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High Performance Lox Hydrogen Upper Stage with Pistonless Pump

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A scalable pistonless pumped upper stage is proposed. This stage uses an expansion cycle powered set of pistonless pumps to power a regeneratively cooled, moderate pressure thrust chamber. The exhaust from the pistonless pumps is used to power a set of vernier engines. The system ISP is nearly the same as the ISP of the RL-10 expander cycle engine, but this system is scalable and no precision parts are required. This system will be much quicker and less expensive to develop than a turbopump based system, due to the simplicity of the design and the fact that the integration of the thrust chamber and the pump is similar to a pressure fed design, with no complex tuning required. The required mass flow and heat flow rates are described for a typical upper stage. The expected ISP based on the chamber pressure and nozzle diameter has been calculated to be 446 seconds for the combination of a main engine and two verniers. The pump can also be used to pump liquid metals and fluorine to achieve an ISP of 524-580 seconds.

Nomenclature

EELV	=	Evolved Expendable LaunchVehicle.
ISRU	=	In Situ Resource Utilization
NPSH	=	Net Positive Suction Head
PMD	=	Propellant Management Device
RCS	=	Reaction Control System
RTG	=	Radioisotope Thermal Generator

I. Introduction

A high performance upper stage which is scalable will allow for a robust space launch capability. Currently, both EELVs use the RL-10 (A or B) engine for their upper stage. While this engine has an excellent history, there is concern with relying on a sole source for upper stage propulsion. Futhermore, if an upper stage engine were able to be scaled up or down easily, there would be more options to design exploration and satellite missions. The tall pole in the vehicle development is the turbopump, which is the single most expensive and time consuming part of the vehicle. An upper stage with one engine of 36 kblf thrust is one possible scenario that will be described in this paper. Developing a new turbopump will take too long. and using many off the shelf engines drives up costs. A regenerativly cooled 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 thermodynamics of the proposed system. The pistonless pump system comes within a few seconds of the performance of the Rl-10, but the pump works well with low NPSH, so it can utilize propellants which are very close to saturation temperature, or which are stored in very lightweight composite tanks. The development time, price and reliability are also attractive A typical pistonless

Figure 1. Pistonless pump with stacked cylindrical chambers

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pump design for use with autogenous pressurization is shown in Fig. 1. A model of this pump has been used to pump LN_2 with compressed air and has been tested up to 1000 psi with water.

II. Description of the Pump Technology

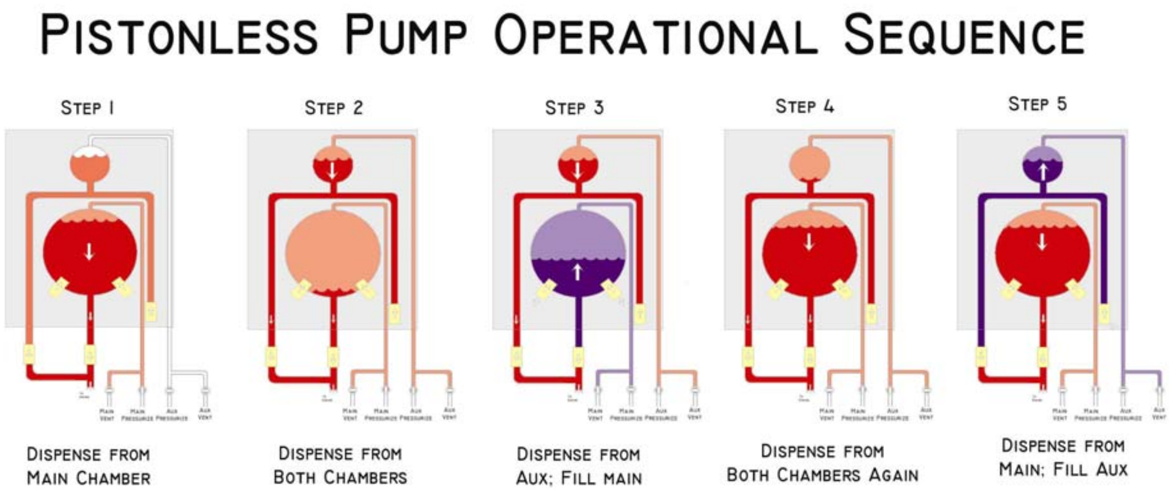

Figure 2. Pistonless pump operational cycle

1. Basic Concept

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, a main chamber and an auxiliary chamber, with overlapping cycles provide steady output pressure. A detailed description is available in Ref. 1. A diagram of the pump operation is shown in Figure 2. This diagram shows spherical chambers, but cylindrical chamber are more appropriate for use with autogenous pressurization. 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 chambers during a short transient period (Step 2) until full flow is established from the auxiliary 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 (see figure 3). 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 application for NASA Glenn is shown in Figure 3.

