Automated Electrolyte Delivery System for Batch Desalination in an Electrochemical Flow Cell - Final Report

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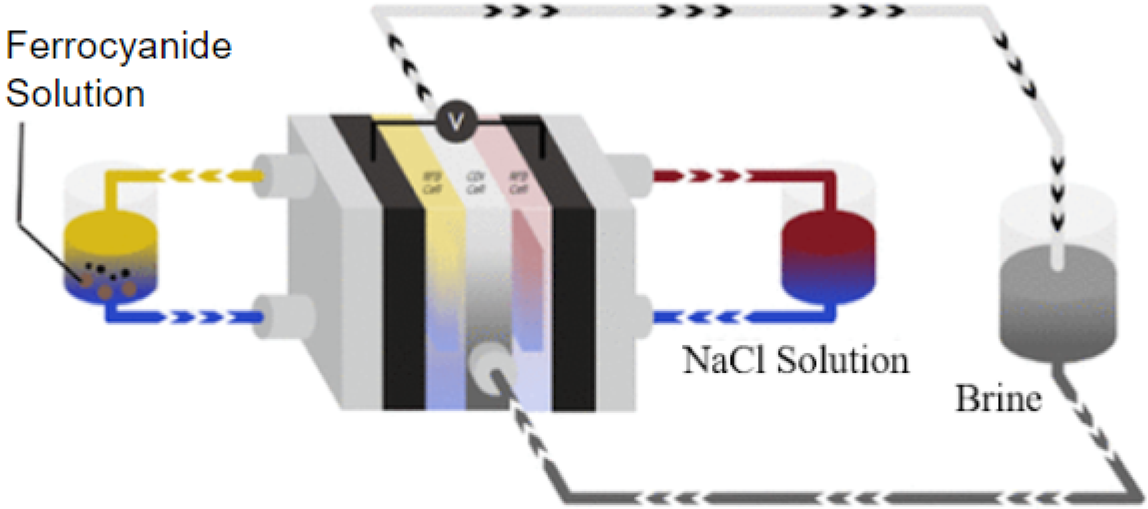

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Table of Contents

ABSTRACT

The goal of this project is to construct an automated electrolyte delivery system for electrochemical desalination. Multiple cycles are required for the salt concentration in the desalinate to reach the desired threshold. The electrolyte delivery system will pump the desalinate into the flow cell at a fixed flow rate until the end of the desalination half-cycle; the system will then clear the fluid lines, pump the salinate into the flow cell until the salination half-cycle is complete; and repeat as required. The ideal design will have a low footprint and should operate with minimal supervision.

PROJECT INTRODUCTION AND BACKGROUND

The goal of this project is to conceive an automated electrolyte delivery system for batch desalination in an electrochemical flow cell handled by Professor David Kwabi and the Kwabi Lab. The Kwabi Lab's electrochemical flow cell operates in batch mode, switching between desalination and salination half-cycles. A fraction of salt is first removed from a sodium chloride solution which is undergoing desalination, and the salt is then discharged into a different waste electrolyte reservoir during the subsequent salination half-cycle. The waste electrolyte used in the current tests is high concentration brine. One cycle alone is not enough for a meaningful amount of desalination to take place. Therefore, the desalination-salination cycle is repeated numerous times for the sodium chloride solution to eventually reach a desired drinkable threshold.

The desalinate is pumped into a flow cell at a constant flow rate during the desalination phase, and an external electric signal is emitted to indicate the end of each half-cycle. In order to clear the lines from any desalinate or salinate residue and avoid cross-contamination between the two reservoirs, air will need to flow through the system before the beginning of each half-cycle and purge the lines into the previously connected reservoir.

The automated electrolyte delivery system will reside in the same fume hood within which the desalination-salination cycles take place, and it will operate efficiently with a low footprint and minimum energy consumption. It will operate without the need for human intervention for up to a week, automatically switching between reservoirs after the end of each half-cycle and avoiding cross-contamination between the sodium chloride solution and the salinate.

INITIAL DESIGNS/STAKEHOLDER ANALYSIS

We are working with Professor Kwabi of the Kwabi Lab, which focuses on flow battery and carbon capture research. We will be primarily working with Ph.D. Candidates Siddhant Singh and Sanat Modak. Siddhant's work novel because it is hybrid flow cell and uses a single nasicon

(Sodium Chloride Super Ionic Conductor) membrane.[14] The flow cell uses a 0.6 M NaCl solution (seawater) to a 0.1-0.2 M (brackish water) NaCl solution for the desalinate. The process utilizes batch desalination with a manual flip between half cycles to change from desalination to salination. It is beneficial to have an automated system so Siddhant would not have to monitor the experiment constantly in order to gather the needed data.[14] If this system can be shown to be usable on a small scale, it can be used on a larger scale to improve the quality of life for people around the world. There were no intellectual property rights to worry about with this project. Below shows an ecosystem map for our project.

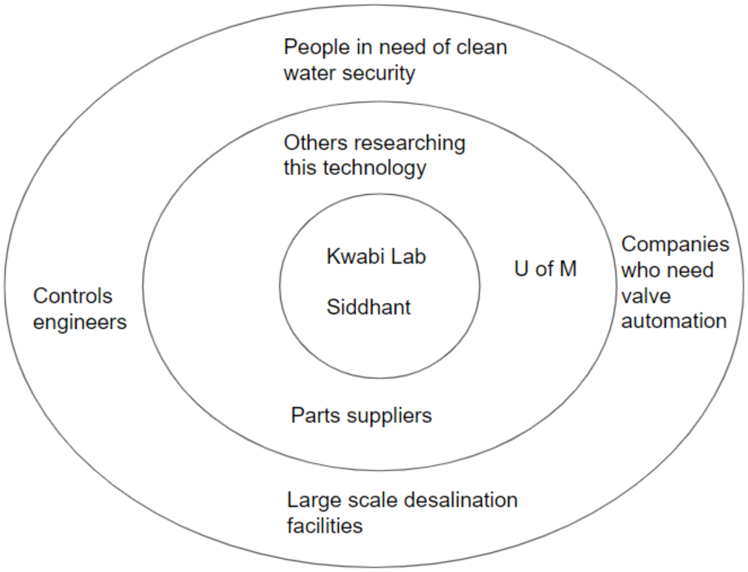
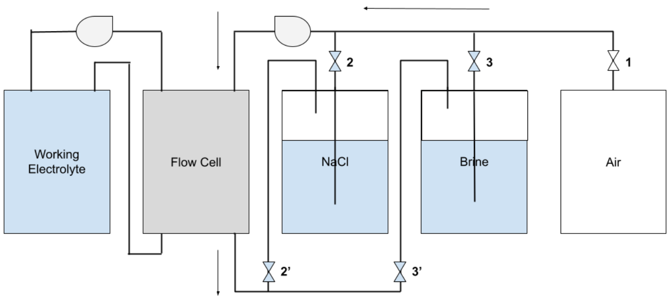


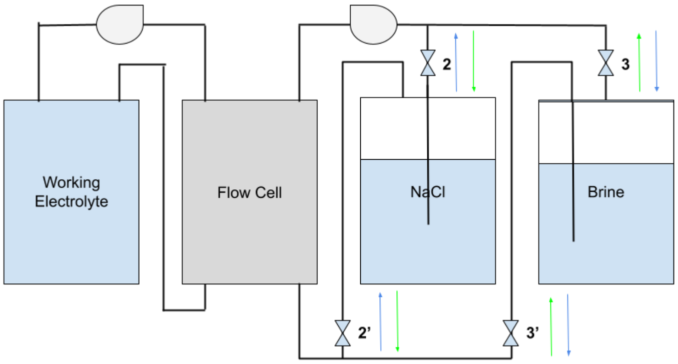
Figure 1. An ecosystem map showing groups of people affected by our project.

