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HAN-Based Monopropellant Propulsion System With Applications

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ABSTRACT

NASA is developing a new monopropellant propulsion system for small, cost-driven spacecraft with ΔV requirements in the range of 10-150 m/sec. This system is based on a hydroxylammonium nitrate (HAN)/water/fuel monopropellant blend which is extremely dense, environmentally benign, and promises good performance and simplicity. State-of-art (SOA) small spacecraft typically employ either hydrazine or high pressure stored gas. Herein, a "typical" small satellite bus is used to illustrate how a HAN-based monopropellant propulsion system fulfills small satellite propulsion requirements by providing mass and/or volume savings of SOA hydrazine monopropellants with the cost benefits of a stored nitrogen gas.

INTRODUCTION

In recent years, government and commercial mission designers have searched for more cost effective ways to accomplish their missions. Drivers such as design and development time, launch costs, and risk mitigation have led program-managers to move towards small spacecraft which can typically be built quickly and launched on small vehicles or as secondary payloads. Both development costs and associated program risks are therefore reduced. However, small spacecraft often are volume and power limited and thus, propulsion options are limited.

The state-of-art (SOA) propulsion systems for small spacecraft are stored nitrogen gas and hydrazine monopropellant systems. Stored nitrogen gas systems offer the simplest, lowest cost option. They require essentially no power, and use an inert propellant, typically nitrogen, which requires no special ground handling procedures. Specific impulse (I_{sp}), however, is only 60 seconds and the storage density is quite low (~0.23 g/cc). Liquid monopropellant systems offer significantly higher I_{sp} (~223 sec) and storage density (1.0 g/cc) with only modest power requirements (for catalyst bed heaters). However, the SOA monopropellant (hydrazine) is toxic, carcinogenic, and flammable and so requires extensive infrastructure and ground handling procedures. [1,2] The cost associated with the use of hydrazine often eliminates it as a viable propulsion candidate for small spacecraft.

An improved propulsion system for these small satellites would have the high performance and high density of the SOA hydrazine monopropellant system, but with the safety and handling benefits, and hence cost, of a stored nitrogen gas system. The hydroxylammonium nitrate (HAN)-based monopropellant system under development is targeted to provide precisely this.

HAN-based monopropellants have been pursued by the Army as Liquid Gun Propellants (LGP) for many years. Through the Army liquid gun program, HAN-based propellants have shown promise in the areas of environmental health and safety, energy, and storage density. Two HAN-based formulations developed by the Army are LP1846 and LP1898. These formulations both contain nominally 60% HAN and 20% water and differ only in the carbon containing component. LP1846 uses triethanolammonium nitrate (TEAN) and LP1898 uses diethylhydroxlammonium nitrate (DEHAN). These formulations are salts dissolved in water. HAN is oxygen rich, and is commonly referred to as the oxidizer, the other salt is fuel rich and is referred to as the fuel. Variations on these formulations are being developed for rocket monopropellant applications. They are being derived from the aforementioned Army formulations as aqueous mixtures of HAN and a fuel.

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Issues specific to rocket monopropellants, such as reliable, repeatable low pressure ignition and combustion with clean exhaust, are being considered. [3]

FIGURE OF MERIT

The quantitative figures of merit to be presented in this paper are wet propulsion system mass and volume. Simply, smaller is better. Some qualitative merits of the HAN-based monopropellant propulsion system will also be discussed in terms of relative operating cost. By exploring these figures of merit for several sample spacecraft, the potential advantages of HAN-based monopropellants are illustrated.

