

DESIGN AND TEST OF AN ECONOMICAL COLD GAS PROPULSION SYSTEM

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***ABSTRACT** - Small Satellites are emerging as the preferred platform for a wide variety of earth orbit and even interplanetary missions. These spacecraft are, by their very nature, extremely limited in budget, volume, mass and power. Existing fluid propulsion options are too large, costly and complex for many small satellite applications. In an attempt to address this problem VACCO has produced an inexpensive, modular system specifically designed for the special needs of small satellites. This paper documents the results of a development program conducted for NASA and administered by the Applied Physics Laboratory of Johns Hopkins University.*

The Cold Gas Propulsion System (CGPS) resulting from this effort is unique in several ways. It utilizes a simple “blow down” architecture which requires the entire system to operate at up to full storage tank pressure. The traditional pressure regulator has been eliminated. This required the development of unique thrusters capable of functioning with inlet pressures to 207 bar. To minimize power consumption, the thrusters feature latching valves that require an electrical pulse to open and another to close. Between pulses the thruster is magnetically latched in either the open or closed position as required. This dramatically reduces the power required by the thruster valves while preserving small impulse bit capability.

In order to minimize mass and cost, the system uses only four thrusters. By mounting these thrusters in a double canted orientation to the spacecraft, pitch, yaw and roll control as well as delta V can be accomplished.

In conclusion, the subject Cold Gas Propulsion System represents an important advance in propulsion technology suitable for small satellites. As a result of this work, the size, mass, power requirements and cost of these systems has been reduced.

1 - Introduction

The Cold Gas Propulsion System (CGPS) resulting from this effort is unique in several ways. It utilizes a simple “blow down” architecture which requires the entire system to operate at full storage tank pressure. The

traditional pressure regulator has been eliminated. This required the development of unique thrusters capable of functioning with inlet pressures to 207 bar. The thrusters are also unique in that they utilize a latching valve design that requires a short electrical pulse to open and another to close. Between pulses the

thruster is magnetically latched in either the open or closed position as required. This dramatically reduces power required by the thruster valves while preserving the option for small impulse bits.

In order to minimize mass and cost, the system uses only four thrusters. By mounting these thrusters in a double canted orientation to the spacecraft, pitch, yaw and roll control as well as delta V can be accomplished.

Our approach was to define a set of requirements that would be relevant to a substantial segment of the small satellite industry. We began by developing a set of propulsion requirements based on a hypothetical, but realistic spacecraft and mission. This included the real-world constraints of mass, envelope and cost.

From this we developed the system design concept. Component performance requirements were then derived and suitable component designs selected. Piece parts were fabricated or procured for one unit. Each component was individually assembled and tested. The module was then integrated and tested in the VACCO Aerospace Products facility in South El Monte, California.

2 - Requirement Definition

For the purposes of this study, satellites in the 20-100 kg class are considered “small”. Their mission and system requirements have a broad range depending on the details of their specific mission. This nitrogen cold gas propulsion system is aimed at missions with low available power, mass constraints and rather meager delta V and therefore small total impulse requirements. The required thrust level could vary up or down within the range of 0.1N to 5.0N depending whether attitude control precision or the time available to impart a

given delta V dominate the impulse requirements. A strawman mission has been generated to illustrate the advantages of the proposed system.

2.1 - Strawman Mission Description

The mission is a communication constellation of small spacecraft that are launched into multiple planes of a 700 km orbit inclined 63°. It has a 5-year mission lifetime since technology improvements will most likely make it obsolete beyond that time frame. A target spacecraft mass of 30 kg is established assuming an advanced miniaturized bus that is earth pointing and maintains 3-axis attitude control via wheels and torquer bars.

