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DESIGN, TESTING AND ANALYSIS OF AN INLINE ONE-WAY VALVE FOR DEVELOPING WORLD AGRICULTURAL WATER TRANSFER APPLICATIONS

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ABSTRACT

In developing world agricultural applications, the critical process of transferring irrigation water from a source to an irrigation channel has proved an economic and technical challenge to many NGO's, as well as the United Nations' Food and Agriculture Organization. The goal of this research was to identify and quantify the performance characteristics of limiting components within the world's most common apparatus, the treadle pump, used in this transfer process. This research led to the thesis that a redevelopment of the check valve, or one-way valve, would lower the overall cost of the treadle pump and significantly aid in the community adoption of this technology globally. A one-way valve was developed with the final cost 24% of the original commercial component. The new valve was tested for key physical performance parameters such as head loss across the valve under normal flow conditions to validate the design. The results from this experimentation show that the new valve is more suitable for developing world agriculture than current commercial valves. The new valve also possesses increased manufacturability that can aid in its implementation and maintenance by local groups, reducing their reliance on international manufacturers. This design significantly reduces component costs while maintaining acceptable performance. In addition, the design process employed demonstrates that using an appropriate design specific to the developing world can reduce the need for subsidies by successfully employing user-centric design.

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1 Introduction

1.1 Background and Motivation

Case studies demonstrate that the implementation of treadle pump designs for micro-irrigation systems in the developing world can dramatically increase farmer income by as much as an order of magnitude (Egan, 1997). Implementation of treadle pumps worldwide has been expedited by not-for-profit corporations, most notably International Development Enterprises (iDE), because of their portability, simplicity in operation, and low start-up costs. Although designs of treadle pumps vary from developer to developer, each functions based upon a common principle. This common principle is that all treadle pumps deliver water from a source to a specific destination, generally for field irrigation, via the input of a human's power. The device uses the leg power of the user to lift and compresses cylinders. This reciprocating cylinder then creates an alternating pressure and suction force to draw water from a subsurface water source and displace that water at surface level. The average treadle pump is able to draw water from a subsurface water source of up to 7 meters in depth. Current pump designs have tremendous effects on farms when implemented via governmental initiatives and NGO activities in a developing country, as they provide a labor-intensive yet effective method of displacing 1 to 2 cubic meters of water per hour to crop sources (Hayes, Jere, Bunderson, Cornish, & Banda, 2002).

Current treadle pump designs have many barriers. The foremost of these barriers is the lack of local pump manufacturing. Current designs are complex designs and require skilled laborers and complex hardware to maintain the product. Recognizing this issue, iDE, the leading design organization in treadle pump technology, released ten guiding principles for future design of treadle pumps (Egan, 1997). The most crucial focus of these principles calls for organizations to design a treadle pump that can be produced and manufactured locally. The most readily available treadle pumps do not have locally available valves, the most crucial components in the system's operation. Without a valve that can be procured locally, the treadle pump's sustainable operation in the developing world is substantially hindered. Farming communities require a valve design that is easily and affordably maintained locally. Therefore, an appropriate valve design is desirable. This redesign of existing valve technology must take into account multiple factors including readily and locally available resources to allow for a sustainable treadle pump in target communities within the developing world.

Allowing for the sustainable operation of a water extraction technology, such as the treadle pump, is vital for the food security of a developing world community. The act of securing and sustaining agriculture is paramount in supporting developing world economies and societies, as well as for feeding members of a community. Markin et al define "food security" as, "ensuring consistent food supply to the current and future generations" (Markin & Khaziakhmetov, 1999). In order to ensure food security in developing nations, various explicit agricultural inputs must be present to effectively yield crops. Of all of these inputs, fresh water is one of the most critical. The motivation of this thesis is to enhance the current method of delivering fresh water for small-scale irrigation purposes from a basin or aquifer source to a planted field using appropriate technology. Appropriate methods with regards to technological development are an expanding field of study related to the social and cultural outcomes of technology implementation.

Appropriate technology addresses the development of an engineered solution, promoting the design of products that are produced with readily-available raw materials, and that can be maintained with readily-available tools and methods. Existing methods of water transport in developing world communities possess distinct design drawbacks. These drawbacks are rooted in the failure to incorporate the users' true needs. True needs are only able to be obtained through actually using the apparatus, and empathically searching for needs that are not apparent to a design team who might only look at the quantitative needs of the tool. The failure of meeting these needs led to the inappropriate design of the treadle pump which has caused implementation failures in several developing world applications.

The ground-breaking work done by the non-governmental organization (NGO) iDE to popularize the use of treadle pumps in countries such as Bangladesh motivated this research to advance the treadle pump design. iDE received 27 million USD over four years to develop technology to enhance the performance of the treadle-pump to provide micro-irrigation solutions for India. In an effort to promote this campaign, iDE and the Gates Foundation produced videos interviewing rural farmers who explained the expansion in farming production since the advent of treadle pumps in Bangladesh. Treadle pump technology provided access to deep water tables that previously went unexploited for rural agriculture, thus providing more food for farmers and their families, as well as increased income in some cases (Egan, 1997).

iDE's technically efficient design was not the sole reason for the efficient adoption diffusion of their product in local towns of Bangladesh. Instead the diffusion occurred quickly due to iDE's approach to advertisement; iDE implemented value chain engineering tailored to the specific client base and leveraged "social marketing interventions" (Egan, 1997). The interventions placed the treadle pump within access of the farmers that the design was specifically tailored to, and the people on the ground could show farmers the difference between their new design and current practices. iDE published these interventions as the ten criteria for a successful product launch. The ten "guiding principles" were: (1) make the pumping technology affordable (affordable cost), (2) sell to individual farmers (target group), (3) do not give subsidies (non-subsidized), (4) sell a viable product (viability), (5) use local manufacturers, (6) work with the private sector, (7) develop a critical mass, (8) advertise, (9) provide service and maintenance, (10) have a coordinating agency. These guiding principles produced successful design launches that iDE claims generated 200-500 USD in additional wealth each year to the farmers (Egan, 1997). This additional income is derived because the treadle pump allows for a supplemental growing season in winter, which would have not been otherwise possible given the technologies available prior to the advent of the treadle pump. The overall added aggregate production for farmers in Bangladesh was estimated at nearly half a billion USD yearly (Egan, 1997).

The work of iDE to effectively design, manufacture, and promote the fast and effective social adoption of the treadle pump in Bangladesh inspired this thesis' research endeavor to decrease the overall pump price while not sacrificing the viability of the pump, therefore increasing the pump's availability to more of the target market.

1.2 Overview of Thesis

The goal of this research was to identify and quantify the performance characteristics of limiting components within the world's most common developing world water transfer apparatus, the treadle pump. This research led to the thesis assumption that a redevelopment of the check valve, or one-way valve, would lead to a drastically lower overall cost of the treadle pump and significantly aid in the community adoption of this technology globally.

Current treadle pump implementation has only had a few successful launches to date, most notably iDE's launch. Although iDE's launch, mentioned above, attempted to reduce the lead for a large maintenance infrastructure, most successful launches require significant governmental financial subsidies and call for large spare part repositories for out-of-service pumps. By redesigning key, expensive parts a significant decrease in the overall capital start-up cost of implementation and maintenance of the pump can be realized. The secondary focus of this thesis concerns the social interaction of this technology with the end-user. The adoption of treadle pumps encounters difficulty when the pump becomes physically exhaustive for the operators. Adopters will cease to use the pump if they feel as though it is less exhausting to instead bucket and carry water to the location of choice.

Through this thesis I will define the needs of the users of the technology, analyze the prior design work of other organizations that have developed existing technology, and develop a design using appropriate design principles. The appropriate design principles will lead to a redesign of critical components that will provide a comparable technology that is less exhaustive and less expensive for the end-user.

1.3 Specific Research Goals and Approach

The development of an appropriate technology requires the incorporation of the theories of empathic and appropriate design within the framework of the engineering design process. The engineering design process yields a detailed design that can be constructed and tested. The constructed components can then be tested against the developed set of design specifications. The component in this case is the treadle pump valve which is critical to its operation.

The research goals of this project are to validate the designed valve’s technical capability through experimentation. This testing will first require the dynamic modeling of the valve within a pump in a simulation suite. Using calculation and computer-simulation to understand the operative dynamic flow characteristics, the experiment can define the boundary conditions of flow rates such that the valve can be properly configured to operate within the given specifications within those defined boundary conditions. The testing of valves and seals within the treadle pump under the conditions derived from the simulation provides valuable feedback on the design process' success.

1.4 Thesis Outline

The thesis is organized into chapters of the following subjects. The second chapter of the thesis includes a literature review of published material on the topic of treadle pump technology, in addition to competitive technologies in developing countries, and offers an overview of the general treadle pump design, and the specific facet of interest for redesign, the check valve. The third chapter provides general theory applicable to pumping technology and relevant fluid mechanics, such as a dynamic control theory that governs the empathic engineering design process of the valve and seals, and the engineering design and appropriate design theory applied to the treadle pump to redesign each selected component. The fourth chapter provides the experimental designs, and the acquired data and analysis which validate the new design. The fifth chapter includes a discussion of the outcomes of the design and testing process, and their meaning within the context of the implementation of treadle pump technology within targeted communities. The sixth chapter identifies shortcomings and suggested directions for improvements in future research on similar treadle pump technology.

2.0 Literature Review

This chapter reviews current farming practices relevant to the research, existing technologies outside of the treadle pump, and the current designs of treadle pump technology.

2.1 Agricultural Applications of Appropriate Technology Theory

Water extraction technologies in the developing world vary from region to region, globally, but all perform a similar task: they move water from point A to point B. Technologies that are appropriate in locations such as Guatemala or Peru may not also be appropriate for locations in Malawi or India. The “appropriateness” of a technology is not merely a function of the economic state of the target community; it is also a function of the environment within which the community exists, the societal structure that governs who might be the user of the technology, and the culture of the community which defines the meaning of that technology within the society. Determining the appropriateness of a technology is a multivariable analysis that serves in some cases to reanalyze a technically efficient design that fails in implementation for reasons related to the environment, society, or culture.

Appropriate technology design is widely discussed because it seeks to prevent design failures that occur not because of technical flaws but because of cultural or socioeconomic factors. Appropriate design is most commonly interpreted as “technology that is suitable to the social and economic conditions of the geographic area in which it is to be applied, is environmentally sound, and promotes self-sufficiency on the part of those using it” (Merriam-Webster). This definition has a vast scope that the designer of a technology must navigate to produce a successful design. Although it might seem a simpler task to design a culturally appropriate treadle pump versus designing a technically capable pump, this is often not true. In the "Field Guide to Appropriate Technology" the author cites a specific instance of a pump's early obsolescence from an appropriate design failure: "Cultural factors are significant; a pump was not accepted in the Sudan because the users thought the operators would sit in an undignified positions - use of the pump violated the local custom" (Hazeltine & Bull, 2003). This specific example in Sudan confronts the designer with the reality that the community must accept the technology designed for a true design impact to be made. Therefore simply analyzing and optimizing the fluid mechanics of the pump is not sufficient to successfully implement the pump within a community. To successfully implement the pump, the designer must couple a sustainable technical design for water extraction with an emphasis on community-focused design factors. This coupled effort will not only increase adoption diffusion of the technology, but from that diffusion also increase crop yields.

The most notable development since the 1970's in developing world farming technology was the replacement of motorized groundwater extraction with human-powered extraction methods. Motorized groundwater extraction can be difficult to maintain primarily because of the unavailability or high cost of diesel or gasoline motor parts. Motorized groundwater extraction is also expensive as it requires the purchase of gasoline and diesel-powered pumps and fuels. Lastly, motorized pumps are generally oversized for a single farm's use, forcing farmers into a shared ownership (e.g. through a cooperative) to own and operate the pump. In the target communities, diesel motors are not appropriate as the village often does not have money to spare to operate the machine, or the resources or knowledge to repair the machine. Farmers who have unsuccessfully tried motorized groundwater extraction commonly revert back to human-powered technology.

Treadle pumps are often more appropriate than motorized pumps because many farms are of a size that can be irrigated with this human-powered technology. Approximately 85% of developing-world farmers farm less than five acres of land (Astyk, 2011). Typical farms are small and therefore need smaller solutions such as treadle pumps to develop their land at a low-cost.

Treadle pump use expanded in Bangladesh in the 1970's when 185,000 PVC and bamboo twin-cylinder pump-heads were sold and distributed across the country. Where small developing world farms once had trouble raising capital or procuring institutional credit to obtain expensive motorized pumps, the treadle pumps provided a relatively low-cost and low-output alternative suited for small farming operations (Orr, 1991). Figure 1 highlights the highest and lowest costs for small farmers in Bangladesh, and provides costs for the development from bamboo pump heads. These costs translate to approximately 20 USD. This price is one of the lowest for a treadle pump, as it represents a low-flow and low-reliability pump. The positive aspects of this design are that materials are locally available and the required tooling and knowledge to build and maintain this specific bamboo pump is relatively low.

TABLE 1.2 : COST OF TREADLE PUMP AND BAMBOO TUBEWELL, 1987-88.

No.	Item	No/qty	Price (Taka)	
			High range	Low range
1.	$3\frac{1}{2}$inch pumphead and all metal parts	1	290	250
2.	Bamboo for pipe, filter, and frame	3	120	105
3.	Netting for filter	3 yds	40	20
4.	Pitch	0.5 kg	10	2
5.	GI wire (No. 14)	2 *chataks*	5	5
6.	Polythene	1 sheet	2	2
7.	Installation charge for 30-40 foot pipe	1	150	100
	Total		631	495

Figure 1 - Cost-sheet for Treadle Pump and Bamboo Tubewell (Orr, 1991)

Although 20 USD may be a relatively insignificant price in comparison to that of available motorized pumps, many farmers have even lower levels of available capital, and micro-financing may not always be available. The development of a lower-cost, higher-reliability, and open-source design where pump heads may be procured and manufactured by locals is imperative. In Orr's analysis, over 45% of the cost is centered in the pump cylinder (pump head) and metal parts. Although Orr points to the agricultural success of the treadle pump, there are many problems in using human-power to irrigate farms. In comparative studies on the performance of treadle pumps, the treadle pump was found to be easier to operate than other types of manual pumps for irrigation systems and make the pumping action more efficient as switching from arms and hands to feet and legs to power the manual pump was determined to be "one of the most important innovations brought by the treadle pump" (Pereira, J., Gaspar, & Ventura, 2006).

Other case-studies indicate the root-cause of the lack of treadle pump adoption in developing world farms was the tiring work necessary to power it. A case-study in Zimbabwe analyzed a cooperative of farmers that pooled finances to purchase treadle equipment to irrigate their farms. Over the duration of the study, many farmers began to opt out because the pumping was tiring. The users were also not satisfied because while the treadle pumps are generally designed for men they are often operated by the women and children of the community, and their needs were not accommodated for in the design. The women felt uncomfortable being elevated on the pump where their dresses might be blown by winds and results in parts of their bodies becoming exposed. The men of the community also displayed dismay because their wives were more tired than they were from simply bucketing water. This case specifically points out that this treadle pump was not designed with an understanding of the actual *users* of the pump, who are often the women and children of developing world communities. These social and physical ramifications of treadle pump use have stifled adoption diffusion in other developing world communities as well (Kay & Brabben, 2000). While in most cases users claim that the tiring effects of the treadle pumps are the chief source of premature obsolescence, social implications of the operation of the treadle pump may have a stronger implication in the discontinued use of the pump than previously thought. Design of a pump taking into consideration the social stigmatism of the physical motion will yield better results in the technological adoption in the target communities.

2.2 Current State of Irrigation in Developing World Agriculture

Another technological shortcoming for developing world farmers is in the transportation of the extracted groundwater to their farming plot. Some sophisticated irrigation systems perform this task efficiently and effectively, but are more expensive than what individual farmers can afford. To crowd-source the risk of capital investment, group of farmers often form a cooperative to build shared channels throughout their plots with spouts at each plot. Often irrigation companies also form to build these channel networks, the irrigation company then charges a price to flood water into the channels on your property. Although problems exist with these cooperative and commercial arrangements, the economics of the channels allows for communities to determine which method is most appropriate and economical and employ that solution.

Channel design has been approached by many authors. Channels carry the water from the pump to the fields via a network of lined ditches of engineered channeling. The problems associated with channel design are soil erosion and significant water losses (Fraenkel, 1986). These problems cannot be tackled with slight design modifications. Soil erosion in the channel can negate the increased efficiency of the water transfer apparatus by allowing the water pumped to be lost before it exits the channel to the field. These water losses incur losses that can significantly increase the amount of human work needed to irrigate certain acreage of crops

(Singh, Rahman, & Sharma, 2008). A lower-cost technology called Low Energy Water Application (LEWA) converts the potential energy of water into rotational energy of a mechanical device used to irrigate crops and minimize soil erosion; LEWA is more effective and efficient than open-flow, ditch channels that cause evident soil erosion and allows for more sustainable agricultural practices (Singh, Rahman, & Sharma, 2008). This increased sustainability is derived from LEWA's distinct ability to irrigate without causing soil erosion and therefore allows for a greater percentage of water pumped reaching the crops. The LEWA uses the energy of the water pumped from the subterranean source to rotate the device which acts like a sprinkler. Soil erosion can have significantly negative impacts on agricultural sustainability and therefore food security of a community, and channel networks with high-flow have been pointed to as a large contributor to this problem. Although the case studies had a positive impact on water savings and crop yield, the system itself costs nearly 575 USD, prohibiting any adoption of this technology in developing world communities. The costs associated with this system are itemized in Indian currency in Figure 2. Although this research points to erosion sustainability, it also calls attention to the need for each piece of technology to fit within an environmentally sustainable agricultural system from the well-source to the field.

Impact sprinkler				
Sl no.	Items	Quantity	Rate (Rs.)	Total cost (Rs.)
1	Main line HDPE 50 mm	7 length (of 6 m each)	600	4200
2	Lateral lines HDPE 50 mm	15 length (of 6 m each)	600	9000
3	Coupler with valve	2 nos.	800	1600
4	Sprinkler nozzle	10 nos.	175	1750
5	Riser 1″ (1 m length GI)	10 nos.	110	1100
6	Lateral connecter with riser connecting arrangement	10 nos.	300	3000
	Sub-total			20650
7	10% for other fitting cost			2065
	Grand total			22715
	Approximate total cost say			Rs. 23,000/-

Figure 2 - Problems and options displaying the costs associated with the LEWA technology implementation (Singh, Rahman, & Sharma, 2008)

2.2 Freshwater Sustainability Practices

Studies have shown that the implementation of sustainable agricultural practices can provide crop yield increases of 80% within four years (American Chemical Society, 2006). Although sustainable agricultural practices may face a number of challenges outside of water sustainability, treadle pumps have had net positive impacts on farm sustainability as farmers tend to want to expend their labor efforts only on water they need. In other words, farmers are less likely to pump more water than necessary for a crop if the pump they are using is human-powered and not mechanically powered by a river or diesel fuel.

Agriculture utilizes the largest amount of fresh water globally; therefore water-use practices must be ecologically and economically stable in the developing world to ensure both successful agricultural output and positive societal impact to the community (García-Tejero, Durán-Zuazo, Muriel-Fernández, & Rodríguez-Pleguezuelo, 2011). Current irrigation practices in developing world agriculture have quickly depleted valuable groundwater sources and forced expensive drilling. This practice can be unsustainable both economically when drilling is required and ecologically to the wildlife that depends on those groundwater sources if not correctly analyzed. The unsustainable utilization of freshwater sources results in the over-use of rivers and lakes, drying up these water resources, harming both fish and wildlife in the process. This practice can lead to the jeopardy of future crop yields, and polluting of essential community water supplies. There is a need to reduce the amount of fresh water used in food production. Although increased irrigation yields substantial farm profits, this increased use ultimately sustains damage to the ecological systems the communities depend on. Only 8% of crop types grown in farms worldwide deplete underground aquifers faster than they can replenish (García-Tejero, Durán-Zuazo, Muriel-Fernández, & Rodríguez-Pleguezuelo, 2011). To utilize the most accessible water resources, developing world communities use the most accessible fresh water resources, generally rivers or lakes. If those sources become dry or unusable, communities often drill into underground aquifers to access vital freshwater for drinking or irrigation purposes.

Sustainable water resource planning for a community is a difficult task to accomplish, and outside of the scope of a treadle pump design. For a community to reach a water usage level that can be deemed sustainable, specific geographical information and analysis must occur on the ground in these communities. As many communities cannot afford a groundwater assessment, projects have developed to help produce open-source information for general groundwater assessment. To help these developing world communities select sources of groundwater to sustainably exploit, "The Grey Data Project" spearheaded by multiple organizations including the Southern African Development Community (SADC), the British Geological Survey (BGS) and the South African Water Research Commission (WRC), and financially backed by the German Organization for Technical Cooperation have brought together unpublished and small-scale published groundwater data for developing world countries in Africa. "The Grey Data

Project" now offers an accessible database of groundwater information to help make sustainable agriculture and sustainable water resources in Africa a reality (Cobbing & Davies, 2011).

2.3 Existing Competitive Water Transport Technologies in General

The most pivotal link of water sources to the fields for farmers is the technology that transfers water from a source to their channel networks. An appropriate delivery method must be developed to transport the water from that source to the point of use, and this subchapter will analyze current technologies that accomplish this task. Water transport and delivery systems exist in many forms in the developing world. The agricultural technology most widely discussed by NGO's in the last thirty-years has been the treadle pump. In Table 1, the depth range and distinguishing characteristics of water pumps has been tabulated.

Table 1 - Types of water transport technology, the corresponding depth range and distinguishing characteristics of the technology (Stewart, 2003).

Type	Depth Range	Distinguishing Features
	Shallow	
Row pump	6 m (19 ft)	Easy to make of PVC pipe
Suction hand pump	7 m (23 ft)	Very common traditional design
Foot Pedal (Treadle) pump	7 m (23 ft)	Powered by your legs instead of arms
	Intermediate	
Direct Action Plunger pump	12 m (39 ft)	Lower cost direct action pump
Bucket pump	15 m (49 ft)	Many buckets on a continuous loop
Direct Action pump	15 m (49 ft)	Discharges water on up and down stroke
	Deep	
Diaphragm pump	45 m (148 ft)	May work in curved bore holes
Rope & Disk pump	60 m (197 ft)	Easy to make in low income countries
Progressive cavity pump	60 m (197 ft)	Continuous output from rotary motion
Piston pump	90 m (295 ft)	Deepest capability

2.3.1 Bucket and Cased Well

Technologies and processes competitive with the treadle pump have existed within cultures and have been passed down through generations of farmers. The simplest of these processes and the least expensive is the water well and bucket process. The community can dig a well to their desired (and site-specific) depth and casing diameter. The water can then be extracted using a container, generally a bucket, and mechanically lifted by a pulley and hand-crank. Today, many developing world communities have limited access to even the simplest of pumps and resort to this process. For even the smallest of farms, the amount of time and energy that must be spent in lifting the amount of water necessary to irrigate the crops is difficult. Although time may be more abundant in these communities than monetary resources, the amount of time spent on irrigation significantly hinders farmers from expanding their crop yields. The greatest advantage of bucket and well is the greater depths achievable versus pumping technologies. The bucket has a depth range of nearly 15 meters, versus the 7 meter limit of treadle pumps (Stewart, 2003).

Some communities have implemented continuous bucketing systems to increase the volumetric output of the operation. This operation is requires industrial manufacturing facilities, and is rated by the FAO as one of the most power intensive machines to transport high-volumes of water from sources (Fraenkel, 1986). The continuous bucketing system is similar in output specifications to the treadle pump, but is more expensive and failure prone mechanically. Some continuous bucket processes have developed from the Persian design called the "zawaffa", traditionally classified as a water wheel.

2.3.2 Water Wheels

North of the Indian sub-continent, the use of water wheel technology increased as the bucket and well process proved time intensive and the need for fresh water for drinking and agriculture increased. The Persian-designed zawaffa is the seminal technology behind the water wheel (Figure 4). The zawaffa's flow is proportional to the volume of each bucket on the wheel and the angular velocity of the wheel. As the buckets pass over the wheel, they must tip to spill their content into the channel for irrigation. Therefore, the increased heights of the zawaffa require that more spacing must exist between the buckets to allow for this tipping motion to occur (Fraenkel, 1986). Although the water wheel is mechanically efficient there can be significant losses in output efficiency. The main source of output inefficiency for this design is the unintentional spilling from the buckets that occurs during the higher speed operations.

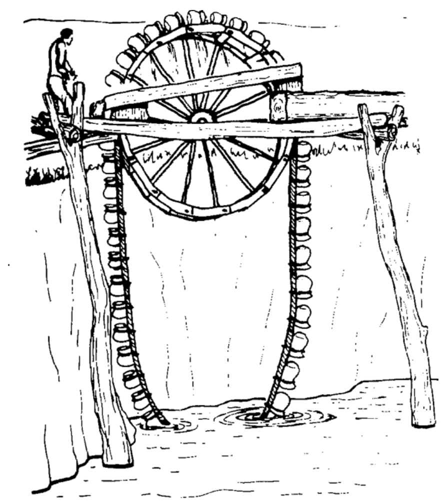

Figure 3 - An illustration of the Persian "zawaffa" (Fraenkel, 1986)

Table 2 - Adapted Table of Taxonomy of Pumps and Water Lifts (Fraenkel, 1986)

Category and Name	Construction	Head range (M)	Power range (W)	Output	Efficiency	Cost	Suction Lift?	Status for Irrigation
I DIRECT LIFT DEVICES								
Reciprocating/cyclic								
Pivoting gutters and "dhones"	2	1-1.5	*	**	**	**	x	√
Rope & bucket and windlass	1	5-50	*	*	*	*	x	√
Self-emptying bucket	2	3-8	**	***	*	**	x	√

Rotary/continuous								
Continuous bucket pump:	2	5-50	* *	**	***	**	x	√
Persian when', or "tablia"	2	3-10	**	***	***	**	x	√
"Zawaffa"	2	3.15	***	****	****	***	x	√
Waterwheels or "noria"	2	>5	*	**	**	**	x	√
II DISPLACEMENT PUMP								
Reciprocating/cyclic								
Diaphragm pumps	3	5-10	**	***	****	***	√	√
Rotary/continuous								
Coil and spiral pumps	2	>6m	**	**	***	***	x	√
Flash-wheels & treadmills	2& 3	>2 m	**	****	**	**	x	√
Peristaltic pump	3	>3m	*	*	***	***	√	X
III VELOCITY PUMPS								
Reciprocating/cyclic								
Inertia and "joggle" pumps	2& 3	2-4	*	**	****	**	x	√
Flap valve pump	1 & 2	2-4	*	*	**	*	x	√
VI GRAVITY DEVICES								
Syphons	1, 2 & 3	1.(1-10)	–	*****	–	**	–	√
CONSTRUCTION: 1 - BASIC, 2 - TRADITIONAL, 3 - INDUSTRIAL STAR RATINGS: * (1) VERY-LOW, ** (2) LOW-MEDIUM, * (3) MEDIUM, **** (4) MEDIUM-HIGH, ***** (5) HIGH AVAILABILITY: √ - YES, ? - PLAUSIBLE, X - NO**								

2.4 Treadle Pumps

2.4.1 System Overview

The basic treadle pump is a human-powered irrigation apparatus composed of an intake, two pumping cylinders (generally termed in some field manuals as "pump-heads"), and a discharge hose. Two treadles (long sturdy beams to walk on) power the pump and a handle is available to balance the operator. A piston rope mechanically couples the stroke of the treadles and the pistons, and a pulley mechanically links the pistons and treadles. A visual representation of a treadle pump can be found in Figure 4.