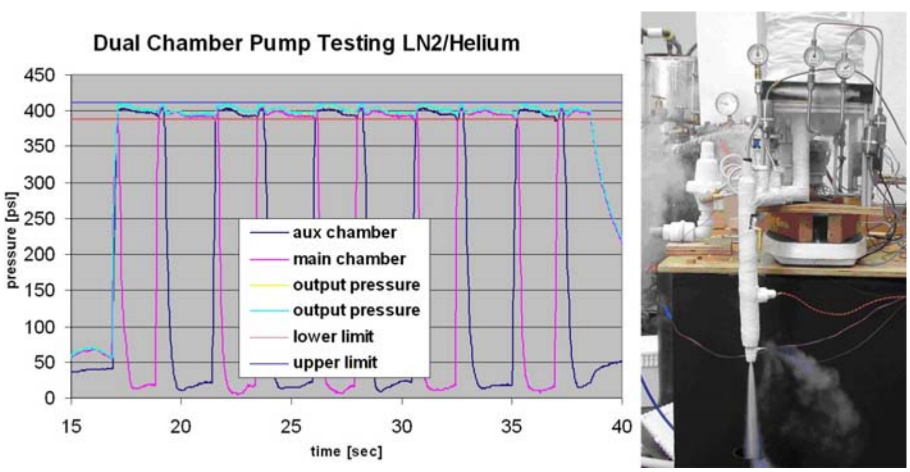

Figure 3. Pistonless Pump Performance with LN_2

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-described below). For pumps of any reasonable size, if the pressurant gas is sufficiently diffused, the thermal time constant of the pressurant gas is much longer than the cycle time of the pump, so collapse of the gas is not an issue. This basic pump design has been around for many years [3,4].

2. Pump System Performance Comparisons

The increase in the available payload for two recent pressure fed exploration missions if they were to use a Flometrics pump has been evaluated based on the methods developed by Schneider et al[5]. In these cases, the systems analyzed used storable propellants, but for low-density propellants, the benefits of a pump are much greater. For a pistonless pump system, as compared to a pressure fed system, the tanks are lighter and the ISP is higher, just like a centrifugal pumped system. In contrast to the centrifugal pump system, the Flometrics pump can be pressurized and can stay pressurized forever with no propellant heating, and there is no need for development of a gas generator or electric pump drive. However the Flometrics pump does require helium in approximately the same quantity as a regulated pressure fed system, so when the pressure is increased for additional ISP, the Helium and pressurant tank mass increases proportionally. The Flometrics pump does offer the benefit of reduced helium mass at the end of the burn, and the helium from the pump vent could be injected partway down the rocket nozzle for additional thrust. These options have not been addressed in the following analysis.

Tank mass estimate is based on a 50 psi tank pressure, and the tank is pressurized with the pump exhaust so no helium is required for tank pressurization. Pressurant and helium tank mass is based on twice the pressure of the original system. A real system would have some pressurant loss due to pump ullage, approximately 2-5%, but this does not have a large effect on system performance and would be offset by reduced helium mass at the end of the burn. The "pumped" results assume no mass is used to power the pump. The results of these analyses are shown in tables 1 and 2.

NEAR Propulsion System Model					
Beginning of Life	Kg	805			
Payload	Kg	55			
Delta-V	m/sec	1176			
Propellants		NTO/MMH			
MR		2			
Pressurant	KPa	29670			
System		S.O.A.	Advanced	Pumped	*Flometrics*
Feed pressure		300 psi (2MPa)	300 psi (2MPa)	600 psi (4MPa)	600 psi (4MPa)
Isp	sec	312	330	338	338
Tank Pressure	KPa	2070	2070	690	200
Propellant	kg	304.1	292.7	287.9	287.9
Tanks(Ref. 6)	kg	15.3	15.0	8.9	7.7
Tanks (Ref. 7)	kg	13.2	12.6	4.2	3.5
He Tank	kg	4.6	4.6	2.3	8.4
He	kg	1	0.9	0.3	2
Est. Pump Mass	kg	N/A	N/A	4.2	2.5
Propellant Saved	kg	N/A	11.4	16.2	16.2
Tank Mass Saved	kg	N/A	.4	9.4	1.7
Total Mass Saved kg	kg	N/A	11.8	21.4	15.4
%Payload (55 kg)		**N/A**	**21%**	**39%**	**28%**

