# Ram Pump, Spring 2017

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**Abstract**

The purpose of the Ram Pump team is to fabricate a properly functioning hydraulic ram pump, or hydram, for implementation in AguaClara plants. The hydram is designed to deliver outgoing water initially flowing towards the distribution tank back to the facility for utilization in chemical stock tanks or to collect water at higher elevations for other plumbing needs (toilets in the plant etc.). The team's main goals for this semester are to determine which parameters are effective in allowing the system to work at minimal driving head as well as developing an audio-based diagnostic system for plant operator use in order to identify specific issues and apply correct solutions.

## Introduction

The main function of a ram pump is to take a fraction of hydraulic flow and, exploiting the properties of negative gauge pressure and momentum, deliver this water to a higher elevation. This technique is very suitable for implementation in AguaClara water treatment plants since the system requires no electricity to function, is sustainable, and can operate for extended periods of time without maintenance. Once this water is pumped back to the treatment facility, the plant is able to continually provide water for the coagulant and chlorine tanks as well as additional water for plumbing needs. This eliminates the need for manual labor or the use of electricity.

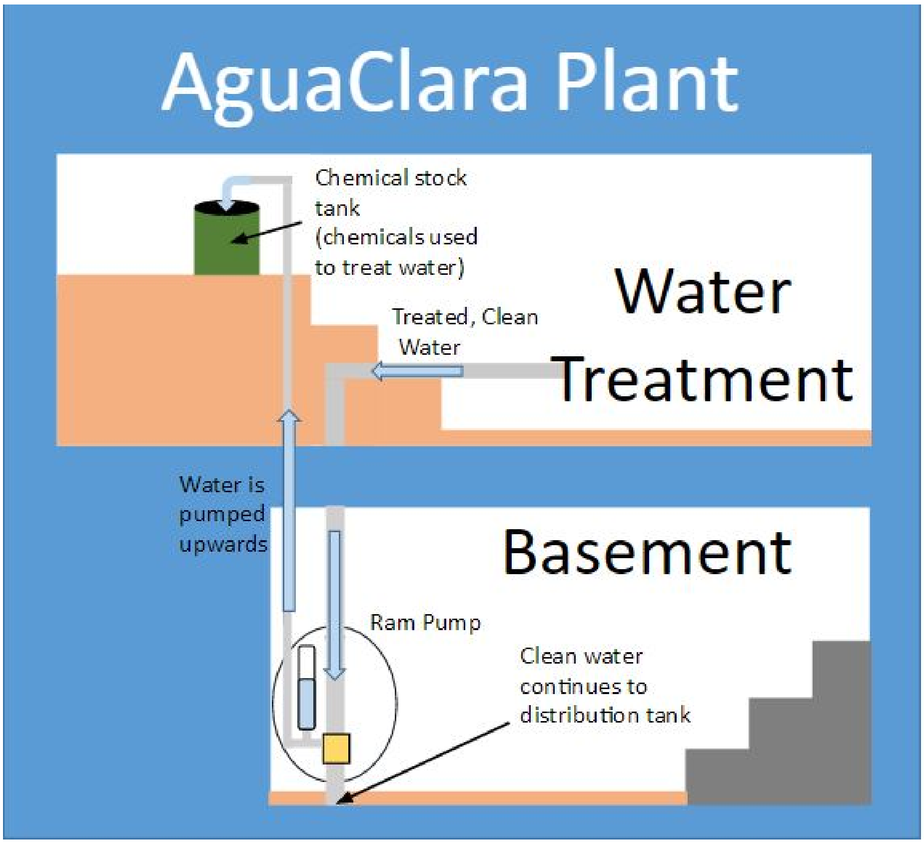


Figure 1: This image shows the overall concept behind the implementation of the ram pump design. Treated water flowing from the plant above reaches the pump below where it is then delivered back to the beginning of the treatment process. This allows coagulant and chlorine tanks to be replenished autonomously.(Aggarwal and Guzman, 2016)

During the Winter of 2017, the team visited Honduras and attempted to implement the ram pump in the Las Vegas AguaClara plant. Although the ram pump still delivered water, its rhythm was inconsistent and sporadic, implying a dysfunctional ram pump. Professor Monroe Weber-Shirk hypothesized that this was the result of the reduced driving head unique to the Las Vegas plant. Driving head, also known as pressure head, is the distance between the inlet and the outlet of water flow which signifies the available potential energy of the pumping system. The outlet of water is also referred to as the piezometer bottom. The lower the driving head, the less energy available for pumping action by the hydram. This relationship can be described by the following equation:

$$\psi = \frac{P}{\gamma} = \frac{P}{\rho g}$$

where $\gamma$ is the weight of the liquid, P is the gauge pressure (Force per unit area), $\rho$ is the density of water, and g is the acceleration due to gravity.

The Las Vegas plant has about 50% less available driving head than that of the ram pump simulated in the AguaClara lab at Cornell which has a maximum of about 2 meters (210 cm). This hypothesis was confirmed through a simple demonstration of raising the distribution tubing's piezometer bottom (see Figure 13 for a visualization of driving head). It was observed that as the height from the floor increased and the driving head decreased, the ram pump's cycles became slower and inconsistent, eventually failing. At some reduced driving heads, the team was able to replicate the "resonance" sound that was reported in Las Vegas. At others, the team observed new sounds of the "stop-and-go" type which occurred before complete failure of the pumping mechanism. In order to create a versatile ram pump that can function at varying driving heads, this semester's team will focus on various driving heads as well as what parameters may be manipulated to maximize pump function at reduced driving heads.

By researching the pump's function with various configurations and driving heads, ram pump function may be improved and easily tailored for different plants. This will ideally make the plants more self-contained and self-sufficient, thus lowering operation costs.

# Literature Review

The hydraulic ram pump is one of many hydro-powered devices that was conceived centuries prior to electrical power. Ram pumps are typically utilized in settings where preexisting steady, continuous fluid flows to power them, such as streams, rivers, or water treatment plants like AguaClara's. In such settings, the ram pump can intake the flowing fluid into a reservoir with: two outlets, a waste valve that re-feeds into the original input stream, and a delivery valve that feeds into the desired output location (usually a storage tank). As fluid feeds into the reservoir, it flows out the waste valve until flow increases, at which point the waste valve closes. With the waste valve shut, pressure builds in the reservoir, eventually opening the delivery valve (also known as the effluent valve) and forcing water up to the storage tank, where it can be used for plumbing, chemical stock tanks, and more. The waste valve is then reopened by an oscillatory mechanism, in our case a spring, but in others a weighted gate. The reopening of the waste valve is paired with the closing of the delivery valve and the process repeats.

Thus, a relatively large volume of water with high kinetic energy can be manipulated to pump a small volume of water to a higher elevation.

As the search for sustainable energy alternatives gains momentum, more studies have been done on hydraulic ram pumps, because they do not require electricity and can be easily implemented in less developed areas.

One such study attempted to design an affordable downdraft ram pump built from inexpensive, easily attainable parts for increased accessibility in underdeveloped, rural communities. Having developed mathematical models for ram pump parameters, Arnold's team was able to create multiple functional pumps from a drive pipe, an inlet ball valve, a swing valve, a spring valve, a discharge ball valve, and PVC pipes; at all implementation locations throughout the Philippines, where the parts are readily attainable at nearby hardware stores. All these pumps were able to convert a 1' fluid fall into an 8' fluid lift, for agricultural and household use. Most significantly, Arnold's team concluded that their pumps resulted in 85% savings as compared to commonly used gasoline powered pumps. This relates to AguaClara's program because a key goal is ensuring that the plants remain affordable. Additionally, creating ram pumps from easily attainable parts is ideal for addressing issues encountered in Honduras such as part replacement and troubleshooting. (Dumaoal et al., 2000)

Another study conducted in KwaZulu Natal, South Africa utilized mathematical and experimental data to design a ram pump for irrigating a community garden. A key component of their experimental studies was fine tuning to site specific conditions, the issue AguaClara's ram pump team is currently undertaking. They found that efficiency decreased non-proportionally to increased waste valve weight, which is analogous to the spring constant in AguaClara's system. The efficiency also decreases with stroke length, which is analogous to AguaClara's initial displacement and plate amplitude measurements. While stroke length and weight could be manipulated for optimum delivery flow, the experiments were not broad enough to develop mathematical models for this relation, and were trial-and-error tested until finding an optimal parameter. (Zoller et al., 2004)

# Previous Work

The main focus of recent previous work on the ram pump was creating a closed system that is connected to distribution piping to better simulate treatment plant conditions. These alterations have made it possible to test different pump parameters and characterize pump efficiency in relation to driving head.

## Ram Pump Setup

To simulate clean water flowing from a water treatment facility, the ram pump setup in the laboratory utilizes an electric sump pump. The pump carries water to an elevated tank, and the water from this tank moves down the drive pipe, as shown in Figure 2, to the ram pump, which will subsequently begin to pump. It is important to note that the high available driving head simulated by the head tank is what allows the hydram to pump against gravity by creating an input of kinetic energy.

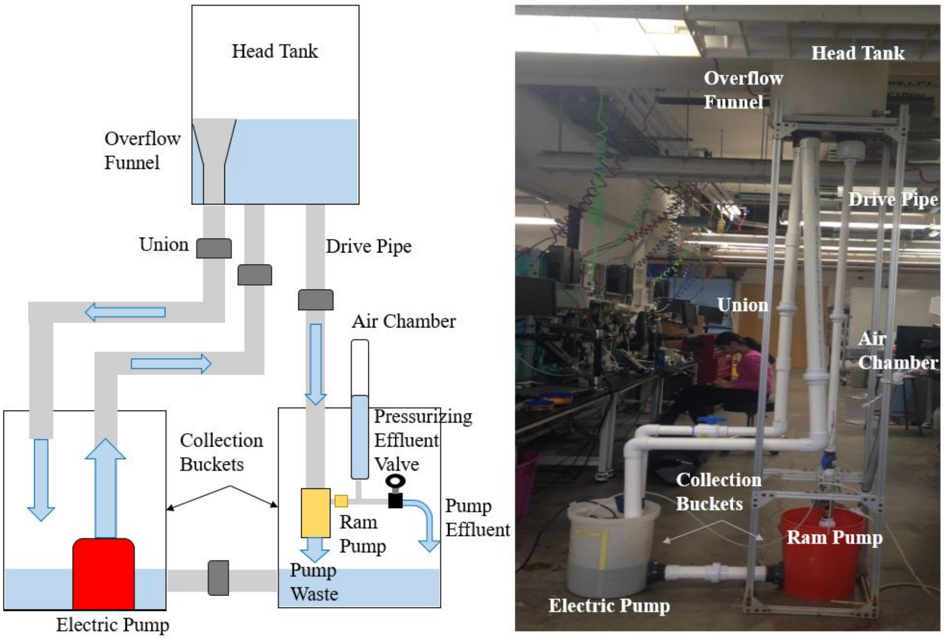


Figure 2: The electric sump pump delivers water to the head tank at the top of the system. From there, the water flows down the drive pipe and into the ram pump itself. While most of the water exits through the bottom as pump waste, a portion is pumped as effluent.(Aggarwal and Guzman, 2016)

To better understand on the inner workings of the ram pump, such as the check valve, spring function, and purpose of the primary air chamber, refer to the Fall 2016 research report (Galantino et al., 2016).

## Collar Design

During the visit to Honduras in January 2016, there were issues with the plate within pumps getting stuck in the open and closed positions. In response to this, a collar was added beneath the plate so its range would be limited. With this addition, a consistent plate amplitude could be set by manipulating the height of the jam nuts, allowing more reliable adjustments (Fig 3). The Spring 2016 team tested the effect of plate amplitude on flow rate with this new collar and jam nut configuration.