ANALYSIS

Sample Spacecraft

The Orbital Sciences Corporation (OSC) MicroStar (Figure 1) bus is chosen as a representative example of a small satellite for comparison of the monopropellant and stored gas propulsion systems. MicroStar is a representative 50-100 kg class satellite with a dry bus mass of ~40 kg and a typical payload of ~50 kg. The baseline spacecraft structure is a 0.981 m diameter x 0.114 m deep ring providing a disc shaped area which contains the bus subsystems (e.g. the batteries, electronics, and propulsion) as well as the payload.[4,5,6] While this space may be increased by adding more structural rings, the baseline configuration is first assumed in this study because it is anticipated to be realistic for constellation and secondary payload applications. A second case with no volume limitations is also considered.
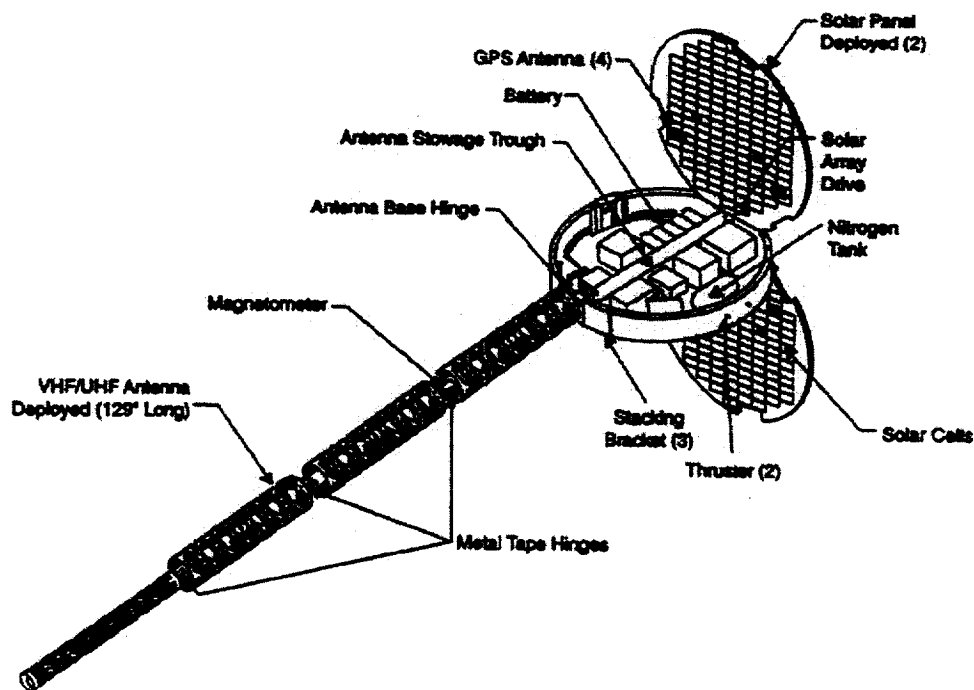

Figure 1. Orbital Science's Corporations MicroStar Bus

Several variations of the MicroStar bus are chosen for this study to evaluate systems for a range of missions. Four of the five sample spacecraft are variations on the generic MicroStar bus. They have an initial mass of 90 kg. [4] The MicroStar and MicroStar Enhanced variations have defined ΔVs of 11 and 75 m/sec, respectively. In order to illustrate the benefits of new technology for aggressive small satellite missions two other ΔV examples are added: 100 and 150 m/sec. These examples are termed MicroStar (100) and MicroStar (150). The fifth spacecraft considered is the ORBCOMM satellite. It is a specific application of the MicroStar bus that was first launched in April of 1995 from a Pegasus. [6] The initial mass in this application is ~40 kg and the ΔV requirement is 11 m/sec. This spacecraft is chosen as an example because it is a "real" mission that used the MicroStar bus. Table I contains the five sample missions with the assumed initial mass and ΔV.

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Sample Spacecraft	Satellite Initial Mass (kg)	ΔV (m/sec)
ORBCOMM	40	11
MicroStar	90	11
MicroStar Enhanced	90	75
MicroStar (100)	90	100
MicroStar (150)	90	150

