Conceptual Design Document (CDD):

Pneumatically Energized Auto-throttled Pump Operated for a Developmental Upper-stage (PEAPOD)

University of Colorado, Department of Aerospace Engineering Sciences, ASEN 4018

Project Customers

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I. Project Description

A. Project Overview

The objective of this project is to develop a proof-of-concept helium-powered pneumatic pump for a liquid propellant rocket engine. This pump must be able to pump two liquid hypergolic propellants (dinitrogen tetroxide (NTO) and unsymmetrical dimethylhydrazine (UDMH)). The full throttle total mass flow rate shall be 3 kg/s and the outlet pressure shall be between 625 psi and 700 psi. Additionally, the mass flow rate of each propellant must be individually controllable by a digital throttle and the total mass flow rate must be throttleable between 0.3 kg/s and 3.0 kg/s. The pump's capabilities and safe operation will be demonstrated using water-flow testing.

B. Specific Objectives

Level	Qualitative Requirements	Performance Requirements
1	• A pneumatically powered, digitally throttle-able pump system shall be designed and manufactured. • This pump shall be capable of independently and simultaneously pumping two hypergolic propellant simulants without allowing the propellants to come into contact. However, the materials from which the pump is constructed do not need to be compatible with the specified hypergolic propellants.	• The pump shall be designed to maintain a 625-700 ± 15 psi full-throttle outlet pressure and a total mass flow rate of 3 kg/s during operation. • The pump shall be designed with a structural factor of safety of 2.5. • A test of the pump shall be conducted in which the pump is operated at the required full throttle pressure and flow rate for no less than 500 seconds.
2	• In addition to the level one qualitative requirements, the pump shall be designed such that the throttling of each propellant can be controlled independently.	• The pump shall be designed to be throttle-able such that the outlet pressure and mass flow rate achieve a simulated engine thrust from 10% to 100%. • The start-up transient outlet pressure and mass flow rate transient shall last no longer than 2 seconds.
3	• The pump shall be fully compatible with all client-specified hypergolic propellants, per ref. [26].	• The start-up transient outlet pressure and mass flow rate transient shall last no longer than 2 seconds. • The pump shall be tested with fluids of similar viscosity as the client-specified propellants.

C. Functional Requirements

This section lists the overarching functional requirements of the pump system that we will be constructing for SAS. The motivation for each functional requirement is listed in Section II. Additionally, the quantitative design requirements that flow down from each functional requirement are also listed in Section II.

1. The pump shall be pneumatically driven using compressed helium.
2. The outlet pressure and mass flow rate of the propellants shall be individually controlled by a digital throttle which will be capable of varying the total mass flow rate of the propellants from 10% to 100% of full throttle. Additionally, the pump shall deliver a relatively constant outlet pressure at all throttle settings.
3. The pump shall be able to run a provided throttle profile for the full duration of an upper stage burn. Additionally, the pump system shall have the ability to be restarted after a period during which there is no fluid flow through the pump.

4. The pump system shall be constructed from materials that are compatible with the client-specified hypergolic propellants. Additionally, the pump shall be tested using propellant simulants with similar density and viscosity.

5. The pump system shall designed and manufactured such that a structural factor of safety of 2.5 is maintained on all components.

D. Functional Block Diagram

A functional block diagram of the pump system is shown in Figure 1, detailing the components to be produce and the elements that will be provided for testing. A CONOPS diagram is also displayed below showing how our system will be verified and how it will fit into the overall mission for which it is being developed.

