public health implications of a low-cost device that is able to provide water free of uranium, arsenic, and bacteria is researched. These impacts shall be considered for both the Bennett Freeze area and other economically disadvantaged areas that may have similar water contamination.

TASK FOUR: DESIGN AND DESIGN TESTING

Design and testing of the treatment device are required. The following subsections detail the subtasks that must be addressed in order to complete the design and testing.

SUBTASK 4.1: DEVELOPMENT OF DESIGN CRITERIA AND CONSTRAINTS

In this subtask, the design criteria and constraints are fully developed. Adherence to the criteria and constraints must occur in subtasks 4.2, Identification of Alternative Designs, 4.5, Final Design Selection, 4.6, Construction of Bench-Scale Model, and 4.7, Laboratory Testing of Model.

SUBTASK 4.2: IDENTIFICATION OF ALTERNATIVE DESIGNS

This subtask involves the identification of multiple alternative designs to achieve the design objective. These alternatives are based upon task three, Literature Review. Any design ideas that would require special permitting from the Navajo Nation are excluded at the request of the client, including any designs that would be implemented at the water source.

SUBTASK 4.3: MATERIAL PURCHASING AND ACQUISITION

Any materials or equipment necessary for the preliminary testing or for the selected design of the bench-scale model must be purchased.

SUBTASK 4.4: PRELIMINARY TESTING OF DESIGN COMPONENTS

Before decisions are made for the final design, preliminary testing of various alternative designs or sub-components may be necessary. Design ideas are tested and analyzed for their efficacy using sample or synthetic water. Testing procedures follow those determined in task two, Water Sample Analysis.

SUBTASK 4.5: FINAL DESIGN SELECTION

Decision matrices are developed and utilized to determine which of the designs best meets the design criteria and constraints established in subtask 4.1. Analysis of the decision matrices leads to the selected final design.

SUBTASK 4.6: CONSTRUCTION OF BENCH-SCALE MODEL

A bench-scale model for the design selected in subtask 4.5, Final Design Selection, must be constructed. Materials purchased and acquired in subtask 4.3 are utilized. A full-scale model for implementation will not be built. Therefore, full-scale construction and implementation is excluded.

SUBTASK 4.7: LABORATORY TESTING OF MODEL

The bench-scale model constructed under subtask 4.6 must be tested for its efficacy in adherence with the design criteria and constraints developed in subtask 4.1. The testing follows the procedures for water analysis as described in task two, Water Sample Analysis. All testing of the bench-scale model will be completed in a laboratory setting. Field testing is excluded.

If testing shows design failure, adjustments will be made. An iterative design approach will be followed, and the Sublime Engineering team will repeat subtasks 4.4-4.7 if necessary.

SUBTASK 4.8: OPERATIONS AND MAINTENANCE MANUAL

This subtask includes the formulation of an operations and maintenance manual for any potential users of the final device as designed. The operations and maintenance manual shall include:

- Descriptions on how the device should be operated, stored, and cleaned
- Details on the frequency of maintenance required for the device and any removable components such as filters.
- A disposal plan for any radioactive or hazardous waste

SUBTASK 4.9: ECONOMIC ANALYSIS OF FINAL DESIGN

An economic analysis of the final design is performed using engineering economic principles. The economic analysis shall provide a cost estimate to build, operate, and maintain a full-scale device. The potential for mass production may also be considered.

SUBTASK 4.10: 50% COMPLETION DESIGN REPORT

This subtask includes the formulation of the 50% Completion Design Report to be delivered to the client, technical advisor, and Capstone course instructors.

SUBTASK 4.11: INTERIM PRESENTATION

An interim presentation is given, summarizing the 50% Completion Design Report.

SUBTASK 4.12: FINAL PRESENTATION

A final presentation is given summarizing the Final Design Report.

SUBTASK 4.13: FINAL DESIGN REPORT

This subtask includes the formulation of the Final Design Report to be delivered to the client, technical advisor, and Capstone course instructors. This design report is to include an analysis of the potential impacts of the final design. These impacts may concern improvement to public health or may address cultural, social, or economic impacts.

TASK FIVE: WEBSITE

This task involves the creation of a website via the use of Dreamweaver software to present information about the project to the interested observer. The website must include, at a minimum, the following webpages:

- Home Page
- Project Information Page
- Documents Page

Appendix B: Water Quality Analysis for Upper Lake Mary

Introduction

The purpose of the water quality testing is to establish the background characteristics of the water obtained from Upper Lake Mary in Flagstaff, AZ. The intent is to assure that the final design considers the effects of variations in characteristics of the acquired water. Common water characteristics that are considered include turbidity, hardness, bacteria count and alkalinity. In this report, water quality results and data analysis will be presented.

High concentration of suspended solids are associated with warmer water, less light, and less oxygen which makes it harder for some forms of life to survive. Turbidity is associated with the colloidal levels of binding areas for contaminants that may be associated with disease carrying capacity.

Materials

- Graduated cylinder
- Deionized water
- Buret
- Pipette bulb
- Pipette(s)
- Upper Lake Mary water samples
- Turbidimeter (aka Nephelometer)
- Two burette clamps
- 50mL graduated cylinder
- Beaker
- Ring stand
- Stir bar
- Stir plate
- 0.02N EDTA
- Sodium hydroxide
- Ring Stand
- Indicators: BCG-MR, Calcium IND HNB, hardness IND calmagite
- PH meter
- 0.623N H_2SO_4
- Agar plate
- Flask
- Filters
- M-endo broth
- Filtration units
- Beaker(s)

Methods

Turbidity: The Standard Method 2130 2130 (Standard Method, 2014) will be used for testing turbidity of the samples. The Nephelometer model type used must be documented and calibrated properly according to manufacturer-specific instructions. Five samples were tested.

Hardness: The Standard Method 2340 C. Titration Method 2130 (Standard Method, 2014) will be used for testing hardness of the samples. Only total hardness and calcium hardness will be measured. The end point of titration is the color of the sample water changing from purple to blue. Three trials will be conducted.

Alkalinity: The Standard Method 2320 B. EDTA Titration Method 2130 (Standard Method, 2014) will be used for testing alkalinity of the samples. Three tests will be conducted in order to obtain accurate results. The sample was titrated until reaching a pH of 4.5.

Coliforms: The Standard Method 9222 B. Standard Total Coliform Membrane Filter Procedure 2130 (Standard Method, 2014) will be used for preparing and counting colony forming units (CFUs).

Results

Turbidity:

Table 1 outlines the resulting turbidity data for water from Lake Mary Treatment Plant as compared to the United States Environmental Protection Agency (USEPA) Maximum Contaminant Limit (MCL).

Table 1: Turbidity Data

		Sample						
	USEPA MCL	DI Water	1	2	3	4	5	Average of 1-5
Turbidity (NTU)	5	0.12	53.4	54.4	54.1	53.2	52.7	53.6

Alkalinity:

Table 2 presents the resulting alkalinity data for water from Upper Lake Mary. Lab data used to determine the alkalinity can be found in the Appendix. There is no MCL from the USEPA for alkalinity.

Table 2: Alkalinity Data

Titration	Alkalinity (mg $CaCO_3$ /L)
1	36.8
2	44.9
3	29.9
Average	37.2

Hardness:

Table 3 shows the resulting hardness data for water from Upper Lake Mary. There is no MCL from the USEPA for hardness.

Table 3: Total Hardness and Calcium Hardness

Trial	Calcium hardness (mg $CaCO_3$ /L)	Total hardness (mg $CaCO_3$ /L)
1	30	44
2	24	30
3	30	30
Average	28	35

Coliforms:

Table 4 shows the resulting total coliforms for water from Upper Lake Mary as compared to the USEPA MCL. If a sample has too many coliforms, too numerous to count, it is listed as TNTC.

Table 4: CFUs for Upper Lake Mary

		Sample						
	USEPA MCL	DI Water	1	2	3	4	5	6
Coliforms (CFU/100 mL)	No more than one sample testing total coliform-positive per month	0	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC

Conclusion

The coliform tests showed that the total coliforms in Upper Lake Mary were all too numerous to count. The average calcium hardness was 28 mg/L as $CaCO_3$, and the average total hardness was 35 mg/L as $CaCO_3$, indicating that the calcium hardness contributed to almost all of the total hardness. The alkalinity was determined to be 37.2 mg $CaCO_3$ /L, and the average turbidity was 53.6 NTU.

