Novel Pump for Flow Chemistry Applications with Increased Reliability

by

Michael Rodrigo

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Abstract

Commercial pumps tested at MIT’s Jensen lab for applications pumping highly corrosive materials at medium pressure (100-300 psi) and a low flow rate (less than 50 mL/min) have proven unreliable. The most common failures observed have been check valve failure and insufficient chemical compatibility. Some of these pumps use dual reciprocating pistons to drive the fluid, requiring the use of four check valves. This lowers the reliability of the pump as a whole to an undesirable level. A novel pump system design could operate without the need for any check valves. Operating three diaphragm pumps in series creates a pseudo-peristaltic pump, but requires check valves on both sides of each diaphragm pump. Instead, a diaphragm pump was designed such that the diaphragm can completely seal at the apex of each stroke, eliminating the need for check valves between the pumps. Proper timing of the draw and pump phases of the cycle of each pump eliminates the need for check valves at the ends of the series as well. Thus, each stroke of the pump is able to drive fluid forward and seal to allow adjacent pumps to draw effectively and prevent them from creating backflow. Additionally, current pumps have problems with chemical compatibility due to poor material selection. Thus, this new pump could be made to be more reliable and more robust against corrosion by choosing materials with high chemical compatibility. The scope of this thesis is only the design of one of the diaphragm pumps to be used within the three pump system described above.

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1. Introduction

Reliability is critical for any system. When a system operates in series, its overall reliability is heavily dependent on its least reliable component. Thus, a single unreliable component can often have a great impact on the reliability of the entire system. This project aims to increase the reliability of a system by reducing the impact of its least reliable component.

The Jensen Lab at MIT has used many commercially available pumps at a low flow rate (less than 50 mL/min) and medium pressure (100-300 psi) for highly corrosive materials, and they have proven themselves unreliable. The largest reliability problems for these pumps are the check valves. Particulates can become lodged in the seat of the valve, preventing the ball from properly sealing and causing a leak. While they can be problematic, check valves are extremely useful and very effective when functioning properly, and it is undesirable to remove them from a system that has been designed to include them. In many cases, they can be cheaply replaced when they fail. However, this is still a cause for concern due to the maintenance required and the downtime caused. Additionally, in corrosive environments requiring more expensive check valves made with exotic materials, cost can become a larger issue.

Some commercially available pumps use dual reciprocating pistons to drive the fluid, requiring the use of four check valves, lowering the reliability of the pump as a whole to an undesirable level. A novel pump system design can operate without any check valves. Operating three reciprocating pumps in series can create a pseudo-peristaltic pump, but would require check valves on both sides of each pump. Instead, a diaphragm pump was designed such that at the diaphragm can completely seal at the apex of each stroke, eliminating the need for check valves between the pumps. The timing of the draw and pump phases of each pump can be used to eliminate the need for the check valves at the ends of the series as well. Thus, each stroke of the pump is able to drive fluid forward and seal fully, in order to prevent any backflow. The elimination of check valves can make a significant increase in reliability of the system if the other diaphragm components can be made to operate with a high degree of reliability. However, as changes are made to the design in order to use fewer check valves, it is important to consider how they will affect the reliability of the system as well. If another component within the pumping system becomes more unreliable than the check valves, then reducing the number of check valves in the system becomes less impactful on the overall reliability of the system.

Finally, current pumps have problems with chemical compatibility due to poor material selection. Thus, this new pump could be made to be more robust against corrosion by choosing the correct materials according to its intended purpose. This is less important to the design process than the elimination of check valves due to its lesser effect on overall reliability, but is still a worthwhile feature to add to the pump. While it is not discussed at length within the review of this design because of its smaller impact, it remained a factor in the decisions made throughout the design process.

It must be noted that the scope this thesis does not include the entirety of the pumping system. It only includes the design of the pump element (that is, one diaphragm pump out of the three pumps and various other components needed for the entire system), and describes the entire system as motivation for the design of this specialty pump.

