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# Pistonless Pump System for Accelerated Development of a Heavy lift LOX Hydrocarbon Engine

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**This paper will discuss an alternative to turbopump technology to address the necessity for a low cost, reliable heavy lift propulsion system. The pistonless pump can provide cost, reliability and development and integration time improvements that will allow for the propulsion system development in a reduced time frame, so that the program will achive sustainable political momentum. The pump and gas generator system analysis design and test are described in full, along with test results for an LN2 pump that provides 400 psi at 2 gpm with less than 3% pressure variations and test results for a zero gee pump. For the purposes of this paper, a pump for a LOX Kerosene first stage engine with 2 MLBF (9MN) thrust and 1500 psia (10MPa) chamber pressure will be described.**

## Nomenclature

$T_f$ = Time for chamber to fill
$T_v$ = Time for chamber to vent
$T_p$ = Time for chamber to pressurize
$T_d$ = Time for chamber to dispense

## I. Introduction

A heavy lift rocket with man rating capability is necessary for human exploration of the solar system. The key is to develop a vehicle quickly, before the design process gets politicized. The tall pole in the launch vehicle development is the turbopump, which is the single most expensive and time consuming part of the vehicle. A vehicle with 5 engines of 2 million lbs thrust is one possible scenario. Developing a new 2 Mlbf turbopump will take too long. Building a vehicle with strap on solids will be too risky, and using many of off the shelf engines drives up costs. An upgraded F-1a thrust chamber with a pistonless pump gets around this problem with a quick and straightforward design, test and integration process. This paper will include a description of the pump technology, a step by step guide to the pump design process, and a list of operational and development advantages. The pistonless pump does not have the performance of a staged combustion engine, but the development time, price and reliability areattractive A Typical pistonless pumped vehicle stage is shown in Fig. 1. This stage has only one engine, but the basic layout for a 5 engine design would be similar.

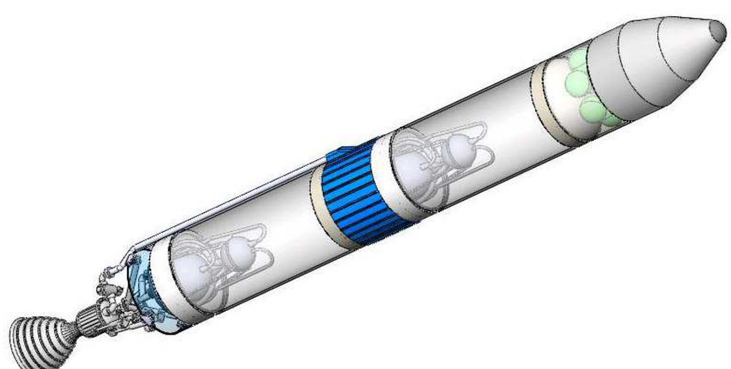

**Figure 1. Pistonless pumped Stage**

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## II. Description of the Pump Technology