Table I. Sample Missions used for analysis

Propulsion System Assumptions

For the analysis, three propulsion system configurations are used to fulfill the mission ΔV requirements; a SOA nitrogen stored gas system, a SOA hydrazine monopropellant system, and a (projected) HAN-based monopropellant system. Figure 2 shows a schematic of the propulsion systems and Table II provides a breakdown of the assumed component masses.
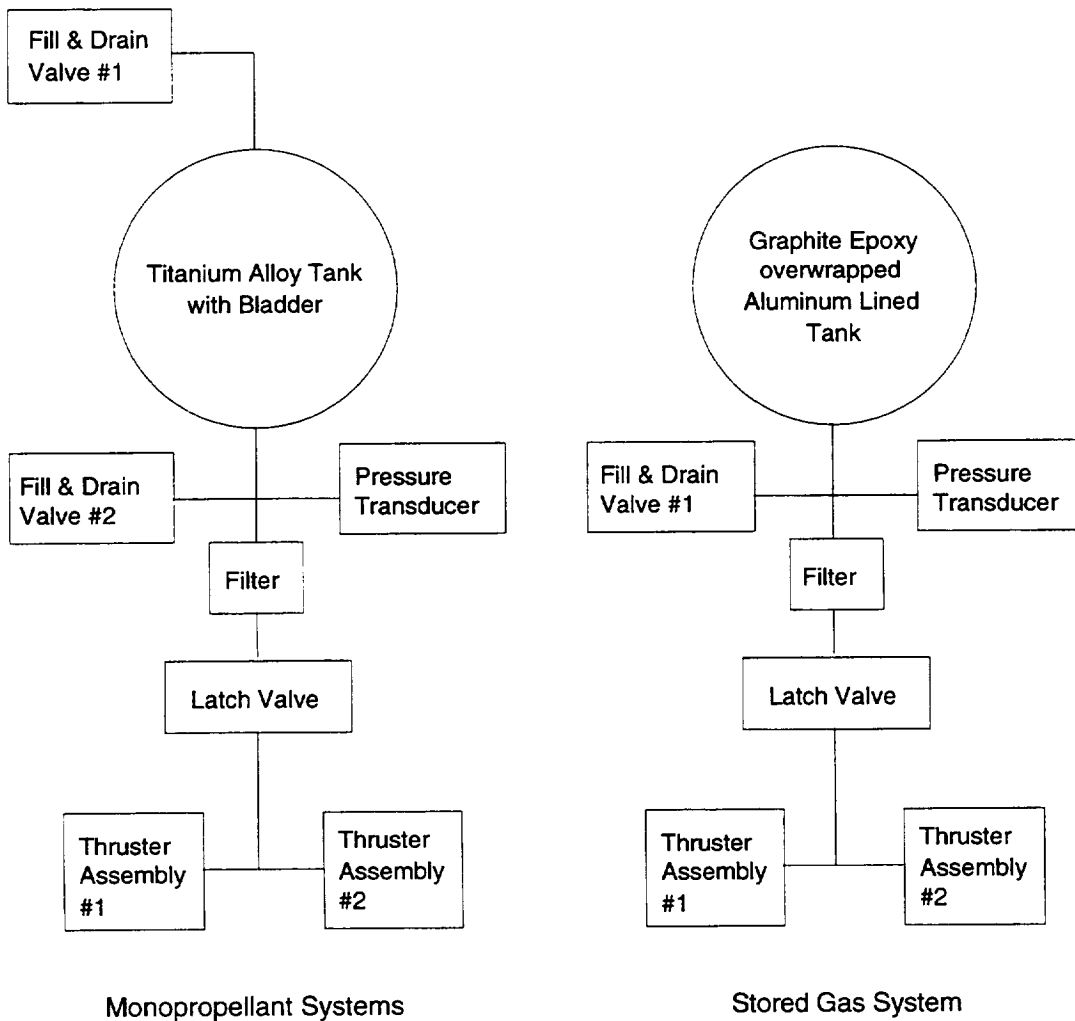

Monopropellant Systems   Stored Gas System

Figure 2. Schematic of Propulsion Systems

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System Component	Propulsion System Mass (kg)		
	Stored Gas	Hydrazine	HAN-based
Fill & Drain Valve #1	0.145	0.145	0.145
Fill & Drain Valve #2	0.000	0.145	0.145
Pressure Transducer	0.230	0.230	0.230
Filter	0.227	0.227	0.227
Latch Valve	0.250	0.250	0.250
Valve/Thruster Assembly #1	0.270	0.340	0.340
Valve/Thruster Assembly #2	0.270	0.340	0.340
Total	1.392	1.677	1.677

Table II. Propulsion System Component Mass

The stored gas system assumes a gaseous nitrogen propellant with a specific impulse of 60 seconds and a storage density of 0.225 g/cc at 3000 psi. Cylindrical graphite overwrapped, aluminum lined, composite tanks are assumed as are off-the-shelf fill and drain valve, pressure transducer, filter, latch valve, and two 3.3N thrusters operating in a blowdown mode.

For the hydrazine monopropellant system, a specific impulse of 223 seconds and a storage density of 1.00 g/cc are assumed. SOA spherical titanium alloy tanks with bladders, pressurant fill and drain valves, propellant fill and drain valve, filter, latch valve, are assumed along with two 3.3N thrusters operating with a 5:1 blowdown ratio.

The HAN-based monopropellant, with a projected I_{sp} of 210 seconds and a storage density of 1.43 g/cc, assumes a system dry mass identical to that of the hydrazine system except for the reduction in tankage attributable to a higher propellant density.

For each test case, the spacecraft structural ring internal depth (0.114 m), is used as the maximum allowable tank diameter. As mission ΔV is increased, additional tanks are added to the system when this tank diameter limitation is exceeded. The stored nitrogen gas system's cylindrical tanks are further limited to 0.400 m in length so that they would easily fit in the structural ring of the spacecraft. These tankage assumptions help show the impact of fuel density and I_{sp} on the available spacecraft volume.