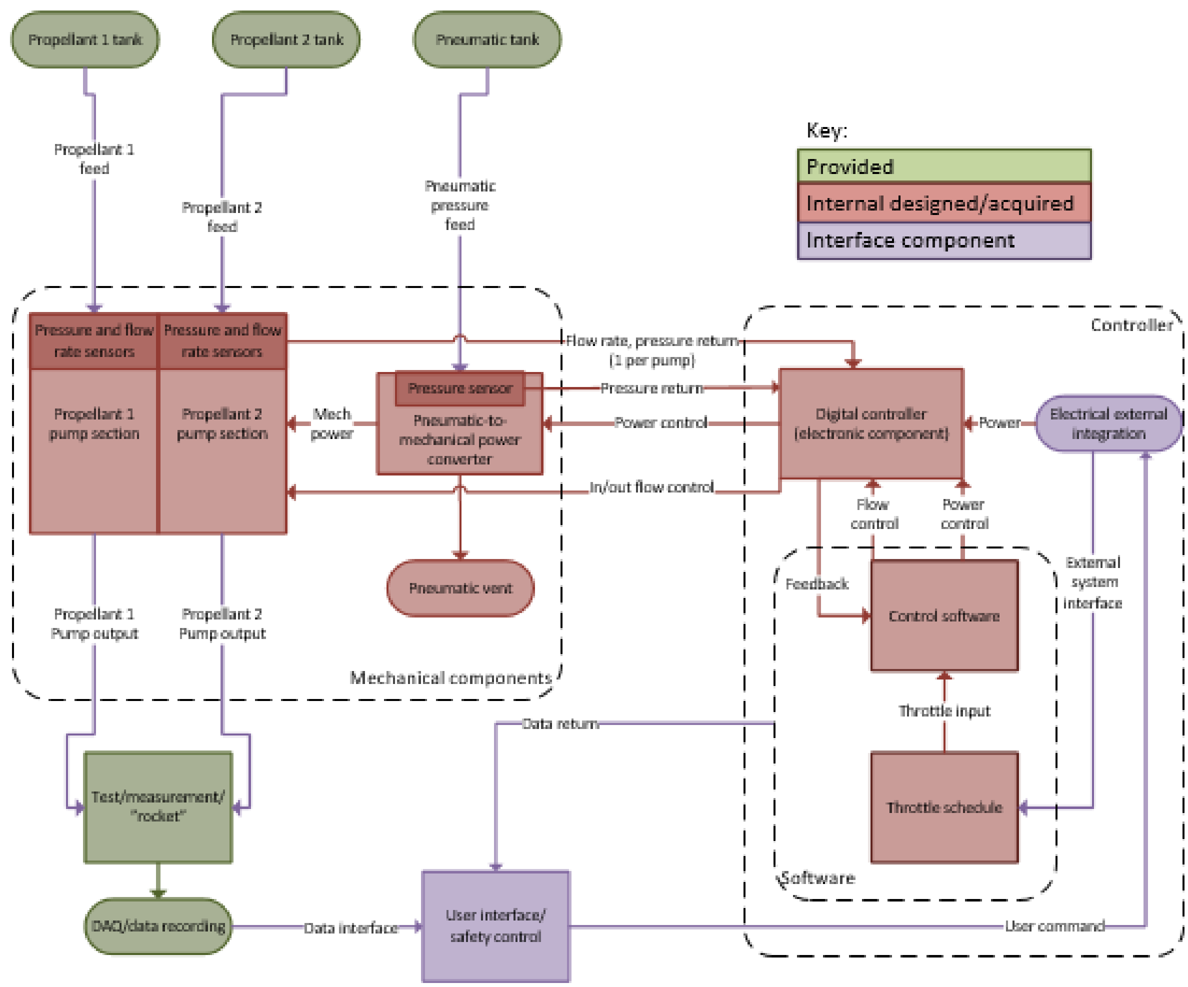


Figure 1: Functional Block Diagram

E. Concept of Operations

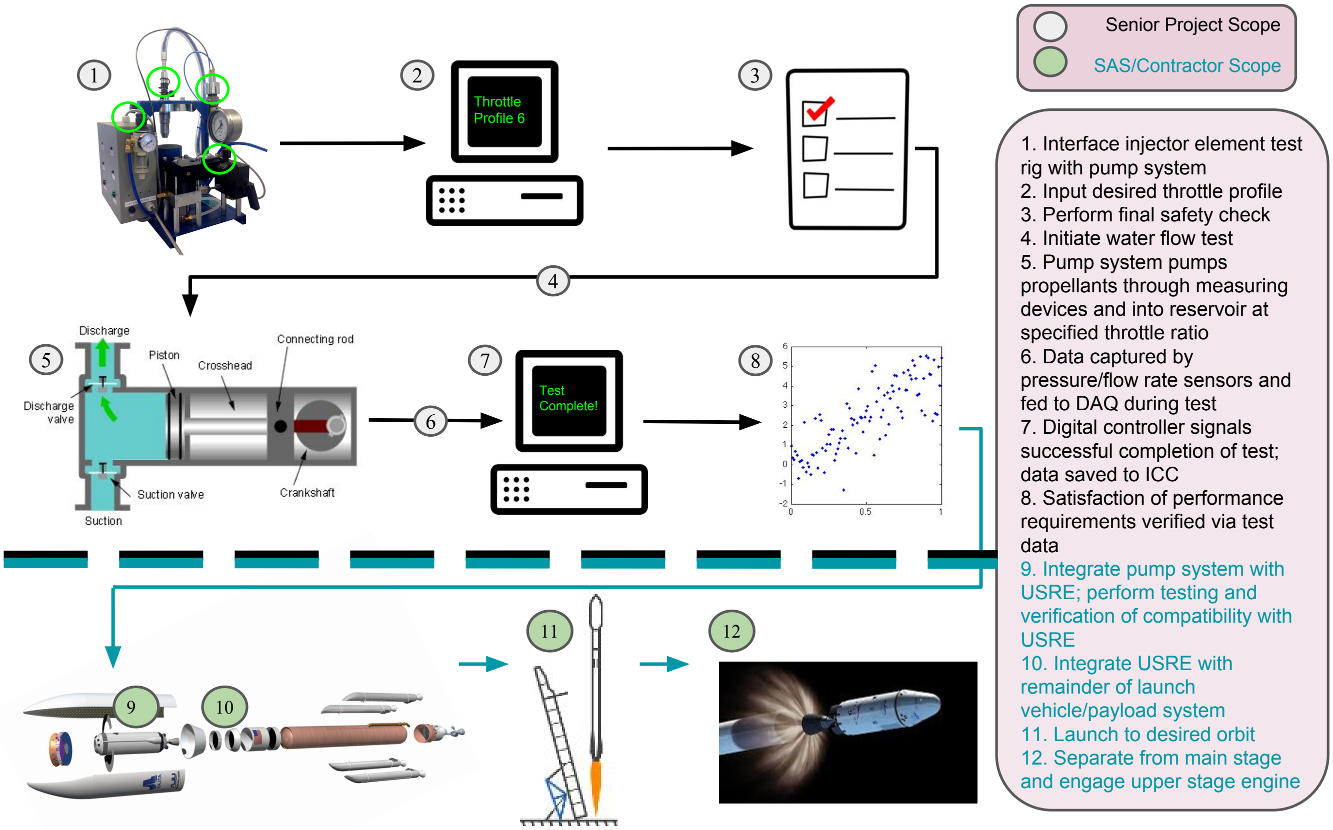


Figure 2: Concept of Operations

II. Design Requirements

Functional Requirement 1 - The pump shall be pneumatically driven using compressed helium.

Motivation: Customer requirement. Helium is the most common gas used to power pneumatic components on rockets because it is inert and has a low molecular mass. The low molecular mass means that compressed helium can be used to store more mechanical energy per unit weight than any other inert gas. Hot gas generators are frequently used to power the propellant pumps on many engines; however, in this case, the use of cold helium will simplify the design of the pump because it will eliminate the need to design the drive system of the pump to be compatible with the hot gases produced by a gas generator.

> **Design Requirement 1.1** - The drive system of the pump shall be powered using room temperature, compressed helium at a pressure between 2000 psi and 6000 psi.
>
> Verification - Testing/demonstration of the pump system on an SAS-provided test stand.

Functional Requirement 2 - The outlet pressure and mass flow rate of the propellants shall be individually controlled by a digital throttle which will be capable of varying the total mass flow rate of the propellants from 10% to 100% of full throttle. Additionally, the pump shall deliver a relatively constant outlet pressure at all throttle settings that has limited high-frequency oscillation.

Motivation: Customer requirement. This pump shall be used to provide pressurized propellants to an upperstage rocket engine or to the descent engine for a small lander. In either case, the engine must be able to successfully vary its throttle over a wide range. Additionally, the outlet pressure of the pump must be relatively constant to avoid pulses in thrust and to avoid triggering combustion instabilities in the engine.

> **Design Requirement 2.1** - A digital throttle shall be implemented to individually control the mass flow rate of the propellants. The total mass flow rates of the propellants must vary from 3.0 kg/s to 0.3 kg/s.

Verification - CFD modeling/analysis and testing/demonstration of the pump system on an SAS-provided test stand.

Design Requirement 2.2 - At full throttle, the pump shall be designed to maintain an outlet pressure between 625 psi and 700 psi. The outlet pressure of the pump shall oscillate with an amplitude of less than 15 psi at all throttle settings.

Verification - CFD modeling/analysis and testing/demonstration of the pump system on an SAS-provided test stand.

Design Requirement 2.3 - The target/nominal O/F ratio shall be 2.

Verification - CFD modeling/analysis and testing/demonstration of the pump system on an SAS-provided test stand.

Functional Requirement 3 - The pump shall be able to run a provided throttle profile for the full duration of an upper stage burn. Additionally, the pump system shall have the ability to be restarted after a period during which there is no fluid flow through the pump.

Motivation: Customer requirement. This pump is being developed for an upper stage rocket engine or for a small lander. The client has required that the pump be demonstrated to run a provided throttle profile for the full duration of a representative upper stage burn.

Design Requirement 3.1 - The pump must be designed such that it can be run for the full duration of a 500 second burn.

Verification - Testing/demonstration of the pump system on an SAS-provided test stand.

Design Requirement 3.2 - The outlet pressure and mass flow rate of the pump shall reach the desired setting within 1 second of pump start-up. If this cannot be achieved, the client has specified that a start-up transient of 2 seconds would be acceptable, although less desirable.

Verification - Testing/demonstration of the pump system on an SAS-provided test stand.

Design Requirement 3.3 - The pump must be designed such that it can be started from 0 mass flow rate.

Verification - Testing/demonstration of the pump system on an SAS-provided test stand.

Functional Requirement 4 - The pump system shall be constructed from materials that are compatible with the client-specified hypergolic propellants. Additionally, the pump shall be tested using propellant simulants with similar density and viscosity.

Motivation: Customer requirement. This pump is being developed for an upper stage rocket engine or for a small lander. The client has required that the pump be demonstrated to run a provided throttle profile for the full duration of a representative upper stage burn.

Design Requirement 4.1 - The pump system shall be manufactured using materials that are compatible with dinitrogen tetroxide (NTO) and unsymmetrical dimethyldydrazine (UDMH).

Verification - Adherence to the indormation in ref. [26].

Design Requirement 4.2 - The pump shall be demonstrated by using it to pump propellant simulants with similar density and viscosity to NTO and UDMH.

Verification - Testing/demonstration of the pump system on an SAS-provided test stand.

Functional Requirement 5 - The pump system shall designed and manufactured such that a structural factor of safety of 2.5 is maintained on all components.

Motivation: Customer requirement. This pump is a proof of concept and must be structurally robust to avoid any hardware failures that could damage the pump. Additionally, holding a high factor of safety on the pump structure will ensure that any test personnel who are running tests on the pump remain completely safe.

Design Requirement 5.1 - All components of the pump and pump housing that will be used to contain high pressure gas or liquid. The pump must be designed to withstand those high pressures with a structural factor of safety of 2.5 on material yield or failure.

Verification - FEM and structural/material analysis. Component proof testing will also be used to verify the minimum factor of safety.

Design Requirement 5.2 - All components of the pump that will experience high compressive, tensile, torque or other mechanical loads will be designed to withstand those loads with a factor of safety of 2.5 on material yield or failure.

Verification - FEM and structural/material analysis. Component proof testing will also be used to verify the minimum factor of safety.

Design Requirement 5.3 - All other components that will experience high stress or strain due to operation of the pump must be designed to withstand those high stresses and strains with a structural factor of safety of 2.5 on material yield or failure.

Verification - FEM and structural/material analysis. Component proof testing will also be used to verify the minimum factor of safety.

III. Key Design Options Considered

Here we have included a brief introduction to the systems and materials that we will be considering in the trade studies included in this paper. First, we have listed the four different types of pumps we have considered in our trade study. The following section lists the pneumatic drive systems we will use to convert the mechanical power in compressed helium into mechanical power that is used to drive the pump. The final section lists the various materials that will be used to construct the various components of the pump, as well as the compatibility of these materials with the client specified hypergolic fuels.

A. Pneumatic Pump System

Over ten pump designs were initially considered; however, the design space was quickly narrowed down to eight options after preliminary investigations ruled out six pump designs due to their inability to meet the design requirements such as pressure and mass flow rates. Many of these, pump designs are repetitive and are covered in brevity. All of the options left are positive displacement pumps, in which a fixed volume of fluid is transferred in a single cycle of the pump.

1. Linear Drive Pump

Piston, plunger and diaphragm pump designs all use a similar method to drive fluid; each of these designs can use the working gas to directly apply pressure to the fluid through either a rigid (piston or plunger) or flexible (diaphragm) interface. With this approach, the drive system is directly integrated into the pump rather than being a separate system.