To operate the treadle pump, the operator stands on the treadles, holding onto the handle for balance, and presses down on one treadle while the pulley lifts the other treadle and connected piston. This action of lifting the piston creates a suction to draw water from the inlet, and then discharges the water with pressure in the subsequent downward stroke.

Treadle pumps designs also use more ergonomic user-input actions such as bicycling to achieve the same pump mechanics. Operators usually pump for only 20 to 30 minutes at a time to prevent exhaustion; however this varies from individual to individual. The amount of power required to operate the pump is directly related to the vertical distance between the water source and the pump location, which can vary. Considering a relatively small vertical distance from the source, most pumps with a 50 mm delivery hose can deliver 1 liter per second for 5 hours a day, which is equivalent to 18,000 liters per day under normal operation. In Malawi, this output can irrigate approximately 0.3 hectares per day (Hayes, Jere, Bunderson, Cornish, & Banda, 2002).

Because of the relatively large rate of water displacement, most field operations manuals for treadle pumps recommend that source wells should be at least 4.5 meters in depth to have a sustainable volume of water to pump, and the water table to be less than 2 meters from the surface for ease of pump operation. The amount of work a user must input into the system to produce 1 liter per second is proportional to the depth to the water table (Hayes, Jere, Bunderson, Cornish, & Banda, 2002). As the distance to the water table from the pumping surface increases, so too does the work required to lift the water. Although this design requirement eliminates many water sources, wells that are dug in water table aquifers are viable for irrigation and water supply uses. Since this is currently a common practice for irrigation purposes, this thesis seeks to further the efficiency of the pump that will move water from a source to a small farm for irrigation.

The treadle pump exists in two types: suction and pressure. A suction treadle pump is designed to draw water from a well of a limited depth to ground level for delivery. Alternatively, a pressure treadle pump is designed to apply head pressure to a ground level water source to deliver the water through a piping system, or to a higher elevation for storage.

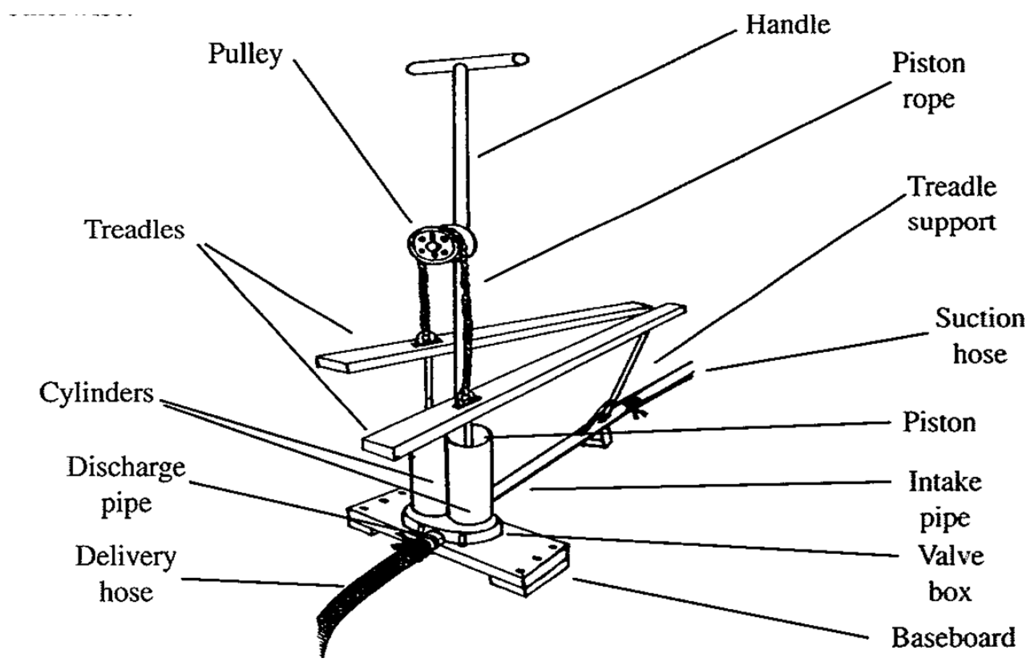

Figure 4- Schematic of a generic treadle pump design (Hayes, Jere, Bunderson, Cornish, & Banda, 2002)

2.4.2 Adoption Diffusion of Treadle Pumps in Developing World Communities

iDE’s 1980's Bangladesh launch involved the purchase of 1.5 million treadle pumps over 15 years at a total investment of 49.5 million USD. These same farmers yielded an additional 150 million USD per year in ongoing net income directly from increased crop yields, making this one of the most pivotal case studies for the use of treadle pumps in small agricultural operations (Molden, 2007). This case shows that the treadle pumps’ implementation has potential to increase not only a farmer’s individual wealth, but to increase an entire region’s wealth and GDP. Still, many factors hold the design back from further success.

The factors holding back the further use and implementation of the technology are the high cost of the highest quality units, maintenance difficulty for piston seals rendering older units obsolete, and cultural taboos stigmatizing the action of operating a treadle pump by women. This research seeks to eliminate these factors by employing engineering design methods such as empathic design to understand the user’s culture and knowledge to better design a treadle pump.

2.4.3 Improvable Subcomponents of Treadle Pumps

The two most actionable items for improvement are the piston seals and check valves. The chief concern is that to maintain pump effectiveness, the seal on the inner-annulus of the pump-head should be airtight to hold suction. Achieving an airtight seal between piston and cylinder increases the friction in normal operation without lubrication. Although friction has been reduced in some designs by changing seal materials, even reduced friction designs induce heavy fatigue in workers and results in premature obsolescence of the treadle pump. Pump designers recommend that the inner-annulus of the pump cylinder should be greased to reduce the friction and therefore work of the operator. The designers documented the use of simple greases such as Vaseline with users experiencing significantly reduced friction results (Hayes, Jere, Bunderson, Cornish, & Banda, 2002). This lubrication application becomes a burdensome task for pump operation, and some types of grease may taint the water supply and render the water non-potable. To reduce the necessity for grease application, while also maintaining a reduced friction, some designers have applied leather to the inner-annulus of the pump-head. Although effective corrected-grain thin-ply leathers are available in many first-world sewing stores, these leathers are not available in developing world countries to the level where one could consider them to be appropriate technology. A development which replaces the processed leather or rubber o-ring seals on the inner annulus of the pump-head is critical in the construction of a sustainable treadle pump.

Next, the improvement of capital cost required to purchase a high quality and reliable treadle pump must be investigated. When observing the cost sheets of commercially available treadle pumps, the most expensive parts on the cost sheets are reliable check valves. A check valve is a mechanical flow valve that allows minimal head-loss flow on one direction and completely obstructs reverse flow. Commercially available check valves vary in cost, but for PVC check valves in 3.81cm (1 ½") socket-weld sizes, the price is approximately 15 USD on McMaster-Carr's database (McMaster-Carr). These check valves also require a minimum of 3.45 kPa (0.5 psi) cracking pressure to allow flow, nearly disallowing any siphon flow that may occur from residual vacuum that occurs during the pump's operation. This high cracking pressure significantly reduces the valve's efficiency in normal operation. Four check valves are required for operation of a high-volume treadle pump. Some low-flow designs incorporate flap valves, but fail under normal pump usage because under high-volume the flap valves will wear significantly. After extended operation, these worn flap valves stop maintaining their seal and dry-rot. Development of a lower-cost and highly reliable check valve in the treadle pump would be a significant total cost reduction, enabling acquisition of the same product without the high capital investment needed with current designs.

2.5 Specific Technology of Focus

The specific technology selected within this thesis to analyze and refine is the check valve. A check valve has two ports, one port for the incoming flow and one for the discharge flow. In hydraulic schematics, designers of a piping or hydraulic system indicate which direction the check valve allows flow with an arrow symbol. This technology is a matured commercial product in first-world applications, but has very little literature available on technology development targeted at developing world applications.

The most readily available literature on developing world check valve design related to treadle pump technology has been cataloged by an online website called the "Build Your Own Treadle Pump Blog". The blog has documented and described the design process of the treadle pump built for Haiti Fund Inc. The blog documents the development of a check valve for the treadle pump because "four of the most expensive parts are the check valves" (Sylivant, 2007). The designers use a simple check valve design using a ball and o-ring seal within standard PVC fittings. The reverse flow forces the ball into an o-ring sealed socket that creates a tight face seal and quickly stops the reverse flow. Sylivant first used low-cost glass marbles for the ball component to stop the flow, but found that the sand and particulates in the water would scratch the glass in a short period of time. These scratches allow for minute back-flow through the valve and ruin the valve's ability to seal. The designers then changed to a material with significantly better abrasion resistance called polyoxymethylene (Delrin), which is a resin with properties similar to that of nylon. The design uses standard PVC fittings and the polyoxymethylene ball to restrict flow, and in testing performed well. The blog claims that in mass-production the price of the valve should be around 3 USD, but is much higher in the smaller quantities purchased for testing as the polyoxymethylene ball is an expensive component in small orders. The design is displayed in Figure 5 (Sylivant, 2007).

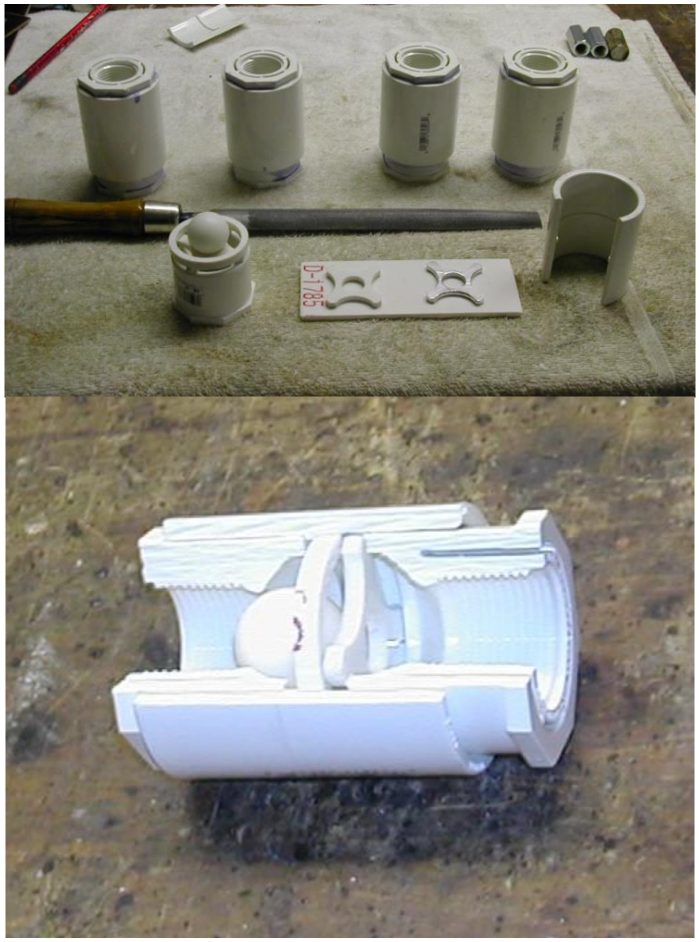

Figure 5 - Check valves designed for developing world agriculture applications (Sylivant, 2007)

As a check valve has little direct social or cultural connotations, the most important aspects of the valve itself with respect to culture and social acceptance must be price, maintainability, and ease of manufacturability. Applying appropriate design methodology to the check valves can produce a less expensive version of the developed valve by Sylivant.   The new developed valve's total cost will be compared to both the cost of commercially available check valves and the valve developed by Haiti Fund Inc.

3.0 Theory

3.1 General Pump Theory

Sizing and design of a pump is a function of specific factors such as desired volumetric flow rate ($\dot{V}\ or\ Q_{line}$), pipe selection, and source selection. Analyzing flow conditions within a pipe and the pump itself help to unify the many mechanical characteristics of a treadle pump. The treadle pump can be characterized as a single-acting reciprocating pump. John E. Miller, in a seminal book on the subject of reciprocating pumps classifies this pump as, "a mechanical device used to impart a pulsating, dynamic flow to a liquid and consisting of one or more single- or double-acting positive-displacement elements (pistons or plungers). The elements in the liquid end are driven in a more or less harmonic motion…The liquid flow generated by this reciprocating motion is directed from the pump inlet (suction) to the pump outlet (discharge) by the selective operation of self-acting check valves located in the inlet and outlet of each displacement element." In this definition, Miller fully encapsulates that which must be technically analyzed to develop a functional reciprocating pump. The items which are of key importance are the pistons or plungers and the check valves. These two mechanisms will be analyzed with regards to their interactions that impact the general dynamics of the pump, including the flow rate and requisite power to operate (Miller, 1995).

Premature obsolescence of pump technology occurs recurrently from pump technology that requires an amount of energy from the operator that induces fatigue. Fatigue is induced from pump operation when the power necessary for the pump operator to run the pump is exceptionally high. The forces that fatigue the operator can be associated directly or indirectly with many mechanical sources. These sources include overall system head loss and the friction between the inner annulus of the pump cylinder and the seal. The most general equation for pumping power is as follows in Equation 1:

$P_{hyd} = \rho g H_a$

Equation 1- Hydraulic Power of a Pump

where:

$\rho = density\ of\ pumped\ fluid\ \left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)$

$g = gravity\ \left(\frac{\mathrm{m}}{\mathrm{s}^2}\right)$

$H_a = gross\ head\ of\ pumping\ operation\ (m)$

$Q = \dot{V} = average\ flow\ rate\ of\ pump$ (L/s)

This equation can be visually described by Figure 6.

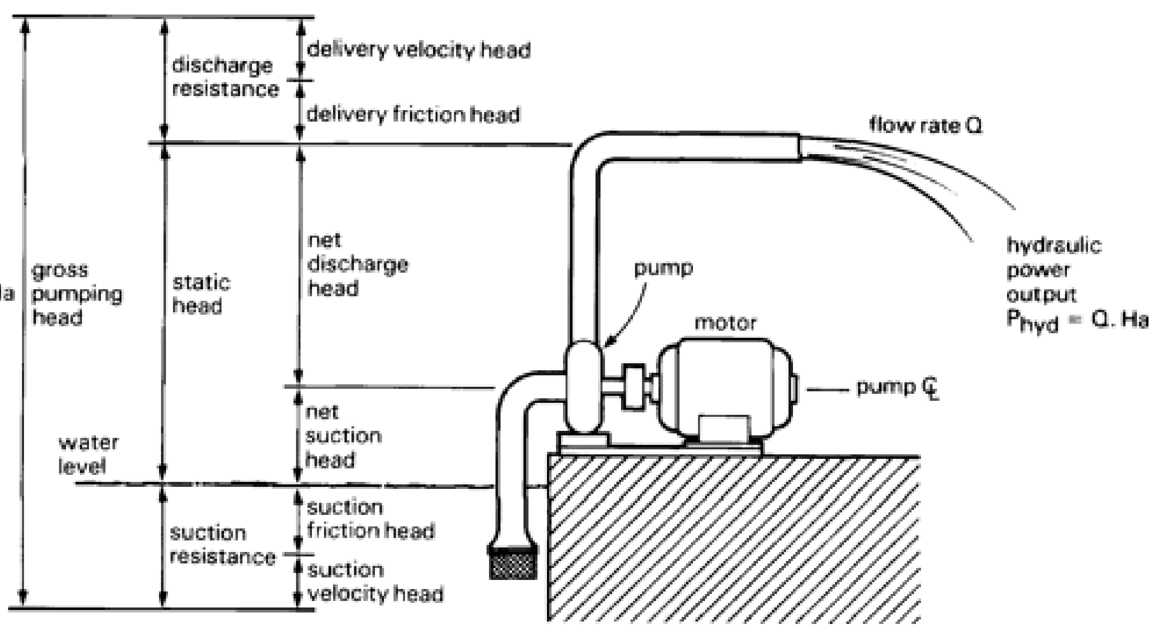

Figure 6 - The figure physically illustrates the variables in the overall power analysis of a water-displacement pump (Fraenkel, 1986)

Flow velocity (v) is a key design parameter in water-displacement pumps (Fraenkel, 1986). The channels that carry the water displaced by the pump will sustain irreversible erosion or damage if velocities exceed the maximum velocity for the channel. This constraint limits the maximum average flow velocity of the pump. Indirectly, the volumetric flow ($\dot{V}$) of the pump is also limited by this, as the volumetric flow of water is dependent upon both the cross-sectional area of the pipe (A_{line}) and average flow velocity. The pump designer's only controllable design variable with a fixed water source is therefore the discharge area. In scenarios for which this treadle pump would be operated, the designer can increase the area of the discharge line to increase overall volumetric flow rate of the pump.

This thesis will focus on primitive channels such as unlined ditches, and particularly on the generalized geology of sand, clays, and rock. These selections afford a nominal maximum flow velocity for the water. The maximum average velocity that should be delivered through an unlined sand channel, for instance, is between 0.3 and 0.7 meters per second, with an exceptionally high coefficient of roughness compared to all other sources (Fraenkel, 1986). Although clays and rock have higher maximum average velocities allowable, they also have high coefficients of roughness. These surfaces may not sustain significant damage if the flow instantaneously rises to a higher velocity, however continuous operation with a high pump discharge velocity on these surfaces will overly erode the channel and damage channel. The velocity limits for the discharge channel provide boundary constraints for the system, with which the suction requirements for the inner annulus seal of the cylinder, as well as flow through the designed check valve can be analyzed.

3.2 General Pipe Flow and Suction Theory

The next system-level constraint on the pump is the maximum suction lift that can theoretically be obtained by the pump. The theoretical maximum lift from suction is derived from fluid statics principles as in Equation 2:

$$\frac{P_{atm}}{\rho_{water}} = H_{maximum\ from\ suction}$$

Equation 2 - Theoretical Maximum Lift from Suction

Dividing the atmospheric pressure on the water surface by the density of the water that is being pumped derives the theoretical maximum height ($H_{maximum\ from\ suction}$) from which suction can draw water within a lossless pumping system. As there are pressure losses in the suction pipe, and inefficiencies in the pump's sealing mechanism, this maximum is purely theoretical and in practice could never be achieved without ideal pipes and seals (Cengel & Cimbala, 2010). This maximum does not consider altitude changes in pumping (Δz), suspended particulates, energy losses in the piping, or the inability to create a perfect vacuum. Because of these limits, most pumps can draw water from 60-75% of this maximum theoretical height, based on the pipe selection for the suction line and the efficiency of the piston or plunger seals. Pipe selection can be pivotal in reducing these losses, as the friction factor of the pipe (ϵ) is the governing constant in calculating head loss for a specific pipe material.

Lewis Moody drew upon Darcy's head loss equation to derive a diagram of a pipe's friction factor (f) and related that friction factor to the Reynolds number of the flow (Re_D). Moody developed a computational method to analyze frictional losses in a pipe with steady flow. Utilizing Darcy's empirical relationship for head-loss, Moody provided a context for the use of friction factors within the flow regime of the pipe. As the turbulence and therefore Reynolds number increases, the friction factor has different effects on the flow. Darcy's equation for head loss and the Reynolds number can be derived as in Equation 3 and Equation 4, respectively:

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

Equation 3 - Total Head Loss within a Pipe

where:

$h_f = total\ head\ loss$ (m)

$f = friction\ factor\ (dimensionless\ value)$

$g = gravity$ (m/s^2)

$L = length\ of\ pipe\ section\ (m)$

$D = diameter\ of\ the\ pipe\ section$ (m)

$v = average\ velocity\ of\ the\ pipe\ flow\ (m/s)$

$$Re_D = \frac{\rho v D}{\mu}$$

Equation 4 - Reynolds Number for Flow in a Pipe

where:

$Re_D = Reynold's\ Number\ (dimensionless)$

$\rho = density\ of\ the\ pumped\ fluid$ (kg/m^3)

$D = diameter\ of\ the\ pipe\ section$ (m)

$v = average\ velocity\ of\ the\ pipe\ flow\ (m/s)$

$\mu = dynamic\ viscocity\ of\ the\ pumped\ fluid$ (m^2/s)

The equation shows a linear relationship between head-loss (h_L) and length of a pipe. This relationship provides a proportional linear pressure drop along the length of the pipe in the direction of the flow. This pressure drop can be reduced by increasing in the diameter of the pipe (D), or decreasing flow velocity (v). The effect of velocity on head-loss is the most dominant of all control parameters. Velocity is directly related to the diameter; therefore alteration of the pipe diameter plays a large role in head-loss reduction with a fixed volume-flow through the pipe section. As the flow can be considered incompressible, mass-flow and volume-flow may be used interchangeably when referring to the flow (Cengel & Cimbala, 2010).

Using these two relationships, Moody analyzed the effect of the Reynolds number and the relative roughness on the friction factor of the pipe. Moody's chart confirmed the Colebrook Equation with a practical chart that could predict flow characteristics given the relative roughness of the pipe section and the Reynolds number of the flow through that pipe section. The relative roughness (ε) denotes the standard height deviation from the average height of the pipe wall: a relative roughness of 0, zero, indicates a perfectly smooth pipe. The larger the relative roughness becomes, the rougher the pipe wall. Although subtle differences may exist between new pipe of common material and composition, tabulated values are available for design purposes. The ratio of relative roughness to pipe diameter is the second key input on Moody's chart. Most commercially available materials for pipe such as galvanized steel, polyvinyl chloride, and copper have average tabulated values for engineers to predict the head loss in a piping section. Moody's chart is presented in Figure 7 (Moody, 1944).

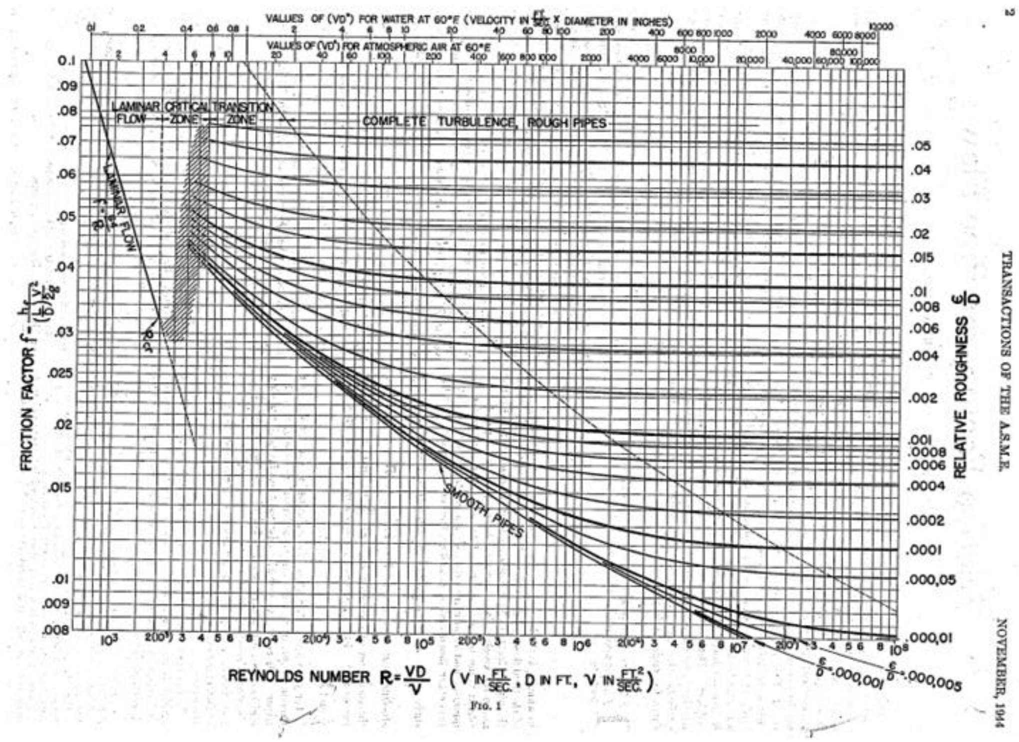

Figure 7 - The relationship between friction factor, relative roughness, and the Reynolds number for a specific flow (Moody, 1944)

Using the tabulated value of the relative roughness of the pipe selection (generally polyvinyl chloride for treadle pumps) and the average velocity that is dictated by the type of channel used for irrigation, the maximum theoretical suction can be predicted. Since the inner-annulus seal cannot be assumed perfect, data must be collected on the hydraulic conductivity ("permeability") of the seal. As discussed previously, although the maximum suction available can be theoretically calculated for an ideal pump, this thesis seeks the practical suction availability to calculate the system dynamics of the pump mechanism and internal flow. The suction required to overcome line losses and other minor losses in the system, as well as to add head to the water for delivery can sometimes cause the internal pressure of the liquid to be low enough to cause local boiling (cavitation). To prevent the caustic damage caused by the bubbles of this local boiling, pump designers stay within a suction that will not induce pressures changes that can cause pump damage. The pressure threshold to prevent cavitation is the net positive suction head (NPSH). Therefore, the NSPH value can analyze the suction available. The NSPH is defined by Cengel and Cimbala as "the difference between the pump's inlet stagnation pressure head and the vapor pressure head" (Cengel & Cimbala, 2010). The derivation of NPSH is given in Equation 5:

$$NPSH = \left(\frac{P}{\rho g} + \frac{v^2}{2g}\right)_{pump\ inlet} - \frac{P_v}{\rho g} = \left(\frac{P - P_v}{\rho g}\right) + \Delta z - h_L$$

Equation 5 - Equations for Derivation of NPSH of a Given Pump

$NPSH = net\ postivite\ suction\ head\ available\ (m)$

$\rho = density\ of\ the\ pumped\ fluid\ (kg/m^3)$

$P = Atmospheric\ pressure\ at\ water\ surface\ (Pa)$

$P_v = Vapor\ or\ saturation\ pressure\ of\ the\ fluid\ (Pa)$

$g = gravity\ (m/s^2)$

$\Delta z = height\ difference\ from\ suction\ to\ discharge\ (m)$

$h_L = minor\ and\ major\ headlosses\ from\ suction\ to\ discharge\ (m)$

$v = average\ velocity\ of\ the\ pipe\ flow\ (m/s)$

The NPSH can be calculated using either of these two equations based on the known parameters. NPSH physically describes the amount of suction pressure force that is residual once all potential energy, minor, and major losses have affected the system. This is the residual suction head with which the pump can operate and do functional work with, and as such is a central parameter in pump design.

