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Comparative Analysis of Locally Available Materials for Treadle Pump Seals in Senegal, West Africa

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COMPARATIVE ANALYSIS OF LOCALLY AVAILABLE MATERIALS FOR TREADLE PUMP SEALS IN SENEGAL, WEST AFRICA

By

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Abstract

For rural farmers in Senegal, West Africa, pulling water for irrigation can be a laborious but necessary task during the dry season to earn income from vegetable gardening. Traditional water pulling methods are inexpensive but require great physical effort, while modern machines decrease the labor burden but at a high financial cost. This study looked at an intermediate water pulling technology, the treadle pump, and how it could be improved to become more desirable for use in agricultural irrigation. A treadle pump was built and tested during field work in a rural Senegalese village. Observations from field testing prompted a single component of the treadle pump, the piston seals, to be further investigated for improvement. Locally available materials were procured to make novel, experimental piston seals that were preliminarily field tested. Problems arising during field testing created the need for more consistent tests in a controlled environment. Laboratory testing was performed to draw conclusion about the new materials regarding operation force and performance of the piston seal. Results showed that three of the six materials tested had the potential to serve as functional replacements for the standard treadle pump piston seals. These materials shared similar properties as they were all foams and performed within a close range of one another. A financial comparison showed these materials to cost 97.3% less than the standard seals leading to a 16.4% reduction in the overall cost of the treadle pump. While the recommended materials could presently work as functional piston seals, future work is recommended to determine the lifetime of the materials.

1.0 Background: Senegal and Water Pulling Methods for Agriculture

This report is based on my experience and work as a Peace Corps Volunteer in the country of Senegal. My work as an Agroforestry Extension Agent brought me in close contact with farmers engaged in various agricultural activities, including field crop farming and market gardening, allowing me to see the daily challenges associated with providing adequate water for agriculture and how different technological solutions have been proposed to meet these challenges.

With a large rural population dependent on agriculture for subsistence and income, water resources play an important role in daily life in Senegal. In rural villages, water is mostly obtained from hand-dug wells using simple rope and bucket methods. More advanced methods, such as gasoline pumps, are utilized by some people for garden irrigation but constitute a minority of gardeners. Water pulling methods between these two extremes exist but have not been widely adopted, creating the need for improved technologies to fill this gap.

1.1 Overview of Senegal and Village Experience

The country of Senegal, officially called République de Sénégal, is the westernmost country on the African continent mainland, as shown in Figure 1.1. It is located south of Mauritania, north of Guinea and Guinea-Bissau, west of Mali and bordered by the Atlantic Ocean on the west. Senegal lies within the Sahel, the semi-arid geographic region between the Sahara desert to the north and the tropical climate to the south [1]. The population of Senegal was estimated at 13,975,834 in 2015 with 56.3% of the population classified as rural [2]. On the Human Development Index, a United Nations ranking of countries based on life expectancy, years of education, and gross national product, Senegal is ranked 170 out of 188 countries, putting it in the category of low human development countries [3].

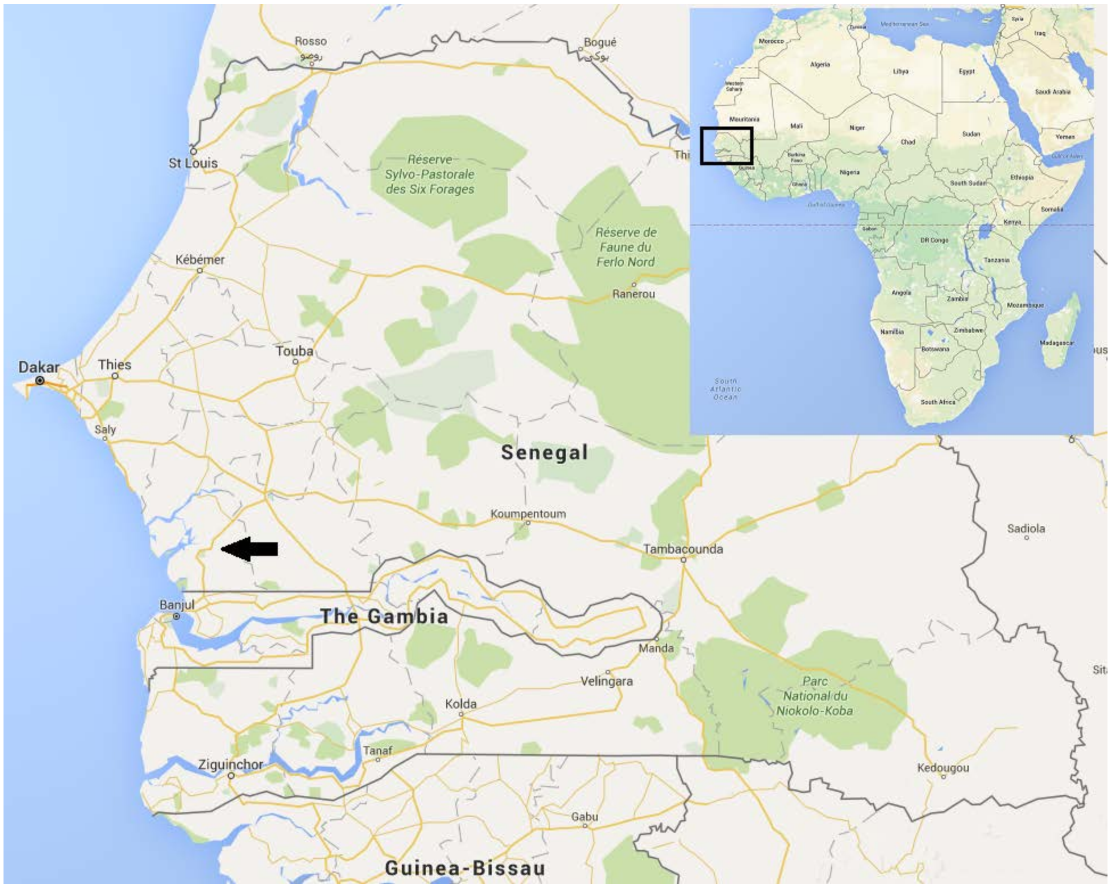

Figure 1.1: Map of Senegal. Arrow denotes location of village during Peace Corps service. (Image adapted from Google Maps)

Agriculture is an important activity for the Senegalese population, both for subsistence and income generation with 77.5% of the labor force engaged in agricultural activities [2]. While a variety of crops are grown across the country, in the Peanut Basin, a geographic area comprising a large portion of center of the country, millet and peanuts are two of the most common crops. Millet is traditionally a subsistence crop while peanuts serve as a main source of income for many farmers [4]. Gardening is an additional agricultural practice in Senegal that can provide additional income for a family which can significantly supplement household income in the developing world [5].

I gained first-hand experience in Senegal during my time as a Peace Corps volunteer from September 2013 to November 2015. Serving as an Agroforestry Extension Agent, I worked closely with farmers in the rural village of Niokholokho in the Fatick region. My main work duties involved assisting male and female farmers and gardeners with incorporating different tree species into their existing agricultural systems. The overall goal of this work was to bring about agricultural, ecological, and economic benefits for the individuals and the village as a whole. Much of this work was performed in household gardens and provided opportunities for direct experience and observations of the everyday challenges faced by people doing agricultural work in this region of Senegal.

Niokholokho is a rural village located in the Fatick region which borders The Gambia to the south and the Atlantic Ocean to the West. The village is approximately two kilometers from the national highway and five kilometers from the larger town of Sokone, which contains multiple hardware stores, metalworkers, woodworkers, a large weekly market, and access to most necessary goods and services. Niokholokho has a population of approximately 250 residents with almost all residents being of the Sereer ethnic group, a minority ethnic group in Senegal compromising 15% of the country's population [2]. The village lacks connection to the electrical grid, but at one time many households had partial electrification from small solar power systems with some residents still using these systems after making necessary repairs. Two public water taps are located in the village that connect to a water tower serving multiple villages in the area which charges on a volume basis. In addition to the water taps, various hand dug wells are located in and around the village and are more frequently used for water than the taps.

Every household in Niokholokho is engaged in one or more forms of agricultural production. During the rainy season, starting in June or July and ending in September or October, field crop farming occurs with every household growing millet and the majority also growing peanuts. Corn is also grown by a small group of farmers. After field crop season, many residents have gardens in the dry season. Male gardeners often grow a variety of vegetables, including tomato, eggplant, hot peppers, onions, bitter tomato, and green pepper, to be sold at nearby markets while women mostly grow hibiscus intensively for leaf production which is harvested multiple times throughout the season and sold to buyers who visit the village.

Usage of land for gardening and the gardening space itself is organized in different ways depending on various factors. While many people establish their own gardens on their own land, others will create a garden space on another person's land if permission is given or will be given a plot of land within another person's garden space for the gardening season. These borrowed and shared garden space arrangements result in wells being accessed by multiple people for watering, often at the same time.

Since gardening takes place during the dry season after the field crop season has finished when no rainfall events occur, watering must be done on a daily basis. This is also necessary due to low humidity and sandy, quick draining soils. Watering methods are similar for most gardeners in the village. All gardens either have a hand dug well located within their perimeter or one located a short distance from the garden entrance. Water depths in the wells around Niokholokho range between 5-7 meters below the surface depending on the time of year. The majority of gardeners use a simple rope-bucket-pulley system to bring this water to the surface. Watering is usually done during the cooler parts of the day, either in the morning or late afternoons. While each person is responsible for watering their own garden or plot within a garden, adults often utilize their children as extra labor in this task. Due to the strenuous work of pulling water from a well and transporting the water by bucket to the garden space to be watered, sometimes over 20 meters away, this generally means teenagers, both male and female, are more capable of the task while younger children help where they were able.

Within the village and surrounding gardens and fields owned by residents of the village, 17 hand-dug wells were in active use in 2015. Figure 1.2 below shows the location of these wells. Of these wells, two were public wells located within the main village and primarily provided water for domestic uses. Three wells were located within the boundaries of their owner's homes and used for both domestic and agricultural purposes.

Another well was located at the village primary school and provided water for a school garden as well as providing drinking water to the students. The remaining 11 wells were located in gardens away from the residential area of the village and used primarily for agriculture while occasionally used for domestic purposes, such as clothes washing.

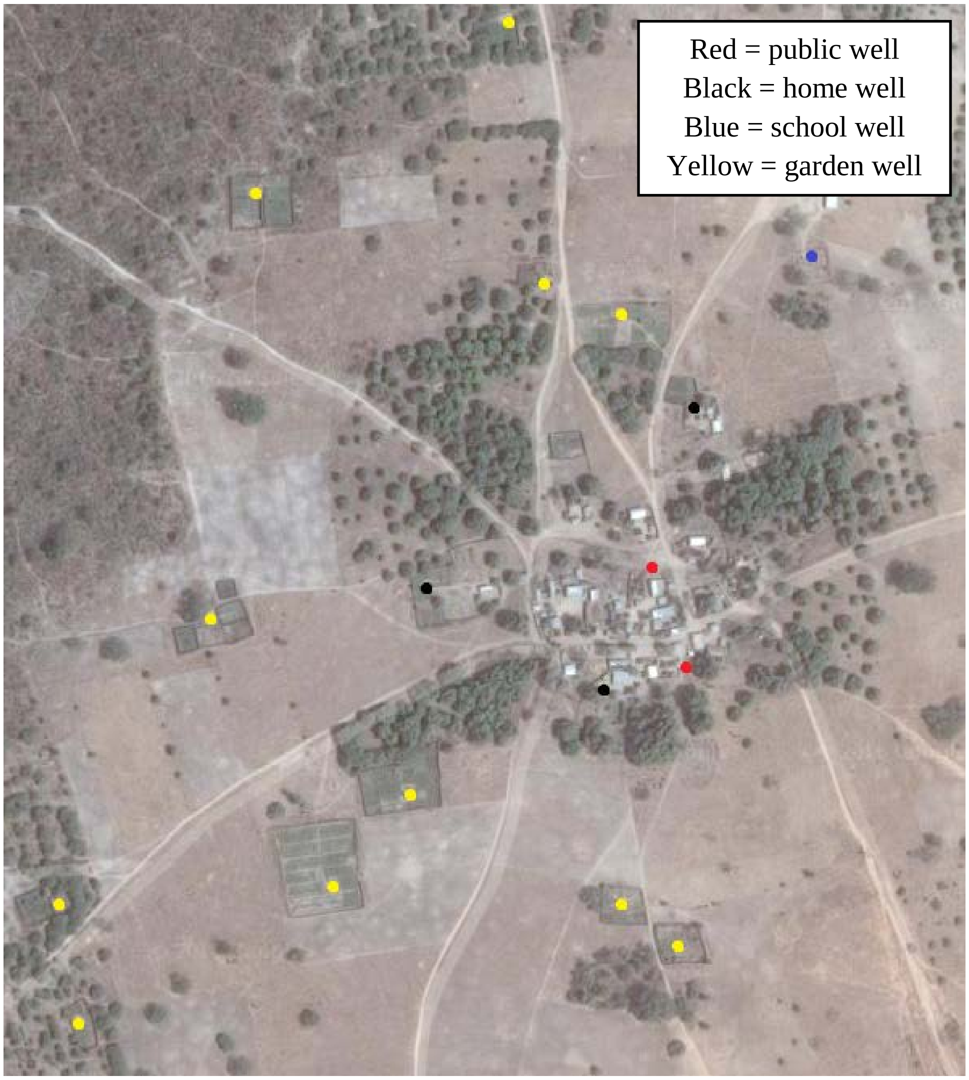

Figure 1.2: Map of wells in the village and surrounding areas.
(Image adapted from Google Maps)

As the name implies, these hand-dug wells are dug into the ground using only manual labor and hand tools. Since soils in the village are sandy with only small layers of rock, power equipment is not necessary. Wells are dug either by the owner of the land where the well is being built or, more commonly, by hired men who dig wells for a living. Wells are circular in shape and vary from 1-2 meters in diameter depending on the requirements of the well owner. Construction features of wells can vary with the desires of the owner and the money available they have to invest in the well. The simplest well is a hole dug in the ground until water is reached and an adequate water depth is available in the bottom of the well. This is achieved by having one person digging in the well with a shovel and pick while another person at the surface uses a rope and bucket to extract the dirt. Figure 1.3a shows the inside of a typical well used by multiple people.

(a) (b)

Figure 1.3: Hand dug wells. (a) Inside of an unlined well. (b) Typical well superstructure.

A superstructure exists above most wells. A typical superstructure is shown in Figure 1.3b. Superstructures usually include two parts, a wall around the hole that extends a certain height above ground level to add a level of protection against falling into the well and a frame from which a pulley can be hung and used to pull water from the well. Walls are usually made of earth bricks and often coated in cement. Some wells, if located within the village itself and used for domestic purposes as opposed to agricultural purposes, may also have a cap placed on them that covers the majority of the well opening but leaves an opening for a bucket to be used to pull water out. All well frames in the village were made of two tree branches put in the ground as posts on opposite sides of the well with another branch spanning the diameter of the well connected to the two posts.

Lining the wall of the well is an important process to increase the lifetime of the well but is not always done due to cost constraints. Lining the well involves applying cement with rebar reinforcements to the inside walls of the well either partially from the top or the complete depth of the well. Unlined wells, with only exposed soil acting as the walls of the well, can last for many years, but also have a greater chance of collapsing in on themselves during the rainy season when the soil is saturated and less stable. Lining the well helps prevent well collapse but is more expensive since it requires more purchased materials. An approximate cost for a 2 meter diameter unlined well is 100,000 FCFA, about $200 USD, compared to a same sized cement lined well with an estimated cost of 250,000 FCFA, about $500 USD.

Depending on climate factors, wells sometimes need to be re-dug to provide adequate water. While this situation does not occur every year, during the 2015 dry season, between the months of January and May, many garden wells had to be dug deeper either due to the water level dropping too low to provide enough water or due to low recharge rates when the well did not refill with water as quickly as it was being withdrawn. In the instance of low recharge rates, farmers would often use all the water available in the well to irrigate their gardens, then wait until later in the day to finish what remained if they did not dig their well deeper.