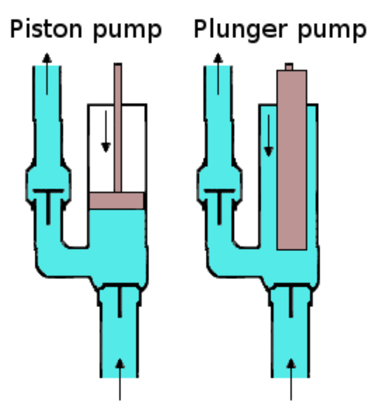


Figure 3: Piston and Plunger Pump Design. [5]

While these systems have high volumetric efficiency because there is no possibility for backwards leakage of the fluid that is being pumped, their overall efficiency is reduced because of the reciprocating motion of the piston, plunger or diaphragm. These systems are also prone to pulsing of fluid flow due to their reciprocating nature. While pressure pulsation can be reduced by increasing the number of pistons, this option increases the design and manufacturing complexity; as well as, the overall weight and cost. While a linear drive pump could theoretically be powered by a rotary drive system, this would eliminate the desirable characteristic of this type of pump. Namely, the ability to power the pump directly from pressurized helium, without the necessity for a separate drive system that converts the potential energy of pressurized helium into mechanical energy that must be transferred to the pump through a crankshaft. Additionally, the cyclical pulsation of outlet pressure would become even more exaggerated at lower throttle settings as the pistons move slower and the frequency of oscillations decreases. Lienar drive pumps were researched using sources [11] through [14].

Table 1: Pros and Cons of a Linear Drive Pumps

Pros	Cons
Drive system embedded in pump design	Highly pulsating power output
Comparatively lower tolerances required	Poor throttling of output power

2. *External Gear Pump*

The external gear pump is a rotary driven pump. In theory, this pump should maintain a constant flow rate for a given shaft rotation rate, regardless of back pressure. This would result in minimal or easily dampened pressure fluctuations in the outlet flow even at low mass flow rates, regardless of downstream back pressure. Compared to other pump designs considered, the external gear pump would be more easily designable and manufacturable. However, the efficiency and decoupling of mass flow rate and back pressure are highly dependent on the tolerances to which the gears and housing are machined. Poor tolerances result in leakage paths around the gears, which reduces the efficiency and cause back-leakage to occur as a result of high back-pressure. With increased back pressure, there is greater fluid slippage which reduces the volume flow per revolution, if the tolerances are not met. This fluid slippage is relatively constant with back pressure, resulting in reduced volumetric efficiencies at lower commanded flow rates. Unlike the piston/plunger/diaphragm pump, the external gear pump requires a separate rotary power source. Given that flow rate control is directly dependent on axle rotation rate, the throttleability of this pump will be dependent on the ability to control the rpm delivered by the rotary pneumatic power source. The extrenal gear pump was reasearched using sources [15] through [17].

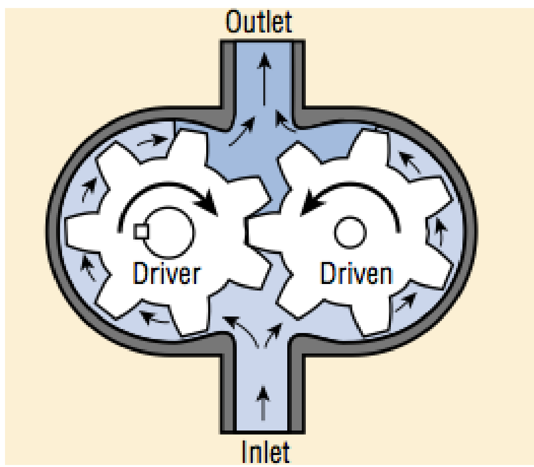


Figure 4: External Gear Pump Design. [1]

Table 2: Pros and Cons of a External Gear Pump

Pros	Cons
Relatively simple to design and manufacture	Low throttle efficiency dependent on tolerances
Minimal flow fluctuation	Requires separate rotary power integration
Common and proven design	

3. *Internal Gear Pump*

The internal gear pump operates in a similar manner to the external gear pump, moving fluid by trapping it between teeth during its rotation. However, the internal gear pump uses a gerotor design in which there is a gear within a gear. This pump exhibits the same flow control behavior in which tolerances can effect the extent to which the pump behaves as a true positive displacement pump. The internal gear design, however, may have fewer 'stages' between the inlet and outlet, resulting in greater pressure differential between any adjacent stages. This can result in reduced volumetric efficiencies if proper clearances are not achieved. Being a rotary pump, the pneumatic source will be required to provide rotary power. Internal gear pumps typically operate at lower rotation speeds, requiring higher torque to achieve the same flow rates. Given the high pressure helium supply, the rotary power source will likely be of a high speed low torque nature, which would require additional gearing that an external gear pump would not. The internal gear pump was researched using sources [16] through [19].

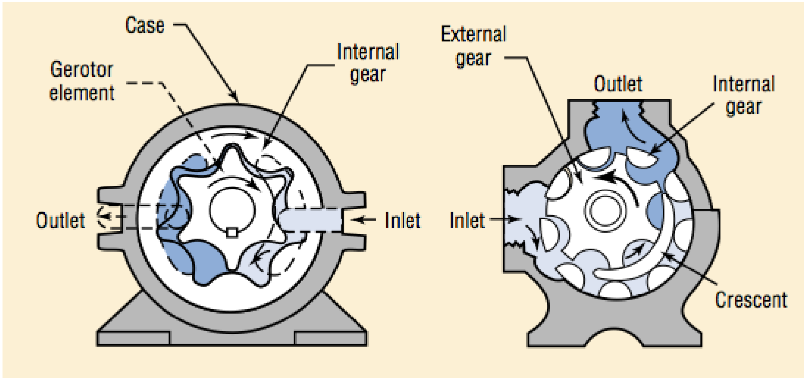


Figure 5: Internal Gear Pump Design. [2]

Table 3: Pros and Cons of a Internal Gear Pump

Pros	Cons
Relatively simple to design and manufacture	Low throttle efficiency dependent on tolerances
Minimal flow fluctuation	Requires lower speed rotary power integration

4. Screw Pump

A screw pump is essentially an infinite linear pump in the sense that it never requires an intake stroke. It operates by creating a cavity between the casing and inter-meshing screws, transporting fluid linearly to the output side when the screws are rotated. In twin screw pumps the screws do not drive each other, instead the screws are driven by external timing gears. This results in there being no contact between screws when properly timed and machined to adequate tolerances. The lack of contact allows for run dry tolerance not present in many other pump designs. As with the gear pumps, the volumetric efficiency is dependent upon the clearances maintained. Due to the screw geometry, specialized machining is necessary to achieve the necessary tolerances; in particular, custom tooling is common and adds to cost and manufacturing times. The screw pump was researched using sources [20] through [22].

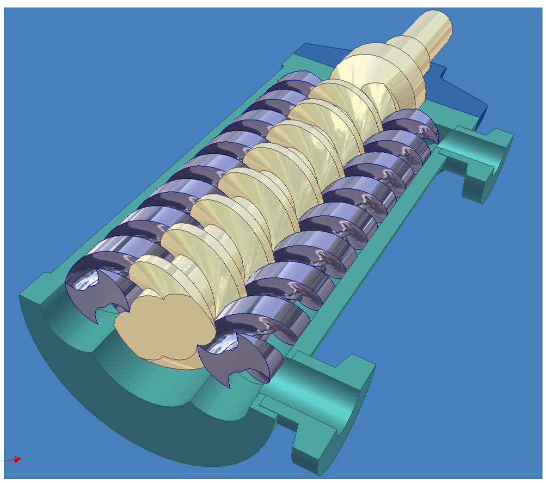


Figure 6: Screw Pump Design. [4]

Table 4: Pros and Cons of a Screw Pump

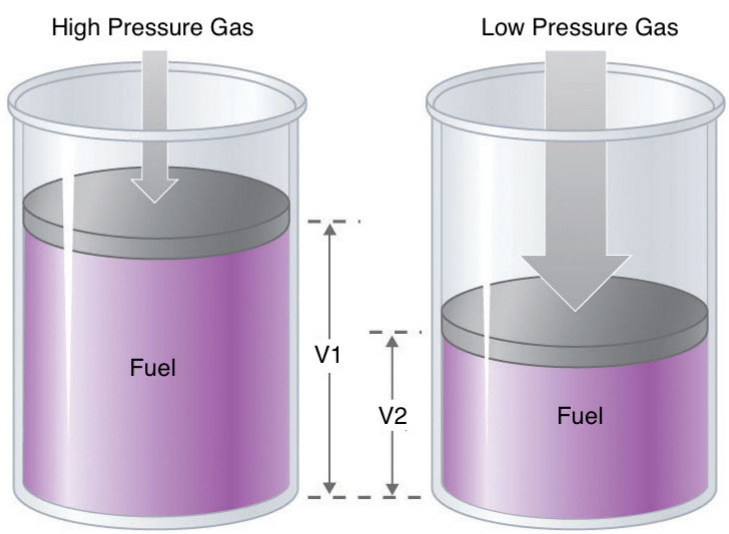
Pros	Cons
Minimal flow fluctuation	Low throttle efficiency dependent on tolerances
Run dry capability	Specialized manufacturing required
	More complex geometry than other pumps

B. Pneumatic Drive Systems

All of the aforementioned pumps require a drive system that supplies power for the pump to drive fluid. The drive system's compatibility with a given pump is absolutely essential to the successful operation of the overall system. Naturally, this compatibility played a large role when considering drive systems. Therefore a study on the pneumatic drive systems is described below, in hope to alleviate drive system restraints on the selected baseline pump design.