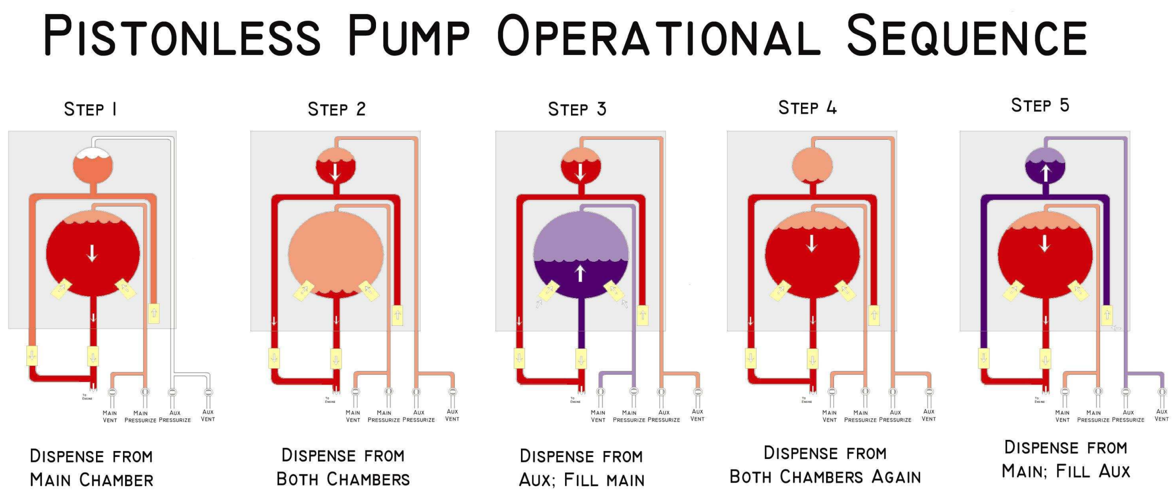


**Figure 2. Pistonless pump operational cycle**

The pistonless pump system is basically a pressure fed pump chamber that is periodically vented and refilled from the propellant tank through a check valve, and then pressurized to deliver propellant to the engine through another check valve. Two chambers, an main chamber and an auxiliary chamber with overlapping cycles provide steady output pressure. A detailed descrioption is available in Ref. 1. A diagram of the pump operation is shown in Figure 2. Two pumping chambers are used in each pump, each one being alternately refilled and pressurized. The pump starts with both chambers filled delivering from the main chamber (Step 1. Once the level gets low in the main chamber, the auxiliary chamber is pressurized; and flow is thereby established from both sides during a short transient period(Step 2) until full flow is established from the auxliiary chamber. Then the nearly empty chamber is vented and refilled. (Step 3) Then flow is again established from both chambers, (Step 4) The auxiliary chamber is refilled and finally the cycle repeats. This results in steady flow and pressure. In general only one chamber needs to have flow margin, so that is why the chamber sizes are asymmetrical. A diagram and photo of a liquid nitrogen pump that was developed for an LOX Methane RCS thruster appliction for NASA Glenn is shown in Figure 4-5. The pressurant gas can be supplied from a source of liquefied gas that is heated at the engine, such as liquid helium, or by heating the propellants themselves (autogenous pressurization). This basic pump design has been around for many years [3,4,5], and systems last a very long time, in fact one pump come with a 25 year guarantee[6]. The pump is much larger than an equivalent turbopump, but since it starts full of propellant, there is no decrease in overall propellant volume. A diagram of a pump that was build and tested is shown in figure 3. This system includes all the necessary parts to test the pump. For example, when pumping cryogenic fluids, all chambers and lines which may be filled with liquefied gas must have pressure relief valves on them.

## III. Pump Design Process

*1. Chamber pressure:*

The first step in the development process is to determine the best combustion chamber pressure. For a pistonless pump system, the pump weight is proportional to the pressure, but the pump weight does not drive the system design. Instead, the weight of the pressurant which drives the pump is the key factor, just as it is for a gas generator turbopump system. For a turbopump operating with a chamber pressure of 1000 psia and LOX HC propellants, the gas generator burns about 2.5% of the of the propellant in the gas generator. At higher pressures, proportionally more propellant is burned, and although the ISP increases with pressure, the optimum chamber pressure is on the order of 1000 psi. For a pistonless pump, the pump can run on helium stored at low temperature and heated at the engine, so the pressurant weighs only .5% of the propellant mass at 1000 psi. Therefore, the optimum output pressure for a pistonless pump system is approximately 1700 psi, which results in an increase in ISP as compared to a gas generator system. At this pressure, the helium weighs about 1% of the propellant mass and the pump weighs about 1% of the thrust. For details on this launch vehicle optimization process, see Ref. 2. Of course a staged combustion system has higher ISP, but it is quite expensive and the higher operating pressures lead to decreased reliability. The other extreme of the reliability and performance curve is a peroxide powered turbopump, as used on the Soyuz launch vehicle, which uses a larger percentage of the propellant to run the turbopump, but has an excellent reliability. The precise chamber pressure for the flight vehicle should be a compromise between performance and reliability, with reliability being more important.