Siddhant and Sanat developed two initial designs that we could use. One of them uses five valves to control the flow into the flow cell, and the other uses four but requires the pump to reverse directions. We also developed a two valve design that utilizes two three-way valves. The flow diagrams and control logic for the designs are presented below.



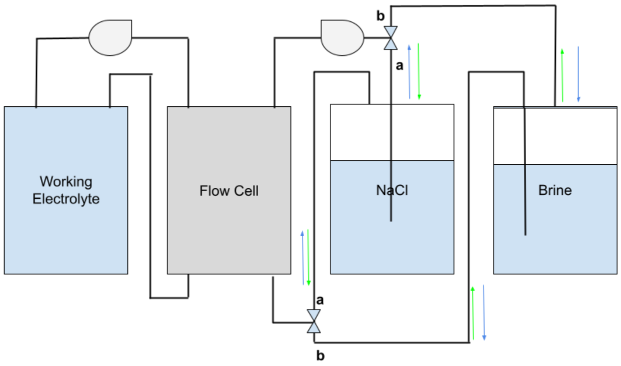
Time	1	2	2'	3	3'
$t < 0$	⊗	○	○	⊗	⊗
$0 \le t < \Delta\tau$	○	⊗	○	⊗	⊗
$\Delta\tau \le t < t_{½}$	⊗	⊗	⊗	○	○
$t = t_{½} + \Delta\tau$	○	⊗	⊗	⊗	○
$t = t_{½} + 2 \cdot \Delta\tau$	⊗	○	○	⊗	⊗

Figure 2. Five valve diagram with corresponding control logic. In the control logic, "○" means open, "⊗" means closed, $\Delta\tau$ is time to purge lines, and $t_{1/2}$ is time for half-cycle.



Time	2	2'	3	3'
$t < 0$	○	○	⊗	⊗
$0 \le t < \Delta\tau$ (Reverse pump direction)	○	○	⊗	⊗
$\Delta\tau \le t < t_{½}$	⊗	⊗	○	○
$t = t_{½} + \Delta\tau$ (Reverse pump direction)	⊗	⊗	○	○
$t = t_{½} + 2 \cdot \Delta\tau$	○	○	⊗	⊗

Figure 3. Four valve diagram with corresponding control logic. In the control logic, "○" means open, "⊗" means closed, $\Delta\tau$ is time to purge lines, and $t_{1/2}$ is time for half-cycle.



Time	1	2
$t < 0$	a	a
$0 \le t < \Delta\tau$ (Reverse pump direction to b)	a	a
$\Delta\tau \le t < t_{½}$	b	b
$t = t_{½} + \Delta\tau$ (Reverse pump direction to a)	b	b
$t = t_{½} + 2 \cdot \Delta\tau$	a	a

Figure 4. Two valve diagram with corresponding control logic. In the control logic, $\Delta\tau$ is time to purge lines and $t_{1/2}$ is time for half-cycle. Valves 1 and 2 have valve positions a and b, corresponding to which way the valve should be open at which part of the desalination process.

We need to ensure that we use the right valves in our design. We need to use a valve that is intended for use with liquids as the seals are different for liquid valves and air valves. We also need to have valves that stay open or closed with no extra input. Valves regulate flow by adjusting positions manually (human) or automatically (pneumatic, hydraulic, electric).[15] Manual automation is time and labor intensive and leads to risk of human error and automation allows for less risk of being exposed to chemicals and more consistency.[10] There are three major types of valves that we could use: control top, solenoid, and motorized. Control top gives real-time info about valve performance (i.e. if the valve is open).[10] Solenoid valves typically need input to stay open or closed (i.e. no input means it will be in the other position).[5] Motorized valves typically go from on to off position and vice versa with current input for small amount of time.[5] To ensure our design meets our requirements, we will most likely need to use motorized valves in our system.

DESIGN CONTEXT

According to a study done by the WHO and UNICEF from 2017, 785 million people had no access to water that could be obtained within 30 minutes and more than 884 million people had no access to safe drinking water. From the same study, around 3 billion people worldwide have no way to safely wash hands, including 75% of sub-Saharan Africans.[9] The UN estimates that by 2030 2.2 billion people will have no access to safe drinking water and 3 billion people will have no way to safely wash their hands.[9] Part of the overarching goal of the project is to make this desalination technology for feasible on a larger scale and thus making clean water more accessible to the masses.

Desalination is used to move excess salts in water to a highly concentrated brine solution. In order to use desalinated water for drinking, further processing is needed, thus making desalinated water suitable for non-potable uses. Two major types of desalination currently exist: thermal distillation and membrane distillation. Thermal distillation is largely used in the Middle East. Thermal distillation can be broken into different categories including multi-stage flash distillation, multi-effect distillation, and vapor compression distillation. In 1980, thermal distillation accounted for ~75% of the world's capacity for desalination.[6] Membrane distillation is largely used in the United States and is broken into categories such as electrodialysis, electrodialysis reversal, and reverse osmosis.[3] In 2011, membrane distillation accounted for up to 60% of world's capacity for desalination.[6] The increase in membrane distillation us due to an increase in availability, efficiency, and reliability coupled with decreased costs.

We do not have much concern regarding the environmental impact of our project. Our pump will run at a very modest power of 37 W and have the least electric consumption possible, with a current input of 0 A required to stay in position; our design does not require a constant input to remain functioning. As a result, we do not estimate much energy consumption. Since we are producing water from brine, we will not have waste production that must be disposed of.

REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Requirements	Specifications	Priority
Use series of valves	No more than 5 valves, no less than 2 valves	1
Reliable with little manual involvement	Operate for up to 7 days unsupervised	2
[1]Use stakeholder's pump	Master Flex Item #EW-07555-00	3
Relatively small volume - must fit inside fume hood	2.5' x 1.5' x 2'	4
[2]Smallest Valves Possible	<12mL total for valves	5
Avoid cross-contamination	< 2mM increase in NaCl solution concentration at end of half-cycle	6
Use an external signal	Trigger signal of +3.5 to +5 Volts	7
[3]Least electric use possible	0 A required to stay in position (i.e. constant input not required to keep closed and/or open)	8

1 Pump is not reversible
2 Volume given by sponsor, changed from priority 8 to 5
3 Since DR1, the valve for the air can be a solenoid valve

Table 1: The table above lists the requirements set by our sponsors and their respective engineering specifications, as well as the estimated priority order our team set for them. Upon initial conversations with our sponsors, a valve system was deemed necessary for their tests and is therefore considered a necessity for our system. The current system the Kwabi Lab is using requires manual input in order to change the reservoir connected to the flow cell, so the objective of our automated system of valves is that of eliminating the need for such manual input. Therefore, we assigned a high priority value to our system's reliability and proficiency in operating for up to one week in an automated manner. In addition, the design must be compatible with the pump that is currently being used to run the desalination and salination half-cycles (which is the Master Flex Item #EW-07555-00), and it must be placed inside the fume hood within which the flow cell resides. Additionally, our valves need to be less than 12mL total, but this is not as high a priority as it would take many ¼" valves to take up 12mL. The efficacy of our design also hinges on its ability to avoid cross-contamination between the sodium chloride

solution reservoir and the brine reservoir, which is why all three of our possible designs allow air to flow in the system between each half-cycle to remove any residues of fluid. The most efficient method to activate the valves' movement was deemed to be an electric signal indicating the end of each half-cycle. In order to maximize the efficiency of the Kwabi Lab's desalination process, our system must consume as little power as possible and the valves must fit the ⅛" pipes without the need of adaptors greater than ¼".

