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Self Pressurizing HTP Feed Systems

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Abstract

Hydrogen peroxide tanks can be pressurized with decomposed HTP originating in the tank itself. In rocketry, this offers the advantage of eliminating bulky and heavy inert gas storage. Several prototype self-pressurizing HTP systems have recently been designed and tested. Both a differential piston tank and a small gas-driven pump have been tried to obtain the pressure boost needed for flow through a gas generator and back to the tank. Results include terrestrial maneuvering tests of a prototype microsatellite, including warm gas attitude control jets.

Introduction

Rocket propellant tanks are typically pressurized with inert gas stored in pressure vessels, especially on spacecraft. While this approach is simple and reliable, there are mass and packaging disadvantages associated with the gas vessels. Another option is to pressurize a tank with gas derived from the propellant itself. For example, simply boiling a small fraction of the propellant has been widely implemented for liquid hydrogen tanks.

In the case of high test hydrogen peroxide (HTP), decomposition yields a mixture of steam and oxygen which can be used for tank pressurization. This can theoretically be accomplished by simply immersing a catalyst inside the tank. However, the reaction rate is difficult to control, and it may be slowed by the coolant effect of the surrounding liquid. An alternative is to controllably pass some of the HTP through a separate catalytic gas generator, and return the gas to the tank.

The work described was motivated by an unmet need for affordable microsatellite propulsion better than cold gas.[1-4] It is attractive to consider minimally toxic liquid propellant, while avoiding gas storage to reduce system mass and volume. Hence, self-pressurizing HTP systems have been fabricated and tested. In 1998 this culminated in maneuvering tests of a 25 kg microsatellite prototype which had no gas vessels. The purpose of this paper is to describe the work and consider other potential applications. For example, self-pressurizing HTP feed systems can be used with hybrid rockets.

System Options

Flow through a gas generator and back to the source tank necessarily has an associated pressure loss, which requires a pressure boost somewhere along the path. This constitutes a positive feedback loop, so flow control is required to avoid over pressurization. Figure 1 shows three options in which HTP exiting the tank has its pressure raised above that of the tank pressurant. Arrows indicate the direction of motion or flow. In each case, a liquid pressure regulator in series with the gas generator controls system pressure. The pressures and HTP concentrations shown are merely examples of what is possible. In all cases, the tanks start full of liquid at low pressure, and come up to operating pressure when the enable valve is opened. This can enhance safety, as no part needs to be above 10 to 50 psi initially (e.g. before launch).

A simple scheme uses a cylindrical tank assembly having two different diameters and a compound internal piston, as shown in Figure 1A. The pressurant gas acts over an area larger than the liquid piston, to amplify pressure. A major drawback is the large empty vented space, i.e. the total volume is twice the liquid capacity. Figure 1B shows another way to implement a pressure boosting cylindrical piston tank. Again the gas area exceeds the liquid area, but the vented space is external, i.e. there merely is no pressure acting on the free end of the rod. As a result, liquid may initially occupy the entire tank volume. The piston seal and rod seal are liquid cooled, whereas the gas piston seal in Figure 1A could be overheated by steam. Another advantage of option B is that the structural loads on the piston are less.

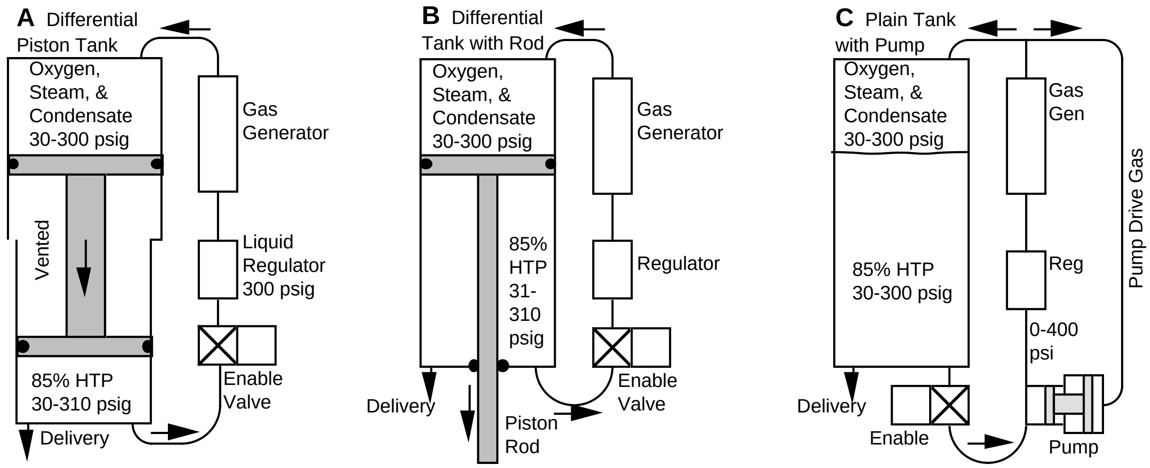


Figure 1. Options for self-pressurizing HTP feed systems.