1.2 Water Pulling Methods

Different methods of pulling, storing, and delivering water for gardening were used in the village. Observations from visiting and working in the gardens showed the most common method of pulling water from wells was using a rope-bucket-pulley system. Every well had this system regardless of whether it also had a more advanced water pulling method. This method is low cost, simple to maintain, and reliable, allowing both children and adults to use it. Water storage techniques varied based partially on the level of permanence of the garden. Perennial gardens used by the same person for multiple years often had more permanent storage structures, such as ferro-cement basins built at ground level that could be filled with water and then used all at once or partially to water the garden. For gardeners who borrowed land or had less investment in their gardens, the common methods of storing water included only pulling enough water to fill the bucket they had, applying the water to the vegetables, and then repeating the cycle, or bringing large plastic basins to the garden, filling them, using the water, then refilling the basins. Figure 1.4 shows an example of a garden using multiple methods of water storage.

Figure 1.4: A garden utilizing multiple water storage methods. Plastic buckets and a basin are in the foreground with a ferro-cement basin right of center. The well with a rope-bucket-pulley system is on the left.

The most common water delivery method was using a bucket to apply water to garden beds, often by throwing the water directly on the bed. Watering cans were utilized in some gardens, but cost at least three times more than simple buckets. At a cost of about $6 USD for a metal watering can compared to $2 USD for a rubber bucket, the watering can cost more than what a typical gardener could expect for daily income from the garden. Both metal and plastic watering cans were also prone to leaking and breaking before buckets did.

More advanced water pulling, storage, and delivery methods, such as gasoline pumps, shown in Figure 1.5, multiple basins, and hoses, were used by certain gardeners in the village. These technologies constituted a small portion of gardeners and were all owned by males. These male gardeners sometimes allowed their wives or female relatives to use these methods, often requiring them to contribute to the cost of fuel.

Figure 1.5: Gasoline pump (center) pulling water from well with discharge into ferro-cement basin (right).

Table 1.1 summarizes the various methods and devices used for pulling, storing, and delivering water.

Table 1.1: Comparison of technologies and methods in garden irrigation.

	Increasing complexity and cost →			
Water pulling method	Rope and bucket	Rope, bucket, and pulley (one or two buckets per rope)	Gasoline powered pump	
Water storage method (temporary or longer)	Watering buckets/cans	Plastic basins (~90 L) taken to and from the garden each day	Permanent ferro-cement basin	Multiple ferro-cement basins connected with plastic pipes
Water delivery method	Water poured or thrown from bucket	Watering cans	Hose from gasoline pump	

Only rope-bucket, rope-bucket-pulley, and gasoline pumps were used in Niokholokho, but other water pulling methods were in use or had been used in neighboring villages. Several intermediate technologies had been used in other villages to varying degrees of success. Rope pumps, shown in Figure 1.6, are simple water lifting devices that use evenly spaced rubber washers on a rope loop to raise water through a pipe by inserting one end of a pipe in a well with one part of the rope loop passing through the pipe and catching water from the well with the washers and bringing it to the surface through the pipe by means of a rotating handle on the surface powered by the user.

Figure 1.6: Rope pump structure without rope and pipe mounted on well cover.

Since the user must be able to reach the handle at its peak position to properly operate the pump, they must be a certain height which can be taller than the pump itself as rope pumps are usually mounted off the ground above the well. The user must also be strong enough to lift the entire column of water in the pipe and maintain it as there are no valves to prevent the pump from rotating backwards and returning all of the water in the pipe back to the well.

Rope pumps were the most commonly found intermediate water lifting technology in the area and while there may have been some in use, none of those seen were in use at the time. All rope pumps had either broken and not been repaired or sat idle despite being made locally and able to be repaired locally.

Another alternative pumping technology, the treadle pump, had been introduced into Senegal in the early 1990's and later promoted in the Fatick region by the USAID Wula Nafaa project in 2008 [6]. This included training three craftsmen in the Fatick region how to fabricate the pumps and setting up demonstrations with various farmers and organizations [7]. In total, the area around Niokholokho had nine treadle pumps installed as a result of this project from 2008-2013 [8]. The closest treadle pump to Niokholokho was located less than 1 kilometer away from the village and was used for pulling water to irrigate a large garden area but had not been functional for a few years. Despite the efforts of the project and having trained craftsmen located in Sokone, treadle pumps were not widely adopted in the area but were known about with some gardeners successfully using them in their gardens before upgrading to gasoline pumps or abandoning them, like the pump in Figure 1.7.

Figure 1.7: Non-functional, abandoned treadle pump.

The lack of treadle pump adoption in the area was likely due to multiple factors. The motion of operation of the pump was different from the common rope-bucket-pulley method and the pump was often seen as requiring a lot of force to operate. Cost was also assumed to play a role in the lack of adoption as the treadle pump cost more than a rope-bucket-pulley system but did not provide as high flow rates as gasoline pumps. Mechanical problems, such as part failure, contributed to the idea that pumps easily broke and often needed repairs. All of these factors combined, plus the heavy influence of unstated opinions towards a new technology, likely resulted in treadle pumps only being used by a few individuals and not the larger population.

After gaining a better understanding of the available methods of water pulling, residents' opinions of these methods, and what could be done to reduce the time and labor burden of pulling water for garden irrigation, I chose to investigate the treadle pump as an alternative means to the most common rope-bucket-pulley method. After gaining experience with treadle pumps in their manufacturing, operation, and maintenance, it was decided to experiment with new piston seal designs as a way to reduce the pump cost and operator force. The remainder of this report discusses the technical details of the project.

2.0 Treadle Pumps

Treadle pumps are human-powered devices that offer an alternative method of pulling water between the simple rope and bucket method and more complex gasoline pumps. These pumps, originating in Southeast Asia, have been modified to fit the conditions of Africa and are available in different configurations based on the desired water discharge state. While many factors affect treadle pump performance, the piston seals that create suction pressure in the pump are a critical component of the pump and have a large influence on the functionality of the pump.

2.1 Treadle Pump Background

Treadle pumps are a human powered water pump developed in 1979 by the Rangpur Dinajpur Rural Service in Bangladesh [9]. Since its inception, the original design has been used in different countries and modified for the unique conditions present in different locations. Design modifications have included changing cylinder diameters, stroke length, number of operators, and mechanical advantage. Various governments and non-governmental organizations have introduced modified treadle pumps in Zambia, Kenya, Zimbabwe, Niger, Malawi, Senegal, and Ghana to varying degrees of success [10][11].

Multiple studies have shown that treadle pumps can reduce poverty among African farmers who adopt them when compared to non-adopters [12][13]. Although treadle pumps have been used successfully in some cases to increase income from agriculture, they may not be appropriate or desirable in every culture and context. One study found that with low flow rates, long pumping hours were required for adequate irrigation and exhaustion from pumping was attributed to sexual inactivity by farmer's spouses whether there was any true correlation or not [14]. This example shows that treadle pump design and operation must consider both technological and cultural perspectives for the technology to be widely accepted.

2.2 Treadle Pump Operation

A treadle pump functions by having an operator stand on two wooden or metal pedals, referred to as treadles, that are linked to two pistons housed inside separate cylinders. A stair-stepping motion is then used to move the treadles and pump water. The pistons are linked by a rope or chain across a pulley or pivot point allowing for one piston to move downward in the cylinder when the operator begins motion while at the same time pulling the other piston upward. The weight of the operator is the principal force that drives the motion of the pistons. On the upstroke, the piston moves upward in the cylinder which creates suction pressure in the cylinder due to a piston seal between the piston and inside wall of the cylinder. This suction pressure causes a one-way valve to open in the pump body below the cylinder which in turn pulls water into the cylinder as it flows from a pipe connected to the pump body on one end with the other end located in the water source. On the downstroke, the inlet valve closes and water is forced out of the cylinder.

Treadle pumps generally fall into one of two categories - suction and pressure pumps. Suction pumps, shown in Figure 2.1a, are treadle pumps designed to pull water from a source using suction and then discharge the water unpressurized from the top of the cylinders. A valve located in the piston opens on the downstroke allowing water to move from below the piston to above it. Then during the upstroke, this water is carried by the piston to the top of the cylinder where it exits the pump.

(a)

(b)

Figure 2.1: Different treadle pump configurations. (a) Suction treadle pump (b) Pressure treadle pump

In contrast, a pressure pump performs the same action for pulling the water from the source into the pump, but instead of a valve in the piston, it uses a second valve in the pump cylinder to force the water out under pressure during the downstroke. While suction pumps must be located vertically higher than any storage basin they are to fill since they do not pressurize the water, pressure pumps can be mounted vertically lower than storage basins or be used directly for irrigation by connecting a pipe or hose to the outlet of the pump, shown in Figure 2.1b as the black pipe near the bottom of the picture, as they discharge water under pressure.

Figure 2.2 shows a basic diagram of the internal components of a pressure treadle pump and the direction of water flow.

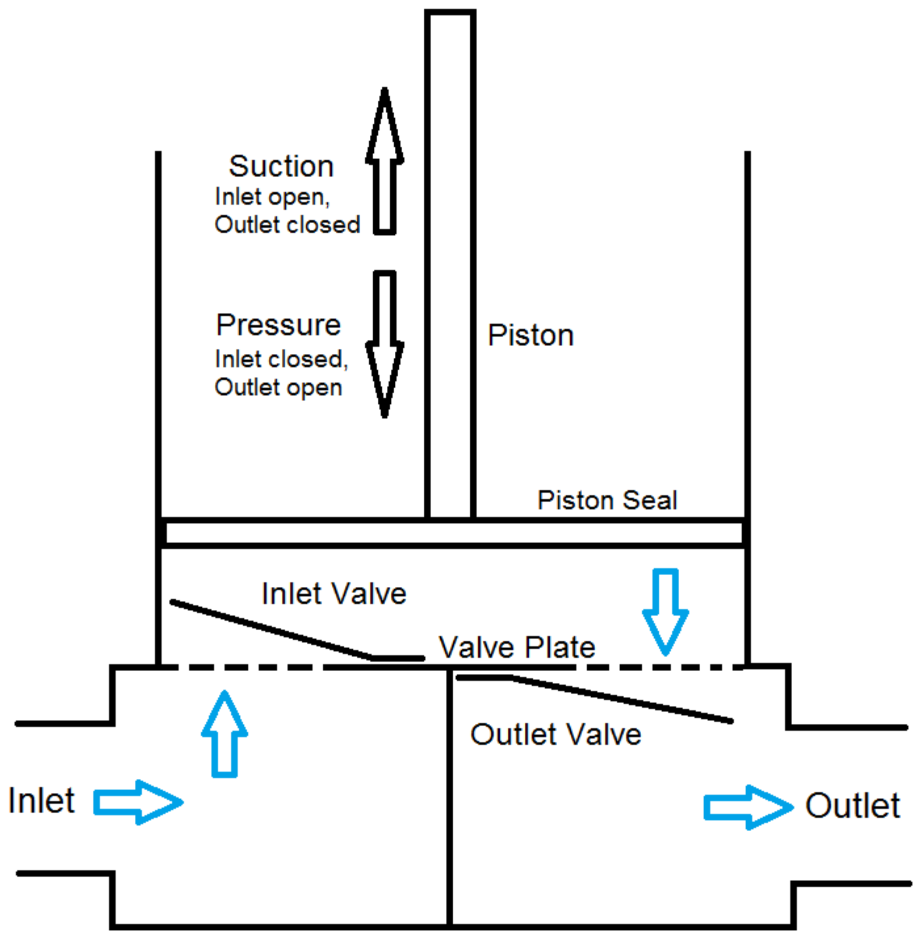

Figure 2.2: Diagram of water flow in a pressure treadle pump.

The cylinder is mounted on the pump body which includes the valve plate, valves, inlet and outlet. A separator divides the pump body between the inlet and outlet sides. The valves are attached to the valve plate and shown as flap valves in the figure but can be one of many different designs. Depending on the pump design, the pump body can be completely self-contained or may be left open on the bottom and mounted to a platform with a gasket to seal leaks.

Due to the inherent nature of using suction pressure to lift water, treadle pumps are limited in their maximum pumping depth. The theoretical limit is governed by the pressure difference acting on the water in the well from the atmosphere and the lower pressure created by the pump. In the case of open hand dug wells at sea level, atmospheric pressure is 101.3kPa, equivalent to about 10.4 meters of water. Therefore, a perfect system could pump water from a 10.4 meter deep well if the pistons are located at the surface [15]. Losses in the pipes, valves, and pump body, along with leaking at the point of contact of the piston seal and the cylinder wall as well as pipe connections, reduce the maximum pumping depth. Depths around 7 meters are more realistic given these losses [10]. Even with all losses accounted for, the available pumping force, dependent on the operator’s weight, is the final factor in whether water will be able to be pumped from a certain depth.

2.3 Piston Seals

Piston seals are important to pump performance as they create the seal between the linearly moving piston and the stationary cylinder which is necessary to create suction. Any leaks at the seal-cylinder interface can limit pump performance or, if large enough, prevent any suction from being created, making the pump inoperable. Friction between the seal and cylinder can cause an excess amount of input force to be wasted in moving the piston instead of contributing to the movement of water, thereby reducing the depth from which an operator of fixed weight can pump water.

The seals are the only internal component of the pump that has constant sliding contact with another surface. As the seal material is softer than the steel cylinder it moves against, it is subject to wear. The presence of wear means that the seal will have a finite lifetime after which it will no longer be able to create acceptable suction pressure. Seal lifetime can also be affected by material degradation in the wet pump environment.

Piston seals can also be a significant contributor to the overall pump cost. They must be made from materials able to withstand the operating conditions while not increasing friction in the system or wearing out before an acceptable amount of use. If made from materials that are not available locally, replacement seals may be hard to obtain and may be more expensive than the owner can afford, therefore locally available materials may be more advantageous. Table 2.1 summarizes important criteria for piston seal materials.

Table 2.1: Desirable criteria for piston seal materials

Low operator force – appropriate force for a variety of different users
Long lifetime – seal lasts an acceptable time before needing replacement
Low price – seal material does not significantly contribute to cost of pump
Locally available – material is easily and quickly available within the local area
Good performance – allows pump to be operated at an acceptable flow rate

Leather is one of the most commonly used materials for piston seals and used in many of the different treadle pumps designs in Africa. It is mostly utilized in a cup seal geometry with one or two seals per piston depending on whether used in a suction or pressure pump. Other materials have also been used for piston seals. Rubber seals have been used in some treadle pump designs with variations including rubber cup seals as well as rubber O-ring seals [10].

Treadle pumps of various designs have been promoted in Africa as an improved method of pulling water for irrigation. Whether a suction or a pressure type pump, treadle pumps offer a unique mechanical solution to the water pulling problem but are still subject to the same constraints on pumping depth as all water pumping devices that rely on suction pressure. In addition, the piston seals in treadle pumps are critical to pump performance and their design must be carefully considered.

Despite treadle pumps having been used for over 30 years in developing countries, they are not perfect devices. Understanding their limitations during real world operation and the problems that arise with their use requires hands-on experience with the pumps in the field. Therefore, a treadle pump was fabricated and tested in a local garden to gain this experience.

3.0 Field Work

It was necessary to gain experience with treadle pumps to better understand their operation and the mechanical aspects that affect their performance, especially as it relates to the piston seals. This involved observing and taking part in all the steps from having a treadle pump made to testing it in the field. Only after going through this process and performing preliminary field testing was it possible to identify important areas of improvement for treadle pumps to be more appropriate and desirable to potential users in the area.

3.1 Pump Fabrication

Observing the fabrication process was the first step in understanding the mechanical aspects of the treadle pump. Since mechanical issues can be inherent in the design of a mechanism or arise from manufacturing errors, being aware of what processes were followed to make the pump was important to be able to later distinguish between problems caused by fabrication and those caused by operation.

I was able to have a treadle pump made in Sokone, a larger town 5 kilometers from Niokholokho, at a metalworking shop that had made some treadle pumps previously from plans provided to them by a development organization. To learn about local manufacturing process, I was present during the fabrication of the treadle pump. While I tried to observe without influencing the manufacturing process to make sure the process was as authentic as possible, I did need to help read the plans and catch fabrication errors that could not have been easily fixed and would have caused the pump to be inoperable. Even though the plans were created with the intention of being able to fit within the capability of West African metal shops, errors in interpreting the plans were easily made by the workers whose normal work includes common designs of doors and gates.