2.2 - Strawman Mission Propulsion Requirements

Each plane of the constellation is populated by the single launch of 6-8 spacecraft into a 700 km circular orbit. After correcting the tip-off rates induced by separation from the dispenser (2.0 degrees/sec) the onboard propulsion system must provide impulse to evenly distribute the spacecraft around the orbital plane. This is accomplished by raising the apogee or lowering the perigee of a spacecraft while adjusting the inclination to match the nodal drift rate of the baseline constellation. The spacecraft will then be allowed to drift around the orbit until it has achieved the desired position and finally lowering the apogee or raising the perigee and adjusting the inclination to match the baseline orbit. If the dispenser were able to do the initial orbital adjustments, the required delta V would be halved. The required delta V is a function of the duration allowed to accomplish drifting as well as how far the spacecraft is required to drift around the orbit. For this study it is

assumed that there are 30 days available for the drifting and the drift distance is the maximum of 180°. This results in a tip off rate cancellation propellant mass requirement of 0.011 kg and a constellation establishment delta V requirement of 30 m/sec. Any delta V required to correct the initial launch vehicle injection error is assumed to be included in the 30 m/sec.

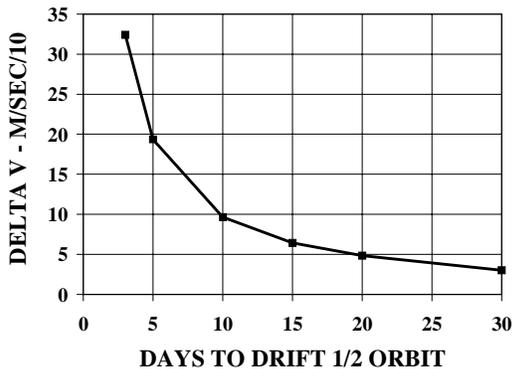


Figure 1: Constellation Establishment Delta V vs. Days to Drift 1/2 Orbit

Maintaining the desired spacing between each spacecraft during the mission lifetime requires additional delta V. Data from IRIDIUM indicates that about 4 m/sec/year is sufficient allowance for this function. For the 5-year mission life this results in a 20 m/sec requirement.

On spacecraft with a lot of functional redundancy, thrusters are often used to backup the wheels for attitude control and the torquer bars for momentum dumping. For this multiple spacecraft constellation no backup function from the propulsion system is required. For a spacecraft this size however, momentum dumping for 5 years would only require about 0.2 kg of gas and the attitude control backup requirement could most likely be accommodated by the planned impulse margin.

De-orbiting the spacecraft at the end of its useful life is a capability sometimes required of the propulsion system. Unfortunately, it usually dominates the mission propellant requirements and is identified as an optional requirement for this spacecraft. The NASA 1740.8 requirement for LEO satellites is to place the spacecraft in an orbit that will naturally re-enter in 25 years. This mission's 700 km orbit and 0.01 m²/kg spacecraft area to mass ratio requires lowering the orbit perigee to 550 km which results in a de-orbit delta V requirement of 40 m/sec.

Once the baseline requirements are established it is prudent to provide propellant capacity for creep, leakage and an adequate safety margin. Early in the formation of a program 20% is the value of margin usually allocated. After CDR the comfort zone is 10%. The subject system is so simple that leakage can be predicted with confidence. For this reason a margin of 10% is adequate. The cold gas system leak sources include the thruster seats (2X10⁻⁵ sccs each), the fill/drain valve, the tank, the pressure transducer (future) and the manifold (1X10⁻⁶ sccs). Over a 5 year mission this amounts to 0.016 kg of propellant. If excess capacity exists in the propulsion system at launch, any unused dry mass margin can be loaded as propellant. Table 1 summarizes the propellant requirements for the 30 kg spacecraft assuming a GN2 Isp of 65 sec.