A potentially useful feature of the external piston rod is that it indicates the quantity of remaining propellant. However, a drawback is that external space must be provided for the lengthening rod exposure. While this is undoubtedly possible, it is impractical for some applications. The final more complex alternative shown in Figure 1C is to use a plain tank with an external pressure boosting component. As indicated, this may be a small gas-driven pump which uses the differential area principle. In effect, such a pump is a refillable differential piston tank. The pump must cycle back and forth, and hence it has valves (not shown) for receiving and discharging both liquid and gas.

The differential area principle is an old idea in rocketry, and it can be used with different propellants. In 1932, Robert H. Goddard et al built a bellows pump driven by a bellows engine to operate with liquid and gaseous nitrogen. Between 1950 and 1970, all three options in Figure 1 were proposed in various forms for small rocket propelled vehicles operating in the atmosphere.[5-7] While self-pressurizing liquid systems would be compact to minimize drag, solid rockets instead came into widespread use for this type of application. More recently, self-pressurizing systems using hydrazine and differential pistons have been tested for specialized applications.[8&9] The term "warm gas pressurization" is often used.

There are other options for providing a pressure boost, such as gravity and electric pumps. However, the pressure which can be obtained from gravity is very limited. The electric option would most likely be more massive. An electric drive would also need a controller to avoid continuous energy consumption when the system is at full pressure without flow (liquid regulator shut). The all-fluid designs in Figure 1 inherently operate over a wide flow range at a nearly constant pressure without external control. Control could be added, e.g. reduced pressures can be obtained using the enable valve.

There are a number of reasons why it is important to characterize storage and operational timelines before implementing self-pressurization. For example, if the system in Figure 1C is required to have a long life after initial startup, one concern would be the potential migration of catalytic material from the gas generator into the tank. Peak temperatures of the tank wall and pump seals are another consideration depending on duty cycles.

The liquid delivery ports indicated in Figure 1 may feed one or more thrust chambers. Similarly, a branch on a warm gas line could meet auxiliary gas requirements. Given a single source reservoir, there is no need to separately budget for liquid and gas needs in advance. If a large flow of gas is drawn off intermittently, system pressure would vary. To avoid this, a separate gas generator may receive liquid from the self-pressurizing tank. For example, Figure 2A shows that a small self-pressurizing rod tank could feed a gas generator which in turn pressurizes a much larger HTP tank. In this case it would be much easier to provide room for the extending rod than if the main tank is made to be self-pressurizing.

Hardware weight can be reduced further in many cases by using high throughput pumps to feed thrust chambers directly from low pressure tanks. This is practical for high delta-v maneuvers at low to moderate acceleration, if low pressure tanks can be made very lightweight (as on launch vehicles). Conversely, self-pressurization is lighter for extreme acceleration at low delta v, since pump-fed engine weight would exceed potential tank weight savings.

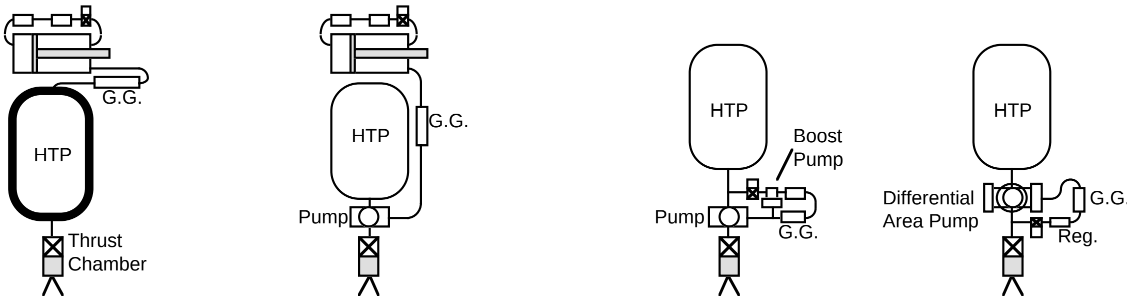


Figure 2. A. Staged pressurization. B. Pump-fed thrust chamber. C&D. Self-boosting pump-fed propulsion.

Note that self-pressurizing features can be combined with a pump-fed system. The example of Figure 2B shows a self-pressurizing rod tank which delivers HTP to a gas generator, which drives a pump to feed thrusters. Pump fed HTP using only low pressure tanks (2C-D) is being explored, and will be described in a future paper. Technological overlaps enhance synergistic development efforts. For example, the temperature and lifetime capability of fluoroelastomer seals, fluorinated greases, and aluminum alloys is important to all these concepts, as are valves, regulators, and gas generators.

