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A. NCER Assistance Agreement Project Report Executive Summary

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Project Title: AguaClara's Ram Pump for Zero Electricity Drinking Water Treatment

Faculty Advisor(s), Departments, and Institutions: PI, Dr. Monroe Weber-Shirk (mw24@cornell.edu), Civil and Environmental Engineering, Cornell University

Student Team Members, Departments, and Institutions:

- Cheer Tsang, Biological and Environmental Engineering, Cornell University
- Alyssa Ju, Mechanical and Aerospace Engineering, Cornell University
- Ching Pang, Mechanical and Aerospace Engineering, Cornell University
- Maile McCann, Civil and Environmental Engineering, Cornell University

Project Period: 12/01/2018 through 11/30/2019

Description and Objective of Research:

AguaClara Cornell is a multidisciplinary program at Cornell University that researches and installs sustainable water treatment solutions committed to long-term environmental, social, and economic sustainability. Since 2005, the AguaClara program has been steadily improving water treatment technology performance with a specific focus on increasing the accessibility of safe drinking water to those who cannot afford the traditional water treatment plant. With the themes of economic accessibility and environmental sustainability in mind, AguaClara water treatment plants are designed to be completely electricity-free and locally sourced, and were implemented in Honduras. The plants use fluid mechanics principles to eliminate the need for mechanical controls; by reducing the number of moving parts, the AguaClara plants have far fewer failure modes than conventional mechanical plants. AguaClara produces cleaner water with lower capital and operating costs than conventional plants in Honduras, and thus, there is an effort underway to bring AguaClara technologies to the United States.

The proposed work is to design and fabricate a novel inline (vertical pipeline with zero waste) ram pump, which uses potential energy to lift a small amount of water to a higher elevation. While a standard ram pump wastes the water used for energy extraction, the AguaClara ram pump returns that low-energy water for use as potable water by the community. Conventional ram pumps that discharge wasted water to the environment have been researched extensively, but there is no research on AguaClara's vertical-flow, waste-free ram pump (ACVRP). Our research goal is to improve the efficiency of this design, as the inline ram pump is essential to making AguaClara water treatment plants electricity-free and easy to operate. The ACVRP will be implemented in plants to lift treated water to the top of the plant for preparing coagulant and chlorine stock solutions.

Summary of Results (Outputs/Outcomes):

The team designed, fabricated, and tested an inline, zero-waste ram pump that was able to lift water up to 6 meters of elevation. Equations describing the ram pump theoretical performance were derived and the ram pump performance was compared to ideal performance. The experimental volume of water pumped per cycle was only 8.6% of the theoretical value. Measurements reveals that the pressure above the ram pump waste valve was much higher than expected. Analysis of the pump physics further revealed that although the ram pump average high pressure flow rate is much smaller than the pumping water flow rate, that the instantaneous maximum rates for high pressure and pumping flows are identical. Thus the flow passages for the high pressure flow must be similar in size to the low pressure side of the pump.

Conclusions:

The problem of inefficiency of the current design of the ram pump was concluded to be due to the ratio between the diameter of the driving pipe and the high pressure effluent. The diameter of the high pressure effluent was ¼ of that of the driving pipe, which means that velocity in the high pressure check valve is 16 times faster than that in the drive pipe, causing the minor head loss to be 256 times greater than designing a high pressure effluent with 1 in diameter. Therefore, the excess energy of water from the driving pipe was not utilized. A new design (Figure 1) was proposed with increased diameter of the high pressure effluent so that both diameters are the same in order to reduce head loss at the effluent.

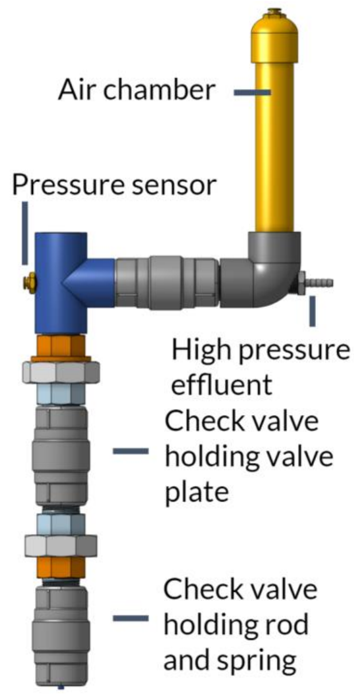

Figure 1. Normal View of the modified design of ACVRP with the diameter of the high pressure check valve increased to the same diameter as that of the driving pipe.

Proposed Phase II Objectives and Strategies:

Phase II work will involve the optimization of the ram pump efficiency and usability with the modified design after adjusting the high pressure effluent to be the same diameter as the drive pipe. In order to further reduce the headloss of water at the pump that is hypothesized to cause the inefficiency, we will experiment with different geometries of the position of the effluent valve in relation to the drive pipe. Simultaneously, we will account for the adaptability of the pump to the varying heights of the driving head in AguaClara plants by testing the ACVRP at different flow rates with different sizes of check valves. The modified ACVRP as shown in Figure 1 will be adjustable by the tuning of the spring inside the pump to accommodate this variable. In addition, Phase II research will also look into different control system of the ACVRP such as a weight based system, which would allow for easy fabrication but a more complicated control system. The modified ACVRP will be implemented and tested in AguaClara plants that are currently in operation in January 2020. And further assessment on the ACVRP will be conducted to improve its efficiency and operation based on the operators' feedback.

Publications/Presentations: Spring 2019 Ram Pump Manual, Spring 2019 Final Presentation, EPA Conference Presentation

Supplemental Keywords: Gravity-powered pump, hydraulic ram pump, AguaClara Vertical Ram Pump (ACVRP), drinking water treatment, plant plumbing; sustainable; green engineering; gravity; physics; accessible; economical; portable; zero waste; reuse

Relevant Websites: AguaClara Cornell, Ram Pump GitHub Repository

B. Summary of Phase I Results

I. Background and Problem Definition

The AguaClara Vertical Ram Pump (ACVRP) is an innovation that will enable water to be pumped from lower elevations to higher elevations utilizing the driving force of elevation head and kinetic energy of flowing water. Figure 2 shows where the ACVRP will be implemented into the AguaClara plants. In an AguaClara drinking water treatment plant, flow through a plant is driven solely by gravity, so treated water exits the plant at the lowest point of the plant. Thus, in order to fill higher elevation chemical stock tanks with treated water, operators must carry buckets of water up multiple flights of stairs from the outlet at the lowest point of the plant to prepare the calcium hypochlorite and polyaluminum chloride solutions used for treatment. The ACVRP creates a constant, gravity powered plant plumbing system to eliminate the need for plant operators to move water up multiple flights of stairs to the chemical stock tanks.