Mission Analysis

For simplicity, the missions are represented by a velocity change increment (denoted as ΔV). Thus, ΔV includes such mission functions as orbit insertion, drag makeup, constellation maintenance, and disposal as required by the mission design. Mission ΔV is related to the spacecraft propulsion system by:

$$\Delta V = (Isp) * (g) * \ln (\text{initial spacecraft mass} / \text{final spacecraft mass}) \qquad (1)$$

Equation (1) is used to calculate final spacecraft mass from the assumed ΔV and initial spacecraft mass (Table I) and I_{sp} (Propulsion System Assumption section). The difference between initial and final spacecraft masses provides fuel mass. Required tank volume is calculated from fuel mass and propellant density by eq. (2) for the stored gas and eq. (3) for the monopropellant systems:

$$\text{tank volume} = (\text{fuel mass}) * (\text{fuel density}) \qquad (2)$$

$$\text{tank volume} = (\text{fuel mass}) * (\text{fuel density}) * (1\text{-blowdown ratio}^{-1})^{-1} \qquad (3)$$

Tank masses are calculated from tank volume. Tank mass along with the assumed component masses (Table II) are summed to obtain the propulsion system dry mass. The figures of merit (wet propulsion system mass and volume) for each of the three propulsion systems for each of the five sample spacecraft are then compared.

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Quantitative Results: Mass and Volume

The figures of merit (wet propulsion system mass and volume) of each of the three propulsion systems for each of the five sample spacecraft are calculated as described above. The wet propulsion system masses and volumes for the 11 m/sec ORBCOMM and baseline MicroStar cases along with the 75 m/sec enhanced MicroStar case are shown in Table III; results for all the cases are shown graphically in the Figures 3 and 4. (Note: Spacecraft ΔV increases from left to right, first is the ORBCOMM, second the MicroStar and continuing to the MicroStar (150) at the far right.)

| Propulsion System | Mission | | | | | | | | |
| | ORBCOMM | | | MicroStar Baseline | | | MicroStar Enhanced | | |
	Stored Gas	hydra-zine	HAN-based	Stored Gas	hydra-zine	HAN-based	Stored Gas	hydra-zine	HAN-based
Fuel Density (g/cc)	0.225	1.000	1.430	0.225	1.000	1.430	0.225	1.000	1.430
Thruster ΔV (m/sec)	11	11	11	11	11	11	75	75	75
Thruster Isp (sec)	60	223	210	60	223	210	60	223	210
Initial Mass (kg)	40.3	40.3	40.3	90.0	90.0	90.0	90.0	90.0	90.0
Fuel Mass (kg)	0.746	0.202	0.215	1.67	0.451	0.479	10.8	3.03	3.22
Tankage Volume (m^3)	3.32E-3	2.53E-4	1.88E-4	7.41E-3	5.64E-4	4.19E-4	4.79E-2	3.79E-3	2.81E-3
Tank Diameter (m)	0.114	0.780	0.710	0.114	0.103	0.930	0.114	0.113	0.110
Tankage Mass (kg)	1.64	1.22	1.21	3.37	1.24	1.23	20.6	6.27	5.00
# of Tanks	1	1	1	2	1	1	12	5	4
Prop. Component Dry Mass (kg)	1.39	1.68	1.68	1.39	1.68	1.68	1.39	2.26	2.11
Propulsion System Wet Mass (kg)	3.78	3.10	3.11	6.43	3.37	3.39	32.8	11.6	10.3
Net Mass (initial - wet propulsion) (kg)	36.5	37.2	37.2	83.6	86.6	86.6	57.2	78.4	79.7
Total Impulse (N-sec)	439	442	442	981	988	987	6338	6636	6629