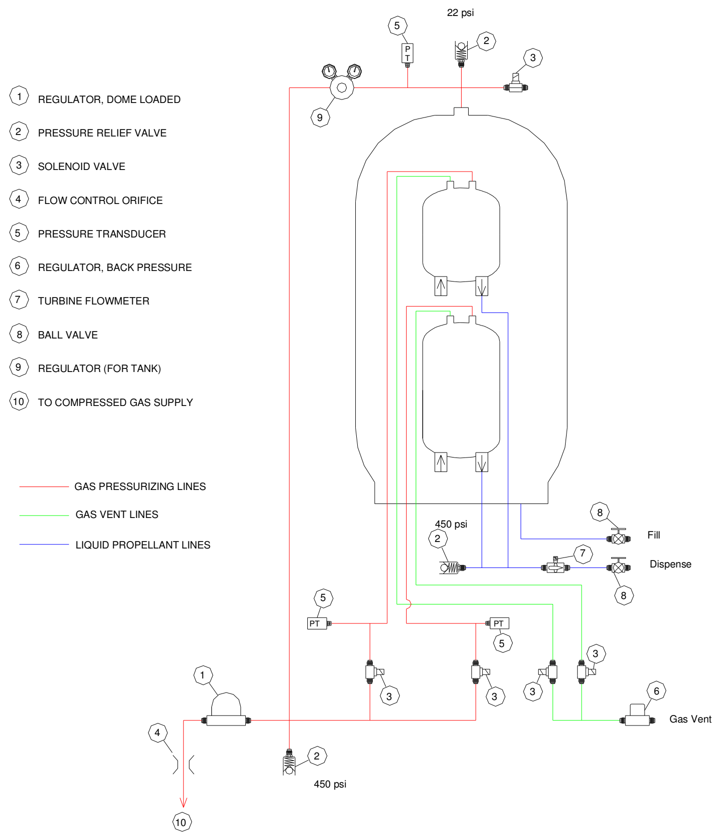


**Figure 3. Schematic for dual chamber pump.**

*2. Pump chamber design:*

The pump chambers can be spheres, cylinders or any other pressure vessel shape. In order to minimize the mass of the pressurant gas, it is best to use heated gas pressurant. This leads to a requirement to use metallic chambers, and stainless steel is best for heat resistance and specific strength. The optimum shape for a metallic pressure vessel is a sphere. The mass of the pump chambers is easily determined based on the pressure and volume requirements. The pump chamber volume is based on the cycle time and the required flow rate. The next step is to determine the required cycle time.

*3. Cycle time*

The pump cycle time should be as fast as possible to minimize the volume and thereby the mass of the pump chamber. However, the cycle time is limited by the response time of the valves and the time required to vent, fill and the pressurize pump chambers. The time required to dispense from the chamber should be longer than the other times, so that the main chamber can vent, refill and pressurize during the time that the auxiliary chamber is dispensing. The vent time is the time required for the pump chamber pressure to fall below the tank pressure so that the chamber can begin filling. Assuming that we are starting with a nearly empty pump chamber which is still full of pressurant gas, the first step is to open the vent valve, which takes about 30 ms. Then the pressurant gas flows through the valve under choked and then subsonic conditions. The vent valve is designed to open under a high delta pressure and then close under low deltaP, so the valve actuator power is low for a given valve flow area. For the given design, the vent valve diameter is 20 inches. The time to vent is ~100 ms. The next step is the fill process, wherein propellant flows from the tank into the pump chamber, In this step, the key is to diffuse the flow entering the pump chamber so as to minimize foaming or bubble entrainment of the incoming flow. We have developed a proprietary method of doing this which works very well. The time required to fill an 8 Ft diameter pump chamber is approximately 300 ms, with 2 24 inch diameter check valves. Just before the propellant reaches the top of the pump chamber, the flow is halted by the pressurization step. The propellant level can be sensed by a float based or capacitive level sensor. The pressurize time is a function of the flow rate of the pressurize valve and regulator, and if the pump chamber is nearly full of propellant at the end of the fill cycle, the mass of pressurant required is small, so this is can be a fast process, taking less than 100 ms. Then the dispense step can proceed while the auxiliary pump chamber is vented refilled and repressuuized. Ideally the dispense process is much longer than the vent, fill and pressurize process. A 3 second dispense time works well. This allows us to determine the main pump chamber volume, in this case it is 1800 gallons(7 $m^3$) The auxiliary pump chamber size is approximately 2/3 of the main chamber volume. The exact volumes can be determined based on optimization of the various portions of the cycle.

*4. Plumbing design*

The duct sizes can be quickly determined by the requirement that the dynamic pressure be much less than the static pressure, a few percent at most. Placing the pump chamber inside the tank can solve the issue of water hammer, fill duct sizing and thermal conditioning. This will require high pressure plumbing to the engine, but this problem has been solved for various pressure fed systems.

*5. Valves and Regulators*

The pistonless pump valve design or selection process is as follows. For the check valves, they operate slowly, with predictable changes in pressure, so the valves may be selected based on weight and reliability, and chatter is easily avoided. The outlet check valves need to be sized for low-pressure drop at the outlet flow rate, perhaps 2 to 4 psi. (less than 1% of the output pressure) The inlet valves need to be sized for about twice the flow rate of the outlet valves, so that the pump chambers can fill more quickly than they dispense. The pressure drop for the inlet check valves is based on the tank pressure and the desired inlet dynamic pressure. A check valve which is too small and has a high operating deltaP may require an elaborate diffuser to allow the pump chamber to fill without entraining residual pressurant gas, so the best solution is to use valves of excess capacity on the inlet check valves. If the pump is placed inside the tank, the valve seat can be built into the pump chamber wall, so the weight penalty for a large valve is low. The check valves need not be bubble tight, as a small check valve leak will not negatively impact the pump operation. A stainless valve with a brass or Kel-F sealing surface will work with most propellants. A system which uses two check valves in parallel in the main chamber allows the propellant to flow in evenly, so this is preferred arrangement.