3.3 Minor Losses: Valves and Fittings

Even within the least complicated of the treadle pump designs, the working fluid must flow through numerous valves, fittings, elbows, tees, inlets, bushings, expansions, and contractions. Each specific component affects the flow in a different way; however they all interrupt the velocity of the fluid and induce additional energy losses in the system. These losses are referred to as minor losses. In systems where there are long stretches of pipe, the losses in fittings and valves are minor compared to the frictional pressure loss in pipe walls called major loss (Cengel & Cimbala, 2010). In the overall irrigation system, although the valve and fittings losses will be minor, the majority of pressure losses will be related to these minor losses and they must therefore be analyzed.

Minor losses in a system of fittings and valves are described by the loss coefficient, or resistance coefficient (K_L) in Equation 6:

$$K_L = \frac{h_L}{\left(\frac{v^2}{2g}\right)}$$

Equation 6 - Resistance Coefficient

$$h_L = K_L \frac{v^2}{2g}$$

Equation 7 - Minor Loss

$$h_{L,total} = h_{L,major} + h_{L,minor} = \sum_i f_i \frac{L_i}{D_i} \frac{v_i^2}{2g} + \sum_j K_{L,j} \frac{v_j^2}{2g}$$

Equation 8 - Total Head Loss (General)

$f = friction\ factor\ (dimensionless\ value)$

$g = gravity$ (m/s^2)

$L = length\ of\ pipe\ section\ (m)$

$D = diameter\ of\ the\ pipe\ section$ (m)

$v = average\ velocity\ of\ the\ pipe\ flow\ (m/s)$

$K_L = loss\ coeffcient\ (dimensionless)$

$h_L = head\ loss\ (m)$

(Cengel & Cimbala, 2010)

The relationship of flow rate, the corresponding efficiency curve, and head loss has been derived (Fraenkel, 1986). Pipeline efficiency becomes significantly lower as the head loss increases, which occurs as flow rate increases. This relationship is displayed in Figure 8.

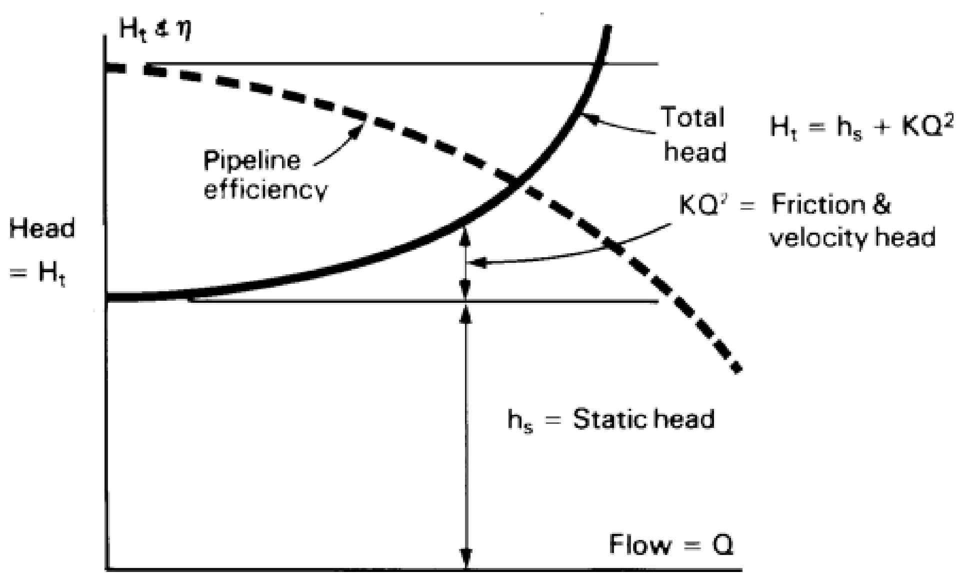

Figure 8 - A graph relating flow characteristics to pipeline efficiency (Fraenkel, 1986)

Each particular hydraulic fitting has an approximate loss coefficient derived from the fitting's geometry. The geometry defines the change in flow diameter or turn of the flow. This loss coefficient helps to calculate the predicted head loss through that fitting given a specific flow rate, as in Equation 7. Cengel and Cimbala have tabulated useful loss coefficients for common hydraulic fittings available for use in the treadle pump prototype in Appendix 4 (Cengel & Cimbala, 2010).

3.4 Modeling of Pump System Dynamics

Considering the suction requirements, major losses of pipe sections, minor losses of fittings, and necessary pump characteristics, modeling the dynamics of the pump necessitates defining the overall geometry of the pump. This modeling requires that the specific fittings and the engineered components that allow for the correct operation of a reciprocating pump be tabulated and placed into a physically operating model. Double-acting reciprocating pumps may use flap seals or gate valves; however with single-acting reciprocating pumps, check valves are necessary for reliable operation. The geometry of each treadle pump will differ by manufacturer; a general pump schematic applicable to most single-acting reciprocating treadle pumps is illustrated in Figure 9.

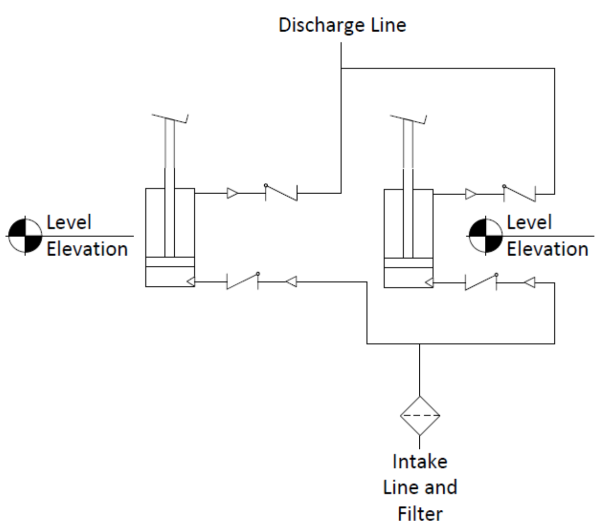

Figure 9 - The single-acting reciprocating treadle pump schematic detailing to cylinders, four check valves, and intake/suction and discharge lines

For the hydraulic modeling performed in this thesis, OpenModelica was used (OpenModelica.org). The specific pump components were purchased and assembled to provide validation for the hydraulic model. The prototype is displayed in Figure 10 in hand-operation, and can be assumed symmetric around the intake and discharge tees. A bill of material for the prototype can be found in Table 3. The bill of material includes: (1) a numbering of each part for descriptive purposes (2) a description of the part (with English dimensions for purchasing information), (3) the quantity of that part in the system and (4) the head-loss of that part as a function of flow velocity. For the pipes, the head-loss equation in Table 4 is developed using the table from Cengel and Cimbala (2010), and a power-law curve fit generated in Excel to determine an equation with an r-squared value of over 99% of the data described. The curve fit allows for the simulation tool to accurately determine the instantaneous head-loss from the pipe dynamically, as a table cannot be imported into OpenModelica's computational model.

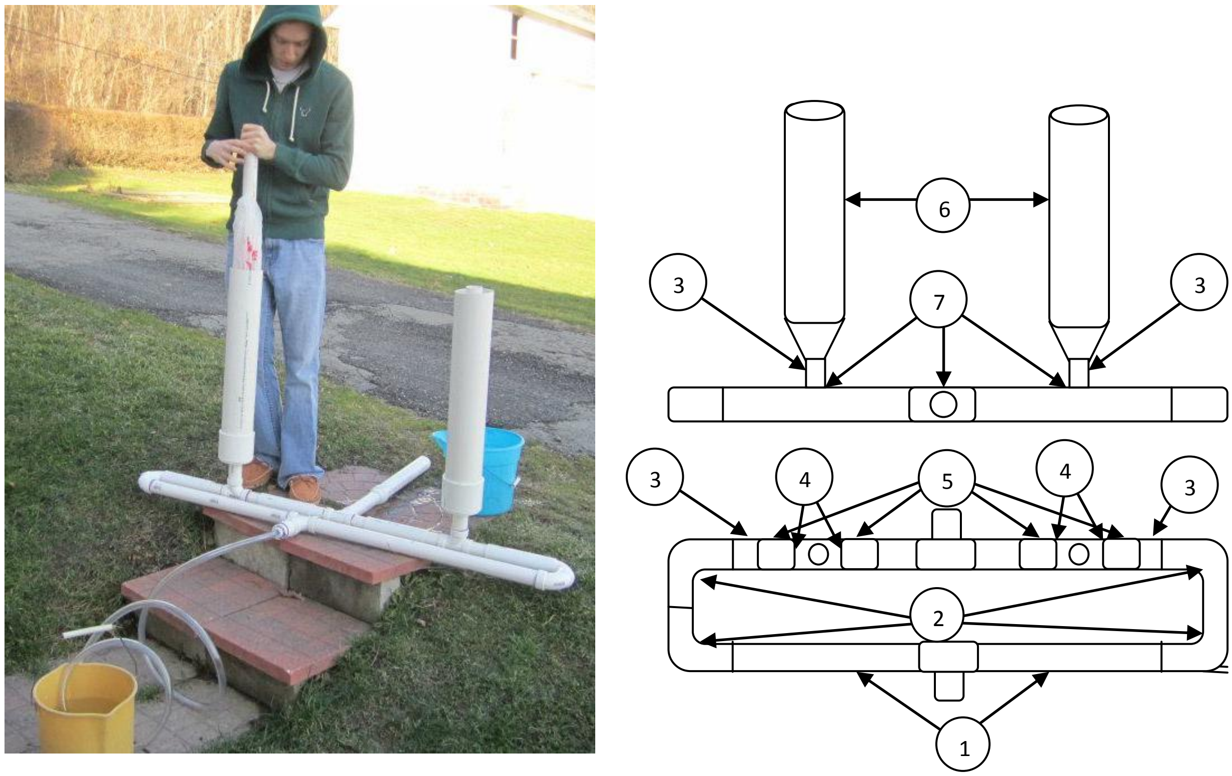

Figure 10 - A photograph and diagram of the pump prototype for model validation including the in-line check valves with two single-acting cylinders.

Table 3 - The prototype pump bill of material with associated quantities and minor or major losses through the specific part

Part No.	Description of Part	Qty.	Major/Minor Losses Associated in Flow Through Part
1	66 cm L, 3.81 cm D Straight PVC Pipe	2	$f = 774127(45.6 * v)^{1.8886}$
2	3.81 D 90 Degree Elbow	4	$K_L = 0.9$
3	7.62 cm L, 3.81 cm D Straight PVC Pipe	4	$f = 774127(45.6 * v)^{1.8886}$
4	5.08 cm L, 3.81 cm D Straight PVC Pipe	4	$f = 774127(45.6 * v)^{1.8886}$
5	Swing Check Valve (for Approx.)	4	$K_L = 2.0$
6	35.56 L, 10.06 cm D Straight PVC Pipe	2	$f = 8123.1(324.3 * v)^{1.878}$
7	3.81 cm D Straight Pipe Tee	4	Branch Flow: $K_L = 2$ | Line Flow: $K_L = 0.9$

When evaluating the overall dynamics of the pumping system, a state space model was developed to analyze the system. While the head loss coefficients were parameters in this state space model, the true governing parameters of this equation are directly related to energy. In deriving the state equations, the total energy input into the pump must be linked to other state variables of the system. To perform this, the analysis must start with the work of the user in Equations 9 and 10:

$$\dot{W}_{user} = \frac{\rho \dot{V} g\left[(z_2 - z_1) + h_{L,total}\right]}{\eta_{pump}}$$

Equation 9 - Total Required Work of Pump Operator

$$\eta_{pump} = \frac{E_{out}}{E_{in}}$$

Equation 10 - Overall Mechanical Efficiency of the Pump

$$\eta_{pump} = pump\ efficiency\ (unitless)$$

The work of the user is directly related to the mechanical effiency (η_{pump}) as that efficiency relates the work done by the user to the useful work of the pump. As this thesis is analyzing only minor components, for ease of calculation the mechanical efficiency will be assumed to be 1. This physically represents that all work of the user is converted into useful work of the pump. The user input of power is tabulated in Table 4. The work from the user also is related to the frictional force between the seal and the pump cylinder.

Table 4- A table of age and average power in watts that user can provide during the time of operation (Fraenkel, 1986)

Age	Human power by duration of effort (in watts)					
Years	5 min	10 min	15 min	30 min	60 min	180 min
20	220	210	200	180	160	90
35	210	200	180	160	135	75
60	180	160	150	130	110	60

The force of friction is approximated as the amount of lubrication, the effect of a water-permeated seal and other factors affect the friction force. Laboratory experiments conducted at

The University of British Columbia defined the average frictional force from a treadle seal as approximately 15 N (Kroeker, 1989). For the purposes of computational analysis of the dynamics of the pump, the force from the seal was modeled as a constant frictional force of 15 N opposing the direction of the piston (Figure 11). The equation for the energy loss from this friction is Equation 11.

$$\dot{W}_{friction} = F_{friction} v$$

Equation 11 - Energy Loss from Force

$$v = velocity\ of\ the\ piston\ motion\ (m/s)$$

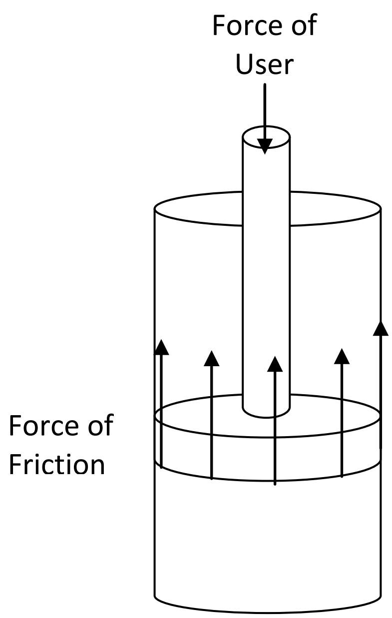

Figure 11 - An illustration of the mechanical forces of the user and friction forces on the piston rod

Given the force diagram of the pump, the characteristics of the system that are most useful to mathematically model are the location of the piston in the cylinder in the pump, and the piston's instantaneous velocity. Therefore, using state-space form the first state variable, x_1, may be defined as the location of the piston in the axis of the piston rod, with the datum being at the lowest position the piston can go in the cylinder, and the maximum stroke being 30.48 cm. The second state variable, x_2, is defined as the velocity of the piston rod in the axis of the piston rod. The derivative of x_2 is the acceleration of the piston rod which is governed by the user input (u_1) that will define the motion of the pump. This selection of state variable is convenient, as it is meaningful in the energy of the system, yet it's time derivative in state-space form is the time derivative of the first state variable:

x_1: *the displacement of the piston* (m)

x_2: *the velocity of the piston* (m/s)

$\dot{x}_1 = x_2$

To define the derivative of the second state variable (x_2) in the state-space model, the inputs of the pump cylinder area (A_{cyl} defined in Equation 12), flow-line area (A_{line} defined in Equation 13), and user input (u_1) must also be defined. To simplify the user input, u_1 is defined as the acceleration the user imparts upon the piston rod. The user input is the function of the acceleration constant and a sinusoidal function. The acceleration constant represents the maximum amplitude of acceleration provided to the piston. The sinusoidal function represents the sinusoidal nature of the piston motion required for proper operation. The dynamic model will output the necessary force needed by the user to operate the pump. These inputs are defined below:

$$u_1 = 0.01\, sin(\pi * \ time)$$

$$A_{cyl} = \pi \left(\frac{D_{cyl}}{2}\right)^2$$

Equation 12 - Area of the Pump Cylinder

$$A_{line} = \pi \left(\frac{D_{line}}{2}\right)^2$$

Equation 13 - Area of the Pipeline

The variables representing the area of the cylinder and the area of the pipeline will then be used to calculate the instantaneous velocity in the line in Equation 14, given the flow rate governed by continuity. Using these velocities, dimensionless values derive the flow in the pipe. The most important dimensionless value to derive the flow conditions is the Reynolds number. Given the Reynolds number of the flow in Equations 16 and 17, the Colebrook model for friction factor provides a framework in Equations 18 and 19 to derive the head loss in a pipe. The overall head loss of the piping network can also be determined assuming the mechanical efficiency of the pump is 100%, or that all of the user's power is converted to useful power for the flow. Given the derived friction factor, input power, and Reynolds number of the flow the instantaneous volumetric flow rate of the pump for the specific time can be derived. The volumetric flow rate is the most desirable output of this mathematical model as it provides a useful calculation for pump sizing:

$$v_{line} = \frac{\dot{V}}{A_{line}}$$

Equation 14 - Velocity of Flow in the Pipeline

$$v_{cyl} = \frac{\dot{V}}{A_{cyl}}$$

Equation 15 - Velocity of Flow in the Pump Cylinder

$$Re_{line} = \frac{\rho \, v_{line} D_{line}}{\mu}$$

Equation 16 - Reynolds Number of Flow in the Pipeline

$$Re_{cyl} = \frac{\rho \, v_{cyl} D_{cyl}}{\mu}$$

Equation 17 - Reynolds Number of Flow in the Pump Cylinder

$$f_{line} = \left(\frac{1}{-1.8 log \left(\frac{6.9}{Re_{line}} + \left(\frac{\frac{0.0000015}{D_{line}}}{3.7} \right)^{1.11} \right)} \right)^2$$

Equation 18 - Friction Factor of Flow in the Pipeline

$$f_{cyl} = \left(\frac{1}{-1.8\ log \left(\frac{6.9}{Re_{cyl}} + \left(\frac{\frac{0.0000015}{D_{cyl}}}{3.7} \right)^{1.11} \right)} \right)^2$$

Equation 19 - Friction Factor of Flow in the Pump Cylinder

$$\eta_{pump} = 1$$

$$\dot{V} = \pi \left(\frac{D_{cyl}}{2} \right)^2 x_2 = Q_{line}$$

Equation 20 - Derived Instantaneous Volumetric Flow Rate of the Pump

The newly derived velocity of the flow in the line can be coupled with the derived friction factor from the Colebrook equation to yield head loss in each individual component in Equations 21 through 29. This head loss can then summed in Equation 30 and be used to calculate the total required power for operation (Equation 31), given the input condition of u_1. The assumed head loss for each connection is based on the values and empirical relationships in Table 3. The head loss calculation assumes a similar architecture of the prototype that appears in Figure 10 in order to derive an overall system flow rate. This includes an intake diameter of 1.91 cm, expanding to a flow diameter of 4.09 cm. Subsequent to the intake, the flow then passes through a pipe tee to split the flow between the two cylinders, each cylinder having an intake pipe of equal diameter of 4.09 cm with a length of 66 cm. The flow then passes up each cylinder and through two elbows to another pipe termed "short pipe 1" of equal line diameter of 4.09 cm with a length of 7.62 cm. The flow then enters the first check valve. Next, the flow passes to the pipe termed "short pipe 2" with diameter of 4.09 cm and length 5.08 cm, and then into the tee leading to the cylinder. The location of the piston rod (x_1) governs the length through which the flow passes. This configuration is displayed in the previously shown Figure 10. Then the flow passes back through the tee, through an identical check valve and "short pipe 1" into the final stage tee and into the discharge line with similar diameter ratios of the intake. The head loss and input power of each component is calculated as:

$$h_{l_{intake\ connector}} = \frac{\left(1.05\left(1-\frac{0.01905^2}{0.040894^2}\right)^2 \ v_{line}^2\right)}{(2g)}$$

Equation 21 - Head Loss through Intake Reducer

$$h_{l_{intake\ tee}} = \frac{2.0\left(\frac{\dot{V}}{D_{line}}\right)^2}{2g}$$

Equation 22 - Head Loss through Intake Pipe Tee

$$h_{l_{intake\ pipe}} = f_{line}\left(\frac{0.66}{D_{line}}\right)\frac{v_{line}^2}{2g}$$

Equation 23 - Major Loss, Head Loss through Pipe Part No. 1

$$h_{l_{elbow}} = \frac{0.9\ v_{line}^2}{2g}$$

Equation 24 - Head Loss through 90 Degree Elbow

$$h_{l_{shortpipe1}} = \frac{f_{line}\left(\frac{0.0762}{D_{line}}\right)(v_{line}^2)}{2g}$$

Equation 25 - Major Loss, Head Loss through Pipe Part No. 3

$$h_{l_{shortpipe2}} = \frac{f_{line}\left(\frac{0.0508}{D_{line}}\right)(v_{line}^2)}{2g}$$

Equation 26 - Major Loss, Head Loss through Pipe Part No. 4

$$h_{l_{check\ valve}} = \frac{2.0v_{line}^2}{2g}$$

Equation 27 - Head Loss through a Metal Gate Check Valve

$$h_{l_{pump\ tee}} = \frac{2.0v_{line}^2}{2g}$$

Equation 28 - Head Loss through a Pump Tee into the Pump Cylinder

$$h_{l_{pump\ cylinder}} = \frac{f_{cyl}\left(\frac{x_1}{D_{cyl}}\right)(v_{cyl}^2)}{2g}$$

Equation 29 - Major Loss, Head Loss through Pump Cylinder Pipe Part No. 6

$$h_{l_{total}} = 2h_{l_{pump\ tee}} + h_{l_{pump\ cylinder}} + h_{l_{intake\ connector}} + h_{l_{intake\ tee}} + h_{l_{intake\ pipe}} + 2\,h_{l_{elbow}} + 2h_{l_{shortpipe1}} + 2h_{l_{shortpipe2}} + 2h_{l_{check\ valve}}$$

Equation 30 - Total Head Loss of Prototype Treadle Pump for Each Cylinder

$$\dot{E} = \rho g \dot{V}\left(\frac{v_{line}^2}{2g} + h_{l_{total}} + \Delta z\right)$$

Equation 31 - Total Required Power to Operate Pump with Provided Head Loss and Depth of Well

Given the calculated head loss and instantaneous power required to operate the pump, the derivative of the state variable x_2, or the acceleration of the piston rod, can be defined as:

$$\dot{x_2} = 0.75\, sin(\frac{\pi}{0.4} x_1)$$

The constant 0.75 was derived iteratively using the OpenModelica code. This constant was used to provide an acceleration that yields a realistic output power, while also providing a useful output flow of the pump. The code outputs consist of both the flow rate of the pump ($\dot{V}$) and the power required from the operator ($\dot{E}$).

$$y_1 = \dot{V}$$

$$y_2 = \dot{E}$$

The code and output graphs can be found in Appendix 2. The average user power input stabilized at approximately 385 Watts with an average flow rate of .0024 cubic meters per second (144 liters per minute), assuming four metal gate valves are used in the treadle pump instead of the commercial valve.

3.5 Engineering Design Theory

3.5.1 Part Count Reduction Theory

The theories of part reduction in engineering design are derived from systems engineering principles to reduce overall systems costs, enhance systems reliability, or enhance overall system performance. Reducing the number of parts in a systems design can enable adoption diffusion in many ways. First, a lower overall part count, specifically a lower unique part count, can enhance the manufacturability of a design by reducing the amount of tooling and manufacturing flexibility required to effectively launch a product. In the developing world, producing a small part count design comprised of locally manufactured parts is of utmost importance in the consideration of an appropriate design. If parts are not locally available in the event of a mechanical failure, the design is rendered obsolete.

Part count reduction has been analyzed by three specific design methodologies, the Theory of Inventive Problem Solving (TIPS), Axiomatic Design, and Highly Optimized Tolerance. The first is the larger focus for this thesis, as it pertains mostly to the specific part reduction in check valve technology.

The design theory TIPS (also abbreviated as TRIZ) is governed by the "law of ideality". This law views design as a development of technology towards an ideal state without the need for governance, where the design "requires no material to be built, consumes no energy, and does not need space and time to operate" (Frey, 2006) as stated by the theory's inventor, Alschuller. The theory focuses on three major aspects of technology design: remove components that are not needed for operation, remove components that can be replaced with a more useful action of the original system, and remove components and assign the action to be actuated by the environment. The theory calls for the evaluation of the component’s actions to identify realistic alternatives from the system's environment to perform a task in normal operation. In this way, the theory acts to remove components that might pose redundancy in the system itself. TIPS design theory is sometimes difficult to apply to systems. However, it is utilized in the part reduction of sufficiently matured products that might have been fully analyzed with other design methodologies, such as check valve technology (Frey, 2006).

In the development of commercial check valve technology applicable to treadle pumps, the replacement of commercial seals and spring actuation is productive in cost reduction. The complex spring and seal actuation of commercially available valves allows for very reliable function, but this reliability increases the cost substantially. These cost increases may be justified in many first-world applications; however, in developing world applications, a less reliable functionality may be acceptable with a significant cost decrease. The part count can be effectively reduced to one spring by replacing the multiple springs that aid in the self-alignment of the commercial seal and instead harnessing the environment to align the seal. This new type of actuation must be present in the new design to replace current technology.