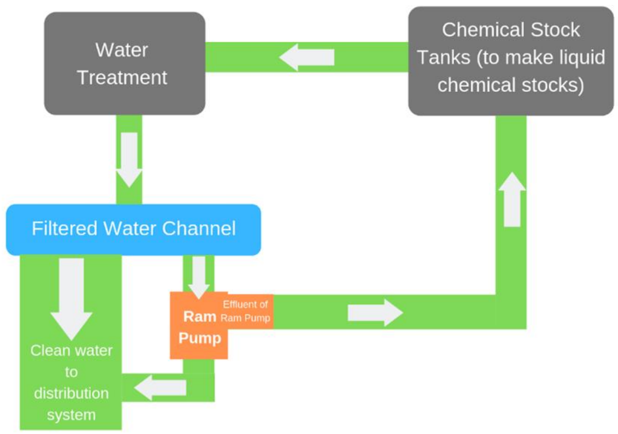

Figure 2: Schematic of the ACVRP in AguaClara plants. Treated water exiting the stacked rapid sand filters (Adelman, et al., 2013) drops into the filter pipe gallery to reach the ACVRP. The ACVRP pumps a fraction of the flow up to the chemical platform. The water that passes through the ACVRP continues to the distribution system (Aggarwal and Guzman, 2016).

Conventional Ram Pump and Its Design Problems

The ACVRP builds on principles utilized in a conventional ram pump. A conventional ram pump consists of a feed pipe, an air chamber, and two exit valves. Figure 3 illustrates how a conventional ram pump operates. The ram pump discharges water until the drag force on the valve is great enough to close the valve, at which point a small volume of water is pumped to a higher elevation while the water in the feed pipe rapidly decelerates.

Conventional ram pumps have been installed in several AguaClara plants, but since they were oriented horizontally, a tank had to be constructed around the pump to collect water that was not pumped and return it to the distribution system. The tank construction added to the capital cost of the plants and was difficult to incorporate into the pipe gallery.

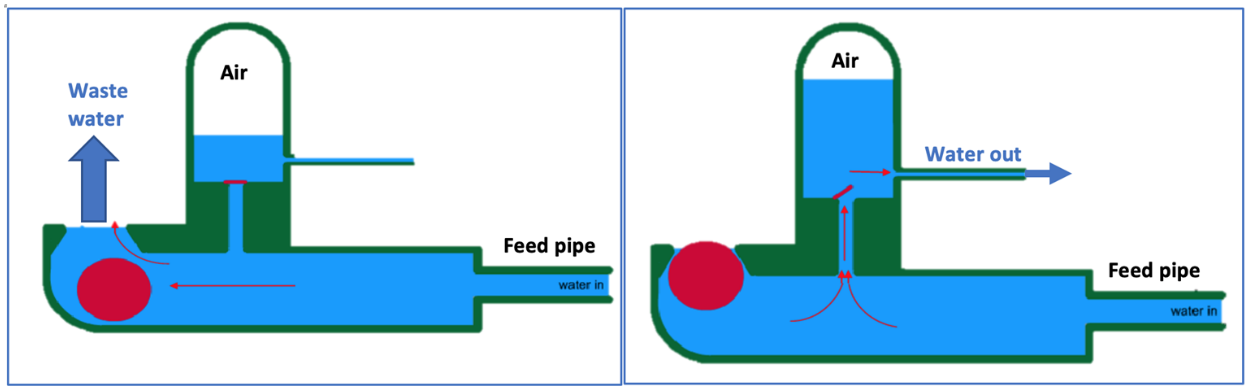

Figure 3: (Left) In a conventional ram pump, water travels through the feed pipe, accelerating until the velocity of the water is great enough to cause the ball to shut the waste valve. Water is not being pumped at this point and is thus being discharged to the environment. (Right) Once the waste valve is closed, water can then be pumped, allowing the effluent valve to open to allow water to travel through the air chamber. Once there is a decrease in pressure, the waste valve will open once again. (Figure adapted from Schou, 2000)

AguaClara's Solution: A Vertical Ram Pump (The ACVRP)

The AguaClara Vertical Ram Pump (ACVRP) is entirely enclosed in a vertical pipe, thus no high quality drinking water is wasted like in a conventional ram pump. An ACVRP will be easy to install in existing AguaClara plants and easy to include in new designs.

An exploded view of the internal parts of an ACVRP is pictured in Figure 4. The upper check valve housing includes the original manufactured check valve plate. Below the valve plate is the first set of nuts that adjust the maximum height of the plate when it is fully opened. The second set of nuts adjust the force of the spring by changing the length that the spring is compressed. The spring rests on a cross bar within the lower check valve housing. The lower check valve housing does not have a check valve plate, as it is only used to guide the extended valve stem. The pumped water goes through the spring loaded check valve (effluent valve) which is threaded into the side of the first check valve.

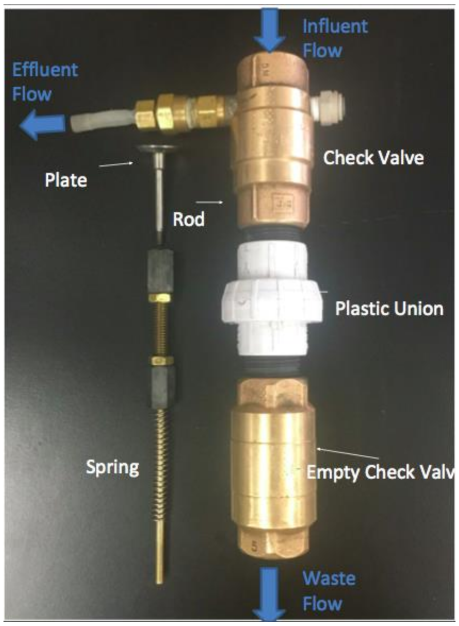

Figure 4: The internal parts of the ACVRP; the valve plate, spring, and rod (left) are installed inside the two check valves on the right (Galantino et al., 2016)

A spring loaded check valve is attached to the side of the upper check valve, which is where the high pressure water exits. When the valve plate is open the velocity of the water in the drive pipe accelerates, eventually reaching a terminal velocity. The drag force of the water in the drive pipe closes the plate, and the water is redirected through a smaller effluent check valve, travelling to a higher elevation by extracting kinetic energy from the fast moving water in the drive pipe. The column of water in the drive pipe begins to decelerate after the waste valve closes, until the water is static in the drive pipe. Then, the force of the spring is enough to overcome the static force of the water column, and the waste valve opens again. Subsequently, the water in the drive pipe begins to accelerate again. Figure 5 shows how the internal forces of the ram pump behave in both the open and closed positions.