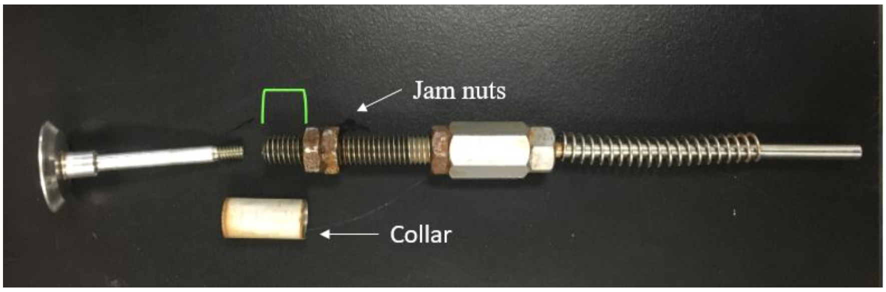


Figure 3: The length indicated in green shows the distance between the top of the rod and the nuts. The placement of the nuts determines the length of spring compression and therefore the amplitude of the check-valve plate. Notice the rigid length of the collar, which is placed above the jam nuts to ensure a reliable plate amplitude during each oscillation of the ram pump.

They concluded that increasing constriction to plate amplitude leads to higher effluent flow rates at lower head values. At the average plant head of 7m, the collar height changes did not make a significant difference in flow rate (Aggarwal et al., 2015). The Fall 2016 team found that the collar was deteriorating (Galantino et al., 2016) and it was replaced this semester with a sturdier standoff piece which is discussed later in the report.

## Spring Manipulation

The Spring 2015 team tested the effect of changing the spring force on flow rate in a previous iteration of the ram pump design. They found that the pump failed at spring forces of both lower than 3.5 lbs and about 9 lbs, but through different failure mechanisms for low and high spring forces. For forces lower than 3.5 lbs, the pump began to have an inconsistent flow rate. For spring forces higher than 9 lbs the opposite occurred and the plate was unable to be compressed and the waste valve remained open. The system worked best at low spring forces, that were above 3.5 lbs. In addition, they did not find a significant correlation between spring length and flow rate, as shown in the table below.

| Compressed Length = 2,04 in | | Average Head Loss (m) | Average Effluent Flow Rate (L/min) | Linear Fitting | Expected Flow Rate @ 4m Head Loss | Delta X (in) |
|---|---|---|---|---|---|---|
| Spring 1<br>k = 4,1 lb/in | Length 1<br>L0 = 2,955 in<br>Force=3.7515 | 3.20 | 0.480 | y = -0,0345x + 0,5729 | 0.4349 | 0.915 |
| | | 9.60 | 0.250 | $R^2$ = 0,9594 | | |
| | | 5.30 | 0.364 | | | |
| | Length 2<br>L0 = 3,27 in<br>Force=5.043 | 2.20 | 0.400 | y = -0,0446x + 0,5056 | 0.3272 | 1.23 |
| | | 6.80 | 0.226 | $R^2$ = 0,981 | | |
| | | 8.90 | 0.092 | | | |
| | Length 3<br>L0 = 3,71 in<br>Force=6.847 | 4.10 | 0.226 | y = -0,0204x + 0,3158 | 0.2342 | 1.67 |
| | | 8.00 | 0.154 | $R^2$ = 0,9924 | | |
| | | 2.60 | 0.267 | | | |
| Spring 2<br>k = 19,31 lb/in | Length 1<br>L0 = 2,955 in<br>Force=17.66865 | -- | -- | | | |
| | | -- | -- | | | |
| | | -- | -- | | | |
| | Length 2<br>L0 = 2,25 in<br>Force=4.0551 | 5.50 | 0.293 | y = -0,0332x + 0,4955 | 0.3627 | 0.21 |
| | | 4.80 | 0.353 | $R^2$ = 0,9409 | | |
| | | 9.00 | 0.200 | | | |
| | Length 3<br>L0 = 2,465 in<br>Force=8.20675 | 10.30 | 0.203 | y = -0,0301x + 0,5061 | 0.3857 | 0.425 |
| | | 2.70 | 0.429 | $R^2$ = 0,9937 | | |
| | | 7.60 | 0.267 | | | |
| Spring 3<br>k = 10,6 lb/in | Length 1<br>L0 = 2,955 in<br>Force=9.699 | -- | -- | | | |
| | | -- | -- | | | |
| | | -- | -- | | | |
| | Length 2<br>L0 = 2.465 in<br>Force=4.505 | 6.50 | 0.288 | y=-.0583x+.6417 | 0.4085 | 0.425 |
| | | 4.80 | 0.353 | $R^2$ = 0,92233 | | |
| | | 7.40 | 0.194 | | | |
| | Length 3<br>L0 = 2.515 in<br>Force=5.035 | 2.70 | 0.429 | y=-.0286x+.5105 | 0.3961 | 0.475 |
| | | 5.00 | 0.374 | $R^2$ = 0,99692 | | |
| | | 10.00 | 0.222 | | | |

Figure 4: The table above contains collected data relating varying spring forces and lengths obtained by the Spring 2015 team in order to observe the effect on flow rate.(Aggarwal et al., 2015)

Further testing on spring constants was performed by the Spring 2016 team. A graph of their conclusive data can be found in Figure 5 below.

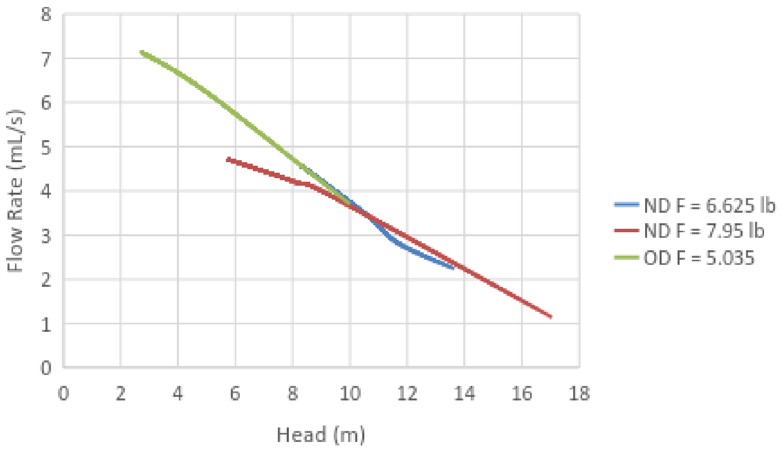


Figure 5: This graph represents the flow rates various spring constants were capable of producing at different heads. Each line represents 4 data points. It can be observed that weaker spring forces allowed for higher flow rates, but at reduced heads, while stronger spring forces could pump to high heads, but at a reduced flow rate.(Aggarwal and Guzman, 2016)

It was found that weaker springs yielded higher flow rates, but were only capable of pumping to smaller heads. On the other hand, stronger springs caused the pump to function at higher heads, but at reduced flow rates. The Spring 2017 team will continue testing on this variable and hopefully attain conclusive data on the effects of spring force in relation to driving head and collar distance.

## Threshold and Efficiency Testing

The bulk of the work done by the Fall 2016 team involved creating threshold and efficiency testing methods for the pump. An issue that previous semesters encountered was the absence of a quick and consistent method for obtaining flow rates at various heads. The Fall 2016 initially performed a cup and timer test which proved difficult because of human error and the requirement for many data points. This led them to develop the threshold test which is done by closing the effluent valve and measuring the analogous change in the volume of water in the attached air chamber (Figure 6).

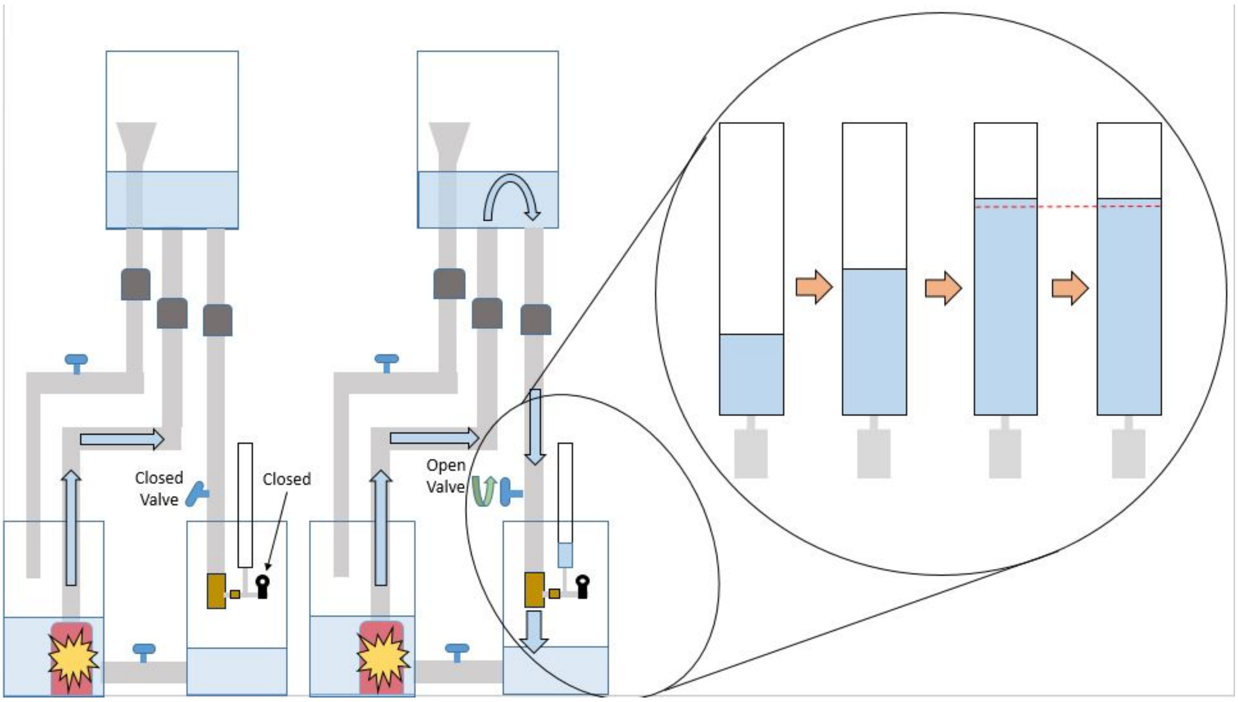


Figure 6: To begin the threshold test, the effluent valve is completely closed and the sump pump is turned on. Then, the drive pipe valve is opened, allowing water to move through the pump. As the test persists, the water level in the air chamber rises until the pressurized air restricts further inflow of water. Separately, pump waste falling through the ram pump is brought back to the sump bucket where it can be reintroduced to the head tank.(Galantino et al., 2016)

Using pressure-volume equivalence in the air chamber between the water and air, the elevation head could be tabulated. This allowed the team to create head versus flow rate graphs that can more accurately characterize how flow changes in relation to head (Figure 7).