Table 1. Increased Payload due to addition of Pump to Near mission

Pump mass estimate is based on a very conservative pump thrust to weight ratio of 20. The pump mass might be higher if all the valves are quad redundant, as might be required for failure tolerant systems, but the results are not sensitive to pump mass. The helium can be heated at the engine for reduced helium consumption if desired. As can be seen in the charts above, the Flometrics pistonless pump system has increased performance similar to the centrifugal pump system, but the development costs are substantially less than for a gas generator, turbine and pump system and system design impacts are less than for an electric centrifiugal pump powered by a solar or RTG system. Also, the pistonless pump can use multiple valves in a quad redundant arrangement to insure against single string failures. The performance gains area greater for LOX methane and LOX Hydrogen systems.

Cassini Propulsion System Model					
Beginning of Life	kg	5609			
Payload	kg	684			
Delta-V	m/sec	2039			
Propellants		NTO/MMH			
MR		2			
Pressurant	KPa	29650			
System		S.O.A.	Advanced	Pumped	*Flometrics*
Feed pressure		300 psi (2MPa)	300 psi (2MPa)	600 psi (4MPa)	600 psi (4MPa)
Isp	sec	312	330	338	338
Tank Pressure	KPa	2070	2070	690	200
Propellant	kg	2865.0	2753.0	2705.9	2705.9
Tanks(Ref. 6)	kg	89.5	86.1	29.8	16.8
Tanks (Ref. 7)	kg	95.8	93.6	30.5	17
He Tank	kg	28.2	27	9.5	59
He	kg	9	8.7	2.7	19.8
Est. Pump Mass	kg	N/A	N/A	4.2	2.5
Propellant Saved	kg	N/A	112	159	159
Tank Mass Saved	kg	N/A	3.5	84.7	44.5
Total Mass Saved kg	kg	N/A	115.5	239.6	203.5
%Payload (684 kg)		**N/A**	**17%**	**35%**	**29%**

Table 2. Increased Payload due to addition of Pump to Cassini mission

3. Autogenous Pressurization Concept

The concept is based on heating the propellants at the engine and using the heated propellants to run the pump, similar to an expander cycle turbopump design. A typical system design is shown in Figure 4. This system is designed for a 10 minute burn at 36,000 lbf with a propellant pressure of 350 psi and a pressurant temperature of 540 R (similar to RL-10). The smaller pressurant pumps act as gas generators converting liquid propellant (LOX or LH_2) to gas (GOX or GH_2). The pressurant pumps run on helium gas which is then vented into the main propellant tanks to provide pressurization. The pressurant pump vent gas is not enough to pressurize the tanks completely, so they require additional helium pressurant as well. The liquid output from the pressurization pumps is connected to a nozzle-mounted heat exchanger where it is vaporized to a gas and then used as the pressurant for the main pumps. The pressures, temperatures and flows are not critical and the system can be scaled up or down as required. It will also work with liquid methane or other fuels and the pressurant need not be the same as the propellant, for example, a storable system could use nitrous oxide to pump NTO and propane to pump MMH and the vent gas could be burned in a vernier.

4. Description of Operation

Each propellant tank has a pressurant pump and a propellant pump that is inside the tank so that the pump chambers are thermally conditioned at startup. The pressurant pumps run on helium that is heated as it flows from a storage tank, either at the thrust chamber or in an intermediate heat exchanger by one of the heated pressurants. The output of the pressurant pump is a high-pressure liquid that is plumbed down to the thrust chamber where it is heated at the engine. The now gaseous pressurant is used to run a larger set of pumps that supply pressurized propellant to the main engine. The system can start slowly with a tank head start, like an RL-10, by initially running at low pressure and flow rates. The exact temperature of the pressurant can be controlled by a bypass valve on the heat exchangers.