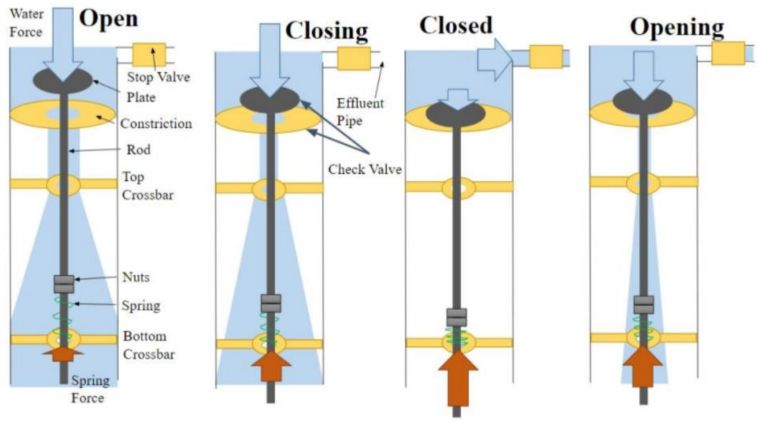

Figure 5: This illustrated internal forces in ACVRP, as plate opens, the suction force from below causes the plate to slam shut. This creates a pressure gradient and an effluent stream is pumped upward as the waste valve opens due to the spring force (Galantino et al., 2016)

The target maximum velocity that should trigger the valve to close must be less than the terminal velocity (Aggarwal et al., 2017). This will ensure that the drag force closes the plate in the waste valve. In addition, the acceleration of the water in the vertical drive pipe decreases as head loss through the waste valve increases. Thus the optimal maximum velocity must be slightly less than the terminal velocity. This parameter will be tuned as part of Phase II research.

As shown in Figure 6, the amount of water pumped is the area underneath the deceleration period on the velocity vs. time curve multiplied by the cross sectional area of the drive pipe. The waste valve would reopen when the drive pipe water stops and hydrostatic pressure is reached.

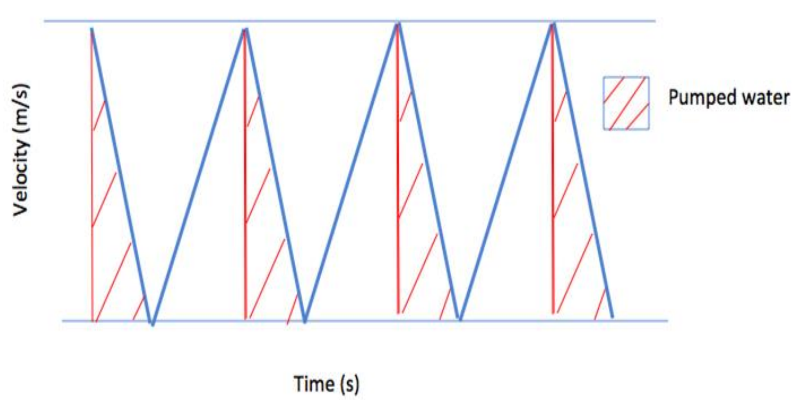

Figure 6: A velocity profile of the ACVRP, showing the cycle when water is pumped into the high pressure effluent.

Relationship to People, Prosperity, and the Planet

People

The ACVRP has the potential to reduce the cost of installing a conventional ram pump and reduce the cost of electricity, which would make it more accessible to the communities with AguaClara plants. The inline ram pump also provides ease for the operator, eliminating the need to carry buckets of water to mix the chemicals in the stock tanks and for daily plant operation. The ACVRP has the potential to provide an electricity free plant plumbing system, which allows for a better quality of life for operators working in an AguaClara plant. Additionally, the ACVRP would allow a small number of homes at higher elevations than the plant to receive treated water, as the current distribution system utilizes an elevation difference to transport water to homes.

Prosperity

The AguaClara water treatment plants provide safe water on tap in communities that previously had untreated river water on tap. The ram pump allows AguaClara plants to provide safe drinking water without using any electricity. Because AguaClara is an open-source program, the research conducted will be easily accessible, and therefore, there is an abundant potential for adoption and implementation of these technologies. Additionally, AguaClara has a model of social sustainability, which includes partnerships with local organizations for implementation, training of operators, and maintenance, which allows for a strong connection with the local communities, and creates a long term plan for social prosperity.

Planet

AguaClara plants are completely electricity-free and built using locally sourced materials, making AguaClara water treatment plants some of the most sustainable water treatment technologies available with an incredibly reduced carbon footprint. In addition to the zero emissions treatment plant, the availability of affordable drinking water also reduces plastic water bottle waste. Compared with the alternatives, such as energy intensive package plants shipped from overseas or bottled water with inconsistent quality shipped across the country, the AguaClara plant offers a very affordable, sustainable, and environmentally-conscious option.

Implementation of the P3 Award Project as an Education Tool

The AguaClara Cornell program began in Fall 2005. AguaClara is an innovation system that engages Cornell students to research, invent, and design electricity-free novel water treatment technologies that are needed in both the United States and the Majority World. The program initially included undergraduates and M.Eng. students and then added Ph.D. students in 2007. To date, more than 650 undergraduates, 100 Master of Engineering, and 5 Ph.D. students have participated in the program for academic credit. Each semester, about 90 students participate in the program. Undergraduate and Masters students come from across the university, with the majority from engineering, and currently over 70% are female.