Table III. MicroStar Baseline and Enhanced Cases with Tank Dimension Constrained

In the low initial mass, small ΔV example (ORBCOMM, 40 kg, 11 m/sec case), the monopropellant systems have similar mass performance and only a small volume advantage over the stored nitrogen gas system. However, as the initial spacecraft mass is increased to 90 kg in the baseline MicroStar case, the savings in mass and volume of the hydrazine and HAN-based liquid monopropellant systems increases even with the small 11 m/sec ΔV requirement. In general, it can be seen in the figures that as more aggressive mission (high ΔVs) are considered, the better performance of the hydrazine and HAN-based monopropellant systems require less wet mass and fuel volume than the stored nitrogen gas system. The need for a liquid monopropellant for small spacecraft is further illustrated in Figure 4 by how the stored gas system's fuel volume begins to take up the entire spacecraft bus for the high ΔV (total impulse) missions.
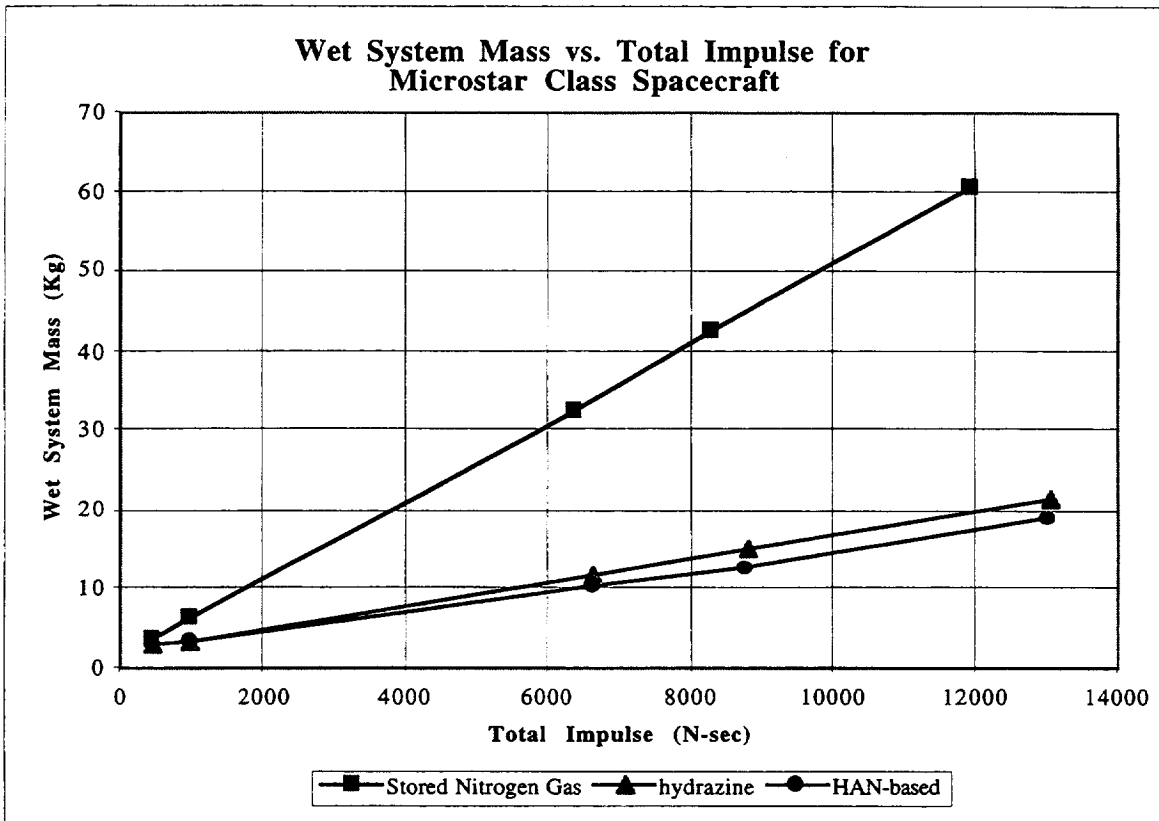
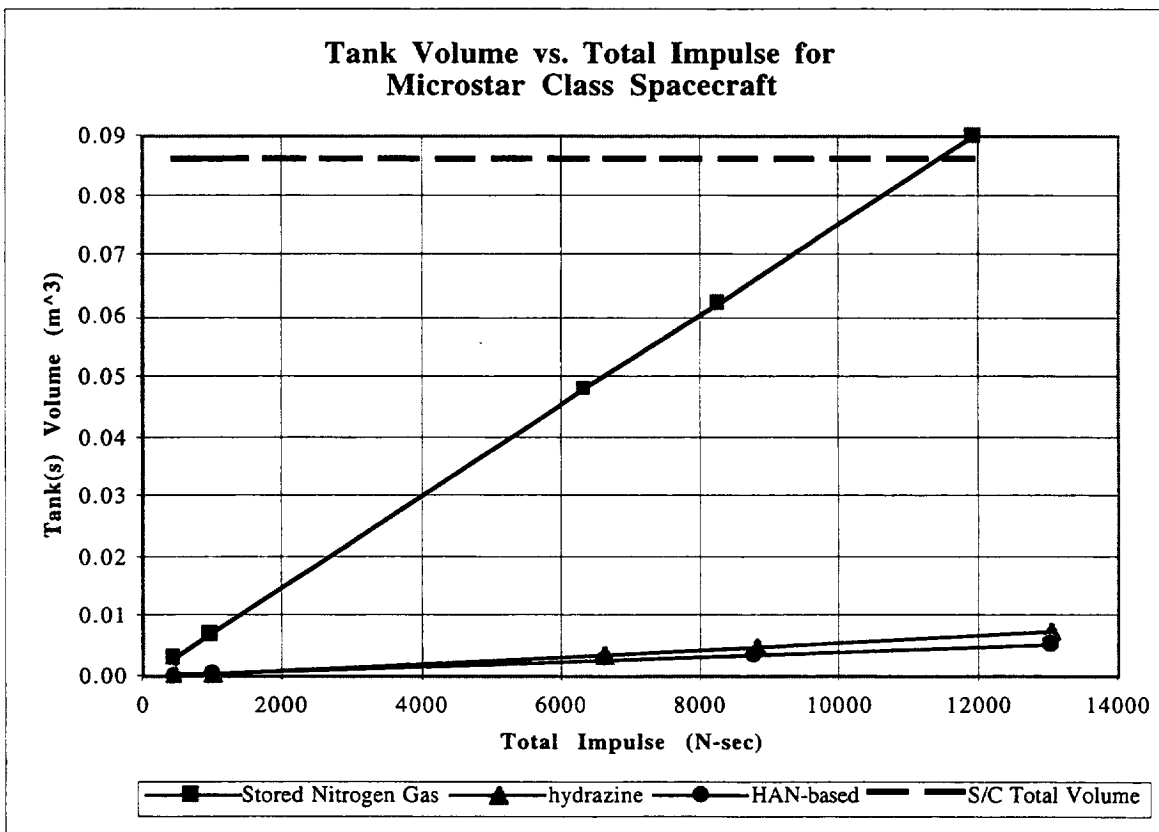Figure 3. Propulsion System Wet Mass with Tank Dimension Constrained