2. Design of the Pump Component

Several types of pumps were considered and investigated, and the diaphragm pump was chosen for its simplicity in sealing and achieving chemical compatibility. Additionally, a specially designed diaphragm pump can form a seal at the apex of its stroke, replacing a potential check valve. This also brings into question whether the diaphragm needs to be normally open, normally closed, or if it does not affect the performance. The entire system needs to be normally closed in case of power outage or other failure in order to prevent backflow from the high pressure system into the atmospheric pressure supply (and a potential spill). However, the timing of the three diaphragm pumps can always have one sealed, thus rendering the system as a whole normally closed.This reasoning led to some normally closed but more complex design ideas being eliminated in favor of ideas that were not normally closed but were easier to design and implement. The design was modeled in Dassault Systèmes' SolidWorks and prototyped by Proto Labs' Firstcut. For simplicity and cost, the prototype uses aluminum and a standard rubber elastomer instead of more expensive chemically compatible materials and was tested with only water.

2.1 Summary of the Design

The design of the diaphragm pump component, as well as the rationale behind some of the design decisions, follows. An exploded view of the SolidWorks model is shown in Appendix A.

The main structure of the component consists of 1/16" fluid channels embedded in a metal block made of a nickel superalloy such as Haynes International's Hastelloy or Special Metals Corporation's Inconel. These materials were chosen due to their high degree of chemical corrosion resistance. The fluid channels lead to the pressure chamber where the diaphragm is actuated. The diaphragm is made of a chemically compatible elastomer such as DuPont's Kalrez. The diaphragm is held in place by a press disc, which is fastened with set screws in a cap. The piston's forward travel is limited by the cavity and a second cap limits its rearward travel. (Note that this second cap exists only for the testing prototype; it would not be present in a production model. This will be explained in more depth in the following section.) The fasteners and fittings are neither pictured nor described in detail because they are simple sourced parts.

2.2 Detailed Design of Each Component

2.2.1 Cavity

The cavity is pictured below in Figure 1:

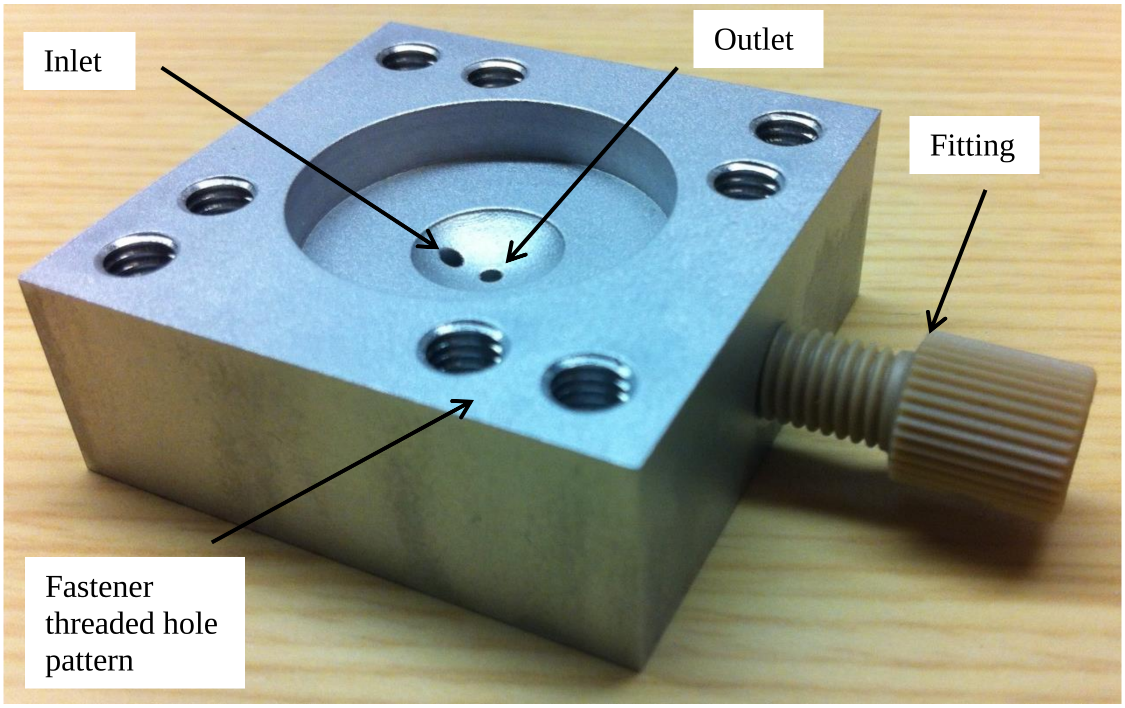

Figure 1: Cavity

The cavity's design is mostly just to contain the inlet and outlet channels and the pressure chamber. It is considerably larger than necessary for simplicity in fastening using manageably large screws and to confirm that strength is not an issue, even under high load. It has threaded inlet and outlet ports for fittings on the sides so that it will sit securely on a bench. The diaphragm is designed to be actuated by a piston driven by a cam. The piston uses the diaphragm to not only drive fluid flow but also to seal the chamber at the apex of the stroke. It was reasoned that only the outlet flow needed to be completely sealed to prevent backflow, although it was advantageous to seal both. Thus, the outlet hole was positioned in the center of the chamber, where it is expected to be sealed the most reliably, whereas the inlet hole is off center. Depending on the manufacturing process of the production model, the inlet and outlet holes should have filleted edges in order to reduce drag on the fluid and to create better seals with the diaphragm.

2.2.2 Diaphragm

The diaphragm and press disk are pictured below in Figure 2:

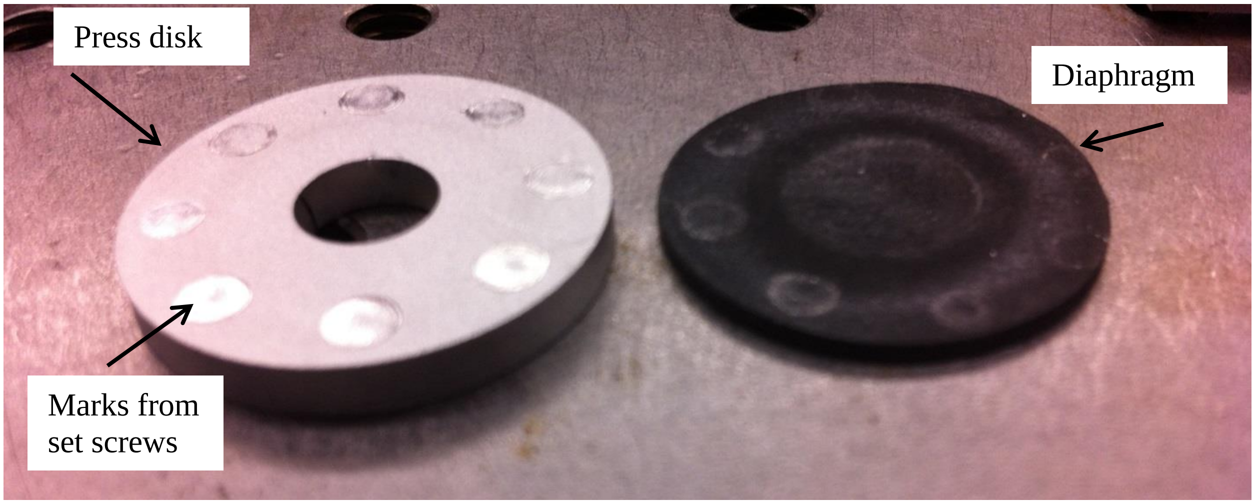

Figure 2: Press disk and diaphragm (left to right)

The diaphragm is simply a circular piece of rubber, somewhat arbitrarly chosen to be 0.9mm thick. The only important design decision for this component is the material, which is chosen for chemical compatibility.