References

Standard Methods. (2014, February). *Standard Methods Online*. Retrieved from Standard Methods for the Examination of Water and Wastewater: http://www.standardmethods.org/Store/index.cfm

Appendix C: Water Dilution Report

Introduction

The purpose of the water dilution test is to determine the necessary ratio of groundwater to Upper Lake Mary water from Flagstaff, AZ to correctly model the amount of colony forming units per 100 mL (CFU/100mL) in the groundwater wells in the Bennett Freeze Area of the Navajo Nation. In the dilution test, water from Lake Mary Treatment Plant and a private residential groundwater well are mixed. The methods of the test and the results of the colony forming units (CFUs) will be presented and discussed.

Materials

- 100 mL graduated cylinder
- Deionized water
- Pipette(s)
- Lake Mary Treatment Plant water samples
- Beakers
- M-endo broth
- Sterile absorbent pads
- Filtration units
- Filter
- Agar plates

Methods

In order to determine the proper ratio of groundwater to Upper Lake Mary water, the serial dilution method was utilized. The basic steps of the serial dilution are as follows:

1. Label the 2 sterile test graduated cylinders.
2. The blanks containing deionized water (DI) and the well water will also be tested.
3. Add 10 mL of Lake Mary water to each graduated cylinder.
4. Add 90 mL of the well water into the first graduated cylinder.
5. Mix thoroughly before proceeding to the next step.
6. Use another clean pipette. Withdraw 1 mL of the diluted bacterial suspension from the first graduated cylinder and pipette that into the second graduated cylinder.
7. Add 99 mL of the well water into the second graduated cylinder.
8. The standard method 9222.B (Standard Method Committee, 2014) will be used for putting the samples onto agar plates and counting CFUs.
9. Put the agar plates in a 35 degree incubator for 24 hours.
10. After 24 hours, count CFUs and calculate the amount of bacteria in each plate.

Results

Coliforms:

Table 1 outlines the total coliform results. "100%", "10%", and "1%" mean that the water has a dilution factor of 0, 10, and 100, respectively. The results are compared to the United States Environmental Protection Agency Maximum Contaminant Limit for Total Coliforms. Groundwater is represented as GW and Lake Mary is represented as LM.

Table 1: CFUs Results

		Sample									
	USEPA MCL	DI Water #1	DI Water #2	GW #1	GW #2	LM 1% #1	LM 1% #2	LM 10% #1	LM 10% #2	LM 100% #1	LM 100% #2
Coliforms (CFU/100 mL)	No more than one sample testing total coliform-positive per month	0	0	0	0	3	4	20	10	35	39
Average (CFU/100 mL)		0		0		3.5		15		37	

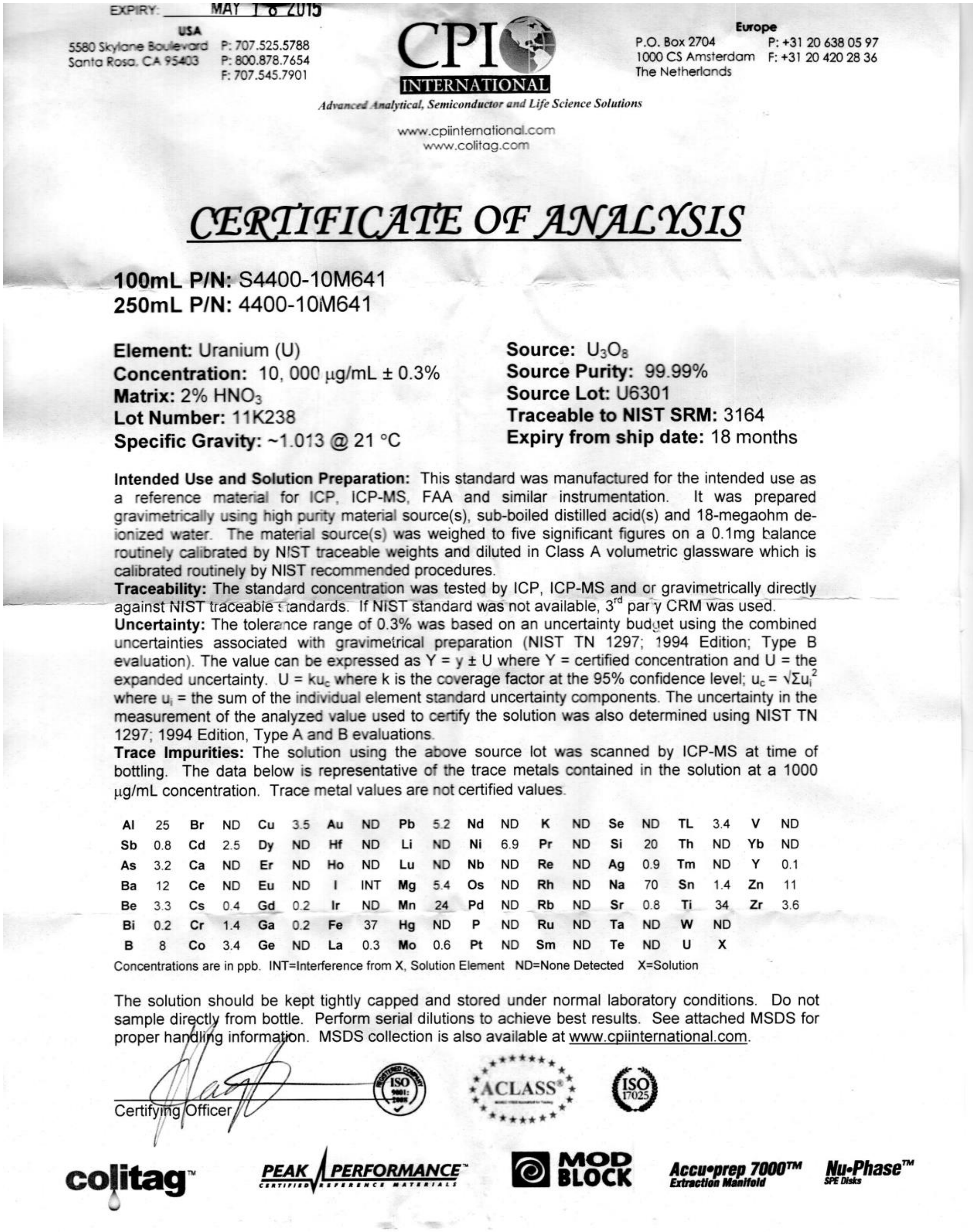
Conclusion

From the dilution test results, Lake Mary 10% was finally determined to be the best option since it contains a level of CFUs/100mL more representative of the Bennett Freeze Area (BFA). Additionally, it contains 90% groundwater, which better models the groundwater wells in the BFA. Lake Mary 1% is an inappropriate choice because the CFUs/100mL is too low for the purposes of this project.

References

Standard Methods. (2014, February). *Standard Methods Online*. Retrieved from Standard Methods for the Examination of Water and Wastewater: http://www.standardmethods.org/Store/index.cfm

Appendix D: Uranium Stock Solution Chemical Information



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CERTIFICATE OF ANALYSIS

100mL P/N: S4400-10M641
250mL P/N: 4400-10M641

Element: Uranium (U)
Concentration: 10, 000 µg/mL ± 0.3%
Matrix: 2% HNO_3
Lot Number: 11K238
Specific Gravity: ~1.013 @ 21 °C

Source: U_3O_8
Source Purity: 99.99%
Source Lot: U6301
Traceable to NIST SRM: 3164
Expiry from ship date: 18 months

Intended Use and Solution Preparation: This standard was manufactured for the intended use as a reference material for ICP, ICP-MS, FAA and similar instrumentation. It was prepared gravimetrically using high purity material source(s), sub-boiled distilled acid(s) and 18-megaohm de-ionized water. The material source(s) was weighed to five significant figures on a 0.1mg balance routinely calibrated by NIST traceable weights and diluted in Class A volumetric glassware which is calibrated routinely by NIST recommended procedures.
Traceability: The standard concentration was tested by ICP, ICP-MS and or gravimetrically directly against NIST traceable standards. If NIST standard was not available, 3^{rd} party CRM was used.
Uncertainty: The tolerance range of 0.3% was based on an uncertainty budget using the combined uncertainties associated with gravimetrical preparation (NIST TN 1297; 1994 Edition; Type B evaluation). The value can be expressed as Y = y ± U where Y = certified concentration and U = the expanded uncertainty. $U = ku_c$ where k is the coverage factor at the 95% confidence level; $u_c = \sqrt{\Sigma u_i^2}$ where u_i = the sum of the individual element standard uncertainty components. The uncertainty in the measurement of the analyzed value used to certify the solution was also determined using NIST TN 1297; 1994 Edition, Type A and B evaluations.
Trace Impurities: The solution using the above source lot was scanned by ICP-MS at time of bottling. The data below is representative of the trace metals contained in the solution at a 1000 µg/mL concentration. Trace metal values are not certified values.