Differential Tank Test

The option of Figure 1B was implemented by the author in 1997-1998. Figure 3 shows the low cost test hardware, which uses a differential piston tank made from a length of 3 inch diameter by .065 wall aluminum tubing, with ends held in place by snap rings. Welds were avoided, to reduce cost and to simplify changes and post-test inspections.

This self-pressurizing HTP system was tested on the benchtop using commercial solenoid valves and low cost instrumentation, in a transparent polycarbonate enclosure to permit safe direct observation. The schematic diagram corresponds exactly to the hardware pictured. In addition to the gas immersion thermocouple shown, temperatures were measured on the tank and gas generator. Although the aluminum parts would melt at the reaction temperature of 85% HTP, hardware temperatures remained acceptably low due to limited flow rates with external heat losses.

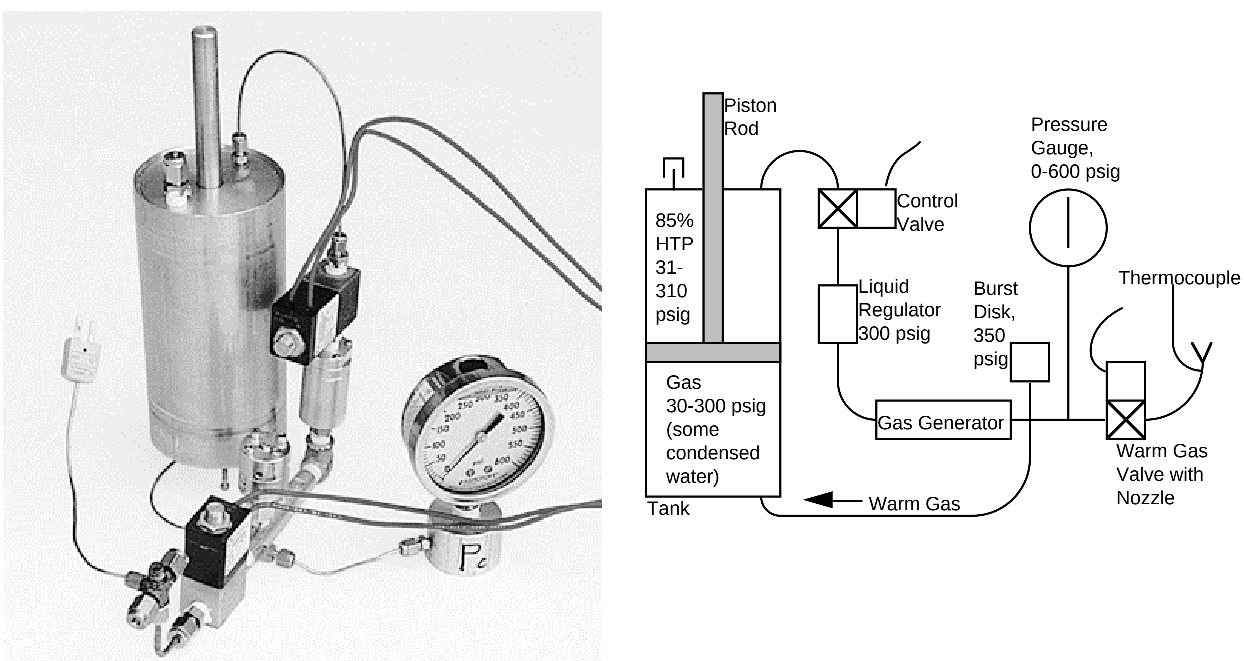


Figure 3. Self pressurizing HTP test setup with differential piston tank.

Numerous starts were demonstrated using an initial air charge of 30 psig. Oscillations of the decomposition reaction at ~1 Hz were observed during startup. The reaction in the gas generator caused some reverse flow of gas, after which liquid did not reach the catalyst again until the gas flowed forward into the tank. While the oscillation could be prevented by a check valve (e.g. at the gas generator inlet), the small amounts of reverse flow did not heat the regulator above 100 F. The tank temperature remained well below 200 F during pressure regulated operation.

Throughout full pressure tank expulsion, the regulator inlet pressure remained within a narrow range. Therefore, the complex art of conventional aerospace regulator design is unnecessary here. The 60 gram regulator had only four turned parts in addition to springs, seals, and fasteners. A soft seal provided a positive shutoff. This simple axial flow design is possible because it need not be pressure balanced with respect to the inlet. In contrast, sensitivity to inlet pressure is unacceptable for the gas pressurant regulators used on satellites, because the pressure in helium tanks varies widely.