CONCEPT GENERATION

After we had reviewed the preliminary flow diagrams, we expanded upon our ideas by combining the diagrams and changing them as necessary. We also thought of new ways to deliver the salinate and desalinate to the pump, such as using gravity or utilizing robotic arms to move the tubing between reservoirs. In the end, we decided that it was simpler to stick with valves.

We now had to decide what valves were going to be used and what configuration they should be placed. This was accomplished by looking at flow diagrams of different configurations as well as the flow paths within different valves. We ended up with 5 specific flow diagrams that are all discussed in this report, including the 5-valve, 4-valve, 3-valve, and two different 2-valve options. We narrowed in on concepts by discussing the feasibility of each design, whether that be extra hardware we would have to purchase or if the pump needed to be reversed for the design to work. After all factors were considered, we had three feasible concepts that are explained more thoroughly in the sections below.

FINAL CONCEPT SELECTION

Our initial design concepts were all iterations of three original designs: a 5 one-way valve system, a 4 one-way valve system, and a 4 one-way valve system. However, upon further discussion with our sponsors and examination of their testing apparatus, we determined that The Kwabi Lab's pump is only reversible via manual switching - and a more complicated and costly design would have been required to either modify that or completely change the pump altogether in order to reverse the flow direction in an automated manner. Both the 4-valve system and the 2-valve system relied on the basic assumption that the pump's flow could be reversed without the need of human intervention. Therefore, we eliminated all the iterations of those two designs from considerations and reverted our focus to those derived from the original 5-valve system. This allowed us to converge on a significantly smaller sample of possible solutions and carefully examine the pros and cons of each one.

Figure 5: The above figure shows the three original systems from which our array of possible solutions were derived. The 4-valve and the 2-valve systems assumed the automated reversibility of The Kwabi Lab's pump, which upon further inspection was not feasible under the budget offered by our sponsors. We therefore decided to focus on our four design iterations of the 5-valve system.

In all of these four designs, we were able to use fewer than 5 valves by using combinations of one-way, two-way, three-way, and four-way valves. Nevertheless, the fluid flows and the timing of each remained the same as our original 5 one-way valve system.

The first of our updated designs included 2 three-way electric ball valves and 1 one-way solenoid valve. Our sponsor was already in possession of a one-way solenoid valve (which we would have used for the air line), however it was incompatible with the tubing we would have had to use for the rest of the system.

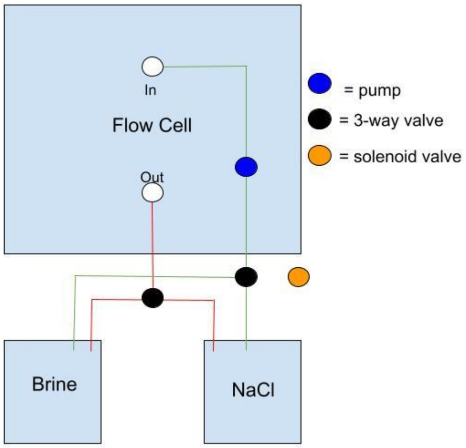


Figure 6: The above figure shows the first of our four updated designs. The 2 three-way valves would connect the fluid reservoirs to the flow cell, and the solenoid valve would allow for air to

flow through the system at the end of each desalination/salination half-cycle to prevent any residue from contaminating the system.

The second updated design included 1 three-way and 1 four-way electric ball valve. We encountered issues in finding a four-way electric ball valve small enough to be compatible with the tubing at our disposal, which represented our main concern with this design.

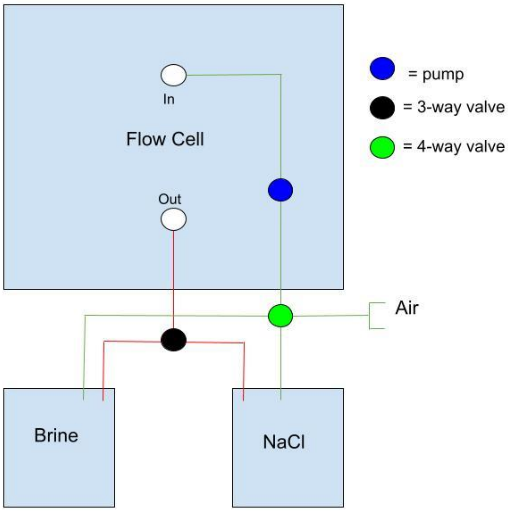


Figure 7: The figure above shows the second of our four updated designs. The three-way valve would allow fluid to flow back from the flow cell into the reservoirs, while the four-way valve would allow fluid to flow from the two reservoirs to the flow cell and air to clean the system.

The third updated design included 3 two-way electric ball-valves, 1 three-way electric ball valve, and a manifold. The latter would be used to direct the flow coming from the reservoirs through the two-way valves and into the flow cell, as well as the airflow to clean the lines. The three-way valve, much like the previous design, would allow fluid to flow back into the reservoirs from the flow cell. This design met all our requirements, yet we did notice how the manifold and the presence of numerous valves would take up a significantly larger volume in The Kwabi Lab's fume hood compared to our other updated designs.

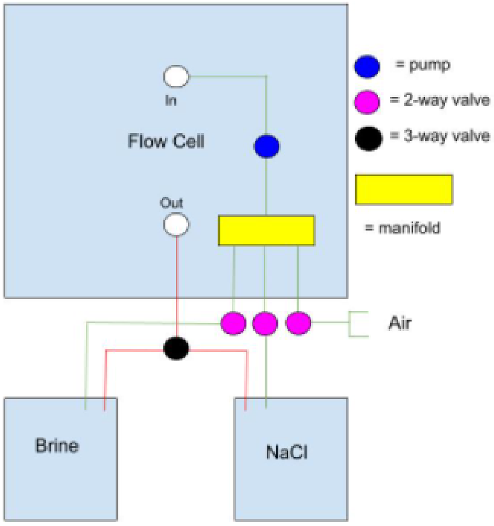


Figure 8: The above figure shows the third of our four updated designs. The two-way valves allow the fluid to flow from the reservoirs into the flow cell and air to clean the lines. The manifold redirects the flows from the two-way valves into the flow cell. The three-way valve allows desalinate and salinate to flow back into their respective reservoirs.

Item	Number	Price per Item	Total
Arduino	1	~$23	$23.00
Two-way Valves	3	$26.99	$80.97
Three-way Valve	1	$64.99	$64.99
Manifold	1	$16.36 (aluminum) or $29.26 (plastic)	$16.36 (aluminum) or $29.26 (plastic)
1/4" NPT Barbed Fitting	10	$9.21	$92.10
1/8" NPT Barbed Fitting	3	$10.79	$32.37
Various Tubing		Supplied by Sponsor	
Total (aluminum)			$309.79
Total (plastic)			$322.69

Table 2: The table above shows the costs associated with the assembly and production of the system shown in Figure 7.

The fourth (and last) of our updated designs included 3 three-way electric ball valves. Each three-way valve was responsible for directing the flow of the fluids as illustrated in the figure below. This design proved to be the most space and cost efficient, and it also met all of our requirements. Moreover, this system would require one less fitting and four less valves than our third updated design, and it also would allow us to implement it without the need to purchase and install a manifold.

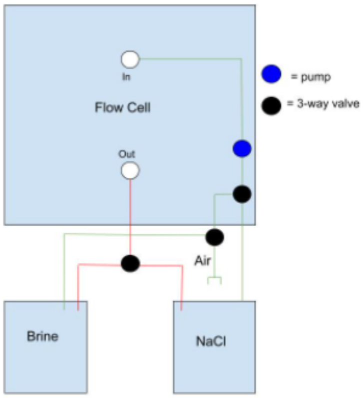


Figure 9: The figure above shows the fourth updated designs. 3 three-way valves are used to have liquid flow between the two reservoirs and air to clean the pipes between each desalination and salination half-cycle.