Al	25	**Br**	ND	**Cu**	3.5	**Au**	ND	**Pb**	5.2	**Nd**	ND	**K**	ND	**Se**	ND	**TL**	3.4	**V**	ND
Sb	0.8	**Cd**	2.5	**Dy**	ND	**Hf**	ND	**Li**	ND	**Ni**	6.9	**Pr**	ND	**Si**	20	**Th**	ND	**Yb**	ND
As	3.2	**Ca**	ND	**Er**	ND	**Ho**	ND	**Lu**	ND	**Nb**	ND	**Re**	ND	**Ag**	0.9	**Tm**	ND	**Y**	0.1
Ba	12	**Ce**	ND	**Eu**	ND	**I**	INT	**Mg**	5.4	**Os**	ND	**Rh**	ND	**Na**	70	**Sn**	1.4	**Zn**	11
Be	3.3	**Cs**	0.4	**Gd**	0.2	**Ir**	ND	**Mn**	24	**Pd**	ND	**Rb**	ND	**Sr**	0.8	**Ti**	34	**Zr**	3.6
Bi	0.2	**Cr**	1.4	**Ga**	0.2	**Fe**	37	**Hg**	ND	**P**	ND	**Ru**	ND	**Ta**	ND	**W**	ND		
B	8	**Co**	3.4	**Ge**	ND	**La**	0.3	**Mo**	0.6	**Pt**	ND	**Sm**	ND	**Te**	ND	**U**	X		

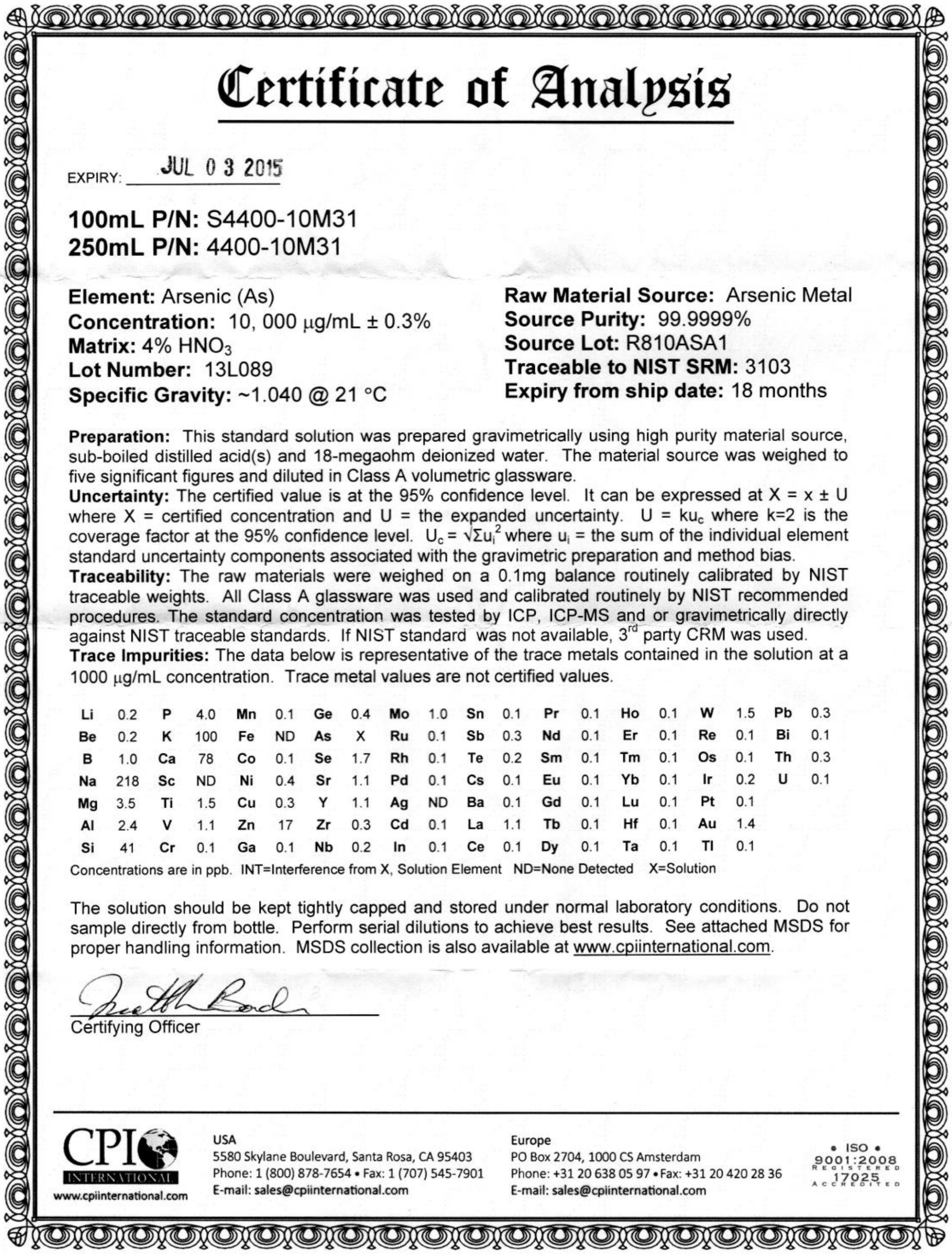
Concentrations are in ppb. INT=Interference from X, Solution Element ND=None Detected X=Solution

The solution should be kept tightly capped and stored under normal laboratory conditions. Do not sample directly from bottle. Perform serial dilutions to achieve best results. See attached MSDS for proper handling information. MSDS collection is also available at www.cpiinternational.com.

Certifying Officer

colitag™ PEAK PERFORMANCE™ CERTIFIED REFERENCE MATERIALS MOD BLOCK Accu•prep 7000™ Extraction Manifold Nu•Phase™ SPE Disks

Appendix E: Arsenic Stock Solution Chemical Information



Certificate of Analysis

EXPIRY: JUL 0 3 2015

100mL P/N: S4400-10M31
250mL P/N: 4400-10M31

Element: Arsenic (As)
Concentration: 10, 000 μg/mL ± 0.3%
Matrix: 4% HNO_3
Lot Number: 13L089
Specific Gravity: ~1.040 @ 21 °C

Raw Material Source: Arsenic Metal
Source Purity: 99.9999%
Source Lot: R810ASA1
Traceable to NIST SRM: 3103
Expiry from ship date: 18 months

Preparation: This standard solution was prepared gravimetrically using high purity material source, sub-boiled distilled acid(s) and 18-megaohm deionized water. The material source was weighed to five significant figures and diluted in Class A volumetric glassware.
Uncertainty: The certified value is at the 95% confidence level. It can be expressed at X = x ± U where X = certified concentration and U = the expanded uncertainty. $U = ku_c$ where k=2 is the coverage factor at the 95% confidence level. $U_c = \sqrt{\Sigma u_i^2}$ where u_i = the sum of the individual element standard uncertainty components associated with the gravimetric preparation and method bias.
Traceability: The raw materials were weighed on a 0.1mg balance routinely calibrated by NIST traceable weights. All Class A glassware was used and calibrated routinely by NIST recommended procedures. The standard concentration was tested by ICP, ICP-MS and or gravimetrically directly against NIST traceable standards. If NIST standard was not available, 3rd party CRM was used.
Trace Impurities: The data below is representative of the trace metals contained in the solution at a 1000 μg/mL concentration. Trace metal values are not certified values.

Li	0.2	**P**	4.0	**Mn**	0.1	**Ge**	0.4	**Mo**	1.0	**Sn**	0.1	**Pr**	0.1	**Ho**	0.1	**W**	1.5	**Pb**	0.3
Be	0.2	**K**	100	**Fe**	ND	**As**	X	**Ru**	0.1	**Sb**	0.3	**Nd**	0.1	**Er**	0.1	**Re**	0.1	**Bi**	0.1
B	1.0	**Ca**	78	**Co**	0.1	**Se**	1.7	**Rh**	0.1	**Te**	0.2	**Sm**	0.1	**Tm**	0.1	**Os**	0.1	**Th**	0.3
Na	218	**Sc**	ND	**Ni**	0.4	**Sr**	1.1	**Pd**	0.1	**Cs**	0.1	**Eu**	0.1	**Yb**	0.1	**Ir**	0.2	**U**	0.1
Mg	3.5	**Ti**	1.5	**Cu**	0.3	**Y**	1.1	**Ag**	ND	**Ba**	0.1	**Gd**	0.1	**Lu**	0.1	**Pt**	0.1		
Al	2.4	**V**	1.1	**Zn**	17	**Zr**	0.3	**Cd**	0.1	**La**	1.1	**Tb**	0.1	**Hf**	0.1	**Au**	1.4		
Si	41	**Cr**	0.1	**Ga**	0.1	**Nb**	0.2	**In**	0.1	**Ce**	0.1	**Dy**	0.1	**Ta**	0.1	**Tl**	0.1		

Concentrations are in ppb. INT=Interference from X, Solution Element ND=None Detected X=Solution

The solution should be kept tightly capped and stored under normal laboratory conditions. Do not sample directly from bottle. Perform serial dilutions to achieve best results. See attached MSDS for proper handling information. MSDS collection is also available at www.cpiinternational.com.