Figure 4. Tank Volume vs. Total Impulse for MicroStar Class Spacecraft

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The HAN-based system outperforms the hydrazine system in both mass and volume in all cases. The 40% higher density HAN-based monopropellant, even with the slightly lower I_{sp}, leads to fewer tanks, as shown in Figure 5, this also reduces fittings, structure, and complexity (cost).
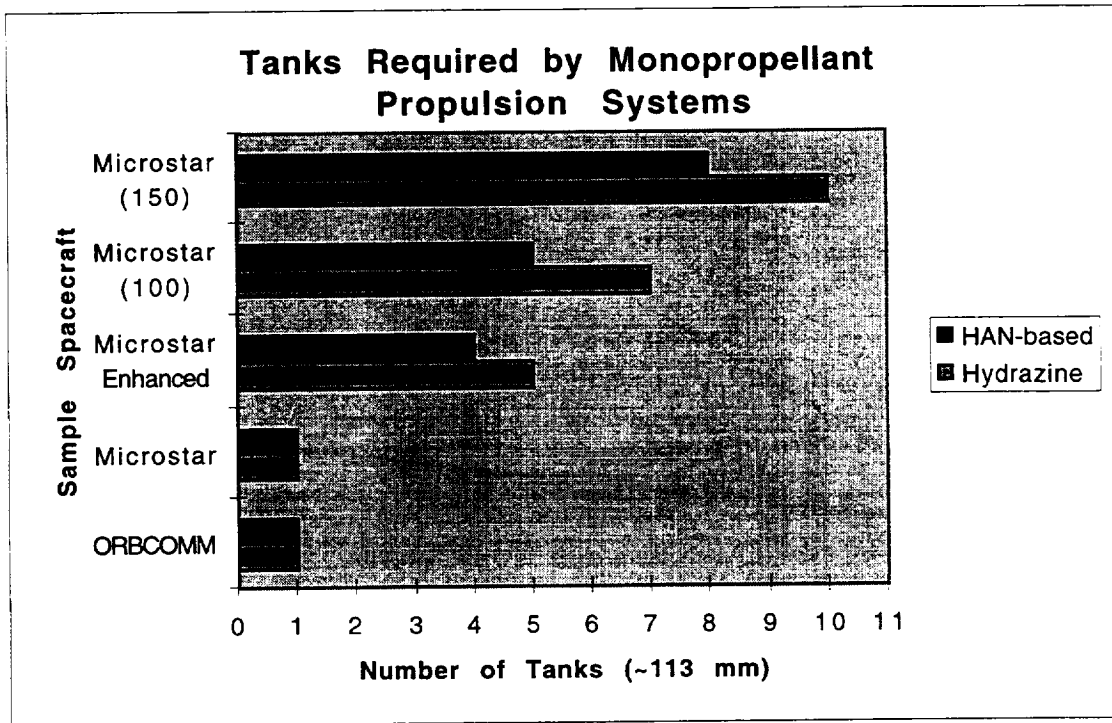