The treadle pump created was a Bielenberg model pump, a modified design of the original treadle pump for use specifically in West Africa. The pump was designed by

Carl Bielenberg for CARE International with the design, manufacturing methods, operation, and maintenance of the pump described in [6]. The Bielenberg pump is a pressure pump that allows for two person operation. The fabrication plans and drawings available at the metal shop were produced by a non-governmental organization, Centre Ecologique Albert Schweitzer, and provided to the shop in French.

Mild steel was the main material used in the pump. Since the metal shop did not stock any new steel in the specified dimensions for the pump, all steel was either ordered from out of town or scrap material at the shop was used. No new steel was used since all ordered material was salvaged because new steel in the correct dimensions was too expensive or unavailable.

Due to limited metalworking machines, manual methods were used for fabrication of many of the pump components. Since no bandsaw was available, metal cutting was limited to using a hacksaw, mainly for tubing and rods, a shear, for small plate metal pieces, or a hammer and cold chisel for large plate metal components. The later method was used often when cutting curved geometries or long pieces of plate steel, such as when making the valve plate in Figure 3.1 and pump body as well as the piston disks, and an angle grinder was usually used to improve the edge of the cuts due to the jagged nature of using a chisel. A drill press was available to drill all of the holes during fabrication and a lathe was used to make the piston disks uniformly circular. Arc welding is a common task in metal shops resulting in multiple arc welders and skilled metalworkers in welding. In some cases, the metal shop did not have the exact size drill bit that was needed, and instead of purchasing the specified size, the closest available size was used.

Figure 3.1: Making the valve plate using a cold chisel and hammer.

The most difficult component of the pump to layout was the valve plate. As shown in Figure 3.2, this piece required many holes to be properly marked for the pump to operate correctly. Due to a small figure in the fabrication plans that was difficult to understand, I had to correct the layout of the holes after seeing errors in how it was originally marked.

Figure 3.2: Valve plate with complex hole layout.

The rubber flaps used for the valves were made from rubber tire tube. The fabrication plans specified using a minimum thickness rubber of 4mm but only 2mm was available. This thinner rubber was initially used to make the valve flaps.

Alignment of certain pump components proved difficult. Since no jigs were used to align parts, all alignment was done by eye. This method was functional, but did not create perfect alignment, as was seen in the treadle axle and its support being slightly misaligned causing the treadles to not be perfectly centered over the cylinders. Misalignment also resulted from welding. The cylinders showed good perpendicularity to the valve body before welding, but after welding they had slight angles to them. This was most likely caused by the cylinders shifting during welding since they were not clamped to the valve body and from the thermal effects of welding.

One modification to the provided plans that I had implemented was making the treadles longer by 20 cm. This change was made in anticipation of the pump requiring a high operator force for operation therefore, by making the treadles longer a greater mechanical advantage could be obtained.

The original seals called for in the fabrication plans were made from cow leather. Proper leather was not available locally and had to be purchased from the capital city, Dakar, and sent to the metal shop. The plans called for four cup seals, two for each cylinder. To form the seals from flat leather, the leather was first soaked in water overnight to make it soft and formable. A mold was then used to form the leather into the cup seal shape. The mold, shown in Figure 3.3, consisted of two circular pieces that the leather was positioned between. A bolt was then put in the center of all three pieces and used to clamp the mold together around the leather. This created a circular cup form out of the planar leather.

Figure 3.3: Leather cup seal being formed in a two piece mold.

The leather stayed clamped in the mold for several minutes. Before being removed, excess material that protruded out of the mold was trimmed off. The resulting seal is shown in Figure 3.4.

Figure 3.4: Finished leather cup seal with piston disk inserted.

The complete piston assembly in Figure 3.5 included two opposing leather cup seals per piston, one for suction and one for pressure. The seals were mounted on the piston with each seal having a 3mm thick metal disk placed in the cup portion of the seal and a metal disk acting as a separator between the two seals. These disks helped the cup seals maintain their form during operation.

Figure 3.5: Completed pistons with leather cup seals.

Initial installation of the pistons into the cylinders was difficult due to the seals having a very close fit and were finally forced into the cylinder using a hammer. Dry testing the pump at the metal shop showed that moving the pistons was difficult but did create good suction with air.

By observing the pump fabrication process, it was seen how a treadle pump can be made in a typical Senegalese metal shop using the available machines and materials even when they differ from the specifications. Errors in the fabrication were also observed, such as misalignment of the treadle axle and cylinders. This showed that while a local metal shop is capable of making a treadle pump, the fabrication process can impart deviations from the specified plans, with these deviations potentially affecting pump performance and the results of any tests performed with the pump.

3.2 Pump Installation

A pump is of no use if it is not connected to a water source. For a treadle pump, the installation process and configuration can have effects on pump operation as it defines how the pump interacts with not only the water it is pumping but other environmental factors around it. Therefore, errors in installation, such as leaking pipe connections or an improperly located inlet pipe, can impact pump performance.

The finished pump was installed in the garden of a female gardener in Niokholokho. This location was chosen because it was adequately protected, had a locked gate when no one was present, was not frequented by children who may misuse the pump, and the garden owner was a personal friend and work partner who allowed me to install the pump. The well from which the pump was drawing water had a distance of 6.5 meters from ground level to the top of the water, a representative depth of the majority of wells in the village

Installation required properly positioning the pump so that it would be close to the well and be aligned with a basin into which the pumped water would be delivered, and installing the necessary piping. Piping included horizontal sections to bring water to the pump inlet from the well and then from the pump outlet to the basin, and a vertical section to go from ground level down to the water in the well. Unconventional methods of joining pipes of the same diameter with no flanged connections had to be used. This involved starting a small fire, heating one end of a pipe until soft as seen in Figure 3.6, then forming it over the other pipe it was to be joined to. While an adhesive was used for pipe connections, this did not always create an airtight seal. To seal the connections further, rubber strips from old tire tubes were wrapped tightly around the connections like those in Figure 3.7. For connections between the plastic pipe and the metal pipe on the pump, only rubber strips were used to attached and seal the connection.

Figure 3.6: Heating plastic pipes over a fire to form pipe connections.

Figure 3.7: Wrapping pipe connections with rubber strips to seal connections.

A foot valve was installed at the entrance to the inlet pipe placed in the well as shown in Figure 3.8. This valve was a purchased component that acted as a one-way valve to maintain prime in the pump by preventing water in the vertical inlet pipe from flowing back into the well. The metal foot valve was joined to the plastic pipe by heating the pipe until soft and inserting it into the internally threaded connector on the valve. This consequently created matching external threads on the pipe that allowed for the valve to be easily removed from the pipe if necessary.

Figure 3.8: Foot valve at entrance of inlet pipe.

The garden where the pump was installed had a preexisting ferro-cement basin for holding water. Therefore the outlet pipe was configured to go horizontally from the pump outlet to the basin, then vertically from the base of the basin to a height above the top of the basin, followed by a 90° elbow to direct the water from the pipe into the basin. This configuration resulted in about 1 meter of vertical head on the outlet of the pump.

Installation of the pump required methods that, while not uncommon in Senegal, may have created locations for air leaks in the system. If present, these leaks would cause air to enter the system and take up volume that would otherwise be occupied by water. This scenario would cause the water flow rate to be lower than ideal giving the impression that the pump had performance issues.

3.3 Repairs and Modifications

Earlier concerns about potential problems stemming from the design, fabrication, and installation of the pump quickly proved to be partially true once the pump was ready to be used. New issues also arose that had not been identified previously but were major impediments to operation. These problems, as well as the need to change the design of the pump, resulted in several modifications to make the pump more robust and easier for one person operation.

While the pump was functional after installation, it did not perform as expected. It was difficult to prime the pump and there was an audible leaking noise coming from the cylinders. The cause was identified as poor sealing of the valves. The valves on the inlet side were not closing well due to inherent curvature of the rubber tire material used for the flaps. By flipping one of the valves over to get a better fit it was possible to improve pump performance slightly. The outlet valves also did not close well, which caused air from the outlet side to be pulled into the cylinder during the suction stroke instead of drawing in water from the inlet side. This was determined to be caused by the valve flaps being made from thinner rubber than was specified in the plans. Since the outlet flaps are opened by gravity and closed by suction in the cylinder, the thinner material fell further away from the valve plate when open, and during suction there was not enough force on the thin rubber to pull them into good contact with the valve plate, therefore air could leak past them into the cylinder. To correct the valve problems, new valve flaps were made by gluing two pieces of 2mm tire tube together and cutting out new flaps. After installing the new flaps, adjustments still had to be made by trimming the flaps so they did not contact the cylinder wall which prevented them from closing all the way.

Initial testing also resulting in the failure of one of the treadles. Due to the orientation of the wood grain in the treadle, force from the operator standing on the treadles was applied in such a way as to cause the wood to break along the grain. Since this happened early on in testing and was not a result of sustained use, it was assumed that this type of failure could happen again, therefore metal reinforcements were designed for the treadles. This design was based off treadle reinforcements seen on a different style treadle pump being used by a farmer in a different village. The reinforcements included adding metal 90 degree angles along the length of two sides of the wood treadle and joining them at various points along their length to create an external structure to support the applied force as shown in Figure 3.9.

Figure 3.9: Metal reinforcements on wooden treadles.

The original pump was designed for two-person operation, which decreased the input demands of a single user but did not allow for single-person use, especially with larger suction heads. To make the logistics of testing the pump easier and to allow for the single garden owner to operate the pump, modifications were made to allow for single user operation. This involved changing the mounting location of the treadles on the pump to increase the mechanical advantage of the user. This was easily done by rotating the treadles 180° to make the end of the treadle that the operator previously stood on the new end mounted to the treadle pivot since the slot in the treadle for the piston was positioned at a location along the treadle to allow for this change to obtain the desired mechanical advantage. The treadle axle mount had to be relocated closer to the cylinders to accommodate this change but was simply accomplished by grinding it off and welding it back on at the correct location. Figure 3.10 shows the pump before and after modification. This modification led to a change in mechanical advantage of approximately 2.25 for two operators to a maximum of 3 for one operator.

(a)

(b)

Figure 3.10: Treadle pump in one and two person configurations. (a) Pump with original treadles, (b) Pump with modified treadles

Negative consequences of altering the operator position on the treadles did result. With the operator now standing further away from the pump base, a larger moment was placed on the pump causing it to tilt in the direction of the operator. This was counteracted by adding counterweight in the form of sandbags to the front of the pump to keep it balanced.

The foot valve initially functioned properly but over time became problematic to the operation of the pump. Many times after operating the pump, the suction prime would be lost shortly after ceasing operation. The cause was determined to come from the foot valve because a properly functioning foot valve should maintain prime in the pump by keeping the inlet pipe full of water. By removing the inlet pipe and looking at the foot valve it was found to be stuck in an open position allowing water to flow back into the well. The cause was most likely sand in the water interrupting smooth movement of the check valve and keeping it stuck in the open position. The valve was easily freed and rinsed each time this occurred but would usually become stuck again only a few days later. While the pump was operational even with a faulty foot valve, it made pumping difficult by requiring prime to be regained after stopping operation for more than a couple minutes and priming the pump was found to be one of the more physically demanding components of operation.

Other minor repairs and maintenance of the pump were performed during its period of use. This included replacing broken pipe connections, replacing deteriorating rubber strips around those connections, and keeping the inlet pipe properly located in the well with changing water depth.

The need for repairs and modifications to the pump before it was used on a regular basis indicated that the processes to fabricate the pump and the pump design itself were prone to errors that were detrimental to pump performance, in some cases rendering it inoperable. Even though these problems were addressed as well as possible, they still most likely affected pump operation. These effects would then be present in any performance testing of the pump making it difficult to differentiate between normal pump performance and unintended problems in operation.

3.4 Field Performance of Seals

After installing the pump and making it fully functional, qualitative observations were made about pump performance and operation. These observations were focused on the piston seals, a critical component of the pump. In addition to the original leather seals, other materials were tested to gain a preliminary understanding of their performance and how well they met the desirable criteria for piston seals. Due to a lack of equipment to collect accurate data, results from preliminary tests were limited to observations about a seal's ability to pump water, including any leaks around the seal, and personal reflections about the perceived effort to operate the pump.

3.4.1 Leather Seals

The original leather cups seals that came with the pump were functional in pumping water at the beginning but quickly started to show deficiencies. Problems manifested themselves in one of two ways. Water would either leak around the seal on the downstroke causing it to accumulate on top of the piston and eventually spill out onto the ground around the pump, or air would be pulled into the cylinder on the upstroke meaning water was not filling the cylinder as it should. The latter problem could often be mitigated by pouring water on top of the piston to create a better seal, but this water would soon be pulled into the piston also and had to be replaced, sometimes as often as every 30 seconds. Examination of the seals showed that there were wrinkles present in the leather, as shown in Figure 3.11, which created locations where the seal did not have good contact with the cylinder wall, resulting in leaks.

Figure 3.11: Leather piston seal with wrinkled and inward folding edges.

It was also seen that the flanged ends of the leather seal tended to fold inward towards the center of the cylinder instead of pressing against the cylinder wall, also leading to a weaker seal with the cylinder wall.

In an attempt to mitigate these effects, additional metal disks were added to the seals. While disks were already present at the bottom of each seal to help it maintain shape, there was no support at the top of the flanged ends where the seals had poor contact with the cylinder. Another metal disk was added to the seal with metal washers used to space it further up the flanged ends of the seal. Due to limitations on the length of the mounting bolt on each piston, this could only be done for one of the two seals on each piston. The top seal was chosen to receive this extra support since it was easily seen while pumping and was most important to maintaining suction. This modification to the leather seals only provided a small improvement to seal performance. While there was better contact between the seal and the cylinder, leaking still occurred.

The leather seals also suffered from the effects of constant wetting and drying. For the leather to create a good seal it needed to be wet and pliable otherwise it would not conform well to the cylinder wall. This often required soaking the seals in water for several minutes before use and then working them into the proper form by hand once softened. These cycles of wetting and drying combined with wear from rubbing against the cylinder surface during operation created visible cracks and wear marks in the leather.

Pumping was perceived as being strenuous and it was hypothesized that this may be partially due to friction between the seal and cylinder wall. Certain resources indicated shea butter can be used as a lubricant for leather piston seals [6]. Since shea butter could be easily and cheaply purchased in the local market, it was experimented with as a lubricant. After drying the seal out completely, shea butter was worked into the leather by hand until it appeared to be absorbed into the leather. Operating the pump with the lubricated seals seemed to slightly reduce operator force but was not enough to make a significant difference.

3.4.2 Alternative Seals

Due to the performance issue with the original leather piston seals, alternative seal materials were investigated. Materials were chosen based on what was locally available, inexpensive, and most likely to create functional seals. These criteria resulted in all materials being various foams and rubbers used to make and repair footwear. Table 3.1 lists the alternative materials obtained for experimentation.

Table 3.1: Attributes of alternative materials used for piston seals

Material	Composition	Average Thickness
Material 0	Medium Foam	5.25 mm
Material 1	Medium Foam	6.23 mm
Material 2	Hard Foam	4.23 mm
Material 3	Soft Rubber	2.63 mm
Material 4	Hard rubber	3.04 mm
Material 5	Medium Foam	6.82 mm

The new materials were also accompanied with a change in seal geometry. Due to the materials not having the same formability properties as leather and with the desire to eliminate the need for custom molds to form the seals, the cup seal geometry was replaced with a simple flat circular disk shape. The seal was sandwiched between two metal disks to provide rigidity and prevent it from losing shape during operation. Figure 3.12 shows the alternative seal design.

Figure 3.12: Alternative piston seal in a circular disk shape.

Initially the diameter of the seal was chosen to match the cylinder diameter of 107mm. Calipers were used to scribe the shape on the material and then scissors were used to cut the seal out of the material. As can be seen in Figure 3.12, using scissor did not create a smooth, uniform surface on the edge of the seal but was the simplest method available.