3.5.2 Engineering Design Process of a Check Valve for Developing World Application

Using the engineering design process to develop an appropriate check valve is essential to identify technical specifications of the technology and define the valve's architecture. This process seeks to highlight the technical and non-technical shortcomings of competitive check valve technology and determines a technically feasible design that will fit within the assumed treadle pump architecture.

3.5.2.1 Concept Development

In the field of check valves, the most commonly used design is termed the "swing check" valve. This design primarily functions similar to a flap valve in that the swing check valve is a concentric seal which opens with positive flow and closes with negative flow with respect to the intended flow direction. Often the valve will close with a spring-assisted hinge to reduce closing time and create a tight seal with small backpressure. Swing check valves are ideal in large piping systems. The TIPS method, on the other hand, would suggest that using a hinge with a spring is unnecessary because the spring alone can guide the sealing mechanism even without a hinge. The spring can be removed from the check valve design leaving just the hinge, but this has negative consequences for low pressure sealing because flow will escape through the lightly sealed swing gate.

Using TIPS in this way, customer needs do not exist in the traditional sense. Instead of seeking end-user input, customer needs for the sub-component are derived from the needs of the system and product specifications. Customer needs have been studied and tabulated in Table 5.

Table 5: The mapping of "Qualitative Engineering System Needs" of the subcomponent to the product specifications related to that need

Qualitative Engineering System Needs	**Product Specifications**
The product must be safe to use with agricultural-use fresh water	The selected materials should not leach any dangerous chemicals or culture organisms that would damage crop health
The product must have less head loss than the commercial valve to prevent increased exhaustion	The tested head loss for the designed valve must be less than the tested for the commercial valve
The product must reduce the cost of the treadle pump	The price of the designed valve must be less than commercial valves as well as Sylivant's valve.
The product must have a rapid closure when reverse flow begins	Valve closure is < 0.2 seconds in normal operating reverse flow velocity.
The produce must not fail in less than 1 million cycles	Seal material and mechanical assist must be rated to last 1 million standard cycles with a safety factor

Each specific need carries a different level of importance in the overall design. To account for these differences in the qualitative engineering system needs, the needs were ranked using the analytic hierarchy process (AHP). The AHP analyzes each need's relative importance to each other and derives a percentage weighting of each need. Each weighting was defined based on knowledge extracted from the literature review. The AHP is displayed in Table 6.

Table 6: The Analytic Hierarchy Process for the evaluation of the needs related to the redesign of a check valve

Criteria	Safety	Head Loss	Cost	Rapid Closure	Durability	**Total**	**Weighted**	**%**
Safety	1.00	0.25	0.5	0.33	0.4	2.48	0.06	6
Head Loss	4	1.00	0.2	2	4	11.2	0.26	26
Cost	2	5	1.00	1	3	12	0.28	28
Rapid Closure	3	5	1	1.00	2	12	0.28	28
Durability	2.5	0.25	0.33	0.5	1.00	4.58	0.11	11

The AHP pinpoints the most critical design criteria which include: rapid valve closure in reverse flow conditions, a lowered cost resulting in a reduced treadle pump cost, and the reduced head loss which requires less work by the operator for similar output flows. The secondary requirements are durability and safety of the component. By understanding the relative weight of each need, the design can focus on a low head loss, cost effective, and rapid closing design that is durable and meets safety requirements.

To design a check valve, an engineer must first evaluate all necessary mechanical functions of that valve. The functions can be isolated and reassembled from the input to the output of the system, as shown in Figure 12. The diagram within the black-box links the internal actions of the product that translate the received input to the desired output. For instance, if the check valve is operating properly, the received input would be positive or desirable flow and the valve should act like a straight pipe. In other words, ideally, the minor losses of the product would be zero and the only loss would result from the major losses of a homogenous straight pipe. When that same valve receives an input of reverse or undesirable flow, the valve should experience a rapid closure and seal. This closure will ideally prevent all flow in zero seconds. Since that is a physically unattainable value, reducing the time from open to closed is an important design factor. A problem decomposition diagram links inputs mechanically to the desired output. The problem decomposition specifically displays the material, energy, and signal flows within a system. A thin line is representative of energy transfer, storage, or conversion. A thick line represents the movement of a material. The dashed line signifies the introduction of a control or feedback signal within the system (Ulrich & Eppinger, 2008).

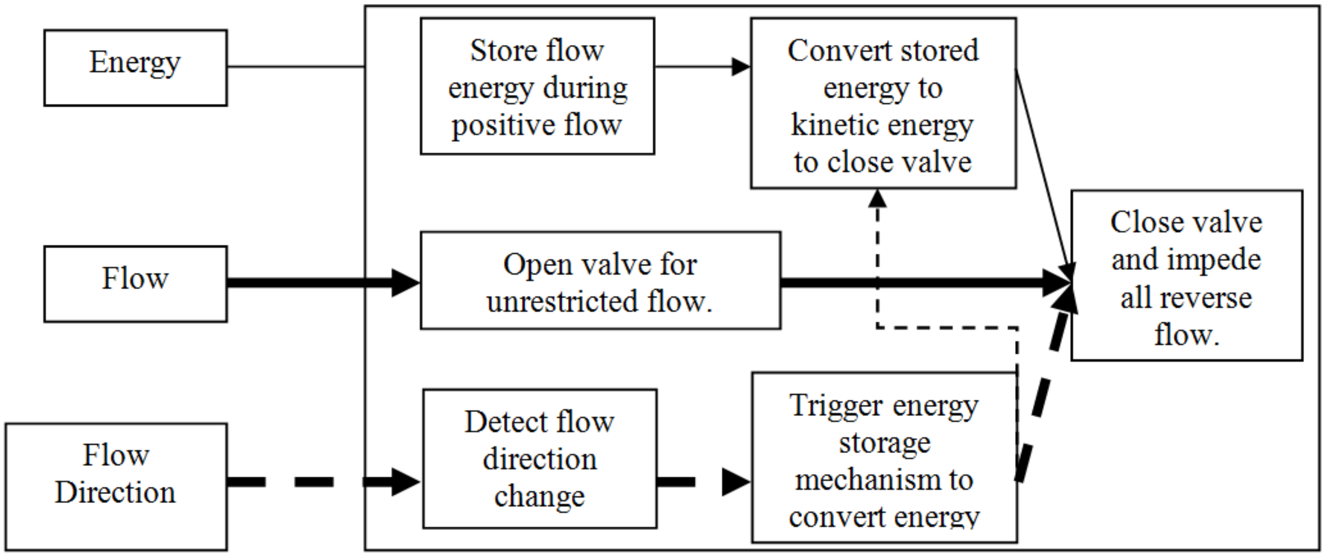

Figure 12- Function diagram of a treadle pump check valve for use in developing world applications displaying both the overall system and subsequent sub-functions

The problem decomposition suggests that the flow itself can act as a signal to activate the valve. This action, as a mechanical signal, releases the energy of the storage mechanism to close the valve. For some swing valves, the flow itself cannot force the gate inside the valve to close the gate, but the lack of positive pressure will allow the spring-hinge to do so. These valves generally have a higher rate of minor losses than others because of the swing gate's flutter. The flutter and the tendency to swing back into the flow induce local wakes and pressure changes that produce unpredictable valve head loss characteristics.

To prevent the adverse effects of valve flutter in the pipeline flow, other types of valves have been investigated that incorporate linear springs. The linear spring is seated in-situ within the line, and the spring closes the valve when no forces are active. The force that opens the valve is positive flow. A key specification of a check valve is the amount of positive flow pressure required to open the valve, known as the cracking pressure. The minimum operating flow pressure for competitive commercial technologies is between 0.5 and 5 PSI (3.5 kPa to 35 kPa). This technology is much better suited for predictable head loss, cost, and predictable rapid closure because the pressure's force on the valve is related to the designed area of the valve. Therefore the deflection of the spring can be known for certain flow pressures, and the valve can be predictably designed to operate effectively at a nominal line pressure. This predictability is a positive attribute; however the head loss of spring valves is higher than that of swing valves.

To compare current technologies and generated solution concepts, a list of general concepts must first be compiled and scored according to the needs of the valve. The scoring matrix is commonly called a concept scoring matrix. The concepts to be evaluated are: rubberized flap valves, PVC or metal gate valves, single-spring valves, and multi-spring valves. These four general concepts are the most common check valve architectures for the line-sizes analyzed in this thesis. A scoring matrix using empathic principles aids in the determination of the most appropriate valve for treadle pump application. The scores applied to each category are weighted based on the previous AHP. The concept scoring matrix can be seen in Table 7. The concept scoring matrix shows that although a multi-spring design is the most functional for the technology, the costs associated with the improved head loss characteristics and rapid closure far outweigh their benefits for the target user. Empathic design helped to identify that although flap valves are cheaper than single-spring rubber valves they also incur undue maintenance issues. By applying the principles of empathic design to the AHP, the concept scoring matrix points to the single-spring rubber valve as the most appropriate technology for development within the context of the application.

Table 7- The concept scoring matrix for the development of an appropriate check valve in developing world treadle pump technology

Check Valve - Concept Scoring Matrix									
Note: Ratings are included on a 1-10 scale, with 1 as the least desirable scoring.									
		Rubberized Flap Valves		PVC or Metallic Gate Valves		Single-Spring Rubber Valves		Multi-Spring Rubber Valves	
	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Safety	0.06	*10*	0.6	6	0.36	9	0.54	9	0.54
Head Loss	0.26	*7*	1.82	4	1.04	7	1.82	9	2.34
Cost	0.28	*6*	1.68	2	0.56	9	2.52	4	1.12
Rapid Closure	0.28	*3*	0.84	5	1.4	8	2.24	9	2.52
Durability	0.11	*2*	0.22	10	1.1	9	0.99	8	0.88
Total Score		5.16		4.46		8.11		7.4	
Continue?		***No***		***No***		***Develop***		***No***	

As the concept scoring matrix selected the single-spring rubber valves as the most appropriate, there are many design steps to derive a valve of this type that functions properly and maintains a minimal cost to the end-user. The two main mechanical components comprising this type of valve are the spring and the sealing mechanism. The sealing mechanism engages via the force of the spring, and lodges the seal into a concentric orifice and fully impedes the flow. Therefore the design of an appropriate spring and seal, given the boundary conditions of the dynamic model is necessary.

3.5.2.3 Spring Design

A spring is defined as a set of mechanical components which "provide a force over a significant deflection and/or store potential energy" (Norton, 2011). Springs, independent of their design, inherently have a spring rate (k), which defines the ratio of force and corresponding deflection of that spring. For a spring with a linear spring rate, the following Equation 32 and 33 is true:

$$k = \frac{F}{y}$$

Equation 32 - Spring Rate (Constant) as a Function of Force and Deflection

$$k = \frac{d^4 G}{8D^3 N_a}$$

Equation 33 - Spring Rate as a Function of Spring Design Parameters

$G = shear\ modulus\ of\ the\ material\ (Pa)$

$d = wire\ diameter\ (m)$

$D = coil\ diameter\ (m)$

$N_a = active\ coils\ (unitless)$

$k = spring\ rate\ \left(\frac{N}{m}\right)$

$F = force\ (N)$

$y = deflection\ (m)$

This relationship connects the pressure force and corresponding deflection, given a known spring rate. The relationship also provides design parameters for the spring that relate to the spring's rate of deflection. The static pressure of the flow induces a force on the frontal area of the designed seal. The product of these values corresponds to the force acting on the spring. Also, given that minor losses through the valve decrease as flow area expands, it is favorable to have a spring with significant deflection. This increased deflection allows the valve to increase the active flow area when positive flow pressure is induced to the valve. Conversely, when negative pressure acts on the valve, the area should go to zero as the spring decompresses and seats the valve.

The design constraints on the spring are related to operational life and deflection. The operational life should be at minimum able to operate past one million cycles. Given the boundary conditions of pressure and therefore force on the spring, there is enough information to design the suitable spring. From the OpenModelica modeling of the pump, the highest pressures of the flow equate to 66 kPa, and the frontal area of a rubber valve would be approximately 2 cm (0.8") if an economically feasible rubber furniture cover is utilized, as pictured in Appendix 3 - Drawing 5. This valve is selected due to its conical nature, low price, and ability to fit within most fittings and bushings of a 3.81 cm line size. The force over that area would then be 21.83 N. Due to the limited length of the check valve, the amount of deflection must be chosen by the designer. This length is preliminarily chosen to be 1 cm for purpose of calculation. Therefore, this force should displace the spring approximately 1 cm to have enough space to increase the flow area around the valve, but be small enough to quickly reseal the valve during backflow. This deflection constraint can either be addressed by an increased spring rate or, alternatively, a mechanical device to limit the deflection to 1 cm. The desired spring rate can then be calculated using the above formula to derive a spring rate (k) of approximately 2182 N per meter. Using this k value, the rest of the parameters of the spring may be defined to design the spring.

Although this high spring constant would work, the resulting function of the spring would not be desirable for the flow because the spring would only unseat the valve under the highest pressures in the line. The optimal spring would have a minimal spring constant that allows the flow to fully compress the spring under lower pressure. Therefore the spring, more appropriately, will be designed with a spring constant specification of 32 N per meter. This will make the cracking pressure much lower; however, this will significantly increase the torsional stresses on the spring. The increased in torsional stresses effectively reduce the lifecycle of the spring when the cyclical high pressure forces act on the spring during operation. To design this spring, the spring gauge will be 0.066 cm (0.0260") diameter; it will have a length of 5.84 cm

(2.30"), a coil diameter of 1.697 cm (0.668"), and possess 12 active coils effectively resulting in a spring with a spring constant of 32.5 N per meter. With these parameters, a fatigue analysis can be conducted using Equations 34 through 43.

$S_{ut} = Ad^b$

Equation 34 - Ultimate Tensile Strength of the Material

$A = coefficient\ of\ steel\ (MPa)$

$d = wire\ diameter\ (d)$

$b = exponent\ of\ steel\ (dimensionless)$

For a steel of the given wire diameter, A229 Oil Tempered Steel is the most likely material to use providing:

$A = 1831.2\ MPa$

$d = 0.66\ mm$

$b = -0.1833$

$S_{ut} = 1976\ MPa$

$S_{us} \cong 0.67 S_{ut}$

Equation 35 - Calculated Ultimate Shear Strength

$S_{us} \cong 1323.9\ MPa$

$S_{ut} = calculated\ ultimate\ tensile\ strength\ of\ the\ material\ (MPa)$

$S_{us} = calculated\ ultimate\ shear\ strength\ of\ the\ material\ (MPa)$

$S_{es} = calculated\ endurance\ strength\ of\ the\ material\ (MPa)$

$S_{fw} = calculated\ fatigue\ strength\ of\ the\ material\ (MPa)$

$S_{ew} = endurance\ limit\ of\ the\ material\ (MPa)$

$C = spring\ index\ (dimensionless)$

$\tau_{max} = maximum\ torsional\ stress\ on\ the\ spring\ (MPa)$

$\tau_{min} = minimum\ torsional\ stress\ on\ the\ spring\ (MPa)$

$F_{max} = maximum\ force\ on\ the\ spring\ (MPa)$

$F_{min} = minimum\ force\ on\ the\ spring\ (MPa)$

$K_w = Wahl's\ Factor\ (dimensionless)$

$N_{fs} = safety\ factor\ for\ torsional\ fatigue\ (dimensionless)$

The fatigue strength for the wire material (assuming an unpeened specimen) can be calculated:

$$S_{fw} \cong 0.33\ S_{ut}$$

Equation 36 - Calculated Fatigue Strength of the Material

$$S_{fw} \cong 652\ MPa$$

$$S_{ew} \cong 310\ MPa\ (for\ unpeened\ springs)$$

Equation 37 - Endurance Limit of the Unpeened Material

$$S_{es} = \frac{0.5(S_{ew}S_{us})}{S_{us} - 0.5S_{ew}} = 175.45\ MPa$$

Equation 38 - Calculated Endurance Strength of the Material

$$C = \frac{D}{d} = 25.69$$

Equation 39 - Spring Index

$$\tau_{max} = \frac{\left(1 + \frac{0.5}{C}\right) 8FD}{\pi d^3}$$

Equation 40 - Maximum Torsional Stress on the Spring

$$F_{max} = 21.83\ N$$

$$F_{min} = 1.0\ N$$

$$\tau_{max} = 2.257\ \mathrm{MPa}$$

$$K_w = \frac{4C - 1}{4C - 4} + \frac{0.615}{C} = 1.054$$

Equation 41 - Wahl's Factor

$$\tau_{min} = K_w \frac{8F_{min}D}{\pi d^3} = 0.1069\ MPa$$

Equation 42 - Minimum Torsional Stress on the Spring

$$N_{fs} = \frac{S_{es}(S_{us} - \tau_{\max})}{S_{es}\tau_{\max} + S_{us}\tau_{\min}} = 431.396$$

Equation 43 - Safety Factor for Torsional Fatigue

This torsional safety factor in Equation 43 of over 400 provides a clear indication that this spring should last during the average life of a treadle pump, and likely will not be the cause of failure for the valve. The stresses experienced by the spring could dramatically increase if the spring buckles during operation. Therefore a spring stabilizing component is advantageous to prevent any failures due to buckling, as well as to minimize deflection to a desirable quantity. Buckling may also permanently unseat the valve, rendering the valve permanently closed or open. This permanently unseated valve is an effective mechanical failure of the system as without the seal of the check valves, the pump can no longer obtain suction to draw water from a subsurface.

3.5.2.4 System-Level Design

The check valve system, given the validated spring selection, must be able to fit into a 3.81 cm (1.5") intake and discharge line without additional parts. To design the system, the physical boundaries of the connectors must be provided to design a valve that can link the treadle pump piping network at the intake and discharge lines. Standard PVC fittings are the selected parts for this design and are assumed to be easily obtained. Therefore, local manufacturers can rely solely on machining and assembling the standard parts, which is much less burdensome than producing custom PVC fittings in the developing world. There are standard fittings that can conjoin the valve to the intake and discharge lines and provide an exoskeleton for the valve internal. These fittings are called couplings, and one will be used for each pipe. The seal, valve seat, spring, and spring stabilizer can all be placed within this exoskeleton. The selected part for the prototype was a LASCO 1 1/2" straight coupling Model #429015RMC (Appendix 3 - Drawing 7). This part can be adhered to the intake and discharge lines via a method known as solvent welding. This method uses common chemicals to locally melt the PVC part to be conjoined.

With the couplings on the intake and discharge ends of the valve, the internals of the valve may now be selected. On the upstream portion, or from the intake pipe, the valve and valve seat must align to open during positive flow. For the valve seat, the LASCO 1 1/2" x 1" Schedule 40 bushing was selected to perform this function as its internal diameter deceases to allow for a conically shaped valve to seat (Appendix 3 - Drawing 6). A conically shaped valve would not work for the 3.81 cm (1.5") diameter intake/discharge line, but this diameter reduction within the fitting allows for the shape to concentrically seal when fully seated. When positive flow occurs, it allows the valve to unseat and retract for flow to pass.

Next a component must be selected to seat the spring beneath the conical valve (Appendix 3 - Drawing 5). As discussed in the spring design, a stabilizing component must also be placed within the spring column to prevent the spring from buckling. The selected component for this function is a wooden dowel rod (Appendix 3 - Drawing 3) cut to 3.12 cm (1.23") with a diameter of 1.16 cm (0.457"), slightly smaller than the internal diameter of the spring. This smaller diameter allows for swelling of the wood in response to water saturation such that its swelled diameter approximates that of the internal spring diameter. The spring and dowel are seated within a machined end cap (Appendix 3 - Drawing 5) with an internal diameter sufficiently large to fit the spring and swelled dowel. The end cap is machined with a taper that allows the cap to be concentrically adhered within a bored cylinder within a standard LASCO 1 1/2" x 3/4" bushing (Appendix 3 - Drawing 4). The LASCO bushing is unique as it has a center bore attached to the outer wall by four extruded legs of PVC. This configuration allows flow around the central bore with a total flow diameter of approximately 2.66 cm^2 (0.412 in^2). Although this flow area is much smaller compared to a straight pipe of the same diameter, many check valves' increased head losses result from this required reduction in flow area. This resulting head loss will be derived in later testing of the prototype. The LASCO bushing has a hex-end and cannot naturally fit within the circular pipe, so a simple saw cut of the end of the bushing according to the drawing is required (Appendix 3 - Drawing 4). However, the tooling necessary is quite minimal for this alteration of the fitting.

This overall design was placed into the operating prototype built for testing and sealed properly during the operation. After and during operation, a Milwaukee fiber-optic camera as seen in Figure 12 was used to visualize the seating of the valve in line. A picture of the seated valve can be seen in Figure 13 and 14.

Figure 13 - Picture of the valve seating monitor via the Milwaukee fiber-optic camera

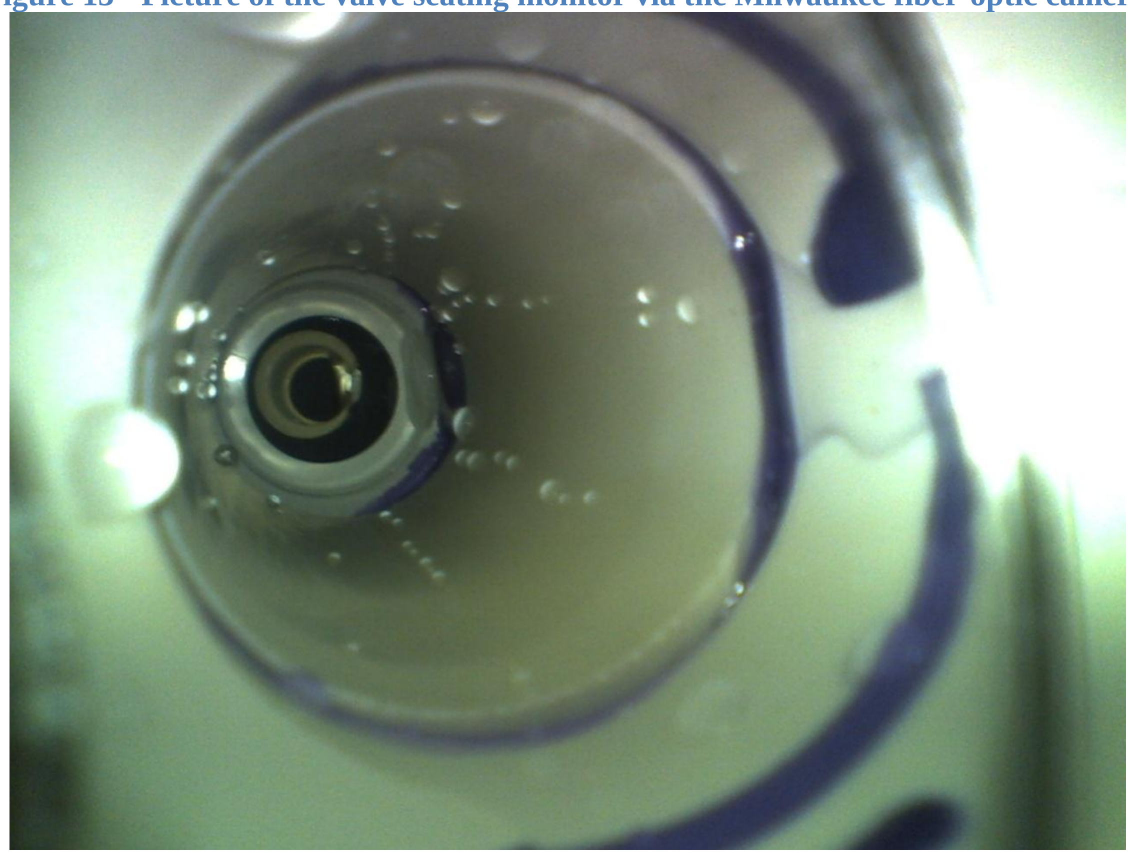

Figure 14 - An intra-pipe picture of the seated valve during operation of the prototype treadle pump with the developed valve

These seven unique components (eight overall components) comprise the assembly (Drawing 1) for the proposed check valve. Purchasing these components at retail prices from Lowe's Companies, Inc. came to a total of $3.48, versus the cost of the similar commercial valve of $14.99, a cost reduction of 76%. This greatly reduced cost to the end-user could be lowered further by bulk purchasing components versus the purchasing of individual pieces. However, the retail price is the most appropriate to compare against the retail price of the commercial valve as no bulk order pricing information is available from retailers currently. The cost is not inclusive of any tooling costs for purchase of saws or solvent welding chemicals. However, the small costs of tooling and chemicals over a large scale production of treadle pumps would be easily absorbed by the reduction in the costs of standard fitting purchased in bulk quantities.

Table 8 - A bill of materials and overall retail cost of the prototyped alternative valve minus any tooling or manufacturing costs

System Item No.	Description	Quantity	Cost	Total Cost
1	2.3565" Compressed Spring, 0.0260" Gauge Spring Steel	1	$0.03	$0.03
2	Balsa Wood Dowel Rod, Diameter 0.457"	1	$0.03	$0.03
3	Machined 3/4" Schedule 40 - PVC 1 End Cap	1	$0.35	$0.35
4	1 1/2" x 3/4" Schedule 40 - PVC 1 Bushing	1	$0.23	$0.23
5	7/8" I.D. Rubber Chair Tip - Item #: 246501 - Model #: 4441595N	1	$0.57	$0.57
6	1 1/2" x 1" Schedule 40 - PVC 1 Bushing	1	$1.06	$1.06
7	1 1/2" NSF Schedule 40 - PVC 1 Straight Coupling	2	$0.61	$1.22
			Total Cost of Prototype Valve	$3.48

4.0 Experimental Data and Procedure

4.1 Seal Testing Procedure

To perform the analysis of pump cylinder seal integrity, a testing set-up was developed to measure a declining column of water in a 7.62 cm (3") PVC pipe over time. Initially, at the highest head, the leakage rate should be at its highest, as the amount of leakage in the seal is related to the pump's instantaneous pressure. From the graphs in Figures 20 through 22 derived from this testing, the flow rate across the seal of the pump cylinder at a certain pressure may be derived. It can be assumed that the water that flows across the pump cylinder seal and discharged from the top of the cylinder is lost from the pump's operating discharge flow rate, and may also be considered negligible for normal pump operating conditions.