Figure 5. Number of Tanks Required by Monopropellant Propulsion Systems

Adding extra structural rings would remove the tank dimension limits imposed by the single ring configuration (see Sample Spacecraft Section). Thus when one tank of any size is assumed, the hydrazine system slightly outperforms the HAN-based system in terms of mass as shown in Table IV and Figure 6. This one tank assumption may require an unreasonable number of spacecraft structural rings: severely impacting launch vehicle payload volume.

	Mission								
	ORBCOMM			MicroStar Baseline			MicroStar Enhanced		
Propulsion System	Stored Gas	hydra-zine	HAN-based	Stored Gas	hydra-zine	HAN-based	Stored Gas	hydra-zine	HAN-based
Fuel Density (g/cc)	0.225	1.000	1.430	0.225	1.000	1.430	0.225	1.000	1.430
Thruster ΔV (m/sec)	11	11	11	11	11	11	75	75	75
Thruster Isp (sec)	60	223	210	60	223	210	60	223	210
Initial Mass (kg)	40.3	40.3	40.3	90.0	90.0	90.0	90.0	90.0	90.0
Fuel Mass (kg)	0.746	0.202	0.215	1.67	0.451	0.479	10.8	3.03	3.22
Tank Volume (m^3)	3.32E-3	2.53E-4	1.88E-4	7.41E-3	5.64E-4	4.19E-4	4.79E-2	3.79E-3	2.81E-3
Tank Diameter (m)	0.114	0.780	0.710	0.114	0.103	0.930	0.114	0.194	0.175
Tank Mass (kg)	1.64	1.22	1.21	2.14	1.24	1.23	7.12	1.47	1.40
# of Tanks	1	1	1	1	1	1	1	1	1
Prop. Component Dry Mass (kg)	1.39	1.68	1.68	1.39	1.68	1.68	1.39	1.68	1.68
Propulsion System Wet Mass (kg)	3.78	3.10	3.11	5.20	3.37	3.39	19.3	6.20	6.31
Net Mass (initial - wet propulsion) (kg)	36.5	37.2	37.2	84.8	86.6	86.6	70.7	83.8	83.7
Total Impulse (N-sec)	439	442	442	981	988	987	6338	6636	6629

Table IV. MicroStar Baseline and Enhanced Cases with Tank Dimension Unconstrained

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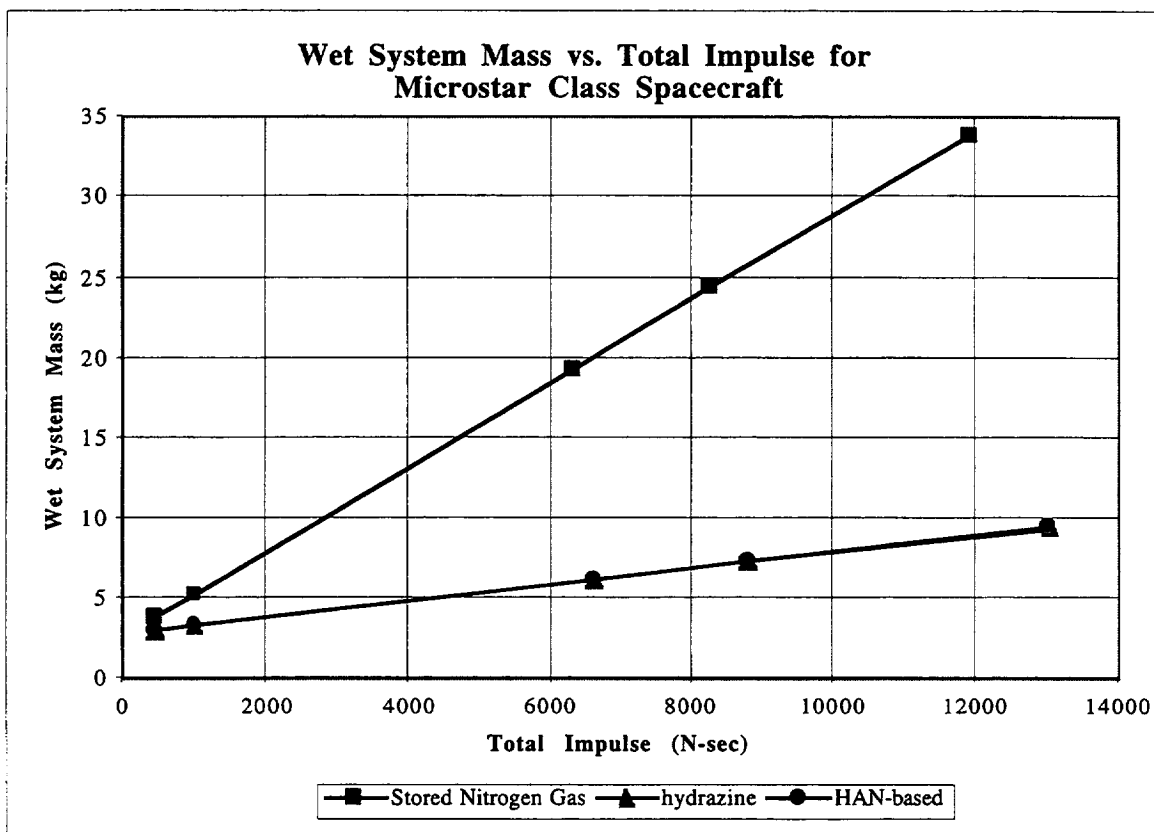## Wet System Mass vs. Total Impulse for Microstar Class Spacecraft