2.2.3 Press Disk

Securing the diaphragm with a disk was an experimental design decision. Dr. Adamo had previous experience securing diaphragms through holes cut near their edges, but they sometimes tore near these stress concentrations. In order to prevent this, the diaphragm is held with the disk and secured by set screws. It was a risk that the compression needed to hold the diaphragm firmly enough would cause enough deformation of the material to cause it to bulge in the middle. This effect could reduce the volume of (or even remove entirely) the fluid packet being displaced in each stroke. The prototype would determine how feasible this idea is.

2.2.4 Cap

The cap is shown below in Figure 3:

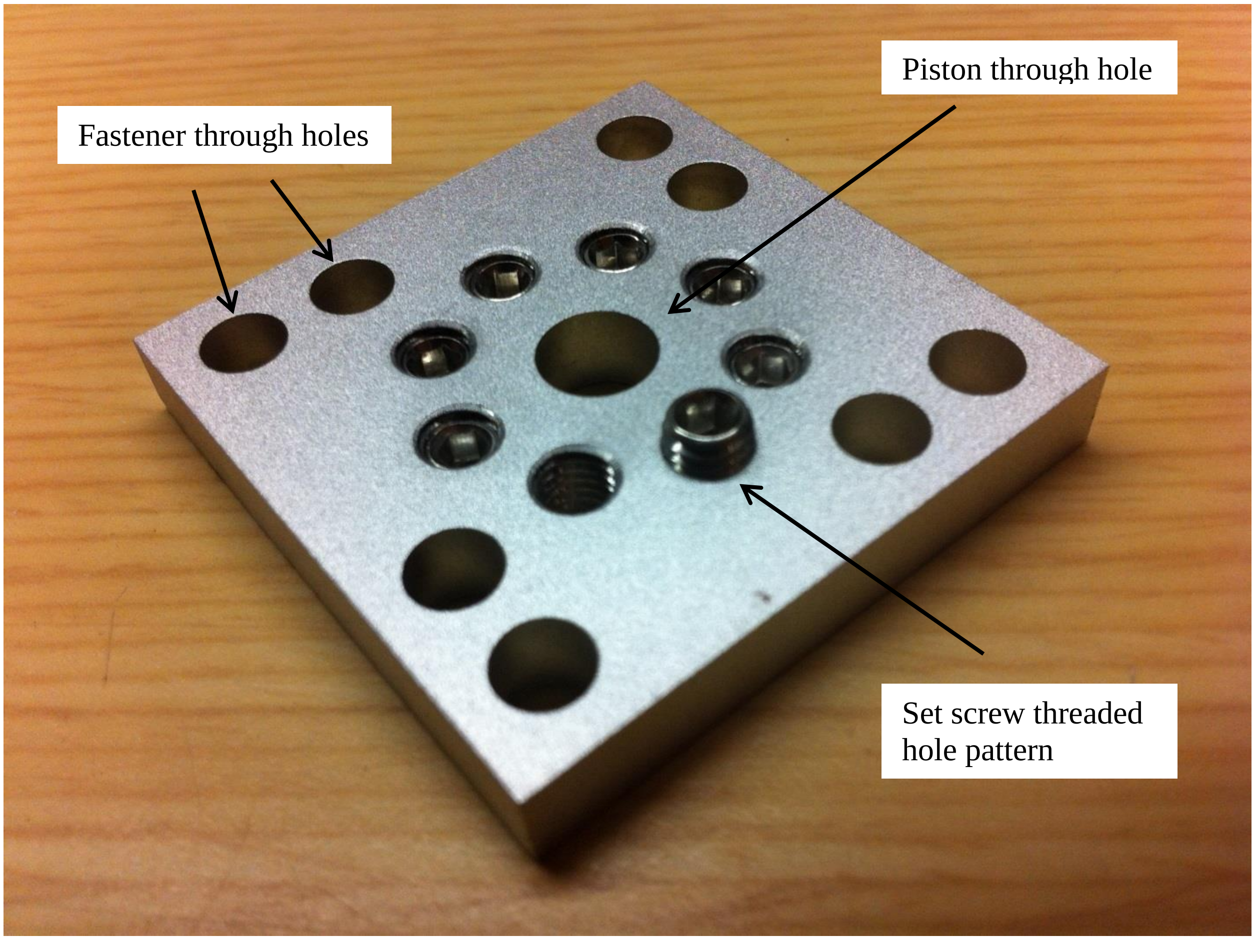

Figure 3: Cap

The cap can be secured to the cavity using screws, after which the set screws can be tightened to secure the press disk and diaphragm. A large number of set screws were added to help ensure an even distribution of force across the press disk and to prevent the disk from deforming.