1. Pneumatic Linear Drives

Linear drive systems are best suited for the piston/plunger/diaphragm pump design mentioned previously because the pressurized helium can be used to directly power a piston or diaphragm that is then used to move fluid. In fact, these drive systems can be directly integrated into the pump design. This is in contrast to a rotary style drive system in which the mechanical power is transferred from the drive system to the pump through a crankshaft. Linear actuators are extremely simple drive systems, and they operate by inserting pressurized gas into the "dry" side of a piston at its top dead center (TDC) where it then expands, driving the piston down the chamber, generating work. The depressurized gas is then vented and the piston returns to TDC where high pressure gas is introduced into the cylinder, completing the full drive cycle.



Generating linear mechanical power through expansion

[9]

This drive system, while simply designed, comes with significant drawbacks. The most obvious drawback is the inherent pulsation associated with linear drive systems due to the necessity of an intake stroke; the intake stroke is inevitable, and during this stroke, power is not generated, which results in inconsistent outflow of fluid. Tabulated below are the significant pros and cons of a pneumatic linear actuator.

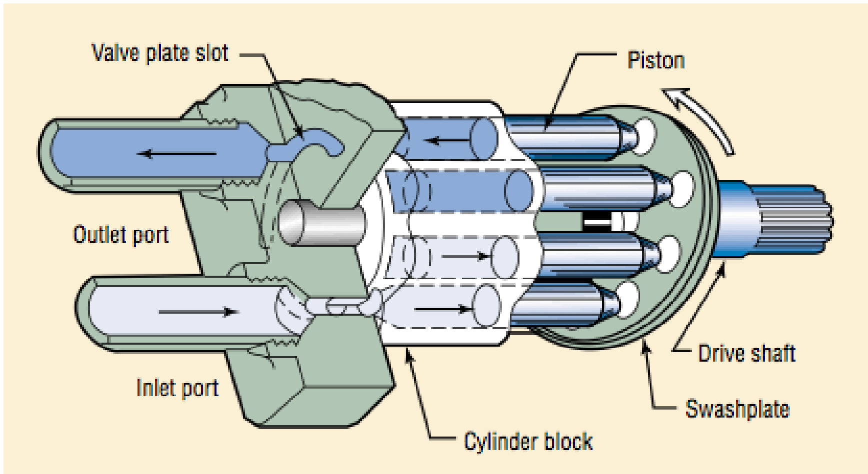
Table 5: Pros and Cons of a Linear Drive System

Pros	Cons
Simple drive system design	High manufacturing tolerances
Drive system embedded in pump design	Highly pulsating power output
	Poor throttling of output power

2. Axial Flow Variable Displacement Piston Motor

An axial piston motor operates by rotating a number of pistons on a angled plate so to have all the pistons go through their full range of motion. At the base of the pistons is a level plate with inlet and outlet slots. The inlet slot delivers high pressure gas to fully compressed pistons. The gas expands pushing the piston out and causing the slanted plate to rotate. This then places the piston over the outlet, at which point the piston is fully expanded and vents the low pressure gas it contains. Having numerous pistons on this system increases the power output as well as minimizing pulsation.

The diagram below depicts this system.



[6]

This system can be furthermore improved by varying the angle of the drive plate which regulates how much of the potential energy of the gas is used to drive the system. This allows for throttling of the power produced by this motor.

This Pros and Cons of this drive system are tabulated below.

Table 6: Pros and Cons of a Axial Piston Motor

Pros	Cons
Can rotate in both directions	High design and manufacturing complexities
Can be throttled	Includes numerous pistons, which require maintenance

3. Rotary Vane Pneumatic Motor

The rotary vane pneumatic motor consists of a circular rotor with several protruding vanes rotating inside of a chamber into which pressurized gas is fed. The rotor is placed inside of the chamber such that its center does not directly align with the center of the chamber. This means that the distance from the rotor to the chamber wall changes as a function of the angle along the rotor, but the vane length does not change. As a result, as the rotor rotates, the vanes slide in and out of their chambers sealing the edges, creating what are known as vane chambers. The fluid in each chamber is driven from inlet to outlet while work is done on it. The diagram below depicts this drive system.

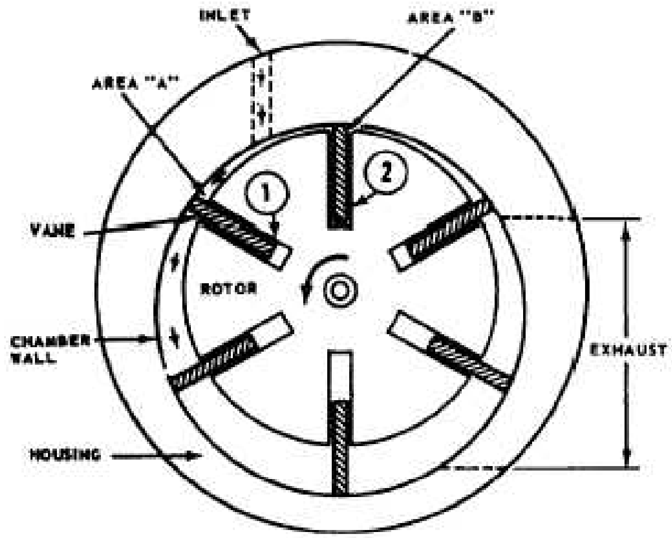


Figure 7: Rotary Vane Drive System Schematic [7]

As pressurized gas is delivered through in the inlet, it expands freely within its respective vane chamber. The vane chamber's volume is greater on its "leading side" (counterclockwise from the inlet in Figure 7), meaning that the expanding gas will want to fill this volume as quickly as possible. As a result, a "leading force" is exerted on the surface of the leading vane, causing the rotor to rotate in a counter-clockwise direction. This vane chamber is then pushed further counterclockwise as the next vane chamber goes through the expansion process. Rotational mechanical power is delivered through a shaft connected to the rotor. The most relevant pros and cons of this drive system are tabulated below.

Table 7: Pros and Cons of a Rotary Vane Motor

Pros	Cons
Easy integration	Only operates in one direction
Can be throttled	

4. Radial Piston Motor

This motor operates by expanding gas in numerous pistons placed within a rotor and in contact with a cylinder block. This cylinder block contains a valve system to both provide high pressure gas that will expand in the pistons and vent the low pressure gases that result of this expansion.

The diagram below depicts this system.

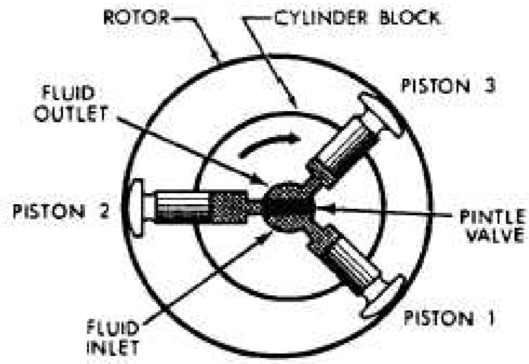


Figure 8: Radial Piston Drive System Schematic [8]

The rotation of the cylinder block is imparted by the expansion of the gas in piston from stages 1 to 2. From 2 to 3, the low pressure gas is vented through the valve assembly. This figure simplifies this design by only considering three pistons, as most industry grade Radial Piston Pumps include around 8 pistons. Increasing the number of piston increases the power the motor can deliver as well as minimizing pulsation effects.

The Pros and Cons of this drive system are tabulated below.

Table 8: Pros and Cons of a Radial Piston Motor

Pros	Cons
Can rotate in both directions	High design and manufacturing complexities
Can be throttled	Includes numerous pistons, which require maintenance

C. Hypergolic Compatible Materials

Within the scope of our project, SAS wanted the pump system to be hypergolic compatible with dinitrogen tetroxide (N_2O_4), unsymmetrical dimethylhydrazine (UDMH) and possibly hydrogen peroxide (H_2O_2). Hypergolic compatibility whether our team designed the pump using hypergolic materials, or the team suggested equipment replacements was requested from SAS. As the team looked into developing a hypergolic compatible system, it became apparent that the housing, seals, piping and lubricants all had to be compatible. This increased the possible complexity of the system if all criteria were to be met. As a result, a study into the hypergolic materials was conducted to see if these materials were within the scope of our project and our budget. Below is some of the findings on hypergolic material compatibility [26].