Students engage with hands-on, project based learning to research, invent, and design improved water technologies. The project course is offered every semester. The curriculum also includes a theory course, CEE 4520: Sustainable Safe Water on Tap, that provides the basis of the AguaClara water treatment technologies and serves as a repository for the growing body of knowledge generated by the program. The final course, CEE 4560-1, is the preparation and reflection course that bookends the two-week engineering-in-context trip to Honduras. The students do not build the water treatment plants during the trip to Honduras. That is the purview of Agua Para el Pueblo, APP, in collaboration with the communities. Municipal water treatment plant construction projects typically take 6 months to a year for the construction phase and are much too large for a student team. The engineering-in-context trips provide an opportunity for an exchange of ideas within the cultural context, with Cornell students demonstrating new technologies to APP and learning about water treatment successes and failures from the Hondurans. Those successes and failures are lessons learnt that are taken back to Cornell to guide the next innovation cycle. The AguaClara project courses are part of a revolution in engineering education. Students from first year to Master of Engineering and even PhD join forces and combine their skills to develop new and improved water and wastewater treatment technologies. Students learn from each other and are highly motivated, knowing that what they discover will be used to provide safe drinking water for communities in Honduras, Nicaragua India and soon for communities in the United States.

The proposed research will be conducted by students in Cornell University's AguaClara program as part of our RIDE (Research, Invent, Design, and Empower) innovation system. Student teams collaborate with partner organizations to Research, Invent, and Design improved water treatment technologies and then to Empower implementation partners to build the facilities and assist communities with their maintenance and operation. The AguaClara project presently consists of approximately 100 students working on 25 different project teams. The teams are researching all of the unit processes in surface water treatment plant, several different wastewater treatment processes, refining the design code for surface water treatment plants, developing draft design code for upflow anaerobic sludge blanket digesters, inventing fabrication methods for a village-scale water treatment plant, in addition to the research into a gravity-powered vertical ram pump that is the subject of this proposal.

Multidisciplinary Teamwork

Sustained collaboration between faculty and students fostered the productive research that was obtained in Phase I of this research. Biological, mechanical and civil engineering students participated on the design process and application of physics and material properties to fit the given constraints of the ram pump design. The ACVRP team collaborated with AguaClara Cornell's Sensor Development team to construct and configure sensors tailored to the ram pump experimental setup. These dedicated researchers form the foundational relationships that will be brought into the proposed Phase II research.

II. Purpose, Objectives, and Scope

AguaClara research teams have demonstrated in the past that the use of the ram pump to pump treated water from lower to higher elevations allows for easier plant operation; in particular, it reduces the burden on the plant operator to manually carry buckets of water upstairs to fill chemical stock tanks. Conventional ram pumps waste water during the acceleration phase of the drive pump water. The acceleration phase is always the longest phase in a ram pump cycle. The water that is being used in the AguaClara ram pump is high quality drinking water that cannot be wasted. In the first implementation of a ram pump in an AguaClara plant this problem was solved by building a tank to catch the wasted water and route it to a distribution tank. Plant operators found this early prototype of the "conventional" ram pump difficult to install and repair. Therefore, the AguaClara Vertical Ram Pump (ACVRP), as an inline ram pump, removes the necessity to fabricate an additional tank, and can be installed directly into the existing pipe exiting the plant to the distribution system. Therefore, "wasted" water is recovered without any danger of contamination.

Phase I research measured the forces that are involved in the pumping cycle and the system's terminal velocity. This provides the basis for selection of the spring that will be used to automate the cycling of the waste valve. Based on the Phase I results, the ACVRP has the potential to eliminate the need for plant operators to carry water and will allow the ram pump to be installed without requiring the addition of a tank to capture waste water. These improvements will make water treatment more affordable and accessible to communities in the Majority World.

III. Data, Findings, Outputs/Outcomes

Force Balance Calculations

In order to determine sources of inefficiency in the ram pump and to optimize the designed spring constant, the forces required to open and to close the plate was calculated. A set-up was designed to experimentally calculate these forces. Figure 7 is a schematic of the setup for a force balance experiment. In order to determine the force necessary to open the plate, a two-pulley system was designed to connect the plate in the check valve to a plastic bottle via a wire.

The force to open the valve was calculated by obtaining the weight of the bottle right before the plate was closed and by applying the force balance equations in Figure 7, where W_{rod} was the weight of the plate and rod in water; W_{bottle} was the weight of the bottle, which was used to experimentally determine the force required to lift and open the check valve; T was the tension force of the pulley string; F_{water} was the force of water in the drive pipe on the plate.

The resulting force (F_{water}) acting on the plate was calculated for each trial. The average force required to open the valve is 12.5 newtons. The force required to close the valve, the drag force from the falling water, was calculated similarly as the force to open the valve. The average force to close the valve is 4.2 newtons.

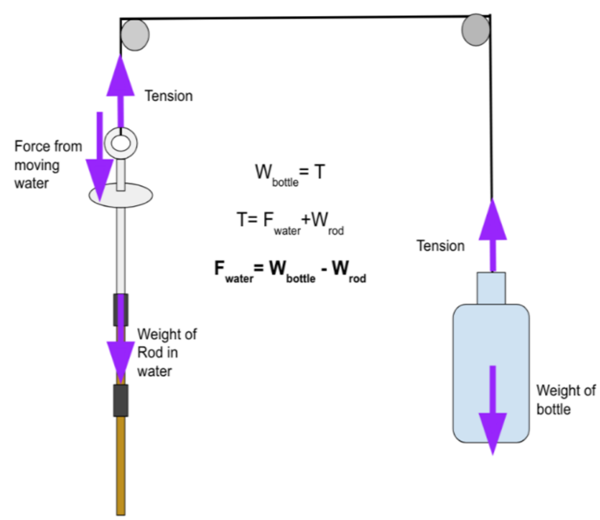

Figure 7: Free body diagram of forces acting on the check valve in the ACVRP in a pulley system (Storch and Snyder, 2018) The weight of the bottle was adjusted by adding water to the bottle.

Measuring Terminal Velocity

The average of the terminal velocity was calculated by first calculating the average flow rate, Q (L/s), which was 1.0 L/s, and then dividing Q by the cross-sectional area of the drive pipe to the terminal velocity of 2.3 m/s.