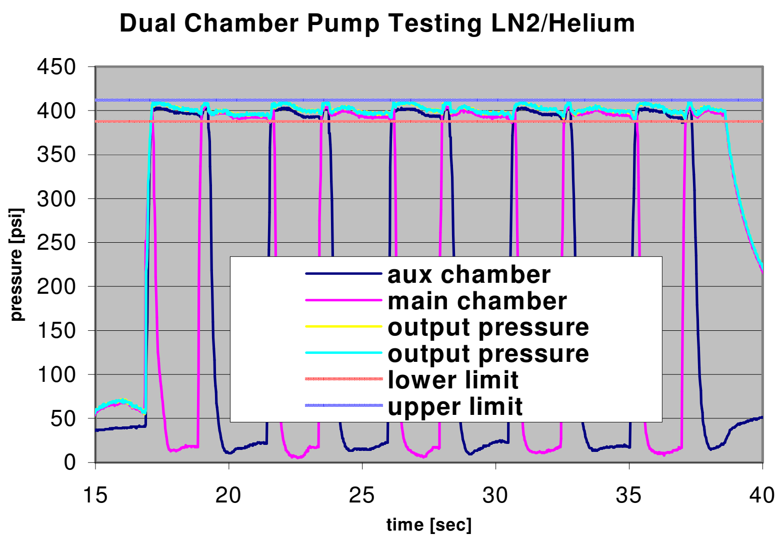


**Figure 4. Cryogenic pumping ($LN_2$ with helium) at 2 gpm**

The pressurize valves may be sized based on a pressurant flow rate of about twice the average flow rate so that the tank may be pressurized quickly. All of the gas valves shut under a low pressure differential, so a the valve actuator may be designed to take advantage of the situation, and use the force of the upstream gas to open the valve.

The vent valve must be larger than the pressurize valve, because in need to have a high flow rate of low pressure, low density gas in order to vent the chamber quickly. The vent valve may be sized based on the requirement that the chamber needs to vent in about 100 ms. A sonic/subsonic flow calculation can easily determine the required valve opening area. . Balanced poppet valves must have large balance flow ports, because sudden changes in pressure are normal for the pump chamber, and balanced poppet vent valves may burp when the chamber is pressurized

As the vehicle achieves high altitude, the vent system will need to maintain an adequate back pressure to prevent boiling of the propellant. The back pressure regulator must have a sufficient capacity to allow for quick venting of the pump chamber.

The pressurize regulator needs to be able to handle the sudden changes in flow rate as the pump cycles, without excess overshoot. During the pump chamber pressurization process, the flow will increase and then suddenly reduce as the chamber reaches the target pressure. The regulator needs to be able to handle the sudden changes in flow rate.

One way to deal with this is to use a regulator with a much greater flow capacity than is indicated by steady state flow conditions. This will reduce the required poppet movement and inertia, so that the overshoot and thereby the pressure spikes in the flow output will be minimized. Also, the demand curve of the pump is very predictable, so the regulator dynamics can be designed to minimize overshoot. For example the poppet mass and spring may be selected so that as the pressure reaches the target value, the spring and poppet are just rebounding towards the valve seat. The dynamics of dome loaded pressure regulators are well known[7].

*6. Gas Generator design*

The pistonless pump is a positive displacement system so the pump runs on gas volume, instead of dynamic pressure as a turbine does. Therefore, the lightest gas will result in the best performance. The preferred system uses a Dewar of liquid helium which is maintained at a pressure of approximately 100 psi. A gas powered piston pump pressurizes the supercritical helium to deliver it to the engine mounted heat exchanger. Pumps of this type have been described in reference 8 . Liquid helium pressurization was used successfully in the Apollo Lander and it currently used in the LOX tank pressurization system for the Ariane 5. For a launch vehicle, the pump system can be started with GHe from GSE equipment. The Helium can be heated using a nozzle mounted heat exchanger, or it can be heated by contact with the fuel. The nozzle mounted heater will provide the helium at approximately 500 F (260 C) The heater will be located in the aft portion of the nozzle, the exact switchover point from fuel cooled to helium cooled nozzle will be determined based on heat transfer calculations.

There is some concern that this vehicle will consume too much helium, but even at 12 launches per year it would consume less than 1% of the US helium production[9]. Helium used during ground test can be reclaimed.

*7. Control System:*

The control system uses information about the chamber levels, pressures and flow rate to determine when to actuate the pressurize and vent valves. Using more sensors than absolutely necessary allows the system to implement integrated vehicle health monitoring. For example the pump would normally actuate the valves based on the level in the chambers, but if propellant volume rate of change based the level sensors did not agree with the turbine meter output, the system could verify the flow rate based on the thrust chamber pressure and determine which sensors to ignore. It could then utilize the turbine meter signal, the level sensor signal or just timing to actuate the valves. The control system could also be redundant, or have a back up system based on timing alone. The control system would also be able to conduct preflight tests of the pressurization and vent valves. Slow valve actuation times could indicate that valves are becoming sticky. Shorter than normal cycle times could indicate leaking check valves, or longer than normal fill times could indicate sticky inlet check valves.