Item	Number	Price per Item	Total
Arduino	1	~$23	$23.00
Three-way Valve	3	$64.99	$194.97
1/4" NPT Barbed Fitting	9	$9.21	$82.89
Various Tubing	Supplied by Sponsor		
Total			$300.86

Table 3: The above table shows the costs associated with the assembly and production of the system shown in Figure 8:

We deemed this final design to provide us with the most effective and efficient solution to our problem. We would be able to meet all of our sponsor's requirements while operating at the lowest possible cost and in the most efficient manner. Therefore, we then proceeded to develop the flow schematic and control logic for our final design.

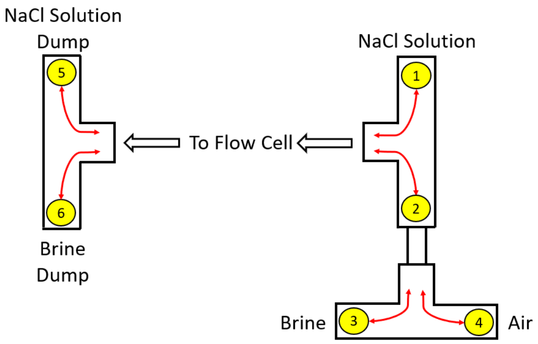
FINAL CONCEPT DESIGN

The following sections give a more detailed explanation of the flow states associated with our final design, the Arduino code which will control the valves, the circuit diagram for controlling the valves, and analysis of the pressure drop estimates of the flowing water.

FLOW STATES

Our final design includes three three-way valves that will be able to change between four different flow states. The figure below shows the position of the valves for each state along with arrows to show the path of a fluid particle for each state.

Process	Valve Positions	Arrow
NaCl Desalination	1, 4, 5	------------->
NaCl Line Clear	2, 4, 5	------------->
Brine Salination	2, 3, 6	------------->
Brine Line Clear	2, 4, 6	------------->



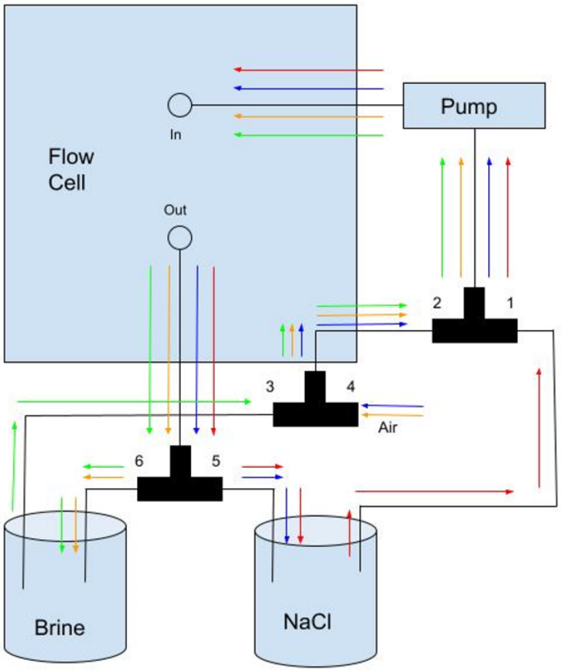


Figure 10: The figure above depicts the flow schematic and control logic of our selected final design.

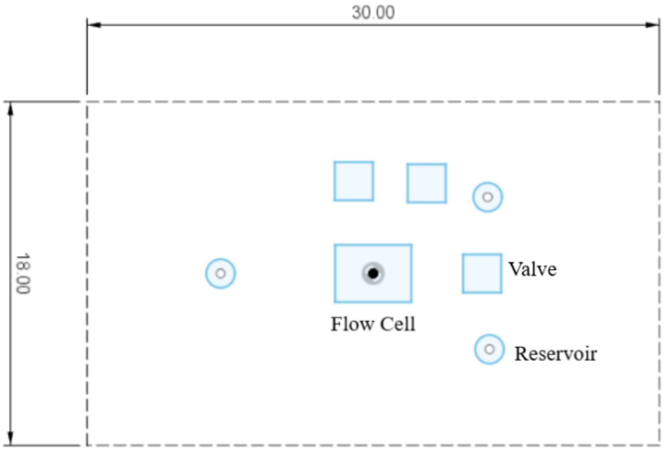
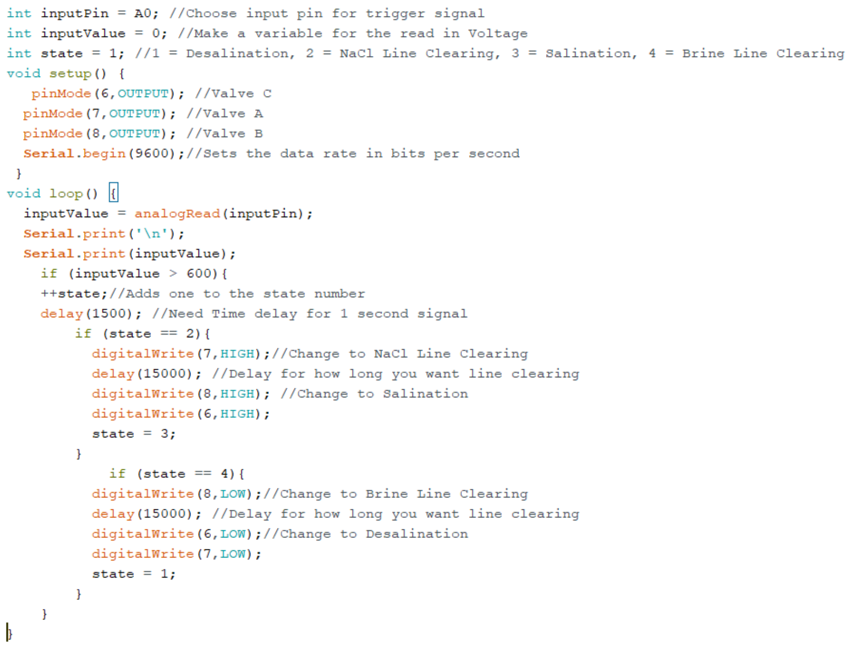


Figure 11: This figure shows that the footprint of our initial final design fits within the 2.5’ x 1.5’ x 2’ box. The height dimension is not shown as no components are taller than roughly 3 inches. Sizes of the flow cell and reservoirs were estimated using a ruler and the size of the valves is estimated based on known dimensions and the picture on Amazon.

ARDUINO CODE

Code was written on the computer and flashed to the Arduino using a USB cable. The code that our Arduino runs can be found below in Figure 11. This code uses the fact that we have four different flow states, as shown above in Figure 9.



```
int inputPin = A0; //Choose input pin for trigger signal
int inputValue = 0; //Make a variable for the read in Voltage
int state = 1; //1 = Desalination, 2 = NaCl Line Clearing, 3 = Salination, 4 = Brine Line Clearing
void setup() {
   pinMode(6,OUTPUT); //Valve C
  pinMode(7,OUTPUT); //Valve A
  pinMode(8,OUTPUT); //Valve B
  Serial.begin(9600);//Sets the data rate in bits per second
 }
void loop() {
  inputValue = analogRead(inputPin);
  Serial.print('\n');
  Serial.print(inputValue);
    if (inputValue > 600){
    ++state;//Adds one to the state number
    delay(1500); //Need Time delay for 1 second signal
        if (state == 2){
          digitalWrite(7,HIGH);//Change to NaCl Line Clearing
          delay(15000); //Delay for how long you want line clearing
          digitalWrite(8,HIGH); //Change to Salination
          digitalWrite(6,HIGH);
          state = 3;
        }
            if (state == 4){
          digitalWrite(8,LOW);//Change to Brine Line Clearing
          delay(15000); //Delay for how long you want line clearing
          digitalWrite(6,LOW);//Change to Desalination
          digitalWrite(7,LOW);
          state = 1;
        }
    }
}
```

Figure 12: The code that the Arduino will run to use a trigger signal to change between NaCl desalination and brine salination half cycles.