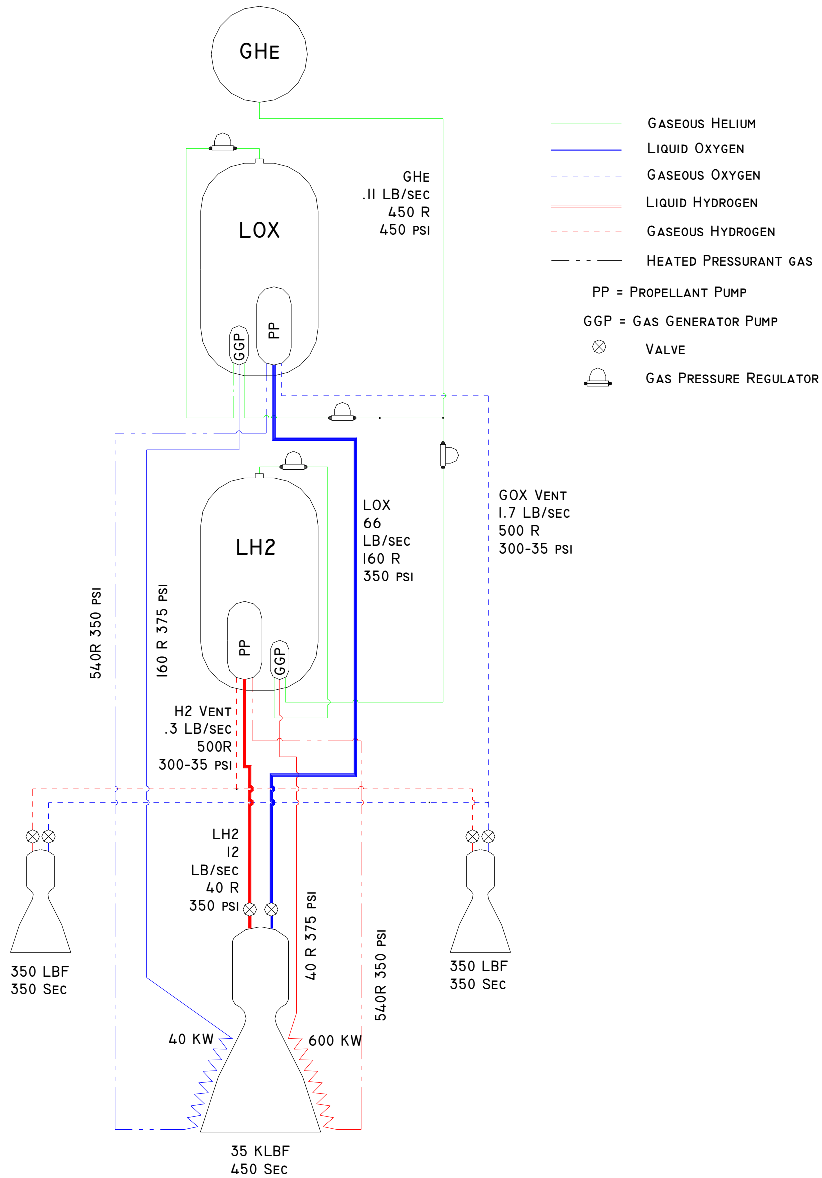

Figure 3. Schematic for autogenous pressurization system

III. Autogenous Pump Thermodynamic Analysis

1. Chamber pressure and heat balance:

The first step in the development process is to determine the best combustion chamber pressure, based on the required thrust and what kind of expansion ratio can be accommodated by the vehicle design. Higher pressures will also result in more pressurant that goes through the verniers at lower Isp. A typical regneratively cooled engine puts a few percent of the heat energy into the fuel, less for larger engines. For example, the RL-10 has a turbine inlet temperature of about 350 R and it extracts 2% of the available heat to drive the pumps, based on the LHV of hydrogen. In the pistonless pump system, 0.2% of the propellant heat is used to run the pumps. For a pistonless pump system, the pump weight is proportional to the pressure, but the pump weight does not drive the design. The only things that reduce the ISP from the theoretical maximum are the mass of helium used to run the pressurant pumps, which is about 0.55% of the propellant mass and the reduced ISP from the verniers, which are about 4% of the propellant mass at about 80% of the main engine ISP . The vernier engines run on gaseous propellant at lower pressure, so their combustion efficiency is excellent, and the cstar is very high but the expansion ratio is limited. The flow and thrust from the verniers is pulsatile, with the performance at the end of each pump vent cycle being less than nominal. The pump vent will need to regulated so that the pressure cannot drop below the vapor pressure of the propellant to prevent boiling in the pump chamber. The overall system ISP is a function of the weighted average of the main and vernier engine ISP, which is primarily limited by the outer mold line of the vehicle which limits the maximum expansion ratio. Higher pressures result in smaller engines, but require more of the pressurant flow going to the verniers. The final design would depend on the size of the fairing that the thrust chambers would need to fit into. Cooling for the engine cluster should not be a problem, since hydrogen is an excellent coolant. A math model of the system was developed which assumed that the Isp of the main engine was 450 seconds, the Vernier average is 350 seconds, the pressurant gas was heated to either 540 or 900 R, the collapse factor[6] was 1.5 (1.5 times more pressurant is used than would be needed assuming no heat transfer from the pressurant to the pump chamber), the injector pressure drop was 100 psi and the helium from the pump exhaust and in the propellant tank was 450 R, and the propellant tanks were at 35 psi. The analysis methods are described in previous papers[1,2]. The results are shown in Tables 3 and 4. Reducing the chamber pressure increases the ISP because more of the propellant can flow through the main chamber. For the lower pressurant temperature and higher pressure cases, the helium mass is driven by the pump requirements, but at the higher pressurant temperature and lower pressurant temperature cases, the helium mass is driven by the tank pressurization requirements. Based on these data, the pressurant temperature and pressure were chosen to be 350 psi and 540 R for maximum system reliability with good performance.