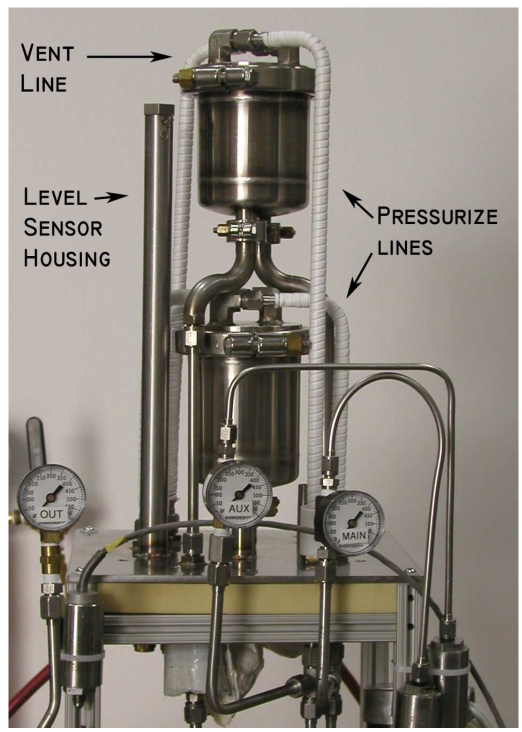


**Figure 6. Dual chamber pump with insulated pressurize and vent lines, and less tank**

*8. Tank pressurization system.*

A vent valve would be placed in between the pump chamber and the tank so that the pump vent gas could be used to maintain tank pressure. This valve would be placed in parallel with the auxiliary or main vent valve so that both valves could be open at once in order to maintain the quick vent operation. The tank pressure could be determined based on structural considerations, since the pump only needs 3-5 psi of pressure to fill quickly.

*9. Heat transfer.*

The heat transfer from the heated pressurant to the propellant should be limited in order to maintain consistent propellant density at the thrust chamber. The heat transfer to the propellant can be minimized by diffusing the pressurant gas as it enters the pump chamber in order to reduce the velocity and turbulence at the liquid to gas interface. In addition, during the initial pressurization process, the gas which is initially in the chamber will be heated by adiabatic compression. If the propellant is close to its boiling point, it may be subject to heating by adiabatic compression as well. At the end of the pump cycle, the chamber will be subject to adiabatic expansion of a larger sample of pressurant gas, so the net effect will in general be one of cooling. The exact amount of cooling or heatin can be calculated based on computational fluid dynamics.

*10. Pump Calculations Summarized*

The pump chamber volume can be sized based on a cycle time of 3 seconds. The auxiliary chamber should be about 2/3 the volume of the main chamber. The wall thickness of the pump chamber can be determined based on the pressure and required safety factor. Composites, aluminum, stainless steel or titanium can be used depending on propellant compatibility and heat resistance. For the current case of a 2 MLbF (MN) LOX kerosene system, the LOX flow rate is 30,000 gpm (2 $m^3$/sec) so the main LOX chamber diameter is 8 ft (2.2m) with a volume of 1500 gallons (5.7 $m^3$). A 16 inch duct can flow the required amount of LOX with a dynamic pressure of 5 psi.

The Cv for the outlet check valve can be determined, it is about 15000. A 20 inch valve with this Cv is available. 2 of the 24 inch valves can be used as the fill valves on the main chamber. For the auxiliary chamber, one 24 inch valve could be used for the fill line, and one 20 inch valve could be used for the dispense line. The output from both chambers should be connect together such that the head loss from either chamber is the same, this will minimize the change in output pressure as the flow is switched from one chamber to the other.

The Cv for the pressurize valve can be determined to be such that the pressure drop through the valve is also less than 1% of the static pressure. The required orifice size is about 8 inches to flow the required 42 kg/sec of helium with a low pressure drop.

For the vent valve, the calculation of vent time is more involved. The flow through the vent valve is initially sonic, and then becomes subsonic. A step-by-step calculation of pressure vs time is required. For this case, a 20 inch valve will reduce the tank pressure to less than 50 psi in .092 seconds.

Pressure regulator design

A dome loaded pressure regulator can be used to supply the pressurant to the pump. The regulator design may be guided by the steady state flow and the need to pressurize the pump chamber without excess overshoot. When the pressurize valve first opens, the pressure downstream of the regulator falls quickly and the regulator responds by opening abruptly. Once the space above the propellant in the pump chamber fills, then the regulator needs to switch to a steady state flow. If the regulator does not respond to the decrease in flow, pressure spikes will be the result. Ideally the volume in the lines leading to the pump chamber from the pressurize valve will be small and the pump chamber will be nearly full..