Calculating Spring Constants

Using the experimentally determined forces to open and close the valve, a range of ideal spring constants was determined. Hooke's Law was used to obtain the optimal spring constant from the force and compression length. Since, Hooke's Law depends on the compression length, Δx, k' was defined as an intrinsic material property of the spring dependent on the actual length of the spring rather than its compression length, such that Hooke's Law could be written as:

$$F = \frac{k'x}{L} \quad \text{where} \quad k' = kL$$

Using the above equation, equations were derived for the two states in the valve:

$F_{open} = \frac{k'x_1}{L}$ and $F_{close} = \frac{k'x_2}{L}$, where F_{open} is the force required to open the waste valve opened; F_{close}: force required to close the valve; x_1 is the compression length when the valve was closed;

x_2 is the compression length when the valve was open; k' is the intrinsic material property of the spring that is defined by L and k; L is the length of the spring

Combining the last two equations, an equation for k' in terms of the spring length, L was derived: $F_o - F_c = \frac{k'}{L}\Delta x$, where $F_{open} = 12.5\ N$; $F_{close} = 4.2\ N$; $\Delta x = 3.5$ cm, which is the compression length difference between open and closed states. The desired k constant can be obtained using k' with modification of the length of the spring. The linear relationship between the length of the spring, L [cm], and the intrinsic spring constant, k' was defined by the following equation: $k'[N] = 2.4 \left[\frac{N}{cm}\right] * L[cm]$

Efficiency Calculations

The time required for the water in the drive pipe to accelerate to 70% of terminal velocity can be calculated from the following equation.

$$t_{0.7V_f} = \frac{\tanh^{-1}(0.7)}{\sqrt{\frac{g}{2H_{drive}}(\Sigma K)}} \quad (1)$$

where H_{drive} is the height and length of the drive pipe, ΣK is the minor loss coefficient, and g is the acceleration due to gravity. For the laboratory configuration, the time required to accelerate the water in the drive pipe is approximately 1 second.

The amount of water that could theoretically be pumped in one valve cycle can be calculated by assuming that the pressure above the check valve is equal to the high pressure that the pump is delivering to while the drive pipe water decelerates at a constant rate to a stop, given by the following equation.

$$V_{cycle} = A\frac{v_f^2}{2g}\frac{H_{drive}}{H_{pump}} \quad (2)$$

where V_{cycle} is the theoretical volume of water pumped in one cycle, H_{pump} is the height above the top of the drive pipe that water is pumped to, A is the cross sectional area of the pipe, and v_f is the terminal velocity of the water in the drive pipe.

This equation shows that obtaining a high terminal velocity in the drive pipe results in a dramatic increase in the potential volume of water pumped per cycle. The measured volume of water pumped in one cycle was compared with the theoretical volume of water that could be pumped according to equation 2. The amount pumped was less than 10% of the theoretical value, which suggested that part of the ram pump was not performing as expected. A second analysis of the pressure in the ram pump that occurs when the waste valve closed demonstrated that the pressures were much higher than expected. The pressure measurements above the waste valve and in the high pressure air chamber were measured during manual operation (Figure 8). The pressure was so high that it broke multiple pressure sensors that had a proof pressure of 42 m (60 psi) even though the expected pressure based on the pressure in the air chamber was only 6 m.

The pressure cycles with a cycle time of 150 ms that occur after each change in valve position (see Figure 8) were initially thought to be due to pressure waves that travel the length of the drive pipe and then reflect at the free surface and return to the waste valve. The time required for a full cycle is equal to 4 L/a where L is the drive pipe length and a is the velocity of the pressure wave. Given that the drive pipe is 1.74 m long this corresponds to a velocity of 46 m/s. The theoretical pressure wave velocity, a, was determined by the bulk modulus of elasticity of water and the elasticity of the pipe wall.

$$a = \sqrt{\frac{K/\rho_0}{1 + \frac{K}{E}\frac{D}{t}}} \tag{3}$$

where K is the bulk modulus of elasticity (2.2 GPa), D is the inner diameter of the pipe, t is the pipe wall thickness, and E is the modulus of elasticity of PVC (2.4 - 4.1 GPa). Equation 3 indicates that the theoretical pressure wave velocity in the drive pipe was over 500 m/s and thus these pressure fluctuations were not due to the pressure wave in the drive pipe. These much slower fluctuations were due to the pressure oscillations in the tubing that connected the ram pump apparatus to the pressure sensor. Those pressure fluctuations were much slower because of a significant volume of air in those tubes.

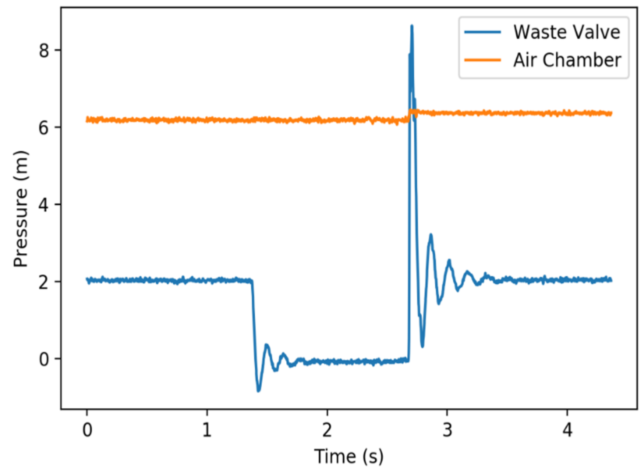

Figure 8: The pressure of the air chamber was observed as the valve was opened and closed manually with a pulley system. The air chamber increases in pressure when the waste valve slams closed due to successful pumping of water into the high pressure side of the pump. The pressure oscillations are due to the pressure wave traveling between the check valve and the free surface in the supply tank. (Cabrera et. al., 2019)

This analysis of the pressure waves provided the additional insight that the pressure traces that were obtained were significantly damped by the presence of compressible air in the tubing that connected the ram pump to the pressure sensors. Thus the pressure spikes were likely significantly higher than what was measured. The team will correct this measurement error by moving the pressure sensors as close as possible to the ram pump and thereby eliminate the tubing with the trapped air.

The low pumping efficiency and the high pressures above the waste valve confirm that version 1 of the inline pump must be redesigned to have a larger high pressure effluent to improve efficiency. The high pressure above the waste valve was due to head loss between the drive pipe and the air chamber and the need to accelerate the water to begin the flow into the high pressure side of the pump. A hydraulic analysis revealed that the diameter of the high pressure check valve was inadequate. The velocity in the high pressure effluent of ¼ in diameter is 16 times that in the drive pipe of 1 in diameter. This means that the ratio between the high pressure effluent and the drive pipe would increase minor head loss by 256 times.