Table 9: Hypergolic Information and Material Compatibility [26][30]

	Hydrogen Peroxide	Dinitrogen Tetroxide	UDMH
Compatible Metals	*Al 1060, 1260, 1360, 5254, 5652, Tantalum, Zirconium	Moisture content <0.1%: Carbon steel, Inconel-X, Nickel Al 1100, 5052, 6061, 6066, 356, B356, Stainless steel: 300 and 400 series Moisture content >0.1%: 300 series Stainless Steel	Nickel, Monel, Stainless Steel 303, 304, 314 *Al may be used, but corrosive damage is found to be proportional to amount of water in the solution
Compatible Non-metals	*Teflon, Kel-F, Aclar	Teflon, graphite, polyethylene, many more	Teflon, Kel-F, polyethylene, Garlock Gasket 900, Nylon, Glass Pyrex
Compatible Lubricants	*No Class I lubricants Class II: Fluorolubes, Kel-flo polymers, Halocarbon oils, perfluorolube oils	Fluorolube series, Graphite (dry), Nordcoseal-147 and DC 234S Molycote Z, Teflon tape, Redel Reddy lube	Apiezon L, Reddy Lube 200
Viscosity [cp @ 20C] [27] [28][29]	1.245	0.396	0.56
Density [g/cm^3][27] [28][29]	1.45	1.44246	0.791
Sensitive to shock/friction	Depends	No	No
Hypergolic with:	Hydrazine, UDMH	UDMH, Hydrazine	Dinitrogen Tetroxide, Hydrogen Peroxide
Other notes:	No Stainless steel *Different Class Types for materials: Class I was chosen if applicable.	Depends on Moisture Level Tables 1-3 from source provide extra information	

IV. Trade Study Process and Results

The design requirements listed in Section II were used to drive the trade studies that we conducted on the pumps, drive systems and materials. For simplicity, the design requirements are summarized below.

1.1 The drive system of the pump shall be powered using room temperature, compressed helium at a pressure between 2000 psi and 6000 psi.

2.1 A digital throttle shall be implemented to individually control the mass flow rate of the propellants. The total mass flow rates of the propellants must vary from 3.0 kg/s to 0.3 kg/s.

2.2 At full throttle, the pump shall be designed to maintain an outlet pressure between 625 psi and 700 psi. The outlet pressure of the pump shall oscillate with an amplitude of less than 15 psi at all throttle settings.

3.1 The pump must be designed such that it can be run for the full duration of a 500 second burn.

3.2 The outlet pressure and mass flow rate of the pump shall reach the desired setting within 1 second of pump start-up. If this cannot be achieved, the client has specified that a start-up transient of 2 seconds would be acceptable, although less desirable.

3.3 The pump must be designed such that it can be started from 0 mass flow rate.

4.1 The pump system shall be manufactured using materials that are compatible with dinitrogen tetroxide (NTO) and unsymmetrical dimethyldydrazine (UDMH).

4.2 The pump shall be demonstrated by using it to pump propellant simulants with similar density and viscosity to NTO and UDMH.

5.1 All components of the pump and pump housing that will be used to contain high pressure gas or liquid. The pump must be designed to withstand those high pressures with a structural factor of safety of 2.5 on material yield or failure.

5.2 All components of the pump that will experience high compressive, tensile, torque or other mechanical loads will be designed to withstand those loads with a factor of safety of 2.5 on material yield or failure.

5.3 All other components that will experience high stress or strain due to operation of the pump must be designed to withstand those high stresses and strains with a structural factor of safety of 2.5 on material yield or failure.

A. Pump System Trade Study

The trade study started by researching a list of different types of pump. This list was reduced based on the basic requirements for the pump, some of these basic requirements are: maintain maximum outlet pressure between 625 to 700 psi, pump fluids with viscosity similar to water, power the pump using compressed helium, and throttle the mass flow rate from 3 kg/s to 0.3 kg/s. These basic requirements were used to narrow the search.

These design requirements were used to form several of the metrics which were used to compare the capabilities of each pumping system. Additional metrics were then added to capture the ease which the system could be manufactured and integrated. These main criteria were then weighted, in percentage, based on the requirements of the PDD and how important they are for the success of the project. Each criteria was broken down into sub-criteria which were given a portion of the weighting of the main criteria that they fit under. The justifications for the weightings of each criteria and sub-criteria are given below and the final weighting applied to each criteria and subcriteria are given in Table 10.

Throttleability - The ability to throttle the pump from 0.3 kg/s to 3 kg/s is a critical project element, as well as a reason that the client cannot simply buy and off-the-shelf pump. Therefore, throttleability has received 20% of the overall weighting.

Throttleability (pump controlled) - 16% of this weight going to the ability to control the mass flow rate by throttling the pump because the pump must be able to throttle from 10% to 100% or it will not have fulfilled the client specified requirement.

Slew rate (start up) - 4% of the weight goes to the ability to the start-up slew rate of the pump because a slow start-up transient, though undesireable, would not cause the entire project to be considered a failure.

Pressure Fluctuation - It is important to maintain the pressure fluctuations below the the client specified ±15 psi. However, there are components that can be added to the system to reduce pressure fluctuation after the system is completed. Therefore, pressure fluctuation was considered to be an important factor, but not a make-or-break metric and was awarded 14% of the total weight.

Efficiency - This was not a client specified requirement, so we did not consider this metric to be highly important. However, since efficiency governs how much helium is needed to run the pump, we deemed that pump efficiency (at full throttle) was still important enough to be considered, albeit with a fairly small relative weighting of 4% .

Manufacturability - This metric captures the time required to manufacture the pump components as well as the ability to hit the required tolerances with in-house machining resources. This was found to be an important metric with a relative weighting of 16% .

Ability to hit tolerances (for best efficiency) - This is a metric of our ability to machine custom-parts for the pump in-house. This will give us increased flexibility in machining time and allow us to iterate over different designs. This metric directly affects how feasible the pump is; if it cannot be built, then there is no purpose in designing it.

Manufacture time - This is a metric of the rough amount of time that will be expended by our team in planning and overseeing the manufacturing of various components of the pump. It is critical since it must be done before the pump can be tested or demonstrated to the customer. Manufacture time and ability to hit tolerances is weighed equally at both half of 16% .

Designability - It is critical that we are able to design this pump in the required time. If this does not occur the project will fail. This metric is weighted the most highly (tied with throttleability) because it is a critical project element that could easily cause the failure of this project. It is weighted at 20 percent.

Complexity - This is an important sub-criteria in Designability because this is a metric of the amount of work that will be required to design the pump - a time cost.

Pneumatic Integration - This is a metric of how easily a pneumatic drive system can be integrated into the pump system. This metric has a moderate weight since the pump must be pneumatically powered, but it will be possible to integrate a pneumatic drive system with any of the selected pumps.

Designability - This metric was added to ensure that we accounted for any design specific challenges that were not related directly to part count or pump complexity, such as the ability to model the pump.

Easy access - This metric refers to the ease with which the pump can be disassembled and maintained. This was not a requirement from the client but may be useful if anything damages the pump.

Cost - This criteria covers direct monetary costs that our team will have to consider. We considered both the relative amount of outsourced machining that would be required as well as the availability of off-the-shelf components. This section is weighted at 10 percent.

Outsourced machining - A higher relative cost of out-sourced machining was considered to be worse because this would significantly cut down on our flexibility and could result in long lead times which would affect critical path.

Off-the-shelf component availability - Due to the tight schedule and short build and integration phase of this project, the more of the pump that can be assembled from off-the-shelf components the better.

Reliability - This criteria covers the reliability and restartability of the pump and is essentially a measure of how robust the pump is. It is weighted at 16 percent.

Reliability - this is a measure of how long the pump can be run in both nominal and off nominal conditions without requiring maintenance or repair.

Restartability - this metric is a measure of the ease with which the pump can be restarted from 0 mass flow rate. In order to achieve good restartability the pump must be self-priming and able to start from off nominal conditions such as vapor-lock. This metric is moderately weighted.

Table 10: Weighting of Pump System Criteria

Criteria	Sub-Criteria	Percentage Criteria	Percentage Sub-criteria
Throttleability		20	
	Throttleability (pump controlled)		16
	Slew rate (start-up)		4
Pressure Fluctuation		14	
	Pressure Fluctuation Magnitude		14
Efficiency		4	
	Pump Efficiency (at full throttle)		4
Manufacturability		16	
	Ability to hit tolerances (for best efficiency)		8
	Manufacture time		8
Designability		20	
	Complexity (pump only)		10
	Pneumatic integration		4
	Designability (pump only)		4
	Easy access (pump only)		2
Cost		10	
	Outsourced machining (cost)		6
	Off-the shelf component availability		4
Reliability		16	
	Reliability		10
	Restartability		6
Total		100	100

After assigning a relative weight to each criteria and sub-criteria, we developed metrics by which we could assess each pump. These metrics ranged from one to five and are shown in Table 11. In all cases, a five is the highest ranking a pump could earn and indicates that the pump would perform well in that criteria or sub-criteria.