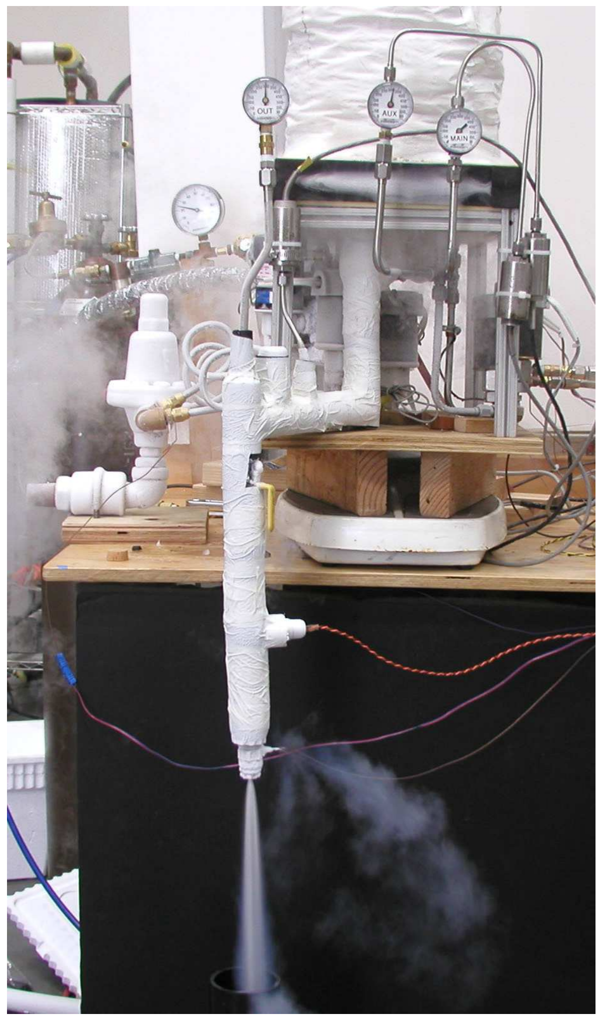

**Figure 7. Dual chamber pump undergoing cryogenic testing**

Pressurant Gas Calculation

The pressurant gas quantity can be determined based on the volume flow rate of the pump and the pressure and temperature of the pressurant. Because the pressurant is only in contact with the propellant for a short time, not much heat will transfer. For a large pump the time constant for the gas temperature is more than 10 times longer than the cycle time. This way the pressurant will stay hot for the duration of the pump cycle, and less pressurant mass is needed than for a pressure fed system of similar pressure and flow capacity. The pressurant flow rate needs to be increased by the ullage volume in the pump chamber, but this can be less than 5%.

*11. Pump development process.*

As discussed above, the cycle time, sizes and specifications of all the pump elements such as valves and regulators can be determined based on the required flow and pressure. One area that will need to be investigated more carefully is the filling process, to ensure that the liquid fills the entire chamber quickly with a minimum amount of gas entrainment and surface waves. This process can be optimized using CFD, and it can be tested with a low-pressure pump chamber model, since the dispense process is largely independent of the filling process. During this process, baffles and diffusers can be developed and tested to keep the phases separate. Once the fill process has been optimized using a low-pressure model chamber, a workhorse pump can be assembled and tested. Pumping fuel is quite easy, because there are no thermal issues. For cryogenic testing, the pump can be connected to a orifice and tested with LN2 at first, and then switched over to LOX with no design changes. Integration with the thrust chamber is straightforward because the pump provides full pressure at any flow, so there is no need to tune the pump and the engine together because as far as the thrust chamber is concerned, it is hooked up to a pressure fed system. The entire propulsion system can be designed based on a number of parallel paths for the pump, the thrust chamber and the gas generator, with well defined interfaces to facilitate final integration

*12. Pump design summary*

The pump for a 2 million lb LOX RP engine would have the following characteristics. (LOX pump)

| | | |
|---|---|---|
| Main Chamber Dia | 90 in | 2.2 m |
| Aux Chamber Dia | 62 in | 1.6 m |
| Inlet Check valve Dia | 24 in | .61 m |
| Outlet Check valve Dia | 20 in | .51 m |
| Pressurize Valve Dia | 8 in | .2 m |
| Vent Valve Dia | 20 in | .51 m |

**Table 1. Pump Component Sizing for LOX Pump for flow rate of 30,000 GPM (2 $m^3$/sec)**

The flow of pressurant would be 45 kg/sec, so 10% of the propellant volume would be devoted to helium. This could be injected partway down the engine nozzle, where it would provide additional thrust.

## IV Testing completed to date,

A number of different pump models have been built and tested for various applications. The pump has been tested with water at up to 100 gpm, liquid nitrogen at 400 psi and 2gpm and it has been tested with an Atlas Vernier rocket engine. It has also been tested pumping water under zero g. A pump was designed for NASA Glenn for the purpose of pumping propellants for a LOX Methane ACS. The goal was to pump LN2 at 2gpm with pressure fluctuations of under 3%, and the pump achieved the goals. The pump is shown in figure 5. It used pump chambers consisting of short pieces of sanitary stainless tubing. The entire pump assembly was placed inside a tank which was filled with LN2. In this case the pump cycle was controlled by timing and by monitoring the flow rate out of the pump using a turbine meter. A photo of the pump under test is shown in figure 6. This pump also included a back pressure regulator to keep the LN2 from boiling. For use on a high altitude vehicle, the back pressure regulator would need to be used to prevent boiling of the propellant as the pump chambers were vented.