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Appendix F: Synthetic Water Standards and Spiking Calculations

Synthetic Water Development - Standard and Synthetic Water Calculations

Definition of Terms

C1	Concentration of stock solution (10,000,000µg/L)
V1	Volume of stock solution needed
C2	Desired concentration for standard (1,000,000µg/L)
V2	Total volume of standard (1L)
C3	Concentration of standard (Equivalent to C2)
V3	Total volume of standard needed to make synthetic water
C4	Desired concentration in synthetic water
V4	Total volume of synthethetic water (60 gallons=227.1L)

Uranium		
C1	10000000	µg/L
V1	0.1	L
C2	1000000	µg/L
V2	1	L
C3	1000000	µg/L
V3	0.02271	L
C4	100	µg/L
V4	227.1	L

Arsenic		
C1	10000000	µg/L
V1	0.1	L
C2	1000000	µg/L
V2	1	L
C3	1000000	µg/L
V3	0.015897	L
C4	70	µg/L
V4	227.1	L

Calculations:

C1V1=C2V2			C1V1=C2V2		
V1=	0.1	L	V1=	0.1	L
	100	mL		100	mL
C3V3=C4V4			C3V3=C4V4		
V3=	0.02271	L	V3=	0.015897	L
	22.71	mL		15.897	mL
Lake Mary/GW Blend =	227.1	L	Lake Mary/GW Blend =	227.1	L
	60.0	gallons		60.0	gallons

URANIUM

Step One: We need ____ of the stock solution. DI water is added up to 1000mL to make the 1L standard

100 mL

Step Two: We need ___ of the standard.

22.7 mL

ARSENIC

Step One: We need ____ of the stock solution. DI water is added up to 1000mL to make the 1L standard

100 mL

Step Two: We need ___ of the standard.

15.9 mL

Appendix G: Synthetic Water Quality Analysis

Introduction

The purpose of the water quality testing is to establish the background characteristics of the synthetic water. The intent is to assure that the final design considers the effects of variations in characteristics of the acquired water. Common water characteristics that are considered include hardness, alkalinity, solids and colony forming units (CFUs). In this report, data analysis, water quality results and discussion will be presented.

Materials

- Graduated cylinder
- Deionized water
- Buret
- Pipette bulb
- Pipettes
- Turbidimeter (aka Nephelometer)
- Two burette clamps
- 50mL graduated cylinder
- Beaker
- Ring stand
- Stir bar
- Stir plate
- 0.02N EDTA
- Sodium hydroxide
- Indicators: BCG-MR, Calcium IND HNB, hardness IND calmagite
- PH meter

Methods

Turbidity: The Standard Method 2130 (Standard Method, 2014) will be used for testing turbidity of the samples. The Nephelometer model type used must be documented and calibrated properly according to manufacturer-specific instructions. Since samples can be run very quickly, 5 samples were used.

Hardness: The Standard Method 2340 C. Titration Method 2130 (Standard Method, 2014) will be used for testing hardness of the samples. Only total hardness and calcium hardness will be measured. The end point of titration is the color of the sample water changing from purple to blue. Three trials will be conducted.

Alkalinity: The Standard Method 2320 B. EDTA Titration Method 2130 (Standard Method, 2014) will be used for testing alkalinity of the samples. Three tests will be conducted in order to obtain accurate results. The sample was titrated until reaching a pH of 4.5.

Coliforms: The Standard Method 9222 B. Standard Total Coliform Membrane Filter Procedure 2130 (Standard Method, 2014) will be used for preparing and counting colony form units (CFUs).

Solids: The amount of Total Dissolved Solids (TDS) in the synthetic water can be determined with a HANNA Instruments HI9828 that has a meter for TDS, measured in parts per million (ppm).

Results

Alkalinity:

Table 1 presents the resulting alkalinity data for the synthetic water. There is no Maximum Contaminant Limit (MCL) from the United States Environmental Protection Agency (USEPA) for alkalinity.

Table 1: Alkalinity Data

Titration	Alkalinity (mg $CaCO_3$ /L)
1	98.90
2	104.65
3	102.35
Average	101.97

Hardness:

Table 2 shows the hardness data for the synthetic water. There is no MCL from the USEPA for alkalinity.

Table 2: Total Hardness and Calcium Hardness

Trial	Calcium hardness (mg $CaCO_3$ /L)	Total hardness (mg $CaCO_3$ /L)
1	99	106
2	97	101
3	96	99
Average	97	102

Solids:

The solids result is determined using a mode HI 9828 conductivity meter. The TDS is 139 ppm with the conductivity of 265 µs/cm. The USEPA MCL for TDS is 500 ppm.

Coliforms:

The average total coliforms of the synthetic water is determined to be 2 CFUs/100mL.

Turbidity:

Table 3 outlines the resulting turbidity data for synthetic water.

Table 3: Turbidity Data

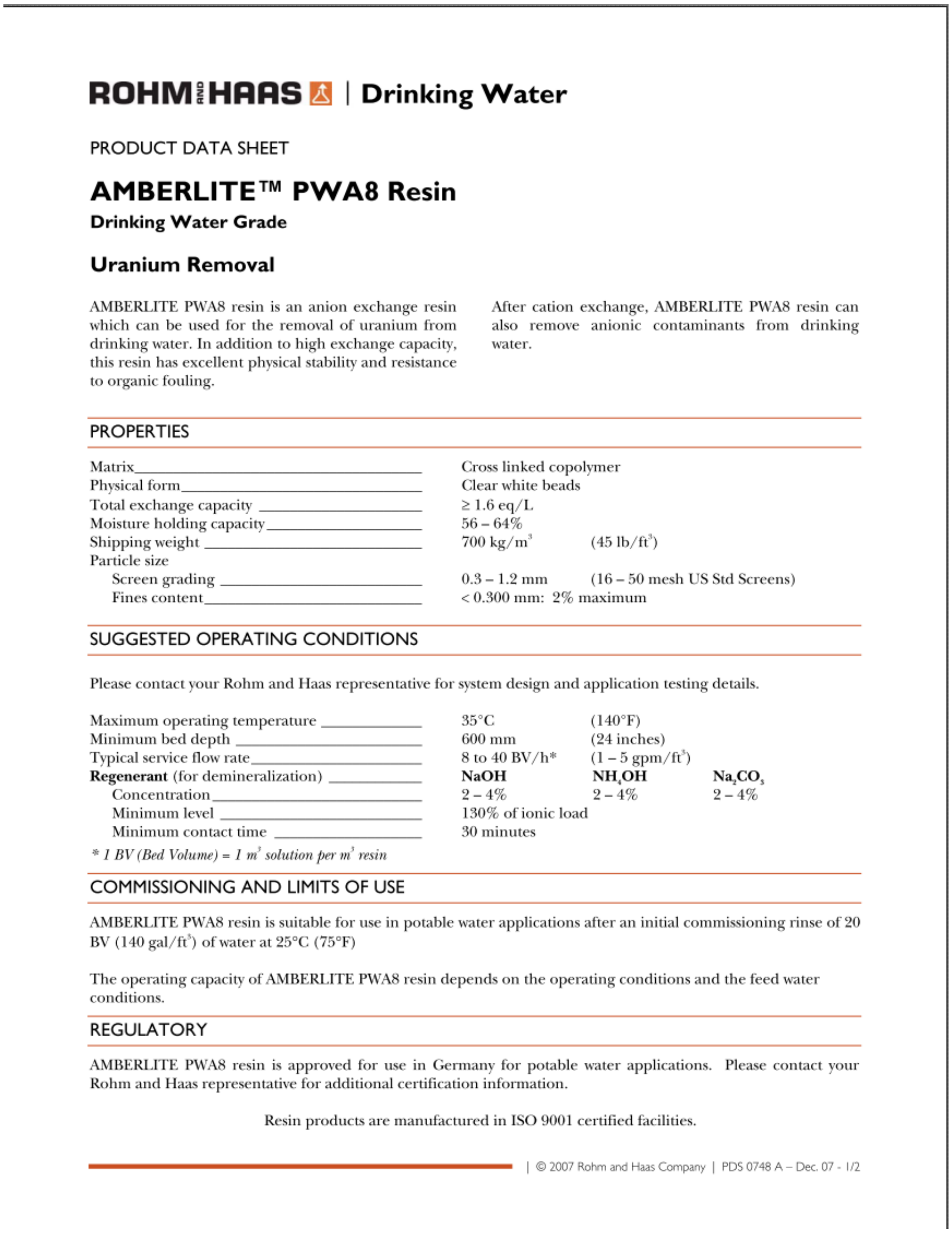
		Sample						
	USEPA MCL	DI Water #1	DI Water #2	1	2	3	4	Average of 1-4
Turbidity (NTU)	5	0.1	0.1	8	7.8	7.8	7.8	7.85