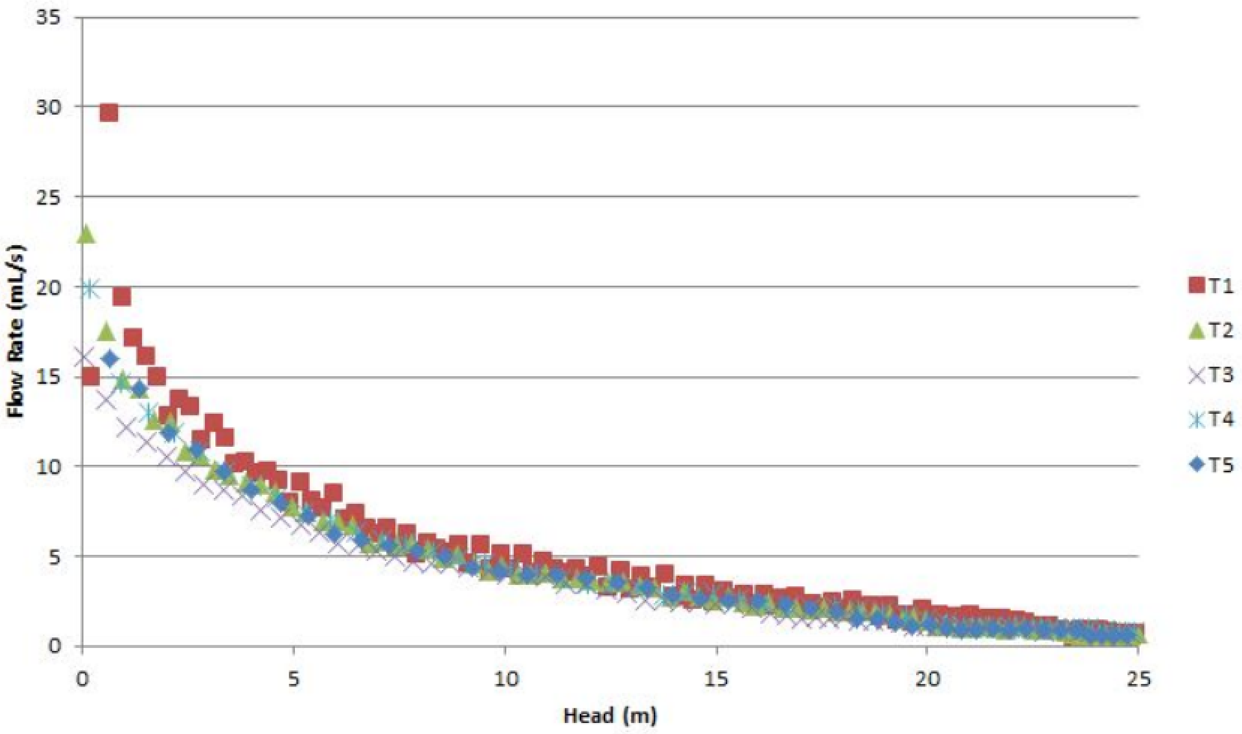


Figure 7: This graph depicts the decrease in flow rate as pressure in the air chamber is increased. Notice the smooth decline until the flow becomes minuscule. The repeatability of the data makes it clear that this test is consistent in providing reasonable values for flow rate at varying heads.(Galantino et al., 2016)

Efficiency testing occurs when the system is at equilibrium. To do this, water level in the air chamber remains constant in order to eliminate pressure as a factor. Figure 8 provides a schematic on how the efficiency test is prepared.

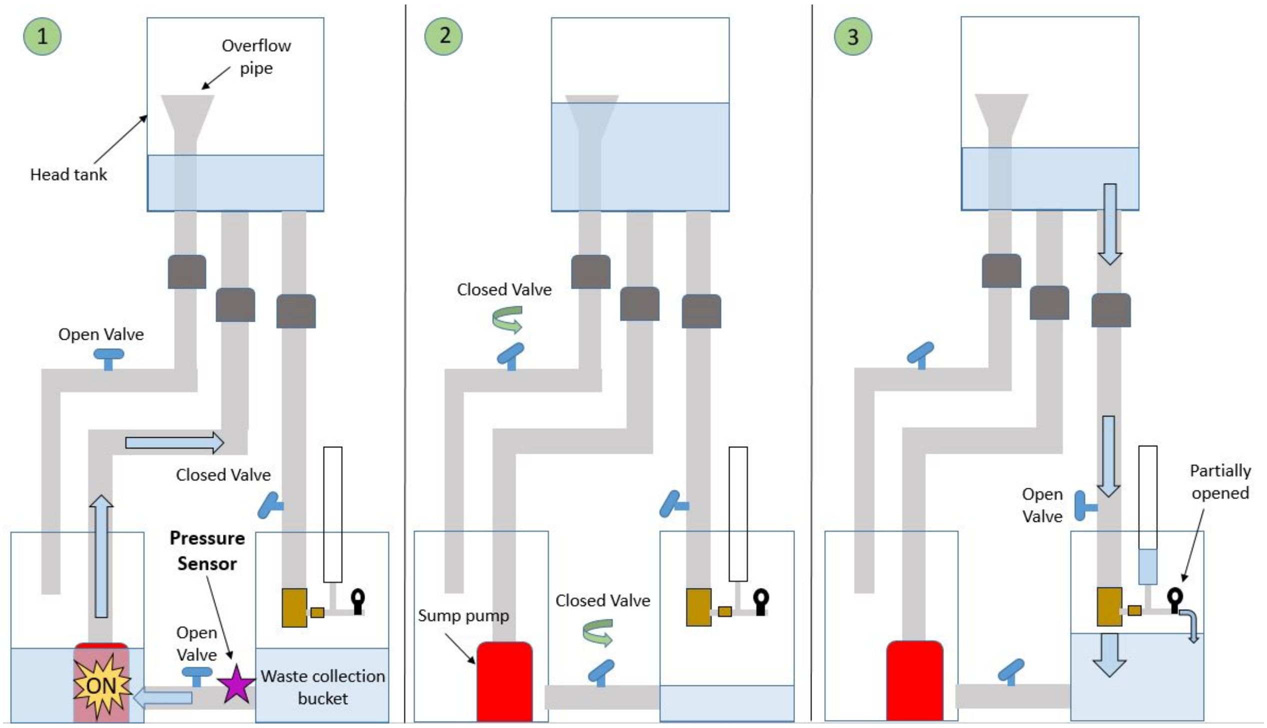


Figure 8: The efficiency test is a three step process that ultimately helps determine the flow rate of the pump waste that has not been pumped by the hydram. This flow rate can then be used to calculate the energy out of the waste valve and, in turn, find the efficiency performed by the pump. First, all the water is pumped to the head tank above. To prevent water from flowing back down to the sump pump, the valve on the overflow pipe is shut. The bucket connector valve is shut as well. It is important that the water level in the rightmost bucket does not fall below the bucket connector's opening in order to obtain an accurate pressure reading. To begin the test, the drive pipe valve is opened and water flows freely through the ram pump.

(Galantino et al., 2016)

To calculate efficiency, the energy of the pumped flow was divided by that of the wasted flow.

$$Efficiency = \frac{(Qh)_1}{(Qh)_2} \times 100 \tag{1}$$

where $Q_1$ is the flow rate of the effluent, $Q_2$ is the flow rate of the entire system minus the flow rate of the effluent (wasted flow), and $h_1$ and $h_2$ are the respective heads. This was then plotted against head to describe the relationship and determine the maximum efficiency which, under the conditions of Fall 2016 ram pump configuration, was between 10-15 m of head (Fig 9).

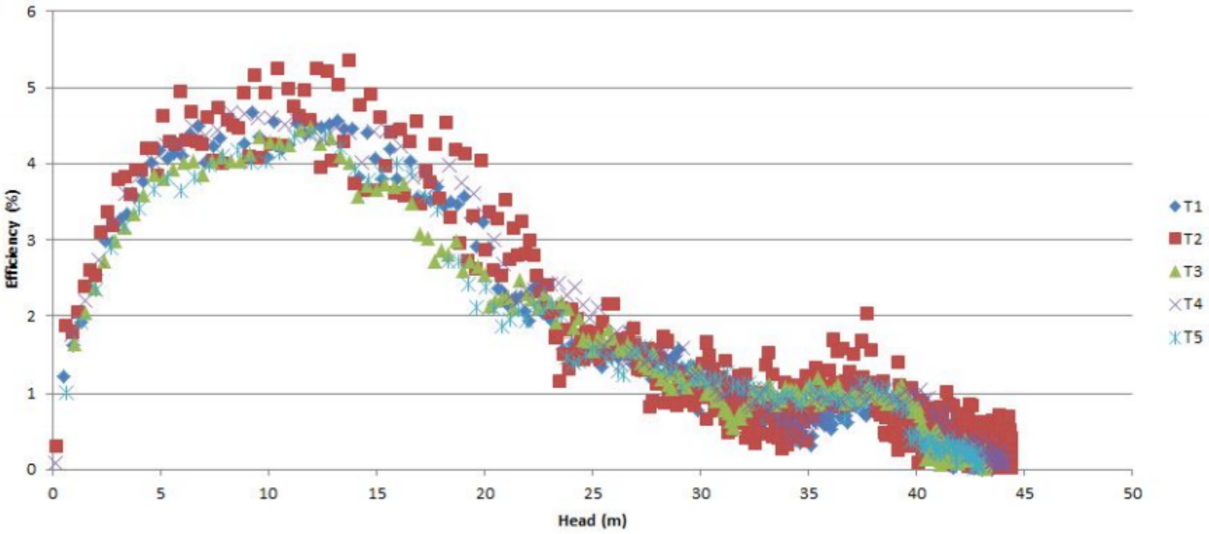


Figure 9: This graph shows how efficiency changes according to head. Peak performance occurred when the hydram was pumping to between 10 and 15 m of head (Galantino et al., 2016)

Finally, the Fall 2016 team was able to combine these two tests by running the pump with the effluent valve closed. Efficiency is found as a function of head and the threshold test is completed in the same manner (Galantino et. al, 2016). This tool can now be used later by the Spring 2017 team's analysis this semester.

## Adding the Distribution System

The distribution system was added during Fall 2016 to better represent treatment plant conditions. In an AguaClara water treatment plant, the ram pump is intended to be part of a closed system in which the treated water flows through the hydram and is either pumped back to the top of the plant or continues on to the distribution tank, so to not waste any potable water. The working hydram is to be connected in-line with the pipe that carries clean, chlorinated water from filters to the distribution tank instead of depositing the pump waste to an unenclosed container like the pump waste box that is currently used.

Using the aforementioned testing methods they were able to determine that the distribution system decreased the pump efficiency from 11.8% to 5.97%. (Galantino et. al, 2016)

Figure 10: In order to simulate a completely submerged ram pump, distribution piping was added to the bottom of the apparatus using flexible plastic tubing and a barbed adapter fitting. (Galantino et al., 2016)

## Second Air Chamber

It was hypothesized that some of the efficiency issues, as well as function failure, with the distribution system were stemming from a vacuum created underneath the plate when it was closed. To amend this, a second air chamber was attached (Fig 11). This second air chamber made it more difficult to start the pump, particularly during a threshold test, and decreased the maximum pumping head from 20 m to 16 m. The flow rate remained stable (Galantino et. al, 2016).

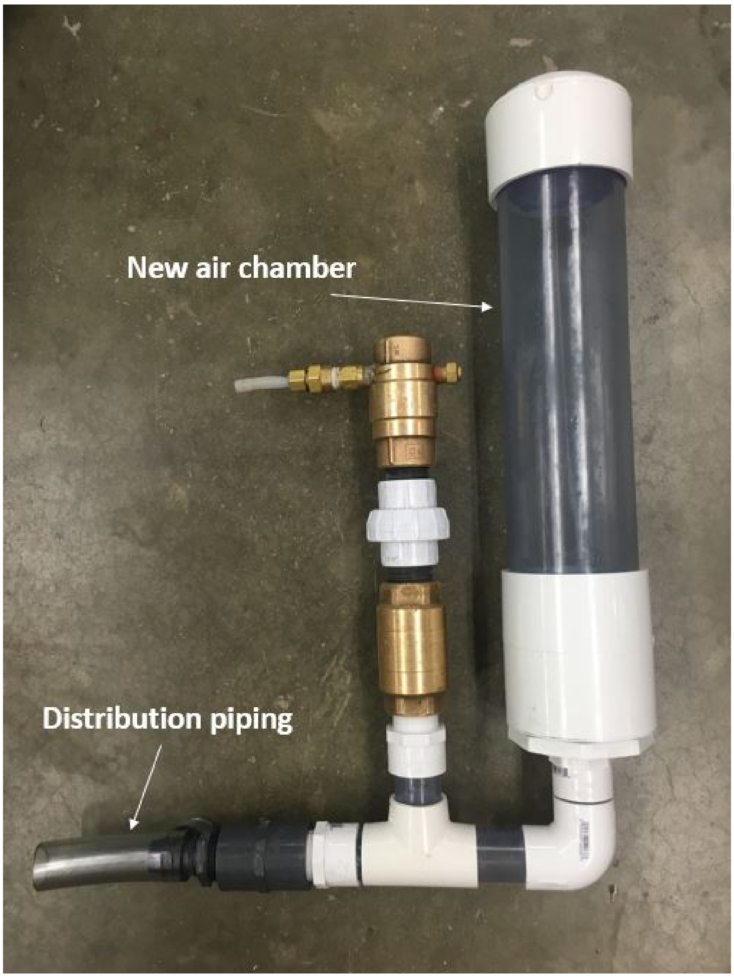


Figure 11: A second air chamber was installed next to the ram pump exit and behind the distribution piping in order to eliminate the vacuum effect. (Galantino et al., 2016)

# Methods

## Experimental Apparatus

An electric water pump is used to pump water from a collection bucket to a head tank at a greater height, gaining potential energy. This becomes kinetic energy as water falls down a pipe into the ram pump. The ram pump then pumps fluid through another tube, with varying output height, depending on the driving head of a given experiment. Notably, the ram pump is also attached to an air chamber, described in Previous Work.