Figure 6. Wet System Propulsion Mass with No Constraints on Tank Size

Overall for the small satellite class of spacecraft, the monopropellant systems are superior to the stored nitrogen gas system in terms of mass and volume. Among monopropellants themselves, the hydrazine and HAN-based systems are roughly equivalent on a mass basis. It is in terms of operability and cost that the monopropellants can differentiate themselves.

<u>Qualitative Discussion: Operability and Cost</u>

Propulsion systems traditionally have been judged mainly on rocket performance. However, with the move towards small, more cost effective spacecraft, factors such as environmental safety and operability have increased in importance.

For the small satellite program manager the cost of ground operations associated with the propellant can be a large program cost.[7,8] It is for this reason that high performing propulsion system options, such as hydrazine monopropellants, have often been dismissed as too expensive due to the extensive ground operations procedures required to handle a flammable, toxic, carcinogenic propellant. Low I_{sp} options such as stored nitrogen gas systems are very attractive because of the low cost associated with the operability of an inert gas system.

Qualitatively, the ground operations costs of a HAN-based monopropellant system can be more closely equated to a stored gas system than a hydrazine monopropellant system. HAN-based monopropellants pose only a very limited hazard when compared to hydrazine because the HAN-based formulations are non-flammable and non-explosive at atmospheric pressure, are non-carcinogenic, and have a vapor head composed only of water. Personnel hazards are limited to skin absorption. Coveralls, gloves and faceshields are sufficient for protection.[3,9,10]

By using HAN-based monopropellants, ground operations required to handle the SOA monopropellant (hydrazine) can be modified in a number of ways. First, because there are no vapor hazards associated with HAN-based monopropellants the need for Self-Contained Atmospheric Protective Ensemble (SCAPE) and

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the associated training should be eliminated, along with simplification of health monitoring procedures for ground operations crews. This reduces the support required by environmental health and safety personnel. Second, because there is no vapor hazard and the propellant is non-flammable at atmospheric pressure, fueling procedures can be simplified by reducing and/or eliminating fire personnel during fueling. Other savings can be realized by the elimination of access restrictions during fueling and the simplification of the disposal of rinse water and propellant.

CONCLUDING REMARKS

In recent years both government and some commercial mission designers have made a commitment to reduce the cost of space missions. This is especially true in the small satellite area. Simple, high performance, cost effective propulsion systems for these small satellites will be required to meet mission performance and cost goals. The simplest, least expensive SOA propulsion option available is stored nitrogen gas, but these systems are heavy and have low I_{sp}, both of which limit mission performance. Hydrazine is higher in both density and I_{sp}, but its vapor is toxic, flammable, and carcinogenic which introduces extensive ground operations that are not cost effective. HAN-based monopropellant propulsion systems are being developed to provide an operationally efficient, cost effective, high performance propulsion option. A side-by-side performance estimate for the MicroStar spacecraft demonstrated the mass and volume advantages of HAN-based propulsion systems when compared to SOA stored nitrogen gas and hydrazine systems. The HAN-based system's advantages are most pronounced for the higher ΔV, volume limited MicroStar spacecraft. These higher ΔV missions represent extended small spacecraft lifetimes and/or enable secondary payloads to reach preferred orbits.

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