Table 11: Pump Metrics

Scale	1	2	3	4	5
Throttleability (Volume Flow Capability)	65%-100%	50%-100%	35%-100%	20%-100%	5%-100%
Pressure Fluctuation	Near impossible to minimize	Needs extra components to minimize fluctuations	Possibly a problem	Some fluctuation but not enough to worry about	No fluctuation
Efficiency	<20%	21%-40%	41%-60%	61%-80%	80%-100%
Manufacturability (tolerances/difficulty)	<0.001 mm	0.005 mm	0.01 mm	0.05 mm	0.1 mm <
Complexity/ Pneumatics Integration	20+ moving parts and difficult pneumatic integration	14-20 moving parts and difficult pneumatic integration	7-13 moving parts and moderate pneumatic integration	3-6 moving parts and easy pneumatic integration	1-2 moving parts and easy pneumatic integration
Cost ($)	5000-4401	4400-3801	800-3201	3200-2601	<2600
Off the shelf (% of cost)	0%-29%	30%-49%	50%-69%	70%-89%	>90%
Restartability/ Reliability	Requires constant maintenance	Most parts need to be replaced between testings	Multiple parts need to be replaced after each test	A couple of parts need to be replaced after each test	Minimal maintenance needed after each test
Percent cost of outsourced machining	80%+	51-80%	26-50%	16-25%	0-15%+

The metrics were then used to quantify the performance of the pump designs; Piston/Diaphragm/Plunger pump, External Gear pump, Internal Gear pump, and Screw pump, in each of the criteria or sub-criteria. The other pumps described above were not included in our study. These rankings were scaled by the relative weightings of each criteria and were then summed to obtain the final score for each pump. Table 12 shows the final trade study that was conducted using the weightings from Table 10 and the metrics from Table 11.

Table 12: Pump Trade Study Matrix.

	Piston/Diaphragm/Plunger		External Gear		Internal Gear		Screw	
	Points	Ratio	Points	Ratio	Points	Ratio	Points	Ratio
Throttleability								
Throttleability (pump controlled)	3	0.48	4	0.64	4	0.64	4	0.64
Slew rate (start-up)	5	0.2	5	0.2	5	0.2	4	0.16
Pressure Fluctuation								
Pressure Fluctuation Magnitude	2	0.28	4	0.56	4	0.56	4	0.56
Efficiency								
Pump Efficiency (at full throttle)	5	0.2	5	0.2	5	0.2	5	0.2
Manufacturability								
Ability to hit tolerances (for best efficiency)	5	0.4	3	0.24	3	0.24	3	0.24
Manufacture time	3	0.24	4	0.32	4	0.32	2	0.16
Designability								
Complexity (pump only)	2	0.2	4	0.4	4	0.4	4	0.4
Pneumatic integration	5	0.2	3	0.12	3	0.12	3	0.12
Designability (pump only)	4	0.16	5	0.2	4	0.16	3	0.12
Easy access (pump only)	3	0.06	4	0.08	3	0.06	3	0.06
Cost								
Outsourced machining (cost)	5	0.3	3	0.18	2	0.12	1	0.06
Off-the shelf component availability	3	0.12	5	0.2	3	0.12	2	0.08
Reliability								
Reliability	3	0.3	5	0.5	4	0.4	5	0.5
Restartability	4	0.24	5	0.3	5	0.3	5	0.3
Total		3.38		4.14		3.84		3.6

A sensitivity study of each weighting was conducted on this trade study by individually setting each weighting to zero. A further sensitivity study set each weighting to the same value to determine how much weighting influenced the pump selection in general. The results of this sensitivity study can be seen in the appendix.

B. Drive system trade study

The following table describes how the different criterion were weighted for each criterion listed in Table 13.

Table 13: Weighting of Drive System Criteria

Criteria	Sub-Criteria	Percentage Criteria	Percentage Sub-criteria
Throttleability (in power)		25	
	Throttleability		20
	Slew rate (start-up)		5
Efficiency		5	
	Motor Efficiency (at full power)		5
Cost		25	
	Cost to buy off-the-shelf motor		25
Cooling/Lubrication Requirements		5	
	Cooling Requirements		2
	Lubrication		3
Integration with Pump		20	
	Ease of Integration with Pump		20
Reliability		20	
	Reliability		12
	Restartability		8
Total		100	100

These criterion were weighted differently depending on how important the group deemed their fulfillment to the success of the project. Below is a table detailing the weighting for the drive system criterion. These criterion were selected based on the the following reasoning.

Throttleability - The ability to control the flow rate of the pump between 10 and 100 %.

Throttleability (Output power) - Because power input to the pump relates directly to the flow rate output of the pump, the power output of the drive system must be controllable. This criteria is crucial to drive system choice, as it directly affects the throttleability of the subsequent pump that the system drives. If a drive system can achieve high throttleability it significantly reduces the complexity involved in throttling propellant flow.

Slew rate (start up) - Similar to the pump system, the slew rate will not be a critical element of success for the project. However it is still a client requirement. The slew rate is the rate at which the pump can go from 0% to 100%.

Efficiency (motor) - The efficiency, although not required by the client, will help to decrease the helium used to the power output.

Cost - The ability to acquire materials for minimal monetary and temporal value will be critical to project success. Do to time constraints, the drive system will most likely be purchased commercially for both pumps. This is further discussed in Part B of the Baseline Design Selection.

Cooling/Lubrication Requirements - Basic requirements for the pump to work optimally for the full duration of the burn.

Cooling requirements - The ability not to use a separate cooling system in order for the drive system to work properly.

Lubrication requirement - This requirement will be driven by how often lubrication will need to be applied in order for efficiency to be at working levels.

Integration with pump - The ease of integration of the drive system within the pump is weighted highly because the drive system is the main component of the pump. Meeting this criteria will also reduce any extra design and manufacturing requirements. This will allow the team to allocate the resulting man hours to more pertinent tasks of the pumpsystem design Therefore, ease of integration is paramount in order to properly manufacture and run the pump.

Reliability - Reliability will determine the life span of the drive system and its ability to operate.

Reliability - Reliability is the duration of the life span for the drive system and its parts. In order to lower risk, time, and cost, a reliable drive system is necessary.

Restartability - It is the ability to start the drive system repeatedly, with low risk of failure.

Table 14: Drive System Metrics

Scale	1	2	3	4	5
Throttleability (Power Output Capability)	65%-100%	50%-100%	35%-100%	20%-100%	5%-100%
Efficiency (at full power)	<20%	21%-40%	41%-60%	61%-80%	80%-100%
Cost ($)	>2000	2000-1500	1500-1000	1000-500	<500
Reliability	Requires constant maintenance	Most parts need to be replaced between testings	Multiple parts need to be replaced after each test	A couple of parts need to be replaced after each test	Minimal maintenance needed after each test
Cooling/Lubrication	Presents a major design consideration	Presents an important design consideration	Presents a moderate design consideration	Presents a small design consideration	No additional considerations
Pump Integration	Presents a major system design challenge	Presents an important system design challenge	Presents a moderate system design challenge	Presents a small system design challenge	Drive system integrated into pump

With this in mind, the four drive system options mentioned in Section B were evaluated using the criterion and metrics in Tables 13 and 14 respectively. The resulting trade study matrix is given below.

Table 15: Trade Study Matrix for Pump Drive Systems

	Axial Flow Var. Displacement		Radial Piston		Vane		Linear	
	Points	Ratio	Points	Ratio	Points	Ratio	Points	Ratio
Throttleability (in power)								
Throttleability	5	1.25	4	1.00	5	1.25	4	1.00
Slew rate (start-up)	5	0.25	5	0.25	4	0.2	4	0.20
Efficiency								
Motor Efficiency (at full throttle)	5	0.25	5	0.25	5	0.25	5	0.25
Cost								
Cost to buy off-the-shelf motor	3	0.60	2	0.40	4	0.80	5	1
Cooling/Lubrication Requirements								
Cooling Requirements	4	0.08	4	0.08	4	0.08	4	0.08
Lubrication Requirements	3	0.09	3	0.09	3	0.09	5	0.15
Integration with pump								
Ease of integration with pump	3	0.60	3	0.60	3	0.60	5	1.00
Reliability								
Reliability	5	0.60	5	0.60	5	0.60	4	0.48
Restartability	5	0.40	4	0.32	4	0.32	5	0.40
Total		4.12		3.59		4.19		4.56

C. Hypergolic Materials Trade Study

When comparing the different hypergolic propellants, it became evident that material compatibility with all three propellants (UDMH, dinitrogen tetroxide, and hydrogen peroxide) was not possible. Hydrogen peroxide was the outlier because it was not compatible with stainless steels. This finding further verified SAS's initial request for UDMH and dinitrogen tetroxide compatibility. Table 16 below summarizes the findings and suggested materials for UDMH and dinitrogen tetroxide. These materials were suggested for both propellants. In the initial research of the hypergolic materials (Table 9), density and viscosity were also included in the analysis. They were included in the analysis to make sure there could not be the possibility of structural/pump constraints based on the density or viscosity. Upon further research no constraints were found. The densities of both liquid propellants are within the ranges for the pumps analyzed above and the viscosities were even less than water. Overall, the hypergolic material trade study boiled down to the viability of materials interacting with hypergolic fluids at this stage in the design process. Further analysis must be done to see if the use of these materials are within the scope and budget of the project, or if supplying SAS with material modifications is more appropriate. Also structural analysis with the various materials must be performed to decide what variation of the material must be used (i.e. what specific 300 series stainless steel will best serve our needs).