2.2.5 Piston

The piston is pictured below in Figure 4:

Figure 4: Piston

The head of the piston is designed to mate with the entire bottom surface of the pressure chamber, taking into account the thickness of the diaphragm. The end of the larger radius section is used as a backstop in the detent of the second cap shown below for the testing prototype. In a production model, a cam would drive the piston. Thus, the cam follower would limit its rearward travel. This eliminates the need for a second cap.

2.2.6 Second Cap

The second cap is picture below in Figure 5:

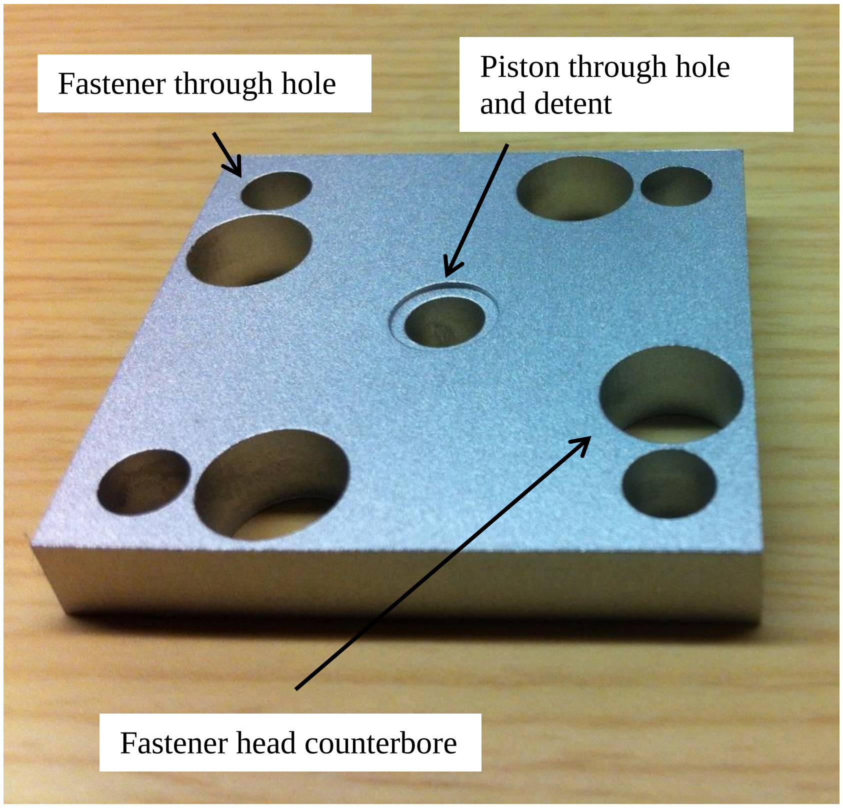

Figure 5: Second cap

The second cap fits over the heads of the screws that hold the cap in place and is fastened in the same way as the other cap. The detent holds the piston at a defined position as the rear apex of its stroke. As previously mentioned, this part is only for a hand-operated testing prototype; it would be eliminated in the cam-operated production model.