The first test of the alternative seal design with Material 0 was able to create suction and pump water. While there was leaking present around the seal, the initial test showed that this seal design may be a functional replacement for the leather seals. Seals with identical geometry were made from three other materials and tested in the pump.

While no reliable quantitative data is available, from my experience using the pump with both the leather seals and seals made from the alternative materials, some observations were made. All alternative seals at some point during their operation needed water poured on top of them to reduce air leaking into the cylinder during suction. The alternative seals were also perceived as being more difficult to operate, requiring more operator input force than the leather seals. Since Material 0 appeared to perform the best of the alternative materials tested in the field and since a larger quantity of it was immediately available, it was used most extensively in field testing.

Several attempts were made to make different geometries from the alternative materials. Since leaking between the seal and cylinder wall may have been occurring due to the seal being sized for the exact cylinder diameter but having an imperfect edge creating small gaps between the seal and wall, different seals were made by oversizing the seal. A seal of Material 0 with a diameter of 110mm, 3mm larger than the cylinder diameter, was tested and found to be functional but the material in excess of the cylinder diameter was cut by the edge of the cylinder when being inserted and then completely trimmed off during operation due to the forces acting on it. More aggressively oversized disks of Material 0 were created with diameters of 120mm and 130mm. When inserted into the cylinder, these seals folded into the shape of a cup seal and were able to pump water but were also perceived to be more difficult than the leather seals.

In another attempt to reduce leaking, multiple flat disks of 107mm were used at one time on the piston. Different configurations were tested by using two or three seals on each piston and by adding metal spacer disks between the seals. All multiple seal configurations pumped water and did not leak but were much more difficult to operate than the leather seals.

One attempt was made to see if lubrication could reduce friction between the seal and cylinder wall. Material 0 was coated with melted shea butter in an attempt to have it absorbed into the material to act as a lubricant. During testing of this seal, it seemed to initially require less operator force at the start of testing but as testing progressed the force increased. This was likely due to the shea not being able to adhere well to the material and being removed as pumping occurred.

Table 3.2 summarizes the observations from field testing, noting that while all seals were functional they did not perform perfectly or equally.

Table 3.2: Preliminary seal testing results

Seal Type	**Material**	**Diameter**	**Observations**
Flat disk	Material 0 Material 2 Material 3 Material 4	107mm	All materials pumped water but required more force than leather seals
Oversized flat disk	Material 0	110mm	Pumped water, required more force than leather seal and excess material was trimmed off in the cylinder
Multiple flat disks	Material 0	107mm	Pumped water but required more force than single flat disk
Flat disk lubricated with shea butter	Material 0	107mm	Pumped water. Initially required less force than leather seals but later became more difficult than leather seals.

3.4.3 Flow Rate Testing

Basic flow rate testing of the pump was performed to quantify how fast it could pump water. This test included capturing the water from the pump in a basin, shown in Figure 3.13, over a measured time interval and measuring the amount of water pumped. Results are shown in Table 3.3.

Figure 3.13: Flow rate test setup. The black and grey pipe on the left was attached to the pump with water exiting the grey elbow and entering the black basin.

Error in the test was present due to not all of the water being completely captured by the basin but was assumed to be a small enough amount to not induce significant error in the test results.

Table 3.3: Results of flow rate testing with Material 0 flat disk seal

Time (minutes)	Strokes	Water Volume (L)	Flow Rate (L/min)
2	131	66	33
2.23	155	65	29.1
2	149	62	31

The flow rate of the treadle pump was compared to the amount of water that can be pulled from a well using a rope-bucket-pulley system. Over a 2 minute interval 53 L of water was pulled for an equivalent flow rate of 26.5 L/min. Since pulling water by hand using this method can depend on various factors, including depth of well, size of bucket, quality of pulley, and strength of the person, this data point only serves as a rough comparison between hand pulling water at this specific well and using a treadle pump.

Field testing provided important insights into the functionality of the original leather piston seals as well as the alternative materials. The leather seals, while functional, showed deficiencies in performance as leaking was common and the leather suffered from wear and the effects of constant wetting and drying. The alternative foam and rubber materials proved to make functional seals in a flat disk geometry but were also perceived to require more force for operation according to operator observations. Simple flow rate testing also provided basic quantification of the possible flow rate for an alternative piston seal.

While field testing of the leather seals and the alternative seal materials was useful in gaining a preliminary understanding of their functionality, it did not allow for accurate data to be gathered from which informed comparisons about seal performance could be made. One reason for this was a lack of adequate data collection equipment for force measurement. With no access to electricity, engineering data acquisition equipment requiring excitation and a computer to capture the data could not be used if it were available, and while simpler non-electronic methods of measuring force may have been adequate, they were not easily available or configured. Despite attempts to measure the operation force using simple methods, no acceptable data was collected. The previously stated problems arising from fabrication errors, installation, and components external to the pump, such as the foot valve, also hampered accurate data collection since these problems affected pump performance in different ways at different times making consistent data collection difficult. All of these factors combined created the need for more consistent and controlled laboratory testing from which accurate conclusions could be drawn.

4.0 Laboratory Testing

Discerning performance issues stemming from unintended conditions and those actually associated with the piston seals was nearly impossible in the field. Therefore, laboratory testing needed to be done to obtain quantifiable data for the required operating force of each seal material and to make accurate conclusions about which of the alternative materials could be suitable replacements for the original leather seals. While this testing did not simulate real world operating conditions of the pump, it was undergone to provide a numerical basis from which to identify which alternative material had the best performance compared to the others.

Laboratory testing required creating an experimental pump that could be easily instrumented for data collection and eliminate or reduce many of the factors affecting pump performance that were present in field testing. Once a test system was assembled, properly instrumented to measure operation force, and an appropriate test procedure was identified, testing was performed on the alternative seal materials. This test data was used to make performance comparisons between the materials to identify which materials are better suited for use as piston seals in treadle pumps.

4.1 Testing Setup

Since a treadle pump could not easily be brought back to campus from the field, a modified version of the pump used in Senegal was fabricated. This experimental pump, shown in Figure 4.1, maintained the same operating principles of the field pump but in a modified configuration.

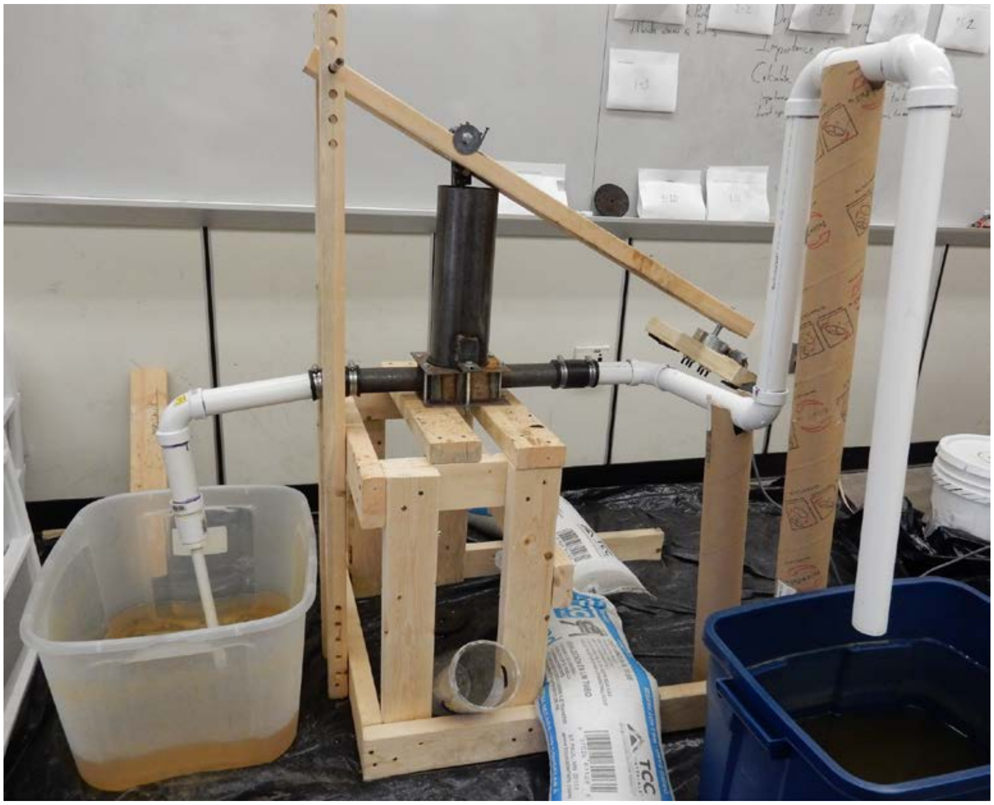

Figure 4.1: Experimental pump for laboratory testing. The pump is mounted on a wooden frame and located in the center with the inlet pipe and basin on the left and outlet pipe and basin on the right.

Instead of using two cylinders and pistons, the experimental pump was reduced to a single cylinder and piston. This reduced the complexity of the pump and allowed for experimentation to focus only on a single cylinder and piston. With a single cylinder and piston, treadle operation was no longer required, therefore operation was changed from standing on treadles to using a single pump arm as a handle that the user operated with their upper body. While this no longer made the pump a treadle pump by definition, it allowed for easier instrumentation of the pump to measure force. The pump body was also changed to allow for disassembly so the working parts of the pump could be examined. Instead of having all parts permanently welded together as was done with the field pump, parts were clamped together with sealing gaskets between them. The cylinder, valve plate, pump body, and base plate were assembled with this method. No geometry of the internal components of the pump, such as the valves, were changed, however, different yet equivalent materials were used for the valves since the same rubber tube used in the field pump was not available. Table 4.1 outlines the major differences between the field and experimental pumps.

Table 4.1: Comparison of field and experimental pumps

Field Treadle Pump	**Experimental Pump**
Treadle operation	Hand pump operation
2 cylinders – 107 mm diameter each	1 cylinder – 108 mm diameter
Welded pump body	Pump body able to be disassembled
Mechanical Advantage – 3	Mechanical Advantage - 3.6
Vertical Suction Depth – 6.5 m with constant pipe diameter	Vertical Suction Depth – 0.6 m with reduced diameter sections

Water was supplied to the pump from a plastic basin and discharged into another basin. With the pump located in a laboratory setting that had no space to accommodate a large pumping depth, head loss was built into the inlet pipe by reducing the size of the inlet pipe. Figure 4.2 shows a diagram of the pump piping system.

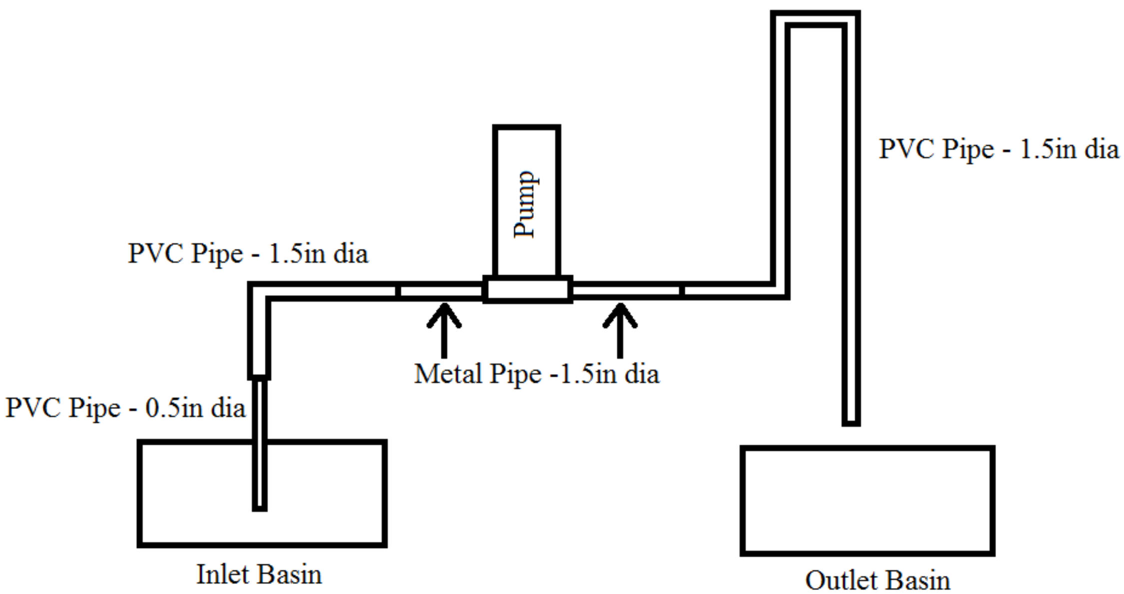

Figure 4.2: Diagram of pipes for laboratory testing.

While the pipe connection to the pump was a combination of 1.5 inch nominal diameter steel and PVC pipe, a reduced section of pipe with a nominal diameter of 0.5 inch was used at the pipe inlet in the water basin. A total of 56cm of 1.5 inch pipe and 33cm of 0.5 inch pipe were used with corresponding reducers. This reduced diameter pipe section added major losses to the pipe sections, while the reducers and a 90° elbow added minor losses. This configuration did not create a head loss equivalent to the head loss in field testing, but did create more than would have been present with no reduction in pipe diameter. To ensure that there was enough back pressure on the outlet valve for it to close properly, a discharge head of approximately 0.5 meters was built into the outlet pipe.

Instrumentation was used to measure the force input by the operator during testing. A 100lb load cell was mounted on the pump handle arm on one side and an operator handle was mounted on the other. This created a connection, shown in Figure 4.3, where all of the operator force would be transferred by the load cell to the pump, therefore the input force could be accurately measured.

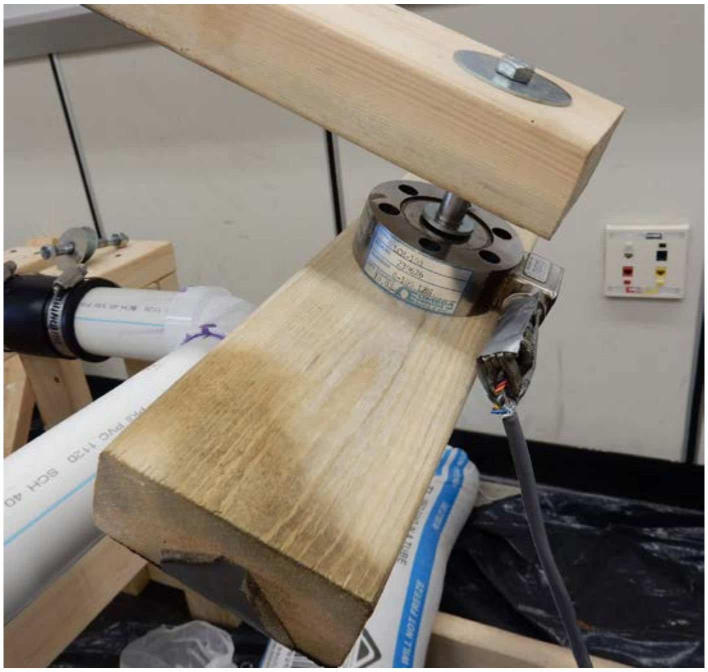

Figure 4.3: Load cell mounted on pump handle arm. The operator holds the wood handle in the foreground while force is transferred through the load cell in the center.

Data acquisition was accomplished by the load cell with a National Instruments NI 9219 analog input module, a 10V power source, and a computer with appropriate software for capturing the raw data. MATLAB was used to post-process the data to convert it from raw data to force values using calibration equations for the load cell output. With the operator force, $F_{Operator}$, being measured by the load cell, the measured values were then used to calculate the force acting at the piston, F_{Piston}, using the sum of the moments at the pump arm pivot according to the diagram of the pump arm in Figure 4.4.