The experiment was conducted with a 7.68 cm (3") diameter PVC Schedule 40 pipe. The piston-plunger was either hand-cut, with imperfections, or machined with a lathe to be exactly 0.2 mm (0.008") less than the inner-annulus diameter of the 7.68 cm (3") Schedule 40 pipe, providing for a very tight press fit with the low-density polyethylene seal. The leather cup seal was constructed of 1.6 mm (0.0625") leather obtained from a craft store for sewing use. The machined piston-plunger had a radius reduced by 3.2 mm (0.125") for the leather clearance on each side, and 0.08 mm (0.003") to allow for press-fit clearance. After the seal was press-fit into the cylinder, the cylinder was filled with a column of water and timed measurements were taken as the water level eclipsed each graduation. In Figures 20 through 22, the experimental data can be viewed. For tabulated values from experiments, refer to Appendix 1.

4.2 Valve Testing Procedure

The check valve implementation has two primary factors that can be tested to assure the operation of the pump. First, the valve must be tested to stop back flow, or flow opposite to the intended flow direction. This test can be quite simple. A normal operating check valve stops back flow at low pressures. And as system pressure increases, due to the lowering plungers in the cylinders, the valve fully seats to assure no flow will occur between the valve and the wall. This qualitative test confirms the ability of the valve to act correctly as a one-way valve. As the tested valve performs correctly as a one-way valve, the next test must be to evaluate the head loss through the valve under normal flow conditions. The head loss is a function of flow rate through the pipe or valve. Therefore a range of flow rates through the valve must be tested to evaluate the head loss under each flow rate. A testing set-up was utilized for head loss calculation to evaluate this loss through a straight 3.81 cm (1.5") pipe, a commercial check valve made by American Valve Company, and the valve developed for this thesis. The testing procedure has been adapted from Professor John Cimbala's fluids laboratory to accommodate the needs of testing the valve.

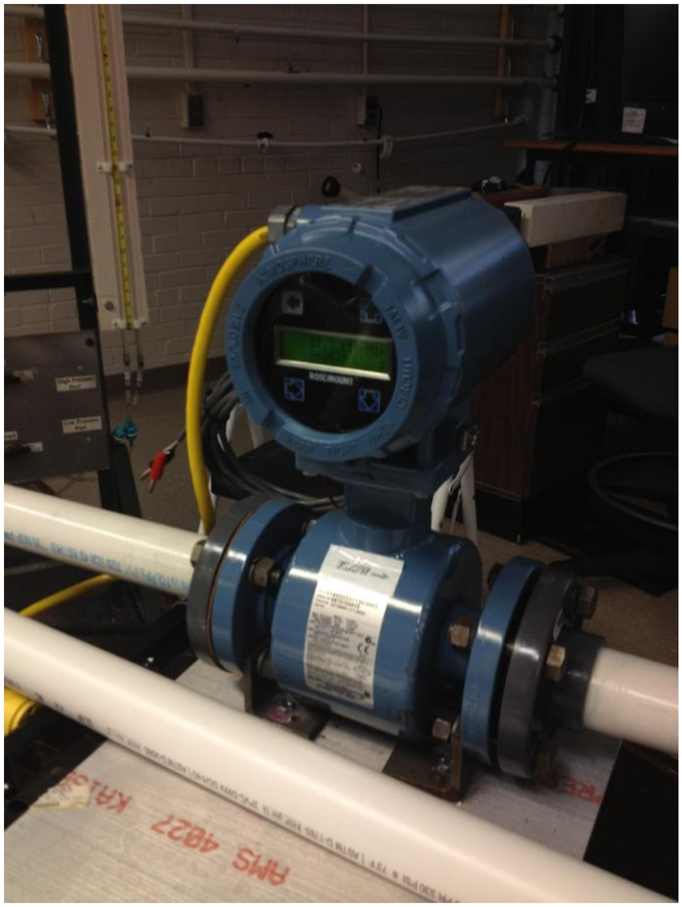

Figure 15 - A picture of the flow meter during the head loss test of the commercial valve

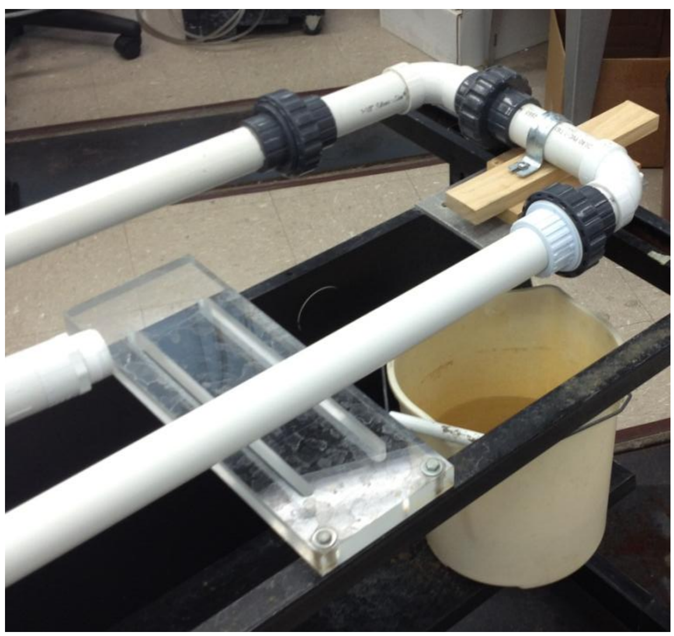

Figure 16 - A picture of the unions used to attach the specimen to the testing rig

The testing set-up uses a tank reservoir with an electric submersible pump with capabilities to pump up to 90 liters per minute of water past an in-line magnetic resonance flow-meter, and through a 180 degree turn to a test section. The magnetic resonance flow-meter, shown in Figure 15, non-obstructively analyzes the flow through the line, allowing for minimal loss through the meter. The flow meter used has an accuracy of 0.1 liters per minute. The test section is fitted with union disconnects on each side to attach a test specimen, shown in Figure 16. At the end of the second union disconnect, a globe valve exists to regulate discharge flow back into the reservoir. Within the test specimen are static pressure taps built into the line at lengths determined so that the flow may re-develop after the circulation from the 180 degree bend. To greater simplify the task of measuring the pressure differential and recording this data, the pressure taps are attached to an electronic pressure transducer. The Validyne pressure transducer utilizes a stainless steel diaphragm within the chamber. The high pressure tap pressurizes one side of the diaphragm, and the low pressure side pressurizes the other side. The high and low pressures are associated with the upstream pressure and downstream pressure from the valve, respectively. When the flow rate through the pipe increases, the pressure drop associated with the major losses of the piping and the minor losses of the valve reflect in a pressure differential across the diaphragm. The pressure differential induces small deflections in the diaphragm, which are measured electronically by the Validyne transducer and converted to an output DC voltage between -2 and 2 volts. The transducer's voltage signal is interpreted by a data acquisition system made by National Instruments' DAQ I/O board, and rendered graphically by the LabView software suite. A graphical representation of the testing set-up appears in Figure 14. A flow pump is embedded in the reservoir to generate a flow and head pressure in the system. The specific test section is attached by quick connects or unions to the test stand, and a flow control valve regulates the flow to help develop the entire head loss curve for each valve (Cimbala, 2012).

Figure 17 - A picture of the overall testing rig set up using the commercial valve

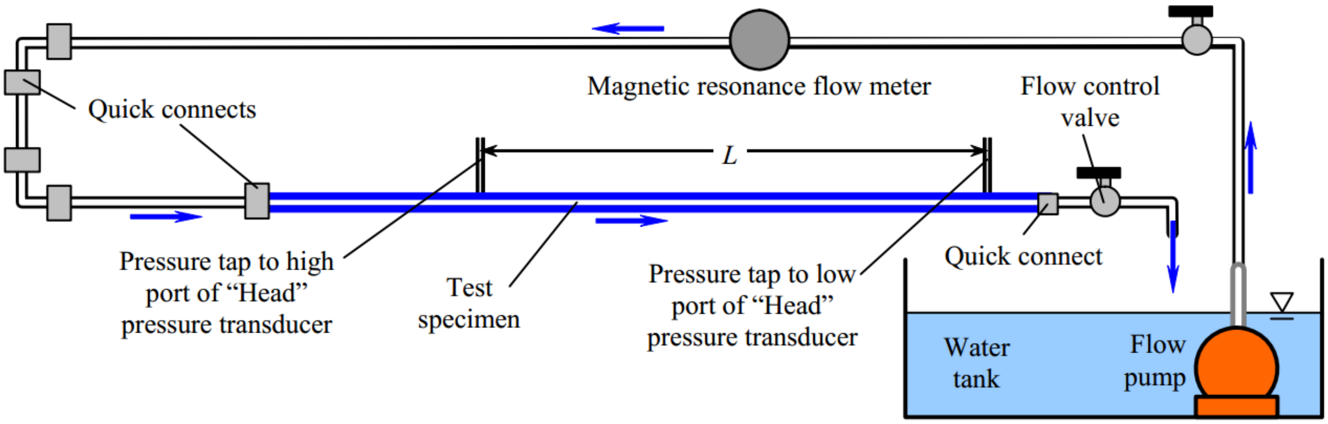

Figure 18 - A schematic of the head loss test set-up from The Pennsylvania State University's Fluid Flow Laboratory (Cimbala, 2012)

The test specimens were attached via a union to the testing rig and had a distance of 129.54 cm (51") between the upstream and downstream pressure taps. The valves were placed at identical locations downstream of the connection to provide similar flow conditions for each test. The valve selected as the standard commercial test valve is the American Valve 1.5" NSF check valve Model #79653 and is pictured in Figure 19. The prototyped version of the designed valve was the second set-up. Each version was tested between the lowest and highest obtainable flow rates. The lowest obtainable flow rate was the flow rate with a resulting static pressure below the valve's cracking pressure. The highest obtainable flow rate was the maximum flow the submersible pump could provide based on the head loss in the line.

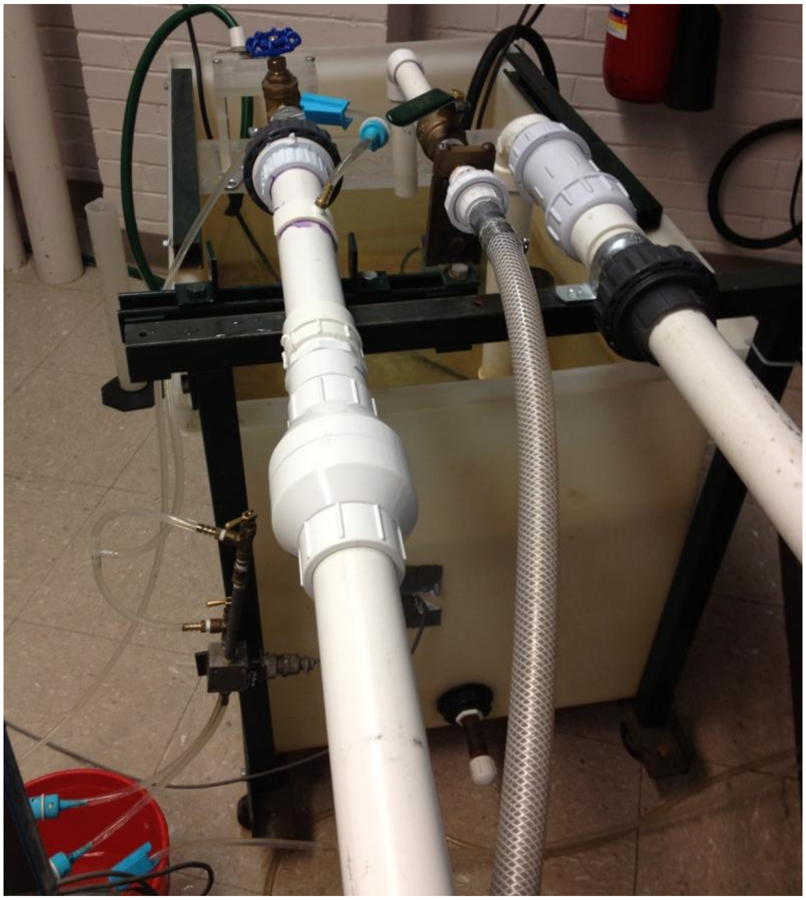

Figure 19 - A picture of the commercial valve in testing

5.0 Discussion of Data Results

5.1 Seal Data Discussion

The seal tests provided results indicating the need for further testing of LDPE as an appropriate alternative to leather piston seals in developing world reciprocating pump technology. As compared to leather, LDPE outperformed in permeability of the seal in terms of time elapsed versus the mass flow of water across the seal as shown by Figures 20 and 21. As displayed in the data in Figure 22, however, the hand-cut piston followed the predicted logarithmic nature of the mass flow across the seal with a lower R^2 value of 63%. This can be attributed to the variation in the shape of the piston. Locations have less contact pressure between the piston and the cylinder wall because of the non-concentric nature of the hand-cut piston. When the piston was turned on a lathe to ensure a concentric fit with the annulus of the cylinder, the results were much more favorable than the permeable leather.

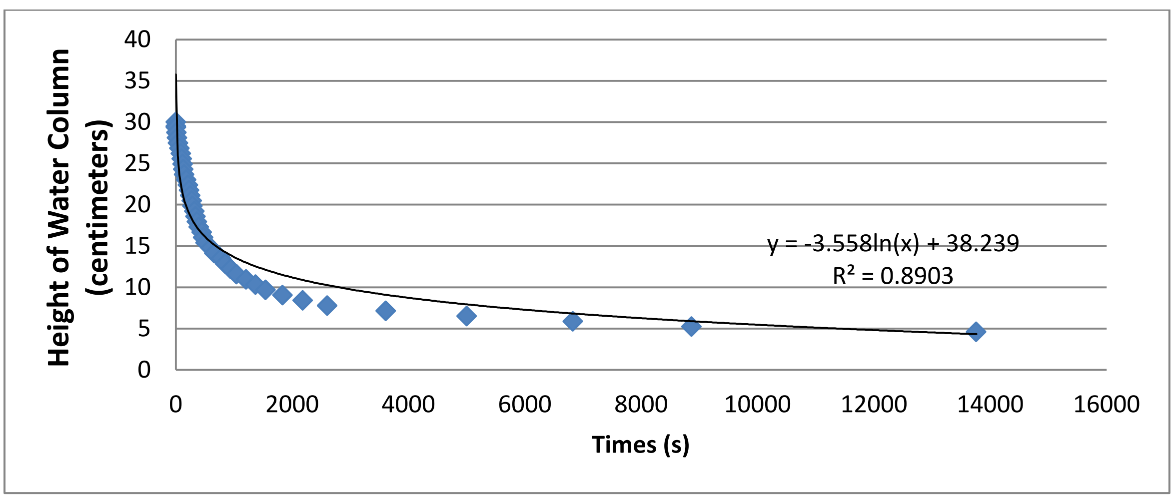

Figure 20 - Graph of height in water in a column in centimeters versus the time of the trial for a machined piston using a leather cup seal

The next interesting phenomenon of this data set is the final height at which the water could no longer permeate the seal. This height corresponds to the height in water in a column, which is head or pressure. Below this pressure, water cannot cross the seal in pump operation. The machined piston with the leather cup seal and the hand-cut LDPE seal both behave in similar manners with a threshold pressure of approximately 5.08 cm (2"), where the machined LDPE seal had a threshold of nearly twice that value. This much increased pressure threshold also allows for a reduced mass flow across the seal under higher pressures. This allows for a higher mechanical efficiency of the treadle pump in operation versus the current leather use in annular seals of the piston. Figure 23 illustrates the similarity of the performance of the leather seal on a machined piston versus the hand-cut LDPE seal clearly.

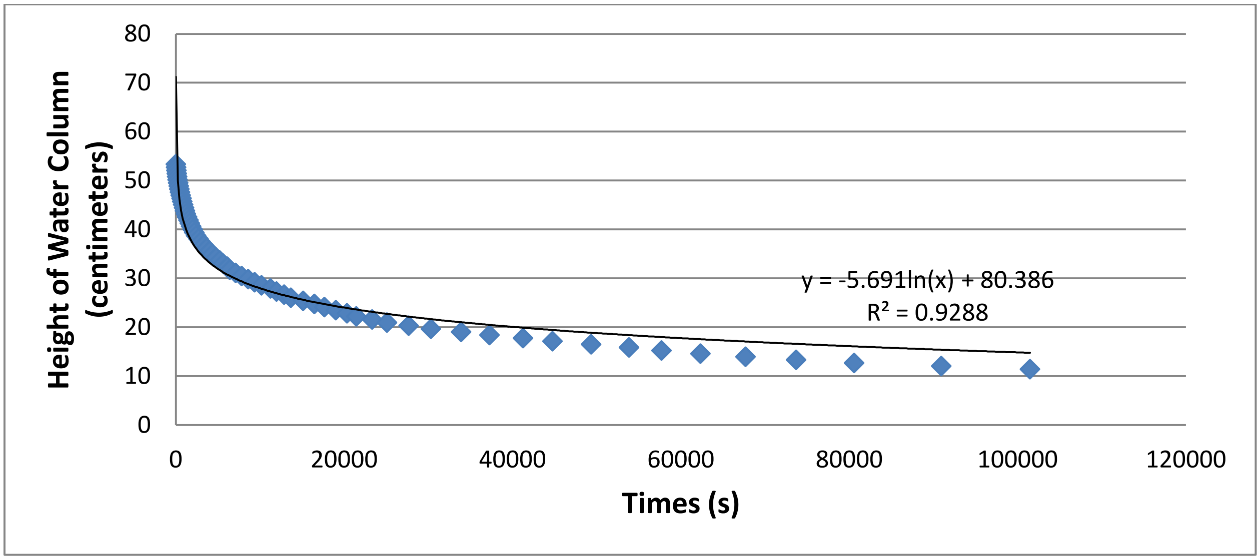

Figure 21 - Graph of height in water in a column in centimeters versus the time of the trial for a machined piston using an LDPE seal.

Although repeatability of these tests was difficult as they required thorough observation over extended periods of time, the data place a value on the continued research into the use, life cycle, and friction of the LDPE piston rod seal in treadle pump applications. Further studies will be required to validate the repeatability of these tests and the usefulness of LDPE as a seal in treadle pump applications.

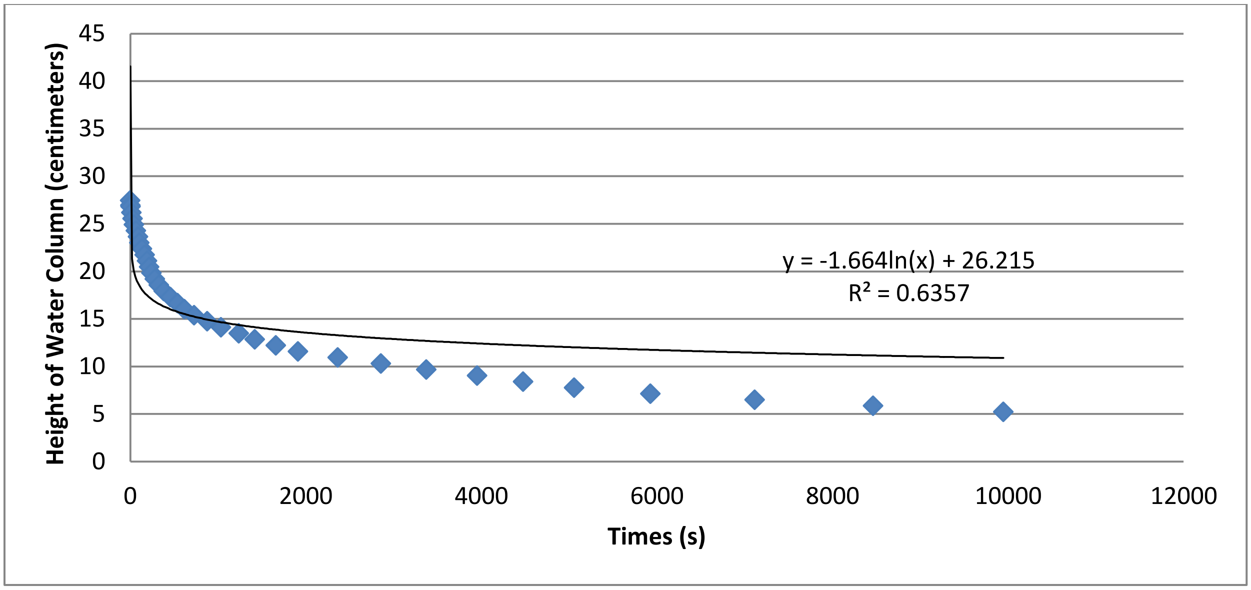

Figure 22 - Graph of height in water in a column in centimeters versus the time of the trial for a hand-cut piston using a LDPE seal

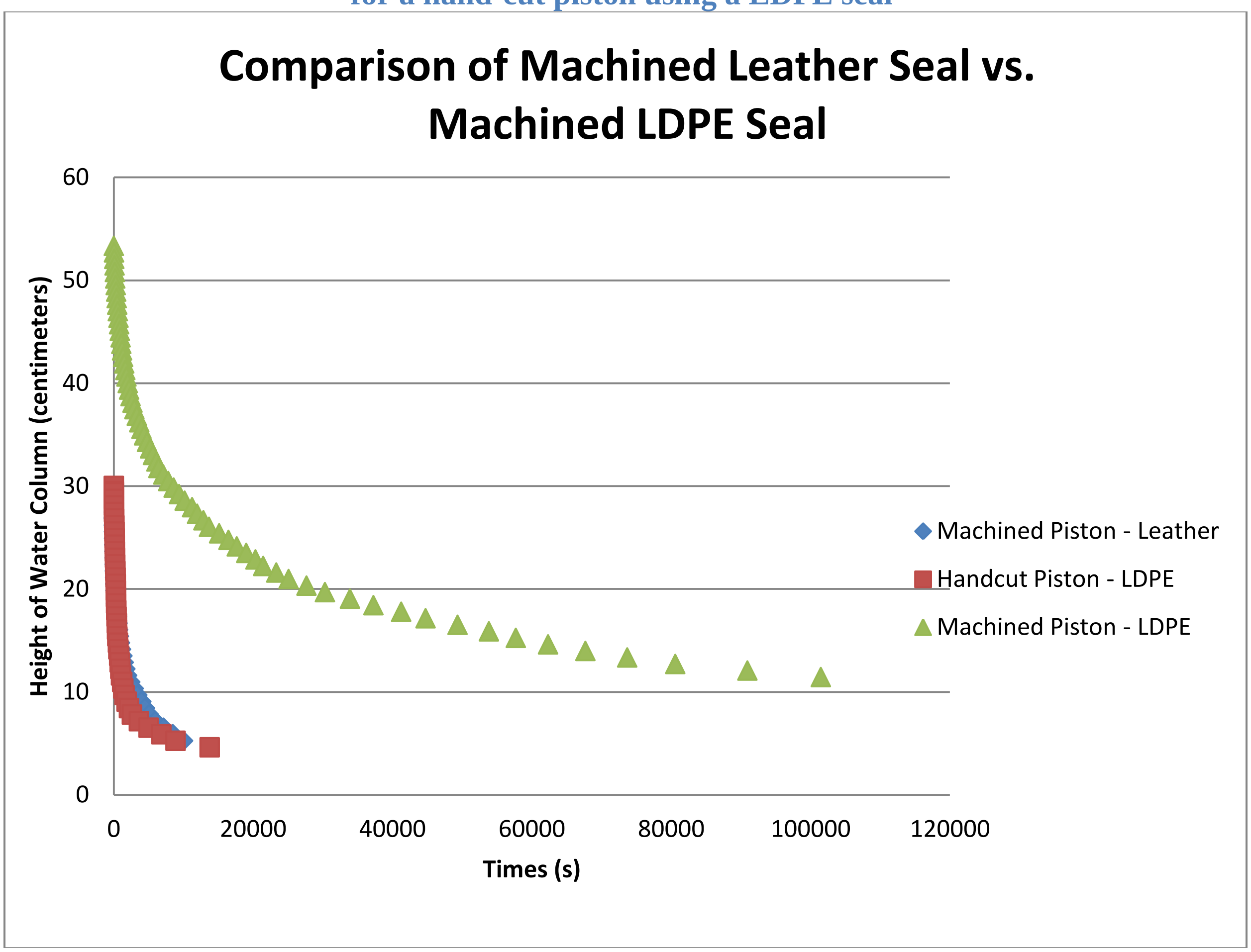

Figure 23 - Comparison of seal tests showing that the hand-cut piston using an LDPE seal performs similarly to the machined piston using a leather seal

5.2 Valve Data Discussion

The head loss experiment comparing the American Valve Model #79653 and the developed check valve yielded positive results for low-flow applications. As seen in Figure 24, the developed check valve has more favorable results in low-flow regions of the graph; however above a flow of 30 liters per minute, it becomes clear that the valve no longer can comparably perform versus the commercial valve.

The data from the experiment fit a first order exponential curve with an R^2 greater than 0.98 in both cases, and was repeatable. The points with the largest variation came near the shut-off flow where the pressure of the flow in the line was nearing the cracking pressure. The location of the valve relative to its seat is very dynamic in this flow scenario. This represents a phenomenon known as valve flutter, which can cause slight variations in the flow regime causing variable head loss around the same volumetric flow rate condition. In the higher volumetric flow rates, the head loss increased in a highly predictable manner as the valve was fully unseated and the head loss was a function of the difference in the flow areas through the valve.

The American Valve data behaved as predicted, as the valve has an expanded diameter region between its intake and discharge of approximately 2.5". This expansion allows for an increased flow area and lower required velocity to pass through the valve given a specific volumetric flow rate. This reduced velocity translates into a reduced friction factor and yields a lower head loss through the valve. The commercial valve was intended for a much higher flow rate than that of a treadle pump, as the shut-off flow for the valve occurred at 3.4 liters per minute, versus the flow to provide cracking pressure for the developed valve of 3.3 liters per minute. Although these flows seem relatively similar, the commercial valve experienced significantly more head loss at low flow as it has a complex spring mechanism. The flow could only pass through parts of the valve, as it was only partially activated. This caused an increased head loss compared to the developed valve. During the testing, under low flow conditions near the 3.4 liters per minute shut-off flow, the commercial valve made slamming noises and the flow was continually disrupted as sputtering at the discharge pipe was observed. This sputtering did not fully end until the flow rate had reached nearly 15 liters per minute.