3. Experimental Evaluation of the Component

After receiving the prototype from Firstcut, the parts were inspected and measured to ensure that they were accurate. Minor problems included holes not drilled to the appropriate depth and holes being slightly undersized. After repairing these issues, the pieces fit together snugly and were able to attain the proper motion without binding. However, once it was tested with water, more problems began to surface. The experimental setup is shown below in Figure 6:

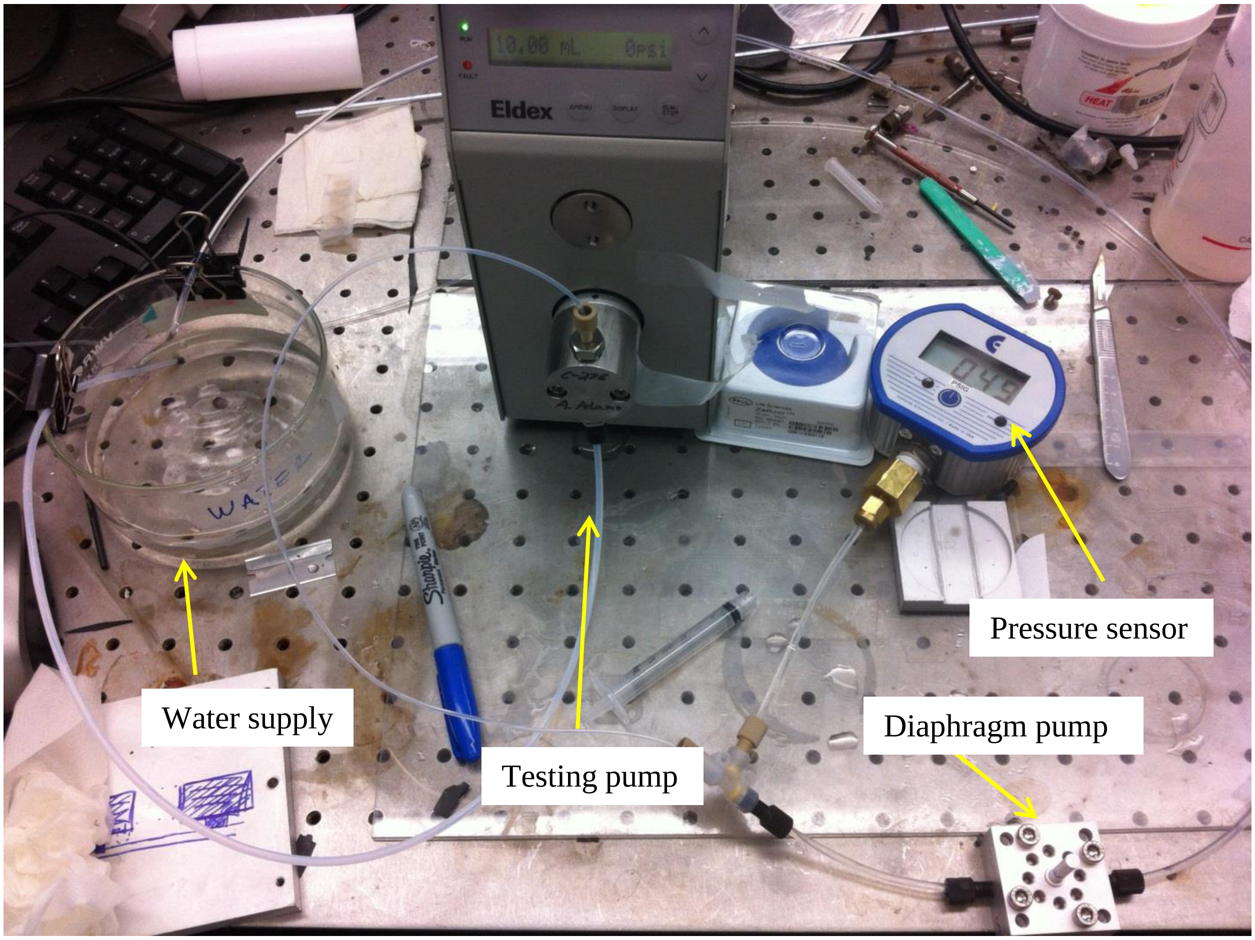

Figure 6: Experimental setup

The first test was whether the diaphragm could properly seal, thus blocking the flow of the pressurized water provided by the pump. First, the pump was assembled: the fastening screws were heavily tightened, while the set screws were only lightly tightened. The device did not leak when the pump was engaged, and depressing the piston halted all flow. Unfortunately, once the pressure grew above 100 psig, the device began to leak (water rose from the piston hole and the set screw holes). The set screws were tightened in order to better secure the diaphragm. After tightening, the diaphragm was visibly deformed when viewed through the piston through hole. When the pump was turned on, flow resumed but the pressure sensor read 40-50 psig. However, when the piston was depressed, the device was sealed and the system pressure peaked at ~300 psig before other fittings began to leak. None of the leaks were due to the diaphragm pump, and it was determined that 300 psig was high enough for this prototype. Thus, troubleshooting other pieces of the setup was unnecessary.

As the testing continued, it became clear that the diaphragm was slipping towards the center as the piston dragged it down. The press disk could not hold it tight enough without compressing the material so much that it expanded into the cavity, obstructing the flow. In an attempt to combat this problem, the press disk was machined to compress a smaller volume of diaphragm. The hypothesis was that if the disk pressed on a smaller area, in would cause less deformation and thus the diaphragm would expand less into the cavity. Unfortunately, due to time and resource restraints a new part could not be made. Thus, the existing part was machined; the thickness was turned down, leaving a ring of a much smaller diameter near the piston through hole. (It would have been preferred to have the ring on the outside of the disk, but that was too difficult to fixture. Instead, the disk was pressure turned from the outside edge.) The remachined press disk was tested in the same setup and still deformed the diaphragm, but to a lesser extent than it did originally. However, it again could not prevent the diaphragm from slipping while leaving the diaphragm in a functional state. Additionally, check valves were added to the system and the diaphragm pump proved it could