Within the ram pump, two standoffs and jam-nuts are being used on the threaded portion of the rod to manipulate the springs range of motion in addition to plate amplitude. These are pictured below in Figure 12. How water flows through the ram pump is shown in Figure 31.

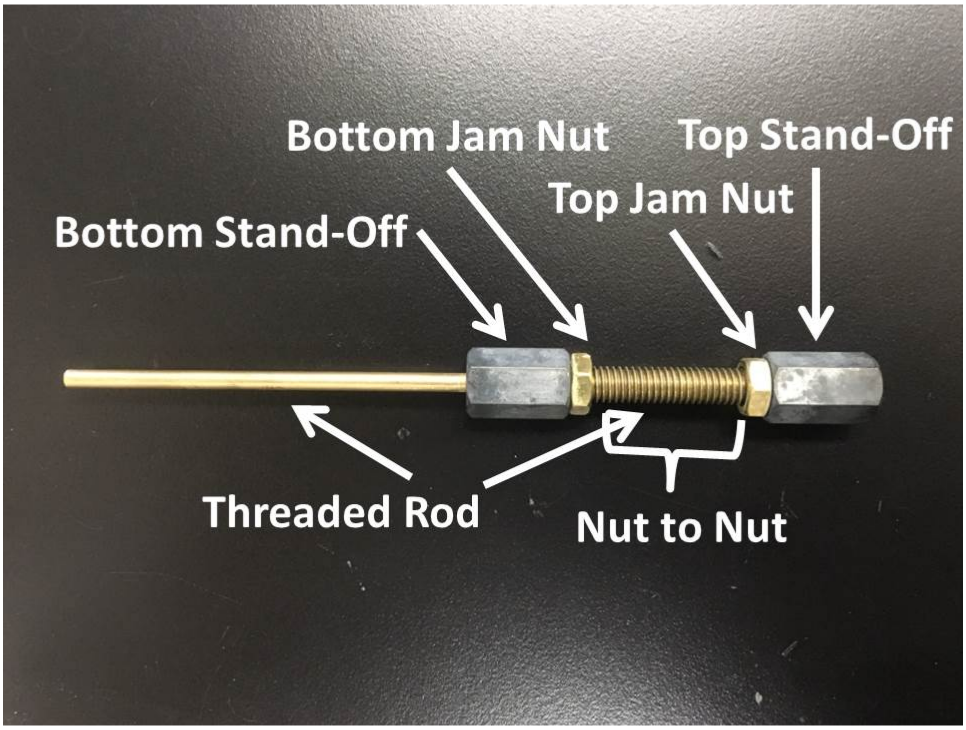


Figure 12: This shows the jam nut assembly. The standoffs and jam nuts are moved up and down the rod to manipulate initial compression and collar distance.

**Design** The team is testing various ram pump variables at various driving heads. The configurations differ based on plate amplitude (manipulated by changing top standoff displacement), initial compression (manipulated by changing bottom standoff displacement), and spring force (manipulated by using springs of varying stiffness). For each of these configurations, the driving head threshold for pumping (aka the maximum outlet height before pumping ceases) is recorded. Pumping at subsequent driving heads is also recorded, at intervals of 15 cm, ranging from the threshold to 180 cm.

**Complications in construction**

- Outflow Tube: In order to manipulate the driving head, the output tube was slowly raised, changing the distance between the collection bucket and the output. The bucket for outflowing water is on the ground so, as the tube was raised, it became more difficult to aim the water into the bin to keep the floor and researchers dry. A large clear tube- pictured below- was added to the assembly to feed the output tube into, ensuring water flowed smoothly to the bin.

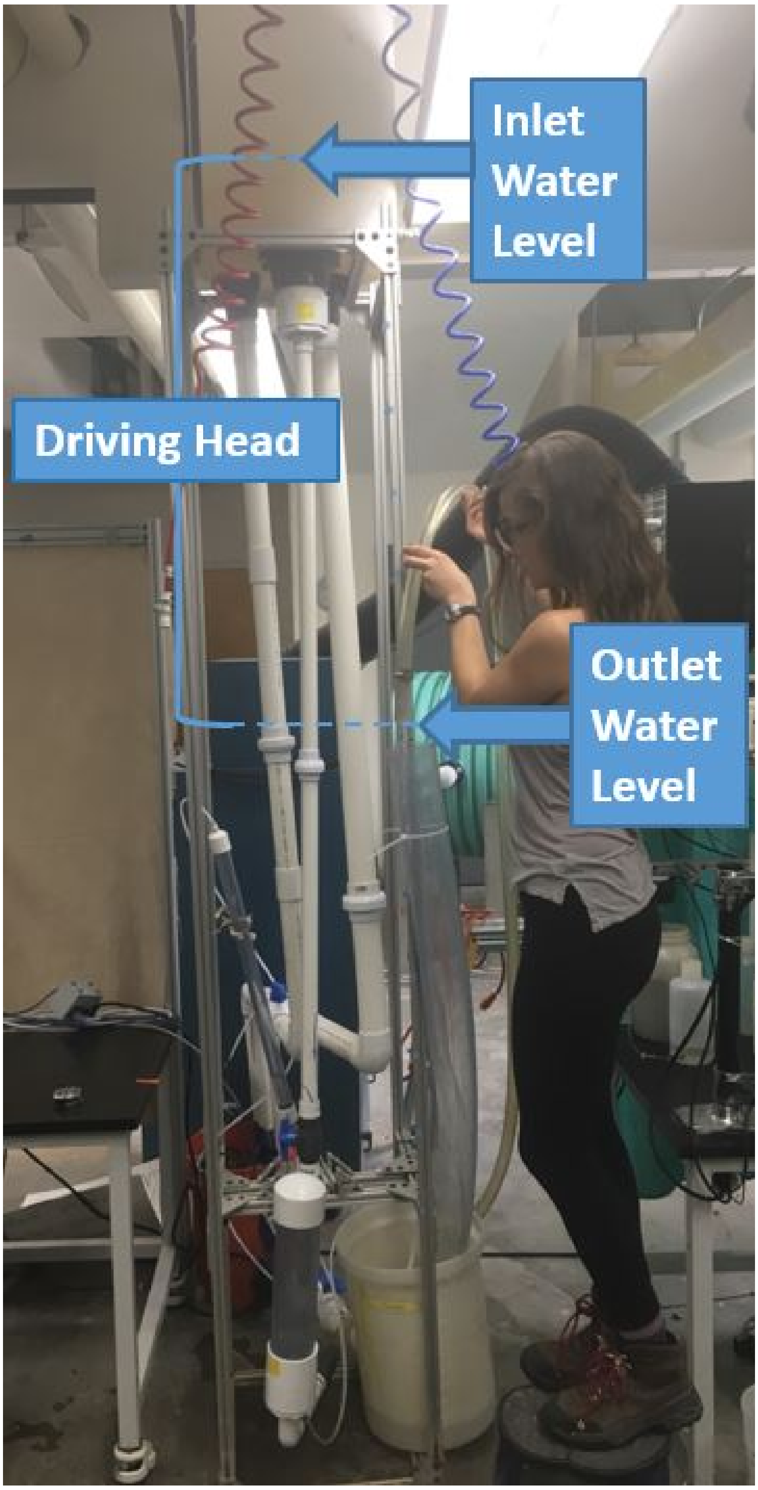


Figure 13: Driving head is the distance between the inlet and the outlet of a given fluid. As depicted in the figure, driving head can be manipulated by altering the outlet height of the distribution piping. Notice the large tube below the outlet which assists in the safe return of water to the collection bucket below.

- Threaded Rod: At one point during the testing, the rod bent out of shape. The unthreaded part of the rod which slides through the empty check valve somehow became bent, causing friction between the rod and the guide hole in the empty check valve. Because of this, when the pump was running, the frictional force would not allow the rod to freely oscillate in accordance with the spring, but instead caused the waste valve to remain closed the whole time. After realizing this was causing dysfunction, the rod was easily bent back into its original straight shape. This complication has potential to reoccur and it is a good aspect to consider checking if the pump is having similar issues again.

## Procedure

### Plate Amplitude Tests (Independent Variable: Top StandOff Displacement)

1. Ensure bottom standoff is at chosen constant point. Measure this with calipers. The zeroed position for the bottom standoff has the entire standoff on the threaded rod, with the bottom flush with the end of the threaded portion of the rod (see Figure 14).

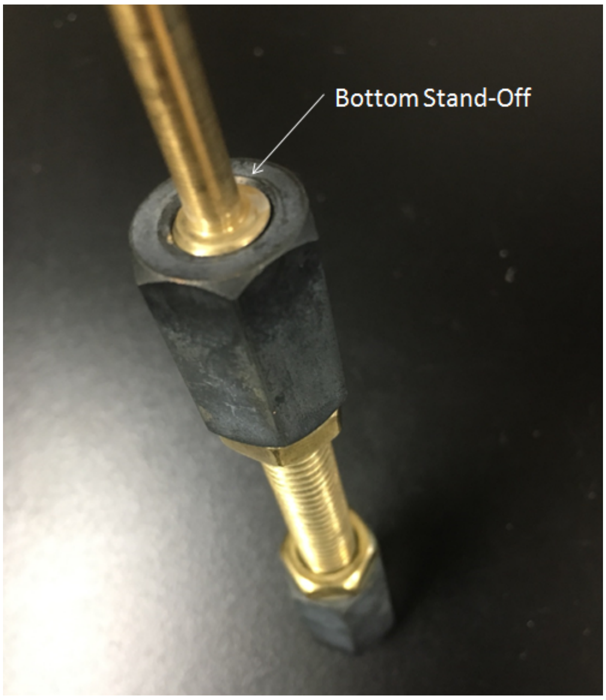


Figure 14: This shows the bottom standoff in its zeroed position. Positive displacement occurs as it travels further up the threaded portion of the rod.

2. Move top standoff to desired position for test, this is the independent variable. Measure this and the nut-to-nut distance with calipers and record prior to test.
3. Assemble ram pump (see Manual section at the end of the report) and turn on pump.
4. Begin slowly raising the outflow tube. As the tube is raised and driving head is diminished, the frequency of the waste-effluent pumping cycles will slow down until it reaches a failure point and stops working. This point at which the pump can no longer function is called the threshold driving head.
5. Check the threshold value multiple times by first lowering the tube until pumping becomes regular, then raising it slowly, until pump no longer functions (no audible sound). Record an average of the values (should be very consistent, same point each time).
6. Record ram pump audio at all driving heads greater than the threshold, by intervals of 15 cm, starting at 90 cm (or smaller if the threshold is less). Thus the test points are 90 cm, 105 cm, 120 cm, 135 cm, 150 cm, 165 cm, and 180 cm.

### Initial Displacement Tests (Independent Variable: Bottom Standoff Displacements)

1. Ensure top standoff is at chosen constant point. Measure this with calipers. The zeroed position for the top standoff has the entire standoff on the threaded rod, with the top flush with the end of the rod (threaded side).