The code starts by assuming the valves are in the desalination position, which is defined as State 1. An analog signal is read into the Arduino as a value between 0 and 1023 which represents a signal of 0-5 Volts. When the analog signal is low it reads a value in the 20's and when the analog signal is high it reads a value in the range 890-930. A high voltage reading is our trigger to move to State 2, the NaCl line clearing. We use an "if" statement that will execute the rest of the code when there is a high trigger signal. The code will move the valves to State 2 for an adjustable amount of time and then to State 3, the salination position. Similarly, when the salination cycle is done a high trigger signal will be read in and the valves will change to State 4, the brine line clearing, for an adjustable amount of time. The valve will then move back to State 1 and the process will repeat. Lastly, a time delay of 1.5 seconds after a high trigger signal is read (length of 1 second total) will ensure that the next time an analog signal is read it will be a low reading and won't prematurely send the valves to the next state.

CIRCUIT DIAGRAM

The circuit for the valve system is achieved by using a MOSFET as a switch, where the valve is controlled using the Arduino board, which is connected to a computer that runs the code talked about in the previous section. Figure 12 below shows a diagram of the circuit for one valve. It is true that our system has three valves, however, all valves are connected in the same way to the Arduino board so this circuit diagram is a simple way to view how every valve is actuated. The power supply is connected to operate the valve. The 10 kΩ resistor ensures that the motor stays off when there is no current flowing through the gate of the MOSFET and also connects the gate and source together. When the MOSFET is switched off, the valve may keep pushing the current forward. To keep the valve safe from damage, the flyback diode keeps the current flowing through it when the MOSFET is off. The source is connected to the 5 V power supply on the Arduino and the digital output is connected to the gate of the MOSFET. [16]

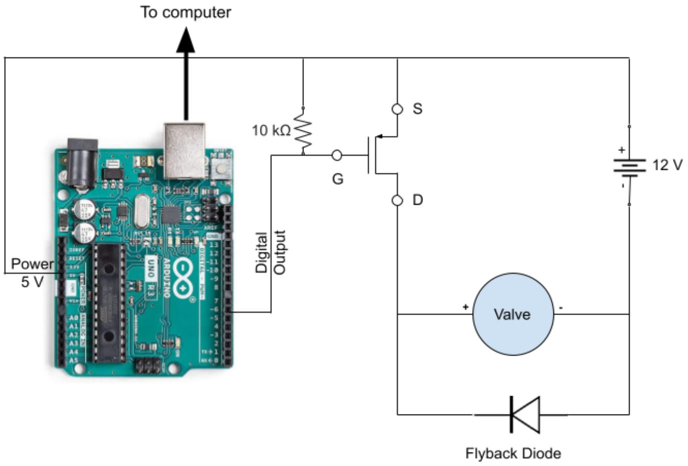


Figure 13. Circuit diagram of the Arduino board connected to a single valve.

ENGINEERING ANALYSIS

We performed analysis on the system including a calculation of valve volumes, an estimate of the power consumption and cost, and an estimate of the pressure drops due to the fluid running through the lines and turning through the valves. Our total valve volume could not exceed 12mL, so we calculated the volume of our valves by the equation

$$V = 3 \cdot \frac{4}{3}\pi r^3$$

Where we multiply by three for three valves, and *r* is the radius of the valve (¼” is the diameter). From this we calculated the total volume of the three valves to be 2.22mL, which is significantly less than the 12mL upper limit. Additionally we estimated power consumption of the valves using data given for a similar ¼” valve .(US Solid Valve Item # USS-MSU00025). Energy consumption is given by the equation

$$E = P \cdot t$$

Where *P* is the power consumption and *t* is the time. From this equation we determined the maximum power consumption per position change is 10 J. Knowing that there are six position changes per desalination cycle, we know that there is a maximum of 60 J consumed per cycle. Using a 10.93 ¢ /kWh average for commercial electricity in Ann Arbor, we determined that one cycle costs roughly 1.8E-4 ¢ .[1]

Lastly, pressure drop was estimated for the lines and the valves that the fluid is running through. Major losses were considered to be the losses through the lines and minor losses were considered to be the losses at the valves, which were modeled as 90 degree elbows. It was also assumed that there is laminar flow in the lines and that there is no change in elevation.The volume flow rate, *Q*, was given by the sponsor to be 20-60 mL/min. Equations below were used to calculate these losses. First we started by calculating the mass flow rate, *m*, and the velocity, *V*, of the fluid with the equations below

$$m = Q\rho \qquad V = \frac{m}{A\rho}$$

Where ρ is density and *A* is area of the fluid flow through the line.We then calculated the Reynold’s Number defined as

$$Re = \frac{DV\rho}{\mu}$$

Where *D* is the diameter of the fluid flow line, *V* is the velocity of the fluid, ϱ is the density of the fluid, and μ is the dynamic viscosity of the fluid. Next we calculated our total losses, h_T, as the sum of the major losses, h_l, and minor losses, h_{lm}. The equation for total losses is as follows

$$h_T = \frac{64}{Re}\frac{L}{D}\frac{V^2}{2} + K\frac{V^2}{2}$$

Where *L* is the length of the line and *K* is the loss coefficient for a 90 degree elbow. Lastly, the pressure drop, ΔP, is calculated as

$$\Delta P = h_T \rho$$

From these calculations we estimate the pressure drop through the lines and the valves to be between 117-334 Pa. Additionally, we know that for pumps we can use the equation

$$P = Q\Delta P$$

Where *W* is the pump power. By these calculations we determined the flow rate would be far too high. This is due to the fact that there is also a pressure drop across the flow cell, ΔP_{Cell}, which can be calculated by the equation

$$\Delta P_{Cell} = e \cdot Re^h$$

Where *e* and *h* are empirically determined constants for each flow cell electrode and geometry.[17] We don't have these constants for our flow cell, but we know we are using a peristaltic pump which can deliver a specific, reliable amount of fluid regardless of pressure drop. The pump being used has variable power consumption and thus variable speed control. Additionally, the pump that is being used is capable of delivering 1.2-2,900 mL/min and the experiment is operating at 20-60 mL/min. Lastly, we are not concerned that these discrepancies will cause a problem because the experiment is currently being run just without the valves. We doubt the addition of valves will cause a pressure drop that becomes a major disruption to the system.

VERIFICATION AND VALIDATION

We have deemed that our team will need to perform tests on our system of valves in order to validate our model and to verify that the specifications have been met. We have identified three of our previously listed requirements whose specs we will be looking to establish empirically.

Third on our priority ranking is the requirement that our system fit inside The Kwabi Lab’s fume hood, which we have quantified as having a volume of 2.5’ x 2’ x 1.5’. However, we must also consider that the flow cell and wiring will also be present inside the fume hood, so we will have to account for that already used up volume when assembling our system. Our design takes up a volume that is considerably smaller than that of the fume hood, and we anticipate that it should not cause any spatial issues during the operation of the flow cell. However, we will set our system up and ensure that it does not cause any impediment to the operators during the preparation phase and the half-cycles.

We have also mentioned how our system of valves must be set up in such a way that cross-contamination must be avoided between the sodium chloride solution and brine reservoirs - increases in the concentration of the NaCl solution must not exceed 2mM. To verify this, we can set up a system analogous to that present in The Kwabi Lab but, instead of reservoirs of NaCl solution and brine, we will use water and food dye (the coloring of the food dye will allow any cross-contamination to be easily observed even before any concentration measurement takes place). At the end of each cycle, we will measure the concentration of food dye present in the water reservoir and ensure that it does not exceed the specified amount.