Propellant Pressure (100 psi injector drop)	Pressurant flow rate (Percentage of main propellant flow) (900 R)	System Specific Impulse (450 main, 350 Vernier)	Nozzle diameter (50:1 (expansion) inch (m)	Helium and He tank mass as a percent of total propellant mass * limited by tank pressurization
350	2.5%	448	70 (1.8)	0.55%*
450	3.1%	447	58 (1.5)	0.55%*
550	3.8%	446	52 (1.3)	0.55%*

Table 3 System performances vs. propellant pressure at 900 R (500 K) pressurant temperature

Propellant Pressure (100 psi injector drop)	Pressurant flow rate (Percentage of main propellant flow) (540 R)	System Specific Impulse (450 main, 350 Vernier)	Nozzle diameter (50:1 (expansion) inch (m)	Helium and He tank mass as a percent of total propellant mass * limited by tank pressurization
350	4%	446	70 (1.8)	0.55%*
450	5.2%	445	58 (1.5)	0.85%
550	6.5%	444	52 (1.3)	1.2%

Table 4 System performance vs. propellant pressure at 540 R (300K)pressurant temperature

2. Pump chamber design:

The pump chambers will need to be cylinders with a float to separate the liquid and gas phases and reduce the collapse of the pressurant gas due to cooling. The pressurant gas temperature may be low, so the pump chambers can be aluminum, stainless or carbon fiber reinforced plastic. The mass of the pump chambers is easily determined based

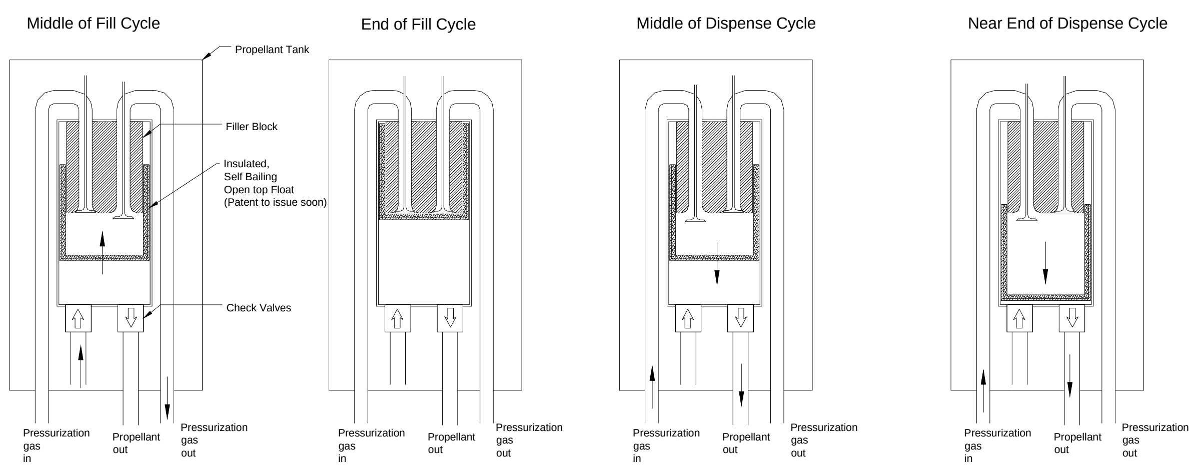

Figure 4. Pump with insulated float system

on the pressure and volume requirements. A conservative pump chamber cycle time is 5 seconds. This allows the dynamic pressure in the pump chamber to be quite low, so that the propellant can be managed under low acceleration. After coast periods, the propellant in the pump chamber may develop a bubble of vapor under the float. The float must allow this propellant vapor to escape the pump chamber while keeping the liquid below the float. A

PMD in the bottom of the pump chamber can prevent bubble from reaching the thrust chamber as long as the system starts up slowly. Once the pump and the thrust chamber are providing acceleration to the vehicle, the vapor can escape along the sides of the float through a helical passage that is configured as a dynamic check valve (described in detail below). The dynamic check valve pumps vapor above the float as the pump cycles. The float must be insulated to prevent excess collapse of the pressurant gas due to contact with the pump chamber walls and the propellant surfaces. An insulated float design is shown in Figure 4. This design prevents heat transfer to the pumped propellant and the propellant in the tank. The top of the pump chamber and the pressurization and vent lines are also insulated. The open top float allows the float to be light enough to float on top of liquid hydrogen.