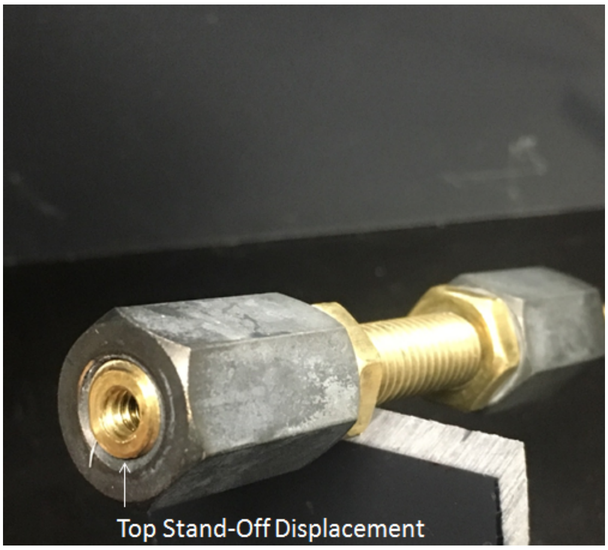


Figure 15: This shows the top standoff in its zeroed position. Positive displacement occurs as it travels further down the threaded portion of the rod.

2. Move bottom standoff to desired position for test, this is the independent variable. Measure this and the nut-to-nut distance with calipers and record prior to test.
3. Go through steps 3-6 mentioned in the above procedure for Plate Amplitude testing.

**Spring Stiffness Tests (Independent Variable: Spring Stiffness)**

1. Establish the stiffness value of the spring (lb/in). This can be done by ascertaining which spring it is on the McMaster-Carr website and recording the value they provide. If that is not possible, one must resort to Compression Testing (see Procedure below and Figure)
2. Establish displacement values for the top and bottom standoffs so these function as constants to compare the springs. Measurements for these values are described in previous testing procedures above.
3. Assemble the ram pump and run it, raising the outlet pipe until it stops pumping, then record the driving head. This is threshold value for the driving head. See more detailed instruction in procedures above.

**Compression Testing: Determining the Spring Constant**

1. Gather the spring of interest, a metal rod with an outer diameter smaller than the inner diameter of the spring, a rigid surface that the rod may be fastened for stabilization, a washer, an electronic scale, and an assortment of weights.
2. Insert the rod into the rigid surface and place on the electronic scale. Proceed to add the spring to the assembly, topped with a washer. The washer will serve as a flat surface for consistent force application to the spring below it.
3. Zero the scale with the entire assembly as it is and measure the initial length of the spring. Begin adding weight to the assembly. Record the scale reading and measure the compressed length of the spring at this given weight.
4. Repeat Step 3 until a reasonable amount of data has been acquired. Then, subtract the respective compressed lengths from the original spring length to obtain the compression.
5. Graph the relationship between the change in length with the associated mass. The slope of this general trend is the spring force constant.

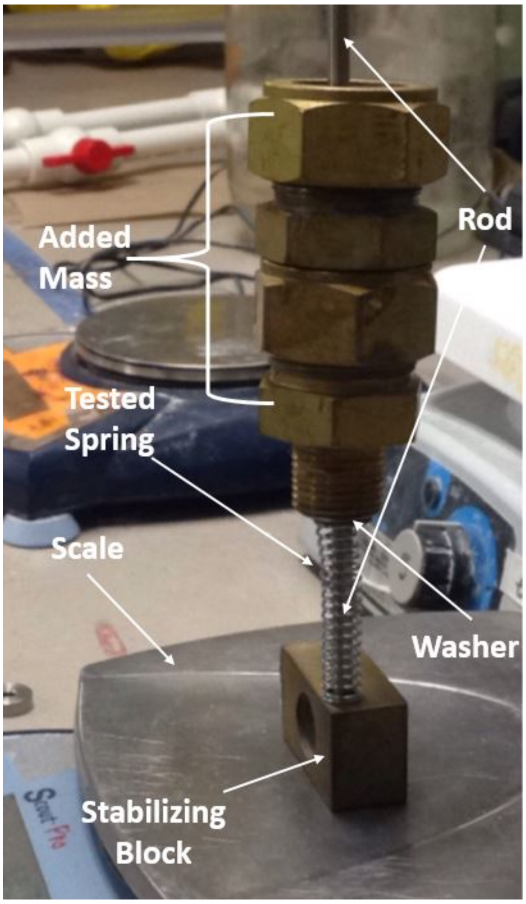


Figure 16: This shows the general assembly that was used in order to obtain an estimate of the spring force constant for a spring of interest.

# Results and Analysis

## Top Standoff Displacement

In testing our three parameters (spring stiffness, plate amplitude, and initial spring compression), the team began with constant initial spring compression (with the the bottom standoff in the zeroed position) and constant spring stiffness (using the spring from the previous semester). The original initial compression graph had a vaguely parabolic from, as can be seen in Figure 17.

This implied a correlation between top standoff displacement and minimum driving head, with optimized driving head results with displacements around 3.5 mm and 5.0 mm. The results also had very promising driving heads, as the pump consistently functioned with driving head values below 100cm, which is similar to the available driving head in Las Vegas and half the driving head of the original simulation and most AguaClara plants.

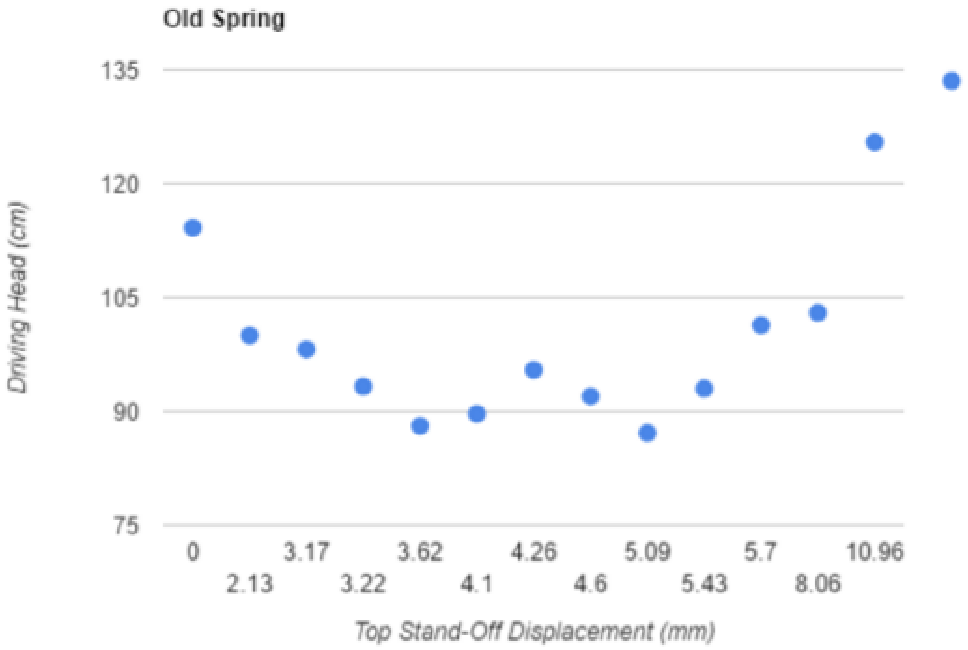


Figure 17: This shows the team's original test data on the spring from Fall 2016, using Google Sheets to generate the plot.

As this data collection continued, the team continued to test top standoff displacements near the optimal values, hence the concentration of data points between 3.0 mm and 5.0 mm. Unfortunately, this was largely misguided because the team did not realize the Google Sheets evenly spaces all data points, regardless of their numeric proximity, skewing Figure 17 until the values were plotted in Excel. Plotting in Excel resulted in Figure 18, below. This exemplifies the lack of correlation in the data.

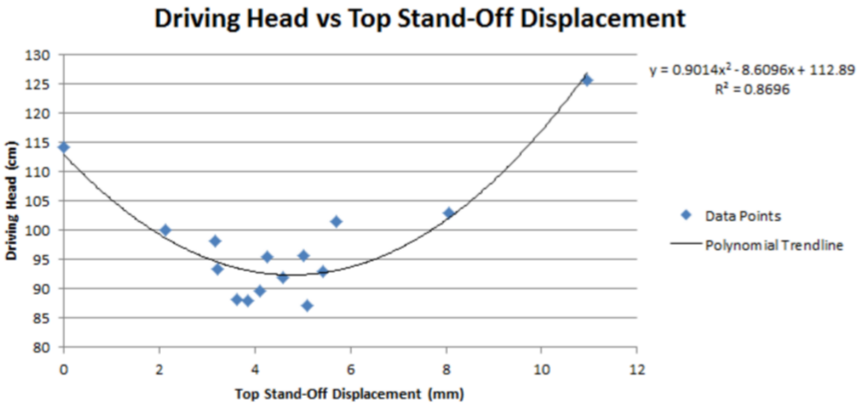


Figure 18: This is the same data as in Figure 17, but plotted in Excel which properly scaled the Top Standoff Displacement distances.

As tests on the old spring continued, the data points became even less correlated, as can be seen in Figure 19, prompting the team to retest previous values. The re-tested data was inconsistent with previous points and, upon inspection, this seemed to be the result of torsional damage that deformed the spring. As a result, the Fall 2016 spring was retired and the team decided to test others.

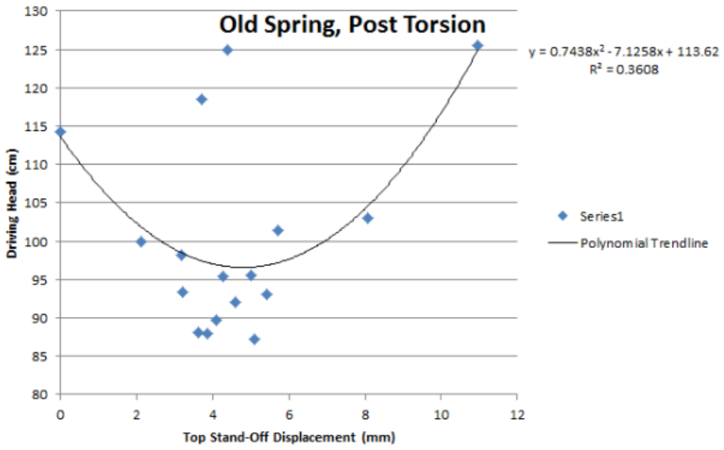


Figure 19: This shows the original test data on the spring from Fall 2016, with a scaled plot from Excel. As the team continued testing, there was less correlation and it was discovered that the spring had suffered irreversible torsion.

The team started by testing what is referred to as the yellow spring.There was an initial effort to test the springs available in the lab and springs were identified by color because there was no readily available method for obtaining the spring constants. Upon organization, it was concluded that the yellow spring was the only one that would work at a low driving head. Although the team initially thought the yellow spring would work well, it had virtually no correlation and fairly poor driving head thresholds, so the team moved on to another spring after obtaining the data displayed in Figure 20.

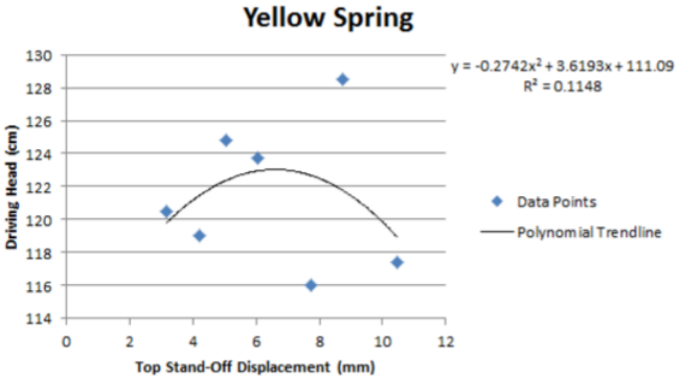


Figure 20: This shows the test data from the yellow spring, which lacked correlation and had poor driving head values.

After the yellow spring, the team moved on to what is currently referred to as the prodigal spring. The prodigal spring allows the pump to function at incredibly low driving head values, as can be seen in Figure 21. The team concluded that overall there was no particular relationship between failure of driving head and top standoff displacement, but perhaps there was a more linear relationship shown as the green section of Figure 21 below. Further testing in this top standoff displacement region was completed resulting in Figure 22. As a result, although the team initially speculated that there would be a correlation between top standoff displacement and failure driving head, it was determined that there was no statistically significant relationship between the two.