Instead of delivering pressurized liquid, this test series exercised the system by pulsing the warm gas valve, with delivery temperatures exceeding 400 F. By pulsing the control valve, it was shown that system pressure could be adjusted to any level between the seal friction threshold and the regulated pressure. This flexibility can be used to control fluid delivery rates. However, attempts at low bandwidth manual control at reduced pressures resulted in significant pressure variations. This increased tank temperatures due to steam condensation as oxygen flowing out of the tank was replaced by a fresh mixture of steam and oxygen. Essentially, there is a choice between using the tank as an accumulator and avoiding additional condensation there. The latter option requires a check valve at the tank pressurant port. Thus it was learned that the most efficient operation requires sizing the components to meet any auxiliary gas demand, rather than relying on the tank ullage to meet peak gas demands.

Pumped Self-Pressurization

When self-pressurization was considered for a microsatellite technology testbed application, packaging considerations ruled out the differential piston tanks in Figure 1. The option of Figure 2A was also contemplated, but the need to load propellant into one or more extra tanks was deemed to be a significant disadvantage. Nevertheless, the rod tank effort was time well spent, because the positive results bolstered confidence that Figure 1C could be readily implemented, moreover with an all-aluminum pump having leaktight elastomer seals.

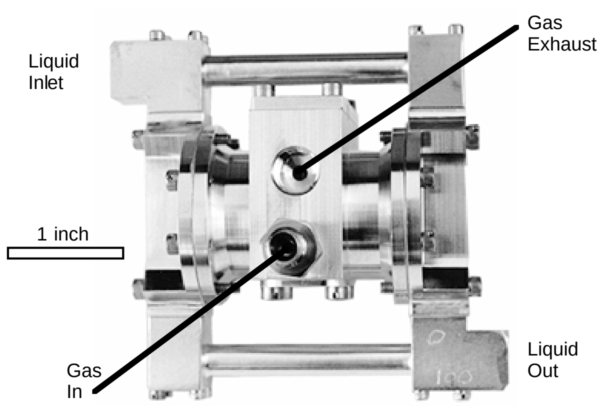
Boost Pump

The pump shown in Figure 4 was designed at LLNL during 1998 specifically for HTP. It worked the first time it was tested, and ultimately proved to be reliable. The design followed a series of prototypes gradually refined during 1994-1997. In the selected configuration, the central gas valving is flanked by a pair of power chambers. The liquid pumping assemblies at the ends have built-in check valves. Double-acting operation permits continuous flow for a steady system pressure. Aluminum construction keeps weight and cost down while aiding liquid cooling of the soft warm gas seals (due to the high thermal conductivity). A related key feature is that gas flow ceases when liquid demand stops at pressure.

Figure 4B is a powerhead subassembly, along with a set of spare parts (fasteners and seals omitted). Each power chamber has a 3-way intake-exhaust valve, pneumatically switched by the main pistons. The springless powerhead avoids force limits which would narrow the operating pressure range. The upper limit is structural, and the lower limit depends on valve friction. Many system restarts can be reliably had, from tank pressures of just tens of psi. In contrast, prior designs for self-pressurizing propulsion had pump springs and/or single-use solid propellant starter cartridges[5-9].

In the rightmost photograph, the inch-diameter power pistons are at the lower left. The four smallest items shown are the moving valve parts. Each intake-exhaust poppet is normally opened by supply pressure. However, pilot pressure pushes on the valve stem to close the intake and vent the power chamber. This arrangement permits the pilot signal to simply be the opposite cylinder's state of pressurization. Interrupting the pilot signal near the end of each power stroke ensures automatic oscillation at a frequency proportional to liquid flow.

Regarding the liquid pumping heads, a primary requirement was to ensure they would operate at very low flow over the entire pressure range, even with gas bubbles present. Therefore, unswept volume was minimized. Also, the check valves were given springs and soft seals to virtually eliminate reverse flow losses.



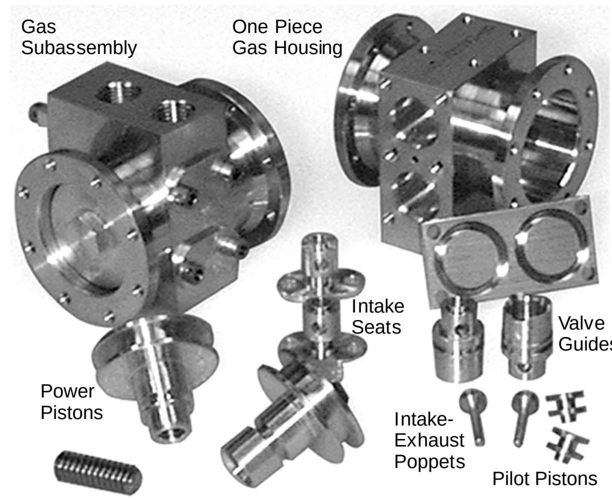


Figure 4. A. The 220 gram aluminum HTP pump. B. The gas housing and valves consist of 13 parts.