Table 16: UDMH and Dinitrogen Tetroxide Material Compatibility [26]

	UDMH and Dinitrogen Tetroxide Compatible Materials
Metals	Stainless Steel 300 Series (303, 304, 321)
Non-Metals	Teflon
Lubricants	Reddy Lube

V. Selection of Baseline Design

A. Selection of Baseline Pump Design

After examining over 10 different pumps and doing an initial elimination based off of the hard requirements for our project (like mass flow rate, pressure capabilities, etc.), the list was narrowed down to four different pump types to do a trade study on. All of these are potential designs that would suit our needs, but the goal was to find the one that would best fit our needs. The final trade study scores for all four pumps were very close. This shows that all of the pumps that we considered are viable options. However, there was a 22% difference in score between the highest and lowest ranked pumps. The two highest ranking pumps are the internal and external gear pump. Based on this, it appears that the internal and external gear pump are very closely related. As a result the team has deemed it appropriate to consider the broader option of a gear pump (which would include both internal and external gear pumps). As a result, we have selected the broader category of "gear pump" as the baseline design. It is likely that, after additional research and preliminary design, we will select the external gear pump as our final choice. However, based on the results of our trade study and the similarity of external and internal gear pumps, it was not deemed necessary to reject either internal or external gear pumps at this point in our analysis.

To start the trade study process, each person in our group examined three or four of the ten pumps. This allowed many of us to become familiar with the pump systems, as well as develop an understanding across our team and allowed for all members to develop enough knowledge to understand and contribute to the subsequent trade study.

The group placed the piston, diaphragm, and plunger pumps together due to their inherent similarity; the only difference is the interface that acts on the fluid (solid piston, flexible material, or a seal). The notable limitation for this type of pump is the the pulsation of outlet pressure. This results in an inconsistent pressure output and mass flow rate. At the heart of the project is pumping two propellants simultaneously. If the flow rates of fuel and oxidizer are not matched at all times there will be discrepancies in the propellant mixture ratio and could potentially damage the engine or pump. Additionally, oscillations in pressure could cause combustion instabilities that would cause pulsation of thrust or even failure of the combustion chamber. The next real failing for these pumps is the complexity leading to designability challenges. The complexity primarily comes from the methods needed to drive the system and/or reduce the pulsation. Most drive systems will exacerbate the pulsation issue if a linear drive system is chosen. Rotational drive systems would need complex mitigation to interface with all the pistons. More pistons, plungers, or diaphragms would have to be added in parallel in an effort to reduce the pulsation at the outlet. The desirable traits for these types of pumps are their manufacturablility, reliability, and efficiency.

We then looked at screw pumps. There are several variations of this - double or triple. The one that would suit our necessary pressures and mass flow rates would be a double screw pump. The major disadvantages of screw pumps are the manufacturability and cost. The complicated screw has to be specially manufactured (which means outsourcing to a shop with proper machinery and capabilities), which could mean long lead times and high costs. The two screws have to interface closely together which means high and tight tolerances, which also adds to cost and special manufacturing capabilities. In all other aspects it would be a fine and capable pump.

Finally, gear pumps are very well rounded, which is why they rose to the top of the study. Internal and external gears have few differences when it comes to the qualities we evaluated in our trade study. The internal gear is slightly harder to design and it would be harder to access and switch out parts during the life cycle of the part. The internal gear is also more expensive since it will require special machining since it is a gear within a gear. It also would not be able to be bought off the shelf. There is a chance that two compatible gears for the internal pump would possibly be available off the shelf. If the off the shelf parts did not interface perfectly, the external gear pump would still function, just at a lower efficiency. Similarly, the internal gear may have lower reliability, as well. This is a result of it having less self-priming capability. External gears are able to self-prime and have better suction which allows for healthier gear interaction (which means it will last longer and continue to run well) and safer operation if there is any captive gas or in the event it must run dry at the beginning of start up.

It should be noted that the sensitivity study supported the choice of the gear pump; it is available in the appendix, in figure 12.

The final results were 3.38, 3.60, 3.84, and 4.14, for the piston/diaphragm/plunger pump, external gear pump, internal gear pump and screw pump, respectively. These are out of a possible 5. These values show that all of our possible pump base designs are viable and competitive. Going forward with the external gear concept, a few sketches of the two possible configurations conceived so far that could achieve pumping two fluids in one device can be seen in Figures 9, 10, and 11.

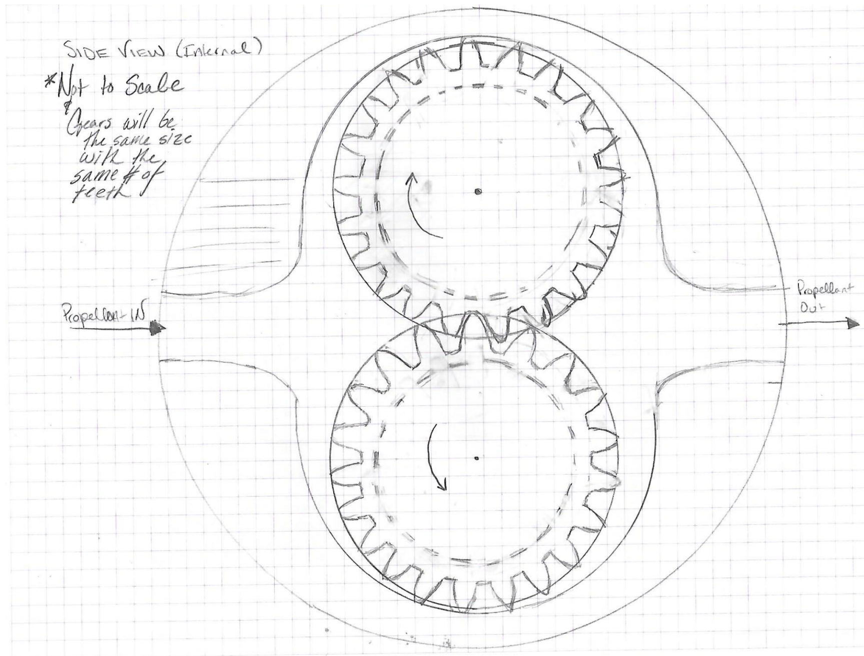


Figure 9: Idea 1 Side View - This is an external gear pump in a cylindrical housing. Wall thicknesses, gear size, gear tooth amount will all depend on further pump and structure design.

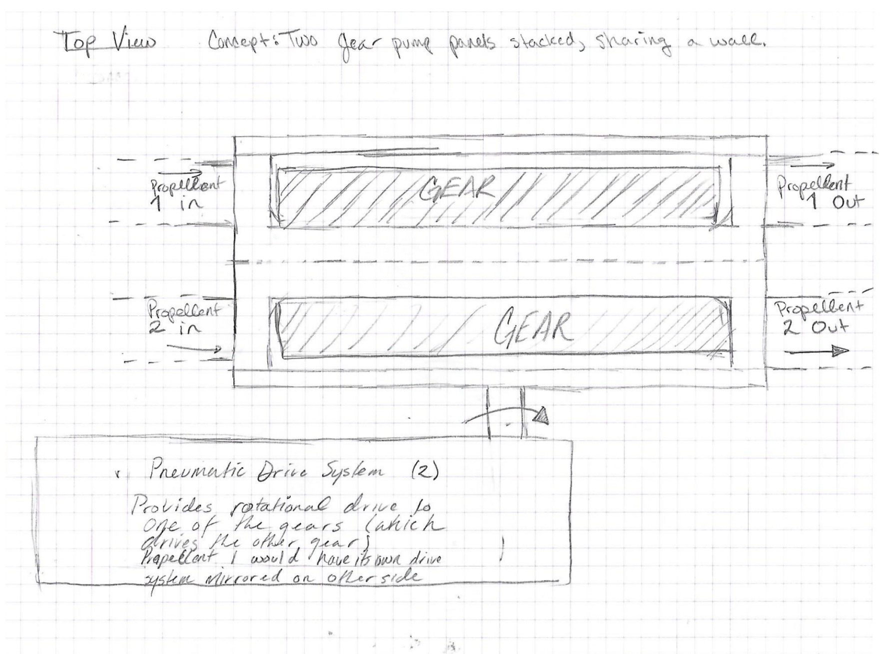


Figure 10: Idea 1 Side View - This shows two external gear pumps stacked opposing each other (so they can be driven from the outside) sharing a wall. A housing system will be designed to encase the pump and drive system. Wall thicknesses, gear size, and gear tooth amount will all depend on further pump and structure design.