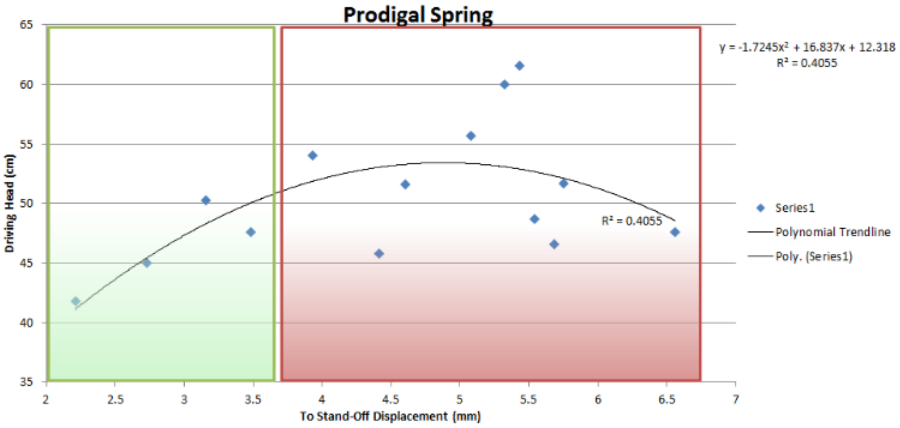


Figure 21: This shows the original test data on the prodigal (Fall 2016) spring, with a scaled plot from Excel. The red section represents the area of poor correlation and the green represents the area with better correlation which we then continued testing afterwards. The reason there is a parabolic trend line is because this was expected based on previous spring data. However, there is a clear deviation from this trend line the farther into the red section one goes.

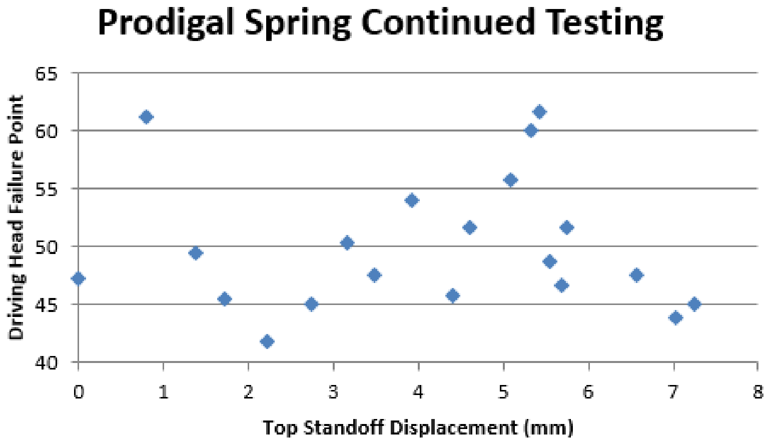


Figure 22: This shows the continued testing of the prodigal spring. Because of this graph, it was concluded that there is no real correlation between top standoff displacement and driving head failure.

## Spring Stiffness and Bottom Standoff Displacement

Though the specific spring constants for the initially tested springs are unknown, the prodigal spring seemed to be the least stiff. It makes sense that a spring with a lower stiffness would allow for optimized pump function because less force is required to push it down, thus less driving head is required to compress the spring.

However, springs with significantly less stiffness (qualitatively) than the prodigal spring were tested and could not perform. The valve would remain closed because the springs were insufficiently stiff to counteract the pressure and re-open the valve. Therefore, in line with the findings of the Spring 2016 team, the current team surmised that decreasing spring stiffness only optimizes function at low driving heads to a certain extent.

In order to test spring stiffness as a parameter, the team purchased springs with different constants. Prior to purchasing, the team tested the prodigal spring's stiffness and found it to be 1.84 lb/in. As mentioned before, the team found multiple springs purchased by previous teams in the ram pump box that were totally ineffective due to their extreme stiffness values; thus the team opted to purchase springs with stiffness values fairly similar to that of the prodigal spring. The four springs purchased have listed stiffness values of 1.1 lb/in (Spring 1), 1.4 lb/in (Spring 2), 2.49 lb/in (Spring 3), and 2.79 lb/in (Spring 4).

Each spring was initially cut to 2 inches and tested for various bottom standoff displacement values, in order to generate a curve and understand each springs full working range. This standard length was picked to eliminate other factors that may effect spring performance and because Spring 2 was initially 2 inches.

Bottom standoff displacement tests began at a minimum 1.1 cm displacement value, which increased by 0.2 cm for each test. The testing range was constrained by the length of the threaded part of the rod, the length of the spring and the length of the bottom standoff. The data from this testing can be viewed in the graph below. The prodigal spring was 2.5 inches long during plate amplitude tests but was then cut to 2 inches for bottom standoff displacement testing to eliminate variation when comparing between all of the springs.

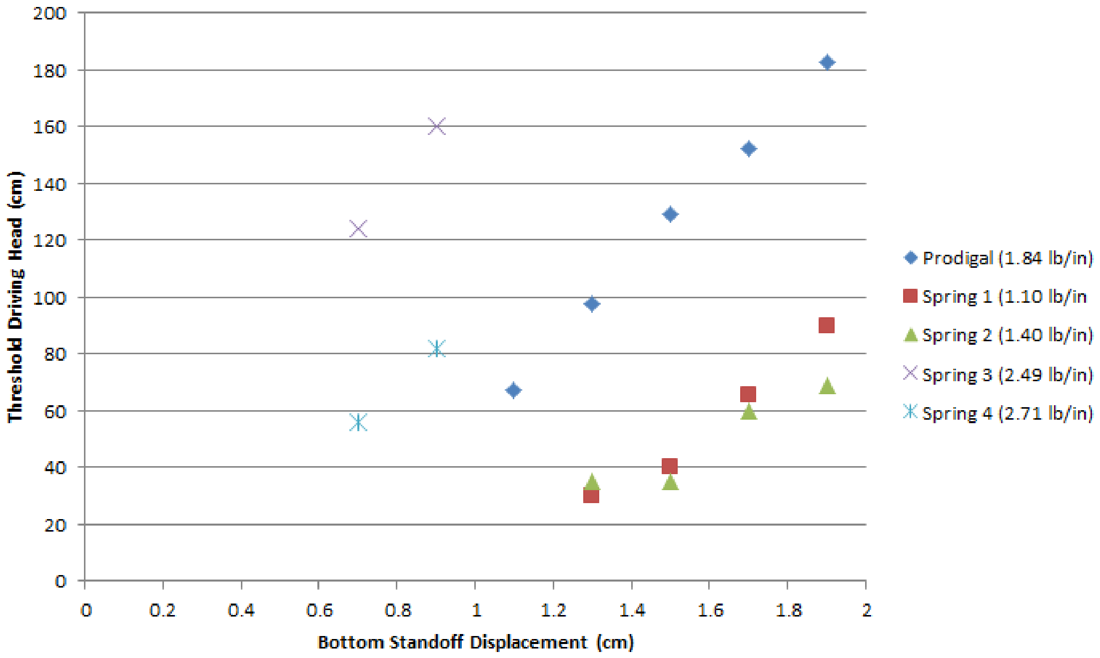


Figure 23: This shows the relationship between spring stiffness and the functional driving head threshold. Notice that the weaker the spring, the less driving head required for proper functioning.

As Figure 23 shows, all springs work best at the lowest initial compression values at which they were able to function. It additionally shows that the weaker the spring is, the larger initial compression must be for the spring to function. All springs were tested for the full range of initial compressions at which they functioned. The team noticed a discrepancy in the data of Springs 3 and 4, where Spring 4 (higher spring force) works at lower threshold than Spring 3 (weaker spring force). As a result, the team manually tested the spring constants of Springs 1-4 and the prodigal spring. A compression testing method was devised to compute the stiffness values of each spring. The results are below in Figure 24.

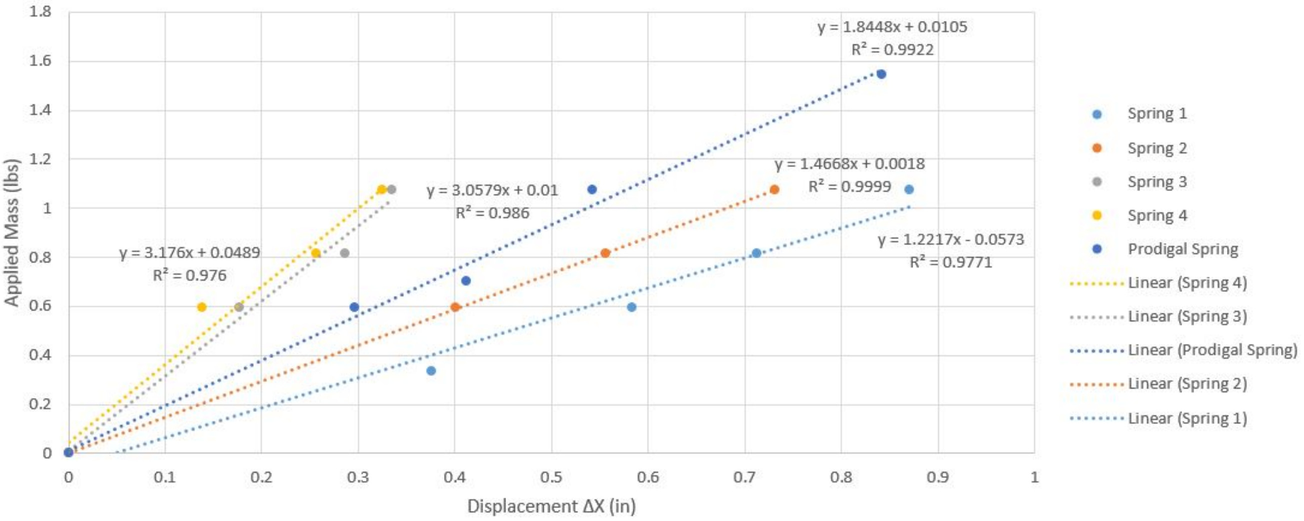


Figure 24: This shows the spring constants that were acquired through spring compression testing methods (see Procedures).

These experimental values for the spring constants of Spring 3 and 4 counter the previous discrepancy in Figure 23. Although they are not extremely accurate (3.176 lb/in rather than 2.71 lb/in), Spring 4 is certainly stiffer than Spring 3. This leads the team to believe there is perhaps another factor for stiffer springs that caused the anomaly seen in Figure 23. Moving forward, the team felt it was best to continue using the spring constant values given by McMaster Carr.

## Mathematical Modeling

Once the team completed the experimental testing outlined for the semester, the end of the semester was used to begin mathematical modeling of the ram pump to compare with experimental data. The goal of this model is to compare the force of the water hitting the plate of the ram pump to the force of the spring. From this, it will then be possible to calculate the optimal spring force needed for a specific driving head.

### Initial Model Theories

To begin, the team modeled the ram pump as a first order mechanical system, with a force acting on a mass, attached to a fixed spring. The force of the spring was modeled as kx(t), where k is spring stiffness and x(t) is a time dependent function for the spring elongation/compression. The force of water was modeled statically as a column of water, creating a force equivalent to $\rho$gh, where $\rho$ is the density of water, g is the force of gravity, and h is the height of the water. As represented in Figure 25, it was initially hypothesized that the plate would begin reopening when the potential energy from the column of water was equivalent to the potential energy of the compressed spring.