The main objective of our project is to allow The Kwabi Lab to operate their continuous desalination and salination half-cycles with little to no manual involvement. Our goal is that our system of valves will enable the flow cell to operate in an automated manner for at least a week. The only way to ensure that this is the case is to set up our system and observe any failures. We were able to run our system of valves for about 3 hours uninterrupted during the design expo. Due to time constraints we were unable to test for a full week.

We have been constantly updating our sponsors to ensure that our model is valid and that its performance meets their requirements. We are confident that our system’s successful functioning will enable The Kwabi Lab to facilitate their operations.

DISCUSSION OF THE FINAL DESIGN

We would have liked to explore changing the direction of the pump more, but communication between our team and the pump manufacturer was too difficult and they did not understand our questions as completely as we would have liked them too. Our design shines in its simplicity, although sometimes that is challenging. During our initial verification during the Design Expo testing the system’s reliability, we discovered that there was more of the salinate creeping into the desalinate We resolved this problem on the fly by increasing the line clearing time because we failed to account for a larger volume of fluid between the two inlet valves. In an updated design, we would like to have one 4-way valve that would replace the two 3-way valves, however the size and cost restraints prohibited our prototype from using one, but a 4-way valve could be used on a larger scale.

REFLECTION

The research on desalination processes that The Kwabi Lab is working on could potentially have an impact on public health, safety, and welfare. If successful in their studies, the applications of a more efficient and effective desalination process could prove, over time, to be beneficial for the worldwide efforts towards helping those areas of the world where clean and drinkable water is not readily available. Our system of valves could be indirectly relevant in these aforementioned applications by allowing The Kwabi Lab to collect data points with more efficiency and a higher frequency. Large-scale production of this system could also prove to be profitable, with the manufacturing costs of the automated electrolyte delivery system representing only a fraction of the cost of the whole desalination system itself. To identify the potential societal impacts of our design, we worked closely with our sponsor to create an ecosystem map, as shown in Figure 1.

Our approach to the design was affected by differences between team members because we come from three different countries and so had differing perspectives on engineering solutions to complex problems. Our relationship with our sponsor affected our design process because Siddhant and Sanat had power over the way the final design should look, as they are the end users. This was most prevalent at the end when we had wiring everywhere and they asked us to package it into some kind of container, which we were able to do successfully.

In the end, we ended up having a similar perspective on the project as our sponsor when it came to how the final design should look and work. Converging on our perspectives took a little while as we were trying to understand the project better and we grew our relationship with our sponsor. They helped us to learn more about desalination and why our project is relevant to them. Team power dynamics did not play much of a role as everyone was listened to and included in the design process. In order to have diverse viewpoints on the design, we held multiple meetings with our stakeholders as the project progressed through different stages. We took everyone's ideas into consideration, but when Siddhant and Sanat had ideas, we would ask if this was something that they really needed or if they would mind if we did it another way. Open communication between our team and our sponsor made it easy to come up with a final product that our sponsor would be happy with.

We didn't face many ethical dilemmas throughout our project, but they are important to consider either way. We sourced our supplies from Amazon and McMaster-Carr, and it is important to consider whether these companies treat their workforce correctly and ethically source their materials and goods.

Ethical issues that could arise if our product was to enter the marketplace include whether the valves and the materials were being ethically sourced. There are a lot of electronics in our product and it could be a source of worry if the metals that are being used are coming from workers and places that are being exploited for a profit.

Our personal ethics are similar to the professional ethics we are expected to uphold by the University of Michigan because we stand for integrity and always doing the right thing. We would expect that these ethics would also be very similar to those expected by a future employer.

RECOMMENDATIONS

On the lab scale project, our first recommendation would be to always keep the circuitry with the arduino board and breadboard inside a casing; this could be a case or box made out of either plastic or sheet metal to keep the circuitry safe from any spillage inside the lab. Holes would need to be cut out within the case to allow for incoming and outgoing wiring. Our second recommendation is to be careful regarding cross-contamination of the brine and pure water solutions. Through testing, we've observed that this occurs in mainly two ways: (i) the time delay (as seen in Figure 11) for line clearing must be sufficiently long enough, which is estimated by us to be around 20 seconds, and (ii) the tubes must not overflow, which we can avoid by making half-cycles sufficiently long. Our third recommendation would be to troubleshoot a fail-safe for the circuit; in our testing, we have damaged two Arduino boards to the point where they would not receive any input anymore. Due to time constraints, we could not add a fuse or circuit-breaker to our project, but this should be looked into as if the project were to be running the full length of its duration, failure of the Arduino board would be dangerous.

When scaling the project up to the industry level, our control logic and valve orientation will remain the same. Appropriate sized valves, fittings and pump would need to be purchased. However, one change we would recommend is to change the use of an Arduino system to a more appropriate control system for industry scale projects.

CONCLUSION

Desalination is a growing and increasingly important technology that can help give more people access to clean water. The Kwabi Lab is studying batch desalination of sodium chloride solutions using a hybrid flow cell. The use of batch desalination requires switching between desalination and salination half cycles. This switch is done by moving the flow lines from one reservoir to another. The Kwabi Lab has asked us to design and build a system of automated valves that can switch between half-cycles while avoiding cross contamination between the NaCl solution and the brine. We have developed a final concept that involves the use of three valves and six valve position changes per full cycle. We have successfully made the system work using an Arduino and MOSFETs as switches to control the valves. We were able to package it up so that it is easy to set up and use. One weakness with our packaging is that if the Arduino stops working it will be possible to replace it but will be annoying to do so. Our design may not be the most robust and would need more work if being used on a larger scale, but it is a good proof of concept that can be used to more efficiently run experiments in the Kwabi Lab.

ACKNOWLEDGEMENTS

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TEAM BIOS

Adalberto Rinaldi

I am a current senior at the University of Michigan completing a Bachelor of Science in Engineering in Mechanical Engineering and a Bachelor of Science in Economics. I was born and raised in Rome, Italy, and growing up I developed a deep fascination for quantitative subjects and sports. I began my collegiate career at Michigan with the desire to learn from some of the most prominent figures in the field of Mechanical Engineering and play for the Michigan Football Team, of which I was a member throughout my freshman year. My ambition is to combine the technical skills necessary to comprehend complex mechanical systems with a refined understanding of the markets within which engineering firms operate, and eventually transition into the management team of a leading engineering firm. I have been involved in research as a PhD Research Assistant and have run tests on a commercial Cummins engine, and have had an internship as a portfolio manager in a private bank in Rome. At the moment, I am working part-time for a New York-based mergers and acquisitions firm as a Junior Associate. I plan on accepting an offer from MIT's 18-month Master of Finance program in Cambridge, MA starting in July 2022.

Robert Sykes

I am a senior completing my Bachelor of Science in Mechanical Engineering with a concentration in Energy and a minor in Music. I am from San Antonio, Texas, and come from a long line of Michigan graduates. I became fascinated with engineering from a young age when I was exposed to food manufacturing machinery when touring plants that my mom would visit as a part of her job. Science and engineering shows on television also helped to steer me towards a career in engineering. Growing up my family would go to our lake or ranch house on the weekends and I would almost always end up helping my dad tinker with random projects. While at Michigan, I have been a part of many different ensembles including the Michigan Marching Band, the Michigan Hockey Band, Trumpet Ensemble, and Campus Band. After graduation, I will be working at the Valero McKee Refinery in Sunray, Texas, as an associate mechanical engineer looking after the fixed equipment in various units in the refinery.