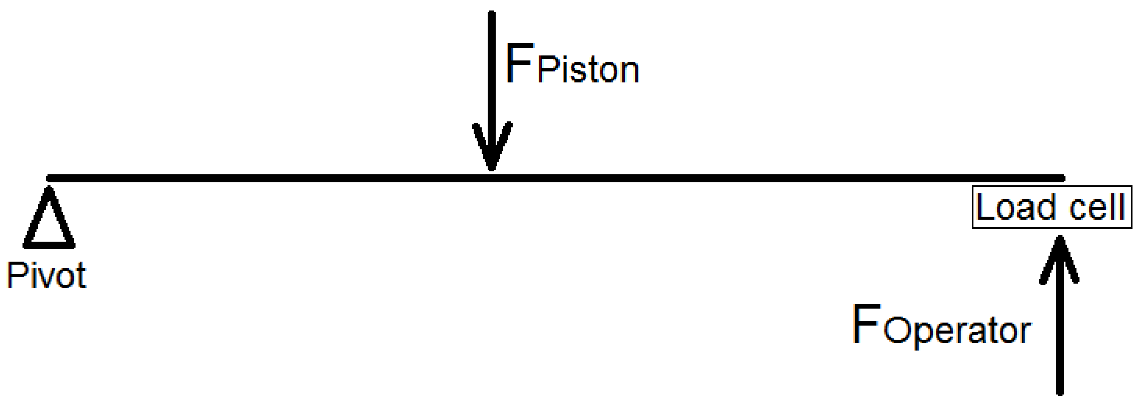

Figure 4.4: Diagram of forces acting on pump arm during testing.

The main parameter of interest for testing was the operator force during the upward suction stroke of the pump. Force on the downstroke was not considered because field testing showed that the vertical distance to pull water from the well was much greater than the vertical distance to push water from the pump to the eventual outlet. The suction force would therefore be greater than the outlet pressure force.

4.1.1 Experimental Piston Seals

A single seal geometry was tested. This geometry was the same flat circular disk design used in the preliminary field experiments but improved upon due to more precise tools for creating the seals. Instead of using scissors as was done in Senegal, a rotary circle cutting tool with a razor blade was used to make a more accurate circular shape than could be done with scissors. This method also created a more uniformly smooth edge on the circumference of the seal.

Due to the steel pipe used for the cylinder not being perfectly round, trial and error were used to find the correct diameter for the seal so that it would make complete contact with the cylinder wall. This resulted in having to oversize the seal by 2 mm, making the final seal 110 mm in diameter. Each seal was mounted to the piston between two metal piston disks 101.5 mm in diameter. This left 4.25mm of material along the seal radius that was unsupported between the metal disks and the cylinder wall.

By design, the portion of the seal that was in excess of the cylinder inner diameter tended to fold in the gap between the metal disks and wall. During operation this extra material would change from being oriented toward the bottom of the cylinder on the upward suction stroke to being oriented towards the top of the cylinder on the downward pressure stroke. It is believed that even though there may have been increased friction in this seal design due to the excess material, it created a better seal with the wall leaving less chances of having air leaks.

Only the alternative seal materials tested in the field and some material obtained after field testing were used in laboratory testing. No regular leather seals were tested. This was due to not being able to get leather to make additional seals before leaving Senegal.

4.2 Test Procedure

A test regime for each seal consisted of multiple test sets with each set having a total of 12 test runs. Each test set began with two warm up test runs that were used to make sure the pump was functioning properly, to prime the pump, to wet all involved surfaces, and to eliminate startup effects from influencing the data. Data from the warm up runs was gathered but not used in analysis. After the two warm up runs, 10 tests runs were conducted. These runs involved operating the pump until an audible noise from the inlet pipe was heard, indicating the water level had reached the level of the inlet pipe. Two more cycles of the piston were performed once the noise was heard and then the test was completed.

Initial testing was done with five gallon buckets as the water reservoir. This only provided a limited amount of water for each test and by looking at the data, it was seen that a longer test would add more data points from which to make better conclusions about the average force for each test. Therefore, the switch from buckets to higher capacity basins was made.

The number of test sets was determined by looking at the data and identifying after which test run no more major changes in pump performance were observed. From this, it was found that after 30 test runs, or three test sets, no major changes were occurring in input force. Therefore three test sets were performed on all seals.

Notes were taken for each test set to track any factors external to the seal that affected test results and are reproduced in Appendix A.1. Events such as the piston coming completely out of the cylinder during testing or the piston becoming jammed in the handle slot were noted and if these events caused noticeable irregularities in the current test run data, that data was not used in the final analysis. Observations were also made about the pump during testing that may have affected pump performance, such as tilting of the piston in the cylinder.

4.3 Results

Seals are identified by their material and sample number, therefore Seal 4-2 is the second seal sample of Material 4. Table 4.2 lists the materials and seals tested with identifying marks used in the graphs of the results.

Table 4.2: Materials used in laboratory testing and sample identifiers

Material	Composition	Average Thickness	Samples Tested
Material 0	Medium Foam	5.25mm	Seal 0-1
			Seal 0-2
Material 1	Medium Foam	6.23mm	Seal 1-1
			Seal 1-3
Material 2	Hard Foam	4.23mm	Seal 2-1
			Seal 2-2
Material 3	Soft Rubber	2.63mm	Seal 3-1
			Seal 3-2
Material 4	Hard rubber	3.04mm	Seal 4-1
			Seal 4-2
Material 5	Medium Foam	6.82mm	Seal 5-1
			Seal 5-2

Figure 4.5 shows the raw data for the input force for one test run of Seal 0-2. By taking the average of the peak values in the figure and for the other test runs of the seal and by calculating the force acting at this piston using the mechanical advantage of the pump arm, a complete graph of the force during testing can be created as shown in Figure 4.6

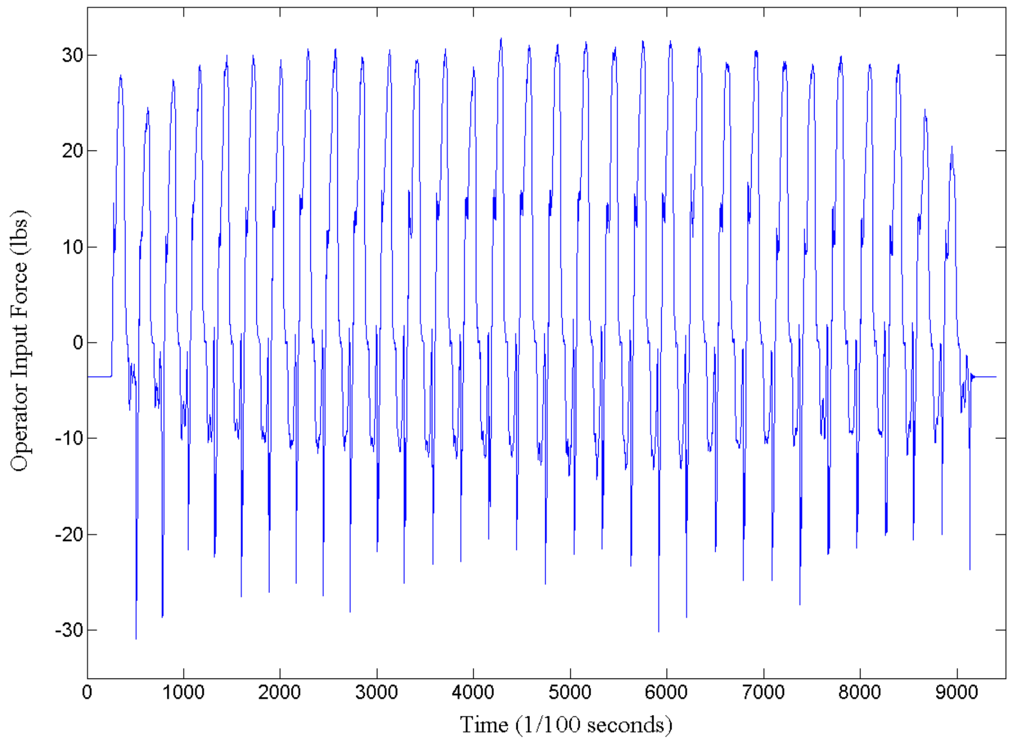

Figure 4.5: Raw data of Seal 0-2 for a single test run

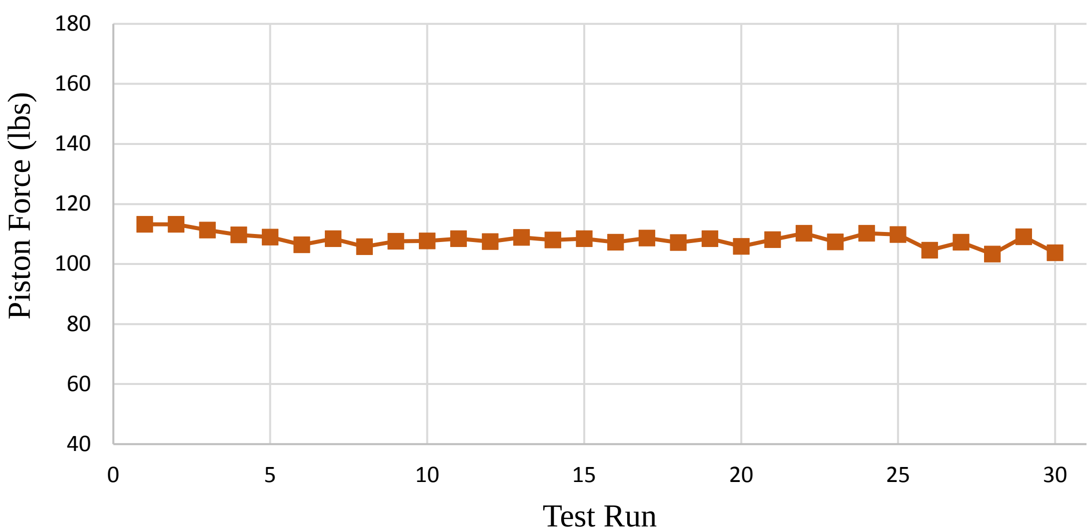

Figure 4.6: Force acting on the piston for Seal 0-2

Figure 4.7 shows the test results for all of the seals. It should be noted that these values also included the force to overcome the weight of the pump arm and the attached load cell. This was done since real treadle pump operation would also include the treadle weight in the operation force.

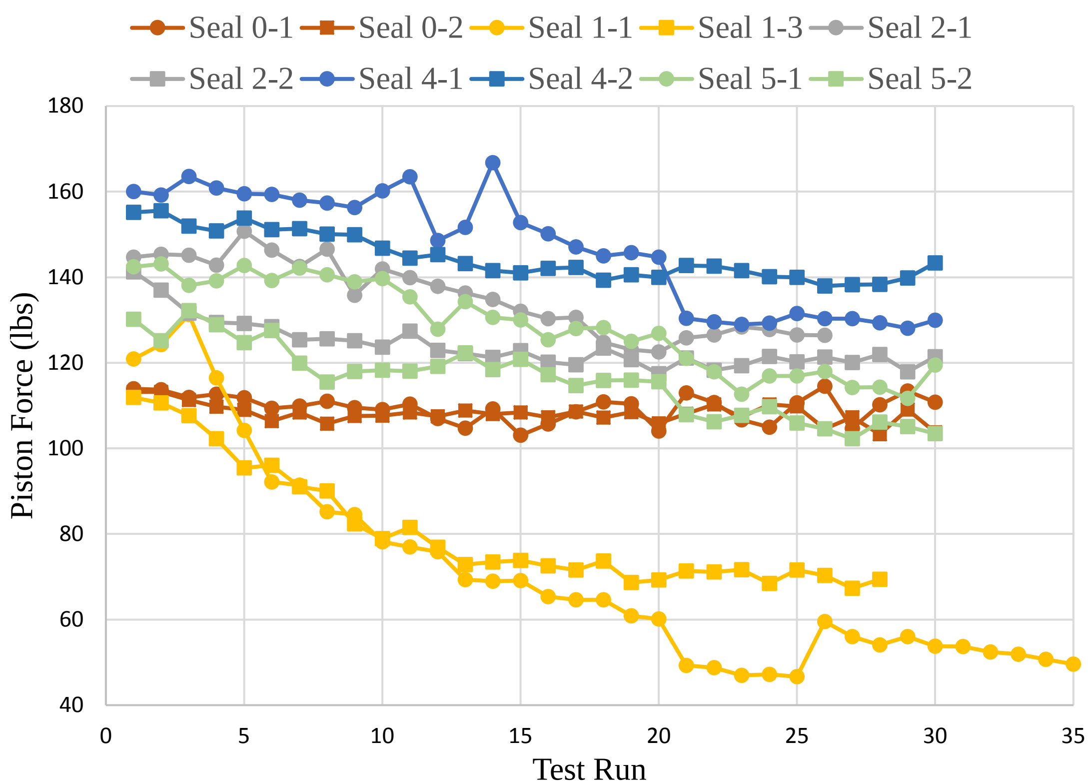

Figure 4.7: Force acting on the piston for each test run

Table 4.3 shows tabulated data for the force at the first test, force at the last test, and the maximum and minimum forces for each seal along with the test run at which they occurred.

Table 4.3: Tabulated force values for each seal

Seal Number	First Test Force (lbs)	Last Test Force (lbs)	Maximum Force (lbs)	Minimum Force (lbs)
Seal 0-1	113.96	110.79	114.54 (Run 26)	103.04 (Run 15)
Seal 0-2	113.18	103.04	113.21 (Run 2)	103.30 (Run 28)
Seal 1-1	120.85	49.61	131.25 (Run 3)	46.67 (Run 25)
Seal 1-3	111.88	69.40	111.88 (Run 1)	67.32 (Run 27)
Seal 2-1	144.66	126.57	150.75 (Run 5)	122.52 (Run 20)
Seal 2-2	141.27	121.43	141.27 (Run 1)	117.41 (Run 20)
Seal 4-1	160.04	129.94	166.78 (Run 14)	128.07 (Run 29)
Seal 4-2	155.12	143.31	155.54 (Run 2)	137.95 (Run 26)
Seal 5-1	142.45	113.96	143.08 (Run 2)	111.66 (Run 29)
Seal 5-2	130.19	103.48	132.22 (Run 3)	102.23 (Run 27)

Seal 1-2 is not listed as it showed a drastic decrease in performance during the first test set. This was likely due to errors in making the seal, therefore another seal of Material 1, Seal 1-3, was tested. No data for Material 3 is reported due to both of the Material 3 seals tested failing before the completion of a whole test set. Separate data for individual seals can be found in Appendix A.2.

4.4 Discussion

The tests performed provided data to analyze the required operation force of a seal and its performance. The force data allowed for a direct comparison of force between the different seal materials. Secondary observations about the number of cycles per test and the pumping rate were used to compare seal performance but also provided insight into what contributed to the operation force to be able to differentiate between the minimum pumping force and the extra force added by friction from the seal.

Operation force is dependent on three main factors: suction head, flow rate, and seal friction. Since the suction head was constant for all tests, it was not a contributing factor to differences between operation forces for the seals. Therefore, flow rate and friction contributed to force variations. Neither flow rate nor friction were directly measured, but by looking at the pumping rate and the number of cycles per test, some observations can be made about the flow rate. If one test is performed at a higher pumping rate than another test, then it could mean that the test had a higher flow rate, but only if it was pulling the same amount of water each cycle. The number of cycles per test must also be looked since if a test had a high flow rate but takes more cycles to pump the same amount of water then the flow rate will be less than assumed by only observing pumping rate. If a test is found to take the same number of cycles to complete as another test but is done at a lower pumping rate and required more force, then seal friction would be a large contributor to the operation force. Conversely, for a test that takes more cycles to complete and is done at a higher pumping rate but requires less force, it can be assumed that there is low seal friction and low flow rate.

From the graph of the results in Figure 4.7 clear differences between operation force can be observed. Material 4 had the highest required force. This is seen not only in the data but was also a personal, subjective observation from testing. Material 2 and Material 5 had similar forces during testing with Material 2 ending at a higher value. Material 0 ended testing with similar force values as Material 5 but generally had lower values throughout testing. Material 1 had the lowest force overall.

Materials 0, 2, 4, and 5 all showed a general trend of decreasing force values as testing progressed. Material 1 showed this trend on an amplified scale. Both seals of Material 1 showed substantial decreases in force during testing before leveling off. Comparing first test run forces to last test run forces, changes in force occurred for Seal 1-1 and Seal 1-3 of 71.24 lbs and 42.48 lbs respectively. These were the largest changes in force for all seals.