3. Heat transfer from pressurant gas to propellant

The pump cycle time should be as fast as possible to minimize the volume and thereby the mass of the pump chamber. This has the added benefit of reducing the time that the pressurant is in contact with the pump chamber walls. For example, as the pump cycles, pressurant enters the cylindrical pump chamber and transfers heat to the walls. The pressurant gas must be diffused so that the heat transfer is minimized. The system may be modeled as a pipe with heat transfer to the walls. The thermal resistance is due to the insulation and the convection on the gas side. Based on empirical relations for heat transfer to a pipe, the heat transfer to the pump chamber walls can be determined based on the Reynolds Number and the thermal conductivity of the gas along with the thermal conductivity of the insulation. For a 1200 GPM (76 liter/sec) LH2 pump with a 20-inch diameter (0.5m) pump chamber, the velocity of the fluid is only 1.2 fps (37 cm/sec).

The compressive strength of the insulation is also a factor in the selection of the chamber pressure. All of this analysis yields the pressurant gas flow rate needed to run the pump, which is less than the consumption of an equivalent pressure fed system due to the reduced time that the pressurant is in contact with the propellant. Alternatively the pressurant consumption may be estimated based on an “instantaneous collapse factor” referred to in Ref 6. However, the collapse factor in the present design is much less than that of a typical pressure fed system due to the short dispense time.

4. Pump development process.

The pump design process is summarized in ref 7 for a heavy lift pump. The design process for an autogenous pump will be similar except for the fact that the pump chamber must be cylindrical and the float must be included to reduce the collapse factor. The LH_2 main pump chamber is a 20x50 inch (.5x1.3m) cylinder, mass 87 lb (40Kg)

5 Float development

The open top, self-bailing float was chosen to act as a physical barrier between the relatively warm gas phase pressurant and the cryogenic liquid. This float was developed using a semi-empirical process discussed below. To allow a loose fit within the pump chamber, yet act as a barrier between the two phases, features were added to the float cylindrical walls. These features called “Tesla grooves” are derived from fluidic Tesla check valves. A drawing from Tesla’s patent 1329559.is shown in Figure 5.

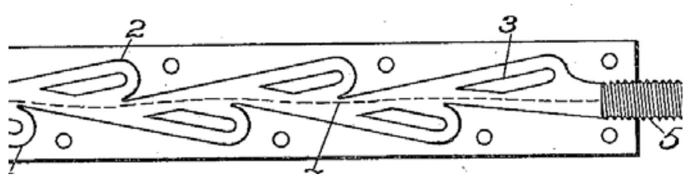

Figure 5: Tesla’s valve, free flow is from right to left.

They allow the flow resistance to be greater in one direction. This allows some of the pressurant gas to act directly on the fluid surface, but minimizes any “blow-by” of the cryogenic liquid, which could be vented out of the pump. A float with a helical Tesla groove was selected, based on testing in a transparent, acrylic pump model where carbonated water was pumped to simulate pumping cryogenic fluid near saturation. The helical Tesla groove concept (with a small vent hole at the top of the helical grove) allowed any bubbles trapped under the float to vent out from under the float more efficiently during the venting portion of the cycle.

To minimize gas usage, the ullage space in each cavity must be a minimum. To accomplish this, a filler block was designed which would mount to the top of each

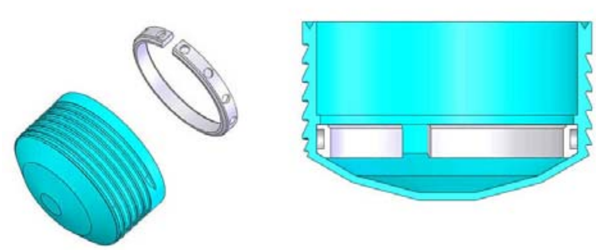

Figure 6: Model of float with Helical Tesla Valve.

chamber and allow the float to nestle over it when the float reaches top-dead-center (see Figure 6). The filler block was tested in a bucket of liquid nitrogen, and it worked to prevent the float from sinking, even when the block and the float were both completely submerged. This was due to the float sealing against the filler block so that as it was pulled up, very little LN_2 could flow in between the float and the filler block. This showed that during the dispense cycle, as the float separates from the filler block, the float was left floating in the LN_2 with a small amount of LN_2 in the float. In the pump system, even if the float fills with LN_2, it will be bailed out during the first vent cycle. For use in a flight vehicle, this would prevent the float from sinking permanently under any situation. The float shown in figure 6 includes a ring which contains magnets for level sensing.