Mission Element	Delta V (m/sec)	Impulse n-sec	Mass (kg)
Injection Trim / Constellation Establishment	30	-	1.379
De-Spin	-	-	0.000
Tip-Off Nullification	-	7.0	0.011
Momentum Dump	-	-	0.000
Constellation Maintenance	20	-	0.927
Leakage Allowance	-	-	0.016
Margin	-	-	0.231
Mission Total	50	7.0	2.564
De-Orbit (optional)	40		1.825

Table 1: Propellant Requirements Summary

2.3 - Derived Propulsion System Requirements

Once the required propellant quantity is determined, tank sizing and system component requirements can be derived. The higher the storage pressure, the more compact the resulting system will be. For the purposes of this study, cost was the dominant factor. In order to utilize existing off-the-shelf components, an MEOP of 207 bar was selected. Given a maximum temperature of 40°C, 2.564 Kg of useable nitrogen would require a storage volume of 13.2 liters. For this demonstration system an off-the-shelf 8 liter tank was selected.

The thrusters are designed to provide a thrust of 0.5N at 21 bar inlet pressure. The vast majority of the propellant will be used for delta V for injection trim and constellation establishment early in the mission when tank pressure is highest. At 207 bar inlet pressure the thrusters will deliver approximately 5N of thrust. Thrust over the blow-down range of 207 to 21 bar will be directly proportional to inlet pressure as shown in Figure 2.

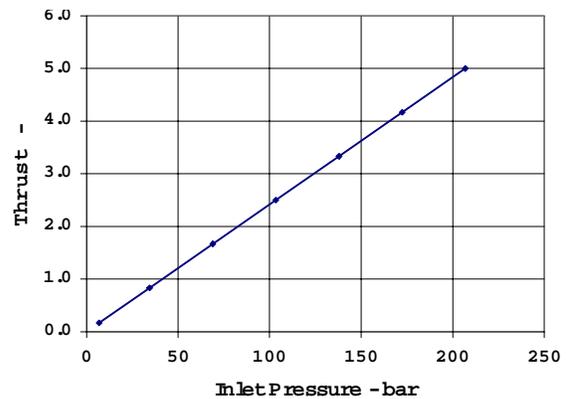


Figure 2: Thrust vs. Inlet Pressure

Low system mass is achieved by using only four double canted thrusters to achieve all the required propulsion maneuvers. By mounting the thrusters in a 15° double canted orientation, 3-axis control and delta V can be achieved. This is illustrated in Figure 3 using unit vectors. When thrusters are fired as delineated in Table 2, the thrust vectors combined to achieve pitch, yaw, roll and translation. These maneuvers also impart a delta V to the spacecraft. If this is undesirable, it can be cancelled with a pure delta V firing.