While having a low force requirement is desirable from the perspective of the pump user, during testing, decreasing force corresponded to a decrease in the amount of water pumped per stroke. Figure 4.8 shows this trend for select seals using the number of piston cycles per test as an indicator of decreased volume per stroke since the same amount of water was used in each test.

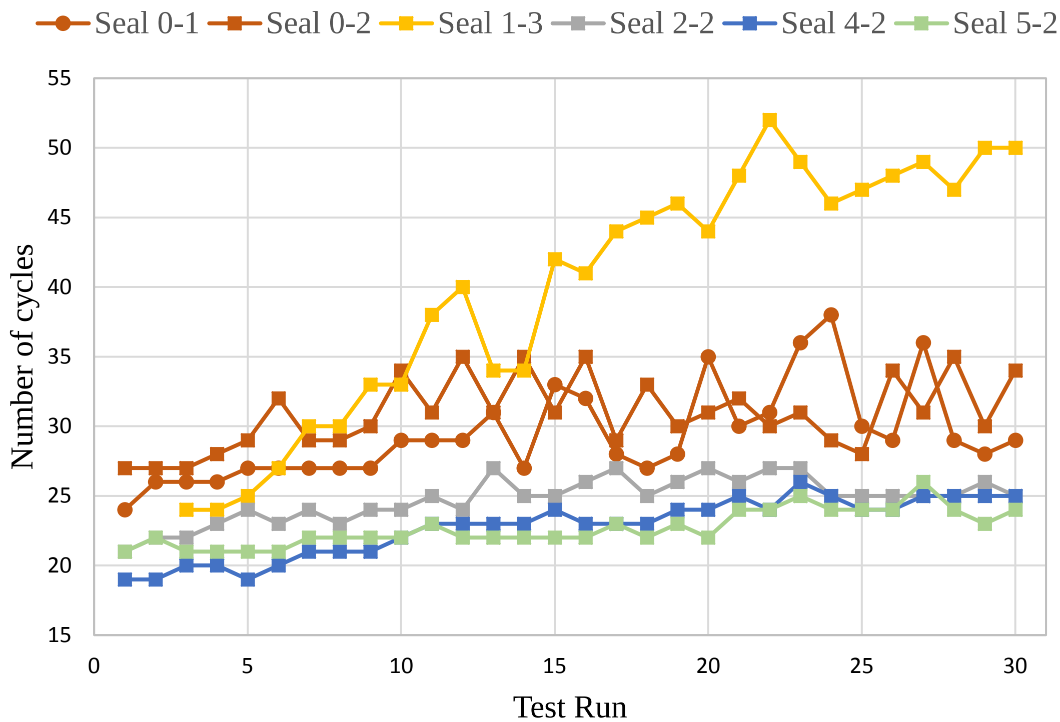

Figure 4.8: Number of cycles per test run for select seals

Seal 1-3 shows a clear trend of increasing number of cycles as testing progressed. This indicates that the seal was wearing out during testing, the result of pump operation requiring the softer seal to slide along the harder cylinder wall, and was not able sustain the same level of suction after continued use. Figure 4.8 shows that Seal 1-3 was greatly affected by this and that the other seals did not exhibit this behavior to the same extent. This behavior also explains why Seal 1-3 has a lower force than other materials in Figure 4.7. As the seal wore it pumped less water, meaning a lower flow rate and less flow losses needed lower forces to overcome as well as less friction with the cylinder.

While the low force of the seals of Material 1 can be attributed to decreased performance based on the number of cycles per test, this cannot be done to explain why seals of Material 4 had the highest forces since they had similar number of cycles as other materials with lower forces. Figure 4.9 must be used to determine how the pumping rate affected the force.

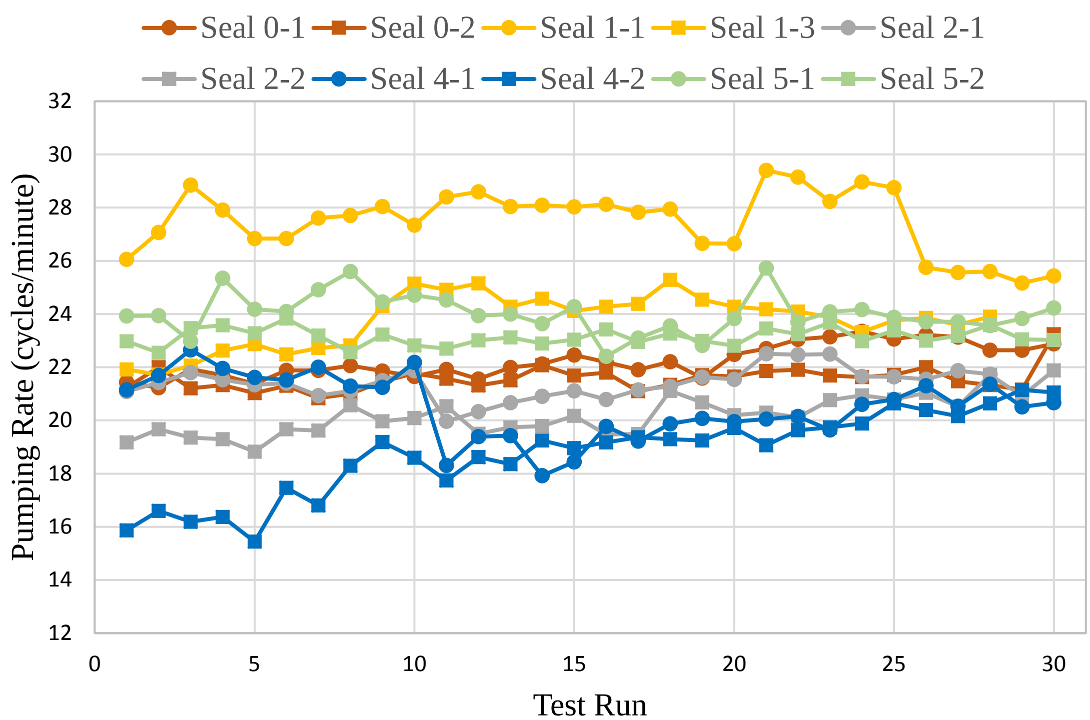

Figure 4.9: Cycles/minute for each test run

From the figure it can be seen that both seals of Material 4 had the lowest pumping rate for the majority of the test runs. This indicates that it must have been operating at a lower flow rate than the materials it shared the same number of cycles with. A lower flow rate would mean lower flow losses, indicating that another factor was contributing to the high operation force, namely friction. Since the piston seals were designed to be oversized for the cylinder by a couple of millimeters, there was excess material that folded into the gap between the metal piston disk and the cylinder wall. Given that Material 4 was harder than all the other materials by inspection, it is reasonable that Material 4 would have a higher friction value as it would not have easily compressed to fit within the gap and would have a greater normal force against the cylinder resulting in greater friction.

While Materials 1 and 4 captured the two extremes of force and performance of the tested seals, Materials 0, 2, and 5 represented the middle range of these factors. For force, these three materials were grouped together over a range of about 20lbs at the end of testing, which distinctly put them in their own group away from Materials 1 and 4. For performance from the number of cycles per test, Materials 2 and 5 grouped with Material 4 to end testing at the lowest number of cycles, which represented the best performance of the materials. Material 0 finished testing with a slightly higher number of cycles per test, but significantly lower than Material 1.

From the viewpoint of the user, the operation force is important as it determines the immediate effort to operate the pump. However, for sustained used, the power requirements to operate the pump can also be important as it is an indicator of the user's overall energy use. Calculating power from the test data was made difficult due to the lack of displacement measurement with time. While the raw test data was uniformly periodic, this did not mean that the rate of displacement of the piston during a cycle was constant. If the displacement rate did change, it would result in a varying power input from the operator. Despite these limitations on the data, an estimate of operation power was made by taking the average velocity of the piston based on cycle time and stroke length and multiplying it by the peak force. Figure 4.10 shows the power values for the last test run of each seal.

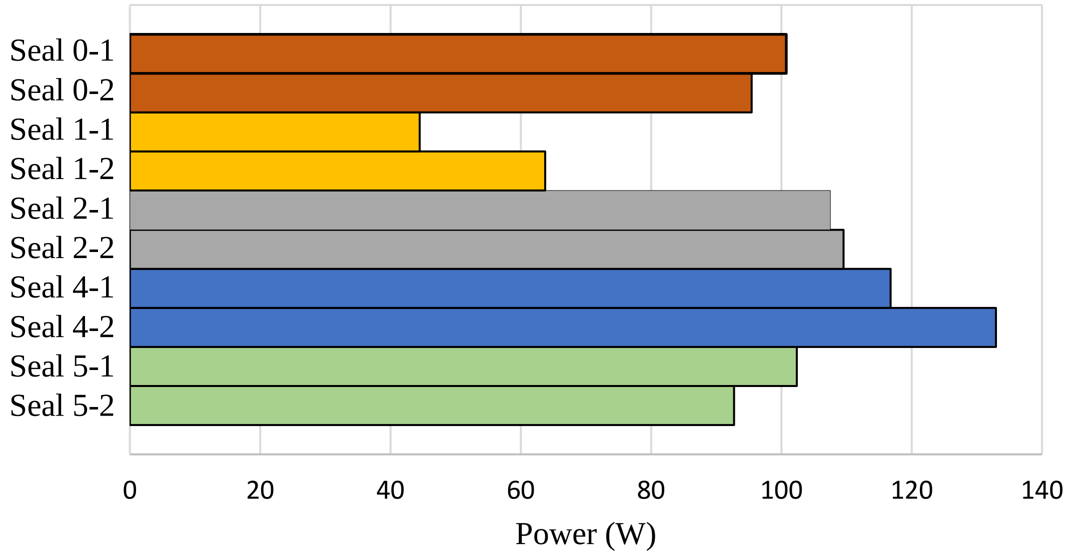

Figure 4.10: Operation power estimates for last test run

The estimated power values follow a similar trend as the final test force values. Both of the Material 4 seals had the highest power values while seals of Material 1 had the lowest values. Small variations in the power from the force value trend was due to differences in the average piston velocity. Since power depends on the velocity, which itself depends on the operator's pumping rate, the power can vary widely based on operating conditions. Therefore, while these estimates provide a preliminary look at the power needed to operate the pump, they do not provide a completely accurate explanation of the true power requirements.

Despite some of the tested seals showing degradation in performance with use, testing did not include using all seals across their entire lifetime. Therefore, no conclusions can be made about how long any of the alternative material seals would be expected to last before needing replacement. Figure 4.8 does show how some materials had a breaking-in period where the number of cycles per test increased until reaching a more constant value. This demonstrated how slight performance changes can be expected for a new seal but do not describe how a seal may perform closer to end of life.

Factors external to the piston seal may also have affected performance. Observations from field testing showed that leaking at the seal may have been caused by side-to-side misalignment of the piston in the cylinder. While the piston was properly aligned in the cylinder during lab testing, it often became tilted in the forward and backward directions during operation due to the piston not moving smoothly at its attachment point to the pump arm. This tilting caused the seal to come out of contact with the cylinder wall resulting in loss of suction.

Material 3 was the only material to fail during testing. The material tore at the point of contact with the edge of the metal piston disks as shown in Figure 4.11. Although Material 3 was preliminarily tested in the field and did not fail during those trials, it was not tested for as many cycles as it was in the lab yet did start to show signs of wear at the same location that the lab tested seals failed at.

Figure 4.11: Failed seal of Material 3.

Material 4 was the only other material to show obvious signs of wear at the same point of contact as Material 3. Other materials showed indentations where the material was compressed between the disks but did not have any wear or tearing at the interface with the metal disk.

Error was present in the test results from multiple sources. For the instrumentation, the load cell had an error of 0.25% for a full-scale output of 100 lbs, equivalent to 0.25 lbs at the location of the load cell or 0.9 lbs at the piston. Resistance to sliding of the piston in the pump arm slot was a source of error from an operational standpoint. During some tests the piston was not able to slide freely in the slot and was tilted causing it to have a poor seal with the cylinder wall which affected the force data. Instances of partial loss of prime between tests also occurred. This usually resulted in the first few cycles of the test having force values lower than the rest of the test as prime was regained and normal water flow restored. These effects were addressed in the data by not including the cycles that occurred before normal operation in the analysis.

4.5 Laboratory Testing Conclusions

Laboratory testing of the alternative piston seal materials provided useful data from which to evaluate the materials on the criteria of operator force and performance related to the ability to create suction to pull water. Since Material 4 had the highest force requirements of all seals, it is undesirable as it would require heavier operators or a treadle pump with a high mechanical advantage. Material 1, while having the lowest force requirements, is also undesirable as it showed to have poor performance by wearing out quickly leading to unacceptably low flow rates.

Table 4.4 shows the ranking of the alternative materials, in a plus/minus ranking system, based on the testing results and analysis of the force data along with the number of cycles per test as an indicator of performance.

Table 4.4: Ranking of alternative seal materials based on testing results

Material	Force	Performance
Material 0	+	+
Material 1	++	-
Material 2	+	++
Material 3	NA	--
Material 4	-	++
Material 5	+	++

Material 2 and Material 5 were the best materials considering both force and performance. Material 0 was very close to these materials, only differing slightly on performance as Material 0 required a slightly higher number of cycles per test. These three materials, in the tested seal geometry, ended testing with similar force values that were between the extremes of Material 4 and Material 1. Although testing was not long enough to determine overall seal lifetime, none of the three seals exhibited severe declines in performance during the testing period. Therefore, given the available information from the laboratory testing, these three materials are recommended to be used as alternative piston seal materials.

All of the materials were purchased from street vendors and no information about their properties or composition was available. Due to the wide array of available materials, identifying common observable properties of the recommended materials is important. All of the recommended materials were dense foams that were soft enough to have a permanent mark left by a thumbnail run across the material and could be slightly compressed by two fingers, but stiff enough to quickly return to their original shape. Aside from Material 1 which also had these properties but did not perform well in testing, the non-recommended materials were rubber and could be identified as being visually different than the foam material and by not deforming when compressed by two fingers.

Force and performance are important factors to consider in identifying suitable piston seal materials but they do not constitute all of the criteria for a desirable material; cost must also be considered. Even though three materials are recommended based on the laboratory test results, they could be deemed financially unviable. Having a high absolute cost or a cost significantly higher than the original leather seals could outweigh any performance benefits.

5.0 Economic Considerations

Cost is an important factor when deciding whether to purchase an unfamiliar technology. For treadle pumps, they must not only be seen as offering a labor benefit to the owner but also a cost benefit when compared to the alternative water pulling methods. The piston seal can contribute a significant portion to the cost of a treadle pump depending on the material and by reducing this cost treadle pumps could be seen as a more desirable water pulling device.

While the information in [6] states that the treadle pump is low cost and includes a price for the treadle pump in Senegal in 1995 in West African CFA francs (FCFA) of 47,000 FCFA, equivalent to $86 USD, the price for the pump from the metal shop was 110,000 FCFA, equivalent to $190 USD in early 2015, a difference of $104 without adjusting for inflation. This price only included the pump and not the pipes or foot valve. While the difference in price may be due to a multitude of factors, including increases in material and labor costs, the current price may not reflect the actual cost of the pump given the economic bartering practices of the Senegalese.

The treadle pump cost must be compared to the other water pulling methods to understand how it stands financially. The three components of a rope-bucket-pulley system can be purchased for about 4,000 FCFA depending on the length of rope or for less if a plastic jerry can is reused as the bucket instead of purchasing one. The rope-bucket-pulley system is therefore significantly less expensive than a treadle pump. According to farmers in the village, a gasoline pump could be purchased for 75,000-95,000 FCFA depending on whether it was bought in Senegal or neighboring The Gambia. This puts gasoline pumps at a lower price range than the treadle pump while delivering water at a higher flow rate but gasoline pumps do have the constant expenditure on fuel for operation as well as potentially expensive repair costs when mechanical problems arise. As an example, one large garden in Niokholokho approximately 0.25 hectares in size required 40,000 FCFA in fuel per month during peak operation. Factoring in these extra costs for the gasoline pump may make it more expensive in the long term depending on the usage.