References

Standard Methods. (2014, February). *Standard Methods Online*. Retrieved from Standard Methods for the Examination of Water and Wastewater: http://www.standardmethods.org/Store/index.cfm\

Appendix H: DOW Chemical Amberlite^{TM} PWA8 Resin Product Data Sheet

* Rohm and Haas is a subsidiary of DOW Chemical



ROHM AND HAAS | Drinking Water

PRODUCT DATA SHEET

AMBERLITE™ PWA8 Resin

Drinking Water Grade

Uranium Removal

AMBERLITE PWA8 resin is an anion exchange resin which can be used for the removal of uranium from drinking water. In addition to high exchange capacity, this resin has excellent physical stability and resistance to organic fouling.

After cation exchange, AMBERLITE PWA8 resin can also remove anionic contaminants from drinking water.

PROPERTIES

Matrix	Cross linked copolymer	
Physical form	Clear white beads	
Total exchange capacity	≥ 1.6 eq/L	
Moisture holding capacity	56 – 64%	
Shipping weight	700 kg/m^3	(45 lb/ft^3)
Particle size		
Screen grading	0.3 – 1.2 mm	(16 – 50 mesh US Std Screens)
Fines content	< 0.300 mm: 2% maximum	

SUGGESTED OPERATING CONDITIONS

Please contact your Rohm and Haas representative for system design and application testing details.

Maximum operating temperature	35°C	(140°F)	
Minimum bed depth	600 mm	(24 inches)	
Typical service flow rate	8 to 40 BV/h*	(1 – 5 gpm/ft^3)	
Regenerant (for demineralization)	**NaOH**	**NH_4OH**	**Na_2CO_3**
Concentration	2 – 4%	2 – 4%	2 – 4%
Minimum level	130% of ionic load		
Minimum contact time	30 minutes		

** 1 BV (Bed Volume) = 1 m^3 solution per m^3 resin*

COMMISSIONING AND LIMITS OF USE

AMBERLITE PWA8 resin is suitable for use in potable water applications after an initial commissioning rinse of 20 BV (140 gal/ft^3) of water at 25°C (75°F)

The operating capacity of AMBERLITE PWA8 resin depends on the operating conditions and the feed water conditions.

REGULATORY

AMBERLITE PWA8 resin is approved for use in Germany for potable water applications. Please contact your Rohm and Haas representative for additional certification information.

Resin products are manufactured in ISO 9001 certified facilities.

HYDRAULIC CHARACTERISTICS

Figure 1 and Figure 2 show the pressure drop data for AMBERLITE PWA8 resin as a function of flow rate and water temperature. Pressure drop data are valid at the start of the service run with clean water and a correctly classified bed. Figure 3 and Figure 4 show the bed expansion of AMBERLITE PWA8 resin as a function of backwash flow rate and water temperature.

Figure 1 Pressure Drop (metric)

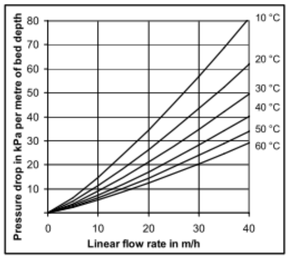


Figure 2 Pressure Drop (US units)

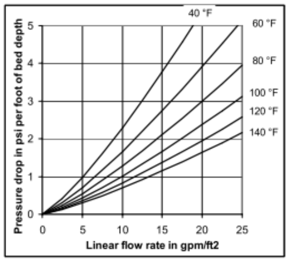


Figure 3 Bed Expansion (metric)

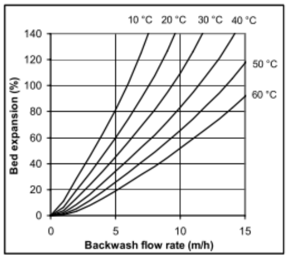
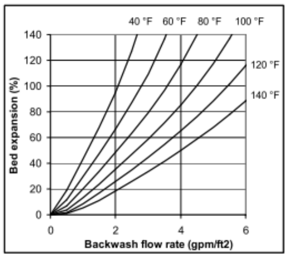


Figure 4 Bed Expansion (US units)



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Ion exchange resins and polymeric adsorbents, as produced, contain by-products resulting from the manufacturing process. The user must determine the extent to which organic by-products must be removed for any particular use and establish techniques to assure that the appropriate level of purity is achieved for that use. The user must ensure compliance with all prudent safety standards and regulatory requirements governing the application. Except where specifically otherwise stated, Rohm and Haas does not recommend its ion exchange resins or polymeric adsorbents, as supplied, as being suitable or appropriately pure for any particular use. Consult your Rohm and Haas technical representative for further information. Acidic and basic regenerant solutions are corrosive and should be handled in a manner that will prevent eye and skin contact. Nitric acid and other strong oxidizing agents can cause explosive type reactions when mixed with Ion Exchange resins. Proper design of process equipment to prevent rapid buildup of pressure is necessary if use of an oxidizing agent such as nitric acid is contemplated. Before using strong oxidizing agents in contact with Ion Exchange Resins, consult sources knowledgeable in the handling of these materials.

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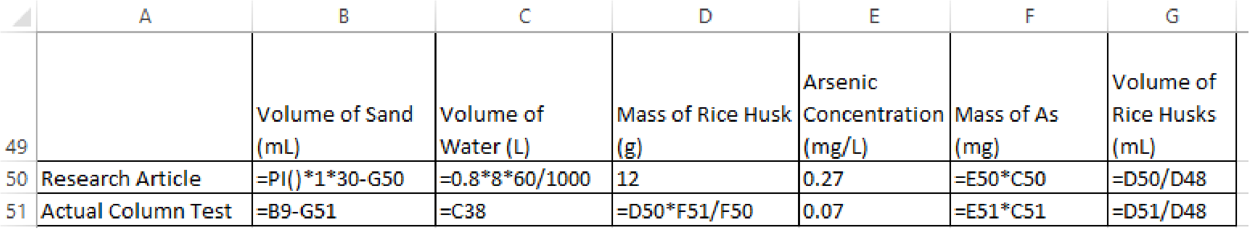
Appendix I: Calculation of Rice Husk Quantity

Note: The article "Removal of Arsenic in Aqueos Solutions by Adsorption onto Waste Rice Husk" has values in Table 2, Sample 1 that were used to model this						
Density of Rice Husk (closest is Rice Bran) from http://www.engineeringtoolbox.com/density-materials-d_1652.html	20	lb/ft^3	0.32	g/cm^3		
	Volume of Sand (mL)	Volume of Water (L)	Mass of Rice Husk (g)	Arsenic Concentration (mg/L)	Mass of As (mg)	Volume of Rice Husks (mL)
Research Article	56.7	0.384	12	0.27	0.10368	37.5
Actual Column Test	585.8	8	65	0.07	0.56	202.5



	A	B	C	D	E	F	G
49		Volume of Sand (mL)	Volume of Water (L)	Mass of Rice Husk (g)	Arsenic Concentration (mg/L)	Mass of As (mg)	Volume of Rice Husks (mL)
50	Research Article	=PI()*1*30-G50	=0.8*8*60/1000	12	0.27	=E50*C50	=D50/D48
51	Actual Column Test	=B9-G51	=C38	=D50*F51/F50	0.07	=E51*C51	=D51/D48