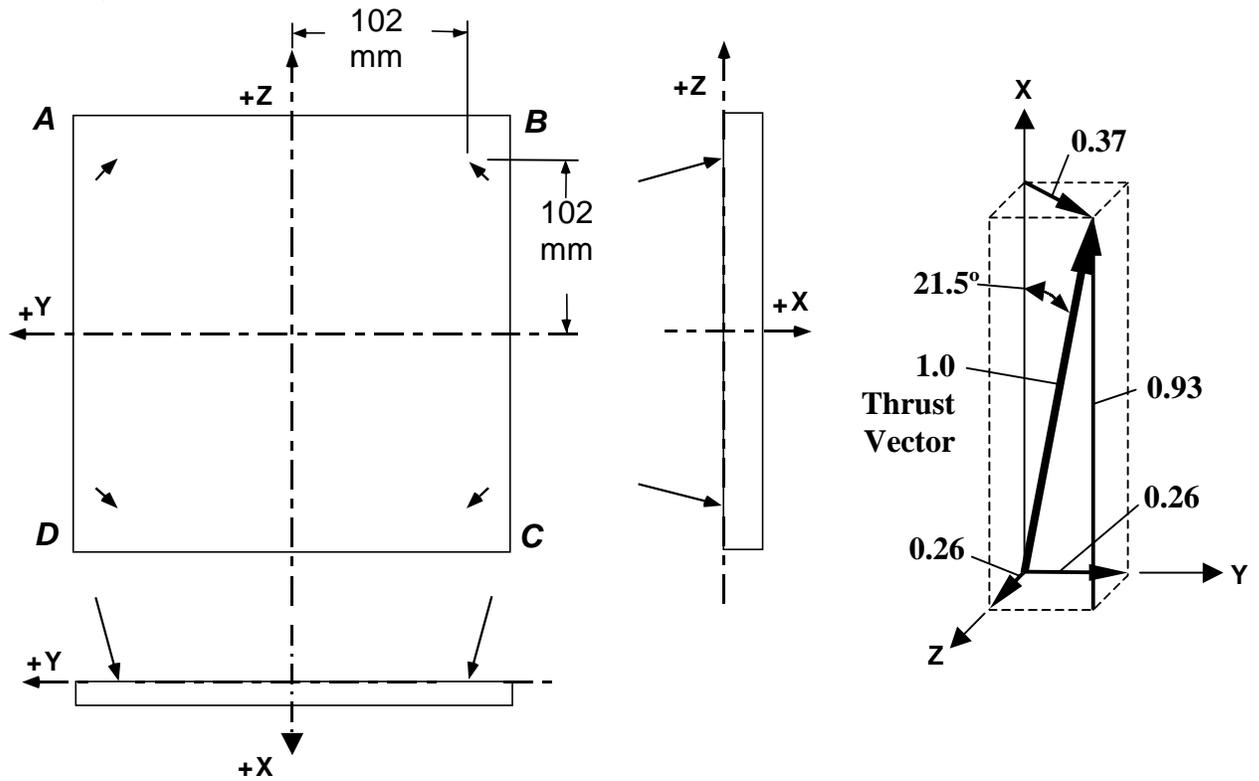


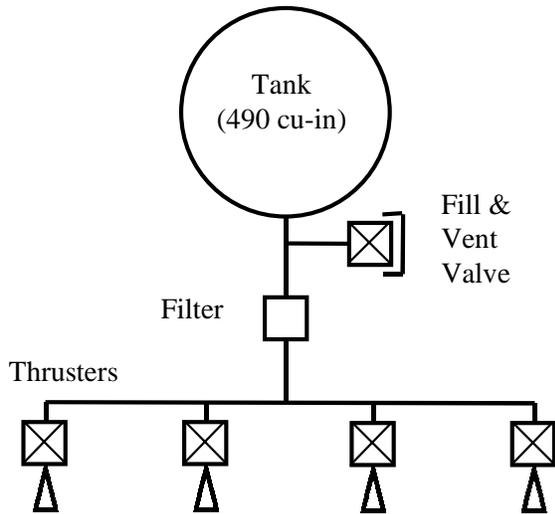
Figure 3: Thrust Vector Diagram

Maneuver	Thruster	Torque/Force
+Pitch	AB	0.948 N-M
-Pitch	CD	0.948 N-M
+Yaw	BC	0.948 N-M
-Yaw	AD	0.948 N-M
CW Roll	AC	0.439 N-M
CCW Roll	BD	0.439 N-M
Delta V	ABCD	18.6 N

Table 2: Thruster Force/Torque

3 - Propulsion System Description

3.1 – Overview The subject propulsion system is a cold gas system using nitrogen as the propellant. To minimize mass and cost, the demonstration system, as shown in Figure 4, is very simple.



Nitrogen is stored at 207 bar in the 8.0 liter Tank. A Fill & Drain Valve facilitates filling and venting nitrogen from the system. This fitting also allows the ground test system to be hooked up to external pressure sensors. A 20 micron filter protects the Thrusters from particulate contamination that might enter the system through the Fill Valve.

As shown in Figure 5, a manifold consisting of ¼" CRES tubing interconnects the functional components of the system. The Mounting Plate acts in conjunction with the Tank as the primary structural element of the system. For the ground test system, the Mounting Plate is fabricated from 6.4mm thick aluminum plate. For an eventual flight unit, this part will be replaced with an aluminum honeycomb or composite plate. The Mounting Plate is connected to the Tank by a harness with four CRES padded straps. Each strap is connected to an arm of the Mounting Plate by a "T" bolt and turnbuckle.