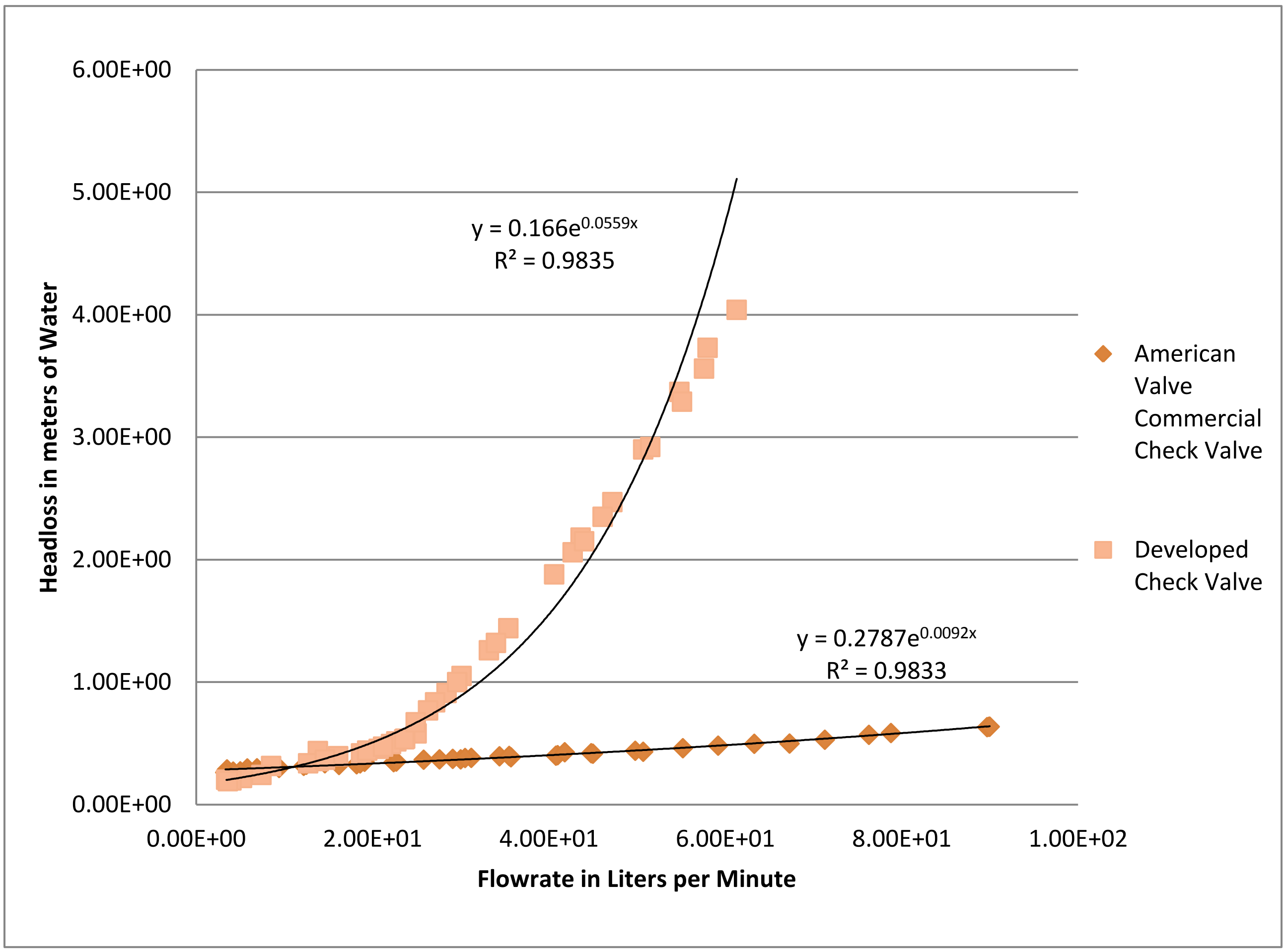

Figure 24 - A graph of head loss in meters of water versus flow rate in LPM of the developed versus the commercial valve produced by American Valve

The flow rate derived for the prototyped full model predicted a flow rate using a metal gate valve of 144 liters per minute. During experimentation, this theoretical value would be nearly impossible to obtain, even with the commercial valve. The head loss predicted through gate valves is not realistic with single- or multi-spring check valves as the effective flow area is drastically different. Given the experimental data, the maximum head loss through the each check valve would comprise approximately 10-15% of the overall head loss through the system, based on the predicted total head loss from the modeling. With four valves, this component quickly becomes a dominating contributor to the total head loss. Therefore, reduction of head loss in the check valve is a key parameter.

As the head loss curve is naturally exponential, the knee of this curve is clearly evident in the developed valve; however, under the conditions of this test, is not evident for the commercial valve. The design of the commercial valve, though not listed in its specifications, is most likely for a more industrial purpose than that of a treadle pump. Cracking pressure and low flow conditions are more relevant to a treadle pump than they might be in industrial application. The data indicates the success of the developed valve in flows less than 20 liters per minute versus the commercial valve.

6.0 Conclusions

6.1 Summary and Additional Research for Check Valve in Developing World Agricultural Water Transfer Applications

This thesis describes the development of a significantly less expensive check valve from standard PVC fittings with comparable low-flow head loss versus a higher cost commercially-available check valve. The data collected illustrate the feasibility of the appropriate development of check valve technology in developing world agricultural water transfer applications. In higher flow conditions, the valve's head loss is significantly higher than the commercial valve. However, this development and experimentation validate the concept that appropriate design principles may be used to develop more effective solutions in developing world technology. Check valve technology has experienced very little advancement pertaining to developing world agricultural applications, and its resulting impact could be far reaching. Although the currently developed design could be further optimized to better suit flows above 30 liters per minute, the design has a reduction in valve cost of 76% to the end-user. This low cost can aid in the adoption diffusion of treadle pump technology to those who previously could not invest in this technology.

The experimentation process of this thesis did not consider the life cycle of the valve or the ramifications of cyclical seating and unseating of the valve that could induce wear on the rubber. This test could validate the maintenance schedule of the pump during normal operation and provide key insights into other materials that have not been explored in check valve internals. This parameter, although not explored, could provide key insights for future development of technology with similar applications.

Although the check valve was designed with intentions of use solely with treadle pump technology, check valves serve purposes that could be more far- reaching across the developing world. Because this research realized significant cost-savings, it may be feasible to use this design in other applications aiming for one-way flow while maintaining low costs as a key parameter in the feasibility of technology implementation. As water treatment systems become more available in the developing world, the use of appropriate design principles to design and procure affordable check valve technology is imperative. This research asserts that complex technology and mechanisms are not necessary to produce check valves. Instead, the use of novel mechanical actuation with standard and highly available parts provides a more appropriate solution.

The largest shortcoming of the procured design is the small flow area for flow even under the fullest actuation of the valve. The flow area is reduced from the 11.4 square centimeter region to 2.66 square centimeters through the valve, grossly increasing the head loss through this valve. A development to increase this area while not significantly increasing cost of the valve would be a breakthrough that would not only reduce fatigue in operators of the pump, but significantly increase the achievable volumetric flow rate of the pump. This is not necessarily an easy task, as the flow area around the valve also needs to be considered. Commercial valves accomplish this via complex spring and seating mechanisms that thwart the effort to make the valve easily maintainable and able to be manufactured locally.

The design is easily manufactured, as the process requires little tooling or training to accurately produce the part. The tolerances on the drawing are not as fine as to need complex measurement tools, and the machining can be performed with simple saws and grinding tools that might be locally available in the target developing communities. This ease-of-manufacture is pivotal in implementing a design in the developing world. If the technology becomes too complex, the result may be premature obsolescence of the technology as previously seen in the implementation of treadle pumps. In reducing the complexity and increasing the ease of maintenance the end-users will more likely take ownership in the technology and understand the necessary requirements to keep their pump in operation over an extended period of time.

6.2 Summary and Additional Research for Low-Density Polyethylene Piston Seals in Developing World Agricultural Water Transfer Applications

The testing of the use of low-density polyethylene (LDPE) in piston seal applications for developing world treadle pumps provided validation that the continued research for the use of LDPE is warranted. LDPE is an abundant resource due to the waste plastic bags found in many developing world countries. This waste has become a nuisance in many countries and too many NGO's. In fact, Penn State cooperatives began research into new applications for LDPE that can turn this waste into a valuable resource. Seals are commonly expensive and not easily obtainable for the maintenance of treadle pumps and have proved to be a reason for premature pump obsolescence. If LDPE can be utilized as a seal, application pumps could be easily maintained with an abundant resource in the developing world. This can significantly reduce the operating cost and extend the life of the technology.

The durability of the material during operation was identified as a key testing parameter of the LDPE during the operation of the prototype model. This durability corroborated the assertion that this material could be utilized effectively for sealing the piston. After an hour of operation, the seal integrity began to greatly degrade and the seal was replaced in order to maintain efficient pump operation. Though this replacement was easy because the pistons were not coupled to a pulley, if the LDPE seal is not analyzed for its mechanical stability as a seal, the solution might not be appropriate from a maintenance standpoint. It was observed, however, that placing multiple plastic bags over the seal increased the friction against the wall but also provided a much longer life span of the seal in operation.

6.3 Summary

Through this research, the testing corroborated the thesis that appropriate design methods applied to technological development of treadle pump for developing world agricultural applications yield designs that are far more appropriate than current practices. Appropriate replacements of valve and seal technology within the field of treadle pumps can magnify the usage and reduce the risk of premature obsolescence of pumps by decreasing the cost to the end-user and making replacements more available to the target communities.

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Appendix 1 - Tabulated Data from Seal and Valve Experimentation

Experiment 1 - Leather Cup Seal

Time (sec)	Actual Head (in)	Measured Head (in)
2	11.8125	-4
2	11.6125	-3.8
4	11.5625	-3.75
12	11.3125	-3.5
22	11.0625	-3.25
39	10.8125	-3
64	10.5625	-2.75
88	10.3125	-2.5
104	10.0625	-2.25
120	9.8125	-2
130	9.5625	-1.75
145	9.3125	-1.5
180	9.0625	-1.25
210	8.8125	-1
230	8.5625	-0.75
250	8.3125	-0.5
276	8.0625	-0.25
288	7.8125	0
321	7.5625	0.25
340	7.3125	0.5
364	7.0625	0.75
396	6.8125	1

447	6.5625	1.25
472	6.3125	1.5
513	6.0625	1.75
602	5.8125	2
663	5.5625	2.25
781	5.3125	2.5
849	5.0625	2.75
944	4.8125	3
1043	4.5625	3.25
1209	4.3125	3.5
1372	4.0625	3.75
1544	3.8125	4
1836	3.5625	4.25
2183	3.3125	4.5
2604	3.0625	4.75
3611	2.8125	5
5002	2.5625	5.25
6827	2.3125	5.5
8867	2.0625	5.75
13761	1.8125	6

Experiment 2 - Hand-cut Piston - LDPE Seal

Time (sec)	Actual Head (in)	Measured Head (in)
0.0001	10.8125	-3
2.2	10.6125	-2.8

4.4	10.5625	-2.75
13.6	10.3125	-2.5
27.2	10.0625	-2.25
42.5	9.8125	-2
65	9.5625	-1.75
89	9.3125	-1.5
104	9.0625	-1.25
134	8.8125	-1
165	8.5625	-0.75
192	8.3125	-0.5
216	8.0625	-0.25
242	7.8125	0
281	7.5625	0.25
326	7.3125	0.5
382	7.0625	0.75
458	6.8125	1
539	6.5625	1.25
617	6.3125	1.5
728	6.0625	1.75
877	5.8125	2
1034	5.5625	2.25
1237	5.3125	2.5
1419	5.0625	2.75
1659	4.8125	3
1911	4.5625	3.25

2364	4.3125	3.5
2856	4.0625	3.75
3373	3.8125	4
3952	3.5625	4.25
4476	3.3125	4.5
5057	3.0625	4.75
5926	2.8125	5
7114	2.5625	5.25
8463	2.3125	5.5
9947	2.0625	5.75
3611	1.8125	6
5002	1.5625	6.25
6827	1.3125	6.5
8867	1.0625	6.75
13761	0.8125	7

Experiment 3 - Machined Piston - LDPE Seal

Time (s)	Head of Water (in)
5	21
34	20.75
72	20.5
113	20.25
159	20
211	19.75

279	19.5
346	19.25
417	19
495	18.75
577	18.5
679	18.25
764	18
866	17.75
979	17.5
1081	17.25
1192	17
1341	16.75
1501	16.5
1657	16.25
1819	16
2004	15.75
2199	15.5
2406	15.25
2685	15
2957	14.75
3304	14.5
3657	14.25
3972	14
4347	13.75
4770	13.5

5212	13.25
5623	13
6119	12.75
6402	12.5
7106	12.25
7816	12
8594	11.75
9362	11.5
10175	11.25
11239	11
11961	10.75
12863	10.5
13664	10.25
15122	10
16461	9.75
17652	9.5
19007	9.25
20333	9
21441	8.75
23319	8.5
25086	8.25
27658	8
30304	7.75
33893	7.5
37267	7.25

41248	7
44751	6.75
49341	6.5
53841	6.25
57702	6
62332	5.75
67688	5.5
73693	5.25
80587	5
90941	4.75
101481	4.5

Experiment 4 - Head Loss for Developed Check Valve

Pt_Num	Flowrate	Flowrate	Flowrate	Velocity	Head_Loss	Re	f
(#)	(LPM)	(m^3/s)	(gpm)	(m/s)	(m_H20)	(-)	(-)
1	5.07E+01	8.45E-04	1.34E+01	5.78E-01	2.90E+00	24881	5.68E+00
2	5.48E+01	9.13E-04	1.45E+01	6.24E-01	3.37E+00	26893	5.64E+00
3	5.80E+01	9.67E-04	1.53E+01	6.61E-01	3.73E+00	28464	5.58E+00
4	6.13E+01	1.02E-03	1.62E+01	6.98E-01	4.04E+00	30083	5.41E+00
5	4.36E+01	7.27E-04	1.15E+01	4.97E-01	2.18E+00	21397	5.77E+00
6	3.54E+01	5.90E-04	9.35E+00	4.03E-01	1.44E+00	17373	5.79E+00
7	2.84E+01	4.73E-04	7.50E+00	3.24E-01	9.11E-01	13937	5.69E+00
8	1.39E+01	2.32E-04	3.67E+00	1.58E-01	3.55E-01	6821	9.24E+00
9	2.27E+01	3.78E-04	6.00E+00	2.59E-01	5.16E-01	11140	5.04E+00
10	3.01E+01	5.02E-04	7.95E+00	3.43E-01	1.05E+00	14772	5.84E+00
11	4.06E+01	6.77E-04	1.07E+01	4.63E-01	1.88E+00	19925	5.74E+00
12	3.40E+00	5.67E-05	8.98E-01	3.87E-02	2.03E-01	1669	8.84E+01
13	8.50E+00	1.42E-04	2.25E+00	9.69E-02	3.15E-01	4171	2.19E+01
14	1.38E+01	2.30E-04	3.65E+00	1.57E-01	4.37E-01	6772	1.15E+01
15	2.21E+01	3.68E-04	5.84E+00	2.52E-01	4.94E-01	10846	5.09E+00
16	2.71E+01	4.52E-04	7.16E+00	3.09E-01	8.35E-01	13299	5.72E+00
17	2.96E+01	4.93E-04	7.82E+00	3.37E-01	1.00E+00	14526	5.75E+00

18	3.32E+01	5.53E-04	8.77E+00	3.78E-01	1.26E+00	16293	5.75E+00
19	7.40E+00	1.23E-04	1.96E+00	8.43E-02	2.42E-01	3632	2.22E+01
20	5.20E+00	8.67E-05	1.37E+00	5.93E-02	2.17E-01	2552	4.05E+01
21	4.00E+00	6.67E-05	1.06E+00	4.56E-02	1.97E-01	1963	6.20E+01
22	3.60E+00	6.00E-05	9.51E-01	4.10E-02	1.91E-01	1767	7.41E+01
23	4.27E+01	7.12E-04	1.13E+01	4.87E-01	2.06E+00	20955	5.68E+00
24	4.72E+01	7.87E-04	1.25E+01	5.38E-01	2.47E+00	23164	5.58E+00
25	4.40E+01	7.33E-04	1.16E+01	5.01E-01	2.15E+00	21593	5.59E+00
26	5.15E+01	8.58E-04	1.36E+01	5.87E-01	2.92E+00	25274	5.55E+00
27	5.51E+01	9.18E-04	1.46E+01	6.28E-01	3.29E+00	27040	5.45E+00
28	5.76E+01	9.60E-04	1.52E+01	6.56E-01	3.56E+00	28267	5.39E+00
29	4.61E+01	7.68E-04	1.22E+01	5.25E-01	2.35E+00	22624	5.56E+00
30	3.40E+01	5.67E-04	8.98E+00	3.87E-01	1.32E+00	16686	5.75E+00
31	1.87E+01	3.12E-04	4.94E+00	2.13E-01	4.18E-01	9177	6.01E+00
32	1.27E+01	2.12E-04	3.36E+00	1.45E-01	3.37E-01	6233	1.05E+01
33	1.61E+01	2.68E-04	4.25E+00	1.83E-01	3.95E-01	7901	7.66E+00
34	1.46E+01	2.43E-04	3.86E+00	1.66E-01	3.66E-01	7165	8.65E+00
35	2.07E+01	3.45E-04	5.47E+00	2.36E-01	4.55E-01	10159	5.34E+00
36	2.50E+01	4.17E-04	6.61E+00	2.85E-01	5.81E-01	12269	4.68E+00
37	1.94E+01	3.23E-04	5.13E+00	2.21E-01	4.41E-01	9521	5.90E+00
38	2.63E+01	4.38E-04	6.95E+00	3.00E-01	7.69E-01	12907	5.59E+00
39	2.37E+01	3.95E-04	6.26E+00	2.70E-01	5.38E-01	11631	4.82E+00
40	2.12E+01	3.53E-04	5.60E+00	2.42E-01	4.73E-01	10404	5.29E+00
41	2.36E+01	3.93E-04	6.24E+00	2.69E-01	5.33E-01	11582	4.82E+00
42	2.49E+01	4.15E-04	6.58E+00	2.84E-01	6.72E-01	12220	5.45E+00

Experiment 5 - Head Loss for American Valve 1.5" Socket Weld Check Valve

Pt_Num	Flowrate	Flowrate	Flowrate	Velocity	Head_Loss	Re	f
(#)	(LPM)	(m^3/s)	(gpm)	(m/s)	(m_H20)	(-)	(-)
1	1.22E+01	2.03E-04	3.22E+00	1.39E-01	3.16E-01	5987	1.07E+01
2	6.90E+00	1.15E-04	1.82E+00	7.86E-02	2.96E-01	3386	3.13E+01
3	3.50E+00	5.83E-05	9.25E-01	3.99E-02	2.87E-01	1718	1.18E+02
4	1.25E+01	2.08E-04	3.30E+00	1.42E-01	3.25E-01	6134	1.05E+01
5	1.46E+01	2.43E-04	3.86E+00	1.66E-01	3.37E-01	7165	7.96E+00
6	1.91E+01	3.18E-04	5.05E+00	2.18E-01	3.49E-01	9373	4.81E+00
7	2.58E+01	4.30E-04	6.82E+00	2.94E-01	3.66E-01	12661	2.76E+00
8	3.12E+01	5.20E-04	8.24E+00	3.56E-01	3.81E-01	15311	1.97E+00
9	3.00E+01	5.00E-04	7.93E+00	3.42E-01	3.69E-01	14723	2.06E+00

10	3.57E+01	5.95E-04	9.43E+00	4.07E-01	3.86E-01	17520	1.53E+00
11	4.10E+01	6.83E-04	1.08E+01	4.67E-01	4.03E-01	20121	1.21E+00
12	4.48E+01	7.47E-04	1.18E+01	5.10E-01	4.19E-01	21986	1.05E+00
13	4.98E+01	8.30E-04	1.32E+01	5.67E-01	4.39E-01	24439	8.90E-01
14	5.52E+01	9.20E-04	1.46E+01	6.29E-01	4.60E-01	27090	7.59E-01
15	5.92E+01	9.87E-04	1.56E+01	6.75E-01	4.81E-01	29053	6.90E-01
16	6.33E+01	1.05E-03	1.67E+01	7.21E-01	4.96E-01	31065	6.23E-01
17	6.73E+01	1.12E-03	1.78E+01	7.67E-01	4.98E-01	33028	5.54E-01
18	7.13E+01	1.19E-03	1.88E+01	8.12E-01	5.29E-01	34991	5.24E-01
19	7.63E+01	1.27E-03	2.02E+01	8.69E-01	5.69E-01	37444	4.92E-01
20	7.88E+01	1.31E-03	2.08E+01	8.98E-01	5.84E-01	38671	4.73E-01
21	8.99E+01	1.50E-03	2.38E+01	1.02E+00	6.35E-01	44119	3.95E-01
22	8.97E+01	1.50E-03	2.37E+01	1.02E+00	6.32E-01	44020	3.95E-01
23	5.80E+00	9.67E-05	1.53E+00	6.61E-02	2.95E-01	2846	4.41E+01
24	9.00E+01	1.50E-03	2.38E+01	1.03E+00	6.36E-01	44168	3.95E-01
25	5.07E+01	8.45E-04	1.34E+01	5.78E-01	4.31E-01	24881	8.43E-01
26	4.50E+01	7.50E-04	1.19E+01	5.13E-01	4.15E-01	22084	1.03E+00
27	4.08E+01	6.80E-04	1.08E+01	4.65E-01	3.99E-01	20023	1.21E+00
28	3.44E+01	5.73E-04	9.09E+00	3.92E-01	3.94E-01	16882	1.68E+00
29	2.91E+01	4.85E-04	7.69E+00	3.32E-01	3.73E-01	14281	2.21E+00
30	2.24E+01	3.73E-04	5.92E+00	2.55E-01	3.46E-01	10993	3.47E+00
31	1.82E+01	3.03E-04	4.81E+00	2.07E-01	3.29E-01	8932	5.00E+00
32	1.62E+01	2.70E-04	4.28E+00	1.85E-01	3.23E-01	7950	6.19E+00
33	9.40E+00	1.57E-04	2.48E+00	1.07E-01	2.99E-01	4613	1.70E+01
34	5.00E+00	8.33E-05	1.32E+00	5.70E-02	2.71E-01	2454	5.45E+01
35	4.20E+00	7.00E-05	1.11E+00	4.79E-02	2.69E-01	2061	7.68E+01
36	3.30E+00	5.50E-05	8.72E-01	3.76E-02	2.62E-01	1619	1.21E+02
37	4.18E+01	6.97E-04	1.10E+01	4.76E-01	4.27E-01	20513	1.23E+00
38	3.05E+01	5.08E-04	8.06E+00	3.48E-01	3.80E-01	14968	2.05E+00
39	2.27E+01	3.78E-04	6.00E+00	2.59E-01	3.51E-01	11140	3.42E+00
40	1.86E+01	3.10E-04	4.91E+00	2.12E-01	3.36E-01	9128	4.88E+00
41	2.76E+01	4.60E-04	7.29E+00	3.14E-01	3.69E-01	13545	2.43E+00
42	3.55E+01	5.92E-04	9.38E+00	4.05E-01	3.97E-01	17422	1.58E+00

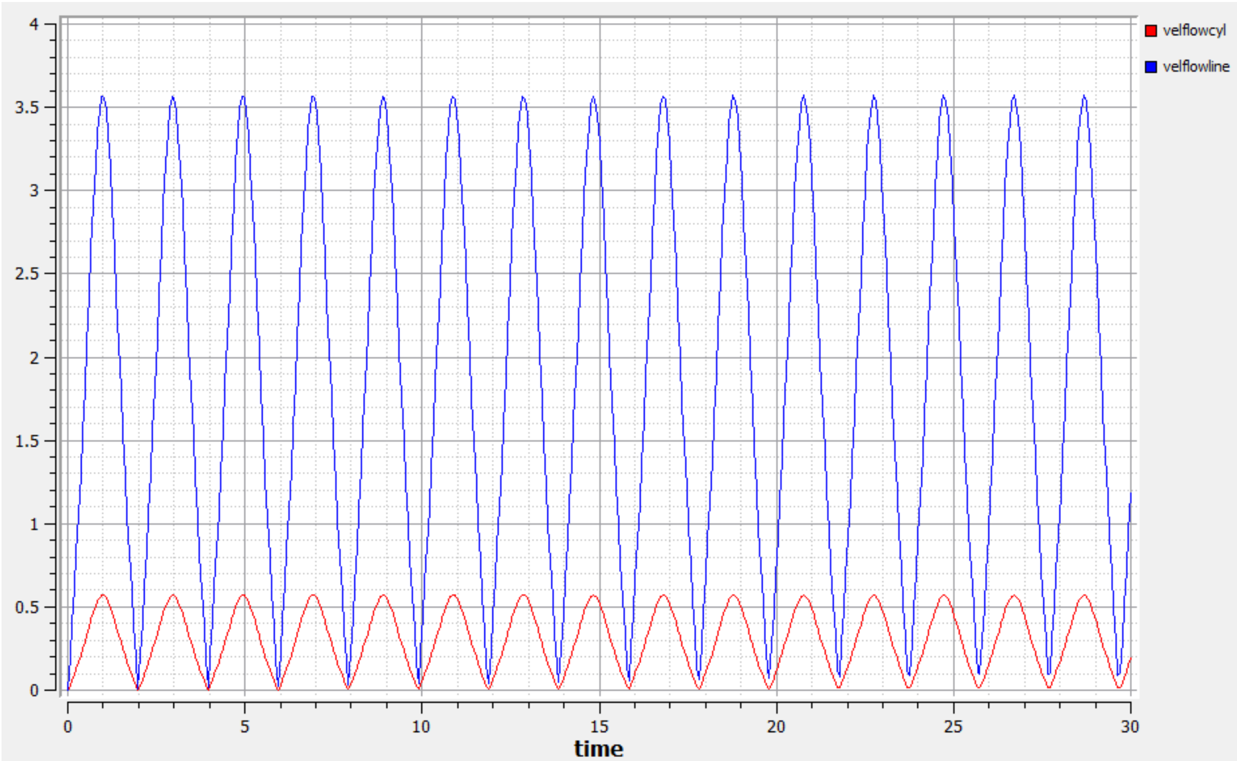
Appendix 2 - Modeling and Graphs of Pump Theoretical Outputs