Thomas Vaughn

I am currently a senior at the University of Michigan working towards a Bachelor of Science in Mechanical Engineering. I am from Oakdale, New York, and come from a family of five engineers. My parents are both electrical engineers and were the ones who first inspired me to go into engineering. In high school, I took a series of classes that involved taking apart and reassembling small internal combustion engines, and from that point on I knew I wanted to do engineering. When the time came to make a decision, I decided to do Mechanical over Aerospace Engineering because I wasn't exactly sure what I wanted to do in the future. At Michigan, I have been a part of the Pi Tau Sigma drone team as well as worked in the NEEC Lab for the past two years. After graduation, I will be working as a civil engineer in Park City, UT.

Ayman Mannan

I am a senior at the University of Michigan finishing my Bachelors of Science in Engineering in Mechanical Engineering. My interests in the field are controls focused as I am interested in mechatronics and electromechanical systems. I grew up in Dhaka, Bangladesh and observed my father working in an industrial environment; he was also very interested in cars, the combination of which synthesized my interest in engineering. I have worked in tutoring and healthcare, so academics is also an interest of mine. After graduation, I hope to work in risk analysis or financial technology.

APPENDIX

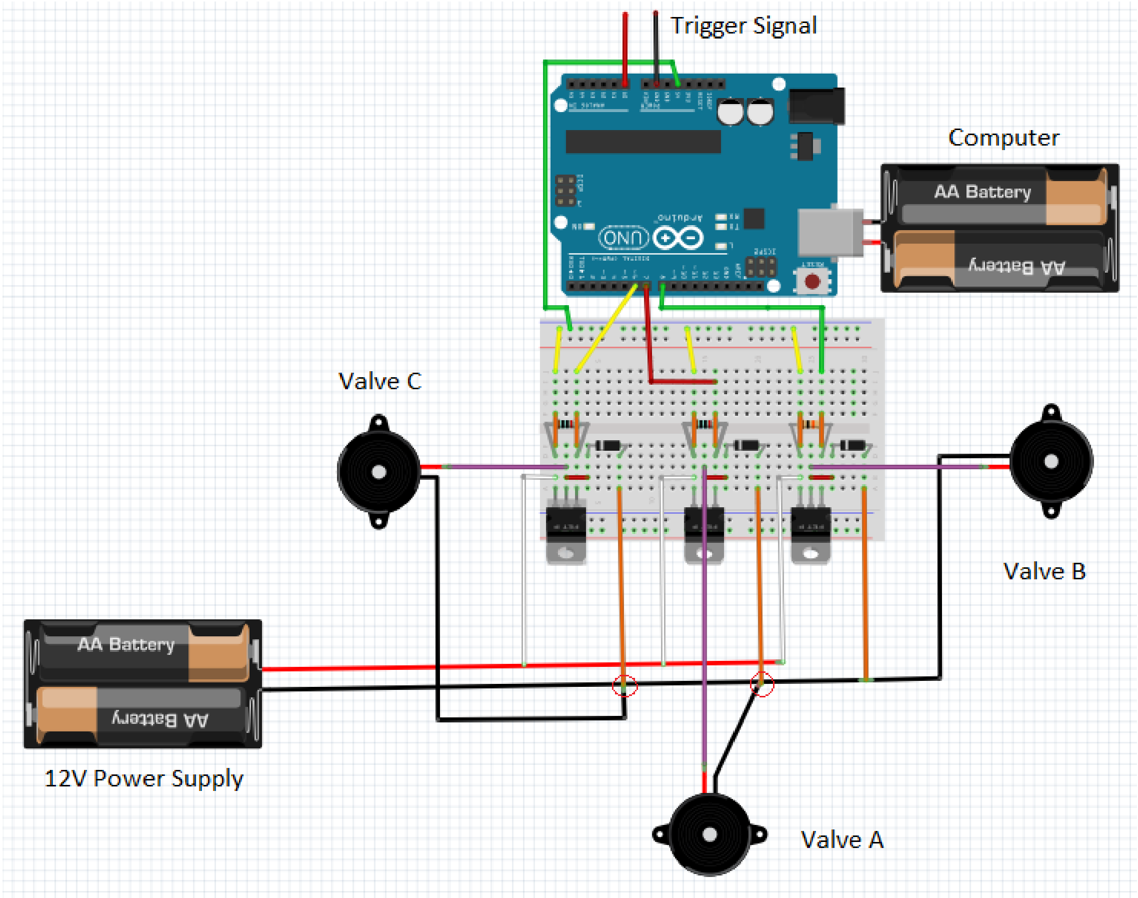
Bill of Materials

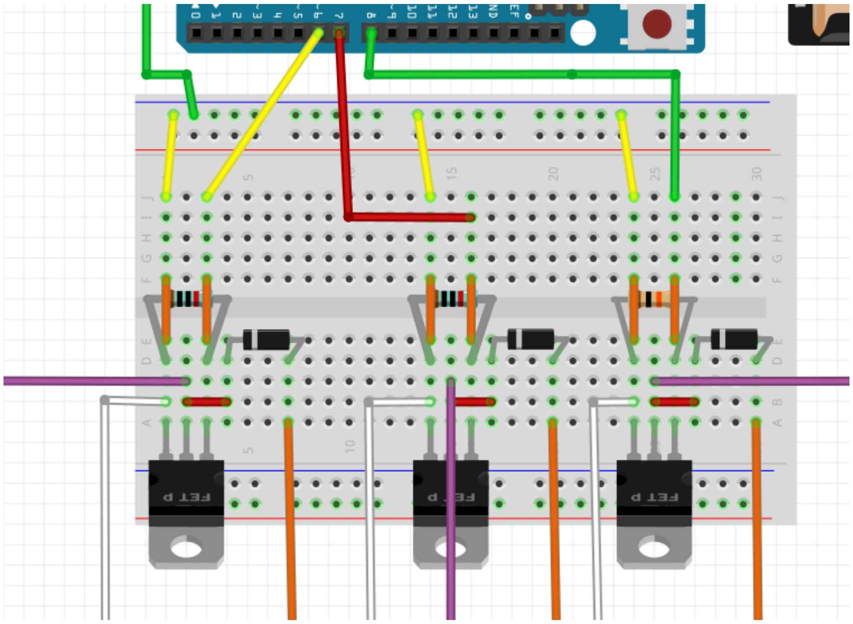
Below is our final Bill of Materials for the system we delivered to our sponsors.

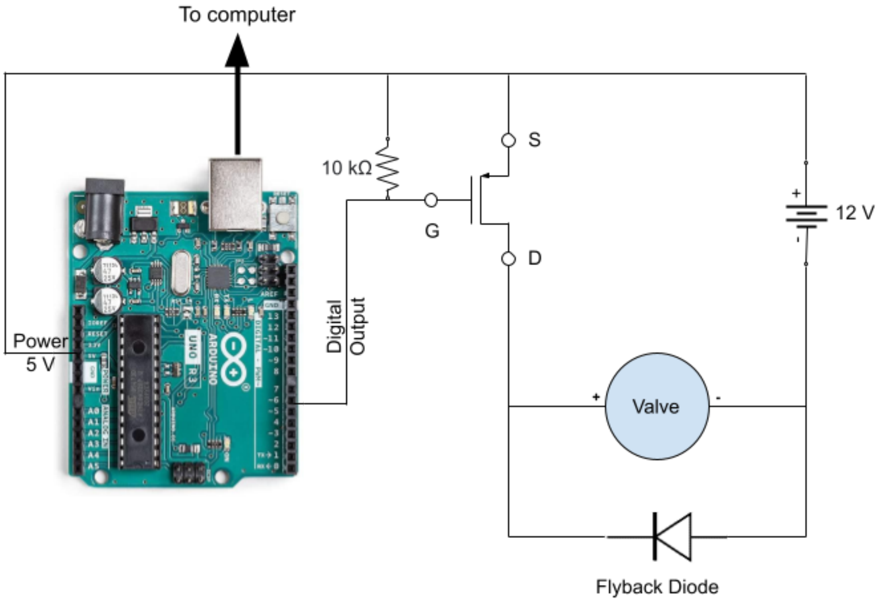
Item	Quantity	Source	Manufacturer	Item Number	Cost (per item)	Comments
HSH-Flo 3 Way 1/4" 12V/24VAC/DC L Type Auto Return Brass Electrical On/Off Motorized Ball Valve	3	Amazon.com	HSH-Flo	T8-B3L-B	$64.99	
Universal-Thread Push-to-Connect Tube Fitting, Nickel-Plated Brass, Straight, 1/8" OD x 1/4 Pipe Size	2	McMaster-Carr	McMaster-Carr	7397N13	$15.20	2 packs of 5
Standard-Wall Brass Pipe Nipple, Threaded on Both Ends, 1/4 NPT, 1-1/2" Long	1	McMaster-Carr	McMaster-Carr	4568K132	$2.97	
P-channel Power MOSFET - TO-220 Package - 25A / 60V	3	X50 Lab	Fairchild Semiconductor	FQP27P06	$2.95	
10 kΩ Resistor	3	X50 Lab				
Flyback Diode	3	X50 Lab				
Arduino Uno SMD Rev3	1	Amazon.com	Arduino	8541585410	$25.35	
Various wiring and connectors		X50 Lab				
1/8 OD 1/16 ID Tubing		Kwabi Lab				
12V 2A DC Power Supply	1	Amazon.com	ShenZhen ZuoEn Technologies Co. Ltd	ISP-NW-PS-12V-WP-UL-24W	$8.89	
Solderless Breadboard	1	X50 Lab				