Each of the four thrusters are fastened to a mounting bracket. The bracket is, in turn, attached to the Mounting Plate. The Thrusters are tilted 21.5° from the X-axis toward the tangent. This is mathematically equivalent to the 15° double canted orientation discussed earlier.

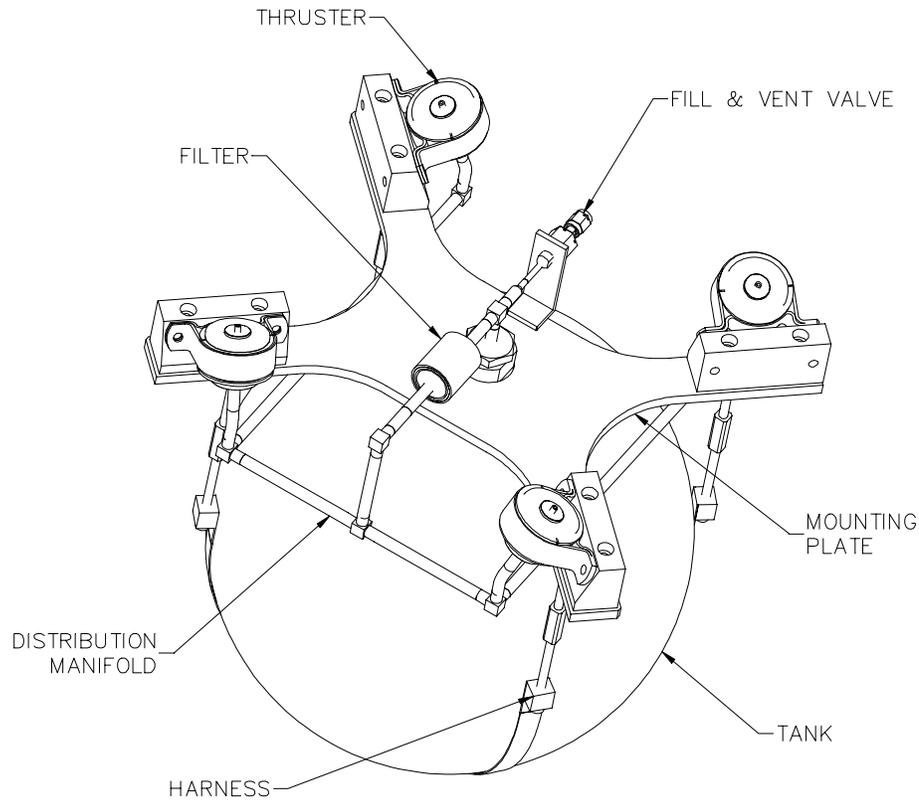


Figure 5: Cold Gas Propulsion Demonstration System

3.2 - Propellant Tank

The primary requirement of the CGPS is to provide the impulse required for various mission phases. Since the propellant is simple pressurized GN₂, a variety of suitable tanks can be utilized. The tank selected for the demonstration CGPS, as shown in Figure 6, is an 8-liter Lincoln Composites unit, P/N 220063. It consists of a spherical aluminum shell with a Kevlar filament over-wrap



Figure 7: VACCO Fill & Vent Valve

This tank has been in production for many years and has been used in a variety of aerospace applications including the Clementine spacecraft.

3.3 - Fill & Vent Valve

The miniature Fill & Vent Valve selected for this application is VACCO Industries P/N VID10874-01 shown in Figure 7. This valve is identical to our production unit except the body is CRES instead of titanium. When closed and capped the valve provides two interrupts against external leakage. Should the valve seat be damaged after installation it can be disassembled and refinished in place.

Using CRES for the Body drives the mass of the valve to about 40 grams.



Figure 7: VACCO Fill & Vent Valve

Hundreds of these valves have been used in applications to pressures as high as 690

3.4 - Filter

The Filter selected for this application is a 20 micron absolute, diffusion-bonded, etched disc design per VACCO P/N F1D10744-01 (Figure 8). This advanced design features hundreds of titanium discs with thousands of individually etched flow passages. Each flow path is held to micro-scale tolerances. This insures that the passages will be small enough to prevent passage of particles greater than 20 microns while providing a large flow area.