The hydraulic analysis led to the insight that the initial flow into the high pressure zone immediately after the waste valve closes is equal to the maximum flow through waste valve at the end of the flow acceleration phase. The high pressure check valve should be designed to handle that high flow rate with minimal head loss. This design constraint can be met by using a high pressure check valve that is the same diameter as the waste valve.

A 30 psi pressure sensor that measured the pressure above the waste valve burst during the pressure cycle readings. That pressure sensor had a proof pressure of 60 psi, which was equivalent to 42 m of water. This high pressure is consistent with the need to switch to a larger diameter high pressure check valve..

IV. Conclusions, Recommendations

Based on experimental efficiency analysis, current design of ACVRP can pump effluent water up to over 6 m, which is the elevation that water needs to be pumped in an AguaClara plant. This shows that the ram pump is a viable solution for providing potable water as needed to a gravity powered, electricity free municipal water treatment plant. This also suggests that the ACVRP could be applied to a distribution system that has to serve community members at higher elevations than the AguaClara plant.

However, the efficiency of the current design of ram pump is less than 10% of its proposed theoretical efficiency value. A significant amount of head loss was found due to the ratio between the ¼ inch diameter of high pressure effluent and the 1 inch diameter of drive pipe. Therefore, in order to improve the efficiency of the ram pump, the diameter of the high pressure check valve will be increased to the same diameter as the drive pipe. The team also recommends reducing the change in flow direction for the high pressure effluent to further reduce head loss.

The ACVRP is designed to be easily installed in both plants that are already in operation and in future facilities. It can be constructed using locally accessible materials that are easily repaired or replaced. It will allow plant operators to efficiently refill the chemical stock tanks for water treatment processes in the 16 AguaClara plants that are already providing safe water on tap to 16 towns and small cities. The ACVRP will make AguaClara facilities even more attractive as a sustainable way to provide reliable safe water on tap.

V. Assurance that research misconduct has not occurred during the project period

The PI has over 20 years of experience in sustainable water treatment and has been guiding student research teams through the research, invent, design, and empower process since founding AguaClara in 2005. The value of carefully measuring and analyzing data is emphasized to all student teams because it the insight into the physics that will enable the team to create new inventions. This process is demonstrated in this proposal with unexpected results leading to new insights into the ram pump pressure cycles. Ram pump pressures and flow rate data will be monitored and measured with the Process Control and Data Acquisition (ProCoDA) software. The raw data and all research reports are compiled on the AguaClara GitHub Ram Pump page (https://github.com/AguaClara/ram_pump) that is open to the public and is shared with AguaClara's engineers in Honduras.

C. Proposal of Phase II

I. P3 Phase II Project Description

Proposal Quality

The Phase I research has made it clear that a vertical, inline, zero-waste, ram pump has significant potential for use as a reliable source of high quality water both within the water treatment plant and for a small number of customers who have homes at an elevation above the treated water storage tank. The first version of the ACVRP was able to pump water to a height of 6 m, but the efficiency was only 10%. The student research team has prioritized the following tasks for phase II:

1. Modify the design to increase the pumping efficiency
2. Simplify tuning for different driving heads and to maximize the flow of high pressure water
3. Test the ACVRP in the field for reliability and ease of use
4. Scale to different sizes of water treatment plants
5. Evaluate alternative designs for simplified fabrication

1. Increase Pumping Efficiency

As mentioned in the conclusions of Phase I report, inefficiency in the pumping cycle is hypothesized to be caused by the small diameter of the high pressure check valve. The proposed change to a high pressure check valve that is the same diameter as the waste valve is shown in Figure 9.

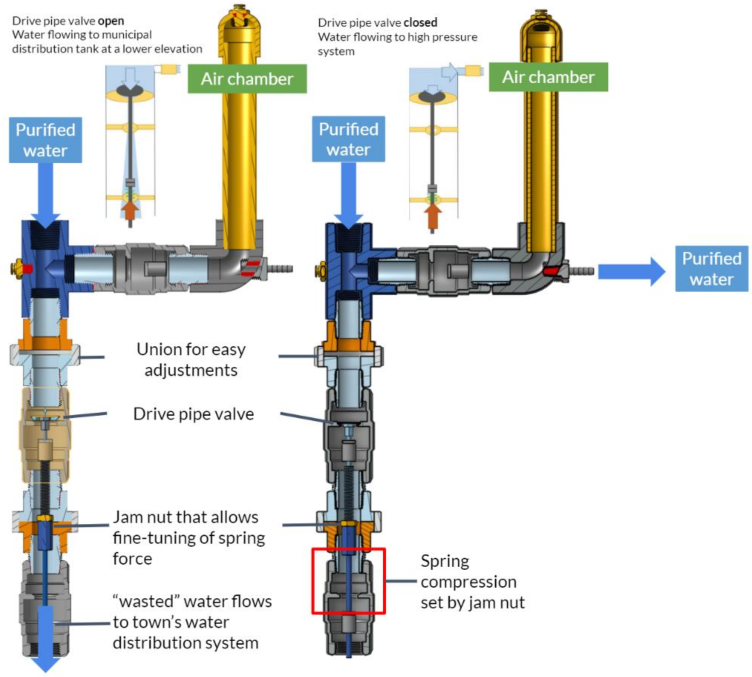

Figure 9: Cross-section view of the modified ACVRP where the diameter of the high pressure effluent is increased. When the plate is closed (right), water is pumped to a higher elevation through the high pressure effluent; when the plate is opened (left), the "wasted" water is exiting through the waste valve and rejoins the flow to the distribution system.

The 90° bend that the water takes to enter the high pressure check valve also causes unnecessary head loss and hence reduced pumping efficiency. Alternative flow geometry with a straighter path for the high pressure line between the waste valve and the air tank would result in higher efficiency. A possible solution to this inefficiency would be changing the geometry of the fitting connecting the drive pipe to the effluent pipe. A Y fitting as shown in Figure 10 would allow water from the drive pipe to enter the top and then either goes straight (to reconnect to a pipe going to the distribution storage tank) or at a small angle to get to the high pressure check valve.

Figure 10: Proposed new Y geometry to reduce head loss.