Manufacturing Plan

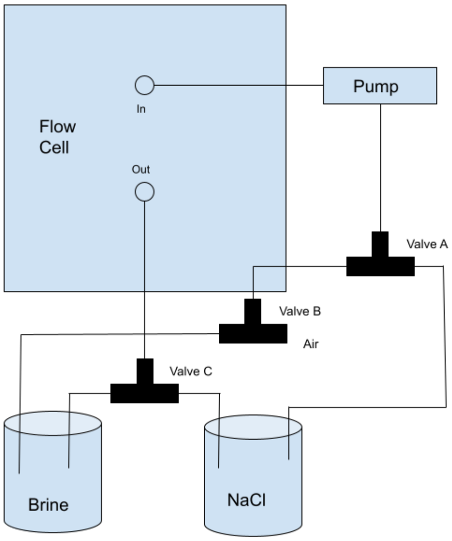
Below is all the electrical setup that is needed for the valves. Notice there are two red circles above Valve A. These circles represent connection points. Any other wires crossing each other are not connected. The Arduino is powered with a USB cable from a computer while the valves are controlled by a 12V power supply. The image following the one below shows a zoomed in view of the breadboard. The direction of the MOSFET and the diode are of importance and it will not work if one or both are in the wrong direction. The MOSFET is placed such that the gate is to the right (in this picture). The direction of the diode can be determined by the narrow band on one side of it. The breadboard is three of the same circuits in parallel. Each circuit has one MOSFET that acts as a switch and controls one valve. The circuit diagram for control of one valve is also given below. The resistors in the circuit are 10k Ω and the MOSFETS are P-channel MOSFETS.



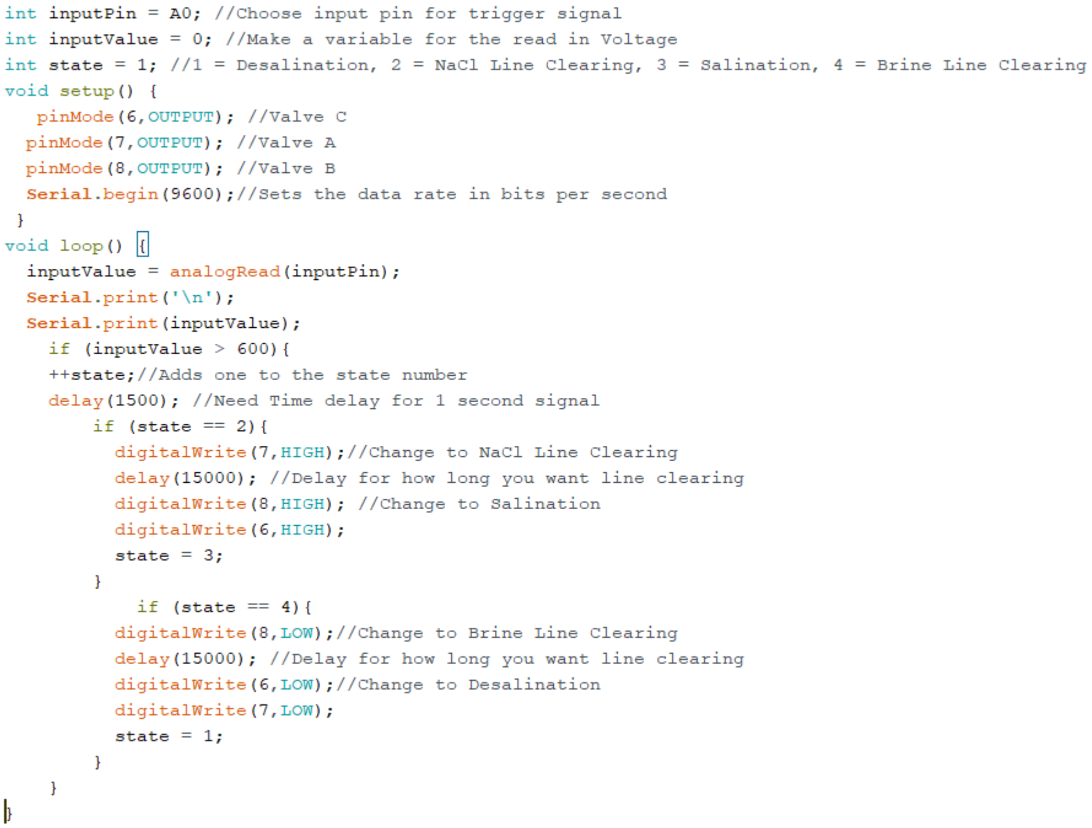

FET P
FET P
FET P


To computer
10 kΩ
S
G
D
+
12 V
-
Power
5 V
Digital
Output
+
Valve
-
Flyback Diode

The image below shows how the valves need to be connected to the pump, the flow cell, and the reservoirs in order for the Arduino to properly run through the four flow states.



Lastly, the Arduino code needed to run the valves is shown below.



```
int inputPin = A0; //Choose input pin for trigger signal
int inputValue = 0; //Make a variable for the read in Voltage
int state = 1; //1 = Desalination, 2 = NaCl Line Clearing, 3 = Salination, 4 = Brine Line Clearing
void setup() {
   pinMode(6,OUTPUT); //Valve C
  pinMode(7,OUTPUT); //Valve A
  pinMode(8,OUTPUT); //Valve B
  Serial.begin(9600);//Sets the data rate in bits per second
 }
void loop() {
  inputValue = analogRead(inputPin);
  Serial.print('\n');
  Serial.print(inputValue);
    if (inputValue > 600){
    ++state;//Adds one to the state number
    delay(1500); //Need Time delay for 1 second signal
        if (state == 2){
          digitalWrite(7,HIGH);//Change to NaCl Line Clearing
          delay(15000); //Delay for how long you want line clearing
          digitalWrite(8,HIGH); //Change to Salination
          digitalWrite(6,HIGH);
          state = 3;
        }
            if (state == 4){
          digitalWrite(8,LOW);//Change to Brine Line Clearing
          delay(15000); //Delay for how long you want line clearing
          digitalWrite(6,LOW);//Change to Desalination
          digitalWrite(7,LOW);
          state = 1;
        }
    }
}
```