Figure 8: VACCO Nitrogen Filter

3.5 - Cold Gas Thrusters

The four cold gas thrusters per VACCO P/N V1E10703-01 (Figure 9) are an adaptation of a latch valve design currently in production. They are unique for a thruster in that they are designed to magnetically latch in their last commanded position when electrical power is removed.

The thrusters are all-welded against external leakage. Materials in contact with the propellant are limited to CRES and Kel-F. Separate coils control opening and closing respectively. The expansion nozzle is built into the thruster valve body immediately downstream of the seat.



Figure 9: Cold Gas Thruster

Power is only consumed during the 20 millisecond electrical pulse while the valve is changing state from open to closed or from closed to open. Unlike typical normally closed thruster valves, they do not consume power during most of the duration of the thruster firing. Assuming a delta V of 50 m/s is required, a conventional normally closed thruster valve will consume approximately 7,600 watt-sec of energy. Assuming 100 thruster firings, the latching thruster valve will

consume only 352 watt-sec of energy. This reduces the power consumed by the valves by over 95%.

4 – System Testing

4.1 - Test Plan

Due to funding constraints, minimal functional testing of the demonstration Cold Gas Propulsion System was performed. The testing was performed per VACCO Test Procedures ETP-XV1E10718 and ETP-V1E10718. All of the components were tested at the component level to verify performance before integration. An outline of the system test plan is as follows:

1. Visual Inspection
2. Proof Pressure Test
3. External Leakage Test
4. Internal Leakage Test
5. Extended Applied Voltage Test
6. Coil Resistance Test
7. Power Consumption
8. Dielectric Strength Test
9. Pull-In Voltage Test
10. Thruster Response Test
11. Flow (Thrust) Test
12. Minimum Impulse Bit Test

Testing was designed to confirm functionality of the design and act as a baseline for comparison against future testing.

4.2 – Test Specimen

The Cold Gas Propulsion System test specimen and control box is shown in Figure 10.



Figure 10: Cold Gas Propulsion System Test Specimen and Control Box

In addition to the CGPS an electronic controller was developed. The electronic control box is a microprocessor-based controller, which has programmable settings between 1 and 65000 millisecond resolution. Three settings are programmed into the controller T1, T2, and T3. T1 is the opening pulse duration, T2 is the "dead time" or lag between open and closing pulses, and T3 is the closing pulse duration. Each of the thruster valve's setting are programmed independently.

4.3 – Test Results

The Cold Gas Propulsion System met or exceeded all of the design requirements established during the design phase. The results of this testing is delineated in Table 3 and Table 4 below.

	THRUSTER VALVE #1	THRUSTER VALVE #2	THRUSTER VALVE #3	THRUSTER VALVE #4
Opening Coil Response @ 21 bar, 24 VDC	3.7 msec	3.75 msec	3.55 msec	3.5 msec
Closing Coil Response @ 21 bar, 24 VDC	4.05 msec	3.75 msec	3.9 msec	3.5 msec
Minimum Pulse Bit @ 21 bar, 24 VDC	7.75 msec	7.5 msec	7.45 msec	7.0 msec
Opening Coil Response @ 69 bar, 24VDC	3.65 msec	3.85 msec	3.6 msec	3.6 msec
Closing Coil Response @ 69 bar, 24VDC	3.95 msec	3.85 msec	3.85 msec	3.6 msec
Minimum Pulse Bit @ 69 bar, 24 VDC	7.6 msec	7.7 msec	7.45 msec	7.2 msec
Opening Response @ 138 bar, 24 VDC	3.65 msec	3.85 msec	3.85 msec	3.6 msec
Closing Response @ 138 bar, 24 VDC	3.85 msec	3.85 msec	3.85 msec	3.55 msec
Minimum Pulse Bit @ 138 bar, 24 VDC	7.5 msec	7.7 msec	7.7 msec	7.15 msec
Opening Response @ 248 bar, 17.2 VDC	6.6 msec	7.8 msec	6.6 msec	6.8 msec
Closing Response @ 248 bar, 17.2 VDC	6.8 msec	6.8 msec	6.2 msec	7.0 msec
Minimum Pulse Bit @ 248 bar, 17.2 VDC	13.4 msec	14.6 msec	12.8 msec	13.8 msec