2. Simplify tuning for different driving heads

Tuning the spring forces to optimize pump efficiency is time-consuming and difficult. Adjustments to the inline ram pump are challenging as the ram pump must be removed from the plumbing system and disassembled to adjust the compression of the spring.

Conventional ram pumps that waste most of the water have an open design that makes it possible to adjust the weight while the pump is operating. This simplifies tuning the ram pump to operate efficiently. The inline pump is operated under pressure and thus it must be completely enclosed. Thus it is impossible to adjust the current design of the inline ram pump without turning the pump off and removing it. The team recognized that the short vertical drive pipe used by the inline ram pump provided an opportunity to move the pump controls up approximately 4 m into the AguaClara water treatment plant main floor. This alternative configuration will be evaluated as it would greatly simplify tuning the pump for optimal performance.

If a weight system as shown in Figure 11 is adopted instead of springs, the check valves will not be significantly modified and the lifespan should be long. The advantage of this weight system is that the controls for the timing of the ram pump will be accessible and the motion of the ram pump will be visible in the weights. This system will only work if the inertia of the weights is low enough that the inertia doesn't significantly slow down the opening and closing of the valve. Cycle time will ideally be around 2 seconds, thus yielding 43,000 strokes per day. Some manufacturers claim 2 million cycles until valve failure, which makes the lifespan of the valve just under 50 days. However, the forces acting on the check valves in the ACVRP are smaller than the forces that act on check valves in high pressure water systems that they were originally designed for. This analysis could be performed with Phase II funding to determine if the current design and component parts used for the ram pump do not optimize its longevity. If this is the case, new materials can be purchased to test fabrication techniques to optimize the life cycle of the ram pump. Thus a weight based ram pump is very promising for achieving our goal of easy adjustment and maintenance. The weight based ram pump would only require that the check valve be modified to attach a cable.

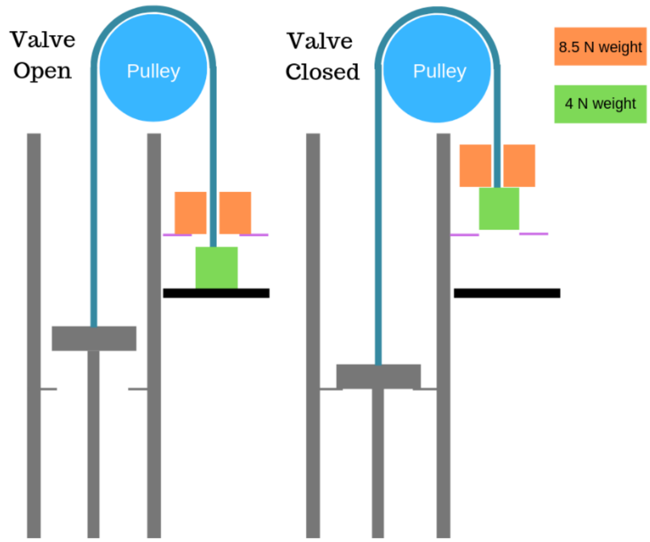

Figure 11: Schematic of the proposed weight based ACVRP system. Two weights would be used to apply the correct force at each end of the valve stroke. The second weight would only be lifted when the valve is fully closed.

3. Reliability and ease of use in field

Reliability and ease of installation, tuning, and operation of the ACVRP is vital to its implementation in the field. The spring and weight systems will be compared and evaluated for ease of installation and use. If it isn't clear which system is better, then they will both be field tested in Honduras.

The pump lifetime will be evaluated by checking for wear on the moving valve stem and spring. With a cycle time of approximately one second the pump could go through a million cycles in less than 2 weeks of continuous operation. Given that the cycles are at much lower forces than the valves were designed to handle it is expected that the check valves will be reliable for many millions of cycles. Any wearing of surfaces within the valve will be causes for concern and if needed the design will be modified to reduce that wear. Field testing will be essential to determine if the ram pump useful life is adequate and to identify any premature failure modes.

4. Scale to different flows

The goal of the ram pump is to work for plants between 10 and 100 L/s. However, with plants of varying flows, the required flow rate of the ram pump changes. Assuming a coagulant stock concentration of 200 g/L and a reasonable dose of 20 mg/L, the necessary dilution factor is 10,000. The stock solution for chlorine requires a much smaller flow and thus can be ignored. To dilute the coagulant by a factor of 10,000, for every L/s of plant flow the ram pump needs to supply 0.1 mL/s of water. At 10% efficiency, the first version of the ACVRP would pump 7 mL/s (estimated based on 4 m drive height and 7 m pump height). Assuming a goal of having the ram pump operating 8 hr/day max, the maximum size of plant that could be served by a single 1" diameter ram pump is 20 L/s. Thus, the efficiency must be significantly increased and/or larger diameter pumps must be researched. Efficiency is expected to be improved with the Phase II proposed changes, however larger diameter pipes and check valves can also be explored.

5. Alternative design of simplified fabrication

To allow for full scale implementation in AguaClara plants, the ACVRP needs to be fabricated easily using locally available resources. Current, the rod in the ACVRP is custom machined with significant lathe time that increases the cost of the ACVRP. Alternative methods of assembling the ACVRP will be evaluated. For example, the threaded and unthreaded portion of the rod could be separated and purchased as standard parts. The two parts could be joined with a significant reduction in fabrication difficulty with a threaded connection or with solder or brazing.

The weight based ram pump would simplify fabrication of the ram pump but would require a more complex control system with adjustable weights. If the weight based ram pump is developed it will benefit from design iteration to create an elegant and robust control system.

Robustness of Sustainability Approach

The ACVRP will eliminate the need for human labor carrying buckets of treated water to fill chemical stock tanks. AguaClara technologies will be even more attractive to communities who are seeking options for safe water on tap. With its inline design feature, the ACVRP can be implemented in the 16 current operating AguaClara water treatment plants by simply attaching pipes to the exit of the filtered water channel. Since, the ACVRP is designed to be easy to fabricate using PVC and brass fittings, the parts can be obtained locally. Water treatment plant operators are already skilled in plumbing and thus they will be able to easily maintain the ACVRP. The design will be field tested and refined as needed using the same innovation process that the AguaClara Cornell team has used to develop multiple new technologies.