pump water effectively for many cycles. However, as piston force increased, the diaphragm began to slip and eventually prevented all flow. It should be noted here that the check valves are only required in this system because this test prototype only includes one diaphragm. This is a test of only that single component, not of the whole system (which includes three diaphragm pumps and various other components). The system as a whole would not require check valves.

4. Summary and Conclusion

The novel pump design proved to be watertight to a reasonable pressure when sealed and able to pump correctly for a number of cycles, but inadequate diaphragm fixturing causing both leaking and pumping problems. Too little clamping force led to leaking and the obstruction of flow by the diaphragm due to slipping, and too much clamping force led to the obstruction of flow by the diaphragm due to deformation. It is expected that a new press disk or other fixturing method would allow this device to function well enough to be studied further. All of the other components of the pump performed well enough that no faults were detected during testing.

This initial work serves as a proof of concept: it is possible to construct a specially designed diaphragm pump that is able to pump liquid as well as seal fully against backflow. It is believed that three of these pumps in series can replace a dual reciprocating pump that requires four check valves. If the rest of the parts would be able to be operated with the same reliability, the diaphragm based pump would have a reliability advantage due its fewer number of check valves. Further work is required in order to prove that this three pump system can be created and operated successfully.

Further work:

The layout of the system must be created to connect the three diaphragms in series and drive them with a cam to operate in correct timing. Many of the necessary parts can be sourced cheaply.

Particulates getting caught in the seats of check valves are a common failure mode. Thus, the use of filtration is worth considering either as a standalone process prior to use in the pump or as a component of the pump itself to be used in real time. This could give a pump that includes check valves a greater degree of reliability, but could add to maintenance costs. Testing of this hypothesis might change the assessment of how impactful a system like the one described in this thesis can be, as filtering could increase existing pumps’ reliability while not affecting the reliability of the system described here.

It should be noted that the cam actuation timing should be set such that there is no time when all three diaphragm pumps are open. Additionally, the diaphragms must not be backdriveable. This prevents backflow in case of power failure or other failure.

Appendix A: Figure 7: Exploded View of SolidWorks Model

Figure 7: Exploded view of SolidWorks model