Appendix J: Results for Testing of Alternative Materials

NAU Water Filtration Team U and As Analysis Spreadsheet

Testing of Alternative Materials

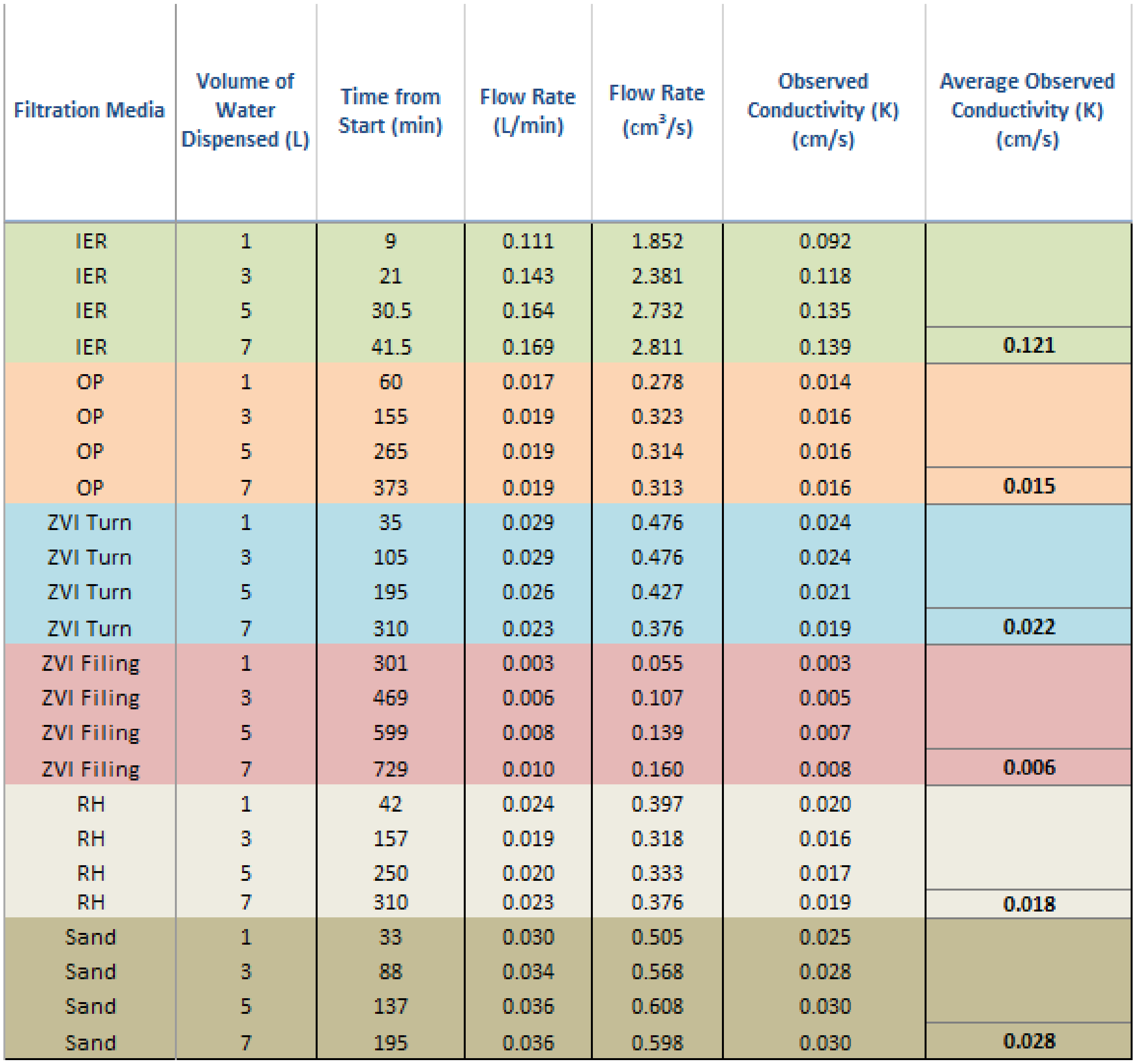
Sample Identifier (Label)	Filtered Water Volume (L)	Filtration Media	Measured Concentration Uranium (ppb)	Measured Concentration Arsenic (ppb)	pH	Turbidity (NTU)	TDS (ppm)	DO (mg/L)	Time from Start (min)
Dilks B1	N/A	N/A: DI Blank	0.02	0	N/A	N/A	N/A	N/A	N/A
Dilks B2	N/A	N/A: DI Blank	0.02	0	N/A	N/A	N/A	N/A	N/A
Dilks B3	N/A	N/A: DI Blank	0.02	0	N/A	N/A	N/A	N/A	N/A
Dilks B4	N/A	N/A: DI Blank	0.02	0	N/A	N/A	N/A	N/A	N/A
Dilks B5	N/A	N/A: DI Blank	0.02	0	N/A	N/A	N/A	N/A	N/A
Dilks B6	N/A	N/A: Synthetic Water	85.88	68.28	N/A	N/A	N/A	N/A	N/A
Dilks B7	N/A	N/A: Synthetic Water	84.86	69.28	N/A	N/A	N/A	N/A	N/A
Dilks B8	N/A	N/A: Synthetic Water	84.61	69.17	N/A	N/A	N/A	N/A	N/A
Dilks B9	N/A	N/A: Synthetic Water	84.65	68.71	N/A	N/A	N/A	N/A	N/A
Dilks B10	N/A	N/A: Synthetic Water	83.55	67.81	7.56	8.0	88	7.46	N/A
Dilks 1	1	Ion Exchange Resin	0.13	2.27	7.80	4.8	131	8.90	9
Dilks 2	3	Ion Exchange Resin	0.09	1.9	7.76	2.9	145	8.90	21
Dilks 3	5	Ion Exchange Resin	0.09	1.84	6.60	2.6	146	8.61	30.5
Dilks 4	7	Ion Exchange Resin	0.09	1.86	6.18	2.6	148	8.47	41.5
Dilks 5	1	Orange Peels	0.82	26.07	6.86	56.9	149	8.49	60
Dilks 6	3	Orange Peels	0.52	48.31	6.96	9.4	131	8.91	155
Dilks 7	5	Orange Peels	0.57	46.35	7.00	3.4	129	7.45	265
Dilks 8	7	Orange Peels	0.52	49.82	7.05	2.5	108	7.45	373
Dilks 9	1	ZVI Turnings	27.91	6.26	7.41	36.9	118	6.90	35
Dilks 10	3	ZVI Turnings	49.64	4.76	7.58	0.7	126	6.56	105
Dilks 11	5	ZVI Turnings	70.92	5.6	7.69	0.9	126	6.60	195
Dilks 12	7	ZVI Turnings	41.69	6.84	7.29	3.2	126	6.94	310
Dilks 13	1	ZVI Filings	0.11	7.92	8.64	9.1	56	8.69	301
Dilks 14	3	ZVI Filings	0.15	2.29	9.04	12.4	63	7.35	469
Dilks 15	5	ZVI Filings	0.14	1.29	8.42	21.4	66	7.63	599
Dilks 16	7	ZVI Filings	0.12	0.79	8.43	15.1	81	7.82	729
Dilks 17	1	Rice Husks	0.77	29.63	6.79	14.5	84	7.28	42
Dilks 18	3	Rice Husks	1.38	51.48	6.85	5.8	114	7.68	157
Dilks 19	5	Rice Husks	7.89	56.36	6.70	8.6	115	7.96	250
Dilks 20	7	Rice Husks	67.41	61.02	7.05	5.5	99	8.11	310
Dilks 21	1	Sand	77.65	38.28	7.73	17.5	101	8.25	33
Dilks 22	3	Sand	77.64	47.12	7.63	22.8	103	8.22	88
Dilks 23	5	Sand	84.13	53.12	7.34	14.8	108	8.50	137
Dilks 24	7	Sand	81.43	55.48	7.72	2.9	111	8.82	195

Appendix K: Scale-up Calculations for Modular Configurations

Step One:

$$\frac{Q}{A} = K_{avg}\left(\frac{h + b_T}{b_T}\right)$$

Where:
Q = Flow rate (cm^3/s)
A = Cross sectional area of column (cm^2)
K_{avg} = Average hydraulic conductivity (cm/s)
h = Head on top of column (cm)
b_T = Total column thickness (cm)