IV Testing Completed to Date

A number of different pump models have been built and tested for various applications. The pump has been cold-flow tested with water at up to 100 gpm and liquid nitrogen at 400 psi and 2gpm and it has been hot-fire tested with an Atlas Vernier rocket engine, pumping RP-1. It has also been tested pumping water under microgravity(see below). A pump was designed for NASA Glenn for the purpose of pumping propellants for a LOX Methane ACS. The goal was to pump LN_2 at 2gpm with pressure fluctuations of under 3%, and the pump achieved the goals. 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 LN_2. 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 3 on the right. A cross sectional view of the same pump is shown in figure 7, illustrating how the float and filler block nest together to minimize the ullage volume. This pump also included a back pressure regulator to keep the LN_2 from boiling. For use on a space vehicle, the back pressure regulator would need to be used to prevent boiling of the propellant as the pump chambers were vented. In the system with the verniers, the back pressure regulator would have a minimal pressure drop until the chamber pressure of the vernier fell below the regulator setting.

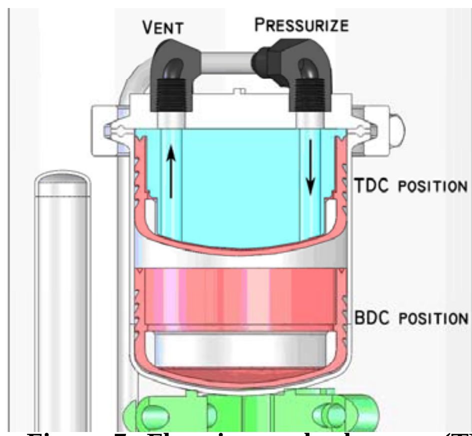

Figure 7: Float in top-dead-center (TDC) and bottom-dead-center (BDC) positions.

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 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. A propulsion system with multiple tanks, valves, and engines could be as reliable as a similar pressure fed system.

VI 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 simulations used sonic and subsonic flow through the valves as a function of time in order to determine vent and pressurize times along with flow rates and pressure drops. The equations were validated by the testing 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. Each process can be modeled separately, and the results of this modeling are available in Ref 12.

VII. Zero-Gee Pump Design, Build and Test

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 7). The pump test system used an onboard air compressor, tank and regulator to supply air to a pressurized 'propellant' tank and the pump chamber (see Figure 9). 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. A Netburner embedded computer controlled the pump operation.