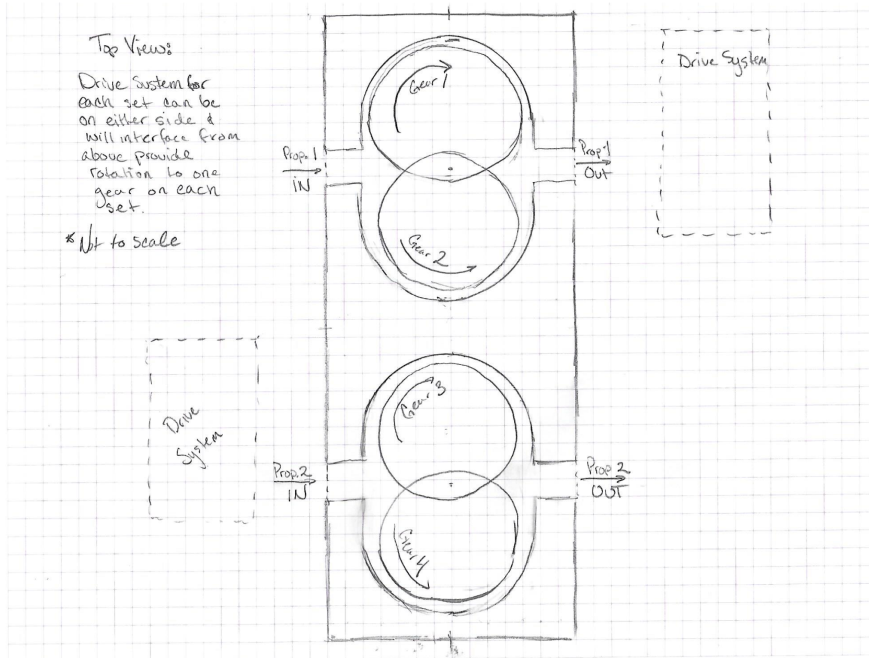


Figure 11: Idea 2 Top View - This shows two external gear pumps next two each other (essentially in parallel). The drive systems will be housed on either side of the column of gears. This will allow a nice, rectangular prism outer casing/shell to house the entire system. Wall thicknesses, gear size, gear tooth amount will all depend on further pump and structure design.

These possible designs will be narrowed down after further design constraints are found using the necessary equations and analysis to dictate gear size, wall thickness and more; one of these configurations will come to light as better or more feasible when it comes to size, cost, manufacturability, and drive capability. These designs are easily adapted to our backup design, the internal gear. There are a few configurations of drive system that will work for either of these. Some might be more compatible, saying they would be easily fixed with mitigation methods to transfer the rotational input to interface properly. A drive system will come to light after we are able to do further analysis to determine the necessary power, torque, and pneumatic fuel. The drive systems will have to be able to achieve the necessary input for rotational speed, while being a reasonable size and using an amount of helium within our budget. In other words, our baseline design is two external gear pumps housed together. Further design specifications will be dictated by further thermal, fluid, and structural analysis now that we have selected the baseline pump design.

B. Selection of Baseline Drive System

In order for the scope of this project to be feasible, the decision was made to completely outsource the drive system. This is because designing both a pump and drive system did not seem worthwhile when there exists drive systems that can easily power the pump. This is in contrast to the pump the group was asked to design, which does not exist. The group believes this decision will save them time, effort, and money which can be put towards pump design and throttle control.

Recall from Section III,B that, of the pumps the group considered, the only one which was compatible with the linear drive system was the piston/plunger/diaphragm variety. Table 12 clearly shows that the piston/plunger/diaphragm pump type is not the best suited for the PEAPOD project, and the previous section also elaborated on this fact. Despite the alluring fact the drive system of the piston/plunger/diaphragm is essentially integrated into the pump design, the drawbacks associated with this type of pump far outweighed its benefits. This means that, although the linear drive system scored the highest in the drive system trade study as indicated in Table 15, the low score of its associated pump type rules the linear drive system out of the design realm.

The next two highest drive system scores were for the axial flow variable displacement piston motor at 4.12, and for the vane motor at 4.19 (out of 5). These two drive systems scored less than 0.1 apart, while the radial piston motor had a much lower score than either the axial flow variable displacement piston motor or the vane motor. It is worth mentioning that the cost estimates for the drive systems considered were very rough because it was difficult to obtain this information online. Most sites required an application to receive a quote for a pump drive system, which the group did not have time to do for this document. This is especially important to keep in mind because cost had a very large weighting in our trade study matrix. That being said, if the cost score of the axial flow variable displacement piston motor were increased from 3 to 4 (which is what the vane motor scored), then the axial flow variable displacement piston motor would have an overall higher score by about 0.10 points. Furthermore, if the cost score of the radial piston pump is increased from 2 to 3 or 4, then it, too, becomes a viable option (though it still scores lower than either the axial flow or vane motors).

This exploration led the group to conclude that either the axial flow variable displacement piston motor or the vane motor would be perfectly suitable off-the-shelf motors to drive the pump system we will be designing. The final drive system selection will be made once in-depth CFD and systems analyses provide more reliable benchmarks for the drive system's requirements. The final drive system decision will also be contingent upon quotes the group receives for off-the-shelf drive systems, since the cost data used in the drive system matrix were not reliable. Regardless, the trade study performed narrowed down the drive system choice to two proven and reliable options, either of which is capable of driving a gear pump.

C. Selection of Baseline Hypergolic Compatible Materials

As discussed above, the compatible materials for UDMH and dinitrogen tetroxide were stainless steels 300 series, Teflon and Reddy Lube. A determination of which of these materials to use (if one, two, three or none at all) cannot be made at the current time. This is due to the complexity of deciding if these materials are within the budget of the project; as well as, any possible manufacturing/structural constraints needed to be determined through analysis. However, if one decision were to be made, it would be the use of Teflon seals due to their relatively low price and reliability. As for the lubricant and metal, more analysis needs to be performed once a baseline design has been created in structural analysis software.

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Appendix 1 - Sensitivity Analysis

									LPDD	RPDD	ExGear	InGear	Screw	RV	Cent
Sensitivity factor	**Result**								7	2	1	3	6	4	5
Equal weightings	Yes	2.6	2.6	2.8	2.55	2.3	2.4	2.5	2	2	1	4	7	6	5
Throttlability	Yes	2.9	3.02	3.38	3.12	2.88	2.98	3.26	6	4	1	3	7	5	2
Slew Rate	No	3.18	3.62	3.86	3.6	3.4	3.46	3.46	7	2	1	3	6	4	4
Pressure fluctuation	Slight	3.1	3.82	4.02	3.76	3.52	3.62	3.58	7	2	1	3	6	4	5
Efficiency	No	3.18	3.66	3.86	3.6	3.36	3.42	3.42	7	2	1	3	6	4	4
Tolerances	Slight	2.98	3.42	3.78	3.52	3.28	3.22	3.26	7	3	1	2	4	6	5
Manufacture time	Yes	3.14	3.66	3.7	3.44	3.36	3.46	3.26	7	2	1	4	5	3	6
Complexity	No	3.18	3.52	3.62	3.36	3.12	3.32	3.08	5	2	1	3	6	4	7
Pneumatic integration	Slight	3.18	3.7	3.9	3.64	3.4	3.5	3.46	7	2	1	3	6	4	5
Designability	No	3.22	3.66	3.82	3.6	3.4	3.46	3.42	7	2	1	3	6	4	5
Maintainability (easy access)	No	3.32	3.76	3.94	3.7	3.46	3.58	3.52	7	2	1	3	6	4	5
Outsourcing	Yes	3.08	3.64	3.84	3.64	3.46	3.5	3.4	7	2	1	2	5	4	6
Off shelf component availability	Slight	3.26	3.7	3.86	3.64	3.44	3.54	3.46	7	2	1	3	6	4	5
Reliability	Yes	3.08	3.32	3.52	3.36	3.02	3.32	3.18	6	3	1	2	7	3	5
Restartability	No	3.14	3.58	3.72	3.46	3.22	3.38	3.34	7	2	1	3	6	4	5

Figure 12: Sensitivity study results. In the diagram, LPDD is the linear piston/diaghpram pump, RPDD is the axial driven plunger pump, ExGear is the external gear pump, InGear is the internal gear pump, Screw is the screw pump, RV is the rotary vane pump, and Cent is the centrifugal pump (examined for reference).