Note in Figure 4A that sizeable discharge and suction manifolds are needed. The extra mass is not detrimental for a self-pressurizing application. However, this configuration may not be preferred for a high flow-to-weight ratio. For example, propellant is pumped directly to thrust chambers in a pump fed rocket engine (Figure 2B,C,D). A central liquid manifold surrounded by power chambers joined by gas plumbing is appropriate for this latter application.[10]

Breadboard System Test

Given a working pump tested with air, the next step was self-pressurizing operation of a hydrogen peroxide tank. In Figure 5, the system components were mounted on a 2 liter aluminum tank. A commercial adjustable pressure regulator (Tescom Ni coated Al) was used for expedience, along with a gas generator manufactured by General Kinetics, LLC.

Assembling and testing this system was a one-week benchtop effort for 1-2 people. This may not have been possible with highly toxic or volatile propellant. Aside from room temperature proof-pressure tests, it was not necessary to subject individual components to predicted operating conditions, or to perform rigorous system leak checks. A polycarbonate enclosure was sufficient to protect personnel from potential test failures. Ventilation combined with the low volatility of HTP would prevent a breathing hazard in the event of a fluid release.

A gas solenoid valve at the tank pressurant port was used to introduce compressed air at a fraction of operating pressure. Also included in Figure 5 but not shown in Figure 1C is a check valve for the warm tank pressurant. This prevented the initial air charge from immediately actuating the dry pump.

In September 1998, the breadboard system pressurized itself on the first try and subsequently without failure. Six successful system starts were achieved from 50 psig down to 15 (lowest tried). This simply required actuating the pump feed valve. Low pressure HTP then flowed through the pump, regulator, and gas generator. As soon as the resulting warm gas reached the pump, the latter's liquid discharge was boosted to a slightly higher pressure. This positive feedback loop amplified pressure while sending steam and oxygen to the tank.

The initial pressurization rate was limited by fluid passageway sizing, notably a small tank pressurant port. The pump cycling rate averaged approximately 1 Hz during system startup. An initially lower frequency rose along with pressure, then it gradually slowed to a stop while leveling off at the regulated pressure.

The hysteresis band was approximately 10 psi wide. After the regulator shut, warm gas pressure reached 310 psi as the propellant remaining in the catalyst bed reacted. Over roughly 10 seconds, it then fell back to 300 psi as the system cooled and remaining steam condensed without further liquid HTP flow. In one test series, an additional gauge on the tank ullage indicated a 5 psi reduction there. This most likely corresponded to the cracking pressure of the warm gas check valve.

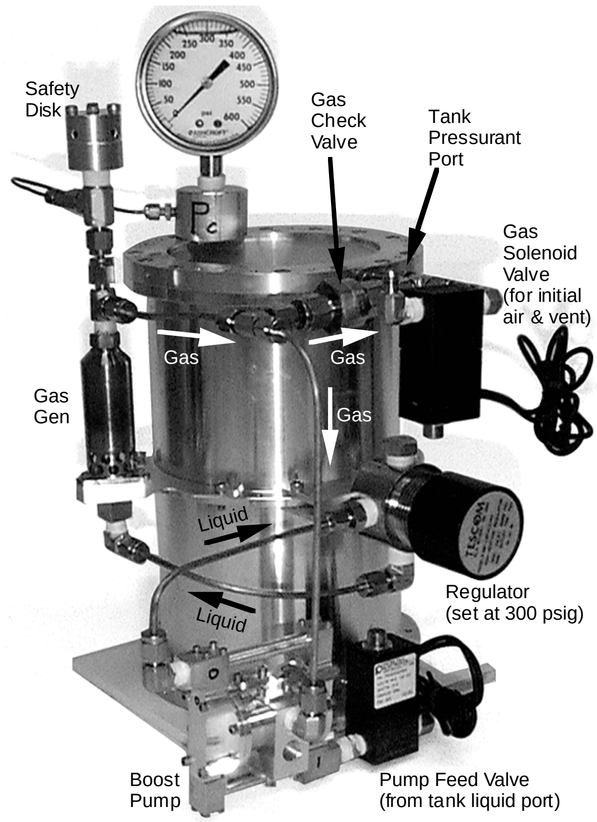


Figure 5. The breadboard self-pressurizing HTP system.

Thermal

Weakening of aluminum tank walls above 400 F is an obvious concern. At a comfortable 300 F, Al-6061-T6 retains 85-90% of its room temperature strength, depending on duration. Fluoroelastomer seals also have a practical limit in the 400-600 F range. Candidate polymers for tank liners are being evaluated as well. Liquid HTP released above its atmospheric boiling point (282 F for 85% concentration) will partly become vapor. Sufficiently concentrated HTP vapor detonates if ignited. For all these reasons, modest temperatures are beneficial.