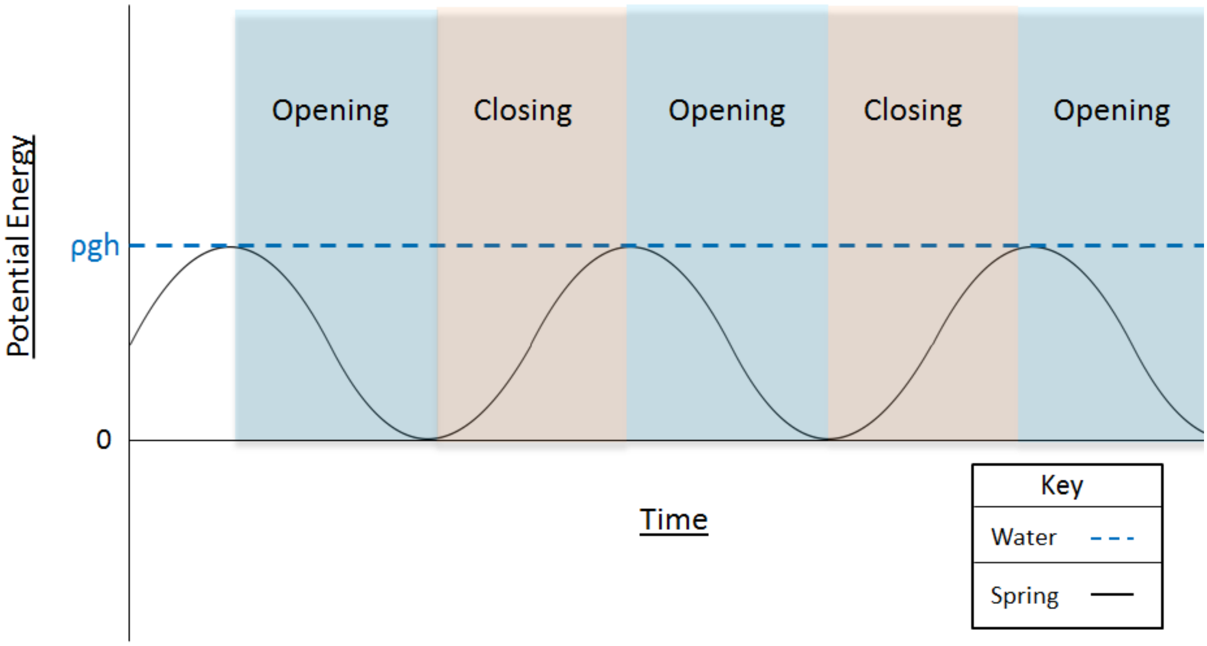


Figure 25: This graph represents the teams initial incorrect hypothesis.

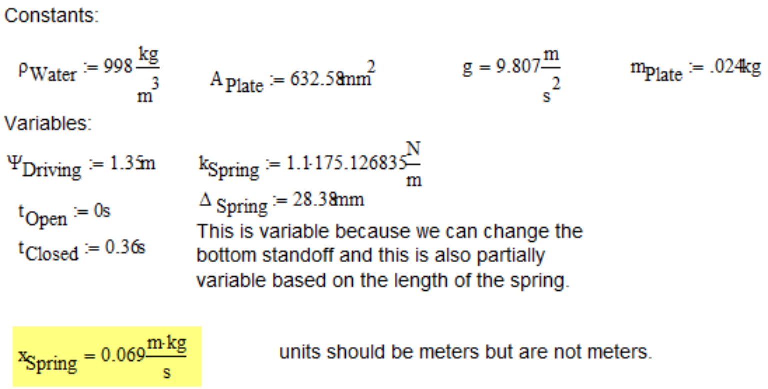
By developing a set of boundary conditions, assuming the force from the water was constant, the team was able to produce an equation describing x(t) as a function of driving head and spring stiffness, using Laplace transforms.

$$x_{Spring} := \frac{\rho_{Water} \cdot g \cdot \Psi_{Driving} \cdot A_{Plate}}{\sqrt{\frac{k_{Spring}}{m_{Plate}}}} \cdot \sin\left(\sqrt{\frac{k_{Spring}}{m_{Plate}}} \cdot t_{Closed}\right)$$

Figure 26: This MathCAD represents the initial Laplace model hypothesized based on modeling the spring as a free body under a static weight, which is not accurate.

The team then ran the ram pump to establish the time it took for the pump to complete a cycle, producing values for time at known x(t) values, such as when the plate audibly hits the check valve.

Once the equation was developed, the known time at the boundary conditions, as well at the known stiffnesses, were inputted into the equation to see if they would output known displacements at those boundaries. Unfortunately, the equation did not fit the data and proved to have inaccurate units. This is likely because the force of water was modeled statically. The initial model results calculated in MathCAD is shown below in Figure 27.



Constants:

$\rho_{Water} := 998\frac{kg}{m^3}$   $A_{Plate} := 632.58mm^2$   $g = 9.807\frac{m}{s^2}$   $m_{Plate} := .024kg$

Variables:

$\Psi_{Driving} := 1.35m$   $k_{Spring} := 1.1\cdot 175.126835\frac{N}{m}$

$t_{Open} := 0s$   $\Delta_{Spring} := 28.38mm$

$t_{Closed} := 0.36s$

This is variable because we can change the bottom standoff and this is also partially variable based on the length of the spring.

$x_{Spring} = 0.069\frac{m\cdot kg}{s}$   units should be meters but are not meters.

Figure 27: This shows that based on the assumed and measured variables, the calculated spring compression does not represent reality both in value and units.

After speaking with Monroe and Juan, the team confirmed that the initial ideas were incorrect. Mainly, it was determined that the force of the water should be modeled dynamically instead of statically and the final product should be a ratio between the force of the water and the force of the spring. The spring force will continue to be modeled as it was previously, but the force of the water will now take into account how velocity (and therefore force) of the fluid above the plate is changing with respect to time.

The team took slow motion video footage to better understand the movement of the pump and analyzed the acceleration patterns as shown in the Figure 28 below. A piece of tubing with a strip of red tape was attached to the bottom of the rod in order to easily visualize the rod's movement during cycles, and therefore the plate's behavior (see Figure 29). The team ran out of time in the semester to develop a full model, but hopes that this model can be developed next semester.

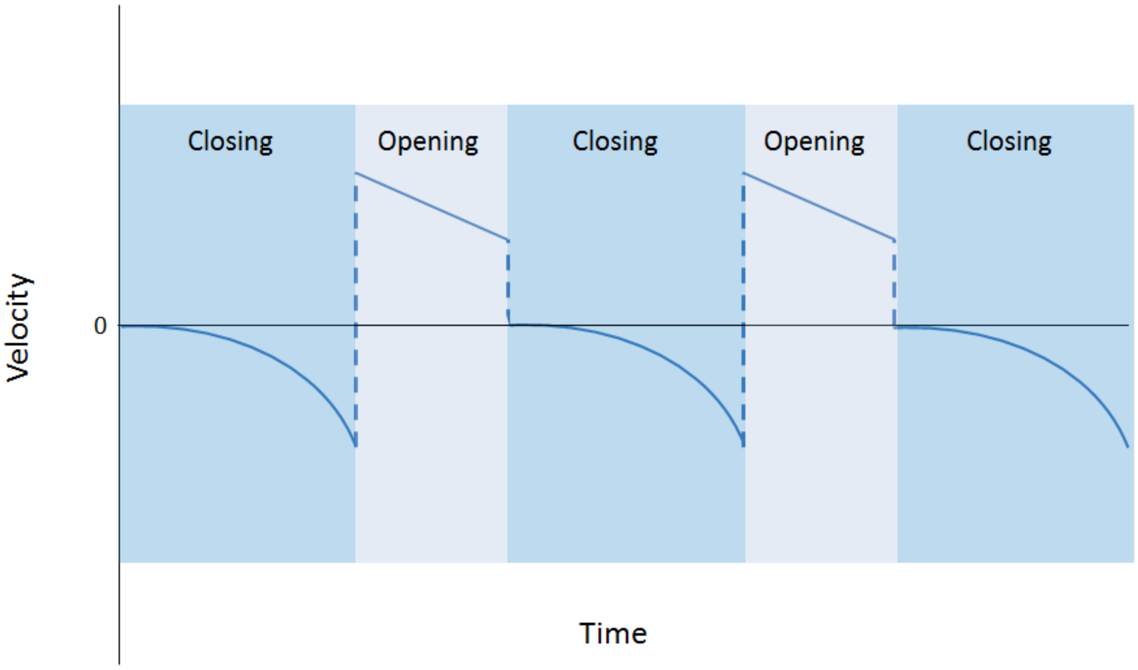


Figure 28: This graph represents the team's current hypothesis for how the ram pump velocity functions and will be the basis for mathematical modeling next semester.

As the water column in the drive pipe reaches the top plate, the spring assembly is accelerated at an increasing rate in the negative y-direction. Before the velocity can hit a critical point, however, the motion of the plate is abruptly halted by the rigid surface of the check valve. This is what produces the distinct noise unique to the AguaClara ram pump. With the spring fully compressed, it begins to expand upwards in the positive y-direction. This displacement is fast-acting and experiences little resistance from the incoming water column. The team believes this happens quickly because of pressure differences above and below the plate. Similar to the downward motion of the plate, the upward motion of the plate is halted when the top standoff reaches the bottom of the check valve. Therefore, there is no elastic stretching of the spring beyond its original length in the configuration. The process then repeats indefinitely.

Below is an artistic rendering to translate what was visually observed in the slow motion video. Every movement of the pump's inner configuration correlates directly with the velocity graph in Figure 28.

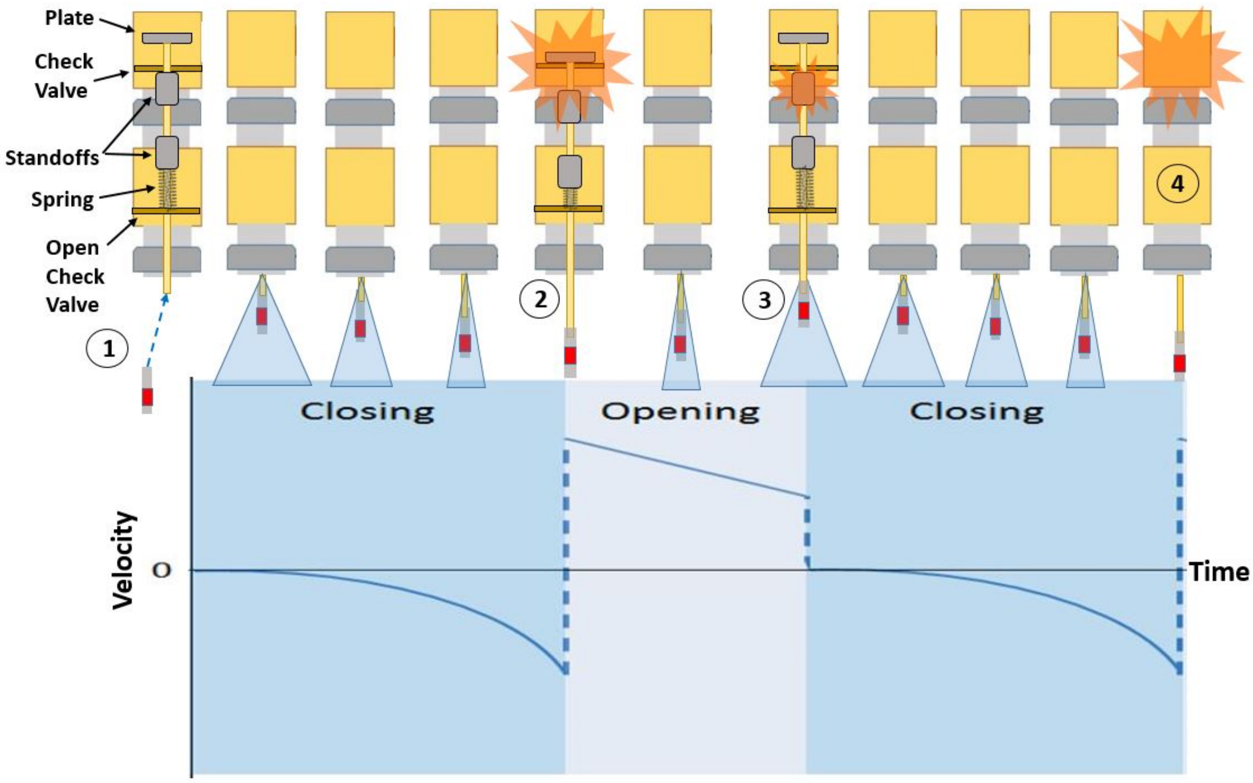


Figure 29: This diagram serves to translate what was observed in the slow motion video of the rod, and therefore the plate's behavior, during pumping cycles so a proper mathematical model may be developed. Step 1 describes the addition of a piece of tubing to the rod, along with a strip of red tape. This allows the team to easily track where the rod is moving and how quickly when analyzing the recording. The louder, more audible noise distinct to the ramp pump is the shutting of the plate over the check valve (Step 2), diverting the water through the stop valve as effluent. This process starts off slow, but gains speed in the negative y-direction due to increasing acceleration. Once at the bottom of its motion, the spring recoils upwards in the positive y-direction. The plate experiences deceleration from water above, but the top standoff hits the bottom of the check valve in a much shorter of amount of time, producing a more subtle noise (Step 3). This process then repeats indefinitely. Step 4 serves as continuity in the diagram.