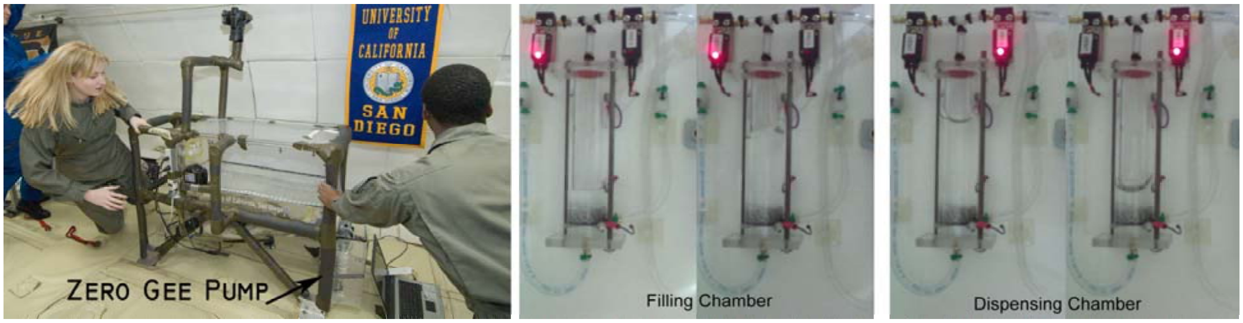

Figure 7: Microgravity Pump test

The experiment involved observing the behavior of water in a clear acrylic chamber as it cycled though pumping and venting stages. The inlet to the pump chamber goes thorough a metal foam disc (Figure 8). The metal foam reduces the dynamic pressure of the incoming liquid and increases the surface tension pressure due to the small pores in the metal foam so that it will not create a bubble in the pump chamber as it is filled or emptied A small high definition video camera recorded the process to investigate the effect of microgravity on the fluid being pumped (Figure 9). A low pressure (~5psi) PVC reservoir filled with water was used to fill a smaller pump chamber. The air in the pump chamber was vented into a collection system in the event that any liquid escaped out the vent (none did). The pump chamber was then pressurized (~10psi). Through a cycle of pressurization and venting, the output water was fed directly back into the supply reservoir which used a bladder to maintain an all liquid feed to the pump chamber. The filling process showed a flat meniscus until the fluid approached the electrode for the conductivity based level sensor, at which point the fluid appeared to be attracted to the sensor electrode. During the dispense process the meniscus was depressed in the center. The experiment worked perfectly, the surface tension of the fluid to the walls of the 1-inch diameter acrylic tube pump chamber was enough to maintain a meniscus that kept the air and water separate . For a system which uses cryogenic fluids in contact with vapor , the surface tension will be much less, but this first experiment show that propellant management is feasible under the moderate dynamic pressures typical for this pump.

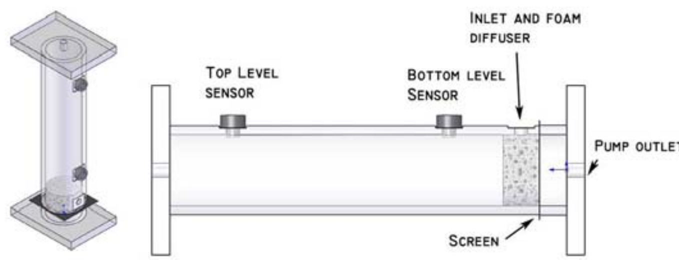

Figure 8: Pump Chamber with PMD

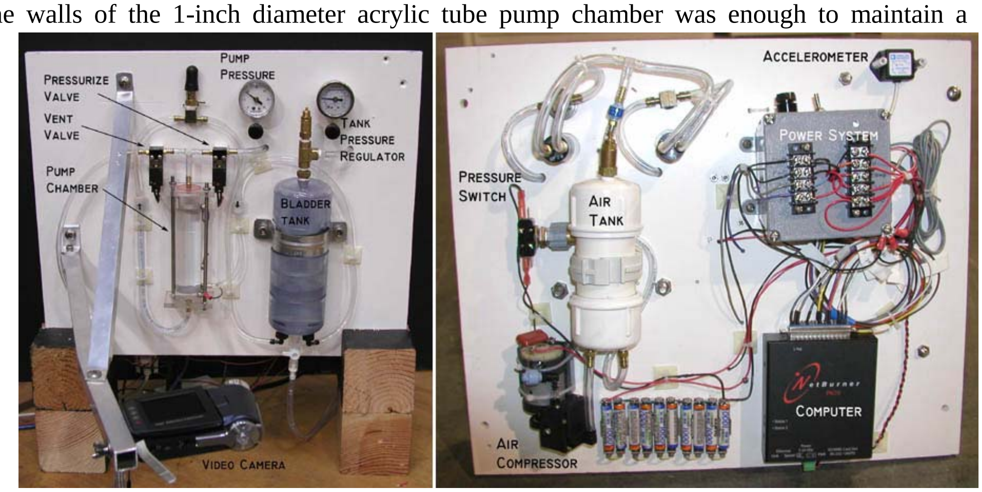

Figure 9: Microgravity flight test hardware

VIII Pumping Difficult Propellants

The pistonless pump can also be used to deal with difficult to pump propellants such as liquid metals or liquid fluorine. These types of propellants have material compatibility issues and pump testing issues that make turbopump development impossible. However, with the pistonless pump, simulant liquids can be used for pump development because the density or viscosity of the material being pumped does not significantly affect pump performance. So a pump that works with LOX or liquid nitrous oxide will work with liquid Fluorine. Also, a pistonless pump could be used to pump liquid aluminum for an ISRU pump system that used regolith or recycled propellant tanks. The pump chamber and valves could be made of Inconel, which has sufficient strength at high temperatures. A pumped tripropellant system that uses liquid lithium, Fluorine and hydrogen has been tested at up to 524 seconds ISP and could theoretically achieve 580 seconds according to a Rocketdyne/NASA study[8].

The pistonless pump could also be used to pump propellants with density variations such as mixtures of water and ammonia such as may be found on asteroids or comets. These may be combined with reactive liquid metals or heated by solar or nuclear power to provide a thrust system that can work on any propellant that can be liquefied, pumped and vaporized in a thrust chamber.

IX Conclusions:

The pistonless pump system provides a pump for a reliable and safe rocket propulsion system. This pump, combined with a pressure fed thrust chamber design, can provide a scalable engine for the large in space propulsion systems 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. It can also broaden the possibilities for game changing technologies that cannot be addressed by the 50-year-old technology that dominates the industry today.

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