In the breadboard tests, the tank's upper end (near the pressurant port) typically reached 250 F upon full pressurization. Additional heat transfer from the steam raised this as high as 290 F. These measurements indicate acceptable avoidance of all the above limits.

Note that this test series was thermally stringent. In particular, a 10% propellant load had little thermal mass to receive heat, compared to a full tank. Simultaneously the 90% ullage volume resulted in a high energy input. It filled in 10 to 30 s (depending on start pressure), with little time for heat dissipation. Thermal stratification in the vertically-oriented ullage would have reduced heat transfer to the liquid, thereby maximizing metal temperatures.

The pump gas housing typically operated near 175 F. System shutdown by closing the pump feed valve resulted in a few seconds of rapid dry pump cycling, a worse thermal condition. During one of these events, the same thermocouple indicated a peak of 245 F.

Based on the number of pump cycles and a ~5 cc volume displacement, roughly 100 grams of HTP flowed into the 2-liter tank ullage to obtain 300 psi. Considering both peak temperatures and the calculated volume of the product oxygen, the observations are consistent with nearly complete condensation of steam in the tank pressurant. The volume of condensate water drained from the tank afterward confirmed this.

In general, tank temperatures resulting from warm gas pressurization in vacuum can be predicted by energy balance calculations. The Appendix outlines such calculations for HTP systems.

Integrated Maneuvering System

A prototype maneuvering system sized for tiny satellites was initially tested in 1997. Figure 6 shows the custom-designed liquid hardware. A pair of piston tanks with connecting structure permits a fixed point c.g. location while also serving as the structural backbone for mounting other subsystems. The translational thrust is in the range 3 to 5 lb and total HTP capacity is 5 kg.

In Figure 6, there is no pressurization system. Initial tests in 1997 used facility pressurization into the long horizontal tube. Tank outlet valves and thruster valves are all located inside the center structure. HTP fill and drain valves are above the tanks at the inboard ends. The total mass of the assembly pictured is under 5 kg.

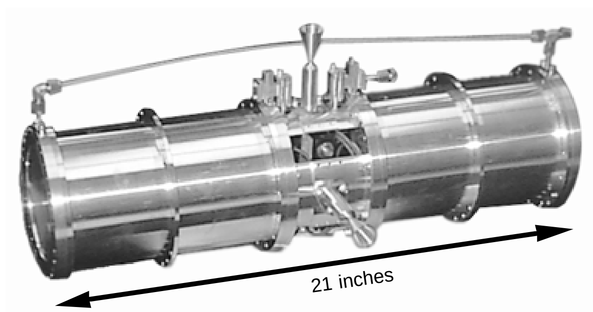
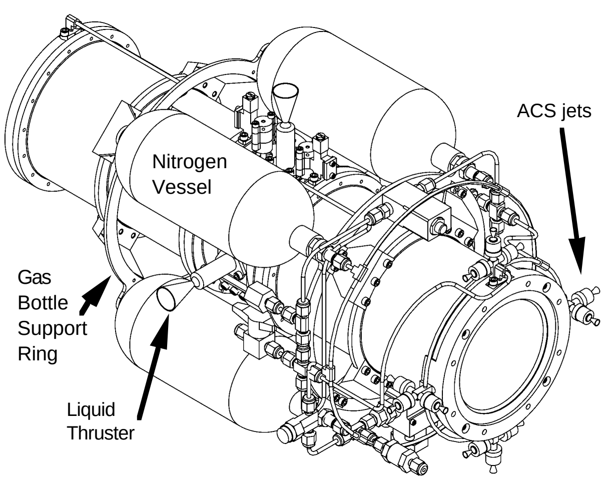


Figure 6. Multi-axis HTP maneuvering system.

As indicated in Figure 7A, an onboard nitrogen pressurization system was installed for tests in 1998.[2] The four carbon fiber composite overwrapped pressure vessels (COPV's) alone massed 2.4 kg, or half that of the liquid subsystem. Their mounting brackets, the high pressure fill valve, and the gas regulator also added weight. All these items were subsequently removed for the self-pressurizing upgrade.