# Conclusions

All three parameters that the team aimed to test at the beginning of the semester have been tested ad nauseam and thus, some conclusions can be drawn for each. There was no consistent correlation between driving head threshold and top standoff displacement, with the exception of extreme cases. If the top standoff displacement is too great or too small, the ram pump will fail, either closed, so no water flows through the system, or open, so no water is pumped through the system.

Meanwhile, bottom standoff displacement does correlate to threshold driving head, in that lower displacement values allow for consistently lower threshold driving heads. (This can be seen in Figure 23.) Changing the bottom standoff displacement is proportionally similar to changing the spring, because spring stiffness is a function of compression (in that the force exerted is in lb/in or N/m) and bottom standoff displacement effects the spring's initial compression and range of motion.

The spring stiffness tests concurred with the conclusions of bottom standoff displacement and indicated that stiffer springs yield higher driving head threshold values and do not function for lower driving heads.

Overall, the team has concluded to ignore top standoff displacement as a parameter and develop a method to manipulate spring stiffness and bottom standoff displacement to ensure ram pump function at any driving head required by AguaClara plants.

# Future Work

Future teams will continue the current teams work on developing a mathematical model to describe the relation between spring force, which is directly proportional to spring stiffness, and the force the water exerts on the plate. This involves developing a transfer function or unitless ratio between the two forces.

The first obstacle the team has faced has been modeling the force of water, because it cannot be calculated statically but rather it varies cyclically. Notably, the team discovered that the spring compresses slowly then pushes up quickly, indicating a non-symmetric cycle. This can potentially be modeled as a step input or impulse input.

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# Semester Schedule

## Task Map

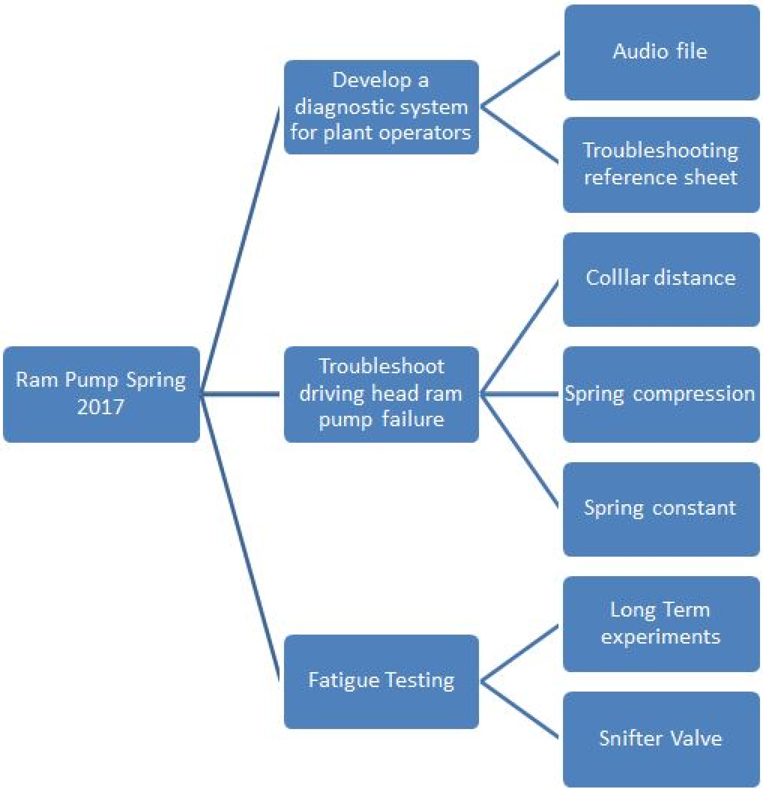

Figure 30: Spring 2017 Task Map

## Task List

You should keep and update your detailed task list from the first assignment in each of your reports. Denote completed tasks and modify your deadlines to reflect your most recently completed progress and any delays.

1. Troubleshoot driving head ram pump failure (March 15) - Chris. Manipulate spring compression, spring constant, and/or collar distance to treat failure at various driving heads.

2. Develop diagnostic system (April 20) - Abby. Investigate potential of audio library. Create reference sheet for plant operators to diagnose issues.

3. Fatigue Testing (May 5) - Ana. Run long-term experiments to assess failure points and then investigate solutions.

**Team Coordinator:** Abby Brown. **Report Proofreader:** Ana Ruess.

# Manual

Hello new ram pump team! We hope you have been enjoying learning all about the ins and outs of how the ram pump operates. This guide is available to describe different testing methods, how to properly set up the pump before each test, and general notes that will help make your experience with the ram pump smoother.

## Setting Up the Ram Pump

The ram pump operates under high pressures and has many detachable parts that may become loose and leaky for a variety of reasons so it is important know how the pump is properly assembled before beginning a test.

### Assembling the Ram Pump

There are two main outer components and three main inner components of the ram pump that you will have to understand to know how to assemble the ram pump.

**Outer Components: check valve and empty check valve**

These two valves are connected by a PVC union which is useful in attaching the pump to the testing apparatus. The top check valve is comprised of a large check valve out the bottom for waste flow which leads to the empty check valve and a small stop valve out the side for pumped flow. The empty check valve attaches to the bottom of the regular check valve and is used to keep the spring in place on the rod. The rod slides through a hole in the bottom check valve and the spring becomes stuck in between the hole and the bottom of the threaded portion of the rod (discussed below). It is highly recommended to watch a few videos of how a ram pump works online, as it can be a confusing process to understand.

**Inner Components: rod, plate and spring**

The inner components are all connected with the purpose of opening and closing the waste valve. The plate slides through the hole in the top check valve and is the mechanism by which the ram pump closes. The bottom of the plate threads onto a rod which is threaded on the top half. The non threaded bottom half of the rod feeds inside the spring- which compresses when the plate is closed and causes the plate to reopen. Warning: the inner components should oscillate freely within the outer components when assembled so if they do not double check that the inner components are not stuck. In particular, the rod is susceptible to bending so make sure it is straight. This is easier to understand visually so make sure to play around with the ram pump!

Additionally, there are two standoffs that are used to adjust how far the plate can open (plate amplitude) and how much the spring can compress. To make sure the standoffs stay on, tighten them against the adjacent nuts using two wrenches. Loosening the jam nuts usually required the use of wrenches. For more information on this and tuning the ram pump, see the Spring 2017 report.

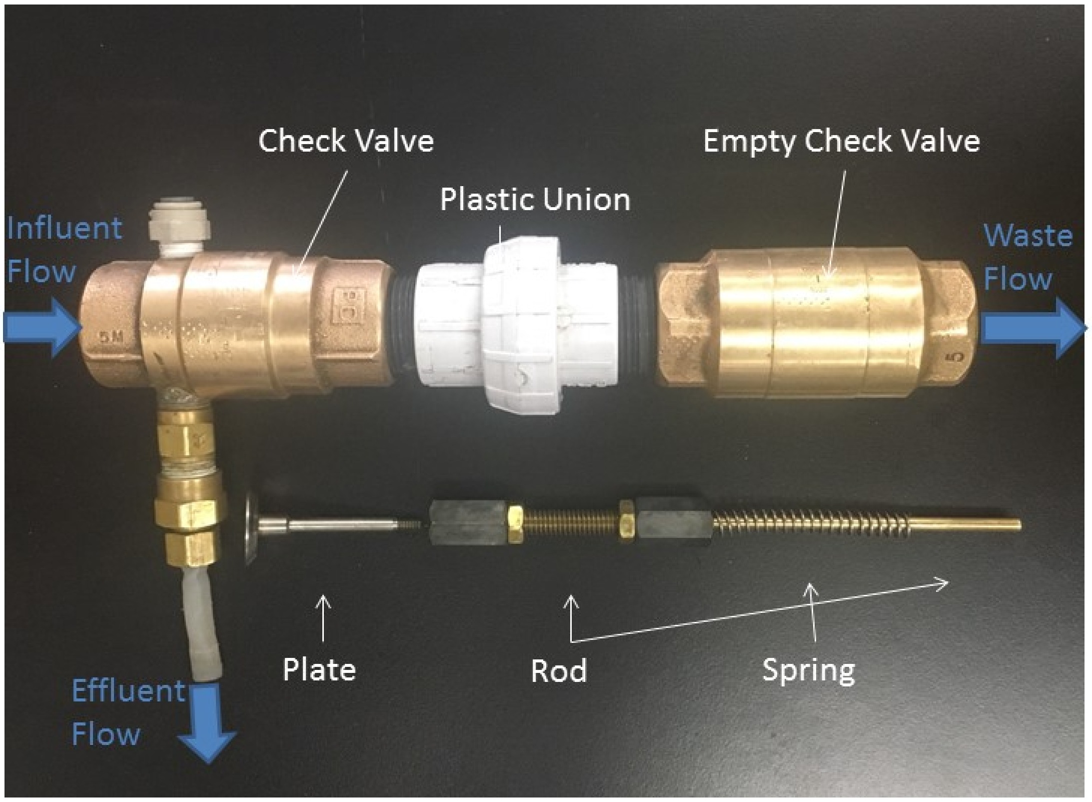

Figure 31: This diagram gives a general overview of the ram pump exterior and interior pieces. The plastic union which joins the two check valves allows for easy access to the standoff configuration within and a convenient means of disassembly.

## Setting up Testing Apparatus

1. Make sure the ram pump is fully assembled before attaching it to the testing apparatus. This is so that the rod will be properly threaded through the empty check valve and therefore the rod will not bend when assembling. In particular, make sure the spring is actually in the pump before moving forward or all of your set up work will be for naught.

2. Screw the bottom portion of the pump to the distribution piping system and be extra careful that it is not askew. It should be fairly easy to thread this on if it is correctly aligned, but could also still go on if it is crooked so make sure to check.

3. Second, loosen the plastic union between the check valves so that you can screw on the top check valve easily without having to turn the whole pumping apparatus (which you cannot actually do as it should be attached to the distribution piping system).

4. Afterwards, make sure all of the twisting pieces above the pump are secured, particularly the union in the middle of the drive pipe as it tends to come loose sometimes. (This can be a major leaking hazard!)

5. Wow! You are so close to having a fully set up ram pump! Now connect the large air chamber to the distribution piping which again should just screw on easily. You should not tighten it excessively

as it can make it difficult to take off at the end of the test.

6. Finally, connect the small distribution tube to the side of the pump and make sure all the small pressure sensor tubing is firmly attached.
7. Now the pump is fully set up! Double check that everything is secured before testing. Turn on/ plug in the sump pump to pump water up to the driving head tank.
8. Open the valve on the vertical pipe to begin testing. Sometimes you will need to prime the pump a little before it begins to run smoothly. This involves opening and closing the blue valve multiple times. An alternative solution is to give the ram pump a gentle tap near the blue valve, which has proven to be very effective. Priming should generally take less than a minute and if you are still having issues perhaps there was a different problem with the set up. Overall, the ram pump can be a temperamental creature and be patient with yourself and your teammates and you will do great work!

### Cleaning Procedure

As aforementioned, the ram pump is prone to leakage so it is good to keep a dry/wet ShopVac around during testing. Additionally, at the end of testing make sure to store the pump parts in a way that they can dry and will not be continually submerged to limit rusting.

## Types of Tests and Where to Find Them

### Threshold and Efficiency Testing

See Fall 2016 Report for details.

### Tuning the ram pump

See Spring 2017 Report for details.

## ProCoDA Method File

Spring 2017 team has yet to require ProCoDA use for experiments.

## Ordering Parts

Ram pump orders parts using the McMaster Carr website. https://www.mcmaster.com/