## V Safety and Reliability

This type of pump is not new; in fact it has been used to pump groundwater out of basements for over 100 years, where reliability is critical. The present design operates much more quickly and works in space and in a zero gee environment, but the key to reliability is the slow moving parts and wide operational

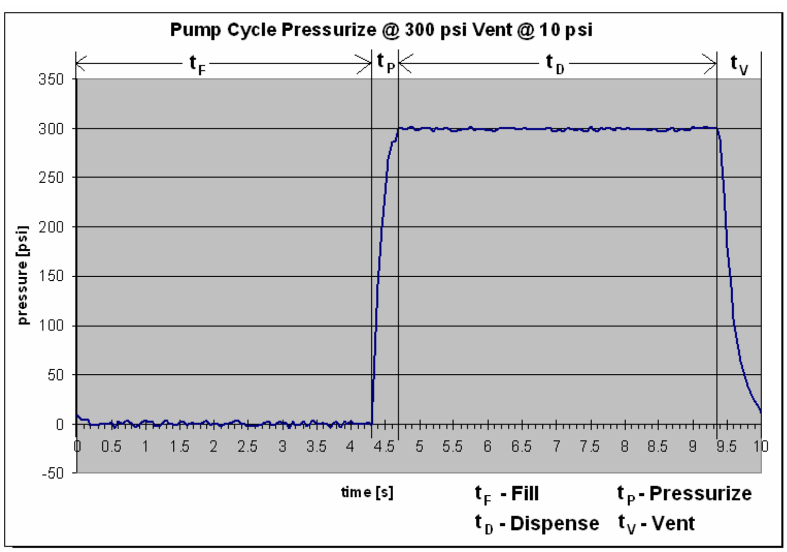


**Figure 8. Four stages of pump cycle as measured.**

tolerances, which allow the pump to work regardless of contamination, leakage or sensor failures. A complete FMECA analysis has shown that many of the failure modes of the pump involve reduction in performance and no single point failure can cause explosion or fire. If the valves on one of the chambers fail, there will be a few seconds in which to execute a safe shutdown of the affected engine.

## V Simulation

A mathematical model of the pump was developed to determine cycle times for a given pump geometry, valve set, pressurization gas, and fuel type. The equations were validated by the respective testing data on a single chamber pump with times calculated for each of the four stages of a pump cycle (pressurize, dispense, vent, & fill). The mathematical model is divided into separate analysis sections based on these divisions. An example of a test cycle performed with water as the liquid and air as a pressurant is shown in Figure 8 where each section of the main chamber pump cycle is clearly labeled.

The vent, pressurization, fill, and valve actuation times of the main chamber determine the sizing of the auxiliary chamber. The 4 stages of the auxiliary chamber are then calculated to provide a complete model of the pump cycle. This is shown in Figure 9. The fill time is based on the flow resistance of the inlet check valve and associated plumbing. The pressurize time depends initially on the choked flow area of the fill valve, and then once the pressure ratio is below about 2 (depending on the pressurant gas) the flow depends on the flow resistance of the valve, regulator and plumbing. The dispense time depends on the flow resistance of the outlet check valves and the flow resistance of the load. Finally the vent time depends initially on the choked flow area of the vent valve, and then once the pressure ratio is below about 2 (depending on the pressurant gas) the flow depends on the flow resistance of the valve, back pressure regulator and plumbing.