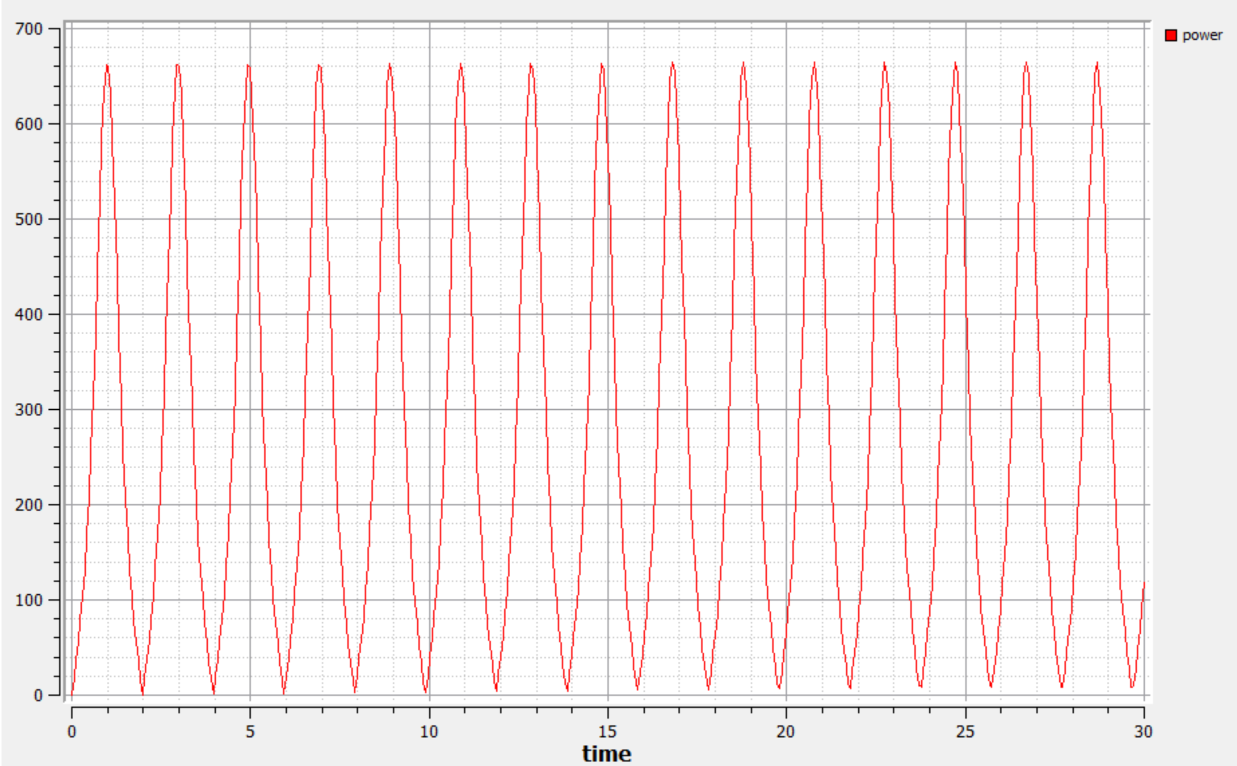
OpenModelica Code

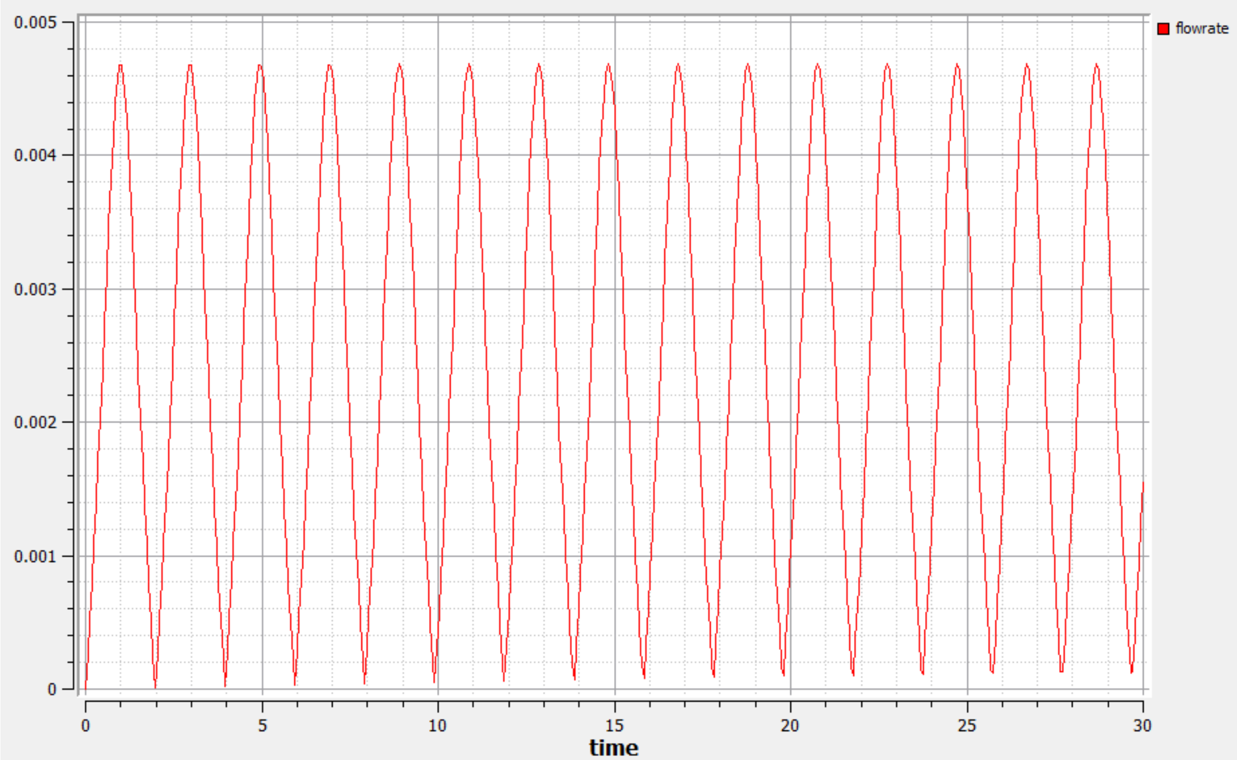
```
model ThesisModel
parameter Real rho = 997.8;
parameter Real g = 9.81;
parameter Real Ffric = 15;
parameter Real Dcyl = 0.10226;
parameter Real Dline = 0.040894;
parameter Real deltaz = 7;
parameter Real mu=0.000547;
Real x1(start = 0.1);
Real x2(start = 0);
Real Acyl;
Real Aline;
Real y1;
Real u1;
Real flowrate;
Real hltotal;
Real etapump;
Real hlintakecon;
Real hlintaketee;
Real hlintakepipe;
Real hlelbow;
Real hlshortpipe1;
Real hlshortpipe2;
Real hlcv;
Real hlpumptee;
Real hlpumpcyl;
Real power;
Real y2;
Real velflowline;
Real velflowcyl;
Real cbrookline;
Real cbrookcyl;
Real Reline;
Real Recyl;
equation
u1 = 0.01 * sin(3.14159 * time)+0.0001;
Acyl = 3.14159 * (Dcyl / 2) ^ 2;
Aline = 3.14159 * (Dline / 2) ^ 2;
velflowline = flowrate / Aline;
velflowcyl = flowrate / Acyl;
Reline= rho * velflowline * Dline / mu;
Recyl= rho * velflowcyl * Dcyl / mu;
```

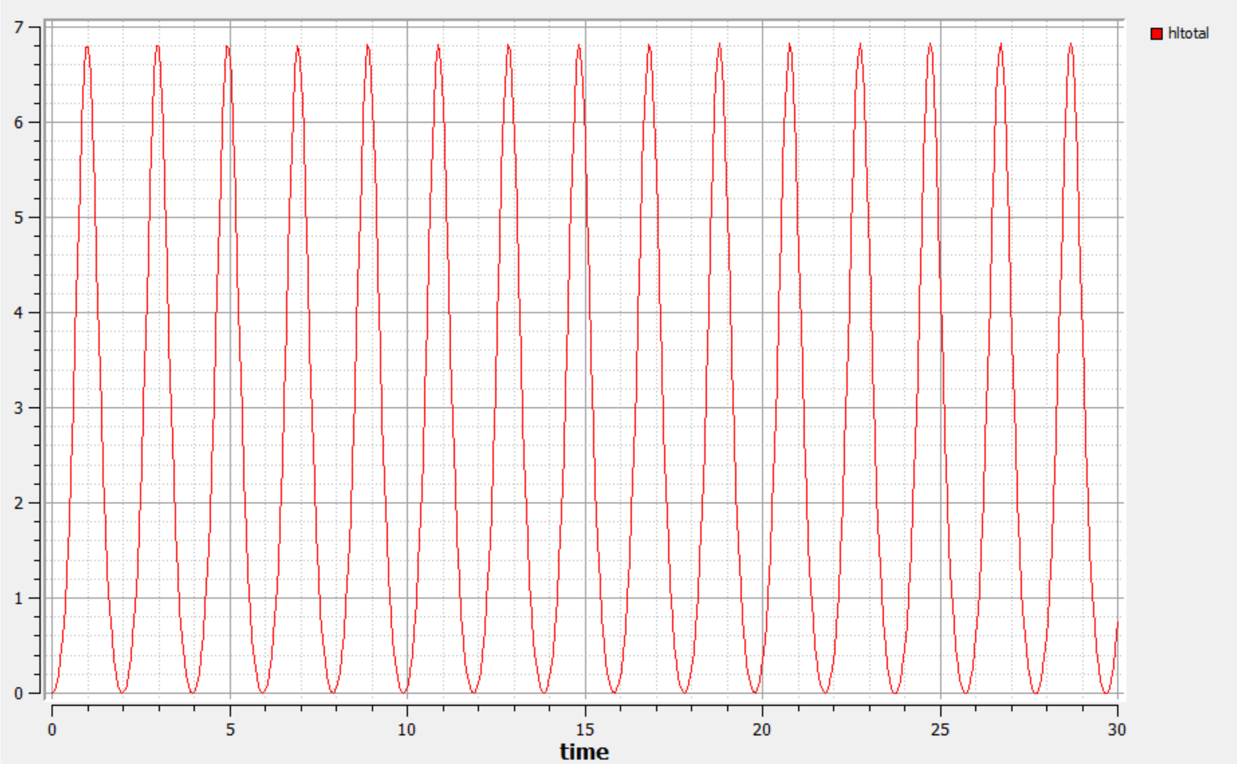
```
cbrookline=(1/(-1.8*log(6.9/Reline+((0.0000015/Dline)/3.7)^1.11)))^2;
cbrookcyl=(1/(-1.8*log(6.9/Recyl+((0.0000015/Dcyl)/3.7)^1.11)))^2;
etapump = 1;
flowrate = abs(3.14159 * (Dcyl / 2) ^ 2 * x2);
power = rho * g * flowrate * (velflowline ^ 2 / (2 * g) + hltotal + deltaz);
hlintakecon = (1.05 * (1 - 0.01905 ^ 2 / 0.040894 ^ 2) ^ 2 * velflowline ^ 2) / (2 * g);
hlintaketee = (2.0 * (flowrate / Dline) ^ 2) / (2 * g);
hlintakepipe = cbrookline * (0.66 / Dline) * (velflowline ^ 2) / (2 * g);
hlelbow = (0.9 * velflowline ^ 2) / (2 * g);
hlshortpipe1 = cbrookline * (0.0762 / Dline) * (velflowline ^ 2) / (2 * g);
hlshortpipe2 = cbrookline * (0.0508 / Dline) * (velflowline ^ 2) / (2 * g);
hlcv = (2.0 * velflowline ^ 2) / (2 * g);
hlpumptee = (2.0 * velflowline ^ 2) / (2 * g);
hlpumpcyl = cbrookcyl * (x1 / Dcyl) * (velflowcyl ^ 2) / (2 * g);
hltotal = 2 * hlpumptee + hlpumpcyl + hlintakecon + hlintaketee + hlintakepipe + 2 * hlelbow +
2 * hlshortpipe1 + 2 * hlshortpipe2 + 2 * hlcv;
der(x1) = x2;
der(x2) = 0.75 * sin(3.14159/0.4 * x1);
y1 = flowrate;
y2 = power;
end ThesisModel;
```

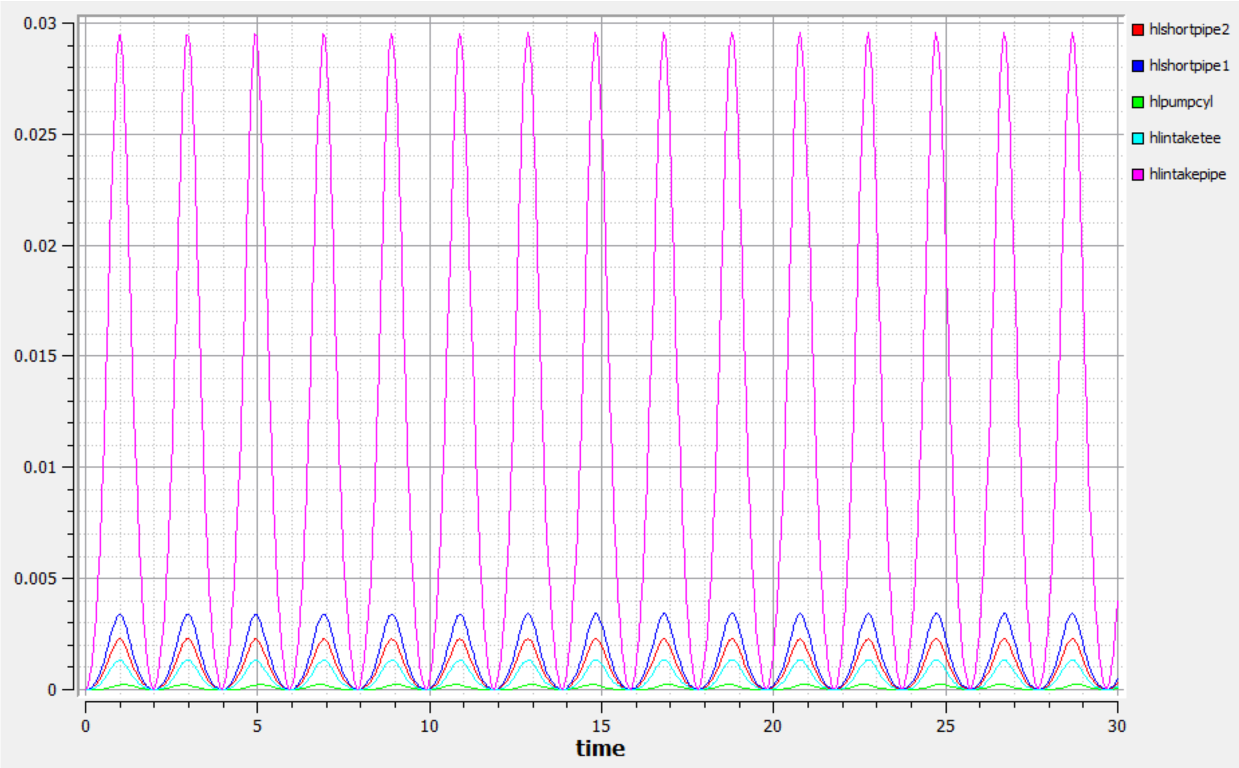
OpenModelica Output Graphs





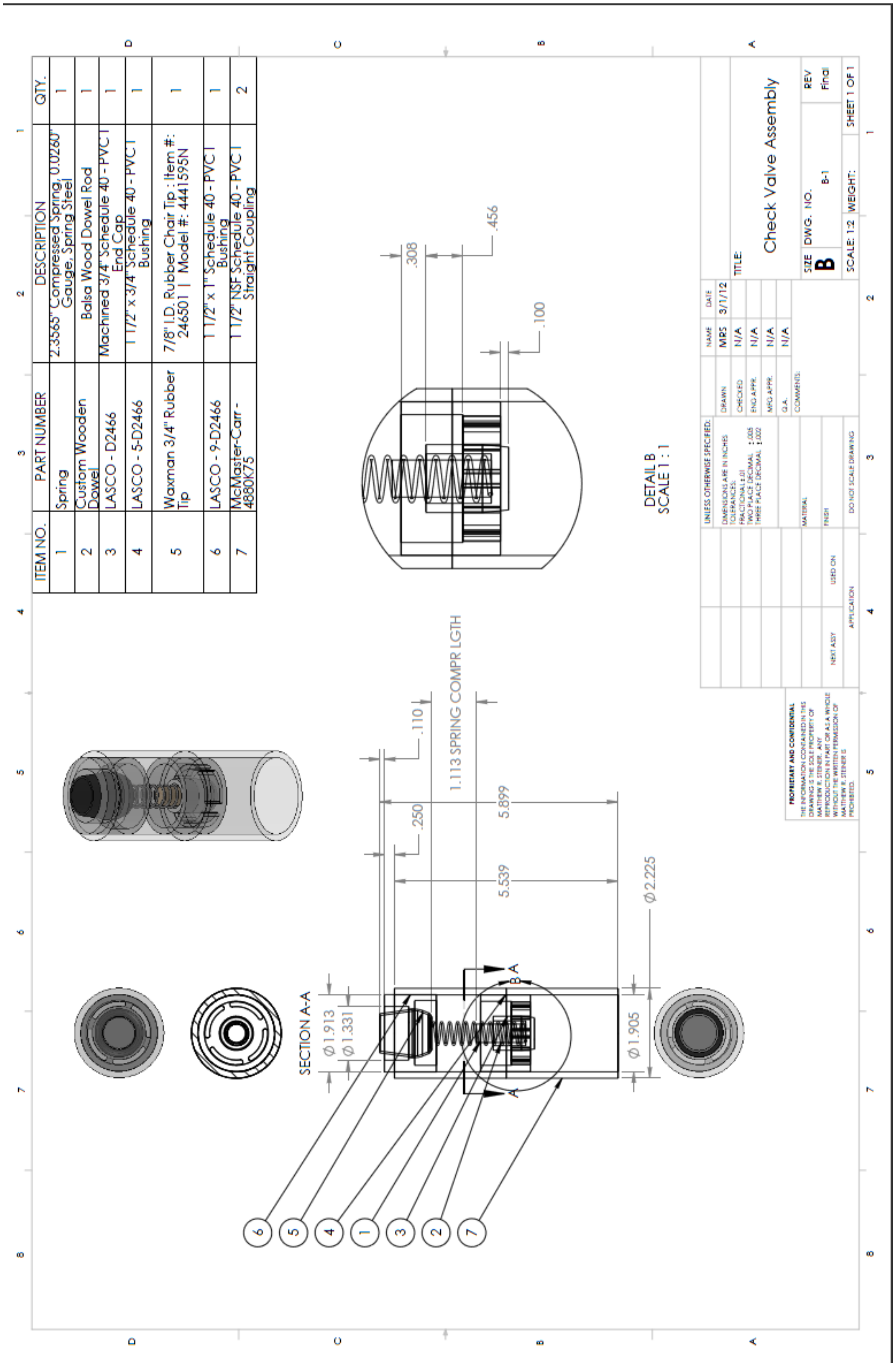

0.005
0.004
0.003
0.002
0.001
0
0
5
10
15
20
25
30
time
flowrate


7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
time
hltotal

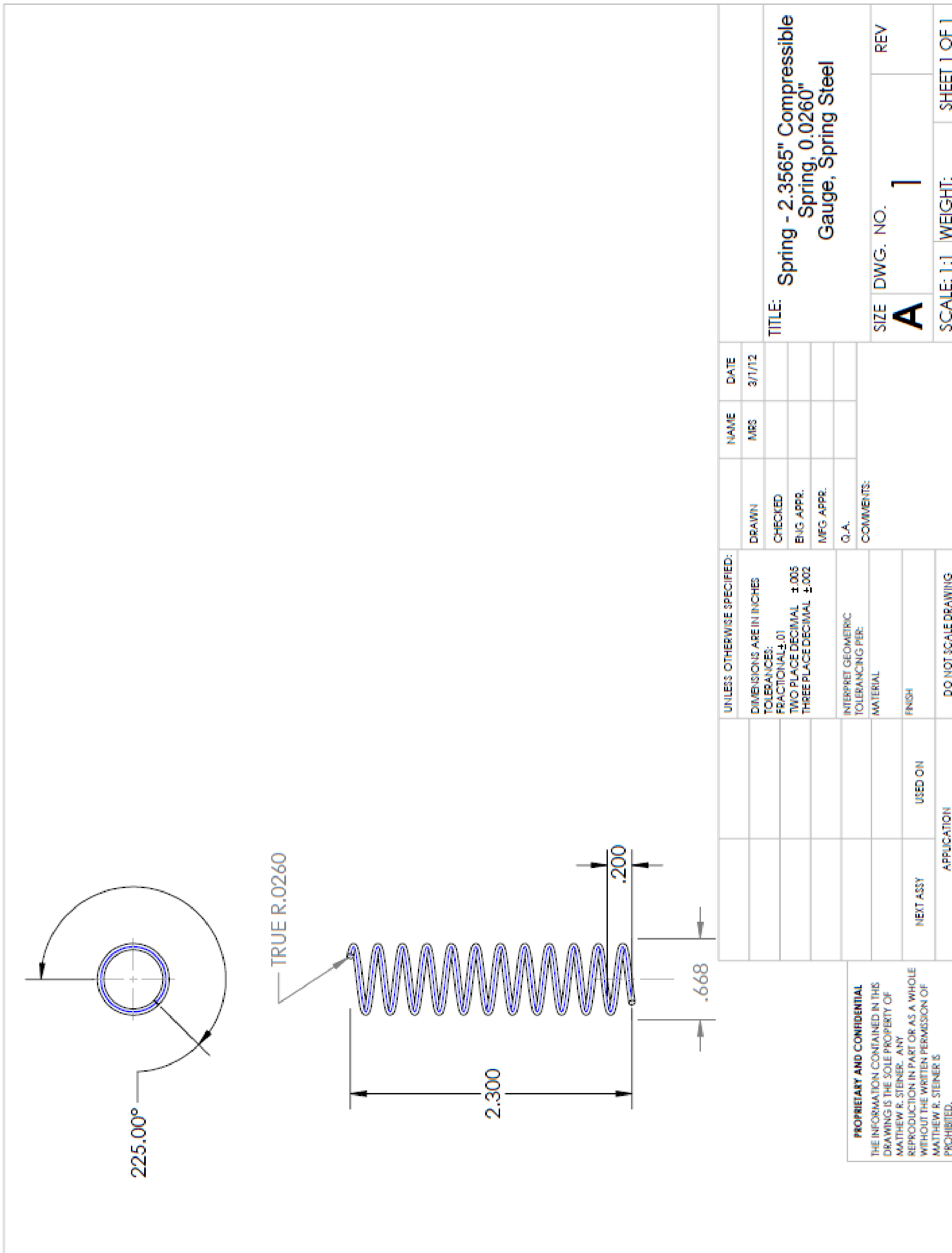

0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20
25
30
time
hlshortpipe2
hlshortpipe1
hlpumpcyl
hlintaketee
hlintakepipe