One of the single largest component costs of the treadle pump was the leather for the piston seals. A complete set of seals required 18,500 FCFA of leather which represented 16.8% of the cost of the pump. Based on the price of the bulk material purchased to make the alternative seals that were tested, it is estimated that a complete seal set for any of the materials could be made for 500 FCFA. This represents a 97.3% decrease in the cost of the seals and a 16.4% reduction in the overall pump cost, bringing the price down to 92,000 FCFA. This reduction would put the treadle pump in the price range of gasoline pumps.

It is unknown as to whether such a reduction in price would increase the adoption of treadle pumps in the area or if they would still be considered too expensive given the perceived performance and difficulty of use. Either way, alternative, locally available materials are substantially less expensive than the traditional leather seals and by reducing the cost of the pump, their use would be a major step towards decreasing the economic barriers to adoption.

6.0 Conclusions and Future Work

This report described the process of testing alternative materials for use as piston seals in treadle pumps with the goal of improving performance and reducing cost. First, observations about water pulling methods used by rural Senegalese farmers were made. Field work was then conducted involving going through the process of having a treadle pump locally manufactured and field tested to understand its performance and problems that affect its operation as well as to gain preliminary insight into alternative materials to replace the original leather piston seals. Based on field testing results and the need for more accurate and consistent data, laboratory testing of the alternative materials was performed. Laboratory tests showed which of the alternative materials functioned well based on operation force and performance. Finally a financial comparison was then done to quantify the cost difference between leather seals and the alternative material seals.

The combined results of field tests, laboratory testing, and financial analysis, revealed that three of the six alternative materials are good candidates for treadle pump piston seals. These materials, all of which were foams, had the best balance of force requirements and pumping performance through the duration of laboratory testing. With these three materials costing roughly the same, further testing of the materials in the field may need to be done to determine their long term performance to see if a single material proves to be better than the rest.

6.1 Conclusions

This study showed that alternative materials that are locally available and lower cost have the potential to be used as functional replacements for leather seals. Preliminary field testing and in-depth lab testing revealed that seals with a simplified geometry made from materials commonly used to repair footwear in Senegal are functional at pumping water when used in a treadle pump. However, all materials do not perform equally as well with some materials requiring more operator force than others and some wearing out quickly leading to low flow rates. Both of these situations are undesirable. Therefore care must be taken to consider multiple options of available materials before recommending one.

Treadle pumps are designed to fill the technological gap between the rope-bucket-pulley method of pulling water and gasoline pumps, but had not been widely adopted in the area of this study. This may have been due to multiple factors including price, performance, and personal preference. A lack of adoption is an indicator that the treadle pump is not filling the gap as was originally intended. The work presented here, while only focused on a single component of the pump, made progress in reducing the cost of pump, bringing the purchase price down from above that of gasoline pumps to around the high end of the price range of gasoline pumps. Unfortunately, this means that even though this specific treadle pump design has a performance within the technological gap, it is outside of the gap from an economic standpoint. Factoring in other costs for gasoline pumps, such as fuel costs, would show the treadle pump to be less expensive over the longer term, but it is difficult to know whether a rural farmer would consider this when deciding if a treadle pump was a worthwhile investment. Therefore, further reduction in the cost of the pump is necessary to firmly place it within the gap.

The findings of this study could also have positive impacts in Senegal and other countries if the benefits of using the alternative material piston seals did increase adoption of treadle pumps. By using a treadle pump for agricultural uses, especially gardening, more land could be irrigated, leading to increased income for farmers and their families in the dry season. In other African countries with more developed treadle pump markets, similar materials may be available and it is assumed they would also be less expensive than leather. A decrease in the cost of pumps in those markets could also lead to increased adoption, which would lead to greater agricultural productivity for treadle pump users as well as business growth for all parties involved in the treadle pump supply chain.

6.2 Future Work

From the insight gained by working with a treadle pump in the field and from the results of lab testing alternative piston seal materials, multiple routes are proposed for continuing and improving upon this study. One route involves continued testing of the materials. The other focuses on design improvements.

Based on the laboratory test results, it is recommended that Materials 0, 2, and 5 be additionally tested to determine final suitability for replacing the leather seals. Testing should focus on determining the lifetime of each seal to identify its frequency of replacement, which is not only important from a performance standpoint but economically as well as a shorter lifetime would result in more expenses for replacement seals. Lifetime testing could be performed in the laboratory or the field. Laboratory testing should involve accelerated life testing using an automated test configuration to allow for the seal to be operated continuously until failure. Field testing for lifetime should include monitoring the usage of the seal during normal operating conditions, specifically noting the time length of use and the number of cycles if possible. The condition for end of life could either be physical failure of the seal rendering it unusable or when the performance has dropped to an unacceptable level as noted by the flow rate of water. This minimum performance level would depend on certain parameters of the pump, such as suction depth, which would normally affect the flow rate. Any testing would need to be properly planned from the beginning to reduce the negative effects of problems from fabrication and installation of the pump that were present during the field work portion of this study.

Design changes to the tested seal geometry should also be investigated to see if an improved design can be created. This study focused only on flat, circular piston seals, but a better performing geometry may be possible with the given materials. Improved geometries may also be able to compensate for certain errors in pump fabrication, such as misalignment of the treadles and cylinders.

While field testing would increase the amount of known information about the performance of these materials as piston seals and design changes could create a better functioning seal, it is possible that the recommended materials could be used successfully as replacement seals given what is known about them at this point. Due to the performance issues experienced with the leather seals and their high cost, the alternative materials could bring immediate benefits through lower cost and better performance. If field testing shows that the alternative materials are deficient in performance compared to leather seals then investigating design changes becomes a higher priority. If it is found that the alternative materials have a shorter lifespan than the leather seals, an analysis would need to be done to determine if it would be more economically viable to use leather seals or to provide replacement seals of the alternative materials given that 37 sets of alternative seals could be made for the same price as one set of leather seals.

Additional testing, design, and analysis could be completed by one of many different parties, such as Peace Corps volunteers, non-governmental organizations working in agriculture, or government research organizations. These groups likely have the necessary resources to complete such activities whereas an ordinary famer may not have the time or financial ability to do them on their own. Even though these groups may lead the testing, design, and analysis, it is important to make sure that final conclusions and recommendations take into account the view of the farmers as they are the people who would ultimately use the treadle pump. Field and laboratory testing may show one result but if farmers do not agree with the conclusion then no matter how well performing a piston seal may be, it will not be accepted.

References

[1] K. Sissoko, H van Keulen, J. Verhagen, V. Tekkan, and A. Battaglini, "Agriculture, livelihoods and climate change in the West African Sahel," *Regional Environmental Change*, vol. 11, pp. 119-125, Mar. 2011.

[2] "Senegal," *The World Factbook*, Central Intelligence Agency, Washington, DC., 2016. [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/geos/sg.html.

[3] United Nations Development Programme, *Human Development Report*. New York: United Nations Development Programme, 2015.

[4] C. Funk, J. Rowland, A. Adoum, G. Eilerts, J. Verdin, and L. Whilte, "A climate trend analysis of Senegal." U.S. Geological Survey, Fact Sheet 2012-3123, 2012. [Online]. Available: http://pubs.usgs.gov/fs/2012/3123.

[5] R. Marsh, "Building on traditional gardening to improve household food security," *Food, Nutrition, and Agriculture*, vol. 22, pp. 4-14, 1998.

[6] C. Bielenberg and H. Allen, *How to Make and Use the Treadle Irrigation Pump.* London: Intermediate Technology Publications, 1995.

[7] United States Agency for International Development, "USAID Wula Nafaa Project Quarterly Report October-December 2011," *International Resources Group*, Jan. 2012. [Online]. Available: http://pdf.usaid.gov/pdf_docs/PA00JFF2.pdf.

[8] United States Agency for International Development, "USAID-Wula Nafaa Program Final Report August 2008-August 2013," *International Resources Group*, Aug. 2013. [Online]. Available: http://pdf.usaid.gov/pdf_docs/pbaaa206.pdf.

[9] A. Orr, A.S.M.N. Islam, and G. Barnes, *The Treadle Pump: Manual Irrigation for Small Farmers in Bangladesh*. Dhaka, Bangladesh: Rangpur Dinajpur Rural Service, 1991.

[10] M. Kay and T. Brabben, “Treadle pumps for irrigation in Africa,” International Program for Technology and Research in Irrigation and Drainage. Rome, Italy: Food and Agriculture Organization, Knowledge Synthesis Report No. 1 – October 2000, 2000.

[11] A. Adeotil, B. Barry, R. Namara, A. Kamara, and A. Titiati, “Treadle pump irrigation and poverty in Ghana,” International Water Management Institute. Colombo, Sri Lanka, IWMI Research Report 117, 2007.

[12] J. H. Mangisoni, “Impact of treadle pump irrigation technology on smallholder poverty and food security in Malawi: a case study of Blantyre and Mchinji districts,” *International Journal of Agricultural Sustainability*, vol. 6, no. 4, pp. 248-266, 2008.

[13] A.I. Adeoti, “Factors influencing irrigation technology adoption and its impact on household poverty in Ghana,” *J. of Agriculture and Rural Development in the Tropics and Subtropics*, vol. 109, no. 1, pp. 51-53, 2009.

[14] C.M. Joseph and M. Yamikani, “Any link between sexual inactivity and treadle pump performance characteristics: The Malawi case,” *Physics and Chemistry of the Earth*, vol 36, no. 14-15, pp. 1047-1050, 2011.

[15] P. Fraenkel, *Water-Pumping Devices, 2nd ed.* London: Intermediate Technology Publications, 1997.

A.1 Appendix: Laboratory Test Notes

Below are the notes recorded during laboratory testing of the piston seals ordered by date. The notes do not include all tests as notes were only taken to identify potential events that could affect the accuracy of the data.

5-26-16:

Seal 3-1: Seal tore where the seal meets the disk. Performance difference noted at test 5.
Seal failed halfway through test 7.

5-31-16:

Seal 4-1: Seal left in pump over 3-day weekend.

Seal 5-1: Piston came out of cylinder during test 4.

6-1-16:

Seal 5-1: Test 1 had to prime since a dry test was run after warm up.
Piston came out of cylinder and put back in mid test during test 10.

6-3-16:

Longer tests begin for all seals

6-6-16:

Seal 5-2: Seal used before start of test

6-20-16:

Seal 2-1: Seal was left in pump for 1 week idle between current and previous test
Test 2 – washer got caught on screw so piston could not move in handle slot.
Also happened in test 1. Test 3 is start of normal runs.

Seal 4-1: Warm up 1 and 2 seemed wrong. Adjusted seal on piston and redid warm ups
Water was draining out suction pipe between tests

Test 4 – piston came out during test, possible inconsistent data.

Seal 3-2: Seal broke at end of test 1

Seal 1-2: Warm ups had very low flow rate. Seal seems to be fully worn and not good enough to keep testing

6-21-16:

Seal 2-2: Warm up 2 – piston bolt binded and had to be adjusted mid-test

Test 3 – piston came out and had to be put back in

6-22-16:

Seal 1-3: Adjusted seal after test 2

6-23-16:

Seal 5-2: Test 4 – showed small air leak on downstroke

7-11-16:

Seal 0-1 and 0-2: Long tests caused by piston not moving right in slot

A.2 Appendix: Laboratory Test Results

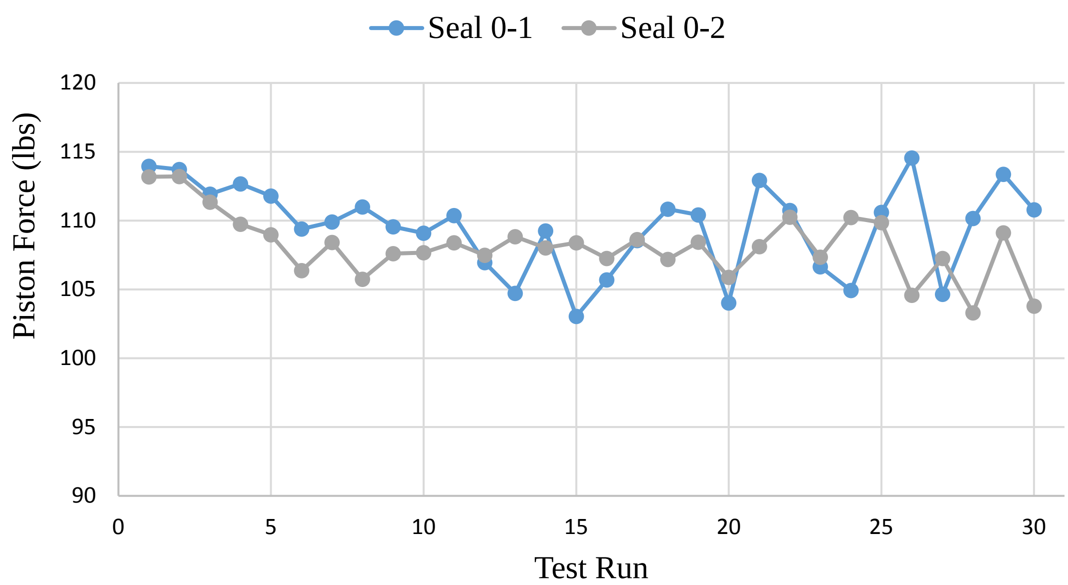

Figure A.1: Pumping force for Material 0

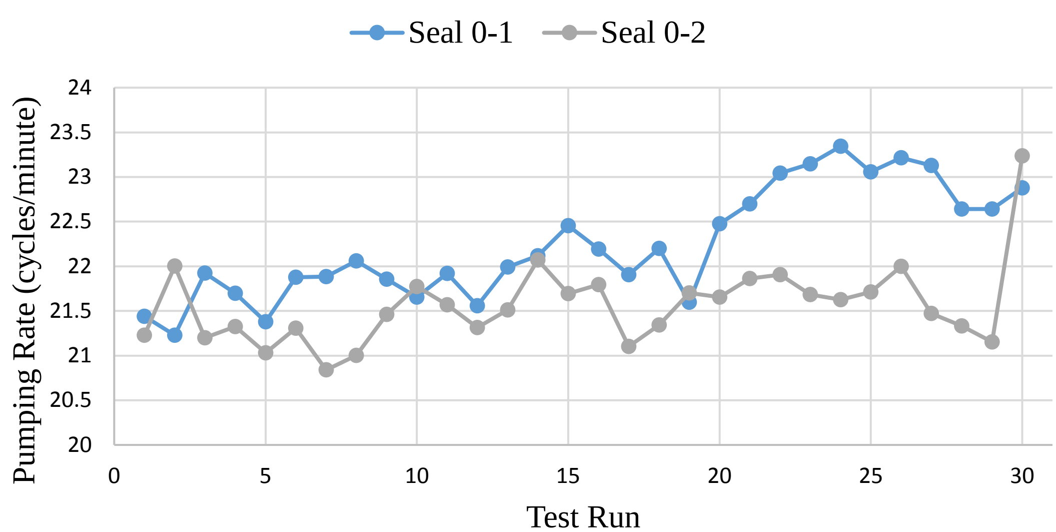

Figure A.2: Pumping Rate for Material 0

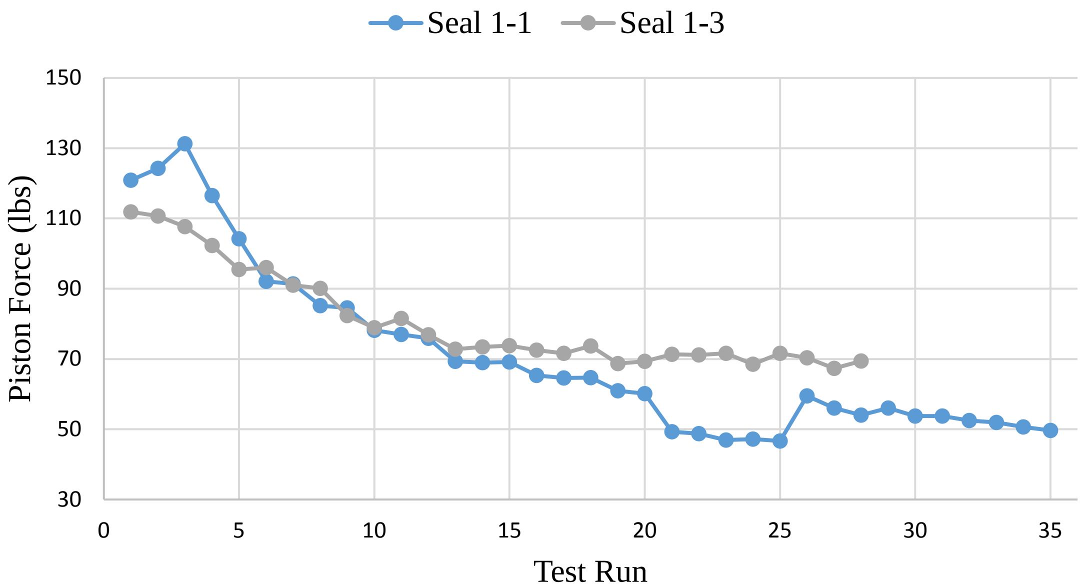

Figure A.3: Pumping Force for Material 1

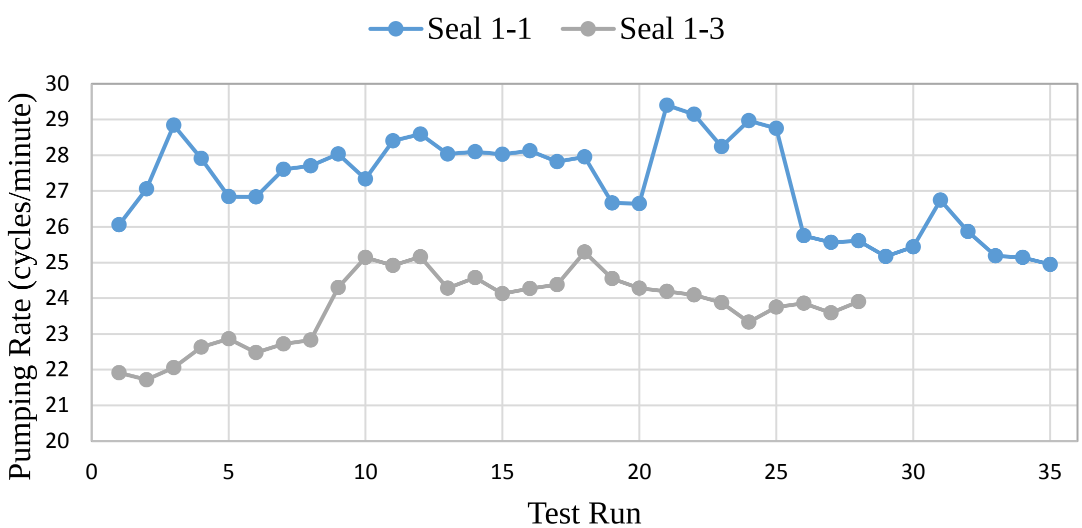

Figure A.4: Pumping Rate for Material 1

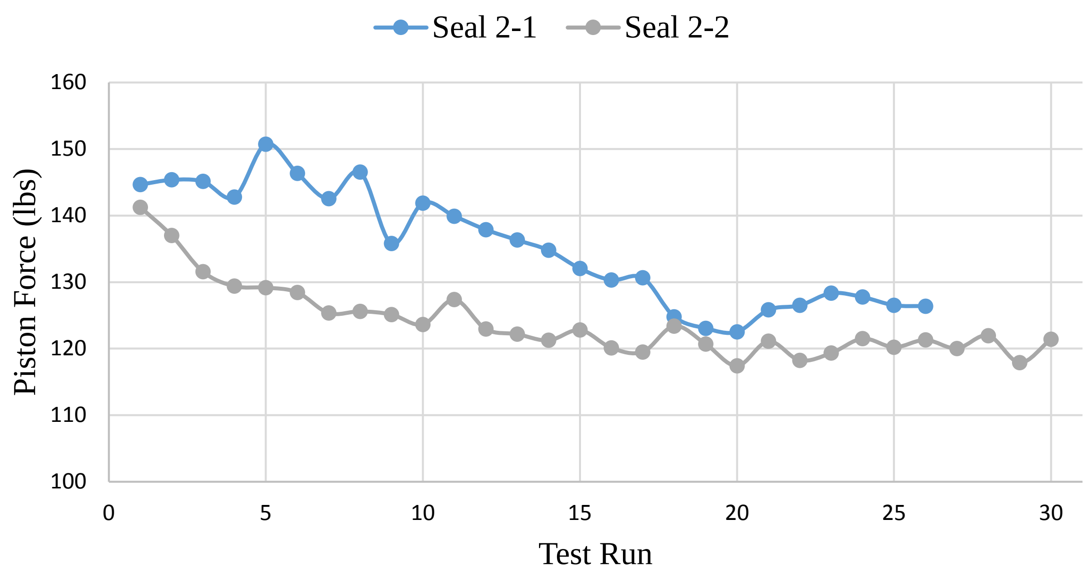

Figure A.5: Pumping Force for Material 2

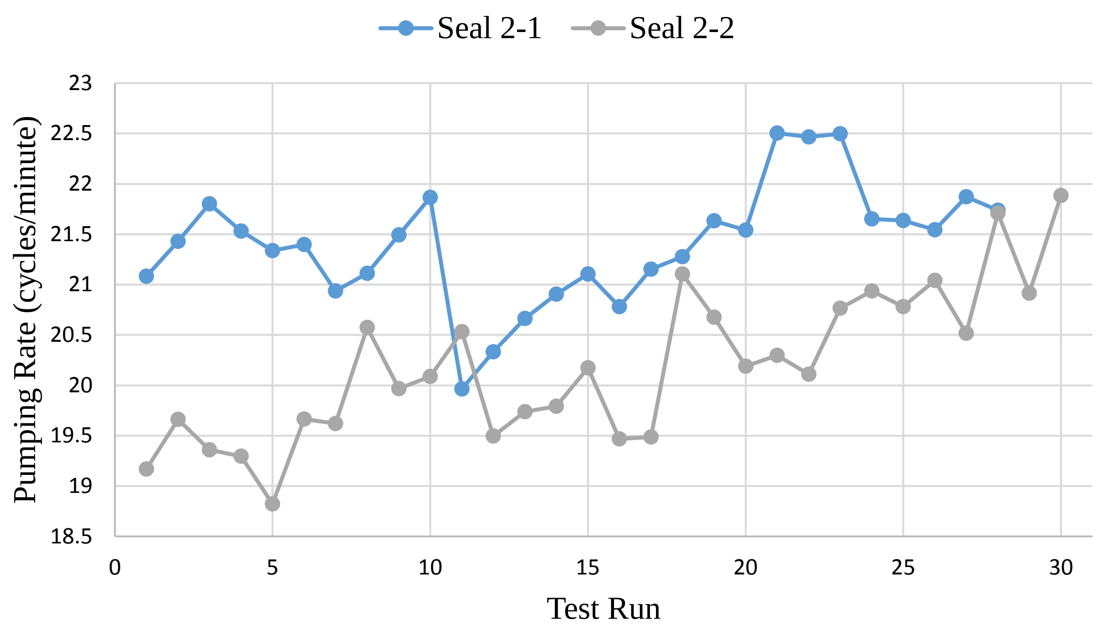

Figure A.6: Pumping Rate for Material 2

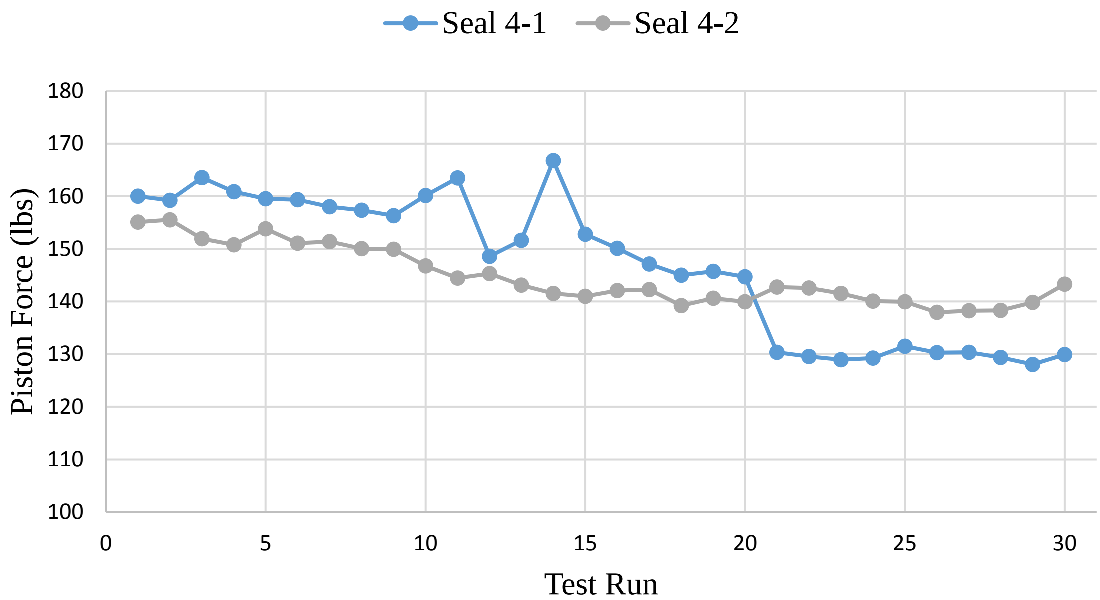

Figure A.7: Pumping Force for Material 4

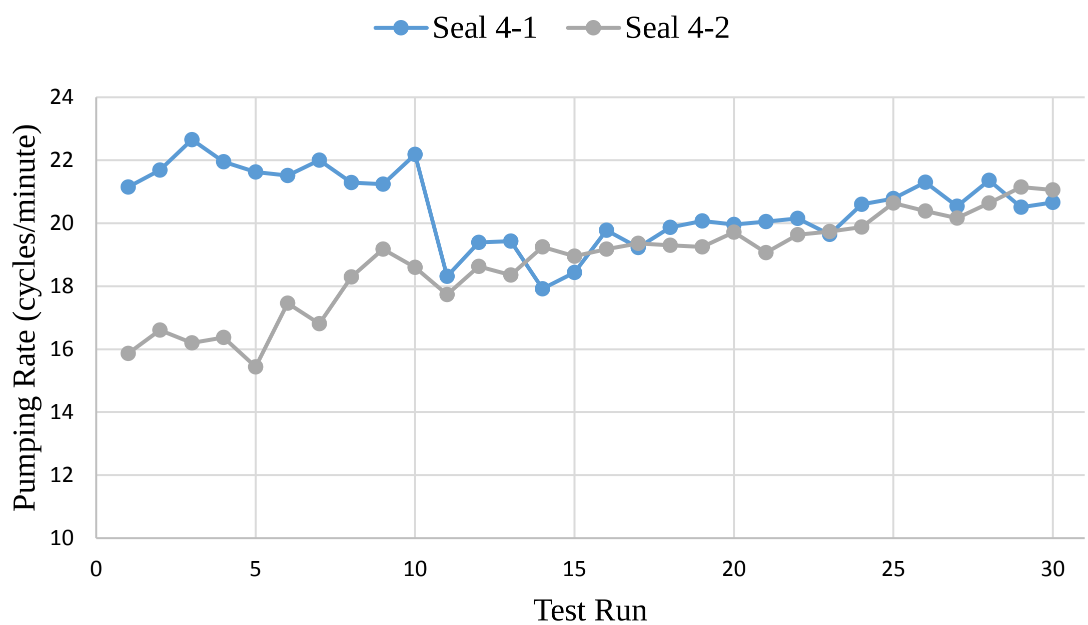

Figure A.8: Pumping Rate for Material 4

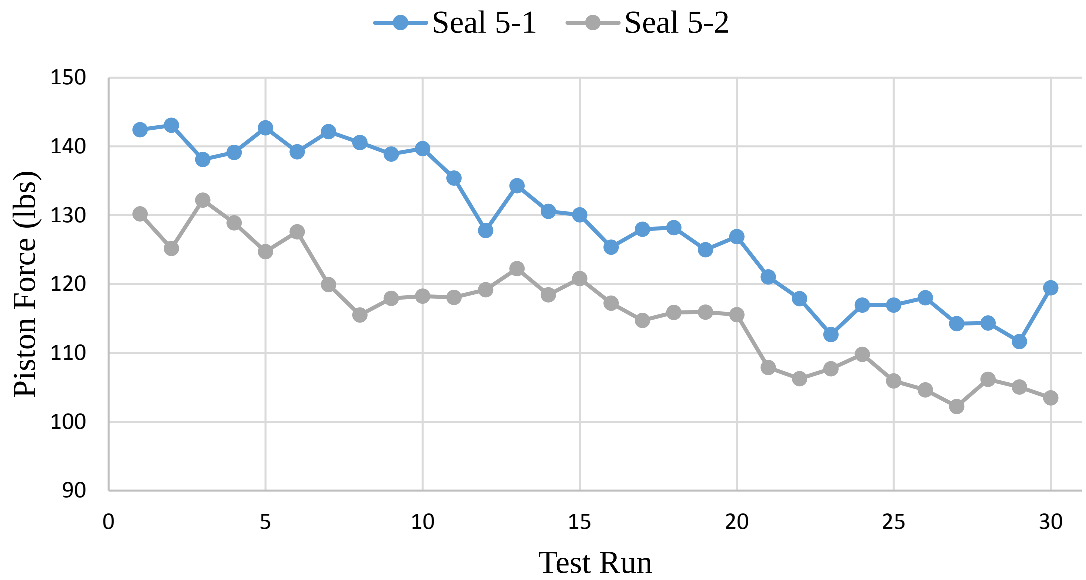

Figure A.9: Pumping Force for Material 5

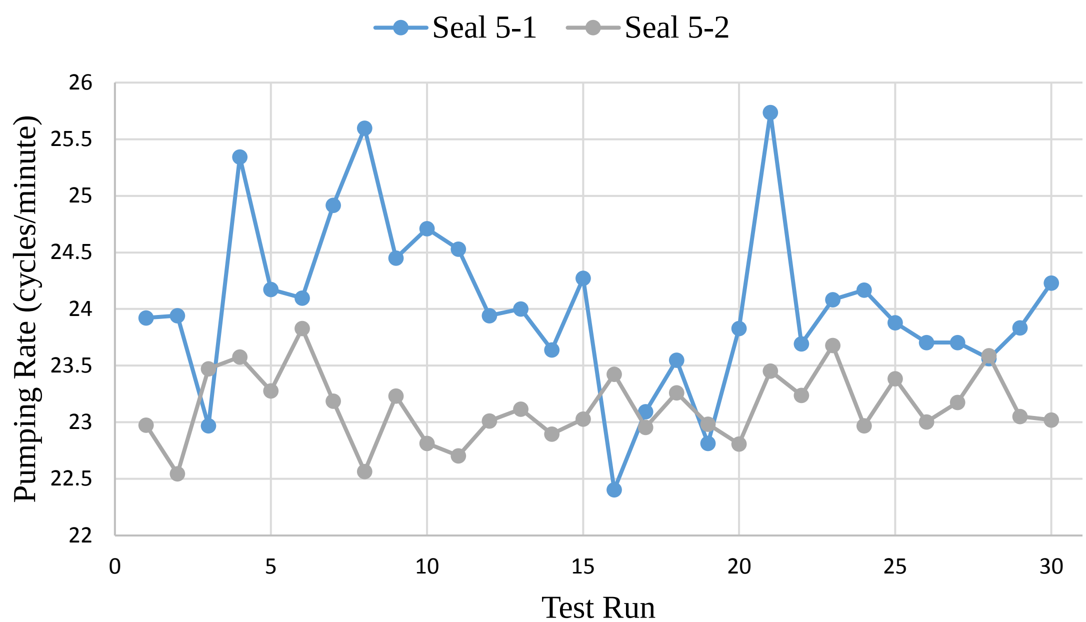

Figure A.10: Pumping Rate for Material 5