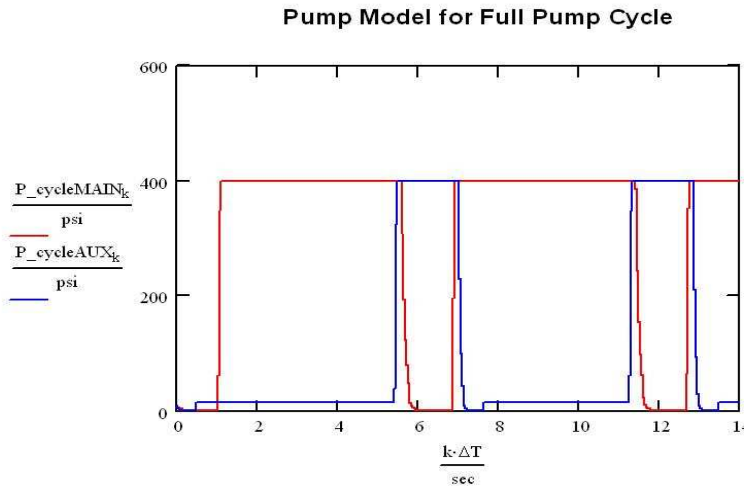


**Figure 9. Theoretical model of complete pump cycle for dual chamber pump with H20 and air.**

## VI. Zero-Gee Pump System

A model of the pump was designed, built and tested to show how the pump works under zero gravity. For successful zero gravity operation, the pump must be filled and emptied of propellant without dispensing any bubbles. Initial testing was done with water in a small pump chamber as a secondary experiment run at the Microgravity University at JSC (figure 10). The pump test system used an onboard air compressor, tank and regulator to supply air to a pressurized 'propellant' tank and the pump chamber. The pump chamber included electrodes to measure the fluid level. The water had 5% vinegar added to it to make it electrically conductive without leaving any residue. The pump system waited until the acceleration was less than 0.2g before it started cycling. The pumped was recorded with a video camera. It worked perfectly every time, with no bubbles in the output the meniscus for 15 parabolic flights,

## VII Pump Advantages

Increases *Safety*, *Reliability* and *Performance* while reducing *cost* and *development time*.

- The pump can be scaled up or down with similar performance and minimal redesign issues.
- Low risk development; pump technology has been demonstrated and prototypes have been built and tested.
- The manufacturing tolerances need not be tight.

- Pump and vehicle use inexpensive materials and processes in their construction
- Minimal pogo effect as tank pressure is decoupled from engine pressure.
- The pump is failure tolerant. A small leak in one of the check valves will only increase the pressurant consumption of the pump; it will not cause a pump failure.
- Software can be designed to keep a pump with redundant valves and sensors operational, despite failed sensors or valves.

**Figure 10. Zero gee pump under test during NASA Microgravity University flight**.

- Unlike other pumps, no problems with seals, cavitation, whirl or bearings
- It can be installed in the propellant tank to minimize vehicle size. Will not reduce volume of propellant tanks because pump chambers hold displaced propellant.
- Due to the simplicity of the pump design the engineering and test costs are low. The pump fluid dynamics can be proven with low cost materials, which can then be replaced with flightweight components.
- With the right choice of materials, the pump will be compatible with NTO, MMH, LOX and RP-1. This means a few pump designs can be used in many applications.
- Easier to integrate than turbopumps; provides constant, controllable pressure, regardless of flow.
- The pump can be run dry with no adverse effects. The pump can even purge the lines leading to the engine. This increases mass ratio over turbopump systems
- Negligible chance of catastrophic failure because typical failure modes are benign and there will be some warning of incipient failure. Astronauts can live through a pump failure.
- Check valves, level sensors and pneumatic valves can be made redundant if necessary. The check valves in particular can be made very reliable, while the pressurant supply and vent valves are small enough to allow redundancy. All these components are currently available as space qualified COTS components.
- Allows for design flexibility, arbitrarily shaped tanks can be located to control CG, and allow for an attractive OML, which is critical for customer or taxpayer acceptance. Very low input pressure required.
- For application in a weightless environment, the pump can be designed to have at least one chamber full at engine cutoff, thereby allowing for zero G restart with the propellant in the pump chamber providing the ullage thrust. This means that the propellant settling maneuvers and propellant control devices for the main tank are not required.
- The pump vent gas can provide roll control or be diffused and/or vented to both sides of the vehicle to minimize inadvertent application of thrust. The vent gas can also be burned for autogenously pressurized systems.
- Easy to start up and shut down, similar to pressure fed systems. No spool up time required.
- The gas and liquid valves are only required to operate for about 100-1000 cycles, so the valves would not be subject to significant wear.
- The pump can also be vented to a low pressure so as to reduce loads on propellant valves with seals subject to creep or degradation for long duration space flights.
- Overall vehicle reliability in emergencies should improve, because pump chambers allow limited propellant storage near the engines that can be used even if tanks lose pressurant.
- The pump also allows for efficient motor throttling with a response time on the order of the pump cycle time, that is 1-3 seconds,
- The pump works well at flow rates from zero to full flow, so it can be used to provide pressurized propellant for attitude control

- Pump can also be used to transfer propellant at low pressures.
- All valves can be made redundant for extra reliability.
- Pump can be powered by a recycling gas generator/radiator system which condenses gas used to run the pump and reuses it. This allows for very high mass ratios because the tank pressure can be very low.

## VIII Conclusions:

The pistonless pump system provides a pump for a reliable and safe rocket propulsion system. This pump, combined with a modestly uprated F-1 thrust chamber, can provide a 2 mlbf engine for the heavy lift needed to mount a Mars expedition, without an expensive and difficult turbopump development program. It can do this while improving the performance, safety and reliability of the vehicle.

## IX Acknowledgements

Thanks to NASA and Steve Schneider for providing support for the pump development program under contract NNX09CD13P. Thanks to Carl Tedesco for the drawing of the rocket with the pump.

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