Education and Teamwork

AguaClara Cornell is a project team where students have the opportunity of direct and hands-on application of basic engineering concepts taught at Cornell University (e.g. fluid mechanics, mechanical synthesis). The ACVRP team is composed of students from three different majors, and collaborated with other teams within AguaClara. One of those teams, the sensor development team configured the pressure sensors for use by the ACVRP team. The ACVRP team also worked with students who visited AguaClara plants in Honduras for exchange of ideas, in order to understand the actual situation and difficulties in the daily operation of water treatment plants.

During each academic term, project team lectures are held weekly by the PI and upper-level undergraduates to educate the current AguaClara members from first-year undergraduates to Master of Engineering of various topics regarding the AguaClara project. Topics include an overview of drinking and wastewater treatment systems, the structure and operation of the AguaClara plants, Python analysis, alumni panels, international outreach, and our purpose as a project team. We plan to continue implementing the P3 approach in designing sustainable, innovative technologies to provide safe water on tap for global communities by explicitly presenting this intent and our open-source philosophy in our weekly lectures. More details can be found in the section above titled Implementation of the P3 Award Project as an Education Tool. In CEE 2550, technical feedback sessions are also held weekly to discuss technical problems that each subteam is facing, and students from other subteams provide insight for solving the problems.

The concepts and methods used in the operation of AguaClara plants are well-documented and explained in the AguaClara textbook. The textbook is a collaborative effort involving hundreds of people, and the AguaClara program was designed to foster global and multidisciplinary interactions between students, faculty, field engineers, plant operators, implementation partner organizations, and community members. These interactions have provided a continuous and rich source of ideas that make it clear that in a collaborative innovative network it is impossible for anyone to claim full ownership of an idea. All subteams in the AguaClara Cornell program publish reports and post data in their Github repositories that are open to the public.

Budget and Project Management

Phase II of the project will be conducted by a team of students working on a semester-based schedule with some traveling to Honduras during the winter for implementation and some working during the summer as research interns. The ACVRP team composed of Biological, Civil and Mechanical students will collectively have mastery of sustainable drinking water treatment practices, force analysis, sustainable development, management, computer-aided drawing, and computer programming. Milestones for each semester are displayed on Table 1.

To provide support and guidance, the team will be advised by a multi-level leadership structure, directed by an upper-class student team leader while also mentored by a senior level research advisor. PI Dr. Weber-Shirk has extensive experience in sustainable drinking water treatment technologies. This multi-level structure is a characteristic of AguaClara teams and ensures accountability and timely completion of milestones as listed in Table 1.

Table 1: Schedule of the proposed research for Phase II.

January 2020	● First test of the new spring-based ram pump at an AguaClara plant in Honduras ● Obtain feedback on strengths and weaknesses of the new design and assess the difficulty associated with tuning a spring-based ram pump for efficient performance
Spring 2020	● Design, assemble, and test a new hydraulic test stand for a spring-based ram pump that is more compact and that is integrated into the ram pump workstation ● Test alternative flow geometry to achieve more efficient performance

Summer 2020	● Explore options for simplifying fabrication ● Develop a tuning protocol and troubleshooting guide that provides detailed steps for maximizing the flow rate ● Design, assemble, and test a 2 inch diameter spring-based ram pump that should be able to deliver 4 times more water and would be suitable for larger AguaClara facilities
Fall 2020	● Design, assemble, and test a hydraulic test stand for a weight-based ram pump that provides easy control of valve stem travel distance and the forces applied during both open and closed positions ● Explore alternative designs for the weight-based control system. Select the best alternative for demonstration in Honduras
January 2021	● First test of a weight-based ram pump at an AguaClara plant in Honduras ● Obtain feedback on strengths and weaknesses of the new design and assess the difficulty associated with tuning a spring-based ram pump for efficient performance
Spring 2021	● Request disassembly and review of the ram pumps in Honduras to check for wear of sliding surfaces ● Select the best option (spring or weight-based) for refining the fabrication methods
Summer 2021	● Create a scalable Onshape 3-d model and add the ram pump to AguaClara water treatment plant designs so that future plants include the ram pump
Fall 2021	● Write the final project report and publish a peer reviewed paper on the design and performance evaluation of the ram pump

The project milestones will serve as a guide to ensure that the team stays on schedule. The PI will review purchases to ensure they are appropriate for meeting the project goals.

The AguaClara Cornell team has a laboratory that is designed for 14 research teams. Each team has a workstation that facilitates setting up experimental apparatus and collecting data. The team is assigned that workstation for the duration of the project.

Progress toward meeting our social, economic and environmental goals will be tracked based on the number of AguaClara facilities in operation and the number of people who are receiving safe water on tap.

Quality Assurance Statement

The PI has over 20 years of experience in sustainable water treatment and have been guiding student research teams through the research, invent, design, and engage process since founding AguaClara in 2005. The performance of the ACVRP will be monitored using the ProCoDA (Process Control and Data Acquisition) software which was authored by the PI and allows for automated control of experimental designs and real-time monitoring of data when interfaced with sensors and meters. This software will allow for control and monitoring of parameters such as flow rate and pressure cycles. In addition, the team's collaboration with the AguaClara plant engineers and operators in Honduras in January 2020 will allow for access to the plant's effluent to the distribution system.

All AguaClara teams work on a multi-level oversight system where members are able to receive feedback regularly on the current progress as well as explore academic questions in private meetings with the PIs and upper-level undergraduates in advisor positions. To ensure proper communication and continuity of the team, results from experimentation and data acquisition are published in semesterly reports compiled on the AguaClara GitHub page under the Ram Pump team repository (https://github.com/AguaClara/ram_pump). These reports are public and are regularly shared with AguaClara's partners and engineers in Honduras and India.

II. Partnerships

The success of this project relies on the support and resources of various partners. Our partners bring multidisciplinary perspective and balance to our program. The focus of AguaClara Cornell on research/invent/design is possible because of our close collaboration with partner organizations. Our partners bring expertise in community engagement and help us choose our research topics. Our annual trips where we meet community members, water sector professionals, and water treatment plant operators forms the basis of our motivation to conduct research that directly connects with needs identified by those partners. Our long-standing partners, AguaClara Reach and Agua Para El Pueblo (APP), provide much expertise in the international development of the AguaClara water treatment facilities. These partners will be crucial in identifying pilot testing locations and planning and implementing the ACVRP in the field. We have included letters of support from these partners with this proposal.

D. References

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