Appendix 3 - CAD Renderings of Developed Check Valve

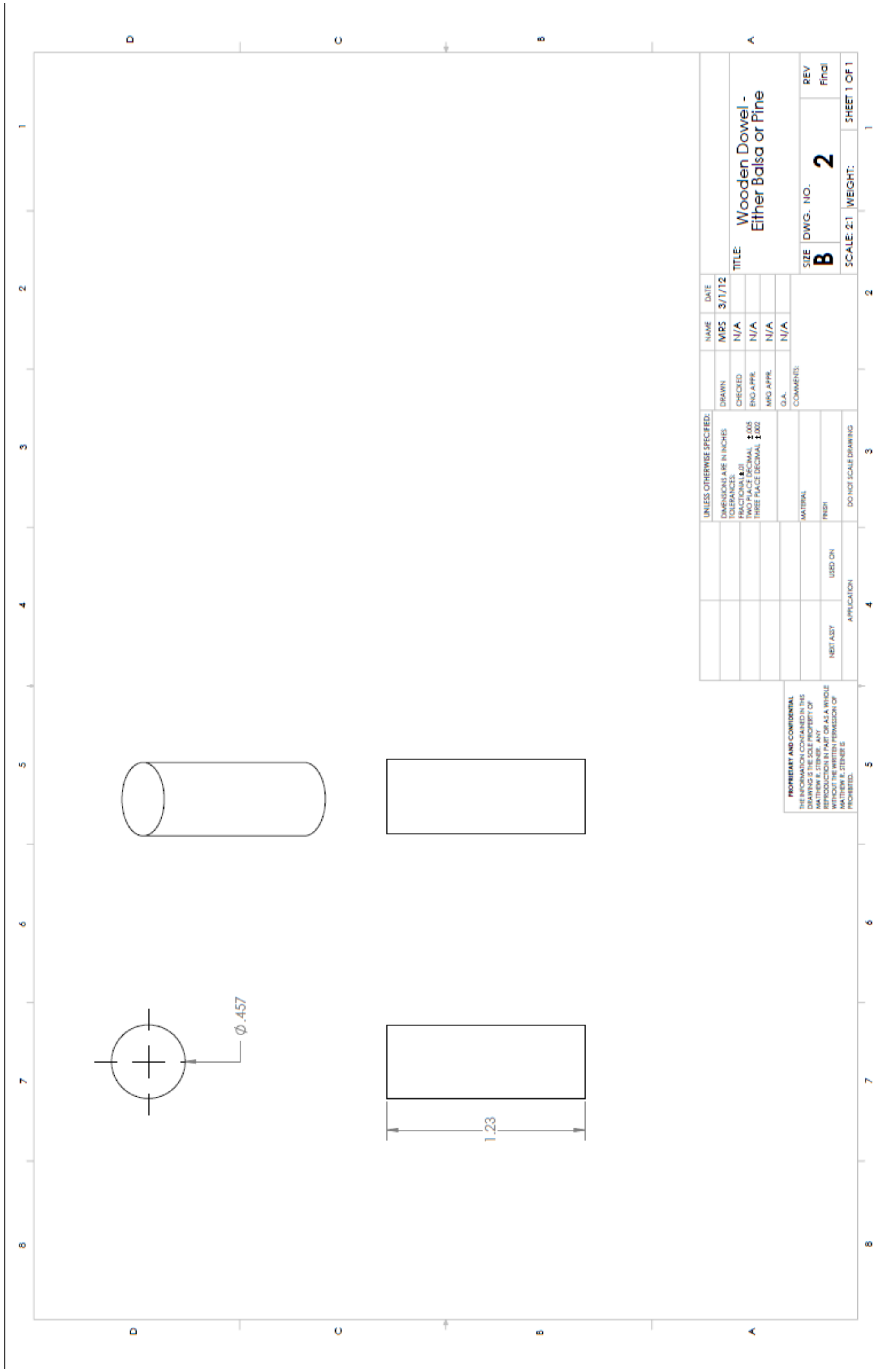
Valve Assembly Drawing



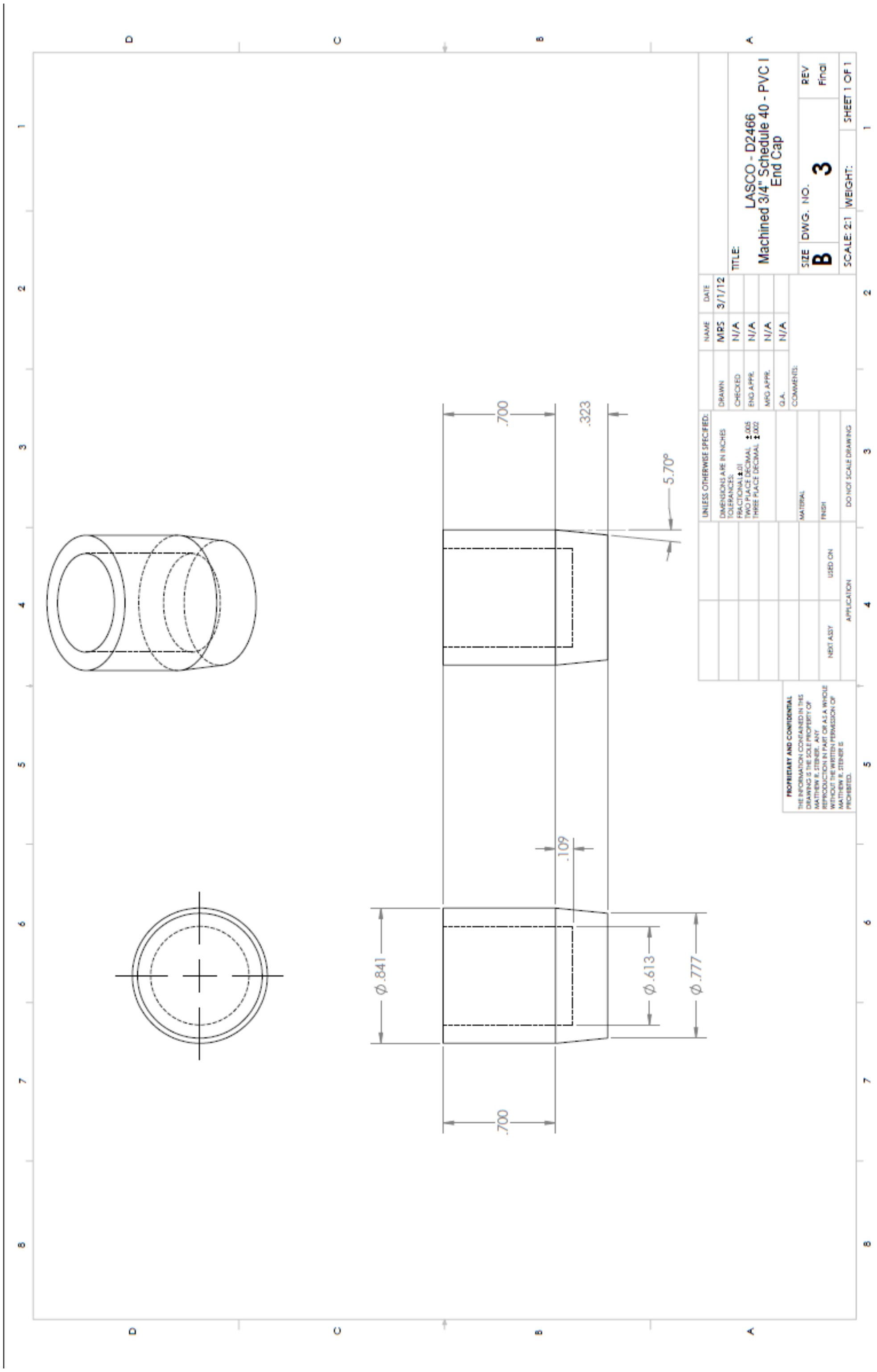
Drawing 1 - Spring Drawing



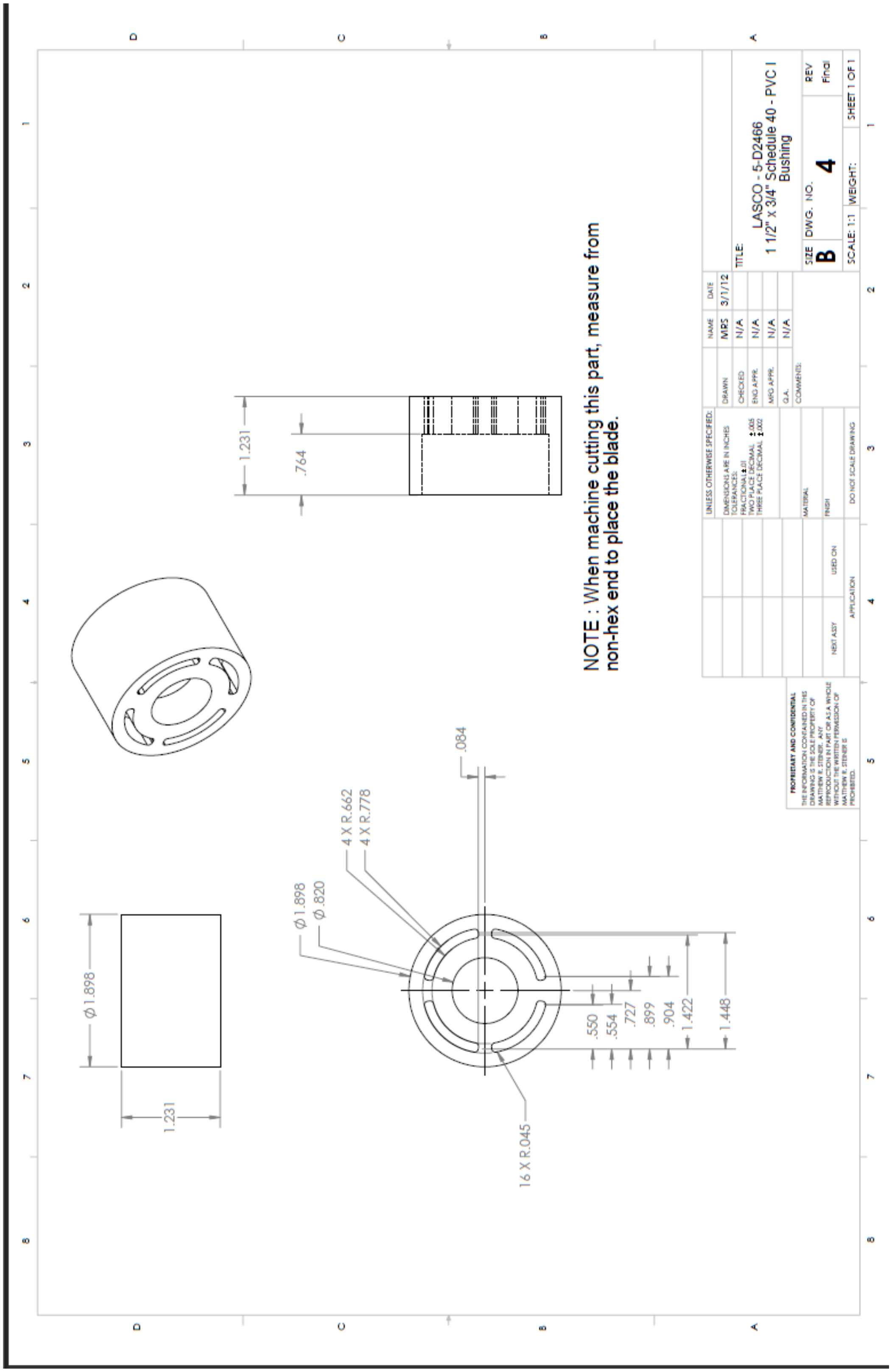
Drawing 2 - Wooden Dowel Drawing



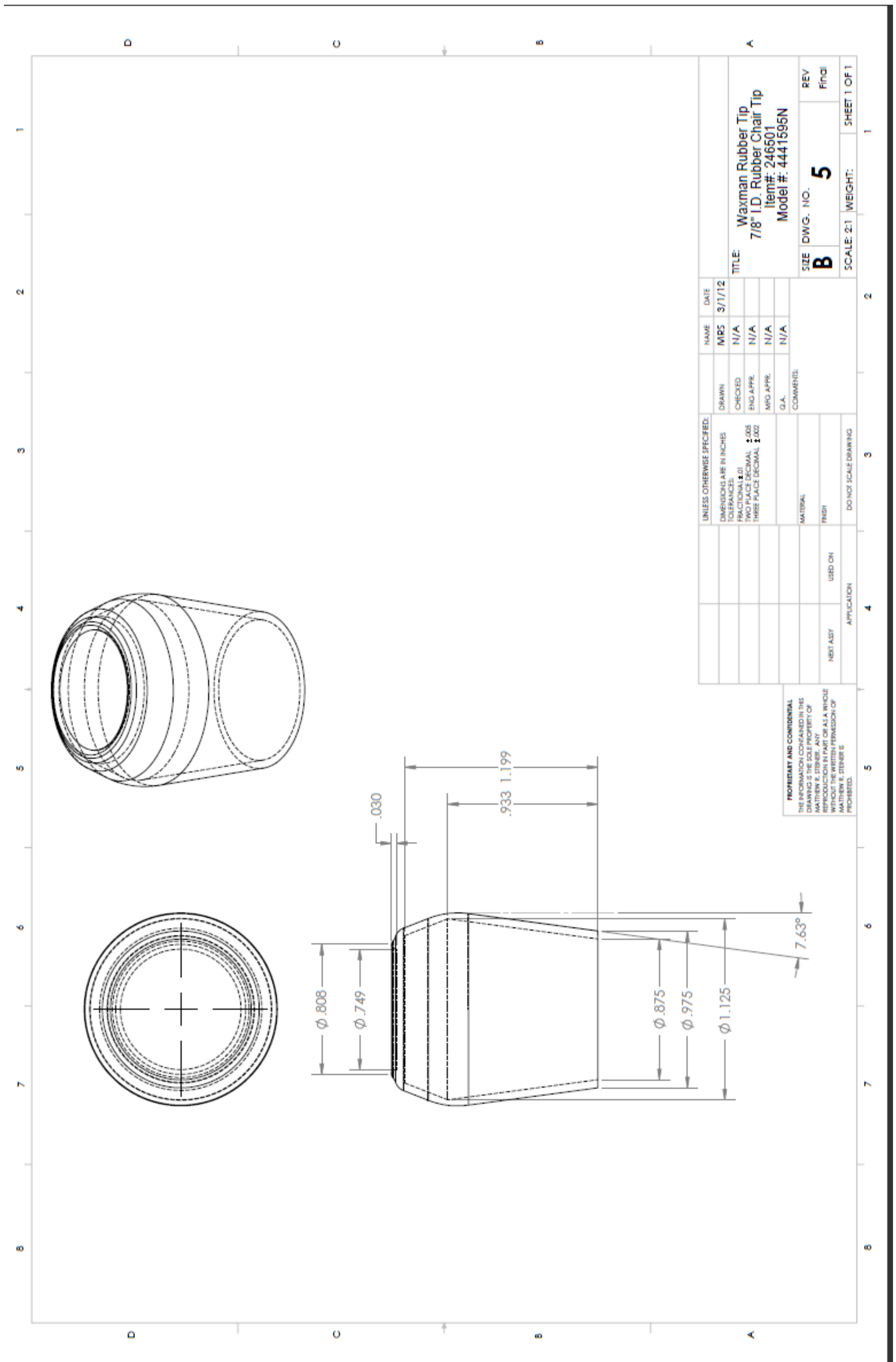
Drawing 3 - LASCO - D2466 Machined 3/4" End Cap Drawing



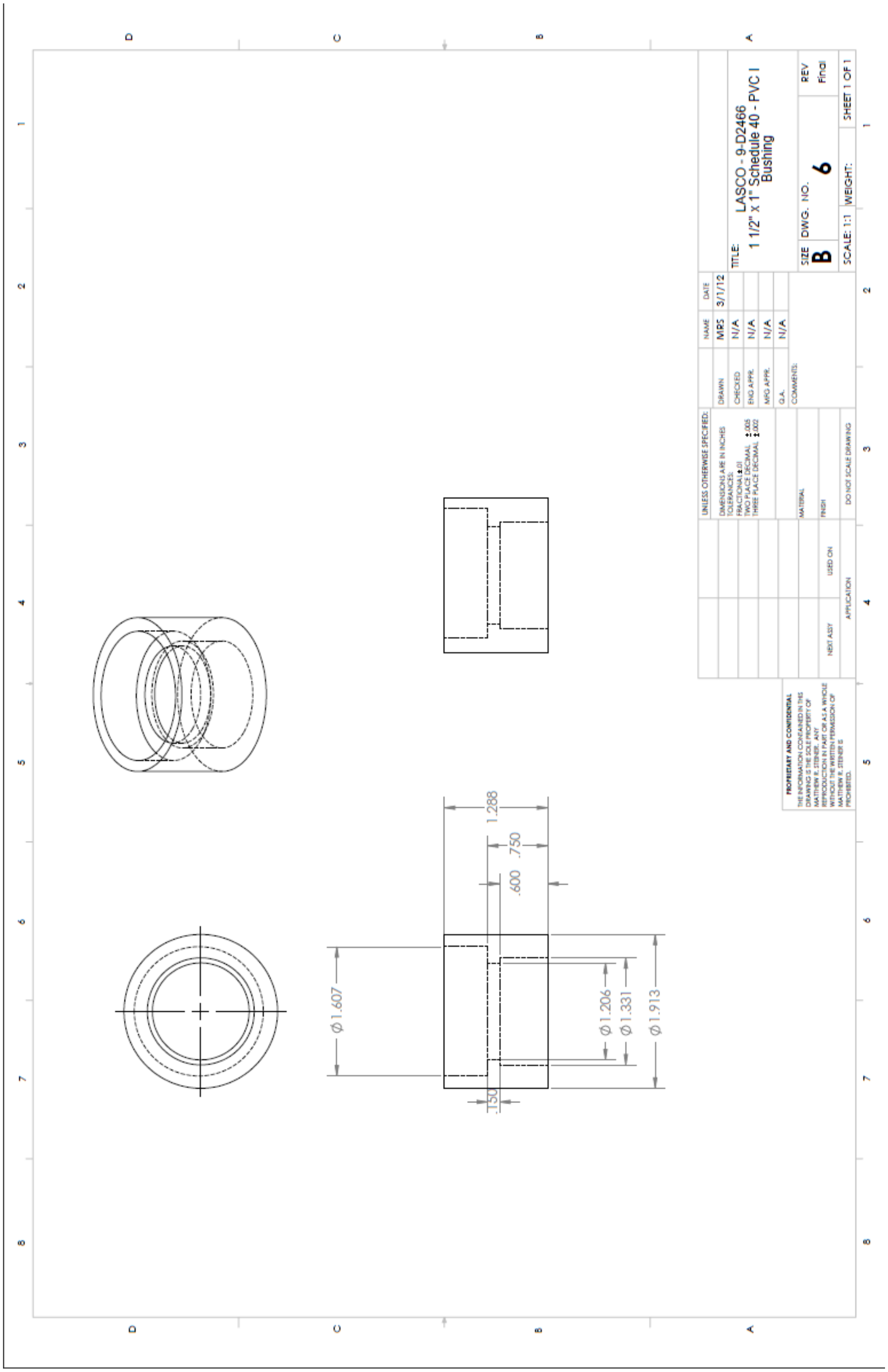
Drawing 4 - LASCO - 5-D2466 1 1/2" x 3/4" Bushing Drawing



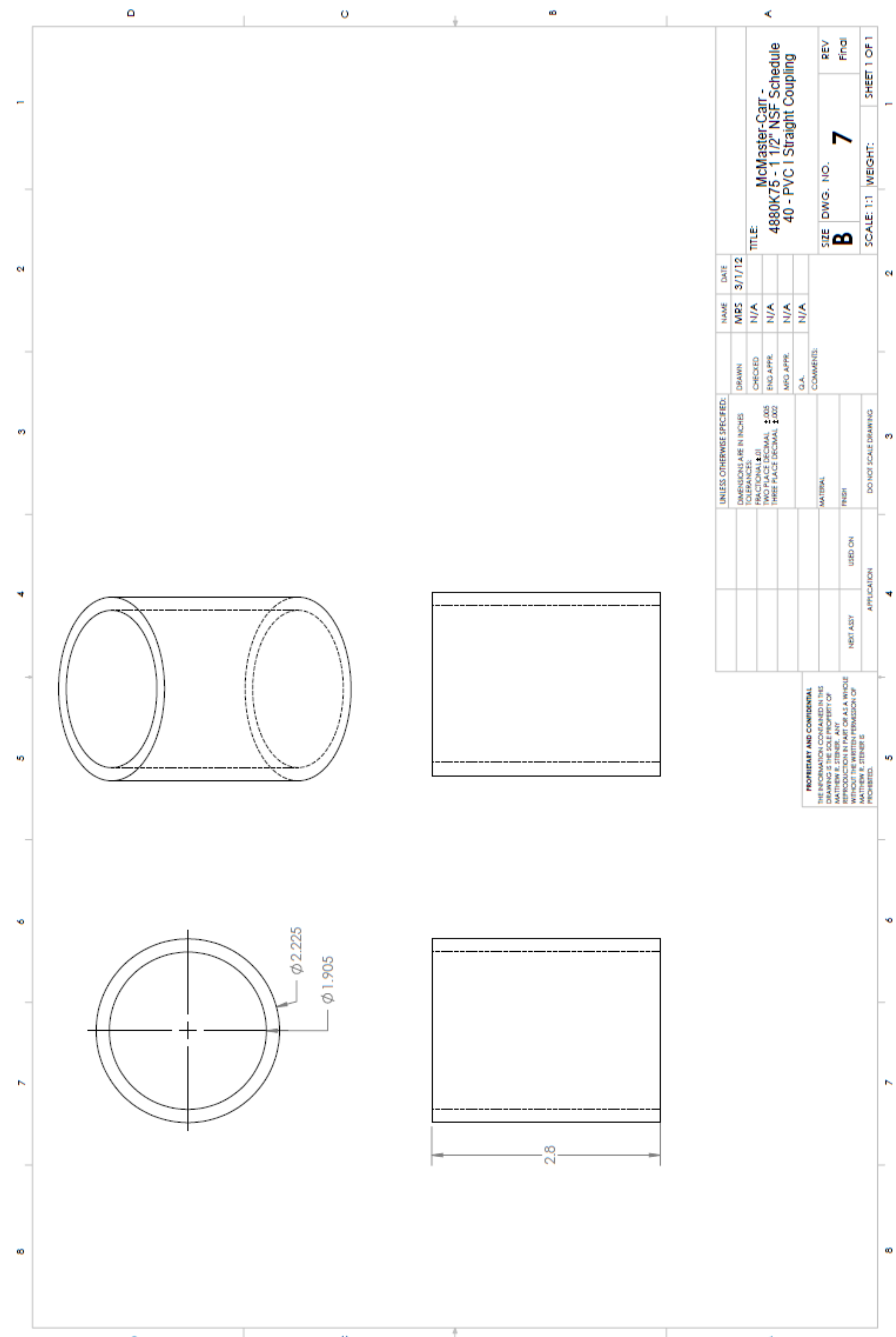
Drawing 5 - 7/8" Waxman Rubber Tip Drawing



Drawing 6 - LASCO - 9-D2466 1 1/2" x 1" Bushing Drawing



Drawing 7 - McMaster-Carr -4880K75 - 1 1/2" Straight Coupling Drawing



Appendix 4 - Minor Losses of Fittings (Cengel & Cimbala, 2010)

Component	**Description**	**K_L**
Pipe Inlet	Re-entrant (pipe thickness is much smaller than pipe diameter, and pipe extension into reservoir is one-tenth the diameter of the pipe)	K_L=0.80
Pipe Inlet	Sharp-edged entrance	K_L=0.50
Pipe Inlet	Well-rounded (radius of edge-filet is greater than two-tenths of the inlet diameter)	K_L=0.03
	Slightly-rounded (radius of edge-filet is equal to than one-tenth of the inlet diameter)	K_L=0.12
Pipe Exit	Reentrant (pipe thickness is much smaller than pipe diameter, and pipe extension into reservoir is one-tenth the diameter of the pipe)	$K_L=\alpha$
Pipe Exit	Sharp-edged	$K_L=\alpha$
Pipe Exit	Rounded	$K_L=\alpha$
Sudden Expansion and Contraction	Sudden Expansion	$K_L = \alpha(1 - \frac{d^2}{D^2})^2$ d: smaller diameter D: larger diameter
Sudden Expansion and Contraction	Sudden contraction	K_L varies from 0.5 when $\frac{d^2}{D^2}$ is 0. And 0 when $\frac{d^2}{D^2}$ is 1.
Gradual Expansion and Contraction	Expansion d/D=0.2 $\theta = 20°$	K_L=0.30
Gradual Expansion and Contraction	Expansion d/D=0.4 $\theta = 20°$	K_L=0.25
Gradual Expansion and Contraction	Expansion d/D=0.6 $\theta = 20°$	K_L=0.15
Gradual Expansion and Contraction	Expansion d/D=0.8 $\theta = 20°$	K_L=0.10
Gradual Expansion and Contraction	Contraction $\theta = 30°$	K_L=0.02
Gradual Expansion and Contraction	Contraction $\theta = 45°$	K_L=0.04
Gradual Expansion and Contraction	Contraction $\theta = 60°$	K_L=0.07
Bends and Branches	90 degree smooth bend	K_L=0.3 (flanged) K_L=0.9 (threaded)
Bends and Branches	90 degree miter bend	K_L=1.1 (without vanes) K_L=0.2 (with vanes)
Bends and Branches	45 degree threaded elbow	K_L=0.4
Bends and Branches	180 degree return bend	K_L=0.2 (flanged) K_L=1.5 (threaded)
Bends and Branches	Tee (branch flow)	K_L=1.0 (flanged) K_L=2.0 (threaded)
Bends and Branches	Tee (line flow)	K_L=0.2 (flanged) K_L=0.9 (threaded)
Bends and Branches	Threaded Union	K_L=0.08
Valves	Globe valve (fully open)	K_L=10.0
Valves	Angle valve (fully open)	K_L=5.0
Valves	Ball valve (fully open)	K_L=0.05
Valves	Swing check valve (fully open)	K_L=2.0
Valves	Gate valve (fully open)	K_L=0.2
Valves	Gate valve (1/4 closed)	K_L=0.3
Valves	Gate valve (1/2 closed)	K_L=2.1
Valves	Gate valve (3/4 closed)	K_L=17

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Education

The Pennsylvania State University
Bachelor of Science in Mechanical Engineering, May 2012
Minor: Engineering Leadership Development
Honors in Mechanical Engineering and Engineering Leadership Development

Schreyer Honors College
Thesis Title: Design, Testing and Analysis of an Inline One-Way Valve for Developing World Agricultural Water Transfer Applications
Thesis Supervisor: Dr. Richard J. Schuhmann

Experience

WESTINGHOUSE ELECTRIC COMPANY May 2011-August 2011
Madison, PA
Turbine-Generator Engineering Intern

- Performed a full turbine-generator outage walk-down with customers and labor contractors at Callaway Nuclear Generating Station
- Designed, qualified, and built a pump-loop to test shaft torque on a reactor coolant pump to support a rapid development project related to a loss-of-coolant accident
- Provided support in the compilation and development of technical descriptions of bids for domestic and international customers' outages
- Developed multiple Android applications to aid on-site project management during field services on nuclear turbine-generator units

OTIS ELEVATOR COMPANY May 2010-August 2010
Farmington, CT
Systems Engineering Intern

- Worked within a global systems team based both in the United States and Japan in the development of high-rise elevators
- Delivered technical presentations regarding my project to company executives, directors, and managers at multiple stages throughout the project's duration

Honors and Awards

- Recipient, Schreyer Academic Excellence Scholarship
- Valedictorian, Yough Senior High School - 2008

Activities

- TEDxPSU, Director of Content, *Spring 2011-Spring 2012*
- The LION 90.7fm - WKPS State College
    - President and General Manager, *Spring 2011-Spring 2012*
    - Community Manger, *Spring 2010-Spring 2011*
    - Director of Programming for Classic Rock/Funk/Indie, *Fall 2010-Summer 2011*
- S.P.A.'s Distinguished Speaker Series Committee, *Spring 2009-Present*
- Phi Sigma Pi - The National Honor Fraternity, Brother *Spring 2009-Present*
- Volunteer, Jefferson Regional Medical Center *(600+ Hours)*