Table 3: Cold Gas Propulsion System Test Data

	<i>THRUSTER VALVE #1</i>	<i>THRUSTER VALVE #2</i>	<i>THRUSTER VALVE #3</i>	<i>THRUSTER VALVE #4</i>
Internal Leakage @ 248 bar	3.2x10 ⁻⁷ sccs GHe	5.4x10 ⁻⁷ sccs GHe	3.2x10 ⁻⁷ sccs GHe	9.0x10 ⁻⁷ sccs GHe
External Leakage @ 248 bar, 17.2 VDC	Not Detectable w/ Pipette.			
Opening Coil Response @ 248 bar, 17.2 VDC	6.6 msec	7.8 msec	6.6 msec	6.8 msec
Closing Coil Response @ 248 bar, 17.2 VDC	6.2 msec	6.8 msec	6.2 msec	7.0 msec
Power Consumption Opening Coil @ 32 VDC	28.2 watts	28.4 watts	28.4 watts	29.0 watts
Power Consumption Closing Coil @ 32 VDC	28.4 watts	28.7 watts	28.4 watts	28.6 watts
Flow Rate @ 21 bar	41.1 l/m	42.5 l/m	39.6 l/m	39.6 l/m
Flow Rate @ 34 bar	68.0 l/m	70.8 l/m	65.1 l/m	66.5 l/m

Table 4: Cold Gas Propulsion System Test Data

5 - Flight System Configuration

Due to the flight-like nature of the demonstration system design, a future flight system will be very similar. In order to minimize size and mass while accommodating

2.564 Kg of nitrogen, the maximum operating pressure would increase to 5000 psia. The design shown in Figure 10 includes an additional latching isolation valve to prevent leakage and a pressure transducer.

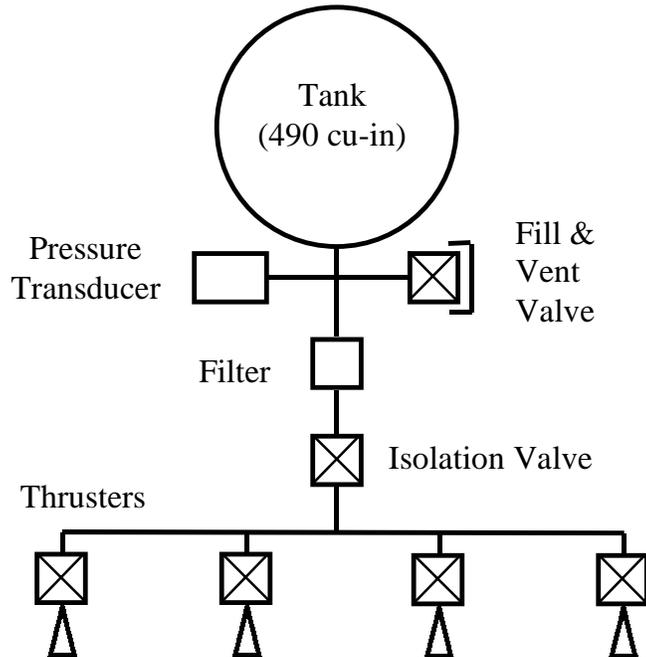


Figure 10: Flight System Schematic

6 - Summary

The subject Cold Gas Propulsion System represents an important advancement in low power propulsion technology suitable for small satellites. As a result of this work, the size, mass, power requirements and cost of these systems has been significantly reduced. The objective of this work is to document the capabilities and attributes of the low power Cold Gas Propulsion System in sufficient detail to allow designers of small satellites to consider it as a practical propulsion system option.

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