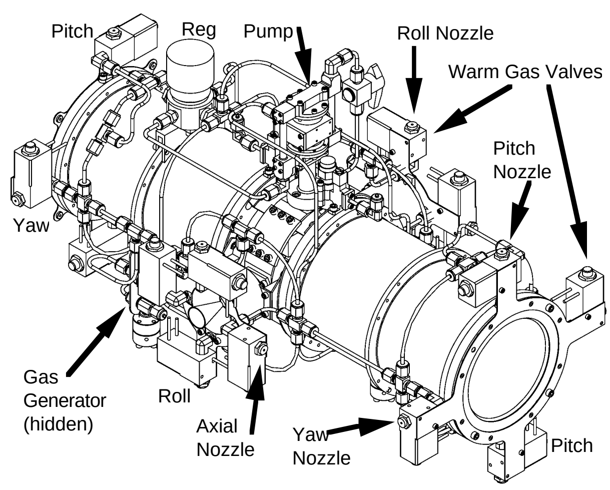


Figure 7. A. Nitrogen bottles are heavy and bulky. B. Complete self-pressurizing maneuvering system.

Self-Pressurizing Upgrade

Most of the components in Figure 5 were transferred onto the liquid maneuvering core within days after the breadboard tests. The pressurization hardware and mounting brackets weighed as little as two of the four avoided nitrogen tanks. This could be halved again by eliminating heavy fittings and building a lightweight regulator.

Figure 7B is a line drawing of the assembled system, which may be directly compared to Figure 7A. Tests were planned for horizontal thrusting only, so the boost pump was connected in place of the upper thruster. The latter's valve remained and was actuated to initiate self-pressurization. The pump orientation causes any rising bubbles in the liquid manifolds to move upstream instead of naturally escaping. Thus, potential problems with gas pockets in microgravity would become evident during ground testing.

Other parts were located for mass balancing, and to confine the hottest tubing runs in a small area around the aft tank. A normally open vent valve was included on the warm gas circuit so the system would safely shut down upon loss of electrical power during ground testing. The initial starting pressurant was also introduced there. Figure 7B represents a 9.85 kg dry propulsion system. This included over 2 kg of heavyweight attitude jets and 1.6 kg of stainless steel fittings, so at least 3 kg could be trimmed.

In order to meet a programmatic milestone, the assembled system was successfully tested on September 30 1998, before the end of the fiscal year. The only glitch was a corroded check valve in the pump, which had resulted from inadvertent wet (water) storage for 9 days. After 3 successful tests, the propulsion system was declared ready for integration into a microsatellite technology testbed.

Microsat Maneuvering Tests

A key goal of LLNL's MicroSat Technologies Program has been to develop user-friendly test capability for translational and rotational maneuvering using actual "hot-fire" propulsion operation. Therefore, the HTP propelled system has been tested with 4 d.o.f. on an outdoor linear air track which is 40 m long. In Figure 8, the linear track and its air bearing carriage are visible. For rotational freedom, the vertical post supports a hemispherical air bearing surface centered within the microsatellite test article. Pitch and roll angles are necessarily restricted, but yaw rotation is unlimited. Several RF links were used, to avoid umbilical forces and limits.

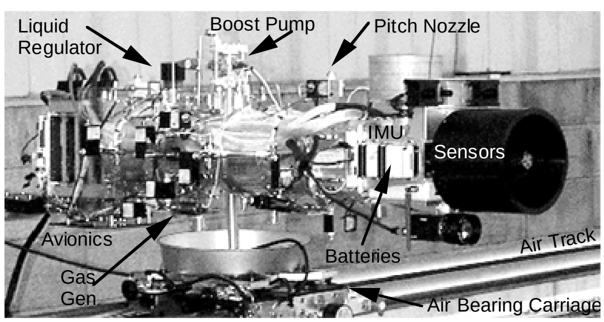


Figure 8. Microsat prototype set up for 4-d.o.f. operation.

Test Highlights

To the best of the authors' knowledge, this was the first miniature vehicle, capable of multi-directional liquid propulsive maneuvering under onboard control, without any high pressure gas stored on board. A relatively fast-paced capability was demonstrated, owing in part to the use of minimally-toxic propellant. During all tests, people were permitted to observe at a 20 ft distance with safety glasses. Before the end of October 1998, translation over the length of the track was accomplished with the liquid catalytic thrusters, simultaneously with 3-axis attitude control using warm gas jets.

One aspect of a fast-paced schedule was that corrosion protection was not at first implemented for the wetted parts. Instead, procedures for air drying were invoked for system storage in excess of a few days. Subsequent disassembly in December nevertheless confirmed surface corrosion, particularly at the steam ends of the tanks. White aluminum hydroxide apparently forms as a result of the hydroxide ions in water. Previously, the metal was left unprotected because the reaction does not readily occur with HTP (HOOH would have to generate an unlikely OH^+ in order to make $OH^–$).

All aluminum parts were anodized, including the tanks and pump. A clear coating was chosen, because HTP bleaches dye from anodized aluminum. Propulsion reassembly in January was completed in one day by two people. The drying step was subsequently omitted. Maneuvering tests were performed in January and February. After 4 more months of wet storage and no refurbishment, the propulsion system operated in late June 1999 without incident. This includes successful pump operation after 6 months of wet storage (residual fluids, not full tanks). In all, the propulsion system pressurized itself approximately 35 times, from under 100 psi to 300 psi. The one notable startup failure was directly attributable to corrosion of a bare aluminum check valve early in the course of the project.