Filtration Media	Volume of Water Dispensed (L)	Time from Start (min)	Flow Rate (L/min)	Flow Rate (cm^3/s)	Observed Conductivity (K) (cm/s)	Average Observed Conductivity (K) (cm/s)
IER	1	9	0.111	1.852	0.092	
IER	3	21	0.143	2.381	0.118	
IER	5	30.5	0.164	2.732	0.135	
IER	7	41.5	0.169	2.811	0.139	**0.121**
OP	1	60	0.017	0.278	0.014	
OP	3	155	0.019	0.323	0.016	
OP	5	265	0.019	0.314	0.016	
OP	7	373	0.019	0.313	0.016	**0.015**
ZVI Turn	1	35	0.029	0.476	0.024	
ZVI Turn	3	105	0.029	0.476	0.024	
ZVI Turn	5	195	0.026	0.427	0.021	
ZVI Turn	7	310	0.023	0.376	0.019	**0.022**
ZVI Filing	1	301	0.003	0.055	0.003	
ZVI Filing	3	469	0.006	0.107	0.005	
ZVI Filing	5	599	0.008	0.139	0.007	
ZVI Filing	7	729	0.010	0.160	0.008	**0.006**
RH	1	42	0.024	0.397	0.020	
RH	3	157	0.019	0.318	0.016	
RH	5	250	0.020	0.333	0.017	
RH	7	310	0.023	0.376	0.019	**0.018**
Sand	1	33	0.030	0.505	0.025	
Sand	3	88	0.034	0.568	0.028	
Sand	5	137	0.036	0.608	0.030	
Sand	7	195	0.036	0.598	0.030	**0.028**

Step Two:

$$K_{avg} = \frac{b_T}{\frac{b_1}{K_1} + \frac{b_2}{K_2} + \frac{b_3}{K_1}}$$

$$K_2 = \frac{b_2}{\frac{b_T}{K_{avg}} - \frac{b_1}{K_1} - \frac{b_3}{K_1}}$$

Where:
b_1 = Thickness of top layer, sand (cm)
b_2 = Thickness of middle layer, material (cm)
b_3 = Thickness of bottom layer, sand (cm)
K_1 = Hydraulic conductivity of top layer, sand (cm/s)
K_2 = Hydraulic conductivity of middle layer, material (cm/s)
K_1 (=K_3) = Hydraulic conductivity of bottom layer, sand (cm/s)

Determination of Hydraulic Conductivity for Each Material

Composite	Average Conductivity for the Composite, K_{avg} (cm/s)	Total Thickness (cm) (b_T)	Layer 1 Material	Layer 1 Thickness (cm) (b_1)	Layer 2 Material	Layer 2 Thickness (cm) (b_2)	Layer 3 Material	Layer 3 Thickness (cm) (b_3)	Conductivity of Sand (K_1) (cm/s)	Conductivity of Material (K_2) (cm/s)
IER/Sand	0.1212	50.80	Sand	7.6	IER	35.6	Sand	7.6	0.0283	0.1212
OP/Sand	0.0152	50.80	Sand	21.6	OP	7.6	Sand	21.6	0.0283	0.0042
ZVI Turning/Sand	0.0218	50.80	Sand	15.2	ZVI Turning	20.3	Sand	15.2	0.0283	0.0162
ZVI Filing/Sand	0.0057	50.80	Sand	15.2	ZVI Filing	20.3	Sand	15.2	0.0283	0.0026
RH/Sand	0.0177	50.80	Sand	11.2	RH	28.4	Sand	11.2	0.0283	0.0136

Step Three:

Composite	Desired Flow Rate (Q) (L/hr)	Layer 1 Material	Layer 1 Thickness (cm) (b_1)	Layer 2 Material	Layer 2 Thickness (cm) (b_2)	Layer 3 Material	Layer 3 Thickness (cm) (b_3)	Total Module Thickness (in) (b_T)	Head on Top of Column (cm) (h) *not to exceed 15 cm
IER/Sand	30.00	Sand	1.50	IER	7.0	Sand	1.50	3.94	5.29
OP/Sand	10.00	Sand	4.25	OP	1.5	Sand	4.25	3.94	10.43
ZVI Turning/Sand	10.00	Sand	2.10	ZVI Turning	2.8	Sand	2.10	2.76	3.00
ZVI Filing/Sand	5.00	Sand	2.10	ZVI Filing	2.8	Sand	2.10	2.76	12.03
RH/Sand	10.00	Sand	3.00	RH	2.3	Sand	3.00	3.26	3.50

Appendix L: Results for Testing of Modular Configurations

Testing of Modular Configurations										
Sample Identifier (Label)	Config-uration #	Filtration Media	Filtered Water Volume (L)	Measured Concentraiton Uranium (ppb)	Measured Concentration Arsenic (ppb)	pH	Turbidity (NTU)	TDS (ppm)	DO (mg/L)	Time from Start (min)
Dilks B1	N/A	N/A: DI Blank	N/A	0.01	0.05	N/A	N/A	N/A	N/A	N/A
Dilks B2			N/A	0.01	0.05	N/A	N/A	N/A	N/A	N/A
Dilks B3			N/A	0.01	0.05	N/A	N/A	N/A	N/A	N/A
Dilks B4			N/A	0.01	0.05	N/A	N/A	N/A	N/A	N/A
Dilks B5			N/A	0.01	0.05	N/A	N/A	N/A	N/A	N/A
Dilks B6	N/A	N/A: Synthetic Water	N/A	91.55	68.65	N/A	N/A	N/A	N/A	N/A
Dilks B7			N/A	91.27	70.57	N/A	N/A	N/A	N/A	N/A
Dilks B8			N/A	92.07	70.01	N/A	N/A	N/A	N/A	N/A
Dilks B9			N/A	91.38	69.88	N/A	N/A	N/A	N/A	N/A
Dilks B10			N/A	91.51	69.92	7.89	4.8	88	7.4	N/A
Dilks 1	1	ZVI Filings, OP	2.5	0.32	8.13	7.32	38.1	182	6.79	56
Dilks 2			5	6.12	8.69	7.31	4.9	112	6.20	100
Dilks 3			7.5	27.32	19.81	7.43	7.8	115	5.84	133
Dilks 4			10	41.23	21.51	7.63	2.3	115	5.43	160
Dilks 5	2	OP, ZVI Filings	12.5	7.83	6.53	8.43	61.8	82	5.82	48
Dilks 6			15	4.16	2.93	8.37	8.3	97	5.89	100
Dilks 7			17.5	3.14	2.14	8.32	7.6	109	5.55	150
Dilks 8			20	2.80	2.27	8.33	23.3	108	5.63	196
Dilks 9	3	OP, ZVI Turnings	2.5	20.17	7.36	7.78	9.0	96	5.41	40
Dilks 10			5	47.42	10.84	7.54	3.7	91	5.26	80
Dilks 11			7.5	50.85	12.08	7.56	3.1	97	5.41	122
Dilks 12			10	67.13	14.98	7.56	2.9	107	5.48	164
Dilks 13	4	ZVI Turnings, OP	12.5	57.11	21.83	7.38	6.6	111	6.08	47
Dilks 14			15	59.34	17.69	7.54	1.9	104	5.86	100
Dilks 15			17.5	72.35	15.58	7.50	1.9	106	5.75	134
Dilks 16			20	73.63	17.88	7.78	1.8	106	5.61	172

Appendix M: Chlorine Dosage Calculations

Step One: Prepare a 1% Stock Solution of 1.0 L

A 1% Stock Solution → $\frac{\text{1 g of Cl}}{\text{100 mL of solution}}$ → $\frac{\text{10 g of Cl}}{\text{1000 mL of solution}}$ → $\frac{\text{10000 mg of Cl}}{\text{1 L of solution}}$

Step Two: Calculate Mass of High Test Hypochlorite Required

$$W = \frac{(1000)VC}{S}$$

Where:
W: grams of HTH required
V: volume of desired stock solution in L
C: concentration of desired solution in %
S: Strength of HTH poweder in % available chlorine

Product= Dry-Tec 68% Calcium Hypochlorite Powdered Chlorine Shock For Swimming Pool 48x1 lb Bags
Supplier= Amazon: http://www.amazon.com/Dry-Tec-Hypochlorite-Powdered-Chlorine-Swimming/dp/B00B9HQ2O6
% Available Cl = 65

W= 15.38 g

*Note this amount should be determined in an easy to use measurement, such as a tablespoon. 14 g is approximately 1 tablespoon, according to: http://dse.healthrepository.org/bitstream/123456789/88/6/How%20to%20prepare%20chlorine%20stock%20solutionv2.pdf

15.38 grams of HTH powder is needed per 1L of water to make the 1% disinfectant solution

Step Three: Calculate Dosage Required

Volume of Water per Day per Capita = 7.5 L

Source: http://www.who.int/water_sanitation_health/publications/2011/9789241548151_ch05.pdf