Temperatures Measured

The avionics visible in Figure 8 included eight thermocouple channels dedicated to propulsion. Reaction temperatures in the gas generator are near 1100 F. As gas is conveyed to points of use, heat is lost through the 1/8 inch tubing walls. The pump is on one branch, 0.5 m from the gas generator. A gas immersion thermocouple is at 0.8 m, on the line to all the attitude jets. An instrumented yaw valve is 0.3 m beyond this. The immersion thermocouple typically reached 600 F when the system was operated for a minute or so. Tank and pump temperatures remained below 200 F during such tests.

Steady-state temperatures were reached during a 7-minute test of fast attitude control maneuvers. This occurred outdoors on a hot dry summer day. Due to the high demand for steam and oxygen, the gas temperature exceeded 800 F for nearly 5 minutes. The yaw valve hovered near 325 F as the valve pulsed at a 12% duty cycle. At 0.5 Hz cycling, the pump gas valve housing gradually rose to 200 F. Simultaneously, the tank pressurant ends reached 275-295 F, just as in the breadboard self-pressurization test. The liquid ends of the tanks warmed up very slowly throughout the run, and never exceeded 200 F.

Discussion

HTP offers the potential for relatively low cost rapid development and testing of unique propulsion systems. In particular, various schemes for pressurizing tanks and driving pumps with decomposed monopropellant have been affordably and safely tested. This is owed to HTP's low toxicity, low vapor pressure, high specific heat, and completely benign decomposition products. In terms of performance and storage lifetime however, HTP does not compete with hydrazine. Thus it is noteworthy that the concepts and results presented herein, once advanced with HTP, can also be implemented with hydrazine. An advantage of decomposed hydrazine is its better performance for pump drive and pressurization, because its constituents have lower molecular weights and do not condense as easily as the water in decomposed HTP.

For higher propulsive performance with HTP, a nontoxic fuel can be included. Either liquid bipropellant or hybrid rocket engines are options. The systems described in this paper are entirely appropriate for these applications.

Acknowledgments

LLNL's MicroSat Program team made it possible to showcase and test the propulsion advances described herein in the context of autonomously-operating prototype satellites. Key individuals include Arno Ledebuhr (Program Leader), Joe Kordas (Deputy Program Leader and Outdoor Test Director), Don Antelman, Eric Breitfeller, Mike Dittman, Ed English, Richard Gaughan, Mark Jones, Larry Ng, Darron Nielsen, Jeff Robinson, Bill Taylor, Dean Urone, and Bruce Wilson.

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Appendix: Tank Temperature Predictions

Pure hydrogen peroxide releases 2889 J/g upon decomposing, or 2456 J/g for 85% HTP. The latter produces 60% water by mass and 40% oxygen. Water requires 2252 J/g to vaporize at 212 F (100 C), falling slightly to 1915 J/g at 400 F (205 C). Notably, about half the reaction energy of 85% HTP is associated with the water phase change.

When decomposed HTP is used for tank pressurization, a quantity of gas proportional to tank volume introduces a proportionate amount of heat into the tank over the course of expulsion. A worst-case tank temperature would result if all the excess energy is absorbed by the tank wall with no losses. This energy balance can be determined from the specific heat and mass of the tank wall.

For example, if decomposed 85% HTP at 300 psi cools to 300 F, approximately 90% of its steam has condensed. The bulk density is near 40 g/l for this two-phase mixture. Multiplying by 2000 J/g indicates that about 80 kJ must be absorbed by the tank walls for each liter of volume.

At 0.9 J/g-C, aluminum accepts 115 J/g upon heating by 128 C, i.e. from 21 C (70 F) to 149 C (300 F). Thus in the worst case of no heat losses, about 700 grams of tank wall is needed per liter of volume. Note that a tank half as heavy at 350 g/l would equilibrate around 400 F, largely because reduced steam condensation yields a reduction in pressurant mass.

The above calculations indicate ideal limits, not tank design criteria. In particular, the liquid propellant in the tank also absorbs heat. The specific heat of 85% HTP is 2.85 J/g-C, or 365 J/g over the 128 C rise considered above. Thus only 220 g of HTP per liter of ullage is enough to accept all the excess pressurant heat at 300 psi and 300 F. In reality, external losses are also significant for operational lifetimes (total time for tank expulsion) exceeding just a few minutes.

High ullage temperatures without steam condensation would theoretically improve system performance. However, the pressurant is a small fraction of system propellant for the HTP systems tested. Therefore, it is a practical compromise to let steam condense in the tank while avoiding excessive temperatures there.