Housedhold Size = 5 People

Volume of Water per Day per Household = 37.5 L

*Note: The household size is arbitrary

Dose based on worst case scenario, Box 18-3= 5 mL

$$\text{Dosage} = \frac{VD}{10L}$$

Where:

Dosage: dose in L/day

V: volume to be treated in L

D: dose added to the test container in mL, as shown in Box 18-3

Dosage= 18.750 mL of the 1% stock solution /day

$$\text{Mass} = \frac{\text{Dosage} \times W}{1000\ \text{mL}}$$

Mass= 0.288 grams of HTH required to treat 37.500 L of water per day

Mass= 105.288 grams of HTH required to treat 13687.500 L of water per year

Step Four: Cost of HTH per Year

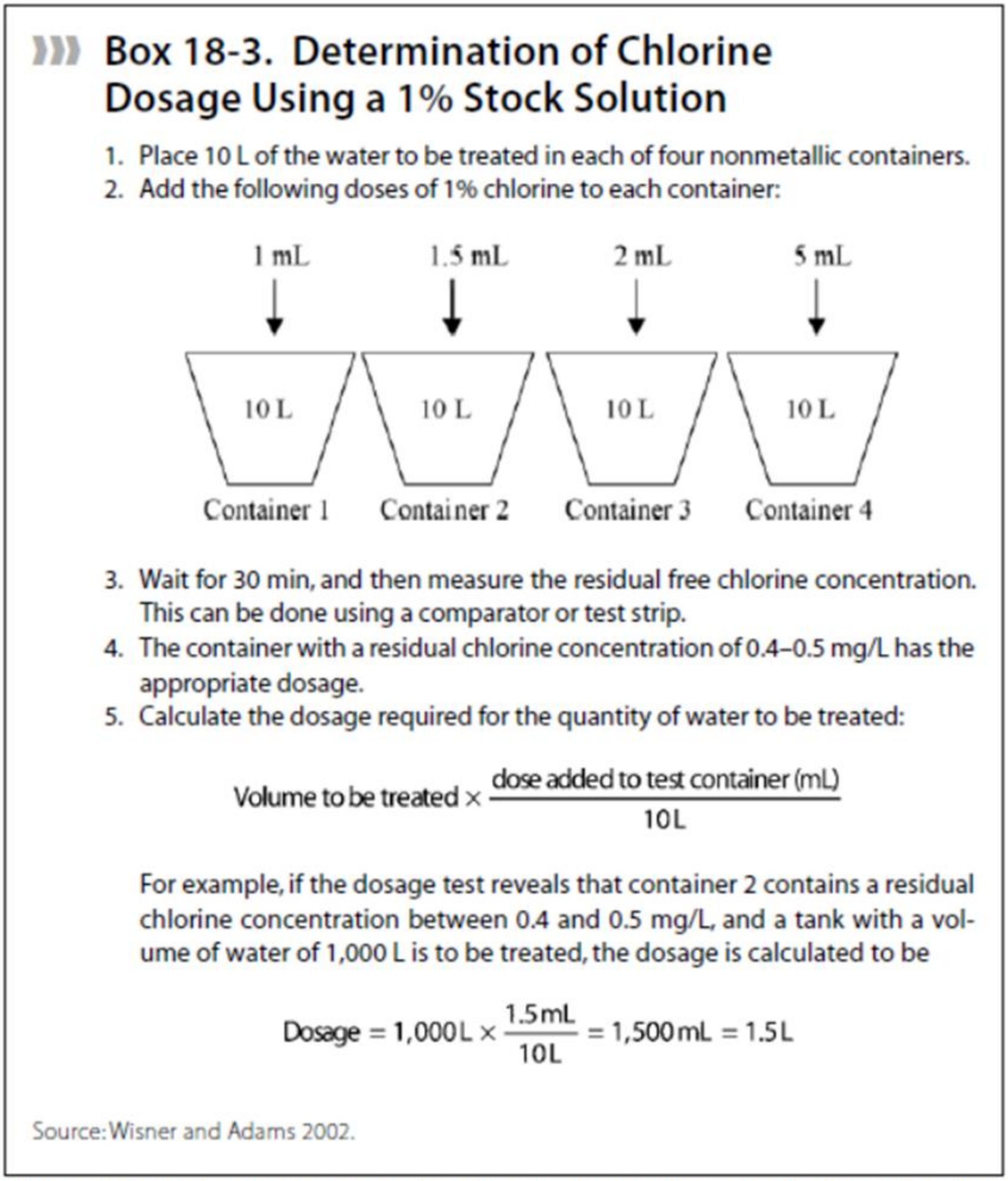
Product= Dry-Tec 68% Calcium Hypochlorite Powdered Chlorine Shock For Swimming Pool 48x1 lb Bags

Supplier= Amazon: http://www.amazon.com/Dry-Tec-Hypochlorite-Powdered-Chlorine-Swimming/dp/B00B9HQ2O6

Total Price ($)	Mass (lb)	Mass (g)	Price ($) per g
144.94	48	21772.416	0.006657

Total Cost per Year ($) = Mass per year (g) x Price ($) per gram

Total Cost per Year ($) = 0.70 per household



Box 18-3. Determination of Chlorine Dosage Using a 1% Stock Solution

1. Place 10 L of the water to be treated in each of four nonmetallic containers.
2. Add the following doses of 1% chlorine to each container:
3. Wait for 30 min, and then measure the residual free chlorine concentration. This can be done using a comparator or test strip.
4. The container with a residual chlorine concentration of 0.4–0.5 mg/L has the appropriate dosage.
5. Calculate the dosage required for the quantity of water to be treated:

$$\text{Volume to be treated} \times \frac{\text{dose added to test container (mL)}}{10\text{L}}$$

For example, if the dosage test reveals that container 2 contains a residual chlorine concentration between 0.4 and 0.5 mg/L, and a tank with a volume of water of 1,000 L is to be treated, the dosage is calculated to be

$$\text{Dosage} = 1{,}000\,\text{L} \times \frac{1.5\,\text{mL}}{10\,\text{L}} = 1{,}500\,\text{mL} = 1.5\,\text{L}$$

Source: Wisner and Adams 2002.

Source: *Field Guide to Environmental Engineering for Development Workers*, ASCE Press

Appendix N: Breakdown of Cost of Project Materials and Chemicals

Filter Materials	**Unit**	**Unit Price ($/Unit)**	**Quantity Purchased (Unit)**	**Cost ($)**	**Source**
Orange Peels	8-lb bag	6.99	4	27.96	Safeway
Ion Exchange Resin	1L	115.00	1	115.00	DOW Website
Rice Husks	2-lb bag	7.90	7	55.30	Amazon
Zero Valent Iron Filings	12oz. Bottle	8.99	4	35.96	Amazon
Gravel	5-gallon bucket	2.50	1	2.50	The Landscape Connection Inc.
Sand	5-gallon bucket	2.50	3	7.50	The Landscape Connection Inc.
Modular Materials	**Unit**	**Unit Price ($/Unit)**	**Quantity Purchased (Unit)**	**Cost ($)**	**Source**
Acrylic Glass (4.75 in outer diameter)	1 foot	26.99	4	107.96	US Plastic Corp.
Acrylic Glass (1.75 in outer diameter)	1 foot	11.32	8	90.56	US Plastic Corp.
Ball Valve	1 valve	15.25	2	30.50	US Plastic Corp.
5 Gallon Bucket	5-gallon bucket	2.78	10	30.15	Home Depot
Mechanical Flexible Coupling	1 coupling	14.56	6	87.36	Home Depot
Epoxy	1 tube	5.47	1	5.47	Home Depot
Cap	1 cap	8.62	2	17.24	Home Depot
120 Mesh Screens	12" x 12" screen	10.45	1	10.45	Pricechef
Nozzles	1 nozzle	1.98	2	3.96	Home Depot
Chemicals	**Unit**	**Unit Price ($/Unit)**	**Quantity Purchased (Unit)**	**Cost ($)**	**Source**
Uranium Standard	250 mL bottle of 10,000 µg/L	250.00	1	270.53	CPI International
Arsenic Standard	250 mL bottle of 10,000 µg/L	65.00	1	85.53	CPI International
			Total Cost of Materials & Chemicals	**983.92**	
Analytical Laboratory Tests	**Unit**	**Unit Price ($/Unit)**	**Quantity Tested (Unit)**	**Cost ($)**	**Source**
U Analysis	1 sample	19.00	60	1140.00	Test America
As Analysis	1 sample	19.00	60	1140.00	Test America
Shipping					
Sample Shipment				10.00	FedEx
			Total Cost of Analytical Lab Tests	**2290.00**	